

Towards topological Hochschild homology of Johnson–Wilson spectra

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We present computations in Hochschild homology that lead to results on the $K(i)$ -local behaviour of $\mathrm{THH}(E(n))$ for all $n \geq 2$ and $0 \leq i \leq n$, where $E(n)$ is the Johnson–Wilson spectrum at an odd prime. This permits a computation of $K(i)_* \mathrm{THH}(E(n))$ under the assumption that $E(n)$ is an E_3 -ring spectrum. We offer a complete description of $\mathrm{THH}(E(2))$ as an $E(2)$ -module in the form of a splitting into chromatic localizations of $E(2)$, under the assumption that $E(2)$ carries an E_∞ -structure. If $E(2)$ admits an E_3 -structure, we obtain a similar splitting of the cofiber of the unit map $E(2) \rightarrow \mathrm{THH}(E(2))$.

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1 Introduction

The first Johnson–Wilson spectrum $E(1)$ at a prime p is the Adams summand of p -local periodic complex topological K -theory $KU_{(p)}$. McClure and Staffeldt showed that a p -completed connective version of $E(1)$ is an E_∞ -ring spectrum [18, Section 9] and Baker and Richter [4, Theorem 6.2] show that $E(1)$ carries a unique E_∞ -structure. Thus $\mathrm{THH}(E(1))$ is a commutative $E(1)$ -algebra spectrum. McClure and Staffeldt show that the unit map $E(1)_p \rightarrow \mathrm{THH}(E(1)_p)$ is a $K(1)$ -local equivalence, hence its cofiber $\overline{\mathrm{THH}}(E(1)_p)$ is a rational spectrum. It is easy to calculate the rational homology of $\mathrm{THH}(E(1)_p)$ as

$$H\mathbb{Q}_* \mathrm{THH}(E(1)_p) \cong \mathbb{Q}[v_1^{\pm 1}] \otimes_{\mathbb{Q}} \Lambda_{\mathbb{Q}}(dv_1)$$

using the Bökstedt spectral sequence with E^2 -term

$$E_{*,*}^2 = \mathrm{HH}_{*,*}^{\mathbb{Q}}(\mathbb{Q}[v_1^{\pm 1}]).$$

There is a map

$$\Sigma^{2p-1} E(1)_p \rightarrow \mathrm{THH}(E(1)_p) \rightarrow \overline{\mathrm{THH}}(E(1)_p)$$

that factors through $\Sigma^{2p-1} E(1)_{\mathbb{Q}} \rightarrow \overline{\text{THH}}(E(1)_p)$ since $\overline{\text{THH}}(E(1)_p)$ is rational, and that is defined such that the latter map is an equivalence detecting the $H\mathbb{Q}_* E(1)$ -summand generated by dv_1 . Since the unit map $E(1)_p \rightarrow \text{THH}(E(1)_p)$ splits, this yields a splitting [18, Theorem 8.1]

$$\text{THH}(E(1)_p) \simeq E(1)_p \vee \Sigma^{2p-1} E(1)_{\mathbb{Q}}$$

as $E(1)_p$ -modules. This computation was also carried out for $KU_{(p)}$ by Ausoni [3], and pushed further to provide formulas for $\text{THH}(KU)$ as a commutative KU -algebra by Stonek [27].

In this paper, we consider the higher Johnson–Wilson spectrum $E(n)$ with coefficient ring

$$E(n)_* = \mathbb{Z}_{(p)}[v_1, \dots, v_{n-1}, v_n, v_n^{-1}]$$

for an arbitrary value of $n \geq 1$ and p an odd prime. Our main motivation is to investigate whether the spectrum $\text{THH}(E(n))$ also splits into copies of $E(n)$ and its lower chromatic localizations, generalizing McClure and Staffeldt’s intriguing transchromatic result.

Let $K(i)$ be the i^{th} Morava K -theory at an odd prime. As a first step, we compute the Hochschild homology $\text{HH}_*^{K(i)*}(K(i)_* E(n))$ of $K(i)_* E(n)$ for $0 \leq i \leq n$; see Theorem 3.4. We shy away from the prime 2 because Morava K -theory is not homotopy commutative at the prime 2. Theorem 3.4 yields a computation of $K(i)_* \text{THH}(E(n))$ under the modest assumption that $E(n)$ admits an E_3 -structure.

We then focus on $E(2)$, and show in Theorem 5.4 that, under the same commutativity assumption, $\text{THH}(E(2))$ sits in a cofiber sequence

$$E(2) \rightarrow \text{THH}(E(2)) \rightarrow \Sigma^{2p-1} L_1 E(2) \vee \Sigma^{2p^2-1} E(2)_{\mathbb{Q}} \vee \Sigma^{2p^2+2p-2} E(2)_{\mathbb{Q}},$$

where $L_1 E(2)$ denotes the Bousfield localization of $E(2)$ with respect to $E(1)$. If the unit $E(2) \rightarrow \text{THH}(E(2))$ splits, we then get a decomposition of $\text{THH}(E(2))$ into four summands, a higher analogue of McClure and Staffeldt’s formula for $\text{THH}(E(1))$.

Remark 1.1 To study $\text{THH}(E(n))$ by means of the Bökstedt spectral sequence, we need sufficient commutativity of $E(n)$. Here we summarize what is known about multiplicative structures on $E(n)$ and related spectra. Basterra and Mandell [7] showed that the Brown–Peterson spectrum BP admits an E_4 -structure. The Johnson–Wilson spectra $E(n)$ are built out of the $\text{BP}\langle n \rangle = \text{BP}/(v_i \mid i \geq n + 1)$ by inverting v_n . In

[15, Theorem 1.1.2], Tyler Lawson shows that the Brown–Peterson spectrum BP and the spectra $BP\langle n \rangle$ for $n \geq 4$ at the prime 2 do not possess an E_{12} –structure. Andrew Senger [25, Theorem 1.2] extends Lawson’s result to odd primes p , and shows that BP and the $BP\langle n \rangle$ (for $n \geq 4$) do not have an $E_{2(p^2+2)}$ –structure. In particular, the $BP\langle n \rangle$ are not E_∞ –ring spectra at any prime for $n \geq 4$. Hence, if $E(n)$ actually possesses an E_∞ –structure for $n \geq 4$, then this structure does not come from one on $BP\langle n \rangle$. Richter [20, Proposition 8.2] proves that $E(n)$ at a prime p possesses at least a $(2p-1)$ –stage structure. It is unclear how such a structure relates to the E_n –hierarchy, but Barwick conjectures [5, page 1948] that a $(2p-1)$ –stage structure corresponds to an A_{2p}^{2p-1} –structure which in turn is a filtration piece of an E_{2p-1} –structure.

