

Twisted Cohomotopy implies level quantization of the full 6d Wess-Zumino term of the M5-brane

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Abstract

The full 6d Hopf-Wess-Zumino term in the action functional for the M5-brane is anomalous as traditionally defined. What has been missing is a condition implying the higher analogue of level quantization familiar from the 2d Wess-Zumino term. We prove that the anomaly cancellation condition is implied by the hypothesis that the C-field is charge-quantized in twisted Cohomotopy theory. The proof follows by a twisted/parametrized generalization of the Hopf invariant, after identifying the full 6d Hopf-Wess-Zumino term with a twisted homotopy Whitehead integral formula, which we establish.

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1 Introduction and results

The expected but elusive quantum theory of M5-branes in M-theory (see [Du99, §3][HSS18, §2]) has come to be widely regarded as a core open problem in string theory, already in its decoupling limit of an expected 6-dimensional superconformal quantum field theory (see [Mo12][HR18]). Most attempts to understand at least aspects of this theory have been based on analogies (such as with the known M2-brane theory) and consistency checks (such as from implications of the expected superconformal structure). But a systematic derivation of the theory from deeper principles has not been possible, since these deeper principles must be those of the ambient M-theory, whose formulation is itself a wide open problem ([Du96, §6][Mo14, §12][Wi19, @21:15][Du19, @17:14]).

Recently in [FSS19a], following [Sa13], we motivated, from rigorous analysis of the super homotopy theory of super p -branes initiated in [FSS13b], a hypothesis about the mathematical foundations of microscopic M-theory:

Hypothesis H. *The M-theory C-field is charge-quantized in J-twisted Cohomotopy theory ([FSS20c], Def. 4.1).*

We proved in [FSS19b][SS19a][SS19b][SS20][FSS20b] that this hypothesis implies a list of subtle consistency conditions that had informally been argued to be necessary for M-theory to exist. This suggests that *Hypothesis H* could indeed be a correct assumption about the mathematical principles underlying microscopic M-theory. If this is the case, further aspects of M-theory must be systematically derivable, by rigorous mathematical deduction.

Here we prove that *Hypothesis H* implies global consistency of the full Hopf-Wess-Zumino term that appears in the Green-Schwarz-type action functional of the M5-brane. This used to be an open problem:

The open problem. The full 6d Hopf-Wess-Zumino-term (Hopf-WZ-term) of the single M5-brane (see (3) below for multiple M5-branes), originally proposed in [Ah96, p. 10], fully established by [BLNPST97, (1)], is a functional of fields on a 6d *worldvolume* manifold Σ^6 that may be expressed in terms of auxiliary extended fields on a cobounding *extended worldvolume* manifold $\widehat{\Sigma}^7$, as follows (full details and generality below in §2, see Table A):

$$\widehat{S}_{\text{WZ}}^{1\text{M5}} = 2\widehat{S}_{\text{WZ}}^{\text{M5}} := 2 \int_{\widehat{\Sigma}^7} \left(\frac{1}{2} \widehat{H}_3 \wedge \widehat{f}^* \widetilde{G}_4 + \widehat{f}^* G_7 \right) \quad (1)$$

Hopf-WZ term

$$\exp \left(2\pi i \left(\widehat{S}_{\text{WZ}}^{1\text{M5}} \right) \right) \in U(1) \quad (2)$$

$\widehat{\Sigma}^7$	Extended worldvolume
\widehat{f}	Extended sigma-model field
\widehat{H}_3	Extended worldvolume higher gauge field
\widetilde{G}_4	Shifted background C-field flux
G_7	Dual background C-field flux

The open problem is to show that this expression (1) is actually well-defined, in that it is independent of the choice of extensions, or at least independent up to integer shifts, so that at least the exponentiated Wess-Zumino action functional (2) is well-defined.

This means, equivalently, that the difference of (1) over any two extensions, hence the integral as in (1) over *closed* 7-manifolds $\widetilde{\Sigma}^7$, is an integer. In supergravity, this closed integral is also known as the *Page charge* [Pa83, (8)][DS91, (43)][BLMP12, (1.5.2)], and a proof of its integrality would be a proof of *Page charge quantization* (full details and generality are given below in Def. 2.9). In this form, the problem was raised in [Mo05], but the details of the solution were left open.

Partial solution in the literature. A suggestive partial solution to this problem was proposed in [In00], by

- (i) assuming that G_4 is not only the form datum underlying a topological cocycle in rational Cohomotopy,¹ but even that of an actual smooth function c_{smth} to the smooth 4-sphere [In00, (5.3)];
- (ii) focusing on the first summand [In00, (2.4)] and disregarding the second summand in (1), leaving its understanding for later [In00, top of p. 16].

With these simplifications imposed, expression (1) reduces on oriented difference manifolds $\widetilde{\Sigma}^7 := \widehat{\Sigma}_1^7 - \widehat{\Sigma}_2^7$ (6) to the classical Whitehead integral formula [Wh47] (see [BT82, Prop. 17.22]) for the *Hopf invariant* $\text{HI}(c_{\text{smth}} \circ \widehat{f})$ of maps to the 4-sphere (recalled as Def. 4.4 below). Since the Hopf invariant is an integer by its homotopy-theoretic definition, [In00] suggests that (2) is satisfied and thus refers to the first summand in (1) as the *Hopf-Wess-Zumino term*, a terminology that was used for other sigma-models before [WZ83][TN89], and which has become widely adopted for the M5 since (e.g. [KS03, §3.2][HN11, (2)][Ar18, (4.13)]). But, since assumption (i) is not supposed to be generally satisfied, so that disregarding the second term (ii) is not generally possible, this is only a partial solution, and the full problem of showing general consistency of (1) by demonstrating (2) had remained open.

Solution by homotopy periods in Cohomotopy. We observe here that the full Hopf-WZ-term (1), including the previously neglected summand $\widehat{f}^* G_7$, has the form of a secondary characteristic class descending from the intersection pairing, originally called a “functional cup product” by Steenrod [St49] and more recently discussed under the name *homotopy period* in [SW08, Ex. 1.9]. That these *homotopy Whitehead integrals* are the proper homotopy-theoretic formulation of the original Whitehead integral formula [Wh47] for the Hopf invariant, was remarked already by Haefliger [Ha78, p. 17]. For the analogous lower-dimensional case of maps from the 3-sphere to the 2-sphere, this had been worked out in [GM81, §14.5].

Our **first main result** here (Theorem 3.4 below) is a transparent proof that the full 6d Hopf-WZ-term (1) (including both summands) is a homotopy period/homotopy Whitehead integral in this sense, which reduces to the Whitehead integral formula for the Hopf invariant in the respective special cases (Remark 4.7 below). In fact, we prove a more general twisted version of the homotopy Whitehead integral, which incorporates also the topological

¹This is an after the fact statement, in that we recast it that way in our formulation. In [In00], the 4-sphere was part of spacetime, whereas in our Cohomotopy formulation it serves as a classifying space that receives maps out of spacetime; and we view the formulation in [In00] as a special case where part of spacetime is identified with that classifying space. The sphere as a classifying space for Cohomotopy cohomology theory generalizes the Eilenberg-MacLane spaces that classify ordinary cohomology. See [FSS20c, §2] for these general concepts and [GS20] for a detailed comparison between cohomology and Cohomotopy.

twists that account for the half-integral shift by $\frac{1}{4}p_1$ demanded by flux quantization of the background C-field (Remark 2.2 below) thus generalizing the 6d Hopf-WZ term (1) to curved backgrounds (Def. 2.6 below).

This shows, in particular, that the two summands in (1) can not be invariantly separated, and hence that it is really the full term (1) which deserves to be called the *Hopf-Wess-Zumino term*. Thereby the puzzlement expressed in [In00, top of p. 8] is resolved: The first summand of (1) by itself does not actually qualify as a Wess-Zumino term, since it is not (the pullback of) a cocycle. The full term *is* a cocycle (Remark 4.3), and in fact a cocycle in integral cohomology if *Hypothesis H* is satisfied, by the proof of our second main result:

Our **second main result** (Theorem 4.8 below) shows that under *Hypothesis H* the 6d Hopf-Wess-Zumino term (1) is generally integral, even in its topologically twisted generalization. This topologically twisted/parametrized generalization of the Hopf invariant thus establishes (2) and hence proves in generality that the 6d Hopf-Wess-Zumino term of the M5-brane is well-defined (namely integral, level-quantized); see (68) for the conclusion.

Consequences. We briefly highlight some consequences of and conclusions drawn from this result:

1. Level quantization. A key argument of [In00, (2.8)] was that the mathematical incarnation of N coinciding M5-branes is in the bare Hopf-WZ term (1) $\widehat{S}_{\text{WZ}}^{\text{M5}} = \int \frac{1}{2} H_3 \wedge \widehat{f}^* G_4 + \dots$ being multiplied by $N(N+1)$, at least in its first summand. Since, by our result here, the two summands cannot be invariantly separated, this means that the full term has to be multiplied this way, hence that for N coincident M5-branes the expression (1) generalizes to

$$\widehat{S}_{\text{WZ}}^{\text{NM5}} := N(N+1) \int_{\widehat{\Sigma}^7} \left(\frac{1}{2} \widehat{H}_3 \wedge \widehat{f}^* \widetilde{G}_4 + \widehat{f}^* G_7 \right) \quad \boxed{N \quad \text{Number of coincident M5-branes}} \quad (3)$$

with the factor of 2 in (1) being the case of $N = 1$. Since $N(N+1)$ is even for all N , the condition that (2) is well-defined up to an integral shift (by Theorems 3.4 and 4.8) implies that

$$\exp \left(2\pi i \left(\widehat{S}_{\text{WZ}}^{\text{NM5}} \right) \right) \in U(1) \quad (4)$$

is also well-defined, for all N . Thus the factor $N(N+1)$ plays the role of the *level* of the 6d Wess-Zumino term of the M5-brane; and its even integral form is the *level quantization* for the 6d Hopf-Wess-Zumino term of the M5-brane, in analogy with integral levels of ordinary Wess-Zumino terms [Wi83].

2. Dimensional generalization and the Hopf invariant one theorem. The full 6d Wess-Zumino term of the M5-brane (1) is evidently the special case $k = 1$ of a sequence of Wess-Zumino terms $S_{\text{WZ}}^{1B(4k+1)}$ that exist for all $k \in \mathbb{N}$ on higher gauged p -brane sigma-model fields with $p = 4k + 1$, hence the notation $B(4k + 1)$. It is precisely these worldvolume dimensions that admit self-dual higher gauge fields. For trivial topological twist τ in (34), the proof of Theorem 3.4 generalizes verbatim to this infinite hierarchy, simply by generalizing the degree of the generator ω_4 in (34) to $2(k + 1)$ and the degree of the generator ω_7 to $4k + 3$. Similarly, Prop. 4.6 generalizes verbatim and shows that for all $k \in \mathbb{N}$ the anomaly functionals $\widetilde{S}_{\text{WZ}}^{1B(4k+1)}$ (Def. 2.9) of these Wess-Zumino terms compute, in the absence of topological twists and under *Hypothesis H*, the Hopf invariant of the composite of the brane's sigma-model field with the cocycle of the background field in Cohomotopy.

It is interesting to note that, from this perspective, we may take the classical *Hopf invariant one theorem* [Ad60] to say that if the oriented difference of extended worldvolumes is the $(4k + 1)$ -sphere $\widetilde{\Sigma}^{4k+1} = S^{4k+1}$, then for almost all values of $k \in \mathbb{N}$ the anomaly functional $\widetilde{S}_{\text{WZ}}^{1B(4k+1)}$ (Def. 2.9) is an even integer, in that the only values of k for which it may take odd integer values are precisely those that correspond to branes which actually appear in string/M-theory:

$k =$	0	1	2
$(4k + 1)$ -brane	string	five-brane	nine-brane

Hypothesis H with the Hopf invariant one theorem singles out the worldvolume dimensions $p + 1 \in \{2, 6, 10\}$ among p -branes admitting self-dual higher gauge fields, as those whose Wess-Zumino anomaly functional $\widetilde{S}_{\text{WZ}}^{1B(4k+1)}$ is integrally indivisible.

3. Unifying role of the quaternionic Hopf fibration. It is noteworthy that the proofs of our main results (Theorem 3.4 and Theorem 4.8) proceed entirely by characterizing lifts in Cohomotopy through the quaternionic Hopf fibration, observing that it is such lifts which reflect, under *Hypothesis H*, the higher gauge field H_3 on the world-volume of the M5-brane [FSS19b, Prop. 3.20]. This tightly connects the discussion of the 6d Wess-Zumino term here to the analogous cohomotopical discussion of its supersymmetric completion in [FSS15][FSS19c] and to the anomaly cancellation conditions on the background fields in [FSS19b][SS20], all rigorously derived from first principles; and thus suggests that a complete derivation of the elusive quantum M5-brane may exist guided by *Hypothesis H*.

4. Outlook – Refinement to differential Cohomotopy. It is well known (see [FSS12b], review in [FSS13a]) that the definition of Wess-Zumino- and Chern-Simons-terms by field extensions over a cobounding manifold, while an elegant method when it applies, is not the most general definition of these terms. In cases where such field extensions do not exist, the WZ- and CS-terms may still exist, now defined as hypervolume holonomies of cocycles in a *differential* cohomology theory (see [FSS20c, §4.3]). For the ordinary WZ- and CS-term this differential cohomology theory is differential ordinary cohomology, represented equivalently as Cheeger-Simons differential characters or as Deligne cohomology or as bundle gerbes with connections, or as $B^n U(1)$ -principal connections.

But for the case of the 6dWZW term of the M5-branes, our results here show that the appropriate differential cohomology theory that generalizes the construction by field extension presented here must be a differential refinement of Cohomotopy cohomology theory. We had constructed one version of such a *differential Cohomotopy cohomology theory* in [FSS15, §4][FSS20c, §5.3], further discussed in [GS20, §3]. Ultimately one should use this to generalize the results we present here to situations where extensions of fields over cobounding manifolds may not exist.

Outline. In §2 we make precise the 6d Hopf-Wess-Zumino term and its anomaly, including topological twisting. In §3 we establish that the full WZ term is a homotopy period/homotopy Whitehead integral. In §4 we prove that *Hypothesis H* implies that the full 6d Hopf-Wess-Zumino term is well-defined.

