Matter Content and Gauge Structure from the Symmetries of the Cosmological Horizon

A Speculative Note II

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Abstract

A companion note showed that the cosmological constant follows from horizon thermodynamics with no free parameters. Here we extend the framework to the matter content and gauge structure of the Standard Model. The metric on any two-sphere decomposes under SO(3) as a rank-2 tensor: $1 \otimes 1 = 0 \oplus 1 \oplus 2$, yielding 1, 3, and 5 degrees of freedom for the $\ell = 0$, 1, and 2 sectors respectively. The metric symmetry $g_{\mu\nu} = g_{\nu\mu}$ suppresses $\ell = 1$; the unfilled thermal capacity of the horizon splits between $\ell = 0$ (baryonic matter, 1 dof) and $\ell = 2$ (dark matter, 5 dof), predicting $\Omega_{\rm dm}/\Omega_b = 5$ exactly. The suppressed $\ell = 1$ residual maps to three neutrino flavors with small masses. When the Planck-area patches of the horizon are quantized, the real SO(3) algebra complexifies into $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$ with $1 + 3 + 8 = 12$ generators. The Cartan decomposition requires $\mathrm{SU}(2) \subset \mathrm{SU}(3)$—the strong interaction cannot close without the weak. The real sectors ($\ell = 0$, $\ell = 2$) give the long-range forces; the complexified sectors are intrinsically short-range. Quantization and time evolution act as dual operations on the horizon algebra: complexification creates gauge structure, decomplexification creates classical reality. If confirmed by forthcoming data, both the matter content and the gauge forces are outputs of the rank-2 tensor geometry of the cosmological horizon.

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1 Context

In a companion note [1], we argued that the cosmological constant Λ is the thermodynamic signature of the cosmological event horizon. The fixed-point condition $\rho_{\rm thermal} = TS/V = \rho_\Lambda$ holds exactly in de Sitter spacetime and uniquely for the maximum-entropy relation $E = TS$, yielding a parameter-free prediction $c = 1$ for the holographic dark energy model [2] and a present-day equation of state $w \approx -0.89$ with $w \geq -1$ at all times. The generalized second law (GSL) drives the universe toward de Sitter as a maximum-entropy attractor on a timescale $t_{\rm eq} \sim 10^{10}$ years.

That note addressed a single question: why does Λ have the value it does? This note asks a broader one: can the same horizon thermodynamics account for the full cosmic energy budget—not only dark energy, but dark matter and baryonic matter as well?

The ingredients are not new. Bekenstein [3] showed that black hole entropy scales with horizon area, not volume. 't Hooft [4] and Susskind [5] elevated this to a general principle: the degrees of freedom of any region are bounded by its boundary area in Planck units [6]. Jacobson [7] derived Einstein's equations from the Clausius relation $\delta Q = T\,dS$ applied to local Rindler horizons—showing that gravity itself may be thermodynamic. Bousso [6] extended the entropy bound to arbitrary spacetimes, including de Sitter. Verlinde [8] proposed that dark matter is an apparent effect of the entropy displacement of the de Sitter vacuum. In loop quantum gravity, Rovelli [9] and Ashtekar and Lewandowski [10] showed that horizon area is quantized in Planck-sized units, each carrying a discrete degree of freedom.

What we add here is a specific chain connecting these ideas to the observed energy budget and gauge structure: horizon microstructure → thermal capacity → SO(3) decomposition → the dark-matter-to-baryon ratio → the Standard Model gauge group.

2 Holographic Microstructure and Energy Budget

The Bekenstein–Hawking entropy of the cosmological event horizon is $S = k_B A/(4\ell_P^2) \sim 10^{122}\,k_B$, where $A = 4\pi r_H^2$ is the horizon area and $\ell_P \approx 1.6 \times 10^{-35}\,\mathrm{m}$ is the Planck length. This entropy counts the number of independent degrees of freedom on the horizon: one bit per each Planck-scale patch of area $4\ell_P^2$ [3].

Standard quantum field theory, by contrast, counts degrees of freedom by volume. A Hubble-sized region contains $(r_H/\ell_P)^3 \sim 10^{183}$ Planck-scale cells, each presumed to carry independent quantum fluctuations. Summing their zero-point energies yields a vacuum energy density $\sim\!10^{120}$ times the observed value—that constitutes the cosmological constant problem [11].

The holographic principle resolves this discrepancy not by cancellation but by correcting the counting. Of the 10^{183} volume modes, only 10^{122} are independent; the rest are holographically redundant, correlated through the gravitational dynamics that the horizon encodes. Each independent degree of freedom resides on a Planck-area patch of the horizon surface.

This picture is not merely formal. In Jacobson's derivation [7], every point in spacetime has a local Rindler horizon—a causal boundary seen by an accelerating observer. Each local horizon is a two-sphere at the Planck scale, carrying Bekenstein–Hawking entropy. Einstein's equations emerge as the equation of state of these local horizons. The cosmological horizon at $r_H \sim 10^{26}\,\mathrm{m}$ is the macroscopic, coarse-grained manifestation of 10^{122} such Planck-scale horizons.

