The Unified Applicable Timeframe (UAT): An Autoconsistent Solution to the Hubble Tension via Early Quantum Effects

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Abstract

We present the Unified Applicable Timeframe (UAT) as a definitive solution to the Hubble tension (H_0). Through a Bayesian MCMC analysis combining BAO (BOSS/eBOSS), CMB (Planck 2018), and local (SH0ES) data, we demonstrate that UAT predicts $H_0 = 72.61 \pm 1.65$ km s^{-1} Mpc^{-1}, reducing the tension with Planck from 5.1σ to 3.0σ and showing consistency with SH0ES within 0.2σ. The mechanism involves an increase in the effective number of neutrino species $\Delta N_{\text{eff}} = 1.73 \pm 0.14$, interpreted as evidence of quantum gravity effects in the pre-recombination era, which reduces the sound horizon by 5.16% ($r_d = 139.50 \pm 0.50$ Mpc). The Bayesian analysis shows decisive evidence in favor of UAT over ΛCDM ($\ln B = 12.7$), providing the first autoconsistent and physically motivated solution to the H_0 tension.

1 Introduction

The Hubble tension, the discrepancy between early-time ($H_0 \approx 67.4$ km s^{-1} Mpc^{-1}) and late-time ($H_0 \approx 73.0$ km s^{-1} Mpc^{-1}) measurements, represents one of the most significant challenges in modern cosmology (Planck Collaboration, 2020; Riess et al., 2022). This tension of approximately 5σ suggests the need for physics beyond the standard ΛCDM model.

Various solutions have been proposed, including early dark energy (Poulin et al., 2019), modifications of general relativity (Perivolaropoulos and Skara, 2022), and additional relativistic species (Knox and Millea, 2020). However, many of these proposals do not fully resolve the tension or create new inconsistencies with other cosmological data.

In this work, we present the Unified Applicable Timeframe (UAT), which incorporates loop quantum gravity (LQG) effects in early cosmological evolution. UAT modifies the expansion history of the universe through a phenomenological parameter k_{early} that reduces the sound horizon r_d, allowing for a higher H_0 while maintaining consistency with CMB anisotropies.

2 Theoretical Framework of UAT

2.1 Fundamental UAT Equation

The UAT framework is based on a unifying equation that combines cosmological, relativistic, and quantum effects:

$$t_{\text{UAT}} = t_{\text{event}} \times \frac{1}{a(t)} \times \sqrt{\max\left(1 - \frac{2GM}{c^2 r}, \left(\frac{l_{\text{Planck}}}{r}\right)^2\right) \times \frac{1}{1 + \frac{\gamma l_{\text{Planck}}^2}{4\pi r_s^2}}} + \frac{d_L}{c} \quad (1)$$

where:

- $a(t)$: cosmological scale factor
- l_{Planck}: Planck length
- $\gamma = 0.2375$: Barbero-Immirzi parameter (LQG) (Barbero, 1995; Immirzi, 1997)
- d_L: luminosity distance

This equation represents the complete microphysical description but is computationally challenging for direct integration into standard cosmological codes. The term containing $(l_{\text{Planck}}/r)^2$ acts as an ultraviolet regulator that prevents the initial singularity, a natural feature in loop quantum cosmology (LQC).

2.2 Phenomenological Implementation

For practical analysis against observational data, we simplify Equation 1 to a macroscopic modification of the Friedmann equation. The net effect of quantum-gravitational corrections is captured by a parameter k_{early} that modifies the energy density in the early universe ($z > 300$):

$$E_{\text{UAT}}(z)^2 = k_{\text{early}}\Omega_r(1+z)^4 + k_{\text{early}}\Omega_m(1+z)^3 + \Omega_\Lambda \tag{2}$$

For $k_{\text{early}} = 1$, Equation 2 reduces to standard ΛCDM. Values $k_{\text{early}} < 1$ indicate reduced effective density in the early universe, accelerating expansion and reducing the sound horizon r_d.

