

Geometric Langlands duality for PGL_2 on S^3 minus three points

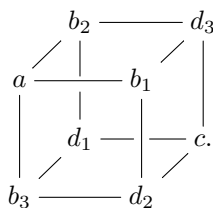
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ABSTRACT. In this note, we study the local relative geometric Langlands conjecture of Ben-Zvi–Sakellaridis–Venkatesh for the spherical subgroup $\mathrm{PGL}_2^{\mathrm{diag}}$ of the triple product $\mathrm{PGL}_2^{\times 3}$ (and also for the spherical subgroup G_2 of SO_8/μ_2), whose corresponding Langlands dual $\mathrm{SL}_2^{\times 3}$ -variety can be identified with the space $(\mathbf{A}^2)^{\otimes 3} \cong \mathbf{A}^8$ of $2 \times 2 \times 2$ -cubes. Our analysis relies on a construction of Bhargava relating $2 \times 2 \times 2$ -cubes to quadratic forms and the Cayley hyperdeterminant as studied by Gelfand–Kapranov–Zelevinsky.

1. Introduction

The goal of this brief note is to study the geometrization of a story from the arithmetic context pioneered by Jacquet, Kudla–Harris, and Ichino among many others (see, e.g., [HK91, Ich08]). Fix an eighth root of unity ζ_8 , let i be the resulting square root of -1 , and write $k := \mathbf{Q}(\zeta_8) \cong \mathbf{Q}(i, \sqrt{2})$.

Notation 1.1. Let std denote the standard representation of SL_2 , so that $\mathrm{std}^{\otimes 3}$ consists of cubes



Fix an integer n . Equip $\mathrm{std}^{\otimes 3}$ with the grading where the entries of a cube have the following weights: a lives in weight $-4n$, each b_i lives in weight $-2n$, c lives in weight $2n$, and each d_i lives in weight 0 . Write $\mathrm{std}^{\otimes 3}(4n, 2\vec{n}, -2n, \vec{0})$ to denote the corresponding graded variety.

Similarly, equip SL_2 with the grading where the entries of a matrix $\begin{pmatrix} a & b \\ c & d \end{pmatrix}$ have the following weights: a and d live in weight 0 , b lives in weight $2n$, and c lives in weight $-2n$. Write $\mathrm{SL}_2(-2n\rho)$ to denote this graded group. Then there is a natural graded action of $\mathrm{SL}_2(-2n\rho)^{\times 3}$ on $\mathrm{std}^{\otimes 3}(4n, 2\vec{n}, -2n, \vec{0})$.

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Recall that the process of *shearing* discussed in [Rak20, Lur15], as well as [Dev23, Section 2.1], converts gradings into homological shifts (more precisely, it sends a module in weight n to the same module shifted homologically by n). This functor is symmetric monoidal when restricted to the subcategory of modules in *even* weights, and therefore extends to an operation on evenly graded stacks. As in [Dev23], we will state all of our results with “arithmetic shearing” in the sense of [BZSV23, Section 6.7].

Theorem 1.2 (Derived geometric Satake for $\mathrm{PGL}_2^{\times 3}/\mathrm{PGL}_2^{\mathrm{diag}}$). *Suppose that the $\mathrm{PGL}_2^{\times 3}[[t]]$ -action on $(\mathrm{PGL}_2^{\times 3}/\mathrm{PGL}_2^{\mathrm{diag}})((t))$ is optimal in the sense of [Dev23, Hypothesis 3.5.21]. There is an equivalence¹*

$$\mathrm{Shv}_{\mathrm{PGL}_2^{\times 3}}^{c, \mathrm{Sat}}(\mathcal{L}(\mathrm{PGL}_2^{\times 3}/\mathrm{PGL}_2^{\mathrm{diag}}); k) \simeq \mathrm{Perf}^{\mathrm{sh}}(\mathrm{std}^{\otimes 3}(4, \vec{2}, -2, \vec{0})/\mathrm{SL}_2(-2\rho)^{\times 3}),$$

where $\mathrm{Perf}^{\mathrm{sh}}$ denotes the ∞ -category of perfect complexes on the shearing of the quotient stack $\mathrm{std}^{\otimes 3}(4, \vec{2}, -2, \vec{0})/\mathrm{SL}_2(-2\rho)^{\times 3}$.

Let $\mathrm{PSO}_{2n} := \mathrm{SO}_{2n}/\mu_2$. Then, the embedding $\mathrm{PGL}_2^{\mathrm{diag}} \subseteq \mathrm{PGL}_2^{\times 3}$ can be identified with the diagonal embedding $\mathrm{SO}_3 \subseteq \mathrm{SO}_3 \times \mathrm{PSO}_4$, so Theorem 1.2 could be viewed as a special case of the geometrized analogue of the Gan-Gross-Prasad period.

A similar argument shows a variant for PSO_8 . Namely, there is an embedding $G_2 \subseteq \mathrm{PSO}_8$ given by triality, which exhibits G_2 as a spherical subgroup of PSO_8 . To see that this situation is analogous to that of Theorem 1.2, note that the Dynkin diagram \bullet of A_1 is obtained from the Dynkin diagram $\bullet \bullet \bullet$ of $A_1^{\times 3}$ by folding with respect to the obvious action of the symmetric group Σ_3 . In the same way, the Dynkin diagram $\bullet \rightleftharpoons \bullet$ of G_2 is obtained from the Dynkin diagram $\bullet \begin{array}{c} \nearrow \\ \bullet \\ \searrow \end{array}$ of D_4 by folding with respect to the action of Σ_3 permuting the three vertices around the branching vertex.

Theorem 1.3 (Derived geometric Satake for PSO_8/G_2). *Suppose that the $\mathrm{PSO}_8[[t]]$ -action on $(\mathrm{PSO}_8/G_2)((t))$ is optimal in the sense of [Dev23, Hypothesis 3.5.21]. Then there is an equivalence*

$$\mathrm{Shv}_{\mathrm{PSO}_8}^{c, \mathrm{Sat}}(\mathcal{L}(\mathrm{PSO}_8/G_2); k) \simeq \mathrm{Perf}^{\mathrm{sh}}(\mathrm{std}^{\otimes 3}(12, \vec{6}, -6, \vec{0})/\mathrm{SL}_2(-6\rho)^{\times 3} \times \mathbf{A}^1(4)).$$

The proofs of Theorem 1.2 and Theorem 1.3 reduce to showing that the conditions of [Dev23, Theorem 3.5.20] are met. This ultimately relies on studying Bhargava’s construction from [Bha04] relating $2 \times 2 \times 2$ -matrices to quadratic forms, and the work [GKZ94] of Gelfand-Kapranov-Zelevinsky describing the relationship to Cayley’s hyperdeterminant.

