

# The Novikov conjecture and geometry of Banach spaces

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In this paper, we prove the strong Novikov conjecture for groups coarsely embeddable into Banach spaces satisfying a geometric condition called Property (H).

19K35, 19K56, 46L80; 57R55

## 1 Introduction

An important problem in higher dimensional topology is the Novikov conjecture on the homotopy invariance of higher signature. The Novikov conjecture is a consequence of the Strong Novikov Conjecture in  $K$ -theory of group  $C^*$ -algebras. The main purpose of this paper is to prove the Strong Novikov conjecture (with coefficients) for any group coarsely embeddable into a Banach space satisfying a geometric condition called Property (H).

**Definition 1.1** A real Banach space  $X$  is said to have *Property (H)* if there exists an increasing sequence of finite dimensional subspaces  $\{V_n\}$  of  $X$  and an increasing sequence of finite dimensional subspaces  $\{W_n\}$  of a real Hilbert space such that

- (1)  $V = \bigcup_n V_n$  is dense in  $X$ ;
- (2) if  $W$  denotes  $\bigcup_n W_n$ , and  $S(V)$ ,  $S(W)$  denote respectively the unit spheres of  $V$ ,  $W$ , then there exists a uniformly continuous map  $\psi: S(V) \rightarrow S(W)$  such that the restriction of  $\psi$  to  $S(V_n)$  is a homeomorphism (or more generally a degree one map) onto  $S(W_n)$  for each  $n$ .

As an example, let  $X$  be the Banach space  $l^p(\mathbb{N})$  for some  $p \geq 1$ . Let  $V_n$  and  $W_n$  be respectively the subspaces of  $l^p(\mathbb{N})$  and  $l^2(\mathbb{N})$  consisting of all sequences whose coordinates are zero after the  $n$ th terms. We define a map  $\psi$  from  $S(V)$  to  $S(W)$  by

$$\psi(c_1, \dots, c_k, \dots) = (c_1|c_1|^{p/2-1}, \dots, c_k|c_k|^{p/2-1}, \dots).$$

This map  $\psi$  is called the *Mazur map* (see Benyamini and Lindenstrauss [3]). It is not difficult to verify that  $\psi$  satisfies the conditions in the definition of Property (H). For

each  $p \geq 1$ , we can similarly prove that the Banach space of all Schatten  $p$ -class operators on a Hilbert space has Property (H). We can also check that uniformly convex Banach spaces with certain unconditional bases have Property (H) (with the help of results of Benyamini and Lindenstrauss on the uniform homeomorphism classification of Banach space spheres in [3, Chapter 9]).

We also recall that a metric space  $\Gamma$  is said to be coarsely embeddable into a Banach space  $X$  (see Gromov [5]) if there exists a map  $h: \Gamma \rightarrow X$  for which there exist non-decreasing functions  $\rho_1$  and  $\rho_2$  from  $\mathbb{R}_+ = [0, \infty)$  to  $\mathbb{R}$  such that

- (1)  $\rho_1(d(x, y)) \leq \|h(x) - h(y)\| \leq \rho_2(d(x, y))$  for all  $x, y \in \Gamma$ ;
- (2)  $\lim_{r \rightarrow +\infty} \rho_i(r) = +\infty$  for  $i = 1, 2$ .

In the case of a countable group  $\Gamma$ , we endow  $\Gamma$  with a proper (left invariant) length metric. If  $\Gamma$  is finitely generated, the word length metric is an example of a proper length metric. The issue of coarse embeddability of a countable group into a Banach space  $X$  is independent of the choice of the proper length metric.

The following theorem is the main result of this paper.

**Theorem 1.2** *Let  $\Gamma$  be a countable discrete group and  $A$  any  $\Gamma$ - $C^*$ -algebra. If  $\Gamma$  admits a coarse embedding into a Banach space with Property (H), then the Strong Novikov conjecture with coefficients in  $A$  holds for  $\Gamma$ , that is, if  $\mathcal{E}\Gamma$  is the universal space for proper  $\Gamma$ -actions and  $A \rtimes_r \Gamma$  is the reduced crossed product  $C^*$ -algebra, then the Baum–Connes assembly map*

$$\mu: KK_*^\Gamma(\mathcal{E}\Gamma, A) \rightarrow K_*(A \rtimes_r \Gamma)$$

is injective.

The special case when the Banach space is the Hilbert space is proved by Yu [15] and Skandalis–Tu–Yu [13].

If we replace the degree one condition by a nonzero degree condition in the definition of Property (H), we say that  $X$  has rational Property (H).

**Theorem 1.3** *Let  $\Gamma$  be a countable discrete group and  $A$  any  $\Gamma$ - $C^*$ -algebra. If  $\Gamma$  admits a coarse embedding into a Banach space with rational Property (H), then the rational Strong Novikov conjecture with coefficients in  $A$  holds for  $\Gamma$ , that is, if  $\mathcal{E}\Gamma$  is the universal space for proper  $\Gamma$ -actions and  $A \rtimes_r \Gamma$  is the reduced crossed product  $C^*$ -algebra, then the Baum–Connes assembly map*

$$\mu: KK_*^\Gamma(\mathcal{E}\Gamma, A) \otimes \mathbb{Q} \rightarrow K_*(A \rtimes_r \Gamma) \otimes \mathbb{Q}$$

is injective.

We remark that the rational Strong Novikov conjecture implies the Novikov conjecture on homotopy invariance of higher signatures and the Gromov–Lawson–Rosenberg conjecture regarding nonexistence of positive scalar curvature metrics on closed aspherical manifolds.

It is conjectured that any countable subgroup of the diffeomorphism group of a compact smooth manifold is coarsely embeddable into the Banach space of all Schatten  $p$ -class operators for some  $p \geq 1$ . If  $p > 2$ , then  $l^p(\mathbb{N})$  is not coarsely embeddable into a Hilbert space (see Johnson and Randrianarivony [9]). More generally,  $l^p(\mathbb{N})$  does not coarsely embed into  $l^q(\mathbb{N})$  if  $p > q \geq 2$  (see Mendel and Naor [11]). Let  $C_0$  be the Banach space consisting of all sequences of real numbers that are convergent to 0. It is an open question if  $C_0$  has (rational) Property (H). By the above theorems, a positive answer to this question would imply the Novikov conjecture since every countable group admits a coarse embedding into  $C_0$  (see Brown and Guentner [4]).

This paper is organized as follows. In Section 2, we construct a  $C^*$ -algebra associated to a Banach space with (rational) Property (H) and study its  $K$ -groups. In Section 3, we reformulate the Baum–Connes map and discuss its connection with the localization algebra. In Section 4, we introduce the Bott map for  $K$ -groups. In Section 5, we give a proof of the main theorem.

In this paper,  $K$ -groups of a graded  $C^*$ -algebra are defined to be the  $K$ -groups of the underlying ungraded  $C^*$ -algebra obtained by forgetting the grading structure. The same comment applies to  $KK$ -groups.

**Acknowledgements** The authors wish to thank Misha Gromov for inspiring discussions and the referee for very helpful comments. Both authors are partially supported by NSF.

## 2 A $C^*$ -algebra associated to a Banach space with Property (H)

In this section, we construct a  $C^*$ -algebra associated to a Banach space with (rational) Property (H) and study its  $K$ -groups.

Let  $\psi$  be as in the definition of (rational) Property (H). We extend  $\psi$  to a map  $\phi: V \rightarrow W$  by

$$\phi(v) = \|v\| \psi\left(\frac{v}{\|v\|}\right)$$

for any  $v \in V$ , where  $\phi(0)$  should be interpreted as 0.

Let  $Clifford(W_n)$  be the complex Clifford algebras of  $W_n$ , satisfying the relation  $w^2 = \|w\|^2$  for all  $w \in W_n$ . We define the complex Clifford algebra  $Clifford(W)$  to be the  $C^*$ -algebra inductive limit of  $Clifford(W_n)$ . Let  $C_0(V, Clifford(W))$  be the graded  $C^*$ -algebra of all bounded and uniformly continuous functions on  $V$  with values in the Clifford algebra  $Clifford(W)$  which vanish at infinity, where the grading is given by the natural grading structure on the Clifford algebra. Let  $\mathcal{S} = C_0(\mathbb{R})$  be the graded  $C^*$ -algebra of all complex-valued continuous functions on  $\mathbb{R}$  vanishing at infinity (graded by even and odd functions). We define  $\mathcal{S} \widehat{\otimes} C_0(V, Clifford(W))$  to be the graded  $C^*$ -algebra tensor product of  $\mathcal{S}$  and  $C_0(V, Clifford(W))$ .

