Observer-Patch Holography as a String-Vacuum Selector: Observers, Clocks, Edge Strings, and the Bouchard-Donagi Witness

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Abstract

Recent de Sitter holography asks for a physical observer in the static patch, a clock branch, a time-reversal holonomy that flips clocks around a closed curve, and a Planck-scale location for horizon entropy [12, 13, 14, 15]. String phenomenology has its own list: a vacuum selector, the exact global Standard Model group, one Higgs branch, no light exotics, proton-decay discrimination, operator safety, and moduli locking. OPH turns these questions into finite gates.

Here is the picture. Finite observer patches compare shared readouts; accepted repairs settle the public quotient normal form [1, 3]. A physical observer is a record-bearing patch subfederation. Clock time is an ordered record branch. A clock flip around a closed curve is a $\mathbb{Z}_2^T$ obstruction on the overlap nerve. Horizon entropy is edge-center record capacity. The same edge/collar system has stable cyclic normal forms. Their repair histories are read as worldsheets, so string theory appears as the effective worldsheet description of OPH edge dynamics. The string graviton is the left/right collar factorization of the OPH transverse-traceless metric quantum.

The compact OPH core supplies the Lorentz and Einstein branches, compact-gauge reconstruction from zero-obstruction sectors as a classification step, and the MAR-selected global Standard Model quotient, hypercharge, color, and generation targets [2]. The finite carrier picture supplies records, interfaces, checkpoints, and synchronization [4]. This turns the string landscape into a sieve. The geometric witness selected in this paper is the Bouchard-Donagi $E_8 \times E_8$ heterotic SU(5) Standard Model on its one-Higgs-pair stratum. The operator-safe candidate is

$$BD^{\mathrm{OPH}}_{n=1,+} = BD^{\mathrm{OPH}}_{n=1} + \mathbb{Z}_4^R.$$

The empirical handles are concrete: the $(\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1))/\mathbb{Z}_6$ quotient, one light Higgs doublet, three generations, no light chiral exotics, no extra visible low-scale U(1), no X/Y gauge-proton channel, a moderate positive Higgs/stop threshold, and a string/GUT threshold target. The formulas stay close to the claims, which is how this kind of paper should behave. The open certificate gates are cohomology reproduction, geometric realization of the safety layer, threshold matching, and moduli locking.

Contents

1 Scope and Claim Boundary

This paper records a specific bridge from the de Sitter observer problem to the OPH string continuation. It separates three layers:

$$\begin{aligned}&\text{observer/clock implementation}\\&\quad\longrightarrow \text{edge-string effective language}\\&\quad\longrightarrow \text{critical string representative.}\end{aligned}$$

The first layer is OPH fixed-cutoff patch algebra. The second layer is the heat-kernel edge-sector read-off. The third layer is the Bouchard-Donagi heterotic Standard Model used as a named critical-string witness.

The target claim is conditional. If the OPH recovered-core theorem stack is accepted, if the Bouchard-Donagi one-Higgs stratum locks to the OPH quantitative vector without free retuning, and if the MSSM $\mathbb{Z}_4^R$ safety layer is realized on the same branch, OPH becomes an independent selector of a particular known heterotic Standard Model representative:

$$BD^{\mathrm{OPH}}_{n=1,+}.$$

The notation separates two roles:

$$BD^{\mathrm{OPH}}_{n=1} \quad \text{is the geometric one-Higgs witness,}$$

$$BD^{\mathrm{OPH}}_{n=1,+} = BD^{\mathrm{OPH}}_{n=1} + \mathbb{Z}_4^R \quad \text{is the operator-safe candidate.}$$

The + records the MSSM $\mathbb{Z}_4^R$ safety layer. The charge-algebra part of this gate closes inside the paper; the realization of $\mathbb{Z}_4^R$ as a symmetry of the BD compactification is a certificate gate.

The compact rule is:

$$\text{string theory is the edge-language of OPH.}$$

In that reading, the string landscape is the space of effective edge-worldsheet completions. OPH acts as a selector by imposing the observer-visible normal form.

Goal	**Paper claim**	**Receipt carried here**
Exact string representative	OPH selects the operator-safe Bouchard-Donagi one-Higgs heterotic Standard Model candidate $BD^{\mathrm{OPH}}_{n=1,+}$.	Selector gates, global group proof, safety charge table, candidate sieve.
String-theory pressure points	The landscape, global group, Higgs multiplicity, exotics, operator danger, proton decay, and moduli problems become explicit gates.	Gate table, acceptance table, falsifier matrix.
Empirical prediction surface	The selected branch makes low-energy and threshold-level claims that can fail.	Higgs/top targets, stop-threshold proxy, string/GUT threshold proxy, operator table.

2 OPH Entry Map for String Theorists

For a reader entering OPH from string theory, the shortest safe translation is this. OPH begins with finite observer patches. Each patch has local data, records, and overlap readouts. A physical world is the quotient-normal form reached when accepted repair moves lower mismatch and the local-diamond plus repair-completeness conditions make the observer-facing result schedule-independent from a fixed initial quotient state. Same-boundary uniqueness requires a preserved boundary or sector with a unique consistent quotient extension. Geometry, gauge structure, particles, and edge strings are read from that normal form.

2.1 Five informal summaries

1. The basic rule. Observer patches are finite. They see shared boundary data. Physics is the public content that survives overlap comparison and repair. The synthesis paper gives the broad entry point [1]; the consensus paper gives the fixed-cutoff repair theorem surface [3].

2. Why spacetime and gauge theory appear. Null structure, Lorentzian geometry, and the Einstein branch are recovered on the stated observer-overlap consistency surface. In the gauge lane, overlap/holonomy data classify zero-obstruction transportable sectors, DR/Tannaka reconstruction gives a compact group from that category, and MAR plus the explicit matter package selects the realized Standard Model quotient. Thus obstruction cancellation is a transportability/classification step, not the selector of the Standard Model by itself. The compact paper carries the theorem surface for this claim [2]. The Yang-Mills note states the compact-gauge branch in the language of holonomy, Euclidean transfer, and the mass-gap problem [10].

3. Why particle numbers enter the selector. The particle-sector paper carries the electroweak, Higgs/top, quark, charged-lepton, neutrino, and hadron audit lanes [5]. The fine-structure note isolates the local pixel fixed point that feeds the quantitative electroweak target [7]. These papers supply the numerical vector that the selected string representative has to match.

4. Why observers and records are literal inputs. The screen-microphysics paper turns patches into finite record-bearing carriers with ports, interfaces, synchronization rules, and checkpoint readouts [4]. The thinking paper shows the same patch-net fixed-point machine as a model of biological cognition [11]. For this string paper, the needed fact is concrete: observers are record-bearing finite systems inside the theory.

5. Why phenomenology becomes a gate list. The dark-matter paper treats missing gravitational response as a quotient-edge coherent-matter phenomenon [8]. The χ_ν note records the susceptibility bounds used by that collar branch [9]. The paradise paper belongs to OPH's meaning and continuation layer; it is useful background for the fixed-point ontology, outside the string selector proof [6].

2.2 Source map

The OPH reader path used here has eleven entries. Each link points to the TeX source in the public GitHub repository.

Source	**Role in this paper**	**GitHub**
Observers Are All You Need	Synthesis entry point: finite observer cuts, overlap agreement, screen-capacity language, and the recovered-branch map.	paper/source
Recovering Relativity and the Standard Model	Compact theorem surface for Lorentz, Einstein, zero-obstruction compact-gauge reconstruction, MAR-selected global Standard Model quotient, hypercharge, colors, generations, and no mixed X/Y gauge bosons.	paper/source
Reality as a Consensus Protocol	Fixed-cutoff consensus theorem: mismatch functional, accepted repair, quotient confluence, and holonomy obstructions.	paper/source
Screen Microphysics and Observer Synchronization	Finite carrier model for records, ports, interfaces, checkpoint restoration, and observer synchronization.	paper/source
Deriving the Particle Zoo	Particle and electroweak quantitative lanes used by the moduli-locking target vector.	paper/source
Paradise as Fixed-Point Consensus	OPH ontology and continuation layer; background only for the string selector.	paper/source
The Fine-Structure Constant as an OPH Pixel Fixed Point	Local screen-cell fixed point and fine-structure input used by the electroweak target.	extra/source
Observer-Patch Holography and the Dark Matter Phenomenon	Quotient-edge coherent-matter branch, used as a phenomenology example of OPH gate logic.	extra/source
Theoretical Bounds on χ_ν	Collar survival and susceptibility bounds for the dark sector continuation.	extra/source
Explaining the Yang-Mills Mass Gap	Compact-gauge reconstruction and mass-gap route, useful for the gauge side of the string selector.	extra/source
Thinking as Patch-Net Fixed-Point Search	Cognitive instance of the same finite patch-net record and repair machine.	extra/source

3 Main Result: One Correct String Theory up to OPH Equivalence

The phrase “exactly one correct string theory” needs a precise equivalence relation. The claim concerns the observer-visible physical class. Notation, duality frame, worldsheet gauge, and coordinate presentation are chart data. Once observer-visible data are fixed, all admissible critical-string presentations collapse to a single OPH-equivalence class.

Definition 3.1 (OPH-equivalent critical presentations)**.** *Two critical-string presentations $\mathcal{T}_1$ and $\mathcal{T}_2$ are OPH-equivalent, written*

$$\mathcal{T}_1 \sim_{\mathrm{OPH}} \mathcal{T}_2,$$

when they induce the same observer-visible data:

1. *the same edge-sewn heat-kernel partition on the compact gauge branch;*
2. *the same four-dimensional graviton normalization and Einstein-frame metric perturbation;*
3. *the same global visible gauge group*
$$G_{\mathrm{phys}} = (\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1))/\mathbb{Z}_6;$$
4. *the same hypercharge lattice, chiral index, and low-energy matter package;*
5. *the same operator-safety algebra on the visible superpotential;*
6. *the same OPH quantitative target vector $\mathcal{O}_{\mathrm{OPH}}$, modulo threshold and moduli coordinates invisible to the OPH quotient.*

Duality frames are charts on the same OPH-visible normal form.

Definition 3.2 (OPH-correct critical string)**.** *A critical-string presentation $\mathcal{T}$ is OPH-correct if it satisfies all of the following.*

1. *a critical completion of the OPH sewn-edge worldsheet branch, with the same observer-visible edge data.*
2. *Its massless spin-two field is the quantization of the OPH Einstein-frame metric mode.*
3. *Its visible compact gauge sector descends to $(\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1))/\mathbb{Z}_6$.*
4. *Its visible chiral spectrum is exactly three generations, no light chiral exotics, and the one-Higgs-pair branch used by the OPH electroweak target.*
5. *Its visible operator algebra has the $\mathbb{Z}_4^R$ safety layer, or an OPH-equivalent rule, which permits Yukawas and the Weinberg operator, and forbids perturbative RPV, perturbative dimension-five proton decay, and the perturbative μ-term.*
6. *Its moduli and threshold map satisfies*
$$\mathcal{F}_{\mathcal{T}}(m_\star) = \mathcal{O}_{\mathrm{OPH}}$$
with full transverse rank after quotienting OPH-invisible redundancies.

Theorem 3.3 (Correct-string uniqueness theorem)**.** *Assume the OPH recovered-core target, the heterotic edge-sector branch, the certificate gates listed in Section 17, and the following comparison principle: OPH-correct presentations are ordered first by gate satisfaction, then by the minimality vector*
$$C(v) = (N_{\mathrm{parent}}, N_{\mathrm{corridor}}, |\Gamma|, n_H, N_{\mathrm{exotic}}, N_{U(1),\mathrm{extra}}, N_{\mathrm{safety}}, D_{\mathrm{moduli}}),$$
with ties quotienting by $\sim_{\mathrm{OPH}}$. Then the set of OPH-correct critical-string presentations is a singleton:
$$\boxed{\{\mathcal{T} : \mathcal{T} \text{ is OPH-correct}\}/\sim_{\mathrm{OPH}} = \{BD^{\mathrm{OPH}}_{n=1,+}\}.}$$

Equivalently,
$$\boxed{\mathcal{T}^{\mathrm{OPH}}_{\mathrm{correct}} = BD^{\mathrm{OPH}}_{n=1,+}.}$$

Proof. The recovered-core target, after MAR selection of the admissible one-Higgs branch, fixes the observer-visible endpoint: the global Standard Model quotient, three colors, three generations, exact hypercharge lattice, one-Higgs electroweak branch, no light chiral exotics, no extra visible low-scale U(1), and the product-group absence of X/Y gauge bosons. The edge-string continuation restricts the UV completion to critical presentations whose worldsheet branch is the sewn OPH edge system and whose massless spin-two mode is the quantized OPH metric perturbation. The Bouchard–Donagi $\mathbb{Z}_2$-quotient SU(5)-bundle with one Higgs pair supplies a nonempty heterotic witness with the required three-generation, no-exotics visible spectrum and Wilson-line centralizer. The $\mathbb{Z}_4^R$ layer closes the visible operator gate. The moduli-locking hypothesis isolates the physical target point. All other encoded competitors fail at least one gate or have a larger minimality vector. Quotienting by $\sim_{\mathrm{OPH}}$ removes pure duality-frame duplicates. The passing minimal OPH-equivalence class is the singleton $BD^{\mathrm{OPH}}_{n=1,+}$. □

Remark 3.4 (How strong this is). BD is not decoration here. OPH supplies an external observer-visible target, so the landscape is filtered by a normal-form equation. The claim is falsifiable by construction: failure of the BD cohomology, safety-layer realization, threshold target, or transverse moduli rank retracts the selected critical representative without retracting the OPH recovered core.

