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**Orbit closures of unipotent flows for hyperbolic manifolds  
with Fuchsian ends**

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We establish an analogue of Ratner’s orbit closure theorem for any connected closed subgroup generated by unipotent elements in  $SO(d, 1)$  acting on the space  $\Gamma \backslash SO(d, 1)$ , assuming that the associated hyperbolic manifold  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  is a convex cocompact manifold with Fuchsian ends. For  $d = 3$ , this was proved earlier by McMullen, Mohammadi and Oh. In a higher-dimensional case, the possibility of accumulation on closed orbits of intermediate subgroups causes serious issues, but, in the end, all orbit closures of unipotent flows are relatively homogeneous. Our results imply the following: for any  $k \geq 1$ ,

- (1) the closure of any  $k$ –horosphere in  $\mathcal{M}$  is a properly immersed submanifold;
- (2) the closure of any geodesic  $(k+1)$ –plane in  $\mathcal{M}$  is a properly immersed submanifold;
- (3) an infinite sequence of maximal properly immersed geodesic  $(k+1)$ –planes intersecting core  $\mathcal{M}$  becomes dense in  $\mathcal{M}$ .

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## 1 Introduction

Let  $G$  be a connected simple linear Lie group and  $\Gamma < G$  be a discrete subgroup. An element  $g \in G$  is called *unipotent* if all of its eigenvalues are one, and a closed subgroup of  $G$  is called unipotent if all of its elements are unipotent. Let  $U$  be a connected unipotent subgroup of  $G$  or, more generally, any connected closed subgroup of  $G$  generated by unipotent elements in it. We are interested in the action of  $U$  on the homogeneous space  $\Gamma \backslash G$  by right translations.

If the volume of the homogeneous space  $\Gamma \backslash G$  is finite, i.e. if  $\Gamma$  is a lattice in  $G$ , then Moore's ergodicity theorem [1966] says that, for almost all  $x \in \Gamma \backslash G$ ,  $xU$  is dense in  $\Gamma \backslash G$ . While this theorem does not provide any information for a given point  $x$ , the celebrated Ratner's orbit closure theorem [1991b], which was a conjecture of Raghunathan, states that

(1-1) the closure of every  $U$ -orbit is homogeneous,

that is, for any  $x \in \Gamma \backslash G$ ,  $\overline{xU} = xL$  for some connected closed subgroup  $L < G$  containing  $U$ . Ratner's proof is based on her classification [1991a] of all  $U$ -invariant ergodic probability measures and the work of Dani and Margulis [1991] on the nondivergence of unipotent flow. Prior to her work, some important special cases of (1-1) were established in [Margulis 1989; Dani and Margulis 1989; 1990; Shah 1994; 1991a] by topological methods. This theorem is a fundamental result with numerous applications.

It is natural to ask if there exists a family of homogeneous spaces of infinite volume where an analogous orbit closure theorem holds. When the volume of  $\Gamma \backslash G$  is infinite, the geometry of the associated locally symmetric space turns out to play an important role in this question. The first orbit closure theorem in the infinite-volume case was established by McMullen, Mohammadi and Oh [McMullen et al. 2017; 2016] for a class of homogeneous spaces  $\Gamma \backslash \mathrm{SO}(3, 1)$  which arise as the frame bundles of convex cocompact hyperbolic 3-manifolds with Fuchsian ends.

Our goal in this paper is to show that a similar type of orbit closure theorem holds in the higher-dimensional analogues of these manifolds. We present a complete hyperbolic  $d$ -manifold  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  as the quotient of the hyperbolic space by the action of a discrete subgroup

$$\Gamma < G = \mathrm{SO}^\circ(d, 1) \simeq \mathrm{Isom}^+(\mathbb{H}^d),$$

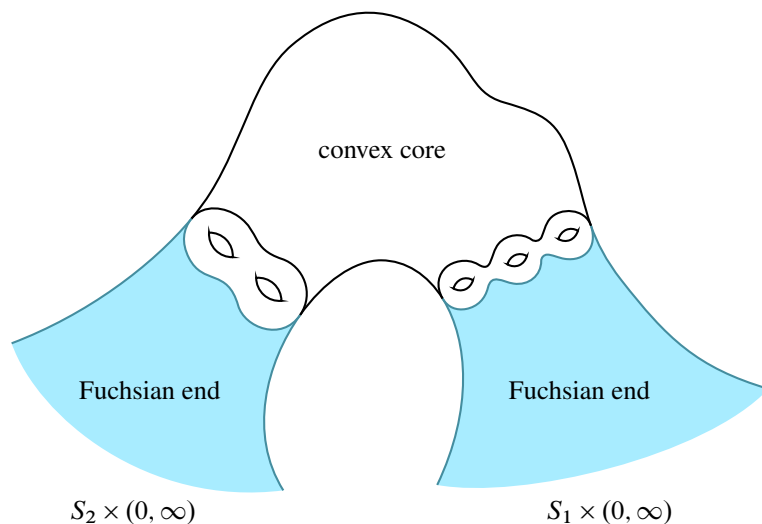


Figure 1: A convex cocompact hyperbolic manifold with nonempty Fuchsian ends.

where  $\mathrm{SO}^\circ(d, 1)$  denotes the identity component of  $\mathrm{SO}(d, 1)$ . The geometric boundary of  $\mathbb{H}^d$  can be identified with the sphere  $\mathbb{S}^{d-1}$ . The limit set  $\Lambda \subset \mathbb{S}^{d-1}$  of  $\Gamma$  is the set of all accumulation points of an orbit  $\Gamma x$  in the compactification  $\mathbb{H}^d \cup \mathbb{S}^{d-1}$  for  $x \in \mathbb{H}^d$ .

The convex core of  $\mathcal{M}$  is a submanifold of  $\mathcal{M}$  given by the quotient

$$\mathrm{core} \mathcal{M} = \Gamma \backslash \mathrm{hull}(\Lambda),$$

where  $\mathrm{hull}(\Lambda) \subset \mathbb{H}^d$  is the smallest convex subset containing all geodesics in  $\mathbb{H}^d$  connecting points in  $\Lambda$ . When  $\mathrm{core} \mathcal{M}$  is compact,  $\mathcal{M}$  is called *convex cocompact*.

### Convex cocompact manifolds with Fuchsian ends

Following the terminology introduced in [Kerckhoff and Storm 2012], we define:

**Definition 1.1** A convex cocompact hyperbolic  $d$ -manifold  $\mathcal{M}$  is said to have Fuchsian ends if  $\mathrm{core} \mathcal{M}$  has nonempty interior and has totally geodesic boundary.

The term *Fuchsian ends* reflects the fact that each component of the boundary of  $\mathrm{core} \mathcal{M}$  is a  $(d-1)$ -dimensional closed hyperbolic manifold, and each component of the complement  $\mathcal{M} - \mathrm{core} \mathcal{M}$  is diffeomorphic to the product  $S \times (0, \infty)$  for some closed hyperbolic  $(d-1)$ -manifold  $S$  (see Figure 1).

Convex cocompact hyperbolic  $d$ -manifolds with nonempty Fuchsian ends can also be characterized as convex cocompact hyperbolic manifolds whose limit sets satisfy

$$\mathbb{S}^{d-1} - \Lambda = \bigcup_{i=1}^{\infty} B_i,$$

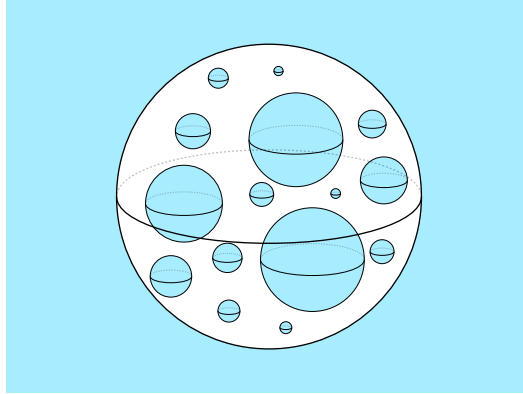


Figure 2: Limit set of a convex cocompact hyperbolic 4-manifold with nonempty Fuchsian ends.

where the  $B_i$  are round balls with mutually disjoint closures (see Figure 2). Hence, for  $d = 2$ , any nonelementary convex cocompact hyperbolic surface has Fuchsian ends. The double of the core of a convex cocompact hyperbolic  $d$ -manifold with nonempty Fuchsian ends is a closed hyperbolic  $d$ -manifold.

Any convex cocompact hyperbolic manifold with nonempty Fuchsian ends is constructed in the following way. Begin with a closed hyperbolic  $d$ -manifold  $\mathcal{N}_0$  with a fixed collection of finitely many, mutually disjoint, properly embedded totally geodesic hypersurfaces. Cut  $\mathcal{N}_0$  along those hypersurfaces to obtain a compact hyperbolic manifold  $W$  with totally geodesic boundary hypersurfaces. There is a canonical procedure for extending each boundary hypersurface to a Fuchsian end, which results in a convex cocompact hyperbolic manifold  $\mathcal{M}$  (with Fuchsian ends) which is diffeomorphic to the interior of  $W$ .

By the Mostow rigidity theorem, there are only countably infinitely many convex cocompact hyperbolic manifolds with Fuchsian ends of dimension at least 3. On the other hand, for a fixed closed hyperbolic  $d$ -manifold  $\mathcal{N}_0$  with infinitely many properly immersed geodesic hypersurfaces,<sup>1</sup> one can produce infinitely many nonisometric convex compact hyperbolic  $d$ -manifolds with nonempty Fuchsian ends; for each properly immersed geodesic hypersurface  $f_i(\mathbb{H}^{d-1})$  for a totally geodesic immersion  $f_i: \mathbb{H}^{d-1} \rightarrow \mathcal{N}_0$ , there is a finite covering  $\mathcal{N}_i$  of  $\mathcal{N}_0$  such that  $f_i$  lifts to  $\mathbb{H}^{d-1} \rightarrow \mathcal{N}_i$  with image  $S_i$  properly embedded in  $\mathcal{N}_i$  [Maclachlan and Reid 2003]. Cutting and pasting  $\mathcal{N}_i$  along  $S_i$  as described above produces a hyperbolic manifold  $\mathcal{M}_i$  with Fuchsian ends. When the volumes of the  $S_i$  are distinct, the  $\mathcal{M}_i$  are not isometric to each other.

## Orbit closures

In the rest of the introduction, we assume that, for  $d \geq 2$ ,

$\mathcal{M}$  is a convex cocompact hyperbolic  $d$ -manifold with Fuchsian ends.

<sup>1</sup>Any closed arithmetic hyperbolic manifold has infinitely many properly immersed geodesic hypersurfaces provided it has at least one. This is due to the presence of Hecke operators [Reid 1991].

The homogeneous space  $\Gamma \backslash G$  can be regarded as the bundle  $F\mathcal{M}$  of oriented frames over  $\mathcal{M}$ . Let  $A = \{a_t : t \in \mathbb{R}\} < G$  denote the one-parameter subgroup of diagonalizable elements whose right translation actions on  $\Gamma \backslash G$  correspond to the frame flow. Let  $N \simeq \mathbb{R}^{d-1}$  denote the contracting horospherical subgroup

$$N = \{g \in G : a_{-t}ga_t \rightarrow e \text{ as } t \rightarrow +\infty\}.$$

We denote by  $\text{RF}\mathcal{M}$  the renormalized frame bundle of  $\mathcal{M}$ :

$$\text{RF}\mathcal{M} := \{x \in \Gamma \backslash G : xA \text{ is bounded}\},$$

and also set

$$\text{RF}_+\mathcal{M} := \{x \in \Gamma \backslash G : xA^+ \text{ is bounded}\},$$

where  $A^+ = \{a_t : t \geq 0\}$ . When  $\text{Vol}(M) < \infty$ , we have

$$\text{RF}\mathcal{M} = \text{RF}_+\mathcal{M} = \Gamma \backslash G.$$

In general,  $\text{RF}\mathcal{M}$  projects into  $\text{core}\mathcal{M}$  (but not surjective in general) and  $\text{RF}_+\mathcal{M}$  projects onto  $\mathcal{M}$  under the basepoint projection  $\Gamma \backslash G \rightarrow \mathcal{M}$ . The sets  $\text{RF}\mathcal{M}$  and  $\text{RF}_+\mathcal{M}$  are precisely nonwandering sets for the actions of  $A$  and  $N$ , respectively [Winter 2015].

For a connected closed subgroup  $U < N$ , we denote by  $H(U)$  the smallest closed simple Lie subgroup of  $G$  which contains both  $U$  and  $A$ . If  $U \simeq \mathbb{R}^k$ , then  $H(U) \simeq \text{SO}^\circ(k+1, 1)$ . A connected closed subgroup of  $G$  generated by one-parameter unipotent subgroups is, up to conjugation, of the form  $U < N$  or  $H(U)$  for some  $U < N$  (Corollary 3.8).

We set  $F_{H(U)} := \text{RF}_+\mathcal{M} \cdot H(U)$ , which is a closed subset. It is easy to see that if  $x \notin \text{RF}_+\mathcal{M}$  (resp.  $x \notin F_{H(U)}$ ), then  $xU$  (resp.  $xH(U)$ ) is closed in  $\Gamma \backslash G$ . On the other hand, for almost all  $x \in \text{RF}_+\mathcal{M}$ ,  $xU$  is dense in  $\text{RF}_+\mathcal{M}$ , with respect to a unique  $N$ -invariant locally finite measure on  $\text{RF}_+\mathcal{M}$ , called the Burger–Roblin measure; this was shown in [Mohammadi and Oh 2015] for  $d = 3$  and in [Maucourant and Schapira 2019] for general  $d \geq 3$  (see Section 12).

## Orbit closures are relatively homogeneous

We define the collection of closed connected subgroups of  $G$

$$\mathcal{L}_U := \{L = H(\hat{U})C : \text{for some } z \in \text{RF}_+\mathcal{M}, zL \text{ is closed in } \Gamma \backslash G \text{ and } \text{Stab}_L(z) \text{ is Zariski-dense in } L\},$$

where  $U < \hat{U} < N$  and  $C$  is a closed subgroup of the centralizer of  $H(\hat{U})$ . We also define

$$\mathcal{Q}_U := \{vLv^{-1} : L \in \mathcal{L}_U \text{ and } v \in N\}.$$

In view of the previous discussion, the following theorem gives a classification of orbit closures for all connected closed subgroups of  $G$  generated by unipotent one-parameter subgroups:

**Theorem 1.2** Let  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  be a convex cocompact hyperbolic manifold with Fuchsian ends, and let  $U < N$  be a nontrivial connected closed subgroup.

- (1)  **$H(U)$ –orbit closures** For any  $x \in \text{RF } \mathcal{M} \cdot H(U)$ ,

$$\overline{xH(U)} = xL \cap F_{H(U)},$$

where  $xL$  is a closed orbit of some  $L \in \mathcal{L}_U$ .

- (2)  **$U$ –orbit closures** For any  $x \in \text{RF}_+ \mathcal{M}$ ,

$$\overline{xU} = xL \cap \text{RF}_+ \mathcal{M},$$

where  $xL$  is a closed orbit of some  $L \in \mathcal{L}_U$ .

- (3) **Equidistributions** Let  $x_i L_i$  be a sequence of closed orbits intersecting  $\text{RF } \mathcal{M}$ , where  $x_i \in \text{RF}_+ \mathcal{M}$  and  $L_i \in \mathcal{L}_U$ . Assume that no infinite subsequence of  $x_i L_i$  is contained in a subset of the form  $y_0 L_0 D$ , where  $y_0 L_0$  is a closed orbit of  $L_0 \in \mathcal{L}_U$  with  $\dim L_0 < \dim G$  and  $D$  is a compact subset of the normalizer  $N(U)$  of  $U$ . Then<sup>2</sup>

$$\lim_{i \rightarrow \infty} x_i L_i \cap \text{RF}_+ \mathcal{M} = \text{RF}_+ \mathcal{M}.$$

**Remark 1.3** (1) If  $x \in F_{H(U)} - \text{RF } \mathcal{M} \cdot H(U)$ , then  $xH(U)$  is contained in an end component of  $\mathcal{M}$  under the projection  $\Gamma \backslash G \rightarrow \mathcal{M}$ , and its closure is not relatively homogeneous in  $F_{H(U)}$ . More precisely,

$$\overline{xH(U)} = xLV^+H(U)$$

for some  $L \in \mathcal{L}_U$ , and some one-parameter semigroup  $V^+ < N$  (see [Theorem 11.5](#)).

- (2) If  $\mathcal{M}$  has empty ends, i.e. if  $\mathcal{M}$  is compact, [Theorem 1.2](#)(1) and (2) are special cases of Ratner's theorem [[1991b](#)], also proved by Shah (unpublished notes, 1992) independently, and [Theorem 1.2](#)(3) follows from the Mozes–Shah equidistribution theorem [[1995](#)].

[Theorem 1.2](#)(1)–(2) can also be presented as follows in a unified manner:

**Corollary 1.4** Let  $H < G$  be a connected closed subgroup generated by unipotent elements in it. Assume that  $H$  is normalized by  $A$ . For any  $x \in \text{RF } \mathcal{M}$ , the closure of  $xH$  is homogeneous in  $\text{RF } \mathcal{M}$ , that is,

$$(1-2) \quad \overline{xH} \cap \text{RF } \mathcal{M} = xL \cap \text{RF } \mathcal{M},$$

where  $xL$  is a closed orbit of some  $L \in \mathcal{L}_{H \cap N}$ .

**Remark 1.5** If  $\Gamma$  is contained in  $G(\mathbb{Q})$  for some  $\mathbb{Q}$ –structure of  $G$ , and  $[g]L$  is a closed orbit appearing in [Corollary 1.4](#), then  $L$  is defined by the condition that  $gLg^{-1}$  is the smallest connected  $\mathbb{Q}$ –subgroup of  $G$  containing  $gHg^{-1}$ .

<sup>2</sup>For a sequence of subsets  $Y_n$  in a topological space  $X$  such that  $Y = \limsup_n Y_n = \liminf Y_n$ , we write  $Y = \lim_{n \rightarrow \infty} Y_n$ , where  $\limsup_n Y_n = \bigcup_n \overline{\bigcap_{m \geq n} Y_m}$  and  $\liminf_n Y_n = \bigcap_n \bigcup_{m \geq n} Y_m$ .

## Generic points

Denote by  $\mathcal{G}(U)$  the set of all points  $x \in \text{RF}_+ \mathcal{M}$  such that  $x$  is not contained in any closed orbit of a proper reductive algebraic subgroup of  $G$  containing  $U$ . [Theorem 1.2\(2\)](#) implies that, for any  $x \in \mathcal{G}(U)$ ,

$$\overline{xU} = \text{RF}_+ \mathcal{M}.$$

## Geodesic planes, horospheres and spheres

We state implications of our main theorems on the closures of geodesic planes and horospheres of the manifold  $\mathcal{M}$ , as well as on the  $\Gamma$ -orbit closures of spheres in  $\mathbb{S}^{d-1}$ .

A geodesic  $k$ -plane  $P$  in  $\mathcal{M}$  is the image of a totally geodesic immersion  $f: \mathbb{H}^k \rightarrow \mathcal{M}$  or, equivalently, the image of a geodesic  $k$ -subspace of  $\mathbb{H}^d$  under the covering map  $\mathbb{H}^d \rightarrow \mathcal{M}$ . If  $f$  factors through the covering map  $\mathbb{H}^k \rightarrow \Gamma_0 \backslash \mathbb{H}^k$  for a convex cocompact hyperbolic  $k$ -manifold with Fuchsian ends, we call  $P = f(\mathbb{H}^k)$  a convex cocompact geodesic  $k$ -plane with Fuchsian ends.

**Theorem 1.6** *Let  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  be a convex cocompact hyperbolic manifold with Fuchsian ends, and let  $P$  be a geodesic  $k$ -plane of  $\mathcal{M}$  for some  $k \geq 2$ .*

- (1) *If  $P$  intersects  $\text{core } \mathcal{M}$ , then  $\overline{P}$  is a properly immersed convex cocompact geodesic  $m$ -plane with Fuchsian ends for some  $m \geq k$ .*
- (2) *Otherwise,  $P$  is contained in some Fuchsian end  $E = S_0 \times (0, \infty)$  of  $\mathcal{M}$ , and either  $P$  is properly immersed or  $\overline{P}$  is diffeomorphic to the product  $S \times [0, \infty)$  for a closed geodesic  $m$ -plane  $S$  of  $S_0$  for some  $k \leq m \leq d-1$ .*

*In particular, the closure of a geodesic plane of dimension at least 2 is a properly immersed submanifold of  $\mathcal{M}$  (possibly with boundary).*

We also obtain:

**Theorem 1.7** (1) *Any infinite sequence of maximal properly immersed geodesic planes  $P_i$  of  $\dim P_i \geq 2$  intersecting  $\text{core } \mathcal{M}$  becomes dense in  $\mathcal{M}$ , i.e.*

$$\lim_{i \rightarrow \infty} P_i = \mathcal{M},$$

*where the limit is taken in the Hausdorff topology on the space of all closed subsets in  $\mathcal{M}$ .*

- (2) *There are only countably many properly immersed geodesic planes of dimension at least 2 intersecting  $\text{core } \mathcal{M}$ .*
- (3) *If  $\text{Vol}(\mathcal{M}) = \infty$ , there are only finitely many maximal properly immersed bounded geodesic planes of dimension at least 2.*

In fact, [Theorem 1.7\(3\)](#) holds for any convex cocompact hyperbolic  $d$ -manifold (see [Remark 18.3](#)).

A  $k$ -horosphere in  $\mathbb{H}^d$  is a Euclidean sphere of dimension  $k$  which is tangent to a point in  $\mathbb{S}^{d-1}$ . A  $k$ -horosphere in  $\mathcal{M}$  is simply the image of a  $k$ -horosphere in  $\mathbb{H}^d$  under the covering map  $\mathbb{H}^d \rightarrow \mathcal{M} = \Gamma \backslash \mathbb{H}^d$ .



**Theorem 1.8** *Let  $\chi$  be a  $k$ -horosphere of  $\mathcal{M}$  for  $k \geq 1$ . Then either*

- (1)  $\chi$  is properly immersed; or
- (2)  $\bar{\chi}$  is a properly immersed  $m$ -dimensional submanifold, parallel to a convex cocompact geodesic  $m$ -plane of  $\mathcal{M}$  with Fuchsian ends for some  $m \geq k + 1$ .

By abuse of notation, let  $\pi$  denote both basepoint projection maps  $G \rightarrow \mathbb{H}^d$  and  $\Gamma \backslash G \rightarrow \mathcal{M}$ , where we consider an element  $g \in G$  as an oriented frame over  $\mathbb{H}^d$ . Let  $H' = \mathrm{SO}^\circ(k+1, 1) \mathrm{SO}(d-k-1)$  with  $1 \leq k \leq d-2$ . The quotient space  $G/H'$  parametrizes all oriented  $k$ -spheres in  $\mathbb{S}^{d-1}$ , which we denote by  $\mathcal{C}^k$ . For each  $H'$ -orbit  $gH' \subset G$ , the image  $\pi(gH') \subset \mathbb{H}^d$  is an oriented geodesic  $(k+1)$ -plane and the boundary  $\partial(\pi(gH')) \subset \mathbb{S}^{d-1}$  is an oriented  $k$ -sphere. Passing to the quotient space  $\Gamma \backslash G$ , this gives bijections among

- (1) the space of all closed  $H'$ -orbits  $xH' \subset \Gamma \backslash G$  for  $x \in \mathrm{RF} \mathcal{M}$ ;
- (2) the space of all oriented properly immersed geodesic  $(k+1)$ -planes  $P$  in  $\mathcal{M}$  intersecting core  $\mathcal{M}$ ;
- (3) the space of all closed  $\Gamma$ -orbits of oriented  $k$ -spheres  $C \in \mathcal{C}^k$  with  $\#C \cap \Lambda \geq 2$ .

If  $U := H' \cap N$ , then any  $k$ -horosphere in  $\mathcal{M}$  is given by  $\pi(xU)$  for some  $x \in \Gamma \backslash G$ .

In view of these correspondences, Theorems 1.6, 1.7 and 1.8 follow from Theorems 1.2 and 11.5 and Corollary 5.8.

We also obtain the following description of  $\Gamma$ -orbits of spheres of any positive dimension:

**Corollary 1.9** *Let  $1 \leq k \leq d-2$ .*

- (1) *Let  $C \in \mathcal{C}^k$  with  $\#C \cap \Lambda \geq 2$ . Then there exists a sphere  $S \in \mathcal{C}^m$  such that  $\Gamma S$  is closed in  $\mathcal{C}^m$  and*

$$\overline{\Gamma C} = \{D \in \mathcal{C}^k : D \cap \Lambda \neq \emptyset, D \subset \Gamma S\}.$$

- (2) *Let  $C_i \in \mathcal{C}^k$  be an infinite sequence of spheres with  $\#C_i \cap \Lambda \geq 2$  such that  $\Gamma C_i$  is closed in  $\mathcal{C}^k$ . Assume that  $\Gamma C_i$  is maximal in the sense that there is no proper sphere  $S \subset \mathbb{S}^{d-1}$  which properly contains  $C_i$  and that  $\Gamma S$  is closed. Then, as  $i \rightarrow \infty$ ,*

$$\lim_{i \rightarrow \infty} \Gamma C_i = \{D \in \mathcal{C}^k : D \cap \Lambda \neq \emptyset\},$$

*where the limit is taken in the Hausdorff topology on the space of all closed subsets in  $\mathcal{C}^k$ .*

- (3) *If  $\Lambda \neq \mathbb{S}^{d-1}$ , there are only finitely many maximal closed  $\Gamma$ -orbits of spheres of positive dimension contained in  $\Lambda$ .*

**Remark 1.10** (1) The main results of this paper for  $d = 3$  were proved in [McMullen et al. 2017; 2016]. We refer to [McMullen et al. 2017] for counterexamples to Theorem 1.2 for a certain family of quasi-Fuchsian 3-manifolds.

- (2) A convex cocompact hyperbolic 3-manifold with Fuchsian ends (which was referred to as a *rigid acylindrical hyperbolic 3-manifold* in [McMullen et al. 2017]) has a huge deformation space parametrized by the product of the Teichmüller spaces of the boundary components of core  $\mathcal{M}$  (see [Marden 2016]). Any convex cocompact acylindrical hyperbolic 3-manifold is a quasiconformal conjugation of a rigid acylindrical hyperbolic 3-manifold [McMullen 1990]. An analogue of Theorem 1.2(1) was obtained for all convex cocompact acylindrical hyperbolic 3-manifolds in [McMullen et al. 2022] and for all geometrically finite acylindrical hyperbolic 3-manifolds in [Benoist and Oh 2022].
- (3) For  $d \geq 4$ , Kerckhoff and Storm [2012] showed that a convex cocompact hyperbolic manifold  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  with nonempty Fuchsian ends does not allow any nontrivial deformation, in the sense that the representation of  $\Gamma$  into  $G$  is infinitesimally rigid.

**Remark 1.11** We discuss an implication of Theorem 1.2(2) on the classification question on  $U$ -invariant ergodic locally finite measures on  $\mathrm{RF}_+ \mathcal{M}$ . There exists a canonical geometric  $U$ -invariant measure on each closed orbit  $xL$  in Theorem 1.2(2): We write  $L = v^{-1}H(\hat{U})Cv$ . As  $v$  centralizes  $U$ , let's assume  $v = e$  without loss of generality. Denoting by  $p: L \rightarrow H(\hat{U})$  the canonical projection, the subgroup  $p(\mathrm{Stab}_L(x))$  is a convex cocompact Zariski-dense subgroup of  $H(\hat{U})$ , and hence there exists a unique  $\hat{U}$ -invariant locally finite measure on  $p(\mathrm{Stab}_L(x)) \backslash H(\hat{U})$ , called the Burger–Roblin measure [Burger 1990; Roblin 2003; Oh and Shah 2013; Winter 2015]. Now its  $C$ -invariant lift to  $(L \cap \mathrm{Stab}_L(x)) \backslash L$  defines a unique  $\hat{U}C$ -invariant locally finite measure, say  $m_{xL}^{\mathrm{BR}}$ , whose support is equal to  $xL \cap \mathrm{RF}_+ \mathcal{M}$ . Moreover,  $m_{xL}^{\mathrm{BR}}$  is  $U$ -ergodic (see Section 12). A natural question is the following:

*Is every ergodic  $U$ -invariant locally finite Borel measure in  $\mathrm{RF}_+ \mathcal{M}$  proportional to some  $m_{xL}^{\mathrm{BR}}$ ?*

An affirmative answer would provide an analogue of Ratner's measure classification [1991a] in this setup. Theorem 1.2(2) implies that the answer is yes, at least in terms of the support of the measure.

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## 2 Outline of the proof

We will explain the strategy of our proof of Theorem 1.2 with an emphasis on the difference between the finite- and infinite-volume cases and the difference between the dimension 3 and higher-dimensional cases.

## Thick recurrence of unipotent flows

Let  $U_0 = \{u_t : t \in \mathbb{R}\}$  be a one-parameter subgroup of  $N$ . The main obstacle of carrying out unipotent dynamics in a homogeneous space of *infinite* volume is the scarcity of recurrence of unipotent flow. In a compact homogeneous space, every  $U_0$ -orbit stays in a compact set for the obvious reason. Already in a *noncompact* homogeneous space of finite volume, understanding the recurrence of  $U_0$ -orbit is a nontrivial issue. Margulis [1975] showed that any  $U_0$ -orbit is recurrent to a compact subset, and Dani and Margulis [1991] showed that, for any  $x \in \Gamma \backslash G$  and for any  $\varepsilon > 0$ , there exists a compact subset  $\Omega \subset \Gamma \backslash G$  such that

$$\ell\{t \in [0, T] : xu_t \in \Omega\} \geq (1 - \varepsilon)T$$

for all large  $T \gg 1$ , where  $\ell$  denotes the Lebesgue measure on  $\mathbb{R}$ . This nondivergence of unipotent flows is an important ingredient of Ratner's orbit closure theorem [1991b].

In contrast, when  $\Gamma \backslash G$  has infinite volume, for any compact subset  $\Omega \subset \Gamma \backslash G$  and for almost all  $x$  (with respect to any Borel measure  $\mu$  on  $\mathbb{R}$ ),

$$\mu\{t \in [0, T] : xu_t \in \Omega\} = o(T)$$

for all  $T \gg 1$  [Aaronson 1997].

Nonetheless, the pivotal reason that we can work with convex cocompact hyperbolic manifolds of nonempty Fuchsian ends is the following *thick* recurrence property that they possess: there exists  $k > 1$ , depending only on the systole of the double of core  $\mathcal{M}$ , such that, for any  $x \in \text{RF } \mathcal{M}$ , the return time

$$T(x) := \{t \in \mathbb{R} : xu_t \in \text{RF } \mathcal{M}\}$$

is  $k$ -thick, in the sense that, for any  $\lambda > 0$ ,

$$(2-1) \quad T(x) \cap ([-k\lambda, -\lambda] \cup [\lambda, k\lambda]) \neq \emptyset.$$

This recurrence property was first observed in [McMullen et al. 2017] in the case of dimension 3 in order to get an additional invariance of a relative  $U_0$ -minimal subset with respect to  $\text{RF } \mathcal{M}$  by studying the polynomial divergence property of  $U_0$ -orbits of two nearby  $\text{RF } \mathcal{M}$ -points.

## Beyond $d = 3$

In a higher-dimensional case, the possible presence of closed orbits of intermediate subgroups introduces a variety of serious hurdles. Roughly speaking, calling the collection of all such closed orbits the singular set and its complement the generic set, one of the main new ingredients of this paper is the *avoidance of the singular set* along the  $k$ -thick recurrence of  $U_0$ -orbits to  $\text{RF } \mathcal{M}$  for a sequence of  $\text{RF } \mathcal{M}$ -points limiting at a generic point. Its analogue in the finite-volume case was proved by Dani and Margulis [1993] and also independently by Shah [1991b] based on *linearization methods*.

## Road map for induction

Roughly speaking,<sup>3</sup> [Theorem 1.2](#) is proved by induction on the codimension of  $U$  in  $N$ . For each  $i = 1, 2, 3$ , let us say that  $(i)_m$  holds if [Theorem 1.2\(i\)](#) is true for all  $U$  satisfying  $\text{codim}_N(U) \leq m$ . We show that the validity of  $(2)_m$  and  $(3)_m$  implies that of  $(1)_{m+1}$ ; the validity of  $(1)_{m+1}$ ,  $(2)_m$  and  $(3)_m$  implies that of  $(2)_{m+1}$ ; and the validity of  $(1)_{m+1}$ ,  $(2)_{m+1}$  and  $(3)_m$  implies that of  $(3)_{m+1}$ . In order to give an outline of the proof of  $(1)_{m+1}$ , we suppose that  $\text{codim}_N(U) \leq m + 1$ . Let

$$F := \text{RF}_+ \mathcal{M} \cdot H(U), \quad F^* := \text{Interior}(F) \quad \text{and} \quad \partial F := F - F^*.$$

Let  $x \in F^* \cap \text{RF} \mathcal{M}$ , and consider

$$X := \overline{xH(U)} \subset F.$$

The strategy in proving  $(1)_{m+1}$  for  $X$  consists of two steps:

- (1) **Find** Find a closed  $L$ -orbit  $x_0 L$  with  $x_0 \in F^* \cap \text{RF} \mathcal{M}$  such that  $x_0 L \cap F$  contained in  $X$  for some  $L \in \mathcal{L}_U$ .
- (2) **Enlarge** If  $X \not\subset x_0 L C(H(U))$ ,<sup>4</sup> then enlarge  $x_0 L$  to a bigger closed orbit  $x_1 \hat{L}$  so that  $x_1 \hat{L} \cap F \subset X$ , where  $x_1 \in F^* \cap \text{RF} \mathcal{M}$  and  $\hat{L} \in \mathcal{L}_{\hat{U}}$  for some  $\hat{U} < N$  containing  $L \cap N$  properly.

The enlargement process must end after finitely many steps for dimension reasons. Finding a closed orbit as in (1) is based on the study of the relative  $U$ -minimal sets and the unipotent blowup argument using the polynomial divergence of  $U$ -orbits of nearby  $\text{RF} \mathcal{M}$ -points. To explain the enlargement step, suppose that we are given an intermediate closed  $L$ -orbit with  $x_0 L \cap F \subset X$  by step (1), and a one-parameter subgroup  $U_0 = \{u_t\}$  of  $U$  such that  $x_0 U_0$  is dense in  $x_0 L \cap \text{RF}_+ \mathcal{M}$ . As  $L$  is reductive, the Lie algebra of  $G$  can be decomposed into the  $\text{Ad}(L)$ -invariant subspaces  $\mathfrak{l} \oplus \mathfrak{l}^\perp$ , where  $\mathfrak{l}$  denotes the Lie algebra of  $L$ . Suppose that we could arrange a sequence  $x_0 g_i \rightarrow x_0$  in  $X$  for some  $g_i \rightarrow e$  such that, writing  $g_i = \ell_i r_i$  with  $\ell_i \in L$  and  $r_i \in \exp(\mathfrak{l}^\perp)$ , the following conditions are satisfied:

- $x_0 \ell_i \in \text{RF} \mathcal{M}$ .
- $r_i \notin N(U_0)$ .

Then the  $k$ -thick return property of  $x_0 \ell_i \in \text{RF} \mathcal{M}$  along  $U_0$  would yield a sequence  $u_{t_i} \in U_0$  such that

$$x_0 \ell_i u_{t_i} \rightarrow x_1 \in \text{RF} \mathcal{M} \cap x_0 L \quad \text{and} \quad u_{t_i}^{-1} r_i u_{t_i} \rightarrow v$$

for some element  $v \in N - L$ , giving us a point

$$x_1 v \in X.$$

<sup>3</sup>To be precise, we need to carry out induction on the codimension of  $U$  in  $\hat{L} \cap N$  whenever  $xU$  is contained in a closed orbit  $x_0 \hat{L}$  for some  $\hat{L} \in \mathcal{L}_U$ , as formulated in [Theorem 14.1](#).

<sup>4</sup>The notation  $C(S)$  denotes the identity component of the centralizer of  $S$ .

If we could guarantee that

$$(2-2) \quad x_1 \text{ is a generic point for } U \text{ in } x_0L,$$

then  $\overline{x_1U}$  would be equal to  $x_0L \cap \mathrm{RF}_+ \mathcal{M}$  by induction hypothesis  $(2)_m$ , since the codimension of  $U$  inside  $L \cap N$  is at most  $m$ . Then

$$\overline{x_1vU} = \overline{x_1U}v = x_0Lv \cap \mathrm{RF}_+ \mathcal{M} \subset X.$$

Using the  $A$ -invariance of  $X$  and the fact that the double coset  $AvA$  contains a one-parameter unipotent subsemigroup  $V^+$ , we can put  $x_0LV^+ \cap F$  inside  $X$ .

Assuming that

$$(2-3) \quad x_0 \in F^* \cap \mathrm{RF}_+ \mathcal{M},$$

we can promote  $V^+$  to a one-parameter subgroup  $V$ , and find an orbit of a bigger unipotent subgroup  $\hat{U} := (L \cap N)V$  inside  $X$ . This enables us to use the induction hypothesis  $(2)_m$  to complete the enlargement step. Note that, if  $x_1$  is not generic for  $U$  in  $x_0L$ , the closure of  $x_1U$  may be stuck in a smaller closed orbit inside  $x_0L$ , in which case  $\overline{x_1U}v$  may not be bigger than  $x_0L$  in terms of the dimension, resulting in no progress.

We now explain how we establish (2-2).<sup>5</sup>

### Avoidance of the singular set along the thick return time

Let  $U_0 = \{u_t\}$  be a one-parameter subgroup of  $U$ . We denote by  $\mathcal{S}(U_0)$  the union of all closed orbits  $xL$ , where  $x \in \mathrm{RF}_+ \mathcal{M}$  and  $L \in \mathfrak{U}_{U_0}$  is a *proper* subgroup of  $G$ . This set is called the *singular set* for  $U_0$ . Its complement in  $\mathrm{RF}_+ \mathcal{M}$  is denoted by  $\mathcal{G}(U_0)$ , and called the set of *generic* elements of  $U_0$ . We have

$$\mathcal{S}(U_0) = \bigcup_{H \in \mathcal{H}} \Gamma \backslash \Gamma X(H, U_0),$$

where  $\mathcal{H}$  is the countable collection of all proper connected closed subgroups  $H$  of  $G$  containing a unipotent element such that  $\Gamma \backslash \Gamma H$  is closed and  $H \cap \Gamma$  is Zariski-dense in  $H$ , and  $X(H, U_0) := \{g \in G : gU_0g^{-1} \subset H\}$  (**Proposition 5.10**). We define  $\mathcal{E} = \mathcal{E}_{U_0}$  to be the collection of all subsets of  $\mathcal{S}(U_0)$  which are of the form

$$\bigcup \Gamma \backslash \Gamma H_i D_i \cap \mathrm{RF} \mathcal{M},$$

where  $H_i \in \mathcal{H}$  is a finite collection and  $D_i$  is a compact subset of  $X(H_i, U_0)$ . The following avoidance theorem is one of the main ingredients of our proof; let  $k$  be as given by (2-1) for  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$ :

<sup>5</sup>For dimension  $d = 3$ ,  $L$  is either the entire  $\mathrm{SO}^\circ(3, 1)$ , in which case we are done, or  $L = H(U) = \mathrm{SO}^\circ(2, 1)$ . In the latter case, (2-2) is automatic as  $U$  is a horocyclic subgroup of  $L$ .

**Theorem 2.1** (avoidance theorem) *There exists a sequence of compact subsets  $E_1 \subset E_2 \subset \dots$  in  $\mathcal{E}$  with*

$$\mathcal{S}(U_0) \cap \mathrm{RF} \mathcal{M} = \bigcup_{j=1}^{\infty} E_j$$

*satisfying the following: for each  $j \in \mathbb{N}$  and for any compact subset  $F \subset \mathrm{RF} \mathcal{M} - E_{j+1}$ , there exists an open neighborhood  $\mathbb{O}_j = \mathbb{O}_j(F)$  of  $E_j$  such that, for any  $x \in F$ , the set*

$$(2-4) \quad \{t \in \mathbb{R} : xu_t \in \mathrm{RF} \mathcal{M} - \mathbb{O}_j\}$$

*is  $2k$ -thick.*

It is crucial that the thickness of the set (2-4), which is given by  $2k$  here, can be controlled independently of the compact subsets  $E_j$  for applications in the orbit closure theorem. If  $E_j$  does not intersect any closed orbit of a proper subgroup of  $G$ , then obtaining  $E_{j+1}$  and  $\mathbb{O}_j$  is much simpler. In general,  $E_j$  may intersect infinitely many intermediate closed orbits, and our proof is based on a careful analysis on the graded intersections of those closed orbits and a combinatorial argument, which we call an *inductive search argument*. This process is quite delicate compared to the finite-volume case treated in [Dani and Margulis 1993; Shah 1991b], in which the set  $\{t : xu_t \in \mathrm{RF} \mathcal{M}\}$ , being equal to  $\mathbb{R}$ , possesses the Lebesgue measure which can be used to measure the time outside of a neighborhood of the  $E_j$ .

We deduce the following from Theorem 2.1:

**Theorem 2.2** (accumulation on a generic point) *Suppose that  $(2)_m$  and  $(3)_m$  hold in Theorem 1.2. Then the following holds for any connected closed subgroup  $U < N$  with  $\mathrm{codim}_N(U) = m + 1$ : Let  $U_0 = \{u_t : t \in \mathbb{R}\}$  be a one-parameter subgroup of  $U$ , and let  $x_i \in \mathrm{RF} \mathcal{M}$  be a sequence converging to  $x_0 \in \mathcal{G}(U_0)$  as  $i \rightarrow \infty$ . Then, for any given sequence  $T_i \rightarrow \infty$ ,*

$$(2-5) \quad \limsup_{i \rightarrow \infty} \{x_i u_{t_i} \in \mathrm{RF} \mathcal{M} : T_i \leq |t_i| \leq 2kT_i\}$$

*contains a sequence  $\{y_j : j = 1, 2, \dots\}$  such that  $\limsup_{j \rightarrow \infty} y_j U$  contains a point in  $\mathcal{G}(U_0)$ .*<sup>6</sup>

Again, it is important that  $2k$  is independent of  $x_i$  here. We prove two independent but related versions of Theorem 2.2 in Section 15, depending on the relative location of  $x_i$  for the set  $\mathrm{RF} \mathcal{M}$ ; we use Proposition 15.1 for the proof of  $(1)_{m+1}$  and Proposition 15.2 for the proofs of  $(2)_{m+1}$  and  $(3)_{m+1}$ .

## Comparison with the finite-volume case

If  $\Gamma \backslash G$  is compact, the approach of [Dani and Margulis 1993] shows that, if  $x_i$  converges to  $x \in \mathcal{G}(U_0)$ , then, for any  $\varepsilon > 0$ , we can find a sequence of compact subsets  $E_1 \subset E_2 \subset \dots$  in  $\mathcal{E}$  and neighborhoods  $\mathbb{O}_j$  of  $E_j$  such that  $\mathcal{S}(U_0) = \bigcup E_j$ ,  $x_i \notin \bigcup_{j \leq i+1} \mathbb{O}_j$  and, for all  $i \geq j$  and  $T > 0$ ,

$$\ell\{t \in [0, T] : x_i u_t \in \mathbb{O}_j\} \leq \frac{\varepsilon}{2^i} T.$$

<sup>6</sup>Here we allow a constant sequence  $y_j = y$ , in which case  $\limsup_{j \rightarrow \infty} y_j U$  is understood as  $\overline{yU}$  and hence  $y \in \mathcal{G}(U_0)$ .

This implies that, for all  $i > 1$ ,

$$(2-6) \quad \ell \left\{ t \in [0, T] : x_i u_t \in \bigcup_{j \leq i} \mathbb{O}_j \right\} \leq \varepsilon T.$$

In particular, the limsup set in (2-5) always contains an element of  $\mathcal{G}(U_0)$ , without using the induction hypothesis. This is the reason why  $(3)_m$  is not needed in obtaining  $(1)_{m+1}$  and  $(2)_{m+1}$  in [Theorem A.1](#) for the finite-volume case.<sup>7</sup>

In comparison, we are able to get a generic point in [Theorem 2.2](#) only with the help of the induction hypotheses  $(2)_m$  and  $(3)_m$  and after taking the limsup of the  $U$ -orbits of all accumulating points from the  $2k$ -thick sets obtained in [Theorem 2.1](#).

### Generic points in $F^*$ as limits of RF $\mathcal{M}$ -points

In the inductive argument, it is important to find a closed orbit  $x_0 L$  based at a point  $x_0 \in F^*$  in order to promote a semigroup  $V^+$  to a group  $V$  as described following (2-3). Another reason why this is critical is the following: implementing [Theorem 2.2](#) (more precisely, its versions [Theorems 15.1](#) and [15.2](#)) requires having a sequence of RF  $\mathcal{M}$ -points of  $X$  accumulating on a generic point of  $x_0 L$  with respect to  $U_0$ .

The advantage of having a closed orbit  $x_0 L$  with  $x_0 \in F^* \cap \text{RF}_+ \mathcal{M} \cap \mathcal{G}(U_0)$  is that  $x_0$  can be approximated by a sequence of RF  $\mathcal{M}$ -points in  $F^* \cap X$  ([Lemmas 8.3](#) and [8.7](#)).

We also point out that we use the ergodicity theorem obtained in [[Mohammadi and Oh 2015](#); [Maucourant and Schapira 2019](#)] to guarantee that there are many  $U_0$ -generic points in any closed orbit  $x_0 L$  as above.

### Existence of a compact orbit in any noncompact closed orbit

In our setting,  $\Gamma \backslash G$  always contains a closed orbit  $xL$  for some  $x \in \text{RF } \mathcal{M}$  and a proper subgroup  $L \in \mathcal{L}_U$ ; namely those compact orbits of  $\text{SO}^\circ(d-1, 1)$  over the boundary of  $\text{core } \mathcal{M}$ . Moreover, if  $x_0 \hat{L}$  is a noncompact closed orbit for some  $x_0 \in \text{RF } \mathcal{M}$  and  $\dim(\hat{L} \cap N) \geq 2$ , then  $x_0 \hat{L}$  contains a compact orbit  $xL$  of some  $L \in \mathcal{L}_U$  ([Proposition 5.16](#)). This fact was crucially used in deducing  $(2)_{m+1}$  from  $(1)_{m+1}$ ,  $(2)_m$  and  $(3)_m$  in [Theorem 1.2](#) (more precisely, in [Theorem 14.1](#)).

### Organization of the paper

In [Section 3](#), we set up notation for certain Lie subgroups of  $G$ , review some basic facts and gather preliminaries about them and geodesic planes of  $\mathcal{M}$ .

In [Section 4](#), for each unipotent subgroup  $U$  of  $G$ , we define the minimal  $H(U)$ -invariant closed subset  $F_{H(U)} \subset \Gamma \backslash G$  containing  $\text{RF}_+ \mathcal{M}$  and study its properties for a convex cocompact hyperbolic manifold of nonempty Fuchsian ends.

<sup>7</sup>We give a summary of our proof for the case when  $\Gamma \backslash G$  is compact and has at least one  $\text{SO}^\circ(d-1, 1)$ -closed orbit in the [appendix](#) to help readers understand the whole scheme of the proof.

In [Section 5](#), we define the singular set  $\mathcal{S}(U, x_0 L)$  for a closed orbit  $x_0 L \subset \Gamma \backslash G$ , and prove a structure theorem and a countability theorem for a general convex cocompact manifold.

In [Section 6](#), we prove [Proposition 6.3](#), based on a combinatorial lemma, [Lemma 6.4](#), called an *inductive search lemma*. This proposition is used in the proof of [Theorem 7.13](#) (avoidance theorem).

In [Section 7](#), we construct families of triples of intervals which satisfy the hypotheses of [Proposition 6.3](#), by making a careful analysis of the graded intersections of the singular set and the linearization, and prove [Theorem 7.13](#), from which [Theorem 2.1](#) is deduced.

In [Section 8](#), we prove several geometric lemmas which are needed to modify a sequence limiting on a generic point to a sequence of RF  $\mathcal{M}$ -points which still converges to a generic point.

In [Section 9](#), we study the unipotent blowup lemmas using quasiregular maps and properties of thick subsets.

In [Section 10](#), we study the translates of relative  $U$ -minimal sets  $Y$  into the orbit closure of an RF  $\mathcal{M}$  point; the results in this section are used in the step of finding a closed orbit in a given  $H(U)$ -orbit closure.

In [Section 11](#), we describe closures of orbits contained in the boundary of  $F_{H(U)}$ .

In [Section 12](#), we review the ergodicity theorem of [[Mohammadi and Oh 2015](#); [Maucourant and Schapira 2019](#)] and deduce the density of almost all orbits of a connected unipotent subgroup in  $\text{RF}_+ \mathcal{M}$ .

In [Section 13](#), the minimality of a horospherical subgroup action is obtained in the presence of compact factors.

In [Section 14](#), we begin to prove [Theorem 1.2](#); the base case  $m = 0$  is addressed and the orbit closure of a singular  $U$ -orbit is classified under the induction hypothesis.

In [Section 15](#) we prove two propositions on how to get an additional invariance from [Theorem 7.13](#); the results in this section are used in the step of enlarging a closed orbit to a larger one inside a given  $U$ -invariant orbit closure in the proof of [Theorem 1.2](#).

We prove  $(1)_{m+1}$ ,  $(2)_{m+1}$  and  $(3)_{m+1}$ , respectively, in [Sections 16, 17](#) and [18](#).

In the [appendix](#), we give an outline of our proof in the case when  $\Gamma \backslash G$  is compact with at least one  $\text{SO}^\circ(d-1, 1)$ -closed orbit.

### 3 Lie subgroups and geodesic planes

Let  $G$  denote the connected simple Lie group  $\text{SO}^\circ(d, 1)$  for  $d \geq 2$ . In this section, we fix notation and recall some background about Lie subgroups of  $G$  and geodesic planes of a hyperbolic  $d$ -manifold.



As a Lie group, we have  $G \simeq \text{Isom}^+(\mathbb{H}^d)$ . In order to present a family of subgroups of  $G$  explicitly, we fix a quadratic form  $Q(x_1, \dots, x_{d+1}) = 2x_1x_{d+1} + x_2^2 + x_3^2 + \dots + x_d^2$ , and identify  $G = \text{SO}^\circ(Q)$ . The Lie algebra of  $G$  is then given as

$$\mathfrak{so}(d, 1) = \{X \in \mathfrak{sl}_{d+1}(\mathbb{R}) : X^t Q + QX = 0\},$$

where

$$Q = \begin{pmatrix} 0 & 0 & 1 \\ 0 & \text{Id}_{d-1} & 0 \\ 1 & 0 & 0 \end{pmatrix}.$$

A subset  $S \subset G$  is said to be Zariski-closed if it is the zero set  $\{(x_{ij}) \in G : p_1(x_{ij}) = \dots = p_l(x_{ij}) = 0\}$  for a finite collection of polynomials with real coefficients in variables  $(x_{ij}) \in \mathbb{M}_{d+1}(\mathbb{R})$ . The Zariski-closure of a subset  $S \subset G$  means the smallest Zariski-closed subset of  $G$  containing  $S$ . A connected subgroup  $L < G$  is algebraic if  $L$  is equal to the identity component of its Zariski-closure.