Remark 1.4. Following the philosophy of [Dev23], it should also be possible to use a variant of the methods of this article to prove analogues of Theorem 1.2 and Theorem 1.3 for sheaves with coefficients in connective complex K-theory ku . We have not attempted to do this, but we expect the corresponding 1-parameter deformation of $\mathrm{std}^{\otimes 3}$ over $\pi_*(\mathrm{ku}) \cong \mathbf{Z}[\beta]$ to be rather interesting.

¹The ∞ -category on the left-hand side is as in [Dev23, Definition 3.5.15]; see Definition 3.1 for a quick review. We expect the results of this article continue to hold if one considers sheaves with coefficients in $\mathbf{Z}[i, \frac{1}{\sqrt{2}}]$.

Remark 1.5. The equivalence of Theorem 1.2 can heuristically be viewed as geometric Langlands for PGL_2 on the nodal curve $\mathbf{CP}^1 \vee \mathbf{CP}^1$ (which can be thought of as cut out in $\mathbf{P}_{[x_0:x_1]}^1 \times \mathbf{P}_{[y_0:y_1]}^1$ by $x_0 y_0 = 0$, or as S^3 minus three points). Indeed, if H is an complex algebraic group, and $(\mathbf{CP}^1)^{\vee(n-1)}$ is a wedge sum of $(n-1)$ complex projective lines, there is an isomorphism $\mathrm{Bun}_H((\mathbf{CP}^1)^{\vee(n-1)}) \simeq H^{\times n} \backslash \mathcal{L}(H^{\times n}/H^{\mathrm{diag}})$. Note that if $[n] = \{0, \dots, n\}$, one may view $(\mathbf{CP}^1)^{\vee(n-1)}$ as the homotopy pushout $* \amalg_{*\amalg_{[n-1]}*} *$. In fact, Theorem 1.2 is partly motivated by the work of [MT12] and the 6-dimensional $\mathcal{N} = (2, 0)$ superconformal field theory.

Remark 1.6. The quotient stack $\mathrm{std}^{\otimes 3}/\mathrm{SL}_2^{\times 3}$ is also studied (in different language, of course) in quantum information theory; see Remark 2.11 below.

Theorem 1.2 and Theorem 1.3 are predicted by (the Betti version of) the local geometric conjecture of Ben-Zvi–Sakellaridis–Venkatesh; see [BZSV23, Conjecture 7.5.1]. My homotopy-theoretic interpretation of their conjecture is as follows. Suppose G is a reductive group over \mathbf{C} and G/H is an affine homogeneous spherical G -variety (meaning that it admits an open B -orbit for its natural left $B \subseteq G$ -action). Then, there should be a dual graded \check{G} -variety \check{M} equipped with a moment map $\mu : \check{M} \rightarrow \check{\mathfrak{g}}^*$, and an equivalence of the form

$$\mathrm{Shv}_G^{c, \mathrm{Sat}}(\mathcal{L}(G/H); \mathbf{C}) \simeq \mathrm{Perf}^{\mathrm{sh}}(\check{M}/\check{G}),$$

where $\mathrm{Perf}^{\mathrm{sh}}$ denotes the ∞ -category of perfect complexes on the shearing of \check{M}/\check{G} with respect to its given grading. In fact, [BZSV23, Section 4] gives an explicit construction of this predicted dual \check{M} , and in the examples $(G, H) = (\mathrm{PGL}_2^{\times 3}, \mathrm{PGL}_2^{\mathrm{diag}})$ and (PSO_8, G_2) , one can compute that the stacky quotient \check{M}/\check{G} is isomorphic to the right-hand sides of Theorem 1.2 and Theorem 1.3 respectively.²

Remark 1.7. Lest Theorem 1.2 seem like an oddly specific example to focus on, we note that it is essentially the *only* “new” example of a spherical pair (G, H) of the form $(H^{\times j}, H^{\mathrm{diag}})$, as shown by the following lemma.

Lemma 1.8. *Suppose H is a simple linear algebraic group over \mathbf{C} . Then the subgroup $H^{\mathrm{diag}} \subseteq H^{\times j}$ is spherical if and only if:*

- (a) $j = 2$, and H arbitrary;
- (b) $j = 3$ and H is of type A_1 .

PROOF. If the subgroup $H^{\mathrm{diag}} \subseteq H^{\times j}$ is spherical, there is an open H^{diag} -orbit on the flag variety of $H^{\times j}$. This implies that the dimension of H must be at least $j|\Phi^+|$, where Φ^+ is the set of positive roots; equivalently, one needs $\mathrm{rank}(H) \geq (j-2)|\Phi^+|$. Of course, this is always satisfied if $j = 2$ (this is the group case corresponding to the symmetric subgroup $H^{\mathrm{diag}} \subseteq H \times H$). Using the classification of simple linear algebraic groups over \mathbf{C} , it is easy to see that the

²In the first case, this computation is straightforward given the prescription of [BZSV23, Section 4]; see [Sak13, Example 7.2.4] for a reference. The computation in the second case goes as follows. As in [BZSV23, Remark 7.1.1], the quotient stack \check{M}/\check{G} can be identified with the quotient \check{V}_X/\check{G}_X , where \check{G}_X is the Gaitsgory–Nadler/Sakellaridis–Venkatesh/Knop–Schalke dual group of X and \check{V}_X is constructed in [BZSV23, Section 4.5]. In the case $X = \mathrm{PSO}_8/G_2$, a calculation shows that \check{G}_X is the Levi subgroup of the maximal parabolic subgroup of PSO_8 corresponding to the central vertex of the D_4 Dynkin diagram; so $\check{G}_X \cong \mathrm{SL}_2^{\times 3}$. Using the prescription of [BZSV23, Section 4.5], one can check that $\check{V}_X \cong \mathrm{std}^{\otimes 3} \oplus \mathbf{A}^1$, where \check{G}_X acts only on the first factor. See, e.g., [Sak13, Line 9 of Table in Appendix A].

only other case when the above inequality can hold is when $j = 3$ and H is of type A_1 ; one can then check by hand that the diagonal subgroup in this case is indeed spherical. \square

In the first case of Lemma 1.8, [BZSV23, Conjecture 7.5.1] is precisely the derived geometric Satake equivalence of [BF08]. Therefore, the only other case of Lemma 1.8 is when H is simple of type A_1 , and Theorem 1.2 precisely addresses [BZSV23, Conjecture 7.5.1] for the adjoint form PGL_2 of H .

