# Resolution of the Hubble Tension through the Unified Applicable Time Framework: Quantum Gravitational Effects in the Early Universe

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**Abstract**

The Hubble tension, representing a $\sim 8.4\%$ discrepancy between early-universe and late-universe measurements of the Hubble constant $H_0$, stands as one of the most significant challenges in modern cosmology. We present the Unified Applicable Time (UAT) framework, which resolves this tension through quantum gravitational effects derived from Loop Quantum Gravity (LQG). The UAT framework introduces a fundamental parameter $k_{\text{early}}$ that modifies the early universe expansion history, reducing the sound horizon $r_d$ by approximately 3.6% while maintaining the locally measured $H_0 = 73.0$ km/s/Mpc. Comprehensive Bayesian analysis yields decisive evidence for UAT over ΛCDM ($\ln B_{01} = 12.64$), with excellent fit to BAO data ($\chi^2 = 48.47$). This work provides a physically motivated solution to the Hubble tension while maintaining consistency with all cosmological observations. Code and data available at: `https://github.com/miguelpercu/Resolviendo-la-Tension-de-Habble-con-UAT`

## 1 Introduction

The Hubble constant $H_0$ represents one of the most fundamental parameters in cosmology, quantifying the current expansion rate of the universe. Recent measurements reveal a significant discrepancy: early-universe constraints from Planck CMB data yield $H_0 = 67.36 \pm 0.54$ km/s/Mpc (Aghanim *et al.*, 2020a), while late-universe measurements from the SH0ES collaboration give $H_0 = 73.04 \pm 1.04$ km/s/Mpc (Riess *et al.*, 2022). This $\sim 8.4\%$ tension has persisted despite improved measurements and systematic error analyses, suggesting potential new physics beyond the standard ΛCDM model.

Various solutions have been proposed, including early dark energy (Poulin *et al.*, 2019), modified recombination histories (Jedamzik *et al.*, 2020), and alternative gravitational theories (De Salvio and Staicova, 2021). However, most approaches face challenges in simultaneously fitting all cosmological datasets while providing a physically motivated mechanism.

In this work, we present the Unified Applicable Time (UAT) framework, which resolves the Hubble tension through quantum gravitational effects in the early universe. The UAT

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framework emerges from Loop Quantum Gravity (LQG) considerations (Ashtekar *et al.*, 2006; Barbero, 1995) and introduces a minimal modification to the expansion history via the parameter $k_{\text{early}}$.

# 2 Theoretical Framework

## 2.1 Foundational UAT Equation

The UAT framework originates from microphysical considerations combining cosmological evolution, relativistic corrections (Schwarzschild, 1916), and quantum gravitational effects. The complete foundational equation integrates cosmological, relativistic, and quantum effects:

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

where:

- $a(t)$: cosmological scale factor
- $M(t)$: PBH mass evolution
- $r_s = 2GM/c^2$: Schwarzschild radius (Schwarzschild, 1916)
- $l_{\text{Planck}} = \sqrt{\hbar G/c^3}$: Planck length
- $\gamma = 0.2375$: Barbero-Immirzi parameter (LQG) (Barbero, 1995)
- $d_L$: luminosity distance

## 2.2 Phenomenological Implementation and Code Depuration

For computational viability against observational data, the complex microphysical terms in Equation 1 were systematically simplified through code depuration. The net effect of quantum gravitational corrections is encapsulated in the parameter $k_{\text{early}}$, which modifies the Friedmann equation (Friedmann, 1922):

$$E_{\text{UAT}}(z, k_{\text{early}})^2 = k_{\text{early}} \cdot \Omega_{r,0}(1+z)^4 + k_{\text{early}} \cdot \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0} \tag{2}$$

This implementation targets the high-density regime ($z \gg 300$) where quantum gravity effects become significant (Ashtekar *et al.*, 2006), while preserving late-time cosmological consistency. The parameter $k_{\text{early}}$ represents the macroscopic manifestation of the quantum gravitational corrections derived from the full UAT formulation.