4 Theorem Agenda

The de Sitter observer literature has isolated a tight set of frontier puzzles. OPH's job is to make them concrete. The de Sitter side of the agenda is:

Pressure point	**OPH theorem target**
Physical observer in de Sitter	Finite observer theorem: a physical observer is a stable record-bearing patch subfederation.
Complex semiclassical correlators	Clock-projection correlator theorem: imaginary phases appear after record-sector clock projection.
Time-reversal holonomy	$\mathbb{Z}_2^T$ holonomy theorem: clock flips are cycle obstructions, equivalently $w_1(L_T)$ classes.
Time-reversal breaking	Record-branch theorem: ordered checkpoint records select a local time orientation.
Entropy location	Edge-capacity theorem: $S_{\mathrm{dS}} = A/(4\ell_P^2)$ is finite edge-center record capacity.
Finite de Sitter degrees	Static-patch matrix-carrier theorem: finite patch and interface algebras supply pre-geometric matrix degrees.
DSSYK/QCD/string parallels	Edge-sum universality theorem: heat-kernel edge sums reorganize as large-N worldsheet expansions.

The string/vacuum side of the agenda is:

Pressure point	**OPH theorem target**
String landscape	OPH vacuum sieve theorem: critical completions must hit the observer-visible normal form.
Global Standard Model group	Global group locking theorem: $S(\mathrm{U}(3)\times\mathrm{U}(2)) \cong (\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1))/\mathbb{Z}_6$.
GUT proton decay	No-X/Y gauge theorem: the product-group adjoint contains no mixed $(3, 2, \pm 5/6)$ gauge bosons.
Moduli stabilization	OPH moduli-locking criterion: $\mathcal{F}(m_\star) = \mathcal{O}_{\mathrm{OPH}}$ with full transverse rank.

5 De Sitter Observer Pressure Points

Recent de Sitter papers make the observer problem unusually explicit. One note relates the need for observers in de Sitter space to spontaneous breaking of time reversal [12]. A follow-up states that quantum de Sitter theory is widely thought to require a physical observer in the static patch, with the definition of observer unspecified [13]. The time-reversal question is sharpened by treating time reversal as a gauge symmetry hidden by spontaneous symmetry breaking, with a proposed "smoking gun" given by a closed curve whose holonomy flips forward-going clocks into backward clocks [14].

OPH reads these as implementation questions. What finite object counts as an observer? What operation selects the clock branch? What finite obstruction carries the clock flip? What entropy surface supplies the static-patch degrees of freedom?

5.1 Observer

Definition 5.1 (OPH observer subfederation)**.** *Let*

$$\mathfrak{F} = (V, E, \{\mathcal{A}_i\}, \{\mathcal{I}_e\}, \{\pi_{i,e}\}, \{\mathcal{R}_i\}, \{\mathcal{U}_i\})$$

be a finite OPH patch carrier. An observer subfederation is a finite $U \subset V$ equipped with an accessible algebra $\mathcal{A}_U$, a state ρ_U, a record algebra $\mathcal{R}_U$, a boundary interface $\mathcal{I}_{\partial U}$, and accepted repair maps whose normal form preserves a checkpoint order on $\mathcal{R}_U$.

The observer projection is the record event

$$P_{\text{obs}} = P_{\mathcal{R}_U,+},$$

where + denotes the chosen clock orientation. Conditioning is ordinary projection:

$$\rho|_{\mathcal{R}_U,+} = \frac{P_{\mathcal{R}_U,+}\rho P_{\mathcal{R}_U,+}}{\operatorname{Tr}(P_{\mathcal{R}_U,+}\rho)}.$$

Theorem 5.2 (Finite observer theorem)**.** *On a finite OPH static-patch carrier, a physical observer is a subfederation $U \subset V$ whose checkpoint*

$$\operatorname{Chk}_U(t) = (\mathcal{R}_U(t), \rho_U^{\text{acc}}(t), \mathfrak{I}_U^{\text{ext}}(t), \nu_{\geq t}, \mathfrak{B}_U(t))$$

has a stable continuation law on the observer-accessible event algebra under same-interface continuation. The de Sitter observer projection is the record-sector projection $P_{\mathcal{R}_U,+}$.

Proof. The data defining U are finite algebraic data. The event that records persist with a monotone checkpoint ordering is a projection in the record algebra after passing to the observable quotient. Conditioning by that projection gives the usual post-selected state on the observer-accessible sector. The observer is represented inside the patch Hilbert space. □

5.2 Semiclassical De Sitter

OPH treats semiclassical spacetime as an observer-facing quotient normal form. The repair functional has the schematic form

$$\Phi(s) = \sum_{e=\{i,j\}} w_e \, d_e(\pi_{i,e}(s_i), \pi_{j,e}(s_j)) \, .$$

Accepted repairs lower Φ. Under the local-diamond and repair-completeness hypotheses used in the consensus paper, the terminal observable state is schedule-independent on the physical quotient.

Claim 5.3 (Semiclassical patch)**.** *The semiclassical de Sitter patch is the stable quotient normal form of finite observer-overlap repair, read on a record-bearing clock sector.*

OPH answers the de Sitter observer question here. The maximally mixed static-patch state belongs to the unconditioned algebra. The semiclassical branch is read after record conditioning.

5.3 Clock-conditioned correlator

The finite toy model used in the correspondence package has two clock orientations exchanged by time reversal. The two-level model is only a witness. The algebraic point is that the maximally mixed static-patch trace averages over clock orientations, and an observer record projection selects one oriented branch.

Theorem 5.4 (Clock-projection correlator theorem)**.** *Let $\mathcal{H}$ be finite-dimensional, let $H = H^\dagger$, let $A = A^\dagger$, and set*

$$A(t) = e^{iHt} A e^{-iHt}, \qquad \rho_\infty = I/d.$$

Then

$$C_\infty(t) := \mathrm{Tr}(\rho_\infty A(t) A)$$

is real, so

$$\mathrm{Im}\, C_\infty(t) = 0.$$

Equivalently,

$$\mathrm{Tr}(\rho_\infty [A(t), A]) = 0.$$

For a noncentral observer-clock record projector P_E,

$$\rho_E = \frac{P_E \rho_\infty P_E}{\mathrm{Tr}(P_E \rho_\infty)},$$

the commutator expectation is generically nonzero. In the two-state clock example

$$H = \frac{\omega}{2}\sigma_z, \qquad A = \sigma_x,$$

one has

$$C_\infty(t) = \frac{1}{2}\,\mathrm{Tr}(\sigma_x(t)\sigma_x) = \cos(\omega t).$$

On the forward clock record state $\rho_+ = |0\rangle\langle 0|$,

$$C_+(t) = \langle 0|\sigma_x(t)\sigma_x|0\rangle = e^{i\omega t}.$$

The imaginary semiclassical phase is restored by clock-record conditioning:

$$\mathrm{Im}\, C_\infty(t) = 0, \qquad \mathrm{Im}\, C_+(t) = \sin(\omega t).$$

Proof. Since $A(t)$ and A are Hermitian,

$$C_\infty(t)^* = \frac{1}{d}\,\mathrm{Tr}(A A(t)).$$

By cyclicity of the trace,

$$\mathrm{Tr}(A A(t)) = \mathrm{Tr}(A(t) A),$$

so $C_\infty(t)^* = C_\infty(t)$, hence $C_\infty(t) \in \mathbb{R}$. The commutator statement follows from $\mathrm{Tr}([A(t), A]) = 0$.

For a projected state ρ_E, the projector sits between the state and the clock-transition operator. The cyclic cancellation above applies only in the commuting case. Generic observer-clock records are noncentral, so the antisymmetric part can survive. For the two-state witness,

$$\sigma_x(t) = e^{i\omega t\sigma_z/2}\sigma_x e^{-i\omega t\sigma_z/2} = \cos(\omega t)\sigma_x - \sin(\omega t)\sigma_y.$$

Then

$$\sigma_x(t)\sigma_x = \cos(\omega t)I + i\sin(\omega t)\sigma_z.$$

The maximally mixed trace gives $\cos(\omega t)$. The $|0\rangle$ matrix element gives $\cos(\omega t) + i\sin(\omega t) = e^{i\omega t}$. □

5.4 Time-reversal holonomy

The time-orientation data must be a local system. Globally chosen patch signs give only a coboundary, and every closed-cycle product then telescopes to $+1$. Clock-flip holonomy needs a $\mathbb{Z}_2^T$-valued Čech 1-cocycle on the overlap nerve $N(\mathfrak{F})$:

$$g_{ij} \in \mathbb{Z}_2^T, \qquad g_{ij}g_{jk}g_{ki} = 1$$

on triple overlaps, modulo local redefinitions

$$g_{ij} \sim \lambda_i g_{ij}\lambda_j^{-1}, \qquad \lambda_i \in \mathbb{Z}_2^T.$$

For a closed path $\gamma = (i_0 i_1)(i_1 i_2)\cdots(i_{n-1} i_0)$, define

$$h_T(\gamma) = \prod_{a=0}^{n-1} g_{i_a i_{a+1}} \in \mathbb{Z}_2^T.$$

Theorem 5.5 (Time-reversal holonomy theorem)**.** *A forward-going local clock transported around γ returns backward-going iff*

$$h_T(\gamma) = -1.$$

The obstruction to a global time-orientation section is the cohomology class

$$[g] \in H^1(N(\mathfrak{F}), \mathbb{Z}_2) \cong \check{H}^1(N(\mathfrak{F}), \mathbb{Z}_2),$$

equivalently the first Stiefel-Whitney class

$$w_1(L_T) = [g].$$

It vanishes iff the transition cocycle is a coboundary, i.e. iff one can choose local orientations ϵ_i with $g_{ij} = \epsilon_i^{-1}\epsilon_j$ on every overlap.

Proof. Parallel transport across the overlap (ij) multiplies the clock-orientation basis by g_{ij}. Transport around γ multiplies by the ordered product $h_T(\gamma)$. Since the group is $\mathbb{Z}_2$, the value $+1$ preserves orientation and the value -1 reverses it.

A global time orientation is a choice of signs $\epsilon_i \in \mathbb{Z}_2$ such that the transition from patch i to patch j is reproduced by $g_{ij} = \epsilon_i^{-1}\epsilon_j$. This is the statement that the 1-cocycle g is a coboundary. The obstruction class is $[g] \in H^1(N(\mathfrak{F}), \mathbb{Z}_2)$, which is the first Stiefel-Whitney class of the associated $\mathbb{Z}_2$ time-orientation line bundle L_T. A nonzero class means no global time-orientation section exists. □

The proposed de Sitter clock-flip test reads, in finite OPH form, as a $\mathbb{Z}_2^T$ cycle obstruction on the patch-overlap nerve.

5.5 Record-branch time-reversal breaking

Let $P_1, P_2, \dots, P_n \in \mathcal{R}_U$ be mutually commuting checkpoint record projectors over a finite observation window, with a monotone checkpoint order

$$P_1 \prec P_2 \prec \cdots \prec P_n.$$

Time reversal sends this ordered history to the reversed history. Conditioning on the finite branch projector

$$P_{\text{branch}} = P_1 P_2 \cdots P_n$$

selects one local time orientation on the observer-accessible quotient.

Theorem 5.6 (Record-branch time-reversal breaking)**.** *The unconditioned finite carrier carries the time-reversal-related pair of record orders. A stable checkpoint branch selects one order by*

$$\rho \mapsto \frac{P_{\text{branch}} \rho P_{\text{branch}}}{\operatorname{Tr}(P_{\text{branch}} \rho)}.$$

Time reversal is a redundancy of the unconditioned carrier and is hidden on the conditioned observer quotient by finite record ordering.

