

String-Theoretic and QCD-Inspired Structure in Swirl-String Theory (SST)

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Abstract

We present *Swirl String Theory* (SST), a novel hydrodynamic effective field theory providing a unified framework for modeling quantum particles and gauge interactions as knotted vortex filaments within a universal incompressible swirl condensate. SST establishes field-level correspondences with both string theory and quantum chromodynamics (QCD) by identifying a set of precise structural analogies: the fundamental string action and non-Abelian gauge fields are mirrored by a 2-form vorticity flux field $B_{\mu\nu}$ and a swirl connection W_μ , respectively. Matter fields arise as topologically stable knots with quantized circulation and twist, while gauge interactions emerge from the fluid's internal orientation dynamics. Glueballs, mesons, and baryons correspond to closed or linked vortex configurations, offering a tangible interpretation of QCD flux tubes and confinement. Crucially, SST introduces a quantization principle based on the golden ratio (ϕ), yielding a discrete spectrum of particle masses via a topological mass functional calibrated on a small number of known particles. The model replicates key Standard Model features, including the $SU(3) \times SU(2) \times U(1)$ gauge group, correct hypercharge assignments, and the weak mixing angle. By embedding string-theoretic and gauge-theoretic concepts in a vortex-based fluid substrate, SST offers a promising topological reformulation of fundamental physics, suggesting that particle spectra and interactions may arise from geometric constraints and quantized flow in a physical vacuum medium.

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Field-Level Lagrangian Correspondences

String Worldsheet Actions vs. Swirl-String Action

In conventional string theory, a one-dimensional string propagating through spacetime is described by the Nambu–Goto action or its equivalent Polyakov form. The Nambu–Goto action is proportional to the invariant area of the string’s worldsheet,

$$S_{\text{NG}} = -T \int d^2\sigma \sqrt{-\gamma},$$

where T is the string tension and γ_{ab} is the induced metric on the worldsheet. The Polyakov action introduces an auxiliary worldsheet metric h_{ab} , yielding a classically equivalent formulation that is more convenient for quantization. These actions govern the embedding $X^\mu(\sigma^a)$ of the string in target space, leading to equations of motion that include surface tension (minimizing area) and couplings to background fields (e.g., a 2-form $B_{\mu\nu}$ field in superstring theory). Notably, a fundamental string can couple to a Kalb–Ramond 2-form field via a term

$$\int_\Sigma B_{\mu\nu} dX^\mu \wedge dX^\nu,$$

endowing strings with a topological charge (in string theory, this coupling yields the B -field charge carried by NS-NS strings).

SST implements an effective field theory in $3 + 1$ dimensions whose action bears direct correspondence with these string concepts. In SST, all matter and force quanta are modeled as closed vortex filaments (swirl strings) in a universal incompressible swirl condensate. The swirl-string action emerges from a hydrodynamic Lagrangian built from fluid dynamical fields and topological terms. Instead of treating a string as a fundamental object in a fixed background, SST’s action describes the dynamics of the swirl condensate and the embedded knotted strings within it. Crucially, SST introduces a 2-form field $B_{\mu\nu}(x)$ analogous to the Kalb–Ramond field: the field strength $H_{\mu\nu\rho} = \partial_{[\mu} B_{\nu\rho]}$ represents the coherent vorticity flux of the medium. Swirl strings couple “electrically” to $B_{\mu\nu}$ via a worldsheet term $\int_\Sigma B$ exactly as fundamental strings couple to the Kalb–Ramond field. The flux of $H = dB$ through a closed surface measures the topological charge of a knotted string, paralleling how string winding or NS-NS charge is measured in string theory. In this way, the field content of SST mimics string theory at the level of differential forms: $B_{\mu\nu}$ in SST provides a common language to describe vorticity flux and string charge, much as the B -field does in bosonic string theory.

The dynamical degrees of freedom also align in a one-to-one structural sense. SST’s condensate features a preferred foliation time and a unit timelike 4-vector

$$u^\mu = \frac{\partial^\mu T}{\sqrt{-\partial_\alpha T \partial^\alpha T}}$$

defining the “ether” rest frame. On spatial slices orthogonal to u^μ , one introduces a triad of swirl director fields $e_a^\mu(x)$ capturing local vorticity orientations. The *non-integrability* of this director frame gives rise to an emergent gauge connection $W_\mu = W_\mu^a T_a$, mathematically defined as a Cartan connection $W_\mu = (\partial_\mu O)O^{-1}$ where $O(x) \in SO(3)$ relates the local triad to a reference frame. This swirl connection W_μ^a plays a role analogous to non-Abelian gauge fields and indeed satisfies a field strength (curvature)

$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + g_{\text{sw}}[W_\mu, W_\nu].$$

The SST action includes kinetic terms for these emergent fields that mirror Yang–Mills theory: under coarse-graining, the leading effective Lagrangian contains a term of the form

$$\mathcal{L}_{\text{eff}} \supset -\frac{\kappa_\omega}{4} W_{\mu\nu}^a W^{a\mu\nu} + \frac{\theta}{4} W_{\mu\nu}^a \tilde{W}^{a\mu\nu} + \dots$$

which is precisely a Yang–Mills kinetic term $-\frac{1}{4}F^2$ plus a topological θ -term for the swirl gauge fields. Here $\widetilde{W}^{a\mu\nu}$ is the dual field strength and θ in SST acts as a helicity or knotting angle analogous to the QCD vacuum θ -angle. Thus, at the Lagrangian level we see a direct correspondence: the Polyakov action’s worldsheet degrees of freedom correspond to the hydrodynamic field degrees in SST (with $B_{\mu\nu}$ playing the role of a worldsheet-coupled field), and the QCD Yang–Mills action’s $-\frac{1}{4}G_{\mu\nu}^a G^{a\mu\nu}$ term finds an echo in the coarse-grained swirl connection’s $-\frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu}$ term. SST’s *single* all-encompassing EFT thus yields both the string-like B -field dynamics and the gauge-field dynamics within one framework.

It is worth noting that SST’s substrate constants and units are chosen to recover familiar scales. For example, SST defines an effective fluid density ρ_F and a swirl energy density

$$\rho_E = \frac{1}{2} \rho_F \|\mathbf{v}_O\|^2,$$

with corresponding mass density $\rho_M = \rho_E/c^2$.

$$\Gamma = \oint \mathbf{v}_{\cdot d\ell=n\kappa} \quad (n \in \mathbb{Z}),$$

reminiscent of how h (Planck’s constant) quantizes action in quantum theory.

QCD Gauge Sector and SST’s Gauge Fields

Quantum chromodynamics is formulated as an $SU(3)$ Yang–Mills gauge theory: the QCD Lagrangian (with no quark masses for simplicity) is

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}G_{\mu\nu}^a G^{a\mu\nu} + \bar{\psi}(i \not{D})\psi + \dots$$

where $G_{\mu\nu}^a$ is the gluon field strength and ψ are quark fields in the fundamental representation. The gluon field A_μ^a mediates interactions via the non-Abelian field strength

$$G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g f^{abc} A_\mu^b A_\nu^c,$$

leading to self-interactions among the gauge fields. Confinement is a key emergent property of this sector: the non-linear self-interactions cause chromo-electric flux to collimate into narrow tubes (QCD flux tubes) between color charges, producing a linearly rising potential that binds quarks together [14]. Indeed, the QCD vacuum can be viewed as a sort of dual superconductor that squeezes field lines into strings or “QCD strings” connecting quark–antiquark pairs [14]. If a flux tube cannot break (in pure Yang–Mills, with no light quarks), its ends must join to form a closed loop—such a closed flux tube is interpreted as a glueball, a particle-like excitation made of pure gauge field energy. In lattice simulations and models, glueballs appear as quantized excitations of closed flux tubes, analogous to closed strings in bosonic string theory [15]. In fact, it has been suggested that glueballs can be understood as closed QCD strings (flux tubes) possibly with knots or twists, whose stability is ensured by topological twists much like a knotted vortex cannot shrink without obstruction [15]. This perspective makes a striking conceptual bridge: the “strings” of QCD flux tubes and the fundamental strings of string theory converge to a similar picture, wherein hadrons correspond to vibrating (or knotted) strings of field flux.

SST embraces this convergence by describing the gauge sector as an emergent property of the fluid’s internal orientational order. As outlined above, the swirl director field $O(x) \in SO(3)$ yields an $SO(3)$ gauge field W_μ . By introducing multiple director fields (one for each internal degree akin to “flavor” of circulation), SST expands the gauge symmetry: for example, with three independent director triads $O^{(a)}(x)$ (with a common global frame factored out), the effective gauge algebra closes into $su(3) \oplus su(2) \oplus u(1)$, the Standard Model gauge structure.

This remarkable result means that the $SU(3)_c$ color gauge field of QCD has an analogue in SST as one part of the multi-director symmetry: the non-Abelian swirl connection W_μ^a decomposes into subalgebras that correspond to color $SU(3)$, weak isospin $SU(2)$, and hypercharge $U(1)$. In other words, what is a fundamental gauge symmetry in QCD is, in SST, a derived symmetry arising from topological coarse-graining of a tangled fluid. The *fidelity* of this correspondence is evidenced by how SST’s gauge sector reproduces known features: the Pontryagin term $\text{tr}(W_{\mu\nu}\tilde{W}^{\mu\nu})$ is quantized and associated with helicity knots (paralleling topological charge in QCD like instanton number), and the coupling of gauge fields to matter is through a covariant derivative $D_\mu\Psi_K = (\nabla_\mu + ig_{\text{sw}}W_\mu^a T^a)\Psi_K$ exactly analogous to minimal coupling in the Standard Model. Here Ψ_K is a field representing a knotted excitation (such as a quark or lepton knot) that transforms under the emergent gauge group representation appropriate to that particle.

From a comparative field-theoretic perspective, we can line up the concepts directly:

- *QCD color field $A_\mu^a \longleftrightarrow \text{Swirl connection } W_\mu^a$* , with $SO(3)$ (or its extensions) playing the role of the gauge group and generating $SU(3)$ upon extension. Just as gluons carry color charge and self-interact, the W_μ field in SST carries swirl topological charge and has self-interaction terms (through the $[W_\mu, W_\nu]$ commutator). The Yang–Mills form of dynamics is common to both.
- *QCD flux tube (confining string) \longleftrightarrow Swirl knotted/tubular flow*. In QCD, the chromo-electric field is squeezed into a flux tube between quarks [14]. In SST, a pair of knotted vortices (quarks) is connected by a link of vorticity flux—essentially a segment of shared vortex flux that behaves like a flux tube binding the two knots. The SST description of a gluon is indeed a “flux-tube–like link excitation” connecting quark knots. This mirrors the idea that the gluon field between quarks is a stretched string; SST makes it a literal tiny vortex link holding the particles together.
- *Glueball (closed color flux loop) \longleftrightarrow Unknotted closed swirl string*. A pure glueball in QCD can be seen as a closed loop of color flux with no quark endpoints. In SST, the simplest closed vortex ring (unknot) with appropriate twist or excitation can serve as a *stand-alone particle state*, analogous to a glueball (though in SST’s particle mapping this state often corresponds to the photon or Higgs depending on twist, as discussed later). Both pictures involve a closed string of field energy. Moreover, SST’s fluid supports stable *knotted* loops beyond the trivial ring, which could correspond to exotic glueball states that are, in QCD language, flux tubes tied into a knot. Mainstream Yang–Mills analysis has indeed entertained that glueballs might correspond to stable knotted flux tubes carrying topological quantum numbers [15]. SST provides a concrete realization of this idea: the stability of a knot in a fluid (prevented from decaying by topological conservation) models how a glueball might be stabilized by a quantized twist or knot in the color flux.

In summary, the QCD gauge sector finds an effective mirror in SST’s swirl gauge sector. The correspondence goes so far that many Standard Model parameters can be derived or identified in SST. In particular, one can derive a hypercharge assignment for each knot such that the emergent charge values match the Standard Model assignments by construction. The framework also yields an electroweak mixing angle θ_W from first principles, with a calculated $\sin^2\theta_W \approx 0.231$, in excellent agreement with the empirical value. This suggests that the SST mapping is not merely qualitative but also quantitative in important cases, providing a one-to-one translation of gauge field concepts: gauge bosons, charges, and flux tubes can be reinterpreted as collective modes, topological invariants, and linking numbers in the swirl condensate.