Each patch has a thermal capacity set by the Gibbons–Hawking temperature $T_{\mathrm{GH}} = \hbar H/(2\pi k_B)$ [12]. The total thermal energy of a fully occupied horizon is $E = Nk_BT_{\mathrm{GH}} = TS$, and the corresponding energy density $\rho = TS/V$ equals the observed dark energy density ρ_Λ—as demonstrated in the companion note [1]. But the horizon today is not fully thermalized. The dark energy fraction $\Omega_{\mathrm{de}} \approx 0.70$ represents the filled capacity; the remaining $\Omega_m \approx 0.30$ is the unfilled fraction—energy not yet converted into featureless, maximum-entropy horizon radiation. This unfilled fraction is what we observe as matter—both dark and baryonic. The question addressed in the next section is: how is this unfilled capacity divided among the different matter sectors?

3 SO(3) Decomposition of the Horizon

The cosmological horizon is topologically a two-sphere S^2. The companion note [1] showed that the GSL drives the universe toward a stable de Sitter state, guaranteeing the existence of this horizon. The natural symmetry group of S^2 is SO(3), the rotation group. The fundamental field describing gravity is the metric tensor $g_{\mu\nu}$—a symmetric rank-2 tensor. Restricting the metric to the horizon surface yields a rank-2 tensor field on S^2, whose components decompose under SO(3) as:

$$1 \otimes 1 = 0 \oplus 1 \oplus 2\,, \tag{1}$$

corresponding to multipole sectors with $2\ell + 1$ degrees of freedom each:

$$\ell = 0:\ 1\ \text{dof}, \qquad \ell = 1:\ 3\ \text{dof}, \qquad \ell = 2:\ 5\ \text{dof}\,. \tag{2}$$

This is the complete decomposition of a rank-2 tensor under SO(3). The origin of the cutoff at $\ell = 2$ is the angular momentum addition rule: each index of the metric $g_{\mu\nu}$ restricted to S^2 transforms as a vector ($\ell = 1$) under rotations, and two $\ell = 1$ representations combine as $1 \otimes 1 = 0 \oplus 1 \oplus 2$. No $\ell \geq 3$ can appear because two spin-1 indices cannot couple to angular momentum greater than 2. This is a property of the *index structure* of the tensor, not of its spatial variation across the sphere. A gravitational wave signal, for instance, contains higher angular multipoles ($\ell = 3, 4, \ldots$) in its radiation pattern, but those arise from the spatial modulation of the $\ell = 2$ degree of freedom over many horizon patches—not from new irreducible representations of the metric tensor on S^2.

The three sectors have distinct geometric characters:

$\ell = 0$ **(trace, 1 dof):** The scalar part of the rank-2 tensor—its trace. It is uniform and isotropic, carries no directional information, and couples universally. In electromagnetism, the monopole is electric charge; a monopole source radiates and is visible. The trace of the metric is a single parity-even scalar; there is no parity-odd (pseudoscalar) trace. A magnetic monopole would require such a second $\ell = 0$ mode with opposite parity. Its absence is not imposed by hand but follows from the metric having exactly one trace.

$\ell = 1$ **(antisymmetric part, 3 dof):** The vector part. For the metric, which is symmetric ($g_{\mu\nu} = g_{\nu\mu}$), the antisymmetric component is suppressed—it vanishes identically in the exact de Sitter limit. On a cosmological horizon, it corresponds to a boost of the observer—pure gauge. The large dipole in the cosmic microwave background (CMB) temperature map ($\sim 3.4\,\text{mK}$, corresponding to a Solar System velocity of $\sim 370\,\text{km/s}$ [13]) is entirely attributed to our motion through the CMB rest frame, not to cosmological physics. A small physical residual could survive in a perturbed universe (Section 4).

$\ell = 2$ **(symmetric traceless part, 5 dof):** The tensor part. This is the physical content of the metric perturbation—the gravitational degree of freedom. In general relativity, there is no gravitational monopole radiation (mass is conserved) and no gravitational dipole radiation (momentum is conserved). The quadrupole is the first and lowest radiative gravitational mode. It distorts spacetime but does not couple to electromagnetism. It is dark by nature.

The metric tensor thus provides all three ingredients at once: the cutoff at $\ell = 2$ (rank-2 tensors contain nothing higher), the near-absence of $\ell = 1$ (the metric is symmetric, so the

antisymmetric part is suppressed), and the physical distinction between $\ell = 0$ (visible) and $\ell = 2$ (dark). These are not separate assumptions; they are properties of a single object—the metric restricted to S^2.

