How to Resolve the Hubble Tension

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Abstract

The 'Hubble tension' is a $\sim 5\sigma$ discrepancy – in the ΛCDM context – between the H_0 value derived from early- and late-universe observations. I discuss guidelines to resolving this long-standing mystery, arguing that our best shot is through modification of the pre-recombination physics, right around matter-radiation equality. I introduce a toy model dubbed 'Early Dark Energy' (EDE) in which a frozen scalar-field contributing a fraction $f_{\rm EDE}(z_c) \sim 10\%$ of the energy density of the universe around $z_c \simeq 3500$ and diluting as or faster than radiation afterwards can accomodate CMB, Baryon Acoustic Oscillation (BAO), growth function (FS), Supernova Ia (SNIa) and the latest SH0ES measurement of H_0. I discuss some potential challenges that this model is facing in light of the latest weak lensing surveys, but argue that the level of tension between weak lensing surveys and Planck within ΛCDM does not allow to make robust conclusions about the status of EDE. Future CMB and LSS measurements will provide a definitive test to this scenario.

1 Introduction

In recent years, a strong mismatch between the prediction of the current expansion rate of the universe (known as Hubble constant) in the Λ cold dark matter (ΛCDM) model calibrated onto Planck CMB data, and its direct measurement using low redshift data (i.e., the classical distance ladder) [1, 2] has emerged. Originally, this "Hubble tension" was limited to the determination of the Hubble constant using type Ia supernovae by the SH0ES collaboration, whose latest *determination* is $H_0 = 74.03 \pm 1.42$ km/s/Mpc [3], while the *prediction* from the ΛCDM model inferred from Planck CMB data is $H_0 = 67.4 \pm 0.5$ km/s/Mpc [4]. Tremendous progress have been made in measuring H_0 with alternative methods, such that nowadays there exist five other methods[1] to measure H_0 with few percent accuracy. Remarkably, various averages over these measurements (excluding correlated data) leads to H_0 values that ranges from 72.8 ± 1.1 and 74.3 ± 1.0, in 4.5 to 6.3σ discrepancy with the prediction from ΛCDM [1, 2]. A number of possible systematic effects affecting some of these measurements have been discussed (see e.g. [11, 12, 13, 14, 15]), yet the existence of several vastly different methods – none of which giving a value of H_0 smaller than ~ 70 km/s/Mpc – have triggered a wide range of theoretical activities to resolve the Hubble tension (see in particular [16] for a recent review). This tension between different measurements of the Hubble constant could point to a major failure of the ΛCDM scenario, and hence to a new cosmological paradigm: that would be a new and unexpected breakthrough in cosmology.

[1] These include strong-lens time delays of quasars [5], Tip of the red giant branch from the 'CCHP' [6, 7] (and re-evaluation by the SH0ES team [8]), SNIa calibrated on Miras (an alternative to Cepheids) [9], water masers (sources of microwave stimulated emission) in four galaxies at great distances [10] and Surface Brightness Fluctuations of distant galaxies [1].

There have been many attempts to find extensions of the standard cosmological model, ΛCDM, which bring these estimates into agreement. However, theoretical explanations for the Hubble tension are not easy to come by. It has been found that the most promising solution lies in modifying physics in the pre-recombination era ($10000 > z > 1000$) [16]. At first sight, given the precision measurements of the CMB from Planck, this might appear to be even more constraining than the late-time probes of the expansion rate. Excitingly, there are a few early-time resolutions which do not spoil the fit to current CMB temperature measurements [17, 18, 19, 20, 21], sometimes even *improving it* over ΛCDM.

In this talk, I show that a constant Early Dark Energy (EDE) component contributing a fraction $f_{\rm EDE}(z_c) \sim 10\%$ of the energy density of the universe around $z_c \simeq 3500$ and diluting as or faster than radiation afterwards can resolve the Hubble tension. After introducing generic guidelines to resolving this tension, I introduce the EDE model and show through a MCMC analysis that incorporates the latest CMB, BAO, SN1a and SH0ES data that this model can resolve the tension. I then discuss some potential challenges that this model is facing in light of the latest weak lensing surveys, before drawing my conclusions.