Topological Excitations and Mass Generation

String Excitations, Mode Numbers, and SST Solitons

In string theory, different particles correspond to different excitation modes of a fundamental string. A vibrating string has harmonics; for example, a closed bosonic string’s lowest modes include a graviton, a Kalb–Ramond B -field, and a dilaton (all massless in the 26D bosonic string), while higher modes are massive with squared mass $M^2 \sim \frac{4}{\alpha'}(N-1)$ (for closed strings), where N is the level number and α' is the inverse string tension. In superstring theories (10D), after compactification, the excitations yield the particle spectrum of the lower-dimensional theory—often including the Standard Model fields if the compactification is chosen appropriately. Winding numbers (how many times a string wraps a compact dimension) and momentum modes in compact dimensions further enrich the spectrum, giving discrete quantum numbers that contribute to a particle’s mass or charge. For instance, in heterotic string models, one may get families of quarks and leptons from different string oscillator states or windings, with charge assignments dictated by the string’s symmetry structure (like the $E_8 \times E_8$ lattice quantum numbers).

SST translates these ideas into its topological framework. Closed swirl strings have quantized topological invariants (quantum numbers) that determine their physical properties. Instead of a Regge trajectory of vibrating strings, SST’s “trajectory” is a discrete set of allowed knot types and excitation levels. Each stable knot or linked combination corresponds to a particle or resonance. The simplest invariant is the circulation quantum number n , analogous to the string mode number N : the circulation $\Gamma = n\Gamma_0$ imposes that each swirl string carries an integer n of circulation units (like a multiple winding of vorticity), where $\Gamma_0 \equiv 2\pi r_c \|\mathbf{v}\|$ is the canonical circulation quantum. However, just n alone does not distinguish particle species; the *knot topology* does. SST identifies particle states with specific knot types—essentially classifying the “vibrational mode” by the knot’s topology (torus knot vs. hyperbolic knot, etc.) rather than a simple harmonic oscillator number. For example, the electron is associated with the trefoil knot 3_1 (a $(2, 3)$ torus knot). This trefoil can be seen as the SST analogue of a fundamental string’s first excited state in a certain sector—it has the minimal nontrivial knot topology (three crossings) which endows it with the right mix of quantum numbers (spin- $\frac{1}{2}$, charge, etc. as will be mapped below). A muon or tau might correspond to a higher-energy excitation of the same trefoil knot (e.g., an excited vibrational mode on the knot or a higher winding of the fluid around the same knot), or possibly a more complex knot of the same family, reflecting their greater mass. Similarly, quarks are mapped to more complex knots (figure-eight-like or other hyperbolic knots with higher crossing numbers).

The mass of a string state in conventional theory comes from two sources: vibrational energy (proportional to mode number) and winding energy (proportional to string length around compact cycles). In SST, mass arises from the soliton energy of the knotted vortex—a purely topological/geometric quantity. SST postulates a calibrated mass functional $M[K]$ for a knotted string of type K , which depends on invariants like the knot’s length, twist, writhe, and self-linking numbers. In leading approximation, this mass functional takes a form consistent with classic vortex energy: for a thin vortex filament in a fluid, the energy per unit length can be estimated and integrated over the closed loop. SST refines this by including knot-specific factors (like a contribution scaling with the knot’s hyperbolic volume or Jones polynomial in some proposals) and a universal constant. Indeed, the Lagrangian paper reports that by fixing a single overall scale and a couple of calibration factors using three benchmark masses (electron e^- , proton p , neutron n), the model predicted all other observed fermion masses within a reasonable error. This is a remarkable claim: it suggests that the complicated pattern of quark and lepton masses ordinarily attributed to arbitrary Yukawa couplings in the Standard Model might emerge from a simple topological rule in SST. The physical insight is that a more topologically complex knot (with larger self-linking or requiring more twists to close) will have a higher tension energy and thus higher mass—much as higher string oscillation modes have more energy. For

example, a second-generation particle could be the same knot type but with one extra twist (a *second harmonic* of the knot’s “vibrational mode”), raising its energy. Alternatively, it could be a different knot with the next level of complexity. The Golden-layer quantization discussed later provides a specific scaling law (involving the golden ratio ϕ) that SST uses to quantize these energy levels in a geometric progression.

An explicit correspondence can be made between string winding/mode numbers and SST knot invariants. A torus knot is characterized by two integers (p, q) indicating how many times it winds around the two cycles of a torus. These could be viewed as analogous to a closed string’s winding numbers around two compact directions of a theoretical torus; in SST, the (p, q) of a torus knot like 3_1 (trefoil) or 5_1 define the “mode” of wrapping in physical space. In fact, the taxonomy in SST identifies torus knots with leptons (which do not participate in color interactions). Torus knots have a single component and can be seen as the simplest closed loops that are not unknotted, characterized by their winding pair (p, q) . We might say, in a poetic sense, the electron’s string has “mode numbers” $p = 3, q = 2$ in SST’s topological space, whereas in string theory the electron might come from a mode on an open string ending on a D-brane or a winding on a compactified dimension depending on the model. The vibrational excitations of an SST knot (small oscillations of the filament, or traveling waves along it) correspond to internal excitations like phonons on the vortex, which SST associates with excitation of internal degrees (possibly leading to higher spin states or resonances). For instance, a photon in SST is literally described as a propagating torsional wave on an unknotted vortex ring—the “R-phase” (wave-like) excitation of the vortex, which maps onto the quantum of the electromagnetic field. This is analogous to saying a photon in quantum field theory is an excitation of the electromagnetic field, but here it’s also an excitation of a topological defect (unknotted string).

In summary, string theory’s tower of particle excitations is translated in SST to a spectrum of knotted and linked solitons. The correspondences include: vibrational mode number \leftrightarrow knot crossing number or twist number; string winding \leftrightarrow number of linked loop components (for multi-component links, e.g., three linked loops for a baryon, analogous to three strings in a baryonic vertex); level spacing \leftrightarrow quantized energy layers (Golden-layer, see below); zero-point energy or intercept a in string Regge formula \leftrightarrow a calibration offset in the mass functional (SST’s calibrations ensure, for example, that the electron knot has the observed mass as the base state). Both frameworks use one dimensionful parameter to set the overall mass scale: the string tension α' in string theory, and the circulation quantum Γ_0 (along with ρ_{core} , the core density) in SST. This is why SST can claim to achieve what string theory often aims for: calculating particle masses in principle from a single fundamental scale. In SST’s case, it yields a concrete formula and specific values that match many known masses, something mainstream string models usually do not do without many free parameters.

QCD Flux Tubes and Glueballs vs. Swirl Knots and Soliton Energies

The non-perturbative spectrum of QCD is dominated by bound states: mesons, baryons, and glueballs. In the flux-tube picture of QCD, mesons are a quark and antiquark connected by a tube of flux, baryons are three quarks connected by a Y-shaped flux junction or a trio of pairwise flux tubes, and glueballs are closed flux rings. These flux tubes have tension (approximately $T_{\text{QCD}} \approx (0.9 \text{ GeV})^2$ in physical units), and their quantized vibrations give rise to excited hadron spectra (the Regge trajectories of mesons can be modeled by rotating strings). When two flux tubes meet, they can reconnect or break if enough energy is available to create quark–antiquark pairs, analogous to string splitting. The linearly confining potential is essentially the energy stored in an unbroken flux tube growing with length until it is energetically favorable to break. Glueballs, being closed loops, have no ends to pull apart, and thus represent stable or metastable knots of the chromo-electric field.

SST provides a strikingly parallel description using its hydrodynamic topological strings. Mesons in QCD (quark–antiquark pairs with a flux tube) correspond in SST to a linked pair

of vortex loops: one loop representing a quark knot and the other an antiquark knot (which in SST would be the mirror-image knot, carrying opposite “swirl charge”). A link of two such loops—essentially a Hopf link or a more complicated two-component link—is the SST meson state. The flux tube between quark and antiquark is mirrored by the geometric linking of the two loops: their vorticity fields are intertwined, and a portion of their flow is shared in a flux tube-like manner. In fact, SST identifies the gluon as *the mediator of the linkage*: a gluon in SST is described as a small loop of flux linking with a quark loop (carrying color flux between them). A virtual gluon exchange between quark knots can be pictured as one loop hooking onto another, changing the linkage state temporarily. For baryons, which in QCD are three quarks bound by color flux, SST assigns a three-component link (or possibly a single three-fold knotted loop in an alternative picture) to each baryon. The proton, for instance, is not just one knotted loop in SST but rather a *link of three knotted loops*: specifically, the document gives *proton* = $5_2 + 5_2 + 6_1$ *composite*. This notation means the proton is modeled as a bound state of two loops of type 5_2 knot and one loop of type 6_1 knot, all linked together. Each loop represents a quark (two up-quark knots and one down-quark knot, presumably), and the linking of all three ensures an overall color-neutral (trivial total linking) state. The *linking number* or a related invariant in this triple link corresponds to the baryon’s color singlet condition. This vividly translates color confinement: no single quark knot is left unlinked—it is only stable when three are bound in a link (or a quark–antiquark pair in a meson link). The QCD requirement that only color-neutral combinations are physical translates to the SST rule that only closed and fully self-contained link groups are stable (open or unlinked vortices would correspond to an isolated color charge, which cannot persist). Indeed, in a superfluid, an isolated open vortex would extend to a boundary or must form a closed ring; analogously, an isolated quark cannot exist, it must be part of a closed network of flux.

Now consider glueballs: in QCD, a glueball can be visualized as a closed flux tube that may have twists or knots. In SST, an unknotted vortex ring could correspond to the simplest glueball-like state. However, SST’s particle taxonomy tends to identify the *unknot* (a simple loop) with the photon or other gauge bosons when it carries a propagating wave, or with the Higgs if excited radially with no twist. A true glueball analog in SST would be a closed loop that carries no charges (color-neutral, etc.) and is massive. This could be a loop with a twist or a more complex knot that is a closed string without requiring constituent knots. Intriguingly, SST’s framework naturally provides for *knotted loops without constituent point particles*, which are essentially solitary knots of flux—exactly the glueball concept. The stability of such a state in SST is topologically guaranteed if it’s knotted; even an unknotted loop in the fluid, if twisted, could be metastable as a “torus vortex mode”. Mainstream theory has speculated that glueballs might require a twist to be stable¹, and in SST the *chirality or twist of a knotted vortex* can distinguish different states (e.g. a left-hand vs. right-hand twist on the same knot might produce parity doublets, akin to 0^{++} vs. 0^{-+} glueballs differing by a topological twist quantum number). This is consistent with suggestions that the lightest scalar and pseudoscalar glueballs could be such a parity doublet of a twisted flux loop², and SST indeed adopts this viewpoint: matter vs. antimatter are distinguished by swirl chirality (the handedness of the circulation), and a “high-symmetry amphichiral configuration” (achiral knot) can correspond to a scalar boson like the Higgs. By extension, a purely gluonic SST state might be an achiral loop (scalar glueball) or a chiral loop (pseudoscalar glueball).

The mass generation for these hadronic-like states in SST follows from the same soliton mass functional described earlier. Notably, SST’s mass functional yields a mass scale for the proton (knotted triple link) that matches observed baryon masses when calibrated. This achievement can be seen as an analog of QCD’s mass gap and constituent quark mass generation: QCD yields a proton mass ~ 938 MeV from strong dynamics (even though current quark masses are

¹<https://inspirehep.net/literature/635469>

²<https://arxiv.org/pdf/hep-ph/0308240>

much lighter), whereas SST yields the proton mass from fluid dynamics and topology (with no elementary mass input). The difference is that SST’s approach is deterministic and algebraic in principle: the proton mass comes from the energy of three linked vortex rings, calculable from first principles given the calibrated constants and the knot/link configuration. In QCD one usually cannot derive the proton mass except via lattice computations, so having a closed-form expression in SST is a significant mapping of concept (though one must remember SST is an EFT, so it effectively encodes QCD’s results in a new language).

Glueball spectra and energy laws also find a correspondence. In QCD, the glueball spectrum (as estimated by lattice) has characteristic gaps and approximate degeneracies (e.g. the 0^{++} and 2^{++} are relatively low, etc.). In models treating the flux tube as a closed string, one obtains an energy formula similar to the Nambu–Goto string’s:

$$E_n \approx \sigma L + \frac{4\pi}{L}(n + \alpha)$$

for a closed loop of length L (with σ the string tension and α a constant related to the Casimir energy). SST’s mass functional for a knot often has a form $E \sim c|\mathcal{I}|^{3/4}$ for certain topological invariants \mathcal{I} (as inspired by Faddeev–Niemi knot soliton energy in Skyrme-like models³). For example, a result cited in knot soliton literature is $E \propto |Q_H|^{3/4}$ where Q_H is the Hopf charge (linking number of field lines)⁴. In SST, a similar relation appears: a vortex loop’s energy grows with something like length¹ times a logarithmic correction, but for knotted loops, additional discrete jumps (the Golden quantization) modulate it. The Golden-layer law in SST essentially says each “layer” of excitation multiplies energy by $\phi^2 \approx 2.618$ (or divides length scale by ϕ). This resonates with the idea of discrete vibrational modes of a flux tube. If one imagines a glueball as a vortex ring that can support standing wave patterns (like a smoke ring oscillating), the allowed modes might be quantized by the boundary conditions around the ring—SST asserts a specific quantization tied to a pentagonal (dodecahedral) symmetry, yielding the golden ratio series. This is beyond anything standard QCD predicts, but it is an SST-specific prediction for how spectra might organize. It maps conceptually to how certain soliton models or string models predict exponential or geometric Regge trajectories rather than linear ones. If experimentally glueball or hadron excitations showed a geometric spacing, that would support SST’s approach; currently, hadron excitations more often follow approximately linear Regge trajectories, so this is an area where SST diverges and makes a novel prediction.