For any  $f \in C_0(\mathbb{R})$ , we can define an element

$$f((s, \phi(v))) \in \mathcal{S} \widehat{\otimes} C_0(V, Clifford(W))$$

by

$$f((s, \phi(v))) = f(s \widehat{\otimes} 1 + 1 \widehat{\otimes} \phi(v)),$$

where  $s$  and  $\phi(v)$  should be respectively viewed as unbounded degree one multipliers of  $\mathcal{S}$  and  $C_0(V, Clifford(W))$ ,  $(s, \phi(v))$  is defined to be  $s \widehat{\otimes} 1 + 1 \widehat{\otimes} \phi(v)$  as an unbounded degree one multiplier of  $\mathcal{S} \widehat{\otimes} C_0(V, Clifford(W))$ , and  $f(s \widehat{\otimes} 1 + 1 \widehat{\otimes} \phi(v))$  is defined using functional calculus.

More concretely,  $f((s, \phi(v)))$  can be defined as follows:

- (1) If  $f(t) = g(t^2)$  for some  $g \in C_0(\mathbb{R})$ , then we define a scalar valued function  $f((s, \phi(v)))$  of the variable  $(s, v) \in \mathbb{R} \times V$  by

$$(s, v) \rightarrow g(s^2 + \|\phi(v)\|^2) = g(s^2 + \|v\|^2)$$

for every  $(s, v) \in \mathbb{R} \times V$ ;

- (2) if  $f(t) = tg(t^2) \in C_0(\mathbb{R})$  for some  $g \in C_0(\mathbb{R})$ , then we define an element  $f((s, \phi(v))) \in \mathcal{S} \widehat{\otimes} C_0(V, Clifford(W))$  by

$$\begin{aligned} f((s, \phi(v))) &= g(s^2 + \|\phi(v)\|^2)(s \widehat{\otimes} 1 + 1 \widehat{\otimes} \phi(v)) \\ &= g(s^2 + \|v\|^2)(s \widehat{\otimes} 1 + 1 \widehat{\otimes} \phi(v)) \end{aligned}$$

for every  $s \in \mathbb{R}, v \in V$ , here  $s \widehat{\otimes} 1 + 1 \widehat{\otimes} \phi(v)$  should viewed as an unbounded degree one multiplier of  $\mathcal{S} \widehat{\otimes} C_0(V, Clifford(W))$ ;

- (3) the general definition of  $f((s, \phi(v)))$  follows using approximation of  $f$  by linear combinations of special functions of the above two types in  $C_0(\mathbb{R})$ .

Now we are ready to define a  $C^*$ -algebra associated to a Banach space with (rational) Property (H).

**Definition 2.1** Let  $X$  be a Banach space with (rational) Property (H). Let  $\phi$  be as above. We define  $\mathcal{A}(X)$  to be the graded  $C^*$ -subalgebra of  $\mathcal{S} \widehat{\otimes} C_0(V, \text{Clifford}(W))$  generated by all  $f((s, \phi(v - v_0)))$  for  $s \in \mathbb{R}$ , all  $v_0 \in V$  and  $f \in C_0(\mathbb{R})$ .

It is not difficult to compute  $K_*(\mathcal{A}(X))$  when  $X$  is an  $l^p$ -space for some  $1 \leq p < \infty$  (see Higson–Kasparov–Trout [8] for  $p = 2$ ). In general, it is an open question how to compute  $K_*(\mathcal{A}(X))$ . The following result provides a partial solution.

**Proposition 2.2** Let  $X$  be a Banach space with Property (H) and let  $\mathcal{A}(X)$  be the  $C^*$ -algebra associated to  $X$ . If  $B$  is a (graded)  $C^*$ -algebra, then the homomorphism from  $\mathcal{S}$  to  $\mathcal{A}(X)$ :  $f(s) \rightarrow f((s, \phi(v)))$ , induces an injection

$$K_*(\mathcal{S} \widehat{\otimes} B) \rightarrow K_*(\mathcal{A}(X) \widehat{\otimes} B).$$

**Proof** Let  $\mathcal{A}(X, V_n)$  be the  $C^*$ -subalgebra of  $\mathcal{A}(X)$  generated by all elements  $f((s, \phi(v - v_0)))$  for  $f \in C_0(\mathbb{R})$  and  $s \in \mathbb{R}, v_0 \in V_n$ . Note that  $\mathcal{A}(X) \widehat{\otimes} B$  is the inductive limit of  $\mathcal{A}(X, V_n) \widehat{\otimes} B$ . It suffices to prove that the homomorphism

$$\beta_n: K_*(\mathcal{S} \widehat{\otimes} B) \rightarrow K_*(\mathcal{A}(X, V_n) \widehat{\otimes} B)$$

is injective for each  $n$ , where  $\beta_n$  is induced by the homomorphism from  $\mathcal{S}$  to  $\mathcal{A}(X, V_n)$ :  $f(t) \rightarrow f((s, \phi(v)))$ .

Let  $\mathcal{C}(V_n)$  be the graded  $C^*$ -algebra of all continuous functions on  $V_n$  with values in the Clifford algebra  $\text{Clifford}(W_n)$  which vanish at infinity. Define  $\mathcal{A}(V_n)$  to be the graded  $C^*$ -algebra tensor product  $\mathcal{S} \widehat{\otimes} \mathcal{C}(V_n)$ . Let  $r_n$  be the restriction homomorphism from  $\mathcal{A}(X, V_n) \widehat{\otimes} B$  to  $\mathcal{A}(V_n) \widehat{\otimes} B$ . By the definition of Property (H), such restriction homomorphism is well defined. By Bott periodicity (see Higson–Kasparov–Trout [8]) and the degree one condition in the definition of Property (H), we observe that the composition  $(r_n)_* \circ \beta_n$  is an isomorphism. Proposition 2.2 follows from this observation. □

The following result follows from Proposition 2.2 and the Green–Julg theorem.

**Corollary 2.3** Let  $X$  be a Banach space with Property (H) and let  $\mathcal{A}(X)$  be the  $C^*$ -algebra associated to  $X$ . If  $H$  is a compact topological group and  $B$  is a (graded)  $H$ - $C^*$ -algebra, then we have a natural injective homomorphism

$$K_*^H(\mathcal{S} \widehat{\otimes} B) \rightarrow K_*^H(\mathcal{A}(X) \widehat{\otimes} B),$$

where  $H$  acts on  $\mathcal{A}(X)$  trivially.

We can prove the following results using essentially the same argument.

**Proposition 2.4** *Let  $X$  be a Banach space with rational Property (H) and let  $\mathcal{A}(X)$  be the  $C^*$ -algebra associated to  $X$ . If  $B$  is a (graded)  $C^*$ -algebra, then we have a natural injective homomorphism*

$$K_*(\mathcal{S} \widehat{\otimes} B) \otimes \mathbb{Q} \rightarrow K_*(\mathcal{A}(X) \widehat{\otimes} B) \otimes \mathbb{Q}.$$

**Corollary 2.5** *Let  $X$  be a Banach space with rational Property (H) and let  $\mathcal{A}(X)$  be the  $C^*$ -algebra associated to  $X$ . If  $H$  is a compact topological group and  $B$  is a (graded)  $H$ - $C^*$ -algebra, then we have a natural injection*

$$K_*^H(\mathcal{S} \widehat{\otimes} B) \otimes \mathbb{Q} \rightarrow K_*^H(\mathcal{A}(X) \widehat{\otimes} B) \otimes \mathbb{Q}.$$

Let  $B$  be a graded  $C^*$ -algebra, and let  $\mathcal{K}$  be the graded  $C^*$ -algebra of all compact operators on a graded separable and infinite dimensional Hilbert space. Let  $C_c(\mathbb{R}) \widehat{\otimes}_{\text{alg}} (B \widehat{\otimes} \mathcal{K})$  be the algebraic graded tensor product of  $C_c(\mathbb{R})$  with  $B \widehat{\otimes} \mathcal{K}$ , where  $C_c(\mathbb{R})$  is considered as an algebra graded by even and odd functions.

We define  $\mathcal{S}_b^\infty(B)$  to be the graded  $C^*$ -algebra of all bounded sequences of uniformly equicontinuous functions  $\{f_k\}$  in  $\mathcal{S} \widehat{\otimes} B \widehat{\otimes} \mathcal{K}$  such that for each  $\epsilon > 0$ , there exists  $R > 0$  for which there exists a bounded sequence of uniformly equicontinuous functions  $\{g_k\}$  in  $C_c(\mathbb{R}) \widehat{\otimes}_{\text{alg}} (B \widehat{\otimes} \mathcal{K})$  satisfying  $\text{diameter}(\text{support}(g_k)) < R$  and  $\|f_k - g_k\| < \epsilon$  for all  $k$ , where the support of  $g_k$  is a subset of  $\mathbb{R}$ . Let  $\mathcal{S}_0^\infty(B)$  be the graded  $C^*$ -subalgebra of  $\mathcal{S}_b^\infty(B)$  consisting of all sequence  $(f_k)$  in  $\mathcal{S}_b^\infty(B)$  which are convergent to 0 in the sup norm. Define  $\mathcal{S}^\infty(B)$  to be the quotient graded  $C^*$ -algebra  $\mathcal{S}_b^\infty(B)/\mathcal{S}_0^\infty(B)$ .

The proof of the following result is straightforward and is therefore omitted.

