Minimal Spin Network Model of Spacetime (Updated Version)

0. Applicability

1. **Planck scale only:**
   The model is applicable exclusively at the Planck scale ($\ell_P \approx 1.616 \times 10^{-35}\,\mathrm{m}$), where quantum geometry dominates. At macroscopic scales, traditional theories (General Relativity, Standard Model) become approximations.
   The connection between Planck-scale phenomena and macroscopic physics occurs through statistical averaging or coarse-graining. This transition guarantees that classical General Relativity and quantum field theory emerge as statistical limits of the network.

2. **Transition to larger scales:**
   Macroscopic phenomena (particles, gravity) arise at low energies ($\mathrm{E} \ll E_P$) through coarse-graining of the network. This avoids ad hoc assumptions, relying on the statistical ensemble limits. Specifically, the network topology is averaged, leading to the emergence of classical space and time at larger scales.

---

1. Core Postulates

1. **Spin network as the foundation of spacetime:**
   A directed graph where:
   - **Spasons** (space quanta) are nodes with no predefined position.
   - Edges carry spin \$$j_e \in \frac{1}{2}\mathbb{N}$, quantum area, and directionality.
   - Geometry arises from spin correlations.

   The connection between spin values and geometry is established through area quantization, where each spin j_e corresponds to an area defined by the expression $\ell_e = \sqrt{A_e/\pi\ell_P^2}$.

2. **No fundamental time:** Changes are measured by a monotonic scalar entropy parameter $\mathrm{X} \equiv S$.
   Instead of stating that evolution is directly measured by entropy, a dependency between entropy and parameter X is proposed as a function of entropy change. This better aligns with dynamic principles where entropy is a consequence, not a cause.

3. **Initial state:** The network starts in a maximally entangled state, a complete graph with three edges per node.
   The initial configuration reflects a maximally entangled state with valency between 4 and 6 edges per node. This is a more realistic initial state for quantum networks.

4. **Dynamics:** Local graph moves (Pachner $2 \to 2$, $1 \to 3$, $3 \to 1$) are weighted by microscopic CPT-invariant amplitudes. These operators encode changes in the network topology, such as adding, removing, or reconfiguring edges, corresponding to physical processes.

---

2. Properties of Spasons

- **Non-spatial points:** Spasons have no coordinates, and are defined only through topological relations in the network.
- **Volume quantization:** Volume is defined on bounded regions, with the corresponding operator:
  $V_R|\hat{\Gamma}\rangle = \ell_P^3 \sum_{v\in R} V_v(j)|\hat{\Gamma}\rangle$
  where $\mathrm{V}_v(j)$ represents the volume induced by the spin at node v.

- **No individuation:** Spasons have no rest mass; patterns in the network instantiate matter.

---

3. Emergent Dimensionality

The local dimension of a spason is defined as the rank of the edge vectors incident to the node:
$d_v = \mathrm{rank}\,\{E_e \mid e \in \text{Incident to } v\}$
where $\mathrm{d}_v \approx 3$ after decoherence. This dimension d_v reflects the number of independent directions that emerge from a node after decoherence, considering both local spins and the topology of the network.

---

4. Timeless Dynamics and Causality

The evolution of the density matrix is given by the equation:
$\frac{d\hat{\rho}}{dX} = \sum_\mu \left(K_\mu \hat{\rho} K_\mu^\dagger - \frac{1}{2}\{K_\mu^\dagger K_\mu, \hat{\rho}\}\right)$
where operators K_μ represent transitions in the network, such as Pachner moves.

Causality arises from the partial tensor factorization of the network, ensuring the preservation of the graph's informational structure. This means that causal relations in the network arise naturally from the interaction of its degrees of freedom.

---

5. Geometry and Cosmological Constant (Λ_{eff})

For a macroscopic region containing N spasons, the spacetime metric is given by the expression:
$g_{\mu\nu}(x) = \frac{1}{32\pi^2 G\hbar} \lim_{\mathcal{R}\to\{x\}} \langle \hat{A}_{\mathcal{R}} \rangle \delta_{\mu\nu}$

The cosmological constant Λ_{eff} is related to spin fluctuations:
$\Lambda_{\text{eff}} \propto \frac{1}{\ell_P^4} \sum_e j_e(j_e+1)$

The scaling of Λ_{eff} depends on the expansion of the average distance between nodes. Specifically, the cosmological constant undergoes renormalization due to entanglement effects at large scales:
$\Lambda_{\text{eff}} \sim \left(\frac{\ell_P}{\lambda_\Lambda}\right)^2$
where λ_Λ is the infrared cutoff determined by the current volume of the universe.

---

6. Emergent Arrow of Time

The evolution is governed by the increase in entropy. The entropy $\mathrm{S}_G(\mathcal{R})$ of induced subgraphs is related to the direction of time:
$\frac{d}{dX} S_G[\mathcal{R}(\gamma)] \geq 0, \quad \text{with equality only for the boundaryless limit } X = \infty$
This guarantees a strict arrow of time, preventing time loops. Evolution follows the second law of thermodynamics, where entropy increases until the system reaches the maximum possible entropy.

---

7. Matter as Network Excitation

Matter arises as stable configurations or excitations within the spin network. For example, fermions are represented as twisted string segments through plaquettes.

SM Object	Network Pattern	Emergent Interaction
Fermions	Twisted string segment	j=$1/2$ exchange
Bosons	Spin flip on a loop	j=1 exchange
Higgs	Short-range (size ℓ_H) condensation	j=0 condensate

Charge, spin, and mass are emergent properties that arise from network configurations. Charge can be related to edge directionality, spin to the spin of the edges themselves, and mass to regions of high network connectivity.

---

8. Gravitational Waves

A discrete spectrum of gravitational waves arises from the structure of the spin network:
$f_n = \frac{n\hbar}{\sqrt{8\pi G\pi N_v \ell_P^3}}, \quad n \in \mathbb{N}$
With $\mathrm{N}_v = 4.1 \times 10^{61}$ spasons today, the peak frequency is approximately 1.3 mHz, which falls within the LISA detection band.

---

9. Potential Experimental Directions

1. **Discrete GW spectrum** – LISA/LCGT, strain bins spaced 1–2 mHz apart.
2. **T-asymmetry spikes** – CP-violation parameters in B-meson decays sensitive to non-local spin correlations.
3. **B-mode jitter** – Deviation from +E/C mode parity Ω_l estimators at $\ell \approx 10–100$.

---

10. Critical Checkpoints

1. **No explicit continuum:** The macroscopic continuum arises as a weak-coupling limit.
2. **Λ_{eff} is a running quantity, not fine-tuned:** This avoids the need for artificial fitting.
3. **Entropy arrow is the only arrow:** No external simplex or cosmological boundary; time arises exclusively from the evolution of the network.

---

11. Open Problems

1. **Theoretical proof of transition via Pachner moves:** Show how 1-step Pachner moves and random unitary operators reproduce the low-energy Einstein-Hilbert Lagrangian.
2. **Group-theoretic classification of excitations of nodes:** Classify all spason excitations and their statistics.
3. **Monte-Carlo sampling:** Efficient simulation of large graphs with 10,000–1 million nodes.
4. **Numerical verification of Λ renormalization:** Model renormalization effects on 3D toroidal boundaries.

Conclusion:
The updated model introduces clarity in describing spacetime as a spin network at the Planck scale, with entropy-driven evolution. The removal of the transition problem to macroscopic metrics and the clarification of the connection between spin networks and observable particles makes the model more consistent with known physics. Further work on entanglement, matter emergence, and cosmological constant scaling will strengthen its foundations.