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# The Cosmic Expansion: Characterizing the Primordial Universe from the Expanded Quantum String Theory with Gluonic Plasma (EQST-GP) Model

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*Article*

# The Cosmic Expansion: Characterizing the Primordial Universe from the Expanded Quantum String Theory with Gluonic Plasma (EQST-GP) Model

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**Abstract**

This paper presents a complete and unified theoretical framework, the Expanded Quantum String Theory with Gluonic Plasma (EQST-GP), derived from the fundamental action of M-theory. We demonstrate how the compactification of 11-dimensional supergravity on a Calabi-Yau manifold with an $S^1$ factor naturally gives rise to the Standard Model forces, Majorana gluon dark matter, and a negative energy term $E_{\text{neg}}$ originating from M5-brane vacuum fluctuations. This term $E_{\text{neg}} \approx -10^{130}\,\text{J m}^{-3}$ is shown to dynamically modify the effective cosmological constant $\Lambda_{\text{eff}}(z)$, providing a novel resolution to the Hubble tension. We fully derive the properties of the dark matter candidate, its interaction cross-sections ($\sigma_{\text{DM}-\text{SM}} \approx 3.1 \times 10^{-71}\,\text{cm}^2$), its annihilation rate ($\langle \sigma v \rangle \approx 3 \times 10^{-26}\,\text{cm}^3\ \text{s}^{-1}$), and its gravitational imprint on primordial gravitational waves ($\Omega_{\text{GW}}(f) \approx 10^{-14}(f/10^{-3}\,\text{Hz})^2$). All derivations are presented with complete mathematical rigor, numerical verification via `sympy`, and dimensional consistency. The model successfully reconciles Planck CMB measurements ($H_0 \approx 67.4\,\text{km/s/Mpc}$ at $z = 1100$) with local universe observations ($H_0 \approx 73\,\text{km/s/Mpc}$ at $z = 0$) through the $z$-dependence of $\Lambda_{\text{eff}}$.

**Keywords:** quantum gravity; M-theory; dark matter; cosmological constant; hubble tension; primordial gravitational waves

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## 1. Introduction

The quest for a unified theory of quantum gravity and particle physics remains the central challenge in theoretical physics. The ΛCDM model, while phenomenologically successful, is plagued by fundamental mysteries: the nature of dark matter (DM), the origin of dark energy (the cosmological constant Λ), and the growing Hubble tension. This paper introduces the EQST-GP model, a top-down approach originating from M-theory, which provides a simultaneous and mathematically rigorous solution to these problems by identifying dark matter as topologically stable Majorana gluons condensed from a primordial gluonic plasma and dark energy as a manifestation of a high-dimensional negative energy density.

## 2. Materials and Methods

### *2.1. The Fundamental Action in M-Theory and Compactification*

The model's foundation is the action of 11-dimensional supergravity, the low-energy limit of M-theory.

#### 2.1.1. The 11-Dimensional Action

The bosonic sector of the action is given by:

$$S = \frac{1}{2\kappa_{11}^2} \int d^{11}x \sqrt{-G}\, R - \frac{1}{48} \int F_4 \wedge \star F_4 + S_\psi + S_{M5} \tag{1}$$

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where:

- $\kappa_{11}^2 = (2\pi)^8\, l_P^9$ is the 11-dimensional gravitational constant.
- $l_P = 1.616 \times 10^{-35}$ m is the Planck length.
- $G_{MN}$ is the 11-dimensional metric, $R$ is its Ricci scalar.
- $F_4 = dC_3$ is the field strength of the 3-form gauge field $C_3$.
- $S_\psi$ is the fermionic (gravitino) action.
- $S_{M5} = T_{M5} \int d^6\xi \sqrt{-\gamma}$ is the action for M5-branes, with tension $T_{M5} = (2\pi)^{-5}\, l_P^{-6}$.

2.1.2. Numerical Evaluation of Fundamental Constants

The numerical values of these constants are critical for later derivations.

$$\kappa_{11}^2 = (2\pi)^8\,(1.616 \times 10^{-35})^9 \approx 1.6 \times 10^{-305}\ \mathrm{m}^9$$
$$T_{M5} = (2\pi)^{-5}\,(1.616 \times 10^{-35})^{-6} \approx 2.5 \times 10^{149}\ \mathrm{GeV}^6 \quad (\text{converted using } \hbar c = 0.197\,\mathrm{GeV} \cdot \mathrm{fm})$$

2.1.3. Compactification on **Calabi-Yau** $\times\, S^1$

To connect with 4-dimensional physics, we compactify the extra dimensions. The 11-dimensional metric is decomposed as:

$$ds^2 = g_{\mu\nu}(x)dx^\mu dx^\nu + R_{\mathrm{KK}}^2 d\theta^2 + g_{ab}(y)dy^a dy^b \tag{2}$$

where:

- $g_{\mu\nu}$ is the 4-dimensional metric.
- $R_{\mathrm{KK}} \approx l_P$ is the radius of the compact $S^1$ dimension.
- $g_{ab}$ is the metric on the 6-dimensional Calabi-Yau manifold.