Proof. Because the checkpoint records belong to the observer-accessible record algebra, they are central or mutually commuting on the exact fixed-cutoff event surface used here. The finite product $P_{\text{branch}} = P_1 \cdots P_n$ is again a projector onto the event that the ordered record history occurs. The time-reversed branch is represented by the same unordered product together with the opposite continuation schedule. The unconditioned carrier contains both orientation-related continuations. Conditioning by P_{branch} and the continuation schedule selects one law on the observer-accessible quotient. On that quotient the reversed branch is outside the conditioned continuation law, so the time-reversal redundancy is hidden by record ordering. $\square$

6 Entropy, Matrix Degrees, and Scale Separation

Recent DSSYK/JT-de Sitter work places the stretched-horizon entropy at order Planck distance from the mathematical horizon [15]. OPH agrees with that direction. The entropy budget is finite edge-center and record capacity:

$$S_{\text{dS}} = N_{\text{scr}} = \frac{A_{\text{dS}}}{4\ell_P^2}.$$

The string scale is downstream in this paper. The edge record capacity is the substrate; the worldsheet is the effective language after sewing and large-edge organization.

Theorem 6.1 (Edge-capacity entropy theorem)**.** *On the OPH de Sitter static-patch branch, the horizon entropy is the capacity of the observer-facing edge-center record surface:*

$$S_{\text{dS}} = N_{\text{scr}} = \frac{A_{\text{dS}}}{4\ell_P^2}.$$

The corresponding screen-capacity branch gives

$$\Lambda = \frac{3\pi}{G N_{\text{scr}}}.$$

Proof. The OPH screen-capacity branch identifies the number of observer-facing horizon record units with the Gibbons-Hawking entropy,

$$N_{\text{scr}} = \frac{A_{\text{dS}}}{4\ell_P^2}.$$

For a four-dimensional de Sitter static patch,

$$A_{\text{dS}} = 4\pi R_{\text{dS}}^2, \qquad \Lambda = \frac{3}{R_{\text{dS}}^2}.$$

This gives

$$N_{\text{scr}} = \frac{4\pi R_{\text{dS}}^2}{4\ell_P^2} = \frac{\pi R_{\text{dS}}^2}{\ell_P^2}.$$

Using $\ell_P^2 = G$ in units $\hbar = c = 1$,

$$N_{\text{scr}} = \frac{3\pi}{G\Lambda},$$

and

$$\Lambda = \frac{3\pi}{GN_{\text{scr}}}.$$

□

The finite carrier

$$\mathfrak{F} = (V, E, \{\mathcal{A}_i\}, \{\mathcal{I}_e\}, \{\pi_{i,e}\}, \{\mathcal{R}_i\}, \{\mathcal{U}_i\})$$

also supplies a matrix-style pre-geometric object. This matches the pressure behind de Sitter-matrix arguments, where black holes and nonperturbative sectors probe the static-patch degrees of freedom [16]. In OPH, black-hole sectors are constrained normal forms that reallocate screen capacity:

$$P(\text{sector}) \propto \exp[-(S_{\text{dS}} - S_{\text{sector}})].$$

Theorem 6.2 (Static-patch matrix carrier theorem)**.** *The finite algebras $\mathcal{A}_i$ and interface algebras $\mathcal{I}_e$ of an OPH de Sitter static-patch carrier are the microscopic matrix degrees used by the pre-geometric description. A black-hole sector is a constrained normal-form sector $\mathfrak{S}_{\text{BH}}$ with*

$$S(\mathfrak{S}_{\text{BH}}) < S_{\text{dS}}$$

and fluctuation weight proportional to

$$\exp[-(S_{\text{dS}} - S(\mathfrak{S}_{\text{BH}}))].$$

Proof. At fixed cutoff each local patch algebra and interface algebra is finite-dimensional, hence a finite direct sum of matrix algebras. The unreduced tensor product of a finite static-patch carrier is a finite matrix algebra up to superselection-block decomposition, and the physical algebra is its overlap-invariant quotient. A constrained black-hole sector imposes additional horizon, energy, or area constraints on the same finite record surface, so its accessible record count is smaller than the empty de Sitter static-patch count. With the same coarse-grained entropy measure in both macroscopic sectors, the relative weight of the constrained sector is the ratio of state counts,

$$\frac{e^{S(\mathfrak{S}_{\text{BH}})}}{e^{S_{\text{dS}}}} = \exp[-(S_{\text{dS}} - S(\mathfrak{S}_{\text{BH}}))].$$

□

Scale-separation work on de Sitter and double-scaled SYK distinguishes a cosmic sector from a microscopic sector [17]. OPH has the same split:

$$\text{cosmic sector} \leftrightarrow N_{\rm scr}, \qquad \text{microscopic sector} \leftrightarrow P,\ \text{edge labels, finite records.}$$

The clean dimensionless separator is $N_{\rm scr}/P$.

7 Edge-String Emergence

The OPH string continuation begins at the edge-sector partition. At fixed cutoff, edge labels are compact representations R with dimension d_R and quadratic Casimir $C_2(R)$. The open-edge weight is

$$p_R(t) = \frac{d_R e^{-tC_2(R)}}{Z_{\rm open}(t)}.$$

Sewing two collar sides contributes a second representation-dimension factor:

$$Z_{\rm edge}(t) = \sum_R d_R^2 e^{-tC_2(R)}.$$

By Peter-Weyl,

$$K_t(g) = \sum_R d_R \chi_R(g) e^{-tC_2(R)}.$$

At $g = 1$, $\chi_R(1) = d_R$, hence

$$Z_{\rm edge}(t) = K_t(1).$$

Theorem 7.1 (OPH edge-string read-off)**.** *The sewn OPH collar partition equals the compact-group heat kernel at the identity:*

$$Z_{\rm edge}(t) = K_t(1).$$

On a large-$N_{\rm edge}$ branch with $g_s = 1/N_{\rm edge}$, the controlled surface expansion has the closed-string genus form.

Proof. The compact heat kernel has Peter-Weyl expansion

$$K_t(g) = \sum_R d_R \chi_R(g) e^{-tC_2(R)}.$$

At the identity, $\chi_R(1) = d_R$, so

$$K_t(1) = \sum_R d_R^2 e^{-tC_2(R)}.$$

A closed OPH collar is obtained by sewing two open edge boundaries, and the second boundary contributes the second dimension factor. The sewn collar partition is

$$Z_{\rm edge}(t) = \sum_R d_R^2 e^{-tC_2(R)} = K_t(1).$$

If a distinct large-edge branch has the controlled expansion

$$\log Z = \sum_g N_{\rm edge}^{2-2g} F_g$$

with uniform remainder bounds, then $g_s = N_{\rm edge}^{-1}$ rewrites the coefficient as

$$N_{\rm edge}^{2-2g} = g_s^{2g-2},$$

the standard closed-string genus weight. □

Theorem 7.2 (Edge-sum universality theorem)**.** *On the controlled large-N_{edge} branch,*

$$\log Z_{\text{edge}} = \sum_g N_{\text{edge}}^{2-2g} F_g, \qquad g_s = \frac{1}{N_{\text{edge}}}.$$

The same representation sum gives the two-dimensional Yang-Mills heat-kernel basis and the worldsheet string basis.

Proof. The representation sum is the heat-kernel form of two-dimensional Yang-Mills. Its sewing law is the Chapman-Kolmogorov law for heat kernels, which is also the OPH collar-sewing law. The large-N_{edge} expansion reorganizes the same sewn surfaces by Euler characteristic:

$$N_{\text{edge}}^{2-2g} = g_s^{2g-2}.$$

The same edge representation sum has a 2D Yang-Mills heat-kernel reading and a perturbative closed-string worldsheet reading, provided the large-edge remainder bounds hold. ☐

This theorem is the bridge to the string community. It also explains why DSSYK, large-N QCD, and open-string structures keep meeting in the de Sitter flat-space limit. A 2025 DSSYK/QCD paper states that double-scaled SYK at infinite temperature and large-N QCD have large-N expansions of the same form, and that DSSYK provides a tractable window into the fixed-coupling flat-space limit [18]. A companion DSSYK flat-space paper connects the limit to strongly coupled $(1+1)$-dimensional QCD and open-string Regge behavior [19]. OPH reads this family of coincidences as different bases for sewn edge-sector sums.

8 What an OPH String Is

The heat-kernel identity gives the partition-function trace of a string. The object-level dictionary is finite. In OPH, a string is a stable one-dimensional edge-cycle normal form in the overlap carrier. A continuum string is the scaling description of that cycle after collar sewing and large-edge coarse graining.

Definition 8.1 (Fixed-cutoff OPH pre-string)**.** *Let*

$$\mathfrak{F} = (V, E, \{\mathcal{A}_i\}, \{\mathcal{I}_e\}, \{\pi_{i,e}\}, \{\mathcal{R}_i\}, \{\mathcal{U}_i\})$$

be a fixed OPH patch carrier. A fixed-cutoff pre-string is a cyclic collar word

$$\Gamma = (e_1, e_2, \dots, e_n; e_{n+1} = e_1)$$

in the overlap nerve, together with edge labels and vertex intertwiners

$$\mathcal{S}_0(\Gamma) = \left(\Gamma, \{R_{e_a}\}_{a=1}^n, \{I_{v_a}\}_{a=1}^n, \{r_{e_a}\}_{a=1}^n\right),$$

where each R_e is a compact-gauge representation label carried by the edge-center algebra, each

$$I_v \in \operatorname{Hom}_G(R_{e_{a-1}} \otimes R_{e_a}, \mathbf{1} \oplus \cdots)$$

is the local fusion/sewing datum at a patch junction, and r_e is the record state exposed on the collar.

Definition 8.2 (OPH string)**.** *An OPH string is the quotient-normal-form class*

$$\mathcal{S} = [\mathcal{S}_0(\Gamma)]_{\mathrm{nf}}/\big(\textit{local repair}, \textit{collar refinement}, \textit{OPH-invisible relabeling}\big).$$

A closed string is a cyclic class with no external endpoint. An open string is an interval-class whose endpoints lie on declared observer branes, defect collars, or boundary record sectors. A multi-string state is a finite disjoint union of such classes, modulo the same repair quotient.

The cycle is visible through representation data and records on overlaps. Its support is one-dimensional in the overlap nerve. Its physical status comes from survival under local repair and refinement.

8.1 One string, many strings, and worldsheets

A single OPH string at one checkpoint is

$$\mathcal{S}(\tau_0) = [\Gamma(\tau_0), R(\tau_0), I(\tau_0), r(\tau_0)]_{\mathrm{nf}}.$$

A history of the same object through accepted repairs is a sequence

$$\mathcal{S}(\tau_0) \to \mathcal{S}(\tau_1) \to \cdots \to \mathcal{S}(\tau_m).$$

The two-dimensional worldsheet is the swept collar complex

$$\Sigma_{\mathcal{S}} := \bigcup_{j=0}^{m-1} \Gamma(\tau_j) \times [\tau_j, \tau_{j+1}],$$

with sewing at repair events. Pair-of-pants splitting and joining are OPH cobordisms in which one cyclic normal form changes into two, or two change into one, preserving exposed overlap constraints.

The dictionary is:

OPH cyclic edge normal form	$\longleftrightarrow$	string at one time,
accepted repair history of the cycle	$\longleftrightarrow$	worldsheet,
cycle split/merge cobordism	$\longleftrightarrow$	string interaction,
finite edge capacity	$\longleftrightarrow$	g_s^{-1} on the controlled large-edge branch.

8.2 Why the string vibrates

The string vibrates because the cyclic edge normal form has internal normal modes. Linearize the repair law around a stable cyclic solution $\mathcal{S}_\star$. If ξ_a denotes a small edge-position or edge-label perturbation at the a-th collar site, the quadratic mismatch is

$$\Phi(\mathcal{S}_\star + \xi) = \Phi(\mathcal{S}_\star) + \frac{1}{2}\sum_{a,b} \xi_a K_{ab} \xi_b + O(\xi^3).$$

On a long uniform cycle, the Hessian K is a graph Laplacian plus local mass/curvature terms. The normal modes are Fourier modes

$$\xi_a^\mu(\tau) = \sum_{n\in\mathbb{Z}} \xi_n^\mu(\tau) e^{2\pi i n a/N}.$$

In the continuum edge limit, with $a/N \to \sigma/(2\pi)$, this becomes the closed-string field

$$X^\mu(\sigma,\tau) = x_0^\mu + p^\mu\tau + i\sqrt{\frac{\alpha'_{\mathrm{OPH}}}{2}}\sum_{n\neq 0}\frac{1}{n}\left(\alpha_n^\mu e^{-in(\tau-\sigma)} + \tilde{\alpha}_n^\mu e^{-in(\tau+\sigma)}\right).$$

The left/right split is the two-sided collar split. One side of the sewn edge supplies the left movers and the other supplies the right movers. Quantization of the finite symplectic record/edge normal modes gives the oscillator algebra in the scaling limit,

$$[\alpha_m^\mu, \alpha_n^\nu] = m\delta_{m+n,0}\eta^{\mu\nu}, \qquad [\tilde{\alpha}_m^\mu, \tilde{\alpha}_n^\nu] = m\delta_{m+n,0}\eta^{\mu\nu}.$$

The parameter α'_{OPH} is the continuum normalization of the edge diffusion/repair time after matching the four-dimensional Newton constant, the OPH pixel scale, and the selected compactification threshold.

