Cosmic Microwave Background Delensing and The Hubble Tension

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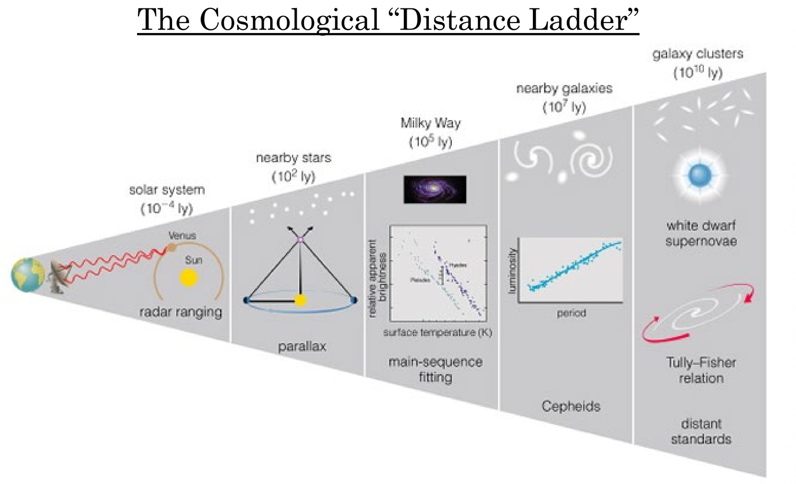
What is the Hubble Tension?

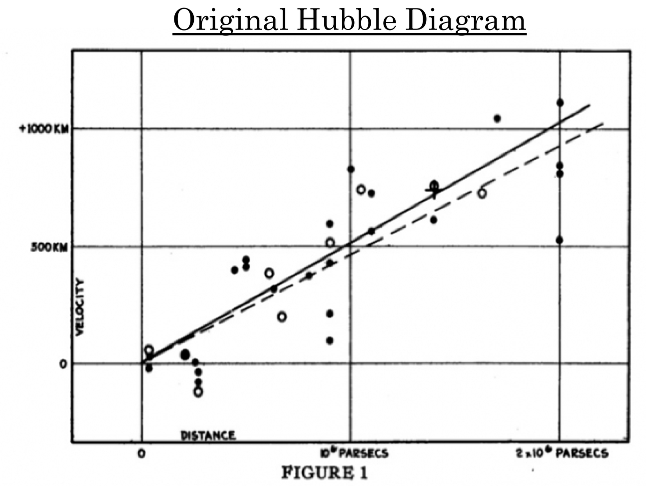
Look into the night sky and you'll see countless galaxies zooming away. This is because the universe, itself, is expanding all around us. One way we can measure the rate of this expansion, the Hubble Constant H_0, is with the "cosmological distance ladder," wherein we string together a series of measurements to determine the distances of far-away objects. By plotting galaxies' distances against their velocities, we can chart and compute this relation, defining H_0 as roughly 70 km/s per Megaparsec away.

The Cosmological "Distance Ladder"



Bennet J, et al. "The Essential Cosmic Perspective"