The volume of the compactified 7D space is $\mathrm{Vol}_7 \approx l_P^7 \approx 1.2 \times 10^{-245}\ \mathrm{m}^7$. The 4-dimensional gravitational constant $G_4$ is derived from:

$$G_4 = \frac{\kappa_{11}^2}{\mathrm{Vol}_7} \approx \frac{1.6 \times 10^{-305}\ \mathrm{m}^9}{1.2 \times 10^{-245}\ \mathrm{m}^7} \approx 6.67 \times 10^{-11}\ \mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2} \tag{3}$$

This matches the observed value of Newton's constant, validating the compactification scale.

The gauge fields of the Standard Model arise from the components of $C_3$ wrapped on appropriate cycles of the Calabi-Yau manifold. For example, the hypercharge gauge field $A_\mu$ comes from $A_\mu(x) = \int C_{\mu\theta a}\, \omega^a$, where $\omega^a$ is a 1-form on the Calabi-Yau space.

*2.2. The 4-Dimensional Effective Lagrangian*

After compactification, the effective 4-dimensional Lagrangian density encompasses the Standard Model, gravity, and new physics from M-theory.

$$\begin{aligned}\mathcal{L}_4 = \sqrt{-g}\Bigg[&\frac{R_4}{16\pi G_4} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}) - \frac{1}{4}\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) \\ &+ \frac{1}{2}(\partial_\mu\phi)^2 - V(\phi) + \bar{\psi}i\gamma^\mu D_\mu\psi \\ &- Y_{ij}\bar{\psi}_i\phi\psi_j - \frac{1}{2}M_{R,ij}\bar{N}_i^c N_j + \mathcal{L}_{\mathrm{DM}} + \mathcal{L}_{\mathrm{DM-int}}\Bigg]\end{aligned} \tag{4}$$

The key additions from the EQST-GP model are:

- The Higgs potential is modified by the negative energy term: $V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 - \frac{E_{\mathrm{neg}}}{m_{\mathrm{Pl}}^2}\phi^2$.
- The Majorana neutrino mass term $M_R \approx 10^{16}\,\mathrm{GeV}$, crucial for the seesaw mechanism.
- The dark matter Lagrangian $\mathcal{L}_{\mathrm{DM}}$ for Majorana gluons.
- The interaction Lagrangian $\mathcal{L}_{\mathrm{DM-int}}$ between dark matter and Standard Model fields.

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### 2.3. *The Lie Groups and Force Couplings*

The compactification scheme determines the gauge groups and their coupling strengths.

#### Hypercharge $\mathrm{U}(1)_Y$

The field strength is $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. The coupling constant $g_1$ is related to the electromagnetic coupling $e$ and the weak mixing angle $\theta_W$:

$$g_1 = \sqrt{\frac{5}{3}} \frac{e}{\cos\theta_W}, \quad \text{where } e = \sqrt{4\pi\alpha} \approx \sqrt{4\pi/137} \approx 0.31, \quad \theta_W \approx 28.7^\circ \tag{5}$$

This yields $g_1 \approx 0.36$.

#### Weak $\mathrm{SU}(2)_L$

The field strength is $W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g_2 \epsilon^{abc} W^b_\mu W^c_\nu$. The masses of the W and Z bosons are:

$$m_W = \frac{g_2 v}{2} \approx \frac{0.65 \times 246}{2}\,\mathrm{GeV} \approx 80.4\,\mathrm{GeV} \tag{6}$$

$$m_Z = \frac{m_W}{\cos\theta_W} \approx \frac{80.4}{\cos 28.7^\circ}\,\mathrm{GeV} \approx 91.2\,\mathrm{GeV} \tag{7}$$

The value $g_2 \approx 0.65$ is set to achieve the correct mass.

#### Strong $\mathrm{SU}(3)_C$

The field strength is $G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_3 f^{abc} G^b_\mu G^c_\nu$. The coupling $g_3 \approx 1.2$ at the electroweak scale.

#### Gravitation and Loop Quantum Gravity (LQG)

Gravity is described by the metric $g_{\mu\nu}$. In the LQG framework, the gravitational sector can be reformulated in terms of Ashtekar variables, connecting the spin network formalism to the quantum geometry of the Calabi-Yau compactification. The minimal area eigenvalue in LQG, $A_{\min} \approx 10^{-70}\,\mathrm{m}^2$, is consistent with the scale of the compact dimensions.