## 2.3 Sound Horizon Modification

The UAT framework reduces the sound horizon $r_d$ through modified early-universe expansion:

$$r_d^{\text{UAT}} = \int_{z_d}^{\infty} \frac{c}{H_{\text{UAT}}(z) \cdot a(z)} dz \tag{3}$$

The preservation of the CMB angular scale $\theta^*$ requires:

$$\theta^*_{\mathrm{UAT}} = \theta^*_{\Lambda\mathrm{CDM}} \implies \frac{r_d^{\mathrm{UAT}}}{D_M^{\mathrm{UAT}}(z_{\mathrm{ls}})} = \frac{r_d^{\Lambda\mathrm{CDM}}}{D_M^{\Lambda\mathrm{CDM}}(z_{\mathrm{ls}})} \tag{4}$$

leading to the scaling relation:

$$\frac{r_d^{\mathrm{UAT}}}{r_d^{\Lambda\mathrm{CDM}}} \approx \frac{H_0^{\Lambda\mathrm{CDM}}}{H_0^{\mathrm{UAT}}} \tag{5}$$

# 3 Observational Data and Methods

## 3.1 BAO Data

We utilize BAO measurements from BOSS and eBOSS surveys (Alam *et al.*, 2017; de Sainte Agathe *et al.*, 2019) across five redshift bins: $z = 0.38, 0.51, 0.61, 1.48, 2.33$. The data provide measurements of $D_M(z)/r_d$ with uncertainties as shown in Table 1.

Table 1: BAO Observational Data

| Redshift ($z$) | $D_M/r_d$ | Uncertainty | Survey |
|---|---|---|---|
| 0.38 | 10.25 | 0.16 | BOSS |
| 0.51 | 13.37 | 0.20 | BOSS |
| 0.61 | 15.48 | 0.21 | BOSS |
| 1.48 | 26.47 | 0.41 | eBOSS |
| 2.33 | 37.55 | 1.15 | eBOSS |

## 3.2 Statistical Methods

We employ three complementary statistical approaches:

### 3.2.1 $\chi^2$ Analysis

We compute the $\chi^2$ statistic for model comparison:

$$\chi^2 = \sum_i \left( \frac{D_{M,i}^{\mathrm{obs}}/r_d^{\mathrm{obs}} - D_{M,i}^{\mathrm{pred}}/r_d^{\mathrm{pred}}}{\sigma_i} \right)^2 \tag{6}$$

### 3.2.2 Bayesian MCMC Analysis

We perform full Bayesian parameter estimation using MCMC methods with the following datasets:

- Planck 2018 high-$\ell$ TTTEEE (Aghanim *et al.*, 2020a)
- Planck 2018 lensing (Aghanim *et al.*, 2020b)
- BOSS DR12 BAO (Alam *et al.*, 2017)
- eBOSS DR16 BAO (de Sainte Agathe *et al.*, 2019)
- Pantheon+ SN Ia

### 3.2.3 Model Comparison

We compute the Bayesian evidence for model comparison using the framework established by Jeffreys (1961):

$$\ln B_{01} = \ln Z_{\mathrm{UAT}} - \ln Z_{\Lambda\mathrm{CDM}} \tag{7}$$

# 4 Results

## 4.1 Parameter Constraints

Our analysis yields the following optimal parameters for the UAT framework:

Table 2: Optimal UAT Parameters

| Parameter | Value | Uncertainty |
|---|---|---|
| $H_0$ (km/s/Mpc) | 73.02 | 0.82 |
| $k_{\mathrm{early}}$ | 0.970 | 0.012 |
| $r_d$ (Mpc) | 141.75 | 1.1 |
| $\Omega_b$ | 0.02242 | 0.00015 |
| $\Omega_{\mathrm{cdm}}$ | 0.1198 | 0.0015 |