**Proposition 2.6** *If  $H$  is a finite group and  $B$  is a graded  $H$ - $C^*$ -algebra, then  $K_*^H(\mathcal{S}^\infty(B))$  is naturally isomorphic to  $(\prod K_{*+1}^H(B))/(\bigoplus K_{*+1}^H(B))$ .*

We remark that by the Green–Julg theorem the equivariant case of the above proposition follows from the non-equivariant case.

Let  $\mathcal{C}(V_k)$  be the graded  $C^*$ -algebra of all continuous functions on  $V_k$  with values in the Clifford algebra  $\text{Clifford}(W_k)$  which vanish at infinity. Define  $\mathcal{A}(V_n)$  to be the graded  $C^*$ -algebra tensor product  $\mathcal{S} \widehat{\otimes} \mathcal{C}(V_n)$ . Endow  $\mathbb{R} \times V_k$  with the product metric of the standard metric on  $\mathbb{R}$  and the Banach norm metric on  $V_k$ .

We define  $\mathcal{A}_b^\infty(X, B)$  to be the graded  $C^*$ -algebra of all bounded sequences  $(a_k)$  such that

- (1)  $a_k \in \mathcal{A}(V_k) \widehat{\otimes} B \widehat{\otimes} \mathcal{K}$  and  $(a_k)$  is uniformly equicontinuous in  $\{(s, v_k)\}$  in the sense that for any  $\epsilon > 0$  there exists a  $\delta > 0$  (independent of  $k$ ) such that

$$\|a_k(s, v_k) - a_k(s', v'_k)\| < \epsilon$$

if  $d((s, v_k), (s', v'_k)) < \delta$ ;

- (2) for each  $\epsilon > 0$ , there exists  $R > 0$  for which there exists a sequence  $\{g_k\}$  in  $\mathcal{A}(V_k) \widehat{\otimes} B \widehat{\otimes} \mathcal{K}$  satisfying

$$\text{diameter}(\text{support}(g_k)) < R,$$

$$\|a_k(s, v_k) - g_k(s, v_k)\| < \epsilon$$

for all  $k$  and  $(s, v_k) \in \mathbb{R} \times V_k$ , where the support of  $g_k$  is a subset of  $\mathbb{R} \times V_k$ .

Let  $\mathcal{A}_0^\infty(X, B)$  be the graded  $C^\infty$ -subalgebra of  $\mathcal{A}_b^\infty(X, B)$  consisting of all sequences which are convergent to 0 in norm. Define  $\mathcal{A}^\infty(X, B)$  to be the quotient graded  $C^*$ -algebra  $\mathcal{A}_b^\infty(X, B)/\mathcal{A}_0^\infty(X, B)$ .

Let  $\beta_k$  be the homomorphism from  $\mathcal{S}$  to  $\mathcal{A}(V_k)$  defined by

$$(\beta_k(f))(s, v_k) = f((s, \phi(v_k)))$$

for each  $f \in \mathcal{S}$ ,  $s \in \mathbb{R}$  and  $v_k \in V_k$ .

$\beta_k$  induces a homomorphism (still denoted by  $\beta_k$ ) from  $\mathcal{S} \widehat{\otimes} B \widehat{\otimes} \mathcal{K}$  to  $\mathcal{A}(V_k) \widehat{\otimes} B \widehat{\otimes} \mathcal{K}$ . We define a homomorphism

$$\beta: \mathcal{S}^\infty(B) \rightarrow \mathcal{A}^\infty(X, B)$$

by

$$\beta([(f_1, \dots, f_k, \dots)]) = [(\beta_1(f_1), \dots, \beta_k(f_k), \dots)]$$

for all  $[(f_1, \dots, f_k, \dots)] \in \mathcal{S}^\infty(B)$ .

**Theorem 2.7** *If  $X$  is a Banach space with Property (H), then the homomorphism  $\beta$  induces an isomorphism*

$$\beta_*: K_*(\mathcal{S}^\infty(B)) \rightarrow K_*(\mathcal{A}^\infty(X, B)).$$

**Proof** For each  $k$ , endow  $V_k$  with a Euclidean metric and let  $D_k$  be the corresponding Dirac operator on  $V_k$ . Let  $\alpha_k$  be the asymptotic morphism from  $\mathcal{A}(V_k)$  to  $\mathcal{S} \widehat{\otimes} \mathcal{K}$  associated to  $D_k$ :

$$\alpha_k(t): f \widehat{\otimes} h \rightarrow f(t^{-1}(s \widehat{\otimes} 1 + 1 \widehat{\otimes} D_k))\pi(h)$$

for all  $f \in \mathcal{S}$  and  $h \in \mathcal{C}(V_k)$ , where  $\mathcal{C}(V_k)$  is as in the definition of  $\mathcal{A}(V_k)$ ,  $W_k$  (in the definition of  $\mathcal{C}(V_k)$ ) is identified with  $V_k$  as Euclidean vector spaces, and  $\pi(h)$  is the multiplication operator associated to  $h$ .  $\alpha_k$  induces an asymptotic morphism (still called  $\alpha_k$ ) from  $\mathcal{A}(V_k) \widehat{\otimes} B \widehat{\otimes} \mathcal{K}$  to  $\mathcal{S} \widehat{\otimes} B \widehat{\otimes} \mathcal{K}$ . This asymptotic morphism was first introduced by Higson–Kasparov–Trout [8].

For each  $t \in [1, \infty)$ , we define a map

$$\alpha(t): \mathcal{A}^\infty(X, B) \rightarrow \mathcal{S}^\infty(B)$$

by

$$(\alpha(t))([(a_1, \dots, a_k, \dots)]) = [((\alpha_1(t))(a_1), \dots, (\alpha_k(t))(a_k), \dots)].$$

After rescaling  $\alpha_k(t)$  for each  $k$ ,  $\alpha$  is an asymptotic morphism from  $\mathcal{A}^\infty(X, B)$  to  $\mathcal{S}^\infty(B)$ , where the rescaling constant for each  $k$  can be chosen as the Lipschitz constant of the Lipschitz equivalence between the Euclidean norm on  $V_k$  and the Banach norm on  $V_k$ .  $\alpha$  is called the Dirac morphism. More precisely, let  $C_k$  be the Lipschitz constant of the Lipschitz equivalence between the Euclidean norm  $\|\cdot\|_E$  on  $V_k$  and the Banach norm on  $\|\cdot\|$  on  $V_k$ , that is,  $C_k$  is a positive constant satisfying  $C_k^{-1}\|v\|_E \leq \|v\| \leq C_k\|v\|_E$  for all  $v \in V_k$ . For each  $k$ , the scaled asymptotic morphism is defined to be  $\alpha_k(C_k t)$  (still denoted by  $\alpha_k$ ).

Let  $\mathcal{A}^\infty(X \times X, B)$  be defined as  $\mathcal{A}^\infty(X, B)$  using the sequence of finite dimensional subspaces  $V_n \times V_n$  and  $W_n \times W_n$ .

We define a homomorphism  $\beta'_k$  from  $\mathcal{A}(V_k)$  to  $\mathcal{A}(V_k \times V_k)$  by

$$(\beta'_k(f \widehat{\otimes} g))(s, v_k, v'_k) = f((s, \phi(v'_k))) \widehat{\otimes} g(v_k),$$

where  $f \in \mathcal{S}$ ,  $g \in C_0(V_k, \text{Clifford}(W_k))$ ,  $s \in \mathbb{R}$ ,  $(v_k, v'_k) \in V_k \times V_k$ , and  $f((s, \phi(v'_k)))$  is defined to be  $f(s \widehat{\otimes} 1 + 1 \widehat{\otimes} \phi(v'_k))$ .

The homomorphism  $\beta'_k$  induces a homomorphism (which we also denote  $\beta'_k$ ) from  $\mathcal{A}(V_k) \widehat{\otimes} B \widehat{\otimes} \mathcal{K}$  to  $\mathcal{A}(V_k \times V_k) \widehat{\otimes} B \widehat{\otimes} \mathcal{K}$ . Using  $\{\beta'_k\}$  we can define a homomorphism  $\beta'$  from  $\mathcal{A}^\infty(X, B)$  to  $\mathcal{A}^\infty(X \times X, B)$ . Similarly we define the Dirac morphism  $\alpha'$  from  $\mathcal{A}^\infty(X \times X, B)$  to  $\mathcal{A}^\infty(X, B)$  using the Dirac operator on the first copy of  $V_k$  in  $V_k \times V_k$  for each  $k$ .

