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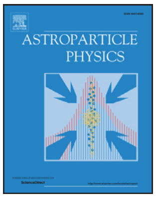

Snowmass2021 - Letter of interest cosmology intertwined II: The hubble constant tension

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ABSTRACT

The current cosmological probes have provided a fantastic confirmation of the standard Λ Cold Dark Matter cosmological model, which has been constrained with unprecedented accuracy. However, with the increase of the experimental sensitivity, a few statistically significant tensions between different independent cosmological datasets emerged. While these tensions can be in part the result of systematic errors, the persistence after several years of accurate analysis strongly hints at cracks in the standard cosmological scenario and the need for new physics. In this Letter of Interest we will focus on the 4.4σ tension between the Planck estimate of the Hubble constant H_0 and the SH0ES collaboration measurements. After showing the H_0 evaluations made from different teams using different methods and geometric calibrations, we will list a few interesting models of new physics that could solve this tension and discuss how the next decade's experiments will be crucial.

State-of-the-art – The 2018 legacy release from the Planck satellite's analysis [1] of the Cosmic Microwave Background (CMB) anisotropies, has provided a fantastic confirmation of the standard Λ Cold Dark Matter (ΛCDM) cosmological model. However, the improvement in estimating the uncertainties has led to statistically-significant tensions in the measurement of various quantities between Planck and independent cosmological probes.

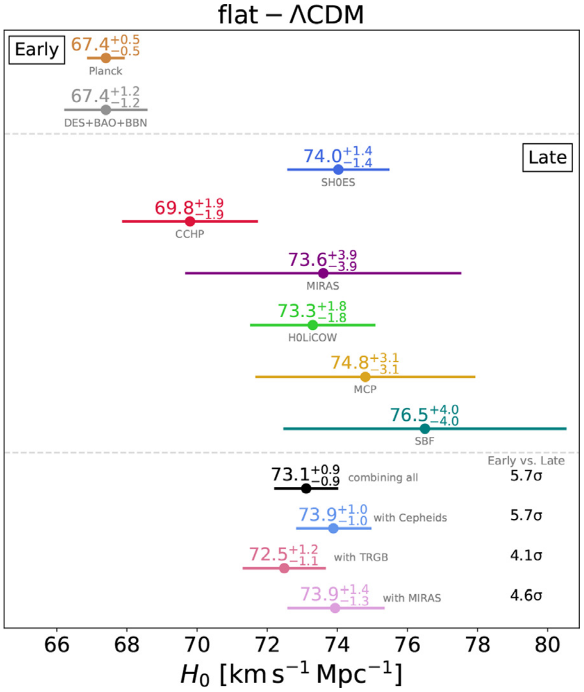

Fig. 1. 68% CL constraint on H_0 from different cosmological probes (from Ref. [4]).

While some of these discrepancies may have a systematic origin, their magnitude and persistence across probes strongly hint at cracks in the standard cosmological scenario and the need for new physics. The most statistically significant tension is in the estimation of the *Hubble constant* H_0 between the CMB (assuming a ΛCDM model) and the direct local distance ladder measurements. In particular, the Planck collaboration [2] finds $H_0 = (67.27 \pm 0.60)$ km/s/Mpc.[1] This constraint is in tension at about 4.4σ with the 2019 SH0ES collaboration (R19 [3]) constraint, $H_0 = (74.03 \pm 1.42)$ km/s/Mpc, based on the analysis of the Hubble Space Telescope observations using 70 long-period Cepheids in the Large Magellanic Cloud.

As shown in Fig. 1, the early-universe estimates of H_0 obtained by Planck and by ACT+WMAP [5] ($H_0 = (67.6 \pm 1.1)$ km/s/Mpc) prefer lower values. The same is true for their combination with Baryon Acoustic Oscillation (BAO) data [6–8], the Y1 measurements of the Dark Energy Survey [9–11], supernovae from the Pantheon catalog [12], and a prior on the baryon density derived from measurements of primordial deuterium [13] assuming standard Big Bang Nucleosynthesis (BBN). A reanalysis of the BOSS full-shape data [14,15], as well as BAO+BBN [16] from BOSS and eBOSS provides $H_0 = (67.35 \pm 0.97)$, while SPTpol [17] finds $H_0 = (71.3 \pm 2.1)$ km/s/Mpc. Standard distance ladder and time delay distances agree on a low-z higher H_0 value, as the SH0ES estimates [18] $H_0 = (73.5 \pm 1.4)$ km/s/Mpc, and the H0LiCOW [19] inferred value is $H_0 = (73.3^{+1.7}_{-1.8})$ km/s/Mpc, based on strong gravitational lensing effects on quasar systems. Next, the strong lensing TDCOSMO+SLACS [20] sample prefers $H_0 = 67.4^{+4.1}_{-3.2}$ km/s/Mpc. Also contributing H_0 constraints are the reanalysis of the Cepheid data by using Bayesian hyper-parameters [21], the local determination of H_0 [22] considering the cosmographic expansion of the luminosity distance, the independent determination of H_0 based on the Tip of the Red Giant Branch [23–25], and that obtained by using the Surface Brightness Fluctuations method [4,26], or the Cosmic Chronometers [27–30]. Finally, a higher value for H_0 is preferred by MIRAS [31] (variable red giant stars), by STRIDES [32], using the Infrared [33] or Baryonic TullyFisher relation [34], or by Standardized Type II supernovae [35]. There is no single type of systematic measurement error in Cepheids that could solve the H_0 crisis, contrary to [36] (e.g., it would not work for Cepheids calibrated in NGC 4258). In any case the high $H_0 = (73.9 \pm 3.0)$ km/s/Mpc found from the Maser Cosmology Project [37] is completely independent from these considerations. When the late universe estimates are averaged in different combinations, these H_0 values disagree between 4.5σ and 6.3σ with those from Planck [38].

