



<b>Publication Year</b>	2021
<b>Acceptance in OA</b>	2025-03-14T08:18:01Z
<b>Title</b>	Snowmass2021 - Letter of interest cosmology Intertwined II: The hubble constant tension
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<b>Publisher's version (DOI)</b>	10.1016/j.astropartphys.2021.102605
<b>Handle</b>	<a href="http://hdl.handle.net/20.500.12386/36780">http://hdl.handle.net/20.500.12386/36780</a>
<b>Journal</b>	ASTROPARTICLE PHYSICS
<b>Volume</b>	131

# Snowmass2021 - Letter of Interest

## *Cosmology Intertwined II: The Hubble Constant Tension*

**Thematic Areas:** (check all that apply /■)

- (CF1) Dark Matter: Particle Like
- (CF2) Dark Matter: Wavelike
- (CF3) Dark Matter: Cosmic Probes
- (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
- (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
- (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
- (CF7) Cosmic Probes of Fundamental Physics
- (Other) [*Please specify frontier/topical group*]

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**Abstract:** The current cosmological probes have provided a fantastic confirmation of the standard  $\Lambda$  Cold Dark Matter cosmological model, that 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 portion 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  $4.4\sigma$  tension between the Planck estimate of the Hubble constant  $H_0$  and the SHOES collaboration measurements. After showing the  $H_0$  evaluations made from different teams using different methods and geometric calibrations, we will list a few interesting new physics models that could solve this tension and discuss how the next decade experiments will be crucial.

**State-of-the-art** – The 2018 legacy release from the Planck satellite<sup>1</sup> of the Cosmic Microwave Background (CMB) anisotropies, has provided a fantastic confirmation of the standard  $\Lambda$  Cold Dark Matter ( $\Lambda$ CDM) 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. While some proportion 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  $\Lambda$ CDM model, and the direct local distance ladder measurements. In particular, the Planck collaboration<sup>2</sup> finds  $H_0 = (67.27 \pm 0.60)$  km/s/Mpc<sup>1</sup>. This constraint is in tension at about  $4.4\sigma$  with the 2019 SH0ES collaboration (R19<sup>3</sup>) 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, preferring smaller values, we have the early universe estimates of  $H_0$ , as obtained by Planck or by ACT+WMAP<sup>5</sup> ( $H_0 = (67.6 \pm 1.1)$  km/s/Mpc), and their combination with Baryon Acoustic Oscillation (BAO) data<sup>6–8</sup>, the Y1 measurements of the Dark Energy Survey<sup>9–11</sup>, supernovae from the Pantheon catalog<sup>12</sup>, and a prior on the baryon density derived from measurements of primordial deuterium<sup>13</sup> assuming standard Big Bang Nucleosynthesis (BBN). A reanalysis of the BOSS full-shape data<sup>14;15</sup>, as well as BAO+BBN<sup>16</sup> from BOSS and eBOSS provides  $H_0 = (67.35 \pm 0.97)$ , while SPTpol<sup>17</sup> finds  $H_0 = (71.3 \pm 2.1)$  km/s/Mpc. In contrast, standard distance ladder and time delay distances agree on a low- $z$  high- $H_0$  value, as the SH0ES estimate<sup>18</sup>  $H_0 = (73.5 \pm 1.4)$  km/s/Mpc, and the H0LiCOW<sup>19</sup> inferred value  $H_0 = (73.3^{+1.8}_{-1.8})$  km/s/Mpc, based on strong gravitational lensing effects on quasar systems. However, the strong lensing TDCOSMO+SLACS<sup>20</sup> sample prefers  $H_0 = 67.4^{+4.1}_{-3.2}$  km/s/Mpc. Then, we have the reanalysis of the Cepheid data by using Bayesian hyper-parameters<sup>21</sup>, the local determination of  $H_0$ <sup>22</sup> considering the cosmographic expansion of the luminosity distance, the independent determination of  $H_0$  based on the Tip of the Red Giant Branch<sup>23–25</sup>, and that obtained by using the Surface Brightness Fluctuations method<sup>4;26</sup>, or the Cosmic Chronometers<sup>27–30</sup>. Finally, a larger value for  $H_0$  is preferred by MIRAS<sup>31</sup> (variable red giant stars), by STRIDES<sup>32</sup>, using the Infrared<sup>33</sup> or Baryonic Tully–Fisher relation<sup>34</sup>, or by Standardized Type II supernovae<sup>35</sup>. There is no single type of systematic measurement error in Cepheids which could solve the  $H_0$  crisis, as speculated in<sup>36</sup> (e.g., it would not work for Cepheids calibrated in NGC 4258), and in any case it could not explain the final result from the Maser Cosmology Project<sup>37</sup>, completely independent from these considerations, that finds  $H_0 = (73.9 \pm 3.0)$  km/s/Mpc. If the late universe estimates are averaged in different combinations, these  $H_0$  values disagree between  $4.5\sigma$  and  $6.3\sigma$  with those from Planck<sup>38</sup>.