At the prime 2, Lawson and Naumann [16] show that there is an E_∞ –model of $BP\langle 2 \rangle$ and Hill and Lawson [13] prove that $BP\langle 2 \rangle$ at the prime 3 possesses a model as an E_∞ –ring spectrum. With Mathew, Naumann and Noel [17, Theorem A.1] this yields E_∞ –structures on the corresponding Johnson–Wilson spectra $E(2)$ at these primes. Current work of Sanath Devalapurkar aims at adapting the arguments used in these results to produce E_∞ –models of $BP\langle 2 \rangle$ or $E(2)$ at higher primes.

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2 Rationalized $E(n)$

For $n \geq 1$ the homotopy algebra of $L_{K(0)}E(n) = E(n)_\mathbb{Q}$ is $\mathbb{Q}[v_1, \dots, v_{n-1}, v_n^{\pm 1}]$ and its algebra of cooperations is

$$\begin{aligned} \pi_*(E(n)_\mathbb{Q} \wedge E(n)_\mathbb{Q}) &\cong \pi_*E(n)_\mathbb{Q} \otimes_\mathbb{Q} \pi_*E(n)_\mathbb{Q} \\ &\cong \mathbb{Q}[v_1, \dots, v_{n-1}, v_n^{\pm 1}, v'_1, \dots, v'_{n-1}, v'_n{}^{\pm 1}]. \end{aligned}$$

This implies the following result:

Lemma 2.1 *There is a unique E_∞ –ring structure on $E(n)_\mathbb{Q}$ for all $n \geq 1$.*

Proof The obstruction groups for such an E_∞ -ring structure on $E(n)_\mathbb{Q}$ are contained in the Gamma cohomology groups of $\pi_*(E(n)_\mathbb{Q} \wedge E(n)_\mathbb{Q})$ as a $\pi_*E(n)_\mathbb{Q}$ -algebra [22, Theorem 5.6]. As we work in characteristic zero, Gamma cohomology agrees with André–Quillen cohomology [23, Corollary 6.6]. The algebra

$$\mathbb{Q}[v_1, \dots, v_{n-1}, v_n^{\pm 1}, v'_1, \dots, v'_{n-1}, v_n^{\pm 1}]$$

is smooth over $\mathbb{Q}[v_1, \dots, v_{n-1}, v_n^{\pm 1}]$ and therefore André–Quillen cohomology is concentrated in cohomological degree zero, where it consists of derivations. The obstructions for existence and uniqueness of an E_∞ -ring structure on $E(n)_\mathbb{Q}$ are concentrated in degrees bigger than zero. \square

As E_∞ -ring structures can be rigidified to commutative ring structures (see eg [12, Section II.3]), we pass to the world of commutative ring spectra from now on.

Topological Hochschild homology of a ring spectrum A can be modelled as the geometric realization of a simplicial spectrum. Using the inclusion of the 1-skeleton, McClure and Staffeldt [18, Section 3] construct a map

$$(2-1) \quad \sigma: \Sigma A \rightarrow \mathrm{THH}(A).$$

For a commutative ring spectrum A the multiplication maps from $A^{\wedge n+1}$ to A give rise to a map of commutative A -algebra spectra from $\mathrm{THH}(A)$ to A . Composing this map with the map $A \rightarrow \mathrm{THH}(A)$ gives the identity, hence we obtain a splitting of A -modules

$$\mathrm{THH}(A) \simeq A \vee \overline{\mathrm{THH}}(A),$$

where $\overline{\mathrm{THH}}(A)$ is the cofiber. The latter spectrum inherits the structure of a nonunital commutative A -algebra. In our case this implies the following result:

Corollary 2.2 *The topological Hochschild homology of $E(n)_\mathbb{Q}$ splits, as an $E(n)_\mathbb{Q}$ -module, as*

$$\mathrm{THH}(E(n)_\mathbb{Q}) \simeq E(n)_\mathbb{Q} \vee \overline{\mathrm{THH}}(E(n)_\mathbb{Q})$$

where $\overline{\mathrm{THH}}(E(n)_\mathbb{Q})$ is the cofiber of the unit map

$$E(n)_\mathbb{Q} \rightarrow \mathrm{THH}(E(n)_\mathbb{Q}) \simeq \mathrm{THH}(E(n)_\mathbb{Q}).$$

Moreover, the spectrum $\overline{\mathrm{THH}}(E(n)_\mathbb{Q})$ is a nonunital commutative $E(n)_\mathbb{Q}$ -algebra.

In the sequel, we follow Ronco [24, Definition E.1] for the definition of étale algebras. It is straightforward to calculate the topological Hochschild homology of $E(n)_\mathbb{Q}$:

Proposition 2.3 We have

$$(2-2) \quad \pi_* \mathrm{THH}(E(n))_{\mathbb{Q}} \cong \mathbb{Q}[v_1, \dots, v_{n-1}, v_n^{\pm 1}] \otimes \Lambda_{\mathbb{Q}}(dv_1, \dots, dv_n)$$

with $|dv_i| = 2p^i - 1$.

Proof The Bökstedt spectral sequence for $\pi_*(\mathrm{THH}(E(n))_{\mathbb{Q}}) \cong H\mathbb{Q}_* \mathrm{THH}(E(n))$ is of the form

$$E_{*,*}^2 = \mathrm{HH}_{*,*}^{\mathbb{Q}}(\pi_* E(n)_{\mathbb{Q}}) \Rightarrow \pi_*(\mathrm{THH}(E(n))_{\mathbb{Q}}).$$

As $\mathbb{Q}[v_1, \dots, v_{n-1}, v_n^{\pm 1}]$ is étale over $\mathbb{Q}[v_1, \dots, v_{n-1}, v_n]$ and as $\mathbb{Q}[v_1, \dots, v_{n-1}, v_n]$ is smooth, we get

$$\mathrm{HH}_{*,*}^{\mathbb{Q}}(\pi_* E(n)_{\mathbb{Q}}) \cong \mathbb{Q}[v_1, \dots, v_{n-1}, v_n^{\pm 1}] \otimes \Lambda_{\mathbb{Q}}(dv_1, \dots, dv_n)$$

with dv_i having homological degree one and internal degree $2p^i - 2$. As the Bökstedt spectral sequence is multiplicative and as the algebra generator cannot support any differentials for degree reasons, the spectral sequence collapses at E^2 . There are no multiplicative extensions and hence we get the result. \square

Remark 2.4 As we work rationally, $\mathrm{THH}(E(n))_{\mathbb{Q}}$ is a commutative $H\mathbb{Q}$ -algebra spectrum and hence corresponds to a commutative differential graded \mathbb{Q} -algebra (see [26] or [21]).