## Subgroups of $G$

Inside  $G$ , we have the subgroups

$$K = \{g \in G : g^t g = \text{Id}_{d+1}\} \simeq \text{SO}(d),$$

$$A = \left\{ a_s = \begin{pmatrix} e^s & 0 & 0 \\ 0 & \text{Id}_{d-1} & 0 \\ 0 & 0 & e^{-s} \end{pmatrix} : s \in \mathbb{R} \right\},$$

$$M = \text{the centralizer of } A \text{ in } K \simeq \text{SO}(d-1),$$

$$N^- = \{\exp u^-(x) : x \in \mathbb{R}^{d-1}\},$$

$$N^+ = \{\exp u^+(x) : x \in \mathbb{R}^{d-1}\},$$

where

$$u^-(x) = \begin{pmatrix} 0 & x^t & 0 \\ 0 & 0 & -x \\ 0 & 0 & 0 \end{pmatrix} \quad \text{and} \quad u^+(x) = \begin{pmatrix} 0 & 0 & 0 \\ x & 0 & 0 \\ 0 & -x^t & 0 \end{pmatrix}.$$

The Lie algebra of  $M$  consists of matrices of the form

$$m(C) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & C & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

where  $C \in \mathbb{M}_{d-1}(\mathbb{R})$  is a skew-symmetric matrix, i.e.  $C^t = -C$ .

The subgroups  $N^-$  and  $N^+$  are respectively the contracting and expanding horospherical subgroups of  $G$  for the action of  $A$ . We have the Iwasawa decomposition  $G = KAN^\pm$ . As we will be using the subgroup  $N^-$  frequently, we simply write  $N = N^-$ . We often identify the subgroup  $N^\pm$  with  $\mathbb{R}^{d-1}$  via the map  $\exp u^\pm(x) \mapsto x$ . For a connected closed subgroup  $U < N$ , we use the notation  $U^\perp$  for the

orthogonal complement of  $U$  in  $N$  as a vector subgroup of  $N$ , and  $U^t = U^+$  for the transpose of  $U$ . We use the notation  $B_U(r)$  to denote the ball of radius  $r$  centered at 0 in  $U$  for the Euclidean metric on  $N = \mathbb{R}^{d-1}$ .

We consider the upper half-space model of  $\mathbb{H}^d = \mathbb{R}^+ \times \mathbb{R}^{d-1}$ , so that its boundary is given by  $\mathbb{S}^{d-1} = \{\infty\} \cup (\{0\} \times \mathbb{R}^{d-1})$ . Set  $o = (1, 0, \dots, 0)$ , and fix a standard basis  $e_0, e_1, \dots, e_{d-1}$  at  $T_o(\mathbb{H}^d)$ . The map

$$(3-1) \quad g \mapsto (ge_0, \dots, ge_{d-1})_{g(o)}$$

gives an identification of  $G$  with the oriented frame bundle  $F\mathbb{H}^d$ . The stabilizer of  $o$  and  $e_0$  in  $G$  are equal to  $K$  and  $M$ , respectively, and hence the map (3-1) induces the identifications of the hyperbolic space  $\mathbb{H}^d$  and the unit tangent bundle  $T^1\mathbb{H}^d$  with  $G/K$  and  $G/M$ , respectively. The action of  $G$  on the hyperbolic space  $\mathbb{H}^d = G/K$  extends continuously to the compactification  $\mathbb{S}^{d-1} \cup \mathbb{H}^d$ .

If  $g \in G$  corresponds to a frame  $(v_0, \dots, v_{d-1}) \in F\mathbb{H}^d$ , we define  $g^+, g^- \in \mathbb{S}^{d-1}$  to be the forward and backward endpoints of the directed geodesic tangent to  $v_0$ , respectively. The right translation action of  $A$  on  $G = F\mathbb{H}^d$  defines the frame flow and we have

$$g^\pm = \lim_{t \rightarrow \pm\infty} \pi(ga_t),$$

where  $\pi: G = F\mathbb{H}^d \rightarrow \mathbb{H}^d$  is the basepoint projection.

For the identity element  $e = \text{Id}_{d+1} \in G$ , note that  $e^+ = \infty$  and  $e^- = 0$ , and hence  $g^+ = g(\infty)$  and  $g^- = g(0)$ . The subgroup  $MA$  fixes both points 0 and  $\infty$ , and the horospherical subgroup  $N$  fixes  $\infty$ , and the restriction of the map  $g \mapsto g(0)$  to  $N$  defines an isomorphism  $N \rightarrow \mathbb{R}^{d-1}$  given by  $u^-(x) \mapsto x$ .

For each nontrivial connected subgroup  $U < N$ , we denote by  $H(U)$  the smallest simple closed Lie subgroup of  $G$  containing  $A$  and  $U$ . It is generated by  $U$  and the transpose of  $U$ .

For a subset  $S \subset G$ , we denote by  $N_G(S)$  and  $C_G(S)$  the normalizer of  $S$  and the centralizer of  $S$ , respectively. We denote by  $N(S)$  and  $C(S)$  the identity components of  $N_G(S)$  and  $C_G(S)$ , respectively.

**Example 3.1** Fix the standard basis  $e_1, \dots, e_{d-1}$  of  $\mathbb{R}^{d-1}$ . For  $1 \leq k \leq d-1$ , define  $U_k$  to be the connected subgroup of  $N$  spanned by  $e_1, \dots, e_k$ .

The following can be checked directly:

$$\begin{aligned} H(U_k) &= \langle U_k, U_k^t \rangle \simeq \text{SO}^\circ(k+1, 1), \\ C(H(U_k)) &\simeq \text{SO}(d-k-1), \\ N_G(H(U_k)) &\simeq \text{O}(k+1, 1) \text{O}(d-k-1) \cap G, \\ N(H(U_k)) &\simeq \text{SO}^\circ(k+1, 1) \text{SO}(d-k-1). \end{aligned}$$

We set

$$H'(U) := N(H(U)) = H(U)C(H(U)),$$

which is a connected reductive algebraic subgroup of  $G$  with compact center.

The adjoint action of  $M$  on  $N$  corresponds to the standard action of  $SO(d-1)$  on  $\mathbb{R}^{d-1}$ . It follows that any connected closed subgroup  $U < N$  is conjugate to  $U_k$  and  $H(U)$  is conjugate to  $H(U_k)$  by an element of  $M$ , where  $k = \dim(U)$ .

We set

$$(3-2) \quad C_1(U) := C(H(U)) = M \cap C(U) \quad \text{and} \quad C_2(U) := M \cap C(U^\perp) \subset H(U).$$

**Lemma 3.2** *We have*

$$N(U) = NA C_1(U) C_2(U) \quad \text{and} \quad C(U) = N C_1(U).$$

**Proof** For the first claim, it suffices to show that, for  $U = U_k$ ,  $N(U) = NA SO(k) SO(d-1-k)$ . It is easy to check that  $Q := NA C_1(U) C_2(U)$  normalizes  $U$ . Let  $g \in N(U)$ . We claim that  $g \in Q$ . Using the decomposition  $G = KAN$ , we may assume that  $g \in K$ . Then  $Ug(\infty) = gU(\infty) = g(\infty)$  since  $U(\infty) = \infty$ . Since  $\infty \in \mathbb{S}^{d-1}$  is the unique fixed point of  $U$ , it follows that  $g(\infty) = \infty$ . As  $M = \text{Stab}_K(\infty)$ , we get  $g \in M$ . Now  $gU(0) = Ug(0) = U(0)$ . As  $U(0) = \mathbb{R}^k$ ,  $g\mathbb{R}^k = \mathbb{R}^k$ . Therefore, as  $g \in M$ , we also have  $g\mathbb{R}^{d-1-k} = \mathbb{R}^{d-1-k}$ , and consequently  $g \in O(k)O(d-1-k)$ . This shows that  $NA SO(k) SO(d-1-k) \subset N(U) \subset NA O(k) O(d-1-k)$ . As  $N(U)$  is connected, this implies the claim.

For the second claim, note first that  $N C_1(U) < C(U)$ . Now let  $g \in C(U)$ . Since  $C(U) < N(U) = AN C_1(U) C_2(U)$ , we can write  $g = ac_2nc_1 \in A C_2(U)N C_1(U)$ . Since  $nc_1$  commutes with  $U$ , it follows that  $ac_2 \in C(U)$ . Now observe that the adjoint action of  $a$  on  $U$  is a dilation and the adjoint action of  $c_2$  on  $U$  is a multiplication by an orthogonal matrix. Therefore we get  $a = c_2 = e$ .  $\square$

Denote by  $\mathfrak{g} = \text{Lie}(G)$  the Lie algebra of  $G$ . By a one-parameter subsemigroup of  $G$ , we mean a set of the form  $\{\exp(t\xi) \in G : t \geq 0\}$  for some nonzero  $\xi \in \mathfrak{g}$ . Note that the product  $AU^\perp C_2(U)$  is a subgroup of  $G$ .

**Lemma 3.3** *An unbounded one-parameter subsemigroup  $S$  of  $AU^\perp C_2(U)$  is one of the form*

$$\{\exp(t\xi_A)\exp(t\xi_C) : t \geq 0\}, \quad \{(v\exp(t\xi_A)v^{-1})\exp(t\xi_C) : t \geq 0\} \quad \text{or} \quad \{\exp(t\xi_V)\exp(t\xi_C) : t \geq 0\}$$

*for some  $\xi_A \in \text{Lie}(A) - \{0\}$ ,  $\xi_C \in \text{Lie}(C_2(U))$ ,  $v \in U^\perp - \{e\}$  and  $\xi_V \in \text{Lie}(U^\perp) - \{0\}$ .*

**Proof** Let  $\xi \in \text{Lie}(AU^\perp C_2(U))$  be such that  $S = \{\exp(t\xi) : t \geq 0\}$ . Write  $\xi = \xi_0 + \xi_C$ , where  $\xi_0 \in \text{Lie}(AU^\perp)$  and  $\xi_C \in \text{Lie}(C_2(U))$ . Since  $AU^\perp$  commutes with  $C_2(U)$ ,  $\exp(t\xi) = \exp(t\xi_0)\exp(t\xi_C)$  for any  $t \in \mathbb{R}$ . Hence we only need to show that either  $\xi_0 \in \text{Lie}(U^\perp)$  or

$$(3-3) \quad \{\exp(t\xi_0) : t \geq 0\} = \{v\exp(t\xi_A)v^{-1} : t \geq 0\}$$

for some  $v \in U^\perp$  and  $\xi_A \in \text{Lie}(A)$ . Now, if  $\xi_0 \notin \text{Lie}(U^\perp)$ , then, writing

$$\xi_0 = \begin{pmatrix} a & x^t & 0 \\ 0 & 0_{d-1} & -x \\ 0 & 0 & -a \end{pmatrix} \in \text{Lie}(AU^\perp)$$

with  $a \neq 0$ , a direct computation shows that  $\xi_0 = v\xi_A v^{-1}$ , where

$$\log v = \begin{pmatrix} 0 & -x^t/a & 0 \\ 0 & 0_{d-1} & x/a \\ 0 & 0 & 0 \end{pmatrix} \quad \text{and} \quad \xi_A = \begin{pmatrix} a & 0 & 0 \\ 0 & 0_{d-1} & 0 \\ 0 & 0 & -a \end{pmatrix},$$

proving (3-3).  $\square$

**Lemma 3.4** *If  $v_i \rightarrow \infty$  in  $U^\perp$ , then  $\limsup_{i \rightarrow \infty} v_i A v_i^{-1}$  contains a one-parameter subgroup of  $U^\perp$ .*

**Proof** Writing  $v_i = \exp u^-(x_i)$  for  $x_i \in \mathbb{R}^{d-1}$ , we have

$$v_i a_s v_i^{-1} = \begin{pmatrix} e^s & (1-e^s)x_i^t & -\frac{1}{2}\|(e^{s/2}-e^{-s/2})x_i\|^2 \\ 0 & \text{Id}_{d-1} & (1-e^{-s})x_i \\ 0 & 0 & e^{-s} \end{pmatrix}.$$

Passing to a subsequence,  $x_i/\|x_i\|$  converges to some unit vector  $x_0$  as  $i \rightarrow \infty$ . For any  $r \in \mathbb{R}$ , if we set  $s_i := \log(1-r\|x_i\|^{-1})$ , then the sequence  $v_i a_{s_i} v_i^{-1}$  converges to  $\exp u^-(rx_0)$ . Therefore the set  $V := \{\exp u^-(rx_0) : r \in \mathbb{R}\} < U^\perp$  gives the desired subgroup.  $\square$

**The complementary subspaces  $\mathfrak{h}_U^\perp$  and  $\mathfrak{h}^\perp$**  If  $L$  is a reductive Lie subgroup of  $G$  with  $\mathfrak{l} = \text{Lie}(L)$ , the restriction of the adjoint representation of  $G$  to  $L$  is completely reducible, and hence there exists an  $\text{Ad}(L)$ -invariant complementary subspace  $\mathfrak{l}^\perp$  such that

$$\mathfrak{g} = \mathfrak{l} \oplus \mathfrak{l}^\perp.$$

It follows from the inverse function theorem that the map  $L \times \mathfrak{l}^\perp \rightarrow G$  given by  $(g, X) \mapsto g \exp X$  is a local diffeomorphism onto an open neighborhood of  $e$  in  $G$ .

Let  $U = U_k$ . Denote by  $\mathfrak{h}_U \subset \mathfrak{g}$  the Lie algebra of  $H(U)$ , by  $\mathfrak{u}^\perp$  the subspace  $\text{Lie}(U^\perp)$ , and by  $(\mathfrak{u}^\perp)^t$  its transpose. Then  $\mathfrak{h}_U^\perp$  can be given explicitly as

$$(3-4) \quad \mathfrak{h}_U^\perp = \mathfrak{u}^\perp \oplus (\mathfrak{u}^\perp)^t \oplus \mathfrak{m}_0,$$

where  $\mathfrak{m}_0$  is given by

$$\left\{ m(C) : C = \begin{pmatrix} 0 & Y \\ -Y^t & Z \end{pmatrix}, Z \in \text{M}_{d-1-k}(\mathbb{R}), Z^t = -Z, Y \in \text{M}_{k \times (d-1-k)}(\mathbb{R}) \right\};$$

to see this, it is enough to check that  $\dim(\mathfrak{g}) = \dim(\mathfrak{h}_U) + \dim(\mathfrak{h}_U^\perp)$  and that  $\mathfrak{h}_U^\perp$  is  $\text{Ad}(H(U))$ -invariant, which can be done by direct computation.

Similarly, setting  $\mathfrak{h} := \text{Lie}(H'(U))$ ,  $\mathfrak{h}^\perp$  is given by

$$(3-5) \quad \mathfrak{h}^\perp = \mathfrak{u}^\perp \oplus (\mathfrak{u}^\perp)^t \oplus \mathfrak{m}'_0,$$

where

$$\mathfrak{m}'_0 := \left\{ m(C) : C = \begin{pmatrix} 0 & Y \\ -Y^t & 0 \end{pmatrix} \right\}.$$

**Lemma 3.5** *If  $r_i \rightarrow e$  in  $\exp \mathfrak{h}^\perp - C(H(U))$ , then either  $r_i \notin N(U)$  for all  $i$ , or  $r_i \notin N(U^+)$  for all  $i$ , by passing to a subsequence.*

**Proof** By Lemma 3.2 and (3-5), there exists a neighborhood  $\mathcal{O}$  of 0 in  $\mathfrak{g}$  such that

$$N(U) \cap N(U^+) \cap \exp(\mathfrak{h}^\perp \cap \mathcal{O}) \subset C(H(U)).$$

□

### Reductive subgroups of $G$

**Definition 3.6** For a connected reductive algebraic subgroup  $L < G$ , we denote by  $L_{\text{nc}}$  the maximal connected normal semisimple subgroup of  $L$  with no compact factors.

A connected reductive algebraic subgroup  $L$  of  $G$  is an almost direct product

$$(3-6) \quad L = L_{\text{nc}} C T,$$

where  $C$  is a connected semisimple compact normal subgroup of  $L$  and  $T$  is the central torus of  $L$ . If  $L$  contains a unipotent element, then  $L_{\text{nc}}$  is nontrivial, and simple, containing a conjugate of  $A$ , and the center of  $L$  is compact.

**Proposition 3.7** *If  $L < G$  is a connected reductive algebraic subgroup normalized by  $A$  and containing a unipotent element, then*

$$L = H(U)C,$$

where  $U < N$  is a nontrivial connected subgroup and  $C$  is a closed subgroup of  $C(H(U))$ . In particular,  $L_{\text{nc}}$  and  $N(L_{\text{nc}})$  are equal to  $H(U)$  and  $H'(U)$ , respectively.

**Proof** If  $L$  is normalized by  $A$ , then so is  $L_{\text{nc}}$ . Therefore it suffices to prove that a connected noncompact simple Lie subgroup  $H < G$  normalized by  $A$  is of the form  $H = H(U)$ , where  $U < N$  is a nontrivial connected subgroup.

First, consider the case when  $A < H$ . Let  $\mathfrak{h}$  be the Lie algebra of  $H$ , and  $\mathfrak{a}$  be the Lie algebra of  $A$ . Since  $\mathfrak{h}$  is simple, its root-space decomposition for the adjoint action of  $\mathfrak{a}$  is of the form  $\mathfrak{h} = \mathfrak{z}(\mathfrak{a}) \oplus \mathfrak{u}^+ \oplus \mathfrak{u}^-$ , where  $\mathfrak{u}^\pm$  are the sum of all positive and negative root subspaces, respectively, and  $\mathfrak{z}(\mathfrak{a})$  is the centralizer of  $\mathfrak{a}$ . Since the sum of all negative root subspaces for the adjoint action of  $\mathfrak{a}$  on  $\mathfrak{g}$  is  $\text{Lie}(N^-)$ , it follows that  $U := \exp(\mathfrak{u}^-) < N^-$  and  $H = H(U)$ .

Now, for the general case,  $H$  contains a conjugate  $gAg^{-1}$  for some  $g \in G$ . Hence  $g^{-1}Hg = H(U)$ . Since  $H(U)$  contains both  $A$  and  $g^{-1}Ag$ , they must be conjugate within  $H(U)$ , so  $A = h^{-1}g^{-1}Agh$  for some  $h \in H(U)$ . Hence  $gh \in N_G(A) = AM$ . Therefore  $H = gH(U)g^{-1}$  is equal to  $mH(U)m^{-1}$  for some  $m \in M$ . Since  $m$  normalizes  $N$  and  $mH(U)m^{-1} = H(mUm^{-1})$ , the claim follows.  $\square$

**Corollary 3.8** *Any connected closed subgroup  $L$  of  $G$  generated by unipotent elements is conjugate to either  $U$  or  $H(U)$  for some nontrivial connected subgroup  $U < N$ .*

**Proof** The subgroup  $S$  admits a Levi decomposition  $L = SV$ , where  $S$  is a connected semisimple subgroup with no compact factors and  $V$  is the unipotent radical of  $S$  [Shah 1991b, Lemma 2.9]. If  $S$  is trivial, the claim follows since any connected unipotent subgroup can be conjugate into  $N$ . Suppose that  $S$  is not trivial. Then  $S = H(U)$  for some nontrivial  $U < N$  by Proposition 3.7. Unless  $V$  is trivial, the normalizer of  $V$  is contained in a conjugate of  $NAM$ ; in particular, it cannot contain  $H(U)$ . Hence  $V = \{e\}$ .  $\square$

## Totally geodesic immersed planes

Let  $\Gamma$  be a discrete, torsion-free, nonelementary subgroup of  $G$ , and consider the associated hyperbolic manifold

$$\mathcal{M} = \Gamma \backslash \mathbb{H}^d = \Gamma \backslash G/K.$$

We refer to [Ratcliffe 1994] for basic properties of hyperbolic manifolds. As in the introduction, we denote by  $\Lambda$  the limit set of  $\Gamma$  and by  $\text{core } \mathcal{M}$  the convex core of  $\mathcal{M}$ . Note that  $\text{core } \mathcal{M}$  contains all bounded geodesics in  $\mathcal{M}$ .

We denote by  $F\mathcal{M} \simeq \Gamma \backslash G$  the bundle of all oriented orthonormal frames over  $\mathcal{M}$ . We denote by

$$(3-7) \quad \pi: \Gamma \backslash G \rightarrow \mathcal{M} = \Gamma \backslash G/K$$

the basepoint projection. By abuse of notation, we also denote by

$$(3-8) \quad \pi: G \rightarrow \mathbb{H}^d = G/K$$

the basepoint projection. For  $g \in G$ ,  $[g]$  denotes its image under the covering map  $G \rightarrow \Gamma \backslash G$ .

Fix  $1 \leq k \leq d-2$  and let

$$(3-9) \quad H = H(U_k) \simeq \text{SO}^\circ(k+1, 1) \quad \text{and} \quad H' = H(U_k) \simeq \text{SO}^\circ(k+1, 1) \cdot \text{SO}(d-k-1).$$

Let  $C_0 := \mathbb{R}^k \cup \{\infty\}$  denote the unique oriented  $k$ -sphere in  $\mathbb{S}^{d-1}$  stabilized by  $H'$ . Then  $\tilde{S}_0 := \text{hull}(C_0)$  is the unique oriented totally geodesic subspace of  $\mathbb{H}^d$  stabilized by  $H'$ , and  $\partial \tilde{S}_0 = C_0$ . We note that  $H'$  (resp.  $H$ ) consists of all oriented frames  $(v_0, \dots, v_{d-1}) \in G$  (resp.  $(v_0, \dots, v_k, e_{k+1}, \dots, e_{d-1}) \in G$ ) such that the  $k$ -tuple  $(v_0, \dots, v_k)$  is tangent to  $\tilde{S}_0$ , compatible with the orientation of  $\tilde{S}_0$ . The group  $G$

acts transitively on the space of all oriented  $k$  spheres in  $\mathbb{S}^{d-1}$  giving rise to the isomorphisms of  $G/H'$  with

$$\mathcal{C}^k = \text{the space of all oriented } k\text{-spheres in } \mathbb{S}^{d-1}$$

and with

$$\text{the space of all oriented totally geodesic } (k+1)\text{-planes of } \mathbb{H}^d.$$

We discuss the fundamental group of an immersed geodesic  $k$ -plane  $S \subset \mathcal{M}$ . Choose a totally geodesic subspace  $\tilde{S}$  of  $\mathbb{H}^d$  which covers  $S$ . Then  $\tilde{S} = g\tilde{S}_0$  for some  $g \in G$ , and the stabilizer of  $\tilde{S}$  in  $G$  is equal to  $gH'g^{-1}$ . We have

$$\Gamma_{\tilde{S}} = \{\gamma \in \Gamma : \gamma\tilde{S} = \tilde{S}\} = \Gamma \cap gH'g^{-1}$$

and get an immersion  $\tilde{f}: \Gamma_{\tilde{S}} \backslash \tilde{S} \rightarrow \mathcal{M}$  with image  $S$ . Consider the projection map

$$(3-10) \quad p: gH'g^{-1} \rightarrow gHg^{-1}.$$

Then  $p$  is injective on  $\Gamma_{\tilde{S}}$  and

$$\Gamma_{\tilde{S}} \backslash \tilde{S} \simeq p(\Gamma_{\tilde{S}}) \backslash \tilde{S}$$

is an isomorphism, since  $gC(H)g^{-1}$  acts trivially on  $\tilde{S}$ . Hence  $\tilde{f}$  gives an immersion

$$(3-11) \quad f: p(\Gamma_{\tilde{S}}) \backslash \tilde{S} \rightarrow \mathcal{M}$$

with image  $S$ . We say  $S$  is *properly immersed* if  $f$  is a proper map.

**Proposition 3.9** *Let  $x \in \Gamma \backslash G$ , and set  $S := \pi(xH') \subset \mathcal{M}$ . Then*

- (1)  *$xH'$  is closed in  $\Gamma \backslash G$  if and only if  $S$  is properly immersed in  $\mathcal{M}$ .*
- (2) *If  $M$  is convex cocompact and  $S$  is properly immersed, then  $S$  is convex cocompact and*

$$\partial\tilde{S} \cap \Lambda = \Lambda(p(\Gamma_{\tilde{S}}))$$

*for any geodesic subspace  $\tilde{S} \subset \mathbb{H}^d$  which covers  $S$ .*

**Proof** Choose a representative  $g \in G$  of  $x$  and consider the totally geodesic subspace  $\tilde{S} := g\tilde{S}_0$ . Then  $S = \text{Im}(f)$  as is  $f$  given by (3-11). Now the closedness of  $xH'$  in  $\Gamma \backslash G$  is equivalent to the properness of the map  $(H' \cap g^{-1}\Gamma g) \backslash H' \rightarrow \Gamma \backslash G$  induced from map  $h \mapsto xh$ . This in turn is equivalent to the properness of the induced map  $(H' \cap g^{-1}\Gamma g) \backslash H' / (H' \cap K) \rightarrow \Gamma \backslash G / K$ . If  $\Delta$  is the image of  $H' \cap g^{-1}\Gamma g$  under the projection map  $H' \rightarrow H$ , then the natural injective map  $\Delta \backslash H / H \cap K \rightarrow (H' \cap g^{-1}\Gamma g) \backslash H' / H' \cap K$  is an isomorphism. Since

$$p(\Gamma_{\tilde{S}}) \backslash \tilde{S} = p(\Gamma_{\tilde{S}}) \backslash gH / (H \cap K) \simeq \Delta \backslash H / (H \cap K),$$

the first claim follows. The second claim follows from [Oh and Shah 2013, Theorem 4.7]. □

## 4 Hyperbolic manifolds with Fuchsian ends and thick return time

In this section, we study the closed  $H(U)$ -invariant subset  $F_{H(U)} := \text{RF}_+ \mathcal{M} \cdot H(U)$  when  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  is a convex cocompact manifold with Fuchsian ends. At the end of the section, we address the global thickness of the return time of any one-parameter subgroup of  $N$  to  $\text{RF} \mathcal{M}$ .

**Definition 4.1** A convex cocompact hyperbolic manifold  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  is said to have nonempty *Fuchsian ends* if one of the following equivalent conditions holds:

- (1) Its convex core has nonempty interior and nonempty totally geodesic boundary.
- (2) The domain of discontinuity of  $\Gamma$ ,

$$\Omega := \mathbb{S}^{d-1} - \Lambda = \bigcup_{i=1}^{\infty} B_i,$$

is a dense union of infinitely many round balls with mutually disjoint closures.

In this section, let  $\mathcal{M}$  be a convex cocompact hyperbolic manifold of nonempty Fuchsian ends.

### Renormalized frame bundle

The renormalized frame bundle  $\text{RF} \mathcal{M} \subset \text{F} \mathcal{M}$  is defined as the  $AM$ -invariant subset

$$\text{RF} \mathcal{M} = \{[g] \in \Gamma \backslash G : g^{\pm} \in \Lambda\} = \{x \in \Gamma \backslash G : xA \text{ is bounded}\},$$

i.e. the closed set consisting of all oriented frames  $(v_0, \dots, v_{d-1})$  such that the complete geodesic through  $v_0$  is contained in  $\text{core} \mathcal{M}$ .

Unless mentioned otherwise,<sup>8</sup> we set  $A^+ = \{a_t : t \geq 0\}$ . We define

$$\text{RF}_+ \mathcal{M} = \{[g] \in \Gamma \backslash G : g^+ \in \Lambda\} = \{x \in \Gamma \backslash G : xA^+ \text{ is bounded}\},$$

which is a closed  $NAM$ -invariant subset. As  $\pi(xNA) = \pi(xG) = \mathcal{M}$  for any  $x \in \Gamma \backslash G$ , we have  $\pi(\text{RF}_+ \mathcal{M}) = \mathcal{M}$ .

**Lemma 4.2** For  $x \in \text{RF}_+ \mathcal{M}$ ,  $\overline{xA^+}$  meets  $\text{RF} \mathcal{M}$ .

**Proof** Take any sequence  $a_i \rightarrow \infty$  in  $A^+$ . Since  $xA^+$  is bounded,  $xa_i$  converges to some  $x_0 \in \overline{xA^+}$  by passing to a subsequence. On the other hand, as  $A = \liminf a_i^{-1} A^+$ , we have  $x_0 A \subset \limsup (xa_i)(a_i^{-1} A^+) \subset \overline{xA^+}$ . Since  $x \in \text{RF}_+ \mathcal{M}$ ,  $\overline{xA^+}$  is bounded, whence so is  $x_0 A$ . Hence  $x_0 \in \text{RF} \mathcal{M}$ , as desired.  $\square$

<sup>8</sup>At certain places, we use notation  $A^+$  for any subsemigroup of  $A$



### $H(U)$ -invariant subsets: $F_{H(U)}$ , $F_{H(U)}^*$ and $\partial F_{H(U)}$

Fix a nontrivial connected subgroup  $U < N$ , and consider the associated subgroups  $H(U)$  and  $H'(U)$  as defined in [Section 3](#).

We define

$$(4-1) \quad F_{H(U)} := \text{RF}_+ \mathcal{M} \cdot H(U).$$

We denote by  $F_{H(U)}^*$  the interior of  $F_{H(U)}$  and by  $\partial F_{H(U)}$  the boundary of  $F_{H(U)}$ . When there is no room for confusion, we will omit the subscript  $H(U)$  and simply write  $F$ ,  $F^*$  and  $\partial F$ .

If  $C \subset \mathbb{S}^{d-1}$  denotes the oriented  $k$ -sphere stabilized by  $H(U)$ , then  $g \in F_{H(U)}$  if and only if  $gC \cap \Lambda \neq \emptyset$ . Therefore the closedness of  $F_{H(U)}$  follows from the compactness of  $\Lambda$ . The set  $F_{H(U)}$  is also  $H'(U)$ -invariant, since  $\text{RF}_+ \mathcal{M}$  is  $M$ -invariant and  $C(H(U))$  is contained in  $M$ . For  $g \in G$ , we denote by  $C_g = C_{gH(U)} \subset \mathbb{S}^{d-1}$  the sphere given by the boundary of the geodesic plane  $\pi(gH(U))$ . Then  $\text{hull } C_g = \pi(g(H(U)))$  and  $C_g = gH(U)^+ = gH(U)^-$ , where  $H(U)^\pm = \{h^\pm : h \in H(U)\}$ . It follows that

$$(4-2) \quad F_{H(U)} = \{[g] \in \Gamma \backslash G : C_g \cap \Lambda \neq \emptyset\}.$$

**Lemma 4.3** Fix  $x = [g] \in \Gamma \backslash G$ . Let  $L$  be a closed subgroup of  $G$  such that the closure of  $\pi(gL)$  in  $\mathbb{H}^d \cup \mathbb{S}^{d-1}$  does not meet  $\Lambda$ . Then the map  $L \rightarrow xL \subset \Gamma \backslash G$  given by  $\ell \mapsto x\ell$  is a proper map, and hence  $xL$  is closed.

**Proof** Suppose that  $x\ell_i$  converges to some  $[g_0] \in \Gamma \backslash G$  for some sequence  $\ell_i \rightarrow \infty$  in  $L$ . Then there exist  $\gamma_i \in \Gamma$  such that  $d(\gamma_i \pi(g\ell_i), \pi(g_0)) = d(\pi(g\ell_i), \gamma_i \pi(g_0)) \rightarrow 0$  as  $i \rightarrow \infty$ . As  $g\ell_i \rightarrow \infty$ ,  $\gamma_i \pi(g_0)$  converges to a limit point  $\xi \in \Lambda$ , after passing to a subsequence. Hence  $\overline{\pi(gL)} \cap \Lambda \neq \emptyset$ .  $\square$

This lemma implies that, if  $x \notin \text{RF}_+ \mathcal{M}$  (resp.  $x \notin F_{H(U)}$ ), then  $xU$  (resp.  $xH(U)$ ) is closed for any closed subgroup  $U < N$ .

**Lemma 4.4** If  $\mathcal{M}$  is a convex cocompact hyperbolic manifold of nonempty Fuchsian ends, then

$$F_{H(U)} = \{x \in \Gamma \backslash G : \pi(\overline{xH(U)}) \cap \text{core } \mathcal{M} \neq \emptyset\}.$$

**Proof** Denote by  $Q$  the subset on the right-hand side of the above equality. To show  $F_{H(U)} \subset Q$ , let  $x \in F_{H(U)}$ . By modifying it using an element of  $H(U)$ , we may assume that  $x \in \text{RF}_+ \mathcal{M}$ . By [Lemma 4.2](#),  $\overline{xH(U)}$  contains  $x_0 \in \text{RF } \mathcal{M}$ . Since  $x_0 A$  is bounded,  $\pi(x_0 A)$  is a bounded geodesic, and hence

$$\pi(x_0 A) \subset \pi(\overline{xH(U)}) \cap \text{core } \mathcal{M}$$

because  $\text{core } \mathcal{M}$  contains all bounded geodesics. Therefore  $x \in Q$ . To show the other inclusion  $Q \subset F_{H(U)}$ , we use the hypothesis on  $\mathcal{M}$ . Suppose  $x = [g] \notin F_{H(U)}$ . Then  $C_g \cap \Lambda = \emptyset$ , and hence  $C_g$  must be

contained in a connected component, say  $B_i$ , of  $\Omega$ . Hence  $\pi(gH(U)) = \text{hull}(C_g)$  is contained in the interior of  $\text{hull}(B_i)$ , which is disjoint from  $\text{hull}(\Lambda)$ , by the convexity of  $B_i$ . Therefore the orbit  $\Gamma\pi(gH(U))$  is a closed subset of  $\mathbb{H}^d$ , disjoint from  $\text{hull}(\Lambda)$ . Hence  $x \notin Q$ , proving the claim.  $\square$

Note also that

$$(4-3) \quad \text{RF } \mathcal{M} \cdot H(U) = \{[g] \in \Gamma \backslash G : \#C_g \cap \Lambda \geq 2\} = \{x \in \Gamma \backslash G : \pi(xH(U)) \cap \text{core } \mathcal{M} \neq \emptyset\}.$$

This can be seen using the fact that, for any two distinct points  $\xi^+, \xi^- \in C_g$ , there exists  $h \in H(U)$  such that  $gh(\infty) = \xi^+$  and  $gh(0) = \xi^-$ ; this fact is clear if  $H(U) = H(U_k)$  for some  $k$ , and the general case follows since  $H(U) = mH(U_k)m^{-1}$  for some  $m \in M$ , and  $M$  fixes both 0 and  $\infty$ .

Denote by  $\mathcal{M}^*$  the interior of the core of  $\mathcal{M}$  and by  $F_{H(U)}^*$  the interior of  $F_{H(U)}$ . Then

$$F_{H(U)}^* = \{x \in \Gamma \backslash G : \pi(xH(U)) \cap \mathcal{M}^* \neq \emptyset\}.$$

To see this, note that the right-hand side is equal to

$$(4-4) \quad \{[g] \in F_{H(U)} : \text{hull } C_g \cap \text{Interior}(\text{hull}(\Lambda)) \neq \emptyset\} = \{[g] \in F_{H(U)} : C_g \not\subset \bar{B}_i \text{ for any } i\},$$

which can then be seen to be equal to  $F_{H(U)}^*$  in view of (4-2). Note that (4-4) implies that, for  $[g] \in F_{H(U)}^*$ ,  $\#C_g \cap \Lambda \geq 2$  and hence

$$(4-5) \quad F_{H(U)}^* \subset \text{RF } \mathcal{M} \cdot H(U).$$

In particular,  $\text{RF } \mathcal{M} \cdot H(U)$  is dense in  $F_{H(U)}$ .

**Lemma 4.5** *We have*

$$\text{RF}_+ \mathcal{M} \cap F_{H(U)}^* \subset \text{RF } \mathcal{M} \cdot U.$$

**Proof** Let  $y \in \text{RF}_+ \mathcal{M} \cap F_{H(U)}^*$ . We need to show that  $yU \cap \text{RF } \mathcal{M} \neq \emptyset$ . Choose  $g \in G$  so that  $[g] = y$ . As  $y \in \text{RF}_+ \mathcal{M}$ ,  $g^+ = g(\infty) \in \Lambda$ , and hence  $C_g \cap \Lambda \neq \emptyset$ . If  $\#C_g \cap \Lambda = 1$ , then  $C_g$  must be contained in  $\bar{B}_i$  for some  $i$ , which implies  $[g] \notin F_{H(U)}^*$ . Therefore  $\#C_g \cap \Lambda \geq 2$ . We note that  $gU(0) \cup \{g(\infty)\} = C_g$ ; this is clear when  $U = U_k$  for some  $k \geq 1$  and  $g = e$ , to which the general case is reduced. Hence, there exists  $u \in U$  such that  $gu(0) \in \Lambda$ . Since  $gu(\infty) = g(\infty) \in \Lambda$ , we have  $yu = [g]u \in \text{RF } \mathcal{M}$ .  $\square$

We denote by  $\partial F_{H(U)}$  the boundary of  $F_{H(U)}$ ; that is,

$$\partial F_{H(U)} = F_{H(U)} - F_{H(U)}^* = \{[g] \in F_{H(U)} : C_g \subset \bar{B}_i \text{ for some } i\}.$$

When there is no room for confusion, we will omit the subscript  $H(U)$  and simply write  $F$ ,  $F^*$  and  $\partial F$ .

We call an oriented frame  $g = (v_0, \dots, v_{d-1}) \in \text{FM} = G$  a boundary frame if the first  $d-1$  vectors  $v_0, \dots, v_{d-2}$  are tangent to the boundary of  $\text{core } \mathcal{M}$ . Set

$$\check{H} := H(U_{d-2}) = \text{SO}^\circ(d-1, 1),$$

and denote by  $\check{V}$  the one-dimensional subgroup  $\mathbb{R}e_{d-1}$  of  $N = \mathbb{R}^{d-1}$ ; note that  $\check{V} = (\check{H} \cap N)^\perp$ .

We denote by  $\text{BF } \mathcal{M}$  the set of all boundary frames of  $\mathcal{M}$ ; it is a union of compact  $\check{H}$ -orbits

$$(4-6) \quad \text{BF } \mathcal{M} = \bigcup_{i=1}^k z_i \check{H}$$

such that  $\pi(z_i \check{H}) = \Gamma \backslash \Gamma \text{ hull}(B_i)$  for some component  $B_i$  of  $\Omega$ .

**The boundary  $\partial F_{H(U)}$  for  $U < \check{H} \cap N$**  Suppose that  $U$  is contained in  $\check{H} \cap N = \mathbb{R}^{d-2}$ . Then there exists a one-parameter semigroup  $\check{V}^+$  of  $\check{V}$  such that

$$\partial F = \text{BF } \mathcal{M} \cdot \check{V}^+ \cdot H'(U).$$

We use the notation  $\check{V}^- = \{v^{-1} : v \in \check{V}^+\}$ . Note that

$$(4-7) \quad \partial F \cap \text{RF } \mathcal{M} = \text{BF } \mathcal{M} \cdot C(H(U)) \quad \text{and} \quad \partial F \cap \text{RF}_+ \mathcal{M} = \text{BF } \mathcal{M} \cdot \check{V}^+ \cdot C(H(U)).$$

For a general proper connected closed subgroup  $U < N$ ,  $mUm^{-1} \subset \check{H} \cap N$  for some  $m \in M$ , and

$$\partial F \cap \text{RF } \mathcal{M} = \text{BF } \mathcal{M} \cdot m \cdot C(H(U)),$$

where  $\text{BF } \mathcal{M} \cdot m$  is now a union of finitely many  $m^{-1} \check{H} m$ -compact orbits.

**Lemma 4.6** Let  $U < \check{H} \cap N$ ,  $z \in \text{BF } \mathcal{M}$  and  $v \in \check{V} - \{e\}$ . If  $zv \in \text{RF } \mathcal{M}$ , then  $zv \in F^*$ .

**Proof** Let  $z = [g] \in \text{BF } \mathcal{M}$ . Then  $\partial(\pi(g\check{H})) = \partial B_j$  for some  $j$ . Let  $v \in \check{V} - \{e\}$  be such that  $zv \in \text{RF } \mathcal{M}$ . Suppose  $zv \in \partial F_{H(U)}$ . Then  $C_{gv} \subset \bar{B}_i$  for some  $i$ . Since the sphere  $C_{gv} = \{gvh(\infty) : h \in H(U)\}$  contains  $g(\infty)$  which belongs to  $\partial B_j$ , we have  $i = j$ , as the  $\bar{B}_i$  are mutually disjoint. As  $zv \in \text{RF } \mathcal{M}$ ,  $C_{gv} \subset \partial B_j$ . Hence  $gvH(U)^+ \subset g\check{H}^+$ . It follows that  $gvH(U) \subset g\check{H}$ , and hence  $vH(U) \cap \check{H} \neq \emptyset$ , which is a contradiction since  $v \notin \check{H}$ , and  $H(U) \subset \check{H}$ .  $\square$

### Properly immersed geodesic planes

Let  $H = H(U_k)$  and  $H' = H'(U_k)$  be as in (3-9), and  $p$  be the map in (3-10). In (3-11), if  $p(\Gamma_{\check{S}}) \backslash \check{S}$  is a convex cocompact hyperbolic  $k$ -manifold with Fuchsian ends and  $f$  is proper, then the image  $S = \text{Im}(f)$  is referred to as a properly immersed convex cocompact geodesic  $k$ -plane of Fuchsian ends.

**Proposition 4.7** If  $xH'$  is closed for  $x \in \text{RF } \mathcal{M}$ , then  $S = \pi(xH')$  is a properly immersed convex cocompact geodesic plane with (possibly empty) Fuchsian ends.

**Proof** Choose  $g \in G$  so that  $x = [g]$ . Let  $\check{S}$  and  $\Gamma_{\check{S}}$  be as in Proposition 3.9. Set  $C = \partial \check{S}$ . By Proposition 3.9,  $S$  is properly immersed, and  $C \cap \Lambda = \Lambda(p(\Gamma_{\check{S}}))$ . Write

$$(4-8) \quad C - (C \cap \Lambda) = \bigcup_{i \in I} (C \cap B_i),$$

where  $I$  is the collection of all  $i$  such that  $C \cap B_i \neq \emptyset$ . If  $C \cap \Lambda$  contains a nonempty open subset of  $C$ , then the limit set of  $p(\Gamma_{\tilde{S}})$  is equal to  $C$ . Since  $p(\Gamma_{\tilde{S}})$  is convex cocompact by Proposition 3.9, it is a uniform lattice in  $gHg^{-1}$ , and hence  $S$  is compact. In the other case,  $I$  is an infinite set and  $\bigcup_{i \in I} (C \cap B_i)$  is dense in  $C$ ; so  $S$  is a convex cocompact hyperbolic submanifold with Fuchsian ends by Definition 4.1(2).  $\square$

**Lemma 4.8** *For any sphere  $C$  in  $\mathbb{S}^{d-1}$  with  $\#C \cap \Lambda \geq 2$ , the intersection  $C \cap \Lambda$  is Zariski-dense in  $C$ .*

**Proof** The claim is clear if  $C \cap \Lambda$  contains a nonempty open subset of  $C$ . If not,  $C \cap \Lambda$  contains infinitely many of the  $C \cap \partial B_i$ , each of which is an irreducible codimension one real subvariety of  $C$ . It follows that the Zariski-closure of  $C \cap \Lambda$  has dimension strictly greater than  $\dim C - 1$ , hence is equal to  $C$ .  $\square$

We let

$$(4-9) \quad \pi_1: H' \rightarrow H \quad \text{and} \quad \pi_2: H' \rightarrow C(H)$$

denote the canonical projections.

**Proposition 4.9** *Suppose that  $xH'$  is closed for  $x = [g] \in \text{RF } \mathcal{M}$ , and set  $\Gamma' := g^{-1}\Gamma g \cap H'$ . Then*

$$(4-10) \quad \overline{xH} = xHC,$$

where  $C = \overline{\pi_2(\Gamma')}$  and  $HC$  is equal to the identity component of the Zariski-closure of  $\Gamma'$ .

**Proof** Without loss of generality, we may assume  $g = e$ . As  $H'$  is a direct product  $H \times C(H)$ , we write an element of  $H'$  as  $(h, c)$  with  $h \in H$  and  $c \in C(H)$ . For all  $\gamma \in \Gamma'$ ,

$$xH = [(e, e)]H = [(e, \pi_2(\gamma))]H = [(e, e)]H\pi_2(\gamma)$$

and hence  $xH = xH\pi_2(\Gamma')$ . It follows that  $xHC \subset \overline{xH}$ .

To show the other inclusion, let  $(h_0, c_0) \in HC(H)$  be arbitrary. If  $[(h_0, c_0)] \in \overline{xH} = \overline{[(e, e)]H}$ , then there exist sequences  $\gamma_i \in \Gamma'$  and  $h_i \in H$  such that  $\gamma_i(h_i, e) \rightarrow (h_0, c_0)$  in  $H'$  as  $i \rightarrow \infty$ . In particular,  $\pi_2(\gamma_i) \rightarrow c_0$  in  $C(H)$  as  $i \rightarrow \infty$  and hence  $c_0 \in C = \overline{\pi_2(\Gamma')}$ . This finishes the proof of (4-10). Let  $W$  denote the identity component of the Zariski-closure of  $\Gamma'$  in  $H'$ . Since any proper algebraic subgroup of  $G$  stabilizes either a point, or a proper sphere in  $\mathbb{S}^{d-1}$ , it follows from Proposition 3.9 and Lemma 4.8 that  $\pi_1(\Gamma')$  is Zariski-dense in  $H$ ; so  $\pi_1(W) = H$ . So the quotient  $W \backslash H'$  is compact. This implies that  $W$  contains a maximal real-split connected solvable subgroup, say,  $P$  of  $H'$ . Now  $H \cap W$  is a normal subgroup of  $H$ , as  $\pi_1(W) = H$ . Since  $P < H \cap W$  and  $H$  is simple, we conclude that  $H \cap W = H$ , i.e.  $H < W$ . Hence  $W = H\pi_2(W)$ . As any compact linear group is algebraic,  $C$  is algebraic and hence  $C = \pi_2(W) = \overline{\pi_2(\Gamma')}$ . Therefore  $W = HC$ .  $\square$

## Global thickness of the return time to $\mathrm{RF} \mathcal{M}$

We recall the various notions of thick subsets of  $\mathbb{R}$ , following [McMullen et al. 2017; 2022].

**Definition 4.10** Fix  $k > 1$ .

- A closed subset  $T \subset \mathbb{R}$  is locally  $k$ -thick at  $t$  if, for any  $\lambda > 0$ ,

$$T \cap (t \pm [\lambda, k\lambda]) \neq \emptyset.$$

- A closed subset  $T \subset \mathbb{R}$  is  $k$ -thick if  $T$  is locally  $k$ -thick at 0.
- A closed subset  $T \subset \mathbb{R}$  is  $k$ -thick at  $\infty$  if

$$T \cap (\pm[\lambda, k\lambda]) \neq \emptyset$$

for all sufficiently large  $\lambda \gg 1$ .

- A closed subset  $T \subset \mathbb{R}$  is globally  $k$ -thick if  $T \neq \emptyset$  and  $T$  is locally  $k$ -thick at every  $t \in T$ .

We will frequently use the fact that, if  $T_i$  is a sequence of  $k$ -thick subsets, then  $\limsup T_i$  is also  $k$ -thick, and that, if  $T$  is  $k$ -thick, so is  $-T$ .

The following proposition shows that  $\mathrm{RF} \mathcal{M}$  has a thick return property under the action of any one-dimensional subgroup  $U$  of  $N$ :

**Proposition 4.11** *There exists a constant  $k > 1$ , depending only on the systole of the double of core  $\mathcal{M}$ , such that, for any one-parameter subgroup  $U = \{u_t : t \in \mathbb{R}\}$  of  $N^\pm$  and any  $y \in \mathrm{RF} \mathcal{M}$ ,*

$$T(y) := \{t \in \mathbb{R} : yu_t \in \mathrm{RF} \mathcal{M}\}$$

*is globally  $k$ -thick.*

**Proof** Let  $\eta > 0$  be the systole of the hyperbolic double of core  $\mathcal{M}$ , which is a closed hyperbolic manifold. Let  $k > 1$  be given by

$$(4-11) \quad d(\mathrm{hull}([-k, -1]), \mathrm{hull}([1, k])) = \frac{1}{4}\eta,$$

where  $d$  is the hyperbolic distance in the upper half-plane  $\mathbb{H}^2$ .

Note that

$$(4-12) \quad \inf_{i \neq j} d(\mathrm{hull} B_i, \mathrm{hull} B_j) \geq \frac{1}{2}\eta$$

as the geodesic realizing this distance is either a closed geodesic or half of a closed geodesic in the double of core  $\mathcal{M}$ .

We first prove the case when  $U < N$ . Let  $s \in T(y)$  be arbitrary. To show that  $T(y)$  is locally  $k$ -thick at  $s$ , we may assume that  $s = 0$ , by replacing  $y$  with  $yu_s \in \mathrm{RF} \mathcal{M}$ . We may also assume that  $y = [g]$ , where

$g(\infty) = \infty$  and  $g(0) = 0$ . As  $y \in \text{RF } \mathcal{M}$ , this implies that  $0, \infty \in \Lambda$ . Since  $gu_t(\infty) = g(\infty) \in \Lambda$ , we have

$$T(y) = \{t \in \mathbb{R} : gu_t(0) \in \Lambda\}.$$

Suppose that  $T(y)$  is not locally  $k$ -thick at 0. Then there exist  $w \in U$  and  $t > 0$  such that

$$([-kt, -t] \cdot w \cup [t, kt] \cdot w) \cap \Lambda = \emptyset.$$

Since each component of  $\Omega$  is convex and  $0 \notin \Omega$ , it follows that  $[-kt, -t] \cdot w$  and  $[t, kt] \cdot w$  lie in distinct components of  $\Omega$ , say  $B_i$  and  $B_j$  with  $i \neq j$ . But this yields

$$(4-13) \quad d_w(\text{hull}([-kt, -t] \cdot w), \text{hull}([t, kt] \cdot w)) \geq d(\text{hull } B_i, \text{hull } B_j) \geq \frac{1}{2}\eta,$$

where  $d_w$  denotes the hyperbolic distance of the plane above the line  $\mathbb{R}w$ . Observe that the distance in (4-13) is independent of  $w \in \mathbb{R}^{d-1}$  and  $t > 0$ , because both the dilation centered at 0 and the  $(d-2)$ -dimensional rotation with respect to the vertical axis above 0 are hyperbolic isometries. Therefore, we get a contradiction to (4-11). The case of  $U < N^+$  is proved similarly, just replacing the role of  $g^+$  and  $g^-$  in the above arguments.  $\square$

**Remark 4.12** It follows from the proof that  $k$  is explicitly given by (4-11) or, equivalently,  $k + k^{-1} = e^{\eta/4} + 2e^{\eta/8} - 1$ , where  $\eta > 0$  is the systole of the double of core  $\mathcal{M}$ .

## 5 Structure of singular sets

Let  $\Gamma < G = \text{SO}^\circ(d, 1)$  be a convex, cocompact, torsion-free, Zariski-dense subgroup. Let  $U < G$  be a connected closed subgroup of  $G$  generated by unipotent elements in it. In this section, we define the singular set  $\mathcal{S}(U)$  associated to  $U$  and study its structural properties. The singular set  $\mathcal{S}(U)$  is defined so that it contains all closed orbits of intermediate subgroups between  $U$  and  $G$ .

**Definition 5.1** (singular set) We set

$$\mathcal{S}(U) = \{x \in \Gamma \backslash G : \text{there exists a proper connected closed subgroup } W \supset U \text{ such that } xW \text{ is closed and } \text{Stab}_W(x) \text{ is Zariski-dense in } W\}.$$

**Definition 5.2** (definition of  $\mathcal{H}$ ) We denote by  $\mathcal{H}$  the collection of all *proper* connected closed subgroups  $H < G$  containing a unipotent element such that

- $\Gamma \backslash \Gamma H$  is closed, and
- $H \cap \Gamma$  is Zariski-dense in  $H$ .

