Quantum-Classical Conversion Calculator: Bridging Quantum Correlations and Cosmological Parameters

Jacob Woods

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Abstract

This paper presents a computational framework for modeling quantum and classical correlations in a cosmological context, integrating quantum information theory with cosmological parameters. Utilizing Qiskit, a quantum computing library, we simulate a multi-qubit Greenberger-Horne-Zeilinger (GHZ) state to compute quantum correlation parameters and compare them with their classical counterparts. The model incorporates cosmological effects, such as redshift and dark matter density, to explore potential quantum-classical analogies in an expanding universe. We derive key formulas for quantum and classical correlations, cosmological time scales, and density matrix scaling, and analyze their interrelations. The results demonstrate how quantum entanglement measures can be contextualized within cosmological frameworks, offering insights into the interplay between quantum mechanics and cosmology.

1 Introduction

The interplay between quantum mechanics and cosmology has garnered significant interest, particularly in exploring how quantum correlations might manifest in macroscopic, astrophysical phenomena. This paper introduces a quantum-classical conversion calculator implemented in Python using Qiskit, which computes quantum correlation parameters for an n-qubit GHZ state and contrasts them with classical analogs. Additionally, the model integrates cosmological parameters, such as redshift and dark matter density, to study their influence on quantum states via density matrix scaling.

The quantum framework is based on ambisonic theory (Gerzon, 1975). Ambisonics is a surround sound format that creates a spherical wavestate from its individual sources by routing the signals directionally through a Hadamard matrix. This forms a local quantum state comprised of sound waves, but the routing is nearly identical for matter.

The calculator serves as a tool to bridge quantum information theory with cosmological dynamics, providing a framework to quantify correlations and explore their behavior under cosmological evolution. This paper outlines the theoretical foundations, derives the key formulas, describes their computational implementation, and discusses the correlations between quantum and classical parameters.

2 Theoretical Framework

2.1 Cosmological Parameters

The calculator incorporates a flat ΛCDM cosmological model, defined by the density parameters for radiation (Ω_r), matter (Ω_m), dark energy (Ω_Λ), and curvature (Ω_k), with values:

$$\Omega_r = 9.05 \times 10^{-5}, \quad \Omega_m = 0.3, \quad \Omega_\Lambda = 0.7, \quad \Omega_k = 1 - \Omega_m - \Omega_\Lambda - \Omega_r.$$

The Hubble parameter at scale factor a is given by:

$$H(a) = H_0 \sqrt{\frac{\Omega_r}{a^2} + \frac{\Omega_m}{a} + \Omega_k + \Omega_\Lambda a^2},$$

where $H_0 = 2.268 \times 10^{-18}\,\mathrm{s}^{-1}$ is the Hubble constant. The age of the universe at scale factor a is computed via:

$$t(a) = \frac{1}{H_0} \int_0^a \frac{da'}{\sqrt{\frac{\Omega_r}{a'^2} + \frac{\Omega_m}{a'} + \Omega_k + \Omega_\Lambda a'^2}}.$$

The redshift z is related to the scale factor by $z = \frac{1}{a} - 1$. For a given lookback time t (time ago from the present age $t_0 = 13.8 \times 10^9$ years), the redshift is computed by solving:

$$t_{\text{effective}} = t_0 - t = \frac{1}{H_0} \int_0^a \frac{da'}{\sqrt{\frac{\Omega_r}{a'^2} + \frac{\Omega_m}{a'} + \Omega_k + \Omega_\Lambda a'^2}},$$

using numerical root-finding to determine a.

The effective speed of light $c_{\text{eff}}(t)$ accounts for a hypothetical decay, modeled as:

$$c_{\text{eff}}(t) = c\left(1 - \delta e^{-t/\tau}\right),$$

where $c = 3.00 \times 10^8$ m/s, $\delta = 0.1$, and $\tau = 1.0 \times 10^9$ years. The dark matter number density N_{DM} is scaled by the effective speed of light and redshift:

$$N_{\text{DM}}(t, z) = N_0 \frac{c_{\text{eff}}(t_0)}{c_{\text{eff}}(t)} (1 + z)^3,$$

where $N_0 = 3.0 \times 10^6\,\mathrm{m}^{-3}$ is the present dark matter density.

2.2 Quantum Correlations

The quantum correlations are computed for an n-qubit GHZ state, defined as:

$$|\psi\rangle = \frac{|0\rangle^{\otimes n} + |1\rangle^{\otimes n}}{\sqrt{2}}.$$

The quantum circuit is constructed with a Hadamard gate on the first qubit followed by CNOT gates to entangle subsequent qubits. The expectation value of the operator $Z_1 Z_2 \cdots Z_n$ is calculated from measurement outcomes in the computational basis:

$$\langle Z_1 Z_2 \cdots Z_n \rangle = P(|0\rangle^{\otimes n}) + P(|1\rangle^{\otimes n}) - \sum_{\text{other states}} P(\text{state}),$$

where $P(\text{state})$ is the probability of measuring a given state, obtained from 10^5 shots on the Qiskit AerSimulator. The quantum correlation parameter S_{quantum} is:

$$S_{\text{quantum}} = 2\sqrt{2}\sqrt{N} \langle Z_1 Z_2 \cdots Z_n \rangle,$$

where N is the number of particles. The parameter W is:

$$W = S_{\text{quantum}} \sqrt{2}.$$

The parameter M_{quantum} depends on the parity of N:

$$M_{\text{quantum}} = \begin{cases} W\sqrt{N}/\sqrt{2} & \text{if } N \text{ is even}, \\ W\sqrt{N}/\sqrt{N+1} & \text{if } N \text{ is odd}. \end{cases}$$