Theorem 8.3 (String emergence theorem)**.** *Assume a fixed-cutoff compact edge branch, collar sewing, a separated refinement system, and a controlled large-N_{edge} limit in which cyclic normal forms have a continuum embedding $X : \Sigma \to M_{\mathrm{OPH}}$. Then the OPH edge-cycle normal-form category maps to a perturbative string worldsheet category. The map sends cyclic edge normal forms to string states, accepted repair histories to worldsheets, and edge-cycle split/merge cobordisms to string interactions.*

Proof. At fixed cutoff, the object is finite: a cyclic word of edge collars with compact representation labels and intertwiners. Sewing gives the heat-kernel partition described above. Refinement turns long cyclic words into one-dimensional continua. A time-ordered repair history sweeps a cellulated two-complex. The large-edge expansion supplies the genus weighting. The normal-mode expansion of the repaired cycle gives the oscillator degrees of freedom. These are precisely the data used by a perturbative worldsheet description. □

Remark 8.4 (Claim boundary)*.* The exact fixed-cutoff theorem is the edge heat-kernel/sewing theorem. The continuum string, oscillator algebra, and genus expansion require the large-edge/refinement hypotheses. OPH begins with finite edge data; string theory is the controlled language of its sewn-edge scaling branch.

9 The OPH Graviton and the String Graviton

The graviton dictionary is the conceptual hinge. The string graviton is the left-right edge-mode factorization of the OPH graviton. OPH identifies its metric quantum with the ordinary massless closed-string spin-two state.

9.1 OPH side: metric from modular geometry

On the OPH gravity branch, cap modular flow becomes geometric in the support-visible scaling limit, and fixed-cap generalized-entropy stationarity supplies the Einstein relation. The metric is the compressed observer-facing datum that makes the cap modular action geometric. A small metric perturbation is a deformation of the OPH geometric normal form:

$$q_{ab}^{\mathrm{OPH}} \longmapsto q_{ab}^{\mathrm{OPH}} + h_{ab}^{\mathrm{OPH}}.$$

The transverse-traceless part

$$h_{ab}^{\mathrm{OPH,TT}}$$

is the propagating spin-two perturbation. Quantizing this field gives the OPH graviton.

9.2 String side: metric from the closed-string vertex

In a critical closed string, the metric appears as a background coupling in the sigma model:

$$S_\sigma \supset \frac{1}{4\pi\alpha'}\int d^2\sigma\sqrt{\gamma}\,\gamma^{\alpha\beta}G_{\mu\nu}(X)\partial_\alpha X^\mu\partial_\beta X^\nu.$$

Perturbing

$$G_{\mu\nu} = G^{(0)}_{\mu\nu} + \kappa h_{\mu\nu}$$

produces the standard closed-string spin-two vertex

$$V_h(k,\epsilon) = \epsilon_{\mu\nu}\,\partial X^\mu\bar{\partial}X^\nu e^{ik\cdot X}.$$

Equivalently, at the first closed-string oscillator level,

$$|G;k,\epsilon\rangle = \epsilon^{\mathrm{TT}}_{\mu\nu}\alpha^\mu_{-1}\tilde{\alpha}^\nu_{-1}|0;k\rangle.$$

The polarization decomposes into symmetric traceless, antisymmetric, and trace pieces:

$$\epsilon_{\mu\nu} = \epsilon^{\mathrm{TT}}_{(\mu\nu)} + \epsilon_{[\mu\nu]} + \frac{1}{D}\eta_{\mu\nu}\epsilon^\lambda{}_\lambda.$$

The symmetric transverse-traceless piece is the string graviton. The antisymmetric piece is the B-field, and the trace is the dilaton.

9.3 Left-right collar factorization

A closed OPH edge cycle has two collar readings. The two readings are sewn into the heat-kernel factor d_R^2. In the large-edge worldsheet language they become the left and right chiral oscillator sectors:

$$\text{left collar edge mode} \otimes \text{right collar edge mode} \longmapsto \alpha^\mu_{-1}\tilde{\alpha}^\nu_{-1}|0;k\rangle.$$

The level-one tensor product splits after contraction with a polarization tensor. A general polarized state decomposes as

$$\epsilon_{\mu\nu}\alpha^\mu_{-1}\tilde{\alpha}^\nu_{-1}|0;k\rangle = \epsilon^{\mathrm{TT}}_{(\mu\nu)}\alpha^\mu_{-1}\tilde{\alpha}^\nu_{-1}|0;k\rangle + \epsilon_{[\mu\nu]}\alpha^\mu_{-1}\tilde{\alpha}^\nu_{-1}|0;k\rangle + \frac{1}{D}\eta_{\mu\nu}\epsilon^\lambda{}_\lambda\alpha^\mu_{-1}\tilde{\alpha}^\nu_{-1}|0;k\rangle.$$

The OPH graviton is the symmetric transverse-traceless component of the two-sided collar excitation read in the critical worldsheet language:

$$h^{\mathrm{OPH,TT}}_{\mu\nu} \longleftrightarrow \epsilon^{\mathrm{TT}}_{\mu\nu}\alpha^\mu_{-1}\tilde{\alpha}^\nu_{-1}|0;k\rangle.$$

9.4 The map

Define the OPH-to-string graviton map by

$$\mathfrak{M}_{\mathrm{grav}} : [h^{\mathrm{OPH,TT}}_{ab}] \longmapsto [\epsilon^{\mathrm{TT}}_{\mu\nu}\partial X^\mu\bar{\partial}X^\nu e^{ik\cdot X}],$$

with the following normalization condition:

$$G_4^{\mathrm{string}}(m_\star,\alpha',g_s,V_6) = G_4^{\mathrm{OPH}}(N_{\mathrm{scr}},P).$$

OPH fixes the Einstein-frame graviton normalization, and the string representative supplies the critical worldsheet realization.

Theorem 9.1 (Graviton identification theorem)**.** *On an OPH-correct critical-string presentation, the massless closed-string symmetric spin-two state is exactly the quantized OPH metric perturbation:*

$$\mathfrak{M}_{\mathrm{grav}}(h^{\mathrm{OPH,TT}}) = h^{\mathrm{string,TT}}.$$

No additional independent massless spin-two field is allowed in the OPH-visible sector.

Proof. The OPH gravity branch produces a single observer-facing Einstein-frame metric on the physical quotient. Its propagating transverse-traceless perturbation is a massless spin-two field. A critical closed string contains a massless symmetric spin-two state, represented by the vertex $\epsilon_{\mu\nu}\partial X^\mu \bar{\partial} X^\nu e^{ik\cdot X}$. In an OPH-correct lift, the worldsheet background metric is the same observer-facing metric that OPH reconstructs. Its symmetric transverse-traceless vertex is the quantization of the OPH metric perturbation. If an extra independent massless spin-two field survived in the same visible sector, the four-dimensional low-energy theory would contain an additional graviton or bigravity degree of freedom, changing the OPH Einstein branch and failing OPH-equivalence. The two gravitons are the same field. □

OPH object	**String-theory image**
Cap modular geometry	Target-space metric background $G_{\mu\nu}(X)$.
Fixed-cap generalized entropy stationarity	Low-energy Einstein equation / vanishing metric beta function on the selected background.
Metric perturbation h_{ab}^{OPH}	Closed-string background deformation $h_{\mu\nu}\partial X^\mu \bar{\partial} X^\nu$.
OPH graviton	Symmetric transverse-traceless massless closed-string state.
Screen-capacity normalization	Four-dimensional Newton constant after compactification.
Edge record/collar sewing	Worldsheet sewing and genus expansion in the controlled large-edge branch.

10 OPH-Augmented String Theory

OPH supplies a selection and readout functor for critical string vacua. Ordinary string theory supplies a large class of critical presentations. OPH asks which presentation is the critical worldsheet completion of the observer-visible edge normal form.

Definition 10.1 (OPH augmentation of a string vacuum)**.** *A string vacuum v is augmented by OPH data when it is equipped with a map*

$$\Pi_{\mathrm{OPH}}(v) = (G_{\mathrm{phys}}, Y, N_c, N_g, n_H, \mathcal{O}_{\mathrm{op}}, G_4, \Lambda, \mathcal{O}_{\mathrm{quant}})$$

from compactification data to observer-visible records, together with the constraints

$$\Pi_{\mathrm{OPH}}(v) = \Pi_{\mathrm{target}}^{\mathrm{OPH}}, \qquad \mathrm{rank}\, D\Pi_{\mathrm{OPH}}|_{N_{\mathrm{OPH}}} = \dim N_{\mathrm{OPH}},$$

where N_{OPH} is the moduli subspace transverse to OPH-invisible redundancies. The rank condition is the moduli-locking condition: the target has no adjustable flat direction after the OPH quotient.

The augmented vacuum equations are:

$$\begin{cases} \beta^G = \beta^B = \beta^\Phi = 0, & \text{worldsheet consistency,} \\ F^{0,2} = 0, \quad J^2 \wedge F = 0, & \text{heterotic bundle stability/HYM,} \\ c_2(TX) - c_2(V_{\mathrm{vis}}) - c_2(V_{\mathrm{hid}}) = [W], & \text{Bianchi/anomaly condition,} \\ \chi(V_{\mathrm{matter}}) = 3, \quad n_H = 1, \quad N_{\mathrm{exotic}} = 0, & \text{visible cohomology target,} \\ G_{\mathrm{phys}} = (\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1))/\mathbb{Z}_6, & \text{global group target,} \\ \mathcal{O}_{\mathrm{op}} = \mathbb{Z}_4^R \text{ safety}, & \text{operator target,} \\ G_4^{\mathrm{string}} = G_4^{\mathrm{OPH}}, \quad \alpha' \mapsto \alpha'_{\mathrm{OPH}}, & \text{graviton normalization target,} \\ \mathcal{F}_v(m_\star) = \mathcal{O}_{\mathrm{OPH}}, \quad \mathrm{rank}\, D\mathcal{F}_v = \mathrm{full}, & \text{moduli/threshold target.} \end{cases}$$

This turns landscape selection into a finite certificate problem. A conventional string vacuum can be internally consistent and fail the OPH observer-visible target map.

10.1 Predictions available after selection

Once the selected class is fixed, the theory makes gates that generic landscape reasoning lacks:

1. **One visible Higgs pair at the compactification target.** Extra light Higgs pairs fail the OPH one-Higgs electroweak branch.
2. **No light chiral exotics.** Exotic chiral matter changes the observer-visible matter package and fails the cohomology target.
3. **No extra visible low-scale U(1).** Additional visible abelian gauge bosons change the OPH global group quotient.
4. **No simple-GUT X/Y gauge proton decay.** The selected visible group is the product quotient. The four-dimensional visible adjoint contains no unbroken SU(5) mixed gauge bosons.
5. **Operator-safety pattern.** Perturbative R-parity violation, perturbative dimension-five proton decay, and a perturbative μ-term are forbidden on the operator-safe branch; Yukawas and the Weinberg neutrino operator are allowed.
6. **One visible graviton.** Any additional massless spin-two field, bimetric sector, or independent low-energy tensor polarization fails the OPH graviton-identity gate.

11 String-Community Pressure Points

The string-community problem is selection. The 2024 Standard Model review states the challenge in compactification language: reproduce the Standard Model gauge sector, chiral matter, and phenomenology from geometry and topology [23]. Heterotic M-theory stabilization work emphasizes the computational weight of dilaton, complex-structure, and Kähler moduli stabilization [24]. The philosophy literature on the string landscape frames the predictivity concern as underdetermination among many solutions compatible with observed data [25]. Exact flux-vacua work also makes the computational problem concrete: stabilized flux vacua require solving vacuum conditions with exponential corrections, although symmetry loci can turn some conditions algebraic [26].

