COMPUTING COSMOLOGICAL PRIMORDIAL FLUCTUATIONS

from the full covariant quantum theory

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ENGAGING SCIENCE.

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FROM SPINFOAMS TO COSMOLOGY

Primordial fluctuations from quantum gravity, with F. Gozzini

- **Quantum Regime**
- Graph Approximation
- Hartle-Hawking State
- Transition Amplitude
- Computational Method

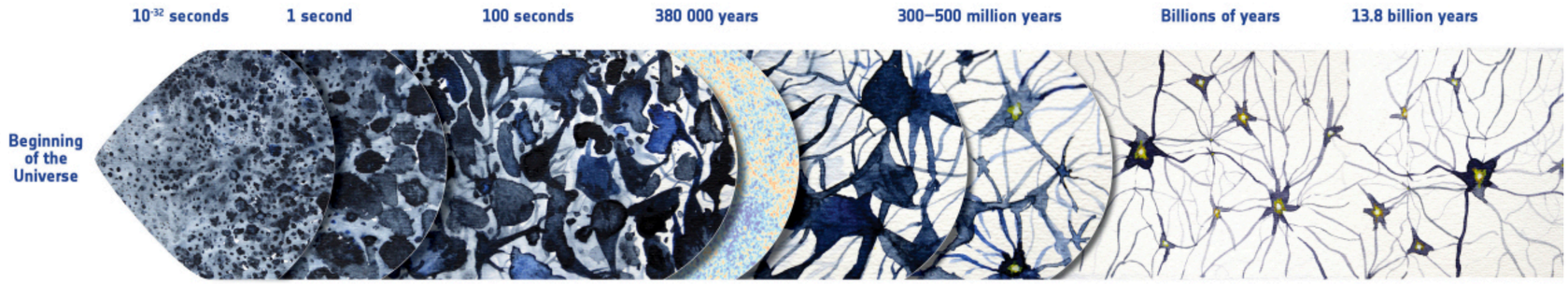

Image credit: ESA

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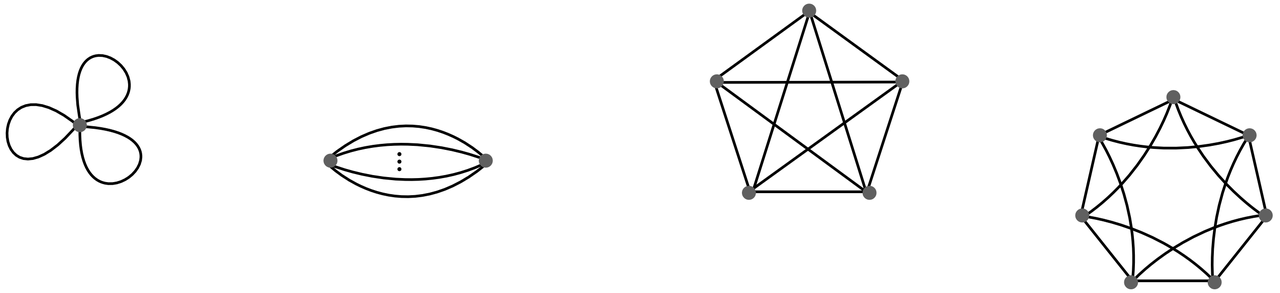

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Toward Spinfoam Cosmology, with E. Bianchi and C. Rovelli

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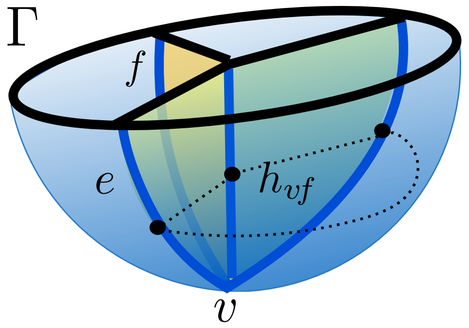


APPLYING SPINFOAMS TO COSMOLOGY

Toward Spinfoam Cosmology, with E. Bianchi and C. Rovelli

- Quantum Regime
- Graph Approximation
- Hartle-Hawking State
- **Transition Amplitude**

$$W_{\mathcal{C}}(h_l) = \int_{SU(2)} dh_{vf} \prod_f \delta(h_f) \prod_v A(h_{vf})$$

- Computational Method

APPLICATION TO COSMOLOGY

- Quantum Regime
- Graph Approximation
- Hartle-Hawking State
- Transition Amplitude
- **Computational Method**

$$W(j_l, i_n) = \sum_{l_f, k_e} \left(\prod_e (2k_e + 1) B(j_l, l_f; i_n, k_e) \right) \{15j\}(l_f, k_e)$$

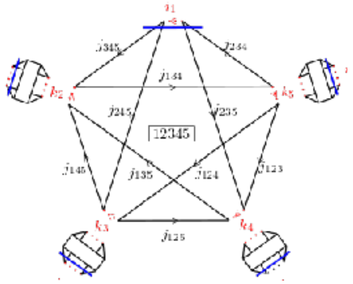
OBSERVABLES

Primordial fluctuations from quantum gravity, with F. Gozzini

- Area
- Volume $\qquad \langle \mathcal{O} \rangle = \langle \psi_o | \, \mathcal{O} \, | \psi_o \rangle$
- Dihedral Angles $\Rightarrow$ Curvature $\qquad$ *spread*
- **Correlations** $\qquad C(\mathcal{O}_1, \mathcal{O}_2) = \dfrac{\langle \psi_o | \, \mathcal{O}_1 \mathcal{O}_2 \, | \psi_o \rangle - \langle \mathcal{O}_1 \rangle \langle O_2 \rangle}{(\Delta \mathcal{O}_1) \, (\Delta \mathcal{O}_2)} \qquad \Delta \mathcal{O} = \sqrt{\langle \psi_o | \, \mathcal{O}^2 \, | \psi_o \rangle - \langle \mathcal{O} \rangle^2}$
- **Entanglement Entropy** $\qquad S_A = - \, Tr \left(\rho_A \log \rho_A \right)$

5-CELL MODEL

- Simplest regular 4-polytope



- Regular triangulation of S_3

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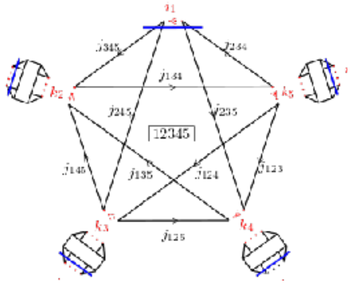

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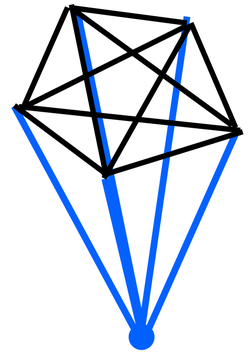
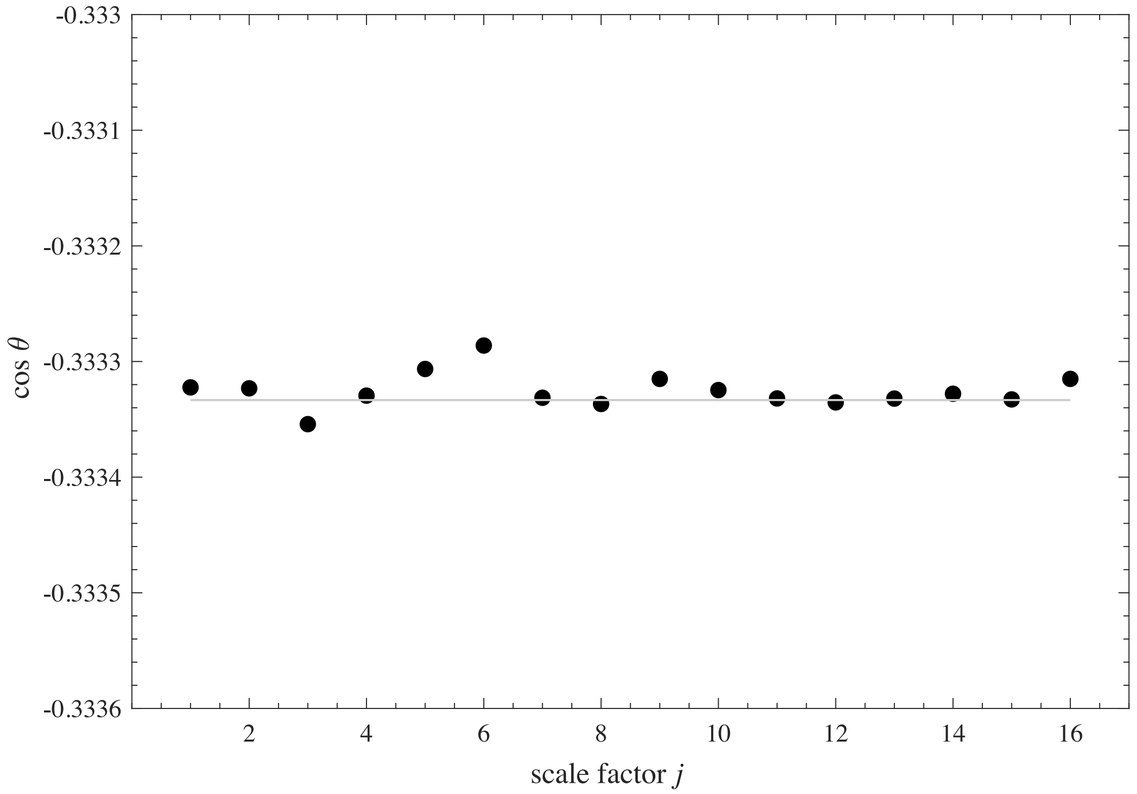