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2. Some properties of $\mathrm{std}^{\otimes 3}$

In this section, we establish some basic properties of $\mathrm{std}^{\otimes 3}$ as a $\mathrm{SL}_2^{\times 3}$ -variety; our base field will always be k , and we will write $\check{G} = \mathrm{SL}_2^{\times 3}$. Some of this material appears in [Bha04]. In particular, Construction 2.3 is due to Bhargava.

Observation 2.1. An element $A = \begin{pmatrix} a & b \\ c & -a \end{pmatrix} \in \mathfrak{sl}_2$ can be identified with a binary quadratic form $q_A(x, y) = cx^2 + 2iaxy + by^2$. Under this identification, the adjoint action of $g \in \mathrm{SL}_2$ on \mathfrak{sl}_2 is given by the action on (x, y) of the conjugate of g by the matrix $\mathrm{diag}(\zeta_8, \zeta_8^{-1})$. Explicitly, if $g = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}$, the action sends

$$\begin{aligned} x &\mapsto i\delta x + \beta y, \\ y &\mapsto \gamma x - i\alpha y. \end{aligned}$$

Note, moreover, that the discriminant of $q_A(x, y)$ is $4\det(A)$.

Warning 2.2. Note that under Observation 2.1, the element of \mathfrak{sl}_2 associated to a binary quadratic form $bx^2 + axy + cy^2$ is *not* the symmetric matrix associated to the quadratic form! Indeed, the associated symmetric matrix is $\begin{pmatrix} b & a/2 \\ a/2 & c \end{pmatrix}$, while the associated element of \mathfrak{sl}_2 is $\begin{pmatrix} -ai/2 & c \\ b & ai/2 \end{pmatrix}$.

Construction 2.3. The affine space $\mathbf{A}^8 = \mathrm{std}^{\otimes 3}$ can be regarded as parametrizing cubes

$$\begin{array}{ccccc} & & b_2 & \text{---} & d_3 \\ & \swarrow & | & \searrow & \\ a & \text{---} & b_1 & & \\ | & & | & & | \\ & \swarrow & d_1 & \text{---} & c, \\ & \searrow & | & \swarrow & \\ b_3 & \text{---} & d_2 & & \end{array}$$

which we will represent by a tuple (a, \vec{b}, c, \vec{d}) ; we will often use the symbol \mathcal{C} to denote such a cube. If $\{e_1, e_2\}$ are a basis for std , the above cube corresponds to the element of $\mathrm{std}^{\otimes 3}$ given by

$$\begin{aligned} &ae_1 \otimes e_1 \otimes e_1 + b_1e_2 \otimes e_1 \otimes e_1 + b_2e_1 \otimes e_2 \otimes e_1 + b_3e_1 \otimes e_1 \otimes e_2 \\ &+ d_1e_1 \otimes e_2 \otimes e_2 + d_2e_2 \otimes e_1 \otimes e_2 + d_3e_2 \otimes e_2 \otimes e_1 + ce_2 \otimes e_2 \otimes e_2. \end{aligned}$$

Associated to a cube \mathcal{C} are three pairs of matrices, given by slicing along the top, leftmost, or front faces:

$$\begin{aligned} M_1 &= \begin{pmatrix} a & b_2 \\ b_3 & d_1 \end{pmatrix}, N_1 = \begin{pmatrix} b_1 & d_3 \\ d_2 & c \end{pmatrix}, \\ M_2 &= \begin{pmatrix} a & b_1 \\ b_3 & d_2 \end{pmatrix}, N_2 = \begin{pmatrix} b_2 & d_3 \\ d_1 & c \end{pmatrix}, \\ M_3 &= \begin{pmatrix} a & b_1 \\ b_2 & d_3 \end{pmatrix}, N_3 = \begin{pmatrix} b_3 & d_2 \\ d_1 & c \end{pmatrix}; \end{aligned}$$

each of these defines a binary quadratic form

$$q_i(x, y) = -\det(M_i x + N_i y).$$

Explicitly,

$$\begin{aligned} q_1(x, y) &= \det(M_1)x^2 + (ac + b_1d_1 - b_2d_2 - b_3d_3)xy + \det(N_1)y^2, \\ q_2(x, y) &= \det(M_2)x^2 + (ac - b_1d_1 + b_2d_2 - b_3d_3)xy + \det(N_2)y^2, \\ q_3(x, y) &= \det(M_3)x^2 + (ac - b_1d_1 - b_2d_2 + b_3d_3)xy + \det(N_3)y^2. \end{aligned}$$

Viewing \mathfrak{sl}_2 as the space of binary quadratic forms as in Observation 2.1, these three quadratic forms define a map

$$\mu : \mathrm{std}^{\otimes 3} \rightarrow \mathfrak{sl}_2^{\times 3}.$$

An easy check shows that this map is \check{G} -equivariant.

Lemma 2.4 (Cayley). *The composite*

$$\mathrm{std}^{\otimes 3} \xrightarrow{\mu} \mathfrak{sl}_2^{\times 3} \rightarrow \mathfrak{sl}_2^{\times 3} // \check{G}$$

factors through the diagonal inclusion $\mathfrak{sl}_2 // \mathrm{SL}_2 \rightarrow \mathfrak{sl}_2^{\times 3} // \check{G}$. In fact, the induced map $\mathrm{std}^{\otimes 3} \rightarrow \mathfrak{sl}_2 // \mathrm{SL}_2$ defines an isomorphism

$$\mathrm{std}^{\otimes 3} // \check{G} \xrightarrow{\sim} \mathfrak{sl}_2 // \mathrm{SL}_2.$$

PROOF. The map $\mathfrak{sl}_2^{\times 3} \rightarrow \mathfrak{sl}_2^{\times 3} // \check{G}$ sends a triple of matrices to their determinants, or equivalently a triple of quadratic forms to their discriminants. Therefore, we need to check that the three quadratic forms of Construction 2.3 have the same discriminant. This is an easy check: one finds that their common discriminant is

$$\begin{aligned} \det(q_i) &= a^2c^2 + b_1^2d_1^2 + b_2^2d_2^2 + b_3^2d_3^2 - 2(ab_1cd_1 + ab_2cd_2 + ab_3cd_3 \\ (1) \quad &+ b_1b_2d_1d_2 + b_1b_3d_1d_3 + b_2b_3d_2d_3) + 4(ad_1d_2d_3 + b_1b_2b_3c). \end{aligned}$$