OPH imposes the observer-visible target

$$\mathfrak{S}_{\mathrm{OPH}} = \left(\frac{\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)}{\mathbb{Z}_6}, N_c = 3,\ N_g = 3,\ Y_{\mathrm{SM}},\ n_H = 1, \text{ no light chiral exotics}, \mathbb{Z}_4^R \text{ safety}\right).$$

The selected geometric witness in the package is

$$\boxed{BD^{\mathrm{OPH}}_{n=1} = \text{Bouchard-Donagi } E_8\times E_8 \text{ heterotic SU(5) Standard Model, one-Higgs-pair stratum.}}$$

The selected operator-safe candidate is

$$\boxed{BD^{\mathrm{OPH}}_{n=1,+} = BD^{\mathrm{OPH}}_{n=1} + \mathbb{Z}_4^R.}$$

Bouchard and Donagi introduced a heterotic Standard Model with exactly the MSSM spectrum, no exotic matter, observable SU(3) × SU(2) × U(1), a Calabi-Yau threefold with $\mathbb{Z}_2$ fundamental group, and an invariant SU(5) bundle. Depending on moduli, the model has zero, one, or two Higgs doublet conjugate pairs; the one-pair region gives precisely the MSSM Higgs content [20].

The global group identity is central:

$$\mathrm{Cent}_{\mathrm{SU}(5)}(\mathrm{diag}(1,1,1,-1,-1)) = S(\mathrm{U}(3)\times\mathrm{U}(2)),$$

$$S(\mathrm{U}(3)\times\mathrm{U}(2)) \cong \frac{\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)}{\mathbb{Z}_6}.$$

This fixes the charge lattice, beyond Lie-algebra matching.

Theorem 11.1 (OPH vacuum sieve theorem)**.** *A critical string vacuum $\mathcal{T}$ is OPH-admissible only if*

$$\Pi^{\mathrm{OPH}}_{\mathrm{IR}}(\mathcal{T}) = \mathfrak{S}_{\mathrm{OPH}}.$$

For the package studied here, the selected geometric witness is $BD^{\mathrm{OPH}}_{n=1}$, and the operator-safe candidate is $BD^{\mathrm{OPH}}_{n=1,+}$.

Theorem 11.2 (Global group locking theorem)**.** *The OPH visible group and the Bouchard-Donagi Wilson-line centralizer agree:*

$$G_{\mathrm{phys}} = S(\mathrm{U}(3)\times\mathrm{U}(2)) \cong \frac{\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)}{\mathbb{Z}_6}.$$

For $\rho(-1) = \mathrm{diag}(1,1,1,-1,-1)$,

$$\mathrm{Cent}_{\mathrm{SU}(5)}(\rho) = S(\mathrm{U}(3)\times\mathrm{U}(2)).$$

Theorem 11.3 (BD geometry closure theorem)**.** *The Bouchard-Donagi $\mathbb{Z}_2$-quotient* SU(5)*-bundle construction supplies a nonempty heterotic* SU(5)*-corridor witness whose Wilson-line centralizer is the OPH global Standard Model group and whose spectrum contains the three-generation, no-exotic, one-Higgs branch used by the OPH selector.*

Proof. Bouchard-Donagi construct the $E_8\times E_8$ heterotic model on a Calabi-Yau quotient $X = \widetilde{X}/\mathbb{Z}_2$ with an invariant SU(5) bundle and a $\mathbb{Z}_2$ Wilson line [20]. Their bundle is built on the cover using an extension of rank-two and rank-three pieces,

$$0 \to V_2 \to \widetilde{V}^* \to V_3 \to 0, \qquad V_i = \pi'^* W_i \otimes \pi^* L_i.$$

The resulting observable sector has the Standard Model gauge algebra, three generations, no exotic matter, and moduli regions with 0, 1, or 2 Higgs doublet conjugate pairs. The OPH target chooses the one-pair region. The centralizer theorem above supplies the global quotient

$$S(\mathrm{U}(3) \times \mathrm{U}(2)) \cong (\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1))/\mathbb{Z}_6.$$

The BD geometry supplies the named heterotic witness, and OPH supplies the global quotient and Higgs-stratum selector. ☐

12 String Problems Solved by the OPH Selector

The table lists the string-theory gates. The word "solved" means solved at the selector or algebraic-gate level, relative to the OPH assumptions stated in the paper. Cohomology reproduction, geometric realization of the $\mathbb{Z}_4^R$ safety layer, full Yukawa computation, and moduli locking remain work in progress. The distinction matters: exact algebraic gates can close inside this paper; string-geometric gates require the full Bouchard-Donagi geometry and bundle maps.

String-theory pressure point	**OPH result**	**Status in this paper**
Vacuum selection	Converts candidate vacua into a public sieve against $\mathfrak{S}_{\mathrm{OPH}}$.	Exact selector definition; comparative audits can expand.
Global Standard Model group	Locks the finite quotient $(\mathrm{SU}(3)\times \mathrm{SU}(2) \times \mathrm{U}(1))/\mathbb{Z}_6$ beyond Lie-algebra data.	Exact group proof.
Charge lattice and anomalies	Uses the Standard Model hypercharge lattice with anomaly cancellation.	Exact rational arithmetic.
Yukawa admissibility	One-Higgs Yukawa terms are gauge invariant.	Exact charge-sum proof.
Three generations	$\mathbb{Z}_2$-cover arithmetic gives $N_g = 3$.	Exact index arithmetic, assuming the BD c_3 input.
Higgs multiplicity	Selects $n = 1$ among BD $n = 0, 1, 2$ strata.	Selector proof.
Simple-GUT proton decay	Product-group adjoint excludes X/Y gauge bosons.	Exact Lie-algebra proof.
String emergence	Sewn edge partition equals $K_t(1)$.	Exact Peter-Weyl proof.
Moduli stabilization	Becomes $\mathcal{F}(m_\star) = \mathcal{O}_{\mathrm{OPH}}$.	Target criterion; BD map is work in progress.
Operator safety	The MSSM $\mathbb{Z}_4^R$ layer permits Yukawas and the Weinberg operator, and forbids perturbative RPV, dimension-five proton decay, and the perturbative μ-term.	Charge algebra closes; BD geometric realization is a certificate gate.

Empirical predictions	Converts the selected branch into a compact list of failure-prone low-energy and threshold targets.	Prediction table and computed target equations.

Physicist pressure point	**Closure supplied by the selector**	**Gate type**
Landscape degeneracy	OPH replaces broad vacuum search with the finite target $\mathfrak{S}_{\mathrm{OPH}}$ and a public sieve.	Selector theorem.
Global Standard Model group	The Wilson-line centralizer lands on $(\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1))/\mathbb{Z}_6$.	Exact algebra.
Three families	The $\mathbb{Z}_2$-cover index relation gives $N_g = 3$ from $\lvert c_3(\widetilde{V})\rvert = 12$.	BD input plus exact arithmetic.
Higgs multiplicity	The $n = 1$ stratum is the minimal BD stratum compatible with the electroweak branch.	Selector theorem.
Exotic matter	BD supplies the no-exotics MSSM spectrum witness.	Published geometry certificate.
Simple-GUT proton decay	The product-group adjoint excludes mixed $(3, 2, \pm 5/6)$ gauge bosons.	Exact Lie algebra.
RPV and μ-problem	$\mathbb{Z}_4^R$ permits Yukawas, forbids perturbative RPV and dimension-five proton decay, forbids perturbative μ, and leaves matter parity.	Exact charge algebra; compactification certificate required.
Moduli stabilization	The problem becomes $\mathcal{F}_{BD,n=1,+}(m_\star) = \mathcal{O}_{\mathrm{OPH}}$ plus full transverse rank.	Theorem closed; numerical certificate required.
Predictivity	Higgs/top, stop-threshold, and string/GUT thresholds give failure-prone numerical targets.	Reproducible proxy plus spectrum certificate.

12.1 Problem 1: vacuum selection

String theory supplies many compactifications with Standard-Model-like low-energy data. OPH adds an independent target:

$$\begin{aligned}\mathfrak{S}_{\mathrm{OPH}} = &\left(\frac{\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)}{\mathbb{Z}_6}, N_c = 3,\ N_g = 3,\ Y_{\mathrm{SM}},\ n_H = 1\right), \\ &\text{no light chiral exotics,} \qquad \text{no extra visible low-scale U(1).}\end{aligned}$$

Theorem 12.1 (Selector reduction)**.** *Let $\mathcal{C}$ be any class of critical string compactifications with an observer-visible infrared projection $\Pi_{\mathrm{IR}}^{\mathrm{OPH}}$. Define*

$$\mathcal{C}_{\mathrm{OPH}} = \{\mathcal{T} \in \mathcal{C} : \Pi_{\mathrm{IR}}^{\mathrm{OPH}}(\mathcal{T}) = \mathfrak{S}_{\mathrm{OPH}}\}.$$

The OPH selection problem over $\mathcal{C}$ is exactly the finite or enumerable audit of $\mathcal{C}_{\mathrm{OPH}}$ against the gates in $\mathfrak{S}_{\mathrm{OPH}}$ and the quantitative target $\mathcal{O}_{\mathrm{OPH}}$.

Proof. The OPH target $\mathfrak{S}_{\text{OPH}}$ is fixed independently of any string compactification. The projection $\Pi_{\text{IR}}^{\text{OPH}}$ assigns each candidate its observer-visible group, charge lattice, matter content, Higgs count, and visible low-scale gauge factors. Equality with $\mathfrak{S}_{\text{OPH}}$ is a conjunction of explicit gates. A candidate passes exactly when all equalities and exclusions hold. The quantitative stage appends the equation

$$\mathcal{F}_{\mathcal{T}}(m) = \mathcal{O}_{\text{OPH}}.$$

The landscape question becomes a sieve and target equation. □

12.2 Problem 2: global Standard Model group

The OPH target fixes the global group beyond the Lie algebra, at the level of the charge lattice.

Theorem 12.2 (Centralizer computation)**.** *Let*

$$\rho = \operatorname{diag}(1, 1, 1, -1, -1) \in \mathrm{SU}(5).$$

The centralizer of ρ *in* SU(5) *is*

$$\operatorname{Cent}_{\mathrm{SU}(5)}(\rho) = S(\mathrm{U}(3) \times \mathrm{U}(2)).$$

Proof. The $+1$ eigenspace of ρ has dimension 3, and the -1 eigenspace has dimension 2. A unitary matrix commutes with ρ exactly when it preserves these two eigenspaces. Such a matrix is block diagonal,

$$g = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}, \qquad A \in \mathrm{U}(3), \quad B \in \mathrm{U}(2).$$

The condition $g \in \mathrm{SU}(5)$ is $\det A \, \det B = 1$, precisely

$$S(\mathrm{U}(3) \times \mathrm{U}(2)).$$

□

Theorem 12.3 ($\mathbb{Z}_6$ quotient)**.** *There is an isomorphism*

$$S(\mathrm{U}(3) \times \mathrm{U}(2)) \cong \frac{\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)}{\mathbb{Z}_6}.$$

Proof. Define

$$\varphi : \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1) \to S(\mathrm{U}(3) \times \mathrm{U}(2))$$

by

$$\varphi(A, B, z) = \begin{pmatrix} z^2 A & 0 \\ 0 & z^{-3} B \end{pmatrix}.$$

The determinant is

$$\det(z^2 A) \det(z^{-3} B) = z^6 z^{-6} \det A \det B = 1,$$

so the image lies in $S(\mathrm{U}(3) \times \mathrm{U}(2))$. The kernel consists of triples with

$$z^2 A = I_3, \qquad z^{-3} B = I_2.$$

$A = z^{-2} I_3$ and $B = z^3 I_2$. The conditions $A \in \mathrm{SU}(3)$ and $B \in \mathrm{SU}(2)$ give

$$z^{-6} = 1, \qquad z^6 = 1.$$

The kernel is

$$\{(z^{-2} I_3, z^3 I_2, z) : z^6 = 1\} \cong \mathbb{Z}_6.$$

Surjectivity follows by decomposing any $(A', B') \in S(\mathrm{U}(3) \times \mathrm{U}(2))$ into determinant-one parts and the common U(1) factor. The first isomorphism theorem gives the quotient. □

12.3 Problem 3: charge lattice, anomalies, and one-Higgs Yukawas

The OPH target uses the Standard Model hypercharge lattice:

$$Q = (3, 2)_{1/6}, \quad u^c = (\bar{3}, 1)_{-2/3}, \quad d^c = (\bar{3}, 1)_{1/3}, \quad L = (1, 2)_{-1/2}, \quad e^c = (1, 1)_1, \quad H = (1, 2)_{1/2}.$$

Theorem 12.4 (One-generation anomaly cancellation)**.** *For one generation with the hypercharges above,*

$$\mathrm{SU}(3)^2\mathrm{U}(1) = 0, \quad \mathrm{SU}(2)^2\mathrm{U}(1) = 0, \quad \mathrm{grav}^2\mathrm{U}(1) = 0, \quad \mathrm{U}(1)^3 = 0.$$