If the unfilled thermal capacity ($\Omega_m \approx 0.30$) is distributed among the dominant degrees of freedom—$\ell = 0$ (1 dof) and $\ell = 2$ (5 dof)—by equipartition (equal energy per degree of freedom, i.e. the maximum-entropy distribution), the split is:

$$\Omega_b = \tfrac{1}{6}\,\Omega_m \approx 0.05\,, \qquad \Omega_{\rm dm} = \tfrac{5}{6}\,\Omega_m \approx 0.25\,. \tag{3}$$

The predicted ratio $\Omega_{\rm dm}/\Omega_b = 5$ is a geometric property of rank-2 tensors on any two-sphere—it follows from the structure of the metric, not from particle physics. The equipartition is not a statement about the dynamics of the early-universe plasma; it is the maximum-entropy condition of a thermal system at the Gibbons–Hawking temperature. The ratio is set by the horizon geometry, not by a kinetic freeze-out process.

The identification with observed matter is then:

- $\ell = 0$ (1 dof): baryonic matter;
- $\ell = 2$ (5 dof): dark matter.

This identification is reinforced by the spin content of the fundamental interactions. Gravity is mediated by a spin-2 field; its lowest radiative mode on a sphere is the quadrupole, $\ell = 2$. Electromagnetism is mediated by a spin-1 field; the vector mode on a sphere is $\ell = 1$, which is gauge. The only electromagnetic degree of freedom that survives the gauge projection is the scalar charge: the monopole, $\ell = 0$. The Standard Model contains two additional forces—the weak and the strong—but both are short-range and do not propagate classically to the horizon. At the classical level, only the two long-range forces project onto the horizon sphere, populating $\ell = 0$ and $\ell = 2$. (The short-range forces re-emerge through quantization; see Section 5.)

This decomposition does not require the cosmological event horizon specifically. Any causal boundary in 3+1 dimensions is topologically S^2 and carries the same rank-2 tensor structure. In Jacobson's framework [7], every local Rindler horizon at every spacetime point carries the same decomposition. The $5:1$ ratio is therefore not a late-time phenomenon tied to the formation of the cosmological horizon; it is a property of the metric geometry at all epochs. A crucial corollary: distinct observers have distinct causal horizons, but the SO(3) decomposition, the $5{:}1$ ratio, and the gauge structure derived in Section 5 are identical for all of them—because these depend only on the topology of S^2 and the rank of the metric, both of which are universal. The physics is observer-independent even though the boundary is not.

4 Neutrinos as the Dipole Residual

In a perfect de Sitter spacetime, the horizon is an exact two-sphere, the metric is exactly symmetric, and the antisymmetric $\ell = 1$ component vanishes identically. But the real universe

is not exactly de Sitter: it contains matter, the horizon is perturbed, and the metric symmetry is not exact. The dipole mode is therefore not entirely absent—a small residual survives.

The $\ell = 1$ sector plays several roles in this framework. As a contribution to the *energy budget*—the unfilled thermal capacity of the horizon—it is the subject of this section: the residual dipole carries mass, and we identify it with the neutrino sector. (In Section 5, the same $\ell = 1$ sector will acquire a second role through complexification as the $\mathfrak{su}(2)$ gauge algebra.)

The $\ell = 1$ residual has three degrees of freedom. We propose that the partially physical $\ell = 1$ sector is the neutrino sector. Several features of neutrino physics follow naturally from this identification:

- **Three flavors.** The dipole on S^2 has exactly three components ($m = -1, 0, +1$). The number of neutrino flavors is not arbitrary; it is required by SO(3).
- **Small mass.** Neutrino masses are tiny ($\sum m_\nu \lesssim 0.1$–$0.5\,\mathrm{eV}$ [14, 15]) compared to all other fermions. In this framework, the smallness reflects the near-gauge nature of $\ell = 1$: the antisymmetric part of a symmetric tensor vanishes identically in the exact de Sitter limit, and the residual mass is proportional to the departure from exact symmetry.
- **Normal hierarchy preferred.** The metric symmetry $g_{\mu\nu} = g_{\nu\mu}$ suppresses the antisymmetric sector maximally, so the total neutrino mass sum should be as small as allowed—pointing to the normal hierarchy ($\sum m_\nu \gtrsim 0.058\,\mathrm{eV}$) rather than the inverted hierarchy ($\sum m_\nu \gtrsim 0.10\,\mathrm{eV}$). Global fits to oscillation and cosmological data now show strong evidence ($> 3\sigma$) for the normal hierarchy [14, 16].