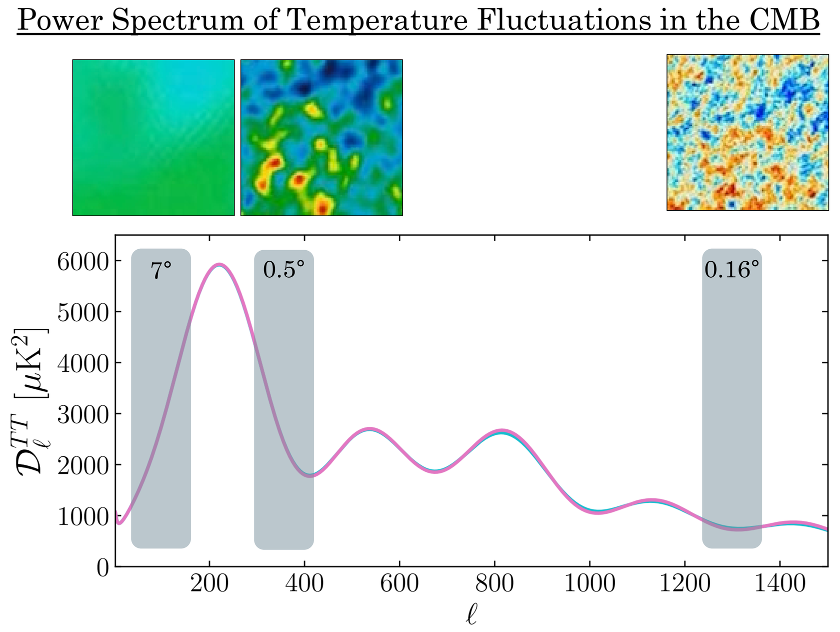
Original Hubble Diagram



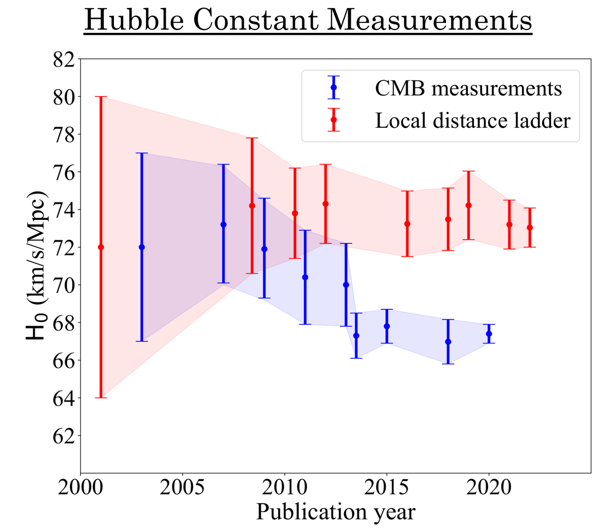
Hubble E. A relation between distance and radial velocity among extra-galactic nebulae. *Proceedings of the National Academy of Sciences* 15 (3): 168–173, 1929.

Alternatively, we can measure this value through the Cosmic Microwave Background (light from when the universe first became transparent). The statistics and patterns of the CMB's fluctuations at different angular scales (as shown through its power spectra) tell us about the physics from billions of years ago, meaning we can extrapolate the universe's expansion history, including the Hubble Constant.

Power Spectrum of Temperature Fluctuations in the CMB



Hubble Constant Measurements



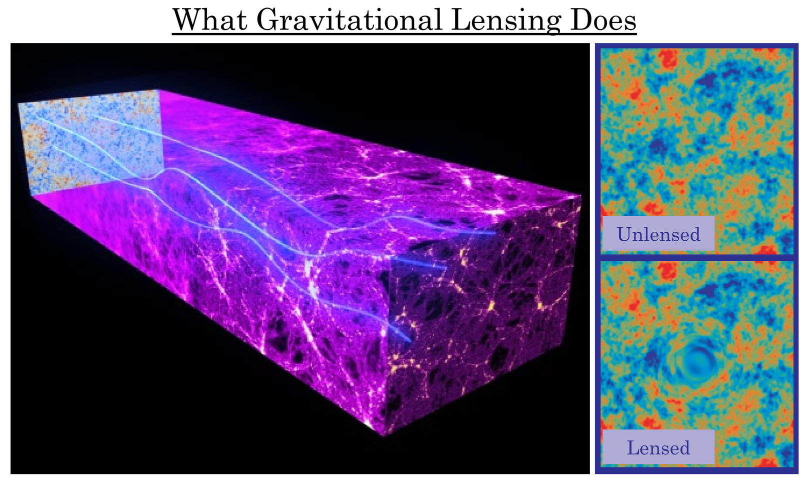
Hu J-P, Wang F-Y. Hubble Tension: The Evidence of New Physics. *Universe* 9: 94, 2023. https://doi.org/10.3390/universe9020094

But as time has gone on, these two measurements of what should be the same physical property have diverged. Somewhere in our story, there's a discrepancy to be solved!

What is CMB Delensing?

