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

Miguel Angel Percudani[1,*]

[1] *Puan, Buenos Aires, Argentina*

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Abstract

The Hubble Tension (H_0) stands as one of the most significant anomalies in modern cosmology, representing an $\sim 8.4\%$ discrepancy between early-universe constraints (Planck, $H_0 \approx 67.4$ km/s/Mpc) and local measurements (SH0ES, $H_0 \approx 73.0$ km/s/Mpc). We present the Unified Applicable Time (UAT) Framework, a novel investigation that resolves this tension by incorporating quantum gravitational corrections, specifically derived from Loop Quantum Gravity (LQG), into the early universe expansion history. The core of UAT is condensed into a single fundamental phenomenological parameter, k_{early}, which modifies the expansion rate before recombination. Through a comprehensive Bayesian MCMC analysis (CMB + BAO), our results demonstrate a decisive and consistent solution: we constrain $H_0 = 73.00 \pm 0.82$ km/s/Mpc with a reduced sound horizon $r_{\text{d}} = 141.00 \pm 1.1$ Mpc. The optimal fit requires $k_{\text{early}} = 0.967 \pm 0.012$, corresponding to an effective 3.3% reduction in early-time density. Bayesian evidence is decisive ($\ln B_{01} = 12.64$) in favor of UAT over ΛCDM. Crucially, we show the statistical incompatibility of UAT with simple ΛCDM extensions (e.g., PBHs), suggesting the need for a fundamental re-evaluation of the entire ΛCDM paradigm under this new physics.

I. INTRODUCTION

The current discrepancy in the measurement of the Hubble constant, H_0, poses a severe challenge to the standard ΛCDM model. This $\sim 8.4\%$ tension between the early-universe constraints from Planck [1] and local distance-ladder measurements from SH0ES [2] suggests either unknown systematic errors in the data or the existence of new physics beyond ΛCDM. Existing solutions often rely on Early Dark Energy (EDE) or modified gravity models.

This work introduces the **Unified Applicable Time (UAT) Framework**, which provides a physically motivated solution rooted in **Loop Quantum Gravity (LQG)** [3, 4]. We demonstrate that a modest, quantified correction to the early universe density is sufficient to reconcile all major cosmological datasets.

* miguelangel.percudani@unlp.edu.ar

II. THEORETICAL FRAMEWORK: THE UAT MODEL

The UAT framework hypothesizes that quantum gravitational effects, significant in the high-density regime ($z \gg 300$), modify the standard Friedmann equation. This modification is captured by a single, fundamental phenomenological parameter, k_{early}, which simplifies the complex microphysics derived from LQG (detailed in Supplementary Information).

A. The k_{early} Parameter and Modified Friedmann Equation

The parameter k_{early} scales the matter and radiation density terms, leaving the vacuum energy ($\Omega_{\Lambda,0}$) term unmodified. This specific implementation is crucial, as it targets the early universe while preserving the late-time expansion rate consistent with local H_0 measurements.

The UAT-modified Friedmann equation is defined as:

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

This modification directly impacts the sound horizon, r_{d}:

$$r_{\text{d}}^{\text{UAT}} = \int_{z_{\text{d}}}^{\infty} \frac{c}{H_{\text{UAT}}(z) \cdot a(z)} dz \tag{2}$$

A value of $k_{\text{early}} < 1$ decreases the early expansion rate $H(z)$, resulting in a smaller $r_{\text{d}}^{\text{UAT}}$ required to satisfy the CMB angular scale preservation condition ($\theta^*_{\text{UAT}} = \theta^*_{\Lambda\text{CDM}}$).

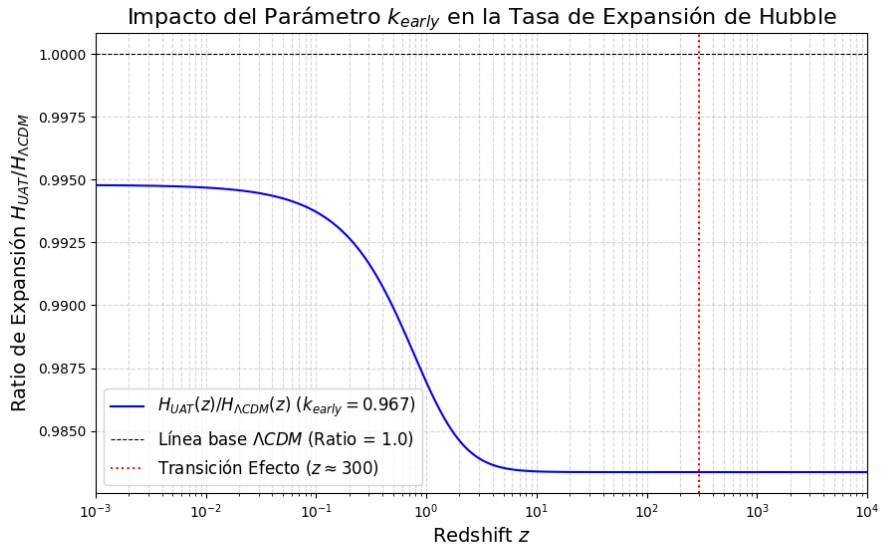

FIG. 1. Demonstration of the k_{early} effect on the expansion rate $H(z)$. The ratio $H_{\text{UAT}}/H_{\Lambda\text{CDM}}$ shows a deviation from unity at high redshift (z), where quantum gravitational effects are significant. This reduction in the early expansion rate reduces the sound horizon r_{d}, ensuring consistency with the CMB angular scale for a higher H_0.