The neutrino contribution to the energy budget is $\Omega_\nu = \sum m_\nu/(93.14\,h^2\ \mathrm{eV})$. Because massive neutrinos cluster gravitationally at late times, they are partially degenerate with cold dark matter in CMB fits. The measured Ω_{dm} could therefore include a neutrino contamination. If the true dark-matter-to-baryon ratio is exactly 5 (from the SO(3) decomposition), the observed ratio is:

$$\frac{\Omega_{\mathrm{dm}}^{\mathrm{observed}}}{\Omega_b} = 5 + \frac{\Omega_\nu}{\Omega_b} = 5 + \frac{\sum m_\nu}{93.14\,h^2\,\Omega_b\ \mathrm{eV}}\,. \tag{4}$$

This is a parameter-free relation connecting three independent observables: the dark-matter-to-baryon ratio, the geometric prediction of 5, and the neutrino mass sum. Using Planck 2018 central values [13] ($\Omega_{\mathrm{dm}} = 0.265$, $\Omega_b = 0.050$, $h = 0.674$), the ratio $\Omega_{\mathrm{dm}}/\Omega_b \approx 5.3$ inferred under ΛCDM is consistent with the prediction for $\sum m_\nu$ in the range 0.1–0.5 eV.

A critical caveat: all cosmological bounds on $\sum m_\nu$ assume ΛCDM ($w = -1$). The companion note [1] predicts $w \approx -0.89$; refitting cosmological data within the holographic dark energy model would shift the extracted values of Ω_b, Ω_{dm}, and $\sum m_\nu$, potentially bringing the corrected ratio closer to 5. This point is developed further in the observational tests (Section 7).

5 Complexification and the Standard Model Gauge Group

There is an exact algebraic relationship between the SO(3) decomposition of the metric on S^2 and the Standard Model gauge group SU(3)×SU(2)×U(1). In the preceding sections, the

three SO(3) sectors ($\ell = 0, 1, 2$) were identified with components of the *energy budget*: baryons, neutrinos, and dark matter. Here, the same sectors acquire a second identity as components of the *gauge structure*: the electromagnetic, weak, and strong interactions. The bridge between the two is quantization—the passage from real classical geometry to complex quantum algebra. Geometric derivations of the Standard Model gauge group have been explored before—notably through Calabi–Yau compactifications in ten dimensions [17], grand unified embeddings in SU(5) [18], and attempts to unify all interactions within the exceptional Lie group E_8 [19]—but those approaches require extra dimensions, abstract internal spaces, or algebraic structures far larger than the Standard Model. The construction here uses only the metric on the physical two-sphere of the cosmological horizon in 3+1 dimensions. We present this as a mathematical observation; its physical interpretation—whether the quantization of horizon patches is the correct operation connecting classical geometry to gauge structure—remains conjectural.

The metric on the horizon is a real symmetric rank-2 tensor, decomposing under SO(3) into representations of dimension 1, 3, and 5. The combined $5 + 3 = 8$ degrees of freedom of the $\ell = 2$ and $\ell = 1$ sectors match the dimension of $\mathfrak{su}(3)$, which consists of the 3×3 complex traceless hermitian matrices. These decompose into a real traceless symmetric part (5 parameters, the $\ell = 2$ sector) and an imaginary antisymmetric part (3 parameters, the $\ell = 1$ sector):

$$\mathfrak{su}(3) = \underbrace{\text{traceless symmetric}}_{\ell=2,\ 5\ \text{dof}} \oplus i\ \underbrace{\text{antisymmetric}}_{\ell=1,\ 3\ \text{dof}}\,. \tag{5}$$

This is a mathematical identity. Explicitly: of the eight Gell-Mann generators $\lambda_1, \ldots, \lambda_8$, five ($\lambda_1, \lambda_3, \lambda_4, \lambda_6, \lambda_8$) are real symmetric and three ($\lambda_2, \lambda_5, \lambda_7$) are imaginary antisymmetric. Their commutation relations satisfy the Cartan decomposition: denoting $\mathfrak{p} = \ell = 2$ and $\mathfrak{k} = i\,\ell = 1$,

$$[\mathfrak{k}, \mathfrak{k}] \subset \mathfrak{k}\,, \qquad [\mathfrak{k}, \mathfrak{p}] \subset \mathfrak{p}\,, \qquad [\mathfrak{p}, \mathfrak{p}] \subset \mathfrak{k}\,, \tag{6}$$

verified for all 28 independent commutator pairs. The decomposition (5) is thus not merely a vector-space splitting but a symmetric-space (Cartan) structure of $\mathfrak{su}(3)$. This identification is unique: $\mathfrak{su}(3)$ is the only simple Lie algebra of dimension 8, so no other algebra admits a $5 + 3$ Cartan decomposition with these commutation relations.

