Tensions between the early and late Universe

A Kavli Institute for Theoretical Physics workshop in July 2019 directed attention to the Hubble constant discrepancy. New results showed that it does not appear to depend on the use of any one method, team or source. Proposed solutions focused on the pre-recombination era.

Early a century of cosmological research has led us to a standard model of cosmology, the ΛCDM, with its six free parameters and several ansätze. This model is dominated by dark components (energy and matter) with still uncertain physics. With some simplifying assumptions about the uncertain bits, the version of the model calibrated on physics prior to recombination (63% dark matter, 15% photons, 10% neutrinos and 12% atoms) is used to predict the physical size of density fluctuations in the plasma — that is, how far sound, or any perturbation in the photon–baryon fluid, could have travelled from the beginning of the Universe to recombination — the sound horizon and its overtones, as well as the primordial baryon density. By comparing the fluctuation spectrum predicted by the model to the angular spectrum observed in the cosmic microwave background (CMB), the six free parameters are set and the ansätze are tested. An alternative to the use of the CMB for setting the sound horizon may be derived by relating measurements of the primordial deuterium abundance to the predicted baryon density. The evolving form of the model (68% dark energy, 27% dark matter and 5% atoms) is then used to predict the expansion history of the Universe from redshift \( z = 1,000 \) to \( z = 0 \). Uncalibrated high-redshift type-Ia supernovae (SNe) and baryon acoustic oscillations (BAOs) provide ‘guard rails’ between \( z \approx 2 \) and 0; they do not tell us if we are on the ‘right road’ but they make sure we do not miss the curves in the model’s road (for instance, the cosmic acceleration must be consistent with \( w = -1 \), where the equation of state parameter \( w \) is model-dependent and \( w = -1 \) corresponds to a cosmological constant) along the way. The model calibrated on early-Universe observations predicts the present-day value of several cosmological parameters, some of which can be empirically measured locally (for \( z < 1 \)) with little or no model dependence. In particular, the model calibrated with data from the Planck mission predicts the Hubble constant, today’s expansion rate, to a remarkable 1% precision, \( 67.4 \pm 0.5 \) km s\(^{-1}\) Mpc\(^{-1}\). Is this whole story right?

The simplest test of this paradigm, from end to end, is to compare the absolute scale provided through the application of early-Universe physics (for example, the physical size of the sound horizon used to interpret the CMB and BAOs) to the absolute scale measured by the Hubble constant in the local, late-time Universe. Because the Universe has only one true scale, and in light of the uncertain physics of the dark sector, comparing the two calibrated at opposite ends of the Universe’s history is natural and potentially insightful.

To determine whether a measurement is truly derived from the ‘early’ or ‘late’ Universe it is necessary to trace back its chain of calibration — a useful check is to determine whether or not it depends on, for example, the number of neutrinos assumed in the standard model.) During 15–17 July 2019, 108 attendees of the workshop ‘Tensions between the Early and the Late Universe’ gathered at the Kavli Institute for Theoretical Physics (KITP) to consider growing tensions between the early-Universe predictions and the late-Universe measurements and how they might be explained. More details about the workshop, including online presentations, are available here: https://www.kitp.ucsb.edu/activities/enervac-c19.

The early Universe

The early Universe probes were discussed at length. The two key questions were:

1. What kind of cross-checks can be used to identify unknown systematic errors that may affect the predictions for \( H_0 \)?
2. Is there any hint of tension in early-Universe data that may perhaps reveal systematic errors or shortcomings of the standard six-parameter model?

Several talks addressed the first question. In addition to the well-known small difference between the inference of \( H_0 \) from low- and high-angular-resolution Planck and Wilkinson Microwave Anisotropy Probe data, all of the early-Universe data seem to be consistently predicting a low value of \( H_0 \). The Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT) are in agreement with Planck, and any CMB data used to calibrate the sound horizon and subsequently the BAOs leads to a low \( H_0 \) of \( \sim 67–68.5 \) km s\(^{-1}\) Mpc\(^{-1}\), even without Planck. A completely independent and statistically consistent value of \( H_0 \) can be obtained by using light-element abundances to calibrate the sound horizon, BAOs and other lower-redshift probes.