2 The full 6d Hopf-WZ term of the M5-brane

In this section we present a precise definition, paraphrasing from the informal literature, of the 6d Hopf-Wess-Zumino term of the M5-brane, refine it to include topological twists reflecting the shifted quantization condition on the C-field flux, and then prove that the corresponding anomaly functional is a homotopy invariant.

First we state (in Def. 2.4 below) the 6d WZ term for “small” sigma-model fields as found in the original articles [Ah96, p. 11][BLNPST97, (1)], then we consider its globalization via extension to cobounding extended worldvolumes as in [In00, (5.4)] (Def. 2.6 below). Throughout, we include the half-integral shift of G_4 by $\frac{1}{4}p_1$, demanded by the flux quantization of the C-field [Wi97a]; see Remark 2.2 below. Finally, we discuss the corresponding anomaly functional (Def. 2.9 below) and show that it is a homotopy invariant on the space of gauged sigma-model fields (Lemma 2.10).

To be precise, we begin by introducing the relevant ingredients:

Definition 2.1 (Background C-field and higher gauged sigma-model fields).

(i) Let X^8 be a smooth 8-manifold which is connected, simply connected² and spin, to be called the *target spacetime*³.

(ii) Let Σ be a smooth manifold, which is compact and oriented, to be called

(a) the *worldvolume* if it is 6-dimensional $\Sigma := \Sigma^6$ without boundary;

(b) the *extended worldvolume* if it is 7-dimensional $\Sigma := \widehat{\Sigma}^7$, with collared boundary

$$\Sigma^6 = \partial\widehat{\Sigma}^7 \xrightarrow{(\text{id}, 0)} (\partial\widehat{\Sigma}^7) \times [0, 1] \hookrightarrow \widehat{\Sigma}^7. \quad (5)$$

(c) the *oriented difference of extended worldvolumes* if it is 7-dimensional $\Sigma := \widetilde{\Sigma}^7$ and arising as the oriented difference

$$\widetilde{\Sigma}^7 = \widehat{\Sigma}_1^7 - \widehat{\Sigma}_2^7 := \widehat{\Sigma}_1^7 \cup_{\Sigma^6} (\widehat{\Sigma}_2^7)^{\text{op}} \quad (6)$$

(where $(-)^{\text{op}}$ denotes orientation reversal) of two collared coboundary extension $\widehat{\Sigma}_{1,2}^7$ (5) of the same world-volume $\partial\widehat{\Sigma}_{1,2}^7 = \Sigma^6$; in particular $\widetilde{\Sigma}^7$ has no boundary.

(iii) A *background field* configuration on X^8 is

(a) an affine Spin(8)-connection ∇ on the tangent bundle⁴ TX^8 ;

(b) a pair of differential forms

$$\begin{aligned} G_4 \in \Omega_{\text{dR}}^4(X^8) & \quad \text{such that} & \quad dG_4 = 0, \\ 2G_7 \in \Omega_{\text{dR}}^7(X^8) & & \quad d2G_7 = -G_4 \wedge G_4 + (\tfrac{1}{4}p_1(\nabla)) \wedge (\tfrac{1}{4}p_1(\nabla)), \end{aligned} \quad (7)$$

where the Pontrjagin 4-form (e.g. [KN63, §XII.4])

$$p_1(\nabla) := \langle R_\nabla \wedge R_\nabla \rangle \quad (8)$$

is the value of the curvature 2-form R of ∇ in the normalized Killing form invariant polynomial $\langle -, - \rangle$ on $\mathfrak{so}(8)$. Notice that in terms of the shifted flux form [Wi97a, (1.2)][Wi97b, (1.2)][FSS19b, §3.4][FSS20b]

$$\widetilde{G}_4 := G_4 + \tfrac{1}{4}p_1(\nabla) \quad (9)$$

the second condition in (7) [Wi97b, (3.6)][FSS19b, §3.3] equivalently reads

$$d2G_7 = -(\widetilde{G}_4 \wedge \widetilde{G}_4 - \tfrac{1}{2}p_1(\nabla) \wedge \widetilde{G}_4). \quad (10)$$

(iv) A *higher gauged*⁵ *sigma-model field* is a pair

$$(f, H_3) = \left(\Sigma \xrightarrow{f \text{ smooth}} X, dH_3 = f^*(G_4 - \tfrac{1}{4}p_1(\nabla)) \right) \quad (11)$$

consisting of

(a) a smooth function f from the (extended) worldvolume to spacetime,

(b) a smooth differential 3-form H_3 on the (extended) worldvolume, which trivializes the pullback along f of the difference between G_4 from (7) and $\tfrac{1}{4}p_1(\nabla)$ from (8),

²All results in the following readily generalize to non-connected X , but nothing essential is gained thereby. The assumption that X is simply connected is to allow the use of Sullivan model analysis in §3 and §4 (as in [FSS19b, Rem 2.6][FSS20c, Rem. 3.53]). For this it would be sufficient to assume that X is *nilpotent* [FSS20c, Def. 3.52] in that it has nilpotent fundamental group acting nilpotently on homotopy and homology groups of its universal cover. This assumption should not be necessary, but without it all proofs will become much more involved.

³This pertains to M-theory on 8-manifolds, see [FSS19b, Remark 3.1]. We will often just write X for X^8 .

⁴The theorems below hold, as general statements about the 6d WZ term, for ∇ a connection on any Spin bundle. But application to the actual M5-brane system requires ∇ to be a tangent connection on spacetime.

⁵This is the higher analog of abelian gauging of 2d WZW model fields (e.g. [Fo03, (5)]), making the 6d Wess-Zumino term the action functional of a *higher gauged Wess-Zumino model* [FSS13b].

both required to have *sitting instants* on any collared boundary (5), in that in some neighborhood of the boundary they are constant in the direction perpendicular to it [FSS10, Def. 4.2.1];

(v) A *gauge transformation* or *homotopy* between two higher gauged sigma-model fields (11)

$$(f_0, (H_3)_0) \xrightarrow{(\eta, (H_3)_{[0,1]})} (f_1, (H_3)_1) \quad (12)$$

is a pair consisting of a smooth homotopy η from f_0 to f_1 and a differential 3-form $(H_3)_{[0,1]} \in \Omega_{\text{dR}}^3(\Sigma \times [0,1])$ gauging η and restricting to $(H_3)_{0,1}$ at the boundaries of the interval:

$$\begin{array}{ccc}
 \Sigma & & (\tilde{H}_3)_0 \\
 \downarrow (\text{id}, 0) & \nearrow f_0 & \uparrow (\text{id}, 0)^* \\
 \Sigma \times [0, 1] & \xrightarrow{\eta \text{ smooth}} & X \\
 \uparrow (\text{id}, 1) & \searrow f_1 & \downarrow (\text{id}, 1)^* \\
 \Sigma & & (H_3)_1
 \end{array}
 \quad d((H_3)_{[0,1]}) = \eta^*(G_4 - \frac{1}{4}p_1(\nabla)). \quad (13)$$

(vi) We write $\text{Maps}_{\text{smth}}^{\text{ggd}}(\Sigma, X) := \{(f, H_3)\}$, $\pi_0(\text{Maps}_{\text{smth}}^{\text{ggd}}(\Sigma, X)) := \{(f, H_3)\} / \sim_{\text{homotopy}}$ (14)

for the sets⁶ of higher gauged sigma-model fields (11) and of their *homotopy classes* (12), respectively.

Remark 2.2 (Shifted flux quantization corrections to the Hopf-WZ term). The existing literature on the Hopf-WZ term [Ah96, p. 11][BLNPST97, (1)][In00, (2.4)] [KS03, §3.2][HN11, (2)][Ar18, (4.13)] disregards any topological correction terms to the C-field flux proportional to $p_1(\nabla)$, shown in (9), (10). Hence, in comparing to this literature (as in Def. 2.4, Def. 2.6 below), one has to restrict to the special case that $p_1(\nabla) = 0$ (for instance in that $\nabla = 0$, hence that spacetime is assumed to be flat). Beyond this special case, such correction terms are famously thought to be required, by circumstantial arguments provided in [Wi97a][Wi97b]. The result of [FSS19b, §3.3] (recalled as Remark 3.3 below) is that charge quantization of the C-field in J-twisted Cohomotopy theory [FSS20c, §5.3] implies exactly these corrections (10); and the main Theorem 4.8 below says that with these p_1 -corrections and this cohomotopical charge quantization, the full Hopf-WZ term is actually guaranteed to be anomaly-free (namely: integral, level-quantized).

As an important example of Def. 2.1, we offer the following:

Lemma 2.3 (The 7-sphere as an extended worldvolume). *In the situation of Def. 2.1, let the oriented difference of extended worldvolumes be the 7-sphere: $\Sigma := \tilde{\Sigma}^7 := S^7$. Then the set (14) of homotopy classes of extended gauged sigma-model fields is the set underlying the 7th homotopy group of target spacetime X :*

$$\pi_0(\text{Maps}_{\text{smth}}^{\text{ggd}}(S^7, X)) \simeq \pi_7(X). \quad (15)$$

Proof. Since homotopy classes of continuous functions between smooth manifolds are given by smooth homotopy classes of smooth functions (e.g. [BT82, Cor. 17.8.1]) it follows that already smooth homotopy classes of ungauged sigma-model fields are in bijection to $\pi_7(X)$ (since the target spacetime X is assumed to be connected there is no dependence on a basepoint). Hence it only remains to show that, for any extended sigma-model field \tilde{f} , there exists at least one gauging \tilde{H}_3 (11) and that, for any two such gaugings $(\tilde{f}, (\tilde{H}_3)_0)$ and $(\tilde{f}, (\tilde{H}_3)_1)$ of the same extended sigma-model field \tilde{f} , there exists a gauged homotopy (12)

$$(\tilde{f}, (\tilde{H}_3)_0) \xrightarrow{(\tilde{\eta}, (\tilde{H}_3)_{[0,1]})} (\tilde{f}, (\tilde{H}_3)_1)$$

⁶The inclined reader will notice (see [FSS13b] for exposition) that the set $\text{Maps}_{\text{smth}}^{\text{ggd}}(\Sigma, X)$ is, of course, the underlying set of global sections of the atlas for the smooth *moduli 2-stack* of higher gauged sigma-model fields on Σ [FSS20c, §4.3], and $\pi_0(\text{Maps}_{\text{smth}}^{\text{ggd}}(\Sigma, X))$ is the set of connected components of the geometric realization of this moduli 2-stack. All of the following discussion lifts to the higher differential geometry of moduli stacks of fields, but for the sake of brevity we will not further consider this here.

between them. For the existence of the gauging \tilde{H}_3 for a given \tilde{f} , we only need to notice that because $H_{\text{dR}}^4(S^7) \cong H^4(S^7; \mathbb{R}) = 0$, we have $f^*[G_4 - \frac{1}{4}p_1(\nabla)] = 0$ and so there exists $\tilde{H}_3 \in \Omega_{\text{dR}}^3(S^7)$ such that $d\tilde{H}_3 = f^*(G_4 - \frac{1}{4}p_1(\nabla))$. Similarly, given two gaugings $(\tilde{H}_3)_0$ and $(\tilde{H}_3)_1$ of \tilde{f} , since $H_{\text{dR}}^3(S^7) = 0$ and $(\tilde{H}_3)_1 - (\tilde{H}_3)_0 \in \Omega_{\text{dR}}^3(S^7)$ is closed by assumption, there exists

$$\alpha \in \Omega_{\text{dR}}^2(S^7) \quad \text{such that} \quad d\alpha = (\tilde{H}_3)_1 - (\tilde{H}_3)_0.$$

Thus

$$(\tilde{\eta} : (x, s) \mapsto \tilde{f}(x), (\tilde{H}_3)_{[0,1]} := (\tilde{H}_3)_1 + (s-1) \cdot d\alpha + (ds) \wedge \alpha)$$

constitutes a homotopy as required. \square

We now consider the 6d Hopf-WZ term in its various incarnations, surveyed in Table A.

$\text{Maps}_{\text{smth}}^{\text{ggd}}(\Sigma^6, X^{11}) \xrightarrow{S} \mathbb{R}$	Hopf-WZ action functional on worldvolume Σ^6	Def. 2.4
$\text{Maps}_{\text{smth}}^{\text{ggd}}(\hat{\Sigma}^7, X^{11}) \xrightarrow{\hat{S}} \mathbb{R}$	Extended Hopf-WZ functional on coboundary $\partial\hat{\Sigma}^7 = \Sigma^6$	Def. 2.6
$\text{Maps}_{\text{smth}}^{\text{ggd}}(\tilde{\Sigma}^7, X^{11}) \xrightarrow{\tilde{S}} \mathbb{R}$	Hopf-WZ anomaly functional on oriented difference $\tilde{\Sigma}^7 = \hat{\Sigma}_1^7 - \hat{\Sigma}_2^7$	Def. 2.9

Table A – Incarnations of the Hopf-WZ term. The 6d Hopf-WZ term functional $S := S_{\text{WZ}}^{\text{M5}}$ is a priori defined on gauged sigma-model fields on Σ^6 . Its global definition involves an extension \hat{S} to extended fields on a coboundary $\hat{\Sigma}^7$. The difference of any two extensions is the anomaly functional \tilde{S} on fields on the oriented difference $\tilde{\Sigma}^7 = \hat{\Sigma}_1^7 - \hat{\Sigma}_2^7$.