2.3 Classical Correlations

Classical correlations are computed as simpler analogs to the quantum parameters:

$$S_{\text{classical}} = 2\sqrt{N}, \quad W_{\text{classical}} = \frac{S_{\text{classical}}}{\sqrt{2}}, \quad M_{\text{classical}} = W_{\text{classical}}.$$

These assume a classical system with no entanglement, providing a baseline for comparison.

2.4 Density Matrix and Cosmological Scaling

The density matrix ρ for the GHZ state is computed from the statevector:

$$\rho = |\psi\rangle\langle\psi|.$$

When a redshift z is provided, the density matrix is scaled by $(1+z)^3$ to reflect cosmological expansion effects, and normalized to ensure $\text{Tr}(\rho) = 1$:

$$\rho' = \frac{\rho(1+z)^3}{\text{Tr}(\rho(1+z)^3)}.$$

The purity of the density matrix is:

$$\gamma = \text{Tr}(\rho^2).$$

The expectation value of $Z_1 Z_2 \cdots Z_n$ is also computed using the projector:

$$P = |0\rangle^{\otimes n}\langle 0|^{\otimes n} + |1\rangle^{\otimes n}\langle 1|^{\otimes n},$$

$$\langle Z_1 Z_2 \cdots Z_n\rangle = \langle\psi|P|\psi\rangle.$$

3 Implementation

The calculator is implemented in Python using Qiskit for quantum simulations and SciPy for numerical integration and root-finding. The main components are:

- **Redshift Calculation**: Computes z for a given lookback time t by solving for the scale factor a using Brent's method.
- **Quantum Simulation**: Constructs an n-qubit GHZ state, simulates measurements, and computes S_{quantum}, M_{quantum}, and the density matrix.
- **Classical Calculation**: Computes $S_{\text{classical}}$ and $M_{\text{classical}}$ for comparison.
- **Cosmological Parameters**: Calculates c_{eff} and N_{DM} based on t and z.

The code includes debugging statements to verify intermediate values and convergence, ensuring numerical stability. A histogram of measurement outcomes is saved for visualization.

4 Quantum-Classical Correlations

The quantum and classical correlation parameters exhibit distinct behaviors. For a GHZ state, $\langle Z_1 Z_2 \cdots Z_n \rangle \approx 1$ ideally, leading to:

$$S_{\text{quantum}} \approx 2\sqrt{2}\sqrt{N}, \quad S_{\text{classical}} = 2\sqrt{N}.$$

Thus, S_{quantum} exceeds $S_{\text{classical}}$ by a factor of $\sqrt{2}$, reflecting the enhanced correlations due to quantum entanglement. The parameter M_{quantum} introduces an N-dependent scaling that modulates the quantum advantage, particularly for odd N, where the denominator $\sqrt{N+1}$ slightly reduces the magnitude compared to even N.

The density matrix scaling by $(1+z)^3$ models the effect of cosmological expansion on quantum states, analogous to the scaling of matter density. The purity $\gamma \approx 1$ for the GHZ state confirms its coherence, while deviations in $\langle Z_1 Z_2 \cdots Z_n \rangle$ between measurement and statevector methods highlight numerical precision limits in simulations.

5 Results and Discussion

For $N = 10$, $n_{\text{qubits}} = 3$, and a lookback time $t = 1.0 \times 10^9$ years, the calculator yields:

- Redshift $z \approx 0.087$, computed numerically.
- $S_{\text{quantum}} \approx 8.944$, $M_{\text{quantum}} \approx 11.255$ (odd N), compared to $S_{\text{classical}} = 6.325$, $M_{\text{classical}} = 4.472$.
- $c_{\text{eff}} \approx 2.973 \times 10^8$ m/s, $N_{\text{DM}} \approx 3.773 \times 10^6$ m^{-3}.
- Density matrix purity $\gamma \approx 1.0$, with $\langle Z_1 Z_2 \cdots Z_n \rangle \approx 0.999$.

The quantum correlations consistently exceed classical ones, demonstrating the impact of entanglement. The cosmological scaling of ρ suggests a framework for studying quantum states in an expanding universe, potentially relevant to quantum cosmology models. Future work could extend the model to include decoherence effects or alternative quantum states.

6 Conclusion

The quantum-classical conversion calculator provides a novel approach to studying quantum correlations in a cosmological context. By integrating Qiskit simulations with cosmological parameter calculations, it offers insights into the interplay between quantum entanglement and macroscopic phenomena. The derived formulas and their computational implementation enable quantitative comparisons, highlighting the quantum advantage in correlation strength and the influence of cosmological expansion on quantum states. By linking the Z vector of the quantum state to the temporal reaction of dark matter decoherence, we restore the negative phase of the timestream that may be phased outside of our perception along this vector.