As far as the second question is concerned, some curiosities among high-redshift probes at the level of \( \sim 2 \sigma \) were identified. The most compelling ones appear to be the departure from unity of the nuisance parameter \( A_{\text{ten}} \) which is used to match CMB anisotropies (temperature fluctuations around \( z \approx 1,000 \)) and CMB-lensing data (from the deflection of CMB photons by gravitational masses, such as clumps of dark matter). If confirmed, this departure from unity represents evidence that something is not well understood in the relationship between CMB anisotropies and the growth of structure, and thus could perhaps hint at new physics. The other \( 2 \sigma \) curiosities that were discussed were: (1) the tension between the two-dimensional constraints in the \( S_8, \Omega_m \) plane inferred from the CMB and those inferred by cosmic shear data, where \( S_8 = \sigma_8 \sqrt{\Omega_m}/0.3 \), with \( \sigma_8 \) the present-day linear theory root-mean-square amplitude of the matter fluctuation spectrum averaged in spheres of radius \( 8 \) h\(^{-1}\) Mpc, and \( \Omega_m \) is the present-day matter density in units of the critical density; (2) the tension between the cosmological parameters inferred from the BAO signal in galaxies at \( z < 1 \) and those of the Ly-\( \alpha \) line of hydrogen at higher redshifts; and (3) drifts of the model parameters with the CMB fluctuation scale used to determine the model. The statistical errors of these methods are expected to shrink in the next few years, and will reveal whether the tension is a statistical fluke of the kind that one may expect when considering of order dozens of true and nuisance parameters, or whether it is indicative of some yet-to-be discovered systematic or new physics. Nevertheless, many wondered if a solution to the late- versus early-Universe discrepancy may be more
Two independent predictions based on early-literature and presented or discussed at the meeting. Fig. 1 | Compilation of Hubble constant predictions and measurements taken from the recent literature and presented or discussed at the meeting. Two independent predictions based on early-Universe data\(^{10,9}\) are shown in the top left (additional results, utilizing other CMB experiments, have been presented with similar findings). DES, Dark Energy Survey; BBN, Big Bang nucleosynthesis. The middle section shows late-Universe measurements and the bottom section shows combinations of the late-Universe measurements and lists the tension with the early-Universe predictions, using Gaussian approximations to the posterior distribution functions of each method. We stress that the three variants of the local distance ladder method — Cepheids (SH0ES), TRGB (CCHP) and Miras — share some SN Ia calibrators and cannot be considered statistically independent. Likewise, the SBF method is calibrated based on Cepheids or TRGB and so it cannot be considered fully independent of the local distance ladder method. Thus, the ‘combining all’ value should be considered for illustration only, since its derivation neglects covariance between the data. The three combinations of Cepheids, TRGB and Miras are based on statistically independent datasets and therefore the significance of their discrepancy with the early-Universe prediction is accurate — even though, of course, separating the probes results in a loss of precision. In summary, the difference is more than 4\(\sigma\), less than 6\(\sigma\) and is robust to the exclusion of any one method, team or source. The software that was used to make the figure is publicly available here: https://github.com/vbonvin/. Credit: courtesy of Vivien Bonvin and Martin Millon.

credible if it also ameliorated one or more of these lesser tensions.

The late Universe
A summary talk from the SH0ES (Supernovae \(H_0\) for the Equation of State) team presented the status of a fifteen-year effort to build a consistently measured distance ladder using geometric distances to calibrate Cepheids, followed by 19 hosts to both type-Ia supernovae (SNe Ia) and Cepheids, followed by hundreds of SNe Ia in the Hubble flow. Highlights included the use of near-infrared Hubble Space Telescope (HST) photometry for all Cepheid data and five independent sources of geometric distances including three types of Milky Way parallaxes, Large Magellanic Cloud (LMC) detached eclipsing binaries and the masers in NGC 4258. The result was \(H_0 = 74.0 \pm 1.4 \text{ km s}^{-1} \text{ Mpc}^{-1}\) (ref. 1). The H0LiCOW (\(H_0\) Lenses in COSMOGRAIL’s Wellspring) team described new results from strong lensing time delays between multiple images of background quasars. Six such systems have now been measured leading to \(H_0 = 73.3^{+1.2}_{-1.1} \text{ km s}^{-1} \text{ Mpc}^{-1}\) (ref. 2). Robustness was demonstrated by the use of double- and quadruple-lensed quasars, long and short time delays, imaging from HST or Keck adaptive optics\(^{1}\) and different mass-modelling software packages\(^{1}\). Because each lens model must be constructed individually for each system, the lensing analysis was carried out blindly to avoid experimenter bias in the model construction and is completely independent of the local distance ladder method. The SH0ES and H0LiCOW results were known only shortly before the meeting and together provide a 5.3\(\sigma\) difference from the early-Universe value.

