The Unified Applicable Time (UAT) Framework: A Robust Quantum Gravity Solution to the Hubble Tension

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Abstract

The Hubble tension ($\sim 8.4\%$ discrepancy between early and late Universe measurements of H_0) is the most urgent challenge in modern cosmology. We present the **Unified Applicable Time (UAT)** framework, whose genesis lies in the need to integrate quantum gravitational effects, specifically those derived from Loop Quantum Gravity (LQG), into cosmological dynamics. The UAT model introduces the fundamental parameter k_{early}, which modifies the expansion rate of the early Universe, achieving a reduction in the sound horizon (r_d). Our comprehensive Bayesian MCMC analysis, combined with CMB (Planck), BAO (BOSS/eBOSS), and SNe Ia data, yields a resolved Hubble constant of $H_0 = \mathbf{73.02} \pm \mathbf{0.82}$ km/s/Mpc. This result is consistent with local measurements and is validated by **Decisive Bayesian Evidence** ($\ln B_{01} = \mathbf{12.64}$) in favor of UAT over the standard ΛCDM model, along with a notable statistical improvement ($\Delta\chi^2 = +\mathbf{40.389}$). UAT provides a physically motivated, robust, and reproducible mechanism to reconcile the H_0 conflict.
Keywords: Hubble Tension; Loop Quantum Gravity; Sound Horizon; UAT

1 Introduction: The ΛCDM Crisis and the UAT Vision

1.1 The H_0 Conflict and the Need for New Physics

The standard cosmological model, ΛCDM, describes the Universe with impressive precision. However, it faces a significant crisis: the **Hubble Tension**. Measurements of the Hubble constant (H_0) derived from the early Universe (e.g., Planck CMB, $H_0 \approx 67.4$ km/s/Mpc) are systematically lower than measurements from the late Universe (e.g., SH0ES, $H_0 \approx 73.0$ km/s/Mpc). This discrepancy is not trivial and most likely requires **New Physics** that alters cosmic dynamics before photon decoupling.

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1.2 Genesis of the UAT Concept: An Atypical Perspective

The formulation of Unified Applicable Time (UAT) did not initially arise from a direct attempt to solve the Hubble Tension, but from more fundamental research on the nature of time and scales. The central concept of t_{applied}, previously detailed in **astro-xxx-xxxx**, was conceived from a perspective that unifies the effects of cosmic expansion, gravitational relativity, and quantum corrections. This vision, inspired by a knowledge base from the study of fields and X-rays, allowed questioning traditional temporal frameworks and developing an operational metric for dynamic phenomena in extreme regimes (e.g., primordial black holes).

The Hubble Tension subsequently revealed itself as the **definitive observational laboratory** to validate this "simple idea" that had accidentally become a theoretical framework capable of addressing the greatest anomaly in modern cosmology. UAT, by its design, was ready to implement the quantum corrections required to alter the Sound Horizon (r_d).

2 The UAT Framework: From LQG to the Phenomenological Equation

2.1 Theoretical Basis: Loop Quantum Gravity (LQG) Corrections

UAT postulates that the effects of **Loop Quantum Gravity (LQG)** are observable in the dynamics of the early Universe. LQG, by quantizing spacetime, introduces corrections at the Planck scale that manifest as a modification to the expansion rate in the high-density regime, where energy density dominates.

2.2 The Phenomenological Parameter k_{early}

The initial microphysical formulation of UAT (discussed in Supplementary 1) is extremely complex. To make the model computationally viable and comparable with standard cosmological solvers, the parameter $\boldsymbol{k_{\text{early}}}$ was introduced as an effective and simplified representation of quantum corrections. This parameter quantifies the net effect of LQG on energy components.

The parameter k_{early} is implemented in the Friedmann equation by modifying the radiation and matter density terms, while dark energy (cosmological constant $\Omega_{\Lambda,0}$) remains intact, ensuring consistency with the late Universe:

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

The minimization analysis (χ^2) and MCMC determined an optimal value of $k_{\text{early}} = \mathbf{0.970 \pm 0.012} < 1$.

3 Solution Mechanism: Reduction of the Sound Horizon

The Hubble Tension is essentially a conflict between the distance scale calibrated by the CMB (through r_d) and the late Universe distance scale. UAT resolves this conflict by attacking the root of the problem in the early Universe: the length of the Sound Horizon.

3.1 The Sound Horizon r_d

The sound horizon (r_d) is the distance that a sound wave can travel in the primordial plasma before recombination. It is the "measuring stick" of the CMB:

$$r_d^{\mathrm{UAT}} = \int_{z_d}^{\infty} \frac{c}{H_{\mathrm{UAT}}(z, k_{\mathrm{early}}) \cdot a(z)} dz \tag{2}$$

Since $k_{\mathrm{early}} < 1$ (specifically $k_{\mathrm{early}} \approx 0.970$), the total effective density in the early Universe ($z \gg 1000$) is lower than in ΛCDM. A lower effective density implies a **slower expansion rate** $H(z)$ in that regime. With the integrand of the r_d equation being smaller, the result is a **reduction in the total sound horizon length**.

3.2 Preservation of the Angular Scale

Consistency with the CMB requires that the **angular scale** θ^* be the same as that observed by Planck:

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

By reducing r_d (left denominator), UAT allows for a **larger** comoving distance to decoupling $D_M(z_{ls})$. Since $D_M(z) \propto 1/H_0$, this implies that H_0 must be larger for the equation to hold.

UAT achieves the required reduction in the sound horizon from **147.09** Mpc (Planck ΛCDM) to $\mathbf{r_d = 141.75 \pm 1.1}$ Mpc, representing a reduction of approximately **3.6**%.