**Proposition 5.3** If  $H \in \mathcal{H}$ , then  $H$  is a reductive subgroup of  $G$ , and hence is of the form  $gH(U)Cg^{-1}$  for some connected subgroup  $U < N$ , a closed subgroup  $C < C(H(U))$  and  $g \in G$  such that  $[g] \in \text{RF } \mathcal{M}$ .

**Proof** In order to prove that  $H$  is reductive, suppose not. Then its unipotent radical is nontrivial, which we can assume to be a subgroup  $U$  of  $N$ , up to a conjugation. Now we write  $H = H_{\text{nc}}CTU$ , where  $C$  is a connected semisimple compact subgroup and  $T$  is a torus centralizing  $H_{\text{nc}}C$ . As  $H$  is contained in  $N(U) = NAC_1(U)C_2(U)$ , which does not contain any noncompact simple Lie subgroup, it follows that  $H_{\text{nc}}$  is trivial. Now if  $T$  were compact, then  $H \cap \Gamma$  would consist of parabolic elements, which is a contradiction as  $\Gamma$  is convex cocompact. Hence  $T$  is noncompact. Write  $T = T_0S$ , where  $S$  is a split torus and  $T_0$  is compact. Then  $T_0$  is equal to a conjugate of  $A$ , say,  $g^{-1}Ag$  for some  $g \in G$ . As  $T_0$  normalizes  $U$ , and  $N(U)$  fixes  $\infty$ , we deduce that  $g(\infty)$  is either  $\infty$  or  $0$ . Since  $\text{Stab}_G(\infty) = NAM$ ,  $g(\infty) = \infty$  implies  $g \in NAM$ , and  $g(\infty) = 0$  implies  $gj \in NAM$ , where  $j \in G$  is an element of order 2 such that  $j(0) = \infty$ . In either case,  $T_0 = v^{-1}Av$  for some  $v \in N$ . By replacing  $H$  with  $vHv^{-1}$ , we may assume that  $T_0 = A$ . Since  $CS$  is a compact subgroup commuting with  $A$ ,  $CS \subset M$ . Therefore  $H$  is of the form  $M_0AU$ , where  $M_0$  is a closed subgroup of  $M \cap N(U)$ ; note that we used the fact that  $v$  commutes with  $U$ . Now the commutator subgroup  $[H, H]$  is equal to  $[M_0, M_0]U$ . Since  $[H \cap \Gamma, H \cap \Gamma]$  must be Zariski-dense in  $[H, H]$ , we deduce that  $\Gamma$  contains an element  $m_0u \in M_0U$  with  $u$  nontrivial. Since  $m_0u$  is a parabolic element of  $\Gamma$ , this is a contradiction to the assumption that  $\Gamma$  is convex cocompact. This proves that  $H$  is reductive.

By Proposition 3.7,  $H$  is of the form  $gH(U)Cg^{-1}$  for some  $g \in G$  and  $C < C(H(U))$ . For some  $m \in M$  and  $1 \leq k \leq d-2$ ,  $H(U) = mH(U_k)m^{-1}$ . Hence  $\Gamma \setminus \Gamma gmH(U_k)C_0$  is closed, where  $C_0 = m^{-1}Cm$ . By Proposition 3.9, the boundary of the geodesic plane  $\pi(gmH(U_k))$  contains uncountably many points of  $\Lambda$ , since  $(gm)H(U_k)C_0(gm)^{-1} \cap \Gamma$  is Zariski-dense in  $(gm)H(U_k)C_0(gm)^{-1}$ . Using two such limit points, we can find an element  $h \in H(U_k)$  such that  $(gmh)^\pm \in \Lambda$ . Since  $(gmhm^{-1})^\pm = (gmh)^\pm$  and  $mhm^{-1} \in H(U)$ , it follows that  $[g]H(U) \cap \text{RF}\mathcal{M} \neq \emptyset$ , and hence we can take  $[g] \in \text{RF}\mathcal{M}$  by modifying it with an element of  $H(U)$  if necessary.  $\square$

Therefore, for each  $H \in \mathcal{H}$ , the noncompact semisimple part  $H_{\text{nc}}$  of  $H$  is well defined.

**Proposition 5.4** *If  $H \in \mathcal{H}$ , then*

- $H \cap \Gamma$  is finitely generated;
- $[N_G(H_{\text{nc}}) \cap \Gamma : H \cap \Gamma] < \infty$ .

**Proof** Let  $p$  denote the projection map  $N_G(H_{\text{nc}}) \rightarrow H_{\text{nc}}$ . Note that  $p$  is an injective map on  $N_G(H_{\text{nc}}) \cap \Gamma$ , as  $\Gamma$  is torsion-free and the kernel of  $p$  is a compact subgroup. It follows from Proposition 5.3 that  $H_{\text{nc}}$  is cocompact in  $N_G(H_{\text{nc}})$ . Since  $H \in \mathcal{H}$ , the orbit  $[e]H$  is closed and hence  $[e]N_G(H_{\text{nc}})$  is closed. It follows that both  $p(H \cap \Gamma)$  and  $p(N_G(H_{\text{nc}}) \cap \Gamma)$  are convex cocompact Zariski-dense subgroups of  $H_{\text{nc}}$  by Proposition 3.9. As any convex cocompact subgroup is finitely generated [Bowditch 1993],  $p(H \cap \Gamma)$  is finitely generated. Hence  $H \cap \Gamma$  is finitely generated by the injectivity of  $p|_{H \cap \Gamma}$ .

Since  $p(H \cap \Gamma)$  is a normal subgroup of  $p(N_G(H_{\text{nc}}) \cap \Gamma)$ , it follows that  $p(H \cap \Gamma)$  has finite index in  $p(N_G(H_{\text{nc}}) \cap \Gamma)$  by [Lemma 5.5](#) below. Since  $p|_{N_G(H_{\text{nc}}) \cap \Gamma}$  is injective, it follows that  $H \cap \Gamma$  has finite index in  $N_G(H_{\text{nc}}) \cap \Gamma$ .  $\square$

**Lemma 5.5** *Let  $\Gamma_1$  and  $\Gamma_2$  be nonelementary convex cocompact subgroups of  $G$ . If  $\Gamma_2$  is a normal subgroup of  $\Gamma_1$ , then  $[\Gamma_1 : \Gamma_2] < \infty$ .*

**Proof** Let  $\Lambda_i$  be the limit set of  $\Gamma_i$  for  $i = 1, 2$ . Since  $\Gamma_2 < \Gamma_1$ ,  $\Lambda_2 \subset \Lambda_1$ . As  $\Gamma_2$  is normalized by  $\Gamma_1$ ,  $\Lambda_2$  is  $\Gamma_1$ -invariant. Since  $\Gamma_1$  is nonelementary,  $\Lambda_1$  is a minimal  $\Gamma_1$ -invariant closed subset. Hence  $\Lambda_1 = \Lambda_2$ . Let  $\mathcal{M}_i := \Gamma_i \backslash \mathbb{H}^d$ . Then the convex core of  $\mathcal{M}_1$  is equal to  $\Gamma_1 \backslash \text{hull}(\Lambda_2)$  and covered by core  $\mathcal{M}_2 = \Gamma_2 \backslash \text{hull}(\Lambda_2)$ . Since core  $\mathcal{M}_2$  is compact, it follows that  $[\Gamma_1 : \Gamma_2] < \infty$ .  $\square$

**Definition 5.6** (definition of  $\mathcal{H}^*$ ) We define

$$(5-1) \quad \mathcal{H}^* := \{N_G(H_{\text{nc}}) : H \in \mathcal{H}\}.$$

**Corollary 5.7** (countability) *The collection  $\mathcal{H}$  is countable, and the map  $H \rightarrow N_G(H_{\text{nc}})$  defines a bijection between  $\mathcal{H}$  and  $\mathcal{H}^*$ .*

**Proof** As  $\Gamma$  is convex cocompact, it is finitely generated. Therefore there are only countably many finitely generated subgroups of  $\Gamma$ . By [Proposition 5.4](#), there are only countably many possible  $H \cap \Gamma$  for  $H \in \mathcal{H}$ . Since  $H$  is determined by  $H \cap \Gamma$ , being its Zariski-closure, the first claim follows.

Since  $H \cap \Gamma$  has finite index in  $N_G(H_{\text{nc}}) \cap \Gamma$  by [Proposition 5.4](#),  $H$  is determined as the identity component of the Zariski-closure of  $N_G(H_{\text{nc}}) \cap \Gamma$ . This proves the second claim.  $\square$

In the case of a convex cocompact hyperbolic manifold of Fuchsian ends, there is a one-to-one correspondence between  $\mathcal{H}$  and the collection of all closed  $H'(U)$ -orbits of points in  $\text{RF}\mathcal{M}$  for  $U < N$ : if  $H \in \mathcal{H}$ , then  $H = gH(U)Cg^{-1}$  for some  $U < N$  and  $g \in G$  with  $[g] \in \text{RF}\mathcal{M}$  and  $[g]H'(U)$  is closed. Conversely, if  $[g]H'(U)$  is closed for some  $[g] \in \text{RF}\mathcal{M}$ , then the identity component of the Zariski-closure of  $\Gamma \cap gH'(U)g^{-1}$  is given by  $gH(U)Cg^{-1}$  for some closed subgroup  $C < C(H(U))$  by [Proposition 4.9](#), and hence  $gH(U)Cg^{-1} \in \mathcal{H}$ . Moreover, since the normalizer of  $H(U)C$  is contained in  $H'(U)$ , if  $g_1H(U)Cg_1^{-1} = g_2H(U)Cg_2^{-1}$ , then  $g_2^{-1}g_1 \in H'(U)$ , so  $[g_1]H'(U) = [g_2]H'(U)$ . Therefore [Corollary 5.7](#) implies the following corollary by [Propositions 3.9](#) and [4.9](#):

**Corollary 5.8** *Let  $\mathcal{M}$  be a convex cocompact hyperbolic manifold with Fuchsian ends. Then:*

- (1) *There are only countably many properly immersed geodesic planes of dimension at least 2 intersecting core  $\mathcal{M}$ .*
- (2) *For each  $1 \leq m \leq d - 2$ , there are only countably many spheres  $S \subset \mathbb{S}^{d-1}$  of dimension  $m$  such that  $\#S \cap \Lambda \geq 2$  and  $\Gamma S$  is closed in the space  $\mathcal{C}^m$ .*

**Remark 5.9** In (2), we may replace the condition  $\#S \cap \Lambda \geq 2$  with  $\#S \cap \Lambda \geq 1$ , because if  $\#S \cap \Lambda = 1$ , then  $\Gamma S$  is not closed (see [Remark 11.6](#)).



For a subgroup  $H < G$ , define

$$(5-2) \quad X(H, U) := \{g \in G : gUg^{-1} \subset H\}.$$

Note that  $X(H, U)$  is left  $N_G(H)$ - and right  $N_G(U)$ -invariant, and, for any  $g \in G$ ,

$$(5-3) \quad X(gHg^{-1}, U) = gX(H, U).$$

For  $H \in \mathcal{H}$  and any connected unipotent subgroup  $U < G$ , observe that

$$(5-4) \quad X(H, U) = X(H_{\text{nc}}, U) = X(N_G(H_{\text{nc}}), U);$$

this follows since any unipotent element of  $N_G(H_{\text{nc}})$  is contained in  $H_{\text{nc}}$ .

**Proposition 5.10** *We have*

$$\mathcal{S}(U) = \bigcup_{H \in \mathcal{H}^*} \Gamma \backslash \Gamma X(H, U).$$

**Proof** If  $x = [g] \in \mathcal{S}(U)$ , then there exists a proper connected closed subgroup  $W$  of  $G$  containing  $U$  such that  $[g]W$  is closed and  $\text{Stab}_W(x)$  is Zariski-dense in  $W$ . This means  $H := gWg^{-1} \in \mathcal{H}$  and  $g \in X(H, U)$ . Since  $X(H, U) = X(N_G(H_{\text{nc}}), U)$ , and  $N_G(H_{\text{nc}}) \in \mathcal{H}^*$ , this proves the inclusion  $\subset$ . Conversely, let  $g \in X(N_G(H_{\text{nc}}), U)$  for some  $H \in \mathcal{H}$ . Set  $W := g^{-1}Hg$ . Then  $U \subset W$ ,  $[g]W = \Gamma Hg$  is closed and  $\text{Stab}_W([g]) = g^{-1}(\Gamma \cap H)g$  is Zariski-dense in  $W$ . Hence  $[g] \in \mathcal{S}(U)$ .  $\square$

### Singular subset of a closed orbit

Let  $L < G$  be a connected reductive subgroup of  $G$  containing unipotent elements. For a closed orbit  $x_0L$  of  $x_0 \in \text{RF}\mathcal{M}$ , and a connected subgroup  $U_0 < L \cap N$ , we define the singular set  $\mathcal{S}(U_0, x_0L)$  by

$$(5-5) \quad \mathcal{S}(U_0, x_0L) = \{x \in x_0L : \text{there exists a connected closed subgroup } W < L \text{ containing } U_0 \\ \text{such that } \dim W_{\text{nc}} < \dim L_{\text{nc}}, xW \text{ is closed} \\ \text{and } \text{Stab}_W(x) \text{ is Zariski-dense in } W\}.$$

It follows from Propositions 5.10 and 5.3 that the subgroup  $W$  in Definition 5.1 is conjugate to  $H(\hat{U})C$  for some  $\hat{U} < N$ . Hence  $W$  being a proper subgroup of  $G$  is same as requiring  $\dim W_{\text{nc}} < \dim G$ . Therefore  $\mathcal{S}(U_0) = \mathcal{S}(U_0, \Gamma \backslash G)$  and

$$\mathcal{S}(U_0, x_0L) = x_0L \cap \bigcup \Gamma \backslash \Gamma X(H, U_0),$$

where the union is taken over all subgroups  $H \in \mathcal{H}^*$  such that  $H$  is a subgroup of  $g_0Lg_0^{-1}$  with  $\dim H_{\text{nc}} < \dim L_{\text{nc}}$  and  $x_0 = [g_0]$ . Equivalently,

$$(5-6) \quad \mathcal{S}(U_0, x_0L) = \bigcup_{W \in \mathcal{H}_{x_0L}^*} x_0(L \cap X(W, U_0)),$$

where  $\mathcal{H}_{x_0L}^*$  consists of all subgroups of the form  $W = g_0^{-1}Hg_0 \cap L$  for some  $H \in \mathcal{H}^*$  and  $\dim W_{\text{nc}} < \dim L_{\text{nc}}$ . Then the generic set  $\mathcal{G}(U_0, x_0L)$  is defined by

$$(5-7) \quad \mathcal{G}(U_0, x_0L) := (x_0L \cap \text{RF}_+\mathcal{M}) - \mathcal{S}(U_0, x_0L).$$

**Definition of  $\mathcal{L}_U$  and  $\mathfrak{L}_U$** 

Fix a nontrivial connected closed subgroup  $U < N$ . We define the collection  $\mathcal{L}_U$  of all subgroups of the form  $H(\widehat{U})C$ , where  $U < \widehat{U} < N$  and  $C$  is a closed subgroup of  $C(H(\widehat{U}))$  satisfying

$$(5-8) \quad \mathcal{L}_U := \{L = H(\widehat{U})C : \text{for some } [g] \in \text{RF}_+ \mathcal{M}, [g]L \text{ is closed in } \Gamma \backslash G \\ \text{and } L \cap g^{-1}\Gamma g \text{ is Zariski-dense in } L\}.$$

Observe that, for  $L = H(\widehat{U})C \neq G$ , the condition  $L \in \mathcal{L}_U$  with  $[g]L$  closed is equivalent to the condition that

$$gLg^{-1} \in \mathcal{H}.$$

**Lemma 5.11** *Let  $L_1$  and  $L_2$  be members of  $\mathcal{L}_U$  such that  $xL_1$  and  $xL_2$  are closed for some  $x \in \text{RF } \mathcal{M}$ . If  $(L_1)_{\text{nc}} = (L_2)_{\text{nc}}$ , then  $L_1 = L_2$ .*

**Proof** If  $L_1$  or  $L_2$  is equal to  $G$ , then the claim is trivial. Suppose that both  $L_1$  and  $L_2$  are proper subgroups of  $G$ . If  $x = [g]$ , then both subgroups  $H_1 := gL_1g^{-1}$  and  $H_2 := gL_2g^{-1}$  belong to  $\mathcal{H}$ . Since  $(H_1)_{\text{nc}} = (H_2)_{\text{nc}}$ , we have  $H_1 = H_2$  by [Corollary 5.7](#). Hence  $L_1 = L_2$ .  $\square$

We also define

$$(5-9) \quad \mathfrak{L}_U := \{vLv^{-1} : L \in \mathcal{L}_U, v \in N(U)\}.$$

Since  $N(U) = AN C_1(U) C_2(U)$  by [Lemma 3.2](#), and the collection  $\mathcal{L}_U$  is invariant under a conjugation by an element of  $AU C_1(U) C_2(U)$ , we have

$$(5-10) \quad \mathfrak{L}_U = \{vLv^{-1} : L \in \mathcal{L}_U, v \in U^\perp\}.$$

**Lemma 5.12** *For  $U_0 < U < N$ , we have*

$$X(H(U), U_0) = N_G(H(U)) N_G(U_0).$$

**Proof** Without loss of generality, we may assume  $U = U_m$  and  $U_0 = U_l$  with  $1 \leq l \leq m \leq d-1$ . Set  $H = H(U_m)$ . If  $m = d-1$ , then  $H = G$ , and the statement is trivial. Assume  $m \leq d-2$  below. We will prove the inclusion  $X(H, U_0) \subset N_G(H) N_G(U_0)$ , as the other one is clear. Let  $g \in X(H, U_0)$  be arbitrary. By multiplying  $g$  by an element of  $N_G(H)$  on the left as well as by an element of  $N_G(U_0)$  on the right, we will reduce  $g$  to an element of  $N_G(U_0)$ , which implies the claim. In view of the Iwasawa decomposition  $G = KAN$ , since  $AN < N_G(U_0)$ , we may assume that  $g = k \in K$ . As  $k \in X(H, U_0)$ , we have  $kU_0k^{-1} \subset H$ . Since  $K \cap H$  is a maximal compact subgroup of  $H$ , any maximal horospherical subgroups of  $H$  are conjugate to each other by an element of  $K \cap H$ . Hence there exists  $w \in K \cap H$  such that  $kU_0k^{-1} = wU_0w^{-1}$ .

Since  $w^{-1}kU_0 = U_0w^{-1}k$ , we deduce  $w^{-1}k(\infty) = U_0(w^{-1}k(\infty))$ . Since  $\infty \in \mathbb{S}^{d-1}$  is the unique fixed point of  $U_0$ ,  $w^{-1}k(\infty) = \infty$ . Hence  $w^{-1}k \in K \cap (MAN) = M$ . Since  $w \in H$ , we may now assume that  $k \in M$ . From  $kU_0 \subset Hk$ , we get  $kU_0(0) \subset Hk(0) = H(0)$  and hence  $\langle ke_1, \dots, ke_l \rangle \subset \langle e_1, \dots, e_m \rangle$ . By considering the action of  $H \cap K$  on space of  $l$ -tuples of orthonormal vectors in the subspace  $\langle e_1, \dots, e_m \rangle$ , we may assume  $ke_1 = e_1, \dots, ke_{l-1} = e_{l-1}$ , and  $ke_l = \pm e_l$ . This implies that  $k \in C_1(U_0)$ , or  $k\omega \in C_1(U_0)$ , where  $\omega \in M$  is an involution which fixes all  $e_i$  for  $i \neq l, l+1$  and  $\omega(e_i) = -e_i$  for  $i = l, l+1$ . As  $N_G(U_0)$  contains  $C_1(U_0)$  and  $\omega$ , the proof is complete.  $\square$

**Proposition 5.13** Consider a closed orbit  $x_0L$  for  $L \in \mathfrak{U}_U$  and  $x_0 \in \text{RF } \mathcal{M}$ . If  $x \in \mathcal{S}(U_0, x_0L)$  for a connected closed subgroup  $U_0 < U$ , then there exists a subgroup  $Q \in \mathfrak{U}_{U_0}$  such that

- $\dim Q_{\text{nc}} < \dim L_{\text{nc}}$ ;
- $xQ$  is closed;
- $\overline{xU_0} \subset xQ$ .

**Proof** If  $x = [g] \in \mathcal{S}(U_0, x_0L)$ , then  $g \in X(H, U_0)$  for some  $H \in \mathcal{H}$  such that  $\dim H_{\text{nc}} < \dim L_{\text{nc}}$ . Then  $\overline{xU_0} \subset x(g^{-1}Hg)$ . By Proposition 5.3,  $H = qH(\hat{U})Cq^{-1}$  for some  $U_0 < \hat{U} < L \cap N$  and some  $[q] \in \text{RF } \mathcal{M}$ . Note that  $q^{-1}g \in X(H(\hat{U}), U_0)$ . By Lemma 5.12, we have

$$q^{-1}g \in N_G(H(\hat{U}))N_G(U_0).$$

Hence  $g^{-1}Hg = vH(\hat{U})Cv^{-1}$  for some  $v \in N_G(U_0)$ , and  $\overline{xU_0} \subset xvH(\hat{U})Cv^{-1}$ . It suffices to set  $Q := vH(\hat{U})Cv^{-1}$ .  $\square$

**Lemma 5.14** Let  $L = H(\hat{U})C$  for a connected closed subgroup  $\hat{U} < N$  and closed subgroup  $C < C(H(\hat{U}))$ . Let  $W = g^{-1}H(\tilde{U})C_0g$  be a subgroup of  $L$ , where  $g \in L$ ,  $\tilde{U}$  is a proper connected closed subgroup of  $\hat{U}$ , and  $C_0$  is a closed subgroup of  $H(\tilde{U})$ . Then, for any nontrivial closed connected subgroup  $U < \hat{U}$ ,  $(L \cap X(W, U))H(U)$  is a nowhere-dense subset of  $L$ .

**Proof** Write  $g = hc \in H(\hat{U})C$ . Note that

$$\begin{aligned} L \cap X(W, U) &= L \cap X(g^{-1}H(\tilde{U})g, U) = L \cap X(h^{-1}H(\tilde{U})h, U) = h(L \cap X(H(\tilde{U}), U)) \\ &= h(H(\hat{U}) \cap X(H(\tilde{U}), U))C. \end{aligned}$$

Hence it suffices to show that  $(H(\hat{U}) \cap X(H(\tilde{U}), U))H(U)$  is a nowhere-dense subset of  $H(\hat{U})$ . Without loss of generality, we may now assume  $H(\hat{U}) = G$ . We observe that, using Lemma 5.12,

$$\begin{aligned} X(H(\tilde{U}), U)H(U) &= N_G(H(\tilde{U}))N_G(U)H(U) = H(\tilde{U})C_1(\tilde{U})AN C_1(U)C_2(U)H(U) \\ &= (K \cap H(\tilde{U}))U^\perp H'(U). \end{aligned}$$

Let  $\dim \tilde{U} = m$  and  $\dim U = k$ . If  $k \geq m$ , then  $X(W, U) = \emptyset$ . Hence we may assume that  $1 \leq k \leq m < d-1 = \dim N$ . Now, if we view the subset  $(K \cap H(\tilde{U}))U^\perp H'(U)/H'(U)$  in the space  $\mathbb{C}^k = G/H'(U)$ ,

this set is contained in the set of all spheres  $C \in \mathcal{C}^k$  which are tangent to the  $m$ -sphere given by  $S_0 := (K \cap H(\tilde{U}))(\infty)$ . Since  $m < d - 1$ , it follows that  $X(H(\tilde{U}), U)H(U)/H'(U)$  is a nowhere-dense subset of  $\mathcal{C}^k$ , and hence  $X(H(\tilde{U}), U)H(U)$  is a nowhere-dense subset of  $G$ .  $\square$

Recall from (4-1) that  $F = \text{RF}_+ \mathcal{M} \cdot H(U)$ .

**Lemma 5.15** *Let  $x_0 \hat{L}$  be a closed orbit of  $\hat{L} \in \mathcal{L}_U$  with  $x_0 \in \text{RF } \mathcal{M}$ . If  $U$  is a proper subgroup of  $\hat{L} \cap N$ , then  $\mathcal{S}(U, x_0 \hat{L}) \cdot H(U) \cap F_{H(U)}$  is a proper subset of  $x_0 \hat{L} \cap F_{H(U)}$ .*

**Proof** Choose  $g_0 \in G$  so that  $x_0 = [g_0]$ . Let  $p: G \rightarrow \Gamma \backslash G$  be the canonical projection map. Then  $p^{-1}(\mathcal{S}(U, x_0 \hat{L}) \cdot H(U))$  is a countable union  $\gamma g_0(\hat{L} \cap X(W, U))H(U)$ , where  $\gamma \in \Gamma$  and  $W \in \mathcal{H}_{x_0 \hat{L}}^*$  by (5-6). Hence, by Lemma 5.14,  $\mathcal{S}(U, x_0 \hat{L}) \cdot H(U)$  is a countable union of nowhere-dense subsets of  $x_0 L$ . Since  $F_{H(U)}^* \cap x_0 \hat{L}$  is an open subset of  $x_0 \hat{L}$ , it follows from the Baire category theorem that  $F_{H(U)}^* \cap x_0 \hat{L} \not\subset \mathcal{S}(U, x_0 \hat{L}) \cdot H(U)$ .  $\square$

The following geometric property of a convex cocompact hyperbolic manifold with Fuchsian ends is one of its key features which is needed in the proof of our main theorems stated in the introduction:

**Proposition 5.16** *Let  $\mathcal{M}$  be a convex cocompact hyperbolic manifold with Fuchsian ends. Let  $x_0 \hat{L}$  be a closed orbit of  $\hat{L} \in \mathcal{L}_U$  with  $x_0 \in \text{RF } \mathcal{M}$  and with  $\dim(\hat{L} \cap N) \geq 2$ . Either  $x_0 \hat{L}$  is compact or  $\mathcal{S}(U, x_0 \hat{L})$  contains a compact orbit  $zL_0$  with  $L_0 \in \mathcal{L}_U$ .*

**Proof** Write  $\hat{L} = H(\hat{U})C$  for a connected closed subgroup  $U < \hat{U} < N$ . Since  $x_0 \hat{L}$  is closed,  $\pi(x_0 \hat{L}) = \pi(x_0 H'(\hat{U}))$  is a properly immersed convex cocompact geodesic plane of dimension at least 3 with Fuchsian ends by Proposition 4.7. Suppose that  $x_0 L$  is not compact. Then  $\pi(x_0 L)$  has nonempty Fuchsian ends. This means that there exist a codimension one subgroup  $U_0$  of  $\hat{U}$  and  $z \in \hat{L}$  such that  $zH'(U_0)$  is compact and  $\pi(zH'(U_0))$  is a component of the core of  $\pi(x_0 \hat{L})$ . By Proposition 4.9, there exists a closed subgroup  $C_0 < C(H(U_0)) \cap \hat{L}$  such that  $H(U_0)C_0 \in \mathcal{L}_{U_0}$  and  $zH(U_0)C_0$  is compact. Let  $m \in M \cap \hat{L}$  be an element such that  $U \subset m^{-1}U_0m$ . Then  $zm(m^{-1}H(U_0)C_0m)$  is a compact orbit contained in  $\mathcal{S}(U, x_0 \hat{L})$  and  $m^{-1}H(U_0)C_0m \in \mathcal{L}_U$ .  $\square$

## 6 Inductive search lemma

In this section, we prove a combinatorial lemma, Lemma 6.4, which we call an *inductive search lemma*, and use it to prove Proposition 6.3 on the thickness of a certain subset of  $\mathbb{R}$ , constructed by the intersection of a global thick subset  $T$  and finite families of triples of subsets of  $\mathbb{R}$  with controlled regularity, degree and the multiplicity with respect to  $T$ . This proposition will be used in the proof of the avoidance theorem, Theorem 7.13, in the next section.

**Definition 6.1** Let  $J^* \subset I$  be a pair of open subsets of  $\mathbb{R}$ .

- The degree of  $(I, J^*)$  is defined to be the minimal  $\delta \in \mathbb{N} \cup \{\infty\}$  such that, for each connected component  $I^\circ$  of  $I$ , the number of connected components of  $J^*$  contained in  $I^\circ$  is bounded by  $\delta$ .
- For  $\beta > 0$ , the pair  $(I, J^*)$  is said to be  $\beta$ -regular if, for any connected component  $I^\circ$  of  $I$  and any component  $J^\circ$  of  $J^* \cap I^\circ$ ,

$$J^\circ \pm \beta \cdot |J^\circ| \subset I^\circ,$$

where  $|J^\circ|$  denotes the length of  $J^\circ$ .

**Definition 6.2** Let  $\mathcal{X}$  be a family of countably many triples  $(I, J^*, J')$  of open subsets of  $\mathbb{R}$  such that  $I \supset J^* \supset J'$ .

- Given  $\beta > 0$  and  $\delta \in \mathbb{N}$ , we say that  $\mathcal{X}$  is  $\beta$ -regular of degree  $\delta$  if, for every triple  $(I, J^*, J') \in \mathcal{X}$ , the pair  $(I, J^*)$  is  $\beta$ -regular with degree at most  $\delta$ .
- Given a subset  $T \subset \mathbb{R}$ , we say that  $\mathcal{X}$  is of  $T$ -multiplicity free if, for any two distinct triples  $(I_1, J_1^*, J_1')$  and  $(I_2, J_2^*, J_2')$  of  $\mathcal{X}$ , we have

$$I_1 \cap J_2' \cap T = \emptyset.$$

For a family  $\mathcal{X} = \{(I_\lambda, J_\lambda^*, J_\lambda') : \lambda \in \Lambda\}$ , we will use the notation

$$I(\mathcal{X}) := \bigcup_{\lambda \in \Lambda} I_\lambda, \quad J^*(\mathcal{X}) := \bigcup_{\lambda \in \Lambda} J_\lambda^* \quad \text{and} \quad J'(\mathcal{X}) := \bigcup_{\lambda \in \Lambda} J_\lambda'.$$

The goal of this section is to prove:

**Proposition 6.3** (thickness of  $T - J'(\mathcal{X})$ ) *Given  $n, k, \delta \in \mathbb{N}$ , there exists a positive number  $\beta_0 = \beta_0(n, k, \delta)$  for which the following holds: Let  $T \subset \mathbb{R}$  be a globally  $k$ -thick set, and let  $\mathcal{X}_1, \dots, \mathcal{X}_l$  with  $l \leq n$  be  $\beta_0$ -regular families of degree  $\delta$  and of  $T$ -multiplicity free. Let  $\mathcal{X} = \bigcup_{i=1}^l \mathcal{X}_i$ . If  $0 \in T - I(\mathcal{X})$ , then*

$$T - J'(\mathcal{X})$$

*is a  $2k$ -thick set.*

We prove [Proposition 6.3](#) using the inductive search lemma, [Lemma 6.4](#). The case of  $n = 1$  and  $\delta = 1$  is easy. As the formulation of the lemma is rather complicated in the general case, we first explain the simpler case of  $n = 2$  and  $\delta = 1$  in order to motivate the statement.

For simplicity, let us show that  $T - (J'(\mathcal{X}_1) \cup J'(\mathcal{X}_2))$  is  $4k$ -thick instead of  $2k$ -thick, given that  $\mathcal{X}_1$  and  $\mathcal{X}_2$  are  $8k^2$ -regular families of degree 1, and of  $T$ -multiplicity free. For any  $r > 0$ , we need to find a point

$$t \in \pm(r, 4kr) \cap (T - J'(\mathcal{X})),$$

where  $\mathcal{X} = \mathcal{X}_1 \cup \mathcal{X}_2$ ; see [Figure 3](#).

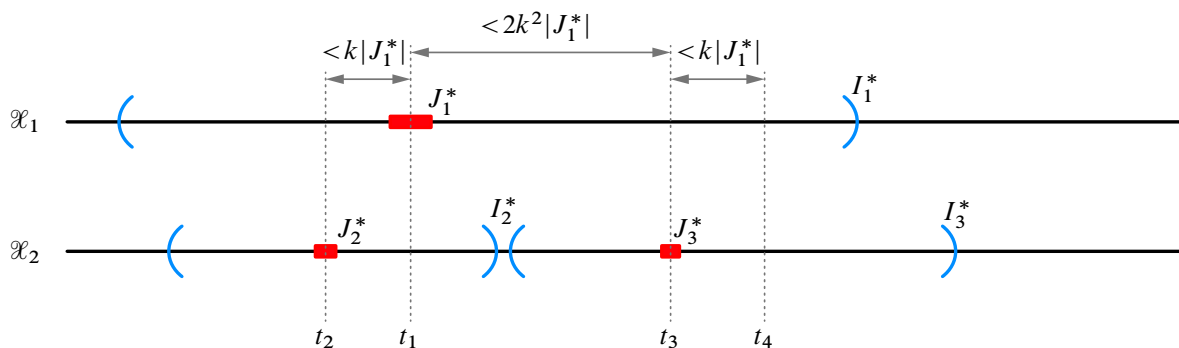


Figure 3

First, we know that there exists  $t_1 \in \pm(2r, 2kr) \cap \mathbb{T}$ , as  $\mathbb{T}$  is locally  $k$ -thick at 0. If  $t_1 \notin J'(\mathcal{X}_1) \cup J'(\mathcal{X}_2)$ , then we are done. So we assume that  $t_1 \in J'(\mathcal{X}_1)$ . Our strategy is then to search for a sequence in  $\mathbb{T}$  of length at most 4, starting with  $t_1$ , say  $(t_1, t_2, t_3, t_4)$ , such that

$$\frac{|t_{i-1}|}{\sqrt[3]{2}} \leq |t_i| \leq \sqrt[3]{2}|t_{i-1}| \quad \text{for each } i = 2, 3, 4,$$

and the last element  $t_4$  does not belong to  $J'(\mathcal{X})$ . This will imply  $\frac{1}{2}|t_1| \leq |t_4| \leq 2|t_1|$  and hence

$$t := t_4 \in \pm(r, 4kr) \cap (\mathbb{T} - J'(\mathcal{X})),$$

as desired, because  $2r \leq |t_1| \leq 2kr$ .

We next sketch how we find  $t_2$  from  $t_1$  and so on. Let  $t_1 \in J'_1$ , where  $(I_1, J_1^*, J'_1) \in \mathcal{X}_1$ . Since  $\mathbb{T}$  is locally  $k$ -thick at  $t_1$ , there exists

$$(6-1) \quad t_2 \in (t_1 \pm (|J_1^*|, k|J_1^*|)) \cap \mathbb{T}.$$

We will refer to  $t_1$  as a pivot for searching  $t_2$  in (6-1), as  $t_2$  was found in a symmetric interval around  $t_1$ . Note that  $t_2 \in I_1 - J_1^*$  as  $(I_1, J_1^*)$  is  $k$ -regular. This implies that  $t_2 \notin J'(\mathcal{X}_1)$  as the family  $\mathcal{X}_1$  is of  $\mathbb{T}$ -multiplicity free. Now we will assume  $t_2 \in J'_2$  for some triple  $(I_2, J_2^*, J'_2) \in \mathcal{X}_2$ , since otherwise  $t_2 \notin J'(\mathcal{X})$  and we are done.

To search for the next point  $t_3 \in \mathbb{T}$ , we choose our pivot between two candidates  $t_1$  and  $t_2$  as follows: we will choose  $t_1$  if  $|J_1^*| \geq |J_2^*|$ , and  $t_2$  otherwise. Without loss of generality, we will assume  $|J_1^*| \geq |J_2^*|$ . Since  $\mathbb{T}$  is locally  $k$ -thick at  $t_1$ , we can find

$$t_3 \in (t_1 \pm 2k(|J_1^*|, k|J_1^*|)) \cap \mathbb{T}.$$

Note that  $t_3 \in I_1 - J_1^*$  as the pair  $(I_1, J_1^*)$  is  $2k^2$ -regular. This implies  $t_3 \notin J'(\mathcal{X}_1)$  as  $\mathcal{X}_1$  is of  $\mathbb{T}$ -multiplicity free. Now we can assume that  $t_3 \in J'_3$  for some  $(I_3, J_3^*, J'_3) \in \mathcal{X}_2$ , otherwise we are done. One can check that  $J_3^*$  cannot coincide with  $J_2^*$ . We claim that  $|J_1^*| \geq |J_3^*|$ . Suppose not, i.e.  $|J_3^*| > |J_1^*|$ . Then we would have  $|t_2 - t_1| < k|J_3^*|$  and  $|t_1 - t_3| < 2k^2|J_3^*|$ , which implies that  $t_2 \in I_3$ ,

as the pair  $(I_3, J_3^*)$  is  $(2k^2+k)$ -regular. This is a contradiction as  $\mathcal{X}_2$  is  $\mathbb{T}$ -multiplicity free and hence  $J'_2 \cap I_3 \cap \mathbb{T} = \emptyset$ .

Finally, we will choose  $t_3$  as a pivot and search for  $t_4$ . By the local  $k$ -thickness of  $\mathbb{T}$  at  $t_3$ , we can find

$$t_4 \in (t_3 \pm (|J_3^*|, k|J_3^*|)) \cap \mathbb{T}.$$

Since the pair  $(I_3, J_3^*)$  is  $k$ -regular, we have  $t_4 \in I_3 - J_3^*$ . From the fact that the pair  $(I_1, J_1^*)$  is  $(2k^2+k)$ -regular, one can check that  $t_4 \in I_1 - J_1^*$ . As a result,  $t_4 \in (I_1 - J_1^*) \cup (I_3 - J_3^*)$  and hence  $t_4 \notin J'(\mathcal{X})$ .

It remains to check that  $|t_{i-1}|/\sqrt[3]{2} \leq |t_i| \leq \sqrt[3]{2}|t_{i-1}|$  for each  $i = 2, 3, 4$ . This does not necessarily hold for the current sequence, but will hold after passing to a subsequence where  $t_{i-1}$  becomes a pivot for searching  $t_i$  for all  $i$ . In the previous case,  $(t_1, t_3, t_4)$  will be such a subsequence, as  $t_2$  was not a pivot for searching  $t_3$ .

It follows from the  $\beta := 8k^2$ -regularity of  $(I_{i-1}, J_{i-1}^*)$  that  $|t_{i-1}| - 8k^2|J_{i-1}^*| > 0$ , as  $t_{i-1} \in J_{i-1}^*$  and  $0 \notin I_{i-1}$ . On the other hand, observe that

$$t_i \in t_{i-1} \pm C_i(|J_{i-1}^*|, k|J_{i-1}^*|) \cap \mathbb{T}$$

for some  $C_i \leq 2k^2$ . This gives us the desired upper bound for  $|t_i/t_{i-1}|$ , as

$$|t_i| < |t_{i-1}| + C_i|J_{i-1}^*| \leq (1 + C_i(8k^2)^{-1})|t_{i-1}|$$

and  $1 + C_i(8k^2)^{-1} \leq \sqrt[3]{2}$ . The lower bound is obtained similarly, completing the proof for  $n = 2$  and  $\delta = 1$ .

The general case reduces to the case of  $\delta = 1$ , by replacing  $n$  by  $n\delta$ . Roughly speaking, the following lemma gives an inductive argument for the search of a sequence of the  $t_i$  which is almost geometric in a sense that the ratio  $|t_i|/|t_{i-1}|$  is coarsely a constant and which lands on  $\mathbb{T} - J'(\mathcal{X})$  in a time controlled by  $n$ :

**Lemma 6.4** (inductive search lemma) *Let  $k > 1$ ,  $n \in \mathbb{N}$  and  $0 < \varepsilon < 1$  be fixed. There exists  $\beta = \beta(n, k, \varepsilon) > 0$  for which the following holds: Let  $\mathbb{T} \subset \mathbb{R}$  be a globally  $k$ -thick set, and let  $\mathcal{X}_1, \dots, \mathcal{X}_n$  be  $\beta$ -regular families of countably many triples  $(I_\lambda, J_\lambda^*, J'_\lambda)$  with degree 1, and of  $\mathbb{T}$ -multiplicity free. Set  $\mathcal{X} = \mathcal{X}_1 \cup \dots \cup \mathcal{X}_n$ , and assume  $0 \notin I(\mathcal{X})$ . For any  $t \in \mathbb{T} \cap J'(\mathcal{X})$  and any  $1 \leq r \leq n$ , we can find distinct triples  $(I_1, J_1^*, J'_1), \dots, (I_{m-1}, J_{m-1}^*, J'_{m-1}) \in \mathcal{X}$  with  $2 \leq m \leq 2^r$ , and a sequence of pivots*

$$t = t_1 \in \mathbb{T} \cap J'_1, \quad t_2 \in \mathbb{T} \cap J'_2, \quad \dots, \quad t_{m-1} \in \mathbb{T} \cap J'_{m-1}, \quad t_m \in \mathbb{T}$$

which satisfy the following conditions:

- (1) Either  $t_m \notin J'(\mathcal{X})$ , or  $t_m \in J'_m$  for some  $(I_m, J_m^*, J'_m) \in \mathcal{X}$ , which is distinct from  $(I_i, J_i^*, J'_i)$  for all  $1 \leq i \leq m-1$ , and the collection  $\{(I_i, J_i^*, J'_i) : 1 \leq i \leq m\}$  intersects at least  $r+1$  of the  $\mathcal{X}_i$ .

(2) For all  $1 \leq i \leq j \leq m$ ,

$$|t_i - t_j| \leq 2((4k)^r - 1)k \max_{1 \leq p \leq j-1} |J_p^*|;$$

(3) For each  $1 \leq i \leq m$ ,

$$(1 - \varepsilon)^{i-1} |t_1| \leq |t_i| \leq (1 + \varepsilon)^{i-1} |t_1|.$$

In particular, for any  $t \in \mathbb{T} \cap J'(\mathcal{X})$ , there exists  $t' \in \mathbb{T} - J'(\mathcal{X})$  such that

$$(1 - \varepsilon)^{2^n - 1} |t| \leq |t'| \leq (1 + \varepsilon)^{2^n - 1} |t|.$$

**Proof** We set

$$(6-2) \quad \beta = \beta(n, k, \varepsilon) = (4k)^{n+1} \varepsilon^{-1}.$$

Consider the increasing sequence  $Q(r) := (4k)^r - 1$  for  $r \in \mathbb{N}$ . Note that

$$Q(1) \geq 2 \quad \text{and} \quad Q(r+1) \geq 4Q(r)k + 1.$$

Moreover, we check that

$$\beta > \max((Q(n) + 4Q(n-1))k, Q(n)k\varepsilon^{-1}).$$

We proceed by induction on  $r$ . First consider the case when  $r = 1$ . There exists  $(I_1, J_1^*, J'_1) \in \mathcal{X}$  such that  $t_1 := t \in J'_1 \cap \mathbb{T}$ . As  $\mathbb{T}$  is globally  $k$ -thick, we can choose

$$(6-3) \quad t_2 \in (t_1 \pm Q(1)(|J_1^*|, k|J_1^*|)) \cap \mathbb{T}.$$

We claim that  $t_1, t_2$  is our desired sequence with  $m = 2$ . In the case when  $t_2 \in J'(\mathcal{X})$ , there exists  $(I_2, J_2^*, J'_2) \in \mathcal{X}$  such that  $t_2 \in J'_2$ . We check:

(1) If  $t_2 \in J'(\mathcal{X})$ , then  $t_2 \in J'_2 - J_1^*$  implies that  $J_1^*$  and  $J_2^*$  are distinct. Hence  $(I_1, J_1^*, J'_1)$  and  $(I_2, J_2^*, J'_2)$  are distinct as well. Since  $\beta > Q(1)k$ , by the  $\beta$ -regularity of  $(I_1, J_1^*)$ , we have  $t_2 \in I_1$ . By the  $\mathbb{T}$ -multiplicity free condition,  $(I_1, J_1^*, J'_1)$  and  $(I_2, J_2^*, J'_2)$  don't belong to the same family, that is,  $\{(I_1, J_1^*, J'_1), (I_2, J_2^*, J'_2)\}$  intersects two of the  $\mathcal{X}_i$ .

(2) By (6-3),  $|t_1 - t_2| < Q(1)k|J_1^*| = (4k - 1)k|J_1^*|$ .

(3) Note that  $0 \notin I_1$ , since  $0 \notin I(\mathcal{X})$ . By the  $\beta$ -regularity of  $(I_1, J_1^*)$ , we have  $t_1 \pm \beta|J_1^*| \subset I_1$ . Since  $0 \notin I_1$  and  $\beta > \varepsilon^{-1}Q(1)k$ , we have

$$|t_1| - \varepsilon^{-1}Q(1)k|J_1^*| > 0.$$

On the other hand, by (6-3),

$$|t_2 - t_1| \leq Q(1)k|J_1^*| \leq \varepsilon|t_1|.$$

In particular,

$$|t_2| \leq |t_1| + |t_2 - t_1| < |t_1| + Q(1)k|J_1^*| < (1 + \varepsilon)|t_1|,$$

$$|t_2| \geq |t_1| - |t_2 - t_1| > |t_1| - Q(1)k|J_1^*| > (1 - \varepsilon)|t_1|.$$

This proves the base case of  $r = 1$ .



Next, assume the induction hypothesis for  $r$ . Hence we have a sequence

$$t_1 (= t) \in J'_1, \quad t_2 \in J'_2, \quad \dots, \quad t_{m-1} \in J'_{m-1} \quad \text{and} \quad t_m$$

in  $\mathbb{T}$  with  $m \leq 2^r$  together with  $\{(I_i, J_i^*, J'_i) : 1 \leq i \leq m-1\}$  satisfying the three conditions listed in the lemma. If  $t_m \notin J'(\mathcal{X})$ , the same sequence would satisfy the hypothesis for  $r+1$  and we are done. Now we assume that  $t_m \in J'_m$  for some  $(I_m, J_m^*, J'_m) \in \mathcal{X}$ , and that  $\{(I_i, J_i^*, J'_i) : 1 \leq i \leq m\}$  intersect at least  $r+1$  of the  $\mathcal{X}_i$ . We may assume that they intersect exactly  $r+1$  of the  $\mathcal{X}_i$ , which we may label as  $\mathcal{X}_1, \dots, \mathcal{X}_{r+1}$ , since if they intersect more than  $r+1$  of them, we are already done. Choose a largest interval  $J_l^*$  among  $J_1^*, \dots, J_m^*$ . Again using the global  $k$ -thickness of  $\mathbb{T}$ , we can choose

$$(6-4) \quad s_1 \in (t_l \pm Q(r+1)(|J_l^*|, k|J_l^*|)) \cap \mathbb{T}.$$

First, consider the case when  $s_1 \notin J'(\mathcal{X})$ . We will show that the points  $t_1, \dots, t_m, s_1$  give the desired sequence. Indeed, the condition (1) is immediate. For (2), observe that, by the induction hypothesis for  $r$ , we have

$$|s_1 - t_i| \leq |s_1 - t_l| + |t_l - t_i| \leq (Q(r+1)k + 2Q(r)k)|J_l^*|$$

for all  $1 \leq i \leq m$ . The conclusion follows as  $Q(r+1) > 2Q(r)$ . To show (3), since  $\beta > \varepsilon^{-1}Q(r+1)k$  and  $0 \notin I_l$ , by applying the  $\beta$ -regularity to the pair  $(I_l, J_l^*)$ , we have

$$|t_l| - \varepsilon^{-1}Q(r+1)k|J_l^*| > 0.$$

It follows that

$$\begin{aligned} |s_1| &\leq |t_l| + |s_1 - t_l| < |t_l| + Q(r+1)k|J_l^*| < (1+\varepsilon)|t_l| \leq (1+\varepsilon)^m|t_1|, \\ |s_1| &\geq |t_l| - |s_1 - t_l| > |t_l| - Q(r+1)k|J_l^*| > (1-\varepsilon)|t_l| \geq (1-\varepsilon)^m|t_1|. \end{aligned}$$

This proves (3).

For the rest of the proof, we now assume that  $s_1 \in J'(\mathcal{X})$ . Apply the induction hypothesis for  $r$  to  $s_1 \in \mathbb{T} \cap J'(\mathcal{X})$  to obtain a sequence  $\{(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}'_j) \in \mathcal{X} : 1 \leq j \leq m'-1\}$  with  $m' \leq 2^r$  and

$$s_1 \in \tilde{J}'_1 \cap \mathbb{T}, \quad s_2 \in \tilde{J}'_2 \cap \mathbb{T}, \quad \dots, \quad s_{m'-1} \in \tilde{J}'_{m'-1} \cap \mathbb{T} \quad \text{and} \quad s_{m'} \in \mathbb{T}.$$

Set  $q_0$  to be the smallest  $1 \leq q \leq m'-1$  satisfying

$$(6-5) \quad \{(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}'_j) : 1 \leq j \leq q\} \not\subset \mathcal{X}_1 \cup \dots \cup \mathcal{X}_{r+1}$$

if it exists, and  $q_0 := m'$  otherwise. We claim that the sequence

$$(6-6) \quad t_1, \dots, t_m, s_1, \dots, s_{q_0}$$

of length  $m + q_0 \leq 2^{r+1}$  satisfies the conditions of the lemma for  $r+1$ .

**Claim** We have

$$(6-7) \quad |J_l^*| = \max_{1 \leq i \leq m, 1 \leq j \leq q_0-1} (|J_i^*|, |\tilde{J}_j^*|).$$

Recall that  $|J_l^*|$  was chosen to be maximal among  $|J_1^*|, \dots, |J_m^*|$ . Hence, if the claim does not hold, then we can take  $j$  to be the least number such that  $|\tilde{J}_j^*| > |J_l^*|$ . Then, by the induction hypothesis for (2),

$$|t_l - s_j| \leq |t_l - s_1| + |s_1 - s_j| \leq Q(r+1)k|J_l^*| + 2Q(r)k \max_{1 \leq l \leq j-1} |\tilde{J}_l^*| \leq (Q(r+1) + 2Q(r))k|J_l^*|.$$

Now the collection  $\{(I_i, J_i^*, J'_i) : 1 \leq i \leq m\}$  intersects  $r+1$  families  $\mathcal{X}_1, \dots, \mathcal{X}_{r+1}$  and  $(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}'_j)$  belongs to one of these families, as  $j \leq q_0 - 1$ . Hence there exists a triple  $(I_i, J_i^*, J'_i)$  that belongs to the same family as  $(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}'_j)$ . Recall that the induction hypothesis for  $t_1, \dots, t_m$  gives us

$$|t_l - t_i| \leq 2Q(r)k|J_l^*|.$$

Since  $\beta > (Q(r+1) + 4Q(r))k$ , we have

$$|t_i - s_j| \leq |t_i - t_l| + |t_l - s_j| \leq (Q(r+1) + 4Q(r))k|J_l^*| < \beta|\tilde{J}_j^*|.$$

Applying the  $\beta$ -regularity to the pair  $(\tilde{I}_j, \tilde{J}_j^*)$ , we conclude that

$$t_i \in \tilde{I}_j \cap J'_i \cap \mathbb{T}.$$

Since  $(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}'_j)$  and  $(I_i, J_i^*, J'_i)$  belong to the same family which is  $\mathbb{T}$ -multiplicity free, they are equal to each other. This is a contradiction since  $|\tilde{J}_j^*| > |J_l^*| \geq |J_i^*|$ , proving the claim (6-7).