Definition 2.4 (6d Hopf-WZ term for small sigma-model fields). In the setting of Def. 2.1, let $U \subset X^8$ be a chart (a contractible open subset). For Σ^6 any closed orientable 6-manifold, write $\text{Maps}_{\text{smth}}^{\text{ggd}}(\Sigma^6, U) \subset \text{Maps}_{\text{smth}}^{\text{ggd}}(\Sigma^6, X)$ for the subset of those higher gauged sigma-model fields (14) which factor through $U \subset X$ (the “ U -small sigma-model fields”). As the de Rham cohomology of U is trivial in positive degree, we may choose local potentials $C_3^U \in \Omega_{\text{dR}}^3(U)$ for $\iota_U^*(G_4 + \frac{1}{4}p_1(\nabla))$ and $2C_6^U \in \Omega_{\text{dR}}^6(U)$ for $\iota_U^*2G_7 + C_3^U \wedge \iota_U^*(G_4 - \frac{1}{4}p_1(\nabla))$.

$$\begin{aligned} dC_3^U &= \iota_U^*(G_4 + \frac{1}{4}p_1(\nabla)) \\ d2C_6^U &= \iota_U^*2G_7 + C_3^U \wedge \iota_U^*(G_4 - \frac{1}{4}p_1(\nabla)) \end{aligned} \quad (16)$$

$$\begin{aligned} dG_4 &= 0 \\ d2G_7 &= -G_4 \wedge G_4 + (\frac{1}{4}p_1(\nabla)) \wedge (\frac{1}{4}p_1(\nabla)) \end{aligned}$$

Then the *M5 6d Wess-Zumino term action functional* on these small fields is the function

$$\begin{aligned} \text{Maps}_{\text{smth}}^{\text{ggd}}(\Sigma^6, U) &\xrightarrow{S_{\text{WZ}}^{\text{M5}}} \mathbb{R} \\ (f_U, H_3) &\mapsto S_{\text{WZ}}^{\text{M5}}(f_U, H_3) := \frac{1}{2} \int_{\Sigma^6} (-H_3 \wedge f_U^* C_3^U + f_U^* 2C_6^U). \end{aligned} \quad (17)$$

Lemma 2.5 (Independence of choices). *The functional $S_{\text{WZ}}^{\text{M5}}(f_U, H_3)$ (17) is indeed well defined, in that it does not depend on the choice of the local potentials C_3^U and C_6^U (16).*

Proof. A different choice of local potentials is of the form $(C_3^U + \alpha_3^U, 2C_6^U + 2\alpha_6^U)$, with differentials $d\alpha_3^U = 0$ and $d2\alpha_6^U = \alpha_3^U \wedge \iota_U^*(G_4 - \frac{1}{4}p_1(\nabla))$. As the local chart U is contractible, this implies $\alpha_3^U = d\alpha_2^U$ and $2\alpha_6^U =$

$\alpha_2^U \wedge \iota_U^*(G_4 - \frac{1}{4}p_1(\nabla)) + d\alpha_5^U$. Therefore, we have

$$\begin{aligned}
& \int_{\Sigma^6} \left(-H_3 \wedge f_U^*(C_3^U + \alpha_3^U) + 2f_U^*(C_6^U + \alpha_6^U) \right) - \int_{\Sigma^6} \left(-H_3 \wedge f_U^*(C_3^U) + f_U^*(2C_6^U) \right) \\
&= \int_{\Sigma^6} -H_3 \wedge df_U^*(\alpha_2^U) + f_U^*(\alpha_2^U \wedge \iota_U^*(G_4 - \frac{1}{4}p_1(\nabla))) + df_U^*(\alpha_5^U) \\
&= \int_{\Sigma^6} -H_3 \wedge df_U^*(\alpha_2^U) + f_U^*(\alpha_2^U) \wedge f^*(G_4 - \frac{1}{4}p_1(\nabla)) + df_U^*(\alpha_5^U) \\
&= \int_{\Sigma^6} -H_3 \wedge df_U^*(\alpha_2^U) + f_U^*(\alpha_2^U) \wedge dH_3 + df_U^*(\alpha_5^U) \\
&= \int_{\Sigma^6} d \left(H_3 \wedge f_U^*(\alpha_2^U) + f_U^*(\alpha_5^U) \right) = 0.
\end{aligned}$$

□

Now we globalize this definition, following the well-known procedure originally introduced in the 2-dimensional case in [Wi83].

Definition 2.6 (Global 6d Hopf-Wess-Zumino term via extended worldvolumes). In the situation of Def. 2.1, for Σ^6 a given worldvolume, let $\widehat{\Sigma}^7$ be a compact oriented smooth collared cobounding 7-manifold⁷ according to (5)

$$\Sigma^6 := \partial\widehat{\Sigma}^7. \quad (18)$$

Then we say that the corresponding *extended action functional* for the 6d Hopf-WZ-term on the closed manifold Σ^6 is the function

$$\begin{aligned}
& \text{Maps}_{\text{smth}}^{\text{ggd}}(\widehat{\Sigma}^7, X) \xrightarrow{\widehat{S}_{\text{WZ}}^{\text{M5}}} \mathbb{R} \\
& (\widehat{f}, \widehat{H}_3) \mapsto \widehat{S}_{\text{WZ}}^{\text{M5}}(\widehat{f}, \widehat{H}_3) := \frac{1}{2} \int_{\widehat{\Sigma}^7} \left(\widehat{H}_3 \wedge \widehat{f}^*(G_4 + \frac{1}{4}p_1(\nabla)) + \widehat{f}^*2G_7 \right)
\end{aligned} \quad (19)$$

on the set of extended gauged sigma-model fields (11). (For flat backgrounds, $\nabla = 0$, this reduces to the (1), see Remark 2.2.)

Lemma 2.7 (Global Hopf-WZ-term restricts to local Hopf-WZ-term). *In the situation of Def. 2.4, consider a worldvolume Σ^6 . Then, for every choice of extended worldvolume $\widehat{\Sigma}^7$ (18) the corresponding extended action functional \widehat{S} (Def. 2.6) coincides, for any chart $U \subset X$, on U -small extended sigma-model fields $\widehat{f} = \iota_U \circ \widehat{f}_U$ (16) with the local action functional S (Def. 2.4) evaluated on the boundary values $f := \widehat{f}|_{\Sigma^6}$ of the extended fields:*

$$\begin{array}{ccc}
\text{Maps}_{\text{smth}}^{\text{ggd}}(\widehat{\Sigma}^7, U) & \xrightarrow{\widehat{S}_{\text{WZ}}^{\text{M5}}} & \mathbb{R} \\
\downarrow (-)|_{\partial\widehat{\Sigma}^7} & \nearrow S_{\text{WZ}}^{\text{M5}} & \\
\text{Maps}_{\text{smth}}^{\text{ggd}}(\Sigma^6, U) & &
\end{array}
\quad \widehat{S}_{\text{WZ}}^{\text{M5}}(\widehat{f}, \widehat{H}_3) = S_{\text{WZ}}^{\text{M5}}\left(f := \widehat{f}|_{\partial\widehat{\Sigma}^7}, H_3 := (\widehat{H}_3)|_{\partial\widehat{\Sigma}^7}\right).$$

Proof. Observe, with (11) and (16), that

$$\begin{aligned}
d \left(-\widehat{H}_3 \wedge \widehat{f}_U^* C_3^U + \widehat{f}_U^* 2C_6^U \right) &= -\underbrace{d\widehat{H}_3}_{\widehat{f}^*(G_4 - \frac{1}{4}p_1(\nabla))} \wedge \widehat{f}_U^* C_3^U + \widehat{H}_3 \wedge \underbrace{f_U^* dC_3^U}_{\widehat{f}^*(G_4 + \frac{1}{4}p_1(\nabla))} + \underbrace{\widehat{f}_U^* d2C_6^U}_{\widehat{f}^*(G_4 - \frac{1}{4}p_1(\nabla)) \wedge \widehat{f}_U^* C_3^U + \widehat{f}^* 2G_7} \\
&= \widehat{H}_3 \wedge \widehat{f}^*(G_4 + \frac{1}{4}p_1(\nabla)) + \widehat{f}^* 2G_7.
\end{aligned} \quad (20)$$

With this, the claim follows by Stokes' theorem:

⁷This always exists, since the oriented cobordism ring in dimension 6 is trivial and by the collar neighbourhood theorem.

$$\begin{aligned}
\widehat{S}_{\text{WZ}}^{\text{M5}}(\widehat{f}, \widehat{H}_3) &:= \frac{1}{2} \int_{\widehat{\Sigma}^7} \left(\widehat{H}_3 \wedge \widehat{f}^* (G_4 + \frac{1}{4} p_1(\nabla)) + \widehat{f}_U^* 2G_7 \right) \\
&= \frac{1}{2} \int_{\widehat{\Sigma}^7} d \left(-\widehat{H}_3 \wedge \widehat{f}_U^* C_3^U + \widehat{f}_U^* 2C_6^U \right) \\
&= \frac{1}{2} \int_{\partial \widehat{\Sigma}^7} \left(-\widehat{H}_3 \wedge \widehat{f}_U^* C_3^U + \widehat{f}_U^* 2C_6^U \right) |_{\partial \widehat{\Sigma}^7} \\
&= \frac{1}{2} \int_{\Sigma^6} \left(-H_3 \wedge f_U^* C_3^U + f_U^* 2C_6^U \right) \\
&=: S_{\text{WZ}}^{\text{M5}}(f_U, H_3). \quad \square
\end{aligned} \tag{21}$$

Example 2.8 (Coboundaries for $\Sigma^6 = S^3 \times S^3$). In the situation of Def. 2.1, consider as worldvolume the product manifold of two 3-spheres (this is considered in [MS15, Example 2] in the non-commutative setting): $\Sigma^6 = S^3 \times S^3$. In this case, there is a canonical choice of cobounding manifold $\widehat{\Sigma}^7$ (18) given by the Cartesian product of the 4-disk D^4 (the closed 4-dimensional ball) with the 3-sphere, in either order (as in [Sa13]):

$$\widehat{\Sigma}_L^7 := D^4 \times S^3 \quad \text{and} \quad \widehat{\Sigma}_R^7 := (S^3 \times D^4)^{\text{op}}. \tag{22}$$

Here we are equipping each of

$$\left. \begin{array}{l} S^3 \times S^3, \\ D^4 \times S^3 = D^4 \times (\partial D^4), \\ S^3 \times D^4 = (\partial D^4) \times D^4, \end{array} \right\} \subset D^4 \times D^4 \subset \mathbb{R}^8$$

with the orientation induced from the canonical embedding into \mathbb{R}^8 , which implies, by the odd-dimensionality of S^3 , that the boundary of $S^3 \times D^4$ is $(S^3 \times S^3)^{\text{op}}$ (opposite orientation). This way, with (22) we indeed have

$$\partial \widehat{\Sigma}_{L,R}^7 = \Sigma^6 := S^3 \times S^3$$

as oriented manifolds. Observe that the union of one of these coboundaries with the orientation reversal of the other is the 7-sphere (as considered in Lemma 2.3):⁸

$$\begin{aligned}
\widetilde{\Sigma}^7 &:= \widehat{\Sigma}_L^7 \cup (\widehat{\Sigma}_R^7)^{\text{op}} = D^4 \times (\partial D^4) \cup (\partial D^4) \times D^4 \\
&= \partial(D^4 \times D^4) \\
&\simeq \partial D^8 \\
&= S^7.
\end{aligned}
\quad
\begin{array}{ccc}
S^3 \times S^3 & \longrightarrow & D^4 \times S^3 \\
\downarrow & \text{(po)} & \downarrow \\
S^3 \times D^4 & \longrightarrow & S^7
\end{array} \tag{23}$$

While Def. 2.6 gives global meaning to the local Hopf-WZ term (Def. 2.4), by Lemma 2.7, this potentially comes at the cost that the global definition depends on the choice of coboundary (18). The following definition measures this potential dependency:

Definition 2.9 (Hopf-WZ anomaly functional/Page charge). In the situation of Def. 2.1, with given worldvolume Σ^6 , consider in Def. 2.6 two choices $\widehat{\Sigma}_{L,R}^7$ of collared cobounding extended worldvolumes (5) $\partial \widehat{\Sigma}_{L,R}^7 = \Sigma^6$. This makes their oriented difference (6) a smooth closed 7-manifold $\widetilde{\Sigma}^7 := \widehat{\Sigma}_L^7 - \widehat{\Sigma}_R^7 := \widehat{\Sigma}_L^7 \cup_{\Sigma^6} (\widehat{\Sigma}_R^7)^{\text{op}}$. Then for

$$\begin{array}{ccc}
\widehat{\Sigma}_L^7 & \xrightarrow{\widehat{f}_L} & X \\
\uparrow \iota_{\partial L} & & \uparrow \\
\Sigma^6 & \xrightarrow{f} & X \\
\downarrow \iota_{\partial R} & & \downarrow \\
\widehat{\Sigma}_R^7 & \xrightarrow{\widehat{f}_R} & X
\end{array}
\quad
\begin{array}{c}
d(\widehat{H}_3)_L = \widehat{f}_L^* G_4 \\
\downarrow \iota_{\partial L}^* \\
dH_3 = f^* G_4 \\
\uparrow \iota_{\partial R}^* \\
d(\widehat{H}_3)_R = \widehat{f}_R^* G_4
\end{array}$$

⁸Note that a different manipulation treats these, untraditionally, as manifolds with corners [Sa14][Sa13].

any pair of gauged extended sigma-model fields (11), extending the same ordinary sigma-model field f over the two choices of coboundaries, respectively, we obtain a gauged extended sigma-model field (\tilde{f}, \tilde{H}_3) on the closed 7-manifold $\tilde{\Sigma}^7$ (6) (which is smooth by the assumption of sitting instantons in (11)):

$$\begin{array}{ccc}
\widehat{\Sigma}_L^7 & \begin{array}{c} \xrightarrow{\hat{f}_L} \\ \downarrow \iota_L \\ \xrightarrow{\tilde{f}} \\ \uparrow \iota_R \\ \widehat{\Sigma}_R^7 \end{array} & X \\
& & \\
d(\widehat{H}_3)_L = \widehat{f}_L^* G_4 & & d(\widehat{H}_3)_R = \widehat{f}_R^* G_4 \\
\uparrow \iota_L^* & & \downarrow \iota_R^* \\
d\tilde{H}_3 = \tilde{f}^* G_4 & & \\
\end{array} \tag{24}$$

In terms of this, the difference between the two extended action functionals (Def. 2.6) corresponding to the two choices of coboundaries may be expressed as a single integral over $\tilde{\Sigma}^7$:

$$\begin{aligned}
\tilde{S}(\tilde{f}, \tilde{H}_3) &:= \widehat{S}(\widehat{f}_L, (\widehat{H}_3)_L) - \widehat{S}(\widehat{f}_R, (\widehat{H}_3)_R) \\
&= \frac{1}{2} \int_{\tilde{\Sigma}^7} (\tilde{H}_3 \wedge \tilde{f}^* (G_4 + \frac{1}{4} p_1(\nabla)) + \tilde{f}^* 2G_7).
\end{aligned} \tag{25}$$

We call expression (25) the *anomaly functional* of the 6d Hopf-Wess-Zumino term. In supergravity this expression is also known as the *Page charge* (traditionally disregarding the shift by $\frac{1}{4} p_1$, see Remark 2.2).