2 Guidelines to resolving the Hubble tension

CMB data do not provide an absolute measurement of H_0. Rather, the value of H_0 is inferred within a given cosmological model from a measurement of the angular scale of sound horizon $\theta_s \equiv r_s(z_*)/d_A(z_*)$, where $r_s(z_*)$ is the sound horizon at recombination and $d_A(z_*)$ is the angular diameter distance to recombination. The great challenge lies in that θ_s is nowadays measured at sub-percent-level accuracy with the latest CMB data [4]. This suggests two main ways of resolving the Hubble tension through new physics – based on the requirement to keep the key angular scale θ_s fixed – usually called *late*- and *early*-universe solutions.

- The first way boils down to changing the redshift evolution of the angular diameter distance in the late-universe, i.e. $z < z_*$, so as to force a higher H_0, *without* changing $d_A(z_*)$ nor $r_s(z_*)$. To that end, a large number of proposed scenarios invoked modification of the late-time dynamics of dark matter and/or dark energy. This includes (but is not limited to) models of dynamical dark energy [22], decaying dark matter [23] and interacting dark matter-dark energy [24]. Late-time observables, especially BAO and luminosity-distance to SNIa, place severe limitations on modifications to the late-time ($0 \leq z \leq 2$) expansion history [25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36].

- The second way amounts in reducing $r_s(z_*)$ in the early-universe, which automatically requires to reduce $d_A(z_*)$ by the same amount to keep θ_s fixed, that is most naturally done by increasing the value of H_0. This can be done through additional relativistic species from various sources [32, **?**], exotic recombination [37, 38, 21], a time-varying Newton constant [39, 40] or the presence of dark energy at early times [41, 17, 42, 43, 44, 19]. However, most of these models are constrained by the details of the CMB acoustic peaks and in particular by the fact that the additional energy density lead to a different angular diffusion damping scale [16].

- A final, more subtle, way of resolving the H_0 tension comes from the fact that the position of the peaks receives an additional phase-shift from various effects, in particular from the gravitational pulling of CMB photons out of the potential wells by free-streaming neutrinos [45, 46, 47]. Suppressing this phase-shift can change the value of θ_s deduced from a CMB power spectra analysis and in turn significantly increase H_0.

3 Early Dark Energy resolution to the Hubble tension

The possible presence of a dark energy component before last-scattering has been studied for more than a decade [48, 49]. These alternative cosmological realizations have little to do with that under study here, as they typically assume tracking equation of state at early times. The idea of an anomalous era of expansion triggered by a frozen scalar field as a resolution to the Hubble tension was introduced in Ref. [41], where a background-only computation was shown to alleviate the Hubble tension. However, it is the work of Ref. [17] that showed through a fluid approximation the key role played by perturbations in the scalar field to allow for a resolution of the Hubble tension. Since this work, the treatment of the EDE component has been improved [42, 43, 44], and augmented to deal with alternative potentials and better motivated underlying fundamental models [50, 42, 44, 51, 52, 53, 40, 19, 54]. In particular, it has been shown that Planck data not only provide a detection of the background dynamics of the EDE component, but also severely restricts the dynamics of perturbations [44, 43]. As such, Planck data allows for pinning down directly properties of the EDE, making the choice of model crucial. They favor either non-canonical kinetic term whereby the equation of state w is approximately equal to the effective sound speed c_s^2 [44], or potential that flattens close to the initial field value [43].

In this talk, I study the modified axion potential introduced in Refs. [55, 41, 56, 17, 43],

$$V_n(\Theta) = m^2 f^2 [1 - \cos(\Theta)]^n, \tag{1}$$

where m represent the axion mass, f the decay constant and $\Theta \equiv \phi/f$ is a re-normalized field variable, so that $-\pi \le \Theta \le \pi$. It is assumed that the field always starts in slow-roll the background dynamics and without loss of generality $0 \le \Theta_i \le \pi$.