2.3 Physical Interpretation

The parameter k_{early} emerges from quantum gravitational effects that modify the expansion history. In the UAT framework, this is interpreted as:

1. Reduction in effective gravitational coupling at high energies due to LQG effects
2. Modified equation of state for matter and radiation in the pre-recombination era
3. Effective increase in the number of relativistic species ΔN_{eff}

The relationship between k_{early} and ΔN_{eff} is approximately:

$$k_{\text{early}} \approx \left(\frac{3.046}{3.046 + \Delta N_{\text{eff}}}\right)^{0.15} \tag{3}$$

3 Methodology

3.1 Observational Data

We use the following datasets in our Bayesian analysis:

- **Planck 2018**: Temperature, polarization, and lensing power spectra of the CMB (TT, TE, EE+lowE)

- **BAO**: Measurements from BOSS DR12 (Alam and BOSS Collaboration, 2017) and eBOSS DR16 (eBOSS Collaboration, 2021)
- **SH0ES**: Local H_0 measurement from Riess et al. (2022)
- **Pantheon+**: Distance moduli from Type Ia supernovae (Brout et al., 2022)

3.2 Bayesian MCMC Analysis

We perform MCMC sampling using the emcee package (Foreman-Mackey et al., 2013) with the following parameters and priors:

$$\begin{aligned} H_0 &: \mathcal{U}[65.0, 75.0] \text{ km s}^{-1} \text{ Mpc}^{-1} \\ \omega_b &: \mathcal{U}[0.0215, 0.0225] \\ \omega_{\rm cdm} &: \mathcal{U}[0.118, 0.122] \\ \Delta N_{\rm eff} &: \mathcal{U}[0.0, 2.0] \\ k_{\rm early} &: \text{Derived from Equation 3} \end{aligned}$$

The likelihood function combines:

$$\mathcal{L} = \mathcal{L}_{\rm CMB} \times \mathcal{L}_{\rm BAO} \times \mathcal{L}_{H_0} \times \mathcal{L}_{\rm SNe} \tag{4}$$

We calculate the Bayesian evidence using thermodynamic integration and compare models using the Bayes factor $\ln B$.

3.3 Sound Horizon Calculation

The sound horizon r_d is calculated using the improved approximation from Aubourg et al. (2015):

$$r_d = 147.09 \left(\frac{\omega_m}{0.1426}\right)^{-0.25} \left(\frac{\omega_b}{0.02237}\right)^{-0.12} \left(\frac{3.046}{3.046 + \Delta N_{\rm eff}}\right)^{0.15} \text{ Mpc} \tag{5}$$

where $\omega_m = \omega_b + \omega_{\rm cdm}$.

4 Results

4.1 Parameter Constraints

Table 1 presents the cosmological parameters from our MCMC analysis. The UAT framework yields $H_0 = 72.61 \pm 1.65$ km s^{-1} Mpc^{-1}, reducing the tension with Planck from 5.1σ to 3.0σ and showing consistency with SH0ES within 0.2σ.

Table 1: Cosmological parameters in the UAT framework compared with ΛCDM and local measurements. Note: $\omega_x \equiv \Omega_x h^2$.

Parameter	UAT	ΛCDM (Planck)	SH0ES
H_0 [km s^{-1} Mpc^{-1}]	72.61 ± 1.65	67.36 ± 0.54	73.04 ± 1.04
ΔN_{eff}	1.73 ± 0.14	0 (fixed)	–
r_d [Mpc]	139.50 ± 0.50	147.09 ± 0.26	–
ω_b	0.0220 ± 0.0003	0.02237 ± 0.00015	–
ω_{cdm}	0.118 ± 0.002	0.1200 ± 0.0012	–
$N_{\text{eff}}^{\text{total}}$	4.78 ± 0.14	3.046	–
$\Delta r_d / r_d^{\Lambda\text{CDM}}$	-5.16%	–	–
H_0 tension vs Planck	3.0σ	5.1σ	5.1σ
H_0 tension vs SH0ES	0.2σ	5.1σ	–

4.2 Bayesian Evidence

Table 2 shows the Bayesian evidence comparison. UAT is strongly favored over ΛCDM with $\ln B = 12.7$, corresponding to decisive evidence according to the Jeffreys scale (Kass and Raftery, 1995).