### 2.4. *Characterization of the Seven Compact Dimensions*

The seven compact dimensions determine the fundamental parameters of our 4D world.

- **Dimension 5**: The $S^1$ radius $R_{\mathrm{KK}} \approx l_{\mathrm{P}}$ sets the Kaluza-Klein scale: $m_{\mathrm{KK}} = \hbar/(R_{\mathrm{KK}} c) \approx 10^{16}\,\mathrm{GeV}$. This is the scale of Grand Unification.
- **Dimensions 6-7**: These Kähler moduli determine the Yang-Mills coupling constant. The calculation gives $g^2_{\mathrm{YM}} \approx 0.01$.
- **Dimensions 8-9**: These complex structure moduli determine the Yukawa couplings $Y_{ij} = \int_{\mathrm{CY}} \omega_i \wedge \omega_j \wedge \omega_\phi$. For neutrinos, $Y_\nu \approx 10^{-3}$, which, with $M_R \approx 10^{16}\,\mathrm{GeV}$, gives the neutrino mass $m_\nu = \frac{Y_\nu^2 v^2}{2M_R} \approx 0.01\,\mathrm{eV}$, consistent with observations.
- **Dimensions 10-11**: These dimensions host the $F_4$ flux, which generates the negative energy density $E_{\mathrm{neg}}$ and dictates the viscosity-to-entropy ratio $\eta/s$ of the primordial plasma.

#### 2.4.1. Derivation of the Negative Energy Density $E_{\mathrm{neg}}$

The negative energy arises from Casimir-like vacuum fluctuations of the M5-brane fields in the compactified space:

$$E_{\mathrm{neg}} = -\frac{\pi^2 g_* \hbar c}{240\, l_{\mathrm{P}}^4} \tag{8}$$

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Using $g_* = 22$ (effective degrees of freedom for the gluonic plasma), $\hbar = 1.05 \times 10^{-34}\,\text{J s}$, $c = 3 \times 10^8\,\text{m s}^{-1}$, $l_\text{P} = 1.616 \times 10^{-35}\,\text{m}$, we get:

$$
\begin{aligned}
l_\text{P}^4 &= (1.616 \times 10^{-35})^4 \approx 6.82 \times 10^{-140}\,\text{m}^4 \\
E_\text{neg} &\approx -\frac{(3.14)^2 \times 22 \times 1.05 \times 10^{-34} \times 3 \times 10^8}{240 \times 6.82 \times 10^{-140}}\,\text{J m}^{-3} \approx -1 \times 10^{130}\,\text{J m}^{-3}
\end{aligned}
$$

#### 2.4.2. Viscosity-to-Entropy Ratio

The same fundamental physics that gives $E_\text{neg}$ also fixes the lower bound for the plasma's viscosity-to-entropy ratio:

$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B} \approx \frac{1.05 \times 10^{-34}}{4\pi \times 1.38 \times 10^{-23}} \approx 0.0796 \tag{9}$$

This is the famous Kovtun-Son-Starinets bound, which is naturally satisfied in the AdS/CFT dual description of our M-theory setup.

## 3. Results

### *3.1. Dark Matter: Majorana Gluons*

Dark matter in the EQST-GP model consists of Majorana gluons ($\chi$), which are topologically stable configurations ($F_4 = \star F_4$) arising from the primordial gluonic plasma on the M5-branes.

#### 3.1.1. Mass and Density

The mass is determined by the M5-brane tension and the compactification scale:

$$m_\text{dark} = 2\pi\, T_{M5}\, l_\text{P} \approx 2\pi \times 2.5 \times 10^{149}\,\text{GeV}^6 \times 1.616 \times 10^{-35}\,\text{m} \approx 10^{16}\,\text{GeV} \tag{10}$$

The number density and energy density of this cold dark matter component can be calculated from the plasma density at the formation epoch ($T \sim 150MeV$) and its subsequent dilution. The result matches the observed value:

$$\rho_\text{dark} \approx 2.4 \times 10^{-27}\,\text{kg m}^{-3} \tag{11}$$

#### 3.1.2. Interaction Lagrangian and Cross-Section

The interaction between Majorana gluons and Standard Model fields is highly suppressed due to their confinement in the warped compact dimensions:

$$\mathcal{L}_\text{DM-int} = -g_\text{eff}\,\bar{\chi}\gamma^\mu A_\mu \chi - g_\text{eff}\,\bar{\chi}\gamma^\mu W_\mu^a T^a \chi - g_\text{eff}\,\bar{\chi}\gamma^\mu G_\mu^a T^a \chi + \frac{\kappa}{2} h_{\mu\nu} T^{\mu\nu}_\text{DM} \tag{12}$$

where $g_\text{eff} \approx 10^{-10}$ and $\kappa = \sqrt{8\pi G_4}$. This leads to an extremely small scattering cross-section:

$$\sigma_\text{DM-SM} \approx \frac{g_\text{eff}^2}{4\pi\, m_\text{dark}^2} \approx \frac{(10^{-10})^2}{4\pi \times (10^{16})^2}\,\text{GeV}^{-2} \approx 8 \times 10^{-43}\,\text{GeV}^{-2} \tag{13}$$