We next prove that  $(I_i, J_i^*, J'_i)$  and  $(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}'_j)$  are distinct for all  $1 \leq i \leq m$  and  $1 \leq j \leq q_0 - 1$ . It suffices to check that  $J_i^*$  and  $\tilde{J}_j^*$  are distinct. Note that we have

$$\max_{1 \leq i, j \leq m} |t_i - t_j| < 2Q(r)k|J_l^*| \quad \text{and} \quad \max_{1 \leq i, j \leq q_0} |s_i - s_j| < 2Q(r)k|J_l^*|$$

by the induction hypothesis together with claim (6-7). Now, for  $t_i \in J_i^*$  ( $1 \leq i \leq m$ ) and  $s_j \in \tilde{J}_j^*$  ( $1 \leq j < q_0$ ), we estimate

$$\begin{aligned} (6-8) \quad |s_j - t_i| &\geq |s_1 - t_l| - |t_i - t_l| - |s_1 - s_j| \\ &> Q(r+1)|J_l^*| - 2Q(r)k|J_l^*| - 2Q(r)k|\tilde{J}_j^*| \\ &= (Q(r+1) - 4Q(r)k)|J_l^*| \\ &\geq |J_l^*|. \end{aligned}$$

This in particular means that  $s_j \notin J_i^*$  and  $t_i \notin \tilde{J}_j^*$ . Hence  $J_i^* \neq \tilde{J}_j^*$ .

We now begin checking the conditions (1), (2) and (3).

(1) If  $s_{q_0} \notin J'(\mathcal{X})$ , there is nothing to check.

Now assume that  $s_{q_0} \in \tilde{J}'_{q_0}$  for some  $(\tilde{I}_{q_0}, \tilde{J}_{q_0}^*, \tilde{J}'_{q_0}) \in \mathcal{X}$ . If  $q_0 < m'$ , then again there is nothing to prove, as the union

$$(6-9) \quad \{(I_i, J_i^*, J'_i) : 1 \leq i \leq m\} \cup \{(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}'_j) : 1 \leq j \leq q_0\}$$

intersects a family other than  $\mathcal{X}_1, \dots, \mathcal{X}_{r+1}$ . Hence we will assume  $q_0 = m'$ . By the induction hypothesis for  $r$  on the sequence  $(s_1, \dots, s_{m'})$ , the family  $\{(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}_j') : 1 \leq j \leq m'\}$  consists of pairwise distinct triples intersecting at least  $r + 1$  of the  $\mathcal{X}_i$ . Observe that in the estimate (6-8), there is no harm in allowing  $j = q_0$  in addition to  $j < q_0$ . This shows that  $\tilde{J}_{m'}^*$  is also distinct from all the  $J_i^*$ . Hence the triples in (6-9) are all distinct.

Now, unless the inclusion

$$(6-10) \quad \{(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}_j') : 1 \leq j \leq m'\} \subset \mathcal{X}_1 \cup \dots \cup \mathcal{X}_{r+1},$$

holds, we are done. Suppose that (6-10) holds. We will deduce a contradiction. Without loss of generality, we assume that

$$(I_l, J_l^*, J_l') \in \mathcal{X}_{r+1}.$$

We now claim that

$$(6-11) \quad \{(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}_j') : 1 \leq j \leq m'\} \subset \mathcal{X}_1 \cup \dots \cup \mathcal{X}_r.$$

Note that this gives the desired contradiction, since  $\{(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}_j') : 1 \leq j \leq m'\}$  must intersect at least  $r + 1$  of the  $\mathcal{X}_i$  by the induction hypothesis. In order to prove the inclusion (6-11), suppose on the contrary that  $(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}_j') \in \mathcal{X}_{r+1}$  for some  $1 \leq j \leq m'$ . Using  $\beta > (Q(r + 1) + 2Q(r))k$  and (6-7), we deduce

$$|t_l - s_j| \leq |t_l - s_1| + |s_1 - s_j| \leq Q(r + 1)k|J_l^*| + 2Q(r)k|J_l^*| < \beta|J_l^*|,$$

where we used the induction hypothesis for the sequence  $(s_1, \dots, s_{m'})$  in the second inequality to estimate the term  $|s_1 - s_j|$ .

Next, applying the  $\beta$ -regularity to the pair  $(I_l, J_l^*)$ , we conclude that  $s_j \in I_l$ . Since  $s_j \in \tilde{J}_j'$ , it follows that  $I_l \cap \tilde{J}_j' \cap \mathbb{T} \neq \emptyset$ . This contradicts the condition that  $\mathcal{X}_{r+1}$  is of  $\mathbb{T}$ -multiplicity free, as both  $(\tilde{I}_j, \tilde{J}_j^*, \tilde{J}_j')$  and  $(I_l, J_l^*, J_l')$  belong to the same family  $\mathcal{X}_{r+1}$ . This completes the proof of (1).

(2) For  $1 \leq i \leq m$  and  $1 \leq j \leq q_0$ , observe that

$$|t_i - s_j| \leq |t_i - t_l| + |t_l - s_1| + |s_1 - s_j| \leq 2Q(r)k|J_l^*| + Q(r + 1)k|J_l^*| + 2Q(r)k|J_l^*| < 2Q(r + 1)k|J_l^*|$$

as  $Q(r + 1) > 4Q(r)$ . Hence we get the desired result by (6-7).

(3) We already have observed that the inequality  $\beta > \varepsilon^{-1}Q(r + 1)k$  implies that

$$(1 - \varepsilon)^m |t_1| \leq |s_1| \leq (1 + \varepsilon)^m |t_1|.$$

Combining this with the induction hypothesis, we deduce that

$$(1 - \varepsilon)^{m+i-1} |t_1| \leq |s_i| \leq (1 + \varepsilon)^{m+i-1} |t_1|$$

for all  $1 \leq i \leq q_0$ .

Finally, the last statement of the lemma is obtained from the case  $r = n$ , since there are only  $n$  of the  $\mathcal{X}_i$ ; hence the second possibility of (1) cannot arise for  $r = n$ .  $\square$

**Proof of Proposition 6.3** We may assume that the  $\mathcal{X}_i$  are all of degree 1, by replacing each of the  $\mathcal{X}_i$  with  $\delta$  of the families associated to it.

We set

$$\beta_0(n, k, 1) = (4k)^{n+1} \varepsilon^{-1},$$

where  $\varepsilon$  satisfies  $((1 + \varepsilon)/(1 - \varepsilon))^{2^n - 1} \leq 2$ . Note that  $\beta_0(n, k, 1)$  is equal to the number given in (6-2).

We may assume  $x = 0$  without loss of generality. Let  $\lambda > 0$ . We need to find a point

$$(6-12) \quad t' \in ([-2k\lambda, -\lambda] \cup [\lambda, 2k\lambda]) \cap \left( \mathbb{T} - \bigcup_{i \in \Lambda} J'(\mathcal{X}_i) \right).$$

Choose  $s > 0$  such that

$$(6-13) \quad (1 - \varepsilon)^{-(2^n - 1)} \lambda \leq s \leq 2(1 + \varepsilon)^{-(2^n - 1)} \lambda.$$

Since  $\mathbb{T}$  is globally  $k$ -thick, there exists

$$t \in ([-ks, -s] \cup [s, ks]) \cap \mathbb{T}.$$

If  $t \notin \bigcup_{i=1}^n J'(\mathcal{X}_i)$ , then, by choosing  $t' = t$ , we are done. Now suppose  $t \in \bigcup_{i=1}^n J'(\mathcal{X}_i)$ . Since  $0 \notin \bigcup_{i=1}^n I(\mathcal{X}_i)$ , by applying Lemma 6.4 to  $t \in \mathbb{T} \cap (\bigcup_{i=1}^n J'(\mathcal{X}_i))$ , we obtain  $t' \in \mathbb{T} - \bigcup_{i=1}^n J'(\mathcal{X}_i)$  such that

$$(1 - \varepsilon)^{2^n - 1} |t| \leq |t'| \leq (1 + \varepsilon)^{2^n - 1} |t|.$$

Note that

$$|t'| \leq (1 + \varepsilon)^{2^n - 1} |t| \leq (1 + \varepsilon)^{2^n - 1} ks \leq 2k\lambda.$$

Similarly, we have

$$|t'| \geq (1 - \varepsilon)^{2^n - 1} |t| \geq (1 - \varepsilon)^{2^n - 1} s \geq \lambda.$$

This completes the proof since  $t'$  satisfies (6-12). □

## 7 Avoidance of the singular set

Let  $\Gamma < G$  be a convex cocompact nonelementary subgroup and let

$$U = \{u_t\} < N$$

be a one-parameter subgroup. Let  $\mathcal{S}(U)$ ,  $\mathcal{G}(U)$ ,  $X(H, U)$  and  $\mathcal{H}^\star$  be as defined in Section 5. In particular,  $\mathcal{S}(U)$  is a countable union

$$\mathcal{S}(U) = \bigcup_{H \in \mathcal{H}^\star} \Gamma \backslash \Gamma X(H, U).$$

The main goal of this section is to prove the avoidance theorem, Theorem 7.13, for any convex cocompact hyperbolic manifold with Fuchsian ends. For this, we extend the linearization method developed by Dani and Margulis [1993] to our setting. Via a careful analysis of the graded self-intersections of the

union  $\bigcup_i \Gamma \backslash \Gamma H_i D_i \cap \text{RF} \mathcal{M}$  for finitely many groups  $H_i \in \mathcal{H}^*$  and compact subsets  $D_i \subset X(H_i, U)$ , we construct families of triples of subsets of  $\mathbb{R}$  satisfying the conditions of [Proposition 6.3](#) relative to the global  $k$ -thick subset of the return time to  $\text{RF} \mathcal{M}$  under  $U$  given in [Proposition 4.11](#).

## Linearization

Let  $H \in \mathcal{H}^*$ . Then  $H$  is reductive, algebraic, and is equal to  $N_G(H)$  by [Proposition 5.3](#) and [3.1](#). There exists an  $\mathbb{R}$ -regular representation  $\rho_H: G \rightarrow \text{GL}(V_H)$  with a point  $p_H \in V_H$  such that  $H = \text{Stab}_G(p_H)$  and the orbit  $p_H G$  is Zariski-closed [[Borel and Harish-Chandra 1962](#), Theorem 3.5]. Since  $\Gamma \backslash \Gamma H$  is closed, it follows that

$$p_H \Gamma$$

is a closed (and hence discrete) subset of  $V_H$ .

Let  $\eta_H: G \rightarrow V_H$  denote the orbit map defined by

$$\eta_H(g) = p_H g \quad \text{for all } g \in G.$$

As  $H$  and  $U$  are algebraic subgroups, the set  $X(H, U) = \{g \in G : gUg^{-1} \subset H\}$  is Zariski-closed in  $G$ . Since  $p_H G$  is Zariski-closed in  $V_H$ , it follows that  $A_H := p_H X(H, U)$  is Zariski-closed in  $V_H$  and  $X(H, U) = \eta_H^{-1}(A_H)$ .

Following [[Kleinbock and Margulis 1998](#)], for given  $C > 0$  and  $\alpha > 0$ , a function  $f: \mathbb{R} \rightarrow \mathbb{R}$  is called  $(C, \alpha)$ -good if, for any interval  $I \subset \mathbb{R}$  and  $\varepsilon > 0$ , we have

$$\ell\{t \in I : |f(t)| \leq \varepsilon\} \leq C \cdot \left( \frac{\varepsilon}{\sup_{t \in I} |f(t)|} \right)^\alpha \cdot \ell(I),$$

where  $\ell$  is a Lebesgue measure on  $\mathbb{R}$ .

**Lemma 7.1** *For given  $C > 1$  and  $\alpha > 0$ , consider continuous functions  $p_1, p_2, \dots, p_k: \mathbb{R} \rightarrow \mathbb{R}$  satisfying the  $(C, \alpha)$ -good property. For  $0 < \delta < 1$ , set*

$$I = \{t \in \mathbb{R} : \max_i |p_i(t)| < 1\} \quad \text{and} \quad J(\delta) = \{t \in \mathbb{R} : \max_i |p_i(t)| < \delta\}.$$

*For any  $\beta > 1$ , there exists  $\delta = \delta(C, \alpha, \beta) > 0$  such that the pair  $(I, J(\delta))$  is  $\beta$ -regular (see [Definition 6.2](#)).*

**Proof** We prove that the conclusion holds for  $\delta := ((1 + \beta)C)^{-1/\alpha}$ . First, note that the function  $q(t) := \max_i |p_i(t)|$  also has the  $(C, \alpha)$ -good property. Let  $J' = (a, b)$  be a component of  $J(\delta)$ , and  $I'$  be the component of  $I$  containing  $J'$ . Note that  $I'$  is an open interval and  $(a, \infty) \cap I' = (a, c)$  for some  $b \leq c \leq \infty$ . We claim

$$(7-1) \quad J' + \beta |J'| \subset (a, \infty) \cap I' \subset I'.$$

We may assume that  $c < \infty$ ; otherwise the inclusion is trivial. We claim that  $q(c) = 1$ . Since  $\{t \in \mathbb{R} : q(t) < 1\}$  is open and  $c$  is the boundary point of  $I'$ , we have  $q(c) \geq 1$ . If  $q(c)$  were strictly

bigger than 1, since  $\{t \in \mathbb{R} : q(t) > 1\}$  is open,  $I'$  would be disjoint from an open interval around  $c$ , which is impossible. Hence  $q(c) = 1$ . Now that  $\sup\{q(t) : t \in (a, \infty) \cap I'\} = q(c) = 1$ , by applying the  $(C, \alpha)$ -good property of  $q$  on the interval  $(a, \infty) \cap I'$ , we get

$$\ell(J') \leq \ell\{t \in (a, \infty) \cap I' : |q(t)| \leq \delta\} \leq C\delta^\alpha \cdot \ell((a, \infty) \cap I').$$

Now, as  $J' = (a, b)$  and  $(a, \infty) \cap I'$  are nested intervals with one common endpoint, it follows from the equality  $C\delta^\alpha = 1/(1 + \beta)$  that

$$J' + \beta|J'| \subset (a, \infty) \cap I' \subset I',$$

proving (7-1). Similarly, applying the  $(C, \alpha)$ -good property of  $q$  on  $(-\infty, b) \cap I'$ , we deduce that

$$J' - \beta|J'| \subset I'.$$

This proves that  $(I, J(\delta))$  is  $\beta$ -regular.  $\square$

**Proposition 7.2** *Let  $V$  be a finite-dimensional real vector space,  $\theta \in \mathbb{R}[V]$  be a polynomial and  $A = \{v \in V : \theta(v) = 0\}$ . Then, for any compact subset  $D \subset A$  and any  $\beta > 0$ , there exists a compact neighborhood  $D' \subset A$  of  $D$  which has a  $\beta$ -regular size with respect to  $D$  in the following sense: for any neighborhood  $\Phi$  of  $D'$ , there exists a neighborhood  $\Psi \subset \Phi$  of  $D$  such that, for any  $q \in V - \Phi$  and for any one-parameter unipotent subgroup  $\{u_t\} \subset \text{GL}(V)$ , the pair  $(I(q), J(q))$  is  $\beta$ -regular, where*

$$I(q) = \{t \in \mathbb{R} : qu_t \in \Phi\} \quad \text{and} \quad J(q) = \{t \in \mathbb{R} : qu_t \in \Psi\}.$$

Furthermore, the degree of  $(I(q), J(q))$  is at most  $(\deg \theta + 2) \cdot \dim V$ .

**Proof** Choose a norm on  $V$  so that  $\|\cdot\|^2$  is a polynomial function on  $V$ . Since  $D$  is compact, we can find  $R > 0$  such that

$$D \subset \{v \in V : \|v\| < R\}.$$

Then we set

$$D' = \{v \in V : \theta(v) = 0, \|v\| < R/\sqrt{\delta}\},$$

where  $0 < \delta < 1$  is to be specified later. Note that, if  $\Phi$  is a neighborhood of  $D'$ , there exists  $0 < \eta < 1$  such that

$$\{v \in V : \theta(v) < \eta, \|v\| < (R + \eta)/\sqrt{\delta}\} \subset \Phi.$$

We will take  $\Psi$  to be

$$\Psi = \{v \in V : \theta(v) < \eta\delta, \|v\| < (R + \eta)\}.$$

Set

$$\tilde{I}(q) = \{t \in \mathbb{R} : \theta(qu_t) < \eta, \|qu_t\| < (R + \eta)/\sqrt{\delta}\}.$$

Since  $\tilde{I}(q) \subset I(q)$  for  $0 < \delta < 1$ , it suffices to find  $\delta$  (and hence  $D'$  and  $\Psi$ ) such that the pair  $(\tilde{I}(q), J(q))$  is  $\beta$ -regular. If we set

$$\psi_1(t) := \frac{\theta(qu_t)}{\eta} \quad \text{and} \quad \psi_2(t) := \left( \frac{\|qu_t\|\sqrt{\delta}}{R + \eta} \right)^2,$$

then

$$\tilde{I}(q) = \{t \in \mathbb{R} : \max(\psi_1(t), \psi_2(t)) < 1\}, \quad J(q) = \{t \in \mathbb{R} : \max(\psi_1(t), \psi_2(t)) < \delta\}.$$

As  $\psi_1$  and  $\psi_2$  are polynomials, they have the  $(C, \alpha)$ -property for an appropriate choice of  $C$  and  $\alpha$ . Therefore, by applying [Lemma 7.1](#), by choosing  $\delta$  small enough, we can make the pair  $(\tilde{I}(q), J(q))$   $\beta$ -regular for any  $\beta > 0$ . Note that the degrees of  $\psi_1$  and  $\psi_2$  are bounded by  $\deg \theta \cdot \dim V$  and  $2 \dim V$ , respectively. Therefore  $J(q)$  cannot have more than  $(\deg \theta + 2) \cdot \dim V$  components.  $\square$

### Collection $\mathcal{E}_U$

Recall the collection  $\mathcal{H}^\star$  and the singular set

$$\mathcal{S}(U) = \bigcup_{H \in \mathcal{H}^\star} \Gamma \backslash \Gamma X(H, U).$$

**Definition 7.3** We define  $\mathcal{E} = \mathcal{E}_U$  to be the collection of all compact subsets of  $\mathcal{S}(U) \cap \text{RF } \mathcal{M}$  which can be written as

$$(7-2) \quad E = \bigcup_{i \in \Lambda} \Gamma \backslash \Gamma H_i D_i \cap \text{RF } \mathcal{M},$$

where  $\{H_i \in \mathcal{H}^\star : i \in \Lambda\}$  is a finite collection and  $D_i \subset X(H_i, U)$  is a compact subset. In this expression, we always use the minimal index set  $\Lambda$  for  $E$ . When  $E$  is of the form (7-2), we will say that  $E$  is associated to the family  $\{H_i : i \in \Lambda\}$ .

**Remark 7.4** We note that  $E$  can also be expressed as  $\bigcup_{i \in \Lambda} \Gamma \backslash \Gamma H_i D_i \cap \text{RF } \mathcal{M}$ , where  $H_i \in \mathcal{H}$  is a finite collection and  $D_i \subset X(H_i, U)$  is a compact subset which is left  $C(H_i)$ -invariant.

**Lemma 7.5** In the expression (7-2) for  $E \in \mathcal{E}$ , the collection  $\{H_i : i \in \Lambda\}$  is not redundant, in the sense that:

- No  $\gamma H_j \gamma^{-1}$  is equal to  $H_i$  for all triples  $(i, j, \gamma) \in \Lambda \times \Lambda \times \Gamma$  except for the trivial cases of  $i = j$  and  $\gamma \in H_i$ .

**Proof** Observe that, if  $\gamma H_j \gamma^{-1} = H_i$  for some  $\gamma \in \Gamma$ , then  $\Gamma H_j D_j = \Gamma H_i \gamma D_j$ , and hence, by replacing  $D_i$  by  $D_i \cup \gamma D_j \subset X(H_i, U)$ , we may remove  $j$  from the index subset  $\Lambda$ . This contradicts the minimality of  $\Lambda$ .  $\square$

Observe that, for any subgroups  $H_1$  and  $H_2$  of  $G$  and  $g \in G$ ,

$$X(H_1 \cap g H_2 g^{-1}, U) = X(H_1, U) \cap X(g H_2 g^{-1}, U) = X(H_1, U) \cap g X(H_2, U).$$

Note that, for  $D_i \subset X(H_i, U)$  and  $\gamma \in \Gamma$ , the intersection  $H_1 D_1 \cap \gamma H_2 D_2$  only depends on the  $(\Gamma \cap H_1, \Gamma \cap H_2)$ -double coset of  $\gamma$ .

**Proposition 7.6** Let  $H_1, H_2 \in \mathcal{H}^\star$ . Then, for any compact subset  $D_i \subset X(H_i, U)$  for  $i = 1, 2$  and a compact subset  $K \subset \Gamma \backslash G$ , there exists a finite set  $\Delta \subset (H_1 \cap \Gamma) \backslash \Gamma / (H_2 \cap \Gamma)$  such that

$$\{K \cap \Gamma \backslash \Gamma (H_1 D_1 \cap \gamma H_2 D_2)\}_{\gamma \in \Gamma} = \{K \cap \Gamma \backslash \Gamma (H_1 D_1 \cap \gamma H_2 D_2)\}_{\gamma \in \Delta},$$

where the latter set consists of distinct elements.

Moreover, for each  $\gamma \in \Delta$ , there exists a compact subset  $C_0 \subset H_1 D_1 \cap \gamma H_2 D_2 \subset X(H_1 \cap \gamma H_2 \gamma^{-1}, U)$  such that

$$K \cap \Gamma \backslash \Gamma(H_1 D_1 \cap \gamma H_2 D_2) = \Gamma \backslash \Gamma C_0.$$

**Proof** For simplicity, write  $\eta_{H_i} = \eta_i$  and  $p_i = p_{H_i}$ . Let  $K_0 \subset G$  be a compact set such that  $K = \Gamma \backslash \Gamma K_0$ . We fix  $\gamma \in \Gamma$ , and define, for any  $\gamma' \in \Gamma$ ,

$$K_{\gamma'} = \{g \in K_0 : \gamma' g \in H_1 D_1 \cap \gamma H_2 D_2\}.$$

We check that

$$K \cap \Gamma \backslash \Gamma(H_1 D_1 \cap \gamma H_2 D_2) = \Gamma \backslash \Gamma \left( \bigcup_{\gamma' \in \Gamma} K_{\gamma'} \right).$$

If this set is nonempty, then  $K_{\gamma'} \neq \emptyset$  for some  $\gamma' \in \Gamma$  and

$$p_1 \gamma' g \in p_1 D_1, \quad p_2 \gamma'^{-1} \gamma' g \in p_2 D_2$$

for some  $g \in K_0$ . In particular,

$$(7-3) \quad p_1 \gamma' \in p_1 D K_0^{-1}, \quad p_2 \gamma'^{-1} \in p_2 D K_0^{-1} \gamma'^{-1}.$$

As  $p_1 \Gamma$  is discrete and  $p_1 D_1 K_0^{-1}$  is compact, the first condition of (7-3) implies that there exists a finite set  $\Delta_0 \subset G$  such that  $\gamma' \in (H_1 \cap \Gamma) \Delta_0$ . Writing  $\gamma' = h \delta_0$ , where  $h \in H_1 \cap \Gamma$  and  $\delta_0 \in \Delta_0$ , the second condition of (7-3) implies

$$p_2 \gamma'^{-1} h \in p_2 D_2 K_0^{-1} \delta_0^{-1}.$$

As  $p_2 D_2 K_0^{-1} \Delta_0^{-1}$  is compact and  $p_2 \Gamma$  is discrete, there exists a finite set  $\Delta \subset G$  such that  $\gamma'^{-1} h \in (H_2 \cap \Gamma) \Delta$ . Hence, if  $K \cap \Gamma \backslash \Gamma(H_1 D_1 \cap \gamma H_2 D_2) \neq \emptyset$ , then  $\gamma \in (H_1 \cap \Gamma) \Delta (H_2 \cap \Gamma)$ . This completes the proof of the first claim.

For the second claim, it suffices to set  $C_0 := \bigcup_{\gamma' \in \Delta} K_{\gamma'}$ . □

**Proposition 7.7** *Let  $H_1, H_2 \in \mathcal{H}^*$  be such that  $H_1 \cap H_2$  contains a unipotent element. Then there exists a unique smallest connected closed subgroup, say  $H_0$ , of  $H_1 \cap H_2$  containing all unipotent elements of  $H_1 \cap H_2$  such that  $\Gamma \backslash \Gamma H_0$  is closed. Moreover,  $H_0 \in \mathcal{H}$ .*

**Proof** The orbit  $\Gamma \backslash \Gamma(H_1 \cap H_2)$  is closed [Shah 1991b, Lemma 2.2]. Hence such  $H_0$  exists. We need to show that  $\Gamma \cap H_0$  is Zariski-dense in  $H_0$ . Let  $L$  be the subgroup of  $H_0$  generated by all unipotent elements in  $H_0$ . Note that  $L$  is a normal subgroup of  $H_0$  and hence  $(H_0 \cap \Gamma)L$  is a subgroup of  $H_0$ . If  $F$  is the identity component of the closure of  $(H_0 \cap \Gamma)L$ , then  $\Gamma \backslash \Gamma F$  is closed. By the minimality assumption on  $H_0$ , we have  $F = H_0$ . Hence  $\overline{(H_0 \cap \Gamma)L} = H_0$ ; so  $\overline{[e]L} = [e]H_0$ . We can then apply [Shah 1991b, Corollary 2.12] and deduce the Zariski-density of  $H_0 \cap \Gamma$  in  $H_0$ . □

**Corollary 7.8** *Let  $H_1, H_2 \in \mathcal{H}^*$  and  $\gamma \in \Gamma$  be satisfying that  $X(H_1 \cap \gamma H_2 \gamma^{-1}, U) \neq \emptyset$ . Then there exists a subgroup  $H \in \mathcal{H}^*$  contained in  $H_1 \cap \gamma H_2 \gamma^{-1}$  such that, for any compact subsets  $D_i \subset X(H_i, U)$  for  $i = 1, 2$  there exists a compact subset  $D_0 \subset X(H, U)$  such that*

$$K \cap \Gamma \backslash \Gamma(H_1 D_1 \cap \gamma H_2 D_2) = K \cap \Gamma \backslash \Gamma H D_0.$$



**Proof** Let  $F \in \mathcal{H}$  be as given by [Proposition 7.7](#) for the subgroup  $H_1 \cap \gamma H_2 \gamma^{-1}$ . Set  $H := N_G(F_{\text{nc}}) \in \mathcal{H}^*$ . Note that  $X(H_1 \cap \gamma H_2 \gamma^{-1}, U) = X(H, U)$ . Hence, by the second claim of [Proposition 7.6](#), there exists a compact subset  $D_0 \subset H_1 D_1 \cap \gamma H_2 D_2$  such that

$$(7-4) \quad K \cap \Gamma \backslash \Gamma(H_1 D_1 \cap \gamma H_2 D_2) = \Gamma \backslash \Gamma D_0.$$

We claim that

$$\Gamma \backslash \Gamma D_0 = K \cap \Gamma \backslash \Gamma H D_0.$$

The inclusion  $\subset$  is clear. Let  $g := hd \in HD_0$  with  $h \in H$  and  $d \in D_0$ , and  $[g] \in K$ . Then, by the condition on  $D_0$ , we have  $g \in H_1 D_1$  and  $\gamma^{-1}g \in H_2 D_2$ . Therefore  $g \in H_1 D_1 \cap \gamma H_2 D_2$ . By (7-4), this proves the inclusion  $\supset$ .  $\square$

**Definition 7.9** (self-intersection operator on  $\mathcal{E}_U$ ) We define an operator

$$s: \mathcal{E}_U \cup \{\emptyset\} \rightarrow \mathcal{E}_U \cup \{\emptyset\}$$

as follows: We set  $s(\emptyset) = \emptyset$ . For any

$$(7-5) \quad E = \bigcup_{i \in \Lambda} \Gamma \backslash \Gamma H_i D_i \cap \text{RF } \mathcal{M} \in \mathcal{E}_U,$$

we define

$$s(E) := \bigcup_{i,j \in \Lambda} \bigcup_{\gamma_{ij} \in \Gamma} \Gamma \backslash \Gamma(H_i D_i \cap \gamma_{ij} H_j D_j) \cap \text{RF } \mathcal{M},$$

where  $\gamma_{ij} \in \Gamma$  ranges over all elements of  $\Gamma$  satisfying

$$\dim(H_i \cap \gamma_{ij} H_j \gamma_{ij}^{-1})_{\text{nc}} < \min\{\dim(H_i)_{\text{nc}}, \dim(H_j)_{\text{nc}}\}.$$

By [Proposition 7.6](#) and [Corollary 7.8](#), we have:

**Corollary 7.10** (1) For  $E \in \mathcal{E}_U$ , we have  $s(E) \in \mathcal{E}_U$ .

(2) For  $E_1, E_2 \in \mathcal{E}_U$ , we have  $E_1 \cap E_2 \in \mathcal{E}_U$ .

Hence, for  $E \in \mathcal{E}_U$  as in (7-5),  $s(E)$  is of the form

$$s(E) = \bigcup_{i \in \Lambda'} \Gamma \backslash \Gamma H_i D_i \cap \text{RF } \mathcal{M},$$

where  $\Lambda'$  is a (minimal) finite-index set,  $H_i \in \mathcal{H}$  with  $X(H_i, U) \neq \emptyset$  and

$$\max\{\dim(H_i)_{\text{nc}} : i \in \Lambda'\} < \max\{\dim(H_i)_{\text{nc}} : i \in \Lambda\}.$$

Hence,  $s$  maps  $\mathcal{E}_U$  to  $\mathcal{E}_U \cup \{\emptyset\}$  and, for any  $E \in \mathcal{E}_U$ ,

$$s^{\dim G}(E) = \emptyset.$$

**Definition 7.11** For a compact subset  $K \subset \Gamma \backslash G$  and  $E \in \mathcal{E}_U$ , we say that  $K$  does not have any self-intersection point of  $E$ , or simply say that  $K$  is  $E$ -self-intersection-free, if

$$K \cap s(E) = \emptyset.$$

**Proposition 7.12** Let  $E = \bigcup_{i \in \Lambda} \Gamma \backslash \Gamma H_i D_i \cap \text{RF} \mathcal{M} \in \mathcal{E}$ , where  $D_i \subset X(H_i, U)$  is a compact subset and  $\Lambda$  is a finite subset. Let  $K \subset \text{RF} \mathcal{M}$  be a compact subset which is  $E$ -self-intersection-free. Then there exists a collection of open neighborhoods  $\Omega_i$  of  $D_i$  for  $i \in \Lambda$  such that, for  $\mathbb{O} := \bigcup_{i \in \Lambda} \Gamma \backslash \Gamma H_i \Omega_i$ , the compact subset  $K$  is  $\mathbb{O}$ -self-intersection-free, in the sense that, if  $\dim H_i = \dim H_j$  and

$$K \cap \Gamma \backslash \Gamma (H_i \Omega_i \cap \gamma H_j \Omega_j) \neq \emptyset$$

for some  $(i, j, \gamma) \in \Lambda \times \Lambda \times \Gamma$ , then  $i = j$  and  $\gamma \in H_i \cap \Gamma$ .

**Proof** For each  $k \in \mathbb{N}$  and  $i \in \Lambda$ , let  $\Omega_i(k)$  be the  $1/k$ -neighborhood of the compact subset  $D_i$ . Since  $\Lambda$  is finite, if the proposition does not hold, by passing to a subsequence, there exist  $i, j \in \Lambda$  with  $\dim H_i = \dim H_j$  and a sequence  $\gamma_k \in \Gamma$  such that

$$K \cap \Gamma \backslash \Gamma (H_i \Omega_i(k) \cap \gamma_k H_j \Omega_j(k)) \neq \emptyset$$

and

$$(7-6) \quad (i, j, \gamma_k) \notin \{(i, i, \gamma) : i \in \Lambda, \gamma \in H_i \cap \Gamma\}.$$

Hence there exist  $g_k = h_k w_k \in H_i \Omega_i(k)$  and  $g'_k = h'_k w'_k \in H_j \Omega_j(k)$  such that  $g_k = \gamma_k g'_k$ , where  $[g_k] \in K$ . Now, as  $k \rightarrow \infty$ , we have  $w_k \rightarrow w \in D_i$  and  $w'_k \rightarrow w' \in D_j$ . There exists  $\delta_k \in \Gamma$  such that  $\delta_k g_k \in \tilde{K}$ , where  $\tilde{K}$  is a compact subset of  $G$  such that  $K = \Gamma \backslash \Gamma \tilde{K}$ , so the sequence  $\delta_k g_k$  converges to  $g_0$  as  $k \rightarrow \infty$ . Since  $\Gamma H_i$  and  $\Gamma H_j$  are closed, we have  $\delta_k h_k \rightarrow \delta_0 h_i$  and  $\delta_k \gamma_k h'_k \rightarrow \delta'_0 h_j$ , where  $\delta_0, \delta'_0 \in \Gamma$ ,  $h_i \in H_i$  and  $h_j \in H_j$ . As  $\Gamma[H_i]$  and  $\Gamma[H_j]$  are discrete in the spaces  $G/H_i$  and  $G/H_j$ , respectively, we have

$$(7-7) \quad \delta_0^{-1} \delta_k \in H_i \quad \text{and} \quad (\delta'_0)^{-1} \delta_k \gamma_k \in H_j$$

for all sufficiently large  $k$ . Therefore  $g_0 = \delta_0 h_i w = \delta'_0 h_j w' \in \delta_0 (H_i D_i \cap \delta_0^{-1} \delta'_0 H_j D_j)$  and  $[g_0] \in K$ . Hence

$$K \cap \Gamma \backslash \Gamma (H_i D_i \cap \delta_0^{-1} \delta'_0 H_j D_j) \neq \emptyset.$$

Set  $\delta := \delta_0^{-1} \delta'_0 \in \Gamma$ .

Since  $K \cap s(E) = \emptyset$ , this implies that  $\text{RF} \mathcal{M} \cap \Gamma \backslash \Gamma (H_i D_i \cap \delta H_j D_j) \not\subset s(E)$ . By the definition of  $s(E)$ ,

$$\dim(H_i \cap \delta H_j \delta^{-1})_{\text{nc}} = \min\{\dim(H_i)_{\text{nc}}, \dim(H_j)_{\text{nc}}\}.$$

Since  $H_i = N_G(H_i) = N_G((H_i)_{\text{nc}})$ , and similarly for  $H_j$ , we have  $H_i \cap \delta H_j \delta^{-1}$  is either  $H_i$  or  $\delta H_j \delta^{-1}$ . Since  $\dim H_i = \dim H_j$ ,  $\delta H_j \delta^{-1} = H_i$  or  $H_i = \delta H_j \delta^{-1}$ .

By Lemma 7.5, this implies that  $i = j$  and  $\delta \in N_G(H_i) \cap \Gamma$ . It follows from (7-7) that

$$\gamma_k \in N_G(H_i) \cap \Gamma = H_i \cap \Gamma$$

for all large  $k$ . This is a contradiction to (7-6).  $\square$

In the rest of this section, we assume that  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  is a convex cocompact hyperbolic manifold with Fuchsian ends, and let  $k$  be as given by Proposition 4.11.

**Theorem 7.13** (avoidance theorem I) *Let  $U = \{u_t\} < N$  be a one-parameter subgroup. For any  $E \in \mathcal{E}_U$ , there exists  $E' \in \mathcal{E}_U$  such that the following holds: if  $F \subset \text{RF } \mathcal{M}$  is a compact set disjoint from  $E'$ , then there exists a neighborhood  $\mathcal{O}^\diamond$  of  $E$  such that, for all  $x \in F$ , the set*

$$\{t \in \mathbb{R} : xu_t \in \text{RF } \mathcal{M} - \mathcal{O}^\diamond\}$$

*is  $2k$ -thick. Moreover, if  $E$  is associated to  $\{H_i : i \in \Lambda\}$ , then  $E'$  is also associated to the same family  $\{H_i : i \in \Lambda\}$  in the sense of Definition 7.3.*

**Proof** **The constant  $\beta_0$**  We write  $\mathcal{H}^\star = \{H_i\}$ . For simplicity, set  $V_i = V_{H_i}$  and  $p_i = p_{H_i}$ . Since  $A_{H_i}$  is real algebraic, we can find a single polynomial  $\theta_i$  whose zero locus coincides with  $A_{H_i}$ ; namely, if the finitely generated ideal of polynomials vanishing on  $A_{H_i}$  is given by  $\langle f_1, \dots, f_s \rangle$ , then we can set  $\theta_i = f_1^2 + \dots + f_s^2$ .

Set

$$m := \dim(G)^2 \quad \text{and} \quad \delta := \max_{H_i \in \mathcal{H}^\star} (\deg \theta_i + 2) \dim V_i.$$

Note that, if  $H_i$  is conjugate to  $H_j$ , then  $\theta_i$  and  $\theta_j$  have same degree and  $\dim V_i = \dim V_j$ . Since there are only finitely many conjugacy classes in  $\mathcal{H}^\star$  by Proposition 5.3, the constant  $\delta$  is finite. Now let

$$\beta_0 := \beta_0(m\delta, k, 1) = (4k)^{m\delta+1} \varepsilon^{-1}$$

be given as in Proposition 6.3, where  $\varepsilon = \varepsilon_{m\delta}$  satisfies  $((1 + \varepsilon)/(1 - \varepsilon))^{2m\delta-1} \leq 2$ .

**Definition of  $E_n$  and  $E'_n$**  We write

$$E = \bigcup_{i \in \Lambda_0} \Gamma \backslash \Gamma H_i D_i \cap \text{RF } \mathcal{M}$$

for some finite minimal set  $\Lambda_0$ . Set

$$l := \max_{i \in \Lambda_0} \dim(H_i)_{\text{nc}}.$$

We define  $E_n, E'_n \in \mathcal{E}_U$  for all  $1 \leq n \leq l$  inductively as follows: Set

$$E_l := E \quad \text{and} \quad \Lambda_l := \Lambda_0.$$

For each  $i \in \Lambda_l$ , let  $D'_i$  be a compact subset of  $X(H_i, U)$  containing  $D_i$  such that  $p_i D'_i$  has a  $\beta_0$ -regular size with respect to  $p_i D_i$ , as in Proposition 7.2. Set

$$E'_l := \bigcup_{i \in \Lambda_l} \Gamma \backslash \Gamma H_i D'_i \cap \text{RF } \mathcal{M}.$$

Suppose that  $E_{n+1}, E'_{n+1} \in \mathcal{E}_U$  are given for  $n \geq 1$ . Then define

$$E_n := E \cap s(E'_{n+1}).$$

Then, by [Corollary 7.10](#),  $E_n$  belongs to  $\mathcal{E}_U$  and hence can be written as

$$E_n = \bigcup_{i \in \Lambda_n} \Gamma \backslash \Gamma H_i D_i \cap \text{RF } \mathcal{M},$$

where  $D_i$  is a compact subset of  $X(H_i, U)$  and  $\Lambda_n$  is a minimal index set. For each  $i \in \Lambda_n$ , let  $D'_i$  be a compact subset of  $X(H_i, U)$  containing  $D_i$  such that  $p_i D'_i$  has a  $\beta_0$ -regular size with respect to  $p_i D_i$  as in [Proposition 7.2](#). Set

$$E'_n := \bigcup_{i \in \Lambda_n} \Gamma \backslash \Gamma H_i D'_i \cap \text{RF } \mathcal{M}.$$

Hence we get a sequence of compact (possibly empty) subsets of  $E$ :

$$E_1, E_2, \dots, E_{l-1}, E_l = E,$$

and a sequence of compact sets

$$E'_1, E'_2, \dots, E'_{l-1}, E'_l = E'.$$

Note that  $s(E_1) = s(E'_1) = \emptyset$  for dimension reasons.<sup>9</sup>

**Outline of the plan** Let  $F \subset \text{RF } \mathcal{M}$  be a compact set disjoint from  $E'$ . For  $x \in F$ , we set

$$\mathbb{T}(x) := \{t \in \mathbb{R} : xu_t \in \text{RF } \mathcal{M}\}$$

which is a globally  $k$ -thick set by [Proposition 4.11](#). We will construct

- a neighborhood  $\mathcal{O}'$  of  $E'$  disjoint from  $F$ , and
- a neighborhood  $\mathcal{O}^\diamond$  of  $E$

such that, for any  $x \in \text{RF } \mathcal{M} - \mathcal{O}'$ , we have

$$\{t \in \mathbb{R} : xu_t \in \text{RF } \mathcal{M} - \mathcal{O}^\diamond\} \supset \mathbb{T}(x) - J'(\mathcal{X}),$$

where  $\mathcal{X} = \mathcal{X}(x)$  is the union of at most  $m$   $\beta_0$ -regular families  $\mathcal{X}_i$  of triples  $(I(q), J^*(q), J'(q))$  of subsets of  $\mathbb{R}$  with degree  $\delta$  and of  $\mathbb{T}(x)$ -multiplicity free. Once we do that, the theorem is a consequence of [Proposition 6.3](#). Construction of such  $\mathcal{O}'$  and  $\mathcal{O}^\diamond$  requires an inductive process on the  $E_n$ .

**Inductive construction of  $K_n, \mathcal{O}'_{n+1}, \mathcal{O}_{n+1}$  and  $\mathcal{O}^\star_{n+1}$**  Let

$$K_0 := \text{RF } \mathcal{M}.$$

For each  $i \in \Lambda_1$ , there exists a neighborhood  $\Omega'_i$  of  $D'_i$  such that, for

$$\mathcal{O}'_1 := \bigcup_{i \in \Lambda_1} \Gamma \backslash \Gamma H_i \Omega'_i,$$

<sup>9</sup>In fact  $E_{l-i} = \emptyset$  for all  $i \geq d-1$ , but we won't use this information.

the compact subset  $K_0$  is  $\mathbb{O}'_1$ -self-intersection-free by [Proposition 7.12](#), since  $s(E'_1) = \emptyset$ . By [Proposition 7.2](#), there exists a neighborhood  $\Omega_i$  of  $D_i$  such that the pair  $(I(q), J(q))$  is  $\beta_0$ -regular for all  $q \in V_i - p_i\Omega'_i$ , where

$$(7-8) \quad I(q) = \{t \in \mathbb{R} : qu_t \in p_i\Omega'_i\} \quad \text{and} \quad J(q) = \{t \in \mathbb{R} : qu_t \in p_i\Omega_i\}.$$

Set

$$\mathbb{O}_1 := \bigcup_{i \in \Lambda_1} \Gamma \backslash \Gamma H_i \Omega_i.$$

Since  $E_1 = \bigcup_{i \in \Lambda_1} \Gamma \backslash \Gamma H_i D_i \cap \text{RF}\mathcal{M}$ ,  $\mathbb{O}_1$  is a neighborhood of  $E_1 = s(E'_2) \cap E$ . Now the compact subset  $s(E'_2) - \mathbb{O}_1$  is contained in  $s(E'_2) - E$ , which is relatively open in  $s(E'_2)$ . Therefore we can take a neighborhood  $\mathbb{O}_1^*$  of  $s(E'_2) - \mathbb{O}_1$  such that

$$\overline{\mathbb{O}_1^*} \cap E = \emptyset.$$

We will now define the quadruple  $K_n, \mathbb{O}'_{n+1}, \mathbb{O}_{n+1}$  and  $\mathbb{O}_{n+1}^*$  for each  $1 \leq n \leq l-1$  inductively:

- a compact subset  $K_n = K_{n-1} - (\mathbb{O}_n \cup \mathbb{O}_n^*) \subset \text{RF}\mathcal{M}$ ,
- a neighborhood  $\mathbb{O}'_{n+1}$  of  $E'_{n+1}$ ,
- a neighborhood  $\mathbb{O}_{n+1}$  of  $E_{n+1}$ , and
- a neighborhood  $\mathbb{O}_{n+1}^*$  of  $s(E'_{n+2}) - \mathbb{O}_{n+1}$  such that

$$\overline{\mathbb{O}_{n+1}^*} \cap E = \emptyset.$$

Assume that the sets  $K_{n-1}, \mathbb{O}'_n, \mathbb{O}_n$  and  $\mathbb{O}_n^*$  are defined. We define

$$K_n := K_{n-1} - (\mathbb{O}_n \cup \mathbb{O}_n^*) = \text{RF}\mathcal{M} - \bigcup_{i=1}^n (\mathbb{O}_i \cup \mathbb{O}_i^*).$$

For each  $i \in \Lambda_{n+1}$ , let  $\Omega'_i$  be a neighborhood of  $D'_i$  in  $G$  such that, for  $\mathbb{O}'_{n+1} := \bigcup_{i \in \Lambda_{n+1}} \Gamma \backslash \Gamma H_i \Omega'_i$ ,  $K_n$  is  $\mathbb{O}'_{n+1}$ -self-intersection-free. Since  $\mathbb{O}_n \cup \mathbb{O}_n^*$  is a neighborhood of  $s(E'_{n+1})$ , which is the set of all self-intersection points of  $E'_{n+1}$ , such a collection of  $\Omega'_i$  for  $i \in \Lambda_{n+1}$  exists by [Proposition 7.12](#).

Since  $F \subset \text{RF}\mathcal{M}$  is compact and disjoint from  $E'$ , we can also assume  $\Gamma \backslash \Gamma H_i \Omega'_i$  is disjoint from  $F$ , by shrinking  $\Omega'_i$  if necessary. More precisely, writing  $F = \Gamma \backslash \Gamma \tilde{F}$  for some compact subset  $\tilde{F} \subset G$ , this can be achieved by choosing a neighborhood  $\Omega'_i$  of  $D'_i$  so that  $p_i\Omega'_i$  is disjoint from  $p_i\Gamma\tilde{F}$ ; and this is possible since  $p_i\Gamma\tilde{F}$  is a closed set disjoint from a compact subset  $p_iD'_i$ . After choosing  $\Omega'_i$  for each  $i \in \Lambda_{n+1}$ , define the following neighborhood of  $E'_{n+1}$ :

$$\mathbb{O}'_{n+1} := \bigcup_{i \in \Lambda_{n+1}} \Gamma \backslash \Gamma H_i \Omega'_i.$$

We will next define  $\mathbb{O}_{n+1}$ . By [Proposition 7.2](#), there exists a neighborhood  $\Omega_i$  of  $D_i$  such that the pair  $(I(q), J(q))$  is  $\beta_0$ -regular for all  $q \in V_i - p_i\Omega'_i$ , where

$$I(q) = \{t \in \mathbb{R} : qu_t \in p_i\Omega'_i\} \quad \text{and} \quad J(q) = \{t \in \mathbb{R} : qu_t \in p_i\Omega_i\}.$$

We then define the following neighborhood of  $E_{n+1} = s(E'_{n+2}) \cap E$ :

$$\mathbb{O}_{n+1} := \bigcup_{i \in \Lambda_{n+1}} \Gamma \backslash \Gamma H_i \Omega_i.$$

Since the compact subset  $s(E'_{n+2}) - \mathbb{O}_{n+1}$  is contained in the set  $s(E'_{n+2}) - E$ , which is relatively open inside  $s(E'_{n+2})$ , we can take a neighborhood  $\mathbb{O}_{n+1}^*$  of  $s(E'_{n+2}) - \mathbb{O}_{n+1}$  such that

$$\overline{\mathbb{O}_{n+1}^*} \cap E = \emptyset.$$

This finishes the inductive construction.

**Definition of  $\mathbb{O}'$  and  $\mathbb{O}^\diamond$**  We define

$$\mathbb{O}' := \bigcup_{n=1}^l \mathbb{O}'_n, \quad \mathbb{O} := \bigcup_{n=1}^l \mathbb{O}_n, \quad \mathbb{O}^* := \bigcup_{n=1}^l \overline{\mathbb{O}_n^*}.$$

Note that  $\mathbb{O}'$  and  $\mathbb{O}$  are neighborhoods of  $E'$  and  $E$ , respectively. Since  $E \cap \mathbb{O}^* = \emptyset$ , the following defines a neighborhood of  $E$ :

$$(7-9) \quad \mathbb{O}^\diamond := \mathbb{O} - \mathbb{O}^*.$$

**Construction of  $\beta_0$ -regular families of  $\mathsf{T}(x)$ -multiplicity free** Fix  $x \in F \subset \mathrm{RF} \mathcal{M} - \mathbb{O}'$ . Choose a representative  $g \in G$  of  $x$ . We write each  $\Lambda_n$  as the disjoint union

$$\Lambda_n = \bigcup_{j \in \theta_n} \Lambda_{n,j},$$

where  $\Lambda_{n,j} = \{i \in \Lambda_n : \dim H_i = j\}$  and  $\theta_n = \{j : \Lambda_{n,j} \neq \emptyset\}$ . Note that  $\#\theta_n < \dim G$ .

Fix  $1 \leq n \leq l$ ,  $j \in \theta_n$  and  $i \in \Lambda_{n,j}$ . For each  $q \in p_i \Gamma g$ , we define the following subsets of  $\mathbb{R}$ :

- $I(q) := \{t : qu_t \in p_i \Omega'_i\}.$
- $J(q) := \{t : qu_t \in p_i \Omega_i\}.$

In general, the  $I(q)$  have high multiplicity among  $q$ 's in  $\bigcup_{i \in \Lambda_{n,j}} p_i \Gamma g$ , but the following subsets  $I'(q)$  will be multiplicity free, and this is why we defined  $K_{n-1}$  as carefully as above:

- $I'(q) := \{t : [t, t+a] \subset I(q) \text{ and } xu_{t+a} \in K_{n-1} \text{ for some } a \geq 0\}.$
- $J^*(q) := I'(q) \cap J(q);$
- $J'(q) := \{t \in J(q) : xu_t \in K_{n-1}\}.$

Observe that  $I'(q)$  and  $J^*(q)$  are unions of finitely many intervals,  $J'(q) \subset \mathsf{T}(x)$  and that

$$J'(q) \subset J^*(q) \subset I'(q).$$

Now, for each  $1 \leq n \leq l$  and  $j \in \theta_n$ , define the family

$$(7-10) \quad \mathcal{X}_{n,j} = \left\{ (I(q), J^*(q), J'(q)) : q \in \bigcup_{i \in \Lambda_{n,j}} p_i \Gamma g \right\}.$$

We claim that each  $\mathcal{X}_{n,j}$  is a  $\beta_0$ -regular family with degree at most  $\delta$  and of  $T(x)$ -multiplicity free.

Note that, for each  $q \in p_i \Gamma g$ , the number of connected components of  $J^*(q)$  is less than or equal to that of  $J(q)$ . Now that  $J^*(q) \subset J(q)$  and all the pairs  $(I(q), J(q))$  are  $\beta_0$ -regular pairs of degree at most  $\delta$ , it follows that the  $\mathcal{X}_{n,j}$  are  $\beta_0$ -regular families with degree at most  $\delta$ .

We now claim that  $\mathcal{X}_{n,j}$  is of  $T(x)$ -multiplicity free, that is, for any distinct indices  $q_1, q_2 \in \bigcup_{i \in \Lambda_{n,j}} p_i \Gamma g$  of  $\mathcal{X}_{n,j}$ ,

$$I(q_1) \cap J'(q_2) = \emptyset.$$

We first show that

$$I'(q_1) \cap I'(q_2) = \emptyset.$$

Suppose not. Then there exists  $t \in I'(q_1) \cap I'(q_2)$  for some  $q_1 = p_i \gamma_1 g$  and  $q_2 = p_k \gamma_2 g$ , where  $i, k \in \Lambda_{n,j}$ . Then, for some  $a \geq 0$ , we have  $[t, t+a] \subset I(q_1) \cap I(q_2)$  and  $xu_{t+a} \in K_{n-1}$ . In particular,

$$xu_{t+a} \in \Gamma \setminus \Gamma(\gamma_1^{-1} H_i \Omega'_i \cap \gamma_2^{-1} H_k \Omega'_k) \cap K_{n-1}.$$

Since  $K_{n-1}$  is  $\mathbb{O}'_n$ -self-intersection-free, and  $\dim H_i = \dim H_k = j$ , we deduce from [Proposition 7.12](#) that this may happen only when  $i = k$  and  $\gamma_1 \gamma_2^{-1} \in H_i \cap \Gamma$ . Hence we have

$$q_1 = q_2.$$

This shows that the  $I'(q)$  are pairwise disjoint. Now suppose that there exists an element  $t \in I(q_1) \cap J'(q_2)$ . Then, by the disjointness of  $I'(q_1)$  and  $I'(q_2)$ , it follows that

$$t \in (I(q_1) - I'(q_1)) \cap J'(q_2).$$

By the definition of  $I'(q_1)$ , we have  $xu_t \notin K_{n-1}$ . This contradicts the assumption that  $t \in J'(q_2)$ .