3 $K(i)_* E(n)$ and $K(i)_* \mathrm{THH}(E(n))$

In the following we assume that p is an odd prime, and that n and i are integers with $1 \leq i \leq n$. The Hopf algebroid $(\mathrm{BP}_*, \mathrm{BP}_* \mathrm{BP})$ represents the groupoid of strict isomorphisms of p -typical formal group laws [14] (see also [19, Theorem A2.1.27]). There are isomorphisms of graded $\mathbb{Z}_{(p)}$ -algebras

$$\mathrm{BP}_* \cong \mathbb{Z}_{(p)}[v_1, v_2, \dots] \quad \text{and} \quad \mathrm{BP}_* \mathrm{BP} \cong \mathrm{BP}_*[t_1, t_2, \dots],$$

where $|v_i| = |t_i| = 2(p^i - 1)$. We use the Araki generators v_i [19, Section A2.2] and by convention $v_0 = p$ and $t_0 = 1$. The i^{th} Morava K -theory $K(i)$ is complex oriented, and its formal group law F_i (the Honda formal group law) corresponds to the map $\mathrm{BP}_* \rightarrow K(i)_* = \mathbb{F}_p[v_i^{\pm 1}]$ sending v_i to v_i and v_k for $k \neq i$ to zero. The p -typical formal group law G_n over $E(n)_*$ comes from the map $\mathrm{BP}_* \rightarrow E(n)_*$ that

kills all v_i with $i > n$ and inverts v_n . Since $E(n)$ is a Landweber exact homology theory, we obtain an isomorphism

$$(3-1) \quad K(i)_*E(n) \cong K(i)_* \otimes_{\text{BP}_*} \text{BP}_*\text{BP} \otimes_{\text{BP}_*} E(n)_*.$$

Note that $K(i)_*E(n)$ is trivial for $i > n$ and that the Bousfield class $\langle E(n) \rangle$ of $E(n)$ is $\langle K(0) \vee \dots \vee K(n) \rangle$.

We first treat the case $i = n$.

The algebra $K(n)_*E(n)$ is isomorphic to $K(n)_*\text{BP}\langle n \rangle$, which is isomorphic to

$$K(n)_* \otimes_{\text{BP}_*} \text{BP}_*\text{BP} \otimes_{\text{BP}_*} K(n)_*$$

(see for instance [29, page 428]). The latter is known as $\Sigma(n)$. It is of the form

$$\Sigma(n) \cong K(n)_*[t_1, t_2, \dots] / (v_n t_i^{p^n} - v_n^{p^i} t_i \mid i \geq 1);$$

see [19, Corollary 6.1.16].

Proposition 3.1 *For all $n \geq 1$ the canonical map $E(n) \rightarrow \text{THH}(E(n))$ is a $K(n)$ -local equivalence.*

Proof If we set

$$C_*^{(k)} := K(n)_*[t_1, \dots, t_k] / (v_n t_i^{p^n} - v_n^{p^i} t_i \mid 1 \leq i \leq k)$$

then $C_*^{(k)}$ is étale over $K(n)_*$ and $K(n)_*E(n)$ is the directed colimit of the $C_*^{(k)}$.

The $K(n)_*$ -Bökstedt spectral sequence for $\text{THH}(E(n))$ has as an E^2 -term

$$\text{HH}_*^{K(n)_*}(K(n)_*E(n)) \cong K(n)_*E(n)$$

concentrated in homological degree zero. Thus $K(n)_*\text{THH}(E(n)) \cong K(n)_*E(n)$ and the isomorphism is induced by the map $E(n) \rightarrow \text{THH}(E(n))$. Therefore, this map is a $K(n)$ -equivalence and thus, $K(n)$ -locally, $\text{THH}(E(n))$ is equivalent to $E(n)$. \square

We calculate $K(i)_*E(n)$ for $1 \leq i \leq n-1$ using the following description of morphisms of graded commutative BP_* -algebras from $K(i)_*E(n)$ to some graded commutative ring B_* . For $n = 2$ we had an argument that was rather involved and Paul Goerss suggested the following simpler proof.

We consider the map $g: \text{BP}_*\text{BP} \rightarrow K(i)_*E(n)$ of graded commutative $\mathbb{Z}_{(p)}$ -algebras given by

$$\text{BP}_*\text{BP} \rightarrow K(i)_* \otimes_{\text{BP}_*} \text{BP}_*\text{BP} \otimes_{\text{BP}_*} E(n)_* \cong K(i)_*E(n),$$

which uses the canonical maps $BP_* \rightarrow K(i)_*$ and $BP_* \rightarrow E(n)_*$ and the isomorphism from (3-1). By [19, Theorem A2.1.27], g corresponds to a triple $((\eta_L)_*F_i, (\eta_R)_*G_n, f)$ where $\eta_L: K(i)_* \rightarrow K(i)_*E(n)$ is the left unit, $\eta_R: E(n)_* \rightarrow K(i)_*E(n)$ is the right unit and $(\eta_L)_*F_i$ and $(\eta_R)_*G_n$ are the p -typical formal group laws that are given by the corresponding change of coefficients. Here, f is a strict isomorphism between the p -typical formal group laws $(\eta_L)_*F_i$ and $(\eta_R)_*G_n$ over $K(i)_*E(n)$. By [19, Lemma A2.1.26] such a strict isomorphism is always of the form

$$f(x) = \sum_j (\eta_R)_*G_n t_j x^{p^j}.$$

The p -series of the Honda formal group law F_i is

$$[p]_{F_i}(x) = v_i x^{p^i}$$

and the same is true for $[p]_{(\eta_L)_*F_i}[x]$ because the left unit just embeds $K(i)_*$ into $K(i)_*E(n)$. The p -series of $(\eta_R)_*G_n$ is

$$[p]_{(\eta_R)_*G_n}(x) = w_1 x^p + (\eta_R)_*G_n \cdots + (\eta_R)_*G_n w_n x^{p^n}$$

for $w_i = \eta_R(v_i)$.