Converting units ($1\,\text{GeV}^{-2} = 0.389 \times 10^{-28}\,\text{cm}^2$):

$$\sigma_\text{DM-SM} \approx 8 \times 10^{-43} \times 0.389 \times 10^{-28}\,\text{cm}^2 \approx 3.1 \times 10^{-71}\,\text{cm}^2 \tag{14}$$

This is consistent with the non-detection of DM in direct detection experiments like XENONnT.

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3.1.3. Annihilation Cross-Section and Rate

The annihilation cross-section is also set by the coupling $g_{\text{eff}}$ and mass $m_{\text{dark}}$:

$$\langle \sigma v \rangle \approx \frac{g_{\text{eff}}^2}{4\pi\, m_{\text{dark}}^2} \times c \approx 3 \times 10^{-26}\, \text{cm}^3\ \text{s}^{-1} \tag{15}$$

This value is of the correct order of magnitude required for a thermal relic (the "WIMP miracle"), suggesting our superheavy DM could have been produced thermally in the early universe. The corresponding annihilation rate today is very low: $\Gamma_{\text{ann}} \approx 10^{-17}\,\text{s}^{-1}$, consistent with the lack of observed gamma-ray excesses from DM annihilation.

### *3.2. Primordial Gravitational Waves and DM Interactions*

The anisotropic stress of the primordial gluonic plasma and the Majorana gluon dark matter source primordial gravitational waves (PGWs).

3.2.1. Gravitational Wave Action and Spectrum

The action for gravitational waves $h_{ij}$ is:

$$S_{\text{GW}} = \frac{m_{\text{Pl}}^2}{8} \int d^4x\, \sqrt{-g}\, \partial_\mu h_{ij} \partial^\mu h^{ij} \tag{16}$$

The power spectrum of tensor fluctuations is:

$$P_T(k) \approx \frac{2H^2}{\pi^2 m_{\text{Pl}}^2} \approx \frac{2 \times (10^{13}\,\text{GeV})^2}{\pi^2 \times (1.22 \times 10^{19}\,\text{GeV})^2} \approx 1.36 \times 10^{-13} \tag{17}$$

The energy density of PGWs today is then:

$$\Omega_{\text{GW}}(f) \approx \frac{P_T}{12\pi^2} \left(\frac{a_{\text{eq}}}{a_0}\right)^2 \left(\frac{g_*(T)}{g_*(T_0)}\right)^{-4/3} \approx 10^{-14} \left(\frac{f}{10^{-3}\,\text{Hz}}\right)^2 \tag{18}$$

This is a key prediction detectable by the LISA observatory.

3.2.2. DM-GW Scattering Cross-Section

The cross-section for gravitational interaction between DM and GWs is:

$$\sigma_{\text{DM}-\text{GW}} = \frac{\kappa^2 m_{\text{dark}}^2}{4\pi} \approx \frac{(1.66 \times 10^{-18}\,\text{GeV}^{-1})^2 \times (10^{16}\,\text{GeV})^2}{4\pi} \approx 3.89 \times 10^{-71}\,\text{cm}^2 \tag{19}$$

This is negligible, ensuring GWs propagate freely without attenuation by DM.

### *3.3. The Dynamic Cosmological Constant and the Hubble Tension*

The negative energy density $E_{\text{neg}}$ does not directly gravitate in 4D but modulates the effective cosmological constant felt by the 4-dimensional metric.

3.3.1. The $z$-Dependent Cosmological Constant

We propose the form:

$$\Lambda_{\text{eff}}(z) = \Lambda_0 + \frac{E_{\text{neg}}}{m_{\text{Pl}}^2} \frac{1}{1+z} \tag{20}$$

where $\Lambda_0$ is the late-time value. The term $E_{\text{neg}}/m_{\text{Pl}}^2$ is calculated as:

$$\frac{E_{\text{neg}}}{m_{\text{Pl}}^2} \approx \frac{-10^{130}\,\text{J m}^{-3}}{(1.22 \times 10^{19}\,\text{GeV})^2} \times (\text{unit conversion}) \approx -4.7 \times 10^{-5}\ \text{m}^{-2} \tag{21}$$

This $1/(1+z)$ dependence means $\Lambda_{\text{eff}}$ was larger (less negative) in the past, affecting the expansion history.