Lemma 2.10 (Hopf-WZ anomaly functional is homotopy invariant). *In the situation of Def. 2.1, let $\Sigma := \tilde{\Sigma}^7$ be a closed 7-manifold. Then the Hopf-WZ anomaly functional (25) is well-defined on the set (14) of homotopy classes of higher gauged sigma-model fields:*

$$\begin{array}{ccc}
\pi_0 \left(\text{Maps}_{\text{smth}}^{\text{ggd}}(\tilde{\Sigma}^7, X) \right) & \xrightarrow{\tilde{S}} & \mathbb{R} \\
[\tilde{f}, \tilde{H}_3] & \mapsto & \frac{1}{2} \int_{\tilde{\Sigma}^7} (\tilde{H}_3 \wedge \tilde{f}^* (G_4 + \frac{1}{4} p_1(\nabla)) + \tilde{f}^* 2G_7)
\end{array} \tag{26}$$

in that the integral on the right is independent of the choice of representative (\tilde{f}, \tilde{H}_3) in its homotopy class.

Proof. Given a gauge transformation/homotopy (12) between two extended gauged sigma-model fields

$$(\tilde{f}_0, (\tilde{H}_3)_0) \xrightarrow{(\tilde{\eta}, (\tilde{H}_3)_{[0,1]})} (\tilde{f}_1, (\tilde{H}_3)_1)$$

we need to show that $\tilde{S}([\tilde{f}_1, (\tilde{H}_3)_1]) = \tilde{S}([\tilde{f}_0, (\tilde{H}_3)_0])$. With the data (13) and using Stokes' theorem we directly compute as follows:

$$\begin{aligned}
\tilde{S}([\tilde{f}_1, (\tilde{H}_3)_1]) - \tilde{S}([\tilde{f}_0, (\tilde{H}_3)_0]) &= \frac{1}{2} \int_{\partial(\tilde{\Sigma}^7 \times [0,1])} \left((\tilde{H}_3)_{[0,1]} \wedge \tilde{\eta}^* (G_4 + \frac{1}{4} p_1(\nabla)) + \tilde{\eta}^* 2G_7 \right) \\
&= \frac{1}{2} \int_{\tilde{\Sigma}^7 \times [0,1]} d \left((\tilde{H}_3)_{[0,1]} \wedge \tilde{\eta}^* (G_4 + \frac{1}{4} p_1(\nabla)) + \tilde{\eta}^* 2G_7 \right) \\
&= \frac{1}{2} \int_{\tilde{\Sigma}^7 \times [0,1]} \underbrace{d \left((\tilde{H}_3)_{[0,1]} \right)}_{\tilde{\eta}^* (G_4 - \frac{1}{4} p_1(\nabla))} \wedge \tilde{\eta}^* (G_4 + \frac{1}{4} p_1(\nabla)) + \tilde{\eta}^* d2G_7 \\
&= \frac{1}{2} \int_{\tilde{\Sigma}^7 \times [0,1]} \tilde{\eta}^* \left(\underbrace{(G_4 - \frac{1}{4} p_1(\nabla)) \wedge (G_4 + \frac{1}{4} p_1(\nabla))}_{=0} + d2G_7 \right) \\
&= 0,
\end{aligned}$$

where in the last step, under the brace, we used the condition (7). □

3 The full M5 Hopf-WZ anomaly is a homotopy Whitehead integral

We first recall from [FSS19b][FSS20c, §5.3] how the background C-field $(G_4, 2G_7)$ is a cocycle in twisted rational Cohomotopy; this is Remark 3.3 below. Then we prove, in Theorem 3.4, that the Hopf-WZ anomaly functional from §2 is equivalently a lift in rational Cohomotopy through the equivariant quaternionic Hopf fibration, hence is in particular a homotopy invariant of both the gauged sigma-model fields and the background fields in Cohomotopy. Further below, in §4, this allows us to identify the anomaly functional as a twisted/parametrized generalization of a homotopy Whitehead integral.

Notions from rational homotopy theory. In the following, we make free use of Sullivan model dgc-algebras in rational homotopy theory (i.e., what in supergravity are called “FDA”s [FSS13b][FSS19a]); see [Su77][BG76] for the original accounts, [Hes06] for introduction, [GM81] for a standard textbook account, and see [FSS16][FSS17][FSS19a][FSS20c] for review streamlined towards our application. As in these references, for X a simply-connected topological space of finite rational type, we write $\text{CE}(IX)$ for its minimal Sullivan model differential graded-commutative algebra (dgc-algebra), indicating that this is the Chevalley-Eilenberg algebra of the minimal Whitehead L_∞ -algebra IX corresponding to the loop group of X (see [FSS20c, Prop. 3.64]). For making Sullivan models explicit, we display the list of differential relations on each generator, thereby declaring what the generators are (see [FSS20c, (99)]), as shown in the following examples.

Example 3.1 (Quaternionic Hopf fibration). We denote the minimal relative Sullivan model for the plain quaternionic Hopf fibration $h_{\mathbb{H}}$ as follows (see [FSS19b, Lemma 3.18]):

$$\begin{array}{ccc}
 S^7 & & \text{CE}(IS^7) = \text{=====} (d\omega_7 = 0) \\
 \downarrow h_{\mathbb{H}} & & \uparrow \text{minimal relative Sullivan model ("FDA")} \\
 S^4 & & \text{CE}(IS^4) = \text{=====} \begin{pmatrix} d\omega_4 = 0 \\ d\omega_7 = -\omega_4 \wedge \omega_4 \end{pmatrix}
 \end{array} \quad (27)$$

topological homotopy theory

dgc-algebraic rational homotopy theory

Example 3.2 (Classifying space of Fivebrane-extended Spin-group). The minimal relative Sullivan model for the homotopy fiber $\widehat{B\text{Sp}(2)}$ of the classifying map for the Euler 8-class χ_8 on the classifying space for the quaternionic unitary group $\text{Sp}(2) \hookrightarrow \text{Spin}(8)$ (see [FSS20b, §A]) is as follows (using [FSS19b, (97)][FSS20c, Lem. 4.24]):

$$\begin{array}{ccc}
 \widehat{B\text{Sp}(2)} \xrightarrow{\cong} \widehat{B\text{Spin}(5)} & \text{homotopy fiber trivializing obstructing 8-class} & \begin{pmatrix} d\theta_7 = \chi_8 \\ d\chi_8 = 0 \\ d\frac{1}{2}p_1 = 0 \end{pmatrix} \xleftarrow{\cong} \begin{pmatrix} d\theta_7 = -\frac{1}{4}p_2 + (\frac{1}{4}p_1)^2 \\ dp_2 = 0 \\ d\frac{1}{2}p_1 = 0 \end{pmatrix} \\
 \downarrow \text{hofib}(\chi_8) & \downarrow \text{hofib}(-\frac{1}{4}p_2 + (\frac{1}{4}p_1)^2) & \uparrow \text{minimal relative Sullivan model} \\
 B\text{Sp}(2) \xrightarrow{\text{tri}} B\text{Spin}(5) \xrightarrow{-\frac{1}{4}p_2 + (\frac{1}{4}p_1)^2} K(\mathbb{Z}, 8) & & \begin{pmatrix} d\chi_8 = 0 \\ d\frac{1}{2}p_1 = 0 \end{pmatrix} \xleftarrow{\text{tri}^*} \begin{pmatrix} dp_2 = 0 \\ d\frac{1}{2}p_1 = 0 \end{pmatrix} \xleftarrow{-\frac{1}{4}p_2 + (\frac{1}{4}p_1)^2 \leftarrow c_8} (dc_8 = 0) \\
 \searrow \chi_8 & & \swarrow \chi_8 \leftarrow c_8
 \end{array} \quad (28)$$

Notice that the higher extension $\widehat{\text{Sp}(2)}$ in (28) is a version of the *Fivebrane 6-group*, and tangential $\widehat{\text{Sp}(2)}$ -structure trivializing this 8-class is a kind of *Fivebrane structure* according to [SSS09][SSS12]: a higher analog of *String structure* (trivializing $\frac{1}{2}p_1$), which itself is a higher analog of *Spin-structure* (trivializing w_2). In higher analogy to how *Spin-structure* is the topological condition on target spacetime needed for anomaly cancellation of the spinning particle [Wi85], and *String-structure* is the topological condition for anomaly cancellation of the (heterotic) string (i.e. for the Green-Schwarz mechanism, see [SSS12][FSS20a][FSS20b]), so *Fivebrane structure* is meant to be the topological condition needed for anomaly cancellation of the (heterotic) five-brane. That this is the case for $\widehat{\text{Sp}(2)}$ -structure, as concerns the Hopf-WZ term of the M5-brane, is brought out by our main Theorems 3.4 and 4.8 below, see Remark 4.3 below.

Rationalization over the real numbers. In order to have a *smooth* non-abelian de Rham theorem ([FSS20c, Thm. 3.87]) involving the real de Rham dg-algebras $\Omega_{\mathrm{dR}}^\bullet(-)$ of smooth differential forms, we take the rational base field to be \mathbb{R} instead of \mathbb{Q} (as in [GM81][FSS20c, Rem. 3.51]), so that our “rational homotopy groups” are actually “real homotopy groups” $\pi(X) \otimes_{\mathbb{Z}} \mathbb{R}$; which makes no essential difference (by [BG76, Lem. 11.7]). Accordingly, for X a simply-connected topological space, we write

$$X \xrightarrow[\text{rationalization}]{\eta_X^{\mathbb{R}}} L_{\mathbb{R}}X \quad (29)$$

for its rationalization (localization over the real numbers, see [FSS20c, Def. 3.55]).

Example 3.3 (Background C-field is cocycle in rational twisted Cohomotopy). The minimal Sullivan model (“FDA”) of the 4-sphere is free on generators ω_4 and ω_7 (in degrees 4 and 7, respectively), subject to differential relations shown on the bottom of (27). This means ([Sa13, §2.5], see also [FSS16, §2][FSS19a, (59)][FSS20c, Ex. 3.81]) that the background C-field data (7) in the case that $p_1(\nabla) = 0$ (8), is equivalently a flat L_∞ -algebra valued differential form [FSS20c, Def. 3.77] with values in the Whitehead L_∞ -algebra $\mathfrak{L}S^4$ [FSS20c, Ex. 3.68], namely a dg-algebra homomorphism from $\mathrm{CE}(\mathfrak{L}S^4)$ to the de Rham algebra of X :

$$X \xrightarrow{(G_4, 2G_7)} L_{\mathbb{R}}S^4 \xleftarrow[\text{[FSS20c, Thm. 3.87]}]{\text{non-abelian de Rham theorem}} \Omega_{\mathrm{dR}}^\bullet(X) \xleftarrow[\text{2}G_7 \leftarrow \omega_7]{G_4 \leftarrow \omega_4} \begin{pmatrix} d\omega_4 = 0 \\ d\omega_7 = -\omega_4 \wedge \omega_4 \end{pmatrix} \quad (30)$$

cocycle in dg-algebra homomorphism
rational 4-Cohomotopy

More generally [FSS19b, Prop. 3.20], consider $X = X^8$ a spin 8-manifold for M-theory compactified on 8-manifolds [FSS19b, Rem. 3.1], hence such that:

(i) the tangent bundle of X^8 is equipped with tangential $\mathrm{Sp}(2) \rightarrow \mathrm{Spin}(8)$ -structure τ (reflecting M2-brane background, see [FSS19b, p. 8 & §2.3]) with compatible connection ∇ (see [FSS20c, Def. 5.25]):

$$\begin{array}{ccc} X^8 & \xrightarrow[\text{tangential } \mathrm{Sp}(2)\text{-structure } \tau]{\tau} & B\mathrm{Sp}(2) \\ & \searrow^{TX^8} & \swarrow \\ & B\mathrm{Spin}(8) & \end{array} \quad \begin{array}{ccc} \Omega_{\mathrm{dR}}^\bullet(X^8) & \xrightarrow[\frac{1}{2}p_1(\nabla) \leftarrow \frac{1}{2}p_1]{\chi_8(\nabla) \leftarrow \chi_8} & \begin{pmatrix} d\chi_8 = 0 \\ d\frac{1}{2}p_1 = 0 \end{pmatrix} \\ & \swarrow^{p_2(\nabla) \leftarrow p_2} & \nearrow^{p_2 \mapsto 4((\frac{1}{4}p_1)^2 - \chi_8)} \\ & \left(\begin{array}{l} dp_2 = 0 \\ dp_1 = 0 \end{array} \right) & \swarrow_{p_1 \mapsto p_1} \end{array} \quad (31)$$

classifying map of spin-structure

(ii) the corresponding Euler 8-form $\chi_8(\nabla)$ trivializes (meaning that the singular M2-brane loci themselves are removed from X^8 , see [FSS19b, §2.5])

$$\Theta_7 \in \Omega_{\mathrm{dR}}^7(X) \quad \text{such that} \quad d\Theta_7 = \chi_8(\nabla) := \mathrm{Pf}(R), \quad (32)$$

which means (by Example 3.2) that the $\mathrm{Sp}(2)$ -structure on X further lifts to $\widehat{\mathrm{Sp}}(2)$ -structure $\widehat{\tau}$:

$$\begin{array}{ccc} X & \xrightarrow{\widehat{\tau}} & \widehat{B\mathrm{Sp}}(2) \\ & \searrow^{\tau} & \swarrow^{\mathrm{hofib}(\chi_8)} \\ & B\mathrm{Sp}(2) & \end{array} \quad \begin{array}{ccc} \Omega_{\mathrm{dR}}^\bullet(X^8) & \xleftarrow[\frac{1}{2}p_1(\nabla) \leftarrow \frac{1}{2}p_1]{\Theta_7 \leftarrow \theta_7} & \begin{pmatrix} d\theta_7 = \chi_8 \\ d\chi_8 = 0 \\ d\frac{1}{2}p_1 = 0 \end{pmatrix} \\ & \swarrow^{\chi_8(\nabla) \leftarrow \chi_8} & \nearrow \\ & \left(\begin{array}{l} \chi_8(\nabla) \leftarrow \chi_8 \\ \frac{1}{2}p_1(\nabla) \leftarrow \frac{1}{2}p_1 \end{array} \right) & \swarrow \\ & \mathrm{CE}(\mathfrak{L}B\mathrm{Sp}(2)) & \end{array} \quad (33)$$

