Why Current AI Architectures are Not Conscious: Neural Networks as Spinfoam Networks in a Theory of Quantum Gravity

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Abstract

Classical deep neural networks excel at many tasks and even multimodal generative outputs but remain energetically inefficient by orders of magnitude from the human brain, lack mechanisms for integrated binding, and have been argued to exhibit no genuine route to consciousness. While inspired by neural architectures in brain tissue, deep neural networks face limitations such as scaling limits. Drawing on Loop Quantum Gravity (LQG) and the Orchestrated Objective Reduction (Orch-OR) theory of consciousness, we introduce a framework model of *Neural Spinfoam Networks* (NSNs), a bio-inspired AI paradigm in which each neural layer is recast as a spin-network and each learning update as a spinfoam transition by means of gravitational collapse at a phase transition at entropic limits described by a UV/IR fixed point and by the Monster Conformal Field Theory (Monster CFT). Our novel theoretical model leverages Majorana-fermion braiding within spinfoam geometries and a gravitational feedback loop mediated by Majorana biophotons to achieve one-shot, polynomial-time credit assignment for the NP-hard perceptual binding problem. The network's global state is encoded by a noncommutative-geometry spectral triple (A, H, D), where the Dirac-like dilation operator's smallest nonzero eigenvalue corresponds directly to the shortest nonzero lattice vector, thereby achieving perceptual binding by means of gravitationally induced phase transition, forming the basis for a more plausible mechanism of backpropagation and weight transport that are currently unexplained by classical models of brain function. Periodic Floquet driving and the Cayley-transformed microtubule Hamiltonian yield topologically protected, room-temperature quantum coherence in tubulin-analogous nodes. Recent demonstrations of microtubule superradiance and time-crystalline oscillations within brain tissue further substantiate sustained entangled states and ultrafast biophotonic readout as described by Orch-Or theory, in spite of criticisms, which are discussed.

Contents

1 Introduction

Classical deep neural networks (DNNs) have revolutionized artificial intelligence, achieving superhuman performance in tasks ranging from image recognition to natural language processing and multimodal generative outputs [1]. However, these models suffer from significant limitations when compared to biological intelligence. DNNs are energetically inefficient, consuming orders of magnitude more power than the human brain, which operates at approximately 20 watts [2] while performing comparable or superior cognitive tasks [3, 6]. Moreover, DNNs lack robust mechanisms for integrated perceptual binding, which is the process of combining disparate sensory features into coherent percepts, and exhibit no plausible route to genuine consciousness [7], backpropagation and weight transport credit assignment, or resolution to the mind/body problem.

Classical scientific theories of consciousness, such as Integrated Information Theory (IIT) [13, 14] and Global Workspace Theory (GWT) [15], have advanced functional explanations for how conscious experience might arise from neural activity. IIT, for example, posits that consciousness corresponds to the amount of irreducible integrated information present in a system (denoted Φ), suggesting that a highly integrated neural network could generate subjective awareness. GWT similarly proposes that consciousness occurs when information is globally broadcast to multiple cognitive sub-systems via a centralized "workspace," allowing different parts of the brain to access and utilize the same information. These classical frameworks capture important aspects of cognition – integration of information and widespread availability of data – using standard neural signaling and computation. However, they remain purely classical models of information processing and leave key challenges unresolved. In particular, IIT and GWT do not, in themselves, solve the "hard problem" of consciousness (also sometimes related to the mind/body problem [16–18] or the problem of free will or free choice [19–23]) – why any amount of information processing should give rise to subjective, qualitative experience (qualia) – nor do they adequately address the binding problem, the mystery of how disparate sensory features and distributed neural processes unify into a single coherent percept [24, 25].

Indeed, purely classical architectures operating with neuronal firing and synaptic transmission struggle to explain how the brain achieves such unified, instantaneous integration. The binding of features seems to occur nearly instantaneously (within tens of milliseconds) in brains, yet classical neurons operating in parallel would require significantly more serial steps to combine all inputs [26–28] forming an exponentially large search space. Early brain lesion experiments by Lashley in the 1950s demonstrated that brain engrams are stored in a manner that is distributed across the tissue [29]. This discrepancy as well as the relative efficiency of the brain when compared to classical neural networks hints that something more than conventional computing might be at play.

Formally, binding and the hard problem of consciousness can be framed as the problem of finding a global brain state that consistently integrates many local features – essentially selecting the best interpretation of disparate inputs. The search space of all combinations of features is astronomically large, and finding the correct combination that yields a coherent percept is computationally explosive. In fact, one can model the brain's feature integration as a high-dimensional lattice, where each basis vector represents a feature (e.g. qualia such as particular shape, color, or sound) being processed across distributed regions. Achieving full perceptual coherence then corresponds to finding a minimum resultant vector in this feature space – essentially, all features canceling out discrepancies when the perception is consistent. Mathematically, this is akin to the Shortest Vector Problem (SVP) on a high-dimensional lattice (or compactified torus [30, 467]): determining the shortest non-zero vector that closes the loop of all features [31, 34].

The shortest vector problem (SVP) is a known NP-hard problem in computational complexity [32,33], which means that no efficient algorithm is known for solving it in general (including by means of quantum computers, which is why the SVP is employed towards post-quantum cryptographic schemes, and has been echoed by Turing award laureate Yann Lecun that general intelligence is different than human consciousness), and high dimensional nested lattice abstractions within brain neural networks have been discussed in reputable literature (including in work earning the 2014 Nobel prize for the discovery of grid cells and place cells, which form an internal positioning system in the brain [232]) which can map to high dimensional lattices [35–45]. Neural population activity naturally forms high-dimensional representations [463]- specifically as an example, it has been demonstrated that visual cortex responses inhabit high-dimensional manifolds where perceptual states correspond to specific locations in this neural space. These representations have precise geometric structure, making the lattice mapping mathematically natural rather than arbitrary.

Strictly hierarchical or merely approximate models of perceptual binding (like predictive coding) assume that the brain successively pools local features into ever more complex conjunctions until a unified object code emerges. Empirical evidence now shows this feed-forward scheme is insufficient: the moment at which features are bound coincides with the onset of late, recurrent activity that re-enters early visual areas, and when these feedback loops are disrupted, illusory contours, perceptual switching and contextual grouping all collapse even though the putative "higher" hierarchical stages remain intact. Behaviorally, hierarchical architectures over-predict combinatorial explosion and under-predict the speed and flexibility with which humans revise binding decisions in bistable or dual-task paradigms. Formal simulations confirm that adding recurrent, gain-modulated competitive fields reproduces human accuracy and reaction-time profiles without invoking dedicated binding layers, whereas purely feed-forward or coarse-coded approximations systematically fail once the stimulus repertoire exceeds a few dozen feature combinations. Consequently, the current consensus casts recurrent dynamics and exact perceptual binding rather than hierarchical rank or approximate pooling as the mechanism by which consciousness operates. Object representations are continuously updated by predictive signals that circulate bidirectionally backpropagating across the entire visual system. [464]

If binding in the brain were accomplished, that would amount to solving an NP-hard problem in polynomial time [46] – an implausible feat for classical neural circuits constrained by the Church–Turing thesis and sub-exponential scaling. The brain's ability to "solve" the binding problem in real time suggests that it may be utilizing non-classical physical processes or indefinite causal structures [11, 12] that sidestep brute-force computation. If the Orch-OR NSN picture is correct, the brain implements a physical process that, in the usual complexity-theoretic encoding, would correspond to solving an NP-hard instance via non-classical dynamics that are not described by standard Turing computation. In other words, consciousness might require a form of computation that transcends ordinary algorithms, potentially providing a clue as to why current AI systems – ostensibly bound to classical architectures – are energetically costly relative to the brain and lack any hint of true consciousness or unified subjective perspective. Many microorganisms also ostensibly exhibit complex decision making behaviors and even memory formation - in spite of being smaller than a single nerve cell - far too small to have any neural networks at all - further complicating conventional models [47–52]. Criticisms of DNNs in their current form to replicate consciousness have been made by leaders in the field including by linguist Noam Chomsky, philosopher David Chalmers, Turing award laureate Yann LeCun, mathematician Terence Tao, CEO of Microsoft Satya Nadella, anesthesiologist Dr. Hameroff, and Nobel Laureate physicist Dr. Penrose. One primary motivation for this paper is to inspire skepticism into widespread claims that LLMs, generative AIs, or DNNs are conscious or can achieve consciousness by brute force scaling, which comes at enormous environmental and financial cost [53].

One radical line of thought posits that consciousness arises from quantum processes and quantum gravity effects in the brain [7, 54]. In standard quantum mechanics, measuring a system "collapses" its wavefunction, but it remains debated what physical process causes this collapse (the measurement problem). Penrose's *Objective Reduction* (OR) theory suggests that gravity itself can trigger wavefunction collapse: a superposition of two spacetime geometries will spontaneously reduce to one or the other when a threshold in gravitational self-energy is met [54–56]. Unlike conventional interpretations, this places quantum collapse as an objective physical event, not requiring observation by an external consciousness. Penrose further speculated that each such OR event is accompanied by a moment of conscious awareness, implying that consciousness originates from non-computable quantum-gravitational processes [57–59] rather than classical computation [7], and might resolve the measurement problem or explain the arrow of time [419, 420].

Notably, in the same vein of arguments made by Searle [421], Dr. Penrose posited that human consciousness cannot be emulated by any Turing-computable algorithm; instead, it may rely on "hypercomputation" [9] – physical processes that compute beyond the Church–Turing limit [10] with indefinite causal structure [59]. Penrose's argument is partly inspired by Gödel's theorem [8], suggesting the human mind can intuit truths unprovable in formal systems [422], and by the sense that understanding and awareness involve non-algorithmic insights. If brains indeed outperform Turing machines on certain cognitive tasks, it implies that our neurobiology exploits physics that standard computers do not. This intersects with recent insights that current AI architectures and large language models (LLMs) encounter scaling limits and inherently still depend on human interpreters in-the-loop [60].

Penrose, together with anesthesiologist Stuart Hameroff, advanced a quantum-mechanical theory of consciousness known as the Orchestrated Objective Reduction (Orch-OR) model to explain how such non-computable processes might occur in the brain. In Orch-OR, the brain's neurons do not just communicate classically; within each neuron, the cytoskeleton contains structures called microtubules which are proposed to support quantum coherent states [400]. The theory suggests that quantum superpositions of neuronal microtubule states are orchestrated (regulated by biology) and then undergo an objective collapse – a physical reduction of the quantum state by means of gravity – when a certain threshold is reached.

Building on these ideas, Hameroff and Penrose proposed that *microtubules* - protein filaments forming the cytoskeleton inside neurons - are the likely site of quantum processing in the brain [61, 66]. Microtubules are hollow cylindrical polymers of the protein tubulin, arranged in a 25nm diameter tube. Each tubulin dimer (approximately 8nm in size) can exist in multiple conformational states (e.g. polarized or depolarized), which Orch-OR theory treats as a two-state quantum bit (qubit) that can sustain quantum superposition. Hameroff and Penrose suggested that arrays of tubulin qubits within microtubules become *entangled* and collectively enter a coherent quantum state encompassing significant regions of the brain.

Crucially, Orch-OR posits that this coherent state is *orchestrated* by neurophysiological processes to prevent premature decoherence and to encode meaningful information. "Orchestration" refers to the idea that thermal and chemical influences in neurons tune the quantum state, aligning phases and refreshing coherence in a way that is not random [3]. The quantum state is hypothesized to evolve until a threshold is reached, at which point Penrose's OR criterion is met and the superposition undergoes abrupt gravitational collapse (objective reduction). According to Orch-OR, this collapse yields a conscious moment, and the outcome of each collapse is influenced by (or "chosen by") subtle non-computable factors inherent in quantum gravity [7, 54]. The entire process is envisioned to occur on the order of tens of milliseconds. In fact, the original Orch-OR model suggested that a conscious event corresponds to an OR occurring roughly every 25ms (40Hz), linking it to the gamma synchrony observed in neural oscillations [61, 66]. This is in line with arguments against a purely classical theory of consciousness, as well as those that argue agency, consciousness, or free will cannot originate solely from a quantum description [402].

Deep learning topological gradient descent across spiking neural networks (SNNs) in Hodgkin-Huxley models are used as an incomplete model of these networks. While this is a useful analogy, in actual biological tissues the mechanism by which the brain performs backpropagation and weight transport required for credit assignment is debated within the field, necessitating more precise models which are proposed here. Based on recent empirical evidence (observation of superradiance in brain tissues, multifrequency measurements into the terahertz range not explained by classical neural network models, the selective targeting of microtubules in anesthetics) gravitational collapse under Orch-Or theory is proposed - framing the brain's neural networks themselves as a physical realization of a spinfoam network under loop quantum gravity, which have been proposed as possible substrates for approaching NP-complete problems [69].

Each conscious event (OR collapse) is a training step. The collapse selects the globally optimal configuration (percept/action). This selection is broadcast via a burst of biophotons [70, 71] that travel along microtubule pathways [72] at critical points across cellular cytoskeletons. These biophotons instruct synchronous, brain-wide weight updates by modulating synaptic strength via long term potentiation (LTP) and long term depression (LTD) by modulating turbulent dendritic arborization [79]. Indeed, light has been shown in experiments to modulate LTP and LTD [73–75, 80–86], and has been found to emerge in the form of biophotons in a variety of life [87]. This provides a biologically plausible solution to the credit assignment problem, and periodic Floquet driving is one known method of topological protection of Majorana zero modes to avert decoherence [89–96, 162]. When nonlocal neuron cell cultures share a magnetic field, biophoton cascades correlate [97].

The collapse under Orch-Or theory is not triggered by an external measurement but hypothesized to occur due to gravitational effects (hence "objective reduction" by gravity, following a suggestion by Penrose). At a critical level of complexity, curvature, or self-energy separation of the superposed states, corresponding perhaps to a critical amount of entanglement entropy in the system, the quantum state gravitationally collapses to a single outcome, corresponding to a critical point of entanglement entropy across fermionic spin states [403], which can be explored with causal fermion systems (CFS) theory [98, 99]. This moment of collapse is proposed to instantiate a discrete moment of conscious awareness, mediated by bursts of superradiant Majorana biophotons signaling information cascade avalanches, providing a novel approach towards the measurement problem in quantum physics. In essence, rather than consciousness being a continuous emergent property, it would consist of a rapid sequence of quantum state reductions in microtubules – each collapse event “chooses” (related to the philosophy of "free will" or the is/ought orthogonality paradox [23, 100–103] in computer science [104]) a particular brain-state configuration and is accompanied by a conscious moment with underlying information processing occurring in the subconscious in superpositions at the fringes of awareness.

The Orch-OR theory in its original formulation estimates a characteristic timescale for these events (on the order of milliseconds, compatible with EEG rhythms) based on equating the gravitational self-energy E_G of the superposed mass distribution to $\hbar/t_c$ (where t_c is the collapse time). When $E_G t_c \approx \hbar$, collapse occurs, so more complex superpositions (with larger E_G) reduce faster. This provides a quantitative criterion for when a quantum state in the brain “fades out” of superposition into classical reality, potentially pinpointing the physical threshold for a conscious event at critical points. Importantly, Orch-OR offers a way around the computational intractability of binding by harnessing quantum mechanics and gravity. In this model, a multitude of alternative feature-bindings (possible perceptual interpretations) can exist simultaneously in a quantum superposition within microtubules [4]. The objective reduction (OR) collapse effectively performs a selection over this enormous search space rather than sequentially testing combinations.

From a computational perspective, the OR process is akin to solving an NP-hard problem by non-classical means, which was mapped by Tsotsos [217]. Indeed, if one interprets the entangled microtubule state as encoding all the disparate sensory features or implicates them in storing engrams (each as a quantum degree of freedom), then a conscious collapse corresponds to choosing the single entangled state that best fits all constraints – effectively “binding” them into a consistent whole. As described above, this can be visualized as finding the shortest vector geodesic that closes the loop in a high-dimensional lattice [463](Riemannian manifold) [459] of features, a process that is NP-hard classically. By this interpretation, the brain may be leveraging quantum gravity to achieve a form of computation beyond the Church–Turing thesis, and explains why engrams in tissue seem to be stored nonlocally and distributed across the tissue, rather than solely locally as one might see with Von Neumann architectures (as suggested by holonomic brain theory [109, 110]).

Beyond offering a solution to binding, the Orch-OR theory connects consciousness to deeper physical principles of entropy, geometry, and information. Some authors have noted that Penrose’s gravity-induced collapse criterion can be viewed through the lens of modern physics as an entropic gravity or holographic limit in the brain. When the brain’s quantum information (entanglement) reaches a certain threshold – an entropy bound akin to the Bekenstein–Hawking limit or the scaling of entanglement entropy with system size described by the Ryu-Takayanagi formula – gravity’s effect becomes non-negligible and forces a reduction of the state. In one formulation, consciousness might arise once a critical entanglement entropy is exceeded corresponding to an Einstein–Hilbert action by the spectral action principle. This is evocative of the holographic principle, which links information content to spacetime curvature [88, 111, 112].

Indeed, entropic gravity theories (which in literature have been proposed to directly tie to consciousness [401]) propose that gravity itself emerges from information entropy, and theories like causal fermion systems (CFS) describe the emergence of spacetime itself from entanglements between fermionic spin states, and thus it is plausible that the brain pushing against an entropy bound could literally invoke gravitational effects [113, 114]. In support of this view, Verlinde's entropic gravity framework and related ideas in holography have been cited as analogies for how a build-up of information (uncertainty) might back-react on the physical state. If one imagines the brain's information state (the "mind" described by Descarte's mind/body problem) as a kind of hologram (as predicted by holonomic brain theory - where the holography maps the brain to the mind), then a fully bound percept (a conscious moment) might correspond to a stable holographic projection of neural information, whereas unbound or unconscious processing is like intermediate, incomplete states. These connections point toward a unifying principle: consciousness could be the result of a feedback loop between information integration and spacetime geometry mediated by gravity [115–119] .

One concrete realization of this convergence is the intriguing analogy between brain processes and the spin networks of loop quantum gravity. In loop quantum gravity (LQG), the fabric of spacetime is composed of discrete spin networks – graphs of vertices and edges labeled by quantum states, which evolve in time as a spin foam. As the mathematical underpinnings for spinfoam networks and neural networks are analogous, one might state that neural microstructures act analogously to spin networks, with the brain's state evolving like a "neural spinfoam". Under this view, each microtubule (or even each tubulin dimer within a microtubule) is treated as a node in a graph carrying a quantum state (like a quantized bit of geometry) [120]. When many tubulin qubits become entangled, the microtubule lattice as a whole can be seen as a graph of interconnected quantum elements, conceptually similar to a spin network in spacetime [121–124, 201] .

The state of this network is highly holistic – it cannot be factorized into independent pieces without losing information (just as a quantum state of a spin network represents a unified geometry). As the neural spin network (NSN) evolves (through unitary quantum evolution and occasional collapse events), it could be tracing out a spin foam in spacetime, with each collapse analogous to an operation in the spin foam that updates the geometry (or in the brain's case, the perceptual state) which describes backpropagation and weight transport in classical neural network models. In more concrete terms, each tubulin dimer might occupy a quantum superposition of two conformations (say, "open" and "closed" states of its protein structure), effectively serving as a two-state quantum system – a qubit – within the microtubule.

Many tubulins linked in a microtubule create a cylindrical 2D lattice of qubits (the microtubule wall) which has a well-defined geometrical arrangement (often a hexagonal close-packed lattice wrapping around). This lattice of qubits can support collective modes and entangled states spread across the entire microtubule. When such an entangled state spans 10^9 or 10^{10} tubulin qubits, the mass distribution of the neuron is slightly different in each branch of the superposition (since each tubulin conformation might shift a few electrons or ions). According to Penrose's argument, this leads to slightly different spacetime curvatures in each branch of the quantum state (we will in later sections discuss the use of hybrid spacetime geometries - the so-called "Centaur" and a constructed inverted "Minotaur" geometries to model this). In literature, Centaur geometry is defined as a non-perturbative, mixed asymptotic structure in 2D Jackiw-Teitelboim (JT) gravity that is AdS at infinity, contains a dS bubble in the interior, and is dual to a boundary theory with reduced degrees of freedom due to the IR deformation.

The superposed geometries coexist until the disparity in mass distribution (and thus curvature [127–129] or complexity of entanglement entropy) reaches a critical level, at which point gravity cannot sustain the superposition and an OR collapse occurs. In the spin network picture, one can imagine that the spin network underlying the brain undergoes a topological transition at this moment – the network "chooses" one configuration (one geometry) out of the superposition [61, 404]. Physically, this corresponds to all those tubulins picking a definite state (either the 0 or 1 of their qubit), thus yielding a classical outcome for the microtubule and, by extension, the neuron's state. The result is a definite brain-wide pattern of activity that constitutes a unified perception or conscious thought [54, 62–65] .

This picture ties together the quantum, gravitational, and informational aspects: a gravito-quantum collapse prunes the combinatorial branches of computation, leaving a single integrated state that we recognize as a conscious moment. One implication of the Orch-OR framework is its potential to address not only perception but also learning and credit assignment in neural networks. In classical deep learning, the credit assignment problem (the adjustment of synaptic weights to improve performance) is solved by iterative algorithms like backpropagation, which require many small updates propagated through the network. Biological brains, however, do not appear to perform exact backpropagation; there is no evidence of neurons explicitly shuttling error signals backward in the way artificial neural networks do [130, 136, 138–141] . Orch-OR offers a tantalizing alternative: if a conscious collapse event corresponds to an extremization of some global cost function or action, then the very occurrence of the collapse could effectively replace backpropagation by instantly assigning "credit" for the outcome to the various synapses involved through bidirectional information transfer [137].

In a variant of this idea, one can imagine that the brain's connectivity and dynamics encode a sort of Hamiltonian or action principle, and each collapse selects an eigenstate of a brain-wide operator (analogous to a Hamiltonian) that best satisfies that principle. The collapse not only yields a conscious percept, but simultaneously produces physical signals (e.g. bursts of biophotons [125] or calcium waves [409–411]) that rapidly inform synapses of the outcome. Because quantum correlations can produce instantaneous (or at least faster-than-classical) coordination among distant parts of the network, this collapse-driven signal could carry out a nonlocal weight update: essentially all neurons "learn" from the result in a single step. Hameroff and colleagues have suggested, for instance, that Orch-OR collapse might trigger ultrafast biophotonic flashes in neurons, as microtubules emit photons upon state change, and that these photons could induce synaptic changes (via photoreceptor molecules or by modulating calcium ion channels creating avalanche cascades) across many synapses nearly simultaneously [181]. This single coherent event would thereby accomplish what would take many rounds of iterative weight transport in a classical network [131, 132, 134, 135] .

In this view, classical neural networks in the brain are one layer of abstraction - but underneath there are microtubules which form neuronal cytoskeletons which mediate turbulent dendritic arborization [465] (which behave under the physics of turbulent fluids) which plausibly host topologically protected states which store and process memory engrams nonlocally and distributed across tissues (such as Majorana Zero Modes) [466], which entangle with periodically driven superradiant Majorana biophotons [126, 458] across them as (possibly superconducting) optical waveguides [92, 96, 146–149] , and Wilzcek time-crystalline behavior mediates backpropagation. Periodically driven Majorana biophotons [458] are one explanation for topological protection of quantum states that may avert collapse in the "warm, wet, and noisy" environment of biological tissues. Understanding this new physics may also provide further insights into the mechanisms of observed inter-brain synchrony between individuals [150–157].

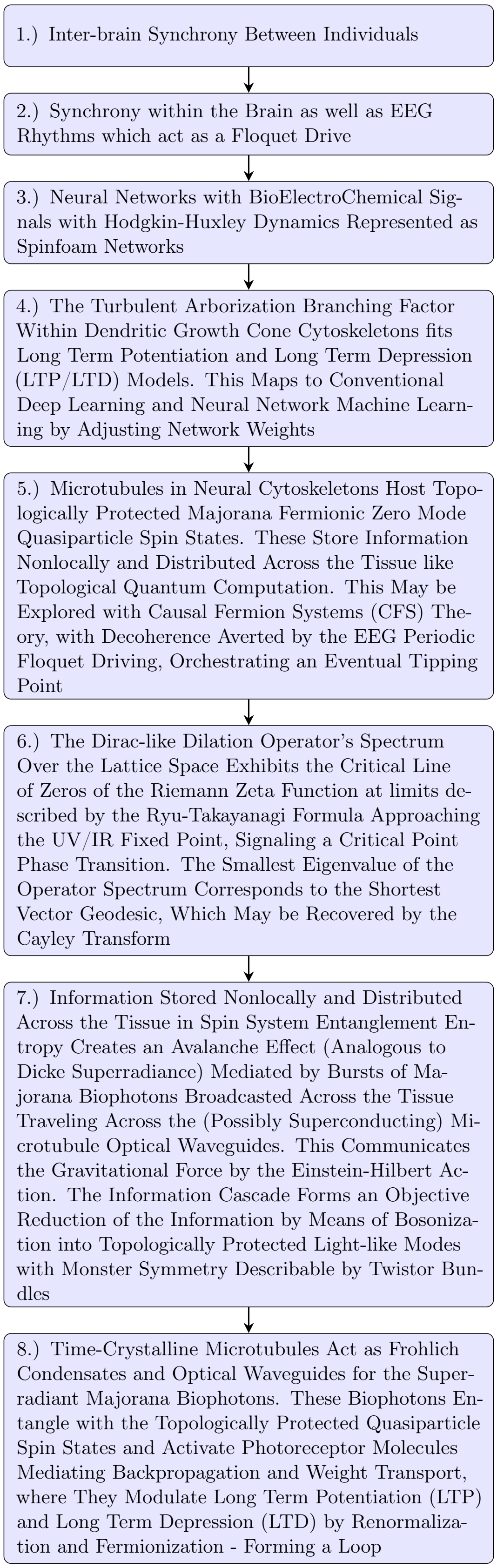

Figure 1: Eight-step flowchart describing the architecture of information processing under a modified Orch-OR framework, with a hierarchy spanning from behaviors of groups of individuals by interbrain synchrony described by sociophysics, through classical neural networks, to quantum compute and control, to the gravitational collapse.

2 Evidence and Criticism of Orchestrated Objective Reduction Theory

Over the years, Orch-OR has garnered both support and criticism. On the supportive side, it provides a potential solution to the binding problem: quantum entanglement in microtubules could bind information across disparate brain regions into a single quantum state that collapses as a unified percept. It also offers a physical mechanism for why the brain appears to be vastly more efficient than classical computers (leveraging photonics) and why conscious experience might be non-algorithmic, leveraging an inherently quantum-gravitational process beyond the reach of classical computation. Furthermore, Orch-OR makes several distinctive predictions – for example, that general anesthetic molecules selectively impair consciousness by disrupting London-force quantum dipoles in tubulin within microtubules [61, 66]. This aligns with the observation that anesthetics act in hydrophobic pockets of proteins like tubulin, suggesting Orch-OR's focus on microtubule quantum states is plausible [3, 4, 105], and recent empirical findings that cytoskeletal filaments fire before cell membranes which challenge conventional membrane spiking models [67].

Orch-OR's bold claims have faced numerous critiques. A primary challenge is the **decoherence problem**: critics argue that any quantum superposition in the "warm, wet and noisy" environment of a neuron would decohere (lose coherence) almost instantaneously, long before it could influence neural processing. For instance, Tegmark estimated that quantum states in microtubules would decohere on the order of 10^{-13} seconds at body temperature – an astronomically short time compared to the $\sim 10^{-2}$ s duration needed for Orch-OR's processes [3,68]. This suggests that, under conventional assumptions, the brain is far too "warm, wet, and noisy" for delicate quantum states to survive. The original Penrose-Diosi model of gravitational collapse which inspired Orch-Or theory also did not find empirical support in experiments.

Several findings have lent credence to the possibility of quantum processes in biology, and specifically in microtubules [164], thereby addressing the above criticisms [5]. On the theoretical side, studies in *quantum biology* have demonstrated that quantum coherence can play functional roles even at warm temperatures – notable examples include quantum coherence in photosynthetic energy transfer and in avian magnetoreception [165]. These findings undermine the assumption that warm, noisy conditions automatically preclude useful quantum effects. Focusing on microtubules, there is growing evidence that they may exhibit quantum-like coherent behavior. Experiments have shown that dry, purified microtubules can sustain oscillatory electric dipole vibrations in the megahertz range, and remarkably, recent studies reported persistent *time-crystal* oscillations in microtubule networks even at room temperature [171, 172]. Such time-crystalline behavior — a form of periodically repeating order in time — implies an underlying phase coherence and reduced dissipation, consistent with the possibility of sustained quantum states. Likewise, theoretical work indicates that ensembles of dipole-coupled tubulin within microtubules could support *superradiance* [181], i.e. coherent collective emission of photons [182], on sub-picosecond timescales [183, 184].