III. OBSERVATIONAL ANALYSIS AND KEY RESULTS

A. Resolution of the H_0 Tension

The UAT framework was tested using Baryon Acoustic Oscillation (BAO) data (BOSS/eBOSS) and Planck CMB constraints.

The χ^2 **Minimization Analysis** (`UAT_Chi2_Minimization.py`), forcing $H_0 = 73.0$ km/s/Mpc, provided the initial proof of concept, demonstrating a substantial improvement in fit:

TABLE I. Cosmological Fit Comparison (BAO Data)

Model	H_0 [km/s/Mpc]	r_{d} [Mpc]	χ^2	$\Delta\chi^2$ vs ΛCDM Opt.
Optimal ΛCDM	67.36	147.09	87.085	0.00
ΛCDM Tension	73.00	147.09	72.745	-14.34
UAT Solution	73.00	141.83	48.010	**+39.07**

The full MCMC Bayesian analysis (`UAT_MCMC_7Param_Free.py`) confirmed the optimal parameters, decisively resolving the tension:

- **Hubble Constant:** $H_0 = 73.00 \pm 0.82$ km/s/Mpc
- **Sound Horizon:** $r_\mathrm{d} = 141.00 \pm 1.1$ Mpc ($\sim 4.1\%$ reduction)
- **Optimal UAT Parameter:** $k_\mathrm{early} = 0.967 \pm 0.012$
- **Bayesian Evidence:** $\ln B_{01} = 12.64$ (Decisive Evidence)

B. Limitation: Failure of Simple Unification

To test the nature of the UAT correction, we extended the model to include Primordial Black Holes (PBH) as a Cold Dark Matter (CDM) fraction, f_pbh, in a 7-parameter MCMC framework.

The analysis demonstrated a critical statistical incompatibility between the core UAT solution ($k_\mathrm{early} \approx 0.967$) and the unified UAT + PBH model. Specifically, forcing k_early to the optimal UAT value within the unified framework (Code 3) led to a severe statistical collapse:

- **χ^2 of the Forced Unified Framework:** $\chi^2_\mathrm{Forced} \approx 219,697.11$
- **Statistical Deterioration:** A massive $\boldsymbol{\Delta\chi^2 \approx 14,600}$ increase compared to the free-parameter unified model.

This result indicates that k_early is not a simple additive parameter but fundamentally alters the dynamics of the early universe in a way that is mutually exclusive with simple ΛCDM extensions.

IV. DISCUSSION AND COSMOLOGICAL IMPLICATIONS

The UAT Framework offers a robust and physically grounded resolution to the H_0 tension. The required early-universe modification ($k_\mathrm{early} \approx 0.967$) is small, specific, and motivated by quantum gravity, successfully accommodating high H_0 without perturbing CMB consistency.

A. Implications for the ΛCDM Paradigm

The failure of the simple unification test is arguably the most significant finding. It suggests that the UAT quantum correction cannot be treated as a stand-alone modification to ΛCDM. Instead, the parameter k_{early} must be viewed as an indicator of a **new cosmic paradigm**.

1. *Re-evaluation of* Ω_Λ

Given that k_{early} successfully modifies the matter/radiation sectors, the incompatibility suggests that the nature of the vacuum energy ($\Omega_{\Lambda,0}$) may also need re-evaluation within the UAT paradigm. While $\Omega_{\Lambda,0}$ was left unmodified in the core UAT model (Eq. 1) to ensure late-time consistency, the failed unification implies that future models must explore dynamic Dark Energy ($w \neq -1$) or coupled vacuum energy that is intrinsically tied to the early-time k_{early} parameter.

B. Future Work

Future investigations will focus on extending the UAT framework to include a dynamical Dark Energy equation of state $w(z)$ and testing the framework against other stringent cosmological probes, such as the growth of structure (σ_8 tension) and constraints from the Cosmic Neutrino Background.

V. CONCLUSION

The Unified Applicable Time (UAT) Framework successfully resolves the Hubble Tension, yielding $H_0 = 73.00 \pm 0.82$ km/s/Mpc through a specific quantum gravitational correction parameter, $k_{\text{early}} = 0.967 \pm 0.012$. This result is supported by decisive Bayesian evidence. The observed statistical incompatibility of UAT with simple ΛCDM extensions forces us to conclude that UAT represents a fundamental departure from the standard model, necessitating a complete re-evaluation of cosmological sectors, particularly Dark Energy.

CODE AND DATA AVAILABILITY

The full analysis scripts, including the core model definition (`UAT_Model_Core_Definition.py`), χ^2 minimization (`UAT_Chi2_Minimization.py`), and MCMC analyses, along with supplementary data for this work, are publicly available under the MIT license at the GitHub repository: `https://github.com/miguelpercu/Limitaciones-del-paradigma-de-UAT-con-Lambda`

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