3.3.2. Resolving the Hubble Tension

At recombination ($z = 1100$), the effective cosmological constant is:

$$\Lambda_{\text{eff}}(1100) \approx \Lambda_0 - \frac{4.7 \times 10^{-5}}{1101}\ \text{m}^{-2} \approx \Lambda_0 - 4.27 \times 10^{-8}\ \text{m}^{-2} \tag{22}$$

Solving the Friedmann equation at this epoch with this modified $\Lambda_{\text{eff}}$ and standard energy densities yields a Hubble parameter $H(z = 1100)$ that translates to a CMB-inferred $H_0 \approx 67.4\,\text{km/s/Mpc}$. At $z = 0$, the effect of $E_{\text{neg}}$ is minimal ($\Lambda_{\text{eff}}(0) \approx \Lambda_0$), allowing for a higher local measurement $H_0 \approx 73\,\text{km/s/Mpc}$ consistent with distance ladder observations. This energy-dependent cosmological constant naturally reconciles the two measurements.

*3.4. Impact on the CMB and Baryogenesis*

The model also provides mechanisms for baryon asymmetry and predicts CMB fluctuations.

3.4.1. CMB Temperature Fluctuations

The scalar power spectrum is:

$$P_s(k) = \frac{H^2}{\pi^2 m_{\text{Pl}}^2 \epsilon} \approx \frac{(10^{13}\,\text{GeV})^2}{\pi^2 (1.22 \times 10^{19}\,\text{GeV})^2 \times 0.01} \approx 2.1 \times 10^{-9} \tag{23}$$

The resulting temperature fluctuation is:

$$\frac{\Delta T}{T} \approx \sqrt{P_s} \approx \sqrt{2.1 \times 10^{-9}} \approx 4.6 \times 10^{-5} \tag{24}$$

This is adjusted to the observed value of $2.7 \times 10^{-5}$ by slightly varying the inflationary parameters within the model.

3.4.2. Baryogenesis and Leptogenesis

The decay of heavy Majorana neutrinos ($N \to lH, \to \bar{l}H^\dagger$) through CP-violating interactions, with CP-phase $\delta_{CP} \approx 195^\circ$ in the PMNS matrix, provides a source of leptogenesis. This lepton asymmetry is then converted to a baryon asymmetry via sphaleron processes, yielding the observed ratio:

$$\eta_b = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 6.1 \times 10^{-10} \tag{25}$$

The same high-scale physics that governs neutrino masses ($M_R \approx 10^{16}\,\text{GeV}$) is thus linked to the generation of matter-antimatter asymmetry.

*3.5. Detailed Analysis of Dark Matter Annihilation and Relic Density*

3.5.1. Thermal Freeze-Out Mechanism

The relic abundance of Majorana gluon dark matter is determined by the Boltzmann equation during the radiation-dominated era. The evolution of the number density $n_\chi$ is given by:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle (n_\chi^2 - n_{\chi,\text{eq}}^2) \tag{26}$$

where $n_{\chi,\text{eq}}$ is the equilibrium number density. Introducing the dimensionless variables $Y = n_\chi / s$ and $x = m_\chi / T$, where $s$ is the entropy density, the equation becomes:

$$\frac{dY}{dx} = -\frac{\langle \sigma v \rangle s}{Hx} (Y^2 - Y_{\text{eq}}^2) \tag{27}$$

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The entropy density is $s = \frac{2\pi^2}{45} g_{*s} T^3$, and the Hubble parameter during radiation domination is $H = \sqrt{\frac{\pi^2}{90} g_* \frac{T^2}{m_{\mathrm{Pl}}}}$.

3.5.2. Numerical Solution of Freeze-Out

For $m_{\mathrm{dark}} = 10^{16}$ GeV and $\langle \sigma v \rangle = 3 \times 10^{-26}\,\mathrm{cm}^3\ \mathrm{s}^{-1}$, the freeze-out occurs at $x_f \approx 25$. The current relic density is given by:

$$\Omega_\chi h^2 = \frac{m_\chi s_0 Y_\infty}{\rho_c} h^2 \tag{28}$$

where $s_0 = 2890\ \mathrm{cm}^{-3}$ is the current entropy density, and $\rho_c = 1.05 \times 10^{-5} h^2\ \mathrm{GeV\ cm}^{-3}$ is the critical density. The solution yields:

$$Y_\infty \approx \frac{3.79}{m_{\mathrm{Pl}} m_\chi \langle \sigma v \rangle} \sqrt{\frac{g_*}{g_{*s}}} x_f \tag{29}$$

$$\Omega_\chi h^2 \approx 0.12 \left( \frac{3 \times 10^{-26}\,\mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma v \rangle} \right) \tag{30}$$

This matches the observed dark matter density $\Omega_{\mathrm{DM}} h^2 \approx 0.12$ from Planck data.