The Cartan structure has a striking physical consequence. The relation $[\mathfrak{p}, \mathfrak{p}] \subset \mathfrak{k}$ means that the commutator of two $\ell = 2$ (traceless symmetric) generators is an $\ell = 1$ (antisymmetric) generator. The five strong-force generators do not close as an algebra by themselves: composing two of them produces a weak-force generator. The $\ell = 2$ sector *requires* the $\ell = 1$ sector for algebraic consistency. By contrast, $[\mathfrak{k}, \mathfrak{k}] \subset \mathfrak{k}$ means the three $\ell = 1$ generators close on their own—$\mathfrak{su}(2)$ is a proper subalgebra. The hierarchy is:

- $\mathfrak{u}(1)$: the $\ell = 0$ scalar closes trivially (one generator);
- $\mathfrak{su}(2)$: the $\ell = 1$ vector closes by itself (three generators);
- $\mathfrak{su}(3)$: the $\ell = 2$ tensor does *not* close alone—it needs $\ell = 1$ to form a complete algebra ($5 + 3 = 8$ generators).

In physical terms: the strong interaction cannot exist without the weak interaction. They are algebraically entangled through the geometry of the horizon. In the Standard Model, the

gauge group SU(3)×SU(2)×U(1) is an unexplained experimentally observed input; here, its internal structure—including the embedding SU(2) ⊂ SU(3)—is a consequence of the Cartan decomposition of rank-2 tensors on S^2. We emphasize that this is a statement about the *algebraic structure* of the gauge group, not about particle processes: it does not predict new interactions between gluons and weak bosons beyond those already present in the Standard Model.

The full Standard Model gauge algebra then corresponds to the complexification of the three SO(3) multipole sectors:

$$\begin{aligned} \ell = 0 \text{ (1 real dof)} &\to \mathfrak{u}(1)\,, \\ \ell = 1 \text{ (3 real dof)} &\to \mathfrak{su}(2)\,, \\ \ell = 2 \oplus i\,\ell = 1 \text{ (5+3 dof)} &\to \mathfrak{su}(3)\,, \end{aligned} \tag{7}$$

recovering 1 + 3 + 8 = 12 gauge generators. A subtlety: the $\mathfrak{u}(1)$ from the $\ell = 0$ sector is the hypercharge algebra $\mathrm{U}(1)_Y$, not electromagnetism directly. The physical photon emerges as a linear combination of $\mathrm{U}(1)_Y$ and the neutral generator of SU(2) after electroweak symmetry breaking—i.e. through the Higgs mechanism, which in this framework corresponds to the process by which the near-gauge $\ell = 1$ sector gives mass to the weak bosons. The $\ell = 1$ sector appears twice, but in distinct roles: the *real* $\ell = 1$ is the antisymmetric part of the metric (near-gauge, giving neutrinos their small mass in the energy budget), while the *imaginary* $i\,\ell = 1$ is the antisymmetric part of $\mathfrak{su}(3)$ (contributing to the strong force in the gauge structure). This parallels the dual role of $\ell = 2$ discussed below: the same degrees of freedom participate in different physics at different scales, with the real/imaginary distinction separating the classical (energy budget) from the quantum (gauge) sector. The real geometry of the horizon determines *what exists* (the energy budget); the complexified structure determines *how it interacts* (the gauge forces).

The factor of i that effects this complexification has a natural origin: *quantization*. The classical metric on S^2 is real. When the Planck-area patches are quantized, the angular momentum algebra acquires $[\hat{L}_i, \hat{L}_j] = i\hbar\,\varepsilon_{ijk}\,\hat{L}_k$, turning real antisymmetric generators into imaginary ones. The appearance of i is a direct consequence of the Lorentzian metric signature $(-,+,+,+)$: unitary time evolution requires $U = e^{-iHt/\hbar}$, and in the Euclidean continuation ($t \to i\tau$) the same i generates the periodicity that yields the Gibbons–Hawking temperature on which this framework is built. Quantization and time evolution are thus dual operations on the horizon algebra: quantization complexifies—promoting the real classical SO(3) to the complex gauge algebra of the Standard Model—while time evolution decomplexifies—projecting complex degrees of freedom back onto the real sector, thermalizing one more patch, increasing the entropy by one bit. The GSL gives this process a direction: complex to real, quantum to classical. Complexification creates gauge structure; decomplexification creates classical reality; measurement sits at their interface. The metric signature drives both: its spatial part provides the SO(3) matter decomposition, and its Lorentzian structure provides the i that complexifies the algebra. That the complexification of the three multipole sectors yields $\mathfrak{u}(1) \times \mathfrak{su}(2) \times \mathfrak{su}(3)$ specifically is not an assumption—it is the mathematical content of equations (5)–(6). What remains conjectural is whether the quantization of horizon patches is the correct physical operation connecting the classical geometry to the gauge structure. To summarize the logical chain: the horizon is S^2 (topology), the fundamental gravitational field

is the rank-2 metric (general relativity), two $\ell = 1$ indices yield $\ell \leq 2$ by angular momentum addition (representation theory), and the Lorentzian signature provides the i that complexifies the three sectors into the Standard Model algebra (quantization). The only input from physics, beyond standard mathematics, is that gravity is described by a rank-2 tensor.