Possible solutions – Models addressing the H_0 tension are extremely difficult to concoct. The simplest possibility is a sample-variance effect, due to an underdense local universe. However, this is a factor of ~ 20 too small to explain the H_0 tension, and thus decisively ruled out [39,40]. This leaves a host of many proposed partial explanations [41–206], but none of them offer a fully satisfactory solution when all other data and parameters are taken into account [207–209]. The models can have a dark energy (DE) explanation or not:

(Y) A DE component with an equation of state $w \neq -1$, i.e. allowing for deviation from the cosmological constant Λ, both constant or dynamical with redshift [2,73–79]. These models usually solve the H_0 tension within two standard deviations at the price of a phantom-like DE, i.e. $w < -1$, because of the geometrical degeneracy present with the DE equation of state w.

(Y) Early dark energy (EDE) which behaves like Λ at $z \geq 3000$ and decays away as radiation or faster at later times [80,81,210]. Related models include: *(i)* coupling of the EDE scalar to neutrinos [153]; *(ii)* a first-order phase transition in a dark sector before recombination which leads to a short phase of EDE [112]; *(iii)* an EDE model with an Anti-de Sitter phase around recombination [155,156]; *(iv)* an evolving scalar field asymptotically oscillating or with a non-canonical kinetic term [88,98], *(v)* an axion-like particle sourcing dark radiation [107], *(vi)* a scalar field with a potential inspired by ultra-light axions [96,97].

(Y) Interacting dark energy (IDE) models, where dark matter (DM) and DE share interactions other than gravitational [52–64,211–214]. The IDE model solves the tension with R19 within one standard deviation, leading to a preference for a non-zero DE-DM coupling at more than 5 standard deviations [62,63], fixing the DE equation of state to a cosmological constant. However, this category can be further extended into two classes [63]: *(i)* models with $w < -1$ in which energy flows from DE to DM, *(ii)* models with $w > -1$ in which energy flows from DM to DE. Related models can be realized in string theory [163–165].

(Y) Phenomenologically Emergent Dark Energy [173–178], where the H_0 tension with R19 is alleviated within one standard deviation without additional degrees of freedom with respect to ΛCDM.

(N) Extra relativistic degrees of freedom at recombination, parametrized by the number of equivalent light neutrino species $N_{\rm eff}$ [215]. For three active massless neutrino families, $N_{\rm eff}^{\rm SM} \simeq 3.046$ [216–218]. For the well-known degeneracy, we can increase H_0 at the price of additional radiation at recombination. Sterile neutrinos, Goldstone bosons, axions, and neutrino asymmetry are typical ingredients to enhance the value of $N_{\rm eff}$ [138–151,219,220]. Future surveys will detect deviations from $N_{\rm eff}^{\rm SM}$ within $\Delta N_{\rm eff} \lesssim 0.06$ at 95% CL, allowing to probe a vast range of light relic models [221,222].

(N) Modified recombination and reionization histories through heating processes, variation of fundamental constants, or a non-standard CMB temperature-redshift relation [157–162].

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[1] All the bounds are reported at 68% confidence level in the text.

(N) Modified Gravity models [166] in which gravity changes with redshift, such that the H_0 estimate from CMB can have larger values [167–172,223–226].

(N) Decaying dark matter [179–188] or interacting neutrinos [45,86,197].

Standard Sirens – In the next decade an important role will be played by standard sirens (GWSS) [227–231], the gravitational-wave (GW) analog of astronomical standard candles. In fact, the observations of the merger of the binary neutron-star system GW170817 [232] provided $H_0 = 70^{+12}_{-8}$ km/s/Mpc. While this constraint is rather weak, it does not require a distance ladder and, unlike the CMB measurement of H_0, it is largely independent of the ΛCDM assumption. At least 25 additional observations of GWSS [233] are needed to discriminate between Planck and R19. An uncertainty of $1-2\%$ in H_0 is expected in the early(mid)-2020s [229], from the analysis of GW events with electromagnetic counterparts. Finally, complementary dark GWSS, as the GW190814 in [234], are expected to provide a $1-4\%$ constraint on H_0 using the second generation of detector networks [235,236].

Looking into the future – Solving the H_0 tension is very much an ongoing enterprise. The resolution of this conundrum will likely require a coordinated effort from the side of theory and interpretation (providing crucial tests of the exotic cosmologies), and data analysis and observation (expected to improve methods and disentangle systematics). This agenda will flourish in the next decade with future CMB experiments such as Simon Observatory and CMB-S4. Combined with large galaxy surveys such as Euclid and LSST, are expected to reach an uncertainty of $\sim 0.15\%$ in H_0. By shedding new light on the H_0 tension, the next generation of experiments will sharply test the currently favored ΛCDM cosmological model.

Declaration of Competing Interest

The authors declare no conflict of interest.

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