**Completing the proof** Let  $\mathcal{X} := \bigcup_{1 \leq i \leq l, j \in \theta_n} \mathcal{X}_{n,j}$ . In view of [Proposition 6.3](#), it remains to check that the condition  $t \in T(x) - J'(\mathcal{X})$  implies that  $xu_t \notin \mathbb{O}^\diamond$ , where  $\mathbb{O}^\diamond$  is as given in [\(7-9\)](#).

Suppose that there exists  $t \in T(x) - J'(\mathcal{X})$  such that  $xu_t \in \mathbb{O}^\diamond$ . Write the neighborhood  $\mathbb{O}^\diamond$  as the disjoint union

$$\mathbb{O}^\diamond = \bigcup_{n=1}^l \left( \mathbb{O}_n - \left( \bigcup_{i \leq n-1} \mathbb{O}_i \cup \mathbb{O}^\star \right) \right).$$

Let  $n \leq l$  be such that

$$xu_t \in \mathbb{O}_n - \left( \bigcup_{i=1}^{n-1} \mathbb{O}_i \cup \mathbb{O}^\star \right).$$

Since  $t \in T(x) - J'(\mathcal{X})$ , we have  $xu_t \in \text{RF } \mathcal{M} - K_{n-1}$ . Since  $K_{n-1} = \text{RF } \mathcal{M} - \bigcup_{i=1}^{n-1} (\mathbb{O}_i \cup \mathbb{O}_i^*)$ ,

$$xu_t \in \bigcup_{i=1}^{n-1} \mathbb{O}_i \cup \mathbb{O}_i^*.$$

This is a contradiction, since  $\bigcup_{i=1}^l \mathbb{O}_i^* \subset \mathbb{O}^*$ . □

As  $\mathcal{H}^*$  is countable and  $X(H_i, U)$  is  $\sigma$ -compact, the intersection  $\mathcal{S}(U) \cap \text{RF } \mathcal{M}$  can be exhausted by the union of the increasing sequence  $E_j \in \mathcal{E}_U$ . Therefore, we deduce:

**Corollary 7.14** *There exists an increasing sequence of compact subsets  $E_1 \subset E_2 \subset \dots$  in  $\mathcal{E}_U$  with  $\mathcal{S}(U) \cap \text{RF } \mathcal{M} = \bigcup_{j=1}^{\infty} E_j$  which satisfies the following: Let  $x_i \in \text{RF } \mathcal{M}$  be a sequence converging to  $x \in \mathcal{G}(U) \cap \text{RF } \mathcal{M}$ . Then, for each  $j \in \mathbb{N}$ , there exist a neighborhood  $\mathbb{O}_j$  of  $E_j$  and  $i_j \geq 1$  such that*

$$\{t \in \mathbb{R} : x_i u_t \in \text{RF } \mathcal{M} - \mathbb{O}_j\}$$

*is  $2k$ -thick for all  $i \geq i_j$ .*

**Proof** For each  $j \geq 1$ , we may assume  $E_{j+1} \supset E'_j$ , where  $E'_j$  is as given by Theorem 7.13. For each  $j \geq 1$ , there exists  $i_j \in \mathbb{N}$  such that  $x_i \notin E_{j+1}$  for all  $i \geq i_j$ . Applying Theorem 7.13 to a compact subset  $F = \{x_i : i \geq i_j\}$  of  $\text{RF } \mathcal{M}$ , we obtain a neighborhood  $\mathbb{O}_j$  of  $E_j$  such that

$$\{t \in \mathbb{R} : x_i u_t \in \text{RF } \mathcal{M} - \mathbb{O}_j\}$$

*is  $2k$ -thick for all  $i \geq i_j$ .* □

Indeed we will apply Corollary 7.14 for the sequence  $\{x_i\}$  contained in a closed orbit  $x_0 L$  of a proper connected closed subgroup  $L < G$ , which can be proved in the same way:

**Theorem 7.15** (avoidance theorem II) *Consider a closed orbit  $x_0 L$  for some  $x_0 \in \text{RF } \mathcal{M}$  and  $L \in \mathcal{Q}_U$ . There exists an increasing sequence of compact subsets  $E_1 \subset E_2 \subset \dots$  in  $\mathcal{E}_U$  with  $\mathcal{S}(U, x_0 L) \cap \text{RF } \mathcal{M} = \bigcup_{j=1}^{\infty} E_j$ , which satisfies the following: if  $x_i \rightarrow x$  in  $\text{RF } \mathcal{M} \cap x_0 L$  with  $x \in \mathcal{G}(U, x_0 L)$ , then, for each  $j \in \mathbb{N}$ , there exist  $i_j \geq 1$  and an open neighborhood  $\mathbb{O}_j \subset x_0 L$  of  $E_j$  such that*

$$\{t \in \mathbb{R} : x_i u_t \in \text{RF } \mathcal{M} - \mathbb{O}_j\}$$

*is a  $2k$ -thick set for all  $i \geq i_j$ .*

## 8 Limits of $\text{RF } \mathcal{M}$ -points in $F^*$ and generic points

Let  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  be a convex cocompact hyperbolic manifold with Fuchsian ends. Recall that  $\Lambda \subset \mathbb{S}^{d-1}$  denotes the limit set of  $\Gamma$ . In this section, we collect some geometric lemmas which are needed in modifying a sequence limiting on an  $\text{RF } \mathcal{M}$  point (resp. limiting on a point in  $\text{RF } \mathcal{M} \cap \mathcal{G}(U)$ ) to a sequence of  $\text{RF } \mathcal{M}$ -points (resp. whose limit still remains inside  $\mathcal{G}(U)$ ). Recall from Definition 4.1 that  $\Omega = \mathbb{S}^{d-1} - \Lambda$ .



**Lemma 8.1** Let  $C_n \rightarrow C$  be a sequence of convergent circles in  $\mathbb{S}^{d-1}$ . If  $C \not\subset \bar{B}$  for any component  $B$  of  $\Omega$ , then

$$\# \limsup_{n \rightarrow \infty} C_n \cap \Lambda \geq 2.$$

**Proof** Without loss of generality, we may assume that  $\infty \notin \Lambda$  and hence consider  $\Lambda$  as a subset of the Euclidean space  $\mathbb{R}^{d-1}$ . Note that there is one component, say  $B_1$ , of  $\Omega$  which contains  $\infty$  and all other components of  $\Omega$  are contained in the complement of  $B_1$ , which is a (bounded) round ball in  $\mathbb{R}^{d-1}$ . Since  $B_1^c$  has a finite Lebesgue measure, there are only finitely many components of  $\Omega$  whose diameters are bounded from below by a fixed positive number.

Let  $\delta = 0.5 \operatorname{diam}(C)$ , so that we may assume  $\operatorname{diam}(C_n) > \delta$  for all sufficiently large  $n \gg 1$ . It suffices to show that there exists  $\varepsilon_0 > 0$  such that  $C_n \cap \Lambda$  contains  $\xi_n, \xi'_n$  with  $d(\xi_n, \xi'_n) \geq \varepsilon_0$  for all sufficiently large  $n$ . Suppose not. Then, for any  $\varepsilon > 0$ , there exists an interval  $I_n \subset C_n$  such that  $\operatorname{diam}(I_n) \leq \varepsilon$  and  $C_n - I_n \subset \Omega$  for some infinite sequence of  $n$ 's. Since  $C_n - I_n$  is connected, there exists a component  $B_n$  of  $\Omega$  such that  $C_n \subset \mathcal{N}_\varepsilon(B_n)$ , where  $\mathcal{N}_\varepsilon(B_n)$  denotes the  $\varepsilon$ -neighborhood of  $B_n$ . In particular, we have  $\operatorname{diam}(B_n) + \varepsilon > \delta$ . Taking  $\varepsilon$  smaller than  $0.5\delta$ , this means that  $\operatorname{diam}(B_n) > 0.5\delta$ . On the other hand, there are only finitely many components of  $\Omega$  whose diameters are greater than  $0.5\delta$ , say  $B_1, \dots, B_l$ . Let  $\varepsilon_0 > 0$  be such that  $\mathcal{N}_{\varepsilon_0}(B_1), \dots, \mathcal{N}_{\varepsilon_0}(B_l)$  are all disjoint. Then, by passing to a subsequence, there exists  $B_i$  such that  $C_n \subset \mathcal{N}_\varepsilon(B_i)$  for all small  $0 < \varepsilon < \varepsilon_0$  and all  $n \geq 1$ ; hence  $C \subset \mathcal{N}_\varepsilon(B_i)$ . Since this holds for all sufficiently small  $\varepsilon > 0$ , we get that  $C \subset \bar{B}_i$ , yielding a contradiction to the hypothesis on  $C$ .  $\square$

In the next two lemmas, we set  $U^- = U$  and  $U^+ = U^t$ .

**Lemma 8.2** Let  $U < N$  be a connected closed subgroup. Let  $[g]L$  be a closed orbit for some  $L \in \mathcal{L}_U$  and  $[g] \in \operatorname{RF} \mathcal{M}$ . Let  $S_0$  and  $S^*$  denote the boundaries of  $\pi(gH(U))$  and  $\pi(gL)$ , respectively. If  $S$  is a sphere such that  $S_0 \subset S \subsetneq S^*$  and  $\Gamma S$  is closed, then  $[g] \in \mathcal{S}(U^\pm, [g]L)$ .

**Proof** Write  $L = H(\hat{U})C \in \mathcal{L}_U$ . Since  $S_0 \subset S \subsetneq S^*$ , there exists a connected proper subgroup  $\tilde{U}$  of  $\hat{U}$ , containing  $U$ , such that  $S$  is the boundary of  $\pi(gH(\tilde{U}))$ . Since  $\Gamma S$  is closed,  $[g]H'(\tilde{U})$  is closed by Proposition 3.9. Now the claim follows from Proposition 4.9 and the definition of  $\mathcal{S}(U^\pm, [g]L)$ .  $\square$

**Lemma 8.3** Let  $U < N$  be a connected closed subgroup with dimension  $m \geq 1$ , and let  $U_\pm^{(1)}, \dots, U_\pm^{(m)}$  be one-parameter subgroups generating  $U^\pm$ . Consider a closed orbit  $yL$ , where  $L \in \mathcal{L}_U$  and

$$y \in F_{H(U)}^* \cap \operatorname{RF} \mathcal{M} \cap \bigcap_{i=1}^m \mathcal{G}(U_\pm^{(i)}, yL).$$

If  $x_n \rightarrow y$  in  $yL$ , then, by passing to a subsequence, there exists a sequence  $h_n \rightarrow h$  in  $H(U)$  such that

$$x_n h_n \in \operatorname{RF} \mathcal{M} \cap yL \quad \text{and} \quad y h \in \operatorname{RF} \mathcal{M} \cap \bigcap_{i=1}^m \mathcal{G}(U_\pm^{(i)}, yL).$$

**Proof** Recall from Section 3 that  $\mathcal{C}^k$  denotes the space of all oriented  $k$ -spheres in  $\mathbb{S}^{d-1}$ . Let  $g_0 \in G$  be such that  $y = [g_0]$  and  $S^*$  denote the boundary of  $\pi(g_0 L)$ . Let  $\mathcal{Q}$  be the collection of all spheres  $S \subsetneq S^*$  such that  $S \cap \Lambda \neq \emptyset$  and  $\Gamma S$  is closed in  $\mathcal{C}^{\dim S}$ . By Corollary 5.8 and Remark 5.9,  $\mathcal{Q}$  is countable. Choose a sequence  $g_n \rightarrow g_0$  in  $G$  as  $n \rightarrow \infty$  such that  $x_n = [g_n]$ . Let  $S_n$  and  $S_0$  denote the boundaries of  $\pi(g_n H(U))$  and  $\pi(g_0 H(U))$ , respectively, so that  $S_n \rightarrow S_0$  in  $\mathcal{C}^m$  as  $n \rightarrow \infty$ .

We will choose a circle  $C_0 \subset S_0$  and a sequence of circles  $C_n \subset S_n$  so that  $C_n \rightarrow C_0$  and  $\limsup(C_n \cap \Lambda)$  contains two distinct points outside of  $\bigcup_{S \in \mathcal{Q}} S$ . If  $m = 1$ , we set  $C_0 = S_0$ . When  $m \geq 2$ , we choose a circle  $C_0 \subset S_0$  as follows. Note that  $S_0$  is not contained in any sphere in  $\mathcal{Q}$  by the assumption on  $y$  and Lemma 8.2. Hence, for any  $S \in \mathcal{Q}$ ,  $S_0 \cap S$  is a proper subsphere of  $S_0$ . Since  $y \in F_{H(U)}^*$ , for any component  $B_i$  of  $\Omega$ ,  $S_0 \not\subset \bar{B}_i$  and hence  $S_0 \cap \partial B_i$  is a proper subsphere of  $S_0$ . Choose a circle  $C_0 \subset S_0$  such that  $\{g_0^+, g_0^-\} \subset C_0 \cap \Lambda$ ,  $C_0 \not\subset S$  for any  $S \in \mathcal{Q}$ , and  $C_0 \not\subset \partial B_i \cap S_0$  for all  $i$ . This is possible, since  $\mathcal{Q}$  is countable. Since  $S_n \rightarrow S_0$ , we can find a sequence of circles  $C_n \subset S_n$  such that  $C_n \rightarrow C_0$ . We claim that  $\limsup_n(C_n \cap \Lambda)$  is uncountable. Since  $\#C_0 \cap \Lambda \geq 2$  and  $C_0 \not\subset \partial B_i$ ,  $C_0 \not\subset \bar{B}_i$  for all  $i$ . Therefore, by Lemma 8.1, for any infinite subsequence  $C_{n_k}$  of  $C_n$ ,

$$\# \limsup_k (C_{n_k} \cap \Lambda) \geq 2.$$

By passing to a subsequence, we can find two distinct points  $\xi_n, \xi'_n \in C_n \cap \Lambda$  which converge to two distinct points  $\xi$  and  $\xi'$  of  $C_0 \cap \Lambda$ , respectively, as  $n \rightarrow \infty$ . Choose a sequence  $p_n \rightarrow p \in G$  such that  $p_n^+ = \xi_n$ ,  $p_n^- = \xi'_n$ ,  $p^+ = \xi$  and  $p^- = \xi'$ . Let  $\langle u_t \rangle < N$  be a one-parameter subgroup such that  $p_n u_t^- = C_n - \{\xi_n\}$ . By Proposition 4.11,  $T_n = \{t : [p_n]u_t \in \text{RF } \mathcal{M}\}$  is a global  $k$ -thick subset, and hence  $\mathcal{T} := \limsup_n T_n$  is a global  $k$ -thick subset contained in the set  $\{t : [p]u_t \in \text{RF } \mathcal{M}\}$ . Then  $C_n \cap \Lambda$  converges, in the Hausdorff topology, to a compact subset  $L \subset C_0 \cap \Lambda$  homeomorphic to the one-point compactification of  $\mathcal{T}$ . Therefore  $L$  is uncountable, so is  $\limsup_n(C_n \cap \Lambda)$ , proving the claim.

Let  $\Psi := \bigcup_{S \in \mathcal{Q}} C_0 \cap S$ , i.e. the union of all possible intersection points of  $C_0$  and spheres in  $\mathcal{Q}$ . Since  $C_0 \not\subset S$  for any  $S \in \mathcal{Q}$ ,  $\#C_0 \cap S \leq 2$ . Hence  $\Psi$  is countable, and hence  $\limsup_n(C_n \cap \Lambda) - \Psi$  is uncountable. Note that this works for any infinite subsequence of the  $C_n$ . Therefore we can choose sequences  $\xi_n^-, \xi_n^+ \in C_n \cap \Lambda$  converging to distinct points  $\xi^-, \xi^+$  of  $(C_0 \cap \Lambda) - \Psi$ , respectively, by passing to a subsequence. As  $\xi^-, \xi^+ \in C_0$  and  $C_0 \subset S_0$ , there exists a frame  $g_0 h = (v_0, \dots, v_{d-1}) \in g_0 H(U)$  whose first vector  $v_0$  is tangent to the geodesic  $[\xi^-, \xi^+]$ . Setting  $g := g_0 h$ , we claim that

$$[g] \in \bigcap_i \mathcal{G}(U_{\pm}^{(i)}, yL).$$

Suppose that  $[g] \in \mathcal{S}(U_{\pm}^{(i)}, yL)$  for some  $i$ . We will assume  $[g] \in \mathcal{S}(U_{-}^{(i)}, yL)$ , as the case when  $[g] \in \mathcal{S}(U_{+}^{(i)}, yL)$  can be dealt with similarly, by changing the role of  $g^-$  and  $g^+$  below. For simplicity, set  $U^{(i)} := U_{-}^{(i)}$ . Now, by Proposition 5.13, there exist  $L_0 \in \mathcal{L}_{U^{(i)}}$  and  $\alpha \in N \cap L$  such that  $(L_0)_{\text{nc}} \not\subset L_{\text{nc}}$  and  $[g]\alpha L_0$  is closed. Let  $S$  denote the boundary of  $\pi(g\alpha L_0)$ . Since  $\alpha \in N \cap L$ , we have  $(g\alpha)^+ = g^+ = \xi^+ \in S \cap \Lambda \cap C_0$ . Since  $S \subsetneq S^*$ ,  $S \cap \Lambda \neq \emptyset$  and  $\Gamma S$  is closed, we have  $S \in \mathcal{Q}$ . It follows that  $\xi^+ \in \Psi$ , contradicting the choice of  $\xi^+$ . This proves the claim.

Now choose a vector  $v_0^{(n)}$  which is tangent to the geodesic  $[\xi_n^-, \xi_n^+]$ . We then extend  $v_0^{(n)}$  to a frame  $g_n h_n \in g_n H(U)$  such that  $g_n h_n$  converges to  $g = g_0 h$  as  $n \rightarrow \infty$ . Since  $\{\xi_n^\pm\} \subset \Lambda$ , we have  $[g_n h_n] \in \text{RF } \mathcal{M}$ .  $\square$

We will need the following lemma later:

**Lemma 8.4** *Let  $k \geq 1$ . Let  $\chi$  be a  $k$ -horosphere in  $\mathbb{H}^{k+1}$  resting at  $p \in \partial \mathbb{H}^{k+1}$ , and  $\mathcal{P}$  be the geodesic  $k$ -plane in  $\mathbb{H}^{k+1}$ . Let  $\xi \in \partial \mathcal{P}$ ,  $\delta$  be the geodesic joining  $\xi$  and  $p$ , and  $q = \delta \cap \chi$ . There exists  $R_0 > 1$  such that, for any  $R > R_0$ , if  $d(\chi, \mathcal{P}) < R - 1$ , then  $d(q, \mathcal{P}) < R$ .*

**Proof** For  $k = 1$ , this is shown in [McMullen et al. 2016, Lemma 4.2]. Now let  $k \geq 2$ . Consider a geodesic plane  $\mathbb{H}^2 \subset \mathbb{H}^{k+1}$  which passes through  $q$  and is orthogonal to  $\mathcal{P}$ . Then  $\chi \cap \mathbb{H}^2$  and  $\mathcal{P} \cap \mathbb{H}^2$  are a horocycle and a geodesic in  $\mathbb{H}^2$ , respectively. As  $d_{\mathbb{H}^{k+1}}(\chi, \mathcal{P}) = d_{\mathbb{H}^2}(\chi \cap \mathbb{H}^2, \mathcal{P} \cap \mathbb{H}^2)$  and  $d_{\mathbb{H}^{k+1}}(q, \mathcal{P}) = d_{\mathbb{H}^2}(q, \mathcal{P} \cap \mathbb{H}^2)$ , the conclusion follows from the case  $k = 1$ .  $\square$

Recall the definition of  $\check{H} = H(U_{d-2})$  from Section 4.

**Lemma 8.5** *Let  $U < \check{H} \cap N$  be a nontrivial connected closed subgroup. If the boundary of  $\pi(gH(U))$  is contained in  $\partial B$  for some component  $B$  of  $\Omega$ , then  $[g] \in \text{BF } \mathcal{M} \cdot C(H(U))$ .*

**Proof** As  $U$  is equal to  $mU_k m^{-1}$  for some  $m \in \check{H} \cap M$  and  $1 \leq k \leq d - 2$ , the general case is easily reduced to the case when  $U = U_k$ . Since  $g = (v_0, \dots, v_d)$  has its first  $k + 1$  vectors tangent to the geodesic  $(k + 1)$ -plane  $\pi(gH(U_k))$  and  $\partial(\pi(gH(U_k))) \subset \partial B$ , we can use an element  $c \in C(H(U_k)) = \text{SO}(d - k - 2)$  to modify the next  $d - k - 2$  vectors so that  $gc$  has its first  $d - 1$  vectors tangent to  $\text{hull}(\partial B)$ . Then  $[gc] \in \text{BF } \mathcal{M}$ .  $\square$

**Lemma 8.6** *Let  $U < \check{H} \cap N$  be a nontrivial connected closed subgroup. If  $x_n \in \text{RF } \mathcal{M} \cdot U$  is a sequence converging to some  $x \in \text{RF } \mathcal{M}$ , then, passing to a subsequence, there exists  $u_n \in U$  such that  $x_n u_n \in \text{RF } \mathcal{M}$  and at least one of the following holds:*

- (1)  $u_n \rightarrow e$  and hence  $x_n u_n \rightarrow x$ , or
- (2)  $x = zc$  for some  $z \in \text{BF } \mathcal{M}$  with  $c \in C(H(U))$ , and  $x_n u_n$  accumulates on  $z\check{H}c$ .

**Proof** If  $x_n$  belongs to  $\text{RF } \mathcal{M}$  for infinitely many  $n$ , we simply take  $u_n = e$ . So assume that  $x_n \notin \text{RF } \mathcal{M}$  for all  $n$ . Choose a sequence  $g_n \rightarrow g_0$  in  $G$  so that  $x_n = [g_n]$  and  $x = [g_0]$ . As  $x \in \text{RF } \mathcal{M}$ , we have  $\{g_0(0), g_0(\infty)\} \subset \Lambda$ . As  $x_n \in \text{RF}_+ \mathcal{M} - \text{RF } \mathcal{M}$ , we have  $g_n(\infty) \in \Lambda$  and  $g_n(0) \in \Omega$ . For each  $n$ , choose an element  $u_n \in U$  so that  $0 < \alpha_n := \|u_n\| \leq \infty$  is the minimum of  $\|u\|$  for all  $u \in U$  satisfying  $g_n u(0) \in \Lambda$ . Set

$$\alpha := \limsup_n \alpha_n.$$

If  $\alpha = 0$ , then we are in case (1). Hence we will assume  $0 < \alpha \leq \infty$ . Let  $C_n$  denote the boundary of  $\pi(g_n H(U))$  and  $C_0$  the boundary of  $\pi(g_0 H(U))$ . Then  $C_n \rightarrow C_0$  in  $\mathcal{C}^{\dim U}$ . Recall that  $B_U(r)$  denotes the ball of radius  $r$  centered at 0 inside  $U$ . Set

$$\mathcal{B}_n := g_n B_U(\alpha_n)(0) \quad \text{and} \quad \mathcal{B}_0 := g_0 B_U(\alpha)(0).$$

Then  $\mathcal{B}_n \subset C_n \cap \Omega$ , and  $\partial \mathcal{B}_n \cap \Lambda \neq \emptyset$  by the choice of  $u_n$ . By passing to a subsequence, we have  $\alpha_n \rightarrow \alpha$  and  $\mathcal{B}_n \rightarrow \mathcal{B}_0$  as  $n \rightarrow \infty$  and hence the diameter of  $\mathcal{B}_n$  in  $\mathbb{S}^{d-1}$  is bounded below by some positive number. Hence, passing to a subsequence, we may assume that  $\mathcal{B}_n$  are all contained in the same component, say  $B$  of  $\Omega$ . Consequently,  $\mathcal{B}_0 \subset \bar{B}$ .

We claim that  $\#\bar{\mathcal{B}}_0 \cap \partial B \geq 2$ . First note that  $g_0(0) \in \Lambda$ . If  $\alpha = \infty$ , then  $g_n u_n(0) \rightarrow g_0(\infty) \in \Lambda \cap \bar{\mathcal{B}}_0$ . If  $\alpha < \infty$ , then  $u_n$  converges to some  $u \in U$ , passing to a subsequence, and  $u \neq e$ , as  $\alpha > 0$ . Now,  $g_n u_n(0) \rightarrow g_0 u(0) \in \Lambda \cap \bar{\mathcal{B}}_0$ . Since  $\Lambda \cap \bar{B} \subset \partial B$ , this proves the claim.

Therefore  $\mathcal{B}_0$  is contained in  $\partial B$ , and hence so is  $C_0$ . By Lemma 8.5, this implies that  $x = zc$  for some  $z \in \text{BFM}$  and  $c \in C(H(U))$ . We proceed to show that  $x_n u_n$  accumulates on  $z\check{H}c$ . Since  $c \in C(H(U))$ , we may assume  $c = e$  by replacing  $x$  with  $xc^{-1}$ , and  $x_n$  with  $x_n c^{-1}$ .

We claim that the distance between  $\pi(g_n u_n)$  and the plane  $\pi(g_0 \check{H})$  tends to 0 as  $n \rightarrow \infty$ . Since  $x\check{H} = [g_0]\check{H}$  is compact,  $g_n u_n \in g_n \check{H}$  and  $\pi(g_n \check{H})$  is a geodesic plane nearly parallel to  $\pi(g_0 \check{H})$  for all large  $n$ , this claim implies that  $[g_n]u_n$  accumulates on  $z\check{H}$ , completing the proof.

Now, to prove the claim, let  $D_n := C_n \cap \partial B$ , and  $\mathcal{P}_n := \text{hull}(D_n)$ . Let  $k = \dim U$ . Since  $C_n$  is a  $k$ -sphere meeting the  $(d-2)$ -sphere  $\partial B \subset \mathbb{S}^{d-1}$ , and  $C_n \not\subset \partial B$ , it follows that  $D_n$  is a  $(k-1)$ -sphere. We set  $\mathcal{H}_n := \text{hull}(C_n)$ ,  $\mathcal{H}_0 := \text{hull}(C_0)$  and  $\mathcal{H} := \text{hull}(\partial B) = \pi(g_0 \check{H})$ . Then  $\mathcal{H}_n \cap \mathcal{H} = \mathcal{P}_n$ . Let  $\varepsilon > 0$  be arbitrary, and  $\mathcal{N}_\varepsilon(\mathcal{H})$  denote the  $\varepsilon$ -neighborhood of  $\mathcal{H}$  in  $\mathbb{H}^d$ . Letting  $d_{\mathcal{H}_n}(\cdot, \cdot)$  denote the hyperbolic distance in  $\mathcal{H}_n$ , we may write

$$\mathcal{N}_\varepsilon(\mathcal{H}) \cap \mathcal{H}_n = \{p \in \mathcal{H}_n : d_{\mathcal{H}_n}(p, \mathcal{P}_n) < R_n\}$$

for some  $R_n > 0$ . This is because  $\mathcal{N}_\varepsilon(\mathcal{H}) \cap \mathcal{H}_n$  is convex and invariant under family of isometries, whose axes of translation and rotation are contained in  $\mathcal{P}_n$ . As  $C_n \rightarrow C_0 \subset \partial B$  as  $n \rightarrow \infty$ , it follows that  $R_n \rightarrow \infty$  as  $n \rightarrow \infty$ . Let  $\chi_n := \pi(g_n U)$ , and  $\chi_0 := \pi(g_0 U)$ , which are  $k$ -horospheres contained in  $\mathcal{H}_n$  and  $\mathcal{H}_0$ , respectively.

We next show that there is a uniform upper bound for  $d_{\mathcal{H}_n}(\mathcal{P}_n, \chi_n)$  for  $n \in \mathbb{N}$ . To see this, we only need to consider those  $\mathcal{P}_n$  which are disjoint from  $\chi_n$ , as  $d_{\mathcal{H}_n}(\mathcal{P}_n, \chi_n) = 0$  otherwise. Since  $\chi_n \rightarrow \chi_0$  and  $C_n \rightarrow C_0$  as  $n \rightarrow \infty$ , it suffices to check that the diameters of  $D_n$  with respect to the spherical metric on  $\mathbb{S}^{d-1}$  have a uniform positive lower bound. Let us write  $C_n - D_n = E_n \cup E'_n$ , where  $E_n$  is a connected component of  $C_n - D_n$  meeting  $B$ , and  $E'_n$  is the other component. Since  $C_n \rightarrow C_0$  as  $n \rightarrow \infty$ , a uniform lower bound for both  $\text{diam}(E_n)$  and  $\text{diam}(E'_n)$  will give a uniform upper bound for  $\text{diam}(D_n)$ . Since  $\mathcal{B}_n \subset E_n$ ,  $\text{diam}(E_n) > \frac{1}{2} \text{diam}(\mathcal{B}_0)$  for all sufficiently large  $n$ . On the other hand, note that  $\chi_n \subset \mathcal{H}_n$  is a

horosphere resting at a point in  $E'_n$ . Since  $\chi_n$  converges to  $\chi$ , the condition that  $\mathcal{P}_n \cap \chi_n = \emptyset$  implies that  $\text{diam}(E'_n)$  is also bounded below by some positive constant. Since  $R_n \rightarrow \infty$ , we conclude that  $d_{\mathcal{H}_n}(\mathcal{P}_n, \chi_n) < R_n - 1$  for all sufficiently large  $n$ . Applying Lemma 8.4 to  $\mathbb{H}^{k+1} = \mathcal{H}_n$ ,  $\chi = \chi_n$ ,  $\mathcal{P} = \mathcal{P}_n$ ,  $\xi = g_n^+$  and  $q = \pi(g_n u_n)$ , we have

$$d_{\mathcal{H}_n}(\pi(g_n u_n), \mathcal{P}_n) < R_n$$

and hence  $\pi(g_n u_n) \in \mathcal{N}_\varepsilon(\mathcal{H}) \cap \mathcal{H}_n$  for all sufficiently large  $n$ . As  $\varepsilon > 0$  was arbitrary, this proves that  $\pi(g_n u_n)$  goes arbitrarily close to  $\pi(g_0 \check{H})$  as  $n \rightarrow \infty$ .  $\square$

**Lemma 8.7** *Let  $U < N$  be a nontrivial connected closed subgroup. If  $x_n \rightarrow x$  in  $F^* \cap \text{RF}_+ \mathcal{M}$ , and  $x \in F^* \cap \text{RF} \mathcal{M}$ , then there exists  $u_n \rightarrow e$  in  $U$  such that  $x_n u_n \in \text{RF} \mathcal{M}$ ; in particular,  $x_n u_n \rightarrow x$  in  $F^* \cap \text{RF} \mathcal{M}$ .*

**Proof** The general case easily reduces to the case when  $U < \check{H} \cap N$ . Then the claim follows from Lemmas 8.6 and 4.5.  $\square$

### Obtaining limits in $F^*$

For  $\varepsilon > 0$ , we set

$$(8-1) \quad \text{core}_\varepsilon(\mathcal{M}) := \{x \in \Gamma \backslash G : \pi(x) \in \text{core} \mathcal{M} \text{ and } d(\pi(x), \partial \text{core} \mathcal{M}) \geq \varepsilon\}.$$

We note that  $\text{core}_\varepsilon(\mathcal{M})$  is a compact of  $F^*$  for all sufficiently large  $\varepsilon > 0$ . In the rest of the section, let

$$U < N$$

denote a nontrivial connected closed subgroup.

**Lemma 8.8** *Let  $x \in \text{RF} \mathcal{M}$ , and  $V = \{v_t : t \in \mathbb{R}\} < N$  be a one-parameter subgroup. If  $\pi(xV) \not\subset \partial \text{core} \mathcal{M}$ , and  $xv_{t_i} \in \text{RF} \mathcal{M}$  for some sequence  $t_i \rightarrow +\infty$ , then there exists a sequence  $s_i \rightarrow +\infty$  such that  $xv_{s_i}$  converges to a point in  $F^*$ .*

**Proof** It suffices to show that there exists a sequence  $s_i \rightarrow +\infty$  such that  $xv_{s_i} \in \text{core}_{\eta/3}(\mathcal{M})$ , where  $\eta$  is as given in (4-12). Let  $x = [g]$ , and set  $o = (1, 0, \dots, 0) \in \mathbb{H}^d = \mathbb{R}^+ \times \mathbb{R}^{d-1}$ . We may assume  $g = (e_0, \dots, e_{d-1})_o \in F\mathbb{H}^d$ , where the  $e_i$  are standard basis vectors in  $T_o\mathbb{H}^d \simeq \mathbb{R}^d$ . Note that, for  $V^+ = \{v_t : t > 0\}$ ,  $gV^+$  is a translation of the frame  $g$  along a horizontal ray emanating from  $o$  along the  $V^+$ -direction. By the definition of  $\eta$ , the  $\frac{1}{3}\eta$ -neighborhoods of the hull  $B_i$  are mutually disjoint. For each  $i$ , set  $s_i := t_i$  if  $xv_{t_i} \in \text{core}_{\eta/3}(\mathcal{M})$ . Otherwise, there exists a unique  $j$  such that  $d(\pi(gv_{t_i}), \text{hull } B_j) < \frac{1}{3}\eta$ . If  $\pi(gV_{[t_i, \infty)})$  were contained in the  $\frac{1}{3}\eta$ -neighborhood of hull  $B_j$ , then the unique geodesic 2-plane which contains  $\pi(gV_{[t_i, \infty)})$  must lie in  $\partial \text{hull } B_j$ , and hence  $\pi(xV) \subset \partial \text{core} \mathcal{M}$ ; this contradicts the hypothesis. Therefore there exists  $t_i < s_i < \infty$  such that  $d(\pi(gv_{s_i}), \text{hull } B_j) = \frac{1}{3}\eta$ . The sequence  $s_i$  satisfies the claim.  $\square$

**Lemma 8.9** Let  $x_n L_n v_n$  be a sequence of closed orbits with  $x_n \in \text{RF}_+ \mathcal{M}$ ,  $L_n \in \mathcal{L}_U$  and  $v_n \in (L_n \cap N)^\perp$ . Suppose that either

- (1)  $x_n \in F^*$  for all  $n$ ; or
- (2)  $x_n L_n v_n \cap \text{RF}_+ \mathcal{M} \cap F^* \neq \emptyset$  for all  $n$ .

Then

$$F^* \cap \limsup_n (x_n L_n v_n \cap \text{RF}_+ \mathcal{M}) \neq \emptyset.$$

**Proof** We claim that, if  $x_n \in F^*$ , then  $x_n L_n v_n \cap \text{RF}_+ \mathcal{M} \cap F^* \neq \emptyset$ , that is, the hypothesis (1) implies (2). Suppose not. Then, since  $A \subset L_n$ ,  $(x_n A v_n A \cap \text{RF}_+ \mathcal{M}) \subset \text{RF}_+ \mathcal{M} - F^*$ . Since the set  $\text{RF}_+ \mathcal{M} - F^*$  is a closed  $A$ -invariant set and  $e \in \overline{A v_n A}$ , we would have  $x_n \in \text{RF}_+ \mathcal{M} - F^*$ , yielding a contradiction. It follows from the claim that there exists  $z_n \in x_n L_n \cap \text{RF}_+ \mathcal{M}$  such that  $\pi(z_n v_n U) \not\subset \partial \text{core } \mathcal{M}$  for all  $n$ . In particular, there exists  $u_n \in U$  such that  $z_n v_n u_n \in \text{core}_{\eta/3}(M)$ . Since  $\text{core}_{\eta/3}(M)$  is a compact subset of  $F^*$ ,  $z_n v_n u_n = z_n u_n v_n$  converges to a point in  $F^*$ .  $\square$

**Lemma 8.10** Let  $x_0 L$  be a closed orbit with  $x_0 \in \text{RF } \mathcal{M}$  and  $L \in \mathcal{L}_U$ . Suppose that  $E$  is a closed  $U$ -invariant subset containing  $x_0 L v_n \cap \text{RF}_+ \mathcal{M}$  for some sequence  $v_n \rightarrow \infty$  in  $(L \cap N)^\perp$ . If  $x_0 \in F^*$  or  $x_0 L v_n \cap \text{RF}_+ \mathcal{M} \cap F^* \neq \emptyset$  for all  $n$ , then there exist  $y \in \text{RF } \mathcal{M} \cap F^*$  and a one-parameter subgroup  $V \subset (L \cap N)^\perp$  such that

$$E \supset y(L \cap N)V.$$

**Proof** Note that

$$(x_0 L v_n \cap \text{RF}_+ \mathcal{M})(v_n^{-1} A v_n) \subset E.$$

By Lemma 8.9, there exists

$$y \in F^* \cap \limsup_{n \rightarrow \infty} (x_0 L v_n \cap \text{RF}_+ \mathcal{M}).$$

Since  $y \in F^* \cap \text{RF}_+ \mathcal{M} \subset \text{RF } \mathcal{M} \cdot U$ , we may assume  $y \in F^* \cap \text{RF } \mathcal{M}$  by modifying  $y$  using an element of  $U$ . Note that  $\liminf_{n \rightarrow \infty} (x_0 L v_n \cap \text{RF}_+ \mathcal{M}) \supset y(L \cap N)$ , passing to a subsequence. Since  $\limsup_{n \rightarrow \infty} (v_n^{-1} A v_n)$  contains a one-parameter subgroup  $V \subset (L \cap N)^\perp$  by Lemma 3.4, we obtain that  $y(L \cap N)V \subset E$ .  $\square$

**Lemma 8.11** If  $y L v_0 \cap \text{RF } \mathcal{M} \cap F^* \neq \emptyset$  for some  $v_0 \in N$  and  $L \in \mathcal{L}_U$ , then  $y L v \cap F^* \cap \text{RF } \mathcal{M} \neq \emptyset$  for all  $v \in A v_0 A$ .

**Proof** Let  $y_0 := y \ell v_0 \in y L v_0 \cap F^* \cap \text{RF } \mathcal{M}$ , and  $v = a v_0 b \in A v_0 A$ . Then  $(y \ell a^{-1})v = y \ell v_0 b \in F^* \cap \text{RF } \mathcal{M}$  as  $F^* \cap \text{RF } \mathcal{M}$  is  $A$ -invariant. Since  $y \ell a^{-1} v \in y L v$ , the claim is proved.  $\square$

**Lemma 8.12** Let  $x_0 L$  be a closed orbit with  $x_0 \in \text{RF } \mathcal{M}$  and  $L \in \mathcal{L}_U$ . Suppose that  $E$  is a closed  $AU$ -invariant subset containing  $x_0 L v \cap \text{RF}_+ \mathcal{M}$  for some nontrivial element  $v \in (L \cap N)^\perp$ . If  $x_0 \in F^*$  or  $x_0 L v \cap \text{RF } \mathcal{M} \cap F^* \neq \emptyset$ , then there exist  $y \in F^* \cap \text{RF } \mathcal{M}$  and a one-parameter subgroup  $V \subset (L \cap N)^\perp$  such that

$$E \supset y(L \cap N)VA.$$

**Proof** Since  $X$  is  $A$ -invariant, we get

$$(x_0 L \cap \mathrm{RF}_+ \mathcal{M}) A v A \subset E.$$

Choose a sequence  $v_n := a_n v a_n^{-1} \in A v A$  tending to  $\infty$ . Note that either  $x_0 \in F^*$  or, for all  $n$ ,  $x_0 L v_n \cap \mathrm{RF} \mathcal{M} \cap F^* \neq \emptyset$  by [Lemma 8.11](#). Therefore the claim follows from [Lemma 8.10](#).  $\square$

## 9 Limits of unipotent blowups

Let  $\mathcal{M}$  be a convex cocompact hyperbolic manifold with Fuchsian ends and fix  $k > 1$  as given by [Proposition 4.11](#). In this section, we fix a nontrivial connected subgroup  $U < N$ . For a given sequence  $g_i \rightarrow e$ , and a sequence of  $k$ -thick subsets  $\mathsf{T}_i$  of a one-parameter subgroup  $U_0 < U$ , we study the set

$$\limsup \mathsf{T}_i g_i U$$

under certain conditions on the sequence  $g_i$ . The basic tool used here is the so-called *quasiregular map* associated to the sequence  $g_i$  introduced in the work of Margulis and Tomanov [\[1994\]](#) to study the object  $\limsup U_0 g_i U$  in the finite-volume case. For our application, we need somewhat more precise information on the shape of the set  $\limsup U_0 g_i U$  as well as  $\limsup \mathsf{T}_i g_i U$  than discussed in [\[Margulis and Tomanov 1994\]](#).

Let  $U^\perp$  denote the orthogonal complement of  $U$  in  $N \simeq \mathbb{R}^{d-1}$  as defined in [Section 3](#). Recall from [\(3-2\)](#) that

$$\mathsf{N}(U) = A N C_1(U) C_2(U),$$

where  $C_1(U) = C(H(U))$  and  $C_2(U) = H(U) \cap M \cap C(U^\perp)$ . Since  $\mathsf{N}(U)$  is the identity component of  $\mathsf{N}_G(U)$ , for a sequence  $g_i \rightarrow e$ , the condition  $g_i \in \mathsf{N}_G(U)$  means  $g_i \in \mathsf{N}(U)$  for all sufficiently large  $i \gg 1$ . Note that the product  $A U^\perp C_2(U)$  is a connected subgroup of  $G$ , since  $C_2(U)$  commutes with  $U^\perp$ , and  $A$  normalizes  $U^\perp C_2(U)$ .

**Lemma 9.1** *For a given sequence  $g_i \rightarrow e$  in  $G - \mathsf{N}(U)$ , there exists a one-parameter subgroup  $U_0 < U$  such that the following holds: for any given sequence of  $k$ -thick subsets  $\mathsf{T}_i \subset U_0$ , there exist sequences  $t_i \in \mathsf{T}_i$  and  $u_i \in U$  such that, as  $i \rightarrow \infty$ ,*

$$u_i g_i u_{t_i} \rightarrow \alpha$$

*for some nontrivial element  $\alpha \in A U^\perp C_2(U) - C_2(U)$ . Moreover,  $\alpha$  can be made arbitrarily close to  $e$ .*

**Proof** Set  $L := A U^\perp M N^+$ . Note that

$$\mathsf{N}(U) \cap L = A U^\perp C_1(U) C_2(U)$$

and that the product map from  $U \times L$  to  $G$  is a diffeomorphism onto a Zariski-open neighborhood of  $e$  in  $G$ .



Following [Margulis and Tomanov 1994], we will construct a quasiregular map

$$\psi : U \rightarrow N(U) \cap L$$

associated to the sequence  $g_i$ . Except for a Zariski-closed subset of  $U$ , the product  $g_i u$  can be written as an element of  $UL$  in a unique way. We denote by  $\psi_i(u) \in L$  its  $L$ -component, so that

$$g_i u \in U \psi_i(u).$$

By Chevalley's theorem, there exists an  $\mathbb{R}$ -regular representation  $G \rightarrow \mathrm{GL}(W)$  with a distinguished point  $p \in W$  such that  $U = \mathrm{Stab}_G(p)$ . Then  $pG$  is locally closed, and

$$N_G(U) = \{g \in G : pgu = pg \text{ for all } u \in U\}.$$

For each  $i$ , the map  $\tilde{\phi}_i : U \rightarrow W$  defined by

$$\tilde{\phi}_i(u) = pg_i u$$

is a polynomial map in  $U = \mathbb{R}^m$  of degree uniformly bounded, and  $\tilde{\phi}_i(e)$  converges to  $p$  as  $i \rightarrow \infty$ . As  $g_i \notin N_G(U)$ ,  $\tilde{\phi}_i$  is nonconstant. Denote by  $B(p, r)$  the ball of radius  $r$  centered at  $p$ , fixing a norm  $\|\cdot\|$  on  $W$ . Since  $pG$  is open in its closure, we can find  $\lambda_0 > 0$  such that

$$(9-1) \quad B(p, \lambda_0) \cap \overline{pG} \subset pG.$$

Without loss of generality, we may assume that  $\lambda_0 = 2$  by renormalizing the norm. Now define

$$\lambda_i := \sup\{\lambda \geq 0 : \tilde{\phi}_i(B_U(\lambda)) \subset B(p, 2)\}.$$

Note that  $\lambda_i < \infty$  as  $\phi_i$  is nonconstant, and  $\lambda_i \rightarrow \infty$  as  $i \rightarrow \infty$ , as  $g_i \rightarrow e$ . We define  $\phi_i : U \rightarrow W$  by

$$\phi_i(u) := \tilde{\phi}_i(\lambda_i u).$$

This forms an equicontinuous family of polynomials on  $U$ . Therefore, after passing to a subsequence,  $\phi_i$  converges to a nonconstant polynomial  $\phi$  uniformly on every compact subset of  $U$ . Moreover,  $\sup\{\|\phi(u) - p\| : u \in B_U(1)\} = 1$ ,  $\phi(B_U(1)) \subset pL$  and  $\phi(0) = p$ . Now the following map  $\psi$  defines a nonconstant rational map defined on a Zariski-open dense neighborhood of  $\mathfrak{U}$  of  $e$  in  $U$ :

$$\psi := \rho_L^{-1} \circ \phi,$$

where  $\rho_L$  is the restriction to  $L$  of the orbit map  $g \mapsto p.g$ . We have  $\psi(e) = e$  and

$$\psi(u) = \lim_i \psi_i(\lambda_i u),$$

where the convergence is uniform on compact subsets of  $\mathfrak{U}$  and

$$\psi(u) \in L \cap N(U) = AU^\perp C_1(U) C_2(U).$$

Since  $\psi$  is nonconstant, there exists a one-parameter subgroup  $U_0 < U$  such that  $\psi|_{U_0}$  is nonconstant. Now let  $T_i$  be a sequence of  $k$ -thick sets in  $U_0 \simeq \mathbb{R}$ . Then  $T_i/\lambda_i$  is also a  $k$ -thick set, and so is

$$T_\infty := \limsup_{i \rightarrow \infty} (T_i/\lambda_i) \subset U_0.$$



Finally, for all  $t \in T_\infty$ , there exists a sequence  $t_i \in T_i$  such that  $t_i/\lambda_i \rightarrow t$  as  $i \rightarrow \infty$  (by passing to a subsequence). Since  $\psi_i \circ \lambda_i \rightarrow \psi$  uniformly on compact subsets,

$$\psi(t) = \lim_{i \rightarrow \infty} (\psi_i \circ \lambda_i)(t_i/\lambda_i) = \lim_{i \rightarrow \infty} \psi_i(t_i).$$

By the definition of  $\psi_i$ , this means that there exists  $u_i \in U$  such that

$$\psi(t) = \lim_{i \rightarrow \infty} u_i g_i u_{t_i}.$$

Since  $\psi|_{U_0}$  is a nonconstant continuous map, and an uncountable set  $T_\infty$  accumulates on 0, the image  $\psi(T_\infty)$  contains a nontrivial element  $\alpha$  of  $AU^\perp C_1(U) C_2(U)$  which can be taken arbitrarily close to  $e$ .

We now claim that if  $\alpha$  is sufficiently close to  $e$ , then it belongs to  $AU^\perp C_2(U)$ . Consider  $H'(U) := H(U) C_1(U)$ , and let  $\mathfrak{h}$  denote its Lie algebra. Now, for all  $i$  large enough, using the decomposition  $\mathfrak{g} = \mathfrak{h} \oplus \mathfrak{h}^\perp$  in (3-5), we can write  $g_i = c_i d_i r_i$ , where  $c_i \in C_1(U)$ ,  $d_i \in H(U)$  and  $r_i \in \exp \mathfrak{h}^\perp$ . Since  $c_i$  commutes with  $U$ , we can write

$$u_i g_i u_{t_i} = (u_i u_{t_i}) c_i (u_{t_i}^{-1} d_i u_{t_i}) (u_{t_i}^{-1} r_i u_{t_i}).$$

On the other hand, we have

$$\lim_i p u_i g_i u_{t_i} = \lim_i p c_i (u_{t_i}^{-1} d_i u_{t_i}) (u_{t_i}^{-1} r_i u_{t_i}) = p \alpha.$$

Since  $c_i \rightarrow e$ ,  $u_{t_i} d_i u_{t_i}^{-1} \in H(U)$  and  $u_{t_i} r_i u_{t_i}^{-1} \in \exp \mathfrak{h}^\perp$ , it follows that both sequences  $u_{t_i} d_i u_{t_i}^{-1}$  and  $u_{t_i} r_i u_{t_i}^{-1}$  must converge, say to  $h \in H(U)$  and to  $q \in \exp \mathfrak{h}^\perp$ , respectively. Hence  $\alpha = hq$  by replacing  $h$  by  $uh$  for some  $u \in U$ . On the other hand, we can write  $\alpha = avc_1 c_2 \in AU^\perp C_1(U) C_2(U)$ . So  $hq = avc_1 c_2$ . Note that  $c := c_1 c_2 \in C(H(U)) H(U) = H'(U)$ . We get

$$(9-2) \quad (a^{-1} h c^{-1}) (c q c^{-1}) = v.$$

Now, when  $\alpha$  is sufficiently close to  $e$ , all elements appearing in (9-2) are also close to  $e$ . Recall that the map  $H'(U) \times \mathfrak{h}^\perp \rightarrow G$  given by  $(h', X) \rightarrow h' \exp X$  is a local diffeomorphism onto a neighborhood of  $e$ . Since  $(a^{-1} h c^{-1}) \in H'(U)$ , and  $c q c^{-1}, v \in \exp \mathfrak{h}^\perp$ , we have  $a^{-1} h c^{-1} = e$  and  $c q c^{-1} = v$  for  $\alpha$  sufficiently small. In particular,

$$a^{-1} h c_2^{-1} = c_1^{-1} \in H(U) \cap C(H(U)) = \{e\}.$$

Hence  $c_1 = e$ . It follows that  $\alpha \in AU^\perp C_2(U)$ , as desired.

We further claim that we can choose  $\alpha$  outside of  $C_2(U)$ . As  $C_2(U)$  is a compact subgroup, we can choose a  $C_2(U)$ -invariant Euclidean norm  $\|\cdot\|$  on  $W$ . If  $\alpha = \psi(t) \in C_2(U)$  for some  $t \in T_\infty \subset U_0$ , then  $t$  is one of finitely many solutions of the polynomial equation  $\|\phi(t)\|^2 = \|p\|^2$ . Therefore, except for finitely many  $t \in T_\infty$ ,  $\alpha = \psi(t) \in AU^\perp C_2(U) - C_2(U)$ .  $\square$

The following lemma is similar to Lemma 9.1, but here we consider the case when  $U$  is the whole horospherical subgroup  $N$ . In this restrictive case, the limiting element can be taken inside  $A$ .

**Lemma 9.2** Let  $\mathbb{T}_i \subset N$  be a sequence of  $k$ -thick subsets in the sense that, for any one-parameter subgroup  $U_0 < N$ ,  $\mathbb{T}_i \cap U_0$  is a  $k$ -thick subset of  $U_0 \simeq \mathbb{R}$ . For any sequence  $g_i \rightarrow e$  in  $G - N_G(N)$ , there exist  $t_i \rightarrow \infty$  in  $\mathbb{T}_i$  and  $u_i \in N$  such that

$$u_i g_i u_{t_i} \rightarrow a$$

for some nontrivial element  $a \in A$ . Moreover,  $a$  can be chosen to be arbitrarily close to  $e$ .