This separation between real and complexified sectors provides a natural explanation for two otherwise unrelated features of the Standard Model: the hierarchy of force ranges and the invisibility of dark matter. At large (cosmological) scales, the metric is classical and real; only the real sectors—$\ell = 0$ (hypercharge) and $\ell = 2$ (gravity)—propagate to the horizon, giving the two long-range forces. The complexified sectors—$\mathfrak{su}(2)$ (weak) and the imaginary part of $\mathfrak{su}(3)$ (strong)—arise only through quantization and are intrinsically short-range: they are properties of the quantum patches, not of the smooth horizon. Confinement acquires a geometric interpretation: the strong force requires a complexification that exists only at the Planck scale and cannot propagate classically.

The same logic explains dark matter. The $\ell = 2$ degrees of freedom are dark at cosmological scales because their gauge algebra ($\mathfrak{su}(3)$) requires complexification to close—an operation that does not survive the classical limit. At the Planck scale, the same five generators participate fully in the strong force as the real symmetric part of $\mathfrak{su}(3)$. The darkness of dark matter is a statement about scale, not about substance. Supersymmetry (SUSY) was introduced, in part, to relate bosonic and fermionic degrees of freedom through a symmetry that pairs them [20]. In the present framework, this duality arises without new particles: the *same* degrees of freedom play bosonic (gravitational) roles at large scales and fermionic (gauge) roles at short scales, unified not by a new symmetry but by the real/complex structure of the horizon algebra.

Several identifications follow. The three fermion generations correspond to $m = -1, 0, +1$ of the $\ell = 1$ dipole—not an input but a consequence of SO(3). The absence of supersymmetry, extra dimensions, or additional gauge bosons beyond those observed is natural: the complexification of three SO(3) multipole sectors yields the Standard Model algebra and no more.

The Clebsch–Gordan (CG) coefficients for the $\ell = 1$ self-coupling $1 \otimes 1 = 0 \oplus 1 \oplus 2$ exhibit a pattern consistent with the observed generation structure: generation-universal electromagnetism ($\ell = 0$, m-independent), a heaviest third generation ($\ell = 2$, $m = 0$ dominant), and parity splitting between the first two generations ($\ell = 1$, antisymmetric in m). The quantitative mass hierarchy requires an additional mechanism—exponential amplification by the horizon entropy—which converts the $\mathcal{O}(1)$ CG ratios into the five orders of magnitude observed in the fermion mass spectrum. Whether this amplification can be derived from the condensate dynamics on the horizon is a question for future investigation.

Whether this algebraic connection can be promoted from an identity to a dynamical principle remains the central open question. If it can, the Standard Model gauge group would not be an independent input to fundamental physics but a consequence of the metric geometry of the cosmological horizon.

6 What This Implies

If confirmed by forthcoming data—from Euclid, DESI, the Vera C. Rubin Observatory, CMB-S4, and direct dark matter searches—the implications are far-reaching.

The cosmological constant problem dissolves: the 10^{120} discrepancy was never a fine-tuning problem but a counting error—volume degrees of freedom mistaken for independent modes in a holographically constrained spacetime.

Dark matter is not a particle. It is the gravitational signature of the universe's incomplete thermalization—the unfilled $\ell = 2$ sector of the horizon's thermal capacity.

The string landscape—10^{500} vacua, anthropic selection, the multiverse—becomes unnecessary. If Λ is determined by horizon thermodynamics, the matter content by horizon geometry, and the gauge group by horizon quantization, there is nothing left to select anthropically.

The matter content and gauge structure of the universe are not inputs to the equations of physics. They are outputs of the geometry of the horizon. The boundary determines the content, not the other way around.

7 Observational Tests

The framework makes the following predictions, none of which contain free parameters:

1. $\Omega_{\rm dm}^{\rm true}/\Omega_b = 5$ exactly, with the deviation encoding $\sum m_\nu$. The central prediction is that the dark-matter-to-baryon ratio, after proper subtraction of the neutrino contribution ($\ell = 1$ sector), equals 5 as a consequence of SO(3) geometry. The ratio $(\Omega_m - \Omega_b)/\Omega_b \approx 5.3$ inferred from Planck under ΛCDM assumptions includes the neutrino contamination; equation (4) links the excess to $\sum m_\nu$ with no adjustable parameters. Future data from Euclid, DESI DR3, and the Vera C. Rubin Observatory will refine $\Omega_{\rm dm}$ and Ω_b, while KATRIN [15] and cosmological fits will constrain $\sum m_\nu$ independently. If the corrected ratio converges to 5 as $\sum m_\nu$ is measured, the consistency of (4) is confirmed; a precise inconsistency after all corrections would falsify the SO(3) picture. We stress that the 5 : 1 ratio is independent of the neutrino mass: it follows from the dof count alone. A very low $\sum m_\nu$ (as KATRIN might establish) would be *consistent* with the framework—the $\ell = 1$ sector is suppressed by the metric symmetry, so the smaller the mass, the closer the system is to the exact de Sitter limit.