Then the general background field data (7) (now including the p_1 -terms, Remark 2.2) may be identified with a cocycle in rational τ -twisted Cohomotopy (see also [FSS20c, Ex. 3.96]):

$$\begin{array}{ccc}
X & \xrightarrow{(G_4, 2G_7)} & L_{\mathbb{R}}(S^4 // \mathrm{Sp}(2)), \\
\searrow \tau & \swarrow & \nearrow \\
& & L_{\mathbb{R}}\mathrm{BSp}(2)
\end{array}
\qquad
\begin{array}{ccc}
\Omega_{\mathrm{dR}}^{\bullet}(X) & \xleftarrow{\begin{array}{c} G_4 \quad \leftarrow \quad \omega_4 \\ 2G_7 - \Theta_7 \quad \leftarrow \quad \omega_7 \end{array}} & \left(\begin{array}{l} d\omega_4 = 0 \\ d\omega_7 = -\omega_4 \wedge \omega_4 + \frac{1}{4}p_1 \wedge \frac{1}{4}p_1 \\ -\chi_8 \end{array} \right) \\
\begin{array}{l} p_1(\mathbb{V}) \leftarrow p_1 \\ p_2(\mathbb{V}) \leftarrow p_2 \\ \chi_8(\mathbb{V}) \leftarrow \chi_8 \end{array} & \swarrow & \nearrow \\
& & \mathrm{CE}(\mathrm{BSp}(2)) \quad \begin{array}{l} p_1 \mapsto p_1 \\ p_2 \mapsto p_2 \\ \chi_8 \mapsto \chi_8 \end{array}
\end{array} \quad (34)$$

cocycle in twisted rational 4-Cohomotopy

relative dg-algebra homomorphism

Our first main Theorem 3.4 says that not only does rational twisted Cohomotopy naturally encode the background C-field, via Remark 3.3, but that it also naturally encodes the gauging (11) of the M5-brane sigma-model fields (as in [FSS19b, Rem. 3.17]) as well as the anomaly functional of the 6d Hopf-WZ term (Def. 2.9) as a homotopy invariant (Lemma 2.10):

Theorem 3.4 (6d Hopf-WZ anomaly functional is lift through $h_{\mathbb{H}}$). *In the situation of Def. 2.1, consider a closed extended worldvolume $\Sigma := \tilde{\Sigma}^7$. Then, under the identification of the background field with a cocycle c in rational twisted Cohomotopy, via Remark 3.3, we have:*

- (i) *The homotopy classes (14) of $\widehat{\text{gaugings}} \tilde{H}_3$ (11) of an extended sigma-model field \tilde{f} are in bijection to homotopy classes of homotopy lifts $c \circ \tilde{f}$ through the quaternionic Hopf fibration $h_{\mathbb{H}}$ (27) of the composite $c \circ \tilde{f}$ of \tilde{f} with the classifying map c (34) of the background C-field:*

$$\pi_0(\mathrm{Maps}_{\mathrm{smth}}^{\mathrm{ggd}}(\Sigma, X))|_{\tilde{f}} \simeq \left\{ \begin{array}{ccc} \tilde{\Sigma}^7 & \xrightarrow{\widehat{c \circ \tilde{f}}} & L_{\mathbb{R}}(S^7 // \mathrm{Sp}(2)) \\ & \swarrow \widehat{c \circ \tilde{f}} & \nearrow L_{\mathbb{R}}(h_{\mathbb{H}} // \mathrm{Sp}(2)) \\ & & L_{\mathbb{R}}(S^4 // \mathrm{Sp}(2)) \end{array} \right\} / \sim_{\text{relative homotopy}} \quad (35)$$

- (ii) *Under this bijection (35), twice the anomaly functional (Def. 2.9) equals the correction by the Euler-potential Θ_7 (32) of the integral*

$$2\tilde{S}(\tilde{f}, \tilde{H}_3) = \int_{\tilde{\Sigma}^7} \left((\widehat{c \circ \tilde{f}})^*(\omega_7) + f^*\Theta_7 \right) \quad (36)$$

of the pullback of the angular cochain $\tilde{\omega}_7$ on the universal 7-spherical fibration (34) which is fiberwise the unit volume form on S^7 and which trivializes minus the universal Euler form:

$$\langle \tilde{\omega}_7, S^7 \rangle = 1, \quad d\tilde{\omega}_7 = -\chi_8. \quad (37)$$

Proof. By [FSS19b, Lem. 3.19] the dgc-algebra model for the situation is as shown on the right in the following diagram, where the generator $\tilde{\omega}_7$ in the top right satisfies (37) by [FSS19b, Prop. 2.5 (39)]:

$$\begin{array}{ccc}
\begin{array}{ccc}
\tilde{\Sigma}^7 & \xrightarrow{\widehat{cof\tilde{f}}} & L_{\mathbb{R}}(S^7 // \mathrm{Sp}(2)) \\
\downarrow \tilde{f} & \nearrow \tilde{H}_3 \simeq & \downarrow L_{\mathbb{R}}(h_{\mathbb{H}} // \mathrm{Sp}(2)) \\
X & \xrightarrow{c} & L_{\mathbb{R}}(S^4 // \mathrm{Sp}(2)) \\
\searrow \tau & & \downarrow \\
\mathrm{BSp}(2) & &
\end{array} & &
\begin{array}{ccc}
\Omega_{\mathrm{dR}}^{\bullet}(\tilde{\Sigma}^7) & \xleftarrow{(2\tilde{S}(\tilde{f}, \tilde{H}_3) - \int_{\tilde{\Sigma}^7} \tilde{f}^* \Theta_7) \cdot \mathrm{vol}_{\tilde{\Sigma}^7} \leftarrow \tilde{\omega}_7} & (d\tilde{\omega}_7 = -\chi_8) \\
\uparrow \tilde{f}^* & \nearrow \eta^* \simeq & \begin{array}{c} \simeq \begin{array}{c} \uparrow \\ 0 \quad \frac{1}{4} p_1 \quad \tilde{\omega}_7 \\ \uparrow \quad \uparrow \quad \uparrow \\ h_3 \quad \omega_4 \quad \omega_7 \end{array} \\ \left(\begin{array}{l} dh_3 = \omega_4 - \frac{1}{4} p_1 \\ d\omega_4 = 0 \\ d\omega_7 = -dh_3 \wedge (\omega_4 + \frac{1}{4} p_1) \\ -\chi_8 \end{array} \right) \\ \uparrow \begin{array}{c} \omega_4 \quad \omega_7 \\ \uparrow \quad \uparrow \\ \omega_4 \quad \omega_7 \end{array} \\ \left(\begin{array}{l} d\omega_4 = 0 \\ d\omega_7 = -\omega_4 \wedge \omega_4 + (\frac{1}{4} p_1)^2 \\ -\chi_8 \end{array} \right) \end{array} \\
\Omega_{\mathrm{dR}}^{\bullet}(X) & \xleftarrow{\begin{array}{c} G_4 \leftarrow \omega_4 \\ 2G_7 - \Theta_7 \leftarrow \omega_7 \end{array}} & \\
\uparrow & \nearrow & \begin{array}{c} p_1 \mapsto p_1 \\ p_2 \mapsto p_2 \\ \chi_8 \mapsto \chi_8 \end{array} \\
\Omega_{\mathrm{dR}}^{\bullet}(X) & & \mathrm{CE}(\mathfrak{lBSp}(2))
\end{array}
\end{array}
\tag{38}$$

Here the right vertical morphism is the relative minimal Sullivan model (e.g. [FSS20c, Prop. 3.17]) of the parametrized quaternionic Hopf fibration, which is a cofibration out of a cofibrant object (e.g. [FSS20c, Prop. 3.43]). Since, moreover, every dgc-algebra is projectively fibrant (e.g. [FSS20c, Rem. 3.37]), any homotopy as on the left in (38) is represented by a homotopy η^* as shown on the right (e.g. [FSS20c, Prop. A.16]).

(i) The diagonal morphism on the right of (38) manifestly exhibits a choice of gauging \tilde{H}_3 of \tilde{f} . So to prove the first claim it just remains to see that this establishes a bijection on homotopy classes. Observe that a homotopy of homotopy lifts is now of this form:

$$\begin{array}{ccc}
\Omega_{\mathrm{dR}}^{\bullet}(\tilde{\Sigma}^7) & \xleftarrow{\begin{array}{c} (\tilde{H}_3)_0 \leftarrow h_3 \\ \tilde{f}^* G_4 \leftarrow \omega_4 \\ \tilde{f}^* 2G_7 - \tilde{f}^* \Theta_7 \leftarrow \omega_7 \end{array}} & \\
\uparrow \tilde{f}^* & \nearrow \eta^* & \begin{array}{c} \left(\begin{array}{l} dh_3 = \omega_4 - \frac{1}{4} p_1 \\ d\omega_4 = 0 \\ d\omega_7 = -dh_3 \wedge (\omega_4 + \frac{1}{4} p_1) - \chi_8 \end{array} \right) \\ \uparrow \begin{array}{c} \omega_4 \quad \omega_7 \\ \uparrow \quad \uparrow \\ \omega_4 \quad \omega_7 \end{array} \\ \left(\begin{array}{l} d\omega_4 = 0 \\ d\omega_7 = -\omega_4 \wedge \omega_4 + (\frac{1}{4} p_1)^2 - \chi_8 \end{array} \right) \end{array} \\
\Omega_{\mathrm{dR}}^{\bullet}(X) & \xleftarrow{\begin{array}{c} G_4 \leftarrow \omega_4 \\ 2G_7 - \Theta_7 \leftarrow \omega_7 \end{array}} &
\end{array}
\tag{39}$$

Hence, since path space objects of de Rham dgc-algebras over X are given by de Rham dgc-algebras over $X \times [0, 1]$ (e.g. [FSS20c, Lem. 3.88]), this is equivalently (e.g. [FSS20c, Prop. A.16]) a dgc-algebra homomorphism making the following diagram commute under $\mathrm{CE}(\mathfrak{lBSp}(2))$ (where s denotes the canonical coordinate function on $[0, 1]$):

$$\begin{array}{ccc}
\begin{array}{c} \Omega_{\text{dR}}^\bullet(\tilde{\Sigma}^7) \\ \begin{array}{c} 0 \ 0 \\ \uparrow \uparrow \\ s \ ds \end{array} \end{array} & \begin{array}{c} (\tilde{H}_3)_0 \quad \leftarrow h_3 \\ \tilde{f}^* G_4 \quad \leftarrow \omega_4 \\ \tilde{f}^* 2G_7 - \tilde{f}^* \Theta_7 \leftarrow \omega_7 \end{array} & \\
\Omega_{\text{dR}}^\bullet(\tilde{\Sigma}^7 \times [0, 1]) & \longleftarrow \eta^* & \\
\begin{array}{c} s \ ds \\ \downarrow \downarrow \\ 1 \ 0 \end{array} & & \\
\Omega_{\text{dR}}^\bullet(\tilde{\Sigma}^7) & \begin{array}{c} (\tilde{H}_3)_1 \quad \leftarrow h_3 \\ \tilde{f}^* G_4 \quad \leftarrow \omega_4 \\ \tilde{f}^* 2G_7 - \tilde{f}^* \Theta_7 \leftarrow \omega_7 \end{array} & \\
(\tilde{H}_3)_{[0,1]} & \longleftarrow h_3 &
\end{array} \left(\begin{array}{l} dh_3 = \omega_4 - \frac{1}{4}p_1 \\ d\omega_4 = 0 \\ d\omega_7 = -\omega_4 \wedge \omega_4 + (\frac{1}{4}p_1)^2 \\ -\mathcal{X}_8 \end{array} \right). \quad (40)$$

But this homotopy diagram (40) manifestly exhibits the same data and conditions as in (13) for a homotopy of gaugings of a sigma-model field \tilde{f} :

$$(\tilde{f}, (H_3)_0) \xrightarrow{(\text{id}, (\tilde{H}_3)_{[0,1]})} (\tilde{f}, (H_3)_1),$$

and hence homotopy classes are equivalent to gauge equivalence classes, as claimed.