To encapsulate, SST recasts flux tubes and glueballs as tangible knotted/tubular flow structures obeying energy laws akin to string energy formulas. Confinement in QCD—the irrelevance of non-singlet states—is mirrored by the requirement that all SST vortex structures be closed and/or linked into color-neutral combinations (no open-ended vortices allowed). Mass gaps in QCD (no massless gluons in physical spectrum, heavy glueballs) correspond to the finite energy required to create a closed vortex ring in the fluid (which is large compared to massless photon-like excitations). And QCD’s glueball as a closed string concept is literally implemented: one could say SST provides a concrete fluid mechanical model of the old idea that glueballs are “knotted fluxtubes”⁵—with the bonus that in SST those knots are stable solitons in an otherwise continuum theory.

Confinement and Chiral Symmetry Breaking: Translation to SST

Color Confinement vs. Knot Binding in Swirl Strings

Color confinement is the phenomenon that colored objects (quarks and gluons) cannot be isolated; they only exist within color-neutral bound states. In the language of QCD, this is encoded

³<https://arxiv.org/pdf/hep-ph/0308240>

⁴<https://arxiv.org/pdf/hep-ph/0308240>

⁵<https://arxiv.org/pdf/hep-ph/0308240>

by the emergence of an infinite energy cost to separate color charges due to the flux tube formation. Visually, one imagines that if one tries to pull a quark out of a proton, the chromo-electric flux tube stretches and eventually snaps into a new quark–antiquark pair rather than yielding an isolated quark. The classical sign of confinement in gauge theory is that Wilson loop operators exhibit an area law, corresponding to a constant nonzero string tension in the potential.

In SST, confinement is not something to be assumed—it is an automatic consequence of the model’s topological nature. All fundamental excitations in SST are closed vortex loops. There is no analog of an “open” string ending on a quark charge, because the fluid’s vorticity must form closed loops (or extend to infinity, which in a closed universe or effectively unbounded fluid still implies a loop). Thus, an “isolated quark” (which would correspond to a single open string with one end at infinity) is non-existent in SST. Instead, a quark is a closed knotted loop with certain properties (like a trefoil-type or hyperbolic knot) that *must* be combined with other loops to form a stable configuration reflecting overall gauge neutrality. SST’s version of a hadron is literally a linked network of loops—the linkage being the analog of color force bonds. For example, as discussed, a proton is three loops linked together, and a meson would be two loops linked. These linked states are the only stable ones. If one attempted to remove one loop from a linked cluster (analogous to pulling a quark out of a baryon), one would have to break the topological link. But breaking a link in a fluid vortex context requires a reconnection event—a violent process where vortices cut and rejoin. In SST such an event would not produce an unlinked single quark loop unless an antiquark loop (mirror knot) is simultaneously produced to carry away the other end of the link (much as in QCD pulling a quark out produces a quark–antiquark pair from the vacuum). Thus the mechanism of flux tube breaking in QCD (pair creation) corresponds to vortex reconnection events in SST that always result in closed loops on both sides. The *prediction I* of the SST Lagrangian paper is “quantized flux impulses from reconnection events”, which aligns well with the idea that when two knotted vortices exchange partners (reconnect), a burst of radiation (gluon flux or analog of meson emission) is released—very much like how in QCD the breaking of a flux tube would create a meson emission. This not only qualitatively reproduces confinement, but gives a concrete physical picture of it: Confinement = all matter is made of vortex loops that cannot end, only link.

Another facet of confinement is the formation of a vacuum condensate that squeezes fields. SST’s entire construction is built on a “swirl condensate” that has a preferred rest frame and behaves like a superfluid. The QCD vacuum is often described metaphorically as a dual superconductor (the dual Meissner effect squeezes flux). SST literally has an incompressible fluid that might be viewed as a medium causing a Meissner-like effect on flow: vorticity is a form of flux, and stable quantized vortices are akin to Abrikosov vortices in a superconductor. If one tries to create a “free” vortex line, the medium responds by ensuring that vortex line forms a stable closed string (to minimize dissipation and comply with quantization). We can therefore map QCD’s vacuum confinement mechanism onto SST’s Kelvin–Helmholtz topological constraint: Kelvin’s theorem (inviscid flow) implies circulation is conserved, so once a vortex ring is formed, it cannot simply dissipate—it is trapped as a stable object, much like a chromoelectric flux tube is trapped unless it breaks by pair production.

Moreover, confinement in QCD implies the existence of hadrons as a “spectrum” of bound states. SST offers a *periodic table of topological bound states*. Within the SST framework, linked knots form a built-in “periodic table” of matter. Each nucleus, each hadron, each composite can be seen as a specific link. For instance, two linked trefoils might represent a deuteron (two nucleons linked by residual flux), and more complex link networks represent larger nuclei. There is even mention of *Z3 closure and 1+12 isotropic shielding* for composites, which sounds like an SST rule corresponding to how nucleons arrange (perhaps 1 core + 12 surrounding loops—possibly a reference to electrons shielding nucleus, or something like magic numbers). The details aside, the point is no free knots with “color” can exist; they must satisfy closure rules analogous to the requirement that the sum of color charges is zero (or multiples of trivial loops). SST’s

color triplet and charge assignments are tied to link numbers: e.g. a quark knot has $L_K = 1, 2$ in the charge mapping ensuring it comes in three varieties (which we interpret as the three colors). Only by combining three different such states (or a quark–antiquark pair) can one achieve a total $L = 0$ (trivial link) overall, which is the gauge singlet. This is exactly analogous to needing three colors summing to white, or a color–anticolor pair summing to neutral. The mapping is particularly direct here:

- Color charge \leftrightarrow topological linking class (whether a loop is linked or not and how) in SST.
- Color neutrality \leftrightarrow all loops in a composite form a closed link group with linking number cancellation (e.g., linking numbers sum to zero).
- Glue (gluon flux) \leftrightarrow mutual linking of loops (flux tube links).
- Confinement scale Λ_{QCD} \leftrightarrow characteristic vortex thickness or core size r_c , which sets when a loop is large enough to reconnect. SST has a core length r_c built in as the scale below which vortex core energy dominates; one can liken this to the QCD flux tube radius (~ 0.5 fm) that is the scale of confinement phenomenon.

Thus, SST does not just mimic confinement qualitatively; it provides a clear dictionary of confinement in topological terms. We can say: *A single quark corresponds to a single knotted loop with nonzero linking requirement—not a physical state by itself.* Only when that loop is “closed” by linking to others (or to its own mirror image in a meson) do we get a permissible state. In QCD, one would phrase that as the requirement of a hadron state being a color singlet; in SST it is the requirement of topological completeness of the knot network.

Chiral Symmetry Breaking and Golden-Layer Quantization Structure

In the light-quark sector of QCD, if quark masses were zero, the theory would have a global $SU(N_f)_L \times SU(N_f)_R$ chiral symmetry. The QCD vacuum, however, is believed to spontaneously break this symmetry to the vector $SU(N_f)_V$, giving mass to quarks (dynamically, on the order of $\Lambda_{\text{QCD}} \sim 200\text{--}300$ MeV for constituent quarks) and yielding nearly massless Goldstone bosons (pions). Chiral symmetry breaking (ChiSB) is thus responsible for most of the visible mass of matter (since protons and neutrons get mass from this mechanism more than the Higgs mechanism)arxiv.org. It also is manifest in parity doubling patterns and selection rules—e.g., left-handed quarks participate differently in weak interactions than right-handed (though that is an explicit breaking by weak interaction, not spontaneous). In QCD, the presence of a quark condensate $\langle \bar{q}q \rangle \neq 0$ is a signal of ChiSB, and the origin of this condensate is non-perturbative dynamics (instantons, strong coupling, etc., often tied conceptually to flux tube formation or other topological effects).

Translating chiral symmetry and its breaking into SST is subtle because “chirality” in SST can refer to two things: swirl chirality (the handedness of a knotted flow, i.e., whether the knot is left-handed or right-handed in topological terms) and internal chiral symmetry (left- vs right-handed spinors for fermions). SST’s framework inherently violates parity in some sectors: for example, the weak interaction in nature is $V - A$ (maximally parity-violating), and SST must reproduce that. The question is how an originally symmetric fluid model picks out a handedness. This is addressed by including a parity-violating term in the effective action that distinguishes left-handed vs right-handed knot configurations. One concrete realization is to add a kinetic helicity term $P = \mathbf{v} \cdot (\nabla \times \mathbf{v})$ to the Lagrangian, which is odd under mirror transformations. This term $L_{PV} = g_5, r_c, \rho_f, P, J_5$ couples the fluid’s helicity density to a chiral current J_5 on the knot (essentially a measure of the loop’s internal chirality). The effect of such a term is to introduce an energy difference between a left-handed knotted string and a right-handed one, thereby *spontaneously selecting a preferred chirality* if g_5 has a nonzero value. In practice, this

aims to recover the Standard Model pattern: left-handed fermion knots should couple differently (carry $SU(2)$ charge, for instance) than right-handed ones (which are singlets except for $U(1)$). In this approach, integrating out fast swirl modes is expected to yield an effective $V - A$ (vector minus axial) structure at low energy, in which left-handed excitations form doublets and right-handed ones are singlets. This directly maps to the electroweak chiral asymmetry of the Standard Model (left-handed quarks and leptons in $SU(2)_L$ doublets, right-handed in singlets).

But what about chiral symmetry breaking in the strong interaction sense? In SST, there is no fundamental distinction between left- and right-handed fermions as separate fields—each knotted string presumably can exist in either a left- or right-chiral form (its mirror image). If the fluid had exact symmetry between mirror knots, one would expect degenerate pairs of states: for every left-handed knot solution, the mirrored right-handed knot would be an equally valid solution with the same energy. Spontaneous breaking of this symmetry would mean the vacuum (the swirl condensate plus the knotted structures) prefers one handedness. It's conceivable that the introduction of L_{PV} (even if small) could cause a small splitting that makes, say, right-handed knots unstable or different in mass, thus breaking the mirror symmetry. SST taxonomically classifies quarks as chiral hyperbolic knots, indicating that the knot itself has a handedness that matters for its identity. A proton being written as $5_2 + 5_2 + 6_1$ without further specification might implicitly mean a specific chirality assignment to those knots such that they bind. The fact that they list two 5_2 (perhaps both left-chiral or one of each?) and one 6_1 could reflect how u and d quark knots differ by chirality or some invariant. This level of detail is not yet fully fleshed out in the canon, which is why it's part of the open issues.

Now, the phrase “Golden-layer quantization structure” comes into play. In SST, a “Golden Layer” is defined as a special value of a rapidity parameter ξ_g related to the golden ratio $\phi = (1 + \sqrt{5})/2$. The Golden Layer is essentially a specific scale or “quantization anchor” in the continuum of possible swirl configurations, which induces discrete scale invariance: radial (scaling) modes come in layers separated by factors of $\phi^2 \approx 2.618$ in energy. This built-in structure leads to what they call a pentagonal resonance pattern. While at first this may seem unrelated to chiral symmetry, it actually provides a mechanism for generating mass ratios and mass gaps in a natural way. In QCD, chiral symmetry breaking gives us a mass gap (no massless chiral partners, pions are pseudo-Goldstone, nucleons are heavy etc.). In SST, Golden-layer quantization gives a mass gap between a base state and the next layer of excitations by a factor ϕ^2 . For example, suppose the electron is at layer $k = 0$, then a hypothetical excited electron (which might be akin to a muon) could be at layer $k = 1$ and have mass $\approx \phi^2 m_e$ times some model-dependent factor. (In reality $\phi^2 \approx 2.618$, whereas $m_\mu/m_e \approx 206.7$, so clearly one layer is not enough to jump from e to μ ; possibly multiple layers or other effects are involved for leptons, or leptons might not follow the same rule if other interactions are at play. The proton to its resonances might be more in line; hard to say without data.) However, SST did claim to predict masses of higher generation particles without extra parameters. It's likely the golden quantization was key to that prediction: using one generation's value to get the next.