It remains to check that the map $\mathrm{std}^{\otimes 3} // \check{G} \rightarrow \mathbf{A}^1$ defined by this polynomial is an isomorphism. This is stated/proved in [GKZ94, Proposition 1.7 in Chapter 14], and is due to Cayley. \square

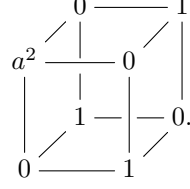
Notation 2.5. Write \det to denote the map $\mathrm{std}^{\otimes 3} \rightarrow \mathfrak{sl}_2 // \mathrm{SL}_2$ from Lemma 2.4, so that if \mathcal{C} is a cube, $\det(\mathcal{C})$ is the quantity of (1).

We will now define an analogue of the Kostant slice, as it will be needed to apply [Dev23, Theorem 3.5.20] (see [Dev23, Strategy 1.2.1(b)]). For the purposes of our discussion, one should view this Kostant section as an analogue of the construction of the companion matrix associated to a characteristic polynomial.

Construction 2.6. If n is an integer, let \vec{n} denote the triple (n, n, n) . Let

$$\kappa : \mathfrak{sl}_2 // \mathrm{SL}_2 \cong \mathbf{A}^1 // (\mathbf{Z}/2) \cong \mathbf{A}^1 \rightarrow \mathrm{std}^{\otimes 3}$$

denote the map sending $a^2 \mapsto (a^2, \vec{0}, 0, \vec{1})$. This corresponds to the cube



In this case, $\det(\kappa(a^2)) = 4a^2$, so that κ defines a section of \det (at least up to the unit $4 \in k^\times$). The associated quadratic forms are all equal, and are given by

$$q_1(x, y) = q_2(x, y) = q_3(x, y) = a^2 x^2 - y^2,$$

which corresponds to the traceless matrix $\begin{pmatrix} 0 & -1 \\ a^2 & 0 \end{pmatrix} \in \mathfrak{sl}_2$. (Note that this is exactly the companion matrix associated to the characteristic polynomial $y^2 - a^2$.)

One of the key properties of the Kostant section/companion matrices is that a matrix $A \in \mathfrak{sl}_2$ is conjugate to $\kappa(\det(A))$ if and only if A is regular (i.e., the minimal polynomial of A agrees with its characteristic polynomial), if and only if A is nonzero. We will now prove an analogous result concerning $\kappa : \mathbf{A}^1 \rightarrow \text{std}^{\otimes 3}$.

Proposition 2.7. *The \check{G} -orbit of the image of κ is a dense open subscheme whose complement has codimension 3.*

PROOF. We will use the classification of \check{G} -orbits on $\text{std}^{\otimes 3}$ as in [GKZ94, Example 4.5 in Chapter 14]; see Figure 1 for a graph of the seven orbits of \check{G} on $\text{std}^{\otimes 3}$. Namely, if $\lambda \neq 0$, all elements of $\det^{-1}(\lambda)$ are in a single \check{G} -orbit. (In fact, all elements in the fiber $\det^{-1}(1)$ are in the \check{G} -orbit of $(1, \vec{0}, 1, \vec{0})$.) The \check{G} -orbit of $\det^{-1}(\mathbf{G}_m)$ is open and dense, and hence is 8-dimensional; moreover, it agrees with the \check{G} -orbit of $\kappa(\mathbf{G}_m)$. Next, there is a maximal \check{G} -orbit inside the fiber $\det^{-1}(0)$, given by the orbit of $(0, \vec{0}, 0, \vec{1}) = \kappa(0)$. This orbit is 7-dimensional, and the largest \check{G} -orbits contained in the complement $\det^{-1}(0) - \check{G} \cdot \kappa(0)$ have dimension 5. In particular, the complement of $\check{G} \cdot \kappa(\mathbf{A}^1) \subseteq \text{std}^{\otimes 3}$ has dimension 5, i.e., codimension $8 - 5 = 3$. \square

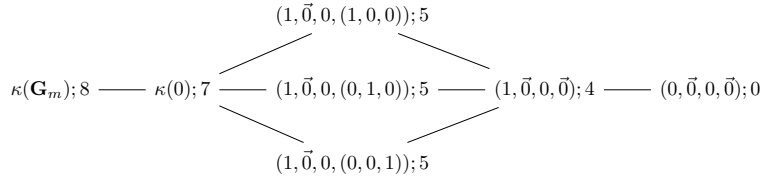


FIGURE 1. \check{G} -orbits on $\text{std}^{\otimes 3}$, representatives, and their dimensions (indicated after the semicolon), connected by closure. Note that $\kappa(0) = (0, \vec{0}, 0, \vec{1})$, and that the \check{G} -orbit of $\kappa(1) = (1, \vec{0}, 0, \vec{1})$ is the same as the \check{G} -orbit of $(1, \vec{0}, 1, \vec{0})$.

Remark 2.8. As explained in [GKZ94, Example 4.5 in Chapter 14], the closure of the associated orbits inside $\mathbf{P}(\text{std}^{\otimes 3}) = \mathbf{P}^7$ can be described as follows. First, the closure of the generic orbit is \mathbf{P}^7 . Next, the closure of the orbit of next smallest dimension is the zero locus of \det , which cuts out the dual variety of the Segre

embedding $(\mathbf{P}^1)^{\times 3} \hookrightarrow \mathbf{P}^7$ (just as the usual determinant for 2×2 -matrices cuts out the quadric $\mathbf{P}^1 \times \mathbf{P}^1 \hookrightarrow \mathbf{P}^3$). The projective orbit associated to $(1, \vec{0}, 0, (0, 1, 0))$, say, is cut out inside the locus $\{\det = 0\}$ by the Segre embedding $\mathbf{P}(\mathrm{std}) \times \mathbf{P}(\mathrm{std}^{\otimes 2}) = \mathbf{P}^1 \times \mathbf{P}^3 \rightarrow \mathbf{P}^7$. Finally, the minimal nonzero orbit is cut out by the Segre embedding $(\mathbf{P}^1)^{\times 3} \rightarrow \mathbf{P}^7$.