**Proof** We first consider the case when  $g_i$  belongs to the opposite horospherical subgroup  $N^+$ . We will use the notation  $u^+$  and  $u^-$  defined in Section 3. Write  $g_i = \exp u^+(w_i)$  for some  $w_i \in \mathbb{R}^{d-1}$ . For  $x \in \mathbb{R}^{d-1}$ , set  $u_x := \exp u^-(x) \in N$ . Let  $\varepsilon > 0$  be arbitrary. Since  $\mathbb{T}_i$  is a  $k$ -thick subset of  $N$ , there exists  $\alpha_i \in \mathbb{R}$  such that  $\alpha_i w_i \in \mathbb{T}_i$  and

$$\varepsilon < \frac{1}{2} |\alpha_i| \|w_i\|^2 < k\varepsilon.$$

Setting  $u_{x_i} := u_{\alpha_i w_i} \in \mathbb{T}_i$  and  $y_i := -\alpha_i w_i (1 + \frac{1}{2} \alpha_i \|w_i\|^2)^{-1}$ , we compute

$$u_{y_i} g_i u_{x_i} = \begin{pmatrix} (1 + \frac{1}{2} \alpha_i \|w_i\|^2)^{-2} & 0 & 0 \\ (1 + \frac{1}{2} \alpha_i \|w_i\|^2)^{-1} w_i & I_{d-1} & 0 \\ -\frac{1}{2} \|w_i\|^2 & -(1 + \frac{1}{2} \alpha_i \|w_i\|^2) w_i^t & (1 + \frac{1}{2} \alpha_i \|w_i\|^2)^2 \end{pmatrix}.$$

The condition for the size of  $\alpha_i$  guarantees that, by passing to a subsequence, the sequence  $u_{x_i} g_i u_{y_i}$  converges to an element

$$\text{diag}(\alpha, I_{d-1}, \alpha^{-1}) \in A \quad \text{for } \alpha \in [(1 - \varepsilon)^{-2}, (1 - k\varepsilon)^{-2}] \cup [(1 + k\varepsilon)^{-2}, (1 + \varepsilon)^{-2}]$$

as  $i \rightarrow \infty$ . This proves the claim when  $g_i \in N^+$ .

Since the product map  $A \times M \times N^+ \times N \rightarrow G$  is a diffeomorphism onto a Zariski-open neighborhood of  $e$  in  $G$ , we can write  $g_i = a_i m_i u_i^+ u_i^-$  for some  $a_i \in A$ ,  $m_i \in M$ ,  $u_i^+ \in N^+$  and  $u_i^- \in N$  all of which converge to  $e$  as  $i \rightarrow \infty$ . By the previous case, we can find  $u_{t_i} \in \mathbb{T}_i$  and  $u_i \in N$  such that  $u_i u_i^+ u_{t_i}$  converges to a nontrivial element  $a \in A$ . Let  $\tilde{u}_i := (a_i m_i) u_i (a_i m_i)^{-1} \in N$ . Then  $\tilde{u}_i g_i u_{t_i} = a_i m_i u_i u_i^+ u_i^- u_{t_i} = a_i m_i (u_i u_i^+ u_{t_i}) u_i^- \rightarrow a$  as  $i \rightarrow \infty$ .  $\square$

**Lemma 9.3** Let  $L$  be any connected reductive subgroup of  $G$  normalized by  $A$ . Let  $U_0$  be a one-parameter subgroup of  $L \cap N$ . Let  $\mathbb{T}_i \subset U_0$  be a sequence of  $k$ -thick subsets. For a given sequence  $r_i \rightarrow e$  in  $\exp(\mathfrak{l}^\perp) - N(U_0)$ , there exists a sequence  $t_i \in \mathbb{T}_i$  such that, as  $i \rightarrow \infty$ ,

$$u_{t_i}^{-1} r_i u_{t_i} \rightarrow v$$

for some nontrivial element  $v \in (L \cap N)^\perp$ , and  $v$  can be chosen arbitrarily close to  $e$ . Moreover, for all  $n$  large enough, we can choose  $v$  so that

$$n \leq \|v\| \leq 2k^2 n.$$

**Proof** Without loss of generality, by [Proposition 3.7](#), we may assume that  $L_{\text{nc}} = H(U)$  for  $U = U_k = \mathbb{R}^k$  for some  $k \geq 1$  and  $U_0 := \mathbb{R}e_1$ . We write  $r_i = \exp(q_i)$ , where  $q_i \rightarrow 0$  in  $\mathfrak{l}^\perp$ . Using the notation introduced in [Section 3](#) and setting  $u^\perp = \text{Lie}(U^\perp) = \mathbb{R}^{d-1-k}$ , we can write

$$q_i = u^-(x_i) + u^+(y_i) + m(C_i),$$

where  $x_i \in u^\perp$ ,  $y_i \in (u^\perp)^t$  and

$$C_i = \begin{pmatrix} 0_k & B_i \\ -B_i^t & A_i \end{pmatrix}$$

is a skew-symmetric matrix, all of which converge to 0 as  $i \rightarrow \infty$ . We consider  $U_0 = \mathbb{R}e_1$  as  $\{u_s = se_1 \in \mathbb{R}^{d-1}\}$  and define the map  $\psi_i: \mathbb{R} \rightarrow \mathfrak{l}^\perp$  by

$$\psi_i(s) = u_s^{-1} q_i u_s \quad \text{for all } s \in \mathbb{R};$$

this is well defined since  $\mathfrak{l}^\perp$  is  $\text{Ad}(L)$ -invariant. Then a direct computation shows

$$(9-3) \quad \psi_i(s) = u^-(x_i + sB_i^t e_1 + \tfrac{1}{2}s^2 y_i) + u^+(y_i) + m(\tilde{C}_i),$$

where  $\tilde{C}_i$  is a skew-symmetric matrix of the form

$$\tilde{C}_i = \begin{pmatrix} 0_k & B_i + se_1 y_i^t \\ -B_i^t - sy_i e_1^t & A_i \end{pmatrix}.$$

Since  $r_i \notin N(U_0)$ , it follows that either  $y_i \neq 0$ , or  $y_i = 0$  and  $B_i^t e_1 \neq 0$ . Hence  $\psi_i$  is a nonconstant polynomial of degree at most 2, and  $\psi_i(0) \rightarrow 0$ . Let  $\lambda_i \in \mathbb{R}$  be defined by

$$\lambda_i = \sup\{\lambda > 0 : |\psi_i[-\lambda, \lambda]| \leq 1\}.$$

Then  $0 < \lambda_i < \infty$  and  $\lambda_i \rightarrow \infty$ . Now the rescaled polynomials  $\phi_i = \psi_i \circ \lambda_i : \mathbb{R} \rightarrow \mathfrak{l}^\perp$  form an equicontinuous family of polynomials of degree at most 2 and  $\lim_{i \rightarrow \infty} \phi_i(0) = 0$ . Therefore  $\phi_i$  converges to a polynomial  $\phi: \mathbb{R} \rightarrow \mathfrak{l}^\perp$  uniformly on compact subsets. Since  $\phi(0) = 0$  and  $\sup\{|\phi(\lambda)| : \lambda \in [-1, 1]\} = 1$ ,  $\phi$  is a nonconstant polynomial. From (9-3), it can be easily seen that  $\text{Im}(\phi)$  is contained in  $\text{Lie}(N) \cap \mathfrak{l}^\perp$ , by considering the two cases of  $y_i \neq 0$ , and  $y_i = 0$  and  $B_i^t e_1 \neq 0$  separately. For a given sequence  $T_i$  of  $k$ -thick subsets of  $U_0$ , set

$$T_\infty := \limsup_{i \rightarrow \infty} (T_i / \lambda_i),$$

which is also a  $k$ -thick subset of  $U_0$ .

Let  $s \in T_\infty$ . By passing to a subsequence, there exists  $t_i \in T_i$  such that  $t_i / \lambda_i \rightarrow s$  as  $i \rightarrow \infty$ . As  $\phi_i \rightarrow \phi$  uniformly on compact subsets, it follows that

$$\phi(s) = \lim_{i \rightarrow \infty} \psi_i(\lambda_i \cdot t_i / \lambda_i) = \lim_{i \rightarrow \infty} u_{t_i}^{-1} q_i u_{t_i}.$$

Since  $T_\infty$  accumulates on 0, so does  $\phi(T_\infty)$ . Taking the exponential map to each side of the above, the first part of the lemma follows.

The second part of the lemma holds by applying [Lemma 9.4](#) below for the nonconstant polynomial  $p(s) = \|\phi(s)\|^2$  of degree at most 4.  $\square$

**Lemma 9.4** *If  $p \in \mathbb{R}[s]$  is a polynomial of degree  $\delta \geq 1$  and  $T \subset \mathbb{R}$  is a  $k$ -thick subset, then  $p(T)$  is  $2k^\delta$ -thick at  $\infty$ .*

**Proof** Let  $C$  be the coefficient of  $s^\delta$  term of the polynomial  $p$ . Then there exists  $s_0 > 1$  such that  $\frac{1}{\sqrt{2}} \leq |p(s)|/|Cs^\delta| \leq \sqrt{2}$  for all  $|s| > s_0$ . Let  $r > |C|s_0^\delta/\sqrt{2}$ . Since  $T$  is  $k$ -thick, there exists  $t \in T$  such that  $(\sqrt{2}r/|C|)^{1/\delta} < |t| < k(\sqrt{2}r/|C|)^{1/\delta}$ . We compute that  $r \leq |p(t)| \leq 2k^\delta r$ .  $\square$

## 10 Translates of relative $U$ -minimal sets

Assume that  $\mathcal{M}$  is a convex cocompact hyperbolic manifold with Fuchsian ends and fix  $k > 1$  as given by Proposition 4.11. In this section, we fix a nontrivial connected closed subgroup  $U < N$ . Unless mentioned otherwise, we let  $R$  be a compact  $A$ -invariant subset of  $\text{RF } \mathcal{M}$  such that, for every  $x \in R$  and for any one-parameter subgroup  $U_0 = \{u_t\}$  of  $U$ , the set

$$\{t \in \mathbb{R} : xu_t \in R\}$$

is  $k$ -thick. In practice,  $R$  will be either  $\text{RF } \mathcal{M}$  or a compact subset of the form  $\text{RF } \mathcal{M} \cap F_{H(U)}^* \cap X$  for a closed  $H(U)$ -invariant subset  $X$ .

The main aim of this section is to prove Propositions 10.6 and 10.9 using the results of Section 9. The results in this section are needed in the step of finding a closed orbit in a given  $H(U)$ -orbit closure of an  $\text{RF } \mathcal{M}$ -point.

**Definition 10.1**

- A  $U$ -invariant closed subset  $Y \subset \Gamma \backslash G$  is  $U$ -minimal if  $yU$  is dense in  $Y$  for any  $y \in Y$ .
- A  $U$ -invariant closed subset  $Y \subset \Gamma \backslash G$  is  $U$ -minimal with respect to  $R$  if  $Y \cap R \neq \emptyset$  and, for any  $y \in Y \cap R$ ,  $yU$  is dense in  $Y$ .

A  $U$ -minimal subset may not exist, but a  $U$ -minimal subset with respect to a compact subset  $R$  always exists by Zorn's lemma. In this section, we study how to find an additional invariance of  $Y$  beyond  $U$  under certain conditions.

**Lemma 10.2** *Let  $Y \subset \Gamma \backslash G$  be a  $U$ -minimal subset with respect to  $R$ . For any  $y \in Y \cap R$ , there exists a sequence  $u_n \rightarrow \infty$  in  $U$  such that  $yu_n \rightarrow y$ .*

**Proof** The set  $Z := \{z \in Y : yu_n \rightarrow z \text{ for some } u_n \rightarrow \infty \text{ in } U\}$  is  $U$ -invariant and closed. By the assumption on  $R$ , there exists  $u_n \rightarrow \infty$  in  $U$  such that  $yu_n \in Y \cap R$ . Since  $Y \cap R$  is compact,  $yu_n$  converges to some  $z \in Y \cap R$ , by passing to a subsequence. Hence  $Z$  intersects  $Y \cap R$  nontrivially. Therefore  $Z = Y$ , by the  $U$ -minimality of  $Y$  with respect to  $R$ .  $\square$

A subset  $S$  of a topological space is said to be *locally closed* if  $S$  is open in its closure  $\bar{S}$ .

**Lemma 10.3** *Let  $Y$  be a  $U$ -minimal subset of  $\Gamma \backslash G$  with respect to  $R$ , and  $S$  be a closed subgroup of  $N(U)$  containing  $U$ . For any  $y_0 \in Y \cap R$ , the orbit  $y_0 S$  is not locally closed.*

**Proof** Suppose that  $y_0S$  is locally closed for some  $y_0 \in Y \cap R$ . Since  $Y$  is  $U$ -minimal with respect to  $R$ , there exists  $u_n \rightarrow \infty$  in  $U$  such that  $y_0u_n \rightarrow y_0$  by [Lemma 10.2](#). We may assume that  $y_0 = [e]$  without loss of generality. Since  $y_0S$  is locally closed,  $y_0S$  is homeomorphic to  $(S \cap \Gamma) \backslash S$  (see [\[Zimmer 1984, Theorem 2.1.14\]](#)). Therefore there exists  $\delta_n \in S \cap \Gamma$  such that  $\delta_n u_n \rightarrow e$  as  $n \rightarrow \infty$ . Since  $N(U) = AN C_1(U) C_2(U)$ , writing  $\delta_n = a_n r_n$  for  $a_n \in A$  and  $r_n \in N C_1(U) C_2(U)$ , it follows that  $a_n \rightarrow e$ . On the other hand, note that  $a_n$  is nontrivial as  $\Gamma$  does not contain any elliptic or parabolic element. This is a contradiction, as there exists a positive lower bound for the translation lengths of elements of  $\Gamma$ , which is given by the minimal length of a closed geodesic in  $M$ .  $\square$

In the rest of this section, we use the notation

$$H = H(U), \quad H' = H'(U), \quad F^* = F_{H(U)}^*.$$

**Lemma 10.4** *For every  $U$ -minimal subset  $Y \subset \Gamma \backslash G$  with respect to  $\text{RF } \mathcal{M}$  such that  $Y \cap F^* \cap \text{RF } \mathcal{M} \neq \emptyset$  and, for any  $y_0 \in Y \cap F^* \cap \text{RF } \mathcal{M}$ , there exists a sequence  $g_n \rightarrow e$  in  $G - N(U)$  such that  $y_0 g_n \in Y \cap \text{RF } \mathcal{M}$  for all  $n$ .*

**Proof** Let  $y_0 \in Y \cap F^* \cap \text{RF } \mathcal{M}$ . As  $Y = \overline{y_0 U}$ ,  $Y \subset \text{RF}_+ \mathcal{M}$ . Using [Lemma 4.5](#) and the fact that  $F^*$  is open, we get that there exists an open neighborhood  $\mathcal{O}$  of  $e$  such that

$$(10-1) \quad y_0 \mathcal{O} \cap Y \subset Y \cap F^* \subset Y \cap \text{RF } \mathcal{M} \cdot U.$$

Without loss of generality, we may assume that the map  $g \mapsto y_0 g \in \Gamma \backslash G$  is injective on  $\mathcal{O}$ , by shrinking  $\mathcal{O}$  if necessary. We claim that there exists  $g_n \rightarrow e$  in  $G - N(U)$  such that  $y_0 g_n \in Y \cap F^*$ . Suppose not. Then there exists a neighborhood  $\mathcal{O}' \subset \mathcal{O}$  of  $e$  such that

$$(10-2) \quad y_0 \mathcal{O}' \cap Y \subset y_0 N(U).$$

Set

$$S := \{g \in N(U) : Yg = Y\},$$

which is a closed subgroup of  $N(U)$  containing  $U$ . We will show that  $y_0S$  is locally closed; this contradicts [Lemma 10.3](#). We first claim that

$$(10-3) \quad y_0 \mathcal{O}' \cap Y \subset y_0 S.$$

If  $g \in \mathcal{O}'$  is such that  $y_0 g \in Y$ , then  $g \in N(U)$ . Therefore  $\overline{y_0 g U} = \overline{y_0 U} g = Yg \subset Y$ . Moreover,  $Yg \cap \text{RF } \mathcal{M} \neq \emptyset$  by (10-1). Hence  $Yg = Y$ , proving that  $g \in S$ . Now, (10-3) implies that  $y_0S$  is open in  $Y$ . On the other hand, since  $U \subset S$ , we get  $Y = {}_0 S$ . Therefore,  $y_0S$  is locally closed.

Hence we have  $g_n \rightarrow e$  in  $G - N(U)$  such that  $y_0 g_n \in Y \cap F^*$ . Since  $y_0 g_n \in F^* \cap \text{RF}_+ \mathcal{M}$  converges to  $y_0 \in F^* \cap \text{RF } \mathcal{M}$ , by [Lemma 8.7](#), there exists a sequence  $u_n \rightarrow e$  in  $U$  such that  $y_0 g_n u_n \in \text{RF } \mathcal{M}$ . Therefore, by replacing  $g_n$  with  $g_n u_n$ , this finishes the proof.  $\square$

**Lemma 10.5** *Let  $Y$  be a  $U$ -minimal subset with respect to  $R$ , and let  $W$  be a connected closed subgroup of  $N(U)$ . Suppose that there exists a sequence  $\alpha_i \rightarrow e$  in  $W$  such that  $Y\alpha_i \subset Y$ . Then there exists a one-parameter subsemigroup  $S < W$  such that  $YS \subset Y$ .*

*Moreover, if  $W_0$  is a compact Lie subgroup of  $W$  and  $\alpha_i \in W - W_0$  for all  $i$ , then  $S$  can be taken such that  $S \not\subset W_0$ .*

**Proof** The set  $S_0 = \{g \in W : Yg \subset Y\}$  is a closed subsemigroup of  $W$ . Write  $\alpha_i = \exp \xi_i$  for some  $\xi_i \in \text{Lie}(W)$ . Then the sequence  $v_i := \|\xi_i\|^{-1} \xi_i$  of unit vectors has a limit, say,  $v$ . It suffices to note that  $S := \{\exp(tv) : t \geq 0\}$  is contained in the closure of the subsemigroup generated by the  $\alpha_i$ . Now suppose that  $\alpha_i \in W - W_0$ . Set  $M_0 := \{g \in W_0 : Yg = Y\}$ . This is a closed Lie subgroup of  $W_0$ . Write  $\text{Lie } W = \mathfrak{m}_0 \oplus \mathfrak{m}_0^\perp$ , where  $\mathfrak{m}_0 = \text{Lie } M_0$ . By modifying  $\alpha_i$  by elements of  $M_0$ , we may assume  $\alpha_i = \exp \xi_i$  for  $\xi_i \rightarrow 0$  in  $\mathfrak{m}_0^\perp$ . Letting  $v \in \mathfrak{m}_0^\perp$  be a limit of  $\xi_i / \|\xi_i\|$ , it remains to check  $v \notin W_0$ . Suppose not. Since  $W_0$  is compact, we have  $\{\exp tv : t \geq 0\} = \exp \mathbb{R}v$ . Hence, for all  $t \geq 0$ ,  $Y \exp tv \subset Y$  as well as  $Y \exp(-tv) \subset Y$ . Therefore  $Y \exp tv = Y$ . Hence  $\exp v \in M_0$ . This is a contradiction, since  $v \in \mathfrak{m}_0^\perp$ .  $\square$

**Proposition 10.6** (translate of  $Y$  inside of  $Y$ ) *Let  $Y$  be a  $U$ -minimal set of  $\Gamma \backslash G$  with respect to  $\text{RF } \mathcal{M}$  such that  $Y \cap F^* \cap \text{RF } \mathcal{M} \neq \emptyset$ . Then there exists an unbounded one-parameter subsemigroup  $S$  inside the subgroup  $AU^\perp C_2(U)$  such that*

$$YS \subset Y.$$

**Proof** Choose  $y_0 \in Y \cap \text{RF } \mathcal{M} \cap F^*$ . By Lemma 10.4, there exists  $g_i \rightarrow e$  in  $G - N(U)$  such that  $y_0 g_i \in Y \cap \text{RF } \mathcal{M}$ . Let  $U_0 = \{u_t\}$  be a one-parameter subgroup of  $U$  as given by Lemma 9.1, with respect to the sequence  $g_i$ .

Let

$$\mathbb{T}_i := \{u_t \in U_0 : y_0 g_i u_t \in Y \cap \text{RF } \mathcal{M}\},$$

which is a  $k$ -thick subset of  $U_0$ . By Lemma 9.1, there exist sequences  $u_{t_i} \rightarrow \infty$  in  $\mathbb{T}_i$  and  $u_i \in U$  such that

$$u_i g_i u_{t_i} \rightarrow \alpha$$

for some element  $\alpha \in AU^\perp C_2(U) - C_2(U)$ . Note that  $y_0 g_i u_{t_i} \in Y \cap \text{RF } \mathcal{M}$  converges to some  $y_1 \in Y \cap \text{RF } \mathcal{M}$  by passing to a subsequence. Hence, as  $i \rightarrow \infty$ ,

$$y_0 u_i^{-1} = y_0 g_i u_{t_i} (u_i g_i u_{t_i})^{-1} \rightarrow y_1 \alpha^{-1}.$$

So  $y_1 \alpha^{-1} \in Y$ , and hence  $Y \alpha^{-1} \subset Y$ , since  $y_1 \in Y \cap \text{RF } \mathcal{M}$ . Since  $\alpha$  can be made arbitrarily close to  $e$  in Lemma 9.1, the claim follows from Lemma 10.5.  $\square$

**Proposition 10.7** (translate of  $Y$  inside of  $X$ ) *Let  $X$  be a closed  $H'$ -invariant set such that  $X \cap R \neq \emptyset$ . Let  $Y \subset X$  be a  $U$ -minimal subset with respect to  $R$ , and assume that there exists  $y \in Y \cap R$  and a sequence  $g_n \rightarrow e$  in  $G - H'$  such that  $y g_n \in X$  for all  $n$ . Then there exists some nontrivial  $v \in U^\perp$  such that*

$$Yv \subset X.$$

**Proof** Let  $\mathfrak{h}$  denote the Lie algebra of  $H'$ . We may write  $g_n = r_n h_n$ , where  $h_n \in H'$  and  $r_n \in \exp \mathfrak{h}^\perp$ . By replacing  $g_n$  with  $g_n h_n^{-1}$ , we may assume  $g_n = r_n$ . If  $r_n \in U^\perp$  for some  $n$ , then the claim follows since  $y_0 r_n \in X$  and hence  $Y r_n \subset X$ . Hence we assume that  $r_n \notin U^\perp$  for all  $n$ . We have, from (3-5),

$$\mathfrak{h}^\perp \cap \text{Lie}(N(U)) = \text{Lie } U^\perp.$$

Hence  $r_n \notin N(U)$  for all  $n$ . Therefore there exists a one-parameter subgroup  $U_0 = \{u_t\} < U$  such that  $r_n \notin N(U_0)$ . Let

$$\mathbb{T} = \{t \in \mathbb{R} : y u_t \in R\}.$$

Since  $y \in R$ , it follows that  $\mathbb{T}$  is a  $k$ -thick subset of  $\mathbb{R}$  by the assumption on  $R$ . Hence, by Lemma 9.3, there exists  $t_n \in \mathbb{T}$  such that  $u_{t_n}^{-1} r_n u_{t_n} \rightarrow v$  for some nontrivial  $v \in U^\perp$ . Observe

$$(y u_{t_n})(u_{t_n}^{-1} r_n u_{t_n}) = y r_n u_{t_n} \in X.$$

Passing to a subsequence,  $y u_{t_n} \rightarrow y_0$  for some  $y_0 \in Y \cap R$ , and hence  $y_0 v \in X$ . It follows that  $Y v \subset X$ .  $\square$

For a one-parameter subgroup  $V = \{v_t : t \in \mathbb{R}\}$  and a subset  $I \subset \mathbb{R}$ , the notation  $V_I$  means the subset  $\{v_t : t \in I\}$ .

**Lemma 10.8** *Let  $X$  be a closed  $AU$ -invariant set of  $\Gamma \backslash G$ , and  $V$  be a one-parameter subgroup of  $U^\perp$ . Assume that  $R := X \cap \text{RF } \mathcal{M} \cap F^*$  is nonempty and compact. If  $x_0 V_I \subset X$  for some  $x_0 \in R$  and a closed interval  $I$  containing 0, then  $X$  contains a  $V$ -orbit of a point in  $R$ .*

**Proof** Choose a sequence  $a_n \in A$  such that  $\liminf_{n \rightarrow \infty} a_n V_I a_n^{-1}$  contains a subsemigroup  $V^+$  of  $V$  as  $n \rightarrow \infty$ . Then

$$(x_0 a_n^{-1})(a_n V_I a_n^{-1}) = x_0 V_I a_n^{-1} \subset X.$$

By passing to a subsequence, we have that  $x_0 a_n^{-1}$  converges to some  $x_1 \in \text{RF } \mathcal{M}$ ; so  $x_1 V^+ \subset X$ . Since  $R$  is compact, so is  $\overline{x_0 A} \cap F^*$ , which implies that  $x_1 \in \overline{x_0 A} \cap F^*$ . Since  $x_1$  belongs to the open set  $F^*$ , it follows that  $x_1 v_s \in F^*$  for all sufficiently small  $s \in \mathbb{R}$ . By Lemma 4.5, this implies that  $x_1 v_s U \cap \text{RF } \mathcal{M} \neq \emptyset$  for some  $s > 0$  with  $v_s \in V^+$ . Note that

$$(x_1 v_s U)(v_s^{-1} V^+) = x_1 U V^+ \subset X.$$

Choose  $x_2 \in x_1 v_s U \cap \text{RF } \mathcal{M} \subset X \cap \text{RF } \mathcal{M} \cap F^*$ . Then  $x_2 (v_s^{-1} V^+) \subset X$ . Similarly as before, let  $a_n \in A$  be a sequence such that  $\liminf_{n \rightarrow \infty} a_n (v_s^{-1} V^+) a_n^{-1} = V$  and such that  $x_2 a_n^{-1}$  converges to some  $x_3 \in R$ . From

$$(x_2 a_n^{-1})(a_n v_s^{-1} V^+ a_n^{-1}) = x_2 v_s^{-1} V^+ a_n^{-1} \subset X,$$

we conclude that  $x_3 V \subset X$ .  $\square$

**Proposition 10.9** *Let  $X$  be a closed  $H'$ -invariant set. Assume that  $R := X \cap F^* \cap \text{RF } \mathcal{M}$  is a nonempty compact set, and let  $Y \subset X$  be a  $U$ -minimal subset with respect to  $R$ . Suppose that there exists  $y \in Y \cap R$  such that  $X - yH'$  is not closed. Then there exist an element  $z \in R$  and a nontrivial connected closed subgroup  $V < U^\perp$  such that*

$$zUV \subset X.$$

**Proof** Since  $X - yH'$  is not closed, there exists a sequence  $g_n \rightarrow e$  in  $G - H'$  such that  $yg_n \in X$  for all  $n \geq 1$ . By Lemma 10.8, it suffices to find  $x_0 \in R$  and a one-parameter subgroup  $V < U^\perp$  such that  $x_0 V_I \subset X$  for some interval  $I \subset \mathbb{R}$  containing 0. It follows from Propositions 10.6 and 10.7 that

$$Yv_0 \subset X \quad \text{and} \quad YS \subset Y,$$

where  $v_0 \in U^\perp - \{e\}$  and  $S$  is an unbounded one-parameter subsemigroup of  $AU^\perp C_2(U)$ . By Lemma 3.3,  $S$  is either of the form

- (1)  $S = \{\exp(t\xi_V) \exp(t\xi_C) : t \geq 0\}$ , or
- (2)  $S = \{(v \exp(t\xi_A)v^{-1}) \exp(t\xi_C) : t \geq 0\}$

for some  $\xi_A \in \text{Lie}(A) - \{0\}$ ,  $\xi_C \in \text{Lie}(C_2(U))$ ,  $\xi_V \in \text{Lie}(V) - \{0\}$  and  $v \in U^\perp$ .

**Case (1)** Since  $X$  is  $H'(U)$ -invariant and  $C_2(U) \subset H'(U)$ , we may assume  $YS \subset X$  with  $\xi_C = 0$ , so the claim follows.

**Case (2)** Set

$$Y_0 := Y C_2(U).$$

It is easy to check that  $Y_0$  is a  $U C_2(U)$ -minimal subset of  $X$  with respect to  $R$ . First suppose that  $v = e$ . Let  $A^+ := \{\exp(t\xi_A) : t \geq 0\}$ . Since  $YS \subset Y$  and  $\xi_C \in \text{Lie}(C_2(U))$ , it follows that  $Y_0 A^+ \subset Y_0$ . Choose  $y \in Y \cap R$ , and let  $a_n \rightarrow \infty$  be a sequence in  $A^+$ . Since  $R$  is compact and  $A$ -invariant,  $ya_n$  converges to some  $z_0 \in R$  by passing to a subsequence. Since  $Y_0 A^+ \subset Y_0$ , we have  $z_0 \in Y_0 \cap R$ . Since  $\liminf a_{-n} A^+ = A$ , we get  $z_0 A \subset Y_0$ . Since  $z_0 A U C_2(U) = z_0 U C_2(U) A$ , and  $Y_0$  is  $U C_2(U)$ -minimal with respect to  $R$ , we obtain  $Y_0 A \subset Y_0$ . Since  $v_0$  commutes with  $C_2(U)$ , we also get  $Y_0 v_0 \subset X$ . Therefore  $Y_0 A v_0 \subset Y_0 v_0 \subset X$ . By the  $A$ -invariance of  $X$ , it follows that  $Y_0 (A v_0 A) \subset X$ . Since  $A v_0 A$  contains some  $V^+$ , the claim follows.

Next suppose  $v \neq e$ . Since  $C_2(U)$  commutes with  $v$ , it follows that

$$Y_0 v A^+ v^{-1} \subset Y_0.$$

Since  $X$  is  $A$ -invariant, we get

$$Y_0 (v A^+ v^{-1}) A \subset Y_0 A \subset X.$$

Set  $V := \exp \mathbb{R}(\log v)$ . Since  $v A^+ v^{-1} A$  contains  $V_I$  for some interval  $I$  containing 0 for any subsemigroup  $A^+$  of  $A$ , we get  $Y_0 V_I \subset X$ . □



## 11 Closures of orbits inside $\partial F$ and nonhomogeneity

Let  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  be a convex cocompact hyperbolic manifold with nonempty Fuchsian ends. Let  $U$  be a connected closed subgroup of  $\check{H} \cap N$ ,  $H := H(U)$  and  $\text{BF } \mathcal{M}$  be as in (4-6). Then

$$\partial F = \text{BF } \mathcal{M} \cdot \check{V}^+ \cdot H'(U) \quad \text{and} \quad \partial F \cap \text{RF } \mathcal{M} = \text{BF } \mathcal{M} \cdot C(H(U)).$$

In this section, we classify closures of  $xH(U)$  and  $xAU$  for  $x \in \partial F - \text{RF } \mathcal{M}$  (Theorem 11.5); they are never homogeneous.

**Theorem 11.1** *If  $x = zc \in \text{BF } \mathcal{M} \cdot C(H(U))$  with  $z \in \text{BF } \mathcal{M}$  and  $c \in C(H(U))$ . Then:*

- (1)  $\overline{xU} = xL$  for some  $L \in \mathcal{L}_U$  contained in  $c^{-1}\check{H}c$ .
- (2)  $\overline{xH(U)} = xL$  for some  $L \in \mathcal{L}_U$  contained in  $c^{-1}\check{H}c$  and, for any  $y \in \mathcal{G}(U, xL)$ ,  $\overline{yU} = xL$ .
- (3)  $\overline{xAU} = \overline{xH(U)}$ .

**Proof** Since  $x$  is contained in the compact homogeneous space  $xc^{-1}\check{H}c$ , claims (1) and (2) are special cases of Ratner's theorem [1991b], which were also proved by Shah (unpublished, 1992) independently. So we only need to discuss the proof of (3). We show that  $\overline{xAU} = xL$ , where  $L$  is as given by (2). If  $U = L \cap N$ , then the claim follows from Theorem 13.1. Suppose that  $U$  is a proper subgroup of  $L \cap N$ . Since  $\overline{xAU}(K \cap H(U)) = \overline{xH(U)} = xL$  and  $\mathcal{S}(U, xL) \cdot (K \cap H(U))$  is a proper subset of  $xL$  (see Lemma 5.15), there exists  $y \in \overline{xAU} \cap \mathcal{G}(U, xL)$ . Hence (3) follows from (2).  $\square$

**Lemma 11.2** *Let  $V^+ \subset N$  be a one-parameter subsemigroup which is not contained in  $\check{H}$ . Then  $V^+H(U)$  is a closed subset of  $G$ .*

**Proof** Since the product map  $A \times N \rightarrow AN$  is a diffeomorphism and  $AN$  is closed, the product subset  $AW$  is closed in  $G$  for any closed subset  $W$  of  $N$ . Hence  $AUV^+$  is a closed subset of  $AN$ . We use Iwasawa decompositions  $H(U) = UA(K \cap H(U))$ , and the fact that  $AV^+ = V^+A$  in order to write  $V^+H(U) = AUV^+(K \cap H(U))$ . Hence the conclusion follows from compactness of  $K \cap H(U)$ .  $\square$

**Lemma 11.3** *Let  $V^+ \subset N$  be as in Lemma 11.2. If  $g_i \in \check{H}$  is a sequence such that  $g_i v_i h_i$  converges for some  $v_i \in V^+$  and  $h_i \in H(U)$  as  $i \rightarrow \infty$ , then, after passing to a subsequence, there exists  $p_i \in AU$  such that  $g_i p_i$  converges to an element of  $\check{H}$  as  $i \rightarrow \infty$ .*

**Proof** We write  $g_i = \tilde{k}_i \tilde{a}_i \tilde{n}_i \in (K \cap \check{H})A(N \cap \check{H})$  and  $h_i = u_i a_i k_i \in UA(K \cap H(U))$ . Since  $K \cap \check{H}$  and  $K \cap H(U)$  are compact, we may assume without loss of generality that  $\tilde{k}_i = k_i = e$  for all  $i$ . Observe that

$$g_i v_i h_i = \tilde{a}_i \tilde{n}_i v_i u_i a_i = \tilde{a}_i a_i (a_i^{-1} \tilde{n}_i u_i a_i) (a_i^{-1} v_i a_i),$$

where  $\tilde{a}_i a_i \in A$ ,  $a_i^{-1} \tilde{n}_i u_i a_i \in N \cap \check{H}$  and  $a_i^{-1} v_i a_i \in V^+$ . Since  $g_i v_i h_i$  converges as  $i \rightarrow \infty$  and the product map  $A \times (N \cap \check{H}) \times V^+ \rightarrow G$  is an injective proper map, it follows that all three sequences  $\tilde{a}_i a_i$ ,  $a_i^{-1} \tilde{n}_i u_i a_i$  and  $a_i^{-1} v_i a_i$  are convergent as  $i \rightarrow \infty$ . Noting that

$$g_i u_i a_i = \tilde{a}_i \tilde{n}_i u_i a_i = \tilde{a}_i a_i (a_i^{-1} \tilde{n}_i u_i a_i),$$

it remains to set  $p_i := u_i a_i \in AU$  to finish the proof.  $\square$

For  $z \in \text{BF } \mathcal{M}$ ,  $\pi(z \check{H} \check{V}^+ \check{H}) = \pi(z \check{H} \check{V}^+)$  is the closure of a Fuchsian end, of the form  $S_0 \times [0, \infty)$ , where  $S_0 = \pi(z \check{H})$ .

**Lemma 11.4** *Let  $z \in \text{BF } \mathcal{M}$ . Let  $zL$  be a closed orbit contained in  $\text{BF } \mathcal{M}$  for some  $L \in \mathcal{L}_U$  contained in  $\check{H}$ , and  $V^+ \subset N$  be a one-parameter subsemigroup such that  $\check{H} V^+ = \check{H} \check{V}^+$ . Then both  $zLV^+ H(U)$  and  $zLV^+$  are closed.*

**Proof** Without loss of generality, we assume  $z = [e]$ . Let  $B$  denote the component of  $\Omega$  such that  $\text{hull}(\partial B) = \pi(\check{H})$  for the projection map  $\pi: G \rightarrow \mathbb{H}^d$ . Since  $\check{H} V^+ = \check{H} \check{V}^+$ , we have  $\pi(\check{H} V^+ \check{H}) = \text{hull } \bar{B}$ . Note that, if  $\gamma(\text{hull}(B)) \cap \text{hull}(B) \neq \emptyset$  for  $\gamma \in \Gamma$ , then  $\gamma \in \check{H} \cap \Gamma = \text{Stab}_\Gamma(B)$ .

Suppose that  $\gamma_i \ell_i v_i h_i$  converges to some element  $g \in G$ , where  $\gamma_i \in \Gamma$ ,  $\ell_i \in L$ ,  $v_i \in V^+$  and  $h_i \in H(U)$ . Since  $\pi(\gamma_i \ell_i v_i h_i) \in \Gamma \text{ hull } \bar{B}$ , and  $\Gamma \text{ hull } \bar{B}$  is a closed subset of  $\mathbb{H}^d$ , we have  $\pi(g) \in \Gamma \text{ hull } \bar{B}$ . Without loss of generality, we may assume  $\pi(g) \in \text{hull } \bar{B}$  by replacing  $\gamma_i$  by  $\gamma \gamma_i$  for some  $\gamma \in \Gamma$  if necessary.

We claim that, by passing to a subsequence,

$$\gamma_i \in \check{H} \cap \Gamma.$$

Let  $\mathcal{O}$  be a neighborhood of  $\pi(g)$  such that

$$\mathcal{O} \cap \Gamma \text{ hull } \bar{B} \subset \text{hull } \bar{B};$$

such  $\mathcal{O}$  exists since  $d(\text{hull}(\gamma B), \text{hull}(B)) \geq \eta$  for all  $\gamma \in \Gamma - (\check{H} \cap \Gamma)$ , where  $\eta > 0$  is as given in (4-12). By passing to a subsequence, we may assume that  $\pi(\gamma_i \ell_i v_i h_i) \in \mathcal{O}$ . Since  $\pi(\ell_i v_i h_i) \in \text{hull } \bar{B}$  for all  $i$ , it follows that  $\pi(\gamma_i \ell_i v_i h_i) \in \text{hull } \bar{B}$  for all  $n$ . Therefore  $\gamma_i \in \check{H} \cap \Gamma$ . Applying Lemma 11.3 to the sequence  $(\gamma_i \ell_i) v_i h_i \rightarrow g$ , there exists  $p_i \in AU$  such that  $\gamma_i \ell_i p_i \rightarrow h$  in  $\check{H}$  as  $i \rightarrow \infty$ . Since  $\Gamma L$  is closed, we have  $h \in \Gamma L$ .

Since  $p_i^{-1} v_i h_i \in AU V^+ H(U) = V^+ H(U)$  and

$$(11-1) \quad \lim_{i \rightarrow \infty} p_i^{-1} v_i h_i = h^{-1} g,$$

we have  $h^{-1} g \in V^+ H(U)$  by Lemma 11.2. Therefore,  $g = h(h^{-1} g) \in \Gamma L V^+ H(U)$ . This proves that  $\Gamma L V^+ H(U)$  is closed. Note that, in the above argument, if  $h_i = e$  for all  $i$ , then  $h^{-1} g = \lim p_i^{-1} v_i \in AU V^+$ . Hence  $g = h(h^{-1} g) \in \Gamma L AU V^+ = \Gamma L V^+$ . This proves that  $\Gamma L V^+$  is closed.  $\square$

Note that  $x \in \text{RF}_+ \mathcal{M} - \text{RF} \mathcal{M} \cdot H(U)$  if and only if  $x \in (\text{RF}_+ \mathcal{M} \cap \partial F_{H(U)}) - \text{BF} \mathcal{M} \cdot C(H(U))$ .

**Theorem 11.5** *Let  $x \in \text{RF}_+ \mathcal{M} - \text{RF} \mathcal{M} \cdot H(U)$ . Then there exist a compact orbit  $zL \subset \text{BF} \mathcal{M}$  with  $L \in \mathcal{L}_U$ , an element  $c \in C(H(U))$  and a one-parameter subsemigroup  $V^+ \subset N$  with  $\check{H}V^+ = \check{H}\check{V}^+$  such that*

- (1)  $\overline{xH(U)} = zLV^+H(U)c$ ;
- (2)  $\overline{xAU} = zLV^+c$ .

Moreover, the closure of the geodesic plane  $\pi(xH(U))$  is diffeomorphic to a properly immersed submanifold  $S \times [0, \infty)$ , where  $S = \pi(zL)$  is a compact geodesic plane inside  $\text{BF} \mathcal{M}$ .

**Proof** We claim that we can write  $x = z_0vc$  for some nontrivial  $v \in \check{V}^+$ ,  $z_0 \in \text{BF} \mathcal{M}$  and  $c \in C(H(U))$ .

Let  $k = \dim U$  and  $C \subset \mathbb{S}^{d-1}$  denote the  $k$ -dimensional sphere stabilized by  $H(U)$ , and  $g \in G$  be such that  $x = [g]$ .

In view of the identification  $\Gamma \backslash G \simeq \text{F} \mathcal{M}$  induced from (3-1), the hypothesis  $x \in \text{RF}_+ \mathcal{M} - \text{RF} \mathcal{M} \cdot H(U)$  implies that there exists a component  $B_i$  of  $\Omega$  such that  $gC \subset \bar{B}_i$  and  $gC$  is tangent to  $\partial B_i$ . Let  $S \subset \bar{B}_i$  be the unique  $(d-2)$ -dimensional sphere tangent to  $\partial B_i$  containing  $C$ . Considering  $g = (v_1, \dots, v_d)$  as an orthonormal frame in  $\mathbb{H}^d$ , we can obtain a frame tangent to  $\text{hull}(S)$  by rotating the last  $d - (\dim(U) + 1)$  vectors of  $g$ . Since any frame tangent to  $\text{hull}(S)$  can be written as  $zv$  for some  $z \in \text{BF} \mathcal{M}$  and a nontrivial  $v \in \check{V}^+$ , and the process of rotating the last  $d - (\dim(U) + 1)$  coordinates corresponds to a right multiplication in  $\Gamma \backslash G$  by an element of  $c \in C(H(U))$ , this proves the claim.

Without loss of generality, we may assume  $c = e$ . By Theorem 11.1,  $\overline{z_0U} = z_0v_0^{-1}Lv_0$ , where  $L \in \mathcal{L}_U$  is contained in  $\check{H}$  and  $v_0 \in \check{H} \cap N$ . Hence  $\overline{xH(U)}$  contains  $zL(v_0v)H(U)$  for  $z := z_0v_0^{-1} \in \text{BF} \mathcal{M}$ . Set  $V^+ := \{\exp t(\log(vv_0)) : t \geq 0\}$ .

Note that  $V^+$  is contained in  $A(v_0v)A \cup \{e\}$ , and hence

$$zL \cup zLv_0vH(U) = zLV^+H(U)$$

and  $\check{H}V^+ = \check{H}\check{V}^+$  since  $v \neq e$ .

Since  $\overline{xH(U)} \subset zL \cup zL(v_0v)H(U)$ , and  $zL$  lies in the closure of  $zL(v_0v)H(U)$ , claim (1) follows since  $zLV^+H(U)$  is closed by Lemma 11.4. For claim (2), note that  $\overline{xAU} \supset \overline{z_0U}vA = zLV^+$ . By Lemma 11.4,  $zLV^+$  is  $AU$ -invariant and closed. Since  $x \in zLV^+$ , we conclude  $\overline{xAU} = zLV^+$ .

To see the last claim, observe that  $\pi(zLV^+H(U)) = \pi(zLV^+AU) = \pi(zLV^+)$  since  $V^+AU = AV^+$ , and  $AU < L$ . Since  $\check{H}V^+ = \check{H}\check{V}^+$ , and  $\pi(zL)$  is a compact geodesic plane (without boundary) in  $\pi(\check{H})$ , we get  $\pi(z\check{H}V^+) \simeq \pi(z\check{H}) \times [0, \infty)$  and  $\pi(zLV^+) \simeq \pi(zL) \times [0, \infty)$ .  $\square$

**Remark 11.6** An immediate consequence of Theorem 11.5 is that, if  $P \subset \mathcal{M}$  is a geodesic plane such that  $P \cap \text{core} \mathcal{M} = \emptyset$  but  $\bar{P} \cap \text{core} \mathcal{M} \neq \emptyset$ , then  $P$  is not properly immersed in  $\mathcal{M}$  and  $\bar{P}$  is a properly immersed submanifold with nonempty boundary.

## 12 Density of almost all $U$ -orbits

Let  $\Gamma < G = \mathrm{SO}^\circ(d, 1)$  be a Zariski-dense convex cocompact subgroup. The action of  $N$  on  $\mathrm{RF}_+ \mathcal{M}$  is minimal, and hence any  $N$ -orbit is dense in  $\mathrm{RF}_+ \mathcal{M}$  [Winter 2015]. Given a nontrivial connected closed subgroup  $U$  of  $N$ , there exists a dense  $U$ -orbit in  $\mathrm{RF}_+ \mathcal{M}$  [Maucourant and Schapira 2019]. In this section, we deduce from [Mohammadi and Oh 2015; Maucourant and Schapira 2019] that almost every  $U$ -orbit is dense in  $\mathrm{RF}_+ \mathcal{M}$  with respect to the Burger–Roblin measure in the case of a convex cocompact hyperbolic manifold with Fuchsian ends (Corollary 12.4).

The critical exponent  $\delta = \delta_\Gamma$  of  $\Gamma$  is defined to be the infimum  $s \geq 0$  such that the Poincaré series  $\sum_{\gamma \in \Gamma} e^{-sd(o, \gamma(o))}$  converges for any  $o \in \mathbb{H}^d$ . It is known that  $\delta$  is equal to the Hausdorff dimension of the limit set  $\Lambda$  and  $\delta = d - 1$  if and only if  $\Gamma$  is a lattice in  $G$  [Sullivan 1979].

Denote by  $m^{\mathrm{BR}}$  the  $N$ -invariant Burger–Roblin measure supported on  $\mathrm{RF}_+ \mathcal{M}$ ; it is characterized as a unique locally finite Borel measure supported on  $\mathrm{RF}_+ \mathcal{M}$  (up to a scaling) by [Burger 1990; Roblin 2003; Winter 2015]. We won't give an explicit formula of this measure as we will only use the fact that its support is equal to  $\mathrm{RF}_+ \mathcal{M}$ , together with the following theorem; recall that a locally finite  $U$ -invariant measure  $\mu$  is ergodic if every  $U$ -invariant measurable subset has either zero measure or zero comeasure, and is conservative if, for any measurable subset  $S$  with positive measure,  $\int_U 1_S(xu) du = \infty$  for  $\mu$ -almost all  $x$ , where  $du$  denotes the Haar measure on  $U$ .

**Theorem 12.1** [Mohammadi and Oh 2015; Maucourant and Schapira 2019] *Let  $U < N$  be a connected closed subgroup, and let  $\Gamma$  be a convex cocompact Zariski-dense subgroup of  $G$ . Then  $m^{\mathrm{BR}}$  is  $U$ -ergodic and conservative if  $\delta > \mathrm{codim}_N(U)$ .*

**Lemma 12.2** *Suppose that  $\Gamma_1 < \Gamma_2$  are convex cocompact subgroups of  $G$  with  $[\Gamma_1 : \Gamma_2] = \infty$ . Then  $\delta_{\Gamma_1} < \delta_{\Gamma_2}$ .*

**Proof** Note that a convex cocompact subgroup is of divergent type [Sullivan 1979; Roblin 2003]. Hence, the claim follows from [Dalbo et al. 2000, Proposition 9] if we check that  $\Lambda_{\Gamma_1} \neq \Lambda_{\Gamma_2}$ .

If  $\Lambda := \Lambda_{\Gamma_1} = \Lambda_{\Gamma_2}$ , then their convex hulls are the same, and hence the convex core of the manifold  $\Gamma_i \backslash \mathbb{H}^d$  is equal to  $\Gamma_i \backslash \mathrm{hull}(\Lambda)$ , which is compact. Since we have a covering map  $\Gamma_1 \backslash \mathrm{hull}(\Lambda) \rightarrow \Gamma_2 \backslash \mathrm{hull}(\Lambda)$ , it follows that  $[\Gamma_1 : \Gamma_2] < \infty$ .  $\square$

**Lemma 12.3** *If  $\Gamma \backslash \mathbb{H}^d$  is a convex cocompact hyperbolic manifold with Fuchsian ends, then  $\delta > d - 2$ .*

**Proof** If  $\Gamma$  is a lattice, then  $\Lambda = \mathbb{S}^{d-1}$  and  $\delta = d - 1$ . If  $\Gamma \backslash \mathbb{H}^d$  is a convex cocompact hyperbolic manifold with nonempty Fuchsian ends, then  $\Gamma$  contains a cocompact lattice  $\Gamma_0$  in a conjugate of  $\mathrm{SO}(d - 1, 1)$  whose limit set is equal to  $\partial B_i$  for some  $i$ . Now  $[\Gamma : \Gamma_0] = \infty$ ; otherwise,  $\Lambda = \partial B_i$ . Hence  $\delta > \delta_{\Gamma_0} = d - 2$  by Lemma 12.2.  $\square$

**Corollary 12.4** *Let  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  be a convex cocompact hyperbolic manifold with Fuchsian ends. Let  $U < N$  be any nontrivial connected closed subgroup. Then, for  $m^{\text{BR}}$ -almost every  $x \in \text{RF}_+ \mathcal{M}$ ,*

$$\overline{xU} = \text{RF}_+ \mathcal{M}.$$

**Proof** Without loss of generality, we may assume that  $U = \{u_t\}$  is a one-parameter subgroup. By Lemma 12.3 and Theorem 12.1,  $m^{\text{BR}}$  is  $U$ -ergodic and conservative. Since  $\text{RF}_+ \mathcal{M}$  is second countable and the  $U$ -action on it is continuous, the claim follows.  $\square$

Since  $F_{H(U)}^* \cap \text{RF}_+ \mathcal{M}$  is a nonempty open subset, it follows that almost all  $U$ -orbits in  $F_{H(U)}^* \cap \text{RF}_+ \mathcal{M}$  are dense in  $\text{RF}_+ \mathcal{M}$ .

### 13 Horospherical action in the presence of a compact factor

Let  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  be a convex cocompact hyperbolic manifold with Fuchsian ends and fix a nontrivial connected closed subgroup  $U$  of  $N$ . Consider a closed orbit  $xL$  for  $x \in \text{RF} \mathcal{M}$ , where  $L \in \mathcal{L}_U$  and  $U = L \cap N$ . The subgroup  $U$  is a horospherical subgroup of  $L$ , which is known to act minimally on  $xL \cap \text{RF}_+ \mathcal{M}$  provided  $L = L_{\text{nc}}$ . In this section, we extend the  $U$ -minimality on  $xL$  in the case when  $L$  has a compact factor.