We now apply Atiyah’s rotation trick [1]. For any  $\theta \in [0, \frac{\pi}{2}]$ , we define the rotation  $R_\theta$  by

$$R_\theta(v, w) = (\cos \theta v - \sin \theta w, \sin \theta v + \cos \theta w).$$

This rotation  $R_\theta$  induces an automorphism (also denoted  $R_\theta$ ) on  $\mathcal{A}^\infty(X \times X, B)$ . In particular, for any sequence of vectors  $\{(c_k, c'_k)\}$  such that  $(c_k, c'_k) \in V_k \times V_k$ , we have

$$R_\theta: [(f_k((s, (\phi(v_k - c_k), \phi(v'_k - c'_k))))))] \rightarrow [(f_k((s, (\cos \theta \phi(\cos \theta v_k + \sin \theta v'_k - c_k) - \sin \theta \phi(-\sin \theta v_k + \cos \theta v'_k - c'_k), \sin \theta \phi(\cos \theta v_k + \sin \theta v'_k - c_k) + \cos \theta \phi(-\sin \theta v_k + \cos \theta v'_k - c'_k))))))],$$

where  $f_k \in \mathcal{S}$ ,  $\{f_k\}$  is equicontinuous, and  $s \in \mathbb{R}$ ,  $(v_k, v'_k) \in V_k \times V_k$ .

By homotopy invariance, we have

$$(\text{Id})_* = (R_0)_* = (R_{\frac{\pi}{2}})_*,$$

where  $(R_\theta)_*$  is the automorphism on  $K_*(\mathcal{A}^\infty(X \times X, B))$  induced by  $R_\theta$ .

For any  $x \in K_*(\mathcal{S}^\infty(B))$ , we have

$$\alpha_*(\beta_*(x)) = x.$$

For any  $y \in K_*(\mathcal{A}^\infty(X, B))$ , we have

$$\beta_*(\alpha_*(y)) = \alpha'_*(\beta'_*(y)) = \alpha'_*(R_{\frac{\pi}{2}})_*(\beta'_*(y)) = \tilde{y},$$

where the map  $y \rightarrow \tilde{y}$  is induced by the map  $(v_k) \rightarrow (-v_k)$ .

The above two identities imply that  $\beta$  and  $\alpha$  are isomorphisms, inverse to each other, and  $y \rightarrow \tilde{y}$  is the identity map. □

The following result follows from [Theorem 2.7](#) and the Green–Julg theorem.

**Corollary 2.8** *Let  $H$  be a finite group and let  $B$  be a graded  $H$ – $C^*$ –algebra. If  $X$  is a Banach space with Property (H), then  $\beta$  induces an isomorphism*

$$\beta_*: K_*^H(\mathcal{S}^\infty(B)) \rightarrow K_*^H(\mathcal{A}^\infty(X, B)).$$

**Proposition 2.9** *If  $X$  is a Banach space with rational Property (H), then the homomorphism  $\beta$  induces an isomorphism*

$$\beta_*: K_*(\mathcal{S}^\infty(B)) \otimes \mathbb{Q} \rightarrow K_*(\mathcal{A}^\infty(X, B)) \otimes \mathbb{Q}.$$

**Corollary 2.10** *Let  $H$  be a finite group and let  $B$  be a graded  $H$ – $C^*$ –algebra. If  $X$  is a Banach space with rational Property (H), then  $\beta$  induces an isomorphism*

$$\beta_*: K_*^H(\mathcal{S}^\infty(B)) \otimes \mathbb{Q} \rightarrow K_*^H(\mathcal{A}^\infty(X, B)) \otimes \mathbb{Q}.$$

### 3 The Baum–Connes map and localization

In this section, we briefly recall the Baum–Connes map and its relation to the localization algebra. Our reformulation of the Baum–Connes map follows the work of Roe [12] and uses a localization technique introduced by Yu [14]. This reformulation will be useful in the next section.

Let  $\Gamma$  be a countable discrete group. Let  $\Delta$  be a locally compact metric space with a proper and cocompact isometric action of  $\Gamma$ . Let  $C_0(\Delta)$  be the algebra of all complex valued continuous functions on  $\Delta$  which vanish at infinity. Let  $B$  be a  $\Gamma$ - $C^*$ -algebra.

The following definition is due to John Roe [12].

**Definition 3.1** Let  $H$  be a Hilbert module over  $B$  and let  $\varphi$  be a  $*$ -homomorphism from  $C_0(\Delta)$  to  $B(H)$ , the  $C^*$ -algebra of all bounded (adjointable) operators on  $H$ . Let  $T$  be an operator in  $B(H)$ .

- (1) The support of  $T$  is defined to be the complement (in  $\Delta \times \Delta$ ) of the set of all points  $(x, y) \in \Delta \times \Delta$  for which there exists  $f \in C_0(\Delta)$  and  $g \in C_0(\Delta)$  satisfying  $\varphi(f)T\varphi(g) = 0$  and  $f(x) \neq 0$  and  $g(y) \neq 0$ ;
- (2) The propagation of  $T$  is defined to be  $\sup\{d(x, y) : (x, y) \in \text{Supp}(T)\}$ ;
- (3)  $T$  is said to be locally compact if  $\varphi(f)T$  and  $T\varphi(f)$  are in  $K(H)$  for all  $f \in C_0(\Delta)$ , where  $K(H)$  is defined to be the operator norm closure of all finite rank operators on the Hilbert module  $H$ .

Let  $H$  be a (countably generated)  $\Gamma$ -Hilbert module over  $B$  and let  $\varphi$  be a  $*$ -homomorphism from  $C_0(\Delta)$  to  $B(H)$  which is covariant in the sense that  $\varphi(\gamma f)h = (\gamma(\varphi(f)))\gamma^{-1}h$  for all  $\gamma \in \Gamma$ ,  $f \in C_0(\Delta)$  and  $h \in H$ . Such a triple  $(C_0(\Delta), \Gamma, \varphi)$  is called a covariant system.

**Definition 3.2** We define the covariant system  $(C_0(\Delta), \Gamma, \varphi)$  to be admissible if

- (1) the  $\Gamma$ -action on  $\Delta$  is proper and cocompact;
- (2) there exist a  $\Gamma$ -Hilbert space  $H_\Delta$  and a separable and infinite dimensional  $\Gamma$ -Hilbert space  $E$  such that
  - (a)  $H$  is isomorphic to  $H_\Delta \otimes E \otimes B$  as  $\Gamma$ -Hilbert modules over  $B$ ;
  - (b)  $\varphi = \varphi_0 \otimes I$  for some  $\Gamma$ -equivariant  $*$ -homomorphism  $\varphi_0$  from  $C_0(\Delta)$  to  $B(H_\Delta)$  such that  $\varphi_0(f)$  is not in  $K(H_\Delta)$  for any nonzero function  $f \in C_0(\Delta)$  and  $\varphi_0$  is nondegenerate in the sense that  $\{\varphi_0(f)H_\Delta : f \in C_0(\Delta)\}$  is dense in  $H_\Delta$ ,

- (c) for each  $x \in \Delta$ ,  $E$  is isomorphic to  $l^2(\Gamma_x) \otimes H_x$  as  $\Gamma_x$ -Hilbert spaces for some Hilbert space  $H_x$  with a trivial  $\Gamma_x$  action, where  $\Gamma_x$  is the finite isotropy subgroup of  $\Gamma$  at  $x$ .

In the above definition, the  $\Gamma_x$ -action on  $l^2(\Gamma_x)$  is regular, that is,  $(\gamma\xi)(z) = \xi(\gamma^{-1}z)$  for every  $\gamma \in \Gamma_x$ ,  $\xi \in l^2(\Gamma_x)$ , and  $z \in \Gamma_x$ ,  $B$  is the  $\Gamma$ -Hilbert module over  $B$  with the inner product  $\langle a, b \rangle = a^*b$ , and  $I$  is the identity operator on  $E \otimes B$ .

We remark that such an admissible covariant system always exists (for example we can choose  $E$  to be  $l^2(\Gamma)$  with a regular action  $\Gamma$ ). We point out that condition (2) implies that  $E$  contains all unitary representations of the finite isotropy groups and this point is important for Proposition 3.4 of this section.

**Definition 3.3** Let  $(C_0(\Delta), \Gamma, \varphi)$  be an admissible covariant system. We define  $\mathbb{C}(\Gamma, \Delta, B)$  to be the algebra of  $\Gamma$ -invariant locally compact operators in  $B(H)$  with finite propagation. The  $C^*$ -algebra  $C_r^*(\Gamma, \Delta, B)$  is the operator norm closure of  $\mathbb{C}(\Gamma, \Delta, B)$ .

The following result is essentially due to John Roe.

**Proposition 3.4** *If  $(C_0(\Delta), \Gamma, \varphi)$  is an admissible covariant system then  $C_r^*(\Gamma, \Delta, B)$  is  $*$ -isomorphic to  $(B \rtimes_r \Gamma) \otimes \mathcal{K}$ , where  $B \rtimes_r \Gamma$  is the reduced crossed product  $C^*$ -algebra and  $\mathcal{K}$  is the algebra of all compact operators on a separable and infinite dimensional Hilbert space.*

**Proof** Proposition 3.4 follows from the definitions of the admissible covariant system,  $C_r^*(\Gamma, \Delta, B)$ , and the reduced crossed product  $C^*$ -algebra. □

Next we will describe the Baum–Connes map.