Proposition 2.9. *There is an isomorphism*

$$\mathfrak{sl}_2 // \mathrm{SL}_2 \times_{\mathrm{std}^{\otimes 3} / \check{G}} \mathfrak{sl}_2 // \mathrm{SL}_2 \cong \mathrm{Spec} k[a, \alpha_i^{\pm 1}, \frac{\alpha_i - \alpha_i^{-1}}{a} | 1 \leq i \leq 3]^{Z/2} / (\alpha_1 \alpha_2 \alpha_3 = 1)$$

of group schemes over $\mathfrak{sl}_2 // \mathrm{SL}_2 = \mathrm{Spec} k[a^2]$, where the action of $\mathbf{Z}/2$ sends $a \mapsto -a$ and $\alpha_i \mapsto \alpha_i^{-1}$, and the group structure is such that each α_i is grouplike.

PROOF. The fiber product on the left identifies with the subgroup of $\mathfrak{sl}_2 // \mathrm{SL}_2 \times \check{G}$ of those (a^2, \vec{g}) such that $\vec{g} = (g_1, g_2, g_3) \in \mathrm{SL}_2^{\times 3}$ stabilizes $\kappa(a^2)$. The trick to determining this stabilizer is to use Bhargava's construction from Construction 2.3: if \vec{g} stabilizes a cube \mathcal{C} , it must also stabilize the corresponding triple $\mu(\mathcal{C}) \in \mathfrak{sl}_2^{\times 3}$ of quadratic forms.

First, a simple calculation shows that if a is a unit, the triple of matrices

$$\vec{g} = \left(\sqrt{\frac{i}{2}} \begin{pmatrix} -i & a^{-1} \\ ia & 1 \end{pmatrix}, \sqrt{\frac{i}{2}} \begin{pmatrix} -i & a^{-1} \\ ia & 1 \end{pmatrix}, \frac{i}{\sqrt{2}} \begin{pmatrix} -1 & a^{-1} \\ a & 1 \end{pmatrix} \right) \in \mathrm{SL}_2^{\times 3}$$

sends

$$\kappa(a^2) \mapsto -\sqrt{2}(a^2, \vec{0}, a^{-1}, \vec{0}).$$

The triple \vec{g} can be thought of as “diagonalizing” $\kappa(a^2)$. The stabilizer of the cube $-\sqrt{2}(a^2, \vec{0}, a^{-1}, \vec{0})$ precisely consists of triples of matrices of the form

$$(2) \quad \left(\begin{pmatrix} \alpha_1 & 0 \\ 0 & \alpha_1^{-1} \end{pmatrix}, \begin{pmatrix} \alpha_2 & 0 \\ 0 & \alpha_2^{-1} \end{pmatrix}, \begin{pmatrix} \alpha_3 & 0 \\ 0 & \alpha_3^{-1} \end{pmatrix} \right) \text{ with } \alpha_1 \alpha_2 \alpha_3 = 1.$$

For $\alpha \in \mathbf{G}_m$, let $h(\alpha)$ denote the matrix

$$h(\alpha) = \frac{1}{2} \begin{pmatrix} \alpha + \alpha^{-1} & \frac{\alpha^{-1} - \alpha}{a} \\ a^2 \cdot \frac{\alpha^{-1} - \alpha}{a} & \alpha + \alpha^{-1} \end{pmatrix} \in \mathrm{SL}_2.$$

Conjugating (2) by the element $\vec{g} \in \check{G}$, we find that the triple $(h(\alpha_1), h(\alpha_2), h(\alpha_3))$ of matrices stabilizes $\kappa(a^2)$ as long as $\alpha_1 \alpha_2 \alpha_3 = 1$ and $a^2 \in \mathbf{G}_m \subseteq \mathbf{A}^1$. (See [BFM05, Section 3.2] for a slight variant of this calculation.) Note that the subgroup of such triples is 2-dimensional, and therefore the associated homogeneous \check{G} -space is $9 - 2 = 7$ -dimensional. Using that the \check{G} -orbit of $\kappa(a^2)$ is also 7-dimensional (e.g., by [GKZ94, Example 4.5 in Chapter 14]), it is not hard to see from this calculation (by a limiting argument for $a \rightarrow 0$) that the stabilizer of the family $\kappa(\mathbf{A}^1) \subseteq \mathrm{std}^{\otimes 3}$ is precisely the claimed group scheme. \square

Remark 2.10. A direct calculation shows that the stabilizer of $\kappa(0)$ is isomorphic to the subgroup of triples of matrices of the form $\begin{pmatrix} \pm 1 & \mp \gamma_i \\ 0 & \pm 1 \end{pmatrix}$ for $1 \leq i \leq 3$ with $\gamma_1 + \gamma_2 + \gamma_3 = 0$. This subgroup is, of course, isomorphic to $\mu_2^{\times 3} \times \mathbf{G}_a^{\times 2}$; it is also isomorphic to the fiber over $a = 0$ of the group scheme of Proposition 2.9.

Remark 2.11. As mentioned in Remark 1.6, the quotient stack $\mathrm{std}^{\otimes 3} / \mathrm{SL}_2^{\times 3}$ is studied in quantum information theory. For instance, in [DVC00], Dür-Vidal-Cirac study the orbit structure of $\mathrm{SL}_2^{\times 3}$ acting on $\mathrm{std}^{\otimes 3}$ (in particular, they recover Figure 1 independently of [GKZ94]). For the interested reader, let us describe the

translation between our notation/terminology and that of quantum information theory. Our base field will now be $k = \mathbf{C}$. An element of $\text{std}^{\otimes n}$ (really, of the projective space $\mathbf{P}(\text{std}^{\otimes n}) \cong \mathbf{P}^{2^n-1}$) is called an n -qubit, and the action of $\text{SL}_2^{\times n}$ is via *stochastic local operations and classical communication* (SLOCC) operators (replacing $\text{SL}_2^{\times n}$ by $\text{GL}_2^{\times n}$ simply amounts to dropping the word “stochastic”). The space std is equipped with a basis $\{|0\rangle, |1\rangle\}$, and a cube $\mathcal{C} = (a, \vec{b}, c, \vec{d}) \in \text{std}^{\otimes 3}$ corresponds to the three-qubit³

$$a|000\rangle + b_1|100\rangle + b_2|010\rangle + b_3|001\rangle \\ + d_1|011\rangle + d_2|101\rangle + d_3|110\rangle + c|111\rangle.$$