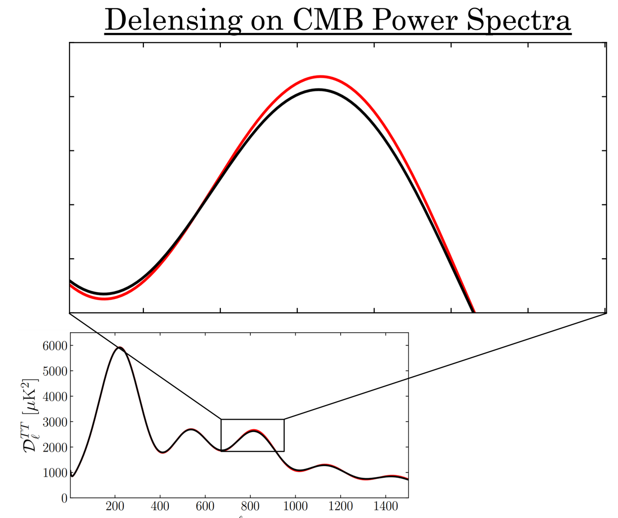
The Cosmic Microwave Background (CMB) doesn't arrive at our eyes unimpeded. Between us and the "surface of last scattering" are galaxies and astronomical objects that act as "gravitational lenses." These massive objects bend the light on its way to us, meaning the CMB we see is a distorted version of the original.

What Gravitational Lensing Does



ESA and the Planck Collaboration | Hu W, Takemi O. Mass Reconstruction with CMB Polarization. *The Astrophysical Journal* 574: 566-574, 2002.

Delensing on CMB Power Spectra

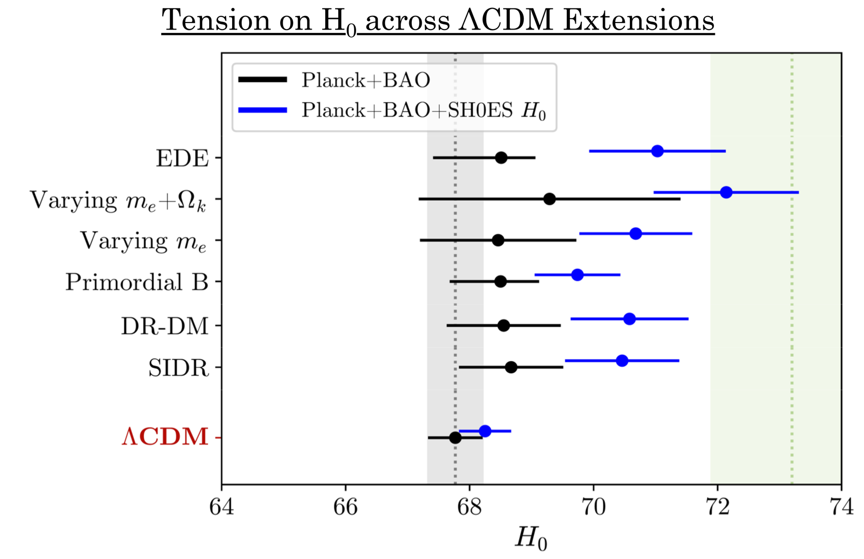


We can track these distortions through the unique statistical characteristics they impart on the CMB (called "non-stationary statistics"). They can be used to reconstruct the "lensing deflection map" and reverse its effects. By performing this iteratively, our CMB maps can come much closer to the unlensed original, which sharpens many key features of the CMB Power Spectra. It allows us to more precisely make inferences of the early universe and constrain the cosmological parameters of our standard ΛCDM model of the universe.

Overview

Potential solutions to the Hubble Tension arise from tackling our understanding of the universe and the expansion history based on the CMB. Maybe there's new physics we're not aware of that's throwing off our inferences! If so, it becomes important to test and constrain these models so we know which ones to support and which to throw out.

Tension on H_0 across ΛCDM Extensions



Schöneberg N, et al. The H0 Olympics: A fair ranking of proposed models. *Physics Reports* 984: 1-55, 2022.

We simulated CMB Power Spectra for models of the universe aimed at resolving the Hubble Tension and performed "Fisher forecasting" to quantify how much information we could glean (and how much degeneracy exists between parameters) from delensing. We calculated the constraint improvements at different noise levels (in terms of μK-arcmin) and the percent improvement across the board for each model.