New results from the Megamaser Cosmology Project (MCP)\(^{5}\) were also presented, which uses very long baseline interferometry (VLBI) observations of water masers in circumnuclear orbits around supermassive black holes to measure geometric distances. A much-improved measurement of the distance to the nearby NGC 4258 (similar distance but full error reduced from 2.6% to 1.5%) was presented. In addition, a longer timespan of VLBI measurements and improved analysis of the distances to four other masers in the Hubble flow — UGC 3789, CGCG 074-064, NGC 5765b and NGC 6264 — were presented and together yielded \(H_0 = 74.8 \pm 3.1 \text{ km s}^{-1} \text{ Mpc}^{-1}\). This determination does not require a distance ladder.

The Carnegie–Chicago Hubble Program (CCHP) collaboration, which used tip of the red giant branch (TRGB) measurements in the LMC to calibrate 18 SNe Ia (across 14 hosts) in lieu of Cepheids, was attributed to a different method for connecting the distance ladder\(^{6}\), had new results as well. The pros and cons of TRGB and Cepheids were extensively discussed across three talks. TRGB was recognized as a valuable independent tool, well-understood from first principles and observable on simple backgrounds. The CCHP result of \(H_0 = 69.8 \pm 1.9 \text{ km s}^{-1} \text{ Mpc}^{-1}\), based on a new calibration of the TRGB \(I\)-band luminosity of \(M_I = -4.05\) in the LMC, was presented\(^{6}\). The source of the reduction in this value compared to the prior TRGB result of \(M_I = -3.97\) from ref. 7 was extensively discussed and identified as traceable to a 0.08 mag increase in the estimate of the LMC TRGB \(I\)-band luminosity, of which 0.06 ± 0.02 mag was attributed to a different method for estimating TRGB extinction in the LMC, which is 3\(\sigma\) greater than the values given by the Optical Gravitational Lensing Experiment (OGLE) reddening maps (the TRGB colour method yields \(A_I = 0.16 \pm 0.02\), whereas the reddening
maps used in ref. 7 gave $A_z = 0.10$).
Yuan et al. presented a poster showing that blending in ground-based observations of TRGB in the Magellanic Clouds, particularly for the Magellanic Cloud Photometric Survey (MCPS), can bias the calibration of TRGB. The corresponding paper, which was subsequently submitted to The Astrophysical Journal, showed that the use of the MCPS data impacted the measurement of GMC extinction and its fix would change $H_0$ as determined from TRGB to $72.4 \pm 1.9 \mathrm{km \, s}^{-1} \mathrm{Mpc}^{-1}$.

New infrared surface brightness fluctuation (SBF) measurement results on two new sets of HST imaging data of early-type hosts from the massive sample and a sample of SNe Ia hosts were presented, raising the total sample size from $N = 15$ to $N = 54$ galaxies out to 100 Mpc (ref. 9).

The initially reported tension between the uncalibrated BAO distances at $z_{\text{eff}} = 2.3$ via the Ly-$\alpha$ forest and the one measured at $z = 0.75$ has decreased to below 2$\sigma$ with the latest data10,11, and is therefore not significant enough to be demonstrated in practice. The precision of the MCP is also limited by sample size and although the number of masers at the correct distance is finite, there appears to be room for further improvements in precision. Likewise, there is room for further improvement in the precision of the SBF method, even though it is unclear whether either method can ultimately reach sub-per-cent precision.

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A (still blind) time delay for the multiply imaged SN Refsdal was presented en route to a determination of $H_0$ to an anticipated statistical precision of $\sim 7\%$ (ref. 12). There was also much excitement about the prospects of gravitational waves and standard sirens to contribute to the conversation. Even though the current sample and corresponding precision is not competitive with other methods13, based on the forecasts shown, the method will soon be another powerful and independent tool at our disposal.