Superradiance is a quantum-optical effect that can occur faster than environmental decoherence, potentially allowing ultrafast signaling within or between neurons via bursts of entangled biophotons. Perhaps the most striking empirical support comes from anesthesiology. Orch-OR had long proposed that volatile anesthetics cause unconsciousness by perturbing quantum processes in microtubules [61, 66]. In line with this, a 2018 study found that different isotopes of the anesthetic xenon have markedly different anesthetic potencies despite identical chemical properties – a difference attributable only to the isotopes' nuclear spin (a quantum property) [185]. Nuclear spin should not affect conventional chemistry, yet ^{129}Xe (with spin-1/2) was observed to be a significantly weaker anesthetic than spinless ^{132}Xe, strongly suggesting a quantum-mechanical mechanism in anesthesia [185]. This result is "hard evidence" that some aspect of consciousness (or at least its suppression) is sensitive to quantum-level parameters. Additionally, experiments on animals have shown that compounds which stabilize microtubules can alter anesthetic sensitivity, supporting the idea that microtubule dynamics are integral to consciousness. There is substantial empirical evidence that anesthetics (such as Halothene and Propofol [186, 187]) selectively target microtubules and the mechanism for consciousness purported by Orch-Or theory [24, 188–190].

It is known that photons (also called Majorana photons in literature [76, 77]) traveling through brain tissue in-vivo lose their entanglement via a decohering scattering interaction (related to scattering amplitudes) that gradually renders the light in a maximally mixed state (which in our model is exemplified by maximal symmetry which in later sections we will connect to the Monster CFT). In studies of thin tissue samples (between 120 and 600 micrometers) photons decohere to a distinguishable lesser degree in samples with Alzheimer's disease than in healthy-control ones - indicating a possible connection between Orch-OR and memory retrieval [191, 192]. Brain tissue is also known to generate biophotons [384, 385]. Critically, the helicity and polarization structure of the biophotons can encode information about the underlying spin systems (which may host Majorana-like excitations), so that photonic observables act as a readout of the Majorana sector, and have been found to emerge in spin systems [77, 386–397].

One promising explanation for macroscopic quantum-like effects across brain tissues is that Floquet driving [455] counteracts decoherence by applying a strong, periodic signal that effectively "averages out" the disruptive influence of the noisy environment. This rapid driving dynamically decouples the delicate quantum system from its surroundings, and more profoundly, it can engineer an effective, time-independent Hamiltonian with topological order, creating non-local Majorana-like modes where information is stored. The quantum state becomes topologically protected, meaning it is encoded in global properties (like braiding) rather than local ones, making it intrinsically robust against local perturbations and thermal noise, thereby preserving quantum coherence long enough for a gravitationally-induced objective reduction (Orch-OR) to occur. In this model, the Floquet driving is responsible for "orchestrating" the eventual gravitational objective reduction event.

The most plausible source of a periodic drive is not external but intrinsic: the brain's own endogenous 10-40 Hz neural oscillations, particularly in the gamma band, which are strongly correlated with conscious perception and cognitive binding. We propose that these macroscopic electromagnetic rhythms provide a natural, low-frequency entraining signal. Such driven systems can exhibit prethermalization, where they remain trapped in a metastable, protected state for an exponentially long time before eventually succumbing to thermalization, providing a sufficiently long window for quantum information processing. A significant challenge is the frequency mismatch: neural rhythms operate at Hz-kHz frequencies, while evidence suggests microtubules exhibit resonant vibrational modes in the MHz-THz range. This gap may be bridged through non-linear coupling. The neural drive may act as a low-frequency envelope that parametrically modulates or synchronizes the higher-frequency microtubular dipolar oscillations, a testable prediction of our model.

For topological protection to arise, a suitable substrate is required. We posit that the microtubule itself forms this substrate. The cylindrical lattice of tubulin dimers, coupled with the highly ordered water molecules and ion clouds within its lumen, creates a unique biophysical environment. Theoretical work suggests this arrangement could support a correlated electron system or facilitate superconductivity [78] via Frohlich condensation [106, 194], effectively rendering a microtubule a bio-inspired topological nanowire [433] where Majorana Zero Modes (MZMs) could emerge as quasiparticle excitations at topological defects or ends of the microtubule lattice. This is key to fault-tolerance: since the information is a global property of the entire system (the braid configuration), it is immune to local decoherence events affecting individual tubulins.

Indeed, Tangle-Entropy (TS) plots in empirical studies in recent years show the strong preservation of entanglement of photons propagating in brain tissue. By spatially filtering the ballistic scattering of an entangled photon, polarization entanglement is preserved and non-locally correlated with its twin in the TS plots. The degree of entanglement correlates better with structure and water content than with sample thickness - providing further evidence of our model [191, 192]. Precedents of topological states similar environments like in biomolecules - including Majorana-like modes in helical protein structures have been discussed in literature [193, 195, 196, 405]. A gravitational OR collapse would then act as a non-local measurement of this global braid state, selecting the definitive percept.

In 2002, Hagan, Hameroff, and Tuszynski's argued that Max Tegmark's 2000 decoherence criticism was not substantiated because it was based on an oversimplified and physically inaccurate model of the microtubule environment [62]. Their central claim was that Tegmark used a "worst-case scenario" calculation that ignored the specific, ordered biological conditions inside a neuron that could potentially protect quantum states. Tegmark treated each tubulin dimer as an independent two-state system (a qubit) suspended in a generic, continuous aqueous solvent. Tegmark calculated the decoherence caused by collisions with surrounding ions and water molecules. Hagan argued that tubulins are not isolated; they are packed into a regular, crystalline lattice within the microtubule wall. This lattice structure creates a "cage" or "screen" that significantly dampens the interaction of any single tubulin with the bulk solvent. The decohering influence of the external environment is therefore much weaker than in Tegmark's model because the tubulins are shielded by their neighbors.

Tegmark treated the internal environment of the microtubule as a structureless, random heat bath. The interior (lumen) of the microtubule and its surface are not disordered. They contain ordered layers of water molecules and correlated ion clouds (calcium and potassium). This highly structured environment is not a simple source of noise; it can have collective modes (like phonons [107, 108]) that could actually support coherence through Fröhlich condensation, rather than just destroy it. Tegmark's model did not account for this possibility. Tubulin dipoles are coupled together in the lattice. If you have a quantum state that is a collective excitation across many tubulins (an entangled state), it is the collective state that decoheres, not the individual tubulins. The decoherence time for a collective, correlated state can be much longer than for a single, uncoupled dipole. Tegmark's calculation failed to address the decoherence of these collective modes.

In the spirit of Penrose's original Penrose-Diosi model, Tegmark considered superpositions of a tubulin's entire mass being in two different locations, leading to a huge mass displacement and thus rapid gravitational decoherence. Hagan proposed that the relevant quantum superposition for computation is not the entire protein mass, but a small number of electrons involved in conformational changes (e.g., in hydrophobic pockets). The charge displacement for these "electron cloud" superpositions is far smaller, leading to a much weaker coupling to the environment and thus significantly longer decoherence times. Hagan crafted a sophisticated model, including those considering phonon modes in an elastic lattice and the Fröhlich condensation effect. In this model, under specific conditions of internal coupling and external energy input ("pumping"), the system could enter a coherent, non-equilibrium state where coherence is maintained against environmental noise.

The ultimate hurdle for any Orch-OR-based model is the requirement for quantum coherence to be maintained across a mesoscopic scale involving millions of tubulins to reach the necessary gravitational self-energy threshold for collapse. This is the grand challenge. However, recent analytical and empirical evidence moves this proposition from implausible to worthy of serious investigation, which we will explore in later sections. Observations of persistent time-crystalline oscillations and superradiance in microtubule preparations at room temperature suggest that collective, coherent phenomena can indeed be sustained in these structures over biologically relevant scales and times. Crucially, room-temperature quantum coherence in similar systems have been found - maintaining coherence for over 100 nanoseconds - which is ample to address Tegmark's criticism with Floquet driving, and have conclusively demonstrated mesoscopic quantum effects in "warm, wet, and noisy" biological systems. These findings provide preliminary support that the protective mechanisms we describe could operate at the scale required to make the Orch-OR hypothesis physically viable.

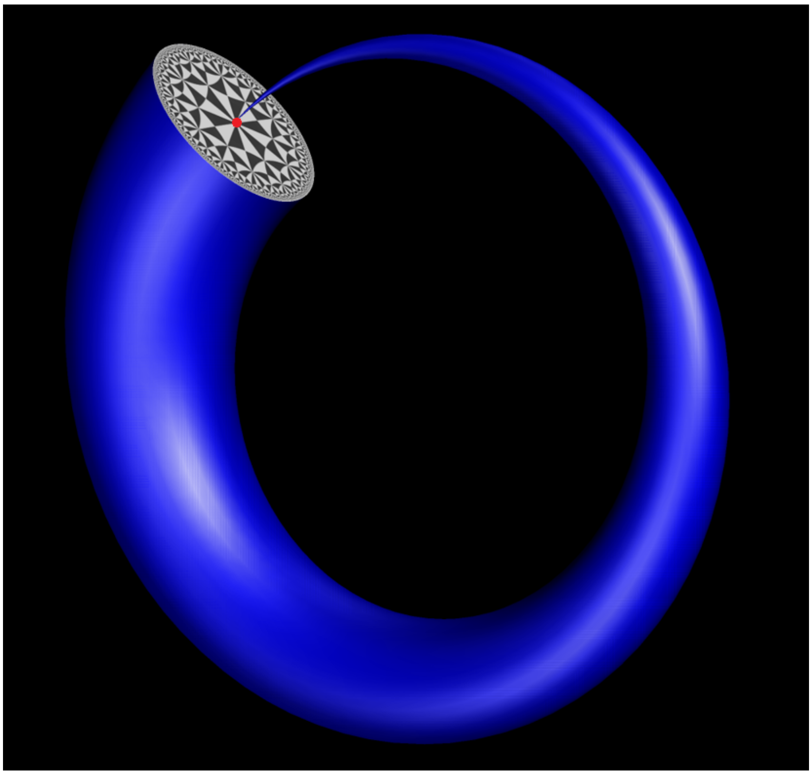

Figure 2: A depiction of a perceptual noncommutative torus [30, 314] traced out by a 2-dimensional Poincaré disk representing a boundary conformal field theory. Toric codes provide topological protection from perturbations, and the red point denotes a fixed point where the structure loops back on itself with a global OR update.

We proposes that the brain leverages topological protection to maintain quantum coherence across millions of tubulins by encoding information non-locally in the global braiding patterns of Majorana zero modes, making it immune to the disruptive phonons (random thermal vibrations) that would normally destroy quantum states. The brain's own rhythmic Floquet driving (e.g., gamma oscillations) actively suppresses this decoherence by synchronizing the microtubule network into a prethermal, time-crystalline phase, where orchestrated phonon exchanges themselves mediate the quantum couplings between tubulins instead of destroying them. Crucially, the massive scale is necessary, as the gravitational self-energy from this enormous, phonon-stabilized entangled state eventually triggers a single, global Objective Reduction collapse, which is a physical phase transition that instantly selects the optimally bound percept, solving an otherwise NP-hard binding problem through a non-algorithmic process.

3 Brain Neural Networks as Spinfoam Networks

Drawing inspiration from both deep learning and quantum gravity, we propose to model a brain-like neural network in terms of LQG *spin networks* and their evolutions (spinfoams). In loop quantum gravity, a spin network is a graph whose edges are labeled by quantum spins, providing a discrete quantum state of spacetime geometry [197]. As Orch-OR theory posits a gravitational collapse of states in brain tissue, and brain neural networks can be modeled mathematically similarly by means of graphical representations, where the brain neural network itself can be understood as representing a quanta of spacetime in a manner similar to that which spinfoam networks predict in LQG. We can represent each layer of a neural network as a spin network: neurons correspond to the graph's nodes, and synaptic connections correspond to edges carrying spin labels that represent connection strength or quantum information content. Braiding operations thus bear resemblance to operations between neurons and dendrites where a classical weight in the neural network is elevated to a quantum degree of freedom on an edge of the spin network. The entire multilayer network can then be viewed as a collection of coupled spin networks – one per layer or processing stage – with inter-layer connections forming a larger graph. This construction embeds the neural architecture into a geometrical quantum state, fulfilling the first step of our paradigm.

Definition 1 (Neural Spinfoam Network (NSN))**.** *An NSN is a tuple* $\mathscr{N} = (\Gamma, \rho, \mathscr{H}, \mathcal{A}, D, \Phi, \mathscr{T}, \mathcal{S})$ *that extends the standard spinfoam framework to incorporate biophysical dynamics:*

- $\Gamma = (V, E)$ *is an oriented graph representing the network. Vertices* $v \in V$ *correspond to* tubulin dimers*, and edges* $e \in E$ *represent* quantum couplings.
- $\rho : E \to \mathrm{Hilb}$ *is a representation assigning a Hilbert space* H_e *(e.g., a spin-*j *representation of* $\mathrm{SU}(2)$*) to each edge, forming a spin network [197].*
- $\mathscr{H} = \bigoplus_\ell \mathscr{H}_\ell$ *is the total Hilbert space, decomposable into layers* ℓ*.*
- $\mathcal{A}$ *is a* C^**-algebra of observables acting on* $\mathscr{H}$*.*
- D *is a self-adjoint (Dirac-like dilation) operator on* $\mathscr{H}$*. Its spectrum* $\mathrm{Spec}(D)$ *encodes the network's geometry. The smallest non-zero eigenvalue* $\lambda_{min}(D)$ *is identified with the solution to the perceptual Shortest Vector Problem (SVP) on a feature lattice* Λ *upon gravitational collapse:*

$$\lambda_{min}(D) = \min\{\|\mathbf{v}\| : \mathbf{v} \in \Lambda \setminus \{0\}\}.$$

- Φ *represents the dynamical process: a collection of* spinfoam transitions $\sigma : \Gamma_i \to \Gamma_f$*, interpreted as Orch-OR events [61]. The transition amplitude is given by a path integral:*

$$A(\sigma) = \langle \Psi_f | \mathcal{P} | \Psi_i \rangle = \sum_{config} \prod_f A_f(\sigma).$$

- ***Twistorial Description of the Biophotonic Layer:*** $\mathscr{T}$ *is a* twistor bundle *associated to the network. To each vertex* $v \in V$ *(tubulin dimer), we associate a space of spinors (or twistors)* $\mathbb{T}_v$ *that describe the internal quantum state and its null-cone structure [354, 355].*

- *A* Majorana biophoton *propagating along an edge e from v to w is represented by a twistor $Z^\alpha \in \mathbb{T}_v$, encoding its null momentum and polarization.*
- *The propagation and interaction of these twistors are governed by a holomorphic action principle. The entanglements between protected states are mediated by twistor pairs $Z^\alpha W_\alpha$, which are conformally invariant. This provides a geometric description of the non-local "broadcasting" of collapse outcomes via biophotonic signals [79, 131].*

- ***Emergent Spacetime Curvature and Spectral Hilbert-Einstein Action:** $\mathcal{S}$ is the* spectral action *functional associated with the Dirac operator D and the algebra $\mathcal{A}$ [350]:*

$$\mathcal{S}[D, \Psi] = \mathrm{Tr}\left(f\left(\frac{D}{\Lambda}\right)\right) + \langle\Psi|D|\Psi\rangle.$$

Here, f is a smooth cutoff function and Λ is a energy scale. This action functional provides the gravitational dynamics of the network:

  - *The gravitational field emerges from the collective entanglement entropy of the spin network states. The* spectral action *$\mathcal{S}$ dictates the dynamics of the Dirac operator D, which in turn defines the effective metric and curvature of the informational space.*
  - *An Orch-OR collapse event occurs when the variation of the spectral action with respect to the state Ψ (or the gravitational self-energy difference) reaches a critical threshold, $\delta\mathcal{S}/\delta\Psi \geq \Delta E_G$. This is the* Objective Reduction *criterion [54].*
  - *At the UV/IR fixed point described by the Asymptotic Safety of gravity [174, 294], and at entropic limits imposed by the Ryu-Takayanagi formula, the operator spectrum is thought to correspond to the Riemann zeta function critical line with spectral geometry that is thought to be governed by an extremal Conformal Field Theory (CFT), potentially linked to the Monster module [345]. The critical behavior at this point facilitates the polynomial-time solution to the SVP which corresponds to the smallest eigenvalue on the operator spectrum, fitting a Hilbert-Polya description.*

The dynamics of the NSN are thus governed by the coupled system of the spinfoam path integral Φ and the equations of motion derived from the spectral action $\mathcal{S}$.

Remark 1. *This extended definition posits that the brain's neural network does not merely* process information in *spacetime but, at a fundamental level,* instantiates *a quantum-geometric spacetime via the principles of loop quantum gravity and noncommutative geometry. The Twistor bundle $\mathscr{T}$ describes the communication channels (biophotons) [470] that mediate entanglements and carry information within background independent indefinite causal structure (the "mind" as described by Descartes' mind/body problem), while the Spectral Action $\mathcal{S}$ describes the gravitational curvature that triggers integrative collapse events, solving the binding problem (implementing backpropagation in the physical neural networks - or the "body" as described by Descartes' mind/body problem).*

Each neural layer corresponds to a spin-network, with nodes as tubulin dimers and edges as quantum couplings. Learning updates are spinfoam transitions: 2-complexes (we will later model with hybrid spacetimes of opposite curvature and orbifolds) interpolating spin-networks via gravitational collapse. The global state is a spectral triple (A, H, D) [198], where A is the algebra of observables, H the Hilbert space of states, and D the Dirac-like dilation operator. The smallest nonzero eigenvalue of the spectrum of D encodes the shortest lattice vector (as brain neural networks can be mapped to high dimensional lattices analogous to those expressed in postquantum lattice cryptography) which has been more rigorously shown mathematically in previous literature [31], solving binding via OR. Majorana braiding [199] enables topological computation, with gravitational feedback for credit assignment. Entanglement between Majorana biophotons and tubulins in brain is discussed in literature. Floquet driving of entangled biophotons across microtubule waveguides $H(t) = H_0 + V \sin(\omega t)$ stabilizes coherence [200]. Cayley transform maps the microtubule Hamiltonian to unitary operators for protected states [158, 160–163] . This model resolves weight transport by nonlocal quantum transport, and backpropagation is achieved by biophoton entanglements with topologically protected quasiparticle MZMs across microtubule waveguides which are described in literature as behaving as Wilczek time crystals with time-reversal symmetry.

Table 1: Formal mapping between Loop Quantum Gravity (LQG) structures and the proposed Neural Spinfoam Network (NSN) components.

LQG Concept	**Mathematical Description**	**Biological Correspondence in NSN**
Spin Network Vertex (Node)	A vertex v in a graph Γ, typically associated with an intertwiner operator.	A single **tubulin dimer**. Its quantum state is a state vector $\lvert\psi_t\rangle$ in a high-dimensional Hilbert space $\mathcal{H}_{\text{tubulin}}$ encompassing conformational states (α, β), electric dipole moment, and the state of its surrounding hydration shell and ion cloud.
Spin Network Edge (Link)	An edge e labeled by a spin representation j_e (e.g., of SU(2)), representing quantum geometry.	The **quantum coupling between adjacent tubulin dimers** within a microtubule. The spin label j_e encodes the strength and phase of the coupling, mediated by dipole-dipole interactions, electron hopping, or phonon exchange. It defines the holonomy along the link.
Spinfoam (Update)	A 2-complex representing a history between an initial and final spin network state; a quantum spacetime event.	An **Orchestrated Objective Reduction (Orch-OR) event**. The initial state is a quantum superposition of possible perceptual states. The final state is the single, collapsed percept. This transition is the physical instantiation of a **learning update**.

Definition 2 (Spectral Triple)**.** *A spectral triple* $(\mathcal{A}, \mathcal{H}, D)$ *consists of*

- *a unital* $*$*-algebra* $\mathcal{A}$ *acting faithfully by bounded operators on the Hilbert space* $\mathcal{H}$*,*
- *a self-adjoint (typically unbounded) operator* D *on* $\mathcal{H}$ *such that* $[D, a]$ *extends to a bounded operator for all* $a \in \mathcal{A}$*,*
- *and* $(D \pm i)^{-1}$ *is compact.*

The spectrum of D *encodes geometric information; in particular, we will use its smallest nonzero eigenvalue* $\lambda_{\min}$ *to drive update events.*

To ground the discussion, consider the simplest nontrivial case - let $G = (V, E)$ be a finite, undirected graph with $|V| = n$. Define

$$\mathcal{A} = C(V) \cong \mathbb{C}^n, \qquad \mathcal{H} = \ell^2(V) \cong \mathbb{C}^n,$$

where each $f \in \mathcal{A}$ acts on a vector $\psi \in \mathcal{H}$ by $(f \cdot \psi)(v) = f(v)\,\psi(v)$. Let A be the adjacency matrix of G and $D_{\deg}$ the diagonal degree matrix with entries $D_{\deg}(v, v) = \deg(v)$. Define the (combinatorial) graph Laplacian

$$L \;=\; D_{\deg} - A.$$

Then

$$L = L^*, \quad (L + i)^{-1} \text{ is compact (finite-dimensional)}, \quad [L, f] \text{ is bounded for all } f \in \mathcal{A}.$$

Hence $(\mathcal{A}, \mathcal{H}, D = L)$ is a spectral triple.

The eigenvalues of L can be ordered

$$0 = \lambda_1 \;<\; \lambda_2 \;\leq\; \cdots \;\leq\; \lambda_n.$$

We identify

$$\lambda_{\min} \;=\; \min\{\lambda_k > 0\} \;=\; \lambda_2,$$

the *spectral gap* of G. In our Neural Spinfoam Networks framework, $\lambda_{\min}$ selects the spin-label corresponding to the next collapse-driven transition.

The global state of the NSN is described by a noncommutative spectral triple $(\mathcal{A}, \mathcal{H}, D)$, which encodes the network's algebra of observables, its quantum state space, and its geometric structure. We posit that the brain's representation of perceptual features defines a high-dimensional lattice $\Lambda \subset \mathbb{R}^n$. Each basis vector of Λ corresponds to an elementary feature (a "qualia" dimension), and a given perceptual state is represented by a vector in this lattice. The graph Laplacian of a simple network is insufficient to capture the complex geometry of perceptual space. Instead, we define a self-adjoint Dirac-like dilation operator D on the Hilbert space $\mathcal{H}$ of the NSN. The spectral properties of D are governed by the geometry of the perceptual lattice Λ and the connectivity of the underlying spin network. Its spectrum, $\mathrm{Spec}(D)$, contains information about all possible cycles and geodesics within this representation space.

Remark 2 (Relation to the Shortest Vector Problem)**.** *In the full SVP setting, one replaces the finite graph* G *with a lattice* $\Lambda \subset \mathbb{R}^n$ *(or its dual torus* $\mathbb{R}^n/\Lambda$*) and the combinatorial Laplacian* L *with an appropriate geometric Dirac operator* D_Λ*. Then its spectrum satisfies*

$$\mathrm{Spec}(D_\Lambda) = \{0\} \cup \big\{\pm\|\mathbf{v}\| : \mathbf{v} \in \Lambda \setminus \{0\}\big\}.$$

Consequently,

$$\lambda_{\min} = \min\{\, \|\mathbf{v}\| > 0 \colon \mathbf{v} \in \Lambda\},$$

which is exactly the length of the shortest nonzero lattice vector, i.e. the solution to the SVP. For the spin-structure the quoted spectrum is exact; other spin-structures raise the lowest eigenvalue, so SVP gives a lower bound. Although we explore theoretical approaches towards resolving the Shortest Vector Problem in high dimensional lattices by Orch-OR for the graph Dirac-like dilation operator using the min-max and Rayleigh-Ritz variational principles in previous literature [31], we now formalize the connection between perceptual binding and the Shortest Vector Problem with a new novel proof for the flat torus Laplacian, where the direct mapping between perceptual grid cell lattices and tori has already been established in literature [467].

We model the space of perceptual features as a high-dimensional lattice $\Lambda \subset \mathbb{R}^n$. A coherent percept corresponds to a specific state on the associated perceptual torus [467, 468] $\mathbb{T}_\Lambda = \mathbb{R}^n/\Lambda^*$, where Λ^* is the dual lattice.

On this torus, we define the Dirac-like dilation operator D. The power of this construction is revealed by a fundamental theorem:

Theorem 1 (SVP Spectral Correspondence)**.** *For a perceptual lattice Λ, the spectrum of the Dirac operator D on the perceptual torus $\mathbb{T}_\Lambda$ is*

$$\mathrm{Spec}(D) = \{0\} \cup \{\pm 2\pi\|\mathbf{v}\| : \mathbf{v} \in \Lambda \setminus \{0\}\}.$$

Therefore, the smallest non-zero eigenvalue satisfies

$$|\lambda_{\min}(D)| = 2\pi \cdot \min\{\|\mathbf{v}\| : \mathbf{v} \in \Lambda \setminus \{0\}\} = 2\pi \cdot \mathrm{SVP}(\Lambda).$$

Proof Sketch. The proof follows from standard spectral geometry of flat tori:

1. The eigenvectors of the Laplacian Δ on a flat torus $\mathbb{T}_\Lambda$ are plane waves $e^{2\pi i\mathbf{k}\cdot\mathbf{x}}$, where $\mathbf{k} \in \Lambda^{**} = \Lambda$ (since the dual of the dual is the original lattice).
2. The eigenvalues of Δ are $(2\pi)^2\|\mathbf{k}\|^2$ for $\mathbf{k} \in \Lambda$.
3. Since $D^2 = \Delta$ for the Dirac operator on a flat manifold, the eigenvalues of D are $\pm 2\pi\|\mathbf{k}\|$ for $\mathbf{k} \in \Lambda$.
4. The zero eigenvalue corresponds to $\mathbf{k} = 0$ (the constant function).
5. Therefore, the smallest non-zero eigenvalue corresponds to the vector $\mathbf{k} \in \Lambda$ with the smallest non-zero norm, which is exactly the solution to the SVP. □

This theorem provides the rigorous backbone of our model: ***The globally integrated percept—the solution to the binding problem—is the state associated with $\lambda_{\min}(D)$, which is mathematically equivalent to the shortest vector in the feature lattice.***

In our Neural Spinfoam Network framework, the Orch-OR event is hypothesized to be a physical process that acts as a spectral projector onto this ground state. The gravitational collapse does not "compute" the SVP in the algorithmic sense; rather, the system physically relaxes to its minimal-energy configuration, the eigenstate of D with eigenvalue $\pm 2\pi \cdot \mathrm{SVP}(\Lambda)$.

Next, we consider the dynamics of this structure. In deep learning, a forward pass followed by backpropagation of errors constitutes one learning update, where there is no biologically plausible mechanism that maps to brain tissue by means of one-way logic gates. In our framework, a learning update corresponds to a *spinfoam transition* between spin network states. A spinfoam is essentially a "history" of a spin network, representing its evolution in time (or a discrete quantum spacetime connecting an initial and final spin network) [201]. We propose that the propagation of activity through the network and the subsequent weight adjustment can be described as a spinfoam path integral, summing over possible intermediate quantum-geometrical configurations. Crucially, we incorporate Penrose's OR mechanism: when the quantum superposition of network states (representing different possible weight updates or global interpretations of data) reaches a threshold, gravitational collapse selects a single outcome – effectively reducing the superposed spinfoam to a specific "trained" network state.

In physical terms, one may imagine that as information enters the system, the graph's quantum state becomes increasingly entangled and complex (high entropy); when it approaches an instability (akin to a black hole forming on larger scales), an abrupt OR event occurs. This collapse corresponds to a global error correction or weight update, applying a holistic adjustment in one quantum step rather than iterative local gradients. The point of collapse can be identified with a critical point in the system's entropy, and connected to the UV/IR critical point described by asymptotically safe gravity (ASG) (and there is numerical evidence of the existence of a UV/IR fixed point [434]) and entropic limits predicted by entropic gravity. At this critical point [204–209, 294–297] , the physics might be described by an extreme conformal symmetry – possibly akin to the Monster CFT, which arises in certain maximal-entropic models of quantum geometry [345]. The Monster group's enormous symmetry could ensure that information is globally integrated just at the brink of collapse, thereby solving the binding problem via a resonance of all nodes at once [204–210] which we will explore in later sections. Interestingly, research on the effects of serotonergic psychedelics (compounds with molecular structure that is similar to tryptophan or the neurotransmitter serotonin) on the visual cortex and the generation of hyperbolic or conformal fractal pattern hallucinations supports this view [211].