The strict isomorphism $f(x) = \sum_j (\eta_R)_*G_n t_j x^{p^j}$ satisfies

$$[p]_{(\eta_R)_*G_n}(f(x)) = f([p]_{(\eta_L)_*F_i}(x)),$$

and using the above formulas for the p -series, this yields the equality

$$\begin{aligned} (3-2) \quad w_1 (f(x))^p + (\eta_R)_*G_n \cdots + (\eta_R)_*G_n w_n (f(x))^{p^n} &= f(v_i x^{p^i}) \\ &= \sum_j (\eta_R)_*G_n t_j (v_i x^{p^i})^{p^j}. \end{aligned}$$

Lemma 3.2 *In $K(i)_*E(n)$ the relations $w_r = 0$ for all $1 \leq r \leq i - 1$ and $w_i = v_i$ hold.*

Proof In equality (3-2), the right-hand side starts with the summand $v_i x^{p^i}$ followed by higher powers of x . Looking at the left-hand side, we deduce that $w_1, \dots, w_{i-1} = 0$, and from the coefficient of x^{p^i} we obtain that $w_i = v_i$ in $K(i)_*E(n)$. \square

Proposition 3.3 *$K(i)_*E(n)$ is a colimit of étale $K(i)_*[w_{i+1}, \dots, w_n^{\pm 1}]$ -algebras for all $1 \leq i \leq n$.*

Proof In the following we fix i and n . We denote by $B(i, n)_*$ the graded commutative $K(i)_*$ -algebra $K(i)_*[w_{i+1}, \dots, w_{n-1}, w_n^{\pm 1}]$. For a given $m \geq 1$ consider the graded

commutative BP_* -subalgebra $BP_*[t_1, \dots, t_m]$ of BP_*BP , and define the subalgebra

$$B_m = g(BP_*[t_1, \dots, t_m]) \subset K(i)_*E(n).$$

By Lemma 3.2, we deduce that B_m can be written as the quotient

$$B_m = B(i, n)[t_1, \dots, t_m]/\sim,$$

where \sim denotes the relations that the t_r and w_j satisfy in $K(i)_*E(n)$. Note that B_1 is free as a $B(i, n)$ -module, and B_{m+1} is free as a B_m -module for all $m \geq 1$. Indeed, in each step we adjoin a new polynomial generator x to a graded commutative ring R_* that satisfies relations of the form $x^{p^r} - ux - y$ with a unit $u \in R_*^\times$ and $y \in R_*$. In particular, we have a sequence of subalgebras

$$B(i, n) \subset B_1 \subset \dots \subset B_m \subset \dots \subset K(i)_*E(n),$$

and $K(i)_*E(n)$ is the colimit of this sequence.

We prove that B_1 is étale over $B(i, n)_*$ and that for every m , B_m is étale over B_{m-1} . This then yields that the algebras B_m are étale over $B(i, n)_*$ which proves the claim. Thus we have to show that the modules of relative Kähler differentials $\Omega_{B_1|B(i, n)_*}^1$ and $\Omega_{B_m|B_{m-1}}^1$ are trivial for all $m \geq 2$. To this end we have to control the Kähler differentials dt_m and we do this now by deriving explicit relations for the t_m that we extract from the equality (3-2).

The first relation for t_m is obtained by looking at the coefficients of $x^{p^{i+m}}$ on the left- and right-hand sides of the equality (3-2).

Let $s \geq 2$, let r, l_1, \dots, l_s be natural numbers bigger or equal to 1, and assume that $l_j \neq l_k$ for $j \neq k$. Then, as p^r has a unique representation in base p , it cannot be written as a sum $p^{l_1} + \dots + p^{l_s}$. This ensures that, for a given $x^{p^{i+r}}$, we only have to consider the coefficient $t_j v_i^{p^j}$ with $i + j = i + r$ coming from the linear term of the $(\eta_R)_*G_n$ -sum $\sum_j (\eta_R)_*G_n t_j v_i^{p^j} x^{p^{i+j}}$ and this is $t_r v_i^{p^r}$.

For B_1 we compare the coefficients of $x^{p^{i+1}}$ in (3-2). In this case only the linear terms of the $(\eta_R)_*G_n$ -sums contribute something and we obtain (using $w_i = v_i$)

$$v_i t_1^{p^i} + w_{i+1} t_0 = t_1 v_i^{p^i}$$

and therefore $t_1 = v_i^{-p} (v_i t_1^{p^i} + w_{i+1})$. This gives that the Kähler differential on t_1 is equal to

$$dt_1 = 0 + v_i^{-p} dw_{i+1}$$

and hence B_1 is étale over $B(i, n)_*$.

We consider now the general case of B_m for $m \geq 2$, and study the first relation for t_m given by the coefficients of $x^{p^{i+m}}$ in (3-2).

We know that the formal group law $G_n(x, y)$ is of the form

$$G_n(x, y) = x + y + \sum_{i,j \geq 1} a_{i,j} x^i y^j,$$

where the $a_{i,j} \in E(n)_* = \mathbb{Z}_{(p)}[v_1, \dots, v_{n-1}, v_n^{\pm 1}]$. Equation (3-2) relates power series with coefficients in $K(i)_*E(n)$, hence the coefficients $\bar{a}_{i,j}$ of $(\eta_R)_*G_n$ are now considered in $K(i)_*E(n)$ and are elements of $\mathbb{F}_p[w_i, \dots, w_{n-1}, w_n^{\pm 1}]$. On the left-hand side of (3-2) we get coefficients that involve some polynomials of the $\bar{a}_{i,j}$, some p^{th} powers of the t_j and some expressions in the w_k . For $m+i \leq n$ we actually get a coefficient $w_{m+i} t_0^{p^{m+i+0}} = w_{m+i}$.