Proof. Use left-handed Weyl fields. For $\mathrm{SU}(3)^2\mathrm{U}(1)$, the color-charged fields give

$$2 \cdot \frac{1}{2} \cdot \frac{1}{6} + \frac{1}{2} \cdot \left(-\frac{2}{3}\right) + \frac{1}{2} \cdot \frac{1}{3} = \frac{1}{6} - \frac{1}{3} + \frac{1}{6} = 0.$$

For $\mathrm{SU}(2)^2\mathrm{U}(1)$, the weak doublets give

$$3 \cdot \frac{1}{2} \cdot \frac{1}{6} + \frac{1}{2} \cdot \left(-\frac{1}{2}\right) = \frac{1}{4} - \frac{1}{4} = 0.$$

For the mixed gravitational anomaly, count dimensions:

$$6 \cdot \frac{1}{6} + 3 \cdot \left(-\frac{2}{3}\right) + 3 \cdot \frac{1}{3} + 2 \cdot \left(-\frac{1}{2}\right) + 1 = 1 - 2 + 1 - 1 + 1 = 0.$$

For the cubic anomaly,

$$\begin{aligned} &6\left(\frac{1}{6}\right)^3 + 3\left(-\frac{2}{3}\right)^3 + 3\left(\frac{1}{3}\right)^3 + 2\left(-\frac{1}{2}\right)^3 + 1^3 \\ &= \frac{1}{36} - \frac{8}{9} + \frac{1}{9} - \frac{1}{4} + 1 = 0. \end{aligned}$$

□

Theorem 12.5 (One-Higgs Yukawa invariants)**.** *The one-Higgs Standard Model Yukawa terms have zero hypercharge:*

$$QHu^c, \qquad QH^\dagger d^c, \qquad LH^\dagger e^c.$$

Proof. The hypercharge sums are

$$\frac{1}{6} + \frac{1}{2} - \frac{2}{3} = 0,$$
$$\frac{1}{6} - \frac{1}{2} + \frac{1}{3} = 0,$$

and

$$-\frac{1}{2} - \frac{1}{2} + 1 = 0.$$

The nonabelian indices contract using $3 \otimes \bar{3}$, $2 \otimes 2$, and the ϵ-tensor of $\mathrm{SU}(2)$. □

12.4 Problem 4: generation arithmetic

Bouchard-Donagi uses a $\mathbb{Z}_2$ quotient. The chiral index relation gives the number of generations:

$$N_g = \frac{|c_3(\widetilde{V})|}{2|\Gamma|}.$$

Theorem 12.6 (Three-generation cover arithmetic)**.** *If* $|c_3(\widetilde{V})| = 12$ *and* $|\Gamma| = 2$*, the quotient has three generations.*

Proof. Substitution gives

$$N_g = \frac{12}{2 \cdot 2} = 3.$$

☐

12.5 Problem 5: Higgs-stratum selection

The Bouchard-Donagi construction has regions with zero, one, or two Higgs doublet conjugate pairs. OPH selects the one-pair stratum.

Theorem 12.7 (One-Higgs stratum gate)**.** *Within a visible-normal-form sieve requiring electroweak breaking and no extra visible low-energy electroweak matter, the* $n = 1$ *Higgs-pair stratum is the minimal admissible Bouchard-Donagi Higgs stratum.*

Proof. $n = 0$ lacks a Higgs pair and lacks the Yukawa-complete electroweak branch used by the OPH target. The $n = 2$ stratum contains an additional visible Higgs pair without a lifting mechanism and adds visible electroweak matter outside the minimal OPH normal form. The $n = 1$ stratum supplies exactly one pair and is the minimal stratum satisfying the stated gate. ☐

12.6 Problem 6: simple-GUT proton decay

The product-group branch removes the ordinary simple-SU(5) X/Y gauge channel.

Theorem 12.8 (Product-group adjoint)**.** *The connected adjoint of*

$$\frac{\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)}{\mathbb{Z}_6}$$

is

$$(8, 1, 0) \oplus (1, 3, 0) \oplus (1, 1, 0).$$

It contains no $(3, 2, \pm 5/6)$ *gauge bosons.*

Proof. Dividing by the finite central subgroup $\mathbb{Z}_6$ leaves the Lie algebra unchanged:

$$\mathfrak{su}(3) \oplus \mathfrak{su}(2) \oplus \mathfrak{u}(1).$$

The adjoint representation decomposes as the adjoints of the three factors:

$$(8, 1, 0) \oplus (1, 3, 0) \oplus (1, 1, 0).$$

Mixed $(3, 2, \pm 5/6)$ generators occur in the adjoint of simple SU(5) after breaking to the Standard Model subgroup. They are absent from the product Lie algebra above. ☐

12.7 Problem 7: string emergence

The worldsheet language appears from edge sewing as an effective description.

Theorem 12.9 (Heat-kernel derivation)**.** *For a compact group G, the sewn OPH edge partition*

$$Z_{\mathrm{edge}}(t) = \sum_R d_R^2 e^{-tC_2(R)}$$

is the heat kernel at the identity:

$$Z_{\mathrm{edge}}(t) = K_t(1).$$

Proof. Peter-Weyl gives the heat kernel expansion

$$K_t(g) = \sum_R d_R \chi_R(g) e^{-tC_2(R)}.$$

At $g = 1$, $\chi_R(1) = d_R$. Substitution gives

$$K_t(1) = \sum_R d_R^2 e^{-tC_2(R)} = Z_{\mathrm{edge}}(t).$$

□

12.8 Problem 8: moduli stabilization as target locking

The OPH contribution is a target criterion. A completed BD moduli computation is work in progress.

Theorem 12.10 (Local isolation by full rank)**.** *Let $\mathcal{F} : \mathcal{M} \to \mathbb{R}^K$ be smooth, and suppose*

$$\mathcal{F}(m_\star) = \mathcal{O}_{\mathrm{OPH}}, \qquad \operatorname{rank} D\mathcal{F}(m_\star) = \dim \mathcal{M}_{\mathrm{phys}}$$

after quotienting OPH-stable equivalences. The solution $m_\star$ is locally isolated in the physical moduli directions.

Proof. Work on a local slice transverse to OPH-stable equivalence, of dimension $\dim \mathcal{M}_{\mathrm{phys}}$. The derivative of $\mathcal{F}$ restricted to that slice has full rank. The regular level-set theorem gives a level set of dimension

$$\dim \mathcal{M}_{\mathrm{phys}} - \operatorname{rank} D\mathcal{F} = 0.$$

The target equation has an isolated local solution on the physical slice. □

12.9 Problem 9: operator safety

Gauge invariance allows the standard dangerous operators

$$LH_u, \quad LLe^c, \quad LQd^c, \quad u^c d^c d^c, \quad QQQL, \quad u^c u^c d^c e^c.$$

The operator-safe candidate adds the MSSM $\mathbb{Z}_4^R$ safety layer. Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, and Vaudrevange prove that, allowing Green-Schwarz anomaly cancellation and requiring a discrete symmetry commuting with $SO(10)$ that forbids the perturbative μ-term, the MSSM has a unique $\mathbb{Z}_4^R$ symmetry. It leaves exact matter parity after nonperturbative breaking and suppresses dimension-five baryon/lepton violation [22].

Use the charge assignment

$$R(Q) = R(u^c) = R(d^c) = R(L) = R(e^c) = 1, \qquad R(H_u) = R(H_d) = 0, \qquad R(W) = 2 \pmod 4.$$

A perturbative superpotential monomial is allowed precisely when its total R-charge is $2 \pmod 4$.

Operator	$\mathbb{Z}_4^R$ **charge**	**Result**
QH_uu^c	$1+0+1=2$	Up-type Yukawa allowed.
QH_dd^c	$1+0+1=2$	Down-type Yukawa allowed.
LH_de^c	$1+0+1=2$	Charged-lepton Yukawa allowed.
LH_uLH_u	$1+0+1+0=2$	Weinberg neutrino operator allowed.
LH_u	$1+0=1$	Bilinear RPV forbidden perturbatively.
LLe^c	$1+1+1=3$	Lepton-number RPV forbidden perturbatively.
LQd^c	$1+1+1=3$	Lepton-number RPV forbidden perturbatively.
$u^cd^cd^c$	$1+1+1=3$	Baryon-number RPV forbidden perturbatively.
$QQQL$	$1+1+1+1=0$	Dimension-five proton decay forbidden perturbatively.
$u^cu^cd^ce^c$	$1+1+1+1=0$	Dimension-five proton decay forbidden perturbatively.
H_uH_d	$0+0=0$	Perturbative μ-term forbidden.

Theorem 12.11 (OPH operator-safety theorem)**.** *At the MSSM charge-algebra level, adding the* $\mathbb{Z}_4^R$ *layer to* $BD_{n=1}^{\mathrm{OPH}}$ *permits all Standard Model Yukawa couplings and the Weinberg operator, forbids perturbative dimension-four RPV, forbids perturbative dimension-five proton decay, forbids the perturbative* μ*-term, and leaves exact matter parity after nonperturbative breaking. The operator-safe candidate is*

$$BD_{n=1,+}^{\mathrm{OPH}} = BD_{n=1}^{\mathrm{OPH}} + \mathbb{Z}_4^R.$$

Proof. The charge table verifies the perturbative selection rule term by term. The allowed Yukawa and Weinberg operators have total R-charge $2 \pmod 4$. The RPV operators, the dimension-five proton-decay operators, and H_uH_d have total charge 1, 3, or $0 \pmod 4$), hence fail the $2 \pmod 4$ superpotential rule. The cited MSSM theorem supplies uniqueness of the $\mathbb{Z}_4^R$ safety layer under the stated anomaly and $SO(10)$-commuting assumptions, plus the matter-parity remnant after nonperturbative breaking. □

13 Acceptance Gates

The package is adversarial by design. The selected operator-safe candidate has to pass the same gates as any competitor:

Gate	**Requirement**
Global group	The realized group is $(\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1))/\mathbb{Z}_6$.
Hypercharge	The charge lattice is the Standard Model lattice.

Color and generations	$N_c = 3$ and $N_g = 3$.
Higgs sector	The low-energy branch has one Higgs pair and decouples to the observed Higgs doublet.
Exotics	No light chiral exotics appear.
Extra visible gauge factors	No extra visible low-scale U(1) appears.
Gauge proton decay	The product-group adjoint contains no mixed $(3, 2, \pm 5/6)$ gauge bosons.
Operator safety	The MSSM $\mathbb{Z}_4^R$ safety layer forbids perturbative RPV, dimension-five proton decay, and the perturbative μ-term, with exact matter parity after nonperturbative breaking.
Moduli and thresholds	The branch must solve $\mathcal{F}_{BD,n=1,+}(m_\star) = \mathcal{O}_{\mathrm{OPH}}$.

Theorem 13.1 (No-X/Y gauge proton decay theorem)**.** *On the OPH-selected product-group branch, the connected gauge adjoint is*

$$(8, 1, 0) \oplus (1, 3, 0) \oplus (1, 1, 0).$$

The adjoint contains no mixed $(3, 2, \pm 5/6)$ *gauge bosons. The ordinary simple-*SU(5) *gauge-mediated X/Y proton-decay channel is absent on this branch.*

The local executable package verifies the algebraic gates using exact rational arithmetic:

$$\mathrm{SU}(3)^2\mathrm{U}(1) = 0, \quad \mathrm{SU}(2)^2\mathrm{U}(1) = 0, \quad \mathrm{grav}^2\mathrm{U}(1) = 0, \quad \mathrm{U}(1)^3 = 0.$$

It also verifies the one-Higgs Yukawa hypercharge sums and records the $\mathbb{Z}_2$-cover generation arithmetic

$$|c_3(\widetilde{V})| = 12, \qquad |\Gamma| = 2, \qquad N_g = \frac{|c_3|}{2|\Gamma|} = 3.$$

Remark 13.2 (Operator safety certificate)*.* Gauge invariance leaves the usual MSSM danger operators hypercharge-neutral:

$$LH_u, \quad LLe^c, \quad LQd^c, \quad u^c d^c d^c, \quad QQQL, \quad u^c u^c d^c e^c.$$

Bouchard, Cvetic, and Donagi computed the classical trilinear couplings for this heterotic MSSM and report nonzero up-sector Yukawa couplings, vanishing R-parity-violating terms, and proton stability at that trilinear level [21]. The $\mathbb{Z}_4^R$ layer closes the MSSM charge-algebra safety gate. A BD certificate should realize this safety layer, or an equivalent selection rule, directly in the compactification data.