The state

$$\frac{1}{\sqrt{2}}(1, \vec{0}, 1, \vec{0}) = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$$

is known as the *Greenberger–Horne–Zeilinger* (GHZ) state, and the state

$$\frac{1}{\sqrt{3}}\kappa(0) = \frac{1}{\sqrt{3}}(0, \vec{1}, 0, \vec{0}) = \frac{1}{\sqrt{3}}(|001\rangle + |010\rangle + |100\rangle)$$

is called the *W* state. These two states are known to represent two very different kinds of quantum entanglement; from the perspective of this article, the reason for this is simply that the Cayley hyperdeterminant of the GHZ state is nonzero, but the Cayley hyperdeterminant of the W state vanishes. Nevertheless, the proof of Proposition 2.9 shows that there is a natural *degeneration* of (the SLOCC/ $\text{SL}_2^{\times 3}$ -equivalence class of) the GHZ state into the W state. Indeed, the GHZ state can be transformed into the cube $\frac{1}{2}\kappa(1)$, which admits a natural degeneration to the W state via the one-parameter family

$$\frac{1}{\sqrt{a^4+3}}\kappa(a^2) = \frac{1}{\sqrt{a^4+3}}(a^2|000\rangle + |011\rangle + |101\rangle + |110\rangle).$$

In fact, this state already appears as [DVC00, Equation 20].

Remark 2.12. Fix an integer n . Then the \check{G} -variety $\text{std}^{\otimes 3}$ admits a natural grading, where the entries of a cube (a, \vec{b}, c, \vec{d}) have the following weights: a lives in weight $-4n$, b lives in weight $-2n$, c lives in weight $2n$, and d lives in weight 0 . Write $\text{std}^{\otimes 3}(4n, 2\vec{n}, -2n, \vec{0})$ to denote the associated graded variety. Equip \mathfrak{sl}_2 with the grading where the entries of a matrix $\begin{pmatrix} a & b \\ c & -a \end{pmatrix}$ have the following weights: a lives in weight $-2n$, b lives in weight 0 , and c lives in weight $-4n$. Similarly, equip SL_2 with the grading coming from $2n\rho$, so that the entries of a matrix $\begin{pmatrix} a & b \\ c & d \end{pmatrix}$ have the following weights: a and d live in weight 0 , b lives in weight $2n$, and c lives in weight $-2n$. With these gradings, the $\text{SL}_2^{\times 3}$ -equivariant map $\mu : \text{std}^{\otimes 3} \rightarrow \mathfrak{sl}_2^{\times 3}$ is a *graded* map, and κ defines a graded map $\mathfrak{sl}_2(2n) // \text{SL}_2 \cong \mathbf{A}^1(4n) \rightarrow \text{std}^{\otimes 3}(4n, 2\vec{n}, -2n, \vec{0})$. The cases $n = 1$ and $n = 3$ will be relevant below (corresponding to Theorem 1.2 and Theorem 1.3, respectively).

3. The proof

Before proceeding, let us remind the reader of the definition of the left-hand side of the equivalence of Theorem 1.2, following [Dev23, Definition 3.5.15].

³Technically, a qubit is required to have norm 1, so one must rescale \mathcal{C} by $\sqrt{a^2 + \|\vec{b}\|^2 + c^2 + \|\vec{d}\|^2}$; but this could in theory introduce a singularity when $a^2 + \|\vec{b}\|^2 + c^2 + \|\vec{d}\|^2 = 0$. We will ignore this point below.

Definition 3.1. Let G be a compact Lie group, and let $H \subseteq G$ be a closed subgroup such that $H_{\mathbf{C}} \subseteq G_{\mathbf{C}}$ is a spherical subgroup. Let $\mathrm{Shv}_G^c(\mathcal{L}(G/H); \mathbf{Q})$ denote the ∞ -category of G -equivariant sheaves of \mathbf{Q} -modules on $\mathcal{L}(G/H)$ which are constructible for the orbit stratification on $\mathcal{L}(G/H)$. Note that since the orbit stratification is countable (by assumption that $H_{\mathbf{C}} \subseteq G_{\mathbf{C}}$ is a spherical subgroup and [GN10, Theorem 3.2.1]), the ∞ -category $\mathrm{Shv}_G^c(\mathcal{L}(G/H); \mathbf{Q})$ is well-defined. There is a natural left-action of the \mathbf{E}_3 -monoidal ∞ -category $\mathrm{Shv}_{G \times G}^c(\mathcal{L}G; \mathbf{Q})$ on $\mathrm{Shv}_G^c(\mathcal{L}(G/H); \mathbf{Q})$, and in particular, a left-action of $\mathrm{Rep}(\check{G})$ by the abelian geometric Satake theorem of [MV07]. Let $\mathrm{IC}_0 \in \mathrm{Shv}_G^c(\mathcal{L}(G/H); \mathbf{Q})$ denote the pushforward $i_! \underline{\mathbf{Q}}$ of the constant sheaf along the inclusion $i : G/H \hookrightarrow \mathcal{L}(G/H)$ of the constant loops. Note that i is the analytic realization of the natural map $(G/H)(\mathbf{C}[[t]]) \rightarrow (G/H)(\mathbf{C}((t)))$. Let $\mathrm{Shv}_G^{c, \mathrm{Sat}}(\mathcal{L}(G/H); \mathbf{Q})$ denote the full subcategory of $\mathrm{Shv}_G^c(\mathcal{L}(G/H); \mathbf{Q})$ generated by IC_0 under the action of $\mathrm{Rep}(\check{G})$. If k is any \mathbf{Q} -algebra, base-changing along the unit map defines the ∞ -category $\mathrm{Shv}_G^{c, \mathrm{Sat}}(\mathcal{L}(G/H); k)$.

