H_0 *Tension and the Cosmological Constant*

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Outline

- A review of the ΛCDM
- Cosmological data sets
- Status of ΛCDM and cosmological tensions
- Our idea: analyze the low-redshift data and then match it to Planck at higher redshift
- Features of our reconstructed dark energy sector
- Summary and Outlook

The ΛCDM

- Various sets of cosmological data has led to the Standard Model of Cosmology, ΛCDM

- According to the SMC our universe has started through an inflationary phase. Inflation has given us an (almost) isotropic and homogeneous cosmic background.

- In SMC the universe at large scales, redshift $z > 0.1$ or so, is described by a flat FLRW cosmology.

- Inflation is then followed by a reheating era.

- After reheating our universe has entered a phase of thermal expansion during which entropy of the universe remains (almost) constant.

- Thermal expansion phase is driven by the matter inside the universe and at cosmological scales it is enough to consider it as a multi-component homogeneous-isotropic perfect fluid.

- The cosmic fluid, according to ΛCDM consists of three main components:

  Radiation, Pressureless Matter, Cosmological Constant.

- Radiation has Equation of State (EoS) $P = \rho/3$.

- Any fluid the mass of its "constituent particles" is much less than its temperature contributes to radiation.

- Energy density of radiation $\rho_{\mathrm{Rad.}} \sim a(t)^{-4}$, where $a(t)$ is scale factor of the universe.

- Pressureless Matter (or Matter in short) has EoS $P \simeq 0$.

- Any non-relativistic matter contributes to pressureless matter. Today the dark matter and baryonic matter are the main contributors to it.

- Energy density of matter falls off as $\rho_{\text{Mat.}} \sim a(t)^{-3}$.

- Cosmological Constant Λ has EoS $P = -\rho = -\Lambda$. Λ does not dilute away with the Hubble expansion of the universe.

- After the reheating we start with a "radiation dominated" phase, which is then followed by a "matter dominated" expansion and now (since the redshift $z \sim 1$), we are in an "accelerated expansion" phase.

- Accelerated expansion of the universe is driven by dark energy.

- ΛCDM is a fairly simple cosmological model which in its simplest form involves six and or nine parameters to be specified from observations

- These parameters include ratios of energy densities of different components of the cosmic fluid, data needed to translate cosmic observations to distances or redshifts and number of relativistic species.

- These parameters are fixed by fitting the model into the cosmological data. In fact the data should be used to reconstruct the cosmological parameters appearing in ΛCDM

- According to ΛCDM dark energy is a *positive* cosmological constant ($\Lambda > 0$).

Cosmological data sets and tensions

- ΛCDM is of course based on analysis of cosmological data which mainly consist of CMB data (given by Planck satellite mission) and some other data sets coming from "late-time cosmology".

- The CMB data is coming from $z \sim 1000$, the early universe and we have low-redshift data sets for $z \lesssim 3$ region.

- CMB Data set: CMB temperature and polarization anisotropy spectra measured by Planck 2015 & 2018.

- The CMB data is very precise, is whole-sky and has a high statistics. It has hence a special weight among cosmological data.

▶ Low redshift cosmological data sets

- Strong & Weak Lensing experiments like H0LiCow & Megamaser Cosmology Project measure acoustic radius r_d, using time delay measurements for $z < 1$. [e.g. see
  S. S. Birrer et al, arXiv:1809.01274],
  M. J. Reid et al., Astrophys. J., 767, 154 (2017);
  C. Kuo et al., Astrophys. J., 767, 155 (2013);
  F. Gao et al., Astrophys. J., 817, 128 (2016).]

- Supernovae (SNe) luminosity distance data,

  Photometry by Hubble Space Telescope of Milky Way Cepheid Standards for Measuring Cosmic Distances, Riess et al. Measures Hubble today H_0.