RESULTS FOR THE 5-CELL MODEL

1. 3-sphere as emerging geometry
2. large fluctuations
3. large correlations



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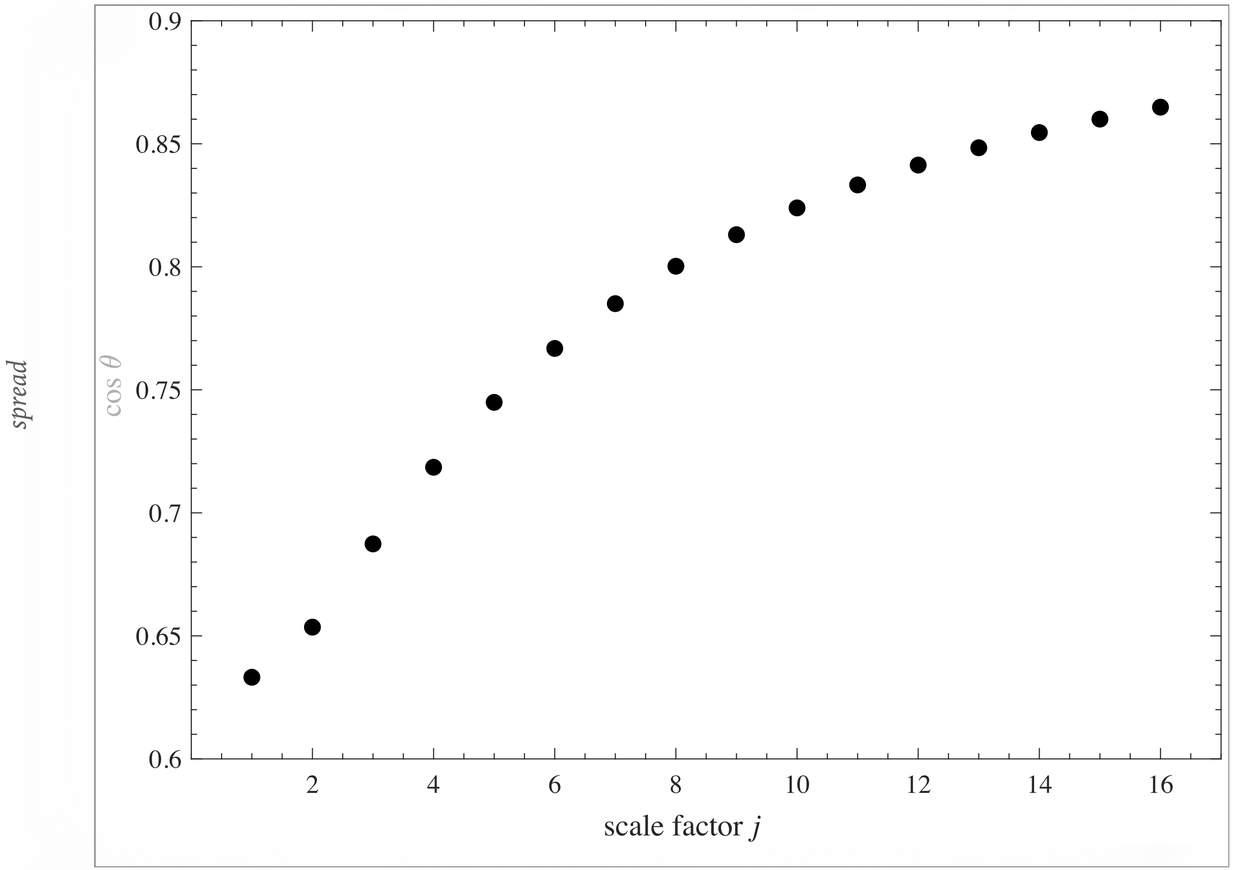

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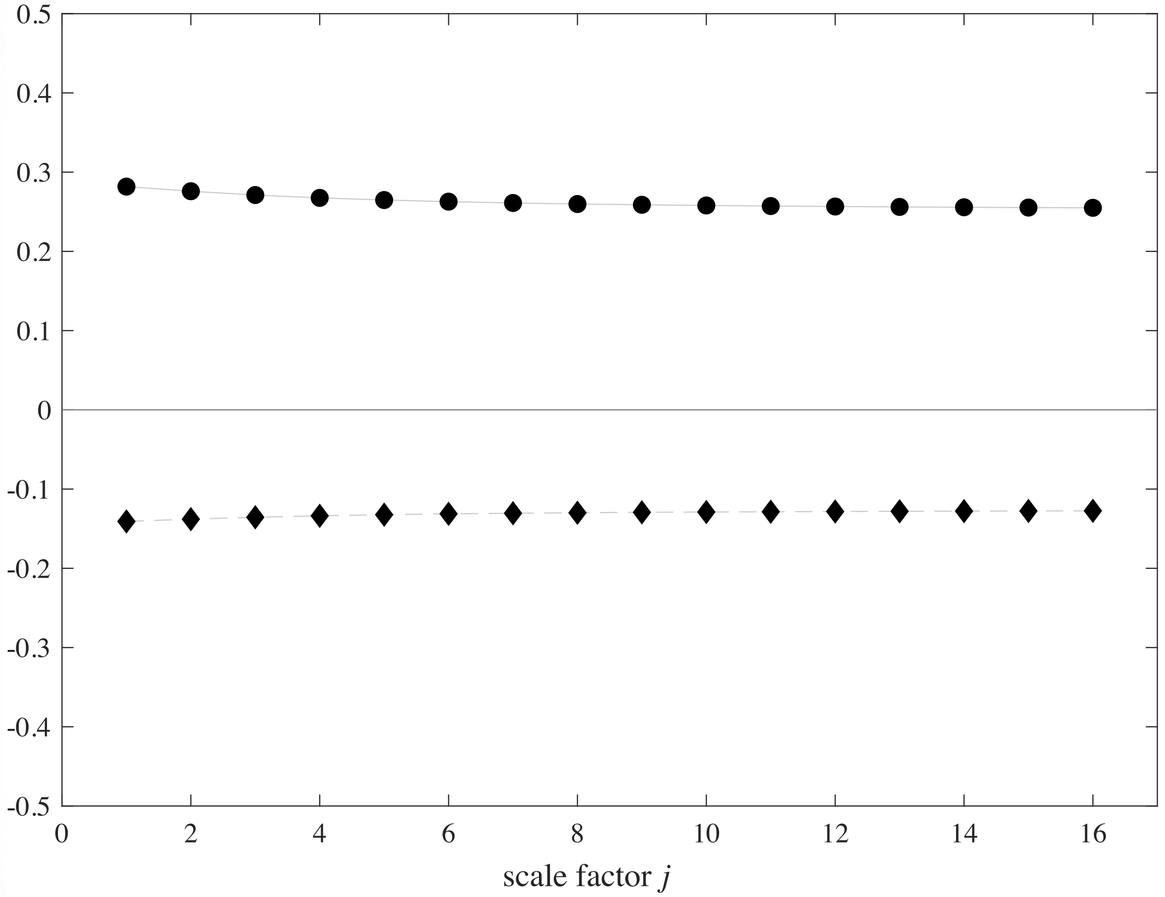

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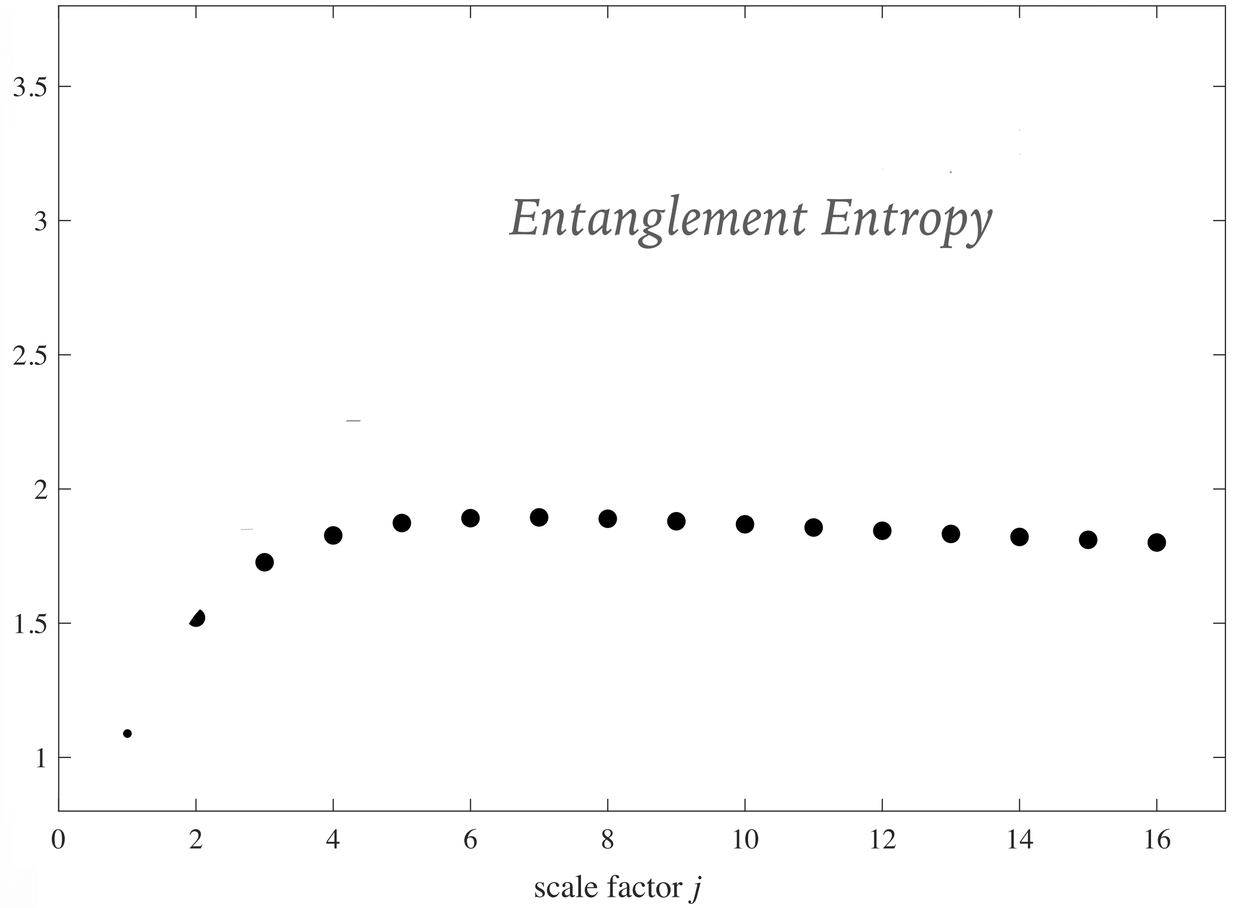
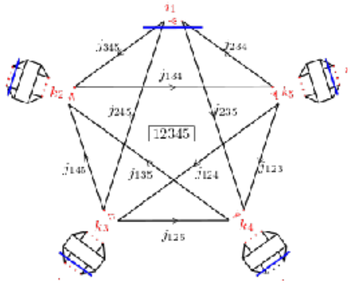


20-CELL MODEL VIA REFINEMENT

MCMC methods for graph refinement in covariant LQG, with P. Frisoni & F. Gozzini



Gozzini'21, A high-performance code for EPRL spin foam amplitudes

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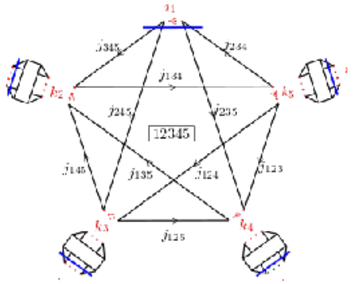