Chiral symmetry breaking in QCD also implies the existence of nearly degenerate parity doublets at high excitations or in glueballs (some models predict that once chiral symmetry is restored, states come in chiral pairs). In SST, the presence of Golden layering in combination with a subtle parity selection could mean that for each knotted state at layer k , there might be an almost degenerate partner of opposite chirality if parity were a symmetry—but since L_{PV} breaks it, those partners could split. The Faddeev-Niemi scenario in the glueball context predicted a nearly degenerate 0^{++} and 0^{-+} glueball pair around 1.4–1.5 GeV arXiv.org. SST might interpret this as the same base knotted flux loop with left vs right twist giving two states, whose small mass difference (90 MeV in that case) could be due to a small parity-violating term or interactionarXiv.org. That is exactly the type of effect L_{PV} could cause: a slight breaking of degeneracy between mirror knots.

From a more general perspective, the chiral condensate in QCD can be thought of as a

topological structure in the QCD vacuum (some argue instantons or related objects cause it). In SST, since all masses come from topology, one could say SST does not have a chiral condensate per se, but it has a swirl condensate that pervades space and from which particle mass and structure emerge. The “effective quark mass” that arises in QCD due to the condensate might be analogous to the effective inertia a knotted vortex has due to dragging the surrounding fluid. In a superfluid, a vortex line can acquire a normal mass (due to the kinetic energy of fluid motion around it). Similarly, a knotted vortex in SST has a rest mass due to the quantized circulation and the structure of flow (in a sense, the *fluid* plays the role of the condensate that in QCD breaks chiral symmetry). So one might map:

- Quark condensate $\langle \bar{q}q \rangle \neq 0 \leftrightarrow$ swirl condensate with permanent vorticity structure. The swirl condensate itself is the medium giving things mass; it’s a bit like saying the QCD vacuum structure is replaced by a tangible fluid with its own density ρ_f and swirl energy ρ_E that can be converted into particle rest mass.
- Pions as Goldstone bosons \leftrightarrow lowest excitation of a linked knot system with small restoring force. Possibly, SST might model pions as something like a linked loop–anti-loop of minimal knot (like two very small rings linked once, which could be easily excited). While pions are not explicitly mapped in the current formulation, an amphichiral high-symmetry loop (maybe an unknot with an internal mode) could be the Higgs, and by analogy maybe an amphichiral low-tension link might be like a pion (nearly chiral symmetric object).

Finally, the Golden Ratio quantization might have a deeper meaning in relation to discrete symmetry breaking. The number ϕ is associated with 5-fold symmetry (the icosahedral group, which appears in some grand unified or composite models, and here appears via dodecahedral patterns in SST). A pentagonal symmetry is parity-violating (a regular dodecahedron is not invariant under mirror reflection without rotation). SST’s pentagonal resonance hypothesis (in electron-photon coupling) suggests the structure of coupling selects a handedness via the geometry of 5-fold symmetry. If nature at some level had a hidden icosahedral order, that could spontaneously break mirror symmetry. While speculative, one can imagine that SST’s golden quantization is tied to a *specific symmetry of the condensate* such that the formation of stable knots inherently breaks some continuous symmetry (like scale invariance or parity) down to a discrete subgroup. This is analogous to how the QCD vacuum breaks $SU(2)_L \times SU(2)_R$ to isospin $SU(2)_V$. SST might break a continuous symmetry (perhaps an arbitrary continuous relabeling of knots?) down to a discrete spectrum. The “bridge between continuous swirl dynamics and discrete spectroscopic structure” mentioned for the Golden Layer is precisely describing a symmetry breaking: continuous scale symmetry (or continuum of allowed radii) breaks to a discrete scale invariance at ϕ intervals. This is a kind of discrete symmetry breaking not usually seen in QCD, but conceptually related: the continuous chiral symmetry in QCD breaks to a discrete left-right distinction (with pions as pseudogoldstones).

In summary, chiral symmetry breaking in QCD finds its SST counterpart in two effects:

1. Intrinsic parity (chirality) selection—SST must introduce terms to prefer one handedness of knots, echoing how weak interactions in nature are chiral and how the QCD vacuum may not treat left vs right the same (through small QCD θ or quark mass differences). This is an open problem being addressed by adding helicity-based terms. Once included, SST can mimic the $V - A$ structure of weak currents and possibly yield parity splitting in hadron spectra, similar to QCD’s hadrons vs mirror hadrons difference.
2. Mass generation for fermions via the condensate—Instead of a $\bar{q}q$ condensate giving quarks an effective mass, the swirl medium’s *topological inertia* gives knotted strings a mass. The pattern of these masses (and their ratios) is governed by the Golden-layer quantization, which acts analogously to how the presence of a condensate sets a scale (the constituent

quark mass ~ 300 MeV is like the first layer for quarks). SST’s golden rule yields a whole ladder of scales, which could be seen as an analogue to how successive excitations in QCD appear (though QCD’s spectrum doesn’t obviously follow a simple geometric series, SST posits it might if viewed correctly).

One might explicitly map the pion decay constant f_π (order 93 MeV) to some property of the swirl medium (perhaps related to a circulation quantum or core size), and the chiral condensate value to the core density ρ_{core} . Interestingly, SST calibrations have $\rho_{\text{core}}c^2$ as an energy density that might link to symmetry breaking scales. Without overreaching, we can at least assert that *both QCD and SST involve a symmetry of the equations that the ground state does not respect fully*. In QCD, it’s chiral $SU(2)_L \times SU(2)_R$; in SST, one could say the equations might be mirror-symmetric in an ideal limit, but the chosen condensate (and possibly the inclusion of L_{PV}) means the realized state is not mirror-symmetric. The explicit identification of this mapping is ongoing research (Open Issue B in SST is exactly this).

To conclude this section, QCD’s confinement and chiral symmetry breaking translate to SST’s knot binding and golden-layer structure in the following way:

- Confinement \equiv all physical entities are closed or linked swirl strings (no open ends), hence only composite color-neutral knots are observed. The “string tension” is mirrored by swirl filament energy, ensuring separated knots prefer to stay linked (confining potential).
- Chiral symmetry breaking \equiv the symmetric state of equal left/right knot configurations is abandoned in favor of a topology (or term in the Lagrangian) that distinguishes chirality, giving rise to mass differences and selecting one handedness in interactions. The resulting spectrum has discrete energy levels (golden layers) instead of continuous scaling symmetry, akin to how QCD’s vacuum selects certain mass scales (pion decay constant, constituent mass, etc.) instead of being scale-invariant. Open questions remain in solidifying this analogy, but the structural correspondence is clear: the phenomena that give hadrons their mass and structure in QCD are reinterpreted in SST as consequences of fluid topology and quantization, with the Golden Ratio intriguingly appearing where QCD uses more prosaic constants.

Gauge Groups and Particle Content Mapping

Emergent Standard Model Gauge Symmetry in SST

Perhaps the central structural result in SST is the emergence of the full $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetry from the fluid dynamics. In conventional string theory, the Standard Model gauge group arises from the string’s internal symmetry or compactification: for instance, in the heterotic $E_8 \times E_8$ string, one of the E_8 groups can break down to $SU(3) \times SU(2) \times U(1)$ (with extra factors) via the Wilson lines in compact dimensions. In Type II string theories, intersecting D-branes can yield the Standard Model gauge group at their intersections. All these require introducing extra dimensions or brane configurations by hand to get the desired group. In contrast, SST claims to get the Standard Model gauge group naturally from three-dimensional flow patterns.

The mechanism, as described earlier, involves having three independent orientational fields (directors) in the condensate. We can denote them as $\mathbf{n}^{(1)}(x)$, $\mathbf{n}^{(2)}(x)$, $\mathbf{n}^{(3)}(x)$, each an $SO(3)$ frame orientation (like three “species” of vortices or three internal degrees of freedom of vorticity). If we had just one such director, the gauge symmetry is $SO(3)$ (equivalent to $SU(2)$) as the local frame rotations. With three, naïvely one might get $SO(3)^3$, but since an overall rotation of all three directors simultaneously is redundant (it does not change relative orientations), factoring that out yields something isomorphic to $SO(3)_1 \times SO(3)_2 \times SO(3)_3 / SO(3)_{\text{diag}}$. In terms of

Lie algebras, $so(3) \sim su(2)$, and if done carefully, the combination produces a direct sum $su(3) \oplus su(2) \oplus u(1)$. Essentially, the structure constants of these combined director fields match those of the Standard Model. The appearance of $U(1)$ reflects that one combination of rotations (the overall phase among the three directors) remains as an Abelian symmetry (analogue of hypercharge), while the relative rotations give non-Abelian $SU(3)$ and $SU(2)$. This is a deep identification: the gauge charges of particles correspond to how a given knotted string “twists” or “orients” within each of the three director fields.

Concretely, SST defines a mapping from knot topology to gauge quantum numbers. Within the SST construction, one can define a function $Y(K)$ (hypercharge of knot K) and $t(K)$ (isospin of knot) such that known particle knots yield correct Y, T_3 values. For example, the electron knot (3_1) is a torus knot which the theory might assign $Y = -1$ (hypercharge) and isospin $T_3 = -\frac{1}{2}$, making it a right-handed singlet or left-handed doublet appropriately. Indeed, SST reports a “hypercharge knot formula” that reproduces the empirical hypercharges. This suggests each knot’s topological numbers (like the sum of its toroidal winding numbers, or maybe its linking with some auxiliary field lines) can be plugged into a formula to get Y . The weak mixing angle came out correctly because the relationship between $U(1)$ and $SU(2)$ couplings in SST’s emergent theory matched the Standard Model values. That implies SST effectively derives $\sin^2 \theta_W = \frac{g'^2}{g^2 + g'^2}$ from geometry, giving 0.231, which matches the observed 0.231 – a highly nontrivial success. In effect, SST predicted the ratio of the squares of the emergent $U(1)$ and $SU(2)$ coupling strengths (perhaps from the inertia of the $U(1)$ director mode vs the $SU(2)$ mode) to be about 1 : 2.3, precisely as needed.

To each SST particle (knot) state we can now attach three “charges”: one $SU(3)$ color index (if it carries color), one $SU(2)$ isospin index (if it is left-handed lepton/quark), and one hypercharge. These correspond in SST to how the knot is embedded in the multi-director field:

- **Color charge:** The color charge of a quark knot is related to which of the three director fields it twists around. If we imagine the three director frames correspond to something like RGB axes, a quark knot might be one that twists preferentially around one axis in internal $SO(3)$ space, giving it a “color”. The existence of three topologically identical but distinct states for a given knot (like three variants of the same knot distinguished only by an internal orientation) corresponds to the three colors of QCD. SST explicitly notes that by setting a knot’s linking number $L_K = 1, 2$, it ensures it transforms as a triplet under $SU(3)$. The detail likely is: a quark knot K has an invariant (maybe the self-linking number or another) which can take 3 distinct values or states, and those correspond to (r,g,b). Only by linking different ones together can that invariant sum to zero (color neutral).
- **Weak isospin:** The weak isospin ($SU(2)_L$) of a fermion in SST is determined by the knot’s twist chirality. They mention S_K controlling weak representation. Possibly S_K stands for “spin of knot” or a specific twist count. A left-handed particle vs a right-handed particle of the same kind might be the same knot but with opposite twist, and only the left version interacts with the $SU(2)$ swirl gauge field. This would align with how only one chirality sees $SU(2)_L$ in Standard Model.
- **Hypercharge:** The hypercharge is likely related to overall linking with the swirling of all three directors or a $U(1)$ phase associated with twisting each director coherently. The hypercharge formula working out means that for each knot (electron, quark, etc.), if you compute some combination of its topological numbers, you get the Y values like $+\frac{1}{3}$ for quarks, -1 for electron, 0 for neutrino (which might be represented by a particular knot, maybe the trefoil with an additional property making it neutral).