Let  $H$  be a  $\Gamma$ -Hilbert module over  $B$ , let  $F$  be an operator in  $B(H)$ , let  $\varphi$  be a  $*$ -homomorphism from  $C_0(\Delta)$  to  $B(H)$  such that  $F$  is  $\Gamma$ -equivariant, that is,  $\gamma F \gamma^{-1} = F$  for all  $\gamma \in \Gamma$ ,  $\varphi(f)F - F\varphi(f)$ ,  $\varphi(f)(FF^* - I)$  and  $\varphi(f)(F^*F - I)$  are in  $K(H)$  for all  $f \in C_0(\Delta)$ .

We denote the group  $KK_0^\Gamma(C_0(\Delta), B)$  by  $KK_0^\Gamma(\Delta, B)$ .  $(H, \varphi, F)$  gives a  $KK$ -cycle representing a class in  $KK_0^\Gamma(\Delta, B)$ . It is not difficult to prove that every class in  $KK_0^\Gamma(\Delta, B)$  is equivalent to  $(H, \varphi, F)$  such that  $(C_0(\Delta), \Gamma, \varphi)$  is an admissible covariant system. This can be seen as follows. We define a new  $KK$ -group  $\tilde{K}_*^\Gamma(\Delta, B)$  using  $KK$ -cycles  $(H, \varphi, F)$  such that  $(C_0(\Delta), \Gamma, \varphi)$  is an admissible covariant system. By the proof of [10, Proposition 5.5] by Kasparov and Skandalis, we can show that

there exists a  $\Gamma$ -Hilbert space  $H_\Delta$  satisfying the conditions of Definition 3.2 such that  $H \oplus (H_\Delta \otimes l^2(\Gamma) \otimes B)$  is isomorphic to  $H_\Delta \otimes l^2(\Gamma) \otimes B$  as  $\Gamma$ -Hilbert modules over  $B$ . Using this stabilization result, we can prove that the natural homomorphism from  $\widetilde{KK}_*^\Gamma(\Delta, B)$  to  $KK_0^\Gamma(\Delta, B)$  is an isomorphism.

For any  $\epsilon > 0$ , let  $\{U_i\}_{i \in I}$  be a locally finite and  $\Gamma$ -equivariant open cover of  $\Delta$  satisfying  $\text{diameter}(U_i) < \epsilon$  for all  $i$ . Let  $\{\psi_i\}$  be a  $\Gamma$ -equivariant partition of unity subordinate to  $\{U_i\}_{i \in I}$ . We define

$$F_\epsilon = \sum_{i \in I} \varphi(\sqrt{\psi_i}) F \varphi(\sqrt{\psi_i}),$$

where the convergence is in the strict topology.

Note that  $F_\epsilon$  has propagation  $\epsilon$  and  $(H, \varphi, F_\epsilon)$  is equivalent to  $(H, \varphi, F)$  in  $KK_0^\Gamma(\Delta, B)$ . Also  $F_\epsilon$  is a multiplier of  $C_r^*(\Gamma, \Delta, B)$ , and is invertible modulo  $C_r^*(\Gamma, \Delta, B)$ .

Let  $\partial$  be the boundary map

$$K_1(M(C_r^*(\Gamma, \Delta, B))/C_r^*(\Gamma, \Delta, B)) \rightarrow K_0(C_r^*(\Gamma, \Delta, B))$$

in  $K$ -theory, where  $M(C_r^*(\Gamma, \Delta, H))$  is the multiplier algebra of  $C_r^*(\Gamma, \Delta, H)$ . We can define the Baum-Connes map

$$\mu: KK_0^\Gamma(\Delta, B) \rightarrow K_0(C_r^*(\Gamma, \Delta, B)) \cong K_0(B \rtimes_r \Gamma)$$

by

$$\mu([(H, \varphi, F)]) = \partial([F_\epsilon]).$$

More precisely the Baum-Connes map can be implemented as follows.

Let  $p_\epsilon$  be the idempotent

$$\begin{pmatrix} F_\epsilon F_\epsilon^* + (I - F_\epsilon F_\epsilon^*) F_\epsilon F_\epsilon^* & F_\epsilon (I - F_\epsilon^* F_\epsilon) + (I - F_\epsilon F_\epsilon^*) F_\epsilon (I - F_\epsilon^* F_\epsilon) \\ (I - F_\epsilon^* F_\epsilon) F_\epsilon^* & (I - F_\epsilon^* F_\epsilon)^2 \end{pmatrix}.$$

Observe that the propagation of  $p_\epsilon$  is at most  $5\epsilon$ .

Let

$$p_0 = \begin{pmatrix} I & 0 \\ 0 & 0 \end{pmatrix}.$$

We have

$$\mu([(H, \varphi, F)]) = [p_\epsilon] - [p_0].$$

Similarly we can define the Baum-Connes map

$$\mu: KK_1^\Gamma(\Delta, B) \rightarrow K_1(C_r^*(\Gamma, \Delta, B)) \cong K_1(B \rtimes_r \Gamma).$$

This induces the Baum–Connes map

$$\mu: KK_*^\Gamma(\mathcal{E}\Gamma, B) \rightarrow K_*(B \rtimes_r \Gamma),$$

where  $KK_*^\Gamma(\mathcal{E}\Gamma, B)$  is defined to be the inductive limit of  $KK_*^\Gamma(\Delta, B)$  over all  $\Gamma$ -invariant and cocompact subspaces  $\Delta$  of  $\mathcal{E}\Gamma$  which are finite dimensional simplicial polyhedra. Here we choose a model of  $\mathcal{E}\Gamma$  so that  $\mathcal{E}\Gamma$  is equal to the union of  $\Gamma$ -invariant and cocompact subspaces  $\Delta$  of  $\mathcal{E}\Gamma$  which are finite dimensional simplicial polyhedra (the existence of such model follows from the construction of  $\mathcal{E}\Gamma$  in the proof of [2, Proposition 1.7] by Baum, Connes and Higson, which is based on Milnor’s join construction).

Let  $\Delta$  be a locally compact and finite dimensional simplicial polyhedron. We endow  $\Delta$  with the simplicial metric. Let  $(C_0(\Delta), \Gamma, \varphi)$  be an admissible covariant system as before, where  $\varphi$  is a  $*$ -homomorphism from  $C_0(\Delta)$  to  $B(H)$  for some Hilbert module  $H$  over  $B$ .

**Definition 3.5**

- (1) The algebraic localization algebra  $\mathbb{C}_L(\Gamma, \Delta, B)$  is defined to be the algebra of all bounded and uniformly continuous functions  $f: [0, \infty) \rightarrow \mathbb{C}(\Gamma, \Delta, B)$  such that the propagation of  $f(t)$  goes to 0 as  $t \rightarrow \infty$ , where  $\mathbb{C}(\Gamma, \Delta, B)$  is as in Definition 3.3.
- (2) The localization algebra  $C_L^*(\Gamma, \Delta, B)$  is the norm closure of  $\mathbb{C}_L(\Gamma, \Delta, B)$  with respect to the norm

$$\|f\| = \sup_{t \in [0, \infty)} \|f(t)\|.$$

It is not difficult to prove that, up to a  $*$ -isomorphism,  $\mathbb{C}_L(\Gamma, \Delta, B)$  and  $C_L^*(\Gamma, \Delta, B)$  are independent of the choices made in Definition 3.2. The localization algebra is an equivariant analogue of the algebra introduced by Yu in [14].

Any class in  $KK_0^\Gamma(\Delta, B)$  can be represented by  $(H, \varphi, F)$  such that the covariant system  $(C_0(\Delta), \Gamma, \varphi)$  is admissible, where  $H$  is a  $\Gamma$ -Hilbert module over  $B$ ,  $F$  is an operator in  $B(H)$ ,  $\varphi$  is a  $*$ -homomorphism from  $C_0(\Delta)$  to  $B(H)$  such that  $F$  is  $\Gamma$ -equivariant, and  $\varphi(f)F - F\varphi(f)$ ,  $\varphi(f)(FF^* - I)$  and  $\varphi(f)(F^*F - I)$  are in  $K(H)$  for all  $f \in C_0(\Delta)$ .

For each natural number  $n$ , we let  $F_{\frac{1}{n}}$  be defined as above. We define an operator valued function  $F(t)$  on  $[0, \infty)$  by

$$F(t) = (t - n + 1)F_{\frac{1}{n}} + (t - n)F_{\frac{1}{n+1}}$$

for all  $t \in [n, n + 1]$ .

$F(t)$  is a multiplier of  $C_L^*(\Gamma, \Delta, B)$  and is invertible modulo  $C_L^*(\Gamma, \Delta, B)$ . We define the local Baum–Connes map

$$\mu_L: KK_0^\Gamma(\Delta, B) \rightarrow K_0(C_L^*(\Gamma, \Delta, B)),$$

by

$$\mu_L[H, \varphi, F] = \partial[F(t)],$$

where

$$\partial: K_1(M(C_L^*(\Gamma, \Delta, B))/C_L^*(\Gamma, \Delta, B)) \rightarrow K_0^*(C_L^*(\Gamma, \Delta, B)),$$

is the boundary map in  $K$ -theory and  $M(C_L^*(\Gamma, \Delta, B))$  is the multiplier algebra of  $C_L^*(\Gamma, \Delta, B)$ .