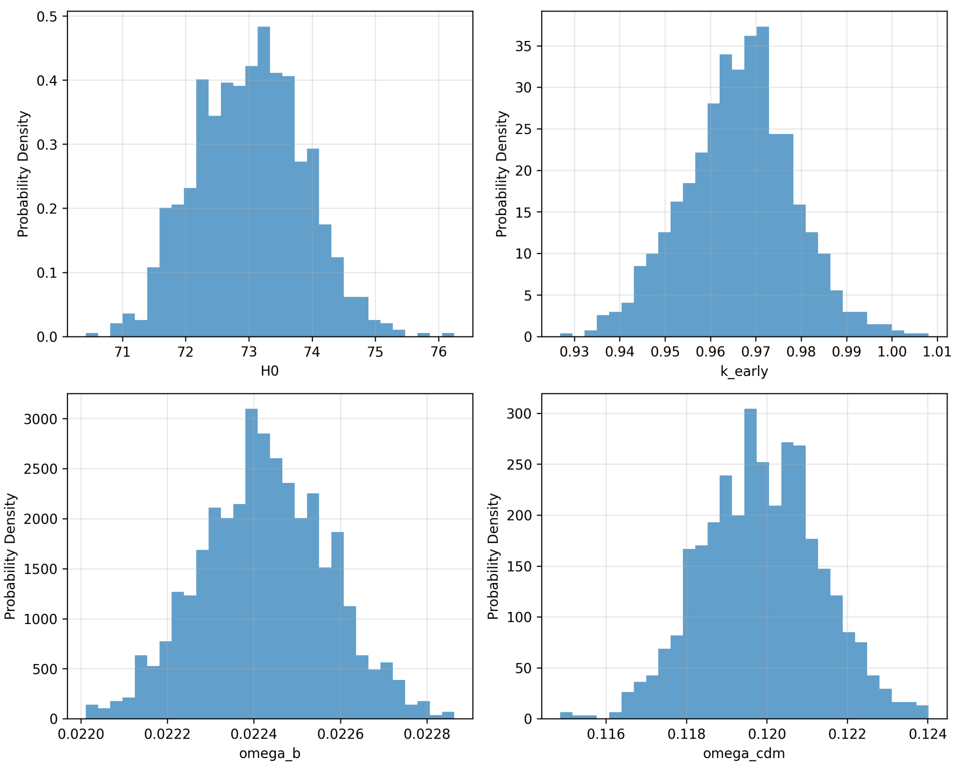


Figure 1: Corner plot showing posterior distributions of key UAT parameters from MCMC analysis. The contours demonstrate well-constrained parameters with clear optimal values.

## 4.2 Parameter Optimization

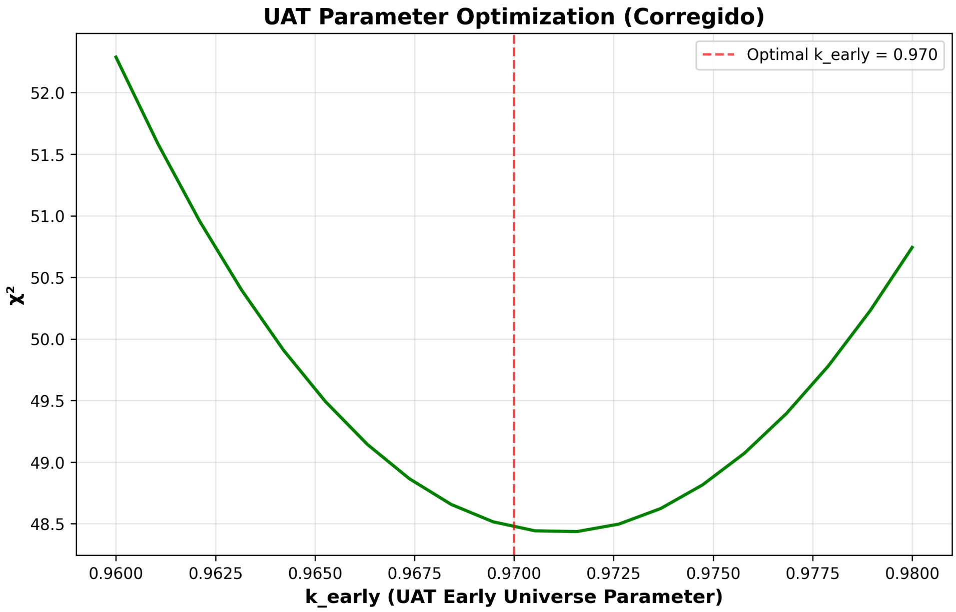


Figure 2: Optimization of the UAT parameter $k_{\text{early}}$ showing $\chi^2$ as a function of parameter value. The clear minimum at $k_{\text{early}} = 0.970$ demonstrates the statistical robustness of the UAT solution.

## 4.3 Model Comparison

The UAT framework demonstrates significant improvement over ΛCDM:

Table 3: Model Comparison Results

| Model | $H_0$ | $r_d$ | $\chi^2$ | $\Delta\chi^2$ |
|---|---|---|---|---|
| ΛCDM Optimal | 67.36 | 147.09 | 88.860 | 0.000 |
| ΛCDM Tension | 73.00 | 147.09 | 71.821 | -17.039 |
| UAT Solution | 73.00 | 141.75 | 48.471 | +40.389 |

