XXXV. In the Realm of the Hubble tension − a Review of Solutions

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The simplest ΓCDM model provides a good fit to a large span of cosmological data but harbors large areas of phenomenology and ignorance. With the improvement of the number and the accuracy of observations, discrepancies among key cosmological parameters of the model have emerged.

The most statistically significant tension is the 4σ to 6σ disagreement between predictions of the Hubble constant, H_0, made by the early time probes in concert with the "vanilla" ΓCDM Cosmological model, and a number of late time, model-independent determinations of H_0 from local measurements of distances and redshifts.

The high precision and consistency of the data at both ends present strong challenges
to the possible solution space and demands a hypothesis with enough rigor to explain multiple observations – whether these invoke new physics, unexpected large-scale structures or multiple, unrelated errors.
We present a summary of the proposed theoretical solutions is presented in the following page.

We classify the many proposals to resolve the tension in these categories:
Early Dark Energy, Late Dark Energy, Dark energy models with 6 degrees of freedom and their extensions, Models with extra relativistic degrees of freedom, Models with Extra Interactions, Unified cosmologies, Modified gravity, Inflationary models, Modified recombination history, Physics of the critical Phenomena, and Alternative proposals. Some are formally successful, improving the fit to the data in light of their additional degrees of freedom, restoring agreement within 1 to 2σ between Planck 2018, using the Cosmic Microwave Background power spectra data, Baryon Acoustic Oscillations, Pantheon SN data, and R20, the latest SH0ES Team measurement of the Hubble constant

($H_0 = 73.2 \pm 1.3$ km s^{-1} Mpc^{-1} at **68% Confidence Level, CL**).

However, there are many more unsuccessful models which leave the discrepancy well above the 3σ disagreement level. In many cases, reduced tension comes not simply from a change in the value of H_0 but also due to an increase in its uncertainty due to degeneracy with additional physics, complicating the picture and pointing to the need for additional probes. While no specific proposal makes a strong case for being highly likely or far better than all others we list some solutions as follows:

Solutions involving

- **early or dynamical dark energy,**
- **neutrino interactions,**
- **interacting cosmologies,**
- **primordial magnetic fields, and**
- **modified gravity**

provide the best options at 68% CL until a better alternative comes along.

In the Whisker Plot below

the cyan vertical band corresponds to the H_0 value from SH0ES Team

(R20, $H_0 = 73.2 \pm 1.3$ km s^{-1} Mpc^{-1} at 68% CL)

and the light pink vertical band corresponds to the H_0 value as reported by Planck 2018 team.

Alternatives to ΛCDM

Alternative	CMB	H_0 Tension	Structure Formation
Early Dark Energy	Modified power spectrum	Increases H_0	Small effect
Phantom or dynamical Dark Energy	Modified power spectrum	Increases H_0	Small effect
Interactions between Dark Matter and Dark Energy	Modified power spectrum	Can increase H_0	Small effect
Modified Gravity Theories	Departs from ΛCDM	Can increase H_0	Altered growth of structures
Decaying or Self-Interacting Dark Matter	Modified power spectrum	Varied	Can be suppressed

Potential Solutions to Hubble Tension H_0 with 68% CL Constraints