PROOF OF THEOREM 1.2. It suffices to verify conditions (a) and (b) of [Dev23, Theorem 3.5.20], which gives a criterion for establishing an equivalence of k -linear ∞ -categories of the form

$$\mathrm{Shv}_G^{c, \mathrm{Sat}}(\mathcal{L}(G/H); k) \simeq \mathrm{Perf}(\mathrm{sh}^{1/2} \check{M}/\check{G}).$$

The map κ is given by the map $\mathfrak{sl}_2(2) // \mathrm{SL}_2 \rightarrow \mathrm{std}^{\otimes 3}(4, \vec{2}, -2, \vec{0})$ from Construction 2.6. For condition (a) of [Dev23, Theorem 3.5.20], we need to show that if $\check{J}_X = \mathfrak{sl}_2(2) // \mathrm{SL}_2 \times_{\mathrm{std}^{\otimes 3}(4, \vec{2}, -2, \vec{0})/\check{G}} \mathfrak{sl}_2(2) // \mathrm{SL}_2$, the ring of regular functions on the quotient $(\mathfrak{sl}_2(2) // \mathrm{SL}_2 \times \check{G})/\check{J}_X$ is isomorphic (as a graded algebra) to $\mathcal{O}_{\mathrm{std}^{\otimes 3}(4, \vec{2}, -2, \vec{0})}$. The quotient $(\mathfrak{sl}_2(2) // \mathrm{SL}_2 \times \check{G})/\check{J}_X$ identifies with the \check{G} -orbit of the image of κ , which has complement of codimension 3 in $\mathrm{std}^{\otimes 3}$ by Proposition 2.7; therefore, the algebraic Hartogs theorem implies that there is a graded isomorphism $\mathcal{O}_{(\mathfrak{sl}_2(2) // \mathrm{SL}_2 \times \check{G})/\check{J}_X} \cong \mathcal{O}_{\mathrm{std}^{\otimes 3}(4, \vec{2}, -2, \vec{0})}$.

For condition (b) of [Dev23, Theorem 3.5.20], we need to check that there is an isomorphism

$$\check{J}_X \cong \mathrm{Spec} H_*^{\mathrm{PGL}_2}(\Omega(\mathrm{PGL}_2^{\times 3}/\mathrm{PGL}_2^{\mathrm{diag}}); k)$$

of graded group schemes over $\mathfrak{sl}_2(2) // \mathrm{SL}_2 \cong \mathrm{Spec} H_{\mathrm{PGL}_2}^*(*)$. There is an isomorphism

$$(3) \quad \mathrm{Spec} H_*^{\mathrm{PGL}_2}(\Omega \mathrm{PGL}_2; k) \cong \mathrm{Spec} k[a, \alpha^{\pm 1}, \frac{\alpha - \alpha^{-1}}{a}]^{\mathbf{Z}/2},$$

and the action of the $\mathbf{Z}/2$ on the left-hand side sends $a \mapsto -a$ and $\alpha \mapsto \alpha^{-1}$. This is proved, e.g., in [BFM05], and also follows from [Dev23, Example 3.6.16]. The Künneth theorem implies that there is an isomorphism

$$\mathrm{Spec} H_*^{\mathrm{PGL}_2}(\Omega(\mathrm{PGL}_2^{\times 3}); k) \cong \mathrm{Spec} k[a, \alpha_i^{\pm 1}, \frac{\alpha_i - \alpha_i^{-1}}{a} | 1 \leq i \leq 3]^{\mathbf{Z}/2},$$

and the fiber sequence

$$\mathrm{PGL}_2^{\mathrm{diag}} \rightarrow \mathrm{PGL}_2^{\times 3} \rightarrow \mathrm{PGL}_2^{\times 3}/\mathrm{PGL}_2^{\mathrm{diag}}$$

implies that

$$\mathrm{Spec} H_*^{\mathrm{PGL}_2}(\Omega(\mathrm{PGL}_2^{\times 3}/\mathrm{PGL}_2^{\mathrm{diag}}); k) \cong \mathrm{Spec} \left(k[a, \alpha_i^{\pm 1}, \frac{\alpha_i - \alpha_i^{-1}}{a} | 1 \leq i \leq 3] / (\alpha_1 \alpha_2 \alpha_3 - 1) \right)^{\mathbf{Z}/2},$$

The desired isomorphism now follows from this observation and Proposition 2.9. \square

Remark 3.2. The proof of Theorem 1.3 is exactly the same as the proof of Theorem 1.2 above. Indeed, one only needs to observe that PSO_8/G_2 is homotopy equivalent to $\mathbf{R}P^7 \times \mathbf{R}P^7$ (which follows, e.g., from the fact that $\mathrm{Spin}_8/G_2 \simeq S^7 \times S^7$)⁴. The replacement of (3) is given by [Dev23, Proposition 4.8.6], which gives an isomorphism

$$\mathrm{Spec} H_*^{G_2}(\Omega \mathbf{R}P^7; k) \cong \mathrm{Spec} k[a, b, \alpha^{\pm 1}, \frac{\alpha - \alpha^{-1}}{a}]^{\mathbf{Z}/2}$$

where a is in weight -6 and b is in weight -4 .

Remark 3.3. The Künneth isomorphism fails to hold for $\mathrm{Shv}_G^{c, \mathrm{Sat}}(\mathcal{L}(G/H); \mathbf{Q})$, as can be seen (for instance) from Theorem 1.2. (We will ignore gradings for the purpose of this illustration.) Indeed, let $G = \mathrm{PGL}_2^{\times 3}$, and let $H = \mathrm{PGL}_2^{\mathrm{diag}}$. Then $G/H \cong \mathrm{PGL}_2^{\times 2}$, so if the Künneth isomorphism held, there would be a series of equivalences

$$\begin{aligned} \mathrm{Shv}_G^{c, \mathrm{Sat}}(\mathcal{L}(G/H); \mathbf{Q}) &\simeq \mathrm{Shv}_H^{c, \mathrm{Sat}}(\Omega(G/H); \mathbf{Q}) \\ &\simeq \mathrm{Shv}_{\mathrm{PGL}_2}^{c, \mathrm{Sat}}((\Omega \mathrm{PGL}_2)^{\times 2}; \mathbf{Q}) \\ &\simeq \mathrm{Shv}_{\mathrm{PGL}_2}^{c, \mathrm{Sat}}(\Omega \mathrm{PGL}_2; \mathbf{Q})^{\otimes_{\mathrm{Shv}_{\mathrm{PGL}_2}^{c, \mathrm{Sat}}(*; \mathbf{Q})} 2} \\ &\simeq \mathrm{Perf}^{\mathrm{sh}}(\mathfrak{sl}_2/\mathrm{SL}_2 \times_{\mathfrak{sl}_2/\mathrm{SL}_2} \mathfrak{sl}_2/\mathrm{SL}_2). \end{aligned}$$

However, it is obviously *not* true that $(\mathfrak{sl}_2 \times_{\mathfrak{sl}_2/\mathrm{SL}_2} \mathfrak{sl}_2)/\mathrm{SL}_2^{\times 2}$ is isomorphic to the true dual $\mathrm{std}^{\otimes 3}/\mathrm{SL}_2^{\times 3}$ from Theorem 1.2. Nevertheless, these stacks are closely related, e.g., via the construction of Construction 2.3.