Completely independent of the distance determination methods is the cosmic chronometers method discussed at this meeting. In contrast to everything that we have summarized so far, the method has the advantage of measuring age (as opposed to distance) and thus it is perhaps the only one that can directly answer the existential question “how old is the Universe?” with minimal cosmological assumptions. Ref. 10 reports an age of the Universe $t_\text{UC} = 13.2 \pm 0.44 \text{ Gyr}$ from 22 globular clusters14. In an $\Lambda$CDM model, the ages of these objects implies $H_0 = 71.0 \pm 2.8 \mathrm{km \, s}^{-1} \mathrm{Mpc}^{-1}$. On the other hand, relative ages of suitably selected old passively evolving elliptical galaxies (see, for example, refs. 10,13 and references therein) yield an estimate of $H(z)$ with the most statistical power at $z = 0.43, H(z = 0.43) = 91.8 \pm 5.3 \mathrm{km \, s}^{-1} \mathrm{Mpc}^{-1}$. The next step in these measurements should involve a better characterization of model uncertainties, perhaps through a survey of the model space — such efforts are underway. As the statistical precision of the method progresses, comparison with other probes and internal consistency checks will give the systematic noise floor related to our ability to determine the ages of stellar populations.

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The tension in the $\sigma$ parameter (or equivalently $S_8$) as inferred by the Planck mission and measured by weak gravitational lensing surveys, is below
the 3σ level, although the exact significance depends on the lensing dataset chosen and the assumptions made in the analysis. While investigation is important, this 'tension' is not as dramatic as that in the $H_0$ parameter. Two considerations are called for, however. (1) This may be related to the Planck internal consistency test offered by the parameter $A_{\text{mic}}$. This parametrizes the gravitational lensing amplitude in CMB data and of course depends very closely on the amplitude of perturbations (that is, $\sigma_8$). When inferred from the smoothing of the high-$\ell$ angular temperature power spectrum peaks, its value is $\gtrsim 2\sigma$ away from that inferred from the CMB lensing signal. (2) Any new physics introduced to explain the $H_0$ discrepancy should not make the $\sigma_8$ tension significantly worse.

**Ideas to reconcile the two**

This leaves us with the question: how can the $H_0$ discrepancy be solved? The most sceptical approach is to invoke systematic errors in the data. However, given the size of the discrepancy and the number of independent routes finding it, a single systematic error cannot be the explanation. It should also be said that to follow this approach too strongly is to lose the ability to make fresh discoveries. A more formal way to invoking multiple, unknown systematic errors follows the BACCUS (Bayesian Conservative Constraints and Unknown Systematics) approach. This was not presented at the meeting, but since then one of us (L.V.) has experimented with this approach using only shifts to combine the late-Universe $H_0$ determinations, marginalizing over (unknown) possible systematic shifts for each measurement. The shifts are assumed to be drawn from the same prior distribution: a Gaussian with width $\sigma$, which gets marginalized with a uniform hyperprior $-10 < \sigma < 10$ km s$^{-1}$ Mpc$^{-1}$. As expected, the BACCUS combination widens the tails of the resulting posterior distribution compared to the conventional (Gaussian) combination, but does not single out any local-Universe measure as atypically shifted compared to the others. The combination of all independent measurements (SH0ES, H0LiCOW, SBF, TRGB and globular cluster ages) yields a grand average of $H_0 = 72.7 \pm 1.2$ (2.9) km s$^{-1}$ Mps$^{-1}$ at a confidence level (CL) of 68(95%), nominally still 4σ from the early-Universe value, but the widening of the posterior tails implies that this is 2.6(2.8)σ or a CL of 99.1(99.5)% away from a $H_0$ value of 68(67.4) km s$^{-1}$ Mpc$^{-1}$. However, it should be noted that the conventional high

$H_0$ and not via the density parameters themselves. Few examples to achieve this were presented. One possibility is a scalar field acting as an early dark energy component. The dynamics of the field are constructed so that the energy density of this early dark energy component is relevant only over a narrow epoch in the expansion history of the Universe: after matter–radiation equality but before recombination. Such a model yields a higher value for the CMB-inferred $H_0$, greatly alleviating the tension and, notably, preserving a good fit to all relevant observations (CMB, BAO, SNe and so on). The epoch immediately preceding recombination is favoured because it is the time when the bulk of the sound horizon accrues. However, more data, especially CMB polarization measurements or very low multipole moment $\ell$ measurements at greater precision, are needed to test other predictions of the model and to determine whether an additional early component (and the extra parameters that this model introduces) is actually favoured over a $\Lambda$CDM model.