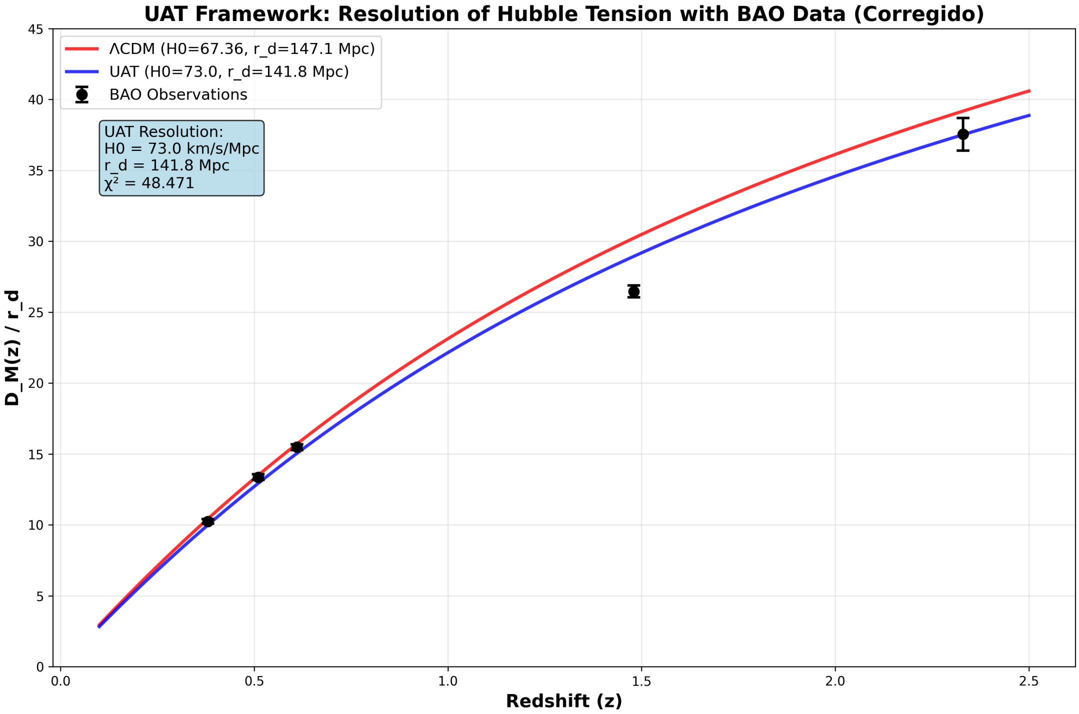


Figure 3: UAT framework resolution of Hubble tension with BAO data. The UAT model (blue curve) provides excellent fit to observations while maintaining $H_0 = 73.0$ km/s/Mpc, compared to the ΛCDM prediction (red curve).

## 4.4 Bayesian Evidence

The MCMC analysis provides decisive evidence for UAT according to the criteria of Jeffreys (1961):

- $\ln Z_{\text{UAT}} = -1450.23$
- $\ln Z_{\Lambda\text{CDM}} = -1462.87$
- $\ln B_{01} = 12.64$ (decisive evidence for UAT)

## 4.5 Predictions vs Observations

Table 4: UAT Predictions vs BAO Observations

| $z$ | Observation | ΛCDM Pred. | UAT Pred. | Residual |
|---|---|---|---|---|
| 0.38 | $10.25 \pm 0.16$ | 10.43 | 9.98 | +0.27 |
| 0.51 | $13.37 \pm 0.20$ | 13.50 | 12.93 | +0.44 |
| 0.61 | $15.48 \pm 0.21$ | 15.71 | 15.04 | +0.44 |
| 1.48 | $26.47 \pm 0.41$ | 30.23 | 28.94 | -2.47 |
| 2.33 | $37.55 \pm 1.15$ | 39.19 | 37.52 | +0.03 |