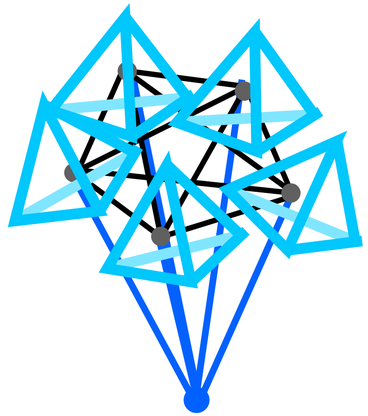

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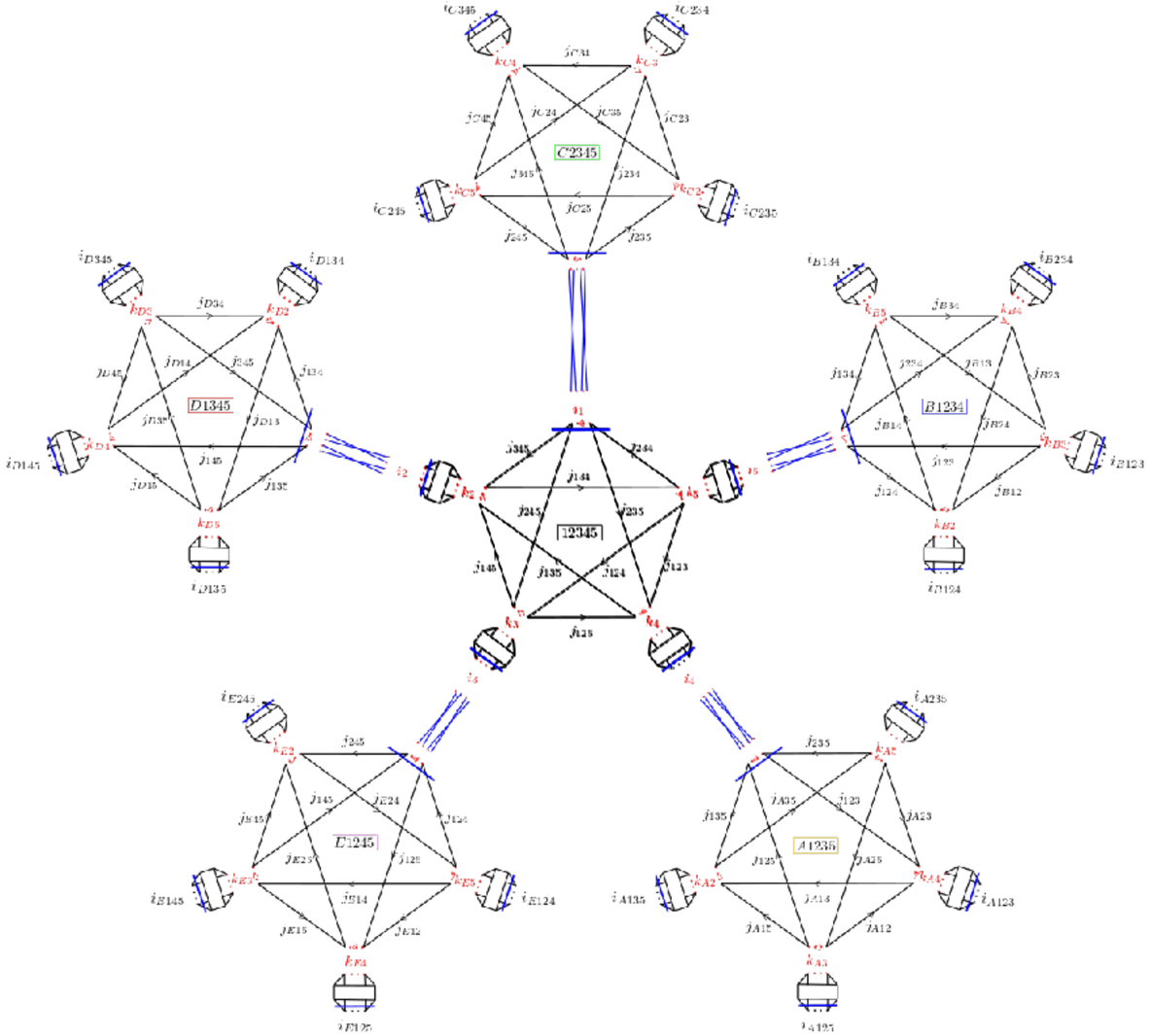

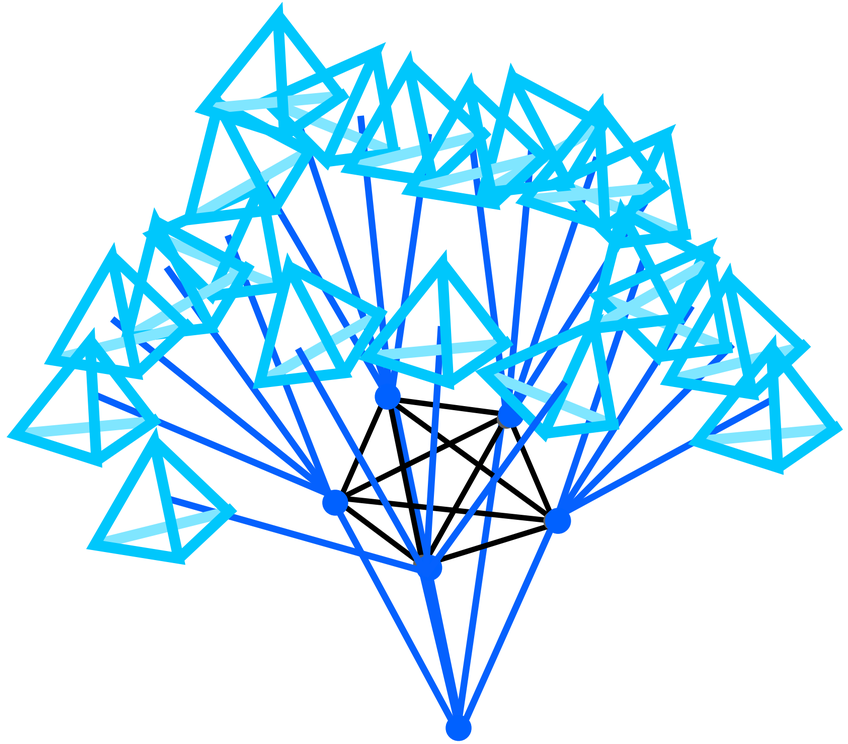

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DIHEDRAL ANGLE

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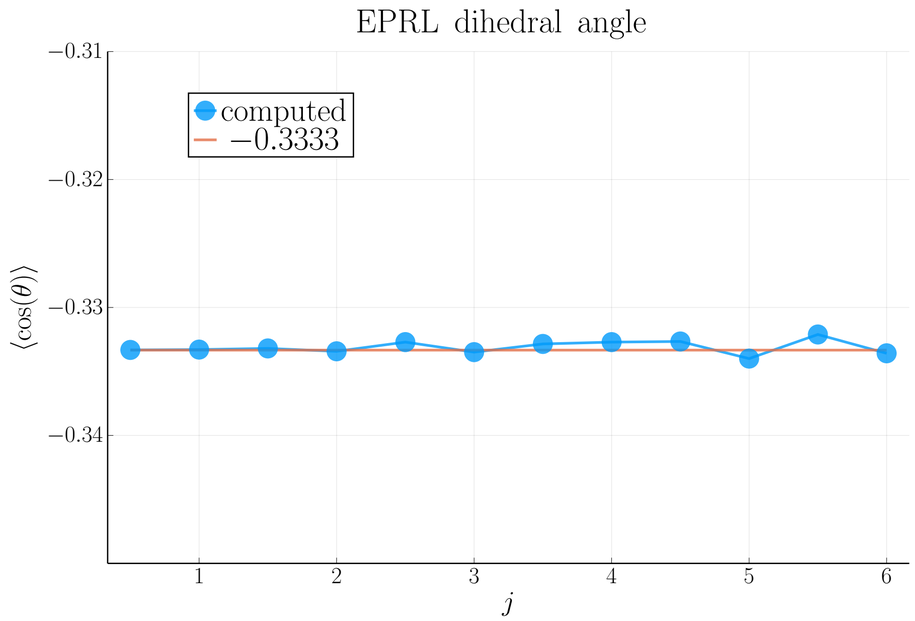