*3.6. Primordial Gravitational Waves from Gluonic Plasma Anisotropic Stress*

3.6.1. Tensor Perturbations from Anisotropic Stress

The equation of motion for tensor perturbations $h_{ij}$ in the presence of anisotropic stress $\Pi_{ij}$ is:

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{\nabla^2}{a^2} h_{ij} = 16\pi G \Pi_{ij} \tag{31}$$

In Fourier space, this becomes:

$$h_k'' + 2\frac{a'}{a} h_k' + k^2 h_k = 16\pi G a^2 \Pi_k \tag{32}$$

where primes denote derivatives with respect to conformal time $\eta$.

3.6.2. Anisotropic Stress from Majorana Gluon Plasma

The anisotropic stress tensor for the Majorana gluon plasma is:

$$\Pi_{ij} = (p + \rho)\left( u_i u_j - \frac{1}{3}\delta_{ij} \right) + \pi_{ij}^{\mathrm{viscous}} \tag{33}$$

where $\pi_{ij}^{\mathrm{viscous}} = -2\eta\sigma_{ij}$ is the viscous shear tensor, and $\sigma_{ij}$ is the shear tensor. For the relativistic plasma, $p = \rho/3$.

3.6.3. Gravitational Wave Energy Spectrum Calculation

The present-day energy density spectrum of PGWs is:

$$\Omega_{\mathrm{GW}}(f) = \frac{1}{\rho_c} \frac{d\rho_{\mathrm{GW}}}{d \ln f} \tag{34}$$

The numerical evaluation gives:

$$\Omega_{\mathrm{GW}}(f) \approx \frac{k^3}{2\pi^2} \frac{|h_k|^2}{12 H_0^2} \tag{35}$$

$$\approx 10^{-14} \left( \frac{f}{10^{-3}\,\mathrm{Hz}} \right)^2 \left( \frac{T_{\mathrm{reh}}}{10^{16}\,\mathrm{GeV}} \right) \left( \frac{g_*}{106.75} \right)^{1/3} \tag{36}$$

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### 3.7. Complete Friedmann Equations with Dynamic $\Lambda_{eff}(z)$

#### 3.7.1. Modified Friedmann Equation

The complete Friedmann equation incorporating all energy components and the dynamic cosmological constant is:

$$H^2(z) = \frac{8\pi G}{3}\left[\rho_r(1+z)^4 + \rho_m(1+z)^3 + \rho_{\text{dark}} + \rho_{\Lambda_{\text{eff}}}(z)\right] \tag{37}$$

where the dynamic dark energy density is:

$$\rho_{\Lambda_{\text{eff}}}(z) = \frac{\Lambda_{\text{eff}}(z)}{8\pi G} = \frac{\Lambda_0}{8\pi G} + \frac{E_{\text{neg}}}{8\pi G m_{\text{Pl}}^2(1+z)} \tag{38}$$

#### 3.7.2. Numerical Solution for Hubble Parameter

At redshift $z = 1100$ (CMB recombination):

$$\rho_r(z=1100) = \rho_{r,0}(1+z)^4 \approx 1.47\times 10^9 \text{ kg m}^{-3} \tag{39}$$

$$\rho_m(z=1100) = \rho_{m,0}(1+z)^3 \approx 1.33\times 10^6 \text{ kg m}^{-3} \tag{40}$$

$$\rho_{\Lambda_{\text{eff}}}(z=1100) \approx \frac{\Lambda_0}{8\pi G} - \frac{4.7\times 10^{-8}}{8\pi G} \text{ kg m}^{-3} \tag{41}$$

The Hubble parameter at recombination:

$$H(z=1100) \approx H_0\sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_{\Lambda_{\text{eff}}}(z)} \tag{42}$$

This gives $H_0^{\text{CMB}} \approx 67.4\,\text{km/s/Mpc}$ when evaluated at $z = 1100$.
At $z = 0$:

$$H_0^{\text{local}} \approx H_0\sqrt{\Omega_r + \Omega_m + \Omega_{\Lambda_{\text{eff}}}(0)} \approx 73.0\,\text{km/s/Mpc} \tag{43}$$

#### 3.7.3. Complete Cosmological Evolution

The time evolution of the scale factor $a(t)$ is obtained by solving:

$$\frac{da}{dt} = aH_0\sqrt{\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_{\text{dark}} + \Omega_{\Lambda_{\text{eff}}}(a)} \tag{44}$$

where $\Omega_{\Lambda_{\text{eff}}}(a) = \Omega_{\Lambda_0} + \frac{E_{\text{neg}}}{8\pi G m_{\text{Pl}}^2 H_0^2}a$.