This is a one-to-one mapping of the Standard Model’s gauge quantum numbers to SST topological taxonomy:

- **Leptons:** (torus knots) carry no color (they might correspond to excitations in only one of the director fields or a symmetric combination that yields color singlet by default), and come in $SU(2)_L$ doublets (e.g. electron and neutrino as two states of one knot type with different twists or linking to the B -field perhaps) and singlets (right-handed electron knot maybe a slightly different topology or mode).
- **Quarks:** (hyperbolic knots) carry color (each quark knot type can manifest in three color ways) and come in weak doublets (up-type and down-type knots might be distinct by an internal twist or sub-knot structure, e.g. the proton's constituents included two of 5_2 and one 6_1 , which might hint that up-quark = 5_2 knot, down-quark = 6_1 knot, which are different but possibly related by a twist addition making one slightly different topology but still in the same family, explaining their differing charges and masses).
- **Gauge bosons:** of the Standard Model are realized as collective modes of the condensate rather than knotted strings:
 - **Photon γ** in SST is a torsional wave on an unknotted loop (the trivial knot). It carries no charge (being an unknot means trivial topology, which corresponds to zero of all charges) and is a propagating oscillation (hence massless).
 - **Gluons g** in SST are not free loops but rather the linking segments themselves. A gluon is essentially represented by a tiny loop of vortex that links a quark knot to another quark knot. There are 8 linearly independent ways these links can behave (corresponding to 8 gluons). Another way to see it: small excitations in the relative orientation of two color-carrying director fields yield gauge bosons with color charge – that's what gluons are in the emergent $SU(3)$.
 - **W^\pm and Z^0 bosons** appear in SST as small loops or twists on loops that are not topologically protected – described as “non-topologically protected loop excitations”. Essentially, a W is like an ephemeral twisted ring that can form and decay (consistent with W 's having a mass and being unstable). They mention a small chiral twist for W^\pm and an achiral excitation for Z^0 . This suggests the W boson corresponds to an unknot with a one-unit twist (so it carries charge, perhaps linking to the hypercharge field in a certain way, and is self-non-protected so it can disappear), and the Z is an unknot with no net twist but an excited state (hence neutral but massive).
 - **Higgs boson H^0** is given an interpretation as a radially excited unknot or a high-symmetry amphichiral configuration. That means if you take the trivial loop (which by itself would be a photon if oscillating or just a vacuum loop if static) and excite it in a uniform, symmetric way (like breathing mode, no handedness), you get a scalar. The Higgs in SST is not fundamental but a composite excitation of the swirl condensate – fitting the idea of some beyond-Standard-Model models where the Higgs is a bound state. SST here provides a unique angle: the Higgs could be literally a spinning or oscillating ring of the fluid, which decays quickly (consistent with the Higgs's short lifetime).

For completeness, neutrinos in SST would be mapped to a knotted structure as well. Perhaps the simplest nontrivial knot after photon (unknot) is none – neutrino might correspond to an almost trivial knot (like an unknot in R-phase, but localized like a T-phase particle, maybe a small, low-twist ring that carries no charge). Or since neutrinos only have weak interaction and no electric charge, maybe they correspond to a trefoil knot of a certain type that yields $Q = 0$, $T_3 = 1/2$, $Y = 0$ for left-handed neutrino. Possibly the same trefoil as electron but with opposite twist giving a neutral state – that would be an elegant mapping (e.g. a left-handed trefoil might behave like a neutrino when not twisted in a way that yields charge).

The Grand Unification roots part of the query likely refers to how these mappings might extend if we seek a unified group larger than $SU(3) \times SU(2) \times U(1)$. In string theory, one often gets $SU(5)$ or $SO(10)$ or E_6 , etc. Does SST have anything analogous? SST's emergent gauge symmetry is minimal in a sense – it got exactly the Standard Model with no obvious larger symmetric group above it (except the fact it originates from something like $SO(3)^3$ factoring out an $SO(3)$, which is not a simple group but a direct product). If one speculates, adding a fourth director field or not factoring out the global rotation might yield a larger group (for example $SO(3)^3$ itself is roughly $SU(2)^3$, which is isomorphic in Lie algebra to $SU(2) \times SU(2) \times SU(2)$; that's not a simple group but if there were symmetry between them perhaps something like an $SO(7)$ could embed them – but $SO(7)$ is too large). $SU(5)$ unification of the Standard Model gauge group typically would require the right representations for matter too. In SST, achieving a GUT might mean finding a topological structure that treats what are separate director fields now as facets of one larger structure. This could correspond to including an additional symmetry in the fluid – say an $SO(4)$ director space or coupling the swirl and clock fields into something larger. The user's mention of “GUT roots” suggests we should comment on this: perhaps acknowledging that SST currently yields the Standard Model gauge group (a big achievement), but a single unified gauge group (like a simple Lie group containing the SM) is not yet realized and remains open. The current emergent symmetry is a direct sum $su(3) \oplus su(2) \oplus u(1)$, not a simple $su(5)$ or $so(10)$ that spontaneously breaks. However, one might interpret the combination of the three director fields as hinting at a larger hidden symmetry of the condensate. For instance, if we consider three director fields, the total configuration space might be something like $SO(3)$ (common) $\times SO(3)/($ common $)$ – not obviously a simple group, but perhaps an $SO(3)$ fibered structure. A truly unified theory in SST might require a more symmetric underlying fluid, such as one with a higher-dimensional order parameter (e.g. an $SO(N)$ internal space with $N > 3$). The canon doesn't mention a GUT group explicitly, implying SST is content with the SM gauge group for now. This can be noted as an open question: could a modified or extended swirl model unify the emergent $SU(3)$, $SU(2)$, $U(1)$ into a single higher symmetry that breaks at lower energy? At the moment, SST's Rosetta Stone covers up to the Standard Model – mapping each piece – but does not yet provide translations for grand-unified gauge bosons (like X , Y bosons of $SU(5)$) or extended symmetries (like $B - L$ gauge fields).

Standard Model Particle Taxonomy as SST Knot Spectrum

Using the above correspondences, we can explicitly list how each type of Standard Model particle is identified with an SST object, forming a one-to-one dictionary:

- **Electron (e^-):** A trefoil knot (3_1) in its T-phase (tightly knotted, localized). It carries one unit of negative charge, which in SST comes from its topological twist (linking with the electromagnetic swirl field). The electron knot is likely left-chiral when part of a doublet and has a right-chiral partner (possibly an untwisted version making it a singlet). The mass arises from the knot's topology (3 crossings, layer $k = 0$ in golden quantization).
- **Neutrino (ν_e):** Possibly an unknotted but twisted loop or a very simple knot (maybe also 3_1 but in an R-phase or different twisting) that carries no electromagnetic charge. It would be part of the same torus knot family as the electron but realized with a different swirl mode. The neutrino interacts only via the swirl W -field, consistent with only weak interaction. SST might treat it as an R-phase of the electron's knot (extended, wave-like, giving it tiny mass or zero if exactly extended).
- **Up quark (u):** A chiral hyperbolic knot, possibly the 5_2 knot (5 crossings). In the mapping $p = 5_2 + 5_2 + 6_1$ for proton, the two identical ones are up quarks (u), the odd one is down (d). Up quark corresponds to 5_2 , carries charge $+2/3$, comes in three color variants, and has higher mass than the electron.

- **Down quark (d):** A chiral hyperbolic knot, presumably the 6_1 knot (6 crossings). It carries charge $-1/3$, is also a color triplet, and forms the other member of the $u-d$ weak isospin doublet. The down knot is slightly heavier than up in reality.
- **Strange quark (s):** $s \leftrightarrow 7_5$ knot (7 crossings). The strange quark is heavier, corresponding to a knot with more crossings. It still has charge $-1/3$ like down, but with greater overall length/tension.
- **Charm quark (c):** 8_{19} knot (8 crossings, knot number 19). Charm has charge $+2/3$ like up, is heavier than strange, and the knot complexity reflects the mass hierarchy.
- **Bottom quark (b):** 8_{20} knot (8 crossings, knot number 20). Bottom has $-1/3$ charge, heavier than charm. Both have 8 crossings, but 8_{20} may have a larger volume or different structure.
- **Top quark (t):** 8_{21} knot (8 crossings, knot number 21). Top has $+2/3$ charge, and 8_{21} may have the largest hyperbolic volume among 8-crossing knots, reflecting top's large mass.
- **Photon (γ):** Not a knot, but an unknotted loop's oscillation. It is a pure wave (R-phase) with no T-phase localization, corresponding to swirl director field oscillations. The photon emerges as a solution of the linearized swirl equations, equivalent to Maxwell's equations.
- **Gluons (g):** Eight modes of the swirl W_μ^a field representing $SU(3)$ color. They are small linked loops connecting color charges. A free gluon cannot exist isolated; in SST, a gluon is a vorticity flux tube segment, always confined within hadrons.
- **W and Z bosons:** Massive electroweak gauge bosons.
 - W^\pm : Short-lived loop excitations with a small chiral twist. W^+ is a closed loop carrying one unit of positive charge, with an internal twist that breaks topological protection (unstable, decays into other knots).
 - Z^0 : Achiral excitation of a loop (untwisted loop excitation, no handedness), not topologically stable, neutral, decays quickly to fermion pairs.
- **Higgs boson (H^0):** An amphichiral (self-mirror) configuration of the unknot in a radial mode (“breathing” mode of the vortex ring with no swirl chirality). It is a scalar (spin 0), unstable, and its role of giving masses to W, Z translates in SST to being a resonance of the fluid that can transfer energy to swirl motions.

With this mapping, SST provides a dictionary for the Standard Model particles: each particle is either a knotted vortex filament (matter fermions), a collective oscillation of the condensate (force bosons), or a combination thereof (Higgs as a bound state).

Open Problems: While the one-to-one assignments are compelling, unresolved details remain. For example, what fixes the generation structure? SST chooses knots by matching masses, but a deeper principle (selection rule or energy minimization) would strengthen the framework. Mixing angles (CKM for quarks, PMNS for neutrinos) are not yet derived by SST. The existence of additional particles (e.g. right-handed neutrinos, axions) would correspond to additional or higher-order knots. This is an open issue and a possible avenue for further predictions.

Nonetheless, this work clearly lays out how each concept and entity in mainstream string theory and QCD corresponds to an element in Swirl–String Theory, mapping field-level actions, topological excitations, confinement, symmetry breaking, gauge groups, and particle content between these frameworks.

Atomic Structure Emergence: From Strings and Flux Tubes to Nested Knot Networks

We turn finally to the question of how composite atomic structures arise when we translate from the language of strings/flux tubes to SST's knotted networks. In traditional atomic physics, an atom (say hydrogen) consists of a nucleus (proton) bound to an electron by electromagnetic fields (photon exchange). The nucleus itself (proton) is three quarks bound by color flux (gluon exchange), and those quarks in turn are excitations of underlying fields (perhaps ultimately vibrating strings if we go to string theory). So there's a hierarchical structure: strings → quarks → nucleons → nuclei → atoms. The user asks how a similar hierarchy is described in SST.

In SST, everything is built from the fundamental building blocks: closed swirl strings (vortex loops). Remarkably, this single construct can span all scales when arranged in networks:

- **Protons and Neutrons (Nucleons):** Each nucleon is a link of three knotted loops. For the proton, linking two 5_2 knots (up quarks) and one 6_1 knot (down quark) yields a tightly bound trio. The linking number between any pair of loops is 1 (each quark loop is linked with the other two once in a Borromean or triangle-like fashion, ensuring overall connectivity). The neutron is similarly three loops (two down-type knots and one up-type knot). This is the hadron level: the strong binding is literally the loops being topologically interlinked. Once linked, they cannot separate unless a reconnection occurs that would involve extremely high energy, corresponding to the stability of nucleons. The residual freedom these loops have (like wriggling relative to each other) might correspond to internal excitation states of baryons (resonances).
- **Nuclei:** Nuclei are bound states of protons and neutrons. In QCD, nuclear force arises from residual color interactions (often modeled by pion exchange). In SST, since nucleons themselves are linked loop composites, a nucleus forms when nucleon loops themselves become linked or interwoven through common flux lines. For instance, a deuteron (hydrogen-2 nucleus of one proton and one neutron) could be realized if one loop from the proton knot and one loop from the neutron knot hook onto each other. Within SST, linked knots describe nuclei and bound states: "Composite knots (baryons, nuclei, atoms) satisfy Z3 closure, 1+12 isotropic shielding, and duality pairing". The "Z3 closure" refers to how three quark loops close in baryons (color neutrality), and "1+12 shielding" might hint at how in atoms one nucleus loop can be surrounded by up to 12 electron loops in shells. Each stable composite becomes a new circulation source, meaning once loops link to form a nucleus, that nucleus as a whole acts like one big source for further linking.

So, a nucleus in SST is literally a link of links – multiple knotted loops interlinked in a network. For example, helium-4 (an alpha particle) has 2 protons and 2 neutrons, total 4 nucleons. In SST, it would be $4 \times 3 = 12$ loops knotted/linked in a single structure. Likely the protons' and neutrons' loops interlink in pairs or clusters to yield a stable configuration. The mention of "periodic table of matter" implies that by systematically linking more loops, you can build up all elements – chemistry and nuclear physics reduce to topological linking rules. SST would categorize each element (or each nucleus) by a link diagram – the ultimate periodic table being a table of link types.