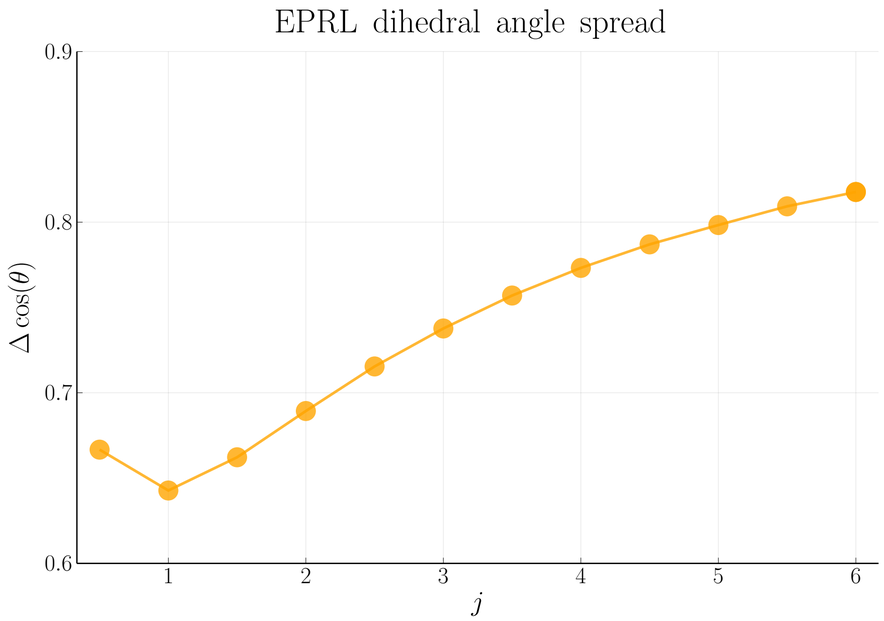

VOLUME

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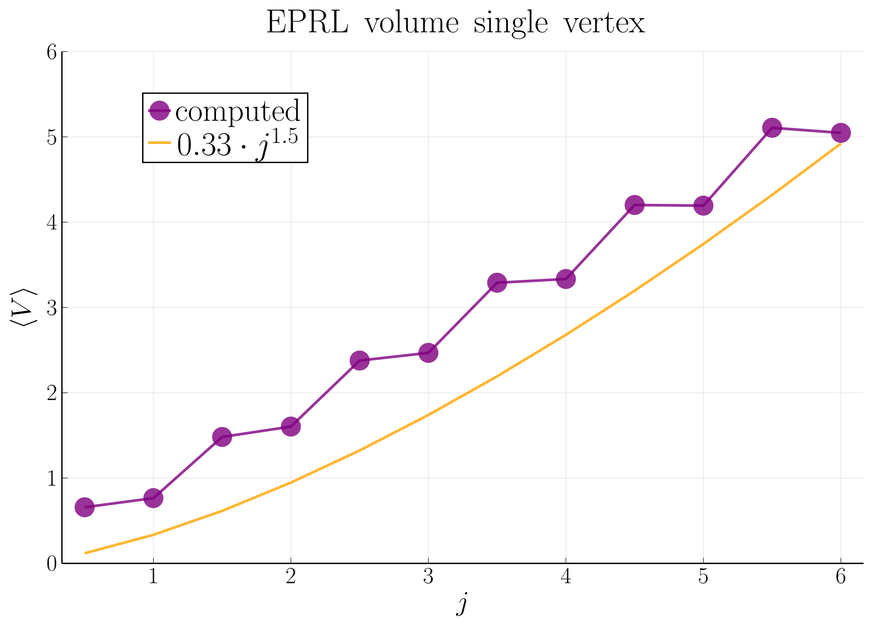

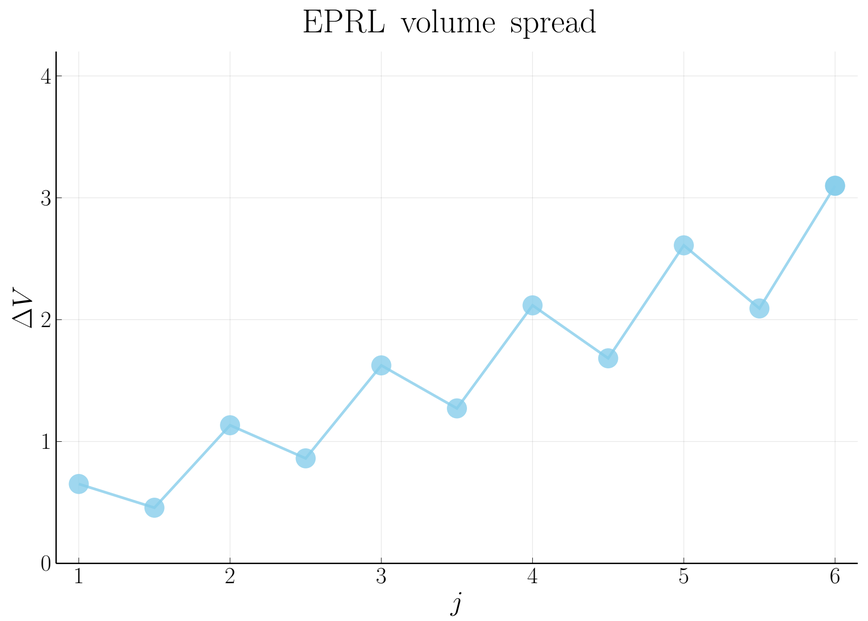

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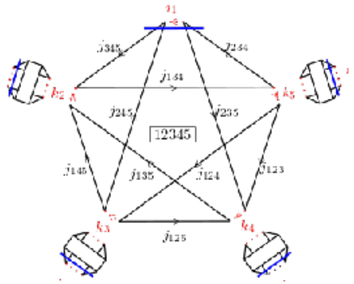
MCMC methods for graph refinement in covariant LQG, with P. Frisoni & F. Gozzini



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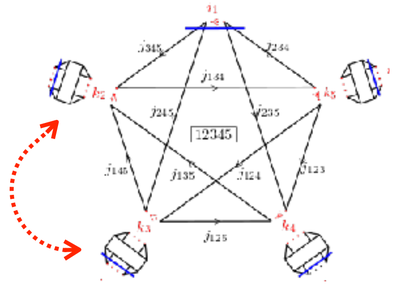

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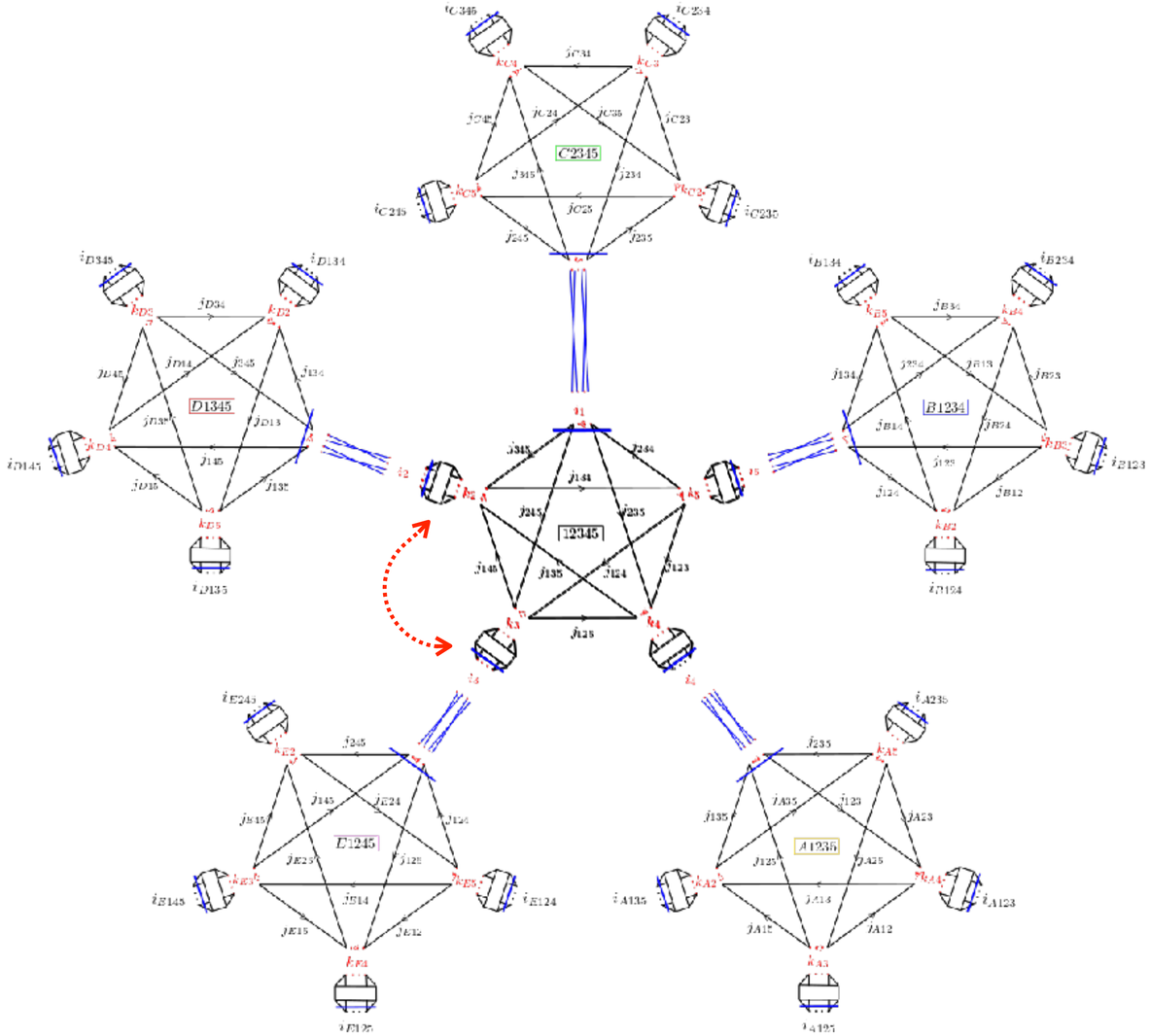

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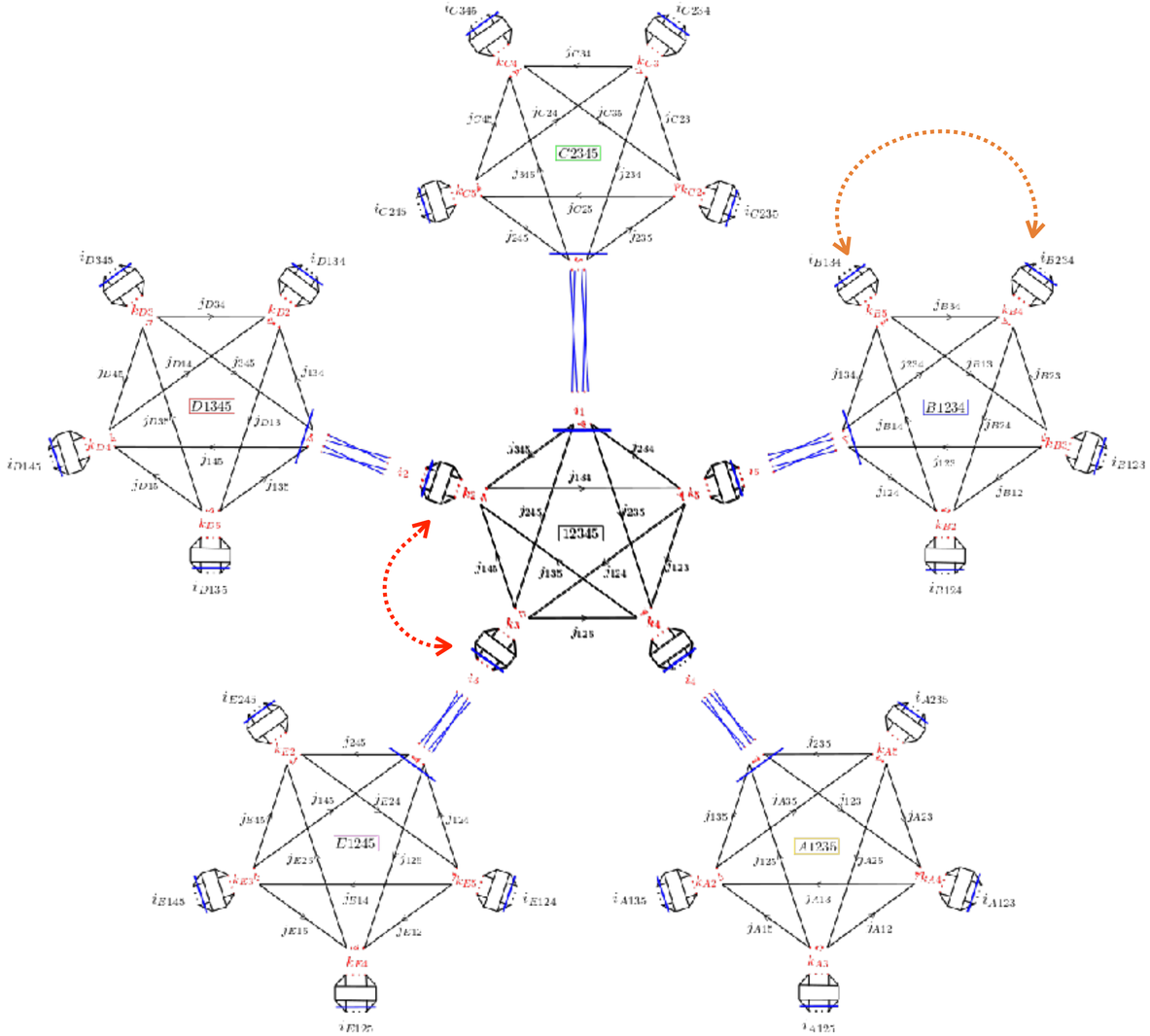