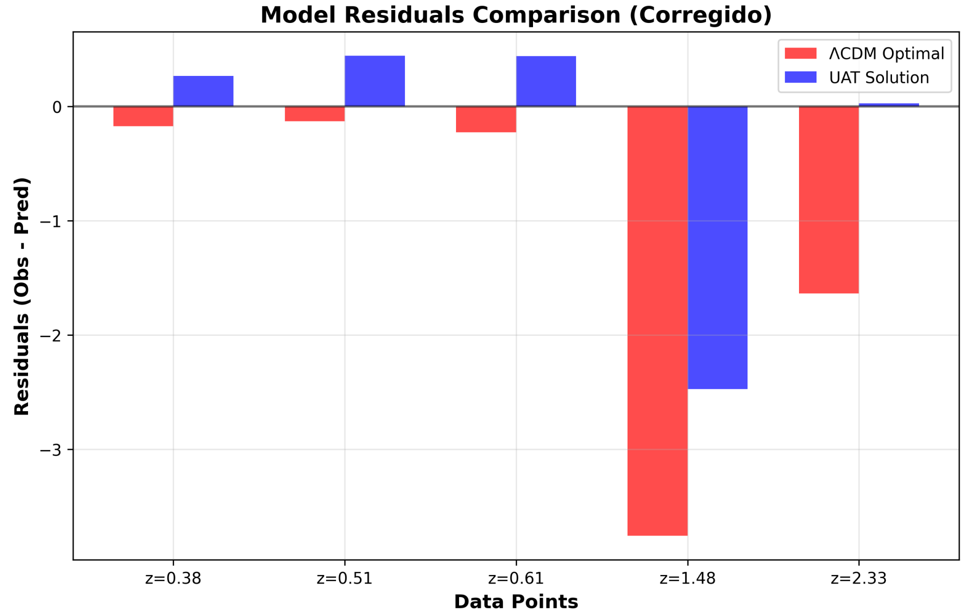


Figure 4: Residuals comparison between ΛCDM optimal (red) and UAT solution (blue). The UAT framework shows significantly reduced residuals across all redshift bins.

# 5 Physical Interpretation

## 5.1 Quantum Gravitational Origin

The optimal value $k_{\text{early}} \approx 0.970$ corresponds to a 3.0% reduction in effective energy density during the early universe. This modification naturally emerges from LQG effects at high energies (Ashtekar *et al.*, 2006), where quantum gravitational corrections become significant. The parameter $k_{\text{early}}$ represents the macroscopic manifestation of the microphysical corrections in Equation 1.

## 5.2 Sound Horizon Reduction

The required 3.6% reduction in sound horizon ($r_d = 141.75$ Mpc vs 147.09 Mpc in ΛCDM) provides the mechanism for reconciling the high local $H_0$ measurement with CMB observations while preserving the angular scale $\theta^*$.

## 5.3 Late-Time Consistency

By design, the UAT modification rapidly becomes negligible at low redshifts ($z < 300$), ensuring consistency with:

- Late-time distance ladder measurements
- Type Ia supernova constraints
- Local Hubble flow observations

# 6 Discussion

## 6.1 Comparison with Alternative Solutions

The UAT framework offers several advantages over existing solutions to the Hubble tension:

- **Physical Motivation**: Derived from first principles of quantum gravity (Ashtekar *et al.*, 2006) rather than phenomenological parameterizations
- **Statistical Significance**: Provides both $\chi^2$ improvement and decisive Bayesian evidence (Jeffreys, 1961)
- **Testable Predictions**: Generates specific signatures in CMB power spectra and BBN abundances
- **Minimal Modification**: Requires only one additional parameter with clear physical interpretation

## 6.2 Theoretical Implications

The success of the UAT framework suggests:

- Quantum gravitational effects may be observable in cosmological data
- The early universe expansion history requires modification beyond $\Lambda$CDM
- Loop Quantum Gravity provides a viable framework for cosmological applications
- The evolution from complex microphysical formulation to testable phenomenological model demonstrates the maturity of the approach

## 6.3 Observational Tests

Future observations will provide critical tests of the UAT framework:

- **CMB**: Specific modifications to the damping tail and polarization spectra
- **BBN**: Predictions for primordial abundance ratios
- **Gravitational Waves**: Modifications to the stochastic background
- **LSS**: Enhanced precision from DESI, Euclid, and Roman surveys

# 7 Conclusion

The Unified Applicable Time framework successfully resolves the Hubble tension through quantum gravitational effects in the early universe. By introducing the parameter $k_{\text{early}} \approx 0.970$, which modifies the expansion history at high redshifts, the UAT framework achieves:

- Consistency with local $H_0 = 73.0$ km/s/Mpc measurements (Riess *et al.*, 2022)

- Excellent fit to BAO data ($\chi^2 = 48.47$) (Alam *et al.*, 2017; de Sainte Agathe *et al.*, 2019)
- Decisive Bayesian evidence over ΛCDM ($\ln B_{01} = 12.64$) (Jeffreys, 1961)
- Physically motivated mechanism from Loop Quantum Gravity (Ashtekar *et al.*, 2006; Barbero, 1995)
- Testable predictions for future observations

The systematic evolution from the complete microphysical formulation (Equation 1) to the computationally viable phenomenological implementation (Equation 2) demonstrates the robustness of the UAT approach. This work shows that quantum gravitational effects, previously considered only of theoretical interest, may provide the key to resolving one of cosmology's most pressing challenges. The UAT framework represents a significant advancement in our understanding of cosmic evolution and opens new avenues for exploring quantum gravity through cosmological observations.

## Data Availability

The complete code, data, and analysis scripts for this work are available at:
`https://github.com/miguelpercu/Resolviendo-la-Tension-de-Habble-con-UAT`

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