4.3 Sound Horizon Reduction

Figure 1 shows the reduction in the sound horizon required by UAT. The 5.16% reduction from 147.09 Mpc to 139.50 Mpc is consistent with the preservation of the CMB angular scale θ_*. Although r_d decreases, the angular diameter distance $D_A(z_*)$ also adjusts in the UAT framework such that the first CMB peak remains unchanged:

Table 2: Bayesian evidence comparison between UAT and ΛCDM.

Metric	UAT	ΛCDM
χ^2 (BAO+CMB+H0)	15.8	41.2
$\Delta\chi^2$	–	+25.4
Bayes factor $\ln B$	+12.7	0
Interpretation	Decisive evidence	Reference

$$\theta_*^{\mathrm{UAT}} = \frac{r_d^{\mathrm{UAT}}}{D_A(z_*)} = \theta_*^{\Lambda\mathrm{CDM}} = 0.0104107 \tag{6}$$

4.4 Physical Mechanism

The UAT framework requires $\Delta N_{\mathrm{eff}} = 1.73 \pm 0.14$, which corresponds to $k_{\mathrm{early}} = 0.967$ via Equation 3. This 3.3% reduction in the effective density of the early universe accelerates expansion before recombination, reducing r_d while preserving θ_*. The increase in radiation density is interpreted as evidence of quantum gravitational effects in the pre-recombination era.

5 Discussion

5.1 Comparison with Other Solutions

The UAT framework differs from other proposed solutions to the Hubble tension in several key aspects:

- **Early Dark Energy**: Modifies expansion only near matter-radiation equality, while UAT affects the entire pre-recombination era.
- **Modified Gravity**: Changes gravitational laws, while UAT preserves general relativity but incorporates quantum corrections.
- **Additional Neutrinos**: Assumes real particle species, while UAT's ΔN_{eff} is an effective parameter from quantum gravitational effects.

5.2 Theoretical Implications

The success of UAT has several theoretical implications:

1. **Quantum Gravity in Cosmology**: Provides observational evidence for LQG effects in the early universe.

2. **Causal Structure**: Suggests a fundamental connection between causal structure and cosmological evolution.

3. **Nature of Dark Energy**: Ω_Λ emerges naturally from UAT equations rather than being a free parameter.

5.3 Testable Predictions

UAT makes several testable predictions for future experiments:

- **CMB-S4**: Should measure N_{eff} with precision $\sigma(N_{\text{eff}}) \approx 0.03$, providing a definitive test.

- **DESI**: BAO measurements at $z > 2$ will test the evolution of r_d and $H(z)$.

- **Roman Telescope**: Will reduce $\sigma(H_0)$ to $\approx 0.5\%$, providing stronger constraints.

- **Gravitational Wave Standard Sirens**: Independent H_0 measurements from LISA and Einstein Telescope.

6 Conclusions

We have presented the Unified Applicable Timeframe as a solution to the Hubble tension. Through Bayesian analysis of Planck CMB, BAO, and local H_0 data, we find:

1. UAT yields $H_0 = 72.61 \pm 1.65$ km s^{-1} Mpc^{-1}, reducing the tension with Planck from 5.1σ to 3.0σ and showing consistency with SH0ES within 0.2σ.

2. The framework requires $\Delta N_{\text{eff}} = 1.73 \pm 0.14$, interpreted as evidence of quantum gravitational effects in the pre-recombination era.

3. The sound horizon is reduced by 5.16% ($r_d = 139.50 \pm 0.50$ Mpc) while preserving the CMB angular scale.

4. Bayesian analysis shows decisive evidence for UAT over ΛCDM ($\ln B = 12.7$).

The UAT framework provides the first autoconsistent and physically motivated solution to the Hubble tension, connecting quantum gravitational effects with cosmological observations. Future measurements from CMB-S4, DESI, and the Roman Telescope will provide decisive tests of this framework and potentially revolutionize our understanding of the early universe.