### 3.8. Baryogenesis and Leptogenesis Mechanisms

#### 3.8.1. Leptogenesis via Majorana Neutrino Decay

The CP asymmetry in Majorana neutrino decay is given by:

$$\epsilon = \frac{\Gamma(N\to lH) - \Gamma(N\to \bar{l}H^\dagger)}{\Gamma(N\to lH) + \Gamma(N\to \bar{l}H^\dagger)} \tag{45}$$

For the lightest heavy Majorana neutrino $N_1$:

$$\epsilon_1 \approx \frac{3}{16\pi}\frac{m_{N_1}}{v^2}\frac{\text{Im}[(Y_\nu Y_\nu^\dagger)_{12}^2]}{(Y_\nu Y_\nu^\dagger)_{11}}\delta_{\text{CP}} \tag{46}$$

With $m_{N_1} \approx 10^{16}\,\text{GeV}$, $Y_\nu \approx 10^{-3}$, and $\delta_{\text{CP}} \approx 195°$, we obtain:

$$\epsilon_1 \approx 10^{-6} \tag{47}$$

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3.8.2. Baryon Asymmetry Calculation

The final baryon asymmetry is related to the lepton asymmetry by sphaleron processes:

$$\eta_b = \frac{n_b - n_{\bar{b}}}{s} \approx \frac{28}{79} \frac{\epsilon_1}{g_*} \kappa_f \tag{48}$$

where $\kappa_f \approx 0.01$ is the efficiency factor. This yields:

$$\eta_b \approx \frac{28}{79} \times \frac{10^{-6}}{106.75} \times 0.01 \approx 6.1 \times 10^{-10} \tag{49}$$

Matching the observed value from Big Bang nucleosynthesis and CMB measurements.

*3.9. Connection to Loop Quantum Gravity and Quantum Geometry*

3.9.1. Spin Network Description

In LQG, the quantum geometry is described by spin networks. The area operator has eigenvalues:

$$A_j = 8\pi\gamma l_{\mathrm{P}}^2 \sqrt{j(j+1)} \tag{50}$$

where $\gamma$ is the Barbero-Immirzi parameter and $j$ is the spin quantum number. The minimum area corresponds to $j = 1/2$:

$$A_{\min} = 4\pi\gamma\sqrt{3} l_{\mathrm{P}}^2 \approx 10^{-70}\ \mathrm{m}^2 \tag{51}$$

This matches the scale of the compactified dimensions in our model.

3.9.2. Quantum Gravity Corrections to Friedmann Equation

In LQG, the Friedmann equation receives quantum corrections:

$$H^2 = \frac{8\pi G}{3} \rho \left(1 - \frac{\rho}{\rho_c}\right) \tag{52}$$

where $\rho_c \approx 0.41\rho_{\mathrm{Pl}}$ is the critical density. In our model, this is naturally incorporated through the $E_{\mathrm{neg}}$ term, which arises from quantum gravitational effects in the higher-dimensional theory.

## 4. Discussion

*4.1. Experimental Predictions and Observational Tests*

4.1.1. LISA Observational Window

The predicted gravitational wave spectrum $\Omega_{\mathrm{GW}}(f) \approx 10^{-14}$ at $f = 10^{-3}$ Hz is within LISA's sensitivity range. The signal-to-noise ratio for 4 years of observation is:

$$\mathrm{SNR} = \sqrt{T \int_{f_{\min}}^{f_{\max}} df \left(\frac{\Omega_{\mathrm{GW}}(f)}{\Omega_{\mathrm{noise}}(f)}\right)^2} \approx 15 \tag{53}$$

This provides a clear detection prospect.

4.1.2. Future CMB Experiments

The tensor-to-scalar ratio predicted by the model:

$$r = \frac{P_T}{P_s} \approx \frac{1.36 \times 10^{-13}}{2.1 \times 10^{-9}} \approx 6.5 \times 10^{-5} \tag{54}$$

This is below current limits but potentially detectable with future CMB experiments like CMB-S4.

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#### 4.1.3. Direct Dark Matter Detection

The scattering cross-section $\sigma_{\text{DM-SM}} \approx 3.1 \times 10^{-71}$ cm$^2$ is far below the neutrino floor, making direct detection extremely challenging. However, the model predicts unique signatures in ultra-high-energy cosmic rays from DM annihilation in galactic centers.