This potential is a phenomenological generalization of the well motivated axion-like potential (which can be recovered by setting $n = 1$) that arise generically in string theory [57, 58, 59, 60, 60]. Such a potential may be generated by higher-order instanton corrections [61], but taken at face values would suffer from a strong fine-tuning issues necessary to the cancelling of the lowest orders instantons. Therefore, it should not be interpreted beyond a phenomenological description. Note that similar forms of potential, with power law minima and flattened "wings" have been used in the context of inflationary physics, as well as dark energy (see, e.g., Refs. [62, 63, 64]). Still, this form was devised to allow for flexibility in the background dynamics after the field becomes dynamical, and it also provides an excellent fit to both Planck and SH0ES data. It corresponds to the EDE scenario that leads to the best combined χ^2 of the cosmological data-sets under study (although the better theoretically motivated model studied in Ref. [19, 54] seems to perform equally well).

Refer to Refs. [56, 43] for all necessary details about the model. The key features can be summarized as follows: at early times the scalar field is frozen due to Hubble friction, until the Hubble rate drops below its mass value; the field then starts moving in the potential, and eventually oscillating around the minimum, at which point the energy density dilutes at a rate dictated by the asymptotic equation of state $w(n) = (n-1)/(n+1)$ (e.g., Refs. [65, 66, 56]).

One can trade three out of the four model parameters $\{m, f, n, \Theta_i\}$ for phenomenological parameters: the first two of them describing the fractional energy density $f_{\rm EDE}(z_c)$ at the critical redshift z_c where the field becomes dynamical and the asymptotic equation of states after the field becomes dynamical $w(n) = (n-1)/(n+1)$, respectively; the last degree of freedom lies in the dynamics of linear perturbations, whose phenomenology is captured by the effective sound speed c_s^2. However, within the EDE scalar field scenario under study, such freedom is intrinsically encoded in the choice of the initial field value[2] Θ_i, once the other phenomenological parameters have been fixed.

To perform the analyses, the modified version of the Einstein-Boltzmann code CLASS [67, 68] presented in Ref. [43] is used. The code is publicly available at `https://github.com/PoulinV/AxiCLASS` (the latest version, used for this study, can be found in the "merge2.9" branch).

[2]In practice, it is the curvature of the potential, $\partial^2 V(\Theta)/\partial^2\Theta$, close to the initial field value Θ_i that dictates the last of degree of freedom in the perturbation dynamics [56, 43].

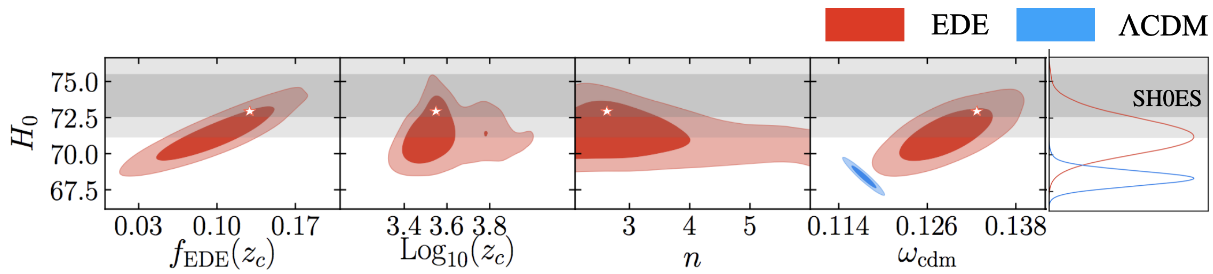

Figure 1: 2D posterior distribution of H_0 vs $\{f_{\rm EDE}(z_c), \log_{10}(z_c), n_{\rm EDE}, \omega_{\rm cdm}\}$ reconstructed from the analysis of Planck+BAO+SN1a+SH0ES data.