(ii) Consider in the following any 7-form on $\tilde{\Sigma}^7$ of unit volume:

$$\text{vol}_{\tilde{\Sigma}^7} \in \Omega_{\text{dR}}^7(\tilde{\Sigma}^7) \quad \text{such that} \quad \int_{\tilde{\Sigma}^7} \text{vol}_{\tilde{\Sigma}^7} = 1. \quad (41)$$

Again using the above path space objects, the homotopy η^* on the right in (38) is a dgc-algebra homomorphism that makes the following diagram commute under $\text{CE}(\text{tBSp}(2))$:

$$\begin{array}{ccc}
\begin{array}{c} \Omega_{\text{dR}}^\bullet(\tilde{\Sigma}^7) \\ \begin{array}{c} 0 \ 0 \\ \uparrow \uparrow \\ s \ ds \end{array} \end{array} & \begin{array}{c} (2\tilde{S} - \int_{\tilde{\Sigma}^7} \tilde{f}^* \Theta_7) \cdot \text{vol}_{\tilde{\Sigma}^7} \leftarrow \omega_7 \\ \frac{1}{4} \tilde{f}^* p_1(\nabla) \quad \leftarrow \omega_4 \\ 0 \quad \leftarrow h_3 \end{array} & \\
\Omega_{\text{dR}}^\bullet(\tilde{\Sigma}^7 \times [0, 1]) & \longleftarrow \eta^* & \\
\begin{array}{c} s \ ds \\ \downarrow \downarrow \\ 1 \ 0 \end{array} & & \\
\Omega_{\text{dR}}^\bullet(S^7) & \begin{array}{c} \tilde{H}_3 \quad \leftarrow h_3 \\ \tilde{f}^* G_4 \quad \leftarrow \omega_4 \\ \tilde{f}^* 2G_7 - \tilde{f}^* \Theta_7 \leftarrow \omega_7 \end{array} &
\end{array} \left(\begin{array}{l} dh_3 = \omega_4 - \frac{1}{4}p_1 \\ d\omega_4 = 0 \\ d\omega_7 = -\omega_4 \wedge \omega_4 + (\frac{1}{4}p_1)^2 \\ -\mathcal{X}_8 \end{array} \right). \quad (42)$$

We claim that such an η^* is given by:

$$\begin{array}{ll}
s\tilde{H}_3 & \longleftarrow h_3 \\
ds \wedge \tilde{H}_3 + s \cdot \tilde{f}^*(G_4) + (1-s)\frac{1}{4}\tilde{f}^*(p_1(\nabla)) & \longleftarrow \omega_4 \\
s \cdot (\tilde{f}^*(2G_7) - \tilde{f}^*(\Theta_7)) + (2\tilde{S} - \int_{\tilde{\Sigma}^7} \tilde{f}^*(\Theta_7)) \cdot (1-s) \cdot \text{vol}_{\tilde{\Sigma}^7} + s(1-s) \cdot \tilde{H}_3 \wedge \tilde{f}^*(G_4 - \frac{1}{4}p_1(\nabla)) + ds \wedge Q_6 & \longleftarrow \omega_7
\end{array}$$

where $Q_6 \in \Omega_{\text{dR}}^6(\tilde{\Sigma}^7)$ is any differential form which satisfies

$$dQ_6 = \left(\tilde{H}_3 \wedge \tilde{f}^*(G_4 + \frac{1}{4}p_1(\nabla)) + \tilde{f}^*(2G_7 - \Theta_7) \right) - \left(\int_{\tilde{\Sigma}^7} \overbrace{\left(\tilde{H}_3 \wedge \tilde{f}^*(G_4 + \frac{1}{4}p_1(\nabla)) + \tilde{f}^*(2G_7 - \Theta_7) \right)}{=: 2\tilde{S} - \int_{\tilde{\Sigma}^7} \tilde{f}^*(\Theta_7)} \right) \cdot \text{vol}_{\tilde{\Sigma}^7}.$$

This exists by (41) and because cohomology classes of differential forms in top degree on compact connected manifolds are in bijection with the values of their integrals (e.g. [La15, §7.3, Thm. 7.5]). It is clear that η^* thus

defined satisfies the required boundary conditions of a homotopy in (42). Hence it only remains to check that it is indeed a dg-algebra homomorphism, in that it respects the differentials on the generators. This is verified by direct computation:

$$\begin{aligned}
d\eta^*(\omega_7) &= d\left(s \cdot (\tilde{f}^*(2G_7) - \tilde{f}^*(\Theta_7)) + (1-s) \cdot \left(2\tilde{S} - \int_{\tilde{\Sigma}^7} \tilde{f}^* \Theta_7\right) \cdot \text{vol}_{S^7} + s(1-s) \cdot \tilde{H}_3 \wedge \tilde{f}^*(G_4 - \frac{1}{4}p_1(\nabla)) + ds \wedge Q_6\right) \\
&= ds \wedge (\tilde{f}^*(2G_7) - \tilde{f}^*(\Theta_7)) - ds \wedge \left(2\tilde{S} - \int_{\tilde{\Sigma}^7} \tilde{f}^* \Theta_7\right) \cdot \text{vol}_{S^7} + ds \wedge \tilde{H}_3 \wedge \tilde{f}^*(G_4 - \frac{1}{4}p_1(\nabla)) \\
&\quad - 2s \cdot ds \wedge \tilde{H}_3 \wedge \tilde{f}^*(G_4 - \frac{1}{4}p_1(\nabla)) - ds \wedge dQ_6 \\
&= ds \wedge \left((\tilde{f}^*(2G_7) - \tilde{f}^*(\Theta_7)) + \tilde{H}_3 \wedge \tilde{f}^*(G_4 - \frac{1}{4}p_1(\nabla)) - \left(2\tilde{S} - \int_{\tilde{\Sigma}^7} \tilde{f}^* \Theta_7\right) \cdot \text{vol}_{S^7} - dQ_6\right) \\
&\quad - 2s \cdot ds \wedge \tilde{H}_3 \wedge \tilde{f}^*(G_4 - \frac{1}{4}p_1(\nabla)) \\
&= ds \wedge \underbrace{\left(\tilde{f}^*(2G_7 - \Theta_7) + \tilde{H}_3 \wedge \tilde{f}^*(G_4 + \frac{1}{4}p_1(\nabla)) - \left(2\tilde{S} - \int_{\tilde{\Sigma}^7} \tilde{f}^* \Theta_7\right) \cdot \text{vol}_{S^7} - dQ_6\right)}_{=0} \\
&\quad - 2 \cdot ds \wedge \tilde{H}_3 \wedge \tilde{f}^*(s \cdot G_4 + (1-s)\frac{1}{4}p_1(\nabla)) \\
&= -\eta^*(\omega_4) \wedge \eta^*(\omega_4) \\
&= \eta^*(d\omega_7).
\end{aligned}$$

Here the crucial non-trivial step is the fourth (third line from below). In the last two steps we used that all 8-forms on $\tilde{\Sigma}^7$ vanish, so that only the 8-forms on $\tilde{\Sigma}^7 \times [0, 1]$ with one factor of ds survive.

The verification on the other two generators is immediate:

$$\begin{aligned}
d\eta^*(h_3) &= d(s\tilde{H}_3) \\
&= ds \wedge \tilde{H}_3 + s \cdot \left(\tilde{f}^*(G_4) - \frac{1}{4}\tilde{f}^*(p_1(\nabla))\right) \\
&= \eta^*(\omega_4) - \frac{1}{4}\tilde{f}^*(p_1(\nabla)) \\
&= \eta^*(dh_3),
\end{aligned}
\qquad
\begin{aligned}
d\eta^*(\omega_4) &= -ds \wedge d\tilde{H}_3 \\
&\quad + d\left(s \cdot \tilde{f}^*(G_4) + (1-s)\frac{1}{4}\tilde{f}^*(p_1(\nabla))\right) \\
&= 0 \\
&= \eta^*(d\omega_4).
\end{aligned}$$

□

4 Hypothesis H implies M5 Hopf-WZ anomaly cancellation

In view of the rational cohomotopical interpretation of background C-field (Remark 3.3) and of the 6d Hopf-WZ anomaly functional (Theorem 3.4) it is natural to hypothesize that the topological sector of the background C-field should be required to be a cocycle in actual twisted Cohomotopy. This non-abelian charge-quantization condition ([FSS20c, §5.3]) is called *Hypothesis H* in [FSS19b]; we recall the precise statement as Def. 4.1 below.

We observe in Prop. 4.6 that, under *Hypothesis H* and in the absence of topological twisting, Theorem 3.4 exhibits the M5 Hopf-WZ anomaly functional as the homotopy Whitehead integral formula (see Remark 4.7 below) for the Hopf invariant (recalled in Def. 4.4 below). This proves the anomaly cancellation (2) for the special case of oriented differences of extended worldvolumes being the 7-sphere and for vanishing topological twist $\frac{1}{4}p_1$ (Remark 2.2). Finally we establish a twisted/parametrized generalization of the integral Hopf invariant in Theorem 4.8, which proves the anomaly cancellation condition (2) generally.

Definition 4.1 (*Hypothesis H* [FSS19b]). In the situation of Def. 2.1 we say that:

- (i) the background fields $(G_4, 2G_7)$ (7) *satisfy Hypothesis H* if they are classified as in [FSS19b, Def. 3.5] by an actual cocycle c in twisted Cohomotopy [FSS19b, §2.1], hence if their classifying map in rational twisted Cohomotopy from Remark 3.3 factors, up to homotopy, through the homotopy quotient $S^4 // \mathrm{Sp}(2)$ of the 4-sphere canonically acted on by $\mathrm{Sp}(2) \simeq \mathrm{Spin}(5)$ (see [FSS20b, Prop. 2.1]), followed by the rationalization map (29);
- (ii) the (extended or not) higher gauged sigma-model fields (\tilde{f}, \tilde{H}_3) (11) *satisfy Hypothesis H* if the corresponding lift (38) through the rationalized parametrized quaternionic Hopf fibration, which classifies them by Theorem 3.4, factors as a lift through the actual parametrized quaternionic Hopf fibration $h_{\mathbb{H}} // \mathrm{Sp}(2)$ ([FSS19b, Prop. 2.22]):

$$\begin{array}{ccccc}
 & \text{rational Hopf-WZ term} & & & \\
 & 2\tilde{S}(\tilde{H}_3, G_4, 2G_7) & & & \\
 \tilde{\Sigma}^7 & \xrightarrow{\text{lift to actual}} & S^7 // \mathrm{Sp}(2) & \xrightarrow{\text{rationalization}} & L_{\mathbb{R}}(S^7 // \mathrm{Sp}(2)) \\
 \downarrow \tilde{f} & \swarrow \tilde{H}_3 & \downarrow \text{Sp}(2)\text{-parametrized} & \downarrow \text{rational} & \downarrow L_{\mathbb{R}}(h_{\mathbb{H}} // \mathrm{Sp}(2)) \\
 X & \xrightarrow{c} & S^4 // \mathrm{Sp}(2) & \xrightarrow{\text{rationalization}} & L_{\mathbb{R}}(S^4 // \mathrm{Sp}(2)) \\
 & \searrow \tau & \downarrow \text{cocycle in rational} & & \\
 & & B\mathrm{Sp}(2) & & \\
 & & \text{cocycle in rational} & & \\
 & & \text{twisted Cohomotopy} & &
 \end{array} \quad (43)$$

Hopf-WZ term in terms of Fivebrane-extended $\mathrm{Sp}(2)$ -structure For transparent formulation of the proof of the following integrality theorem (Theorem 4.8 below), it is useful to re-cast the result of Theorem 3.4 in terms of the Fivebrane-extended $\widehat{\mathrm{Sp}(2)}$ -structure from Example 3.2:

Definition 4.2 (Quaternionic Hopf fibration parametrized over Fivebrane-extended $\mathrm{Sp}(2)$). Consider the homotopy pullback (e.g. [FSS20c, Def. A.23]) of the $\mathrm{Sp}(2)$ -parametrized quaternionic Hopf fibration (43) along the Fivebrane-extension $\widehat{\mathrm{Sp}(2)} \rightarrow \mathrm{Sp}(2)$ (Example 3.2). By the pasting law and the homotopy-restriction map on ∞ -actions (see [SS20b, Prop. 2.23, 2.85]), we may denote this as follows:

$$\begin{array}{ccc}
 S^7 // \widehat{\mathrm{Sp}(2)} & \longrightarrow & S^7 // \mathrm{Sp}(2) \\
 \downarrow h_{\mathbb{H}} // \widehat{\mathrm{Sp}(2)} & \text{(pb)} & \downarrow h_{\mathbb{H}} // \mathrm{Sp}(2) \\
 S^4 // \widehat{\mathrm{Sp}(2)} & \longrightarrow & S^4 // \mathrm{Sp}(2) \\
 \downarrow \hat{\rho}_{S^4} & \text{(pb)} & \downarrow \rho_{S^4} \\
 B\widehat{\mathrm{Sp}(2)} & \xrightarrow{\mathrm{hofib}(\mathcal{X}_g)} & B\mathrm{Sp}(2)
 \end{array} \quad (44)$$

Sp(2)-parametrized quaternionic Hopf fibration
 Sp(2)-parametrized quaternionic Hopf fibration

classifying space for Fivebrane-extended Sp(2)-structure
 classifying space for Sp(2)-structure (BPS M2-brane backgrounds)

Notice, by Example 3.2, that the minimal relative Sullivan model for the $\widehat{\mathrm{Sp}}(2)$ -parametrized quaternionic Hopf fibration on the left of (44) is just like that of the $\mathrm{Sp}(2)$ -parametrized Hopf fibration on the right of (44), as given in (38), except that all entries have the generator θ_7 adjoined, with $d\theta_7 = \chi_8$ (universal rational Fivebrane-structure).

Remark 4.3 (The Hopf-WZ term in terms of Fivebrane $\widehat{\mathrm{Sp}}(2)$ -structure). In terms of the $\widehat{\mathrm{Sp}}(2)$ -parametrized quaternionic Hopf fibration (Def. 4.2), the content of Theorem 3.4 becomes the following transparent statement:

(i) By the assumption (32) that the Euler 8-class of X^8 is equipped with a trivialization, hence that we have $\widehat{\mathrm{Sp}}(2)$ -structure $\widehat{\tau}$ (33) on X^8 , we may pull back the situation in (38) along $B\widehat{\mathrm{Sp}}(2) \xrightarrow{\mathrm{hofib}(\chi_8)} B\mathrm{Sp}(2)$ and regard the twisted Cohomotopy classes c and $c \circ \tilde{f}$ as having local coefficients in the $\widehat{\mathrm{Sp}}(2)$ -parametrized quaternionic Hopf fibration from Def. 4.2.