**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  $\sim 20$  too small to explain the  $H_0$  tension, and thus decisively ruled out<sup>39;40</sup>. This leaves a host of many proposed partial explanations<sup>41–206</sup>, but none of them offer a fully satisfactory solution when all other data and parameters are taken into account<sup>207–209</sup>. The models can have a **dark energy (DE)** explanation or **not**:

- A DE component with an equation of state  $w \neq -1$ , i.e. allowing for deviation from the cosmolog-

<sup>1</sup>All the bounds are reported at 68% confidence level in the text.

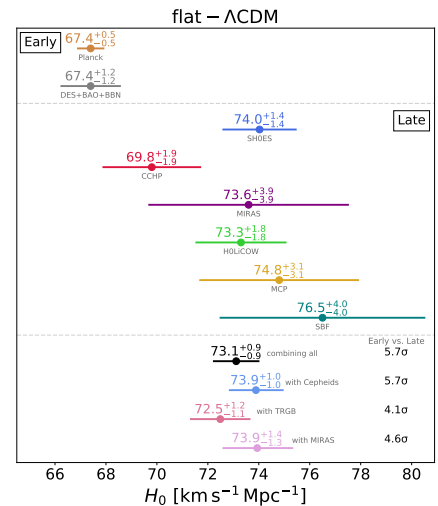


Figure 1: 68% CL constraint on  $H_0$  from different cosmological probes (from Ref. 4).

ical constant  $\Lambda$ , both constant or dynamical with redshift<sup>2;73–79</sup>. 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  $w$ .

- Early dark energy (EDE) which behaves like  $\Lambda$  at  $z \geq 3000$  and decays away as radiation or faster at later times<sup>80;81;210</sup>. Related models include: (i) coupling of the EDE scalar to neutrinos<sup>153</sup>; (ii) a first-order phase transition in a dark sector before recombination which leads to a short phase of EDE<sup>112</sup>; (iii) an EDE model with an Anti-de Sitter phase around recombination<sup>155;156</sup>; (iv) an evolving scalar field asymptotically oscillating or with a non-canonical kinetic term<sup>88;98</sup>, (v) an axion-like particle sourcing dark radiation<sup>107</sup>, (vi) a scalar field with a potential inspired by ultra-light axions<sup>96;97</sup>.
- Interacting dark energy (IDE) models, where dark matter (DM) and DE share interactions other than gravitational<sup>52–64;211–214</sup>. 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<sup>62;63</sup>, fixing the DE equation of state to a cosmological constant. However, this category can be further extended into two classes<sup>63</sup>: (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<sup>163–165</sup>.
- Phenomenologically Emergent Dark Energy<sup>173–178</sup>, where the  $H_0$  tension with R19 is alleviated within one standard deviation without additional degrees of freedom with respect to  $\Lambda$ CDM.
- Extra relativistic degrees of freedom at recombination, parametrized by the number of equivalent light neutrino species  $N_{\text{eff}}$ <sup>215</sup>. For three active massless neutrino families,  $N_{\text{eff}}^{\text{SM}} \simeq 3.046$ <sup>216–218</sup>. 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 examples to enhance the value of  $N_{\text{eff}}$ <sup>138–151;219;220</sup>. Future surveys will detect deviations from  $N_{\text{eff}}^{\text{SM}}$  within  $\Delta N_{\text{eff}} \lesssim 0.06$  at 95% CL, allowing to probe a vast range of light relic models<sup>221;222</sup>.
- Modified recombination and reionization histories through heating processes, variation of fundamental constants, or a non-standard CMB temperature-redshift relation<sup>157–162</sup>.
- Modified Gravity models<sup>166</sup> in which gravity changes with redshift, such that the  $H_0$  estimate from CMB can have larger values<sup>167–172;223–226</sup>.
- Decaying dark matter<sup>179–188</sup> or interacting neutrinos<sup>45;86;197</sup>.

Theoretical efforts to find a dynamic model describing the data have been placed side by side to kinematic models, as the cosmography, where the current expansion is a function of the cosmic time<sup>227–229</sup>.

**Standard Sirens** – In the next decade an important role will be played by standard sirens (GWSS)<sup>230–234</sup>, the gravitational-wave (GW) analog of astronomical standard candles. In fact, the observations of the merger of the binary neutron-star system GW170817<sup>235</sup> provided  $H_0 = 70_{-8}^{+12}$  km/s/Mpc. While this constraint is significantly relaxed, it does not require any form of cosmic ‘distance ladder’ and it is model-independent. It can be important in an extended parameter space<sup>236</sup> in which CMB data are unable to strongly constrain  $H_0$ . At least 25 additional observations of GWSS<sup>237</sup> are needed to discriminate between Planck and R19. An uncertainty of 1 – 2% in  $H_0$  is expected in the early(mid)-2020s<sup>232</sup>, from the analysis of GW events with electromagnetic counterparts. Finally, complementary dark GWSS, as the GW190814 in<sup>238</sup>, are expected to provide a 1 – 4% constraint on  $H_0$  using the second generation of the detector networks<sup>239;240</sup>.

**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, as the Simons Observatory or CMB-S4, that combined with gigantic cosmic surveys, as Euclid and LSST, are expected to reach an uncertainty of  $\sim 0.15\%$  in the  $H_0$  estimate. In summary, the next decade will test the  $\Lambda$ CDM model and build the next-generation experiments that will usher in a new era of cosmology.

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