- Lyman α-forest of Baryon Acoustic Oscillations (BAO), by Baryon Oscillation Spectroscopic Survey (BOSS),

  the BAO angular diameter distance data from the clustering of galaxies (gBAO) or quasar clustering (eBOSS), these measure $H_0 r_d$, for $z < 2.5 - 3$. [e.g. see Arman Shafieloo et al, arXiv:1804.04320 and references therein].

- The low-redshift data can be used to measure H_0 independently of the ΛCDM

- Riess et al have been doing so with an increasing precision:

$$H_0 = 73.5 \pm 1.6 \ km/s/Mpc.$$

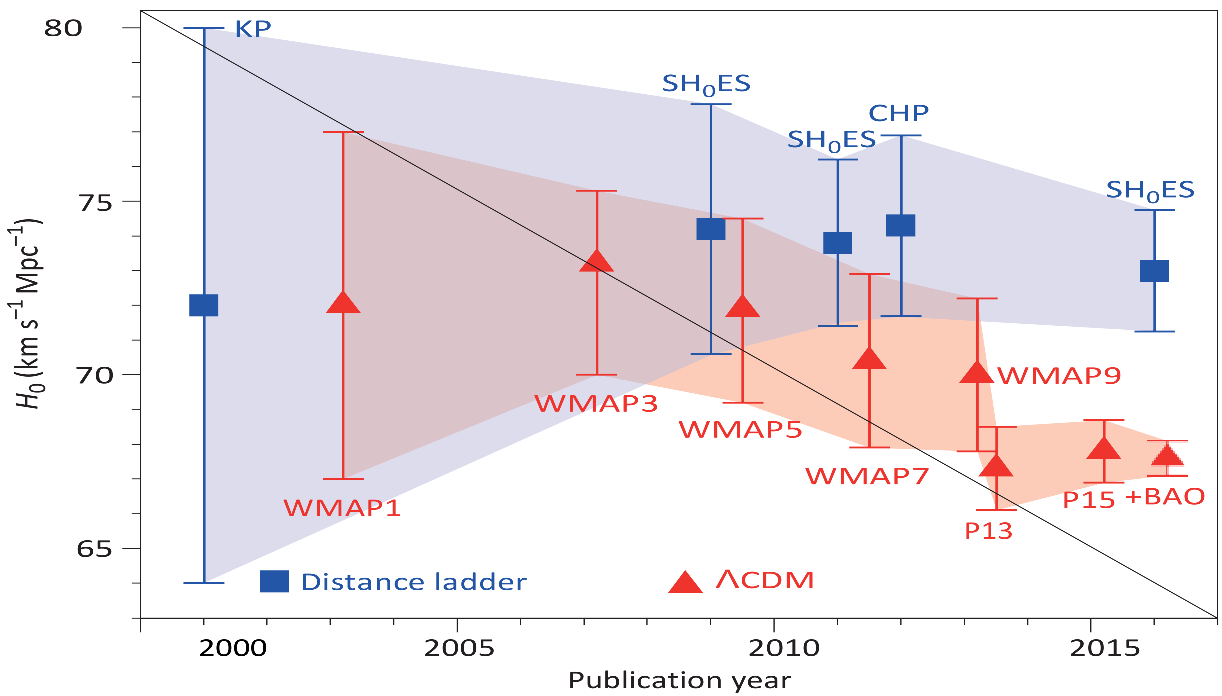
- Best fits of Planck+ BAO data, however, yield

$$H_0 = 66.93 \pm 0.62 \ km/s/Mpc.$$

- The tension between the two has reached 3.5σ significance level and needs to be tackled.

- There are other yet less significant tensions, e.g. σ_8 from Ly-α, which prefers a smaller value of the matter density fraction $\Omega_{\text{Mat.}}$ compared to the CMB, Planck data. (Roughly, $\Omega_{\text{Mat.}} h^2$ is what is fixed or taken as prior.)

Evolution of measured value of H_0 in different experiments in years. Source: W. Freedman, Nature Astronomy 1 (2017).