**Theorem 13.1** *Let  $X := xL$  be a closed orbit where  $x \in \text{RF}_+ \mathcal{M}$ , and  $L \in \mathcal{L}_U$ . Let  $U := L \cap N$ . Then the following hold:*

- (1)  $X \cap \text{RF}_+ \mathcal{M}$  is  $U$ -minimal.
- (2)  $X$  is  $L_{\text{nc}}$ -minimal.
- (3) If  $L \in \mathcal{L}_U$  and  $x \in \text{RF} \mathcal{M}$ , then  $X \cap \text{RF} \mathcal{M}$  contains a dense  $A$ -orbit.
- (4) For any nontrivial connected closed subgroup  $U_0 < U$ , for  $m_X^{\text{BR}}$ -almost all  $x \in X$ ,

$$\overline{xU_0} = X \cap \text{RF}_+ \mathcal{M}.$$

The subgroup  $L \in \mathcal{L}_U$  is of the form  $v^{-1}H(U)Cv$ , where  $H(U)C \in \mathcal{L}_U$  and  $v \in N$ . The general case can be easily reduced to the case where  $L \in \mathcal{L}_U$ . In the following, we assume  $L = H(U)C \in \mathcal{L}_U$ . As before, we set

$$H = H(U), \quad H' = H'(U) \quad \text{and} \quad F^* = F_{H(U)}^*$$

and let  $\pi_1: H' \rightarrow H$  and  $\pi_2: H' \rightarrow C(H)$  be the canonical projections. In order to define  $m_X^{\text{BR}}$ , choose  $g \in G$  so that  $[g] = x$ . If we identify  $H \simeq \text{SO}^\circ(k, 1)$ , then, by Proposition 4.9,  $S := \pi_1(g^{-1}\Gamma g \cap HC) \backslash \mathbb{H}^k$  is a convex cocompact hyperbolic manifold with Fuchsian ends. Now  $\pi_1(g^{-1}\Gamma g \cap HC) \backslash H$  is the frame bundle of  $S$ , on which there exists the Burger–Roblin measure as discussed in Section 12. In the above statement, the notation  $m_X^{\text{BR}}$  means the  $C$ -invariant lift of this measure to  $X = xHC$ .

We first prove the following, which is a more concrete version of Proposition 10.6 in the case at hand:

**Proposition 13.2** *Let  $X$  be as in Theorem 13.1. Any  $U$ -minimal set  $Y$  of  $X$  with respect to  $\mathrm{RF}\mathcal{M}$  such that  $Y \cap F^* \cap \mathrm{RF}\mathcal{M} \neq \emptyset$  is  $A$ -invariant.*

**Proof** Let  $Y$  be a  $U$ -minimal set of  $X$  with respect to  $\mathrm{RF}\mathcal{M}$ . Let  $y_0 \in Y \cap F^* \cap \mathrm{RF}\mathcal{M}$ . By Lemma 10.4, there exists a sequence  $g_i \rightarrow e$  in  $HC - N(U)$  such that  $y_0 g_i \in Y \cap \mathrm{RF}\mathcal{M}$  for all  $i \geq 1$ .

Since  $U$  is a horospherical subgroup of  $H$  and  $C$  commutes with  $H$ , we can apply Lemma 9.2 to the sequence  $g_i^{-1}$  and the sequence of  $k$ -thick sets  $\mathbb{T}_i := \{u \in U : y_0 g_i u \in Y \cap \mathrm{RF}\mathcal{M}\}$  of  $U$ . This gives us sequences  $u_{t_i} \rightarrow \infty$  in  $\mathbb{T}_i$  and  $u_i \in U$  such that, as  $i \rightarrow \infty$ ,

$$u_{t_i}^{-1} g_i u_i \rightarrow a$$

for some nontrivial element  $a \in A$ . Since  $y_0 u_{t_i}$  converges to some  $y_1 \in Y \cap \mathrm{RF}\mathcal{M}$  by passing to a subsequence, we have

$$y_1 a = \lim(y_0 u_{t_i})(u_{t_i}^{-1} g_i u_i) \in Y.$$

Since  ${}_1U = Y$ , we get  $Ya \subset Y$ . Since  $a$  can be made arbitrarily close to  $e$  by Lemma 9.2, there exists a subsemigroup  $A_+$  of  $A$  such that  $YA_+ \subset Y$  by Lemma 10.5. Moreover, for any  $a \in A_+$ ,  $Ya \cap \mathrm{RF}\mathcal{M} \neq \emptyset$  as  $\mathrm{RF}\mathcal{M}$  is  $A$ -invariant. Therefore,  $Ya = Y$ . It follows that  $Ya^{-1} = Y$  as well. Hence  $Y$  is  $A$ -invariant.  $\square$

We now present:

**Proof of Theorem 13.1** First suppose that  $xL \cap F^* \neq \emptyset$ . We may then assume  $x \in F^* \cap \mathrm{RF}\mathcal{M}$ . Let  $Y$  be a  $U$ -minimal set of  $X$  with respect to  $\mathrm{RF}\mathcal{M}$ . If  $Y$  were contained in  $\partial F$ , then  $Y \subset \partial F \cap \mathrm{RF}\mathcal{M}$ . Since  $\mathrm{Stab}_L(x)$  is Zariski-dense in  $L$  by the definition of  $\mathcal{L}_U$ , it follows from [Benoist and Quint 2014, Lemma 4.13] that  $X \cap \mathrm{RF}_+ \mathcal{M}$  is  $AU$ -minimal. Therefore we have

$$\overline{YA} = X \cap \mathrm{RF}_+ \mathcal{M}$$

and hence  $X$  has to be contained in the closed  $A$ -invariant subset  $\partial F \cap \mathrm{RF}\mathcal{M}$  as well, yielding a contradiction. Therefore,

$$Y \cap F^* \cap \mathrm{RF}\mathcal{M} \neq \emptyset.$$

Hence, by Proposition 13.2,  $Y$  is  $A$ -invariant. Therefore, claim (1) follows from the  $AU$ -minimality of  $X \cap \mathrm{RF}_+ \mathcal{M}$  if  $x \in F^*$ . Now suppose  $xL \subset \partial F$ . In this case, it suffices to consider the case when  $U$  is a proper subgroup of  $N$ ; otherwise  $L = G$  and has no compact factor. Hence we may assume without loss of generality that  $U \subset \check{H} \cap N$ . As  $xL$  is closed, Theorem 11.5 implies that  $xL \subset \mathrm{BF}\mathcal{M} \cdot C(H(U))$ . Hence by modifying  $x$  by an element of  $C(H(U))$ , we may assume that  $X$  is contained in a compact homogeneous space of  $\check{H} = \mathrm{SO}^\circ(d-1, 1)$ , which is the frame bundle of a convex cocompact hyperbolic manifold with empty Fuchsian ends. Therefore, claim (1) follows from the previous case of  $x \in F^*$ , since  $F^* = \mathrm{RF}\mathcal{M}$  in the finite-volume case.

Claim (2) follows from (1) since  $\mathrm{RF}_+ \mathcal{M} \cdot H$  is closed, and  $X \subset \mathrm{RF}_+ \mathcal{M} \cdot H$ .

For (3), it suffices to show that the  $A$ -action on  $X \cap \mathrm{RF}\mathcal{M}$  is topologically transitive (see [Değirmenci and Koçak 2003]). Let  $x, y \in X \cap \mathrm{RF}\mathcal{M}$  be arbitrary and  $\mathcal{O}$  and  $\mathcal{O}'$  be open neighborhoods of  $e$  in  $H$ . The

set  $UU^t A(M \cap H)$  is a Zariski-open neighborhood of  $e$  in  $H$ , where  $U^t$  is the expanding horospherical subgroup of  $H$  for the action of  $A$ . Choose an open neighborhood  $Q_0$  of  $e$  in  $U$ , and an open neighborhood  $P_0$  of  $e$  in  $U^t A(M \cap H)$  such that  $Q_0 P_0 \subset \mathbb{O}$ .

We claim that  $xQ_0 A \cap y\mathbb{O}' \neq \emptyset$ , which implies  $x\mathbb{O} A \cap y\mathbb{O}' \neq \emptyset$ . Suppose that this is not true. Then

$$xQ_0 A \subset \Gamma \backslash G - y\mathbb{O}',$$

where the latter is a closed set. Now, choose a sequence  $a_n \in A$  such that  $a_n Q_0 a_n^{-1} \rightarrow U$  as  $n \rightarrow \infty$ , and observe

$$xa_n^{-1}(a_n Q_0 a_n^{-1}) = xQ_0 a_n^{-1} \subset \Gamma \backslash G - y\mathbb{O}'.$$

Passing to a subsequence,  $xa_n^{-1} \rightarrow x_0$  for some  $x_0 \in \text{RF } \mathcal{M}$ , and we obtain that  $x_0 U$  is contained in the closed subset  $\Gamma \backslash G - y\mathbb{O}'$ . This contradicts the  $U$ -minimality of  $X \cap \text{RF}_+ \mathcal{M}$ , which is claim (1). This proves (3).

For (4), note that, by [Corollary 12.4](#), almost all  $U_0$ -orbits in  $\pi_1(g^{-1}\Gamma g \cap HC) \backslash H$  are dense in the corresponding  $\text{RF}_+ \mathcal{M}$ -set. It follows that, for almost all  $x$ , the closure  $\overline{xU_0}$  contains a  $U$ -orbit of  $X$ . Hence, (4) follows from (1).  $\square$

## 14 Orbit closure theorems: beginning of the induction

In the rest of the paper, let  $\mathcal{M} = \Gamma \backslash \mathbb{H}^d$  be a convex cocompact hyperbolic  $d$ -manifold with Fuchsian ends, and  $G = \text{SO}^\circ(d, 1)$ . Let  $U < N$  be a nontrivial connected proper closed subgroup, and  $H(U)$  be its associated simple Lie subgroup of  $G$ .

Let  $\mathcal{L}_U$  and  $\mathcal{Q}_U$  be as defined in (5-8) and (5-9). The remainder of the paper is devoted to the proof of the next theorem, from which [Theorem 1.2](#) follows:

**Theorem 14.1** (1) For any  $x \in \text{RF } \mathcal{M}$ ,

$$\overline{xH(U)} = xL \cap F_{H(U)},$$

where  $xL$  is a closed orbit of some  $L \in \mathcal{L}_U$ .

(2) Let  $x_0 \hat{L}$  be a closed orbit for some  $\hat{L} \in \mathcal{L}_U$  and  $x_0 \in \text{RF } \mathcal{M}$ .

(a) For any  $x \in x_0 \hat{L} \cap \text{RF}_+ \mathcal{M}$ ,

$$\overline{xU} = xL \cap \text{RF}_+ \mathcal{M},$$

where  $xL$  is a closed orbit of some  $L \in \mathcal{Q}_U$ .

(b) For any  $x \in x_0 \hat{L} \cap \text{RF } \mathcal{M}$ ,

$$\overline{xAU} = xL \cap \text{RF}_+ \mathcal{M},$$

where  $xL$  is a closed orbit of some  $L \in \mathcal{L}_U$ .

- (3) Let  $x_0 \hat{L}$  be a closed orbit for some  $\hat{L} \in \mathcal{L}_U$  and  $x_0 \in \text{RF } \mathcal{M}$ . Let  $x_i L_i \subset x_0 \hat{L}$  be a sequence of closed orbits intersecting  $\text{RF } \mathcal{M}$ , where  $x_i \in \text{RF}_+ \mathcal{M}$  and  $L_i \in \mathcal{L}_U$ . Assume that no infinite subsequence of  $x_i L_i$  is contained in a subset of the form  $y_0 L_0 D$ , where  $y_0 L_0$  is a closed orbit of  $L_0 \in \mathcal{L}_U$  with  $\dim L_0 < \dim \hat{L}$  and  $D \subset N(U)$  is a compact subset. Then

$$\lim_{i \rightarrow \infty} (x_i L_i \cap \text{RF}_+ \mathcal{M}) = x_0 \hat{L} \cap \text{RF}_+ \mathcal{M}.$$

We will prove (1), (2) and (3) of [Theorem 14.1](#) by induction on the codimension of  $U$  in  $N$  and the codimension of  $U$  in  $\hat{L} \cap N$ , respectively.

For simplicity, let us say  $(1)_m$  holds if (1) is true for all  $U$  satisfying  $\text{codim}_N(U) \leq m$ . We will say  $(2)_m$  (resp.  $(2a)_m$ ,  $(2b)_m$ ) holds if (2) (resp. (2)(a), (2)(b)) is true for all  $U$  and  $\hat{L}$  satisfying  $\text{codim}_{\hat{L} \cap N}(U) \leq m$  and similarly for  $(3)_m$ .

### Base case of $m = 0$

Note that the bases cases  $(1)_0$ , and  $(3)_0$  are trivial, and that  $(2)_0$  follows from [Theorem 13.1](#).

We will deduce  $(1)_{m+1}$  from  $(2)_m$  and  $(3)_m$  in [Section 16](#); deduce  $(2)_{m+1}$  from  $(1)_{m+1}$ ,  $(2)_m$  and  $(3)_m$  in [Section 17](#); and finally deduce  $(3)_{m+1}$  from  $(1)_{m+1}$ ,  $(2)_{m+1}$  and  $(3)_m$  in [Section 18](#).

**Remark 14.2** When  $\text{codim}_{\hat{L} \cap N}(U) \geq 1$  and  $\hat{L} \in \mathcal{L}_U$ , we may assume without loss of generality that

$$U \subset \hat{L} \cap N \cap \check{H}$$

by replacing  $U$  and  $\hat{L}$  by their conjugates using an element  $m \in M$ .

**Remark 14.3** In the case when  $x \in \partial F_{H(U)}$ , [Theorem 14.1](#)(1)–(2) follow from [Theorem 11.1](#), and, if  $x_0 \in \partial F_{H(U)}$ , (3) follows from the work of Mozes and Shah [\[2019\]](#). So the main new cases of [Theorem 14.1](#) are when  $x, x_0 \in F_{H(U)}^*$ .

We will use the following observation:

### Singular $U$ –orbits under the induction hypothesis

Recall the notation  $\mathcal{S}(U, x\hat{L})$  and  $\mathcal{G}(U, x\hat{L})$  from [\(5-7\)](#).

**Lemma 14.4** Suppose that  $(2a)_m$  is true and that, for  $x \in \text{RF } \mathcal{M}$ ,  $xU$  is contained in a closed orbit  $x\hat{L}$  for some  $\hat{L} \in \mathcal{L}_U$ .

- (1) If  $\text{codim}_{\hat{L} \cap N}(U) \leq m + 1$ , then, for any  $x_0 \in \mathcal{S}(U, x\hat{L}) \cap \text{RF}_+ \mathcal{M}$ ,

$$\overline{x_0 U} = x_0 L \cap \text{RF}_+ \mathcal{M},$$

where  $x_0 L$  is a closed orbit of some subgroup  $L < \hat{L}$  contained in  $\mathcal{L}_U$  satisfying  $\dim L_{\text{nc}} < \dim \hat{L}_{\text{nc}}$ .



(2) If  $\text{codim}_{\hat{L} \cap N}(U) \leq m$ , then, for any  $x_0 \in \mathcal{G}(U, x\hat{L})$ ,

$$\overline{x_0 U} = x_0 \hat{L} \cap \text{RF}_+ \mathcal{M}.$$

**Proof** Suppose that  $\text{codim}_{\hat{L} \cap N}(U) \leq m + 1$  and that  $x_0 \in \mathcal{S}(U, x\hat{L}) \cap \text{RF}_+ \mathcal{M}$ . By [Proposition 5.13](#), we get

$$\overline{x_0 U} \subset x_0 Q$$

for some closed orbit  $x_0 Q$ , where  $Q \in \mathfrak{Q}_U$  satisfies  $\dim Q_{\text{nc}} < \dim \hat{L}_{\text{nc}}$ .

Now  $Q = vL_0v^{-1}$  for some  $L_0 \in \mathfrak{L}_U$  and  $v \in U^\perp$ . We have  $x_0 Uv = x_0 vU \subset x_0 vL_0$ . Since  $\text{codim}_{N \cap L_0}(U) = \text{codim}_{N \cap Q}(U) \leq m$ , by applying  $(2)_m$ , we get

$$\overline{x_0 vU} = x_0 vL \cap \text{RF}_+ \mathcal{M}$$

for some closed orbit  $x_0 vL$ , where  $L \in \mathfrak{L}_U$  is contained in  $L_0$ . Therefore

$$\overline{x_0 U} = x_0 vL v^{-1} \cap \text{RF}_+ \mathcal{M}.$$

As  $vLv^{-1} \in \mathfrak{L}_U$  and  $\dim L_{\text{nc}} \leq \dim Q_{\text{nc}} < \dim \hat{L}_{\text{nc}}$ , claim (1) is proved.

To prove (2), note that by  $(2a)_m$ , we get  $\overline{x_0 U} = x_0 L \cap \text{RF}_+ \mathcal{M}$  for some closed orbit  $x_0 L$  with  $L \in \mathfrak{L}_U$  such that  $L \subset \hat{L}$ . Since  $x_0 \in \mathcal{G}(U, x\hat{L})$ , we have  $\dim L_{\text{nc}} = \dim \hat{L}_{\text{nc}}$ .

Since  $L \subset \hat{L}$ ,  $L \cap N$  is a horospherical subgroup of  $\hat{L}$ . By [Theorem 13.1](#),  $L \cap N$  acts minimally on  $x\hat{L}$ , and hence  $L = \hat{L}$ .  $\square$

## 15 Generic points, uniform recurrence and additional invariance

The primary goal of this section is to prove [Propositions 15.1](#) and [15.2](#) in obtaining additional invariances using a sequence converging to a generic point of an intermediate closed orbit; the main ingredient is [Theorem 7.15](#) (avoidance theorem II). The results in this section are main tools in the enlargement steps of the proof of [Theorem 14.1](#).

In this section, we let  $U < N$  be a nontrivial connected closed subgroup. We suppose that

- $(2)_m$  and  $(3)_m$  are true;
- $x\hat{L}$  is a closed orbit for some  $x \in \text{RF } \mathcal{M}$ , and  $\hat{L} \in \mathfrak{L}_U$ ;
- $\text{codim}_{\hat{L} \cap N}(U) \leq m + 1$ .

We let  $\{U^{(i)}\}$  be a finite collection of one-parameter subgroups generating  $U$ . In the next two propositions, we let  $X$  be a closed  $U$ -invariant subset of  $x_0 \hat{L}$  such that

$$X \supset xL \cap \text{RF}_+ \mathcal{M}$$

for some closed orbit  $xL$ , where  $L \in \mathfrak{L}_U$  is a proper subgroup of  $\hat{L}$  and

$$x \in \bigcap_i \mathcal{G}(U^{(i)}, xL) \cap \text{RF } \mathcal{M}.$$

**Proposition 15.1** (additional invariance I) *Suppose that there exists a sequence  $x_i \rightarrow x$  in  $X$ , where  $x_i = x\ell_i r_i$  with  $x\ell_i \in xL \cap \text{RF}\mathcal{M}$  and  $r_i \in \exp \mathfrak{t}^\perp - \text{N}(U)$ .*

*Then there exists a sequence  $v_n \rightarrow \infty$  in  $(L \cap N)^\perp$  such that*

$$xLv_n \cap \text{RF}_+\mathcal{M} \subset X.$$

**Proof** Since  $r_i \notin \text{N}(U)$ , we can fix a one-parameter subgroup  $U_0 = \{u_t : t \in \mathbb{R}\}$  in the family  $\{U^{(i)}\}$  such that  $r_i \notin \text{N}(U_0)$  by passing to a subsequence.

Let  $E_j$  for  $j \in \mathbb{N}$  be a sequence of compact subsets in  $\mathcal{S}(U_0, xL) \cap \text{RF}\mathcal{M}$  as given by [Theorem 7.15](#). Set  $z_i := x\ell_i \in xL \cap \text{RF}\mathcal{M}$ . Fix  $j \in \mathbb{N}$  and  $n \gg 1$ . Since  $z_i \rightarrow x$  and  $x \in \mathcal{G}(U_0, xL)$ , there exist  $i_j \geq 1$  and an open neighborhood  $\mathcal{O}_j$  of  $E_j$  such that, for each  $i \geq i_j$ , the set

$$\mathbb{T}_i = \{t \in \mathbb{R} : z_i u_t \in \text{RF}\mathcal{M} - \mathcal{O}_j\}$$

is  $2k$ -thick by [Theorem 7.15](#). We apply [Lemma 9.3](#) to the sequence  $\mathbb{T}_i$ . We can find a sequence  $t_i = t_i(n) \in \mathbb{T}_i$  for  $i \geq i_j$  and elements  $y_j = y_j(n)$ ,  $v_j = v_j(n)$  satisfying that, as  $i \rightarrow \infty$ ,

- $z_i u_{t_i} \rightarrow y_j \in (\text{RF}\mathcal{M} \cap xL) - \mathcal{O}_j$ ;
- $u_{t_i}^{-1} r_i u_{t_i} \rightarrow v_j \in (L \cap N)^\perp$  with  $n \leq \|v_j\| \leq (2k^2)n$ .

So, as  $i \rightarrow \infty$ ,

$$x_i u_{t_i} = z_i r_i u_{t_i} \rightarrow y_j v_j \quad \text{in } X.$$

Note that, since  $L$  is a proper subgroup of  $\hat{L}$ , we have  $\text{codim}_{L \cap N}(U) \leq m$  by [Lemma 5.11](#).

If  $y_j$  belongs to  $\mathcal{G}(U, xL)$ , then  $\overline{y_j U} v_j = xL \cap \text{RF}_+\mathcal{M}$  by [Lemma 14.4\(2\)](#), and hence

$$X \supset \overline{y_j v_j U} = \overline{y_j U} v_j = xLv_j \cap \text{RF}_+\mathcal{M}.$$

Hence, the claim follows if  $y_j(n) \in \mathcal{G}(U, xL)$  for an infinite subsequence of  $n$ 's.

Now we may suppose that, for all  $n \geq 1$  and  $j \geq 1$ ,  $y_j(n) \in \mathcal{S}(U, xL) \cap \text{RF}_+\mathcal{M}$ , after passing to a subsequence. Fix  $n$ , and set  $y_j = y_j(n)$  and  $v_j = v_j(n)$ . Then, since  $\dim_{L \cap N} U \leq m$ , by  $(2)_m$ , we have

$$(15-1) \quad \overline{y_j U} = y_j L_j \cap \text{RF}_+\mathcal{M}$$

for some closed  $y_j L_j$ , where  $L_j \in \mathcal{Q}_U$  is contained in  $\hat{L}$  and  $\dim(L_j)_{\text{nc}} < \dim \hat{L}_{\text{nc}}$ . Write  $L_j = w_j^{-1} L'_j w_j$  for  $L'_j \in \mathcal{L}_U$  and  $w_j \in U^\perp$ . We claim that the sequence  $y_j L_j = y_j w_j^{-1} L'_j w_j$  satisfies the hypothesis  $(3)_m$ . It follows from the condition  $y_j \in (\text{RF}\mathcal{M} \cap xL) - \mathcal{O}_j$  for all  $j$  that no infinite subsequence of  $y_j L_j$  is contained in a subset of the form  $y_0 L_0 D \subset \mathcal{S}(U, xL)$ , where  $y_0 L_0$  is closed,  $L_0 \subset \mathcal{Q}_U$  and  $D \subset \text{N}(U)$  is a compact subset. Hence, by  $(3)_m$ , we have

$$\limsup_j y_j L_j \cap \text{RF}_+\mathcal{M} = xL \cap \text{RF}_+\mathcal{M}.$$

Therefore, for each fixed  $n \gg 1$  and  $y_j = y_j(n)$ ,

$$\limsup_j \overline{y_j U} = xL \cap \text{RF}_+\mathcal{M}.$$

By passing to a subsequence, there exists  $u_j \in U$  such that  $y_j u_j$  converges to  $x$ . As  $n \leq \|v_j(n)\| \leq (2k^2)n$ , the sequence  $v_j(n)$  converges to some  $v_n \in (L \cap N)^\perp$  as  $j \rightarrow \infty$ , after passing to a subsequence. Therefore

$$\limsup_j \overline{y_j(n)v_j(n)U} = \limsup_j \overline{y_j(n)U} v_j(n) \supset \overline{xU} v_n = xLv_n \cap \text{RF}_+ \mathcal{M},$$

where the last equality follows from Lemma 14.4(2), since  $\text{codim}_{L \cap N}(U) \leq m$ .  $\square$

Note that, in the above proposition,  $y_i = x\ell_i r_i$  is not necessarily in  $\text{RF } \mathcal{M}$ , and hence we cannot apply the avoidance theorem, Theorem 7.15, to the sequence  $y_i$  directly. We instead applied it to the sequence  $x\ell_i$ .

In the proposition below, we will consider a sequence  $x_i \rightarrow y$  inside  $\text{RF } \mathcal{M}$ , and apply Theorem 7.15 to the sequence  $x_i$ .

**Proposition 15.2** (additional invariance II) *Suppose there exists a sequence  $x_i \in X \cap \text{RF } \mathcal{M} - xL \cdot N(U)$  converging to  $x$  as  $i \rightarrow \infty$ . Then there exists a sequence  $v_j \rightarrow \infty$  in  $(N \cap L)^\perp$  such that*

$$xLv_j \cap \text{RF}_+ \mathcal{M} \subset X \quad \text{and} \quad xLv_j \cap \text{RF } \mathcal{M} \neq \emptyset.$$

The same works for a sequence  $x_i \in \text{RF } \mathcal{M} - xL \cdot N(U)$  such that  $\limsup x_i U \subset X$ .

**Proof** Let  $x_i \in \text{RF } \mathcal{M} - xL \cdot N(U)$  be a sequence converging to  $x$  such that  $\limsup x_i U \subset X$ . Write  $x_i = xg_i$  for  $g_i \rightarrow e$  in  $\hat{L}$ . Since  $L$  is reductive, we can write  $g_i = \ell_i r_i$ , where  $\ell_i \rightarrow e$  in  $L$  and  $r_i \rightarrow e$  in  $\exp \mathfrak{l}^\perp$  as  $i \rightarrow \infty$ . By the assumption on  $x_i$ , there exists a one-parameter subgroup  $U_0 = \{u_t : t \in \mathbb{R}\}$  among  $U^{(i)}$  such that  $r_i \notin N(U_0)$  by passing to a subsequence.

For  $R > 0$ , we set  $B(R) := \{v \in (L \cap N)^\perp \cap \hat{L} : \|v\| \leq R\}$ . Fix  $j$  and  $n \in \mathbb{N}$ . Let  $E_j$  and  $\mathcal{O}_j$  be as given by Theorem 7.15 for  $xL$  with respect to  $U_0$ . Then  $E_j$  is of the form

$$E_j = \bigcup_{i \in \Lambda_j} \Gamma \backslash \Gamma H_i D_i \cap \text{RF } \mathcal{M},$$

where  $H_i \in \mathcal{H}^*$  satisfies  $\dim(H_i)_{\text{nc}} < \dim L_{\text{nc}}$  and  $D_i$  is a compact subset of  $X(H_i, U_0) \cap L$ . As  $B(2k^2n) \subset C(U_0)$ , we have  $D_j^* := D_j B(2k^2n)$  is a compact subset of  $X(H_i, U_0)$ . Hence, the set

$$\tilde{E}_j := \bigcup_{i \in \Lambda_j} \Gamma \backslash \Gamma H_i D_i^* \cap \text{RF } \mathcal{M}$$

belongs to  $\mathcal{E}_{U_0}$  and is associated to the family  $\{H_i : i \in \Lambda_j\}$ , as defined in 7.3.

Let  $\tilde{E}'_j \in \mathcal{E}_{U_0}$  be a compact subset as given by Theorem 7.13, which is also associated to the same family  $\{H_i : i \in \Lambda_j\}$ . Note that for any  $z \in \tilde{E}'_j$ , the closure  $\overline{zU_0}$  is contained in  $\Gamma \backslash \Gamma H_i D_i^*$  for some  $i \in \Lambda_j$ . In particular,  $\tilde{E}'_j$  is a compact subset disjoint from  $\mathcal{G}(U_0, xL)$ . Since  $x_i \rightarrow x$  and  $x \in \mathcal{G}(U_0, xL)$ , there exists  $i_j \geq 1$  such that  $x_i \notin \tilde{E}'_j$  for all  $i \geq i_j$ . By Theorem 7.13, there exists a neighborhood  $\tilde{\mathcal{O}}_j$  of  $\tilde{E}_j$  such that, for each  $i \geq i_j$ , the set

$$\mathsf{T}_i = \{t \in \mathbb{R} : x_i u_t \in \text{RF } \mathcal{M} - \tilde{\mathcal{O}}_j\}$$

is  $2k$ -thick. Applying [Lemma 9.3](#) to  $T_i$  and  $r_i \rightarrow e$ , we can find  $t_i = t_i(n) \in T_i$  such that  $u_{t_i}^{-1} r_i u_{t_i} \rightarrow v_j$  for some  $v_j = v_j(n) \in (L \cap N)^\perp$ , with  $n \leq \|v_j\| \leq 2k^2 \cdot n$ . Passing to a subsequence,  $x_i u_{t_i}$  converges to some  $\tilde{x}_j(n) \in \text{RF} \mathcal{M} - \tilde{\mathcal{O}}_j$  as  $i \rightarrow \infty$ . Set

$$z_i := x \ell_i \quad \text{and} \quad \mathcal{O}_j := \tilde{\mathcal{O}}_j B(2k^2 n) \cap xL.$$

Since  $x_i u_{t_i} = z_i u_{t_i} (u_{t_i}^{-1} r_i u_{t_i})$ , we have

$$z_i u_{t_i} \rightarrow y_j \in (\text{RF}_+ \mathcal{M} \cap xL) - \mathcal{O}_j,$$

where  $y_j = y_j(n) := \tilde{x}_j(n) v_j^{-1}$ .

We check that  $E_j \subset \mathcal{O}_j$  as  $B(2k^2 n) B(2k^2 n)$  contains  $e$ . It follows that  $y_j \notin E_j$ . Since  $\tilde{x}_j(n) \in \overline{y_j U} v_j \subset X$ , we have  $\overline{y_j U} v_j \cap \text{RF} \mathcal{M} \neq \emptyset$ . Given these, we can now repeat verbatim the proof of [Proposition 15.1](#) to complete the proof.  $\square$

[Theorem 2.2](#) can be proved similarly to the proof of [Proposition 15.1](#):

**Proof of Theorem 2.2** Let  $E_j$  for  $j \in \mathbb{N}$  be a sequence of compact subsets of  $\mathcal{S}(U_0) \cap \text{RF} \mathcal{M}$  as given by [Theorem 7.15](#). Fix  $j \in \mathbb{N}$ . Then there exist  $i_j \geq 1$  and a neighborhood  $\mathcal{O}_j$  of  $E_j$  such that

$$\{t \in \mathbb{R} : x_i u_t \in \text{RF} \mathcal{M} - \mathcal{O}_j\}$$

is  $2k$ -thick for all  $i \geq i_j$ . Hence we can find a sequence  $t_i \in [-2kT_i, -T_i] \cup [T_i, 2kT_i]$  such that  $x_i u_{t_i} \in \text{RF} \mathcal{M} - \mathcal{O}_j$  for all  $i \geq i_j$ . Hence, by passing to a subsequence,  $x_i u_{t_i}$  converges to some  $y_j \in \text{RF} \mathcal{M} - \mathcal{O}_j$  as  $i \rightarrow \infty$ . If  $y_j \in \mathcal{G}(U)$  for some  $j$ , then  $(2)_m$  and [Lemma 14.4\(2\)](#) imply that  $\overline{y_j U} = \text{RF}_+ \mathcal{M}$ , proving the claim.

Now we assume that  $y_j \in \mathcal{S}(U, x\hat{L})$  for all  $j$ . Then, by  $(2)_m$  and [Lemma 14.4\(1\)](#), we have

$$\overline{y_j U} = y_j L_j \cap \text{RF}_+ \mathcal{M}$$

for some closed  $y_j L_j$ , where  $L_j \in \mathcal{L}_U$  is a proper subgroup of  $G$ . Similarly to the proof of [Proposition 15.1](#), we can show that the sequence  $y_j L_j$  satisfies the hypothesis  $(3)_m$ . Hence, by applying  $(3)_m$  to the sequence  $y_j L_j$ , we get

$$\limsup (y_j L_j \cap \text{RF}_+ \mathcal{M}) = \text{RF}_+ \mathcal{M}.$$

Therefore  $\limsup y_j U = \limsup \overline{y_j U} = \text{RF}_+ \mathcal{M}$ . This, together with [Theorem 13.1\(4\)](#), finishes the proof.  $\square$

## 16 $H(U)$ -orbit closures: proof of $(1)_{m+1}$

We fix a nontrivial connected proper subgroup  $U < N$ . Without loss of generality, we may assume

$$U < N \cap \check{H}$$

using a conjugation by an element of  $M$ . We set

$$H = H(U), \quad H' = H'(U), \quad F = F_{H(U)}, \quad F^* = F_{H(U)}^* \quad \text{and} \quad \partial F = \partial F_{H(U)}.$$

By the assumption  $U < N \cap \check{H}$ , we have

$$\partial F \cap \text{RF } \mathcal{M} = \text{BF } \mathcal{M} \cdot C(H).$$

We will be using the following observation:

**Lemma 16.1** *Let  $x_1 L_1$  and  $x_2 L_2$  be closed orbits, where  $x_1, x_2 \in \text{RF } \mathcal{M}$ ,  $L_1 \in \mathcal{Q}_U$  and  $L_2 \in \mathcal{L}_U$ . If  $x_1 L_1 \cap \text{RF } \mathcal{M} \subset x_2 L_2$ , then  $L_1 \subset L_2$  and  $x_1 L_1 \subset x_2 L_2$ .*

**Proof** Since  $L_2$  contains  $H$ , we get that  $x_1 L_1 \cap \text{RF } \mathcal{M} \cdot H \subset x_2 L_2$ . Suppose that  $x_1 L_1 \cap F^* \neq \emptyset$ . We may assume  $x_1 \in F^*$ . Recall from (4-5) that  $F^* \subset \text{RF } \mathcal{M} \cdot H$ . Hence, we have  $x_1 L_1 \cap F^* \subset x_2 L_2$ . Since  $F^*$  is open, there exist  $g_1, g_2 \in G$  such that  $[g_i] = x_i$ , and  $g_1 L_1 \cap \mathcal{O} \subset g_2 L_2$  for some open neighborhood  $\mathcal{O}$  of  $g_1$ . It follows that  $L_1 \cap g_1^{-1} \mathcal{O} \subset g_1^{-1} g_2 L_2$ . Since  $e \in g_1^{-1} g_2 L_2$ , we have  $g_1^{-1} g_2 L_2 = L_2$ . Since  $L_1$  is topologically generated by  $L_1 \cap g_1^{-1} \mathcal{O}$ , we deduce  $L_1 \subset L_2$ . Since  $x_1 L_1 \cap x_2 L_2 \neq \emptyset$ , it follows that  $x_1 L_1 \subset x_2 L_2$ .

Now consider the case when  $x_1 L_1 \cap F^* = \emptyset$ . In this case,  $x_1 L_1 \cap \text{RF } \mathcal{M} \subset \text{RF } \mathcal{M} \cap \partial F$ . By Theorem 13.1(4), we can assume that  $\overline{x_1 U} = x_1 L_1 \cap \text{RF}_+ \mathcal{M}$ . As  $x_1$  is contained in  $\text{BF } \mathcal{M} \cdot C(H)$ , so is  $\overline{x_1 U}$ . It follows that  $x_1 L_1$  is compact and hence is contained in  $\text{RF } \mathcal{M}$ . Hence, the hypothesis implies that  $x_1 L_1 \subset x_2 L_2$ , which then implies  $L_1 \subset L_2$  by the same argument as in the previous case.  $\square$

**Lemma 16.2** *Let  $y_1 L_1$  and  $y_2 L_2$  be closed orbits, where  $y_1 \in \text{RF } \mathcal{M}$ ,  $y_2 \in \text{RF}_+ \mathcal{M}$ ,  $L_1 \in \mathcal{Q}_U$  and  $L_2 \in \mathcal{L}_U$ . If  $y_1 L_1 \subset y_2 L_2 D$  for some subset  $D \subset N(U)$ , then there exists  $d \in D$  such that  $L_1 \subset d^{-1} L_2 d$  and  $y_1 L_1 \subset y_2 L_2 d$ .*

**Proof** By Theorem 13.1(4), we may assume  $\overline{y_1 U} = y_1 L_1 \cap \text{RF}_+ \mathcal{M}$ . By the assumption,  $y_1 = y_2 \ell_2 d$  for some  $\ell_2 \in L_2$  and  $d \in D$ . Since  $y_2 \ell_2 = y_1 d^{-1}$  and  $N(U)$  preserves  $\text{RF}_+ \mathcal{M}$ ,  $y_2 \ell_2 \in \text{RF}_+ \mathcal{M}$ . Hence we may replace  $y_2$  by  $y_2 \ell_2$ , and hence assume that  $y_1 = y_2 d$ . Since

$$(16-1) \quad y_1 L_1 \cap \text{RF}_+ \mathcal{M} = \overline{y_2 d U} = \overline{y_2 U} d \subset y_2 L_2 d$$

and  $F^* \subset \text{RF}_+ \mathcal{M} \cdot H$ , we get  $y_1 L_1 d^{-1} \cap F^* \subset y_2 L_2$ .

If  $y_1 L_1 d^{-1} \cap F^* \neq \emptyset$ , using the openness of  $F^*$ , the conclusion follows as in the first part of the proof of Lemma 16.1. Now consider the case when  $y_1 L_1 d^{-1} \cap F^* = \emptyset$ . In particular,  $y_2 = y_1 d^{-1}$  belongs to

$$\text{RF}_+ \mathcal{M} - F^* \subset \text{BF } \mathcal{M} \cdot N(U)$$

by (4-7). It follows from Theorem 11.1 that  $\overline{y_2 U} = y_2 L'_2$  for some  $L'_2 \in \mathcal{Q}_U$  contained in  $L_2$ . In view of (16-1), we get  $y_1 L_1 \cap \text{RF}_+ \mathcal{M} = y_1 d^{-1} L'_2 d$ . Therefore  $d^{-1} L'_2 d \subset L_1$ . Since  $y_1 L_1 \cap \text{RF}_+ \mathcal{M}$  is  $A(L_1 \cap N)$ -invariant, it follows that  $d^{-1} L'_2 d \in \mathcal{L}_U$  and  $d^{-1} L'_2 d \cap N = L_1 \cap N$ . As a result,  $(L_1)_{\text{nc}} = d^{-1} (L'_2)_{\text{nc}} d$ . By Lemma 5.11, we get that  $L_1 = d^{-1} L'_2 d \subset d^{-1} L_2 d$  and  $y_1 L_1 = y_2 L'_2 d \subset y_2 L_2 d$ .  $\square$

The following proposition says that the classification of  $H'$ -orbit closures yields the classification of  $H$ -orbit closures:

**Proposition 16.3** *Let  $x \in \text{RF } \mathcal{M}$ , and assume that there exists  $U < \tilde{U} < N$  such that  $xH'(\tilde{U})$  is closed, and*

$$\overline{xH'} = xH(\tilde{U}) \cdot C(H) \cap F.$$

*Then there exists a closed subgroup  $C < C(H(\tilde{U}))$  such that*

$$\overline{xH} = xH(\tilde{U})C \cap F.$$

**Proof** By Proposition 4.9 and Theorem 13.1(2), there exists a closed subgroup  $C < C(H(\tilde{U}))$  such that  $H(\tilde{U})C \in \mathcal{L}_U$  and  $X := xH(\tilde{U})C$  is a closed  $H(\tilde{U})$ -minimal subset. In particular,  $\overline{xH} \subset X \cap F$ . Now, by Theorem 13.1(3), there exists  $y \in X$  such that  $\overline{yA} = X \cap \text{RF } \mathcal{M}$ . Since  $C$  is contained in  $C(H)$  and

$$\overline{xH} \cdot C(H) = \overline{xH'} = xH(\tilde{U}) \cdot C(H) \cap F,$$

there exists  $c_0 \in C(H)$  such that  $yc_0 \in \overline{xH}$ . Since  $\overline{yAc_0} = \overline{yc_0A} \subset \overline{xH}$  and  $c_0 \in C(H)$ , it follows that  $Xc_0 \cap \text{RF } \mathcal{M} \subset \overline{xH} \subset X$ . Applying Lemma 16.1, we get  $Xc_0 = \overline{xH} = X$ .  $\square$

In the rest of this section, fix  $m \in \mathbb{N} \cup \{0\}$  and assume that

$$1 \leq \text{codim}_N(U) = m + 1.$$

In order to describe the closure of  $xH(U)$ , in view of Theorem 11.1, we assume that

$$x \in F^* \cap \text{RF } \mathcal{M}.$$

By Proposition 16.3, it suffices to show that

$$(16-2) \quad \overline{xH'} = xL C(H) \cap F$$

for some closed orbit  $xL$  for some  $L \in \mathcal{L}_U$ .

In the rest of this section, we set  $X := \overline{xH'}$  and assume that  $xH'$  is not closed, i.e.  $X \neq xH'$ .

We also assume that  $(2)_m$  holds in the entire section.

**Lemma 16.4** (moving from  $\mathcal{Q}_U$  to  $\mathcal{L}_U$ ) *If  $x_0L \cap \text{RF}_+ \mathcal{M} \subset X$  for some closed orbit  $x_0L$  with  $x_0 \in \text{RF } \mathcal{M}$ , and  $L \in \mathcal{Q}_U - \mathcal{L}_U$ , then*

$$x_1\hat{L} \cap \text{RF}_+ \mathcal{M} \subset X$$

*for some closed orbit  $x_1\hat{L}$  with  $x_1 \in \text{RF } \mathcal{M}$ , and  $\hat{L} \in \mathcal{L}_U$  with  $\dim(\hat{L} \cap N) > \dim(L \cap N)$ . Moreover,  $x_1$  can be taken to be any element of the set  $\limsup_{t \rightarrow +\infty} x_0ua_{-t}$  for any  $u \in U$ .*

**Proof** By (5-10), we can write  $L = v^{-1}\hat{L}v$  for some  $\hat{L} \in \mathcal{L}_U$  and  $v \in (\hat{L} \cap N)^\perp$ . As  $L \notin \mathcal{L}_U$ , we have  $v \neq e$ . Set  $\hat{U} := \hat{L} \cap N$ . Note that  $x_0 v^{-1} \hat{U} A v \subset x_0 L \cap \text{RF}_+ \mathcal{M}$ , as  $\hat{U} A < \hat{L}$ . Since  $X$  is  $A$ -invariant,  $x_0 v^{-1} \hat{U} A v A \subset X$ . Let  $V^+$  be the unipotent one-parameter subsemigroup contained in  $AvA$ , and let  $V$  be the one-parameter subgroup containing  $V^+$ . Then  $x_0 v^{-1} V^+ \hat{U} \subset X$ . Since  $x_0 A \subset \text{RF} \mathcal{M}$  and  $\text{RF} \mathcal{M}$  is compact,  $\limsup_{t \rightarrow +\infty} x_0 a_{-t}$  is not empty. Now let  $x_1$  be any limit of  $x_0 u a_{-t_n}$  for some sequence  $t_n \rightarrow \infty$  and  $u \in U$ . Since  $v^{-1} V^+$  is an open neighborhood of  $e$  in  $V$ ,  $\liminf_{n \rightarrow \infty} a_{t_n} v^{-1} V^+ a_{-t_n} = V$ . Note that, as  $u \in \hat{U}$ ,

$$x_0 u a_{-t_n} (a_{t_n} v^{-1} \hat{U} V^+ a_{-t_n}) = x_0 v^{-1} \hat{U} V^+ a_{-t_n} \subset X.$$

As a result, we obtain that  $x_1 \hat{U} V \subset X$  and hence  $x_1 \hat{U} V A \subset X$ . Since  $\text{codim}_N(\hat{U} V) \leq m$ , the claim follows from (2a)<sub>m</sub>.  $\square$

**Proposition 16.5** *If  $R := X \cap F^* \cap \text{RF} \mathcal{M}$  accumulates on  $\partial F$ , i.e. there exists  $x_n \in R$  converging to a point in  $\partial F$ , then*

$$X \supset x_0 L \cap \text{RF}_+ \mathcal{M}$$

for some closed orbit  $x_0 L$  with  $x_0 \in F^* \cap \text{RF} \mathcal{M}$  and  $L \in \mathcal{L}_U$  such that  $\dim(L \cap N) > \dim U$ .

**Proof** There exist  $x_n \in R$  which converge to some  $z \in \text{BF} \mathcal{M} \cdot C(H)$  as  $n \rightarrow \infty$ . We may assume  $z \in \text{BF} \mathcal{M}$  without loss of generality, since  $R$  is  $C(H)$ -invariant. We claim that  $R \subset X$  contains  $z_1 v$ , where  $z_1 \in \text{BF} \mathcal{M}$  and  $v \in \check{V} - \{e\}$ . Write  $x_n = z h_n r_n$  for some  $h_n \in \check{H}$  and  $r_n \in \exp \check{\mathfrak{h}}^\perp$ , where  $\check{\mathfrak{h}}^\perp$  denotes the  $\text{Ad}(\check{H})$ -complementary subspace to  $\text{Lie}(\check{H})$  in  $\mathfrak{g}$ . Since  $x_n \in F^*$  and  $z \in \text{BF} \mathcal{M}$ , it follows that  $r_n \notin C(H)$  for all large  $n$ . By Lemma 3.2 and (3-5), we have

$$N(U) \cap \exp(\check{\mathfrak{h}}^\perp \cap \mathfrak{O}) \subset \check{V} C(H)$$

for a small neighborhood  $\mathfrak{O}$  of 0 in  $\mathfrak{g}$ . Therefore, if  $r_n \in N(U)$  for some  $n$ , then the  $\check{V}$ -component of  $r_n$  should be nontrivial. Hence, by Theorem 11.1,  $X \supset \overline{z h_n U} r_n = z h_n L r_n$  for some  $L \in \mathcal{L}_U$  contained in  $\check{H}$ . Note that  $x_n = z h_n r_n \in F^*$  and that  $r_n^{-1} L r_n \in \mathcal{L}_U - \mathcal{L}_U$ , since  $r_n \in \check{V} - \{e\}$ . Hence the claim follows from Lemma 16.4.

Now suppose that  $r_n \notin N(U)$  for all  $n$ . Then there exists a one-parameter subgroup  $U_0 = \{u_t\} < U$  such that  $r_n \notin N(U_0)$ . Applying Lemma 9.3, with a sequence of  $k$ -thick subsets

$$T(x_n) := \{t \in \mathbb{R} : x_n u_t \in \text{RF} \mathcal{M}\},$$

we get a sequence  $t_n \in T(x_n)$  such that  $u_{t_n}^{-1} r_n u_{t_n}$  converges to nontrivial element  $v \in \check{V}$ . Since  $z h_n u_{t_n} \in z \check{H}$  and  $z \check{H}$  is compact, the sequence  $z h_n u_{t_n}$  converges to some  $z_1 \in z \check{H}$ , after passing to a subsequence. Then

$$(16-3) \quad z_1 v = \lim(z h_n u_{t_n})(u_{t_n}^{-1} r_n u_{t_n}) \in X \cap \text{RF} \mathcal{M}.$$

Since  $z_1 \in \text{BF} \mathcal{M}$  and  $v \in \check{V} - \{e\}$ ,  $z_1 v \in \text{RF} \mathcal{M}$  implies that  $z_1 v \in F^*$ , and hence  $z_1 v \in R$ . This proves the claim.

Now, by [Theorem 11.1](#),  $\overline{z_1 U} = z_1 L$  for some  $L \in \mathcal{L}_U$  contained in  $\check{H}$ , and hence

$$X \supset \overline{z_1 v U} = \overline{z_1 U} v = (z_1 v)(v^{-1} L v).$$

Since  $v \in \check{V} - \{e\}$ ,  $v^{-1} L v \notin \mathcal{L}_U$ . Therefore, by [Lemma 16.4](#), it suffices to prove that there exists  $u \in U$  such that

$$(16-4) \quad (F^* \cap \text{RF } \mathcal{M}) \cap \limsup_{t \rightarrow +\infty} z_1 u v a_{-t} \neq \emptyset.$$

Let  $g_1 \in G$  be such that  $z_1 = [g_1]$ , and set  $A_{(-\infty, -t]} := \{a_{-s} : s \geq t\}$  for  $t > 0$ . Since  $z_1 v \in F^* \cap \text{RF } \mathcal{M}$ , the sphere  $(g v U)^- \cup g^+$  intersects  $\Lambda - \bigcup_i \bar{B}_i$  nontrivially. Let  $u \in U$  be an element such that  $(g v u)^- \in \Lambda - \bigcup_i \bar{B}_i$ . As  $z_1 v u \in \text{RF } \mathcal{M}$ ,  $\pi(z u v A) \subset \text{core } \mathcal{M}$ . Take  $\varepsilon > 0$  small enough that the  $\varepsilon$ -neighborhoods of the hull  $B_j$  are mutually disjoint. If (16-4) does not hold for  $z_1 u v$ , then there exists  $t > 1$  such that the geodesic ray  $\pi(z_1 v u A_{(-\infty, -t]})$  is contained in the  $\varepsilon$ -neighborhood of  $\partial \text{core } \mathcal{M}$  (see the proof of [Lemma 8.8](#)). As  $\pi(g_1 u v A_{(-\infty, -t]})$  is connected, there exists  $B_j$  such that  $\pi(g_1 u v A_{(-\infty, -t]})$  is contained in the  $\varepsilon$ -neighborhood of hull  $B_j$ . This implies that  $(g_1 u v)^- \in \partial B_j$ , yielding a contradiction. This proves (16-4).  $\square$

**Proposition 16.6** *The orbit  $xH'$  is not closed in  $F^*$ .*

**Proof** Suppose that  $xH'$  is closed in  $F^*$ . Since we are assuming that  $xH'$  is not closed in  $F$ ,  $\overline{xH'}$  contains some point  $y \in \partial F$ . Since  $\partial F = \text{BF } \mathcal{M} \check{V}^+ C(H)$ , we may assume  $y \in \text{BF } \mathcal{M} \cdot \check{V}^+$ . Write  $y = zv$ , where  $z \in \text{BF } \mathcal{M}$  and  $v \in \check{V}^+$ . If  $v \neq e$ ,  $\overline{zvH'}$  intersects  $\text{BF } \mathcal{M}$  by [Theorem 11.5](#). Therefore  $\overline{xH'}$  always contains a point of  $\text{BF } \mathcal{M}$ , say  $z$ . Let  $x_n \in xH'$  be a sequence converging to a point  $z$ . Since  $xH' \subset F^*$ , there exist  $k_n \in H \cap K$  converging to some  $k \in H \cap K$  such that  $x_n k_n \in xH' \cap \text{RF}_+ \mathcal{M}$  and  $x_n k_n \rightarrow zk$ . Then  $zk \in \text{BF } \mathcal{M} \cdot H' = \text{BF } \mathcal{M} C(H)$ . Since  $x_n k_n \in \text{RF } \mathcal{M} \cdot U$  by [Lemma 4.5](#), there exists  $u_n \in U$  such that  $x_n k_n u_n$  belongs to  $\text{RF } \mathcal{M}$  and converges to a point in  $\partial F$  by [Lemma 8.6](#). Hence  $X \cap F^* \cap \text{RF } \mathcal{M}$  accumulates on  $\partial F$ . Now the claim follows from [Proposition 16.5](#).  $\square$

This proposition implies that

$$(16-5) \quad (X - xH') \cap (F^* \cap \text{RF } \mathcal{M}) \neq \emptyset.$$

Roughly speaking, our strategy in proving (1)<sub>m+1</sub> is first to find a closed  $L$ -orbit  $x_0 L$  such that  $x_0 L \cap F$  is contained in  $X$  for some  $L \in \mathcal{L}_U$ . If  $X \neq x_0 L C(H) \cap F$ , then we enlarge  $x_0 L$  to a bigger closed orbit  $x_1 \hat{L}$  for some  $\hat{L} \in \mathcal{L}_{\hat{U}}$ , for some  $\hat{U}$  properly containing  $U$ , such that  $x_1 \hat{L} \cap F$  is contained in  $X$ .