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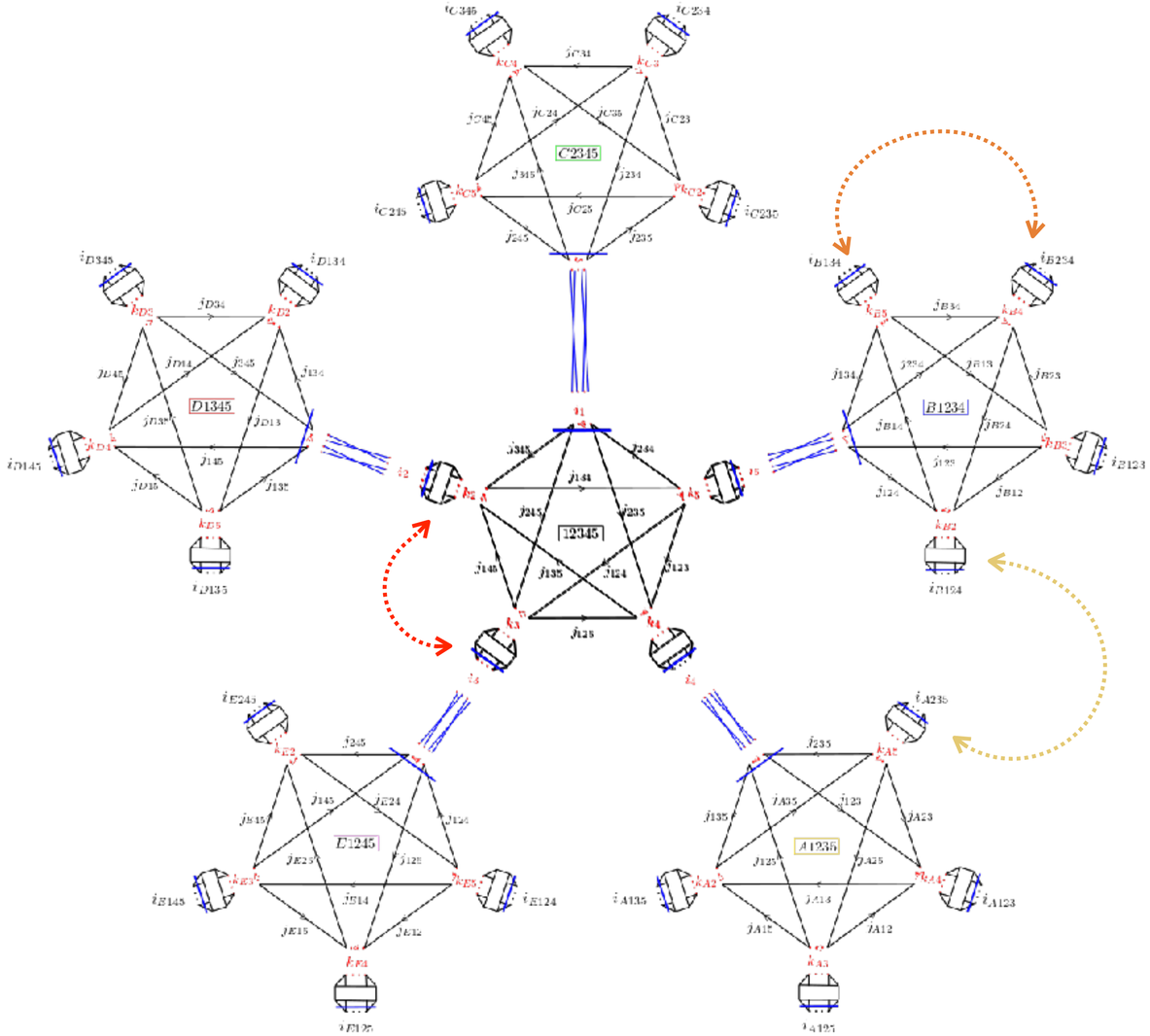

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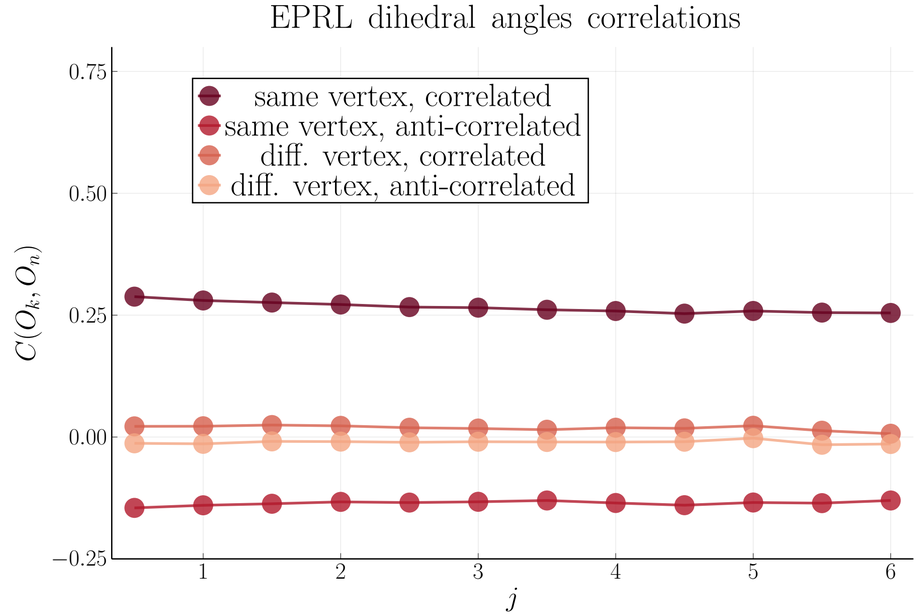

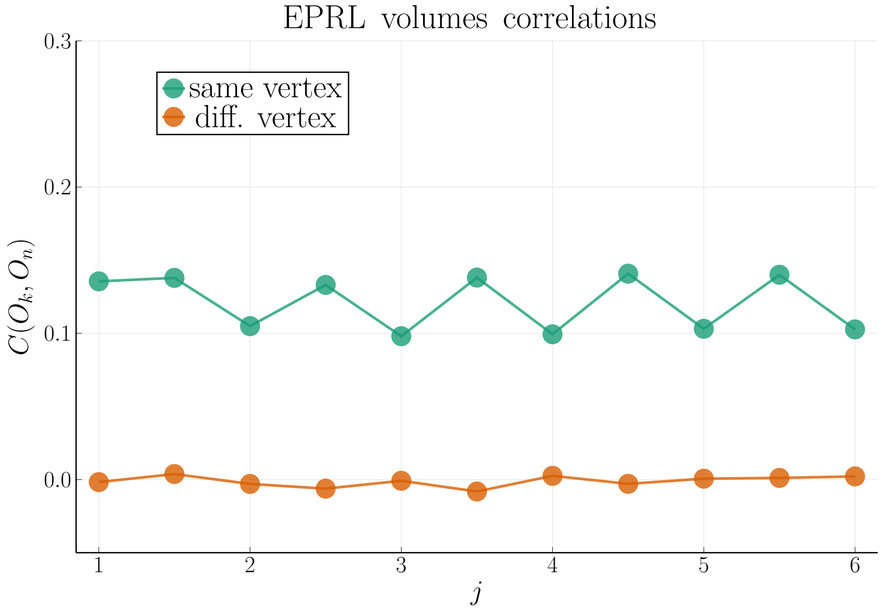

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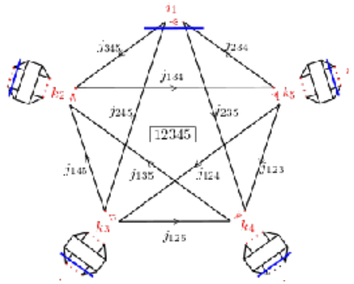

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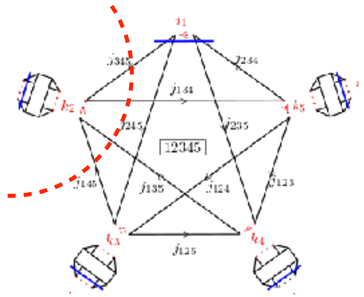