- **Atoms:** Now add electrons. In SST, an electron is a loop (trefoil knot). How does it bind to a nucleus? In the physical world, electrons don't literally tie onto the nucleus; they orbit due to electromagnetic attraction. In SST, electromagnetic attraction is mediated by the swirl flow (Maxwell bridge). The swirl condensate provides a Coulomb-like potential between oppositely "circulating" knots. Specifically, SST introduces a regularized *effective* "Swirl-Coulomb" potential $V_{\text{SST}}(r) = -\Lambda/\sqrt{r^2 + r_c^2}$. Near-field Euler pressure balance

motivates a finite-core regularization, while the far-field $1/r$ tail is modeled as the Green-function response of a local mediator (clock/foliation mode) obeying a Poisson equation on \mathbb{R}^3 . The coefficient Λ is matched to the Coulomb scale (units $J \cdot m$). Using this potential in a Schrödinger equation yields the correct Rydberg series. Physically: an electron loop around a protonic nucleus feels an attraction because the proton loops and electron loop have opposite swirl charge.

However, an electron in an atom is not physically tied to the nucleus by a vortex line. If that were so, the electron would be confined like in a meson, which it's not – it can be ionized continuously. Instead, the binding is through a field, not a permanent topology: the photon field mediates it, and in SST that photon field is the swirl of the medium. The electron can be considered orbiting (or in a standing wave if quantum) around the nucleus, held by the long-range swirl flow field. The swirl Coulomb potential is analogous to Newtonian gravity or Coulomb potential and is chosen to fit hydrogen.

Atomic orbitals in SST are just solutions of the wave equation (Maxwell-like equation for the swirl potential) with that potential, as in standard quantum mechanics. The electron's R-phase (wave aspect) occupies the atomic orbital. The electron's T-phase (particle knot) is delocalized in that orbital as a standing wave – consistent with the dual R-T phase idea. SST might view the atom as a linked state in the sense of fields but not in direct knot linking. The nucleus is a knotted cluster, the electron in an orbital is mostly an extended excitation (R-phase) tied to it by swirl field lines. The electron loop is weakly linked via a large-scale flux looping around the nucleus – not a direct knot link, but the electromagnetic field lines form loops that go from electron to nucleus. SST's B -field (Kalb–Ramond form) couples to the strings, so the electron and nucleus exchange flux quanta as the binding mechanism.

The phrase “isotropic shielding” might refer to how electrons arrange around nucleus to shield charge (as in atomic physics). The mention “1+12 isotropic shielding” could imply a central loop (nucleus) plus up to 12 loops (electrons) arranged isotropically (possibly an icosahedral arrangement).

In any case, an atom in SST is an arrangement where a cluster of nucleus loops at center is surrounded by electron loops whose positions are governed by swirl fields (Maxwell). When electrons occupy stable orbits, that whole structure is a stable composite (just not topologically locked in the same sense as nucleus).

We have essentially traced the chain: string theory's fundamental strings giving atoms translates to SST's knotted fluid strings giving atoms. The levels are:

1. Fundamental strings \rightarrow SST fundamental vortex strings (one-to-one).
2. Strings joining into hadrons (flux tubes connecting endpoints) \rightarrow Vortex loops linking into hadrons (three loops linking for baryons, etc.).
3. Residual strong force flux tubes linking nucleons in nuclei \rightarrow Small vortex links between loops in different nucleons.
4. Electromagnetic attraction binding electrons \rightarrow Swirl flow field binding electrons (photons as swirl waves).
5. Atomic orbitals quantized \rightarrow Swirl Coulomb potential yields quantized orbits.

Each layer of structure formation in conventional physics corresponds to either actual linking of loops (for strong, short-range bound states) or long-range interaction via field (for electromagnetic bound states). Both the short-range links and long-range fields are aspects of the same fluid system in SST.

Finally, consider molecules and beyond: They would form when atoms approach and their electron loops begin to link or merge or form common orbits. Chemical bonds (like covalent bonds) could be seen as two atoms sharing an electron loop between them. In SST, a single electron vortex loop threading around two nuclei loops links them in a loose fashion. If an electron loop can link two nucleus loop clusters at once, that is literally a covalent bond in topological terms.

While molecules are not explicitly asked about, this is a natural extension showing the SST paradigm's unification: everything from quarks to molecules is vortices linking in various configurations.

To summarize atomic structure emergence:

- Electrons, protons, neutrons are all vortex loops or links of loops.
- A proton = three linked loops (quarks). Neutron similar.
- A nucleus = linked network of those loops (all protons/neutrons loops interlink partially).
- An atom = nucleus plus electrons bound by swirl fields; electrons occupy quantized swirl orbits (Maxwellian orbits) around the nucleus.
- The entire atom can be considered a single “knotty” object in a higher sense (the nucleus is a tight knot, the electrons are wide loops around it, not fully knotted through but dynamically linked via field). Each stable atom is then a stable swirl configuration – and the periodic table arises from different numbers of loops arranged (some in nucleus, some as electrons).

This completes the chain of mapping from the smallest scales (strings and glue flux) to the largest (atomic matter).

Open Problems in SST Mapping:

- **Open Issue: Derivation of Emergent Gauge Group** – SST postulates that coarse-graining yields $SU(3) \times SU(2) \times U(1)$, but a rigorous mathematical proof is still pending. Questions remain on uniqueness and possible additional symmetries.
- **Open Issue: Chiral Sector Completion** – SST has identified how to introduce parity-violating terms, but it remains to be shown explicitly that this yields exactly the $V - A$ structure of weak interactions and the correct spectrum of parity violations, without spoiling anomaly cancellation.
- **Open Issue: Quantum Mechanics and Nonlocality** – SST aims to reproduce quantum phenomena with a hidden-variable underlying reality. Whether a deterministic vortex model can exactly replicate quantum statistics is unresolved.
- **Open Issue 4: Incorporation of Gravity** – SST introduces a “swirl gravity” as an emergent effect, but a full relativistic gravity mapping is not fully achieved.
- **Open Issue 5: Grand Unification and Beyond-Standard-Model** – SST yields the Standard Model gauge group but does not yet unify them into a larger simple group. The possibility of an $SU(5)$ or $SO(10)$ -like unification is unexplored.
- **Open Issue 6: Experimental Tests and New Predictions** – SST authors emphasize unique predictions, but these need to be fleshed out and compared with experiment.

- **Open Issue 7: Mathematical Complexity – Solving Knot Dynamics** – The existence and stability of knotted vortex solutions is assumed but not rigorously proven in general. Numerical work is needed to fortify these mappings.

Each of these issues is recognized as part of the open research program of SST. They are labeled here to highlight where the current mapping has missing pieces or uncertainties:

- **Open Issue: Gauge Symmetry Emergence** – Need rigorous proof and understanding of how exactly $SU(3) \times SU(2) \times U(1)$ arises from vortex coarse-graining, and whether any additional symmetry or constraint is required to make it anomaly-free.
- **Open Issue: Chiral Interaction Mechanism** – Need to identify the origin of parity-violating interactions and show how left/right asymmetry and fermion mass generation come out naturally.
- **Open Issue: Quantum Mechanics Reproduction** – Need to demonstrate how quantum nonlocal effects and probabilistic outcomes can emerge from a deterministic swirl model.

By addressing these, SST aims to complete its mapping to all aspects of mainstream physics. Until then, this work serves as a roadmap linking established theories to a novel one, showing impressive concordances and identifying where further work is required to cement the correspondence.

Conclusion: We have presented a comprehensive mapping between mainstream string theory & QCD and Swirl–String Theory. At the field and action level, we identified direct correspondences between the Polyakov/Nambu–Goto string action and SST’s vortex–string Lagrangian, and between QCD’s Yang–Mills fields and SST’s emergent swirl gauge fields. Topologically, we translated string excitations, mode and winding numbers into knot invariants and soliton energy quantization in SST, and related QCD’s flux tubes and glueballs to SST’s knotted flux rings and their mass scaling laws arxiv.org. We showed how QCD confinement is mirrored by the binding of knots (no free ends, only linked composites) and how chiral symmetry breaking finds its analogue in SST’s introduction of a preferred chirality and discrete (golden-ratio) quantization layers. The Standard Model’s gauge group and particle content were explicitly mapped: $SU(3)_c \times SU(2)_L \times U(1)_Y$ arises from multiple swirl director fields, and each particle (quarks, leptons, gauge bosons, Higgs) corresponds to a specific knotted or unknotted excitation in the swirl condensate. Finally, we illustrated how composite structures like nuclei and atoms emerge as linked networks of these knotted strings, with SST naturally reproducing the qualitative behavior of nuclear forces and atomic binding (e.g. Coulomb potential and quantized orbits). Throughout, we identified open issues where the mapping is incomplete or under development: proving the gauge algebra, accounting for parity violation, and recovering quantum statistics from the deterministic model remain challenges. These are flagged as areas for ongoing research. In summary, this work provides a detailed, LaTeX-formulated mapping between the language of string theory and QCD and that of Swirl–String Theory, demonstrating a deep unification in descriptive framework and setting the stage for further validation and refinement of SST’s correspondence with the physical world.

A Dark Matter and Dark Energy in SST (Speculative Outlook)

While the core of Swirl–String Theory focuses on reproducing known particle physics and interactions, it is worthwhile to speculate on how SST might address cosmological puzzles like dark matter and dark energy. These ideas extend beyond the established canon of SST and are presented here as conjectures for future exploration.

Dark Matter

In the SST framework, dark matter could correspond to non-radiating swirl excitations—stable vortex knots or loops that carry gravitational mass but little or no Standard-Model charge. For instance, one might envision a class of sterile swirl strings: vortex loops that do not couple to the emergent gauge fields (and thus are “invisible” to electromagnetic or weak interactions) yet produce gravitational effects. Such objects, perhaps topologically simpler or symmetric configurations of the swirl condensate, would interact primarily through the string-induced gravity of SST. Because the SST medium is inviscid and frictionless, these dark swirl knots could persist over cosmological timescales, behaving as cold dark matter. They would cluster under gravity but, lacking electro-weak interactions, would remain non-luminous and difficult to detect except via their mass. This provides a qualitative SST-based explanation for dark matter: it may be composed of hidden-sector vortex knots—solitonic particles that are part of the swirl condensate’s spectrum but lie outside the usual $SU(3) \times SU(2) \times U(1)$ charge assignments. One speculative example is a twist-neutral loop (an unknotted vortex ring without the internal twist that gives rise to electric charge in SST); such an object would carry mass and spin but no charge, making it a natural dark matter candidate within the theory.

Dark Energy

The SST medium’s properties could also shed light on dark energy. In SST, the physical vacuum is an incompressible condensate characterized by constants like ρ_f and intrinsic swirl pressure/tension. If the swirl condensate possesses a small positive energy density even in its ground state (a “vacuum stress” of the medium), it would act like a cosmological constant. In essence, a pervasive slight vacuum tension in the swirl fluid would give rise to an accelerating expansion of space, as observed in our universe. Because SST’s vacuum is a dynamic medium, its equations might naturally admit a uniform background pressure or an equation-of-state that mimics dark energy on large scales. For example, a tiny imbalance between the swirl pressure and swirl gravitational attraction could produce a repulsive effect at cosmic distances. In SST’s language, this would be a manifestation of the medium’s scalar pressure field behaving effectively like dark energy. This idea is consistent with the presence of an absolute reference frame (the swirl rest frame): such a frame can support a non-zero vacuum energy without violating local Lorentz invariance, much as Einstein–Æther theories demonstrate compatibility with relativity. * (The exact magnitude of any SST vacuum energy would need to be extremely small to match the observed dark energy density—a challenge akin to finetuning in any theory. However, SST offers a conceptual handle: the effective stiffness (K) and density (ρ_f) of the medium set the speed of light $c = \sqrt{K/\rho_f}$, and slight deviations or slow dynamics in these parameters across the cosmos could engender an accelerating expansion.)

In summary, dark matter in SST could be explained by stable, non-interacting knotted vortices that only gravitate, and dark energy might emerge from a small uniform tension of the swirl condensate itself. These scenarios, although speculative, provide testable ideas: for instance, dark swirl knots might produce subtle distortions in large-scale structure or behave differently during cluster collisions than conventional WIMPs, and a swirl-based dark energy would imply the vacuum has measurable fluid-like properties (perhaps accessible indirectly through gravitational wave propagation or vacuum birefringence experiments). Exploring these predictions lies beyond the current SST canon, but they illustrate how the SST framework can be extended to address broader cosmological phenomena.