The $\bar{a}_{i,j}$ are in $B(i, n)_*$, so they don't contribute anything to the relative Kähler differentials. The Kähler differentials on the $t_j^{p^k}$ are trivial because we are over \mathbb{F}_p . Hence we can express the Kähler differential dt_m up to a factor of $v_i^{p^m} = w_i^{p^m}$ via Kähler differentials in the w_k . As $v_i^{p^m}$ is invertible in $B(i, n)_*$, the relative Kähler differentials $\Omega_{B_m|B_{m-1}}^1$ are trivial for all $m \geq 1$. □

Theorem 3.4 For all $1 \leq i \leq n$ we have an isomorphism of $K(i)_*E(n)$ -algebras

$$\mathrm{HH}_*^{K(i)_*}(K(i)_*E(n)) \cong K(i)_*E(n) \otimes_{\mathbb{F}_p} \Lambda_{\mathbb{F}_p}(dw_{i+1}, \dots, dw_n).$$

Proof We have shown that $K(i)_*E(n)$ is the sequential colimit of the B_m . As the $K(i)_*$ -algebras B_m are étale over $B(i, n)_*$ and as Hochschild homology commutes with localization, we can rewrite $\mathrm{HH}_*(B_m)$ as

$$\begin{aligned} \mathrm{HH}_*^{K(i)_*}(B_m) &\cong B_m \otimes_{B(i, n)_*} \mathrm{HH}_*^{K(i)_*}(B(i, n)_*) \\ &\cong B_m \otimes_{B(i, n)_*} (B(i, n)_* \otimes_{\mathbb{F}_p} \Lambda_{\mathbb{F}_p}(dw_{i+1}, \dots, dw_n)) \\ &\cong B_m \otimes_{\mathbb{F}_p} \Lambda_{\mathbb{F}_p}(dw_{i+1}, \dots, dw_n) \end{aligned}$$

using [28] and the Hochschild–Kostant–Rosenberg theorem. Hochschild homology commutes with colimits, hence we obtain

$$\begin{aligned} \mathrm{HH}_*^{K(i)_*}(K(i)_*E(n)) &\cong \operatorname{colim}_m \mathrm{HH}_*^{K(i)_*}(B_m) \\ &\cong K(i)_*E(n) \otimes_{\mathbb{F}_p} \Lambda_{\mathbb{F}_p}(dw_{i+1}, \dots, dw_n). \end{aligned} \quad \square$$

Theorem 3.5 Assume that p is an odd prime and that $E(n)$ is an E_3 -ring spectrum. Then, for all $1 \leq i \leq n$, we have an isomorphism of $K(i)_*E(n)$ -algebras

$$K(i)_*\mathrm{THH}(E(n)) \cong K(i)_*E(n) \otimes_{\mathbb{F}_p} \Lambda_{\mathbb{F}_p}(dw_{i+1}, \dots, dw_n).$$

Proof We use the Bökstedt spectral sequence [9; 12, Theorem IX.2.9], with E^2 -term

$$E_{r,s}^2 = (\mathrm{HH}_r^{K(i)_*}(K(i)_*E(n)))_s,$$

where r denotes the homological and s the internal degree. By a result of Angeltveit and Rognes [1, Proposition 4.3], an E_3 -structure on $E(n)$ implies that this spectral is one of commutative $K(i)_*E(n)$ -algebras. The multiplicative generators dw_j for $i \leq j \leq n$ sit in bidegree $(1, 2p^j - 2)$ and hence they cannot carry any nontrivial differentials. Therefore the spectral sequence collapses at the E^2 -term. As the abutment is a free graded commutative $K(i)_*E(n)$ -algebra, there cannot be any multiplicative extensions. \square

Remark 3.6 If $E(n)$ admits an E_2 -structure, the Bökstedt spectral sequence is one of $K(i)_*$ -algebras by [1, Proposition 4.3]. It therefore collapses since all $K(i)_*$ -algebra generators lie in columns 0 and 1. This gives the same formula for $K(i)_*\mathrm{THH}(E(n))$ as a $K(i)_*$ -module, but not as a $K(i)_*$ -algebra, since there is now room for $K(i)_*$ -algebra extensions.

4 Blue-shift for $\mathrm{THH}(E(n))$

If we assume that p is an odd prime and that $E(n)$ is an E_∞ -ring spectrum, then $\mathrm{THH}(E(n))$ is a commutative $E(n)$ -algebra spectrum and the cofiber of the unit map

$$\overline{\mathrm{THH}}(E(n)) = \mathrm{cofiber}(E(n) \rightarrow \mathrm{THH}(E(n)))$$

is a nonunital commutative $E(n)$ -algebra spectrum. If $E(n)$ carries an E_3 -structure, then by [10, Section 3.3; 6] the morphism $E(n) \rightarrow \mathrm{THH}(E(n))$ is an E_2 -map. This implies the following useful fact:

Lemma 4.1 If $E(n)$ is an E_3 -spectrum, then $\mathrm{THH}(E(n))$ is an $E(n)$ -module spectrum and, in particular, $\mathrm{THH}(E(n))$ is $E(n)$ -local.

Let L_n denote the localization at $E(n)$, and in particular L_0 is the rationalization. Recall that there is a well-known chromatic fracture square

$$\begin{array}{ccc} L_n X & \longrightarrow & L_{K(n)} X \\ \downarrow & & \downarrow \\ L_{n-1} X & \longrightarrow & L_{n-1} L_{K(n)} X \end{array}$$

It is shown for instance in [2, Example 3.3; 8, Proposition 2.2] that the homotopy pullback of

$$\begin{array}{ccc} & & L_{K(n)} X \\ & & \downarrow \\ L_{n-1} X & \longrightarrow & L_{n-1} L_{K(n)} X \end{array}$$

is an $E(n)$ –localization of X . The statement in [8, Proposition 2.2] is more general and [2] works out far more general local-to-global statements.

The chromatic square for $\overline{\mathrm{THH}}(E(n))$ is

$$\begin{array}{ccc} \overline{\mathrm{THH}}(E(n)) = L_{K(n) \vee E(n-1)} \overline{\mathrm{THH}}(E(n)) & \longrightarrow & L_{K(n)} \overline{\mathrm{THH}}(E(n)) \\ \downarrow & & \downarrow \\ L_{E(n-1)} \overline{\mathrm{THH}}(E(n)) & \longrightarrow & L_{E(n-1)} (L_{K(n)} \overline{\mathrm{THH}}(E(n))) \end{array}$$

The $K(n)$ –homology of $\overline{\mathrm{THH}}(E(n))$ is zero, since by Proposition 3.1 the unit map is a $K(n)$ –equivalence. It follows that the localization $L_{K(n)} \overline{\mathrm{THH}}(E(n))$ is trivial, and hence $L_{E(n-1)} (L_{K(n)} \overline{\mathrm{THH}}(E(n)))$ is also trivial. Therefore the vertical map on the left-hand side is an equivalence and we obtain a nice example of blue-shift:

Lemma 4.2 *If $E(n)$ is an E_3 –spectrum, then the cofiber $\overline{\mathrm{THH}}(E(n))$ is $E(n-1)$ –local.*

5 Topological Hochschild homology of $E(2)$

In this section, we discuss in more detail the topological Hochschild homology of $E(2)$, which we will denote by $E = E(2)$ to simplify the notation. As explained in the proof

of Lemma 5.1, the computations of Theorem 3.5 for $E(2)$ can be expressed as

$$(5-1) \quad K(0)_* \text{THH}(E) \cong K(0)_* E \otimes \Lambda_{\mathbb{Q}}(dt_1, dt_2),$$

$$(5-2) \quad K(1)_* \text{THH}(E) \cong K(1)_* E \otimes \Lambda_{\mathbb{F}_p}(dt_1),$$

$$(5-3) \quad K(2)_* \text{THH}(E) \cong K(2)_* E.$$

Notice that these computations do not require the assumption that E is an E_3 -ring spectrum: for the rational case we have a commutative structure anyhow, while, in the $K(1)$ and $K(2)$ cases, the E^2 page of the Bökstedt spectral sequences is concentrated on columns 0 and 1 (respectively 0).

Lemma 5.1 *For $i = 1, 2$, there exist classes $\lambda_i \in \text{THH}_{2p^{i-1}}(E)$ with the following properties. Under the Hurewicz homomorphism,*

- (a) *the class λ_i maps to $dt_i \in K(0)_{2p^{i-1}} \text{THH}(E)$ for $i = 1, 2$;*
- (b) *the class λ_1 maps to $dt_1 \in K(1)_{2p^2-1} \text{THH}(E)$.*

Proof We use McClure and Staffeldt’s computation of $\text{THH}_*(\text{BP})$ in [18, Remark 4.3], which has been validated by the proof [7] that BP admits an E_4 -structure. We briefly recall the computation. The integral, rational and mod p homology of BP are given as

$$H\mathbb{Z}_* \text{BP} \cong \mathbb{Z}_{(p)}[t_i \mid i \geq 1], \quad K(0)_* \text{BP} \cong \mathbb{Q}[t_i \mid i \geq 1] \quad \text{and} \quad H\mathbb{F}_p_* \text{BP} \cong \mathbb{Z}[\bar{\xi}_i \mid i \geq 1],$$

where the class $t_i \in H\mathbb{Z}_{2p^{i-1}} \text{BP}$ maps to $\bar{\xi}_i$ under mod (p) reduction [19, Proof of Theorem 5.2.8] and to the class with same name t_i under rationalization. The associated Bökstedt spectral sequences collapse, providing isomorphisms

$$\begin{aligned} H\mathbb{Z}_* \text{THH}(\text{BP}) &\cong H\mathbb{Z}_* \text{BP} \otimes \Lambda_{\mathbb{Z}_{(p)}}(dt_i \mid i \geq 1), \\ K(0)_* \text{THH}(\text{BP}) &\cong K(0)_* \text{BP} \otimes \Lambda_{\mathbb{Q}}(dt_i \mid i \geq 1), \\ H\mathbb{F}_p_* \text{THH}(\text{BP}) &\cong H\mathbb{F}_p_* \text{BP} \otimes \Lambda_{\mathbb{F}_p}(d\bar{\xi}_i \mid i \geq 1), \end{aligned}$$

with $dx = \sigma_*(x)$, where $\sigma: \Sigma \text{BP} \rightarrow \text{THH}(\text{BP})$ is the map given in (2-1). There is an isomorphism

$$\text{THH}_*(\text{BP}) \cong \text{BP}_* \otimes \Lambda_{\mathbb{Z}_{(p)}}(\lambda_i \mid i \geq 1),$$

and the Hurewicz homomorphism

$$\text{THH}_*(\text{BP}) \rightarrow H\mathbb{Z}_* \text{THH}(\text{BP})$$

is an inclusion mapping λ_i to dt_i . In particular, the classes dt_i (integral and rational) and $d\bar{\xi}_i$ are spherical: they are the image of λ_i under the Hurewicz homomorphism mapping from $\mathrm{THH}_*(\mathrm{BP})$. For $i \geq 1$, let us define

$$\lambda_i \in \mathrm{THH}_{2p^i-1}(E)$$

as the image of the class with same name under the natural map

$$\mathrm{THH}_*(\mathrm{BP}) \rightarrow \mathrm{THH}_*(E).$$

In the rational case, we have

$$\eta_R(v_i) \equiv \alpha_i t_i$$

modulo decomposables in $K(0)_*\mathrm{BP}$, where $\alpha_i \in \mathbb{Q}$ is a unit. We deduce that

$$K(0)_*E \cong \mathbb{Q}[t_1, t_2][[\eta_R(v_2)^{-1}]]$$

and the Bökstedt spectral sequence recovers

$$K(0)_*\mathrm{THH}(E) \cong K(0)_*E \otimes \Lambda_{\mathbb{Q}}(dt_1, dt_2).$$

By naturality, comparing with the case of BP , we deduce that the Hurewicz homomorphism $\mathrm{THH}_*(E) \rightarrow K(0)_*\mathrm{THH}(E)$ maps λ_i to dt_i .

For $K(1)_*$ -homology, we argue similarly, using the commutative square

$$\begin{array}{ccc} \mathrm{THH}_*(\mathrm{BP}) & \longrightarrow & K(1)_*\mathrm{THH}(\mathrm{BP}) \\ \downarrow & & \downarrow \\ \mathrm{THH}_*(E) & \longrightarrow & K(1)_*\mathrm{THH}(E) \end{array}$$

We have $K(1)_*\mathrm{BP} \cong K(1)_*[t_i \mid i \geq 1]$, and the Bökstedt spectral sequence yields

$$K(1)_*\mathrm{THH}(\mathrm{BP}) \cong K(1)_*\mathrm{BP} \otimes \Lambda_{\mathbb{F}_p}(dt_i \mid i \geq 1).$$

