Supplementary Material: The Unified Applicable Timeframe (UAT) and the Resolution of the Hubble Tension

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1 Theoretical Autonomy of the UAT Framework

It is critical to emphasize that the Unified Applicable Timeframe (UAT) is not a mere extension or "plug-in" for the ΛCDM model. Instead, UAT represents a fundamentally different cosmological option[1]. While ΛCDM relies on a rigid dark energy density, UAT emerges from quantum-gravitational principles.

2 Discrepancies in Vacuum Energy and Observational Priority

Based on the mathematical proofs regarding vacuum energy discrepancies detailed in Zenodo (**DOI: 10.5281/zenodo.17411432**), there is a fundamental inconsistency within the standard model.

Since these mathematical inconsistencies in ΛCDM propagate into the final analytical results of any model tested against its background, the UAT

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[1]UAT originates from independent foundational equations and a new theoretical basis that deviates from the ΛCDM paradigm from the earliest stages of cosmological evolution.

framework cannot be fully evaluated through purely theoretical comparisons. Consequently, it is strongly advised to analyze the UAT framework primarily through **direct observational data** (e.g., CMB-S4, BAO, and local H_0 measurements). Full mathematical proof available at: https://doi.org/10.5281/zenodo.17411432

3 Methodological Challenges and Research Limitations

During the development of this research, two primary technical challenges were identified:

1. **Sound Horizon Calibration**: Initial iterations faced significant difficulties in stabilizing the sound horizon (r_d). The non-linear relationship between the Barbero-Immirzi parameter and the early expansion rate required multiple recursive adjustments to prevent over-compression of the acoustic scale.

2. **Computational Distance Underestimation**: Standard Python libraries and cosmological integration scripts initially exhibited a systematic underestimation of luminosity and angular diameter distances at high redshift. This was corrected by implementing a custom integration routine that accounts for the UAT-specific k_{early} modification.

4 Data and Code Availability

The MCMC chains and Python scripts used for the UAT framework analysis are available at the following Zenodo repository (**DOI: 10.5281/zenodo.18114380**):
https://doi.org/10.5281/zenodo.18114380

References