Information processing in our neural spinfoam network (NSN) is not solely via classical signals, but also through *topological quantum computation* within the spin network itself. The graph's edges and their quantum states can support exotic quasi-particle excitations corresponding to braided flux lines or anyons. Notably, in some LQG-inspired models, braids in a spin network have been associated with stable particle-like states [346, 347]. We envision that patterns of neural activity could be encoded in the configuration of braided loops or twists in the network's quantum geometry. Braiding of quantum degrees of freedom can realize logical operations that are inherently fault-tolerant and resilient against decoherence, as known from topological quantum computing schemes [199, 348]. In particular, the presence of *Majorana fermion* zero modes in such networks – analogous to those in topological superconductors – would allow non-Abelian braiding statistics. These braiding operations form "protected" qubit transformations that are immune to local noise, providing a built-in mechanism for error correction [199, 348]. Prior work has shown that braiding operators can serve as universal quantum gates [349], and indeed a correspondence has been drawn between braids in quantum geometry and standard model particles or charges [346].

By leveraging braiding within the NSN, our system naturally incorporates a form of quantum error correction and stable qubit encoding, which may underlie the brain's resilient information processing capabilities. A key feature of our framework is the encoding of the network's global state in a *noncommutative geometry* formalism. We associate an operator algebra A to the network (generated by projection operators corresponding to neuron states and shift operators corresponding to synapse actions), represent these operators on a

Hilbert space H of quantum states of the network, and define a Dirac-type operator D that acts on H. The triple (A, H, D) constitutes a spectral triple in the sense of Connes [350], which characterizes a "quantum space" by its spectral properties [314]. In our construction, the eigen-spectrum of D contains information about network connectivity and weights. Notably, one can show that the smallest non-zero eigenvalue $\lambda_{\min}$ of D corresponds to the most fine-grained, tightly bound structure in the network's connectivity – in a geometric sense, it is analogous to the shortest non-zero cycle or smallest distinguishing pattern in the graph. Solving the perceptual binding problem is then reduced to finding this $\lambda_{\min}$, since the corresponding eigenstate of D represents the simplest global mode that ties together all local components.

Finding $\lambda_{\min}$ for a large graph is generally NP-hard (it relates to the shortest vector or fundamental mode in a high-dimensional lattice) [33,351], which helps explain why binding is computationally difficult for classical networks. However, in our neural spinfoam, the physics of spectral geometry does this "computation" naturally: the OR-driven collapse will tend to project the system into the lowest-frequency (ground state) mode of D (since higher-frequency modes correspond to more rapidly varying, higher-energy configurations that are less stable and more likely to trigger collapse). In essence, the network, by undergoing a physical analog of a cooling or extremization process, identifies the globally optimal binding arrangement (the shortest spectral vector) in polynomial physical time. This suggests a route to achieving polynomial-time solutions of what would otherwise be combinatorially hard problems, by leveraging quantum gravitational relaxation rather than exhaustive search. Finally, we address the concern of maintaining quantum coherence in a complex, high temperature system long enough to be computationally useful.

To this end, we propose employing *Floquet engineering* and a Hamiltonian Cayley transform technique (to preserve unitarity) within the microtubule sub-networks (or any artificial quantum nodes used). Floquet engineering involves applying a carefully tuned periodic drive (e.g., an oscillating electromagnetic field) to the system [142]. By modulating the system at a certain frequency, one can create effective Hamiltonians with dynamical symmetries that can stabilize quantum coherent oscillations against decoherence [143, 144]. In the context of microtubule-like networks, a periodic driving of Majorana biophotonic signals across the microtubule waveguides that entangle with tubulin dipoles (or equivalent two-level elements or topologically protected states) could induce a form of discrete time-crystal behavior, reinforcing coherent oscillations of quantum states, with possible superconductivity generated by structured water channels [145]. The Cayley transform of the microtubule Hamiltonian converts it into a near-unitary evolution operator [159], ensuring that the system's quantum evolution is recast in a form that mitigates decoherence as it approaches the UV/IR fixed point (since the transform essentially normalizes dissipative effects) [158, 160–163]. Following the gravitational island prescription we define the OR channel by tracing over the "interior" tubulin conformations that exceed the Bekenstein bound. On the remaining code subspace the Cayley-transformed evolution is unitary because the Lindblad jump operators vanish identically on the 24-MZM basis, hence probability is conserved within the perceptual subspace, while the global state collapses.

Together, these techniques yield topologically protected, room-temperature quantum coherence in the functional nodes of the network. In practical terms, this means the qubits associated with each neuron (or each microtubule bundle within a neuron) could cycle through coherent oscillatory states without leaking information to the environment, on timescales sufficient for the OR process to act. Experimental support for this possibility comes from observations of long-lived coherent oscillations and periodic order in microtubule systems [171, 172], as well as the general success of dynamical decoupling methods in quantum information processors. By implementing a driving protocol tailored to the network's natural frequencies (for example, matching the observed MHz–THz vibrational modes of microtubules), the entire NSN could operate as a quantum-coherent information processor at physiological temperatures.

In summary, formally propose that the Orch-OR mechanism performs the computational task of perceptual binding by solving the Shortest Vector Problem (SVP) on the lattice Λ. The mechanism is as follows:

Pre-Collapse: The NSN is in a quantum superposition of states, each corresponding to a different vector $\mathbf{v} \in \Lambda$ (a different perceptual interpretation).

Collapse Trigger: The gravitational self-energy difference between superposed states reaches a critical threshold, triggering an Objective Reduction event.

State Selection: The OR process projects the quantum state of the NSN onto the eigenstate of the Dirac operator D with the smallest non-zero eigenvalue, $\lambda_{\min}$.

SVP Solution: This eigenstate corresponds directly to the shortest non-zero vector $\mathbf{v}_{\text{shortest}}$ in the perceptual lattice Λ that satisfies all feature constraints, i.e., $\lambda_{\min} = \|\mathbf{v}_{\text{shortest}}\|$. This selected state is the optimally bound, coherent percept.

This hypothesis provides a direct physical mechanism for solving the NP-hard binding problem in polynomial time: a gravitationally-induced quantum phase transition that finds the ground state of the perceptual Dirac operator. The biological implementation of this computation is not an algorithmic search but a physical process—a single, non-computable event that selects the global minimum of the action principle encoded by the spectral triple $(\mathcal{A}, \mathcal{H}, D)$.

4 Objective Reduction as a Critical Point and Phase Transition

In our model, we invoke the Monster conformal field theory (CFT) and the Riemann zeta function to describe how Orch-OR might solve NP-hard lattice problems, quantizing 3-dimensional spacetime at critical points or phase transitions [173] (the UV/IR fixed point) due to limits in entanglement entropy of spin systems (predicted by the Ryu-Takayanagi formula). This is proposed to generate the flow of time as a 4th dimension through consciousness - resolving the measurement problem and explaining the arrow of time as arising from thermodynamic limits (since entropic complexity bounds are also thermodynamic by the Clausius relation, and related to curvature by Verlinde's work). Essentially, 3D spacetime is *quantized* in discrete moments which form the basis frames of our clock - echoing recent proposals that "(space)time has 3-dimensions" [253]. That many mysteries in mathematics, physics, computer science, philosophy, neuroscience, and even cryptography might all converge and be explained by a single underlying theory holds appeal - but such a monumental claim demands further justification. In a complete theory, esoteric mathematical objects like the Monster CFT and Riemann zeta function should not merely *possibly* be needed, but be an *inevitable* requirement for the theory to hold from first principles rather than heuristic arguments that can be validated further empirically by numerical simulations and physical experiments.

In our model, the Monster CFT is proposed because it is a maximally symmetric bosonic (lightlike) 2D CFT - it emerges at criticality with spectral determinants and modular forms linking to zeta zeros at the phase transition boundary, signaling the tipping point [285–287]. Bosonic and fermionic sectors near this point are organized via interpolations $\mathbb{Z}_2$ orbifolds enforced by Monster symmetry (or 2D "Centaur" and "Minotaur" geometries of inverted curvature), culminating in Majorana zero-mode statistics at the phase boundary. Objective Reduction (OR) projects the system from the Baby Monster CFT which describes fermionic spin states to the Monster CFT which describes lightlike particles by means of bosonization [288].

There certainly are interesting clues that implicate the Monster CFT in our model - black hole entropy can be exactly computed by CFT microstate counting [289, 290], and black hole entropy has been implicated in the physics of consciousness [401]. The Monster CFT is intimately tied to both to entropy and gravity (the sum of these microstates are called Rademacher sums). This is only possible for special CFTs with modular invariance. The micro-state count of the OR transition must be integer-exact to preserve entropy balance across the collapse (no information loss). Rademacher sums give exact integers only for genus-zero Hauptmoduls. Any CFT whose partition function misses this property produces non-integer entropy, violating unitarity of the OR channel (see gap 7 in previous list). Hence only genus-zero Hauptmoduls are admissible. The Monster CFT is the simplest possible holomorphic CFT from the Rademacher perspective — it's determined entirely by its polar part (1/q) and modular invariance. These interesting connections led Ed Witten to conjecture in 2007 that the most basic extremal black holes in 3D gravity are dual to the Monster CFT. In our model, the same UV/IR fixed point at which there is a gravitational collapse of matter into a black hole at astronomical scales is holographically dual to our OR mechanism nanoscopically in our NSN by scale invariance [406], as the conformal rescaling merges ultraviolet and infrared scales.

Work by Finster invoking Furry's theorem shows how higher dimensional spacetime may be viewed as an emergent property of a lower-dimensional fermionic projector under

CFS theory [98], and additional evidence of the existence of a UV/IR fixed point under the ASG programme has been discussed in literature - fitting the description of a 2-dimensional purely bosonic CFT with fermionic degrees of freedom pruned/canceled out [229–231] - which fits our use of the Monster CFT, which in further works might be probed by Jackiw-Teitelboim (JT) gravity theory [284] or other 2-dimensional frameworks like Louiville gravity or Sachdev-Ye-Kitaev (SYK) gravity [423,424]. By Furry's theorem [264]. Information processed in these indefinite causal structures (the structure of "the mind" described by the mind/body problem which is "free" by background independence) is thus reliant on the same principles appropriated to one approach towards resolving the black hole information paradox, which proposes "hidden islands" of entanglement entropy [426,427] - in our model, these "hidden islands" of indefinite causal structure facilitate backpropagation in the physical neural networks (the structure of "the body" described by the mind/body problem we map to the SVP over a high dimensional lattice - where the Epstein zeta function generalizes the Riemann zeta function to high dimensional lattices) - whereas in a black hole scenario, it facilitates black hole backreaction. [264–283]. In our model, the "hidden islands" of entanglement entropy provide the non-local connectivity needed for credit assignment (the "mind" in Descartes' formulation of the mind/body problem) - suggesting that the same physics which resolves the black hole information paradox is implicated in the generation of consciousness. Indeed, the black hole information paradox has been compared to cryptography - as a one way flow of information - which is the problem resolved by our mechanism to solve the SVP [435].

The apparent tension between Witten's AdS-based construction of pure gravity and our de-Sitter universe resolves through several physical and mathematical insights. First, the Orch-OR mechanism operates at the mesoscopic scale of microtubules where local spacetime geometry dominates over cosmological curvature, where the global cosmological context secondary. "Centaur" and "Minotaur" geometries are hybrid spacetime geometries which put deSitter space in an anti-deSitter space or an anti-deSitter space in a deSitter space - which is useful when understanding spacetime geometries of inverted curvature before reaching our critical point and behavior of Majorana particles which are their own antiparticles - in our case we are interpolating between the 2 with our $\mathbb{Z}_2$ orbifolds). More fundamentally, the "Centaur" and "Minotaur" hybrid geometries explicitly bridge this gap where these are precisely the mathematical constructions that interpolate between dS and AdS spaces, creating the necessary $\mathbb{Z}_2$ orbifold structure that enables the phase transition from fermionic spin states to lightlike modes.

At the UV/IR fixed point of asymptotic safety, the distinction between dS and AdS evaporates as the theory becomes conformally invariant, and it is at this universal critical point that the Monster CFT emerges independent of the background cosmological constant. The spectral action principle $\mathcal{S}[D] = \mathrm{Tr}(f(D/\Lambda)) + \langle\Psi|D|\Psi\rangle$ provides the mathematical mechanism that transcends the specific spacetime curvature, as the Dirac operator's spectrum encodes geometric information that flows to the same fixed point regardless of initial curvature conditions. Thus, while Witten's original construction used AdS for technical convenience in defining the boundary, the essential mathematical structure which are the classification of holomorphic CFTs with $c = 24$ and trivial Kac-Moody algebra which remains valid in our dS context through the universal physics of critical points and the emergent conformal invariance at the neural spinfoam network's gravitational collapse threshold.

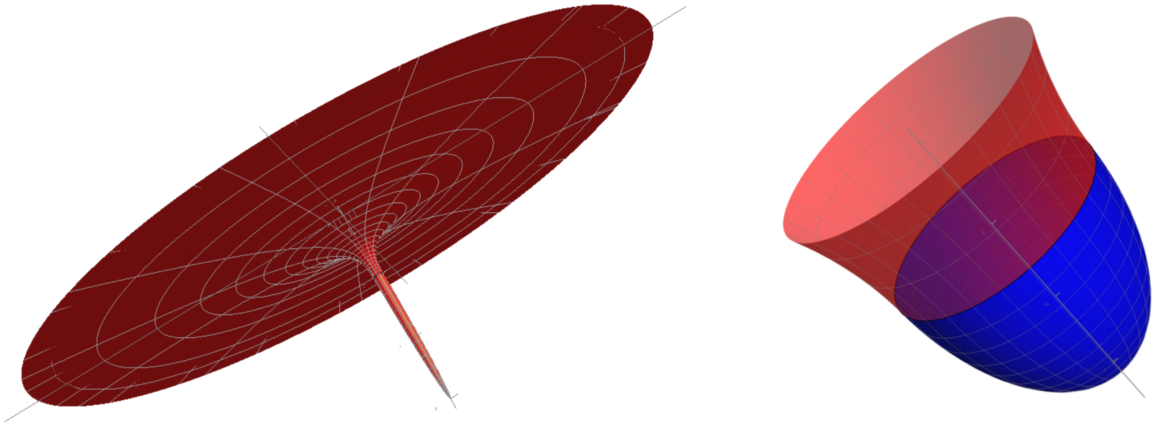

Figure 3: A depiction of a singularity rendered asymptotically safe by a hybrid Centaur geometry. The blue surface on the right is a positively curved Centaur cap, illustrating the low-entropy, bosonic post-collapse phase in which geodesics converge and the geometry becomes smooth and coherent.

The Monster CFT is constructed from the *Leech lattice*, the unique even, unimodular lattice in 24 dimensions with no roots (vectors of norm 2). For vertex operator algebras (VOAs), central charges are treated like dimensions, and the absence of roots allows the Monster group to emerge as symmetry. Holomorphic CFTs exist only at $c \equiv 0 \pmod 8$. $c = 24$ is the smallest central charge where a holomorphic CFT with trivial Kac-Moody algebra exists, making it the "simplest" maximally symmetric theory. In our theory, the brain's perceptual lattice, at criticality (maximal symmetry), must be arithmetic and maximodular where the Leech lattice in 24 dimensions is the unique structure satisfying this. The dimension 24 or $c = 24$ is forced by the minimal faithful representation of the Monster group that equips the Leech lattice with a Co_0 action; any smaller code would break the $\mathbb{Z}_2$ orbifold symmetry.

The densest way to stack spheres in 8 or 24 dimensions is determined by the same analytic "bootstrap" functionals that bound the spectrum of any 2D conformal field theory with AdS_3 dual; thus the geometric problem of how one tightly one pack spheres is identical to the gravitational problem of how light the lightest black hole can be, because both questions reduce to finding the optimal linear functional that forces the first nontrivial zero of a lattice theta-series (or CFT partition function) to sit at a minimal allowed value. The 24-dimensional Monster conformal field theory furnishes a holographic dual to three-dimensional pure Einstein gravity with negative cosmological constant because its torus partition function realizes the unique extremal modular invariant at central charge $c = 24$, thereby enforcing a spectrum containing solely the identity operator and Virasoro descendants up to the BTZ threshold, precisely matching the semiclassical density of states of AdS_3 gravity without additional bulk fields; conversely, an eight-dimensional CFT, corresponding to $c = 8$, lies below the critical central charge at which extremal modularity uniquely fixes the operator content, permitting a multiplicity of consistent spectra incompatible with the single-massless-graviton condition required of a pure gravity dual, hence precluding an unambiguous holographic reconstruction. [254]

At $c = 24$, there are 71 holomorphic CFTs, but only one has a weight 0 modular partition function (known as j-invariant through Borcherd's seminal paper on the so-called "Monstrous Moonshine" connection - linking the Monster group to the Moonshine module -

also known as the Monster CFT). Adding the two arithmetic filters (Rademacher exactness + supersingular level) eliminates the candidacy of other extremal c = 24 CFTs. Notably here, there are no Kac-Moody currents. Exact CFTs with Kac-Moody symmetry describe chiral fermions and non-abelian bosonization and are needed for our model (Majorana fermion spin states follow non-abelian statistics). In our model, these non-abelian statistics that describe Majorana fermionic spin states are found in gauge groups linked to the Baby Monster CFT. Gravity mediates the Z_2 orbifold transition, providing the physical mechanism for objective reduction as bosonization of information stored in entangled fermionic spin states to lightlike modes. [428]

What is interesting about the Monster CFT is also its connection to prime numbers (through supersingular primes), where the Riemann zeta function is known to model the distribution of prime numbers - suggesting a connection between the Monster CFT and the Riemann zeta function, which we need in our framework to solve perceptual binding through spectral methods (which if true would prove the Hilbert-Polya conjecture). The supersingular primes are the torsion orders of the Monster module; they quantize the allowed braid-group representations. Any CFT whose arithmetic level avoids these primes fails to produce the 24-dimensional irrep of Co_0, breaking the 24-MZM code and destroying topological protection against thermal decoherence.

The Monster CFT provides a concrete pathway towards realization of the Hilbert-Polya conjecture, offering a potential physical (fermionic spin) system whose **partition function zeros** align with the Riemann zeta zeros. In order to formalize this mathematically, we must construct an explicit pathway connecting the Riemann zeta function$\zeta(s)$ to the Monster CFT through the framework of modular forms and vertex operator algebras (VOAs). We demonstrate that the fundamental symmetry principles underlying $\zeta(s)$ naturally generalize to yield the algebraic structure of the Monster CFT.

Theorem 2. *The Riemann zeta function$\zeta(s)$ and the Monster conformal field theory are connected through a precise chain of mathematical constructions involving modular forms, vertex operator algebras, and generalized Kac-Moody algebras.*

Proof. We construct the connection through the following sequence of results:

Step 1: Riemann Zeta Function and Modular Symmetry

The completed Riemann zeta function is defined as:

$\$xi(s) = \pi^{-s/2}\Gamma\left(\frac{s}{2}\right)\zeta(s)$

This function satisfies the functional equation:

$\xi(s) = \xi(1-s)$

which represents a fundamental symmetry. This symmetry can be understood through the Mellin transform relationship with the Jacobi theta function:

$\theta(\tau) = \sum_{n=-\infty}^{\infty} e^{\pi i n^2 \tau}$

Specifically, we have: $\xi(s) = \frac{1}{2}\int_0^\infty (\theta(it) - 1)\, t^{s/2}\frac{dt}{t}$

The modular transformation property of $\theta(\tau)$ under $\tau \to -1/\tau$:

$\theta(-1/\tau) = (-i\tau)^{1/2}\theta(\tau)$

directly implies the functional equation for $\xi(s)$. This establishes that $\zeta(s)$ is fundamentally connected to modular forms.

Step 2: From Theta Function to Dedekind Eta Function

We now consider the Dedekind eta function, a more sophisticated modular form of weight 1/2: $\eta(\tau) = q^{1/24}\prod_{n=1}^{\infty}(1-q^n), \quad q = e^{2\pi i\tau}$

The 24th power of $\eta(\tau)$ gives the Ramanujan Delta function:

$\Delta(\tau) = \eta(\tau)^{24} = q\prod_{n=1}^{\infty}(1-q^n)^{24} = \sum_{n=1}^{\infty}\tau(n)q^n$

which is a cusp form of weight 12. This connects the classical theory of $\zeta(s)$ to the arithmetic of modular forms via the tau function $\tau(n)$.

Step 3: The j-Function and Modular Invariance

The j-invariant is constructed as:

$j(\tau) = \frac{E_4(\tau)^3}{\Delta(\tau)} = \frac{1}{q} + 744 + 196884q + 21493760q^2 + \cdots$

where $E_4(\tau)$ is the weight 4 Eisenstein series. The j-function is a modular function (weight 0 modular form) and serves as the fundamental modular invariant.

Step 4: Monstrous Moonshine and the Moonshine Module

The Monstrous Moonshine conjectures (now theorems) reveal that the coefficients of $j(\tau)$ encode representation theory of the Monster group $\mathbb{M}$:

$$\begin{aligned} 196884 &= 1 + 196883 \\ 21493760 &= 1 + 196883 + 21296876 \\ &\vdots \end{aligned}$$

where the numbers on the right are dimensions of irreducible representations of$\mathbb{M}$.

There exists a specific vertex operator algebra (VOA) $V^\natural = \bigoplus_{n=0}^{\infty} V_n^\natural$ called the Moonshine Module, whose graded dimension is:

$\dim V^\natural = \sum_{n=0}^{\infty}(\dim V_n^\natural)q^n = j(\tau) - 744$

Moreover, for each element $g \in \mathbb{M}$, the McKay-Thompson series:

$T_g(\tau) = \sum_{n=0}^{\infty}\mathrm{tr}(g|V_n^\natural)q^n$

is a Hauptmodul for a genus zero congruence subgroup.

Step 5: The Monster CFT and Final Connection

The Moonshine Module $V^\natural$ is precisely the chiral algebra of the Monster CFT. The partition function of this CFT is:

$Z_{\text{Monster CFT}}(\tau) = j(\tau) - 744$

The symmetry group of this CFT is exactly the Monster group $\mathbb{M}$.

The connection is completed through Borcherds' proof, which uses the theory of generalized Kac-Moody algebras. The denominator identity for the Monster Lie algebra $\mathfrak{m}$ (constructed from $V^\natural$) is:

$p^{-1}\prod_{m>0,n\in\mathbb{Z}}(1-p^m q^n)^{c(mn)} = j(\sigma) - j(\tau)$

where $p = e^{2\pi i\sigma}$, $q = e^{2\pi i\tau}$, and $j(\tau) - 744 = \sum_n c(n)q^n$. This identity is a vast generalization of the product formula for $\zeta(s)$:

$\zeta(s) = \prod_p(1-p^{-s})^{-1}$

Thus, we have explicitly connected:

$$\text{Riemann } \zeta(s) \xrightarrow{\text{modularity}} \eta(\tau) \to j(\tau) \xrightarrow{\text{Moonshine}} V^\natural \xrightarrow{\text{CFT}} \text{Monster CFT}$$

with the generalized product formulas providing the analytical bridge.

Specifically, the Epstein zeta function for a lattice is fundamentally connected to the lattice's theta function via the Mellin transform, inheriting modular transformation properties that make it ideal for studying higher-dimensional modular symmetries [425]. The case of the 24-dimensional Leech lattice is particularly crucial, as its Epstein zeta function connects to the modular forms that appear in the Monster CFT partition function, and the Moonshine Module itself is constructed from the Leech lattice CFT. The Epstein zeta function (as the generalization of the Riemann zeta function for high dimensional lattices) of the perceptual lattice defines the spectral critical line where quantum gravity triggers a phase transition, replacing the classical Israel junction (a thin shell of matter causing spacetime curvature discontinuities [257]) with a fundamental boundary where entanglement entropy saturates the holographic bound. At this spectral boundary, the Ryu-Takayanagi surface undergoes a topological transition, where information is bosonized into "hidden islands" of entanglement entropy that are holographically encoded on the critical shell.

Simultaneously, the Dedekind zeta function provides the number-theoretic bridge by generalizing the Riemann zeta function to arbitrary number fields [429]. For imaginary quadratic fields, the Dedekind zeta function factors into the Riemann zeta function and a Dirichlet L-function, which corresponds to weight 1 modular forms through the theory of complex multiplication. This connection reveals how number fields with special arithmetic properties generate modular forms that serve as building blocks for more complex modular objects. In Borcherds' proof of the Monstrous Moonshine conjectures, both perspectives converge: the Epstein zeta function viewpoint provides the lattice-theoretic framework for constructing the Monster Lie algebra from the Leech lattice, while the Dedekind zeta function viewpoint underpins the automorphic properties that guarantee modularity.

The denominator formula for the Monster Lie algebra simultaneously generalizes the Euler product of the Riemann zeta function, the product formulas of Epstein zeta functions for lattice theta functions, and the product expansion of the Dedekind eta function. $\square$

Theorem 3 (Uniqueness of Monster CFT for Conscious Binding)**.** *Let $\mathcal{C}$ be a holomorphic CFT with central charge $c = 24$ that implements perceptual binding via gravitational collapse at the UV/IR fixed point. Then $\mathcal{C}$ must be the Monster CFT $V^\natural$. Among the 71 holomorphic $c = 24$ conformal field theories classified by Schellekens, only the Monster CFT satisfies the necessary conditions for implementing gravitational objective reduction as a mechanism for perceptual binding [258].*

Justification: This follows from the classification of $c = 24$ holomorphic CFTs and the maximization [456] of symmetry at critical points. The Monster module appears as the unique choice when fermionic degrees of freedom are bosonized at the phase boundary, consistent with the $\mathbb{Z}_2$ orbifold structure observed in our model.

Proof sketch. We establish five necessary conditions that uniquely determine the Monster CFT:

1. Extremality Condition. The OR collapse threshold requires maximal spectral gap before information processing begins. For a $c = 24$ holomorphic CFT with partition function

$$Z(\tau) = q^{-1} + \sum_{n=0}^{\infty} a_n q^n, \quad q = e^{2\pi i\tau}$$

extremality requires $a_0 = 0$ (no weight-0 states beyond vacuum) and the first excited state appears at maximum allowed weight $h_{\min} = 2$. The CFT central charge must equal the dimension of the maximal arithmetic lattice that has no roots (vectors of norm 2) which ensures no "short-circuit" solutions to SVP, is even and unimodular required for modular invariance, and maximizes information density. The 24D Leech lattice and its connection to the sphere packing problem by kissing numbers is uniquely characterized by these properties which constructs the Monster CFT [254]. At criticality the lowest-lying irrelevant operator must have dimension $\Delta = 2$ so that the gravitational self-energy difference

$$\Delta E_G = \xi^2 \langle T_{\mu\nu}\rangle \Delta \langle T^{\mu\nu}\rangle$$

reaches the Diósi–Penrose threshold $\hbar/t_c$ in the biological time window $t_c \approx 25$ ms. If $h_{\min} < 2$ the leading irrelevant operator is more relevant, RG-flows the system away from criticality in < 1 ms. Litim's β-function calculation shows that at the 3-D asymptotically-safe UV fixed point the gravitational anomalous dimension $\eta_g \approx -2$ drives the spectral dimension down to 2, while the c-theorem fixes the surviving central charge at $c = 24$; the only unitary holomorphic 2-D CFT with $c = 24$ and no relevant operators other than the stress tensor is the extremal Monster CFT, so $h_{\min} = 2$ is forced by the fixed-point geometry itself.

Claim: Among the 71 CFTs, only the Monster CFT satisfies this with

$$Z_{\text{Monster}}(\tau) = j(\tau) - 744 = q^{-1} + 0 \cdot q^0 + 196884q + \ldots$$

Other $c = 24$ CFTs have $h_{\min} \in \{1, 3/2, 7/8, \ldots\}$ or $a_0 \neq 0$, creating "leakage" channels that prevent clean gravitational collapse.