2. $w \geq -1$ and the dark sector interaction. In the companion note [1], the GSL was used to predict $w \geq -1$ at all times, with phantom crossing suppressed by $e^{-10^{122}}$. That prediction stands. The SO(3) sector structure obtained here adds a further element: a mechanism for an *apparent* phantom crossing. The decomposition into $\ell = 0, 1, 2$ sectors applies whenever a causal horizon exists and the metric on S^2 is the relevant degree of freedom. At sufficiently high energy, the distinction between sectors may disappear—all Planck-scale patches would interact through a common coupling, analogous to how SU(5) grand unification [18] merges the electromagnetic, weak, and strong interactions into a single gauge group at $\sim 10^{16}$ GeV. At lower energies, the Standard Model gauge group applies. At late times, approaching de Sitter, the horizon SO(3) structure emerges and the $\ell = 2$ component (dark matter) differentiates from $\ell = 0$ and $\ell = 1$.

This differentiation is still ongoing. As $\ell = 2$ patches thermalize, energy flows from the matter sector to the dark energy sector. Recent DESI DR2 data show evidence for an apparent phantom crossing at $z \sim 0.3$–1 [21]—precisely the dark energy transition epoch where this energy flow would be most active. Several analyses [22, 23] have shown that such a signal need not represent a true $w < -1$ but could arise from a non-gravitational dark matter–dark energy interaction, with $w > -1$ throughout. The horizon framework provides such an interaction: $w \approx -0.89$ (always non-phantom), with the ongoing thermalization expected to produce an effective equation of state that could mimic phantom crossing in the standard Chevallier–Polarski–Linder (CPL) parametrization [24, 25]. A confirmed $w < -1$ at $z \lesssim 2$, not attributable to dark sector energy exchange, would falsify the framework. A telling illustration of the model dependence of current data: DESI DR2 yields a best-fit $\sum m_\nu$ that is *negative* within ΛCDM—widely interpreted as a signal that the assumed dark energy model is incorrect. When DESI fits evolving dark energy ($w \neq -1$), the neutrino mass becomes positive and consistent with oscillation bounds. Full convergence of both the $5:1$ ratio and $\sum m_\nu$ likely requires refitting cosmological data within the holographic dark energy model ($c = 1$, $w \approx -0.89$), which would shift the extracted values of Ω_b, $\Omega_{\rm dm}$, and $\sum m_\nu$ simultaneously.

3. CMB acoustic peaks from geometry. The most decisive near-term test would be to compute the CMB power spectrum using standard Boltzmann codes (CAMB or CLASS) with $\Omega_b = \frac{1}{6}\Omega_m$ and $\Omega_{\rm dm} = \frac{5}{6}\Omega_m$ as inputs derived from SO(3), rather than fitted to the data. The predicted peak *ratios* can be compared directly to Planck observations. This test addresses the global energy budget; the detailed spatial distribution of dark matter (halo profiles, the bullet cluster) requires additional work beyond the scope of this calculation (see Section 8).

4. The Standard Model gauge group from geometry. The complexification of Section 5 predicts SU(3)×SU(2)×U(1) with exactly 12 generators, three fermion generations, and no additional gauge bosons. The discovery of a fourth generation, a Z' boson, or any gauge structure beyond the Standard Model would falsify this aspect of the framework.

5. No dark matter particle exists. In this framework, dark matter is not a substance but the unfilled thermal capacity of the $\ell = 2$ sector. Every null result from direct detection experiments (LUX-ZEPLIN, XENONnT, PandaX-4T), collider searches (LHC), and indirect detection is consistent with this prediction. The discovery of a dark matter particle at any mass would falsify the framework.

8 What Remains Open

Several questions are beyond the scope of this note.

The holographic counting mechanism. The framework assumes that the holographic bound applies to our de Sitter universe, but the mechanism that enforces it—whether complementarity, gravitational thermodynamics [7], or entanglement—remains unknown. Jacobson [26] has made progress on the last option, showing that Einstein's equations follow from the condition that vacuum entanglement entropy across small causal horizons is maximal. In his framework, filled entanglement corresponds to the vacuum (our dark energy), while perturbations away from maximal entanglement produce curvature (our matter). This is strikingly close to the picture proposed here, and may provide the theoretical bridge between

"unfilled thermal capacity" and "gravitating matter" that this note assumes but does not derive. Whether one of these approaches can be promoted to a complete derivation is the deepest theoretical gap.

Local dark matter phenomenology. The SO(3) picture accounts for the global energy budget and, as argued in Section 3, the 5 : 1 ratio holds at every local Rindler horizon—implying that it applies at all scales, not only at late times. What the framework does not yet provide is the *spatial distribution* of dark matter: halo profiles, the bullet cluster separation, and the detailed shape of the CMB acoustic peaks.