- Our idea is that the H_0 tension is caused by an incorrect way of analyzing the data

- The main idea/observation is that

  - Accelerated expansion of the universe and hence dark energy is a late-time cosmology feature $z \lesssim 1$.

  - CMB data are carrying information from early universe.

- Information of dark energy should be read from low-redshift data which does not imply the "dark energy=CC" paradigm.

- CMB data should be used for redshifts higher than BAO scales $z \gtrsim 2.5$.

- In reading dark energy behavior we should not simply add up Planck + Low-redshift data.

- Our idea is that we replace ΛCDM with XCDM; essentially the same model but with replacing the CC with arbitrary, potentially multi-component cosmic fluid.

- Then, we reconstruct dark energy density and pressure (and its EoS).

- Reconstruction of dark energy EoS has been considered in the last decade or so, and $\omega_{\mathrm{DE}}(z) \neq -1$ seems to be a viable outcome of data.

- In particular, many groups have recently focused only on low-redshift data and tried to reconstruct $H(z)$.

- Some recent papers:
Sahni-Shafieloo-Starobinsky, Astrophys.J. 793 (2014) no.2, L40,
V. Bonvin, Mon.Not.Roy.Astron.Soc. 465 (2017),
Gong-bo Zhao et al., Nat.Astron., 1, 627 (2017),
Y. Wang, L. Pogosian, G. B. Zhao and A. Zucca, arXiv:1807.03772,
S. Capozziello, Ruchika and A. A. Sen, arXiv:1806.03943,
J. Evslin, A. A. Sen, Ruchika, Phys. Rev. D, 97, 103511 (2018),
A. Gomez-Valent and L. Amendola, JCAP, 1804, 051 (2018),
Joan Sola, J. d. C. Perez and A. Gomez-Valent,arXiv:1703.08218 & arXiv:1811.03505
V. Poulin, T. Smith, T. Karwal, M. Kamionkowski,arXiv:1811.04083.

- To reconstruct $H(z)$ we need to make a choice of fitting function.

- Using $H(z)$ we can then reconstruct dark energy density and pressure, if we have basic information from dark matter sector.

Our fitting strategy

- We implement the above ideas to reconstruct $H(z)$ and from there we read dark energy information. Explicitly, we use
  - H_0 of Riess et al as an **input**;
  - three data points from $H(z)$ of Planck, for $z > z_{match}$ as an **input**;
  - we reconstruct $H(z)$ for $z < z_{match}$ using the low redshift data.
- In our analysis we take z_{match} as an input and take it to be 5, 6 or 7.
- Three Planck data points are taken to be $z_{match} - 1,\ z_{match}, z_{match} + 1$.
- Our goal is not to specify the precise value of z_{match}. More comments is to come.

- We use 2nd order **Pade approximation** (instead of CPL):