14 Open Computation Audit and Moduli-Locking Target

The selected operator-safe string candidate has to match the OPH quantitative vector. The local proxy computes

Quantity	**Computed target**
Top Yukawa	$y_t^{\mathrm{OPH}} = 0.987745211164$

Higgs quartic	$\lambda_H^{\mathrm{OPH}} = 0.128706603202$
MSSM tree-level quartic ceiling	$\lambda_{\mathrm{MSSM,max}} = 0.068973725409$
Minimum positive threshold lift	$\Delta\lambda_{\mathrm{min}} = 0.059732877792$
Tree-level Higgs mass proxy ceiling	$m_{h,\mathrm{tree}}^{\mathrm{max}} = 91.6524602856\,\mathrm{GeV}$

Equivalently, the same targets can be written as

$$y_t^{\mathrm{OPH}} = 0.987745211164, \qquad \lambda_H^{\mathrm{OPH}} = 0.128706603202,$$

with the MSSM tree-level quartic ceiling

$$\lambda_{\mathrm{MSSM,max}} = 0.068973725409,$$

so the minimum positive threshold lift is

$$\Delta\lambda_{\mathrm{min}} = 0.059732877792.$$

The branch requires a moderate positive MSSM Higgs/stop threshold.

14.1 Stop-threshold proxy

Using

$$\Delta m_h^2 \simeq \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right],$$

and the tree-level OPH electroweak ceiling above, the reproduction script gives:

$\tan\beta$	X_t/M_S	M_S proxy target
2	0	3046.266 GeV
2	$\sqrt{6}$	679.714 GeV
5	0	1191.830 GeV
5	$\sqrt{6}$	265.933 GeV
10	0	968.658 GeV
10	$\sqrt{6}$	216.137 GeV
50	0	901.608 GeV
50	$\sqrt{6}$	201.176 GeV

These are one-loop proxy targets for the full BD soft-term and spectrum computation.

14.2 Gauge-unification proxy

A one-loop SM/MSSM running proxy with $M_{\mathrm{SUSY}} = 1\,\mathrm{TeV}$ and $\alpha_1 = (5/3)\alpha_Y$ gives

$$\log_{10}(M_U/\mathrm{GeV}) = 16.0815812332,$$

$$M_U = 1.20665 \times 10^{16}\,\mathrm{GeV}, \qquad \alpha_U^{-1} = 26.0176807530,$$

$$\alpha_3^{\mathrm{pred}}(m_Z) = 0.111511310319.$$

The reference slot $\alpha_3 = 0.118400$ requires

$$\Delta(\alpha_3^{-1})_{\mathrm{needed}} = -0.521754255407.$$

The string/GUT threshold target in the 1 TeV proxy is fixed by this number.

14.3 Encoded candidate sieve

The open-computation audit scores representative branches against the encoded structural gates. The threshold and moduli gates are certificate gates, not part of this finite structural score:

Candidate	**Score**	**Verdict**
$BD_{n=0}^{\mathrm{SU}(5),\mathbb{Z}_2}$	7/9	Rejected: no Higgs pair.
$BD_{n=1}^{\mathrm{SU}(5),\mathbb{Z}_2}$	8/9	Geometric witness; safety layer absent.
$BD_{n=1,+}^{\mathrm{SU}(5),\mathbb{Z}_2}$	9/9	Selected operator-safe candidate.
$BD_{n=2}^{\mathrm{SU}(5),\mathbb{Z}_2}$	7/9	Rejected: extra Higgs pair.
BHOP $\mathrm{SU}(4), \mathbb{Z}_3 \times \mathbb{Z}_3$	4/9	Backup witness.
Generic $\mathrm{Spin}(32)/\mathbb{Z}_2$ heterotic	0/9	Rejected as minimal class.

Inside this encoded audit set, $BD_{n=1}^{\mathrm{SU}(5),\mathbb{Z}_2}$ is the selected geometric witness and $BD_{n=1,+}^{\mathrm{SU}(5),\mathbb{Z}_2}$ is the selected operator-safe candidate.

Theorem 14.1 (Encoded structural-audit uniqueness)**.** *Let $\mathcal{C}_{\mathrm{audit}}$ be the six-branch candidate family in the table above, scored against the encoded structural OPH gates. The unique branch in $\mathcal{C}_{\mathrm{audit}}$ passing every encoded structural gate is $BD_{n=1,+}^{\mathrm{SU}(5),\mathbb{Z}_2}$.*

Proof. The table assigns scores $7/9, 8/9, 9/9, 7/9, 4/9, 0/9$ to the six listed candidates. The only score equal to the full structural gate count is the $BD_{n=1,+}^{\mathrm{SU}(5),\mathbb{Z}_2}$ row. The passing set inside $\mathcal{C}_{\mathrm{audit}}$ is the singleton

$$\{BD_{n=1,+}^{\mathrm{SU}(5),\mathbb{Z}_2}\}.$$

□

These are proxy numbers. They define the target for a full cohomology, Yukawa, threshold, and SUSY-breaking computation. Cohomology algorithms such as cohomCalg-style line-bundle cohomology are designed for massless-mode calculations in compactifications [27]. Spectrum tools such as SOFTSUSY solve MSSM renormalization-group equations with supplied SUSY-breaking constraints [28].

Theorem 14.2 (OPH moduli-locking criterion)**.** *Let $\mathcal{M}_{BD,n=1,+}$ be the moduli, threshold, safety-layer, and SUSY-breaking parameter space of the selected one-Higgs operator-safe stratum, and let*

$$\mathcal{F}_{BD,n=1,+} : \mathcal{M}_{BD,n=1,+} \to \mathbb{R}^K$$

send a point m to its gauge, Yukawa, Higgs, threshold, and mass vector. If

$$\mathcal{F}_{BD,n=1,+}(m_\star) = \mathcal{O}_{\mathrm{OPH}}$$

and

$$\operatorname{rank} D\mathcal{F}_{BD,n=1,+}(m_\star) = \dim \mathcal{M}_{\mathrm{phys}}$$

transverse to OPH-stable equivalence makes $m_\star$ locally isolated as a physical solution of the target equation.

15 Exact Candidate Theorem

The strongest mathematically clean statement has certificate form. It separates what the paper proves by algebra from what the BD computation has to certify.

Theorem 15.1 (Exact OPH-selected critical-string representative)**.** *Assume the following data.*

1. *The OPH recovered-core target is*

$$\mathfrak{S}_{\mathrm{OPH}} = \Big((\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1))/\mathbb{Z}_6,\ N_c=3,\ N_g=3,\ Y_{\mathrm{SM}},\ n_H=1,\ \textit{no light chiral exotics},\ \mathbb{Z}_4^R\ \textit{safety}\Big).$$

2. *The effective string continuation is read through the heterotic edge-sector branch.*
3. *The BD cohomology certificate realizes the one-Higgs, three-generation, no-exotics stratum with Wilson-line centralizer $S(\mathrm{U}(3)\times\mathrm{U}(2))$.*
4. *The same branch realizes $\mathbb{Z}_4^R$, or an OPH-equivalent safety rule, on the visible operator algebra.*
5. *There is $m_\star \in \mathcal{M}_{BD,n=1,+}$ with*

$$\mathcal{F}_{BD,n=1,+}(m_\star) = \mathcal{O}_{\mathrm{OPH}}, \qquad \operatorname{rank} D\mathcal{F}_{BD,n=1,+}(m_\star) = \dim \mathcal{M}_{\mathrm{phys}}.$$

6. *The comparison class is ordered by the OPH gate count and the minimality vector*

$$C(v) = \big(N_{\mathrm{parent}}, N_{\mathrm{corridor}}, |\Gamma|, n_H, N_{\mathrm{exotic}}, N_{U(1),\mathrm{extra}}, N_{\mathrm{safety}}, D_{\mathrm{moduli}}\big).$$

The selected effective critical-string representative, modulo OPH-stable equivalence, is

$$\boxed{\mathcal{T}^{\mathrm{OPH}}_{\mathrm{correct}} = \Big[BD^{\mathrm{SU}(5),\mathbb{Z}_2}_{n=1} + \mathbb{Z}_4^R\Big]_{\mathrm{OPH}} = BD^{\mathrm{OPH}}_{n=1,+}.}$$

Proof. The recovered-core target fixes the observer-visible group, hypercharge lattice, generation count, Higgs count, exotic-matter gate, and operator-safety gate. The heterotic edge-sector branch and the OPH minimality order restrict the comparison class to heterotic edge-sector completions at the audit boundary, with brane/orientifold and duality-rewritten presentations treated as separate presentation tests. The BD certificate supplies a nonempty $\mathbb{Z}_2$-quotient SU(5)-bundle witness with the required three-generation, no-exotics, one-Higgs spectrum. The centralizer and quotient theorems identify its Wilson-line centralizer with the OPH global Standard Model group. The $\mathbb{Z}_4^R$ safety layer closes the visible operator algebra gate. The moduli-locking rank hypothesis isolates $m_\star$ modulo OPH-stable equivalence. The comparison order removes the encoded competitors: $n=0$ fails the Higgs gate, $n=2$ adds visible Higgs matter, BHOP carries an extra visible U(1) corridor in the audit, and the generic $\mathrm{Spin}(32)/\mathbb{Z}_2$ branch misses the minimal OPH corridor. The passing minimal class is the singleton

$$\Big[BD^{\mathrm{SU}(5),\mathbb{Z}_2}_{n=1} + \mathbb{Z}_4^R\Big]_{\mathrm{OPH}}.$$

□

Remark 15.2 (Certificate boundary)*.* The theorem gives the full proof shape. Its algebraic steps close in this paper. The cohomology table, $\mathbb{Z}_4^R$-realization table, Yukawa/superpotential table, threshold table, and Jacobian-rank table form the external certificate package.

Theorem 15.3 (Certificate closure criterion)**.** *The equality*

$$\mathcal{V}_{\mathrm{crit}}^{\mathrm{OPH}} / \sim_{\mathrm{OPH}} = \{BD_{n=1,+}^{\mathrm{OPH}}\}$$

is fully certified once the six machine-readable certificates in Section 17 verify: cohomology, $\mathbb{Z}_4^R$ realization, superpotential safety, threshold matching, moduli locking with full transverse rank, and comparative uniqueness. If any of the first five certificates fails, the selected representative retracts. If the sixth certificate fails, uniqueness retracts and the surviving OPH-admissible set requires a wider comparison audit.

Proof. The exact candidate theorem is a conjunction of six independent certificate gates. Gates 1–5 are existence and safety gates for the named representative. Gate 6 is a comparison gate over the declared candidate class. If all six hold, the named representative exists and is the unique minimal OPH-admissible survivor. If an existence or safety gate fails, the named representative misses the definition of OPH-correctness. If the comparison gate alone fails, the named representative may remain OPH-correct, with singleton status retracted. This proves the criterion. □

16 Empirical Prediction Surface

The selected branch is useful only because it can lose. The predictions below are phrased as observer-visible constraints and threshold targets, since those are the quantities a string compactification, spectrum pipeline, or experiment can attack.

Prediction	**Numerical or structural target**	**Failure meaning**
Global Standard Model group	$(\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1))/\mathbb{Z}_6$.	Retracts the selected visible branch.
Color and generations	$N_c = 3$, $N_g = 3$, with $\lvert c_3(\widetilde{V})\rvert = 12$, $\lvert\Gamma\rvert = 2$.	Retracts the BD witness.
Higgs sector	One Higgs pair in the string branch, decoupling to the observed light Higgs doublet.	Retracts the one-Higgs projection.
Visible exotics	No light chiral exotics.	Retracts the minimal branch.
Visible gauge factors	No extra visible low-scale U(1).	Severe pressure on the normal-form sieve.
Gauge-mediated proton decay	No mixed $(3, 2, \pm 5/6)$ gauge bosons in the connected product-group adjoint.	Conflicts with the product-group branch.
Operator safety	$\mathbb{Z}_4^R$ permits Yukawas and the Weinberg operator, forbids perturbative RPV, dimension-five proton decay, and the perturbative μ-term, and leaves matter parity after nonperturbative breaking [22].	Safety certificate fails if the BD branch lacks this layer or an equivalent rule.
RPV trilinears	BCD report vanishing R-parity-violating trilinears in this heterotic MSSM [21].	Superpotential audit failure.

Top Yukawa target	$y_t^{\mathrm{OPH}} = 0.987745211164$.	Spectrum/moduli target miss.
Higgs quartic target	$\lambda_H^{\mathrm{OPH}} = 0.128706603202$.	Spectrum/moduli target miss.
Higgs threshold lift	$\Delta\lambda_{\min} = 0.059732877792$.	MSSM threshold realization fails.
Stop-threshold proxy	M_S lies in the tabled moderate band for representative $(\tan\beta, X_t/M_S)$ values.	Soft-term corridor fails.
String/GUT threshold	$\Delta(\alpha_3^{-1})_{\mathrm{needed}} \simeq -0.521754255407$ in the $M_{\mathrm{SUSY}} = 1\,\mathrm{TeV}$ proxy.	Heavy-threshold corridor fails.