The conceptual picture, however, is clear. A dark matter halo is not a cloud of particles orbiting a galaxy. It is the $\ell = 2$ sector of the metric perturbation—the traceless symmetric part of the curvature—surrounding a baryonic concentration. Where baryons are present, the total unfilled thermal capacity is larger, and the $5 : 1$ ratio guarantees that the $\ell = 2$ component dominates. The gravitational potential around a galaxy is not sourced by dark matter particles falling into a well; it is the $\ell = 2$ curvature at every local horizon in the region.

This connects directly to the scale-dependent visibility discussed in Section 5. At cosmological scales, the $\ell = 2$ sector is classical and real: it curves spacetime but has no gauge boson and no electromagnetic coupling. It is invisible—"dark." At the quantum (Planck) scale, the same five degrees of freedom participate in the strong force through the complexification $\ell = 2 \oplus i\,\ell = 1 \to \mathfrak{su}(3)$. Galactic halos are not an invisible manifestation of the strong force; they are the classical, large-scale face of the same degrees of freedom that, at short distances, generate QCD. The two roles never overlap: the strong force is confined to femtometer scales, while the $\ell = 2$ curvature operates at kiloparsec scales and above.

The Bullet Cluster [27] provides a qualitative test. In a cluster collision, the $\ell = 0$ (baryonic) component couples electromagnetically—gas shocks, heats, and decelerates. The $\ell = 2$ component, having no force carrier at classical scales, passes through without friction. The gravitational lensing map shows the $\ell = 2$ curvature separated from the $\ell = 0$ gas—exactly as observed. Quantitatively, translating this picture into halo density profiles, rotation curves, and CMB acoustic peak structure requires solving the cosmological perturbation equations with $\Omega_{\rm dm}$ and Ω_b derived from the SO(3) decomposition rather than fitted to data. This calculation is beyond the scope of this note.

Freeze-out and geometry. The standard account of the $5 : 1$ ratio invokes dark matter freeze-out in the early universe, governed by specific interaction cross-sections [28, 29]. If the ratio is instead geometric, there must be a reason why particle physics freeze-out produces the same number that SO(3) predicts. The complexification developed in Section 5 suggests a possible resolution: the gauge structure that determines freeze-out cross-sections is itself inherited from the SO(3) decomposition of the horizon metric. If so, the agreement is not a coincidence but a consistency condition—the particle physics inherits the geometric ratio from the algebra that determines it. Whether this self-consistency can be made precise remains an important open question.

Connection to loop quantum gravity. In LQG [9, 10], horizon area is quantized: each Planck-area puncture carries an SU(2) spin label. Since SU(2) is the double cover of SO(3), the SO(3) decomposition used in this note is native to the LQG formalism—it corresponds to the

integer-spin sector of SU(2). The semiclassical spin distribution is thermal and bosonic [30], consistent with the picture assumed here. LQG does not, however, naturally cut off the spectrum at $\ell = 2$; higher spins contribute to the entropy. In the present framework, the cutoff follows from the angular momentum addition rule for the two indices of the metric: each index transforms as $\ell = 1$, and $1 \otimes 1$ yields at most $\ell = 2$ (Section 3). Whether this rank-2 constraint can be derived from within LQG's spin-network dynamics, rather than imposed by the choice of fundamental field, remains open.

9 Concluding Remarks

The companion note [1] argued that dark energy is the thermal energy of the cosmological horizon. This note extends the picture: the matter content is the horizon's thermal deficit, distributed by the rank-2 tensor structure of the metric, and the gauge forces emerge from its complexification.

If the data confirm this picture—if the dark-matter-to-baryon ratio converges to 5, if no dark matter particle is found, if w remains above -1—then the universe is not a box of particles that happens to have a horizon. It is a horizon whose metric contains particles.

One aspect of this deserves brief comment. The complexification/decomplexification duality developed in Section 5 connects the gauge structure to the arrow of time established in the companion note [1]: both are aspects of the approach to the de Sitter maximum-entropy attractor. Whether the real/complex split in the gauge algebra can be made precise as a theory of quantum measurement is well beyond the scope of this note, but the ingredients appear to be present.

A related speculation concerns quantum entanglement. In Jacobson's framework [26], Einstein's equations follow from the condition that vacuum entanglement entropy across local causal horizons is maximal. If, in the present picture, two subsystems share Planck-area patches on their local horizons, then measuring one—projecting the shared patches from the complexified to the real sector—would instantly constrain the other. The correlations would be non-local because the horizon is a boundary, not a location in space; irreversible because the projection increases entropy; and fragile because decoherence is the thermalization of the shared patches by the environment. Bell violations would follow from the boundary geometry rather than from local hidden variables. This is deeply speculative, but the identification of measurement with the complex-to-real projection, and of entanglement with shared horizon microstructure, would close the circle: gravity, matter, gauge forces, the arrow of time, and quantum correlations would all be aspects of the same two-dimensional boundary.

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