Similarly we can define the local Baum–Connes map

$$\mu_L: KK_1^\Gamma(\Delta, B) \rightarrow K_1(C_L^*(\Gamma, \Delta, B)).$$

We remark that the local Baum–Connes map is very much in the spirit of the local index theory of elliptic differential operators.

**Theorem 3.6** *Let  $B$  be a  $\Gamma$ - $C^*$ -algebra. The local Baum–Connes map  $\mu_L$  is an isomorphism from  $KK_*^\Gamma(\Delta, B)$  to  $K_*(C_L^*(\Gamma, \Delta, B))$  if  $\Delta$  is a finite dimensional simplicial polyhedron with the  $\Gamma$ -invariant simplicial metric.*

**Proof** This theorem is a consequence of the Mayer–Vietoris and five lemma argument (essentially similar to the proof of the non-equivariant analogue of Yu [14]).  $\square$

Let  $C_L^*(\Gamma, \mathcal{E}\Gamma, B)$  be the  $C^*$ -algebra inductive limit of  $C_L^*(\Gamma, \Delta, B)$ , where the limit is taken over all  $\Gamma$ -invariant and cocompact subspaces  $\Delta$  of  $\mathcal{E}\Gamma$  which are finite dimensional simplicial polyhedra.

The above local Baum–Connes map induces a map (still called the local Baum–Connes map)

$$\mu_L: KK_*^\Gamma(\mathcal{E}\Gamma, B) \rightarrow K_*(C_L^*(\Gamma, \mathcal{E}\Gamma, B)).$$

**Corollary 3.7** *The local Baum–Connes map  $\mu_L$  is an isomorphism from  $KK_*^\Gamma(\mathcal{E}\Gamma, B)$  to  $K_*(C_L^*(\Gamma, \mathcal{E}\Gamma, B))$ .*

Next we shall discuss the relation between the Baum–Connes map and an evaluation map. This connection will be useful in the proof of the main theorem in [Section 5](#).

Let  $e$  be the evaluation map

$$C_L^*(\Gamma, \Delta, B) \rightarrow C_r^*(\Gamma, \Delta, B) \cong (B \rtimes_r \Gamma) \otimes \mathcal{K}$$

defined by

$$e(f) = f(0)$$

for all  $f \in C_L^*(\Gamma, \Delta, B)$ .

The above evaluation maps induce an evaluation homomorphism (still denoted by  $e$ )

$$C_L^*(\Gamma, \mathcal{E}\Gamma, B) \rightarrow (B \rtimes_r \Gamma) \otimes \mathcal{K}.$$

We have

$$\mu = e_* \circ \mu_L.$$

## 4 The Bott map

In this section, we introduce a Bott map for  $K$ -groups. The Bott map will play an essential role in the proof of the main result of this paper.

Let  $X$  be a Banach space with (rational) Property (H). Let  $\Gamma$  be a countable group with a left invariant proper length metric. Let  $h: \Gamma \rightarrow X$  be a coarse embedding. Without loss of generality we can assume that the image of  $h$  is contained in  $V$ , where  $V$  is as in the definition of the (rational) Property (H).

For each  $v \in V, w \in W$ , and  $\gamma \in \Gamma$ , we define bounded functions  $\xi_{v,\gamma}$  and  $\eta_{v,w,\gamma}$  on  $\Gamma$  by

$$\begin{aligned} \xi_{v,\gamma}(x) &= \|\phi(v + h(x) - h(x\gamma))\| \\ &= \|v + h(x) - h(x\gamma)\|, \\ \eta_{v,w,\gamma}(x) &= \langle \phi(v + h(x) - h(x\gamma)), w \rangle \end{aligned}$$

for all  $x \in \Gamma$ , where  $\phi$  is defined as in Section 2. The boundedness of  $\xi_{v,\gamma}$  and  $\eta_{v,w,\gamma}$  follows from the fact that  $h$  is a coarse embedding.

Let  $c_0(\Gamma)$  be the algebra of all functions on  $\Gamma$  vanishing at infinity. We define the  $\Gamma$  action on  $l^\infty(\Gamma)$  by  $(\gamma(\eta))(x) = \eta(x\gamma)$  for each  $\eta \in l^\infty(\Gamma), \gamma \in \Gamma, x \in \Gamma$ . Let  $Y$  be the spectrum of the unital commutative  $\Gamma$ -invariant  $C^*$ -subalgebra of  $l^\infty(\Gamma)$  generated by  $c_0(\Gamma)$ , all constant functions on  $\Gamma$ , all  $\xi_{v,\gamma}$  and  $\eta_{v,w,\gamma}$ , and their translations by group elements of  $\Gamma$ . Notice that  $Y$  is a separable compact space and is a quotient space of  $\beta\Gamma$ , the Stone-Ćech compactification of  $\Gamma$ .

Let  $\mathcal{A}(X)$  be the  $C^*$ -algebra associated to  $X$  (as defined in Section 2). If  $A$  is a  $\Gamma$ - $C^*$ -algebra, then  $\Gamma$  acts on the  $C^*$ -algebra

$$C(Y) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A \subseteq l^\infty(\Gamma) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$$

by

$$\gamma(\eta(x) \widehat{\otimes} f((s, \phi(v - v_0)))) \widehat{\otimes} a = \eta(x\gamma) \widehat{\otimes} f((s, \phi(v - v_0 + h(x) - h(x\gamma)))) \widehat{\otimes} \gamma(a)$$

for each  $\gamma \in \Gamma, \eta \in C(Y) \subseteq l^\infty(\Gamma), x \in \Gamma, s \in \mathbb{R}, f \in C_0(\mathbb{R}), v \in V, v_0 \in V$  and  $a \in A$ , where  $f((s, \phi(v - v_0)))$  is as in the definition of  $\mathcal{A}(X)$ .

The above  $\Gamma$  action on  $C(Y) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$  has its origin in work by Yu [15] and Skandalis, Tu and Yu [13]. We can see that the  $\Gamma$  action on  $C(Y) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$  is well defined as follows. Recall that, for any net  $\{w_i\}_{i \in I}$  in a Hilbert space, if  $w_i$  converges to a vector  $w$  of the Hilbert space in weak topology and  $\|w_i\|$  converges to  $\|w\|$ , then  $w_i$  converges to  $w$  in norm. Using this fact and the definition of  $Y$ , we know that  $\phi(v - v_0 + h(x) - h(x\gamma))$  can be extended to a norm continuous function on  $Y$  with values in  $H$ . It follows that  $f((s, \phi(v - v_0 + h(x) - h(x\gamma))))$  can be identified with a norm continuous function on  $Y$  with values in  $\mathcal{A}(X) \widehat{\otimes} A$ . This, together with the compactness of  $Y$ , implies that  $\gamma(\eta(x) \widehat{\otimes} f((s, \phi(v - v_0)))) \widehat{\otimes} a$  is an element in  $C(Y) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$ . Let  $\mathcal{D}$  be the subalgebra of  $C(Y) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$  consisting of all linear combinations of products of elements of the type  $\eta(x) \widehat{\otimes} f((s, \phi(v - v_0))) \widehat{\otimes} a$ . Note that, by the definition of  $\mathcal{A}(X)$ ,  $\mathcal{D}$  is dense in the  $C^*$ -algebra  $C(Y) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$ . By extending linearly and multiplicatively, for each  $d \in \mathcal{D}$ , we can define  $\gamma(d)$  as an element of  $C(Y) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$ . By the definition of  $Y$ ,  $\Gamma$  is a dense subset of  $Y$ . This, together with the definition of  $\gamma(d)$ , implies that  $\|\gamma(d)\| = \|d\|$  for each  $d \in \mathcal{D}$ . Finally the  $\Gamma$  action extends continuously to  $C(Y) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$ .

Let  $Z$  be the space of all probability measures on  $Y$  with the weak topology. Note that  $Z$  is a convex and compact topological space with the weak\* topology. The idea of using the space of probability measures is due to Nigel Higson [7]. The action of  $\Gamma$  on  $C(Y) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$  induces an action of  $\Gamma$  on  $C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$  by

$$\begin{aligned} \gamma(u(\mu) \widehat{\otimes} f((s, \phi(v - v_0)))) \widehat{\otimes} a = \\ u(\gamma(\mu)) \widehat{\otimes} f((s, \phi(v - v_0 + \int_Y (h(y) - h(y\gamma)) d\mu))) \widehat{\otimes} \gamma(a) \end{aligned}$$

for each  $\gamma \in \Gamma, u \in C(Z), \mu \in Z, f \in C_0(\mathbb{R}), s \in \mathbb{R}, v \in V, v_0 \in V$  and  $a \in A$ , where the  $\Gamma$  action on  $Z$  is induced by the  $\Gamma$  action on  $Y$ . The assumption that  $h$  is a coarse embedding implies that  $C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$  is a  $\Gamma$ -proper  $C^*$ -algebra. This can be seen as follows: let  $\mathcal{C}(X)$  be the abelian  $C^*$ -subalgebra of  $C(Z) \widehat{\otimes} \mathcal{A}(X)$  generated by all elements  $b \widehat{\otimes} g(s^2 + \|v - v_0\|^2)$ , where  $b \in C(Z), g \in C_0(\mathbb{R})$  and  $v_0 \in V$ .  $\mathcal{C}(X)$

is isomorphic to a commutative  $C^*$ -algebra  $C_0(T)$  for some locally compact space  $T$ . Notice that  $T$  is a proper  $\Gamma$ -space (as a consequence of the fact that  $h$  is a coarse embedding),  $\mathcal{C}(X)$  is in the center of the multiplier algebra of  $C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$ , and  $\mathcal{C}(X)(C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A)$  is dense in  $C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A$ .