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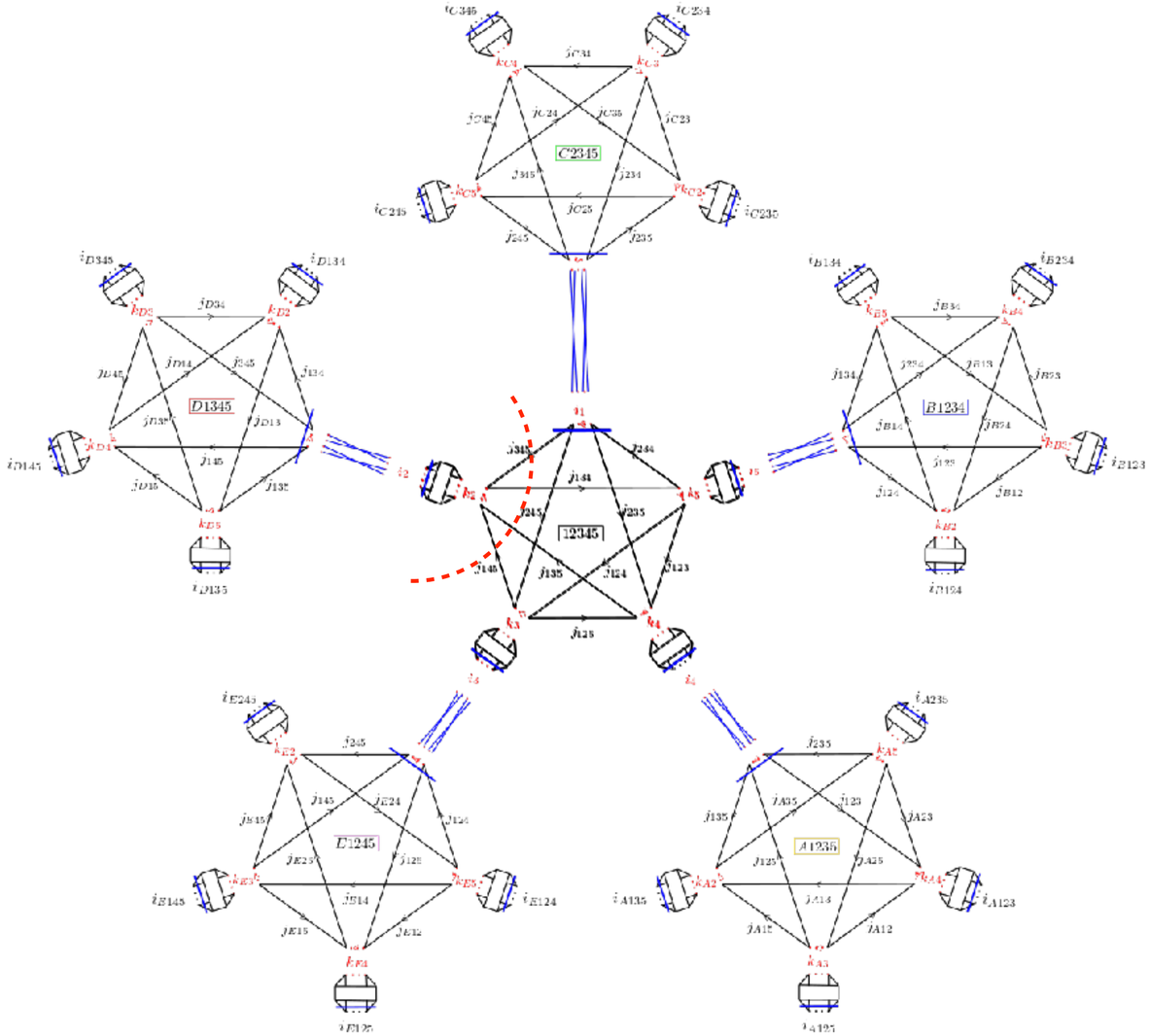

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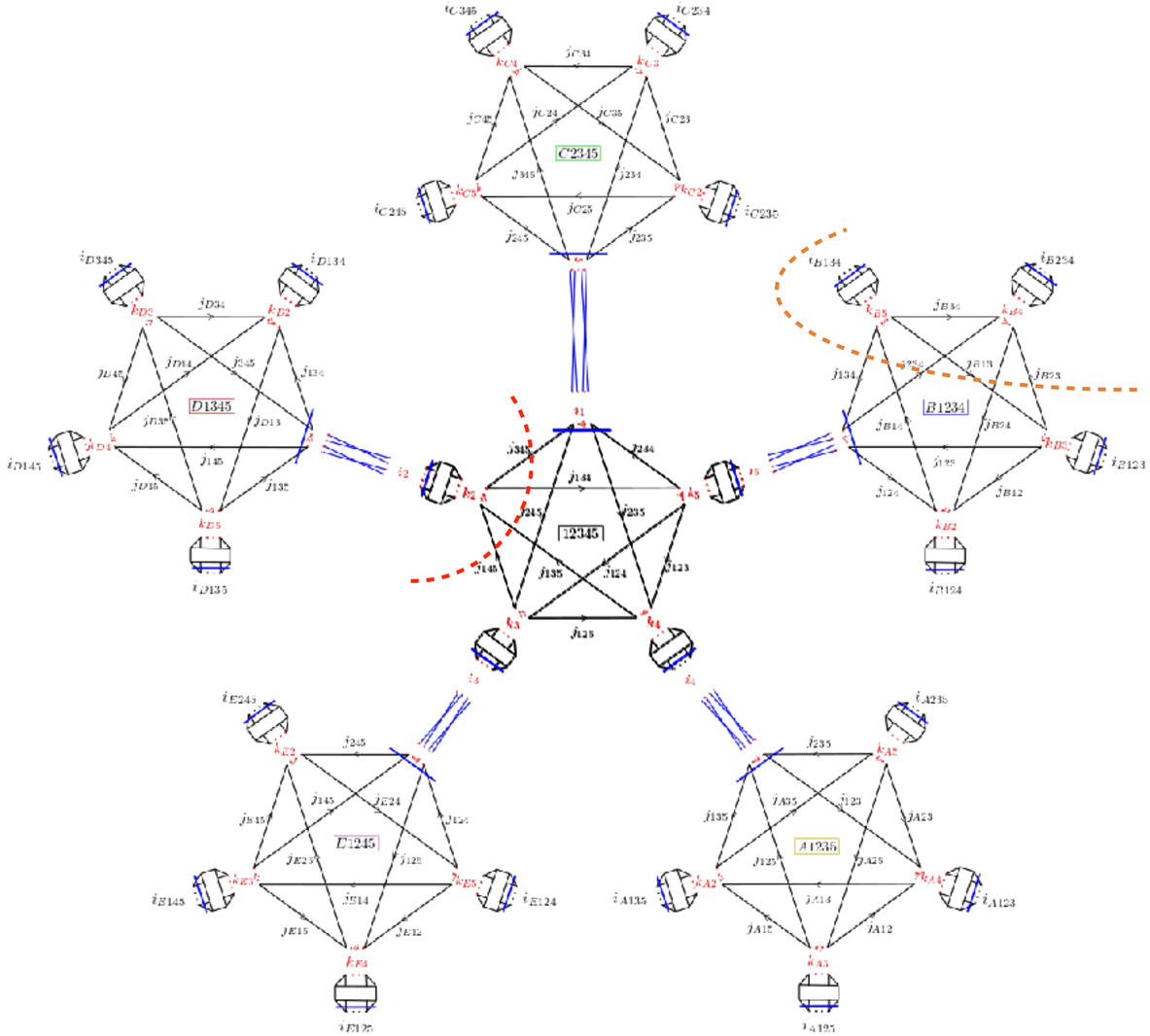

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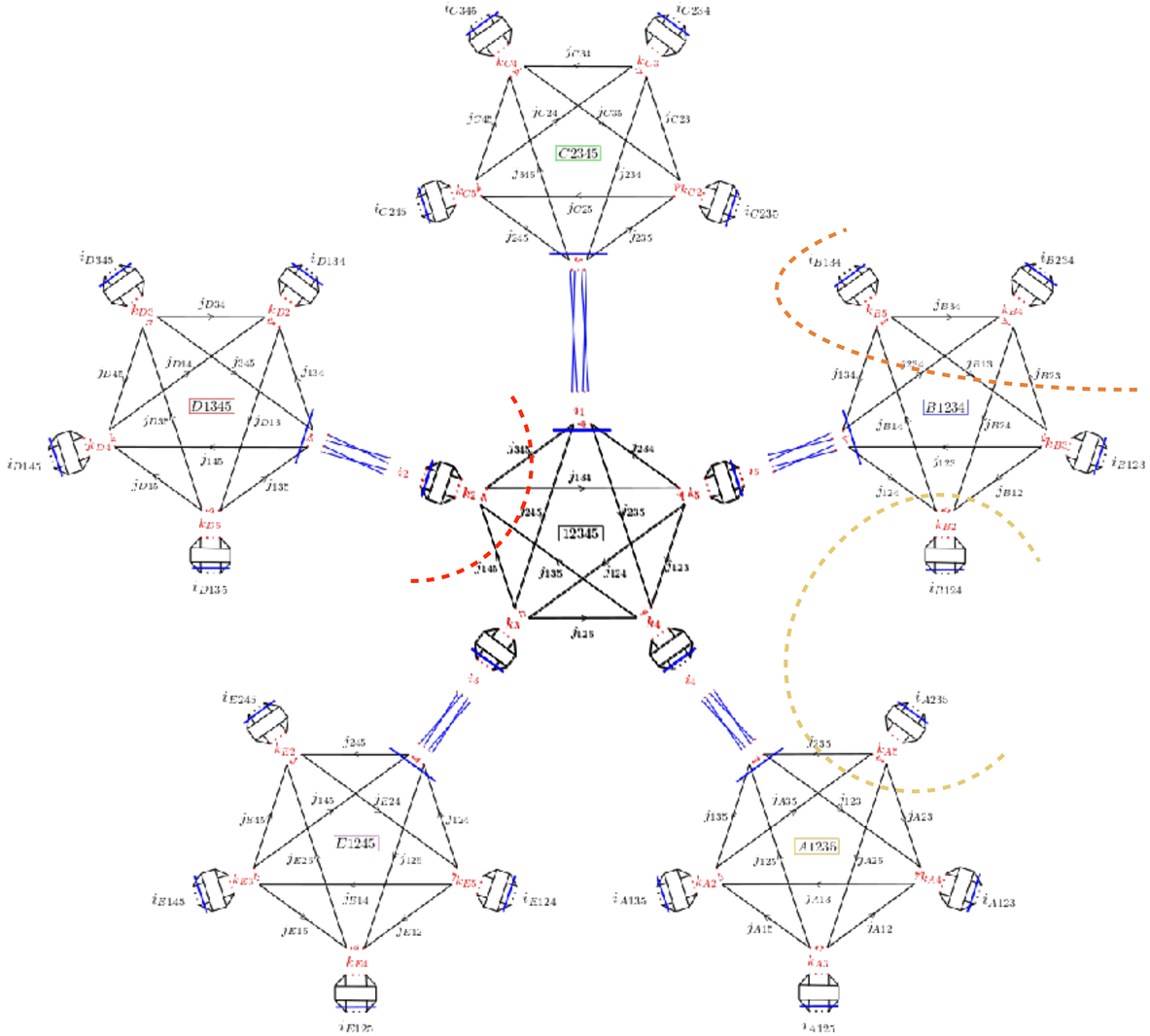