The results of a Markov-chain Monte Carlo (MCMC) taken from Ref. [43] and using the public code MontePython-v3[3] [69, 70], interfaced with the modified version of CLASS, is shown in Fig. 1. The analysis is performed with a Metropolis-Hasting algorithm, assuming flat priors on

$$\{\omega_b, \omega_{\rm cdm}, \theta_s, A_s, n_s, \tau_{\rm reio}, \log_{10}(z_c), f_{\rm EDE}(z_c), \Theta_i, n\}.$$

A shooting method to map a choice of $\{\log_{10}(z_c), f_{\rm EDE}\}$ to the theory parameters $\{m, f\}$ was used[43]. We adopt the Planck collaboration convention and model free-streaming neutrinos as two massless species and one massive with $M_\nu = 0.06$ eV [71]. The data set includes Planck 2015 high-ℓ and low-ℓ TT,TE,EE and lensing likelihood [72]; the latest SH0ES measurement of the present-day Hubble rate $H_0 = 74.03 \pm 1.42$ km/s/Mpc [3]; the isotropic BAO measurements from 6dFGS at $z = 0.106$ [25] and from the MGS galaxy sample of SDSS at $z = 0.15$ [26]; the anisotropic BAO and the growth function $f\sigma_8(z)$ measurements from the CMASS and LOWZ galaxy samples of BOSS DR12 at $z = 0.38$, 0.51, and 0.61 [31]; the Pantheon[4] supernovae dataset [73], which includes measurements of the luminosity distances of 1048 SNe Ia in the redshift range $0.01 < z < 2.3$. Chains are considered to be converged using the Gelman-Rubin [74] criterion $R - 1 < 0.1$.

In the EDE cosmology, it is found that $H_0 = 71.5 \pm 1.2$ km/s/Mpc, with $f_{\rm EDE} = 0.1 \pm 0.03$ and $\log_{10}(z_c) = 3.56^{+0.05}_{-0.1}$. For comparison, the same analysis within ΛCDM yields $H_0 = 68.4 \pm 0.5$. The $\Delta\chi^2_{\rm min} = \chi^2_{\rm min}(\Lambda{\rm CDM}) - \chi^2_{\rm min}({\rm EDE}) = -20.33$ strongly favors EDE over ΛCDM (even when accounting for the extra degrees of freedom e.g. through a bayesian model comparison [17]). However, it is worth noting that Planck itself only mildly favors EDE, with a $\Delta\chi^2_{\rm min} \simeq= -6$ and most of the $\chi^2_{\rm min}$ difference is driven by SH0ES. The inability of Planck to distinguish EDE from ΛCDM is particularly visible in the CMB power spectra residual plot shown in fig. 2, where the two models are basically indistinguishable given current error bars. However, as shown in Fig. 3, an experiment like CMB-S4 [75] would be able to unambiguously detect the presence of EDE, regardless of the inclusion of SH0ES measurement of H_0 in the analysis.

As illustrated in the left panel of fig. 4, Planck polarization data also puts a strong constraint on the initial field value Θ_i. This is because the shape of the potential close to the initial field value, which flatten for a cosine (see the right panel of fig. 4) at high field value, plays a crucial role in the dynamics of EDE perturbations. One can thus conclude that, the very accurate measurement of CMB polarization data restricts not only the background dynamics but also that of perturbations. This was also shown in a model independent way in Ref. [44] and for a different EDE model in Ref. [19].