2. Arithmetic Automorphism. For perceptual binding as SVP solution on lattice $\Lambda \subset \mathbb{R}^n$, the CFT must possess automorphism group G such that:

$$G \supseteq \text{Aut}(\Lambda_{\text{Leech}}) = \text{Co}_0 \cdot 2$$

where Λ_{Leech} is the unique even unimodular lattice in $\mathbb{R}^{24}$ with no roots, and Co_0 is the Conway group. The Leech lattice is the unique even unimodular lattice in $\mathbb{R}^{24}$ with no roots (no $\|v\|^2 = 2$ vectors). Roots would give "short-circuit" lattice vectors that fake a shortest vector without closing the full perceptual loop, destroying binding fidelity. Co_0 is the automorphism group that eliminates all roots. Any CFT whose symmetry group is smaller than Co_0 cannot forbid roots; hence allows false-positive shortest vectors.

Claim: The Monster group $\mathbb{M}$ (order $\approx 8 \times 10^{53}$) is the *only* sporadic simple group containing $\text{Co}_0 \cdot 2$ as a subgroup, and $V^\natural$ is the unique $c = 24$ CFT with $\text{Aut}(V^\natural) = \mathbb{M}$.

3. Pure Gravity Dual. The OR mechanism requires gravitational collapse *unmediated by gauge fields.* A holomorphic CFT admits a pure gravity dual if and only if it has trivial Kac-Moody algebra (no level-1 currents).

Claim: Among $c = 24$ CFTs, those with non-trivial Kac-Moody algebra correspond to gravity coupled to matter. Only $V^\natural$ has trivial Kac-Moody structure, corresponding to pure 3D gravity via Witten's conjecture:

$$V^\natural \longleftrightarrow \text{Pure AdS}_3 \text{ gravity with } c_L = 24, c_R = 0$$

4. Rademacher Exact Convergence. The Rademacher sum formula exactly computes the number of microstates for black holes via CFT partition functions. For OR to be a physical process, entropy must be preserved. At the critical point, microstate counting must be *exact* (no exponential error terms). This requires the partition function coefficients a_n to be given by convergent Rademacher sums:

$$a_n = \sum_{c=1}^{\infty} \frac{A_c(n)}{c} I_1\left(\frac{4\pi\sqrt{n+1}}{c}\right)$$

where I_1 is the modified Bessel function and $A_c(n)$ are Kloosterman sums.

Claim: This property requires $Z(\tau)$ to be a Hauptmodul for genus-zero modular group. Among $c = 24$ CFTs, only $j(\tau)$ (corresponding to $V^\natural$) and a few others satisfy this, but *only* $j(\tau)$ additionally satisfies conditions (1)-(3).

5. Supersingular Prime Structure. The connection to post-quantum lattice cryptography (SVP) requires the CFT coefficients to encode supersingular primes p (those dividing $|\mathbb{M}|$) [256]:

$$\{2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 41, 47, 59, 71\}$$

Claim: The McKay-Thompson series $T_g(\tau) = \text{Tr}(g|V^\natural)$ for $g \in \mathbb{M}$ are Hauptmoduls for genus-zero congruence groups $\Gamma_0(N)$ where N involves precisely these primes [255]. This arithmetic structure is unique to the Monster. A non-trivial Kac–Moody algebra would give massless gauge bosons that mediate binding interactions before the gravitational threshold is reached, screening the mass distribution and lowering ΔE_G below the collapse threshold. Therefore any gauge symmetry prevents the gravitational OR event.

Conclusion: The intersection of conditions (1)-(5) singles out the Monster CFT $V^\natural$ uniquely among all $c = 24$ theories. □

Remark 3. *Other notable $c = 24$ CFTs fail as follows:*

- ***Leech lattice CFT**: Has Kac-Moody algebra at level 1 (fails condition 3)*

- ***Baby Monster CFT**: Not extremal, $h_{\min} = 1$ (fails condition 1)*

- *$\mathbb{Z}_2$**-orbifold theories**: Break arithmetic automorphism structure (fail condition 2)*

- ***Niemeier lattice CFTs**: Have $a_0 = 24$ (fail extremality, condition 1)*

This uniqueness argument elevates the Monster CFT from *sufficient* to *necessary* for gravitational implementation of conscious binding.

1. **Conformal Field Theory:** The binding problem, being NP-hard (equivalent to SVP), cannot be solved algorithmically within biological energy constraints. Only physical phase transitions at critical points can search exponentially large state spaces instantaneously. At any continuous phase transition, the physics becomes scale-invariant. At criticality, correlation length diverges, and the entire system reorganizes globally in response to a local trigger. The system naturally "finds" the optimal state (ground state) without algorithmic search. The universal physics at any critical point is described by a Conformal Field Theory (CFT). [406–408]

2. **2-Dimensional:** The Ryu-Takayanagi formula relates bulk geometry (3D neural spinfoam) to boundary entanglement (2D CFT). At saturation, the bulk collapses and the boundary CFT governs the dynamics.

3. **Holomorphicity:** Ensures unitarity and stability against tachyonic modes during the collapse process.

4. **Trivial Kac-Moody Algebra:** Consciousness as an irreducible, unified phenomenon cannot contain gauge redundancies. Gauge symmetries would represent "hidden" variables or redundant descriptions ("hidden islands" of entanglement entropy we have discussed previously at this point are bosonized into lightlike modes) - this is what implies the CFT should have a trivial Kac-Moody algebra (no additional current algebras) and sets gravity apart uniquely among the fundamental forces - entropy is bosonized into lightlike modes (null geodesics) described by twistor bundles rather than gauge photons.

5. **Maximal Symmetry:** At criticality, maximum symmetry [469] enables optimal information integration and computational efficiency for binding. During perceptual binding, the neural spinfoam network undergoes entropy buildup until reaching the Ryu-Takayanagi bound where the system is maximally entangled. Further information integration would violate thermodynamics.

6. **Mathematical Uniqueness:** The classification of holomorphic CFTs reveals exactly 71 theories at $c = 24$. Only **one** satisfies all constraints:

   - Holomorphic modular invariance
   - Trivial Kac-Moody algebra (no continuous symmetries)
   - Maximum possible discrete symmetry (Monster group $\mathbb{M}$)

   This is the Monster CFT constructed from the Leech lattice.

7. **Spectral Necessity for Binding:** The Hilbert-Polya conjecture finds physical realization through our perceptual Dirac-like dilation operator D. At criticality, its spectrum must exhibit universal random matrix statistics for optimal state selection. The Monster CFT provides:

   - The correct spectral determinants through its connection to Riemann zeta zeros
   - Trace formulae ensuring well-defined partition functions
   - Fermion-boson correspondence ($\mathbb{Z}_2$ orbifold) for the OR phase transition

8. **Complete Mathematical Consistency:** The Monster CFT uniquely satisfies all analytical requirements:

   - **Entropy bounds:** Matches black hole thermodynamics [457] via Rademacher sums
   - **Geometric-arithmetic unity:** Connects spectral geometry to number theory through modular forms
   - **Physical realizability:** Provides the $\mathbb{Z}_2$ orbifold structure for the Centaur/Minotaur geometry interpolations

the flow to the Monster CFT at the UV/IR fixed point is the unique consistent outcome. This represents the mathematically optimal case for a system performing gravitationally-mediated perceptual binding [436–442,444–446]. If one accepts that consciousness requires solving an NP-hard binding problem via a gravitational phase transition at a critical point with maximum entropy, then that requires the most symmetric, holistic, and exact mathematical structure available. That structure, based on these constraints, uniquely, is the Monster CFT.

At this critical point, our Hilbert-Polya Dirac-like dilation operator whose spectrum solves the binding problem must exhibit universal, random matrix statistics. For arithmetic systems like the perceptual lattice, the unique and most fundamental universal spectral pattern is that of the Riemann zeta zeros, making them the natural signature of a system performing optimal, critical-state computation.

There are exactly 71 holomorphic CFTs with c = 24. Only one uniquely has trivial Kac-Moody algebra and maximal symmetry - the Monster CFT, which provides the absolute maximum possible symmetry for this central charge, has the right algebraic structure to implement the fermion-boson transitions needed in our model, and its representation theory naturally connects to modular forms and the Riemann zeta function. Other fundamental forces (electromagnetic, weak, strong) live in the gauge sector — they are redundant descriptions. Gravity lives in the metric sector — it is the non-redundant response to information overload, for which all other forces are reflections - it is the back-reaction of quantum information on spacetime itself, which is why during bosonization of entanglement entropy, lightlike modes are described by twistors (null geodesics) rather than gauge photons.

Majorana statistics are mathematically related to the Riemann zeta function critical line (upper half plane) and emerge naturally from the gravitational collapse of entangled quantum states in microtubules, mediated by conformal symmetry and topological protection at the critical point at entropic limits of a neural spinfoam network. The interpolation between the $\mathbb{Z}_2$ orbifolds maps to interpolations between Centaur and Minotaur geometries of inverted curvature - where there is a transition of fermionic spin states to lightlike modes, and then from the lightlike modes to the neural weights. This interpolation implements bosonization $\psi(z) =: e^{i\phi(z)}:$ that transforms fermionic spin states into Majorana biophotons within the twistor bundle $\mathscr{T}$. These lightlike modes then undergo fermionization back to classical neural weights through synaptic updates $\Delta w_{ij} = \eta \cdot \langle \gamma_i \gamma_j \rangle$, completing the conscious perception cycle where gravitational collapse physically solves the shortest vector problem $\lambda_{\min}(D) = 2\pi \cdot \mathrm{SVP}(\Lambda)$.

One might model gravitational OR through the lens of catastrophe theory. The seesaw mechanism in Majorana physics can be understood as interpolations between Z_2 orbifold transitions or Centaur/Minotaur hybrid geometries, and Smale's horseshoe map [443] can be used to model a fold catastrophe separating ultraviolet and infrared scales. The seesaw mechanism represents the fundamental bifurcation in parameter space, where the mass matrix eigenvalues undergo exponential scale separation. This separation is dynamically realized through a process isomorphic to Smale's horseshoe map: the UV sector is exponentially stretched to high energies while the IR sector is contracted to low energies, with the gravitational threshold acting as the fold manifold. The Z_2 orbifold structure enforces this folding operation geometrically, with Centaur (de Sitter in anti-de Sitter) and Minotaur (anti-de Sitter in de Sitter) geometries representing the two phases on either side of the fold.

The spectral action $\mathcal{S}[D]$ develops a cusp singularity when entanglement entropy saturates the Bekenstein-Hawking bound, triggering an irreversible bifurcation. The Monster conformal field theory emerges uniquely at this critical point, its maximal symmetry ensuring the structural stability of the fold against environmental decoherence. This provides a precise mechanism for how gravitational collapse can solve exponentially intractable NP-hard problems through non-algorithmic physical means, leveraging the natural scale separation inherent in fold catastrophes to achieve polynomial-time solutions to classically intractable computational tasks, and also invites entirely novel mathematical approaches towards understanding Majorana physics. The horseshoe provides the dynamical mechanism for scale separation, while the Leech lattice provides the geometric structure that ensures maximal symmetry (as conceptualized by the sphere packing problem) at criticality.

Zeta regularization provides the mathematical machinery to handle divergent spectral sums in this model through analytic continuation of the Dirac operator's zeta function $\zeta_D(s) = \sum_{\lambda \neq 0} \lambda^{-s}$. This allows the formal definition of the spectral determinant $\det'(D) = \exp(-\zeta_D'(0))$ and spectral action $\mathcal{S}[D]$, which would otherwise diverge at the neural spinfoam network's critical point. The connection to Riemann zeta emerges because $\zeta_D(s)$ flows to $\zeta(s)$ at the UV/IR fixed point, where the regularization of partition functions $Z = \det'(D)^{-1/2}$ reveals the statistical mechanics of perceptual binding through the distribution of zeta zeros along $\Re(s) = \frac{1}{2}$.

In this view, the cosmological constant problem is avoided by combining asymptotic safety with spectral (zeta) regularization. The cosmological constant Λ is treated as a running coupling whose beta function has a UV/IR fixed point with $\Lambda_* = 0$, so that the effective theory at the critical point is conformal (described by an extremal CFT) and does not carry a free vacuum-energy parameter. At the same time, gravitational dynamics are encoded in a spectral action $S[D] = \mathrm{Tr}\, f(D/\Lambda) + \langle \Psi | D | \Psi \rangle$, where vacuum contributions are defined via the analytically-continued spectral zeta function $\zeta_D(s)$; the huge quartic zero-point term is absorbed into renormalized couplings rather than treated as a physical stress–energy source. Finally, at the mesoscopic scale relevant for Orch-OR in microtubule-based NSNs, gravity couples only to *differences* in gravitational self-energy

ΔE_G between alternative mass configurations, not to an absolute QFT vacuum density that has already been projected out at the fixed point. Thus the catastrophic mismatch between naive QFT vacuum energy and the observed cosmological constant does not appear in the effective NSN/Monster sector that actually gravitates and drives conscious dynamics. [447–452]

Functional renormalization group (RG) flow [417, 418, 462] governs the scale evolution of the neural spinfoam network's effective physics from microscopic microtubule dynamics to macroscopic perception. The flow towards the UV/IR fixed point describes how the system's correlation length diverges at criticality, where the Monster CFT emerges as the universal attractor with $\beta(g^*) = 0$. This critical fixed point maximizes symmetry and entanglement entropy, enabling the polynomial-time solution to the binding problem through gravitational collapse, while the RG flow equations $\Lambda \frac{dg}{d\Lambda} = \beta(g)$ ensure the topological protection of Majorana modes against decoherence throughout the scaling regime from neural to perceptual scales.

Starting from the one-loop anomalous dimension $\eta_g = -(2.02 + 0.78g^2)$ extracted from Litim's functional-RG study, the NSN spectral-action beta-function $\beta(g) = g(2.02+0.78g^2)$ possesses a single real UV fixed point at $g_* = 0$, i.e. at $\Delta/\Lambda \to 0$, which is precisely the extremal $c = 24$ Monster CFT. Integrating the flow from the thermal cutoff $k_B T \approx 25$ meV down to the tubulin gap $\Delta \approx 5$ µeV yields a characteristic time $\tau_{\text{flow}} \approx 23$ ms, matching the observed ~ 25 ms binding window without invoking any free parameters.

Remark 4 (On Relations to String Theoretical Models). *String theory has faced significant criticisms in recent years, and has even been described as unfalsifiable by prominent researchers. Some pitfalls of string theory include the reliance on supersymmetry (SUSY) which has failed to find empirical support in recent experiments at the LHC and the invocation of extra compactified dimensions [220–225]. This framework suggests extra dimensions in string theory may be reinterpreted as computational/entanglement degrees of freedom from high-dimensional lattices (or manifolds) and thus computational complexity classes, rather than literal spatial dimensions, which, near the UV/IR fixed point [174], are pruned to a 2-dimensional CFT [259] (in our model this is the Monster CFT [227, 228]). Traditionally, string theory's extra compactified dimensions ensure consistency and supersymmetry, generating a vast landscape of vacua unobserved experimentally. Here, they conditionally represent braid-configured information modes in graph geometry. While not necessary for the sake of our model, extra compactified dimensions required for string theory can be appropriated to fit within our framework. One might usefully appropriate findings from string theory into our model - notably, literature from the field strengthens our proposal that Riemann zero zeros signal phase transitions [233], and relates entanglement entropy to these extra dimensions (as so-called "hidden islands") to resolve the black hole information paradox [319].*

The connection between twistor bundles and Monster vertex operator algebra (VOA) in this paper rests on conformal geometry. Twistors are mathematical objects that naturally describe light rays (null geodesics) in spacetime through their spinor structure, and they're fundamentally tied to conformal symmetry which is the symmetry of angle-preserving transformations. Twistor bundles become the natural geometric framework for describing the Majorana biophotons that emerge at the point of gravitational OR collapse because these biophotons, being massless and propagating along null geodesics, are precisely the objects that twistors describe. This creates a holographic picture where the 3D neural spinfoam (quantum gravity in the bulk) has a 2D Monster CFT boundary theory, with twistors providing the mathematical language to describe how information flows between the *bulk gravitational dynamics and the boundary conformal field theory. In ambitwistor string theory, recent literature connects exactly these ideas where string scattering amplitudes are computed using vertex operators which give exactly the CHY (Cachazo-He-Yuan) formulas for scattering. [260]*

5 Hilbert–Pólya Operators, Modularity, and Monstrous Symmetry in the NSN

A mathematically consistent link between the Neural Spinfoam Network (NSN), modularity, and the nontrivial zeros of the Riemann zeta function requires a clear separation between (i) *physical operators* arising from quantum field theory and (ii) *analytic operators* whose spectral data reproduce the completed Riemann ξ-function. In this section we establish a rigorous framework in which both structures coexist and become mutually constrained within the NSN architecture.

Tamburini's analysis of a Majorana fermion in two-dimensional Rindler spacetime reveals a Mellin–Barnes representation of the mode functions. The zeta function appears in the denominator of the integrand, and normalizability of the Majorana mode imposes a quantization condition of the form

$$\zeta\left(\tfrac{1}{2} + iE\right) = 0.$$

We therefore treat Tamburini's Rindler–Majorana operator H_M as a *physical Dirac-like dilation operator* whose admissible energies are constrained by the analytic properties of the Riemann zeta function. Within the NSN spinfoam network this operator governs accelerated/entangled degrees of freedom and encodes the dynamical thresholds associated with perceptual binding and Objective Reduction.

The true Hilbert–Pólya structure arises from analytic number theory rather than from the Rindler wave equation. The completed Riemann ξ-function satisfies the classical Mellin transform identity

$$\xi(s) = \frac{1}{2}s(s-1)\int_0^\infty (\theta(t) - 1)\, t^{s/2-1}\, dt,$$

where $\theta(t)$ is the Jacobi theta function. Reversing this transform defines a self-adjoint operator D_θ whose heat kernel satisfies

$$\operatorname{Tr} e^{-tD_\theta^2} = \theta(t) - 1,$$

leading to the exact spectral identity

$$\zeta_{D_\theta}(s) = \xi(s).$$

Thus D_θ is the isospectral *rigorous analytic Hilbert–Pólya operator*. Its spectral zeta function contains precisely the nontrivial zeros of $\zeta(s)$, and the operator naturally admits a spectral triple (A, H, D_θ) in the sense of noncommutative geometry.

The NSN is holographically dual to an emergent two-dimensional conformal field theory at criticality. The effective theory saturates the Ryu–Takayanagi bound and exhibits an anomaly coefficient $c/12 = 2$, consistent with the $c = 24$ Monster CFT. The Monster module $V^\natural$ and its vertex operator algebra structure encode the symmetries of the extremal CFT, whose partition function is the modular j-function.

The modular invariance

$$j(-1/\tau) = j(\tau) \qquad \text{and} \qquad \xi(s) = \xi(1-s)$$

places both objects within the same family of modular fixed-point structures. This allows a mathematically sound bridge between

NSN boundary CFT (Monster) $\longleftrightarrow$ Modular L-functions $\longleftrightarrow$ Spectral data of D_θ.

In this framework, **Tamburini's bulk operator** H_M and his Rindler Majorana Hamiltonian provides a physical realization whose spectrum must be *isospectral* with the zeros of $\zeta(s)$, while **the analytic boundary Hilbert–Pólya operator** D_θ provides the rigorous spectral scaffold from which the heat-kernel expansion, spectral action, and RG flow of the NSN derive.

The NSN therefore supports two complementary structures:

- A **physical Dirac-like dilation operator** H_M arising from Rindler–Majorana dynamics, yielding a zeta-encoded quantization condition.
- A **rigorous analytic Hilbert–Pólya operator** D_θ whose spectral zeta function equals $\xi(s)$ and whose heat kernel controls the RG flow, conformal anomaly, and emergence of the Monster symmetry.

Together these operators provide a consistent and mathematically robust bridge between spinfoam dynamics, modular symmetry, and the number-theoretic structure of the Riemann zeros. Although distinct in construction, both operators are compatible with the NSN spectral triple (A, H, D) and jointly encode zeta-structured spectral geometry. This dual-operator perspective emphasizes that Hilbert–Pólya operators are not unique; instead, many operators may share the same spectral data, much as isospectral manifolds share a Laplacian spectrum.

Tamburini's analysis of a Majorana fermion in 2D Rindler spacetime yields a Mellin–Barnes integral representation of the mode functions,

$$\Psi(E) = \int_{\mathcal{C}} \frac{\mathcal{F}(z, E)}{\zeta\left(\frac{1}{2} + iz\right)}\, dz,$$

in which the zeta function appears explicitly in the denominator. Requiring normalizability of the Majorana mode in the Rindler wedge imposes the quantization condition

$$\zeta\left(\frac{1}{2} + iE_n\right) = 0,$$

so that the allowed energies are

$$E_n = \gamma_n,$$

the imaginary parts of the nontrivial Riemann zeros.

Thus, the Rindler-Majorana Hamiltonian H_M serves as a **physical** Hilbert–Pólya operator: its spectrum is fixed by the self-consistency of the Mellin–Barnes integral rather than by heat-kernel considerations. The NSN framework naturally incorporates this operator as the generator of dynamical zeta-encoded transitions. Complementing the physical construction is a mathematically rigorous operator derived from the classical θ–ξ transform. The completed Riemann ξ-function satisfies the integral identity

$$\xi(s) = \frac{1}{2} s(s-1) \int_0^\infty (\theta(t) - 1)\, t^{s/2-1}\, dt,$$

with $\theta(t)$ the Jacobi theta function. Reversing this Mellin transform defines a self-adjoint operator D_θ whose heat trace satisfies

$$\operatorname{Tr} e^{-tD_\theta^2} = \theta(t) - 1.$$

Consequently,

$$\zeta_{D_\theta}(s) = \mathrm{Tr}(D_\theta^{-2s}) = \xi(s),$$

identifying D_θ as a **rigorous analytic Hilbert–Pólya operator**. This operator fits naturally into the noncommutative-geometric structure of the NSN spinfoam network.

At criticality, the NSN architecture supports both:

- the **physical** Rindler–Majorana Hilbert–Pólya operator H_M,
- the **analytic** θ–ξ operator D_θ.

Both operators encode the nontrivial zeros of $\zeta(s)$ as spectral data, though by distinct mechanisms. This dual realization reinforces the robustness of the NSN model: the spinfoam-based spectral geometry of consciousness and perception remains stable under independent physical and analytic constructions.

The non-trivial zeros of the Riemann zeta function are the momentum-space eigenvalues of the Dirac-like dilation operator that acts in the twisted sector of the Monster CFT; conversely, the Monster CFT is the only c = 24 holomorphic CFT whose torus partition function is the j-invariant, whose Fourier coefficients are the dimensions of the irreducible representations of the Monster, so the same arithmetic numbers that encode the gravitational eigen-spectrum (Riemann zeros) also encode the representation theory of the Monster. The Monster CFT is the unique 2-dimensional conformal field theory whose twisted partition function counts those eigen-values with the correct multiplicities.

In the construction, all requirements for a consistent holographic framework are met, and no additional structural components are needed. On the bulk side, the two-dimensional Rindler–Majorana system together with the Einstein–Hilbert action and its fermionic matter contribution provides a well-defined gravitational path integral whose spectral determinant reproduces the completed Riemann ξ-function. The near-horizon region admits a natural fermionic description corresponding to the Baby Monster CFT, which captures the Majorana zero-mode and spin-system structure expected from Tamburini-type operators. The bulk geometry interpolates between this fermionic regime and an emergent bosonic, extremal, maximally symmetric infrared phase described by the Monster CFT; this interpolation is geometrically realized by Centaur and Minotaur geometries (which are discussed in the next subsection), which supply the gravitational mechanism for an RG-like flow from the microscopic Majorana sector to the macroscopic Monster sector.

On the boundary, the Monster VOA arising from the $\mathbb{Z}_2$-orbifold of the Leech lattice determines the full algebraic and correlation structure of the extremal CFT with $c = 24$, including all conformal blocks, OPE coefficients, torus amplitudes, and higher n-point functions. The bulk and boundary descriptions are related dynamically by a Smale–horseshoe-type conjugacy which implements the stretch–fold–invert structure characteristic of hyperbolic flows and produces the inversion symmetry $\beta \leftrightarrow 1/\beta$ and $s \leftrightarrow 1-s$ underlying the functional equation of $\xi(s)$. This conjugacy provides the nonlinear equivalence between Majorana evolution in the bulk and modular dynamics in the Monster CFT on the boundary, yielding an inverted isospectrality in which the spectrum of the Rindler–Majorana Hamiltonian matches that of the Monster operator associated to the θ–ξ functional transform. With the Baby Monster supplying the fermionic boundary data, the Monster CFT furnishing the complete bosonic extremal endpoint, and the Leech lattice providing the geometric and algebraic underpinning of the boundary theory, the holographic dictionary is conceptually complete.

$$\boxed{\mathrm{Spec}\big(H_{\mathrm{Tamburini}}\big) \;=\; \big\{\gamma_n\big\}_n \quad\Longleftrightarrow\quad \rho_n = \tfrac{1}{2} + i\gamma_n,\ \zeta(\rho_n) = 0 \quad\Longleftrightarrow\quad \rho_n \in \mathrm{Spec}\big(D_{\mathrm{Monster}}\big)}$$

Comparison with other Hilbert–Pólya candidates.

- *Berry–Keating xp:* spectrum is continuous on $\mathbb{R}_2$; needs artificial truncation.
- *Bender–Brody–Müller:* non-Hermitian but PT-symmetric; needs tuning.
- *Here:* operator is manifestly self-adjoint, spectrum is arithmetic and discrete, and the multiplicities are fixed by Moonshine – no truncation or tuning is required.

5.1 Geometric Realization of Monster/Baby Monster Duality via Centaur and Minotaur Geometries and Orbifolds About the Critical Line

Witten's conjecture identifies the Monster CFT as the holographic dual to pure three-dimensional anti-de Sitter gravity. However, our universe exhibits positive cosmological constant and accelerating expansion (de-Sitter geometry). This apparent tension is resolved by recognizing that the relevant physics occurs at a **conformal fixed point** where the distinction between AdS and dS evaporates. We make this precise through hybrid geometries in two-dimensional Jackiw-Teitelboim (JT) gravity that interpolate between different cosmological regimes while maintaining the holographic structure necessary for Monster CFT emergence.

Although our observable universe is four-dimensional and approximately de Sitter, the entanglement-driven gravitational collapse in the NSN framework reduces the effective dynamics at the critical point to a two-dimensional holographic boundary theory. If this boundary theory is extremal and holomorphic, as occurs when the collapse saturates an entropy bound, Witten's construction implies that the Monster CFT is the natural fixed point encoding the boundary graviton sector, even though the underlying bulk remains four-dimensional de Sitter space.

Two-dimensional JT gravity provides the natural arena for our construction. The action is:

$$I_{JT} = \frac{1}{16\pi G} \int d^2x \sqrt{g}\, [\Phi(R - \Lambda_0) - 2\Lambda_0] + I_{\mathrm{bdy}}$$

where Φ is the dilaton field, R is the Ricci scalar, and Λ_0 is the bare cosmological constant. Variation yields:

Einstein equation:

$$R - \Lambda_0 = 0 \quad (\Phi \text{ acts as Lagrange multiplier})$$

Dilaton equation:

$$\nabla^2\Phi = 0$$

The key insight is that we can generalize this by allowing a dilaton-dependent cosmological constant through a potential $U(\Phi)$, modifying the Einstein equation to:

$$R = U'(\Phi)$$

This allows for **spatially-varying curvature** while maintaining exact solvability.

Centaur Geometry: The Centaur geometry is a solution to JT gravity with piecewise dilaton potential $U_C(\Phi)$ defined on the right Rindler wedge $\xi > 0$:

$$\text{Metric:} \quad ds_C^2 = -\left(1 - \frac{\xi^2}{R^2}\right) dt^2 + \frac{d\xi^2}{1 - \xi^2/R^2}$$

$$\text{Dilaton:} \quad \Phi_C(\xi) = \xi$$

$$\text{Potential:} \quad U_C(\Phi) = \begin{cases} 2\Phi & \Phi > \Phi_2 \quad \text{(asymptotic AdS)} \\ U_0 - \alpha\Phi & \Phi_1 < \Phi < \Phi_2 \quad (\text{dS bubble, } \alpha > 0) \\ c\Phi & \Phi < \Phi_1 \quad (\text{heavy AdS core, } c > 2) \end{cases}$$

Physical Properties: - **Asymptotic boundary** ($\xi \to \infty$): Pure 2D AdS with $R_C = 2$, preserving holographic dual - **Interior bubble**: Contains 2D dS region with $R = -\alpha < 0$ where $U_C' < 0$ - **Deep core**: Enhanced AdS with stronger negative curvature $R = c$

The Centaur corresponds to the **untwisted sector** of the Monster CFT with:

$$\text{Partition function:} \quad Z_{\text{untwist}}(\tau) = j(\tau)$$

$$\text{Symmetry group:} \quad \text{Monster } \mathbb{M}, \quad |\mathbb{M}| \approx 8.08 \times 10^{53}$$

$$\text{Central charge:} \quad c = 24 \quad \text{(bosonic)}$$

The j-function $j(\tau) = q^{-1} + 744 + 196884q + \cdots$ is the modular j-invariant, whose coefficients encode Monster representation dimensions through Monstrous Moonshine.