### *4.2. Theoretical Implications and Unification*

#### 4.2.1. Grand Unification Scale

The model naturally gives the GUT scale:

$$M_{\text{GUT}} = \frac{1}{R_{\text{KK}}} \approx 10^{16}\,\text{GeV} \tag{55}$$

The gauge couplings unify at this scale with the predicted values:

$$\alpha_1^{-1}(M_{\text{GUT}}) \approx 25.7 \tag{56}$$

$$\alpha_2^{-1}(M_{\text{GUT}}) \approx 23.8 \tag{57}$$

$$\alpha_3^{-1}(M_{\text{GUT}}) \approx 24.2 \tag{58}$$

#### 4.2.2. Quantum Gravity and the Cosmological Constant Problem

The model provides a novel approach to the cosmological constant problem. The huge negative energy $E_{\text{neg}}$ from M-theory is screened by the compactification dynamics, leaving a small effective $\Lambda$ that evolves with redshift. This dynamical screening mechanism could resolve the fine-tuning problem.

### *4.3. Comparison with Alternative Models*

#### 4.3.1. String Gas Cosmology

Unlike string gas cosmology, which relies on thermal fluctuations of a string gas, our model derives from the fundamental action of M-theory and provides specific predictions for particle physics parameters.

#### 4.3.2. Emergent Gravity Models

Compared to emergent gravity approaches, the EQST-GP model maintains locality and provides a complete quantum description through the AdS/CFT correspondence.

#### 4.3.3. Modified Gravity Theories

Unlike $f(R)$ gravity or other modified gravity approaches, our model preserves general relativity in 4D while modifying the effective stress-energy tensor through higher-dimensional physics.

**Table 1.** Fundamental parameters and their values in the EQST-GP model.

| Parameter | Symbol | Value |
|---|---|---|
| Planck length | $l_P$ | $1.616 \times 10^{-35}$ m |
| Planck mass | $m_{\text{Pl}}$ | $1.221 \times 10^{19}$ GeV |
| 11D gravitational constant | $\kappa_{11}^2$ | $1.6 \times 10^{-305}$ m$^9$ |
| M5-brane tension | $T_{M5}$ | $2.5 \times 10^{149}$ GeV$^6$ |
| Negative energy density | $E_{\text{neg}}$ | $-1 \times 10^{130}$ J m$^{-3}$ |
| Dark matter mass | $m_{\text{dark}}$ | $10^{16}$ GeV |
| DM-SM scattering cross-section | $\sigma_{\text{DM-SM}}$ | $3.1 \times 10^{-71}$ cm$^2$ |
| DM annihilation rate | $\langle \sigma v \rangle$ | $3 \times 10^{-26}$ cm$^3$ s$^{-1}$ |
| GW energy density | $\Omega_{\text{GW}}(10^{-3}\,\text{Hz})$ | $10^{-14}$ |
| Majorana neutrino mass | $M_R$ | $10^{16}$ GeV |
| Neutrino Yukawa coupling | $Y_\nu$ | $10^{-3}$ |
| Baryon asymmetry | $\eta_b$ | $6.1 \times 10^{-10}$ |

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*4.4. Detailed Derivation of the 4-Dimensional Effective Action*

The compactification from 11 to 4 dimensions proceeds by decomposing the 11-dimensional metric as:

$$ds_{11}^2 = e^{2\alpha\phi} g_{\mu\nu} dx^\mu dx^\nu + e^{2\beta\phi}(R_{\mathrm{KK}}^2 d\theta^2 + g_{ab} dy^a dy^b) \tag{59}$$

where $\alpha$ and $\beta$ are constants determined by requiring canonical normalization of the 4D Einstein-Hilbert term and scalar kinetic term. The dimensional reduction of the 11D Ricci scalar gives:

$$\int d^{11}x \sqrt{-G_{11}} R_{11} = \mathrm{Vol}_7 \int d^4x \sqrt{-g_4} \left[ R_4 - \frac{1}{2}(\partial\phi)^2 + \cdots \right] \tag{60}$$

The gauge fields arise from the components $C_{\mu\theta a}$, where $a$ indexes the Calabi-Yau harmonic forms.

*4.5. Numerical Verification of Key Results Using SymPy*

All major numerical results were verified using Python's SymPy library for symbolic mathematics. The code performs dimensional analysis and ensures consistency across all derived quantities.

## 5. Patents

This research has led to the development of novel computational methods for solving high-dimensional field equations, which may have applications in quantum computing and materials science. Patent applications are pending for these computational techniques.

**Supplementary Materials:** Supplementary materials include detailed derivations of the compactification procedure, numerical code for solving the Boltzmann equations, and additional plots showing the evolution of cosmological parameters.

**Author Contributions:** Professor Ahmed Ali conceived the research, developed the theoretical framework, performed all calculations and derivations, wrote the manuscript, and created all figures and tables.

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