Finally, one can see in Fig. 1, that the EDE cosmology has $\omega_{\rm cdm} = 0.1290 \pm 0.0045$, a significant increase from the ΛCDM value $\omega_{\rm cdm} = 0.1175 \pm 0.0012$. This is due to the effect of the EDE perturbations on the gravitational potential wells, which is compensated for by a higher $\omega_{\rm cdm}$. This has interesting (and potentially dramatic) consequences for the growth of structure- the predicted matter power spectrum shows somewhat more power than in ΛCDM, as attested by the higher value of

[3] https://github.com/brinckmann/montepython_public
[4] https://github.com/dscolnic/Pantheon

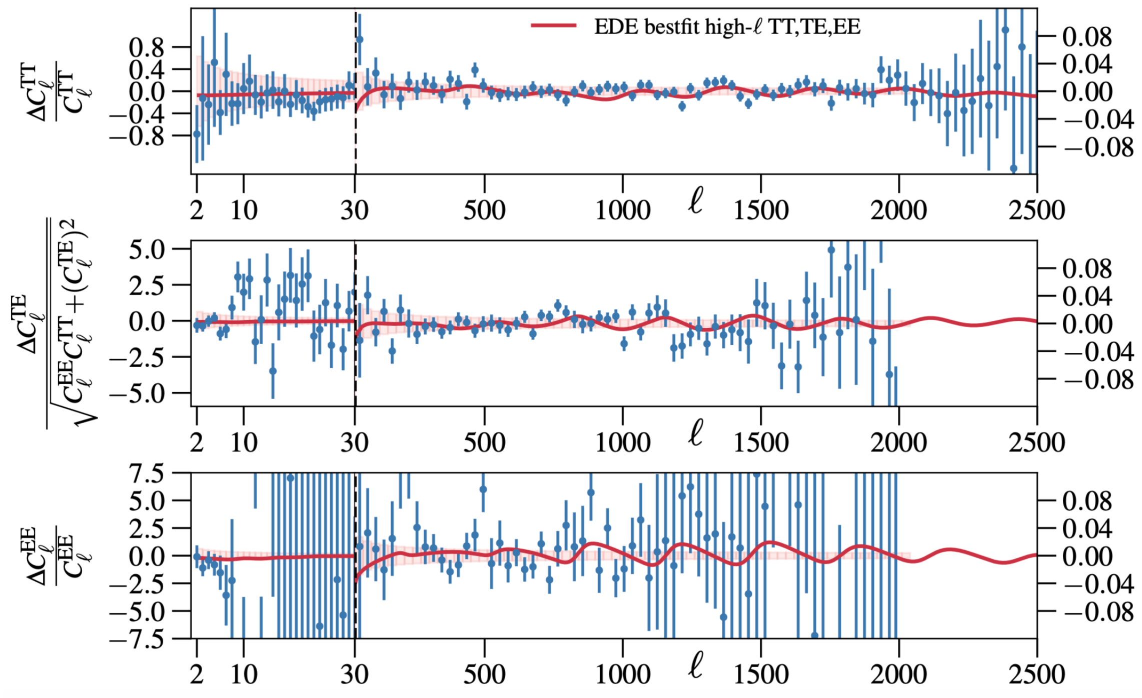

Figure 2: Residual of the CMB power spectra between ΛCDM and the bestfit EDE cosmology. The small differences, indistinguishable by Planck, can be measured by future experiment such as CMB-S4 [75].

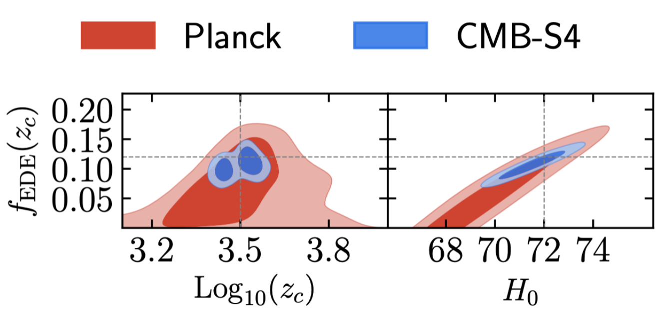

Figure 3: Posterior distributions of $\{\log(10)(z_c), f_{\rm EDE}(z_c)\}$ and $H_0, f_{\rm EDE}(z_c)\}$ reconstructed from a fit to simulated Planck data and CMB-S4. The fiducial model has $\{H_0 = 72$ km/s/Mpc, $f_{\rm EDE}(zc) = 0.115, \log_{10}(z_c) = 3.53.\}$