B Golden-Ratio–Layered Quantization in SST

In this appendix, we explore three rigorous theoretical frameworks that could explain how energy levels or soliton masses in Swirl–String Theory (SST) might be quantized in a geometric series spaced by powers of ϕ^2 (with $\phi = \frac{1+\sqrt{5}}{2} \approx 1.618$). Such golden quantization implies that successive allowed energies E_n scale by a constant factor $\phi^2 \approx 2.618$, i.e. $E_{n+1}/E_n = \phi^2$. Notably, the appearance of the golden ratio in physical spectra is not without precedent: it has been conjectured in neutrino mixing patterns (e.g. a mixing angle related to ϕ) and even observed in spin-chain excitation gaps related to E_8 symmetry [?]. Below we outline three possible first-principles pathways in SST that yield a ϕ^2 layering of energy levels. In each case, we clearly state the additional assumptions (or proposed mechanisms) beyond the current SST formulation and then derive the consequences within that framework.

B.1 Discrete Scale Invariance and Log-Periodic Potentials

Assumption:

We assume that an approximate *scale invariance* in the SST equations (e.g. in a sector of the effective Lagrangian describing self-similar swirl-string excitations) is spontaneously broken down to a *discrete* scaling symmetry. In particular, continuous dilation symmetry $r \rightarrow \lambda r$ (for arbitrary λ) is reduced to invariance only under specific rescalings $r \rightarrow \lambda_0 r$ where $\lambda_0 = \phi^k$ for some fixed k (with $k = 1$ yielding $\lambda_0 = \phi$). In other words, the system admits a discrete scale invariance (DSI) with scaling ratio ϕ (or ϕ^2 , etc.). Under this DSI, if an energy eigenstate or bound-state solution exists at some energy E , then another self-similar state should exist at energy $\phi^2 E$ (since energy often scales as the square of frequencies or inverse length scales) [?]. We posit that $\lambda_0 = \phi$ (so that the fundamental energy scaling is ϕ^2) is built into the swirl-field dynamics.

Proposed Mechanism:

To implement this in SST, one can introduce a *log-periodic modulation* in the effective potential or vacuum structure of the swirl condensate. For example, consider an effective radial potential of the form

$$V_{\text{eff}}(r) = V_0 \left[1 + \epsilon \cos \left(\frac{2\pi}{\ln \phi} \ln \frac{r}{R_0} \right) \right],$$

where R_0 is some characteristic length scale. This $V_{\text{eff}}(r)$ is invariant under $r \rightarrow r\phi$ (since $\ln(r\phi) = \ln r + \ln \phi$ shifts the cosine argument by 2π) and thus embodies a \mathbb{Z} discrete dilation symmetry. As a result, any “layered” bound states in this potential will appear in geometric progression of scale ϕ . More generally, the presence of DSI in the equations of motion leads to log-periodic corrections or oscillations superimposed on otherwise scale-free behaviors [?]. In quantum-mechanical terms, one finds a tower of self-similar solutions: for a given mode with spatial size L (or momentum p), there will be another mode at size L/ϕ (momentum $p\phi$), and so on. Because energy E typically scales inversely with size (and/or as momentum squared), this implies an energy spectrum E_n following a geometric sequence. For instance, a simple one-dimensional scaling argument gives

$$E_{n+1} \approx \phi^2 E_n,$$

realizing the desired ϕ^2 spacing. This mechanism is analogous to known log-periodic phenomena in physics. A famous example is the Efimov effect in quantum three-body systems, where a discrete scaling symmetry leads to a hierarchy of bound states each larger by a factor of ~ 22.7 , and correspondingly each successive binding energy smaller by 22.7^2 [?]. Here we hypothesize a similar behavior with the special value $22.7 \rightarrow \phi \approx 1.618$, so that the “ladder” of SST soliton masses would have $M_{n+1}/M_n \approx \phi^2$.

Mathematically, one can see how a log-periodic potential yields a characteristic equation with periodicity in $\ln E$. For a particle of mass m in the above $V_{\text{eff}}(r)$, the WKB quantization condition might take the form $\int p(r) dr = \pi(n + \frac{1}{2})$ with $p(r) = \sqrt{2m(E - V_{\text{eff}}(r))}$. Because $V_{\text{eff}}(r)$ repeats for $r \rightarrow r\phi$, the phase integral for a state at energy E can be mapped onto that at energy E' if E and E' are related by ϕ^2 . In essence, the quantization condition becomes *log-periodic* in E , leading to a characteristic equation $f(\ln E) = 0$ that has an infinite family of solutions for $\ln E$ differing by $\ln(\phi^2)$ cycles. This yields $E_n \propto \phi^{2n}$ as the allowed eigenvalues (for integer n).

Consequences:

If such a ϕ -based DSI is realized in SST, the energy spectrum of certain excitations (e.g. vortex solitons or bound knots) would exhibit a *hierarchy of levels separated by constant ratios*. An example output would be a mass spectrum $\{M_0, \phi^2 M_0, \phi^4 M_0, \phi^6 M_0, \dots\}$ for some base mass M_0 (or similarly a descending series if M_0 is an upper bound). This is a very strong prediction: it means a log-linear plot of these masses would show equal spacing. Experimentally or observationally, one might detect this as a regular spacing on a logarithmic mass scale – a signature of discrete scale invariance [?]. Such a signature could be looked for in the SST context (e.g. perhaps in the Regge-like trajectories of knotted resonances or in the spacing of “dark” knot energy levels, if those are postulated).

Within the SST Lagrangian, implementing this would require adding terms that introduce a preferred scaling factor. This could be achieved via a *dilatonic* field or modulation: for instance, a field $\sigma(x)$ whose vacuum expectation value oscillates periodically with $\ln r$ would explicitly break continuous scale symmetry to ϕ -scaled steps. Another implementation is through *foliated self-similar boundary conditions*: if the swirl condensate has a fractal substructure (e.g. eddies within eddies) with a self-similarity ratio of ϕ , then any emergent soliton (swirl string) might inherit that scaling quantization. We note that introducing DSI is a theoretical conjecture (not derived from the core axioms of SST), but it is a mechanism seen in other contexts [?]. If true, it directly yields the golden ratio quantization as a derivable consequence: energy levels would obey $E_{n+1}/E_n = \phi^2$ by construction.

It is intriguing that a recent independent framework (QST E8 theory) uses a golden-ratio DSI to predict fundamental scales; for example, it predicts a grand-unification energy $E_{\text{GUT}} \approx \phi^2 M_{\text{Pl}} c^2$ [?]. This hints that using ϕ as a discrete scaling constant can produce quantitatively accurate physics. In summary, the DSI approach provides a clear route to golden ratio spacing: *assume discrete self-similarity in the swirl dynamics, implement via log-periodic potentials or limit-cycle renormalization group flows, and obtain a geometric energy spectrum with ratio ϕ^2 .*

B.2 Icosahedral Symmetry and Golden-Mode Splitting (A_5)

Assumption:

We assume that an *icosahedral symmetry* underlies the swirl-field configuration for a certain class of solutions. The rotational symmetry of a regular icosahedron (or its dual, the dodecahedron) is described by the non-Abelian group A_5 (the alternating group on 5 elements). This A_5 symmetry is remarkable in that it is intimately connected to the golden ratio. In fact, one finds $\phi = 2 \cos(36^\circ)$ [?], and many geometrical relations in an icosahedron involve ϕ . For example, the ratio of the diagonal to edge in a pentagon (which is the face of a dodecahedron) is ϕ , and the eigenangles of 5-fold rotations are related to 72° (whose half-angle cosine yields $\frac{\phi}{2}$). The assumption here is that the SST vacuum or condensate for these excitations is arranged in an icosahedrally symmetric manner. For instance, one might imagine 12 swirl strings arranged at the vertices of an icosahedron forming a “condensate droplet,” or an excited swirl mode whose angular dependence is locked to the icosahedral harmonics. This could either be a literal multi-string configuration with A_5 symmetry, or a single knotted field whose effective symmetry group is A_5 .

Proposed Mechanism:

If a physical system has icosahedral symmetry, its normal modes (small oscillations) or quantum energy eigenstates must transform according to the irreducible representations of A_5 . The irreps of A_5 have dimensions 1, 3, 3, 4, 5 (two different 3-dimensional ones, etc.), and the group structure ensures certain degenerate multiplets and selection rules. Crucially, the *characteristic equations* associated with A_5 often involve the golden ratio. For example, the 3-dimensional faithful representation of A_5 (essentially the rotation of an icosahedron in \mathbb{R}^3) has a matrix for a 5-fold rotation whose trace is $2\cos(72^\circ) = 2\cos(2\pi/5) = \phi - 1 = 1/\phi$. Similarly a 3-fold rotation has trace $2\cos(120^\circ) = -1$, etc. These traces show that the eigenvalues of such rotation matrices are related to ϕ and ϕ^{-1} . Thus, when one sets up the vibrational modes of an icosahedral structure, the secular equations naturally contain $\cos(36^\circ)$ or $\cos(72^\circ)$ terms. A concrete example is provided in neutrino physics: models with A_5 family symmetry predict mixing angles involving ϕ . In one simple A_5 model, the solar neutrino angle comes out as θ_{12} with $\tan \theta_{12} = 1/\phi$, i.e. $\sin^2 \theta_{12} \approx 1/\phi^2 \approx 0.382$. This illustrates how golden ratios emerge from A_5 representation theory.

In our SST context, the mechanism can be envisioned as follows. Suppose the swirl condensate field $\Psi(x)$ has an effective potential (or a boundary condition on some domain) that is minimized by an icosahedrally symmetric configuration. For instance, there could be an angular potential term $V_{\text{ang}}(\hat{n})$ (where \hat{n} is a direction on S^2) with minima at the 12 directions corresponding to the vertices of a regular icosahedron. The field might develop a vacuum expectation aligning with one of these minima, spontaneously breaking the full rotation symmetry down to A_5 . Small oscillations about this vacuum can be expanded in spherical harmonics or other angular functions; however, only those combinations consistent with A_5 symmetry will be actual normal modes (others are disallowed or split off by symmetry). This is analogous to how crystal field theory splits atomic energy levels according to the symmetry of the crystal – here the “crystal” is an icosahedral arrangement of swirl. Because A_5 is non-Abelian and non-orthogonal in \mathbb{R}^3 , the degeneracies will be partially broken. We expect one or more mode frequencies to be related by equations involving ϕ . In fact, one can derive that the Frobenius–Schur indicator or the eigenvalue equation for certain collective motions yields a quadratic equation $x^2 - x - 1 = 0$ (whose positive root is ϕ). For example, consider a collective “breathing” mode versus a “twisting” mode of an icosahedral droplet: their frequencies ω_1, ω_2 might satisfy $\omega_2^2/\omega_1^2 = \phi$ or ϕ^2 , due to coupling through a pentagonal symmetry constraint. Concretely, if one writes down the mass matrix for vibrations in an icosahedral cluster of 12 masses connected by equal springs, the normal mode analysis yields eigenvalues such as $\lambda = 3 - \sqrt{5}$ and $3 + \sqrt{5}$ (for certain symmetric modes) – and indeed $\frac{3+\sqrt{5}}{3-\sqrt{5}} = \phi^2$. In short, the golden ratio can appear in the ratio of two normal-mode frequencies as a consequence of icosahedral symmetry.

Consequences:

Under this framework, we would expect the energy spectrum of the system to reflect the A_5 symmetry by grouping into multiplets and specific ratios. Unlike the DSI case (which yields an infinite self-similar ladder), the icosahedral symmetry would produce a more pattern-based quantization: a finite set of modes related by ϕ . For example, one might find a pair of energy levels E_a, E_b such that $E_b/E_a = \phi^2$, or a triplet of levels with spacings following $1 : \phi^2 : \phi^4$. This could correspond to, say, an excited knotted state splitting into a “golden doublet.” In practical terms, if an SST soliton (like a knotted proton) has an A_5 symmetric substructure, its vibrational excitations could include a low-energy mode and a higher mode at ~ 2.618 times that energy. Detection of such a ratio in lattice simulations or experiments would hint at an underlying icosahedral order.

Embedding this into the SST field equations might involve adding a potential term enforcing A_5 symmetry. For example, one could include a term

$$V_{A_5}(\Omega) = -\kappa \sum_{g \in A_5} (\hat{n} \cdot R(g)\hat{n}_0)^2,$$

where \hat{n}_0 is some reference axis in internal swirl director space and $R(g)$ are the rotations corresponding to the 60 elements of A_5 . This engineered potential would have 12 global minima (when \hat{n} aligns with any of the 12 vertices of an icosahedron relative to \hat{n}_0). In effect, the swirl “director” field (which might encode local orientation of vorticity) could form an icosahedral pattern. Once in this phase, small fluctuations in \hat{n} (or in the associated collective coordinates) would be governed by the symmetry. The assumption of A_5 symmetry is a proposed extension – SST in its core does not demand this, but it could emerge under special conditions (perhaps a resonance or a particular knot family that has icosahedral spatial ordering). The consequence if this assumption holds is that golden ratio relations become derivable from group theory. Using character orthogonality and projecting out invariants, one can derive relations like

$$2\cos(36^\circ) = \phi, \quad 2\cos(72^\circ) = \phi^{-1},$$

and these enter the energy calculations. For instance, the splitting ΔE of an A_5 -invariant doublet might be $E_0(\phi - 1)$ versus $E_0(\phi^0)$, etc., yielding a ratio ϕ .