Varying Fundamental Constants

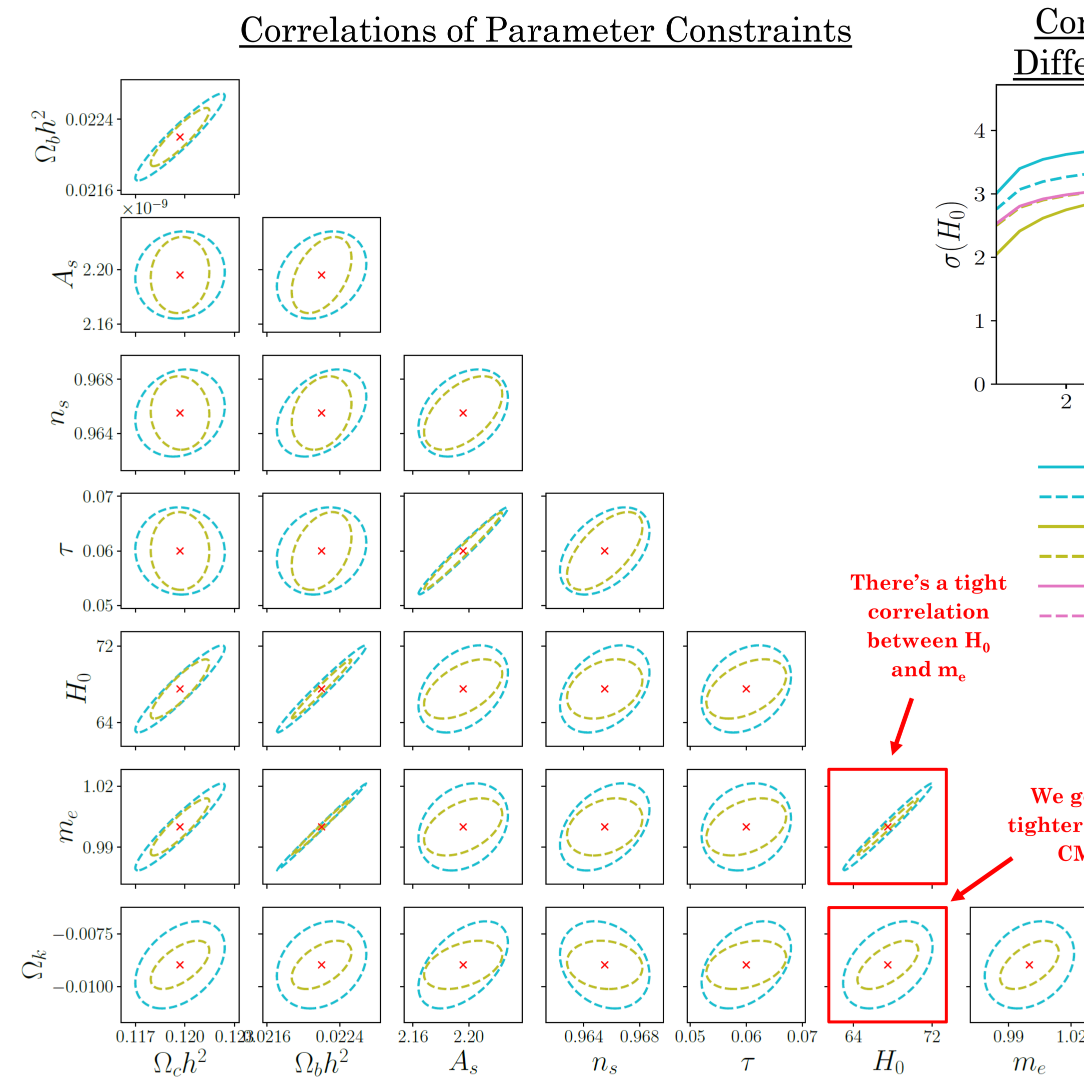
Long ago, the universe was filled with a hot, dense, opaque plasma. Once temperatures cooled enough, "recombination" occurred. After 380,000 years, electrons and protons were finally allowed to form neutral Hydrogen atoms, freeing light and forming the CMB. But if the fundamental constants involved in this interaction (such as electron mass m_e, fine structure constant α, or curvature of the universe Ω_k) were slightly different, this transition would've occurred at a different temperature (and therefore time). If the CMB was produced at a different time than we currently think based on the ΛCDM model of the universe, our inference of the Hubble Constant would necessarily be changed, potentially resolving the Hubble Tension.