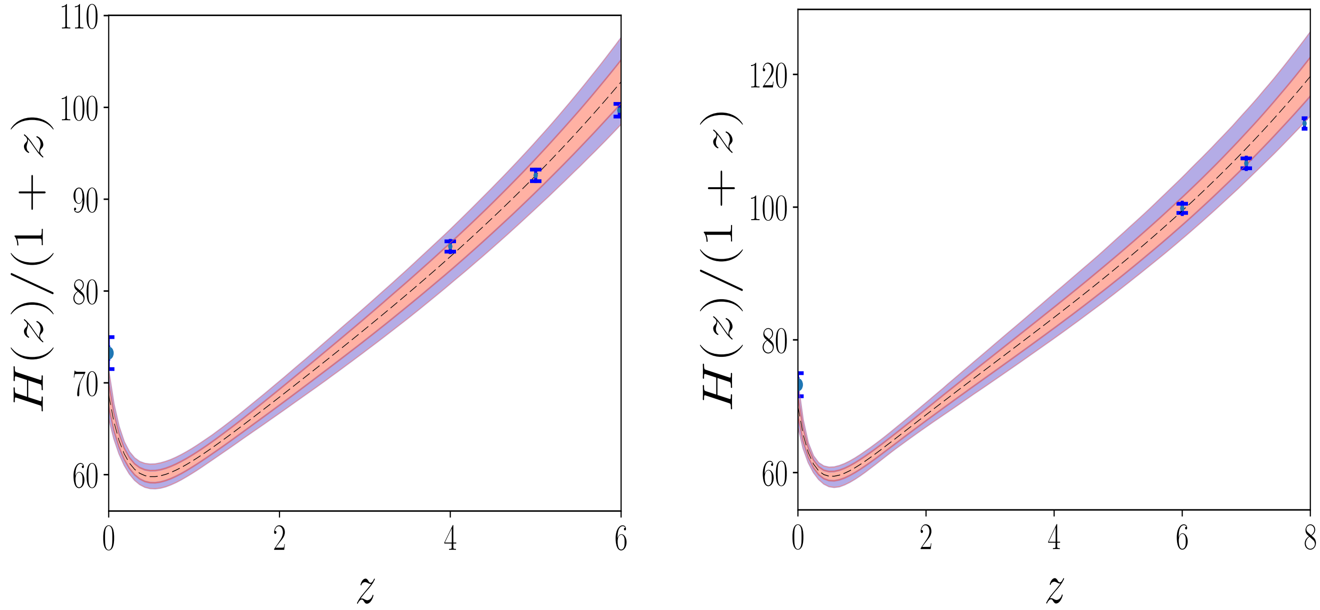
$$H(z) = H_0 \frac{1 + P_1 z + P_2 z^2}{1 + Q_1 z + Q_2 z^2}$$

- Pade approximation with four parameters gives a (much) better convergence behavior than Taylor expansion with the same number of parameters as we want to study z up to 5 or 6.

- The Pade parameters are easily seen to be related to derivatives of the Hubble parameter, like (de)acceleration q, jerk j, snap s, lerk l. See e.g. C. Gruber abd O. Luongo,Phys. Rev. D. 89, 103506 (2014), H. Wei, X. P. Yan and Y. N. Zhou,JCAP 1401, 045 (2014). S. Capozziello, Ruchika and A. A. Sen, arXiv:1806.03943.

- Independent parameters for the data analysis are H_0, q_0, j_0, s_0, l_0 and r_d, the sound horizon at drag epoch. Here the subscript "0" means the value at present ($z = 0$).

Reconstructed Hubble parameter $H(z)$ is depicted below.



The left one is based on Planck $H(z)$ data at $z = 4, 5, 6$ and right one is for $z = 6, 7, 8$.

The dashed line is for mean and inner and outer regions are for 68% and 95% confidence regions.

The blue points with error-bar are for H_0 from R16 as well as $H(z)$ at higher redshifts as measured by Planck-2015.

- The deceleration and jerk parameters at $z = 0$ are:

$$z_{match} = 5: \qquad q_0 = -0.83 \pm 0.10, \quad j_0 = 3.93 \pm 0.53$$

$$z_{match} = 7: \qquad q_0 = -0.94 \pm 0.10, \quad j_0 = 4.31 \pm 0.52$$

- Specific feature of ΛCDM is that it has jerk parameter $j = 1$ for all redshifts; any deviation from $j = 1$, confirms a non-ΛCDM behavior.

- $j_0 = 1$ and hence ΛCDM is ruled out with high confidence level.

- This is consistent with previous results by Zhao et al. [Nat.Astron., 1, 627 (2017)] and Wang et al.[arXiv:1807.03772].

- From $H(z)$, we reconstruct the dark energy:

$$3H^2(z) = \rho_{\rm m} + \rho_{\rm DE} = \rho_{\rm m}^{(0)}(1+z)^3 + \rho_{\rm DE}^{(0)} f(z).$$

  we set $8\pi G = 1$ and "DE" stands for any dark which can be multi-component.