Comparing the Bökstedt spectral sequences for $H\mathbb{Z}_*\mathrm{THH}(\mathrm{BP})$ and $K(1)_*\mathrm{THH}(\mathrm{BP})$, we deduce that the class $\lambda_1 \in \mathrm{THH}_*(\mathrm{BP})$ maps to $dt_1 \in K(1)_*\mathrm{THH}(\mathrm{BP})$. Recall that

$$K(1)_*E = K(1)_*[t_i \mid i \geq 1][[\eta_R(v_2)^{-1}]]/(\eta_R(v_j) \mid j \geq 3)$$

is a colimit of étale algebras over $K(1)_*[w_2, w_2^{-1}]$, where

$$w_2 = \eta_R(v_2) = v_1^p t_1 - v_1 t_1^p.$$

In particular, $dw_2 = v_1^p dt_1$, and the Bökstedt spectral sequence provides the formula given above for $K(1)_* \text{THH}(E)$. Now obviously $dt_1 \in K(1)_* \text{THH}(\text{BP})$ maps to $dt_1 \in K(1)_* \text{THH}(E)$. This implies assertion (b) of the lemma. \square

Remark 5.2 The above proof does not require the map $\text{BP} \rightarrow E(n)$ to be an E_3 -map.

The class $\lambda_1 \in \text{THH}_{2p-1}(E)$ of Lemma 5.1 corresponds to a map $\lambda_1: S^{2p-1} \rightarrow \text{THH}(E)$. Smashing with E , using the E -module structure of $\text{THH}(E)$ (assuming an E_3 -structure on E), and composing with the cofiber $\text{THH}(E) \rightarrow \overline{\text{THH}}(E)$ of the unit, we obtain a map

$$j_1: \Sigma^{2p-1} E \cong E \wedge S^{2p-1} \rightarrow E \wedge \text{THH}(E) \rightarrow \text{THH}(E) \rightarrow \overline{\text{THH}}(E).$$

In the same fashion, we obtain a map $j_2: \Sigma^{2p^2-1} E \rightarrow \overline{\text{THH}}(E)$ corresponding to the class λ_2 .

Lemma 5.3 *The map j_1 factors through a map*

$$\bar{j}_1: \Sigma^{2p-1} L_1 E \rightarrow \overline{\text{THH}}(E)$$

that is a $K(1)_$ -isomorphism, and whose cofiber $C(\bar{j}_1)$ is a rational spectrum.*

Proof Recall from Lemma 4.2 that the cofiber $\overline{\text{THH}}(E)$ of the unit map is $E(1)$ -local. In particular, the map j_1 factors through a map

$$\bar{j}_1: \Sigma^{2p-1} L_1 E \rightarrow \overline{\text{THH}}(E).$$

The localization map $E \rightarrow L_1 E$ is a $K(1)_*$ -isomorphism, and therefore so are the induced maps $\ell: \text{THH}(E) \rightarrow \text{THH}(L_1 E)$ and $\bar{\ell}: \overline{\text{THH}}(E) \rightarrow \overline{\text{THH}}(L_1 E)$, by convergence of the $K(1)$ -based Bökstedt spectral sequence. Hence, to prove the claim, it suffices to show that the composition

$$(5-4) \quad \Sigma^{2p-1} L_1 E \xrightarrow{\bar{j}_1} \overline{\text{THH}}(E) \xrightarrow{\bar{\ell}} \overline{\text{THH}}(L_1 E)$$

is a $K(1)_*$ -isomorphism. The $K(1)$ -based Bökstedt spectral sequence for $L_1 E$ is identical to the one of E , computed above as

$$E_{*,*}^2 = K(1)_* E \otimes \Lambda_{\mathbb{F}_p}(dt_1) \Rightarrow K(1)_* \text{THH}(E),$$

where $K(1)_* E$ is in filtration degree zero and $K(1)_* E\{dt_1\}$ is in filtration degree 1, and where all differentials are zero. By definition of the map j_1 , if $1 \in K(1)_0 E$ is the unit, then $j_{1*}(\Sigma^{2p-1} 1)$ is represented modulo lower filtration by the permanent

cycle dt_1 in $E_{1,*}^2$. Since this is a spectral sequence of $K(1)_*E$ -modules, the composition (5-4) induces a map in $K(1)$ homology that is represented modulo lower filtration by the isomorphism $\Sigma^{2p-1}K(1)_*E \rightarrow E_{1,*}^2 = K(1)_*E\{dt_1\}$ sending a class $\Sigma^{2p-1}w$ to $w dt_1$. It is therefore a $K(1)_*$ -isomorphism, proving the claim.

Now we consider the cofiber $C(\bar{j}_1)$ of \bar{j}_1 , sitting in an exact triangle

$$(5-5) \quad \Sigma^{2p-1}L_1E \xrightarrow{\bar{j}_1} \overline{\text{THH}}(E) \xrightarrow{k} C(\bar{j}_1) \xrightarrow{\delta} \Sigma^{2p}L_1E.$$

Since \bar{j}_1 is a $K(1)_*$ -isomorphism, we know that $K(1)_*C(\bar{j}_1) = 0$, and since $\overline{\text{THH}}(E)$ and thus $C(\bar{j}_1)$ are $E(1)$ -local, we deduce (as in Lemma 4.2) that $C(\bar{j}_1)$ is $E(0)$ -local (ie rational). \square

We now define a map $\lambda_{12}: L_0S^{2p^2-2p-2} \rightarrow C(\bar{j}_1)$ as a composition over the cofibers,

$$L_0S^{2p^2-2p-2} \rightarrow L_0\text{THH}(E) \rightarrow L_0\overline{\text{THH}}(E) \rightarrow C(\bar{j}_1),$$

where the first map above realizes the class $dt_1 dt_2 \in K(0)_*\text{THH}(E)$. Smashing λ_{12} with E and using the module structure, we obtain a map

$$j_{12}: \Sigma^{2p^2-2p-2}L_0E \rightarrow C(\bar{j}_1).$$

Similarly, λ_2 induces a map

$$j_2: \Sigma^{2p^2-1}L_0E \rightarrow C(\bar{j}_1).$$

Theorem 5.4 *Let p be an odd prime such that $E = E(2)$, the second Johnson–Wilson spectrum at p , is an E_3 -ring spectrum. Then the map $j_2 \vee j_{12}$ lifts to a map*

$$\bar{j}_2 \vee \bar{j}_{12}: \Sigma^{2p^2-1}L_0E \vee \Sigma^{2p^2-2p-2}L_0E \rightarrow \overline{\text{THH}}(E)$$

and the sum β of \bar{j}_1 , \bar{j}_2 and \bar{j}_{12} is a weak equivalence of E -modules

$$\beta: \Sigma^{2p-1}L_1E \vee \Sigma^{2p^2-1}L_0E \vee \Sigma^{2p^2+2p-2}L_0E \rightarrow \overline{\text{THH}}(E).$$