Percent Improvement on Parameter Constraints from Delensing

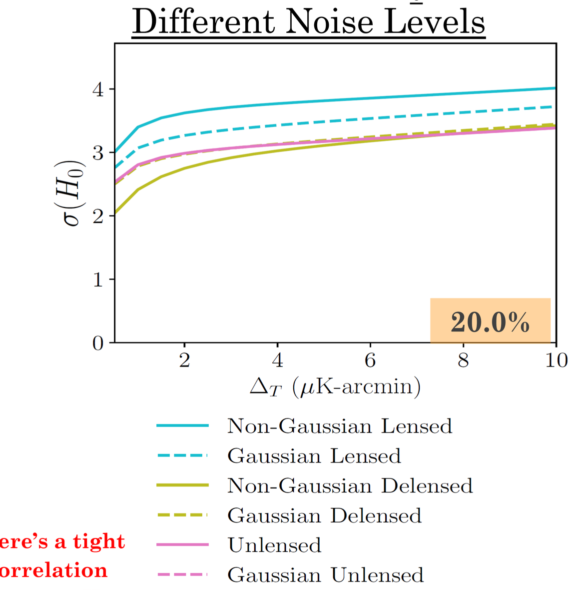
Universe Model	m_e	α	Ω_k	H_0
ΛCDM $+ m_e$	30.5%			30.1%
ΛCDM $+ m_e + \Omega_k$	22.4%		34.8%	20.0%
ΛCDM + α		13.7%		11.5%
ΛCDM $+ \alpha + \Omega_k$		13.9%	42.4%	38.6%
ΛCDM $+ m_e + \alpha$	32.8%	14.5%		32.2%
ΛCDM $+ m_e + \alpha + \Omega_k$	23.9%	14.3%	34.4%	22.5%

Looking at **ΛCDM $+ m_e + \Omega_k$** (the best solution to the Hubble Tension we analyzed):

Correlations of Parameter Constraints



Constraint on H_0 at Different Noise Levels



Early Dark Energy

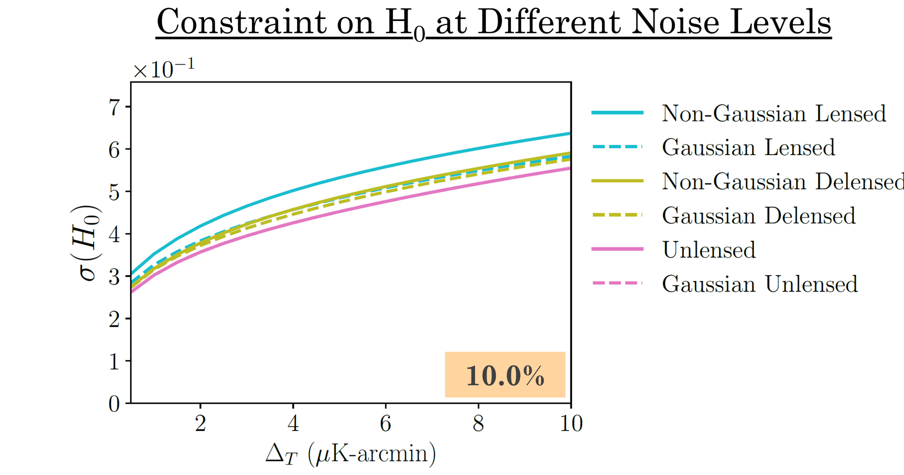
The expansion rate of the universe is dependent on the matter and energy content within. By increasing the expansion rate at early times, a larger Hubble constant could be extrapolated while preserving our large-scale understanding of the universe. Perhaps there was some exotic form of energy that once behaved like a cosmological constant and led to a faster growth of the universe. But once the Hubble rate dropped below the mass of this "early dark energy," it oscillated and rapidly decayed, explaining why we no longer directly observe it. In this case, the Hubble Tension could be resolved with a 3-parameter extension that describes early dark energy with the critical time at which it becomes dynamic (z_c), the overall energy contribution of the field at this time (f_{EDE}), and the properties of its dilution (θ_i).