(ii) In this formulation, Theorem 3.4, says equivalently that there is a single rational 7-class on the total space of the universal $\widehat{\mathrm{Sp}}(2)$ -parametrized 7-sphere fibration, represented by the sum of the generators (37) and (28):

$$2\tilde{\mathbf{S}} := \tilde{\omega}_7 + \theta_7 \in \mathrm{CE}\left(\iota(S^7 // \widehat{\mathrm{Sp}}(2))\right), \quad [\tilde{\mathbf{S}}] \in H^7\left(S^7 // \widehat{\mathrm{Sp}}(2); \mathbb{R}\right) \quad (45)$$

which is the universal avatar of the Hopf-WZ term (Def. 2.6, under $H_{\mathrm{dR}}^7(\tilde{\Sigma}^7) \simeq \mathbb{R}$):

$$\begin{array}{ccc} \begin{array}{ccc} \tilde{\Sigma}^7 & \xrightarrow{c \circ \tilde{f}} & L_{\mathbb{R}}(S^7 // \widehat{\mathrm{Sp}}(2)) \\ \downarrow \tilde{f} & \swarrow \text{cocycle in rational} & \downarrow L_{\mathbb{R}}(h_{\mathbb{H}} // \widehat{\mathrm{Sp}}(2)) \\ X^8 & \xrightarrow{c} & L_{\mathbb{R}}(S^4 // \widehat{\mathrm{Sp}}(2)) \\ \downarrow \widehat{\tau} & \swarrow \text{Fivebrane structure} & \downarrow \\ & & B\widehat{\mathrm{Sp}}(2) \end{array} & \begin{array}{ccc} \Omega_{\mathrm{dR}}^{\bullet}(\tilde{\Sigma}^7) & \xleftarrow{2\tilde{\mathbf{S}}(\tilde{H}_3, G_4, G_7) \leftarrow [2\tilde{\mathbf{S}} := \tilde{\omega}_7 + \theta_7]} & \left(\begin{array}{l} d\theta_7 = \chi_8 \\ d\tilde{\omega}_7 = -\chi_8 \end{array} \right) \\ \uparrow \tilde{f}^* & \swarrow \tilde{H}_3 & \uparrow \\ \Omega_{\mathrm{dR}}^{\bullet}(X^8) & \xleftarrow{\begin{array}{l} \text{fluxes} \\ 2G_7 - \Theta_7 \leftarrow \omega_7 \\ G_4 \leftarrow \omega_4 \end{array}} & \left(\begin{array}{l} d\theta_7 = \chi_8 \\ d\omega_7 = -\omega_4 \wedge \omega_4 + (\frac{1}{4}p_1)^2 \\ -\chi_8 \\ d\omega_4 = 0 \end{array} \right) \\ & \swarrow & \uparrow \\ & & \left(\begin{array}{l} d\theta_7 = \chi_8 \\ d\chi_8 = 0 \\ d\frac{1}{2}p_1 = 0 \end{array} \right) \end{array} \end{array} \quad (46)$$

The plain Hopf invariant via homotopy Whitehead integral. Before analyzing the implications of *Hypothesis H* in the general twisted/shifted case (Remark 2.2), we recall the definition of the plain Hopf invariant and show how this is computed by the untwisted Hopf-WZ term, as a homotopy Whitehead integral.

Definition 4.4 (Hopf invariant (e.g. [MT08, §4])). For $k \in \mathbb{N}$ with $k \geq 1$, let

$$S^{4k-1} \xrightarrow{\phi} S^{2k} \quad (47)$$

be a continuous function between higher dimensional spheres, as shown. Then the homotopy cofiber space of ϕ has integral cohomology given by

$$H^p(\mathrm{cofib}(\phi), \mathbb{Z}) \simeq \begin{cases} \mathbb{Z} & | \quad p \in \{2k, 4k\} \\ 0 & | \quad \text{otherwise} \end{cases}$$

Hence, with generators denoted

$$\omega_{2k} := \pm 1 \in \mathbb{Z} \simeq H^{2k}(\mathrm{cofib}(\phi), \mathbb{Z}), \quad \omega_{4k} := \pm 1 \in \mathbb{Z} \simeq H^{4k}(\mathrm{cofib}(\phi), \mathbb{Z}),$$

there exists a unique integer

$$\text{HI}(\phi) \in \mathbb{Z}, \quad \text{such that} \quad \omega_{2k} \cup \omega_{2k} = \text{HI}(\phi) \cdot \omega_{4k} \quad (48)$$

relating the cup-product square of the first to a multiple of the second. This integer is called the *Hopf invariant* $\text{HI}(\phi)$ of ϕ . It depends on the choice of generators only up to a sign.

We make the following basic observation:

Lemma 4.5 (Recognition of Hopf invariants from Sullivan models). *The unique coefficient in the minimal Sullivan model for a map ϕ of spheres as in (47) is the Hopf invariant $\text{HI}(\phi)$ (Def. 4.4):*

$$\begin{array}{ccc} S^{4k-1} & \xrightarrow{\phi} & S^{2k} \\ (d\omega_{4k-1} = 0) & \xleftarrow{\text{HI}(\phi) \cdot \omega_{4k-1} \leftarrow \omega_{4k-1}} & \left(\begin{array}{l} d\omega_{4k-1} = -\omega_{2k} \wedge \omega_{2k} \\ d\omega_{4k} = 0 \end{array} \right) \end{array} \quad (49)$$

Proof. By cofibrant replacement in the classical model structure on topological spaces (e.g. [FSS20c, Ex. A.7]), the homotopy cofiber is represented by the ordinary pushout of topological spaces as shown in the following diagram on the left. By the fundamental theorem of dg-algebraic rational homotopy theory [BG76, Thm. 9.4] (see [FSS20c, Prop. 3.60]), this is dg-algebraically represented by the pullback of dgc-algebras as shown on the right, which is computed as a fiber product of underlying cochain complexes (e.g. [FSS20c, Prop. 3.41]):

$$\begin{array}{ccc} \begin{array}{ccc} \text{cofib}(\phi) & & \\ \swarrow & & \searrow \\ S^{2k} & \text{(po)} & D^{4k} \\ \swarrow \phi & & \searrow \\ & S^{4k-1} & \end{array} & \begin{array}{ccc} \begin{array}{l} \omega_{2k} \leftarrow \omega_{2k} \\ \omega_{4k-1} \leftarrow \omega_{4k-1} \\ 0 \leftarrow \omega_{4k} \end{array} & \begin{array}{l} \left(\begin{array}{l} d\omega_{4k-1} = -\omega_{2k} \wedge \omega_{2k} \\ \quad \quad \quad + h \cdot \omega_{4k} \\ d\omega_{4k} = 0 \\ d\omega_{2k} = 0 \\ \omega_{2k} \wedge \omega_{4k} = 0 \end{array} \right) & \begin{array}{l} \omega_{2k} \mapsto 0 \\ \omega_{4k-1} \mapsto h \cdot \omega_{4k-1} \\ \omega_{4k} \mapsto \omega_{4k} \end{array} \\ \downarrow & \text{(pb)} & \downarrow \\ \begin{array}{l} \left(\begin{array}{l} d\omega_{4k-1} = -\omega_{2k} \wedge \omega_{2k} \\ d\omega_{2k} = 0 \end{array} \right) & & \begin{array}{l} \left(\begin{array}{l} d\omega_{4k-1} = \omega_{4k} \\ d\omega_{4k} = 0 \end{array} \right) \end{array} \\ \downarrow \begin{array}{l} \omega_{2k} \mapsto 0 \\ \omega_{4k-1} \mapsto h \cdot \omega_{4k-1} \end{array} & & \downarrow \begin{array}{l} \omega_{4k-1} \leftarrow \omega_{4k-1} \\ 0 \leftarrow \omega_{4k} \end{array} \\ & (d\omega_{4k-1} = 0) & \end{array} \end{array} \quad (50)$$

The first differential relation shown in the fiber product dgc-algebra implies on cochain cohomology the relation $[\omega_2 \wedge \omega_2] = h \cdot [\omega_4]$. By the fact that the cochain cohomology of A computes the rational cohomology groups of $\text{cofib}(\phi)$ (see [FSS20c, Prop. 3.57]), comparison with (48) shows that $h = \text{HI}(\phi)$. \square

Using this, we obtain the following consequence of Theorem 3.4:

Proposition 4.6 (Recovering the homotopy Whitehead formula). *In the situation of Def. 2.1, consider the special case where:*

- (i) *the background C-field (7) satisfies Hypothesis H (Def. 4.1);*
 - (ii) *the extended worldvolume is the 7-sphere $\Sigma := \tilde{\Sigma}^7 := S^7$ (as in Lemma 2.3 and Example 2.8);*
 - (iii) *the Spin(8)-bundle over X is trivial, as well as the Spin(8)-connection ∇ , and the trivial trivialization $\Theta_7 = 0$ of $\chi_8(\nabla)$ (32) is chosen.*
- Then twice the Hopf-WZ anomaly functional $2\tilde{S}$ (Def. 2.9, Lemma 2.10) is equal to the Hopf invariant $\text{HI}(c \circ \tilde{f})$ (Def. 4.4) of the composite*

$$S^7 \xrightarrow{\tilde{f}} X \xrightarrow{c} S^4$$

of the extended sigma-model field \tilde{f} (11) with the (untwisted) Cohomotopy cocycle c (43) that classifies the background fields:

$$2\tilde{S}(\tilde{f}, \tilde{H}_3) = \int_{S^7} (\tilde{H}_3 \wedge \tilde{f}^* G_4 + \tilde{f}^* 2G_4) = \text{HI}(c \circ \tilde{f}) \in \mathbb{Z}. \quad (51)$$

First, consider the Gysin sequence (see e.g. [Sw75, 15.30]) for the universal 4-spherical fibration in the bottom right of (44)

$$S^4 \xrightarrow{\text{hofib}(\rho_{S^4})} S^4 // \text{Sp}(2) \xrightarrow{\rho_{S^4}} \text{BSp}(2) .$$

Observe that the integral cohomology groups of the classifying space (see e.g. [Pi91][Ka06, (12)])

$$H^\bullet(\text{BSp}(2), \mathbb{Z}) \simeq \mathbb{Z}[\tfrac{1}{2}p_1, \chi_8] \quad (54)$$

are non-torsion groups concentrated in even degrees. Hence the 5-class controlling this Gysin sequence vanishes, and so the long exact sequence breaks up into short exact sequences of this form:

$$0 \longrightarrow H^\bullet(\text{BSp}(2); \mathbb{Z}) \xrightarrow{\rho_{S^4}^*} H^\bullet(S^4 // \text{Sp}(2); \mathbb{Z}) \xrightarrow{J_{S^4}} H^{\bullet-4}(\text{BSp}(2); \mathbb{Z}) \longrightarrow 0 . \quad (55)$$

Moreover, since the integral cohomology groups (54) have no torsion, these short exact sequences imply that also

$$H^\bullet(S^4 // \text{Sp}(2); \mathbb{Z}) \quad (56)$$

are non-torsion groups.

Now observe, by [FSS19b, Prop. 3.13], that

$$\tilde{\Gamma}_4 := \omega_4 + \tfrac{1}{4}p_1 \in H^4(S^4 // \text{BSp}(2); \mathbb{Z}) \longrightarrow H^4(S^4 // \text{BSp}(2); \mathbb{R}) \quad (57)$$

is an integral class, being the universal integral shifted C-field flux density (9). Hence, by (56), the rational trivialization from (38)

$$\begin{aligned} d\omega_7 &= -\omega_4 \wedge \omega_4 + \left(\tfrac{1}{4}p_1\right)^2 - \chi_8 \\ &= -(\tilde{\Gamma}_4 \wedge \tilde{\Gamma}_4 - \tfrac{1}{2}p_1 \wedge \tilde{\Gamma}_4) - \chi_8 \end{aligned}$$

implies that also the following integral cohomology class vanishes:

$$\left[\tilde{\Gamma}_4 \cup \tilde{\Gamma}_4 - \tfrac{1}{2}p_1 \cup \tilde{\Gamma}_4 + \chi_8 \right] = 0 \in H^8(S^4 // \text{Sp}(2); \mathbb{Z}) . \quad (58)$$

Consider next the integral Gysin sequence corresponding to the 3-spherical fibration which is the parametrized quaternionic Hopf fibration in the top right of (44):

$$S^3 \xrightarrow{\text{hofib}(h_{\mathbb{H}} // G)} S^7 // \text{Sp}(2) \xrightarrow{h_{\mathbb{H}} // \text{Sp}(2)} S^4 // \text{Sp}(2) . \quad (59)$$

Since, rationally, $S^7 // \text{Sp}(2)$ is obtained from $S^4 // \text{Sp}(2)$ by adjoining the relation

$$\begin{aligned} dh_3 &= \omega_4 - \tfrac{1}{4}p_1 \\ &= \tilde{\Gamma}_4 - \tfrac{1}{2}p_1 , \end{aligned} \quad (60)$$

by (38), it follows from [FSS19b, Prop. 2.5 (44)] that $\omega_4 - \tfrac{1}{4}p_1$ is the rational image of the integral Euler class of (59). Consequently,

$$\tilde{\Gamma}_4 - \tfrac{1}{2}p_1 \in H^4(S^4 // \text{Sp}(2); \mathbb{Z}) \quad (61)$$

is the integral 4-class controlling the Gysin sequence of (59), which therefore reads:

$$\dots \longrightarrow H^7(S^4 // \text{Sp}(2); \mathbb{Z}) \xrightarrow{(h_{\mathbb{H}} // \text{Sp}(2))^*} H^7(S^7 // \text{Sp}(2); \mathbb{Z}) \xrightarrow{J_{S^3}} H^4(S^4 // \text{Sp}(2); \mathbb{Z}) \xrightarrow{\cup(\tilde{\Gamma}_4 - \frac{1}{2}p_1)} H^8(S^4 // \text{Sp}(2); \mathbb{Z}) \longrightarrow \dots \quad (62)$$

Now consider pulling back this situation along the homotopy fiber of χ_8 (28) to yield the sequence of spherical fibrations on the left of (44). After this pullback, the Euler class summand in (58) disappears, and we obtain this vanishing class:

$$\left[\tilde{\Gamma}_4 \cup \tilde{\Gamma}_4 - \tfrac{1}{2}p_1(TX) \cup \tilde{\Gamma}_4 \right] = 0 \in H^8(S^4 // \widehat{\text{Sp}(2)}; \mathbb{Z}) . \quad (63)$$

With this, the integral Gysin sequence of the 3-spherical fibration in the top left of (44)

$$S^3 \xrightarrow{\text{hofib}(h_{\mathbb{H}} // G)} S^7 // \widehat{\text{Sp}(2)} \xrightarrow{h_{\mathbb{H}} // \widehat{\text{Sp}(2)}} S^4 // \widehat{\text{Sp}(2)}$$

is seen to be of the following form:

References

- [Ad60] F. Adams, *On the non-existence of elements of Hopf invariant one*, Ann. Math. **72** (1960), 20–104, [jstor:1970147].
- [Ah96] O. Aharony, *String theory dualities from M theory*, Nucl. Phys. **B476** (1996), 470-483, [arXiv:hep-th/9604103].
- [Ar18] A. Arvanitakis, *Brane Wess-Zumino terms from AKSZ and exceptional generalised geometry as an L_∞ -algebroid*, Adv. Theor. Math. Phys., Volume 23 (2019) Number 5, [arXiv:1804.07303].
- [BLMP12] J. Bagger, N. Lambert, S. Mukhi and C. Papageorgakis, *Multiple Membranes in M-theory*, Phys. Rep. **527** (2013), 1-100, [arXiv:1203.3546].
- [BLNPST97] I. Bandos, K. Lechner, A. Nurmagambetov, P. Pasti, D. Sorokin, and M. Tonin, *Covariant Action for the Super-Five-Brane of M-Theory*, Phys. Rev. Lett. **78** (1997) 4332-4334, [arXiv:hep-th/9701149].
- [BT82] R. Bott and L. Tu, *Differential Forms in Algebraic Topology*, Graduate Texts in Mathematics 82, Springer, 1982, [doi:10.1007/BFb0063500].
- [BG76] A. Bousfield and V. Gugenheim, *On PL deRham theory and rational homotopy type*, Mem. Amer. Math. Soc. **179** (1976), [ams:memo-8-179].
- [BMSS19] V. Braunack-Mayer, H. Sati and U. Schreiber, *Gauge enhancement of Super M-Branes via rational parameterized stable homotopy theory* Comm. Math. Phys. **371** (2019), 197-265, [10.1007/s00220-019-03441-4], [arXiv:1806.01115].
- [BSS19] S. Burton, H. Sati, and U. Schreiber, *Lift of fractional D-brane charge to equivariant Cohomotopy theory*, J. Geom. Phys. (2020), [arXiv:1812.09679].
- [Du96] M. Duff, *M-Theory (the Theory Formerly Known as Strings)*, Int. J. Mod. Phys. **A11** (1996), 5623-5642, [arXiv:hep-th/9608117].
- [Du99] M. Duff, *The World in Eleven Dimensions: Supergravity, Supermembranes and M-theory*, IoP Publishing, 1999.
- [Du19] M. Duff, in: G. Farmelo, *The Universe Speaks in numbers*, interview 14, 2019, [grahamfarmelo.com/the-universe-speaks-in-numbers-interview-14]
- [DS91] M. Duff and K. Stelle, *Multi-membrane solutions of $D = 11$ supergravity*, Phys. Lett. **B 253** (1991), 113-118, [doi:10.1016/0370-2693(91)91371-2].
- [FSS10] D. Fiorenza, U. Schreiber, and J. Stasheff, *Čech cocycles for differential characteristic classes – An ∞ -Lie theoretic construction*, Adv. Theor. Math. Phys. **16**(2012), 149-250, [arXiv:1011.4735].
- [FSS12b] D. Fiorenza, H. Sati and U. Schreiber, *Extended higher cup-product Chern-Simons theories*, J. Geom. Phys. **74** (2013), 130-163, [doi:10.1016/j.geomphys.2013.07.011], [arXiv:1207.5449].
- [FSS13a] D. Fiorenza, H. Sati, and U. Schreiber, *A higher stacky perspective on Chern-Simons theory*, in: *Mathematical Aspects of Quantum Field Theories*, Springer (2015), 153-211, [doi:10.1007/978-3-319-09949-1], [arXiv:1301.2580].
- [FSS13b] D. Fiorenza, H. Sati and U. Schreiber, *Super Lie n -algebra extensions, higher WZW models, and super p -branes*, Intern. J. Geom. Meth. Mod. Phys. **12** (2015) 1550018, [arXiv:1308.5264].
- [FSS15] D. Fiorenza, H. Sati, and U. Schreiber, *The WZW term of the M5-brane and differential cohomotopy*, J. Math. Phys. **56** (2015), 102301, [arXiv:1506.07557].
- [FSS16] D. Fiorenza, H. Sati, U. Schreiber, *Rational sphere valued supercocycles in M-theory and type IIA string theory*, J. Geom. Phys. **114** (2017) 91-108, [arXiv:1606.03206].
- [FSS17] D. Fiorenza, H. Sati, and U. Schreiber, *T-duality in rational homotopy theory via L_∞ -algebras*, Geometry, Topology and Mathematical Physics (2018), special issue in honor of Jim Stasheff and Dennis Sullivan, [GMTP:volume-1-2018], [arXiv:1712.00758].
- [FSS19a] D. Fiorenza, H. Sati, and U. Schreiber, *The rational higher structure of M-theory*, Proceedings of the LMS-EPSRC Durham Symposium *Higher Structures in M-Theory*, August 2018, Fortsch. der Phys., 2019 [doi:10.1002/prop.201910017], [arXiv:1903.02834].

- [FSS19b] D. Fiorenza, H. Sati, and U. Schreiber, *Twisted Cohomotopy implies M-theory anomaly cancellation on 8-manifolds*, Commun. Math. Phys. **377** 3 (2020), 1961-2025, [doi:10.1007/s00220-020-03707-2], [arXiv:1904.10207].
- [FSS19c] D. Fiorenza, H. Sati, and U. Schreiber, *Super-exceptional geometry: Super-exceptional embedding construction of M5* J. High Energy Phys. **2020** (2020), 107, [doi:10.1007/JHEP02(2020)107], [arXiv:1908.00042].
- [FSS20a] D. Fiorenza, H. Sati, and U. Schreiber, *Twisted cohomotopy implies twisted String structure on M5-branes*, J. Math. Phys. 2021 [arXiv:2002.11093].
- [FSS20b] D. Fiorenza, H. Sati, and U. Schreiber, *Twistorial Cohomotopy implies Green-Schwarz anomaly cancellation*, [arXiv:2008.08544].
- [FSS20c] D. Fiorenza, H. Sati, and U. Schreiber, *The character map in (twisted differential) non-abelian cohomology*, [arXiv:2009.11909].
- [Fo03] S. Förste, *Deformations of WZW models*, Class. Quant. Grav. **21** (2004), S1517-1522, [arXiv:hep-th/0312202].
- [GS20] D. Grady and H. Sati, *Differential cohomotopy versus differential cohomology for M-theory and differential lifts of Postnikov towers*, [arXiv:2001.07640].
- [GM81] P. Griffiths and J. Morgan, *Rational Homotopy Theory and Differential Forms*, Progress in Mathematics Volume 16, Birkhäuser, 2013, [doi:10.1007/978-1-4614-8468-4].
- [Ha78] A. Haefliger, *Whitehead products and differential forms*, Differential topology, foliations and Gelfand-Fuks cohomology, pp. 13-24, Lec. Notes in Math. **652**, Springer, Berlin, 1978, [doi:10.1007/BFb0063500].
- [HR18] J. Heckman and T. Rudelius, *Top Down Approach to 6D SCFTs*, J. Phys. A: Math. Theor. **52** (2018), 093001, [arXiv:1805.06467].
- [Hes06] K. Hess, *Rational homotopy theory: a brief introduction*, Interactions between homotopy theory and algebra, 175-202. Contemp. Math 436 [arXiv:math.AT/0604626].
- [HN11] S. Hu and D. Nanopoulos, *Hopf-Wess-Zumino term in the effective action of the 6d, (2,0) field theory revisited*, J. High Energy Phys. **1110** (2011), 054, [arXiv:1110.0861].
- [HSS18] J. Huerta, H. Sati, and U. Schreiber, *Real ADE-equivariant (co)homotopy of super M-branes*, Commun. Math. Phys. 371:425. (2019) [doi:10.1007/s00220-019-03442-3], [arXiv:1805.05987].
- [In00] K. Intriligator, *Anomaly Matching and a Hopf-Wess-Zumino Term in 6d, N = (2,0) Field Theories*, Nucl. Phys. **B581** (2000), 257-273, [arXiv:hep-th/0001205].
- [Ka06] J. Kalkkinen, *Global Spinors and Orientable Five-Branes*, J. High Energy Phys. **0609** (2006), 028, [arXiv:hep-th/0604081].
- [KS03] J. Kalkkinen and K. S. Stelle, *Large Gauge Transformations in M-theory*, J. Geom. Phys. **48** (2003), 100-132, [arXiv:hep-th/0212081].
- [KN63] S. Kobayashi and K. Nomizu, *Foundations of Differential Geometry, Volume 1*, Wiley, 1963, [ISBN:9780471157335].
- [La15] J. Lafontaine, *An introduction to differential manifolds*, Springer, New York, 2015, [doi:10.1007/978-3-319-20735-3].
- [MS15] V. Mathai and H. Sati, *Higher abelian gauge theory associated to gerbes on noncommutative deformed M5-branes and S-duality*, J. Geom. Phys. **92** (2015), 240-251, [arXiv:1404.2257].
- [Mo05] G. Moore, *Anomalies, Gauss laws, and Page charges in M-theory*, Comptes Rend. Phys. **6** (2005), 251-259, [arXiv:hep-th/0409158].
- [Mo12] G. Moore, *Applications of the six-dimensional (2,0) theories to Physical Mathematics*, Felix Klein lectures, Bonn 2012, [http://www.physics.rutgers.edu/~gmoore/FelixKleinLectureNotes.pdf]
- [Mo14] G. Moore, *Physical Mathematics and the Future*, talk at Strings 2014, [http://www.physics.rutgers.edu/~gmoore/PhysicalMathematicsAndFuture.pdf]
- [MT08] R. E. Mosher and M. C. Tangora, *Cohomology operations and applications in homotopy theory*, Dover Publications, NY, 2008, [ISBN10:0486466647].

- [Pa83] D. Page, *Classical stability of round and squashed seven-spheres in eleven-dimensional supergravity*, Phys. Rev. **D 28** (1983), 2976-2982, [doi:10.1103/PhysRevD.28.2976].
- [Pi91] H. Pittie, *The integral homology and cohomology rings of $SO(N)$ and $Spin(N)$* , J. Pure Appl. Algebra **73** (1991), 105-153, [doi:10.1016/0022-4049(91)90108-E].
- [Sa13] H. Sati, *Framed M-branes, corners, and topological invariants*, J. Math. Phys. **59** (2018), 062304, [doi:10.1063/1.5007185], [arXiv:1310.1060]
- [Sa14] H. Sati, *M-Theory with Framed Corners and Tertiary Index Invariants*, SIGMA **10** (2014), 024, 28 pages, [arXiv:1203.4179].
- [SS19a] H. Sati and U. Schreiber, *Equivariant Cohomotopy implies orientifold tadpole cancellation*, J. Geom. Phys. **156** (2020) 103775, [arXiv:1909.12277].
- [SS19b] H. Sati and U. Schreiber, *Differential Cohomotopy implies intersecting brane observables via configuration spaces and chord diagrams*, [arXiv:1912.10425].
- [SS20] H. Sati and U. Schreiber, *Twisted Cohomotopy implies M5-brane anomaly cancellation*, [arXiv:2002.07737].
- [SS19a] H. Sati and U. Schreiber, *Equivariant Cohomotopy implies orientifold tadpole cancellation*, J. Geom. Phys. **156** (2020) 103775, [arXiv:1909.12277].
- [SS20b] H. Sati and U. Schreiber, *Proper Orbifold Cohomology*, [arXiv:2008.01101].
- [SSS09] H. Sati, U. Schreiber, and J. Stasheff, *Fivebrane Structures*, Rev. Math. Phys. **21** (2009), 1197-1240, [doi:10.1142/S0129055X09003840], [arXiv:0805.0564] [math.AT].
- [SSS12] H. Sati, U. Schreiber, and J. Stasheff, *Twisted differential String and Fivebrane structures*, Commun. Math. Phys. **315** (2012), 169-213, [10.1007/s00220-012-1510-3], [arXiv:0910.4001] [math.AT].
- [SW08] D. Sinha and B. Walter, *Lie coalgebras and rational homotopy theory II: Hopf invariants*, Trans. Amer. Math. Soc. **365** (2013), 861-883, [arXiv:0809.5084].
- [St49] N. Steenrod, *Cohomology Invariants of Mappings*, Ann. of Math. **50** (1949), 954-988, [jstor:1969589].
- [Su77] D. Sullivan, *Infinitesimal computations in topology*, Publ. Math. I.H.É.S. **47** (1977), 269-331, [numdam:PMIHES_1977__47__269_0].
- [Sw75] R. Switzer, *Algebraic Topology - Homotopy and Homology*, Springer, 1975, [doi:10.1007/978-3-642-61923-6].
- [TN89] H. C. Tze and S. Nam, *Topological Phase Entanglements of Membrane Solitons in Division Algebra σ Models With a Hopf Term*, Ann. Phys. **193** (1989), 419-471, [spire:25058].
- [Wh47] J. H. C. Whitehead, *An expression of Hopf's invariant as an integral*, Proc. Nat. Acad. Sci. USA **33** (1947), 117-123, [jstor:87688].
- [WZ83] F. Wilczek and A. Zee, *Linking Numbers, Spin, and Statistics of Solitons*, Phys. Rev. Lett. **51** (1983), 2250-2252, [doi:10.1103/PhysRevLett.51.2250].
- [Wi97a] E. Witten, *On Flux Quantization In M-Theory And The Effective Action*, J. Geom. Phys. **22** (1997), 1-13, [arXiv:hep-th/9609122].
- [Wi97b] E. Witten, *Five-Brane Effective Action In M-Theory*, J. Geom. Phys. **22** (1997), 103-133, [arXiv:hep-th/9610234].
- [Wi83] E. Witten, *Global aspects of current algebra*, Nucl. Phys. **B223** (1983), 422-432, [spire:13234].
- [Wi85] E. Witten, *Global anomalies in string theory*, in: W. Bardeen and A. White (eds.), *Symposium on Anomalies, Geometry, Topology*, pp. 61-99. World Scientific, 1985 [spire:214913]
- [Wi19] E. Witten, in: G. Farmelo, *The Universe Speaks in numbers*, interview 5, 2019, [grahamfarmelo.com/the-universe-speaks-in-numbers-interview-5].

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