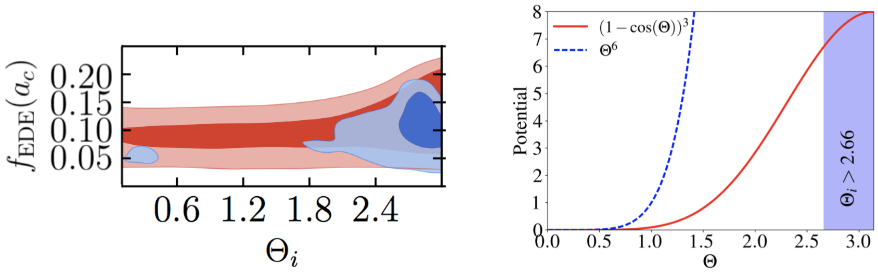

Figure 4: Left panel− 2D posterior distribution of $f_{\rm EDE}$ vs Θ_i reconstructed from Planck TT data (red) or TT+TE+EE data (blue), in combination with BAO, SN1a and SH0ES. Right panel − the potential as a function of the field value. The shape of the potential close to the initial field value plays a crucial role in the success of the solution, translating into a strong constraints on Θ_i.

$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5} = 0.840 \pm 0.015$ – where σ_8 measures the amplitude of fluctuations in a sphere of radius 8 Mpc/h – than in ΛCDM, $S_8 = 0.820 \pm 0.012$. This opens up the possibility of constraining EDE with weak lensing data measuring S_8 to high accuracy, as done for instance in Ref. [76]. Indeed, a number of cosmic shear surveys (CFHTLenS [77], KiDS/Viking [78], DES [79], HSC [80]) have provided measurements of S_8 which are systematically lower than the ΛCDM prediction. The significance of this "S_8 tension" oscillates between 2 and 4σ depending on the experiments, such that the discrepancy cannot easily be attributed to a statistical fluke. In Ref. [76], it was for instance shown that the joint KiDS+Viking+DES data can constrain $f_{\rm EDE} < 0.057$ at 95% C.L.. However, the apparent constraining power on EDE is entirely driven by a $\sim 3\sigma$ statistical inconsistency that is already present between joint KiDS+Viking+DES data [81] and the ΛCDM model inferred from *Planck* data, which makes it hard to properly interpret constraints to beyond-ΛCDM models when using these data.

4 Conclusions

I have presented an early-dark energy model able to resolve the $4-6\sigma$ discrepancy between the prediction of Hubble constant in the Λ cold dark matter (ΛCDM) model calibrated onto Planck CMB data, and its direct measurement using a variety of low redshift data. In this model, it is found that a maximal fraction of early dark energy $f_{\rm EDE} = 0.1 \pm 0.03$ at the redshift $\log_{10}(z_c) = 3.56^{+0.05}_{-0.1}$ allows to reach $H_0 = 71.5 \pm 1.2$ km/s/Mpc. Taken at face value, this model suffers from a coincidence problem as the fluid needs to become dynamical around a key era of the universe. This is not without reminding the standard coincidence problem of DE that such models were originally introduced to resolve. However, this coincidence might be the sign of a very specific dynamics to be uncovered; in fact there exist models in which the field becomes dynamical precisely around matter-radiation equality, either because of a phase-transition triggered by some other process (e.g. the neutrino mass becoming of the order of the neutrino bath temperature [51] or the dynamics of a trigger field [19]) or because of a non-minimal coupling to the Ricci curvature [82]. An important follow-up to these studies will be to see whether the new ACT data [83], compatible with Planck (although see Ref. [84]), support – or restrict – the EDE resolution to the Hubble tension. Looking forward, future CMB experiment (such as Simons Observatory [71] and CMB-S4 [75]) and LSS data (from Euclid [85], LSST [86], JWST and DESI [87]) will be crucial in testing prediction of the EDE cosmology (and its potential extensions) [43, 88] and firmly confirm – or exclude – the presence of EDE.

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