Percent Improvement on Parameter Constraints from Delensing

Universe Model	$\log_{10}(z_c)$	f_{EDE}	θ_i	H_0
ΛCDM $+ z_c + f_{EDE} + \theta_i$	12.6%	13.9%	12.1%	11.8%
ΛCDM $+ z_c + f_{EDE}$	13.0%	13.1%		10.0%
ΛCDM $+ z_c + \theta_i$	12.2%		11.4%	7.8%
ΛCDM $+ z_c$	12.9%			5.4%
ΛCDM $+ f_{EDE} + \theta_i$		13.4%	12.5%	11.9%
ΛCDM $+ f_{EDE}$		12.9%		10.0%
ΛCDM $+ \theta_i$			12.1%	8.3%

Looking at **ΛCDM $+ f_{EDE}$**:

Constraint on H_0 at Different Noise Levels

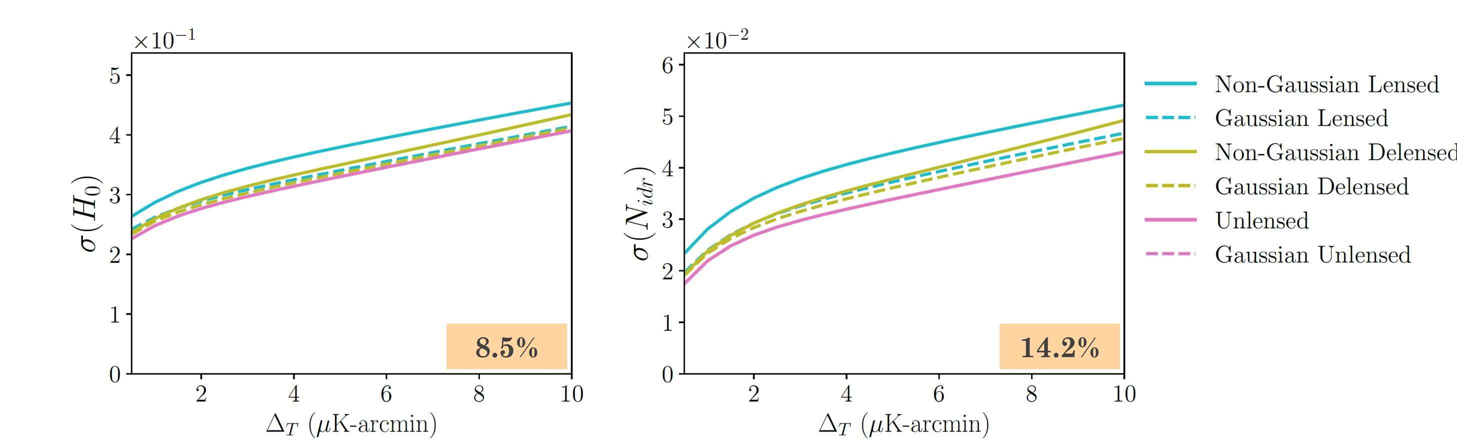


Self-Interacting Dark Radiation

Dark radiation refers to relativistic particles that don't interact with electromagnetic radiation. If true, these dark relics would've contributed to the energy density of the early universe and influenced CMB characteristics (like the acoustic peaks in the power spectra). Free-streaming (non-self-interacting) dark radiation leads to well-known changes on the CMB, but there is also the possibility that it interacts with itself. In this case, the dark radiation would form a large-scale, fluid-like structure that unavoidably alters the content and expansion rate of the universe. As such, the Hubble Tension could be resolved with a 1-parameter extension associated with the density of self-interacting dark radiation (N_{idr}).

Looking at **ΛCDM $+ N_{idr}$**:

Constraint on H_0 and N_{idr} at Different Noise Levels



Conclusion

By reversing the effects of gravitational lensing on CMB maps, we can recover sharper features and tighter constraints on model parameters. We (1) investigated three categories of ΛCDM extensions aimed at resolving the Hubble Tension, (2) simulated power spectra for their lensed and delensed varieties, and (3) used Fisher forecasting to predict the expected constraints across cosmological parameters.

For some models, we found improvements on constraints of H_0 up to and around the 30% mark. For our best-fit model of solving the Hubble Tension, ΛCDM $+ m_e + \Omega_k$, we found an immense 20.0% improvement. We've found delensing has significant merit for improving constraints across the board, notably at the low noise levels of future measurements. Overall, CMB Delensing proves to be an incredibly helpful tool for extracting knowledge from the light of 13 billion years ago.