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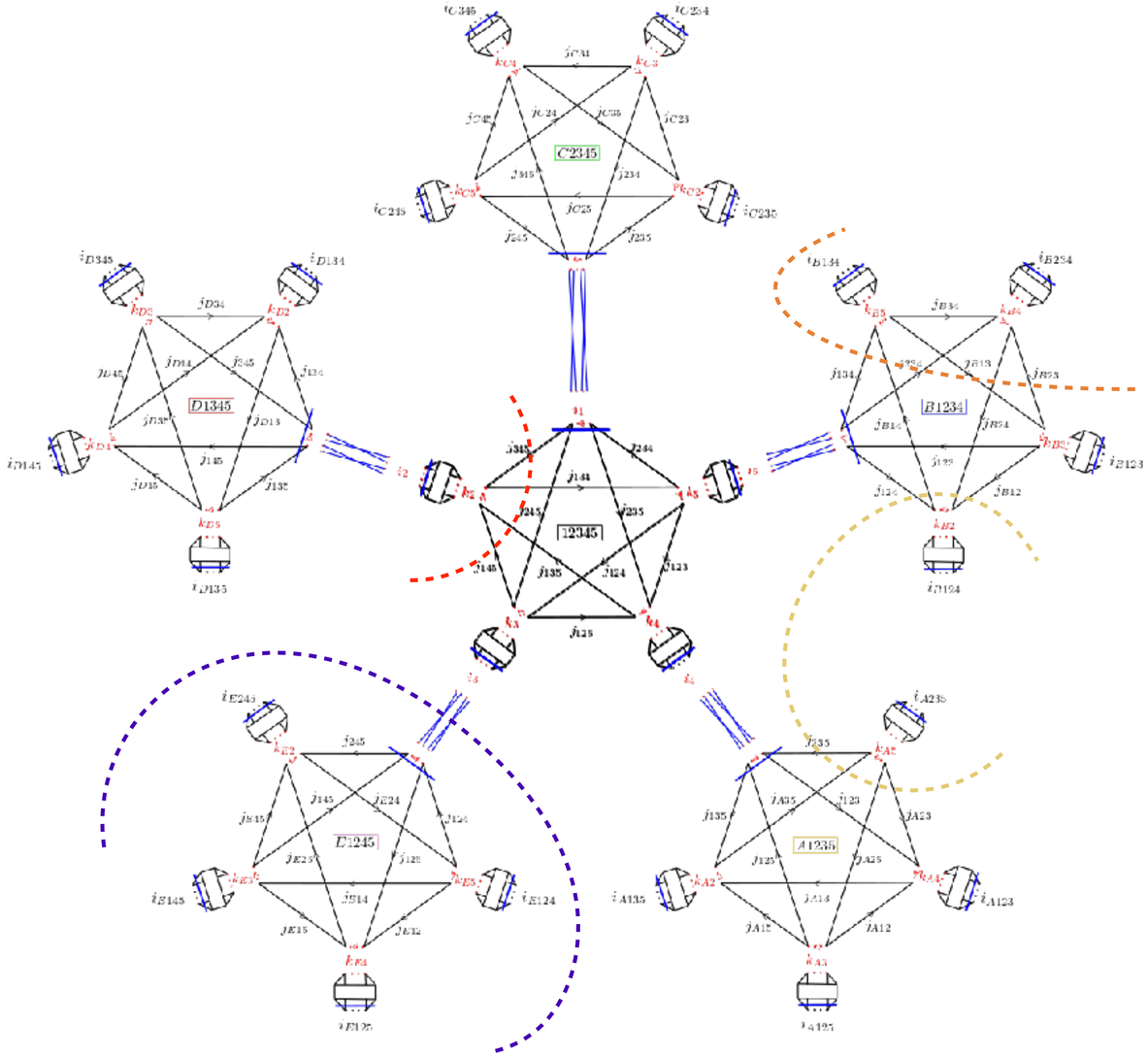
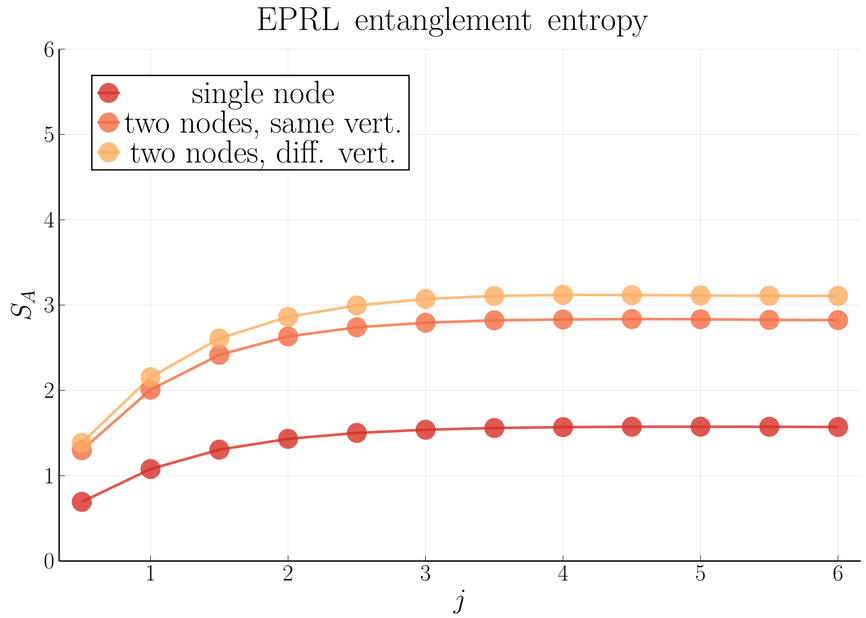
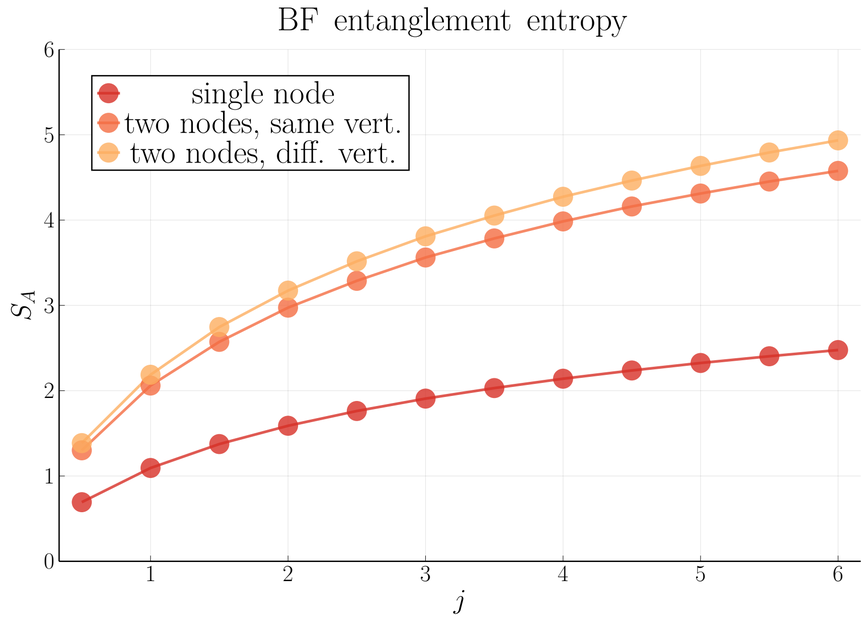


ENTANGLEMENT ENTROPY

- Partition: $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_{\bar{A}}$
- Reduced density matrix: $\rho_A = \frac{1}{Z} Tr_{\bar{A}} \, |\psi_0\rangle\langle\psi_0|$
- Entanglement entropy: $S_A = -Tr\left(\rho_A \log \rho_A\right)$





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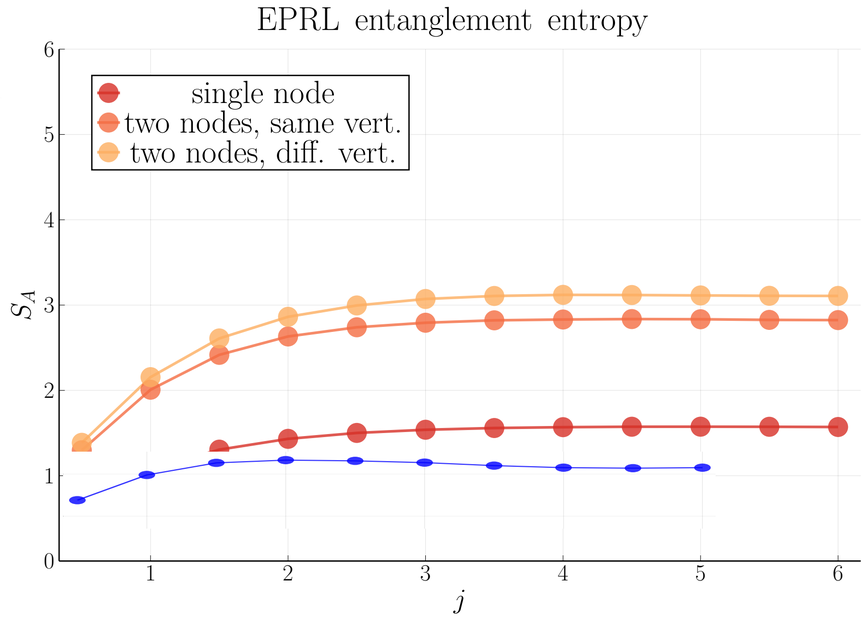