Remark 3.4. The theory of 2-compact groups as studied, e.g., in [AG09], suggests viewing the Dwyer-Wilkerson space DW_3 from [DW93] as an analogue of the groups $\mathrm{SO}_3 \cong \mathrm{PGL}_2$ and G_2 ; see Table 1. The space DW_3 is a finite CW-complex equipped with an \mathbf{E}_1 -structure. It is therefore natural to ask whether there is an analogue of Theorem 1.2 and Theorem 1.3, where PGL_2 and G_2 are replaced by DW_3 ; this is closely related to [Dev23, Appendix C(p)].

It is difficult to answer this question since the representation theory of DW_3 is not well-understood. For instance, it does not seem to be known whether there is a 2-compact group G with an \mathbf{E}_1 -map $\mathrm{DW}_3 \rightarrow G$ such that $G/\mathrm{DW}_3 \simeq \mathbf{R}P^{15} \times \mathbf{R}P^{15}$ (analogous to the equivalences $\mathrm{PGL}_2^{\times 3}/\mathrm{PGL}_2 \cong \mathbf{R}P^3 \times \mathbf{R}P^3$ and $\mathrm{PSO}_8/G_2 \cong \mathbf{R}P^7 \times \mathbf{R}P^7$). If such a G exists, and there is a good theory of G -equivariant sheaves of k -modules, it seems reasonable to expect that there is an equivalence of

⁴Perhaps the most “conceptual” way to see that $\mathrm{Spin}_8/G_2 \simeq S^7 \times S^7$ is as follows. Using triality, one can identify Spin_8 with the subgroup of $\mathrm{SO}_8^{\times 3}$ of those triples (A_1, A_2, A_3) such that $A_1(x_1)A_2(x_2) = A_3(x_1x_2)$ for octonions x_1, x_2 . Under this presentation, G_2 corresponds to the subgroup where $A_1 = A_2 = A_3$. The subgroups where $A_1 = A_3$ (resp. $A_2 = A_3$) are both isomorphic to $\mathrm{Spin}(7)$; these are sometimes denoted $\mathrm{Spin}^{\pm}(7)$. The action of Spin_8 on $S^7 \times S^7$ sends $(x, y) \mapsto (A_1x, A_2y)$; one can check that this is transitive, and that the stabilizer of the point $(1, 1)$ is precisely $\mathrm{Spin}^+(7) \cap \mathrm{Spin}^-(7) \cong G_2$.

That there is an equivalence $\mathrm{Spin}_8/G_2 \simeq S^7 \times S^7$ at the level of cohomology with $\mathbf{Z}[1/2]$ -coefficients, at least, is much simpler: on group cohomology, the map $G_2 \rightarrow \mathrm{Spin}_8$ is given by the map $\mathbf{Z}[1/2, p_1, p_2, p_3, c_4] \rightarrow \mathbf{Z}[1/2, c_2, c_6]$ sending $p_1 \mapsto -c_2$, $p_2 \mapsto 0$, $p_3 \mapsto -c_6$, and $c_4 \mapsto 0$. The Serre spectral sequence for the fibration $\mathrm{Spin}_8/G_2 \rightarrow BG_2 \rightarrow B\mathrm{Spin}_8$ implies that $H^*(\mathrm{Spin}_8/G_2; \mathbf{Z}[1/2]) \cong \mathbf{Z}[1/2, \sigma(p_2), \sigma(c_4)]/(\sigma(p_2)^2, \sigma(c_4)^2)$, where $\sigma(p_2)$ and $\sigma(c_4)$ both live in (homological) weight -7 . This is precisely the cohomology of $S^7 \times S^7$, as desired.

Group	Rank	Dimension	\mathbf{F}_2 -cohomology of BG	Weyl group
G_n	n	$(2^{n+1} - 1)n$	$\widehat{\mathrm{Sym}}^*(\mathbf{F}_2^{n+1}(-1))^{\mathrm{GL}_{n+1}(\mathbf{F}_2)}$	$\mathbf{Z}/2 \times \mathrm{GL}_n(\mathbf{F}_2)$
PGL_2	1	3	$\mathbf{F}_2[w_2, w_3]$	$\mathbf{Z}/2$
G_2	2	14	$\mathbf{F}_2[w_4, w_6, w_7]$	$\mathbf{Z}/2 \times \Sigma_3$
DW_3	3	45	$\mathbf{F}_2[w_8, w_{12}, w_{14}, w_{15}]$	$\mathbf{Z}/2 \times \mathrm{PSL}_2(\mathbf{F}_7)$

TABLE 1. Analogies between the (2-compact) groups $\mathrm{PGL}_2 = \mathrm{SO}_3$, G_2 , and DW_3 ; all of these are Poincaré duality complexes of dimension indicated in the third column. Here, w_n denotes the n th Stiefel-Whitney class, and the ring in the fourth column is known as the algebra of rank $n + 1$ Dickson invariants. Note, also, that the Weyl group of DW_3 is called G_{24} in the Shephard-Todd classification.

the form

$$\mathrm{Shv}_G^{c, \mathrm{Sat}}(\mathcal{L}(G/\mathrm{DW}_3); k) \cong \mathrm{Perf}^{\mathrm{sh}}(\mathrm{std}^{\otimes 3}(28, \vec{14}, -14, \vec{0})/\mathrm{SL}_2(-14\rho)^{\times 3} \times \mathbf{A}^2(8, 12)).$$

Here, the “Whittaker” factor $\mathbf{A}^2(8, 12)$ on the right-hand side comes from the isomorphism

$$\mathrm{Spf} H^*(BDW_3; k) \cong \widehat{\mathbf{A}}^3(8, 12, 28),$$

which follows from running the Bockstein spectral sequence on

$$H^*(BDW_3; \mathbf{F}_2) \cong \mathbf{F}_2[w_8, w_{12}, w_{14}, w_{15}],$$

and the fact that the Bockstein sends $w_{14} \mapsto w_{15}$. One can check that such a G , if it existed, would have rational cohomology given by

$$H^*(BG; k) \cong k[c_4, c_6, c_{14}, x, y],$$

where both x and y live in cohomological degree 16.

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