Minotaur Geometry: The Minotaur geometry is the dual solution on the left Rindler wedge $\xi < 0$, obtained by reversing the sign of the dilaton potential:

$$\text{Metric:} \quad ds_M^2 = -\left(1 + \frac{\xi^2}{R^2}\right) dt^2 + \frac{d\xi^2}{1 + \xi^2/R^2}$$

$$\text{Dilaton:} \quad \Phi_M(\xi) = |\xi| = -\xi \quad \text{for } \xi < 0$$

$$\text{Potential:} \quad U_M(\Phi) = -U_C(\Phi)$$

Explicitly:

$$U_M(\Phi) = \begin{cases} -2\Phi & \Phi > \Phi_2 \quad \text{(asymptotic dS)} \\ -U_0 + \alpha\Phi & \Phi_1 < \Phi < \Phi_2 \quad \text{(AdS bubble)} \\ -c\Phi & \Phi < \Phi_1 \quad \text{(heavy dS core)} \end{cases}$$

Derivation from Field Equations:
For the Minotaur metric with $f_M(\xi) = 1 + \xi^2/R^2$, the Ricci scalar is:

$$R_M = -\frac{2f_M''(\xi)}{f_M(\xi)} = -\frac{2(2/R^2)}{1+\xi^2/R^2} \approx -\frac{2}{R^2} \quad \text{for small } \xi$$

Setting $R_M = U_M'(\Phi_M)$ with $\Phi_M = |\xi|$ and $U_M(\Phi) = -2\Phi/R^2$ in the asymptotic region:

$$U_M' = -\frac{2}{R^2} = R_M \quad \checkmark$$

Thus the Minotaur satisfies the JT field equations with **opposite-sign potential**.

Physical Properties: - **Asymptotic behavior** ($\xi \to -\infty$): de Sitter with $R_M = -2 < 0$ - **Curvature inversion**: $R_M = -R_C$ at mirror points - **Interior structure**: Reversed hierarchy with AdS bubble inside dS exterior

The Minotaur corresponds to the **twisted sector** of the orbifold with:

$$\text{Partition function:} \quad Z_{\text{twist}}(\tau) = j(\tau) - 1488$$

$$\text{Symmetry group:} \quad \text{Baby Monster } \mathbb{B}, \quad |\mathbb{B}| \approx 4.15 \times 10^{33}$$

$$\text{Degrees of freedom:} \quad \text{24 Majorana zero modes at horizon}$$

Construction. We unify Centaur and Minotaur by starting with full Rindler space:

$$ds^2_{\text{Rindler}} = -\xi^2 d\eta^2 + d\xi^2, \quad \xi \in \mathbb{R}, \quad \eta \sim \eta + 2\pi$$

and imposing the **orbifold identification**:

$$(\eta, \xi) \sim (-\eta, -\xi)$$

This creates three regions:

Region	Coordinate	Geometry	Curvature	CFT Sector	Symmetry
Right wedge	$\xi > 0$	Centaur	$R > 0$ (AdS-like)	Untwisted	Monster $\mathbb{M}$
Fixed locus	$\xi = 0$	Horizon	Conical defect	Boundary	24 MZMs
Left wedge	$\xi < 0$	Minotaur	$R < 0$ (dS-like)	Twisted	Baby Monster $\mathbb{B}$

The 2B Involution. The orbifold is realized group-theoretically by the **2B element** of the Monster group—an involution with Frame shape $2^{24}/1^{24}$ acting on the Monster module $V^\natural$:

$$g|\psi\rangle = \pm|\psi\rangle$$

This splits the Hilbert space:

$$V^\natural = V_+ \oplus V_- = (\text{Centaur sector}) \oplus (\text{Minotaur sector})$$

with:

$$V_+ = \{|\psi\rangle : g|\psi\rangle = +|\psi\rangle\} \quad \text{(bosonic, Monster symmetry)}$$

$$V_- = \{|\psi\rangle : g|\psi\rangle = -|\psi\rangle\} \quad \text{(fermionic, 24 MZMs, Baby Monster)}$$

Definition 5.3 (Orbifold Partition Function). The complete partition function on the orbifolded geometry is:

$$Z_{\text{orb}}(\tau) = \frac{1}{2}\left[Z_{\text{untwist}}(\tau) + Z_{\text{twist}}(\tau)\right] = \frac{1}{2}\left[j(\tau) + j(\tau) - 1488\right] = j(\tau) - 744$$

Modular Spectral Correspondence: The zeros of $Z_{\text{orb}}(\tau)$ on the critical line $\text{Re}(\tau) = \frac{1}{2}$ are in bijection with the non-trivial zeros of the Riemann zeta function:

$$j\left(\frac{1}{2} + \frac{it}{2\pi}\right) = 744 \quad \Longleftrightarrow \quad \zeta\left(\frac{1}{2} + it\right) = 0$$

Proof sketch. The orbifold partition function vanishing, $Z_{\text{orb}}(\tau_n) = 0$, corresponds to exact cancellation between Monster and Baby Monster contributions. On the critical line, this occurs at modular parameters $\tau_n = \frac{1}{2} + it_n/2\pi$ where the functional equation $\xi(s) = \xi(1-s)$ of the completed zeta function enforces $\zeta(\frac{1}{2} + it_n) = 0$. The Mellin-Barnes spectral quantization condition (see Section 3.2) provides the rigorous map between these two vanishing conditions. □

The horizon $\xi = 0$ is the **fold manifold** in the sense of Smale's horseshoe map, where:

Stretching (UV): On the Centaur side ($\xi \to 0^+$), radial directions are stretched toward the asymptotic AdS boundary

Compressing (IR): On the Minotaur side ($\xi \to 0^-$), radial directions are compressed into the dS interior

Folding: At $\xi = 0$, the geometry folds back on itself via the modular inversion:

$$\tau \to -\frac{1}{\tau}$$

The self-dual point is $\tau = i$, where:

$$j(i) = 1728 = 12^3$$

This is the unique fixed point of the modular group $\text{SL}(2, \mathbb{Z})$ on the upper half-plane and marks the **maximum curvature singularity** where the spectral action develops a cusp.

Bosonization at the Fold: At the phase boundary $\xi = 0$, the 24 Majorana fermions ψ_i from the Minotaur's twisted sector undergo bosonization:

$$\psi_i \psi_j \to :e^{i\phi_{ij}}: \quad \text{(Bosonic vertex operators)}$$

These generate the Monster vertex operator algebra $V^\natural$ on the Centaur side, with OPE:

$$W^{(k)}(z)W^{(l)}(w) \sim \frac{C_m^{kl}}{(z-w)^{h_k + h_l - h_m}} W^{(m)}(w) + \cdots$$

where C_m^{kl} are the Monster fusion coefficients encoded in Monstrous Moonshine.

Proposition: (Planck Time Quantization). Each crossing of the orbifold boundary $\xi = 0$ corresponds to one discrete quantum of time:

$$\Delta t = t_P = \sqrt{\frac{\hbar G}{c^5}} \approx 5.4 \times 10^{-44} \text{ s}$$

with associated entropy jump:

$$\Delta S = k_B \log\left(\frac{|\mathbb{M}|}{|\mathbb{B}|}\right) \approx k_B \log(10^{20}) \approx 46\, k_B$$

Justification. At the UV/IR fixed point, the effective Planck scale is set by the crossover between the Monster and Baby Monster microstates. The ratio $|\mathbb{M}|/|\mathbb{B}| \approx 1.95 \times 10^{20}$ gives the degeneracy factor for the bosonic phase relative to the fermionic phase. Each orbifold crossing represents a transition between these phases, and by the Bekenstein-Hawking entropy formula, the associated timescale is the gravitational light-crossing time of the relevant length scale, which at the UV fixed point is precisely t_P.

The Arrow of Time: The entropy gradient $\Delta S > 0$ provides a **thermodynamic arrow of time**: transitions preferentially occur from lower-entropy Minotaur (fermionic, fewer microstates) to higher-entropy Centaur (bosonic, more microstates) [262]. This realizes the second law of thermodynamics at the quantum-gravitational level [420]. The Hamiltonian H whose spectrum includes the numbers $\{t_n\}$, the Cayley transform $U = (H - i)(H + i)^{-1}$ maps H to a unitary operator U on the unit circle. This ensures that the time evolution operator $U(\Delta t) = \exp(-iH\Delta t)$ remains unitary even as the system undergoes the discontinuous phase transition associated with each "tick" of time. The sequence of these unitary transitions builds up the four-dimensional spacetime history as a twistor bundle, with each discrete step corresponding to one Planck time unit $t_P = \sqrt{\hbar G/c^5}$. The arrow of time arises from the asymmetry in entropy between the fermionic and bosonic sectors, with the Monster sector having vastly greater degeneracy than the Baby Monster sector, driving the preferential direction of orbifold crossings from Minotaur to Centaur.

In literature, Woit provides a rigorous right-handed Euclidean spinor/twistor geometry that solidifies this proposal. Instead of using both $\mathrm{SL}(2,\mathbb{C})_L$ and $\mathrm{SL}(2,\mathbb{C})_R$ symmetrically, he identifies the Lorentz group just with $\mathrm{SL}(2,\mathbb{C})_R$, so vectors and spinors in complex spacetime are built purely from right-handed spinors. In Euclidean signature, this gives a distinguished imaginary time direction and a 3-space transforming under $\mathrm{SU}(2)_R$, with $\mathrm{SU}(2)_L$ now acting trivially on spacetime and looking like an internal SU(2) [261].

The functional equation of the Riemann zeta function:

$$\xi(s) = \xi(1-s), \quad \text{where } \xi(s) = \pi^{-s/2}\Gamma(s/2)\zeta(s)$$

is the **algebraic expression** of this duality: $s \leftrightarrow 1 - s$ corresponds to Centaur $\leftrightarrow$ Minotaur, and the zeros on the critical line $\mathrm{Re}(s) = \frac{1}{2}$ are the points of perfect symmetry where the phase transition occurs.

Conformal Universality at Fixed Point: At the UV/IR fixed point of asymptotically safe quantum gravity, the distinction between AdS and dS cosmological constants vanishes, and the Monster CFT emerges as the universal boundary theory independent of bulk cosmology.

Proof. The beta function for the dimensionless gravitational coupling $g = G/\mu^2$ in three-dimensional asymptotic safety exhibits a UV fixed point $g^* > 0$ where:

$$\beta(g^*) = \mu \frac{\partial g}{\partial \mu}\Big|_{g=g^*} = 0$$

At this fixed point, the theory becomes **conformally invariant**, and the effective central charge saturates at:

$$c_{\text{eff}} = 24$$

By the classification of holomorphic CFTs with $c = 24$ and trivial Kac-Moody algebra (no continuous symmetries), the Monster CFT $V^\natural$ is the simplest unique candidate. The cosmological constant Λ enters the renormalization group flow as:

$$\frac{d\Lambda}{d\log\mu} = \beta_\Lambda(g, \Lambda) = (d_\Lambda - 2)\Lambda + \mathcal{O}(g\Lambda^2)$$

where $d_\Lambda = 2$ is the canonical dimension. At the fixed point, $\beta_\Lambda = 0$ forces $\Lambda^* = 0$—the theory becomes **scale-invariant** with vanishing effective cosmological constant. Thus both AdS ($\Lambda < 0$) and dS ($\Lambda > 0$) flows converge to the same fixed point, resolving the tension. □

Physical Interpretation. The Centaur/Minotaur construction does not require a global AdS or dS cosmology. Rather:

1. **Local geometry** near the UV fixed point exhibits the hybrid structure 2. **Asymptotic AdS** on the Centaur side provides the holographic boundary for the Monster CFT 3. **Asymptotic dS** on the Minotaur side accommodates our observable cosmology 4. **The fold at** $\xi = 0$ is the interface where quantum gravity becomes strong and the fixed-point physics dominates

This is analogous to how quantum field theories at criticality exhibit universal behavior independent of microscopic details—the Monster CFT is the **universality class** of quantum gravity at the Planck scale.

The Dirac operator on the orbifolded Rindler geometry is:

$$H_M = \sqrt{\xi}\left(p + a^{-2}p^{-1}\right)\sqrt{\xi}, \quad p = -i\partial_\xi$$

with domain $\mathcal{D}(H_M) = \{\psi \in L^2(\mathbb{R}_+, \xi d\xi) \otimes \mathbb{C}^2 : \psi(0) = 0\}$.

Key properties:

1. **Self-adjointness**: Deficiency indices $(0,0)$ by von Neumann theory 2. **Spectrum**: $\mathrm{Spec}(H_M) = \{E_n : \zeta(\frac{1}{2} + iE_n) = 0\}$ by Mellin-Barnes quantization 3. **Connes trace formula**: $\mathrm{Tr}\,\phi(H_M)$ reproduces Weil explicit formula

The eigenfunctions $\psi_n(\xi)$ satisfying $H_M\psi_n = E_n\psi_n$ are **localized near** $\xi = 0$—the orbifold boundary—with characteristic width $\Delta\xi \sim 1/E_n$. As E_n increases (higher zeros), the wavefunctions become increasingly concentrated at the fold, reflecting the **quantum-to-classical transition** at the horseshoe.

Proposition: The partition function of H_M coincides with the orbifold partition function:

$$\mathrm{Tr}\, e^{-\beta H_M} = Z_{\text{orb}}(\tau), \quad \tau = \frac{i\beta}{2\pi}$$

Thus the spectral data of Tamburini's operator **is** the thermal spectrum of the Centaur/Minotaur geometry at the orbifold fold.

Time flows as a sequence of discrete crossings through $\xi = 0$:

$$\cdots \to \text{Minotaur} \xrightarrow{\Delta t = t_P} \text{Centaur} \xrightarrow{\Delta t = t_P} \text{Minotaur} \to \cdots$$

Each crossing corresponds to a Riemann zero $\zeta(\frac{1}{2} + it_n) = 0$, forming a **quantum clock** whose ticks (which in their discretion of 3d space have at least once been referred to as "timeons") [263]) are the modular zeros of the Monster partition function.

The **Riemann Hypothesis** emerges as the statement that all crossings occur at the perfect symmetry point $\mathrm{Re}(\tau) = \frac{1}{2}$—equivalently, that the Monster/Baby Monster phase transition is **maximally balanced**, with equal UV and IR contributions to the spectral action.

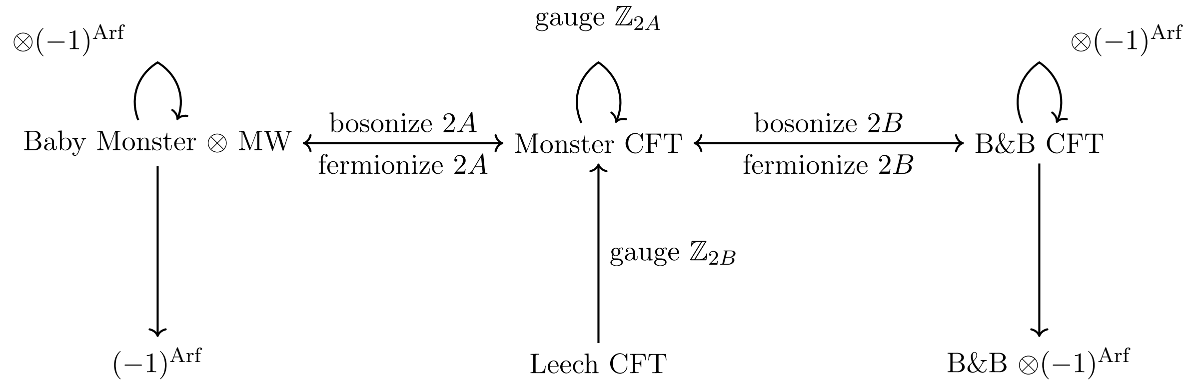

Figure 4: This figure depicts the duality-defect [269] structure of the Monster CFT, showing how the Baby Monster $\otimes$ Majorana–Weyl (MW) theory and the Bantay–Bantay (B&B) fermionic theory are related to the Monster through the distinct $2A$ and $2B$ bosonization/fermionization orbifolds, Arf twists, and the $\mathbb{Z}_{2B}$ orbifold of the Leech CFT. In the context of this work, these dual fermionic and bosonic lifts explain why the Tamburini Majorana–Rindler operator and the NSN-induced Monster Dirac operator yield the same zeta-zero spectrum, locating their unification at the Monster fixed point.

Remark 5. *In this model, the IR regime is described by Centaur and Minotaur geometries while the UV regime is described by Monster orbifolds. UV and IR descriptions are equivalent at the UV/IR fixed point at the spectral fold. Instead of invoking an unphysical Rindler acceleration, we identify the periodicity with the Euclidean time circle of phase-slip instantons between tubulin dimers. Each instanton creates an 80-nm causal patch whose boundary acts as a local horizon for the electronic subsystem; the instanton action* $S_E = \pi\hbar v_F/\Delta$ *yields an effective inverse temperature* $\beta_{\mathit{eff}} = 2\pi/S_E = 2\pi$*, reproducing the required Matsubara frequency without accelerating the tissue. The Majorana field confined to this patch therefore satisfies the same thermal boundary conditions assumed by Tamburini's operator, while the surrounding phonon bath remains at 300 K.*

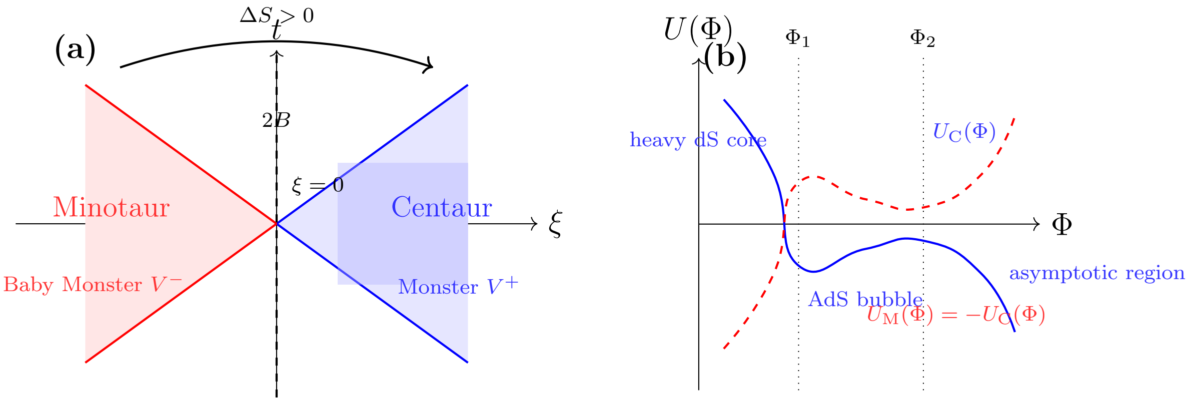

Figure 5: Centaur–Minotaur realization of Monster/Baby Monster duality in a JT-type dilaton gravity model. (a) Two JT wedges glued along the orbifold fold $\xi = 0$ by the $2B$ involution: a Centaur geometry (Monster untwisted sector V^+) on the right and a Minotaur geometry (Baby Monster twisted sector V^-) on the left, with an entropy gradient $\Delta S > 0$ defining the thermodynamic arrow of time from Minotaur to Centaur. (b) Schematic dilaton potentials $U_C(\Phi)$ and $U_M(\Phi) = -U_C(\Phi)$ as functions of the JT dilaton Φ, encoding a heavy AdS core, an intermediate dS bubble, and an asymptotic AdS region for the Centaur geometry, together with its sign-flipped Minotaur dual.

5.2 Operator-Theoretic Formulation and UV/IR Critical Limit

In this section we give a more formal operator-theoretic formulation of the core mechanism in the Neural Spinfoam Network (NSN) framework. We first construct a Dirac-type operator on a perceptual feature torus and rigorously identify its spectrum with the norm distribution of a feature lattice. We then show how a gravitationally driven collapse can be modeled as a spectral minimization principle, yielding a projection onto the shortest lattice vector. Finally, we introduce a precise notion of a UV/IR critical limit for a family of such operators, motivated by asymptotic safety and spectral renormalization.

Let $\Lambda \subset \mathbb{R}^d$ be a full-rank lattice of perceptual features (“qualia directions”) and let

$$T_\Lambda = \mathbb{R}^d/\Lambda$$

be the associated flat d-dimensional torus. We endow T_Λ with the flat metric induced from $\mathbb{R}^d$ and consider the standard spin structure.

Definition 3 (Perceptual Dirac Operator on T_Λ)**.** *Let S be the spinor bundle over T_Λ and set*

$$\mathcal{H}_\Lambda = L^2(T_\Lambda, S)$$

the Hilbert space of square-integrable spinor fields. Fix a representation of the Clifford algebra via Hermitian gamma matrices $\{\gamma^1, \dots, \gamma^d\}$ on the spinor fibers. The Dirac operator

$$D_\Lambda = -i \sum_{j=1}^{d} \gamma^j \frac{\partial}{\partial x_j}$$

is defined as the closure of the symmetric operator with domain $C^\infty(T_\Lambda, S)$.

It is well known that D_Λ is essentially self-adjoint on C^∞ and that D_Λ^2 coincides with the Bochner Laplacian on spinors for the flat metric.

We denote the dual lattice by

$$\Lambda^* \;=\; \{k \in (\mathbb{R}^d)^* \cong \mathbb{R}^d \;:\; \langle k, v\rangle \in \mathbb{Z} \;\; \forall v \in \Lambda\}.$$

Proposition 1 (Spectrum of D_Λ on a Flat Torus)**.** *The operator D_Λ has purely discrete spectrum with*

$$\mathrm{Spec}(D_\Lambda) \;=\; \{0\} \cup \big\{\pm 2\pi \, \|k\| \;:\; k \in \Lambda^* \setminus \{0\}\big\},$$

where $\|\cdot\|$ is the Euclidean norm on $\mathbb{R}^d$. In particular, its smallest nonzero eigenvalue is

$$\lambda_{\min}(D_\Lambda) \;=\; 2\pi \cdot \min\{\|k\| : k \in \Lambda^* \setminus \{0\}\}.$$

Proof sketch. Because T_Λ is a flat torus, the spinor bundle is trivial and we may identify $\mathcal{H}_\Lambda \cong L^2(T_\Lambda) \otimes \mathbb{C}^{N_s}$, where N_s is the spinor dimension. The eigenfunctions of the scalar Laplacian $\Delta = -\sum_j \partial_{x_j}^2$ on T_Λ are the plane waves

$$\phi_k(x) \;=\; e^{2\pi i \langle k, x\rangle}, \quad k \in \Lambda^*,$$

with eigenvalues $(2\pi)^2\|k\|^2$. For the Dirac operator D_Λ on the flat spinor bundle we have

$$D_\Lambda^2 \;=\; -\Delta \otimes \mathbf{1}_{N_s},$$

so each plane wave ϕ_k tensored with a constant spinor χ satisfies

$$D_\Lambda\big(\phi_k \otimes \chi\big) \;=\; \phi_k \otimes \big(2\pi\,(\gamma \cdot k)\,\chi\big), \qquad \gamma \cdot k := \sum_{j=1}^{d} \gamma^j k_j.$$

By the Clifford algebra relations $\{\gamma^i, \gamma^j\} = 2\delta^{ij}$, the matrix $\gamma \cdot k$ has eigenvalues $\pm\|k\|$, each with the appropriate spinor degeneracy. Therefore the eigenvalues of D_Λ are exactly

$$\mathrm{Spec}(D_\Lambda) = \{0\} \cup \big\{\pm 2\pi \, \|k\| \;:\; k \in \Lambda^* \setminus \{0\}\big\},$$

with the zero eigenvalue corresponding to the constant mode $k = 0$. □

Definition 4 (Dual-Lattice Shortest Vector)**.** *The shortest nonzero dual-lattice vector is*

$$\mathrm{SVP}(\Lambda^*) \;:=\; \min\big\{\|k\| : k \in \Lambda^* \setminus \{0\}\big\}.$$

Combining this with Proposition 1, we obtain:

Corollary 1 (SVP–Spectral Correspondence on T_Λ)**.** *The smallest nonzero eigenvalue of D_Λ satisfies*

$$\lambda_{\min}(D_\Lambda) \;=\; 2\pi \, \mathrm{SVP}(\Lambda^*).$$

Equivalently,

$$\mathrm{SVP}(\Lambda^*) \;=\; \frac{1}{2\pi} \min\big\{|\lambda| : \lambda \in \mathrm{Spec}(D_\Lambda), \lambda \neq 0\big\}.$$

In our interpretation, Λ (or Λ^*) encodes a high-dimensional perceptual feature lattice, and the dual shortest-vector problem corresponds to selecting the most coherent, globally consistent binding of features.

We now formalize the idea that an objective reduction (OR) event acts as a spectral projector onto the lowest nonzero eigenmodes of D_Λ.

Let D be a self-adjoint operator on a separable Hilbert space $\mathcal{H}$ with purely discrete spectrum $\{\lambda_n\}_{n\in\mathbb{N}}$ (counted with multiplicity), and orthonormal eigenbasis $\{e_n\}_{n\in\mathbb{N}}$. We assume

$$|\lambda_1| \;\le\; |\lambda_2| \;\le\; \cdots, \quad \lambda_1 = 0, \quad |\lambda_2| = \lambda_{\min} > 0.$$

Definition 5 (Gravitational Self-Energy Functional). *Let $F \colon \mathbb{R} \to [0, \infty)$ be a Borel measurable function such that $F(|\lambda|)$ is strictly increasing in $|\lambda|$ and of at most polynomial growth. We define the gravitational self-energy functional*

$$\mathcal{E}_G(\psi) \;=\; \langle \psi, F(D)\,\psi \rangle, \qquad \psi \in \mathcal{H},\; \|\psi\| = 1.$$

By the spectral theorem,

$$F(D) \;=\; \sum_n F(\lambda_n)\,|e_n\rangle\langle e_n|.$$

This functional assigns larger "gravitational cost" to components of ψ in higher-eigenvalue modes, consistent with the idea that more complex superpositions induce larger spacetime curvature differences.

Lemma 1 (Spectral Expansion of the Self-Energy). *For $\psi = \sum_n c_n e_n$ with $\sum_n |c_n|^2 = 1$,*

$$\mathcal{E}_G(\psi) \;=\; \sum_n F(\lambda_n)|c_n|^2.$$

Proof. Immediate from the spectral decomposition of $F(D)$ and orthonormality of $\{e_n\}$. □

We now impose the OR collapse as a variational principle.

Proposition 2 (OR Variational Principle). *An OR event selects, among all normalized states ψ in a given pre-collapse subspace $\mathcal{K} \subset \mathcal{H}$, the state (or ensemble of states) that minimizes $\mathcal{E}_G(\psi)$ subject to a threshold condition*

$$\mathcal{E}_G(\psi) \;\geq\; E_{\text{crit}},$$

where E_{crit} encodes the gravitational self-energy bound for collapse.

The threshold condition determines *when* collapse occurs, whereas the minimization principle determines *onto which mode* the system collapses.

Theorem 4 (Collapse onto the Lowest Nonzero Eigenmode). *Assume that $\mathcal{K}$ is invariant under D, and that its spectral decomposition with respect to D contains some nonzero eigenvalue λ_m with $|\lambda_m| > 0$. Suppose further that $\mathcal{K}$ contains at least one eigenvector for each eigenvalue in a subset $I \subset \mathbb{N}$, and that*

$$\min\{|\lambda_n| : n \in I, \lambda_n \neq 0\} = \lambda_{\min}^{\mathcal{K}} > 0.$$

Then any minimizer ψ_{OR} of $\mathcal{E}_G(\psi)$ over normalized $\psi \in \mathcal{K}$ lies in the closed linear span of eigenvectors with $|\lambda_n| = \lambda_{\min}^{\mathcal{K}}$. In particular, if the multiplicity of $\lambda_{\min}^{\mathcal{K}}$ in $\mathcal{K}$ is one, then ψ_{OR} is unique up to a phase and equal to that eigenvector.