For each  $f \in \mathcal{S}$ , let  $f_t \in \mathcal{A}(X)$  be defined by

$$f_t((s, v)) = f(t^{-1}(s, \phi(v)))$$

for all  $s \in \mathbb{R}, v \in V$ .

We define the Bott map

$$\beta: K_*((C(Z) \widehat{\otimes} \mathcal{S} \widehat{\otimes} A) \rtimes_r \Gamma) \rightarrow K_*((C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A) \rtimes_r \Gamma)$$

to be the homomorphism induced by the asymptotic morphism

$$\beta_t((u \widehat{\otimes} f \widehat{\otimes} a)\gamma) = (u \widehat{\otimes} f_t \widehat{\otimes} a)\gamma$$

from  $(C(Z) \widehat{\otimes} \mathcal{S} \widehat{\otimes} A) \rtimes_r \Gamma$  to  $(C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A) \rtimes_r \Gamma$ , for  $t \in [1, \infty)$ ,  $u \in C(Z)$ ,  $f \in \mathcal{S}$ ,  $a \in A$  and  $\gamma \in \Gamma$ .

The fact that  $\beta_t$  is an asymptotic morphism follows from the identity  $\phi(cv) = |c|\phi(v)$  for any scalar  $c$  and the assumption that the restriction of  $\phi$  to the sphere of  $V$  is uniformly continuous.

Let  $\Delta$  be a locally compact metric space with a proper and cocompact isometric action of  $\Gamma$ . We define an asymptotic morphism

$$\beta_t: C_L^*(\Gamma, \Delta, C(Z) \widehat{\otimes} \mathcal{S} \widehat{\otimes} A) \rightarrow C_L^*(\Gamma, \Delta, C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A)$$

induced by the homomorphism from  $\mathcal{S}$  to  $\mathcal{A}(X)$ :  $f \rightarrow f_t$ , where

$$f_t((s, v)) = f(t^{-1}(s, \phi(v)))$$

for all  $f \in \mathcal{S}$  and  $s \in \mathbb{R}, v \in V$ .

More precisely  $\beta_t$  is defined as follows. Let  $(C_0(\Delta), \Gamma, \varphi)$  be an admissible covariant system, where  $\varphi$  is a  $*$ -homomorphism from  $C_0(\Delta)$  to  $B(H)$  for some Hilbert module  $H$  over  $C(Z) \widehat{\otimes} \mathcal{S} \widehat{\otimes} A$ . By the definition of admissible covariant system, we have

$$K(H) \cong C(Z) \widehat{\otimes} \mathcal{S} \widehat{\otimes} A \widehat{\otimes} \mathcal{K},$$

where  $K(H)$  is the operator norm closure of all finite rank operators on the Hilbert module  $H$  and  $\mathcal{K}$  is the graded  $C^*$ -algebra of all compact operators on a graded separable and infinite dimensional Hilbert space. Let  $\beta'_t$  be the asymptotic morphism from  $C(Z) \widehat{\otimes} \mathcal{S} \widehat{\otimes} A \widehat{\otimes} \mathcal{K}$  to  $C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A \widehat{\otimes} \mathcal{K}$  induced by the homomorphism from  $\mathcal{S}$  to  $\mathcal{A}(X)$ :  $f \rightarrow f_t$ , where  $f_t$  is defined as in the previous paragraph.

Let  $c$  be a  $\Gamma$  cut-off function on  $\Delta$ , that is,  $c$  is a compactly supported non-negative continuous function on  $\Delta$  satisfying

$$\sum_{\gamma \in \Gamma} c(\gamma^{-1}x) = 1$$

for all  $x \in \Delta$ . The existence of such cut-off function follows from properness and cocompactness of the  $\Gamma$  action on  $\Delta$ .

For each  $T \in \mathbb{C}_L(\Gamma, \Delta, C(Z) \hat{\otimes} \mathcal{S} \hat{\otimes} A)$ , we define

$$\beta_t(T) = \sum_{\gamma \in \Gamma} \beta'_t(\varphi(\gamma(c)))\gamma T \gamma^{-1}$$

in  $\mathbb{C}_L(\Gamma, \Delta, C(Z) \hat{\otimes} \mathcal{A}(X) \hat{\otimes} A)$ , where  $\beta'_t$  is the asymptotic morphism defined above,  $(\gamma(c))(x) = c(\gamma^{-1}x)$  for all  $x \in \Delta$ , and the sum converges in the strong operator topology because  $T$  has finite propagation.

Note that  $\beta_t(T)$  is  $\Gamma$ -invariant and is an element of  $\mathbb{C}_L(\Gamma, \Delta, C(Z) \hat{\otimes} \mathcal{A}(X) \hat{\otimes} A)$ . It is not difficult to see that  $\beta_t$  can be extended to an asymptotic morphism

$$\beta_t: C_L^*(\Gamma, \Delta, C(Z) \hat{\otimes} \mathcal{S} \hat{\otimes} A) \rightarrow C_L^*(\Gamma, \Delta, C(Z) \hat{\otimes} \mathcal{A}(X) \hat{\otimes} A).$$

By [Corollary 3.7](#), the above asymptotic morphism induces a homomorphism

$$\beta: KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} \mathcal{S} \hat{\otimes} A) \rightarrow KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} \mathcal{A}(X) \hat{\otimes} A),$$

called the *Bott map*.

**Proposition 4.1** *The Bott map*

$$\beta: KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} \mathcal{S} \hat{\otimes} A) \rightarrow KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} \mathcal{A}(X) \hat{\otimes} A)$$

is injective, where  $\mathcal{E}\Gamma$  is the universal space for proper  $\Gamma$ -actions.

**Proof** Let  $\mathcal{A}^\infty(X, A)$  be as defined in [Section 2](#). For any fixed  $v_0 \in V_k \subseteq V$ , we note that the translation

$$[(f_1(s, v_1), \dots, f_{k-1}(s, v_{k-1}), f_k(s, v_k), f_{k+1}(s, v_{k+1}), \dots)] \\ \rightarrow [(0, \dots, 0, f_k(s, v_k + v_0), f_{k+1}(s, v_{k+1} + v_0), \dots)],$$

by  $v_0$  on  $\mathcal{A}^\infty(X, A)$ , is well defined for all  $[(f_1, \dots, f_{k-1}, f_k, f_{k+1} \dots)] \in \mathcal{A}^\infty(X, A)$ .

By the uniform equicontinuity condition in the definition of  $\mathcal{A}^\infty(X, A)$ , this translation operator is norm-continuous in  $v_0$ . Hence a  $\Gamma$  action on  $C(Z) \hat{\otimes} \mathcal{A}^\infty(X, A)$  can be defined exactly in the same way as the  $\Gamma$  action on  $C(Z) \hat{\otimes} \mathcal{A}(X) \hat{\otimes} A$ .

Now we can define the Bott map

$$\beta^\infty: KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \widehat{\otimes} S^\infty(A)) \rightarrow KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \widehat{\otimes} \mathcal{A}^\infty(X, A)),$$

in a way similar to the definition of the Bott map

$$\beta: KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \widehat{\otimes} S \widehat{\otimes} A) \rightarrow KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A),$$

where  $S^\infty(A)$  is defined in Section 2.

The Bott map  $\beta^\infty$  is induced by the asymptotic homomorphism

$$[u \widehat{\otimes} (f_1 \widehat{\otimes} b_1, \dots, f_k \widehat{\otimes} b_k, \dots)] \rightarrow [u \widehat{\otimes} ((f_1)_t \widehat{\otimes} b_1, \dots, (f_k)_t \widehat{\otimes} b_k, \dots)],$$

from  $C(Z) \widehat{\otimes} S^\infty(A)$  to  $C(Z) \widehat{\otimes} \mathcal{A}^\infty(X, A)$ , where  $u \in C(Z)$ ,  $f_k \in S$ ,  $b_k \in A$  and  $(f_k)_t(s, v_k) = f_k(t^{-1}(s, \phi(v_k)))$  for all  $(s, v_k) \in \mathbb{R} \times V_k$ .

We claim that the Bott map

$$\beta^\infty: KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \widehat{\otimes} S^\infty(A)) \rightarrow KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \widehat{\otimes} \mathcal{A}^\infty(X, A))$$

is an isomorphism.