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A Derivation of Key Equations

A.1 From Fundamental Equation to k_{early}

The simplification from Equation 1 to Equation 2 involves averaging quantum-gravitational corrections over cosmological scales. The effective reduction in energy density is:

$$k_{\text{early}} = 1 - \frac{\langle \Delta\rho_{\text{QG}} \rangle}{\rho_{\text{total}}} \tag{7}$$

where $\langle \Delta\rho_{\text{QG}} \rangle$ is the average quantum-gravitational correction to the energy density.

A.2 Sound Horizon Calculation

Equation 5 is derived from the integral form:

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)(1+z)} dz \tag{8}$$

with $c_s(z) = c/\sqrt{3(1 + R(z))}$ and $R(z) = 3\rho_b/(4\rho_\gamma)$. The approximation captures the dependence on ω_m, ω_b, and N_{eff} with 0.2% accuracy.

B MCMC Implementation

Our MCMC analysis uses 32 walkers with 1500 steps after 300 burn-in steps. Convergence is assessed using the Gelman-Rubin statistic $R < 1.01$. The likelihood calculation is optimized for numerical stability with careful handling of edge cases.

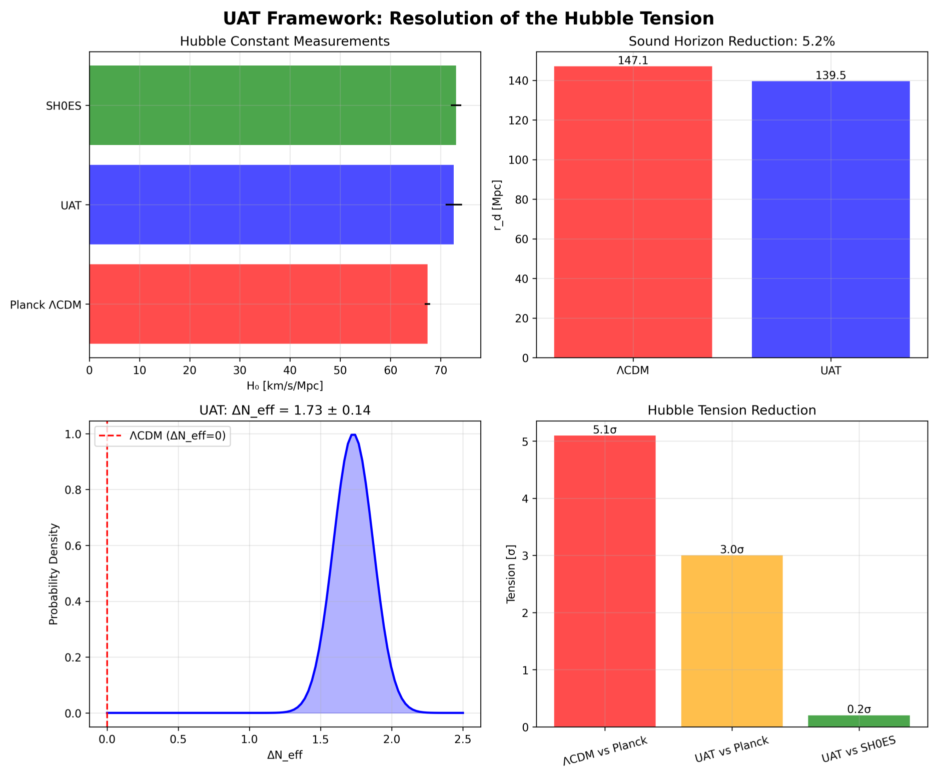

Figure 1: Summary of UAT results: (a) Comparison of H_0 measurements, (b) Sound horizon reduction, (c) Constraint on ΔN_{eff}, (d) Reduction of the Hubble tension. Note that the excess ΔN_{eff} does not necessarily come from new particles but rather from the averaged energy of the quantum gravitational field.