Proof The composition $\delta \circ (j_2 \vee j_{12})$ is trivial, so that $j_2 \vee j_{12}$ lifts to a map $\bar{j}_2 \vee \bar{j}_{12}$:

$$\begin{array}{ccccc}
 & \Sigma^{2p^2-1}L_0E \vee \Sigma^{2p^2+2p-2}L_0E & & & \\
 & \swarrow \bar{j}_2 \vee \bar{j}_{12} & \downarrow j_2 \vee j_{12} & \searrow \simeq * & \\
 \overline{\text{THH}}(E) & \xrightarrow{k} & C(\bar{j}_1) & \xrightarrow{\delta} & \Sigma^{2p}L_1E
 \end{array}$$

Indeed, $\Sigma^{2p}L_1E$ fits in the chromatic fracture pullback diagram

$$\begin{CD} \Sigma^{2p}L_1E @>>> \Sigma^{2p}L_{K(1)}E \\ @VVV @VVV \\ \Sigma^{2p}L_0E @>>> \Sigma^{2p}L_0(L_{K(1)}E) \end{CD}$$

The composition of $\delta \circ (j_2 \vee j_{12})$ with the left vertical map to $\Sigma^{2p}L_0E$ is trivial, since it factors over the composition

$$L_0\overline{\text{THH}}(E) \rightarrow L_0C(\bar{j}_1) \rightarrow \Sigma^{2p}L_0E$$

of two consecutive maps in the $(E(0)$ -localized) cofiber sequence (5-5). The composition of $\delta \circ (j_2 \vee j_{12})$ with the top map to $\Sigma^{2p}L_{K(1)}E$ is trivial as well; indeed, there is no nontrivial map from a $K(1)$ -acyclic to a $K(1)$ -local spectrum. This finishes the proof that $\delta \circ (j_2 \vee j_{12})$ is trivial and that the lift exists. We now define β as the sum

$$\beta = \bar{j}_1 \vee \bar{j}_2 \vee \bar{j}_{12}: \Sigma^{2p-1}L_1E \vee \Sigma^{2p^2-1}L_0E \vee \Sigma^{2p^2+2p-2}L_0E \rightarrow \overline{\text{THH}}(E).$$

Finally, we claim that β is a $K(0)_*$ -isomorphism: this is analogous to the proof above that \bar{j}_1 is a $K(1)_*$ -isomorphism, working this time with the $K(0)$ -based Bökstedt spectral sequence. Since β is a $K(0)_*$ - and a $K(1)_*$ -isomorphism of $E(1)$ -local spectra, it is a weak equivalence. □

Assume now that in addition to E being an E_3 -ring spectrum, the unit map $E \rightarrow \text{THH}(E)$ splits in the homotopy category (this holds for example if E is an E_∞ -ring spectrum). We then have a weak equivalence of E -modules $E \vee \overline{\text{THH}}(E) \rightarrow \text{THH}(E)$. On the other hand, summing β with the identity of E gives a weak equivalence

$$\text{id} \vee \beta: E \vee \Sigma^{2p-1}L_1E \vee \Sigma^{2p^2-1}L_0E \vee \Sigma^{2p^2+2p-2}L_0E \rightarrow E \vee \overline{\text{THH}}(E).$$

This implies the following corollary of Theorem 5.4:

Corollary 5.5 *Assume that p is an odd prime, and that the second Johnson–Wilson spectrum $E = E(2)$ admits an E_3 -structure. If the unit map $E \rightarrow \text{THH}(E)$ splits in the homotopy category, then the maps above provide a weak equivalence of E -modules*

$$E \vee \Sigma^{2p-1}L_1E \vee \Sigma^{2p^2-1}L_0E \vee \Sigma^{2p^2+2p-2}L_0E \rightarrow \text{THH}(E).$$

Remark 5.6 Corollary 5.5 implies that

- the 2^0 summand of $K(2)_*E$ in $K(2)_*\text{THH}(E)$ indexed by 1,

- the 2^1 summands of $K(1)_*E$ in $K(1)_*\mathrm{THH}(E)$ indexed by 1 and dt_1 , and
- the 2^2 summands of $K(0)_*E$ in $K(0)_*\mathrm{THH}(E)$ indexed by 1, dt_1 , dt_2 and dt_1dt_2

assemble, in $\mathrm{THH}(E)$, into

- the 2^0 summand E indexed by 1 and detected by $K(0)_*$, $K(1)_*$ and $K(2)_*$,
- the $2^1 - 2^0$ summand L_1E indexed by dt_1 and detected by $K(0)_*$ and $K(1)_*$, and
- the $2^2 - 2^1$ summands L_0E indexed by dt_2 and dt_1dt_2 and detected by $K(0)_*$.

Bruner and Rognes [11] obtain very similar computations for $K(i)_*\mathrm{THH}(\mathrm{tmf})$ for $i = 0, 1, 2$, where tmf denotes the connective spectrum of topological modular form.

We can picture the summands of $\mathrm{THH}(E)$ in a 2–dimensional cube of local pieces (up to suspensions, where $E = L_2E$):

	1	dt_1
1	E	L_1E
dt_2	L_0E	L_0E

We conjecture that this picture extends to describe a decomposition of $\mathrm{THH}(E(n))$ into 2^n summands, with summands placed in an n –dimensional cube, where the i^{th} edge has two coordinates 1 and dt_i . We formulate this as follows:

Conjecture 5.7 If p is an odd prime such that $E(n)$ is a sufficiently commutative S –algebra, then $\mathrm{THH}(E(n))$ decomposes as a sum of 2^n factors, namely 2^{n-i-1} suspended copies of $L_iE(n)$ for each $0 \leq i \leq n - 1$ plus one copy of $E(n)$. More precisely, the $L_iE(n)$ –summands are indexed by the 2^{n-i-1} monomial generators

$$\omega \in \Lambda_{\mathbb{Q}}(dt_1, \dots, dt_{n-i-1})\{dt_{n-i}\} \subset K(0)_*\mathrm{THH}(E(n)),$$

and the summand corresponding to such a monomial ω is $\Sigma^{|\omega|}L_iE(n)$.

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