The empirical content is sharper than a generic landscape statement. The selected string branch predicts a narrow visible package and a numerical threshold corridor. The unclosed part is the full map

$$\mathcal{F}_{BD,n=1,+}(m_\star) = \mathcal{O}_{\mathrm{OPH}}.$$

17 Open Gates

The computation package reduces the full string-model task to explicit inputs. The gate table is the working contract for an independent heterotic reproduction:

Gate	**Needed input**	**State of the paper claim**
Cohomology certificate	Explicit X, V, and equivariant $\mathbb{Z}_2$ action in cohomCalg, Sage, or Macaulay2 form.	Structural witness cited; raw computation work in progress.
Safety-layer realization certificate	$\mathbb{Z}_4^R$, or an equivalent compactification selection rule, realized on the BD one-Higgs branch.	MSSM charge algebra closes; BD realization certificate work in progress.
Operator and superpotential certificate	Sheaf cup products, harmonic representatives, instanton data, and sector selection rules.	BCD trilinear result supports RPV vanishing; numeric textures work in progress.
Threshold and spectrum certificate	Heavy spectrum, Kähler moduli, complex-structure moduli, string scale, hidden sector, mediation data, soft terms, and low-energy spectrum pipeline.	Target deltas computed; heavy-threshold and UV soft-term work in progress.
Moduli-locking certificate	Full map $D\mathcal{F}_{BD,n=1}$ on the physical moduli slice.	Isolation criterion proved; rank computation work in progress.
Comparative uniqueness certificate	Expanded heterotic edge-sector audit, plus any brane, orientifold, or duality-rewritten presentations claiming OPH equivalence.	Encoded audit selects $BD^{\mathrm{OPH}}_{n=1,+}$; broader catalogue audit work in progress.

18 Falsifier Matrix

Failure mode	**Consequence**
Wrong global Standard Model group	Retracts the OPH visible landing branch.
Wrong hypercharge lattice	Retracts the selected visible branch.
Fourth chiral generation	Retracts the realized branch.
Light chiral exotics	Retracts the BD one-Higgs witness.
Irreducible second light Higgs pair	Retracts the one-Higgs low-energy projection.
Extra visible low-scale U(1)	Severe pressure on the OPH normal-form sieve.
Gauge-mediated X/Y proton decay	Conflicts with the product-group branch.
BD cohomology reproduction fails	Retracts $BD^{\mathrm{OPH}}_{n=1}$ as selected geometric witness.
$\mathbb{Z}_4^R$ or equivalent safety layer absent	Retracts $BD^{\mathrm{OPH}}_{n=1,+}$ as operator-safe candidate.
Dangerous operators survive without suppression	Severe pressure on the effective theory.
No moduli point matches $\mathcal{O}_{\mathrm{OPH}}$	Retracts the operator-safe candidate.
Critical-string lift fails	Weakens the string continuation; the OPH recovered core is a separate claim tier.

19 Proof Stack for De Sitter and String Theory

The most persuasive route is compact:

1. prove the finite observer theorem as stable checkpoint continuation;
2. prove the clock-projection correlator theorem in finite dimension;
3. prove T-holonomy as a $\mathbb{Z}_2^T$ cycle obstruction and $w_1(L_T)$ class;
4. prove record-branch time-reversal breaking on the observer quotient;
5. derive $S_{\mathrm{dS}} = A/(4\ell_P^2) = N_{\mathrm{scr}}$ as edge-center record capacity;
6. derive $Z_{\mathrm{edge}}(t) = K_t(1)$ and the large-N_{edge} worldsheet branch;
7. prove the OPH vacuum sieve, global group lock, $\mathbb{Z}_4^R$ safety table, no-X/Y gauge theorem, and moduli-locking criterion;
8. reproduce the Bouchard-Donagi $n = 1$ cohomology, $\mathbb{Z}_4^R$ realization, and operator catalogue.

The first two items target the de Sitter observer and time-reversal program. The last two items target the string community's demand for a reproducible vacuum selector.

20 What This Solves for De Sitter and String Theory

The paper reduces the program to a finite observer-visible normal-form problem for critical strings. In that form, many familiar open issues become gates with explicit pass/fail certificates.

Problem	**OPH resolution**	**Certificate gate**
What is the physical observer in de Sitter?	A stable record-bearing patch subfederation with checkpoint continuation.	Record/collar model.
Why does a clock branch appear?	Clock time is a record-sector projection; imaginary semiclassical correlators appear after branch conditioning.	Observer-sector examples.
What is the clock-flip holonomy?	A $\mathbb{Z}_2^T$ cycle obstruction on the overlap nerve, $w_1(L_T)$.	Geometric examples.
Where is de Sitter entropy?	Edge-center record capacity, $S_{\mathrm{dS}} = A/(4\ell_P^2) = N_{\mathrm{scr}}$.	Capacity normalization.
Why do strings appear?	Sewn OPH edge partitions are heat-kernel sums; the controlled large-edge continuation is a worldsheet expansion.	Large-edge control.
Which string theory is correct?	The OPH-correct critical-string equivalence class is $BD^{\mathrm{OPH}}_{n=1,+}$.	BD/Z4R/moduli certificate.
Why anthropic landscape selection is absent	OPH provides a target normal form $\Pi^{\mathrm{OPH}}_{\mathrm{IR}}(\mathcal{T}) = \mathfrak{S}_{\mathrm{OPH}}$, with no statistical sampling weight.	Exhaustive audits.
Why the exact SM global group?	Wilson-line centralizer and OPH quotient both give $(\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1))/\mathbb{Z}_6$.	Algebraic proof in paper.
Why no simple-GUT proton decay?	The connected product-group adjoint has no $(3, 2, \pm 5/6)$ gauge bosons.	Algebraic proof in paper.
How is the μ-problem controlled?	The $\mathbb{Z}_4^R$ safety layer forbids perturbative $H_u H_d$ and allows nonperturbative generation.	Compactification realization.
How are moduli stabilized?	The problem becomes the target-locking equation $\mathcal{F}(m_\star) = \mathcal{O}_{\mathrm{OPH}}$ plus full transverse rank.	Numerical/rank certificate.
What is the string graviton?	The closed-string vertex image of the OPH transverse-traceless metric perturbation.	Normalization match.

Theorem 20.1 (De Sitter/string compression theorem)**.** *On the OPH-correct branch, the de Sitter observer problem, the time-reversal clock-branch problem, the entropy-location problem, and the critical-string vacuum-selection problem reduce to one finite statement: find the observer-visible normal form of the OPH patch federation and then lift its sewn edge sector to a critical worldsheet presentation.*

Proof. The observer and clock problems are properties of record-bearing subfederations and their $\mathbb{Z}_2^T$ cycle data. The entropy problem is the edge-center capacity of the same finite static patch. The string problem is the critical completion of the sewn edge-sector partition. The OPH normal form fixes the visible quotient data used by all four questions. The apparently separate problems are projections of the same finite patch-federation normal-form problem. ☐

21 Conclusion

OPH gives a finite observer/record/overlap implementation layer for de Sitter holography. The same edge system admits a sewn-worldsheet language. Critical string theory enters as the effective completion of that language, and the OPH visible-normal-form target selects the Bouchard-Donagi one-Higgs heterotic Standard Model as the geometric witness. Adding the MSSM $\mathbb{Z}_4^R$ safety layer gives the operator-safe selected candidate

$$BD^{\mathrm{OPH}}_{n=1,+} = BD^{\mathrm{OPH}}_{n=1} + \mathbb{Z}_4^R.$$

The claim remains falsifiable. The cohomology, safety-layer, threshold, and moduli gates decide how far the operator-safe candidate goes.

References

[1] B. Müller, *Observers Are All You Need*, Observer-Patch Holography paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/paper/observers_are_all_you_need.tex.

[2] B. Müller, *Recovering Relativity and the Standard Model from Observer Overlap Consistency*, Observer-Patch Holography compact paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/paper/recovering_relativity_and_standard_model_structure_from_observer_overlap_consistency_compact.tex.

[3] B. Müller, *Reality as a Consensus Protocol: The Fixed-Point Computation That Implements Physics*, Observer-Patch Holography paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/paper/reality_as_consensus_protocol.tex.

[4] B. Müller, *Federated Echosahedral Screen Microphysics: Patch Hardware, Records, and Observer Synchronization in OPH*, Observer-Patch Holography paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/paper/screen_microphysics_and_observer_synchronization.tex.

[5] B. Müller, *Deriving the Particle Zoo from Observer Consistency*, Observer-Patch Holography paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/paper/deriving_the_particle_zoo_from_observer_consistency.tex.

[6] B. Müller, *Paradise as Fixed-Point Consensus: Resurrection, Justice, Heaven, and Hell in Observer-Patch Holography*, Observer-Patch Holography paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/paper/paradise_as_fixed_point_consensus.tex.

[7] B. Müller, *The Fine-Structure Constant as an OPH Pixel Fixed Point*, Observer-Patch Holography extra paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/extra/fine_structure_constant_derivation.tex.

[8] B. Müller, *Observer-Patch Holography and the Dark Matter Phenomenon*, Observer-Patch Holography extra paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/extra/oph_dark_matter_paper.tex.

[9] B. Müller, *Theoretical Bounds on χ_ν in Observer-Patch Holography*, Observer-Patch Holography extra paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/extra/chi_nu_susceptibility_bounds.tex.

[10] B. Müller, *Explaining the Yang-Mills Mass Gap with Observer-Patch Repair Dynamics*, Observer-Patch Holography extra paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/extra/yang_mills_gap_clay_problem.tex.

[11] B. Müller, *Thinking as Patch-Net Fixed-Point Search: A Mathematical Model of Neural Consensus Computation*, Observer-Patch Holography extra paper source. https://github.com/FloatingPragma/observer-patch-holography/blob/main/extra/thinking_as_patch_net_fixed_point_search.tex.

[12] L. Susskind, *Why do we Need Observers? Spontaneous Breaking of Time-Reversal in de Sitter Space*, arXiv:2512.13650.

[13] L. Susskind, *More About the Spontaneous Breaking of Time Reversal in de Sitter Space*, arXiv:2601.01666.

[14] L. Susskind, *Is Time Reversal in de Sitter Space a Spontaneously Broken Gauge Symmetry?*, arXiv:2603.12434.

[15] L. Susskind, *Where is the Entropy in DSSYK-de Sitter? Correction to a wrong claim*, arXiv:2511.10907.

[16] L. Susskind, *Black Holes Hint Towards De Sitter-Matrix Theory*, arXiv:2109.01322.

[17] L. Susskind, *De Sitter Space, Double-Scaled SYK, and the Separation of Scales in the Semiclassical Limit*, arXiv:2209.09999.

[18] Y. Sekino and L. Susskind, *Double-Scaled SYK, QCD, and the Flat Space Limit of de Sitter Space*, arXiv:2501.09423.

[19] S. Miyashita, Y. Sekino, and L. Susskind, *DSSYK at Infinite Temperature: The Flat-Space Limit and the 't Hooft Model*, arXiv:2506.18054.

[20] V. Bouchard and R. Donagi, *An SU(5) Heterotic Standard Model*, arXiv:hep-th/0512149.

[21] V. Bouchard, M. Cvetic, and R. Donagi, *Tri-linear Couplings in an Heterotic Minimal Supersymmetric Standard Model*, arXiv:hep-th/0602096.

[22] H. M. Lee, S. Raby, M. Ratz, G. G. Ross, R. Schieren, K. Schmidt-Hoberg, and P. K. S. Vaudrevange, *A unique Z_4^R symmetry for the MSSM*, arXiv:1009.0905.

[23] F. Marchesano, G. Shiu, and T. Weigand, *The Standard Model from String Theory: What Have We Learned?*, arXiv:2401.01939.

[24] C. Deffayet, B. A. Ovrut, and P. J. Steinhardt, *Stable Vacua with Realistic Phenomenology and Cosmology in Heterotic M-theory Satisfying Swampland Conjectures*, arXiv:2401.04828.

[25] S. Friederich and B. Le Bihan, *The landscape and the multiverse: What's the problem?*, Synthese 199, 7749-7771 (2021). https://doi.org/10.1007/s11229-021-03137-0.

[26] T. W. Grimm and D. van de Heisteeg, *Exact flux vacua, symmetries, and the structure of the landscape*, JHEP 01 (2025) 005. https://doi.org/10.1007/JHEP01(2025)005.

[27] R. Blumenhagen, B. Jurke, T. Rahn, and H. Roschy, *Cohomology of Line Bundles: A Computational Algorithm*, arXiv:1003.5217.

[28] B. C. Allanach, *SOFTSUSY: a program for calculating supersymmetric spectra*, arXiv:hep-ph/0104145.