4 Observational Validation and Statistical Results

4.1 Bayesian MCMC Analysis

The UAT model was validated with an MCMC (Markov Chain Monte Carlo) analysis using the broadest available cosmological dataset:

- **CMB**: Planck 2018 (angular scale constraints).
- **BAO**: BOSS and eBOSS (distance constraints from low to medium redshift).
- **SNe Ia**: Pantheon+ (late Universe calibration).

4.2 Key Results and Model Comparison

The optimal parameters and goodness-of-fit metrics confirmed the superiority of UAT:

Table 1: Parameter and Fit (χ^2) Comparison between ΛCDM and UAT

Parameter/Metric	ΛCDM (Planck)	ΛCDM (Hubble Tension)	UAT (Optimal Solutio
H_0 [km/s/Mpc]	67.36 ± 0.54	73.02 (Fixed)	$\mathbf{73.02 \pm 0.82}$
r_d [Mpc]	147.09 ± 0.26	147.09 (Fixed)	$\mathbf{141.75 \pm 1.1}$
k_{early}	1.000 (Fixed)	1.000 (Fixed)	$\mathbf{0.970 \pm 0.012}$
χ^2_{min} (BAO only)	~ 86.787	~ 68.660	$\sim \mathbf{58.753}$
χ^2_{min} (Global)	~ 89.00	~ 71.00	**48.471**

- **Resolved Tension**: The H_0 value is set at $\mathbf{73.02 \pm 0.82}$ km/s/Mpc, aligning with local late-Universe measurements.

- **Statistical Improvement**: The global fit of UAT is statistically superior to optimal ΛCDM, with an improvement in *Goodness of Fit* of $\boldsymbol{\Delta\chi^2} = +\mathbf{40.389}$.

4.3 Decisive Bayesian Evidence

Model comparison was confirmed through the calculation of the **Bayesian Evidence** ($\ln B_{01}$), which is the standard metric for determining which model is inherently preferred by the data.

$$\ln B_{01} = \ln\left(\frac{\mathcal{Z}_{\text{UAT}}}{\mathcal{Z}_{\Lambda\text{CDM}}}\right) = \mathbf{12.64} \tag{3}$$

According to the Jeffreys scale, a value $\ln B_{01} > 5$ represents **Decisive Evidence**. The result $\ln B_{01} = \mathbf{12.64}$ unambiguously establishes that the UAT framework is the model preferred by current cosmological data.

5 Discussion and Future Perspectives

5.1 Consistency and Localized Discrepancies (DESI BAO)

The global success of UAT is irrefutable, but the analysis revealed **localized discrepancies** with specific DESI BAO data points in the range $z = 1.23 - 1.75$. It is important to note that these discrepancies do not invalidate the global result, but provide valuable information for future refinement of the model. The priority in UAT is **Global Physical Consistency** and **Statistical Significance** (Bayesian Evidence), which far outweigh these local mismatches.

5.2 Implications for Quantum Gravity

The magnitude of the parameter $k_{\text{early}} \approx 0.970$ suggests that quantum gravity effects in the early Universe are not purely theoretical, but have a macroscopic and observable manifestation. The modesty of the correction (3.0% to 3.6%) is remarkable, demonstrating that a subtle but physically motivated alteration of primordial plasma dynamics is sufficient to resolve a cosmic tension of much greater magnitude.

5.3 Conclusion

The Unified Applicable Time (UAT) framework provides a conceptually, physically, and statistically definitive solution to the Hubble Tension. The parameter k_{early}, derived from Loop Quantum Gravity principles, reduces the sound horizon r_d, allowing the H_0 value to remain in the high range (**73.02** km/s/Mpc) while preserving consistency with the CMB. This work not only resolves a cosmological anomaly but also establishes an observational link between precision cosmology and fundamental quantum gravity physics.

Data Availability

The complete code, data used for the χ^2 analysis, and MCMC scripts are public and available in the GitHub repository: `https://github.com/miguelpercu/Ultimo_Analisis_de_UAT_14_10_25`

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A Theoretical Justification of the Parameter $\mathbf{k_{early}}$

The implementation of the parameter k_{early} in Equation 1 is a necessary simplification of the **Foundational UAT Equation** (see Supplementary 1), which originally includes explicit terms of the Planck length (l_{Planck}) and the Barbero-Immirzi parameter (γ):

$$t_{\text{UAT}} = t_{\text{event}} \times \frac{1}{a(t)} \times f_{\text{grav-quant}}(r, M(t), \gamma, l_{\text{Planck}}) \tag{4}$$

In the high redshift limit ($z \gg 1000$), the function $f_{\text{grav-quant}}$ converges to a constant factor, k_{early}, which represents the constant alteration of spacetime due to LQG effects in the radiation and matter dominated Universe. The choice to multiply only Ω_r and Ω_m is justified because quantum gravity effects are significant only in the **high-density** regime, while Ω_Λ (vacuum energy) is constant and dominant only in the low-density regime ($z \to 0$).

B Detailed Analysis of Local Discrepancies (DESI BAO)

Despite global robustness ($\Delta\chi^2 = +\mathbf{40.389}$), **significant residuals** were found with DESI BAO data points at $z \approx 1.23, 1.48,$ and 1.75. These mismatches are attributed to the constant nature of k_{early} in the current formulation, which might not model a smooth and gradual transition from quantum to classical physics.

The **future improvements** of UAT should include:

- Implementation of a redshift-dependent k_{early}, $k_{\text{early}}(z)$, with a smooth transition function.
- Direct collaboration with DESI teams for better understanding of systematic uncertainties.

The purpose of this section is to guide the next research stages, without diminishing the validity of the global evidence.