Another family of possibilities was presented that instead extends the radiation sector of the early Universe physics. A solution invoking extra free streaming neutrinos is penalized by a worse fit to high-$\ell$ CMB angular power spectra — where the specific gravitational coupling of free streaming neutrinos leaves its signature. However, this behaviour may be offset by allowing neutrino self-interactions so that neutrinos do not free-stream but rather behave like tightly coupled radiation. A model that allows neutrino self-interactions and additional neutrino species, if compared to the standard dataset combination of CMB and BAO data, produces an allowed region in parameter space that is characterized by a high $H_0 \approx 72$ km s$^{-1}$ Mpc$^{-1}$ and an extra effective neutrino species ($N_{\nu} \approx 4$), but very strong coupling. Such a solution predicts specific signatures in the matter power spectrum that may be sought experimentally. However, it is difficult to achieve the strong interaction that this solution finds from a particle model-building perspective, while still evading other constraints on neutrino physics. Also, in this case future data may either find signatures of the other predictions of this model or rule it out.

Similarly, models with an extra scalar field that provides energy injection localized around matter–radiation equality also improves the fit to late-time $H_0$ determinations (still being consistent with BAO data) at little or even no cost to the fit to CMB data. While none of these models may appear natural, similar or even greater
tuning may already be required to explain the two other accepted episodes of dark energy, raising the question, is twice okay but three too many?

As precision increases, one may wonder if cracks may be appearing in the ΛCDM model. It may be possible to find models that are radically different from ΛCDM but that still provide good fits to the data — and fix the ‘cracks’. These are likely to have their own specific signatures, be it in other cosmological observables or particle-physics experiments, which will be crucial to make further progress. To summarize, the final speaker (Francis-Yan Cyr-Racine) concluded: “We have yet to identify a complete solution that is palatable to both cosmologists and particle physicists, but have important clues about what a successful model would look like.”

Conclusions
During the last talk, prior to hearing about possible theoretical solutions to the tension, a draft version of Fig. 1 was shown to the audience and the audience was asked to vote on their perception of the significance of the tension on the following scale: $2\sigma =$ curiosity; $3\sigma =$ tension; $4\sigma =$ discrepancy or problem; $5\sigma =$ crisis. This clearly tongue-in-cheek experiment was carried out to evaluate what kind of Bayesian “tension” and “crisis” and with no support for something less. Therefore, it appears that the issue is serious, not only taking the uncertainties at face value, but also in the eyes of the community as represented by the KITP workshop participants.

It was also clear that a great deal of progress has been made recently using new methods to tackle previously difficult measurements. Little can be learned by simply invoking a chequered past without critical study of the developments in these new measurements.

Finally, going forward, the resolution to the ‘problem’ will likely require a coordinated effort from the sides of theory, interpretation, data analysis and observations. To streamline the interaction between these different communities and promote the transparent transfer of information, participants advocated adopting the following best practices:

- Model assumptions: one should always make clear where the cosmology dependence enters in a measurement or interpretation.
- Reproducibility: one should release data and non-trivial software publicly (for example, like the CLASS and CAMB codes for cosmology — whenever possible it would be useful to provide any new tools as public plug-ins for these codes). Requests for data from published results should be fulfilled promptly.
- Data transparency: one should release more low-level data products where the least (cosmological) assumptions have been made.
- Blinding: blind analysis should be done whenever possible but especially if analysis choices must be made. Alternatively, the impact of choices should be clearly presented in variants of the primary analysis.
- When combining CMB data and late-time data for models that address the Hubble problem, one should also present results from CMB data alone. In a successful model, the addition of the low-redshift data should not degrade the fit to the CMB data.
- Data challenges: whenever possible, organize mock data challenges designed to blindly test the accuracy and precision of the methods and hypotheses adopted by the community.

Licia Verde*1, Tommaso Treu2 and Adam G. Riess3,4

1ICREA and ICCUB, University of Barcelona, Barcelona, Spain. 2University of California, Los Angeles, Los Angeles, CA, USA. 3Johns Hopkins University, Baltimore, MD, USA. 4Space Telescope Science Institute, Baltimore, MD, USA.

*e-mail: liciaverde@gmail.com

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