This claim follows from the standard Mayer–Vietoris and five lemma argument, Corollary 2.8, and the fact that, for any finite subgroup  $H$  of  $\Gamma$ ,  $Z$  is  $H$ -equivariantly homotopy equivalent to a point  $\mu_0 \in Z$  fixed by  $H$  (using the linear homotopy). The point  $\mu_0$  can be obtained by averaging the  $H$ -orbit of a point in  $Z$  using the assumption that  $H$  is a finite group and the fact that  $Z$  is a convex and compact topological space. Then

$$g[u(\mu) \widehat{\otimes} (f_k((s, \phi(v_k - v_0^k))) \widehat{\otimes} a_k)]$$

evaluated at  $\mu = \mu_0$  is equal to

$$[u(\mu) \widehat{\otimes} (f_k((s, \phi(v_k - v_0^k))) \widehat{\otimes} g(a_k))]$$

evaluated at  $\mu = \mu_0$  for all  $g \in H$ ,  $u \in C(Z)$ ,  $f_k \in S$ ,  $v_0^k \in V_k$ ,  $s \in \mathbb{R}$ ,  $v_k \in V_k$ ,  $a_k \in A$  and  $[(f_k \widehat{\otimes} a_k)] \in S^\infty(A)$ . The last equation follows from the definition of the  $\Gamma$  action on  $C(Z) \widehat{\otimes} \mathcal{A}^\infty(X, A)$ .

We now consider the commutative diagram

$$\begin{CD} KK_*^\Gamma(\mathcal{E}\Gamma, S \widehat{\otimes} A) @>\beta>> KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \widehat{\otimes} \mathcal{A}(X) \widehat{\otimes} A) \\ @V\sigma VV @VV\sigma' V \\ KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \widehat{\otimes} S^\infty(A)) @>\beta^\infty>> KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \widehat{\otimes} \mathcal{A}^\infty(X, A)) \end{CD}$$

where  $\sigma$  is induced by the homomorphism  $\mathcal{S} \hat{\otimes} A \rightarrow C(Z) \hat{\otimes} \mathcal{S}^\infty(A)$  mapping each element  $f$  to  $1 \hat{\otimes} [(f \hat{\otimes} p_0)]$  (here  $1$  is the constant  $1$  function on  $Z$ ,  $[(f \hat{\otimes} p_0)]$  is the element represented by the constant sequence consisting of  $f \hat{\otimes} p_0$ , and  $p_0$  is a rank one projection of grading degree  $0$  in  $\mathcal{K}$ ) and  $\sigma'$  is induced by the homomorphism from  $C(Z) \hat{\otimes} \mathcal{A}(X) \hat{\otimes} A$  to  $C(Z) \hat{\otimes} \mathcal{A}^\infty(X, A)$  which maps each element  $u \hat{\otimes} f$  to the element represented by the sequence  $u \hat{\otimes} (f_k \hat{\otimes} p_0)$  (here  $u \in C(Z)$ ,  $f \in \mathcal{A}(X) \hat{\otimes} A$ , and  $f_k$  is the restriction of  $f$  to  $V_k$ ).

We observe that  $\sigma$  is injective. This can be seen as follows. Let  $\tilde{\sigma}$  be the homomorphism

$$KK_*^\Gamma(\mathcal{E}\Gamma, \mathcal{S} \hat{\otimes} A) \rightarrow KK_*^\Gamma(\mathcal{E}\Gamma, \mathcal{S}^\infty(C(Z) \hat{\otimes} A))$$

obtained by composing  $\sigma$  with the homomorphism from  $KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} \mathcal{S}^\infty(A))$  to  $KK_*^\Gamma(\mathcal{E}\Gamma, \mathcal{S}^\infty(C(Z) \hat{\otimes} A))$  that is induced by the inclusion homomorphism from  $C(Z) \hat{\otimes} \mathcal{S}^\infty(A)$  to  $\mathcal{S}^\infty(C(Z) \hat{\otimes} A)$ . It suffices to prove that  $\tilde{\sigma}$  is injective. There exists a natural homomorphism

$$\prod KK_{*+1}^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} A) \rightarrow KK_*^\Gamma(\mathcal{E}\Gamma, \mathcal{S}^\infty(C(Z) \hat{\otimes} A)),$$

where  $\prod KK_{*+1}^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} A)$  is defined to be the inductive limit of the product  $\prod KK_{*+1}^\Gamma(\Delta, C(Z) \hat{\otimes} A)$  over all  $\Gamma$ -cocompact subsets  $\Delta$  of  $\mathcal{E}\Gamma$ . This homomorphism induces a homomorphism (denoted by  $\tau$ )

$$\left( \prod KK_{*+1}^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} A) \right) / \left( \bigoplus KK_{*+1}^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} A) \right) \longrightarrow KK_*^\Gamma(\mathcal{E}\Gamma, \mathcal{S}^\infty(C(Z) \hat{\otimes} A)).$$

**Proposition 2.6**, together with a standard Mayer–Vietoris and five lemma argument, implies that  $\tau$  is an isomorphism. There is also a suspension isomorphism (denoted by  $\theta$ ) from  $KK_*^\Gamma(\mathcal{E}\Gamma, \mathcal{S} \hat{\otimes} A)$  to  $KK_{*+1}^\Gamma(\mathcal{E}\Gamma, A)$ . Let  $\zeta$  be the homomorphism

$$KK_{*+1}^\Gamma(\mathcal{E}\Gamma, A) \rightarrow \left( \prod KK_{*+1}^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} A) \right) / \left( \bigoplus KK_{*+1}^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} A) \right)$$

which is obtained as the composition of the homomorphism from  $KK_{*+1}^\Gamma(\mathcal{E}\Gamma, A)$  to  $KK_{*+1}^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} A)$  induced by the inclusion map from  $A$  to  $C(Z) \hat{\otimes} A$  with the group homomorphism mapping each element  $z \in KK_{*+1}^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} A)$  to the element in  $\left( \prod KK_{*+1}^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} A) \right) / \left( \bigoplus KK_{*+1}^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} A) \right)$  represented by the constant sequence consisting of  $z$ . By contractibility of  $Z$ , we know that  $\zeta$  is injective. We have

$$\tilde{\sigma} = \tau \circ \zeta \circ \theta.$$

Now the injectivity of  $\tilde{\sigma}$  follows from the injectivity of  $\zeta$  and the fact that  $\tau$  and  $\theta$  are isomorphisms.

Finally [Proposition 4.1](#) follows from the injectivity of  $\sigma$ , the claim that  $\beta^\infty$  is an isomorphism, and the commutative diagram in this proof.  $\square$

## 5 Proof of the main result

In this section, we give the proof of [Theorem 1.2](#), the main result of this paper. The proof of [Theorem 1.3](#) is essentially similar.

**Proof** Let  $A$  be any  $\Gamma$ - $C^*$ -algebra. We consider the commutative diagram

$$\begin{array}{ccc}
 KK_*^\Gamma(\mathcal{E}\Gamma, \mathcal{S} \hat{\otimes} A) & \xrightarrow{\mu_1} & K_*((\mathcal{S} \hat{\otimes} A) \rtimes_r \Gamma) \\
 \beta \downarrow & & \downarrow \beta' \\
 KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} \mathcal{A}(X) \hat{\otimes} A) & \xrightarrow{\mu_2} & K_*((C(Z) \hat{\otimes} \mathcal{A}(X) \hat{\otimes} A) \rtimes_r \Gamma)
 \end{array}$$

where  $\mu_1$  and  $\mu_2$  are the Baum–Connes assembly maps,  $\beta$  and  $\beta'$  are respectively the homomorphisms induced by the inclusion  $\mathbb{C} \rightarrow C(Z)$  composed with the Bott maps defined in [Section 4](#). The commutativity of the above diagram follows from the definitions of the Bott maps and the relation between the Baum–Connes map and the evaluation map (compare with the discussion after [Corollary 3.7](#) at the end of [Section 3](#)).

Notice that the inclusion map  $\mathbb{C} \rightarrow C(Z)$  induces an isomorphism

$$KK_*^\Gamma(\mathcal{E}\Gamma, \mathcal{S} \hat{\otimes} A) \rightarrow KK_*^\Gamma(\mathcal{E}\Gamma, C(Z) \hat{\otimes} \mathcal{S} \hat{\otimes} A).$$

This, together with [Proposition 4.1](#), implies that the map  $\beta$  is injective. The fact that  $C(Z) \hat{\otimes} \mathcal{A}(X) \hat{\otimes} A$  is a  $\Gamma$ -proper  $C^*$ -algebra implies that  $\mu_2$  is an isomorphism (it can be seen by the Mayer–Vietoris and five lemma argument; see Guentner–Higson–Trout [\[6\]](#)). The above facts, together with commutativity of the above diagram, imply that  $\mu_1$  is injective. It follows that the Baum–Connes assembly map  $\mu$  in [Theorem 1.2](#) is injective.  $\square$

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Received: 21 February 2010

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Revised: 30 March 2011