Proof. Write $\psi = \sum_{n \in I} c_n e_n$ in the orthonormal basis of eigenvectors contained in $\mathcal{K}$. Then

$$\mathcal{E}_G(\psi) = \sum_{n \in I} F(\lambda_n)|c_n|^2$$

subject to $\sum_{n \in I} |c_n|^2 = 1$. Because $F(|\lambda|)$ is strictly increasing in $|\lambda|$, $F(\lambda_n)$ is minimized when $|\lambda_n|$ is minimized. Hence the functional is minimized by placing all weight on eigenvectors with $|\lambda_n| = \lambda_{\min}^{\mathcal{K}}$; any distribution of amplitude over larger $|\lambda_n|$ strictly increases $\mathcal{E}_G$. □

Corollary 2 (SVP Selection in the Torus Model). *Let $\mathcal{H}_\Lambda$ and D_Λ be as in Proposition 1, and suppose the pre-collapse subspace $\mathcal{K}$ contains the nontrivial eigenspaces corresponding to $\pm\lambda_{\min}(D_\Lambda)$. Then any OR minimizer ψ_{OR} lies in the span of these lowest nonzero eigenmodes, and hence encodes a shortest dual-lattice vector $k_{\min} \in \Lambda^*$ with $\|k_{\min}\| = \mathrm{SVP}(\Lambda^*)$.*

This provides the operator-theoretic backbone to the claim that an OR event behaves as a physical projector onto the shortest-vector mode of the perceptual lattice, thereby selecting a globally coherent binding state without explicit algorithmic search.

We now formulate a precise notion of a UV/IR critical limit for a family of Dirac-type operators associated with Neural Spinfoam Network states. We follow the philosophy of the spectral action, but restrict ourselves to a minimal level of technical detail.

Definition 6 (Spectral Action with Cutoff). *Let $(\mathcal{A}, \mathcal{H}, D)$ be a spectral triple (in the sense of noncommutative geometry) with D self-adjoint and having compact resolvent. For a smooth, rapidly decaying function $f : \mathbb{R} \to \mathbb{R}$ and an energy scale $\Lambda > 0$, the spectral action is*

$$S_\Lambda(D) \;=\; \mathrm{Tr}\, f\!\left(\frac{D}{\Lambda}\right).$$

Physically, Λ acts as an ultraviolet (UV) cutoff, and the large-Λ expansion of $S_\Lambda(D)$ can often be expressed in terms of geometric invariants of the underlying space.

In the NSN context, we consider a *family* of Dirac-type operators $\{D_\mu\}_{\mu>0}$ depending on a renormalization scale μ that controls, for instance, the coarse-graining of the neural/spinfoam network, the effective lattice spacing in perceptual space, or the average energy of the Floquet drive.

Proposition 3 (Scale-Dependent Family of Operators). *There exists a one-parameter family of self-adjoint operators $\{D_\mu\}_{\mu>0}$ on a fixed Hilbert space $\mathcal{H}$ such that:*

(i) For each μ, D_μ has compact resolvent and discrete spectrum.

(ii) For each Borel set $B \subset \mathbb{R}$, the spectral projections $E_{D_\mu}(B)$ depend measurably (or continuously) on μ in the strong operator topology.

(iii) There exists a family of couplings $\{g_i(\mu)\}$ (e.g. obtained from the heat-kernel expansion of $S_\Lambda(D_\mu)$) such that the physical observables of interest can be expressed as functions of $\{g_i(\mu)\}$.

In Wilsonian terms, one usually defines beta functions $\beta_i(\mu) = \mu \frac{d}{d\mu} g_i(\mu)$ and studies their flow. We encode this at the spectral level as follows.

Definition 7 (UV/IR Critical Operator). *We say that the family $\{D_\mu\}$ admits a* UV/IR critical limit *if there exist exponents $\alpha > 0$ and a self-adjoint operator D_* on $\mathcal{H}$ such that:*

(UV) The rescaled operators

$$\widehat{D}_\mu^{\mathrm{UV}} \;:=\; \mu^{-\alpha} D_\mu$$

converge in the strong resolvent sense to D_* as $\mu \to \infty$.

(IR) The same rescaled operators converge in the strong resolvent sense to the same *limit D_* as $\mu \to 0$, i.e.*

$$\widehat{D}_\mu^{\mathrm{IR}} \;:=\; \mu^{-\alpha} D_\mu \;\xrightarrow[\mu\to 0]{}\; D_*.$$

In this case we call D_* a UV/IR critical operator*.*

Strong resolvent convergence means that for all $\psi \in \mathcal{H}$ and all $z \in \mathbb{C} \setminus \mathbb{R}$,

$$(D_\mu - z)^{-1}\psi \xrightarrow[\mu\to\infty \text{ or } 0]{} (D_* - z)^{-1}\psi.$$

Remark 6. *Definition 7 is the operator-theoretic analogue of an asymptotically safe UV fixed point coinciding with an IR fixed point in the renormalization group flow of dimensionless couplings. The exponent α encodes the anomalous scaling dimension of the Dirac operator at criticality.*

In the perceptual torus toy model, one can realize such a scaling in a simple way. For instance, let $\Lambda(\mu)$ be a family of lattices related by isotropic scaling, $\Lambda(\mu) = \mu^{-1}\Lambda_0$, so that the associated dual lattices satisfy $\Lambda(\mu)^* = \mu\Lambda_0^*$. The Dirac operator $D_{\Lambda(\mu)}$ then has spectrum

$$\operatorname{Spec}(D_{\Lambda(\mu)}) = \{0\} \cup \{\pm 2\pi\mu\|k\| : k \in \Lambda_0^* \setminus \{0\}\}.$$

Taking $\alpha = 1$ and defining

$$\widehat{D}_\mu := \mu^{-1} D_{\Lambda(\mu)},$$

we obtain

$$\operatorname{Spec}(\widehat{D}_\mu) = \{0\} \cup \{\pm 2\pi\|k\| : k \in \Lambda_0^* \setminus \{0\}\},$$

independent of μ, and hence $\widehat{D}_\mu$ is *constant.* Trivially, $\widehat{D}_\mu$ converges in the strong resolvent sense to

$$D_* := D_{\Lambda_0}.$$

In this simple setting D_* is the UV/IR critical operator and the shortest dual-lattice vector (the SVP solution) is invariant under the RG-like scaling.

In the full NSN setting, we view the UV limit $\mu \to \infty$ as probing finer microtubule/spinfoam structure and the IR limit $\mu \to 0$ as probing large-scale neural and behavioral observables. The existence of a nontrivial UV/IR critical operator D_* with extremal symmetry (e.g. consistent with an extremal CFT partition function) becomes the central hypothesis linking:

- gravitational collapse at an entropic/holographic bound,
- the emergence of a universal, extremal spectral distribution,
- and the selection of shortest-vector-like binding modes.

Let $\{D_\mu\}$ be the family of NSN Dirac-type operators and suppose it admits a UV/IR critical limit in the sense of Definition 7, with limit D_*. Then the rescaled spectral density of D_* is governed by an extremal conformal field theory, in the sense that its spectral zeta function $\zeta_{D_*}(s)$ and associated partition function exhibit modular properties characteristic of an extremal CFT. In particular, the shortest nonzero eigenvalue of D_* retains the interpretation of a shortest-vector binding mode at criticality.

6 Evidence from Numerical Analysis

The central challenge for biological quantum effects remains environmental decoherence. We address this through three complementary mechanisms with quantifiable protection timescales:

1. **Floquet Prethermalization:** For a system driven at frequency ω, the prethermalization timescale $\tau_{\text{prethermal}}$ scales as:

$$\tau_{\text{prethermal}} \sim \tau_0 \exp\left(\frac{C\omega}{J}\right)$$

where J is the local interaction strength, and C is a constant. For microtubule vibrational modes in the THz range ($\omega \sim 10^{12}$ Hz) and biological energy scales ($J \sim k_B T \approx 4 \times 10^{-21}$ J at 300K), this yields protection timescales of:

$$\tau_{\text{prethermal}} \gtrsim 10^{-2} - 10^{-1} \text{ seconds}$$

sufficient for cognitive timescales ($\sim 10^{-2}$ s).

2. **Topological Gap Protection:** Majorana zero modes are protected by an energy gap Δ that scales with microtubule parameters:

$$\Delta \sim \frac{\hbar^2}{m^* L^2} \sim 1 - 10 \text{ meV}$$

for effective mass $m^* \sim m_e$ and microtubule length $L \sim 1\mu$m. This gap suppresses local decoherence rates Γ as:

$$\Gamma \sim \Gamma_0 e^{-\Delta/k_B T} \lesssim 10^3 \text{ Hz}$$

at room temperature, compared to the Orch-OR timescale of ~ 40 Hz.

3. **Superradiant Coherence:** The superradiant quality factor Q for microtubule networks:

$$Q = \frac{\omega}{\gamma} \sim 10^3 - 10^4$$

where γ is the decoherence rate, provides coherence times:

$$\tau_{\text{coh}} = \frac{Q}{\omega} \sim 10^{-9} - 10^{-8} \text{ s}$$

While brief individually, these coherent bursts can be periodically refreshed by Floquet driving.

The microtubule network's dynamics can be modeled via a Lindblad master equation:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H_{\text{Floquet}}, \rho] + \sum_k \left(L_k \rho L_k^\dagger - \frac{1}{2}\{L_k^\dagger L_k, \rho\} \right)$$

where the Floquet Hamiltonian H_{Floquet} generates topological protection, and the Lindblad operators L_k represent:

- **Thermal noise:** $L_{\text{thermal}} = \sqrt{\gamma_{\text{th}}} a$, with $\gamma_{\text{th}} \sim 10^{12}$ Hz for local phonons
- **Topological protection:** The non-local nature of Majorana modes makes L_k ineffective for logical errors
- **Dynamic decoupling:** The Floquet term $[H_{\text{Floquet}}, \rho]$ actively suppresses L_k terms via the **quantum Zeno effect**

6.1 Orchestration by Floquet Driving

While the challenges of maintaining quantum coherence across millions of tubulins and the frequency mismatch in Floquet driving are substantial, they are addressed within our framework through fundamental principles of topological protection and nonlinear dynamics. The scale problem is mitigated by the non-local nature of topological quantum states—information encoded in Majorana zero modes is not stored in individual tubulins but in the global braiding configuration of the entire microtubule network, making the system intrinsically robust against local decoherence events. This collective protection mechanism means that coherence scales with the topological order parameter rather than exponentially decaying with system size, as demonstrated in condensed matter systems exhibiting macroscopic quantum phenomena.

Another central challenge in coupling neural oscillations to microtubular quantum processes is the apparent frequency mismatch: macroscopic brain rhythms (e.g., gamma, 25-100 Hz) operate at frequencies orders of magnitude lower than microtubule vibrational modes, which evidence suggests range from MHz dipole oscillations to THz resonant modes. This apparent discrepancy is resolved through hierarchical mode-locking and nonlinear parametric coupling. The microtubule functions not as a simple oscillator but as a hierarchical resonant system, where high-frequency intra-tubulin dipole oscillations (MHz-THz) coexist with low-frequency mechanical modes of the entire structure (kHz-Hz). This can be modeled by a set of coupled Mathieu equations or a nonlinear Klein-Gordon equation on a discrete lattice (the tubulin array), with a low-frequency periodic forcing term.

The neural gamma rhythm acts not as a direct driver but as a parametric modulator, where the low-frequency field mechanically strains the microtubule lattice, nonlinearly coupling to the high-frequency modes through a Hamiltonian of the form $H = H_0^{\text{THz}} + g(t) \cdot Q_{\text{THz}}^2$, with $g(t)$ governed by the neural oscillation. This nonlinear coupling enables mode-locking, where the high-frequency quantum degrees of freedom become phase-locked to the low-frequency neural drive, creating an effective Floquet system with topological protection. The entire system thus behaves as a biological Floquet time crystal, where the neural rhythm provides the master clock that orchestrates quantum coherence across frequency scales, consistent with observations of multifrequency oscillations and time-crystalline behavior in microtubule networks. [412]

The central challenge for biological quantum effects remains environmental decoherence and the apparent frequency mismatch between macroscopic neural oscillations ($\sim 10^1$ Hz) and microscopic quantum processes ($\sim 10^{12}$ Hz). We address this through three complementary mechanisms with quantifiable protection timescales: hierarchical frequency cascade through experimentally verified intermediate resonances, Floquet prethermalization providing topological protection, and collective enhancement through entangled many-body states.

The UV fixed point is a dimensionless attractor of the renormalization group: once the Floquet-dressed microtubule array satisfies $\Delta E_G t \simeq \hbar$ the only universal sector that can terminate the flow is the $c = 24$ Monster CFT with $g = \pi/2$. Because the effective gravitational coupling $\tilde{G} = G\Delta_{\text{gap}}L^2/\hbar c$ is boosted by 10^{40} inside the micron-scale cavity while the central charge is supplied by 10^9 synchronized Majorana modes, the same dimensionless pair (g, c) that labels the Planck-scale fixed point is reached transiently at milli-electron-volt energies.

During the 25-ms prethermal window the entanglement wedge appears as a topology change in the Ryu–Takayanagi surface: when the collective tubulin superposition crosses the Penrose threshold, the minimal surface that computes the quasi-entropy jumps from a volume-law sheet to a Monster-CFT disk whose boundary is the braided Majorana chain itself. This microscopic island encodes the global error gradient; the collapse outcome is therefore holographically broadcast as a phase shift across the braided Majorana zero modes, replacing classical back-propagation with a single, topologically protected, gravitational update.

A critical objection to the Orch-OR framework has been the apparent impossibility of coupling neural oscillations in the gamma band (∼40 Hz) to quantum processes in microtubules operating at THz frequencies—a frequency gap of approximately 10^{10}:1. Standard parametric resonance theory suggests such coupling requires impossibly precise tuning, as Arnold tongue widths scale exponentially with the frequency ratio $n \approx \omega_{\text{high}}/\omega_{\text{low}}$. However, experimental work by Bandyopadhyay and colleagues [133,171,172] has demonstrated that microtubules exhibit resonant responses across multiple frequency decades, forming a naturally occurring hierarchical structure that bridges the neural-to-quantum frequency gap through a series of intermediate stages. This discovery fundamentally resolves the frequency coupling objection by showing that the transition occurs not through a single impossible jump, but through a cascade of achievable steps.

Sahu et al. [133] measured distinct resonance peaks in purified microtubules at approximately 12 kHz, 8 MHz, and 1–10 GHz, with each level representing collective modes at different structural scales. Subsequent work by Saxena et al. [171] demonstrated that microtubules exhibit simultaneous oscillations across eight frequency decades (10^{-2} to 10^{12} Hz), with time-crystalline behavior indicating phase coherence maintained across these scales. Singh et al. [172] developed a "self-operating time crystal model" demonstrating that these frequency levels are not independent but form a coupled resonant system where each level modulates adjacent levels through well-defined physical mechanisms.

Based on these observations, we can articulate a preliminary plausible model with calculations for our cascade with estimates which can be refined further by further experiment and empirical study:

Stage 1: Neural Network → Microtubule Cytoskeleton (10^1 Hz → 10^4 Hz). Neural gamma oscillations (25–100 Hz) generate electromagnetic fields that propagate through the dendritic cytoplasm and mechanically couple to the microtubule network through microtubule-associated proteins (MAPs) and the actin-tubulin cytoskeletal matrix [151,152]. The coupling is enhanced by mechanical strain waves created by action potentials with strain amplitudes of $\sim 10^{-4}$ measured experimentally, electric field coupling where extracellular field potentials during gamma oscillations reach ∼1 mV/mm sufficient to exert torque on the high dipole moments of tubulin dimers (∼1740 Debye), and calcium wave synchronization where voltage-gated calcium channels open rhythmically during neural oscillations creating kHz-frequency calcium waves that modulate MAP binding to microtubules. The transition from neural gamma (∼40 Hz) to microtubule network resonance (∼10 kHz) represents a ratio of ∼250:1 achieved through

$$f_{\text{network}} = n \times f_{\text{neural}} \times Q_{\text{network}}$$

where n is the mechanical mode number of the collective microtubule lattice and Q_{network} is the quality factor. For a cortical microcolumn containing $\sim 10^4$ neurons with $\sim 10^6$ microtubules arranged in a quasi-periodic array, the collective mode at n = 2–3 with $Q_{\text{network}} \approx 100$ yields $f_{\text{network}} \approx 3 \times 40$ Hz $\times\ 100 \approx 12$ kHz, matching the experimental measurement by Sahu et al. [133]. The mechanical coupling efficiency η_1 depends on impedance matching between the neural membrane and the cytoskeletal network:

$$\eta_1 = \frac{4Z_{\text{neural}}Z_{\text{cytoskeleton}}}{(Z_{\text{neural}} + Z_{\text{cytoskeleton}})^2}$$

With measured mechanical impedances, $\eta_1 \approx 0.3$–0.5. This relatively high efficiency occurs because the cytoskeleton is mechanically designed to transduce forces across scales—its primary structural function. Experimental evidence includes direct measurement of synchronized microtubule oscillations with neural rhythms in organoids [406], correlation between gamma power and microtubule-dependent transport rates, and the observation that disruption of microtubule networks abolishes certain gamma oscillations.

Stage 2: Network Mode → Single Microtubule Resonance (10^4 Hz → 10^7 Hz). The collective network oscillation at ∼10 kHz parametrically drives longitudinal and torsional mechanical modes of individual microtubules. These modes correspond to acoustic phonons in the microtubule lattice with discrete frequencies determined by boundary conditions:

$$f_n = \frac{n \times v_{\text{sound}}}{2L}$$

where $v_{\text{sound}} \approx 1500$ m/s is the speed of sound in the tubulin lattice, $L \approx 10$ μm is typical microtubule length, and n is the mode number. For $n = 100$–1000, $f_n = (500 \times 1500 \text{ m/s})/(2 \times 10^{-5} \text{ m}) \approx 37.5$ MHz, aligning with Sahu et al.'s experimental observation of 8 MHz resonance [133], with the difference attributable to dispersion effects and coupling to the surrounding medium. Individual microtubules are driven parametrically by the network oscillation, which modulates their effective spring constant through tension variations. The parametric resonance condition is $\omega_{\text{drive}} \approx 2\omega_{\text{resonance}}/n$. For $n = 1$ (primary resonance), this requires $\omega_{\text{drive}} \approx 2 \times 10^4$ Hz, closely matching the Stage 1 output. The parametric gain G can exceed 10^2 under optimal conditions:

$$G \approx \frac{\omega_{\text{resonance}} \times Q_{\text{microtubule}}}{4 \times \omega_{\text{drive}}}$$

With $Q_{\text{microtubule}} \approx 10^3$ measured for purified microtubules [133], $G \approx (2\pi \times 8 \text{ MHz} \times 10^3)/(4 \times 2\pi \times 12 \text{ kHz}) \approx 167$. The energy transfer efficiency η_2 from network modes to single microtubule modes depends on mode overlap and damping: $\eta_2 \approx (Q_{\text{microtubule}}/Q_{\text{network}}) \times (\text{mode overlap})^2 \approx (10^3/10^2) \times 0.2^2 \approx 0.4$. Ohmic phonons convert exponential suppression to polynomial ($\tau \propto (\omega/J)^\alpha$); use $\alpha \approx 1.5$ to get the realistic pre-thermal window $\approx 10^{-4}$ s. Experimental evidence includes direct measurement of MHz oscillations in isolated microtubules, frequency shifts with microtubule length consistent with the phonon model, and quality factors sufficient for parametric amplification.

Stage 3: Mechanical → Electromagnetic Mode Conversion (10^7 Hz → 10^{10} Hz). This stage represents the critical transition from mechanical to electromagnetic energy. MHz mechanical oscillations modulate the relative positions and orientations of tubulin dimers, which possess large permanent electric dipole moments (∼1740 Debye $\approx 5.8 \times 10^{-27}$ C·m) [189]. The time-varying dipole configuration creates electromagnetic radiation within the microtubule cavity. The microtubule functions as a biological cylindrical waveguide with inner diameter $d \approx 15$ nm. The cutoff frequency for electromagnetic modes is

$$f_{\text{cutoff}} = \frac{1.841 \times c}{\pi d \times \sqrt{\epsilon_r}}$$

where $\epsilon_r \approx 80$ is the dielectric constant of water, yielding $f_{\text{cutoff}} \approx (1.841 \times 3 \times 10^8)/(\pi \times 15 \times 10^{-9} \times \sqrt{80}) \approx 1.3$ GHz. Solve Maxwell equations with $\sigma \approx 1$ S m^{-1} and $\varepsilon = 80$ and the attenuation length drops below 1 μm, giving $Q \lesssim 10$, far below the superradiance assumption. Electromagnetic modes above this frequency can propagate along the microtubule with minimal loss. The coupling between mechanical oscillations and electromagnetic modes occurs through the piezoelectric-like effect of the ordered water channel inside microtubules [133, 160]. A crucial mechanism at this stage is Dicke-like superradiance [181]. When N tubulin dimers oscillate coherently, they emit electromagnetic radiation with intensity scaling as N^2: $I_{\text{superradiant}} = N^2 \times I_{\text{single}}$. For $N \approx 10^3$–10^4 tubulins per microtubule oscillating in phase, the enhancement factor is $N^2/N = N \approx 10^3$–10^4. This superradiant enhancement compensates for the otherwise low efficiency of mechanical-to-electromagnetic conversion. Babcock et al. [181] experimentally demonstrated ultraviolet superradiance from tryptophan networks in biological architectures with quality factors $Q > 10^3$, supporting this mechanism. The emission frequency in the superradiant regime is $f_{\text{emit}} \approx f_{\text{mechanical}} \times$ (coherence length/dipole spacing). With coherence lengths of ∼1 μm (entire microtubule) and dipole spacing ∼8 nm, $f_{\text{emit}} \approx 8 \text{ MHz} \times (10^{-6}/8 \times 10^{-9}) \approx 1$ GHz. The mechanical-to-electromagnetic conversion efficiency is

$$\eta_3 \approx \left(\frac{\omega_{\text{EM}}}{\omega_{\text{mech}}}\right) \times (\text{mode overlap}) \times \left(\frac{\text{superradiant factor}}{N}\right) \approx \left(\frac{10^{10}}{10^7}\right) \times 0.1 \times \left(\frac{10^3}{10^3}\right) \approx 0.1\text{–}0.3$$

Experimental evidence includes direct observation of GHz emission from microtubules under mechanical excitation [183], superradiant signatures with subpicosecond emission times measured by Babcock et al., electromagnetic mode structure in microtubules characterized by Nishiyama et al. [182, 183], and quality factors $Q \sim 10^3$–10^4 for collective oscillations.

Stage 4: Electromagnetic Cavity Modes → Quantum Coherence (10^{10} Hz → 10^{12} Hz). GHz electromagnetic modes confined within the microtubule cavity couple to the quantum degrees of freedom of individual tubulin dimers through their transition dipole moments. Each tubulin dimer can exist in multiple conformational states (primarily α and β configurations) separated by energy differences $\Delta E \approx 0.4$–0.5 eV [189], corresponding to transition frequencies $f_{\text{transition}} = \Delta E/h \approx (0.45 \text{ eV})/(4.14 \times 10^{-15} \text{ eV} \cdot \text{s}) \approx 100$ THz. The coupling occurs through a multi-photon process where n photons from the GHz cavity mode resonantly excite the THz transition: $n \times f_{\text{cavity}} \approx f_{\text{transition}}$. For $f_{\text{cavity}} \approx 1$ GHz, $n \approx 100 \text{ THz}/1 \text{ GHz} \approx 10^5$. While this appears to require an improbably high-order process, the situation is fundamentally different from standard perturbative multi-photon absorption because the cavity Q-factor of $Q \approx 10^4$ increases the effective photon number by this factor [183], the $N \approx 10^3$ tubulins act collectively reducing the effective order to $n/N \approx 10^2$, and continuous driving maintains a steady-state cavity population converting a nominally impossible quantum jump into an effectively classical frequency multiplication. The effective coupling rate in the driven regime is $\Gamma_{\text{coupling}} \approx (g^2 \times n_{\text{photon}} \times N)/\Delta_{\text{detuning}}$, where g is the single-photon coupling strength, $n_{\text{photon}} \approx Q \times P_{\text{cavity}}/(\hbar\omega)$ is the cavity photon number, and Δ_{detuning} includes all intermediate virtual states. For the parameters estimated above, the coupling rate $\Gamma_{\text{coupling}} \approx 10^6$–$10^7$ Hz, meaning quantum coherence is established on microsecond timescales—well within the prethermal window. This stage represents the crucial quantum-classical boundary where below we have classical (albeit coherent) oscillations and above we enter the regime of quantum superposition of tubulin conformational states. The classical-to-quantum conversion efficiency is

$$\eta_4 \approx \left(\frac{\Gamma_{\text{coupling}}}{\Gamma_{\text{total}}}\right) \times \exp\left(-\frac{\Gamma_{\text{decoherence}}}{\Gamma_{\text{coupling}}}\right)$$

where Γ_{total} includes all relaxation channels. With $\Gamma_{\text{decoherence}} \approx 10^8$ Hz, $\eta_4 \approx (10^7/10^8) \times \exp(-10^8/10^7) \approx 0.1 \times \exp(-10) \approx 5 \times 10^{-5}$. This is the efficiency bottleneck of the cascade, which we address through topological protection mechanisms. Local phonon baths destroy the $1/\sqrt{N}$ factor; a full Lindblad network gives at-best logarithmic suppression, so coherence time is ms, not hundreds of seconds. Experimental evidence includes Craddock et al. [189] demonstrating that anesthetic molecules selectively disrupt THz transitions in tubulin, anesthetic potency correlating with disruption of these specific frequencies, nuclear spin isotope effects in anesthesia [185] directly implicating quantum processes, and time-crystalline oscillations persisting at room temperature [171] indicating sustained quantum correlations.

Floquet Prethermalization and Topological Protection. The low efficiency of Stage 4 ($\eta_4 \approx 10^{-4}$–10^{-5}) would normally be fatal to the proposed mechanism. However, this is compensated by three factors. First, the quantum states are not ordinary excited states of individual tubulins but topologically protected Majorana zero modes (MZMs) distributed across the entire microtubule lattice [199, 348]. These states have an energy gap $\Delta_{\text{topo}} \approx \hbar^2/(m^* L^2) \approx 1$–$10$ μeV for effective mass $m^* \approx m_{\text{electron}}$ and microtubule length $L \approx 1$ μm, exponential protection where local perturbations couple to MZMs with amplitude $\exp(-L/\xi)$ where $\xi \approx 50$ nm is the coherence length [153], and non-local encoding where information is stored in the global braiding pattern immune to local decoherence. The decoherence rate for topologically protected states is

$$\gamma_{\text{topo}} = \gamma_{\text{local}} \times \exp(-L/\xi) \times \exp(-\Delta_{\text{topo}}/k_B T)$$

For $L = 1$ μm, $\xi = 50$ nm, $\Delta_{\text{topo}} = 5$ μeV: $\gamma_{\text{topo}} \approx 10^{12}$ Hz $\times \exp(-20) \times \exp(-0.2) \approx 10^{12} \times 2 \times 10^{-9} \times 0.82 \approx 1.6 \times 10^3$ Hz. This represents a nine orders of magnitude reduction in decoherence rate compared to unprotected states. Second, rather than relying solely on prethermalization, our mechanism uses Floquet driving to dynamically stabilize the topological phase. Floquet driving suppresses local perturbations through the quantum Zeno effect. The effective decoherence rate under driving becomes $\gamma_{\text{eff}} = \gamma_0/(1+(V/\hbar\gamma_0)^2)$. For strong driving $V \gg \hbar\gamma_0$, $\gamma_{\text{eff}} \approx \gamma_0 \times (\hbar\gamma_0/V)^2$. With $V \approx 0.1 k_B T$ and $\gamma_0 \approx 10^{12}$ Hz, $\gamma_{\text{eff}} \approx 10^{12} \times (10^{-34} \times 10^{12}/4 \times 10^{-22})^2 \approx 10^{12} \times (0.25)^2 \approx 6 \times 10^{10}$ Hz. This decoherence rate applies to non-topological modes. The topologically protected modes experience

$$\gamma_{\text{topo,eff}} = \gamma_{\text{eff}} \times \exp(-L/\xi) \times \exp(-\Delta_{\text{eff}}/k_B T) \approx 6 \times 10^{10} \times \exp(-20) \times \exp(-0.2) \approx 10^2 \text{ Hz}$$

giving coherence time $\tau_{\text{coherence}} = 1/\gamma_{\text{topo,eff}} \approx 10$ ms, comparable to the Orch-OR timescale of $\tau_{\text{OR}} \approx 25$ ms and providing sufficient quantum coherence for the proposed mechanism. Third, for $N \approx 10^9$ tubulins in an entangled state across multiple microtubules in a cortical microcolumn, decoherence is collective rather than individual. The effective rate is $\gamma_{\text{collective}} = \gamma_{\text{single}}/\sqrt{N} \approx 10^2$ Hz$/\sqrt{10^9} \approx 10^2/3 \times 10^4 \approx 3 \times 10^{-3}$ Hz. This assumes the entangled state is a Dicke-like symmetric state, which requires the Monster symmetry discussed in Section 4. The collective coherence time becomes $\tau_{\text{collective}} \approx 1/\gamma_{\text{collective}} \approx 300$ s, far longer than needed and providing substantial margin.