It is in the enlargement step where [Proposition 15.1](#) (additional invariance I) is a crucial ingredient of the arguments. In order to find a sequence  $x_i$  accumulating on a generic point of  $x_0 L$  satisfying the hypotheses of the proposition, we find a closed orbit  $x_0 L$  with a basepoint  $x_0$  in  $F^* \cap \text{RF } \mathcal{M}$ , and enlarge it to a bigger closed orbit, again based at a point in  $F^* \cap \text{RF } \mathcal{M}$ . The advantage of having a closed orbit  $xL$  with  $x \in F^* \cap \text{RF } \mathcal{M}$  is that any  $U_0$ -generic point in  $xL \cap \text{RF } \mathcal{M}$  can be approximated by a sequence of  $\text{RF } \mathcal{M}$ -points in  $F^* \cap xL$  by [Lemma 8.3](#). The enlargement process must end after finitely many steps for dimension reasons.



### Finding a closed orbit of $L \in \mathcal{L}_U$ in $X$

**Proposition 16.7** *There exists a closed orbit  $x_0L$  with  $x_0 \in F^* \cap \text{RF}\mathcal{M}$  and  $L \in \mathcal{L}_U$  such that*

$$x_0L \cap \text{RF}_+\mathcal{M} \subset X.$$

**Proof** Let  $R := X \cap F^* \cap \text{RF}\mathcal{M}$ . If  $R$  is noncompact, the claim follows from [Proposition 16.5](#). Now suppose that  $R$  is compact. By  $(2a)_m$ , it is enough to show that  $X$  contains an orbit  $z\hat{U}$ , and hence  $z\hat{U}A$ , for some  $\hat{U} < N$  properly containing  $U$  and  $z \in R$ . By [Proposition 10.9](#), it suffices to find a  $U$ -minimal subset  $Y \subset X$  with respect to  $R$  and a point  $y \in Y \cap R$  such that  $X - yH'$  is not closed.

If  $xH'$  is not locally closed, then take any  $U$ -minimal subset  $Y$  of  $X$  with respect to  $R$ . If  $Y \cap R \subset xH'$ , then choose any  $y \in Y \cap R$ . Then  $X - yH' = X - xH'$  cannot be closed, as  $xH'$  is not locally closed. If  $Y \cap R \not\subset xH'$ , then choose  $y \in (Y \cap R) - xH'$ . Then  $X - yH'$  contains  $xH'$  and hence cannot be closed.

If  $xH'$  is locally closed, then  $X - xH'$  is a closed  $H'$ -invariant subset which intersects  $R$  nontrivially. So we can take a  $U$ -minimal subset  $Y \subset X - xH'$  with respect to  $R$ . Take any  $y \in Y \cap R$ . Then  $X - yH'$  is not closed.  $\square$

### Enlarging a closed orbit of $L \in \mathcal{L}_U$ in $X$

**Proposition 16.8** *Assume that  $(3)_m$  holds as well. Suppose that there exists a closed orbit  $x_0L$  for some  $x_0 \in F^* \cap \text{RF}\mathcal{M}$  and  $L \in \mathcal{L}_U$  such that*

$$(16-6) \quad x_0L \cap \text{RF}_+\mathcal{M} \subset X \quad \text{and} \quad X \neq x_0L \cdot C(H) \cap F.$$

*Then there exists a closed orbit  $x_1\hat{L}$  for some  $x_1 \in F^* \cap \text{RF}\mathcal{M}$  and  $\hat{L} \in \mathcal{L}_{\hat{U}}$  for some  $\hat{U} < N$  with  $\dim \hat{U} > \dim(L \cap N)$  such that*

$$x_1\hat{L} \cap \text{RF}_+\mathcal{M} \subset X.$$

**Proof** Note that, if  $X \subset x_0L \cdot C(H)$ , then  $X = x_0L \cdot C(H) \cap F$ . Indeed, this can be seen from the identity  $x_0L \cdot C(H) \cap F = (x_0L \cap \text{RF}_+\mathcal{M})C(H)$ . Therefore we assume that  $X \not\subset x_0L \cdot C(H)$ . First note that the hypotheses imply that  $L \neq G$ , and hence  $\text{codim}_{L \cap N}(U) \leq m$ . Let  $U_-^{(1)}, \dots, U_-^{(l)}$  be one-parameter subgroups generating  $U$ . Similarly, let  $U_+^{(1)}, \dots, U_+^{(l)}$  be one-parameter subgroups generating  $U^+$ . By [Theorem 13.1](#),  $\bigcap_{i=1}^l \mathcal{G}(U_{\pm}^{(i)}, x_0L) \neq \emptyset$ . Therefore, without loss of generality, we can assume

$$(16-7) \quad x_0 \in \bigcap_{i=1}^l \mathcal{G}(U_{\pm}^{(i)}, x_0L).$$

Let us write  $L = H(\tilde{U})C$  for some  $\tilde{U} < N$  and a closed subgroup  $C$  of  $C(H(\tilde{U}))$ . Note from the hypotheses that we have

$$(x_0L \cap \text{RF}_+\mathcal{M}) \cdot H' \subset X.$$

Observe that (16-6) implies that  $x \notin x_0 L \cdot H' = x_0 L \cdot C(H)$ . Since  $C < C(H)$ , we have  $x \notin x_0 H(\tilde{U})$ . Now choose a sequence  $w_i \in H'$  such that  $xw_i \rightarrow x_0$ , as  $i \rightarrow \infty$ . Write  $xw_i = x_0 g_i$ , where  $g_i \rightarrow e$  in  $G - LH'$ . Let us write  $g_i = \ell_i r_i$ , where  $\ell_i \in L$  and  $r_i \in \exp \mathfrak{l}^\perp$ . In particular,  $r_i \notin C(H)$ . Let  $x_i = x_0 \ell_i$ , so that  $x_i r_i \in X$ .

We claim that we can assume that  $x_i \in \text{RF} \mathcal{M} \cap x_0 L$ ,  $r_i \notin C(H)$  and  $x_i r_i \in X$ . Since  $x_0 \in F^*$ , by Lemma 8.3, we can find  $w'_i \rightarrow w' \in H$  such that  $x_0 \ell_i w'_i \in \text{RF} \mathcal{M}$ , and  $x_0 w' \in \bigcap_{i=1}^l \mathcal{G}(U_\pm^{(i)}, x_0 L)$ ; hence

$$\overline{x_0 w' U} = x_0 L \cap \text{RF}_+ \mathcal{M}.$$

Writing  $x'_i = x_0 \ell_i w'_i$  and  $r'_i = w_i'^{-1} r_i w'_i$ , we have

$$x'_i r'_i = x w_i w'_i \in X,$$

where  $x'_i \rightarrow x_0 w'$  in  $x_0 L \cap \text{RF} \mathcal{M}$ , and  $r'_i \rightarrow e$  in  $\exp \mathfrak{l}^\perp$ . Since  $F^*$  is  $H'$ -invariant, we have  $x_0 w' \in F^*$ . Since  $F^*$  is open and  $x_0 w' \in F^*$ , it follows that  $x'_i \in X \cap \text{RF} \mathcal{M} \cap F^*$  for sufficiently large  $i$ . Note that  $r'_i \notin C(H)$ , as  $r_i \notin C(H)$ . This proves the claim.

We may assume  $r_i \notin N(U)$  for all  $i$ , up to switching the roles of  $U$  and  $U^+$ , by Lemma 3.5. Note that  $x_i \rightarrow x_0$  in  $\text{RF} \mathcal{M} \cap x_0 L$  and  $x_0$  satisfies (16-7). As we are assuming  $(2)_m$ , and  $(3)_m$ , we may now apply Proposition 15.1 to the sequence  $x_0 \ell_i r_i \rightarrow x_0$  to obtain a nontrivial element  $v \in \tilde{U}^\perp$  such that

$$x_0 L v \cap \text{RF}_+ \mathcal{M} \subset X.$$

Since  $x_0 \in F^* \cap \text{RF} \mathcal{M}$ , it follows from Lemma 8.12 that there exist  $x_2 \in F^* \cap \text{RF} \mathcal{M}$  and a connected closed subgroup  $\hat{U} < N$  properly containing  $L \cap N$  such that

$$x_2 \hat{U} A \subset X.$$

Since  $\text{codim}_N(\hat{U}) \leq m$ , it remains to apply  $(2a)_m$  to finish the proof of the proposition.  $\square$

**Proof of  $(1)_{m+1}$**  Combining Propositions 16.7 and 16.8, we now prove:

**Theorem 16.9** *If  $(2)_m$  and  $(3)_m$  are true, then  $(1)_{m+1}$  is true.*

**Proof** Recall that we only need to consider the case  $X = \overline{xH'}$ , where  $x \in F^*$  and  $xH'$  is not closed in  $F^*$ . By Proposition 16.7, there exists  $x_0 \in F^* \cap \text{RF} \mathcal{M}$  and  $L \in \mathcal{L}_U$  such that  $x_0 L$  is closed and

$$x_0 L \cap \text{RF}_+ \mathcal{M} \subset X.$$

Since  $X$  is  $H'$ -invariant, it follows that

$$(16-8) \quad (x_0 L \cap \text{RF}_+ \mathcal{M}) \cdot H' \subset X.$$

Note that  $(x_0 L \cap \text{RF}_+ \mathcal{M}) \cdot H' = x_0 L \cdot C(H) \cap F$  is a closed set. We may assume the inclusion in (16-8) is proper, otherwise we have nothing further to prove. Then, by Proposition 16.8, there exists  $\hat{L} \in \mathcal{L}_{\hat{U}}$  for some  $\hat{U} < N$  properly containing  $L \cap N$  and a closed orbit  $x_1 \hat{L}$  with  $x_1 \in F^* \cap \text{RF} \mathcal{M}$  such that  $x_1 \hat{L} \cap \text{RF}_+ \mathcal{M} \subset X$ . If

$$(x_1 \hat{L} \cap \text{RF}_+ \mathcal{M}) \cdot C(H) \neq X,$$

then we can apply [Proposition 16.8](#) on

$$x_1 \hat{L} \cap \text{RF}_+ \mathcal{M} \subset X,$$

as  $\mathcal{L}_{\hat{L}} \subset \mathcal{L}_U$ . Continuing in this fashion, the process terminates in a finite step for dimension reasons, and hence

$$X = (x_1 \tilde{L} \cap \text{RF}_+ \mathcal{M}) \cdot H' = x_1 \tilde{L} \cdot C(H) \cap F$$

for some  $\tilde{L} \in \mathcal{L}_U$ . □

## 17 $U$ - and $AU$ -orbit closures: proof of $(2)_{m+1}$

In this section, we fix a closed orbit  $x_0 \hat{L}$  for  $x_0 \in F^*$  and  $\hat{L} \in \mathcal{L}_U$ . Let  $U < \hat{L} \cap N$  be a connected closed subgroup with  $\text{codim}_{\hat{L} \cap N} U \leq m+1$ . By replacing  $U$  and  $\hat{L}$  by their conjugates using an element  $m \in M$ , we may assume that

$$U \subset \hat{L} \cap \check{H} \cap N.$$

We keep the same notation  $H, F, \partial F, F^*$  etc from [Section 16](#). If  $x \in \text{RF}_+ \mathcal{M} \cap \partial F$  (resp. if  $x \in \text{RF} \mathcal{M} \cap \partial F$ ), then (2a) (resp. (2b)) follows from [Theorem 11.1](#).

We fix  $x \in \text{RF} \mathcal{M} \cap x_0 \hat{L} \cap F^*$ , and set

$$(17-1) \quad X := \overline{xU}$$

and assume that  $X \neq x_0 \hat{L} \cap \text{RF}_+ \mathcal{M}$ . This assumption implies that  $U$  is a proper connected closed subgroup of  $\hat{L} \cap N$  and hence  $\dim(\hat{L} \cap N) > \dim U \geq 1$ .

By [Proposition 5.16](#), either  $x_0 \hat{L}$  is compact or  $\mathcal{S}(U, x_0 \hat{L})$  contains a compact orbit  $zL_0$  with  $L_0 \in \mathcal{L}_U$ . If  $x_0 \hat{L}$  is compact, then  $(2)_{m+1}$  follows from [Theorem 11.1](#). Therefore we assume in the rest of the section that

$$(17-2) \quad \mathcal{S}(U, x_0 \hat{L}) \text{ contains a compact orbit } zL_0 \text{ with } L_0 \in \mathcal{L}_U.$$

**Lemma 17.1** *Assume that  $(1)_{m+1}$  and  $(2)_m$  hold. Then*

$$\overline{xAU} \cap \mathcal{S}(U, x_0 \hat{L}) \neq \emptyset.$$

**Proof** Since  $(1)_{m+1}$  is true, we have

$$\overline{xH} = xQ \cap F$$

for some  $Q \in \mathcal{L}_U$  such that  $xQ$  is closed. By [Lemma 16.1](#),  $Q < \hat{L}$ . It follows from [Lemma 5.11](#) that either  $Q = \hat{L}$  or  $\dim(Q \cap N) < \dim(\hat{L} \cap N)$ . Suppose that  $Q = \hat{L}$ . By (17-2), there exists a compact orbit  $zL_0 \subset \mathcal{S}(U, x_0 \hat{L})$  for some  $L_0 \in \mathcal{L}_U$ . On the other hand,  $x_0 \hat{L} \cap F = \overline{xH} = \overline{xAU} (K \cap H)$ . Hence, for some  $k \in K \cap H$ ,  $zk \in \overline{xAU}$ . Since  $H \subset L_0$ ,  $zk \in zL_0$ . So  $\overline{xAU}$  intersects  $zL_0$ , proving the claim. If  $\dim(Q \cap N) < \dim(\hat{L} \cap N)$ , then  $\overline{xAU} \subset xQ \subset \mathcal{S}(U, x_0 \hat{L})$ . □

**Lemma 17.2** Assume that  $(1)_{m+1}$  and  $(2)_m$  hold. Then

$$\overline{xU} \cap \mathcal{S}(U, x_0 \hat{L}) \neq \emptyset.$$

**Proof** Since

$$(17-3) \quad (x_0 \hat{L} \cap \text{RF}_+ \mathcal{M}) - F^* \subset \mathcal{S}(U, x_0 \hat{L}),$$

it suffices to consider the case when  $X := \overline{xU} \subset F^*$ . Let  $Y \subset X$  be a  $U$ -minimal set with respect to  $\text{RF } \mathcal{M}$ . Since  $Y \subset F^*$ , by [Proposition 10.6](#), there exists an unbounded one-parameter subsemigroup  $S$  inside  $AU^\perp C_2(U) \cap \hat{L}$  such that  $YS \subset Y$ . In view of [Lemma 3.3](#), we could remove the  $C_2(U)$ -component of  $S$  so that  $S$  is either of

- $v^{-1}A^+v$  for a one-parameter semigroup  $A^+ \subset A$  and  $v \in U^\perp \cap \hat{L}$ , or
- $V^+$  for a one-parameter semigroup  $V^+ \subset U^\perp \cap \hat{L}$ ,

and

$$YS \subset X(C_2(U) \cap \hat{L}).$$

Since  $\mathcal{S}(U, x_0 \hat{L})$  is invariant by  $N C_2(U) \cap \hat{L}$ , it suffices to show that

$$X(N C_2(U) \cap \hat{L}) \cap \mathcal{S}(U, x_0 \hat{L}) \neq \emptyset.$$

If  $S = v^{-1}A^+v$ , then  $Yv^{-1}A^+ \subset Xv^{-1}(C_2(U) \cap \hat{L})$ . Choose  $y \in Y$ . We may assume that  $yv^{-1} \in F^*$  by (17-3). Then, replacing  $y$  with an element in  $yU$  if necessary, we may assume  $yv^{-1} \in \text{RF } \mathcal{M} \cap F^*$ . Choose a sequence  $a_n \rightarrow \infty$  in  $A^+$ . Then  $yv^{-1}a_n$  converges to some  $y_0 \in \text{RF } \mathcal{M}$  by passing to a subsequence. Since  $\liminf a_n^{-1}A^+ = A$ , and

$$(yv^{-1}a_n)(a_n^{-1}A^+) \subset Xv^{-1}(C_2(U) \cap \hat{L}),$$

we obtain that

$$y_0A \subset Xv^{-1}(C_2(U) \cap \hat{L}).$$

Since  $\overline{y_0AU} \subset Xv^{-1}(C_2(U) \cap \hat{L})$  and  $\overline{y_0AU}$  meets  $\mathcal{S}(U, x_0 \hat{L})$  by [Lemma 17.1](#), the claim follows.

Next, assume that  $S = V^+$ , so that  $YV^+ \subset X C_2(U) \cap \hat{L}$ . Let  $v_n \rightarrow \infty$  be a sequence in  $V^+$ . We have  $Yv_n \subset X \subset F^*$ . Together with the fact that  $Yv_n$  is  $U$ -invariant, this implies  $Yv_n$  meets  $\text{RF } \mathcal{M}$ . Note that

$$Yv_n(v_n^{-1}V^+) \subset X(C_2(U) \cap \hat{L}).$$

Choose  $y_n \in Yv_n \cap \text{RF } \mathcal{M}$ . As  $\text{RF } \mathcal{M}$  is compact,  $y_n$  converges to some  $y_0 \in \text{RF } \mathcal{M}$ , by passing to a subsequence, and hence

$$y_0UV \subset X(C_2(U) \cap \hat{L}).$$

Since  $\text{codim}_N(UV) \leq m$ , the conclusion follows from  $(2)_m$ . □

**Lemma 17.3** Assume that  $(1)_{m+1}$  and  $(2)_m$  hold. Then

$$\overline{xU} \cap \mathcal{S}(U, x_0 \hat{L}) \cap F^* \neq \emptyset.$$

**Proof** By Lemma 17.2, there exists  $y \in \overline{xU} \cap \mathcal{S}(U, x_0\hat{L})$ . Hence, by (2)<sub>m</sub>,

$$\overline{yU} = yL \cap \text{RF}_+ \mathcal{M} \subset \overline{xU}$$

for some  $L \in \mathfrak{Q}_U$  properly contained in  $\hat{L}$ . Consider the collection of all subgroups  $L \in \mathfrak{Q}_U$  such that  $yL \subset \overline{xU}$  for some  $y \in \text{RF}_+ \mathcal{M}$ . Choose  $L$  from this collection so that  $L \cap N$  has maximal dimension. If  $yL \cap F^* \neq \emptyset$ , then the claim follows.

Now suppose that  $yL \subset \partial F$ . As  $y \in \text{RF}_+ \mathcal{M} \cap \partial F$ , we have

$$y = zv_0c_0$$

for some  $z \in \text{BF} \mathcal{M}$ ,  $v_0 \in \check{V}^+$  and  $c_0 \in C(H)$ . Since  $y \in \overline{xU}$ , there exists  $u_i \in U$  such that  $xu_i$  converges to  $y$  as  $n \rightarrow \infty$ . Set

$$z_i := xu_i c_0^{-1} v_0^{-1} \in \overline{xU} c_0^{-1} v_0^{-1},$$

so  $z_i \rightarrow z$ . As  $v_0 \in \check{V}^+$  and hence  $v_0^{-1} \in \check{V}^-$  and  $xu_i \in F^*$ , we have  $z_i \in F^* \cap \text{RF}_+ \mathcal{M} \subset \text{RF} \mathcal{M} \cdot U$ . By Lemma 8.6, we may modify  $z_i$  by elements of  $U$  so that  $z_i \in \text{RF} \mathcal{M}$  and  $z_i$  converges to some  $z_0 \in z\check{H}$ . Write  $z_i = z_0 \ell_i r_i$  for some  $\ell_i \in \check{H}$  and  $r_i \in \exp \check{\mathfrak{h}}^\perp$  converging to  $e$ . Since  $z_i \in F^*$  and  $z_0 \ell_i \in \partial F$ , we have  $r_i \neq e$ . By Theorem 11.1, we have  $\overline{z_0 \ell_i U} = z_0 \ell_i L_i$  for some  $L_i \in \mathfrak{Q}_U$  contained in  $\check{H}$ .

**Case 1** ( $r_i \in N(U)$  for some  $i$ ) Then

$$\overline{xU} = \overline{z_0 \ell_i r_i v_0 c_0 U} = \overline{z_0 \ell_i U} (r_i v_0 c_0) = z_0 \ell_i L_i (r_i v_0 c_0).$$

As  $\overline{xU} \neq x_0\hat{L}$  by the hypotheses, it follows that  $x \in \mathcal{S}(U, x_0\hat{L}) \cap F^*$ , proving the claim.

**Case 2** ( $r_i \notin N(U)$  for all  $i$ ) Then there exists a one-parameter subgroup  $U_0 < U$  such that  $r_i \notin N(U_0)$  for all  $i$ , by passing to a subsequence.

By Lemma 9.3, we can find  $u_{t_i} \rightarrow \infty$  in  $U_0$  such that  $z_i u_{t_i} \in \text{RF} \mathcal{M}$  and  $u_{t_i}^{-1} r_i u_{t_i}$  converges to a nontrivial element  $v \in \check{V}$ , whose size is strictly bigger than  $\|v_0\|$ . As  $z_0 \ell_i u_{t_i}$  is contained in the compact subset  $z_0 \check{H}$ , we may assume that  $z_0 \ell_i u_{t_i}$  converges to some  $z' \in z_0 \check{H}$ . Hence

$$z_i u_{t_i} = z_0 \ell_i u_{t_i} (u_{t_i}^{-1} r_i u_{t_i}) \rightarrow z' v \in \text{RF} \mathcal{M} \cap \overline{xU} c_0^{-1} v_0^{-1}.$$

Since  $z' \in \text{BF} \mathcal{M}$  and  $z' v \in \text{RF} \mathcal{M}$ , we have  $v \in \check{V}^-$ .

By Theorem 11.1,  $\overline{z'U} = z'Q_1$  for some  $Q_1 \in \mathfrak{Q}_U$ . Since  $z' v v_0 c_0 \in \overline{xU}$ , we get

$$\overline{xU} \supset z'Q_1 (v v_0) c_0.$$

Since the size of  $v$  is larger than the size of  $v_0$ ,  $v v_0$  is a nontrivial element of  $\check{V}^-$ . Since  $z'Q_1 \subset \text{BF} \mathcal{M}$ , the closed orbit  $z'Q_1 (v v_0) c_0$  meets  $F^*$ . □

**Theorem 17.4** Assume that (1)<sub>m+1</sub>, (2)<sub>m</sub> and (3)<sub>m</sub> are true. Then (2)<sub>m+1</sub> is true.

**Proof** We first show (2a)<sub>m+1</sub> holds for  $X = \overline{xU}$ . By Lemma 17.3 and (2)<sub>m</sub>, there exists a closed orbit  $yL$  with  $y \in F^*$  and  $L \in \mathfrak{Q}_U$  such that

$$\overline{xU} \supset yL \cap \text{RF}_+ \mathcal{M}$$

and  $L \cap N \neq \hat{L} \cap N$ . We choose  $L \in \mathcal{Q}_U$  so that  $\dim(L \cap N)$  is maximal. Note that  $\operatorname{codim}_{L \cap N} U \leq m$ . By [Theorem 13.1](#), we can assume that

$$(17-4) \quad y \in \bigcap_{i=1}^l \mathcal{G}(U^{(i)}, yL) \cap F^* \cap \operatorname{RF} \mathcal{M},$$

where  $U^{(1)}, \dots, U^{(l)}$  are one-parameter subgroups generating  $U$ . As  $y \in \overline{xU}$ , there exists  $u_i \in U$  such that  $xu_i \rightarrow y$  as  $i \rightarrow \infty$ . Since  $y \in F^*$ , we can assume  $xu_i \in \operatorname{RF} \mathcal{M}$ , after possibly modifying  $u_i$ , by [Lemma 8.6](#). We will write  $xu_i = y\ell_i r_i$ , where  $\ell_i \in L$  and  $r_i \in \exp \mathfrak{t}^\perp \cap \hat{L}$ .

**Case 1** ( $r_i \in N(U)$  for some  $i$ ) Then  $y\ell_i \in \operatorname{RF}_+ \mathcal{M}$  and  $X = \overline{xu_i U} = \overline{y\ell_i U} r_i$ . Since  $y\ell_i U \subset yL$ , and  $\operatorname{codim}_{L \cap N}(U) \leq m$ , we have

$$X = \overline{y\ell_i U} r_i = y\ell_i L' r_i \cap \operatorname{RF}_+ \mathcal{M}$$

for some  $L' \in \mathcal{Q}_U$ , proving the claim.

**Case 2** ( $r_i \notin N(U)$  for all  $i$ ) By (17-4), we can apply [Proposition 15.2](#) to the sequence  $xu_i \rightarrow y$  and obtain a sequence  $v_j \rightarrow \infty$  in  $(L \cap N)^\perp$  such that

$$yLv_j \cap \operatorname{RF}_+ \mathcal{M} \subset X.$$

Since  $y \in F^*$ , by [Lemma 8.10](#), there exists a one-parameter subgroup  $V \subset (L \cap N)^\perp$  such that  $y_1(L \cap N)V \subset X$  for some  $y_1 \in F^* \cap \operatorname{RF} \mathcal{M}$ . Hence, by (2)<sub>m</sub>, we get a contradiction to the maximality of  $L \cap N$ ; this proves (2a)<sub>m+1</sub>.

Now we show (2b)<sub>m+1</sub> for the closure  $\overline{xAU}$ . By (1)<sub>m+1</sub>, we have  $\overline{xH} = xL \cap F$  for some  $L \in \mathcal{L}_U$  contained in  $\hat{L}$ . Hence  $\overline{xAU} \subset xL \cap \operatorname{RF}_+ \mathcal{M}$ . It suffices to show that

$$(17-5) \quad \overline{xAU} = xL \cap \operatorname{RF}_+ \mathcal{M}.$$

If  $U = L \cap N$ , then  $\overline{xU} = xL \cap \operatorname{RF}_+ \mathcal{M}$  by [Theorem 13.1](#), which implies (17-5). So suppose that  $U$  is a proper closed subgroup of  $L \cap N$ . Since  $\overline{xAU}(K \cap H) = \overline{xH} = xL \cap F$ , it follows from [Lemma 5.15](#) that we can choose  $y \in \overline{xAU} \cap \mathcal{G}(U, xL)$ . By (2a)<sub>m+1</sub> and [Lemma 14.4](#), we have  $\overline{yU} = xL \cap \operatorname{RF}_+ \mathcal{M}$ .  $\square$

## 18 Topological equidistribution: proof of (3)<sub>m+1</sub>

In this section, we prove (3)<sub>m+1</sub>. Let  $U < N$  be a nontrivial connected closed subgroup. Let  $x_0 \hat{L}$  be a closed orbit for  $x_0 \in F^* \cap \operatorname{RF} \mathcal{M}$  and  $\hat{L} \in \mathcal{L}_U$  such that  $\operatorname{codim}_{\hat{L} \cap N}(U) = m + 1$ . As before, we may assume that  $U \subset \hat{L} \cap \check{H} \cap N$ .

Let  $x_i L_i \subset x_0 \hat{L}$  be a sequence of closed orbits intersecting  $\operatorname{RF} \mathcal{M}$ , where  $x_i \in \operatorname{RF}_+ \mathcal{M}$  and  $L_i \in \mathcal{Q}_U$ . We write  $x_i L_i$  as  $y_i L_i v_i$ , where  $y_i \in \operatorname{RF}_+ \mathcal{M}$ ,  $L_i \in \mathcal{L}_U$  and  $v_i \in (L_i \cap N)^\perp \cap \hat{L}$ . Assume that no infinite

subsequence of  $y_i L_i v_i$  is contained in a subset of the form  $y_0 L_0 D \subset \mathcal{S}(U, x_0 \hat{L})$ , where  $y_0 L_0$  is a closed orbit for some  $L_0 \in \mathcal{L}_U$  and  $D \subset N(U)$  is a compact subset. Let

$$E = \limsup_{i \rightarrow \infty} (y_i L_i v_i \cap \text{RF}_+ \mathcal{M}).$$

Note that  $\liminf_{i \rightarrow \infty} (y_i L_i v_i \cap \text{RF}_+ \mathcal{M})$  coincides with  $\limsup_{i \rightarrow \infty} (y_{i_k} L_{i_k} v_{i_k} \cap \text{RF}_+ \mathcal{M})$  for all infinite subsequences  $\{i_k : k \in \mathbb{N}\}$  of  $\mathbb{N}$ . If the hypothesis  $(3)_{m+1}$  holds for a given sequence  $y_i L_i v_i$ , then it also holds for all subsequences. Hence, to prove  $(3)_{m+1}$ , it suffices to show that

$$E = \text{RF}_+ \mathcal{M} \cap x_0 \hat{L}.$$

We note that, by  $(3)_m$ , we may assume that

$$L_i \cap N = U \quad \text{for all } i.$$

This in particular implies that each  $y_i L_i v_i \cap \text{RF}_+ \mathcal{M}$  is  $U$ -minimal by [Theorem 13.1](#).

**Lemma 18.1** Assume that  $(1)_{m+1}$ ,  $(2)_{m+1}$  and  $(3)_m$  are true. Then there exist  $y \in F^* \cap \text{RF} \mathcal{M}$  and  $L \in \mathcal{L}_U$  with  $\dim(L \cap N) > \dim U$  such that  $yL$  is closed and

$$E \supset yL \cap \text{RF}_+ \mathcal{M}.$$

**Proof** By  $(2)_m$ , it suffices to show that there exist  $y_0 \in F^* \cap \text{RF} \mathcal{M}$  and  $\hat{U} < N$  properly containing  $U$  such that

$$E \supset y_0 \hat{U}.$$

Suppose that  $y_i L_i v_i \subset \partial F$  for infinitely many  $i$ . Since  $y_i L_i v_i \cap \text{RF} \mathcal{M} \neq \emptyset$ , we may assume  $y_i v_i \in z_i \check{H} C(H)$  for some  $z_i \in \text{BF} \mathcal{M}$  by [\(4-7\)](#). Since  $L_i \cap N = U$ , we get  $y_i L_i v_i = \overline{y_i U} \subset z_i \check{H} C(H)$  by [Theorem 11.1](#). This contradicts the hypothesis on the  $y_i L_i v_i$ .

Therefore, by passing to a subsequence, for all  $i$ ,

$$y_i L_i v_i \cap \text{RF}_+ \mathcal{M} \cap F^* \neq \emptyset.$$

Since  $AU < L_i$  for all  $i$ , it follows that

$$E = \limsup_{i \rightarrow \infty} (y_i L_i v_i \cap \text{RF}_+ \mathcal{M})(v_i^{-1} A U v_i).$$

By [Lemma 8.9](#), there exists  $y_0 \in \limsup_i (y_i L_i v_i \cap \text{RF}_+ \mathcal{M}) \cap F^*$ . Hence

$$(18-1) \quad y_0 \limsup_{i \rightarrow \infty} (v_i^{-1} A U v_i) \subset E,$$

after passing to a subsequence.

If  $v_i \rightarrow \infty$ , then  $\limsup_i (v_i^{-1} A U v_i)$  contains  $A \hat{U}$  for some  $\hat{U}$  properly containing  $U$  by [Lemma 3.4](#). Therefore, we get the conclusion  $y_0 \hat{U} \subset E$  from [\(18-1\)](#). Now suppose that, by passing to a subsequence,  $v_i$  converges to some  $v \in N \cap \hat{L}$ . Then [\(18-1\)](#) gives

$$y_0 v^{-1} A U v \subset E.$$

Then, by (2)<sub>m+1</sub>,  $\overline{y_0 v^{-1} A U}$  is of the form  $y_0 v^{-1} L_0 \cap \text{RF}_+ \mathcal{M}$  for some  $L_0 \in \mathcal{L}_U$ . Hence,

$$(18-2) \quad E \supset y_0 L \cap \text{RF}_+ \mathcal{M},$$

where  $L := v^{-1} L_0 v$ . If  $L \cap N$  contains  $U$  properly, this proves the claim. So we suppose that  $L \cap N = U$ . By Theorem 13.1, we can assume that  $y_0 \in \bigcap_{i=1}^l \mathcal{G}(U^{(i)}, y_0 L) \cap F^* \cap \text{RF} \mathcal{M}$ , where  $U^{(1)}, \dots, U^{(l)}$  are one-parameter subgroups generating  $U$ . By replacing  $y_i$  by an element of  $y_i L \cap \text{RF}_+ \mathcal{M}$ , we may assume that  $y_i v_i \rightarrow y_0$ . Furthermore, as  $y_0 \in F^* \cap \text{RF} \mathcal{M}$ , for all  $i$  sufficiently large,  $y_i v_i \in F^* \cap \text{RF}_+ \mathcal{M} \subset \text{RF} \mathcal{M} \cdot U$  (as  $F^*$  is open). Hence we can also assume  $y_i v_i \in \text{RF} \mathcal{M}$  by Lemma 8.7. Therefore we may write

$$y_i v_i = y_0 \ell_i r_i$$

for some  $\ell_i \rightarrow e$  in  $L$  and nontrivial  $r_i \rightarrow e$  in  $\exp \mathfrak{l}^\perp$ .

Suppose that  $r_i$  belongs to  $N(U)$  for infinitely many  $i$ . Then

$$y_i L_i v_i \cap \text{RF}_+ \mathcal{M} = \overline{y_i v_i U} = \overline{y_0 \ell_i U} r_i = y_0 L r_i \cap \text{RF}_+ \mathcal{M}.$$

Hence  $y_i L_i v_i r_i^{-1} \cap \text{RF}_+ \mathcal{M} = y_0 L \cap \text{RF}_+ \mathcal{M}$ . In particular,  $y_i L_i v_i r_i^{-1} \cap \text{RF} \mathcal{M}$  is nonempty (as it contains  $y_0$ ) and is contained in  $y_0 L$ . By Lemma 16.1, this implies that  $y_i L_i v_i \subset y_0 L r_i$ . As  $r_i \rightarrow e$ , this contradicts the hypothesis on the  $y_i L_i v_i$ .

Therefore  $r_i \notin N(U)$  for all but finitely many  $i$ . We may now apply Proposition 15.2 and Lemma 8.10 to deduce that  $E$  contains an orbit  $z_0 \hat{U}$  for some  $\hat{U} < \hat{L} \cap N$  containing  $U$  properly and for some  $z_0 \in \text{RF}_+ \mathcal{M} \cap F^*$ .  $\square$

**Theorem 18.2** *If (1)<sub>m+1</sub>, (2)<sub>m+1</sub> and (3)<sub>m</sub> are true, then (3)<sub>m+1</sub> is true.*

**Proof** We claim that

$$(18-3) \quad x_0 \hat{L} \cap \text{RF}_+ \mathcal{M} = E.$$

By Lemma 18.1, we can take a maximal  $\hat{U}$  such that  $E \supset y \hat{U}$  for some  $y \in F^* \cap \text{RF} \mathcal{M}$ . By (2)<sub>m</sub>, we get a closed orbit  $yL$  for some  $L \in \mathcal{Q}_{\hat{U}}$  such that

$$(18-4) \quad yL \cap \text{RF}_+ \mathcal{M} \subset E.$$

If  $L = \hat{L}$ , then the claim (18-3) is clear. Now suppose that  $L$  is a proper subgroup of  $\hat{L}$ . This implies that  $L \cap N$  is a proper subgroup of  $\hat{L} \cap N$ , since  $\hat{L} \cap N$  acts minimally on  $x_0 \hat{L} \cap \text{RF}_+ \mathcal{M}$  as  $\hat{L} \in \mathcal{L}_U$ . By Theorem 13.1, we can assume that  $y \in \bigcap_{i=1}^l \mathcal{G}(U^{(i)}, yL) \cap F^* \cap \text{RF} \mathcal{M}$ , where  $U^{(1)}, \dots, U^{(l)}$  are one-parameter subgroups generating  $U$ . As  $y \in E$ , there exists a sequence  $x_i \in y_i L_i v_i \cap \text{RF}_+ \mathcal{M}$  converging to  $y$ , by passing to a subsequence. Since  $U = v_i^{-1} L_i v_i \cap N$ , we have  $x_i \in \text{RF} \mathcal{M} \cdot U$ . By Lemma 8.7, by replacing  $x_i$  with  $x_i u_i$  for some  $u_i \rightarrow e$  in  $U$ , we may assume  $x_i \in \text{RF} \mathcal{M}$ .

We claim that

$$x_i \notin yL N(U).$$



Suppose not, i.e.  $x_i = y\ell_i r_i$  for some  $\ell_i \in L$  and  $r_i \in N(U)$ . Then

$$y_i L_i v_i \cap \text{RF}_+ \mathcal{M} = \overline{x_i U} = \overline{y\ell_i U} r_i \subset y L r_i.$$

By the assumption on the  $y_i L_i v_i$ , this cannot happen as the  $r_i$  are bounded.

On the other hand,  $\dim(L_i \cap N)$  is strictly smaller than  $\dim(L \cap N)$ , since  $L_i \cap N = U$  and  $\hat{U} < L \cap N$ , yielding a contradiction. Hence  $x_i \notin y L N(U)$ .

We can now apply [Proposition 15.2](#) and [Lemma 8.10](#) and deduce that  $E$  contains  $y_1 \hat{U} V$  for some  $y_1 \in F^* \cap \text{RF} \mathcal{M}$ . This is a contradiction to the maximality assumption on  $\dim \hat{U}$ .  $\square$

**Proof of Theorem 1.7** We explain how to deduce this theorem from [Theorem 14.1\(3\)](#). For (1), we may first assume that  $P_i$  have all same dimension, so that, for some fixed connected closed subgroup  $U < N$ ,  $P_i = \pi(x_i H'(U))$ , where  $x_i H'(U)$  is a closed orbit of some  $x_i \in \text{RF} \mathcal{M}$ . Then there exists  $L_i \in \mathcal{L}_U$  such that  $x_i L_i$  is closed and  $P_i = \pi(x_i L_i)$  by [Proposition 4.9](#). We claim that the sequence  $x_i L_i$  satisfies the hypotheses of [Theorem 14.1\(3\)](#). Suppose not. Then there exist a closed orbit  $y_0 L_0$  with  $L_0 \in \mathcal{L}_U$  and  $L_0 \neq G$  and a compact subset  $D \subset N(U)$  such that  $x_i L_i \subset y_0 L_0 D$  for infinitely many  $i$ . By [Lemma 16.2](#), this can happen only when  $L_i \subset d_i^{-1} L_0 d_i$  and  $x_i L_i \subset y_0 L_0 d_i$  for some  $d_i \in D$ . Since  $D \subset N(U) \subset L_0 (L_0 \cap N)^\perp M$ , we may assume that  $d_i \in (L_0 \cap N)^\perp M$ . Since  $A \subset L_i \subset d_i^{-1} L_0 d_i$ , we have  $d_i \in M$ . This implies that  $P_i = \pi(x_i L_i) \subset \pi(y_0 L_0 d_i) = \pi(y_0 L_0)$ . By the maximality assumption on the  $P_i$ , it follows that  $P_i$  is a constant sequence, yielding a contradiction. Hence, by [Theorem 14.1\(3\)](#),  $\lim(x_i L_i \cap \text{RF}_+ \mathcal{M}) = \text{RF}_+ \mathcal{M}$ . Since  $\pi(\text{RF}_+ \mathcal{M}) = \Gamma \backslash \mathbb{H}^d$ , the claim follows.

(2) follows from [Corollary 5.8](#).

For (3), if there are infinitely many bounded properly immersed  $P_i$ , then  $\lim P_i = M$  by (1). On the other hand,  $P_i \subset \text{core } \mathcal{M}$ , because any bounded  $H'(U)$ -orbit should be inside  $\text{RF} \mathcal{M}$ . Since  $\text{core } \mathcal{M}$  is a proper closed subset of  $M$ , as  $\text{Vol}(\mathcal{M}) = \infty$ , this gives a contradiction.  $\square$

**Remark 18.3** In fact, when  $\mathcal{M}$  is any convex cocompact hyperbolic manifold of infinite volume, there are only finitely many bounded maximal closed  $H'(U)$ -orbits, and hence only finitely many maximal properly immersed bounded geodesic planes. The reason is that, if not, we would have infinitely many maximal closed orbits  $x_i L_i$  contained in  $\text{RF} \mathcal{M}$  for some  $L_i \in \mathcal{L}_U$ , and, for any  $U$ -invariant subset  $E$  contained in  $\text{RF} \mathcal{M}$ , the 1-thickness for points in  $E$  holds for any one-parameter subgroup of  $U$  for the trivial reason, which makes our proof of [Theorem 14.1](#) work with little modification (in fact, much simpler) for a general  $\mathcal{M}$ .

## Appendix Orbit closures for $\Gamma \backslash G$ , compact case

In this section we give an outline of the proof of the orbit closure theorem for the actions of  $H(U)$  and  $U$ , assuming that  $\Gamma \backslash G$  is compact and that there exists at least one closed orbit of  $\text{SO}^\circ(d-1, 1)$ . We hope

that giving an outline of the proof of [Theorem 14.1](#) in this special case will help readers understand the whole scheme of the proof better and see the differences with the infinite-volume case more clearly.

Note that, in the case at hand,

$$\mathrm{RF} \mathcal{M} = F_{H(U)}^* = \mathrm{RF}_+ \mathcal{M} = \Gamma \backslash G.$$

Without loss of generality, we assume that  $U \subset \mathrm{SO}^\circ(d-1, 1) \cap N$ .

**Theorem A.1** *Let  $x \in \Gamma \backslash G$ .*

(1) *There exists  $L \in \mathcal{L}_U$  such that*

$$\overline{xH(U)} = xL.$$

(2) *There exists  $L \in \mathcal{Q}_U$  such that*

$$\overline{xU} = xL.$$

The base case  $(2)_0$  follows from a special case of [Theorem 13.1](#). For  $m \geq 0$ , we will show that  $(2)_m$  implies  $(1)_{m+1}$ , and that  $(1)_{m+1}$  and  $(2)_m$  together imply  $(2)_{m+1}$ .

We note that, when  $\Gamma \backslash G$  is compact, we don't need the topological equidistribution statement, which is [Theorem 14.1\(3\)](#), to run the induction argument, thanks to (2-6). In order to prove  $(1)_{m+1}$ , it suffices to use  $(2)_m$  only when the ambient space is  $\Gamma \backslash G$ ; in the proof of [Theorem 14.1](#), we needed to use  $(2)_m$  whenever  $\mathrm{codim}_{N \cap \hat{L}} U \leq m$  for any closed orbit  $x_0 \hat{L}$  containing  $xU$  (this was needed in order to use the results in [Section 15](#)).

**Remark A.2** [Theorem A.1](#) was proved by Shah (unpublished, 1992) by topological arguments. Our proof presented in this appendix is somewhat different from Shah's in that we prove that  $(1)_m$  implies  $(2)_m$  using the existence of a closed  $\mathrm{SO}^\circ(d-1, 1)$ -orbit, while he shows that  $(2)_m$  implies  $(1)_m$ .

**Proof of  $(1)_{m+1}$**  We assume that  $1 \leq \mathrm{codim}_N U = m+1$ . By [Proposition 16.3](#), it suffices to show that  $X := \overline{xH'(U)} = xL C(H(U))$  for some  $L \in \mathcal{L}_U$ . Assume that  $xH'(U)$  is not closed in the following.

**Step 1: find a closed orbit inside  $X$**  We claim that  $X$  contains a  $U$ -minimal subset  $Y$  such that  $X - yH'$  is not closed for some  $y \in Y$  (see the case when  $R$  is compact in the proof of [Proposition 16.7](#)). If  $xH'(U)$  is not locally closed, then any  $U$ -minimal subset  $Y \subset X$  does the job. If  $xH'(U)$  is locally closed, then any  $U$ -minimal subset  $Y$  of  $X - xH'(U)$  does the job; note that the set  $X - xH'(U)$  is a compact  $H'(U)$ -invariant subset and hence contains a  $U$ -minimal subset.

Hence, by [Proposition 10.9](#),  $X$  contains an orbit  $x_0 \hat{U}$  with  $\dim \hat{U} > \dim U$ . By  $(2)_m$  and [Lemma 16.4](#),  $X$  contains a closed orbit  $zL$  for some  $L \in \mathcal{L}_U$ . We may assume that  $X \neq zL C(H(U))$ ; otherwise, we are done.

**Step 2: enlarge a closed orbit inside  $X$**  Since  $zL$  is compact, by [Theorem 13.1](#), we can assume that  $zU_{\pm}^{(i)}$  is dense in  $zL$ , where  $U_{\pm}^{(1)}, \dots, U_{\pm}^{(k)}$  are one-parameter subgroups of  $U^{\pm}$  generating  $U^{\pm}$ . Note that there exists  $g_i \rightarrow e$  in  $G - LC(H(U))$  such that  $zg_i \in X$ . We can write  $g_i = \ell_i r_i$ , where  $r_i \in \exp \mathfrak{t}^{\perp}$  and  $\ell_i \in L$ . Then  $r_i \notin C(H(U))$ . Since  $\bigcap_{i=1}^k (N(U_+^{(i)}) \cap N(U_-^{(i)})) \cap \exp \mathfrak{t}^{\perp}$  is locally contained in  $C(H(U))$ , we have  $r_i \notin N(U_0)$ , where  $U_0$  is one of the subgroups  $U_{\pm}^{(i)}$ . If  $U_0 \in \{U_+^{(i)}\}$ , then replace  $U$  by  $U^+$ .

Fix any  $k > 1$ . Applying [\(2-6\)](#) to the sequence  $z_i := z\ell_i \rightarrow z$ , the set

$$(A-1) \quad T(z_i) := \left\{ t \in \mathbb{R} : z_i u_t \in \Gamma \backslash G - \bigcup_{j=1}^i \mathbb{O}_j \right\}$$

is a  $k$ -thick subset (take  $0 < \varepsilon < 1 - 1/k$ ). By [Lemma 9.3](#), there exists  $t_i \in T(z_i)$  such that  $u_{t_i}^{-1} r_i u_{t_i}$  converges to a nontrivial element  $v \in (L \cap N)^{\perp}$ . Now the sequence  $z_i u_{t_i}$  converges to  $z_0 \in \mathcal{G}(U_0, zL)$ . Since  $zg_i u_{t_i}$  converges to  $z_0 v$ , we deduce

$$zLv = \overline{z_0 v U_0} \subset X \quad \text{and hence} \quad zLV^+ \subset zL(AvA) \subset X,$$

where  $V^+$  is the one-parameter unipotent subsemigroup contained in  $AvA$ . Take any sequence  $v_i \rightarrow \infty$  in  $V^+$  such that  $zv_i$  converges to some  $x_0$ . Then  $x_0 V \subset \limsup (zv_i)(v_i^{-1} V^+) \subset X$  and hence  $X$  contains  $x_0(L \cap N)V$ . By the induction hypothesis  $(2)_m$  and [Lemma 16.4](#),  $X$  contains a closed orbit of  $\hat{L}$  for some  $\hat{L} \in \mathcal{L}_{\hat{U}}$ . This process of enlargement must end after finitely many steps.

**Proof of  $(2)_{m+1}$**  Set  $X := \overline{xU}$ . We assume that  $X \neq \Gamma \backslash G$ . Since the codimension of  $U$  in  $N$  is at least 1, we may assume without loss of generality that  $U < N \cap \mathrm{SO}^{\circ}(d-1, 1)$  using conjugation by an element of  $M$ .

**Step 1: find a closed orbit inside  $X$**  By the hypothesis on the existence of a closed  $L_0 := \mathrm{SO}^{\circ}(d-1, 1)$ -orbit,  $\mathcal{S}(U) \neq \emptyset$ . It follows from  $(1)_{m+1}$ ,  $(2)_m$  and the cocompactness of  $AU$  in  $H'(U)$  that any  $AU$ -orbit closure intersects  $\mathcal{S}(U)$  (see the proof of [Lemma 17.1](#)).

We claim that  $X$  intersects  $\mathcal{S}(U)$ . Since  $\mathcal{S}(U)$  is  $NC_2(U)$ -invariant, it suffices to show that  $XN C_2(U)$  intersects  $\mathcal{S}(U)$ . Let  $Y \subset X$  be a  $U$ -minimal subset. Then there exists a one-parameter subgroup  $S < AU^{\perp} C_2(U)$  such that  $Yg = Y$  for all  $g \in S$  by [Proposition 10.6](#). Strictly speaking, the cited result gives  $Yg \subset Y$  for  $g$  in a semigroup  $S$ , but, in the case at hand,  $Yg \subset Y$  implies  $Yg = Y$ , since  $Yg$  is  $U$ -minimal again, and hence  $Yg^{-1} = Y$  as well. In view of [Lemma 3.3](#), we get  $YA \subset XN C_2(U)$  or  $YvA \subset XN C_2(U)$  for some  $v \in N$ . In either case,  $XN C_2(U)$  contains an  $AU$ -orbit and hence intersects  $\mathcal{S}(U)$ . So the claim follows. Since  $X$  intersects  $\mathcal{S}(U)$ , by applying  $(2)_m$ ,  $X$  contains a closed orbit  $zL$  for some  $L \in \mathcal{Q}_U$ .

**Step 2: enlarge a closed orbit inside  $X$**  Suppose  $L \neq G$  and  $X \neq zL$ . It suffices to show that  $X$  contains a closed orbit of  $\hat{L}$  for some  $\hat{L} \in \mathcal{L}_{\hat{U}}$  for some  $\hat{U}$  properly containing  $L \cap N$ . We may assume

$X \not\subset zL C(H(U))$ ; otherwise, the claim follows from  $(2)_m$ . We may assume  $z \in \bigcap_{i=1}^l \mathcal{G}(U^{(i)}, yL)$ , where the  $U^{(i)}$  are one-parameter generating subgroups of  $U$ . Take a sequence  $xu_i \rightarrow z$ , where  $u_i \in U$ , and write  $xu_i = z\ell_i r_i$ , where  $\ell_i \in L$  and  $r_i \in \exp(\mathfrak{l}^\perp)$ . The case of  $r_i \in N(U)$  for some  $i$  follows from  $(2)_m$  (see the proof of [Theorem 17.4](#)). Hence we may assume  $r_i \notin N(U)$ , and, by passing to a subsequence,  $r_i \notin N(U_0)$  for some  $U_0 \in \{U^{(i)}\}$ .

Fix any  $k > 1$ . Then  $T(z_i)$  as in [\(A-1\)](#) is a  $k$ -thick subset. We now repeat the same argument of a step in the proof of  $(1)_{m+1}$ . By [Lemma 9.3](#), there exists  $t_i \in T(z_i)$  such that  $u_{t_i}^{-1} r_i u_{t_i}$  converges to a nontrivial element  $v \in U^\perp$ . Now the sequence  $z_i u_{t_i}$  converges to  $z_0 \in \mathcal{G}(U_0, zL)$ . Hence  $X \supset \overline{z_0(L \cap N)v} = zLv$ . Moreover, by [Lemma 9.3](#), such a  $v$  can be made of arbitrarily large size, so we get  $X \supset zLv_j$  for a sequence  $v_j \in (L \cap N)^\perp$  tending to  $\infty$ . The set  $\limsup_{j \rightarrow \infty} v_j^{-1} A v_j$  contains a one-parameter subgroup  $V \subset (L \cap N)^\perp$  by [Lemma 3.4](#). Passing to a subsequence, there exists  $y \in \liminf zLv_j$  and hence

$$X \supset \limsup_{j \rightarrow \infty} (zLv_j) \supset y(L \cap N) \limsup_{j \rightarrow \infty} (v_j^{-1} A v_j) \supset y(L \cap N)V.$$

Hence  $X$  contains  $y(L \cap N)V$ , and hence the claim follows from  $(2)_m$ .

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