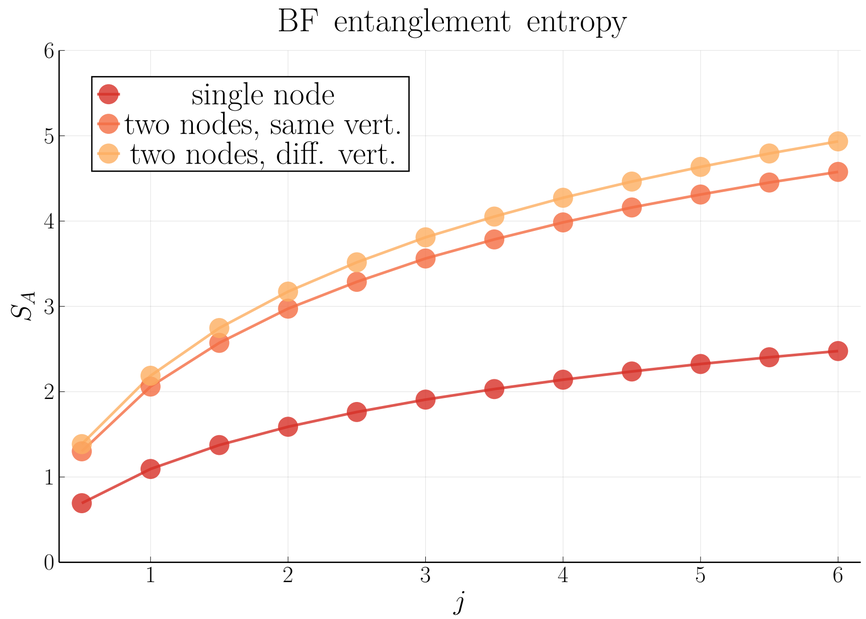

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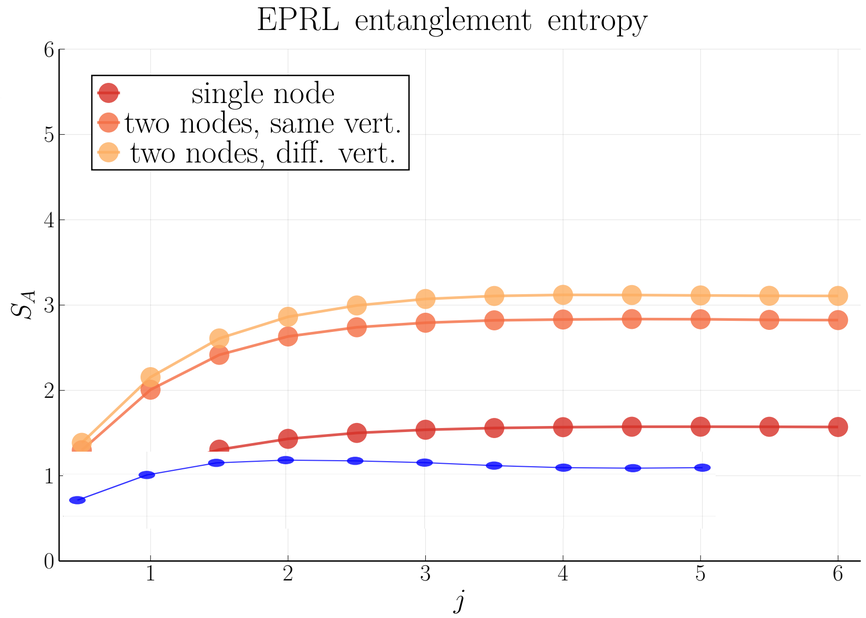

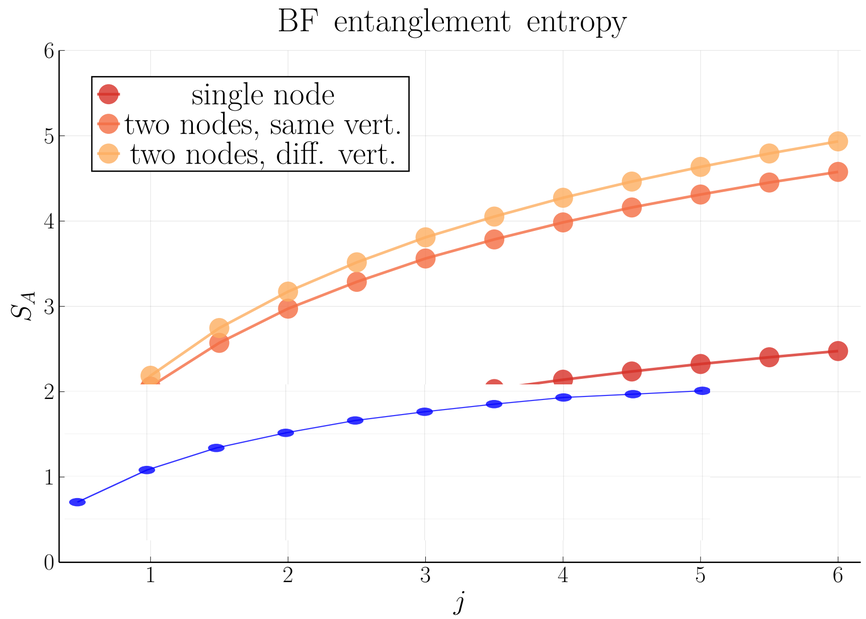

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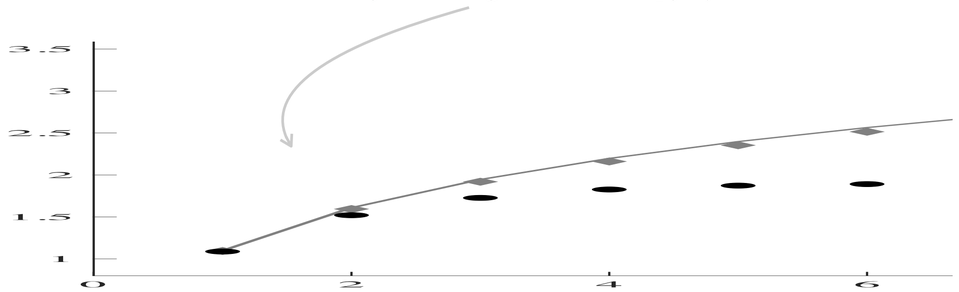
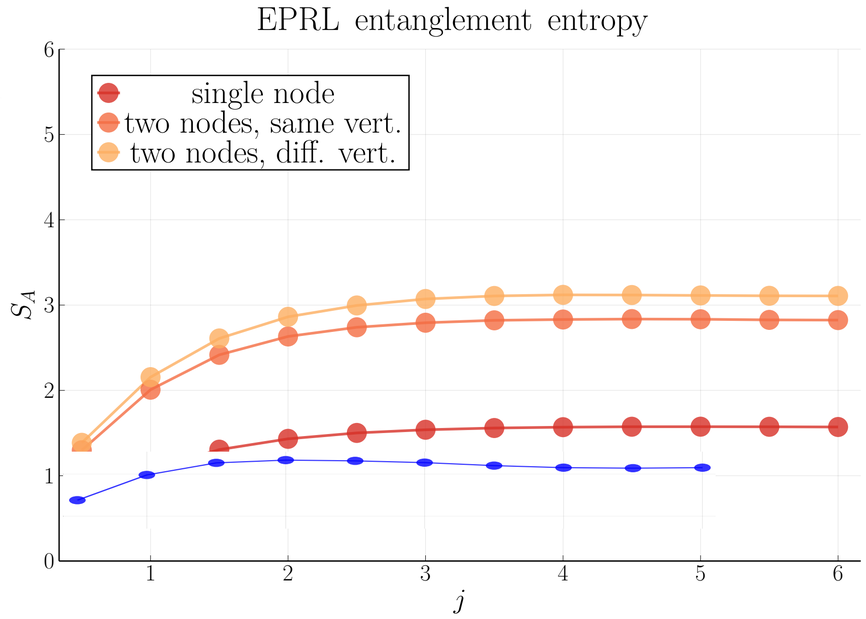
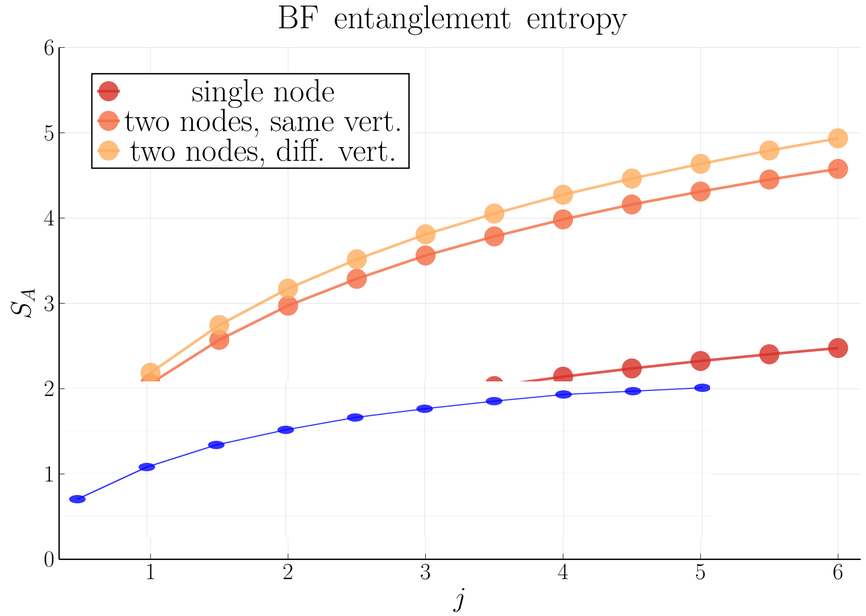
Bianchi, Donà, Vilensky "Entanglement entropy of Bell-network states in LQG"



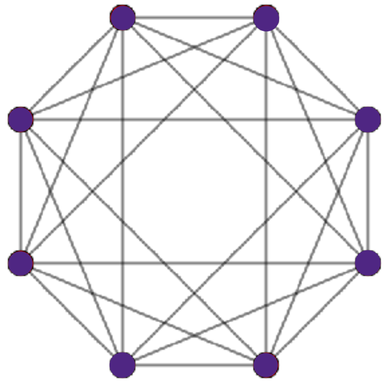




16-CELL MODEL

Primordial fluctuations from quantum gravity: 16-cell model, with P. Frisoni (in preparation)

- The 20-cell refined model is not a regular triangulation of S_3
- 5-cell regular triangulation ⟶ 16-cell regular triangulation
- Results for the dihedral angles: ✓
- Correlations and entanglement entropy?



SUMMARY

- Computing primordial quantum fluctuations from the full theory
  is one of the main goals of a quantum theory of gravity!

- Proposal: use Spinfoam Hartle-Hawking States

- Graph truncation: 5-cell ✓, 20-cell ✓, 16-cell *in progress*

- Computational challenge: compute expectation values for observables (using MCMC?)

- Results:
  1. emerging S_3 geometry
  2. large fluctuations
  3. large correlations (for adjacent nodes) $\longrightarrow$ 16-cell needed for richer structure

RESULTS, RESEARCH DIRECTIONS AND COLLABORATIONS

FIRST SIMPLE MODEL

- 1 vertex
- 5-cells boundary graph
- computation of observables
- high correlations

with Francesco Gozzini (Heidelberg)

RELATION TO COSMOLOGICAL VACUUM

- properties of standard cosmological vacua
- classical limit of the quantum model
- entanglement entropy

with Federico Scali (Pisa)

MORE COMPLEX RELIABLE MODELS

- 1 vertex, 6 vertices
- 16-cells and 20-cells boundary graphs
- MCMC to compute observables
- rich behaviour of correlations

with Pietropaolo Frisoni (Western)

NON-INFLATIONARY MODELS

- cosmological perturbations from an effective highly-correlated vacuum states
- matter bounce as an alternative to the inflationary models

with Mateo Pascual (Western)