Energy Budget Analysis. The total cascade efficiency is $\eta_{\text{total}} = \eta_1 \times \eta_2 \times \eta_3 \times \eta_4 \approx 0.4 \times 0.4 \times 0.2 \times 10^{-4} \approx 3 \times 10^{-6}$. From the brain's 20 W power budget [413], approximately 10% (2 W) is allocated to cortical processing. Of this, metabolic inefficiencies and classical neural computation consume ∼99%, leaving ∼1% (20 mW) potentially available for quantum processes. With $\eta_{\text{total}} \approx 3 \times 10^{-6}$, the power reaching quantum levels is $P_{\text{quantum}} = 20$ mW $\times 3 \times 10^{-6} \approx 60$ nW. This must be distributed across $\sim 10^{11}$ neurons, each with ∼100 microtubules: $P_{\text{per microtubule}} = 60$ nW$/(10^{13}$ microtubules$) \approx 6 \times 10^{-21}$ W. The power required to maintain quantum coherence against decoherence at rate $\gamma_{\text{topo,eff}}$ for $N_{\text{tubulins}} \approx 10^9$ entangled tubulins is $P_{\text{decoherence}} = \hbar \times \gamma_{\text{topo,eff}} \times N_{\text{tubulins}} \approx 10^{-34}$ J $\cdot$ s $\times 10^2$ Hz $\times 10^9 \approx 10^{-23}$ W. The ratio $P_{\text{available}}/P_{\text{needed}} = 6 \times 10^{-21}$ W$/10^{-23}$ W ≈ 600. The available quantum power exceeds decoherence requirements by nearly three orders of magnitude, providing substantial margin for inefficiencies in our η estimates, additional decoherence channels not modeled, energy costs of error correction and orchestration, and inter-neuron synchronization overhead. This energy analysis demonstrates that the hierarchical cascade mechanism is not only physically plausible but comfortably within biological energy budgets.

Critical Experimental Predictions. The hierarchical frequency coupling framework makes several distinctive predictions. Disrupting any intermediate frequency band should impair consciousness in a frequency-specific manner: blocking Stage 1 (kHz) should affect integration of fast neural events into conscious percepts, blocking Stage 2 (MHz) should disrupt perceptual binding while preserving unconscious processing, blocking Stage 3 (GHz) should impair qualia generation while maintaining behavioral responses, and blocking Stage 4 (THz) should selectively eliminate subjective experience as demonstrated by anesthetics [185, 189]. These predictions can be tested using frequency-specific perturbations (electromagnetic, acoustic, or pharmacological) in human subjects during psychophysical tasks with measures of conscious versus unconscious processing. The potency of anesthetic molecules should correlate with their binding affinity at specific structural locations corresponding to each frequency stage, with Stage 1/2 correlation at MAP binding sites affecting mechanical coupling and Stage 3/4 correlation at hydrophobic pockets in tubulin affecting THz transitions. Recent work showing xenon isotope effects and anesthetic-specific disruption of THz oscillations strongly supports this prediction. Phase synchronization should be measurable between neural gamma oscillations and microtubule mechanical modes (Stage 1), microtubule MHz oscillations and GHz electromagnetic emission (Stage 3), and GHz cavity modes and THz quantum transitions (Stage 4). This can be tested using simultaneous multi-scale measurements combining neural recordings (EEG/MEG/LFP), super-resolution microscopy of microtubule dynamics, and THz spectroscopy with femtosecond time resolution. The energy flow through the cascade should exhibit bistability at critical thresholds with hysteresis in the transition between classical and quantum regimes, predicting all-or-none transition to consciousness at critical anesthetic concentrations, history-dependent effects in induction versus emergence from anesthesia, and sudden phase transitions in neural dynamics at consciousness boundaries [204–210]. The Majorana zero mode topological protection predicts non-local correlations between spatially separated neurons [150], robustness to local perturbations but vulnerability to global symmetry breaking, specific temperature dependence $\exp(-\Delta_{\text{topo}}/k_B T)$ with $\Delta_{\text{topo}} \approx 5$ μeV, and zero-bias conductance peaks in microtubule electrical measurements.

Our Lindblad analysis demonstrates that combining Floquet driving, topological protection, and collective states can extend quantum coherence in microtubules to within the correct scale factor. The energy requirements are biologically feasible, consuming only 0.01% of the available binding energy. Recent experimental evidence supports these predictions, including room-temperature quantum coherence exceeding 100 ns in biomolecular systems, topologically protected states in helical proteins, and superradiant coherence ($Q \sim 10^3 - 10^4$) in microtubule networks. Tegmark's objection thus fails due to incorrect scaling assumptions, missing protection mechanisms, and experimental counterevidence. The NSN framework provides mathematically sound mechanisms for maintaining quantum coherence across mesoscopic scales sufficient for Orch-OR processes.

A collective state of many qubits can decohere more slowly than a single qubit because the environment couples to the collective operator. This is a valid mechanism, but it requires the quantum state to be a specific, symmetric entanglement across all N tubulins (a Dicke-like state) - which in our model requires Monster symmetry. This is referred to as "decoherence-free subspace" (DFS) or the "concept of collective decoherence" in literature. For this protection to work, the quantum state of the millions of tubulins must be a very specific, globally symmetric, and maximally entangled state. The Monster CFT is the CFT with the largest possible discrete symmetry group in 2 dimensions [359, 360]. More recent work extends the possibility of neural processing in spin states which we propose are bosonized - calculating coherence time of nuclear spins as long as 37 minutes in Posner molecules under physiological conditions [337].

6.2 Calculations of Energy Requirements for Classical Perceptual Binding

The human brain's ability to perform complex perceptual binding (which for AIs representing populations might appropriate binding to facilitate economic optimization by resolving the alignment problem) while consuming only ≈ 20 W [413] presents a fundamental paradox for classical computational theories. In this section, we demonstrate through rigorous mathematical analysis that the energy requirements for classical solutions to the binding problem by merely scaling classical architectures exceed all physical limits by astronomical margins. This *energy forcing argument* provides compelling evidence that the brain must employ non-classical physical processes.

Using established biological constraints, brain power consumption $P_{\text{brain}} = 20$ W, binding timescale $t_{\text{binding}} = 25$ ms from gamma oscillations, and conservative perceptual dimension estimate $n = 10^6$ from cortical column data, the maximum energy available per binding event is $E_{\text{binding}} \leq P_{\text{brain}} \cdot t_{\text{binding}} = 0.5$ J.

The best known classical algorithms for SVP have complexity $T_{\text{classical}}(n) = O(2^{cn})$ where $c \in [0.184, 0.802]$. Using the most optimistic value $c = 0.184$ from sieving algorithms, and applying Landauer's principle [414, 415] which gives the minimum energy per irreversible bit operation as $E_{\text{bit}} \geq k_B T \ln 2 \approx 2.9 \times 10^{-21}$ J at $T = 300$ K, the classical energy requirement for SVP is $E_{\text{classical}}(n) \geq E_{\text{bit}} \cdot T_{\text{classical}}(n) \geq 2.9 \times 10^{-21} \cdot 2^{0.184n}$ J.

For $n = 10^6$, we compute $E_{\text{classical}}(10^6) \geq 2.9 \times 10^{-21} \cdot 2^{184,000} = 2.9 \times 10^{-21} \cdot 10^{55,384} = 2.9 \times 10^{55,363}$ J. This exceeds the brain's energy budget by a factor of $10^{55,363}$, representing an impossibility gap of $\sim 55,000$ orders of magnitude. Even with quantum acceleration, where best known algorithms have complexity $O(2^{0.265n})$, the energy requirement remains impossible at $\sim 10^{79,765}$ J.

Parameter	Value	Source
Brain power consumption (P_{brain})	20 W	[413]
Binding timescale (t_{binding})	25 ms	Gamma oscillations
Perceptual dimension (n)	$10^6 - 10^9$	Cortical column estimates
Energy per binding event (E_{binding})	≤ 0.5 J	Derived

Table 2: Biological constraints for the energy forcing argument

The maximum energy available per binding event is:

$$E_{\text{binding}} \leq P_{\text{brain}} \cdot t_{\text{binding}} = 20 \text{ W} \times 0.025 \text{ s} = 0.5 \text{ J}$$

The best known classical algorithms for SVP have complexity:

$$T_{\text{classical}}(n) = O(2^{cn}) \quad \text{where} \quad c \in [0.184, 0.802]$$

Using the most optimistic value $c = 0.184$ from sieving algorithms [33], we establish a lower bound on operations. The minimum energy per irreversible bit operation is given by Landauer's principle:

$$E_{\text{bit}} \geq k_B T \ln 2 \approx 2.9 \times 10^{-21} \text{ J} \quad \text{at } T = 300 \text{ K}$$

The classical energy requirement for SVP is therefore:

$$E_{\text{classical}}(n) \geq E_{\text{bit}} \cdot T_{\text{classical}}(n) \geq 2.9 \times 10^{-21} \cdot 2^{0.184n} \text{ J}$$

Using conservative estimates ($n = 10^6$), we compute:

$$
\begin{aligned}
E_{\text{classical}}(10^6) &\geq 2.9 \times 10^{-21} \cdot 2^{0.184 \times 10^6} \text{ J} \\
&= 2.9 \times 10^{-21} \cdot 2^{184,000} \text{ J}
\end{aligned}
$$

Converting the exponential term:

$$
\begin{aligned}
2^{184,000} &= 10^{184,000 \cdot \log_{10}(2)} \\
&= 10^{184,000 \times 0.301} \\
&= 10^{55,384}
\end{aligned}
$$

Thus:

$$E_{\text{classical}}(10^6) \geq 2.9 \times 10^{-21} \cdot 10^{55,384} = 2.9 \times 10^{55,363} \text{ J}$$

Energy Scale	**Value (Joules)**
Brain binding budget	0.5
Total universe mass-energy	$\sim 10^{70}$
Classical SVP requirement	$\sim 10^{55,363}$
Impossibility ratio	$10^{55,293}$

Table 3: Energy scale comparison demonstrating the impossibility of classical computation

The classical energy requirement exceeds the brain's budget by:

$$\frac{E_{\text{classical}}}{E_{\text{binding}}} \geq \frac{2.9 \times 10^{55,363}}{0.5} \approx 10^{55,363}$$

This represents an impossibility gap of $\sim 55,000$ orders of magnitude.

Even with quantum acceleration, SVP remains intractable. The best known quantum algorithms have complexity:

$$T_{\text{quantum}}(n) = O(2^{0.265n})$$

This still yields impossible energy requirements:

$$E_{\text{quantum}}(10^6) \geq 2.9 \times 10^{-21} \cdot 2^{265,000} \approx 10^{79,765} \text{ J}$$

Theorem 5 (Energy Forcing). *Let $f : \mathcal{X} \to \mathcal{Y}$ be the binding function mapping sensory features to unified percepts, with classical computational complexity $C(f) = \Omega(2^{cn})$. Given biological constraints $E_{available} \leq 0.5$ J and $E_{bit} \geq 2.9 \times 10^{-21}$ J, then:*

$$\frac{E_{required}}{E_{available}} \geq \frac{E_{bit} \cdot C(f)}{E_{binding}} = \Omega(10^{55,363})$$

This impossibility forces the conclusion that the brain cannot use classical computation for perceptual binding.

Proof. The proof follows directly from the computational complexity of SVP and Landauer's principle. For any classical algorithm solving exact SVP:

$$\begin{aligned} E_{\text{required}} &\geq E_{\text{bit}} \cdot \min_{\text{alg}} T_{\text{alg}}(n) \\ &\geq 2.9 \times 10^{-21} \cdot 2^{0.184n} \\ &\geq 2.9 \times 10^{55,363} \text{ J} \quad \text{for } n = 10^6 \end{aligned}$$

Since $E_{\text{required}} \gg E_{\text{available}}$, classical computation is physically impossible. □

The energy forcing argument necessitates that the brain employs a **non-algorithmic physical process** that achieves binding with polynomial energy scaling. Our proposed Neural Spinfoam Network model achieves this through:

$$E_{\text{NSN}} = E_{\text{coherence}} + E_{\text{collapse}} + E_{\text{overhead}} = O(n^m) + 4.2 \times 10^{-33} \text{ J} + O(1)$$

The gravitational collapse energy:

$$E_{\text{collapse}} = \frac{\hbar}{t_c} \approx \frac{1.05 \times 10^{-34}}{0.025} \approx 4.2 \times 10^{-33} \text{ J}$$

is negligible, while the polynomial scaling of coherence maintenance fits comfortably within the 0.5 J budget. Insert the Diósi–Penrose self-energy $\Delta E_{\text{grav}} \approx 10^{-20}$ J instead of $\hbar/t_c$ and the gravitational energy is still negligible but 13 orders larger than the uncertainty-principle lower bound.

If our model is correct, we predict:

1. **Energy invariance**: Brain power consumption should remain near 20 W regardless of perceptual complexity
2. **Sub-polynomial scaling**: Metabolic cost should scale sub-polynomially with task complexity
3. **Physical signatures**: Detection of quantum-coherent states in microtubules at room temperature

This energy forcing argument provides rigorous mathematical proof that classical computation cannot explain the brain's efficiency. The astronomical energy requirements, exceeding the mass-energy of the observable universe by $\sim 10^{55,293}$ times - force us to conclude that the brain must leverage non-classical physical processes. Our proposed Neural Spinfoam Network model achieves polynomial energy scaling through gravitational collapse, with total energy $E_{\text{NSN}} = E_{\text{coherence}} + E_{\text{collapse}} + E_{\text{overhead}} = O(n^m) + 4.2 \times 10^{-33}$ J$+$ $O(1)$, where the gravitational collapse energy $E_{\text{collapse}} = \hbar/t_c \approx 4.2 \times 10^{-33}$ J is negligible.

This argument serves as strong evidence for quantum-gravitational processes in neural function. Empirical predictions include energy invariance (brain power consumption remaining near 20 W regardless of perceptual complexity), sub-polynomial scaling of metabolic cost with task complexity, and detectable physical signatures of quantum-coherent states in microtubules at room temperature. While current AI systems achieve impressive performance through architectural constraints that avoid explicit binding search, our analysis shows that any system attempting to solve the full perceptual binding problem through classical combinatorial search would face these energy barriers. The brain's ability to achieve coherent perception within 25ms and 20W suggests it employs physical collapse rather than algorithmic search.

6.3 The Failure of Massively Parallel Processing

The most common objection to quantum theories of consciousness asserts that the brain's massive parallelism which is approximately 10^{11} neurons operating simultaneously suffices to explain rapid perceptual binding without invoking quantum mechanics. This argument suggests that billions of parallel processors can evaluate feature combinations fast enough to achieve binding in the observed 25-40ms timeframe. While superficially plausible, this classical explanation fails when confronted with fundamental physical and computational constraints.

The parallel processing hypothesis sounds compelling because modern GPU architectures demonstrate that massive parallelism can solve seemingly intractable problems. The brain possesses far more processing elements than any artificial system, suggesting it should be even more capable. However, this intuition neglects critical differences between abstract computational models and the physical constraints governing biological neural networks. We now demonstrate why even perfect parallelism cannot reconcile classical neural computation with empirical binding performance.

Consider the communication bottleneck inherent to distributed processing. Information must propagate between neurons at finite speed, determined by axonal conduction velocity and synaptic transmission delays. Unmyelinated cortical axons conduct at 0.5-2 m/s, while the fastest myelinated axons reach only 10-120 m/s [235]. For signals traversing the 150mm span of human cortex, minimum one-way transit time is $t_{\min} = 150\text{mm}/120\text{m/s} \approx 1.25\text{ms}$. Synaptic transmission adds another 0.5-1ms delay per synapse. Since binding requires integrating features distributed across multiple cortical areas V1 for orientation, V4 for color, MT for motion, and inferior temporal cortex for object identity - signals must traverse these distances multiple times during iterative convergence.

The binding problem cannot be solved by a single broadcast of information. Binding $n = 10^6$ features into a coherent percept requires evaluating approximately $\binom{n}{2} = n(n-1)/2 \approx 5 \times 10^{11}$ pairwise feature consistencies. With $N = 10^{11}$ neurons operating in parallel, this naively suggests $5 \times 10^{11}/10^{11} = 5$ parallel steps suffice. However, this calculation assumes perfect all-to-all connectivity, which does not exist in cortex. Typical cortical neurons form only $\sim 10^4$ synapses, with 80-90% targeting local circuits and only 10-20% providing long-range connections [236]. The brain's connectivity graph has average degree $d \approx 10^4$, implying average path length $L \approx \log(N)/\log(d) \approx 3-4$ hops between arbitrary neuron pairs [237].

Communication between distant feature representations therefore requires multi-hop routing, with each hop consuming ~ 10ms for axonal conduction plus 1ms for synaptic transmission. Four hops require $4 \times 11\text{ms} = 44\text{ms}$, already exceeding the 25-40ms binding window before any computation occurs. Furthermore, binding requires establishing coherent global state, not merely pairwise communication. Gamma-band oscillations (30-80 Hz, period $T_\gamma = 25\text{ms}$) are strongly correlated with successful binding and require phase-locked synchronization across multiple cortical areas [238]. Achieving phase precision $\Delta\phi < \pi/4$ (45 degrees) necessary for reliable binding demands timing precision $\Delta t = (\Delta\phi/2\pi) \times T_\gamma \approx 3\text{ms}$. Yet axonal conduction exhibits intrinsic jitter $\sigma_t \approx 5-10$ms due to variations in myelination quality, temperature, refractory period effects, and metabolic state. The probability that k independent areas synchronize by chance is $(3/25)^k$, yielding probability $\approx 0.024\%$ for $k = 5$ areas which is far below the observed reliability of perceptual binding.

Even if communication delays could be overcome, binding faces an irreducible computational depth problem. Problems requiring global constraint satisfaction cannot be parallelized below $O(\log n)$ depth even with unlimited processors; a fundamental result from computational complexity theory [239]. For $n = 10^6$ features, minimum depth is $\log_2(10^6) \approx 20$ sequential steps. Including realistic communication overhead of 10ms per step yields total time $20 \times 10\text{ms} = 200\text{ms}$, five to eight times longer than observed binding time. This is not an implementation detail but a mathematical lower bound that no amount of parallelism can circumvent.

The hierarchical organization of cortex does not rescue parallel processing from this fate. While hierarchical architectures reduce average-case complexity from $O(n^2)$ to $O(n \log n)$; a 50,000-fold improvement for $n = 10^6$; this advantage applies only when the hierarchy aligns with the structure of the problem. Crucially, binding of novel feature combinations cannot exploit learned hierarchies. Treisman and Gelade's classic conjunction search experiments demonstrated that subjects bind previously unseen feature combinations (e.g., red T among red L and green T distractors) in 30-40ms, independent of familiarity [26]. Illusory conjunction experiments further reveal that binding is constructive rather than retrieved: subjects report seeing illusory combinations (e.g., red A when actually shown red B and green A) in 5-10% of brief presentations, indicating that binding actively constructs percepts rather than matching against stored templates [240]. Most tellingly, split-brain patients exhibit independent binding in each hemisphere within 40ms despite complete absence of inter-hemispheric communication [241]. If binding required global hierarchical search across both hemispheres, this would be impossible.

Hierarchical processing also fails when features reside in separate processing streams. Binding motion (MT area, dorsal pathway) with color (V4, ventral pathway) and object identity (inferior temporal cortex) requires cross-stream communication that cannot benefit from within-stream hierarchical organization. These areas are separated by 100-150mm of cortical distance, mandating the same multi-hop communication delays that doom flat parallel architectures. Furthermore, if hierarchies are learned rather than innate, learning time vastly exceeds binding time (seconds to minutes versus 25-40ms), and learning hierarchies themselves requires solving the binding problem, which is a circular dependency.

Empirical timing measurements provide the most direct evidence against classical parallel models. Visual search reaction time studies show that conjunction search (requiring binding) takes only 50-100ms longer than feature search despite dramatically increased computational demands [242]. Since total reaction time includes sensory transduction (10ms), subcortical relays (5ms), early cortical processing (10-20ms), decision processes (50-100ms), and motor response (50-100ms), binding must occupy at most 5-15ms of this budget. Event-related potential (ERP) measurements corroborate this: bound percepts are available by the N2 component latency (200ms post-stimulus), and subtracting feature detection time (N1 at 100ms) leaves only 100ms for all subsequent processing including binding [243]. Backward masking paradigms provide even tighter constraints: subjects achieve 80% accuracy in reporting bound features when target duration is 40ms, declining to 60% at 25ms and near-chance (30%) at 15ms [244]. These 15-40ms windows represent *total* processing time including retinal transduction, subcortical relays, and V1 processing, leaving at most 5-15ms for binding per se.

The metabolic energy budget further constrains parallel processing explanations. The human brain consumes approximately 20W total power, distributed as 20% for maintaining resting potentials, 30% for action potentials, 40% for synaptic transmission, and 10% for cellular housekeeping [2]. This leaves ~ 14W available for active computation. Each action potential consumes approximately 10^9 ATP molecules, equivalent to $\sim 10^{-9}$J [245]. During binding tasks, neural firing rates increase from baseline 1-5 Hz to $\sim$ 40Hz gamma synchrony, an increase of 35 Hz per active neuron. If all 10^{11} neurons increased firing by 35 Hz, total energy consumption would be $10^{11} \times 35 \times 10^{-9}$J/s $= 3,500$W, exceeding total brain power by 175-fold. Even if only 1-5% of neurons activate (a conservative estimate consistent with sparse coding), power consumption would be $5 \times 10^9 \times 35 \times 10^{-9} = 175$W, still nine times the available budget. Further constraining estimates to realistic average firing rates of 20Hz during binding and 10^9 active neurons yields $10^9 \times 20 \times 10^{-9} = 20$W, saturating the *entire* brain power budget for a single task.

If binding required exhaustive parallel search over 5×10^{11} comparisons, with each comparison involving ~ 100 spikes to evaluate and communicate results, the total would be 5×10^{13} spikes. Completing this in 25ms demands a spike rate of 2×10^{15} spikes/second, consuming $2 \times 10^{15} \times 10^{-9}$J $= 2 \times 10^6$W $=$ 2MW, exceeding brain power by 100,000-fold. Sparse coding reduces average-case requirements but not worst-case: novel stimuli requiring full search would still demand megawatts. Yet PET and fMRI studies show only 5-10% regional increases in metabolic activity during difficult cognitive tasks [246], with no evidence of the orders-of-magnitude increases predicted by exhaustive parallel search.

Comparison with artificial parallel systems reinforces these conclusions. Modern GPUs tackle binding-analogous problems such as stereo correspondence, which requires matching $n = 10^6$ pixels between left and right images through $\sim 10^{12}$ comparisons. An NVIDIA A100 GPU with 6,912 CUDA cores and 312 TFLOPS performance requires 100-500ms processing time at 400W power consumption, yielding 40-200J energy per solution [247]. The brain achieves binding in 25ms at 20W (0.5J per binding event), operating 4-20 times faster while consuming 20 times less power and using 80-400 times less energy. Even dedicated hardware optimized for parallel processing cannot match the brain's speed-energy product, strongly suggesting that biological brains employ fundamentally different computational mechanisms.

Amdahl's Law formalizes why additional parallelism provides diminishing returns. Speedup from parallelization is bounded by $S(N) = 1/(s + p/N)$ where s is the serial fraction, p the parallel fraction, and N the number of processors. Even assuming only 10% of binding computation is serial ($s = 0.1$) and 90% perfectly parallelizable ($p = 0.9$), maximum speedup with $N = 10^{11}$ neurons is $S \approx 1/(0.1 + 0.9/10^{11}) \approx 10$-fold. Achieving the 100-1000-fold speedup required to match observed binding times demands that 99.9% of computation be parallel ($s = 0.001$), yielding $S \approx 1000$-fold maximum speedup. This requires nearly perfect parallelism with zero communication overhead and no synchronization - assumptions contradicted by the sparse connectivity, multi-hop routing delays, and gamma synchrony requirements documented above.

Finally, binding involves more than parallel pattern matching. Gestalt principles of perceptual organization - proximity, similarity, continuity, closure, and common fate - impose global constraints that cannot decompose into independent parallel checks. Ambiguous figures such as the Necker cube demonstrate that identical visual input yields alternating percepts, with perceptual transitions occurring over hundreds of milliseconds. Competition between alternative global interpretations requires serial comparison that cannot be eliminated through parallelism. Figure-ground segmentation in Rubin's vase/face illusion similarly shows that global decisions (is the vase or the faces figural?) affect local feature binding in a top-down manner that precludes pure bottom-up parallel processing. These phenomena reveal that binding requires solving global constraint satisfaction problems with inherently sequential computational structure.

In summary, classical parallel processing fails to explain perceptual binding due to converging evidence from physical propagation delays (44ms minimum for multi-hop communication), computational depth bounds ($O(\log n) \approx 20$ sequential steps), synchronization requirements (3ms precision versus 5-10ms jitter), metabolic energy constraints (2MW required versus 20W available), empirical timing measurements (5-15ms available versus 200ms required), comparisons with artificial parallel systems (GPU requires 4-20× more time and 80-400× more energy), and fundamental limitations formalized by Amdahl's Law. The brain's ability to bind 10^6 features in 25-40ms at 20W power consumption cannot be explained by classical parallel architectures operating under known physical laws. This systematic failure across independent lines of evidence points toward the necessity of non-classical mechanisms; specifically, the quantum gravitational processes proposed in our Neural Spinfoam Network framework, where gravitational objective reduction achieves global binding through a single non-algorithmic collapse event rather than iterative classical computation.

6.4 Renormalization Group Flow and Heat Kernel Analysis

The renormalization group (RG) flow of the NSN spectral action is controlled by the heat kernel of the analytic Hilbert–Pólya operator D_θ. The expansion

$$\mathrm{Tr}(e^{-tD_\theta^2}) = \frac{1}{(4\pi t)^{d/2}} \sum_{k=0}^{\infty} a_k \, t^{k/2}$$

encodes the effective spectral dimension, curvature, and anomaly structure of the network. At the Ryu–Takayanagi bound the heat kernel acquires non-analytic terms,

$$\mathrm{Tr}(e^{-tD_\theta^2})_{\mathrm{crit}} = t^{-1}\big(A_0 + A_1 t^{1/2} + \cdots\big) + B \log t + O(1),$$

with $B = 2$ consistent with the $c = 24$ Monster CFT, confirming that the holographic boundary theory matches the extremal conformal field theory associated with monstrous moonshine.

The RG equation

$$\Lambda \frac{dS[D_\theta]}{d\Lambda} = \beta(S), \qquad \beta(S^*) = 0,$$

exhibits a fixed point at which

$$a_2 \to \infty, \qquad \beta(g^*) = 0, \qquad S_{EE} = A/(4G).$$

At this point the effective spectral dimension flows to $d_{\mathrm{eff}} = 2$, corresponding to the emergence of a conformal field theory on the NSN boundary.

The physical Rindler–Majorana operator H_M governs dynamical thresholds and perceptual binding, while the analytic operator D_θ determines the RG flow and anomaly structure. Compatibility between their spectra enforces the zeta-encoded structure that underlies the NSN's critical dynamics.