In summary, the A_5 (icosahedral) pathway explains golden quantization as arising from a symmetry principle: the golden ratio appears because it is the algebraic invariant of 5-fold symmetry. If the SST dynamics can support an icosahedral condensate or saddle point, then by analyzing the normal modes or representation content, we find ϕ and ϕ^2 naturally appearing in the spectrum [?]. This approach distinguishes itself from the DSI case by relying on a large discrete symmetry in physical space, rather than scale symmetry in parameter space.

B.3 Topological Energy Functionals and Knot Spectrum Quantization

Assumption:

We assume that the mass-energy of a swirl-string (especially in the knotted, particle-like T-phase) is determined by a *topological energy functional* – that is, a function of the knot’s topological invariants (and perhaps geometric properties derived from them). SST already suggests that quantum numbers correspond to topological invariants of the vortex filament (linking number, knot class, etc.), and a candidate energy functional can be written as

$$E_{\text{knot}}[K] = \alpha C(K) + \beta L(K) + \gamma H_{\text{vol}}(K) + \dots,$$

inspired by the form introduced in the SST formulation. Here $C(K)$ might represent a *complexity* measure of the knot (e.g. minimal crossing number), $L(K)$ a linking number or self-linking (for a single closed loop this could be taken as the loop’s self-linking number in a ribbon interpretation, which is equal to twist plus writhe), and $H_{\text{vol}}(K)$ the hyperbolic volume of the knot’s complement (for hyperbolic knots). The coefficients α, β, γ would be theory-specific constants or coupling parameters. The key new assumption is that nature chooses these coefficients (or the functional form) such that energy minimization leads to quantized ratios of ϕ^2 . In particular, we posit that stable knotted solutions occur only for certain combinations of twist and writhe that extremize E_{knot} , and that those combinations follow a recursive pattern linked to the Fibonacci sequence (and hence golden ratio). This is a strong assumption, but we can motivate it by analogy to known principles: e.g. in biology, phyllotaxis arranges leaves at $\sim 137.5^\circ$ (the golden angle) to minimize energy overlap; here, a knotted vortex might arrange its twists in an optimal way that results in a golden ratio partition of twist vs writhe.

Proposed Mechanism:

Given a closed vortex filament (swirl string) in SST, its topological state can be characterized by invariants like Twist (Tw), Writhe (Wr), and Linking (Lk). These are related by the Călugăreanu–White formula for a closed ribbon: $Lk = Tw + Wr$ [?]. In a physical vortex, Tw measures how many times the filament’s core twists around its axis, and Wr measures the coiling of the loop in space (informally, the “curliness” or knotting of the central curve). Meanwhile, many nontrivial knots are *hyperbolic* – meaning the space outside the knotted loop admits a

hyperbolic geometry with a well-defined finite volume [?]. This hyperbolic volume H_{vol} can serve as a gauge of knot complexity (more complex knots generally have larger volumes). We now suppose that E_{knot} is minimized for certain rational ratios of Tw and Wr . For instance, consider a one-parameter family of knotted configurations (say, torus knots of increasing winding number): as we increase the total linking number Lk , the vortex might redistribute between Tw and Wr to minimize energy. Setting $\partial E / \partial Tw = 0 = \partial E / \partial Wr$ (with Lk constrained) yields an equilibrium condition. If $E_{\text{knot}} = f(Tw) + g(Wr)$ for simplicity, the equilibrium would satisfy $f'(Tw) = \lambda$ and $g'(Wr) = \lambda$ for some Lagrange multiplier λ (enforcing $Tw + Wr = Lk$). This gives $f'(Tw) = g'(Wr)$, meaning the optimal Tw and Wr are such that the incremental energy cost of adding a twist equals that of adding writhe. In a simple quadratic model, say $E = ATw^2 + BWr^2$ with Lk fixed, one finds the optimum at $Tw = \frac{B}{A+B}Lk$ and $Wr = \frac{A}{A+B}Lk$. The ratio $Tw/Wr = B/A$ is then fixed. If by some physical calibration B/A turns out to be ϕ (or $1/\phi$), then the equilibrium configuration always has $Tw : Wr = \phi : 1$. This would be a special case, but it could emerge if, for example, twist modes and writhe modes have different energetic stiffness in the swirl condensate.

Now, consider incrementing the total linking number Lk by an integer (i.e. adding one extra 2π twist in the filament, which might effectively increase both Tw and Wr by some increments). The system will shift to a new equilibrium of Tw and Wr that still satisfies $Tw/Wr \approx \phi$. Strikingly, the discrete nature of Lk (an integer) together with the irrational ratio ϕ can produce a quantization: the filament cannot maintain the ratio exactly for all Lk unless Tw and Wr adjust in jumps. In fact, this hints at a Fibonacci-like sequence of preferred states. For instance, suppose a particular knotted state has $(Tw, Wr) = (F_{n+1}, F_n)$ for some Fibonacci numbers F_n (so $Tw/Wr \approx F_{n+1}/F_n \rightarrow \phi$ as n increases). If you add one more twist-turn, the next optimal might be (F_{n+2}, F_{n+1}) – basically the next Fibonacci pair – because that pair is the nearest integer solution to the ratio ϕ . In this way, as the knot gets more twisted, it “chooses” configurations whose integer invariants follow the Fibonacci rule: $F_{n+2} = F_{n+1} + F_n$. The consequence is a quantized series of knot states whose properties (like total energy) grow by a factor approaching ϕ^2 . For large n , $F_{n+2}/F_n \rightarrow \phi^2$. Even for moderate n , one might see approximate golden ratios between energies.

To illustrate, imagine a family of knotted vortices where each additional crossing or twist yields the next stable particle: say the lightest knot corresponds to $(Tw, Wr) = (1, 0)$ (an unknot or simple ring), the next to $(1, 1)$ (perhaps a trefoil knot with one twist, one writhe), then $(2, 1)$, $(3, 2)$, $(5, 3)$, ... and so on. These could correspond to different particle generations or resonances. If the energy functional is roughly linear in Lk or crossing number, then $E_n \propto Lk_n \sim F_{n+1} + F_n = F_{n+2}$. Thus $E_{n+1}/E_n \approx F_{n+3}/F_{n+2} \rightarrow \phi$ for large n , or possibly ϕ^2 if comparing every second state. Depending on selection rules, it might be that only every second Fibonacci step is stable (yielding a ratio closer to $\phi^2 \approx 2.618$ between those states). This is speculative, but it shows a plausible combinatorial origin for ϕ -layered spectra in a knotted system.

Another topological ingredient is the hyperbolic volume $H_{\text{vol}}(K)$. For many knots (especially those used to model quarks in SST, e.g. 5_2 or 6_1 in the proton), H_{vol} is a fractional number that increases with knot complexity. If E_{knot} includes a term γH_{vol} , then as one goes to more complex knots, this term grows. Interestingly, some hyperbolic volumes of knots are related by simple formulas. For example, certain sequences of knots (like pretzel knots or augmented knots) have volumes that approach multiples of a fundamental constant. While ϕ does not explicitly appear in standard hyperbolic geometry of knots, one can imagine a scenario where adding a twist increases the hyperbolic volume by a fixed percentage. If that percentage were tuned to correspond to ϕ^2 , then a series of knots each with one more twist would see energies multiplied by ϕ^2 . This would require $\gamma \Delta H_{\text{vol}}/E$ to be constant for each added twist, a condition that might be approximately true in a regime of large, self-similar knots.

Consequences:

Within SST, this topological approach would manifest as a selection rule for allowed knot energies. Not every knot type would correspond to a stable particle, but those that do might fall into a sequence with nearly geometric mass ratios. For instance, suppose the electron (modeled by a trefoil knot 3_1) is the first of a series, the next stable knot is a figure-eight 4_1 or cinquefoil 5_1 which has a mass $\sim \phi^2$ times higher, etc. (This is just a hypothetical mapping for illustration.) The hallmark of this mechanism is that it ties the quantization to integer topological counts, making it naturally exact if the assumptions hold. Once α, β, γ are fixed, the energy of each allowed knot is in principle calculable by evaluating $C(K), L(K), H_{\text{vol}}(K)$, etc. If the extremal condition enforces a golden ratio relation between Tw and Wr , then the energy becomes a function of a single integer (like Lk or crossing number) and yields a spacing that tends to ϕ^2 . In practice, SST could incorporate this by adding a term in the action that penalizes deviations from the optimal twist-to-writhe ratio. For example, a term like $U_{\text{ratio}} = \delta(Tw - \phi Wr)^2$ (with some appropriate definition in a continuous field sense) would make configurations with $Tw \approx \phi Wr$ energetically favorable. Then the stable knotted solutions found by minimizing the total action would inherently satisfy that relation, giving E_{knot} quantized in the manner described.

It is important to distinguish which parts of this idea are hypothesis and which are firm: The existence of topological invariants ($Lk, Tw, Wr, H_{\text{vol}}$) affecting energy is well-grounded [?]. However, the specific golden ratio tuning (e.g. nature choosing $Tw : Wr = \phi : 1$ as optimal, or Fibonacci sequences of knot stability) is a proposal. If future derivations show that the incompressible swirl dynamics indeed minimize energy when twist and writhe distribute in golden proportion, then the ϕ^2 mass quantization becomes a derived consequence of SST's topology. Until then, we consider it a plausible but unproven mechanism. It does, however, offer a unifying narrative: much like quantized circulation in SST (Kelvin's theorem) gives integer multiples of a quantum κ , a discrete topological spectrum could give preferred "quantum knots" spaced by a fixed ratio. The golden ratio, with its unique property $\phi^2 = \phi + 1$, is a natural candidate for such spacing because it arises from recursive relations (like Fibonacci) that might govern the building of complex knots.

Implementation in the Lagrangian:

To implement this idea, SST's effective Lagrangian could include terms that approximate the above energy functional. For example, one might add

$$\mathcal{L}_{\text{knot}} = -M_0 \delta^3(x - \mathcal{C}) - \frac{1}{2} A \Theta(Lk[K] - N)^2 - \frac{1}{2} B (\chi - \chi_0)^2,$$

where \mathcal{C} is the string's core, $\Theta(Lk[K] - N)$ enforces an integer linking (with N an integer and A large to constrain Lk), and χ is a collective coordinate representing the twist/writhe ratio of the configuration (with χ_0 set to ϕ). This is a very schematic form, but it indicates adding a potential that has a minimum when $\chi = \chi_0 = \phi$. The effect is that the vortex will "prefer" to adjust itself such that twist and writhe maintain the golden ratio, and any perturbation will oscillate around that configuration. A small oscillation analysis around the minimum $\chi = \phi$ would show that the next excited state corresponds to χ fluctuating to $\phi \pm \Delta$; if the potential is steep, the system might jump to the next topological state rather than allow a continuous change in χ , thus leading to discrete energy jumps.

In conclusion, the topological energy framework suggests that ϕ^2 quantization could emerge from the arithmetic of knot invariants. By anchoring the energy to quantities that change in Fibonacci-like increments, the theory naturally yields a golden ratio in the spectrum. This approach meshes well with SST's identification of particles with specific knots, offering a tantalizing possibility: the sequence of particle families or resonances might correspond to an increasing sequence of knot complexities whose energies follow a ϕ^2 pattern. Testing this would involve calculating the energy for various knot configurations in the SST model and checking for the predicted ratios, an endeavor for future work.

Each of the above frameworks starts from a different principle (scale invariance, finite group

symmetry, or topological dynamics) and arrives at ϕ -based quantization. This redundancy in derivation strengthens the case that golden ratio layering might be a deep feature of SST, rather than a coincidental numerology. In practice, all three mechanisms could be complementary: DSI might govern an entire sector of the theory (e.g. “self-similar” vacuum fluctuations), A_5 symmetry might emerge in specific bound states (perhaps related to an icosahedral spatial arrangement of flux quanta), and the knot energy functional certainly underpins the rest-mass spectrum qualitatively. It remains to be seen experimentally if ϕ^2 appears in the data of particle masses or transition energies in the SST context; nonetheless, these theoretical pathways provide concrete, testable scaffolding for golden ratio quantization if the required assumptions hold true.

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