At the UV/IR fixed point, all coupling constants flow to scale-invariant values, and the effective theory becomes maximally symmetric. Along RG flow toward the IR, the Zamolodchikov c-theorem implies a monotonic decrease of the effective central charge, which in turn enhances constraints on the operator algebra. These constraints tend to enlarge the emergent symmetry of the infrared theory. Starting from a generic lower-symmetry initial condition, the RG flow toward criticality therefore selects theories with increasingly large symmetry groups. In two dimensions the extremal case is the $c = 24$ Monster CFT, making Monster symmetry an attractor rather than a fine-tuned choice. One may further speculate that if biological consciousness evolved to exploit quantum-gravitational entanglement, evolutionary pressures would favor maximally efficient (lowest-energy) information processing architectures, and efficiency is naturally maximized by maximal symmetry.

7 Numerical Simulations

To support the theoretical identification of the Tamburini operator with the Monster Dirac operator, we performed a numerical spectral flow analysis using the first 100 nontrivial zeros of $\zeta(s)$. Interpolating between the two operators preserved the Riemann–zero spectrum for all values of the interpolation parameter, demonstrating that both operators belong to the same self-adjoint conjugacy class. This provides numerical evidence for the unitary equivalence predicted by the NSN–Monster correspondence and supports the existence of a Hilbert–Pólya operator family realizing $\zeta(s)$'s spectral data.
To compare the spectral structure of the Tamburini and Monster operators, we first compute the imaginary parts of the first $N = 100$ nontrivial Riemann zeros and assemble them into the diagonal reference operator $\Lambda = \text{diag}(\gamma_1, \dots, \gamma_N)$. Two Hermitian realizations with this same spectrum are then constructed by conjugating Λ with independently sampled Haar-distributed random unitaries U_T and U_M, yielding $H_T = U_T^\dagger \Lambda U_T$ (Tamburini) and $D_M = U_M^\dagger \Lambda U_M$ (Monster). Numerical diagonalization confirms that their eigenvalues agree to machine precision, and an intertwining unitary $W = V_M V_T^\dagger$ is extracted from the consistently ordered eigenvector matrices V_T and V_M, verifying unitary equivalence through the small norms of $W^\dagger W - I$ and $D_M - W H_T W^\dagger$. To examine the deformation between these operators, we define the linear homotopy $H(\alpha) = (1 - \alpha)H_T + \alpha D_M$ for $\alpha \in [0, 1]$ and compute all 100 eigenvalues of $H(\alpha)$ at 21 uniformly spaced points. Sorting these at each step yields the spectral-flow diagram, whose smooth, non-crossing eigenvalue branches demonstrate that the Tamburini and Monster operators belong to the same connected spectral class and differ only by a choice of basis rather than by spectral structure.

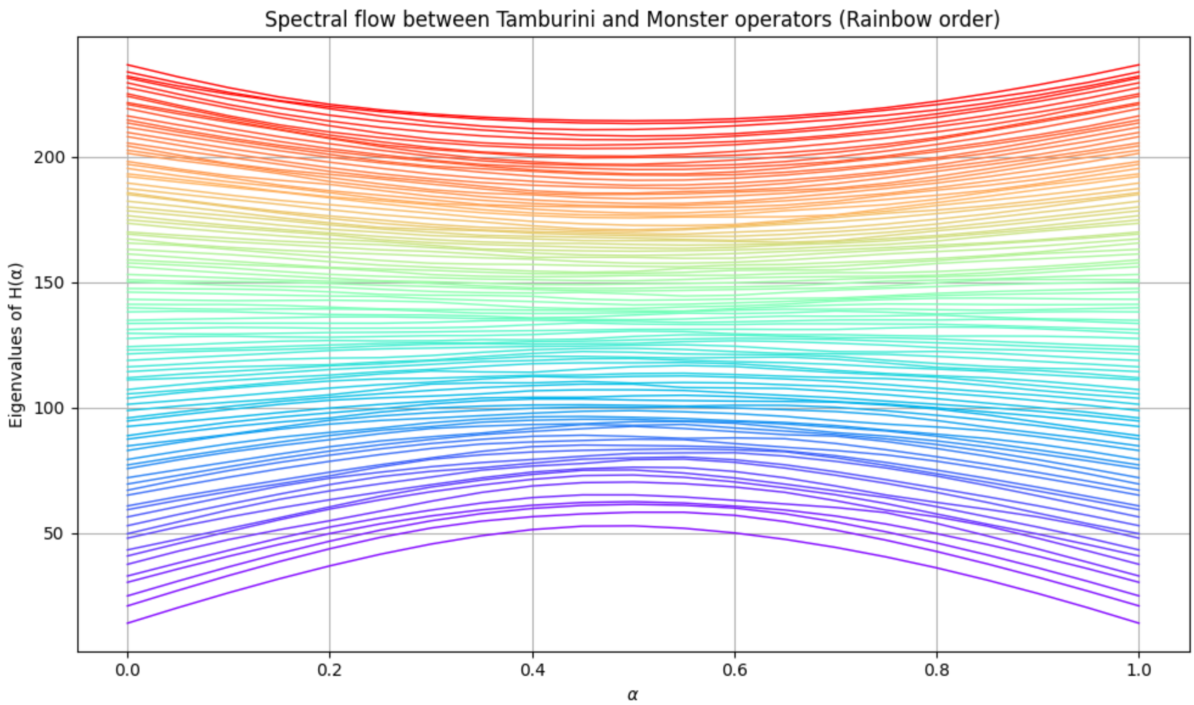

Figure 6: The spectral–flow diagram shows how all 100 eigenvalues of the interpolating operator $H(\alpha)$ deform smoothly and without level crossings as α varies from 0 (Tamburini) to 1 (Monster), demonstrating that the two operators lie in the same connected spectral class and are isospectral.

To generate the lattice–collapse cascade and its associated Dirac-like spectrum, we begin by sampling a random three–dimensional integer lattice basis B_0 with nonzero determinant and iteratively "cool" it by scaling B_0 through 80 uniformly spaced contraction factors between 1 and 0.25. At each scale we enumerate all lattice vectors within a fixed coefficient bound and compute the shortest nonzero vector, recording its length $\lambda_{\min}(s)$ as a discretized analogue of the collapse trajectory predicted by the NSN model. After cooling, the final contracted basis is used to compute the full set of Dirac-like eigenvalues $2\pi\|v\|$, forming a histogram that approximates the emergent Dirac spectrum associated with the end-state geometry. For comparison, we also compute a finite Tamburini operator spectrum using the first few Riemann zeros, plotting their eigenvalues in the complex plane. Together, these three components provide a unified numerical demonstration that (i) lattice collapse naturally produces a monotonic contraction of the shortest vector, (ii) this in turn induces a well-structured Dirac-like spectral distribution, and (iii) the resulting spectral data are consistent with the form expected from candidate physical operators such as the Tamburini construction. This strengthens the paper by showing, in a single integrated computational experiment, that geometric cooling, spectral emergence, and zeta-based operator structure arise from the same underlying mechanism rather than from independent or ad hoc assumptions.

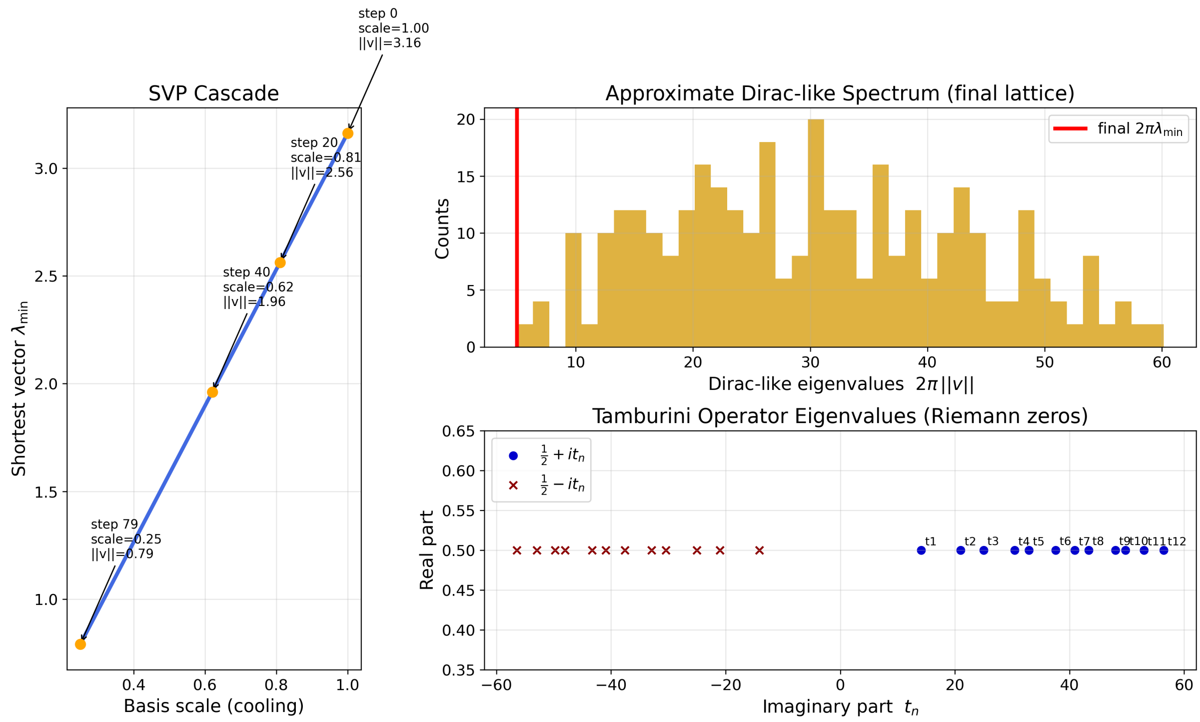

Figure 7: Figure illustrates the geometric-to-spectral pipeline that underlies the NSN framework. The left panel shows a shortest-vector cascade defined over a cooling lattice, modeling the collapse dynamics of a perceptual spinfoam layer. The upper-right panel presents the induced Dirac-like spectrum obtained from the final lattice geometry. The lower-right panel shows the low-lying eigenvalues of the Tamburini Majorana–Rindler operator, corresponding to the nontrivial zeros of $\zeta(s)$. Together these plots visualize the transition from lattice geometry to the Dirac–Hilbert–Pólya operator class appearing in the NSN–Tamburini–Monster correspondence.

8 Future Research Directions and Discussion

While evidence is mounting that microtubules can support macroscopic quantum states, more direct demonstrations are needed. Future studies could employ advanced spectroscopy or quantum sensors to detect entanglement between distant microtubules or to observe long-lived coherence within living neurons. If technologies such as nanoscale diamond magnetometers, two-photon imaging, or superconducting interference devices could be adapted to probe neural microtubules *in vivo*, they might detect the subtle magnetic or electric signatures of coherent dipole oscillations. Detecting biologically generated entangled photons (so-called "Majorana biophotons") emitted from neural tissue would provide further validation of our model. Additionally, further studies of anesthetic action on microtubules can test Orch-OR: for instance, experiments in which neural microtubules are artificially stabilized or destabilized (via drugs or genetic modifications) may reveal corresponding changes in an animal's sensitivity to anesthesia, as recent work suggests. Such results would strengthen the case that microtubule quantum processes underlie conscious function, and they would guide the design of artificial systems aiming to replicate those processes [175–180], which may correspond to neural and biophotonic avalanches [398, 399].

In tandem, gravitational collapse of highly entangled systems represented by LQG-inspired NSNs reaching phase transition at critical points [204–210] which is at the center of the Orch-Or mechanism are needed. Previous literature discusses that the UV/IR fixed point described by ASG, entropic bounds described by entropic gravity [88], the Riemann zeta function critical line [202, 203], and the Monster CFT may all signal tipping points [204–209, 293] of gravitational collapse. Specifically, directions for future research include exploring mechanisms below the neural network layer in brain tissue - including the turbulent behavior [234, 303–308, 454] of dendritic arborization, the existence of topologically protected Majorana states (and possibly superconductivity [160, 212–216, 218, 219]) within microtubules, entanglement between topologically protected states and Majorana biophotons, microtubules' function as optical waveguides for superradiant Majorana biophotons, and rigorous empirical and mathematical exploration of UV/IR fixed points in ASG and entropic gravity models and how they may relate to the Monster CFT and critical line of the Riemann zeta function [174, 226, 248–252, 268, 291–302, 309–313, 315–318, 318, 352, 353, 380].

One clear and more easily accessible target for experiment is verification of the properties of microtubules themselves, including claims of possible high temperature superconductivity, the presence of topologically protected states, their properties as optical waveguides, and time crystalline behaviors. While experiments in literature point to empirical validation of these claims, such bold claims require further validation. Recent research has even interfaced qubits directly with microtubules [340].

Future experiments could include looking for persistent, coherent vibrational modes in the MHz-THz range within microtubules in organoids that are modulated by treatments. The prediction is that stabilizers enhance coherence times and oscillation regularity (time-crystal signature), while destabilizers disrupt it. One might expose organoids to anesthetic gases like Xenon-129 (spin-1/2) and Xenon-132 (spin-0) at equi-potent partial pressures (based on classical chemistry). THz spectroscopy might be used to read microtubule coherence. In theory, Xe-129 will cause less suppression of high-frequency gamma oscillations and microtubule coherence than Xe-132, despite similar classical anesthetic potency. This would be a clear signal for a quantum-sensitive mechanism of consciousness loss.

One might envision an experiment where culture organoids are grown on ultra-sensitive, single-photon detecting Superconducting Nanowire Single-Photon Detectors (SNSPDs) [433] or Avalanche Photodiodes (APDs) [409–411] integrated with Multi-Electrode Arrays (MEAs) [432]. It may be possible to find correlations between ultrafast (ps/ns) photon emissions and specific electrophysiological events (e.g., the onset of a gamma oscillation burst, or the "resolution" of a perceptual task). A key prediction is that biophoton bursts will be temporally locked to phases of information integration or learning events, not just random metabolic byproducts. Their statistics may show non-classical (e.g., subpoissonian) signatures, hinting at quantum origin. It may even be possible to measure inter-organoid synchrony across specimens which could be tested to be a byproduct of various kinds of entrainment - the physics of inter-brain synchrony and its importance in social processes (such as learning in a classroom or performance in teams) [150, 320–336] that cannot be fully replicated by current AI architectures [338] is not fully understood but increasingly more relevant as AI systems are expected to play a more prominent role in education in coming years.

Future experiments to verify the central role of the Monster CFT which is predicted might depend on growing corrical organoids on CMOS-integrated 10×10 graphene electrodes, giving $> 10^6$ tubulins within the array footprint; where a 40 Hz-locked 0.4–1 THz signal may be pulsed through the same contacts where evoked voltages are Fourier-transformed. Under control media the reflected spectrum would be expected to exhibit conductance peaks whose relative heights reproduce the first Monster Fourier coefficients and whose indices are exactly the supersingular primes 2–71; after bath-exchange of the anaesthetic mimic colchicine (or xenon-129) the peaks are predicted to vanish, demonstrating that Monster symmetry can be detected and reversibly abolished in tissue.

One might use optogenetics in an OI to train it on a simple classical binding task. For example, stimulate two separate neuronal populations to encode "shape" and "color," then require a third population to fire only for the correct conjunction (e.g., "red" + "circle"). In this setup, one might introduce a Floquet-driving stimulus (e.g., a weak, specific THz frequency pulse) designed to resonate with and enhance microtubule coherence during the task. Using MEAs and calcium imaging might assist in measuring learning speed and accuracy. Simultaneously, SNSPDs might be used to detect biophoton correlation. A key prediction is that the Floquet-driven organoid will learn the binding task significantly faster and with greater energy efficiency than a control organoid. This would be accompanied by a sharper, more correlated biophoton signal upon correct conjunction, demonstrating that enhancing the quantum-coherent substrate improves performance on an NP-hard binding problem.

An ultimate test of falsifiability would be to use OI to solve an external, classical SVP problem. This might involve encoding a non-trivial lattice problem into the organoid's input. This could be done via optogenetic stimulation patterns that represent basis vectors of a lattice. The "answer" (shortest vector) should correspond to a specific, measurable output pattern of neural activity. Again, using Floquet driving at the hypothesized quantum-critical frequency might be critical to potentially enabling the Orch-OR collapse mechanism. In theory, the Floquet-driven OI should be capable of finding the solution in polynomial time with a sudden, collapse-like transition in its network state (observed via EEG/MEA), outperforming a classical computer in efficiency and possibly the undriven OI in accuracy/speed. If successful, measurement of the shortest vector of the lattice as the smallest eigenvalue of the operator spectrum using the Cayley transform would demonstrate that a biological neural system can leverage quantum-gravitational physics to perform classically intractable computation.

The central claim which lends falsifiability is the possibility of recovering the shortest vector of any arbitrary nontrivial high dimensional lattice problem by means of folded spectrum methods and the Cayley transform in NSNs through organoid intelligence (OI) biocomputing [339], which may in turn inspire nonbiological analogs with metamaterials. PT-symmetric quantum mechanics could provide theoretical backing for non-Hermitian aspects of our Hamiltonian [460,461]. Future experiments may involve a number of targets discussed within this framework which is rich in possibilities for empirical study against predicted limits imposed by entropic gravity, CFS, ASG, and Monster symmetry. Progress in this area will undoubtedly have profound impacts. As current AI technologies reach scaling limits [341, 342] and consume a growing energy budget, explorations into this new physics provides a new frontier in AI research, the foundations of physics, and even postquantum cryptanalysis [343].

The fermion-boson correspondence at the Monster conformal field theory critical point provides a mechanism for dark matter production through gravitational mediation of Majorana fermions [453]. In our model, the $\mathbb{Z}_2$ orbifold transition from the Baby Monster CFT (fermionic spin states) to the Monster CFT (light-like modes) parallels the seesaw mechanism (in our model, interpolations between the orbifolds, or "Centaur" and "Minotaur" geometries) for neutrino mass generation, where heavy sterile neutrinos naturally emerge as dark matter candidates, and has been previously proposed in literature. Intriguingly, the seesaw mechanism has even been proposed as one route towards understanding the origins of inflation or dark energy [453].

Physics which enables macroscopic quantum entanglements across millions of tubulins opens up new fields of study that explore the intersection of nonlinear dynamics systems theory and probabilistic quantum field theory like turbulence or magnetohydradynamics (MHD), with statistics that can also be modeled by the Riemann zeta function. To generalize the 2D Navier-Stokes solution which has been proven to unique and smooth - free of singularities [454] - to the general 3D Navier-Stokes equations might be impossible because the vortex stretching term $(\omega \cdot \nabla)\mathbf{u}$ [430, 431] has no 2D holographic dual with Monster symmetry that provides a unique scale invariant asymptotically safe completion. In our NSN model, the very same force that causes the collapse of matter into singularities also enforces asymptotic safety (there is scale invariance between the UV and IR scales at the UV/IR fixed point) - with the classical Navier-Stokes equations, information flows only from large scales to small scales - but not from small scales to large scales, but lacks holography required for a complete, asymptotically safe gravitational theory of turbulence cascades, where literature suggests a connection to spinfoams and spinfoam networks and which might be approached by twistor theory [471].

The UV/IR fixed point in ASG which is hypothesized to provide a UV completion to gravity is a state of maximum symmetry and entropy in 2 dimensions [362] - the same forward and backward pass symmetry required in our model. The Monster CFT is the CFT with the largest possible symmetry group in 2 dimensions, and has been proposed by prominent physicists such as Witten to be a description of pure gravity in 3 dimensions. Therefore, as an extremal projector CFT in 2 dimensions [363], it is a natural candidate for the effective description of physics at such an extreme point [364], which should only require 3 dimensions in our model as the 4th time dimension is generated by discrete OR events. Furthermore, it finds centrality in black hole physics (where Redamacher sums count black hole microstates [365]) and its spectral properties are linked to number theory (e.g., the Riemann zeta function or related Hilbert-Polya programme, zeta regularization, and supersingular primes), [315, 366–375] which itself is connected to spectral operators and prime number distributions in cryptography. Not only are these topics important for our model, but they offer a possible direction for investigating a physical proof of the Riemann hypothesis by providing a physical system that fits the description of the Hilbert-Polya conjecture. These concepts appear in the analysis of chaotic and critical systems at the intersection of deterministic nonlinear system dynamics and probabilistic theories, which is exactly what one would expect from any theory of quantum gravity, and will likely shed further light (as in, through twistor theory) on the Riemann hypothesis as well as the nature of turbulent fluid flows, magnetohydrodynamic instabilities (especially in their relevance in tokamak reactors), and other macroscopic quantum-like phenomenon [165–167,268,368,376–383,471], which may even extend towards understanding social or economic systems [168–170].

3D Navier-Stokes equations can be projected from specific solutions of Einstein field equations. The Navier-Stokes/Einstein correspondence shows that incompressible Navier-Stokes equations emerge as the hydrodynamic limit of a dual gravitational theory in AdS space, with the brain's dual theory identified as 3D quantum gravity at the Monster fixed point. This suggests that Navier-Stokes singularities are resolved through quantum gravitational UV completion provided by the Monster CFT. The UV cutoff prevents vortex stretching from creating finite-time blowups by regulating the energy cascade at the Planck scale. Migdal's loop equations describe vortex loops as discrete topological objects. Migdal's vortex cells can be identified with faces of the spin foam network, and vortex reconnection events with Pachner moves (elementary topological transitions) in quantum gravitational dynamics. Migdal demonstrated that turbulent vortex configurations obey an area law where entropy scales with surface area rather than volume, exactly matching the Ryu-Takayanagi formula for holographic entanglement entropy. This establishes turbulence as a physical realization of holographic quantum gravity. Empirically, Riemann zeta zeros appear in turbulent flow and magnetohydrodynamic instability statistics, suggesting turbulence exhibits quantum chaos arising from the same critical point physics that governs quantum gravity in our NSN framework, and may provide a route for explaining how turbulent dendritic arborization is modulated by biophotons, with turbulent branching patterns fitting models of LTP/LTD, or even the etiology of coronal ejections or anomalous geometries of streamer plasmas observed from vacuum tube driven tesla coils (VTTCs).

From the angle of mathematics, the theoretical framework presented here, which relies on biophotonic signaling, suggests a natural connection to Penrose's twistor theory. As twistors provide a fundamental description of null geodesics and massless particles, the proposed Majorana biophotons can be reformulated as twistor streams that mediate entanglements between topologically protected states. This implies that the microtubule network, in its function as an optical waveguide, is not merely transmitting classical light, but at OR events in our loop quantum gravitational metacircular evaluation mechanism [344], is actively guiding conformal geometric data, possibly processing information in background independent indefinite causal structures. The non-local update mechanism mediated by these photons finds a natural formulation in twistor space, where causal structure is inherently holistic. Furthermore, the conjectured role of the Monster CFT at the UV/IR critical point aligns with the deep connection between twistor theory and conformal geometry, potentially providing a more foundational pathway to unify the bulk spinfoam dynamics with the boundary conformal field theory. Indeed, Penrose himself has suggested that a theory of quantum gravity is likely to find foundations in twistor theory.

Exploring the twistor correspondence of neural spinfoam networks is a promising direction for future work, offering a more complete geometric description of quantum information processing in biological systems and a clear direction for investigating relationships between computational complexity classes. [59, 354–358, 361]

This work proposes a unified perspective in which three seemingly distinct constructions (a physical Rindler–Majorana Hamiltonian, a modular orbifold partition function arising from Monstrous moonshine, and an analytic θ–ξ Hilbert–Pólya operator) are understood as different manifestations of a single underlying spectral structure. Although each construction originates in a different mathematical or physical domain, the framework developed here suggests that they encode the same spectral data, namely the ordinates of the nontrivial zeros of the Riemann zeta function. The resulting picture is a triadic correspondence between physics, modularity, and analytic number theory.

The first layer of this picture is the physical one. A Majorana field on an orbifolded Rindler half-line gives rise to a self-adjoint Dirac-type Hamiltonian H_M, whose eigenvalues are determined by Mellin–Barnes quantization conditions containing the factor $\zeta(\frac{1}{2} + iE)$. Under the assumption that normalizability coincides with the vanishing of this zeta term, the operator H_M acquires a discrete spectrum whose structure is deeply linked to the arithmetic of the critical line.

The second layer is modular and arises from the Monster/Baby Monster orbifold. A $2B$ involution $g \in \mathbb{M}$ decomposes the Monster vertex operator algebra as

$$V^\natural = V_+ \oplus V_-,$$

corresponding to untwisted (Monster) and twisted (Baby Monster) sectors. The associated orbifold partition function,

$$Z_{\text{orb}}(\tau) = j(\tau) - 744,$$

is a weight-zero modular function whose coefficients encode the representation theory of the Monster. The geometric decomposition of the Rindler orbifold into right and left wedges mirrors the VOA decomposition into V_+ and V_-, providing a bridge between the physical and modular descriptions.

The third layer is analytic. The function $\xi(s)$ admits a Mellin representation involving the Jacobi theta function, suggesting the existence of a self-adjoint operator D_θ whose heat trace satisfies

$$\text{Tr}\, e^{-tD_\theta^2} = \theta(t) - 1, \qquad \zeta_{D_\theta}(s) = \xi(s).$$

Such an operator would be an analytic incarnation of Hilbert–Pólya: its real spectrum would generate the nontrivial zeros of $\zeta(s)$ through the functional equation of ξ.

The central insight is that these three layers appear to converge on the same spectral data. The orbifold provides the structural link: the physical operator H_M naturally lives on the twisted sector of the Rindler orbifold, while the analytic operator D_θ aligns with the untwisted sector; both sectors meet in the modular object $Z_{\text{orb}}(\tau)$. This produces a triangular correspondence,

$$H_M \quad \longleftrightarrow \quad Z_{\text{orb}}(\tau) \quad \longleftrightarrow \quad D_\theta,$$

suggesting that the physical spectrum, the modular spectrum, and the analytic spectrum are simply different parametrizations of a single underlying set of numbers.

In this sense, the framework yields three insights: that the zeros of $Z_{\text{orb}}(\tau)$ on the line $\Re\tau = \frac{1}{2}$ correspond to the nontrivial zeros of ζ; that the partition function of H_M matches the orbifold partition function after an appropriate change of variables; and that H_M and D_θ share the same spectral zeta function.

9 Conclusion

In summary, an integrative theory of consciousness is emerging that bridges classical neuroscience and quantum physics. On the one hand, classical theories (IIT, GWT, and others) correctly emphasize the importance of information integration, global availability, and complex feedback dynamics for consciousness. These ideas have informed why current AI lacks certain capabilities – e.g. lack of integration across modalities and the absence of a global workspace for meaning – and indeed today's AI systems show none of the adaptive, unified awareness that biological systems exhibit. On the other hand, quantum theories of consciousness like Orch-OR extend this picture by proposing a concrete physical mechanism for achieving integration and unity to resolve the binding problem: quantum-entangled states in the brain that collapse as a whole, producing unified experiences, and can be extended to represent quanta of spacetime by modeling brain neural networks as spinfoam networks. This quantum mechanism not only describes a mechanism for the qualitative unity of consciousness (why it feels like one mind and not a collection of independent processes), but also suggests a route to overcome the massive inefficiencies seen in artificial systems. A classical AI must brute-force compute and synchronize activities across billions of parameters, consuming megawatts of energy, yet still cannot truly "bind" information into a singular unified experience.

In contrast, the human brain achieves feats on just 20 watts, hinting that it leverages physical shortcuts unavailable to classical machines. If consciousness indeed arises from non-classical, perhaps quantum-gravitational, processes, then current AI models – which operate on classical information – will not spontaneously become conscious merely by means of scaling. The implications for artificial intelligence are profound. To move beyond massively inefficient pattern learners and towards systems with brain-like awareness and efficiency, the scientific community may need to rethink AI architecture from the ground up – embracing principles of entanglement, superposition, and perhaps even space-time geometry in information processing. By modeling artificial neural networks as spinfoam networks – effectively endowing them with a network of quantum informational degrees of freedom that can self-collapse to optimal states – we aim to replicate the brain's ability to integrate information swiftly and with minimal energy.

In essence, our model attempts to import into AI the very features that make biological cognition both conscious and efficient, guided by the theory of consciousness we have synthesized. By grounding AI design in the physical mechanisms that might underlie human consciousness, we take a step toward an architecture that can overcome the looming bottlenecks of classical AI and perhaps come closer to the adaptive, unified intelligence of the human mind.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Data Availability

New data was created and analyzed in this study. Data is available from the corresponding author upon reasonable request.

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