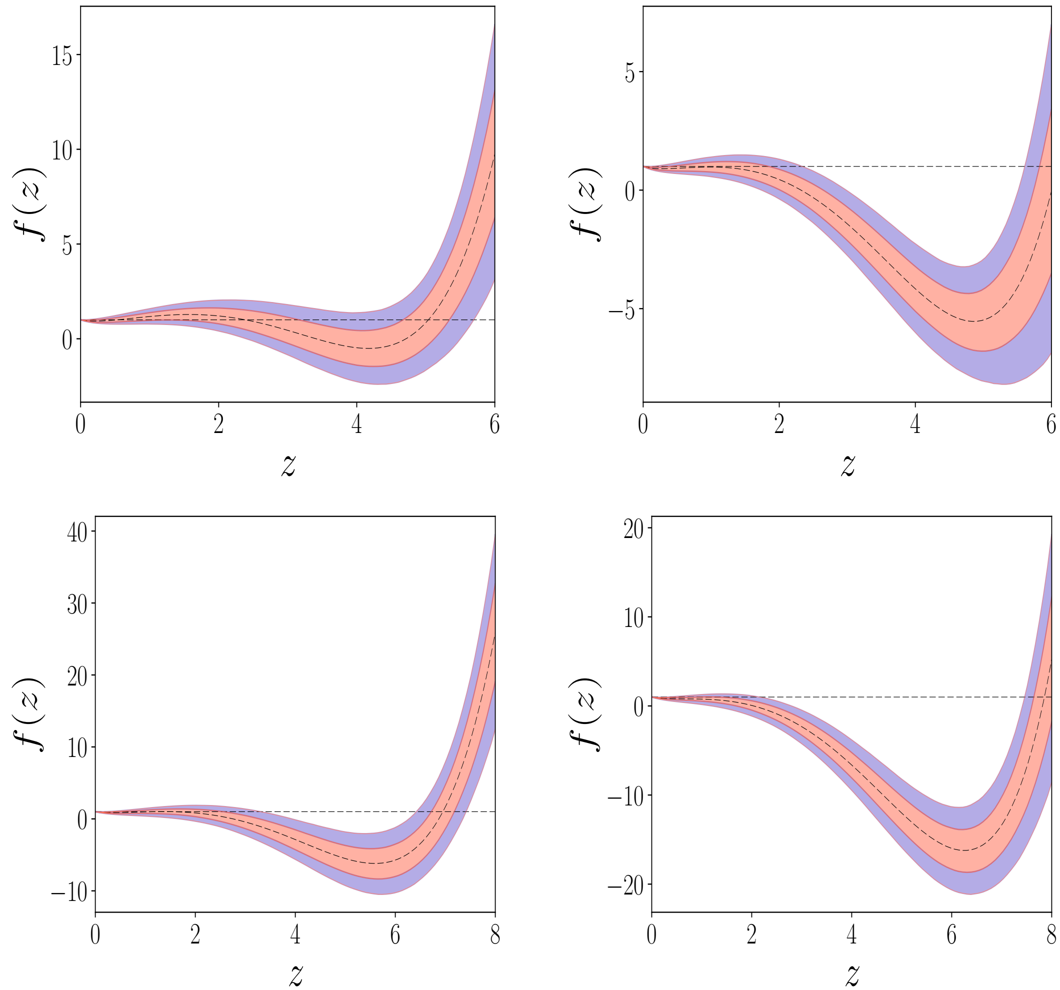
- $f(z)$ is a dimensionless quantity specifies the allowed dark energy evolution.

- Assuming a flat Universe, $\Omega_m + \Omega_{DE} = 1$ and hence

$$\frac{H^2}{H_0^2} = \Omega_m^{(0)}(1+z)^3 + \Omega_{DE}^{(0)} f(z) = \Omega_m^{(0)}(1+z)^3 + (1-\Omega_m^{(0)}) f(z).$$

- $f(z) = 1$ corresponds to cosmological constant.

Reconstructed $f(z)$, for $z_{match} = 5$ (TOP) & $z_{match} = 7$ (BOTTOM).

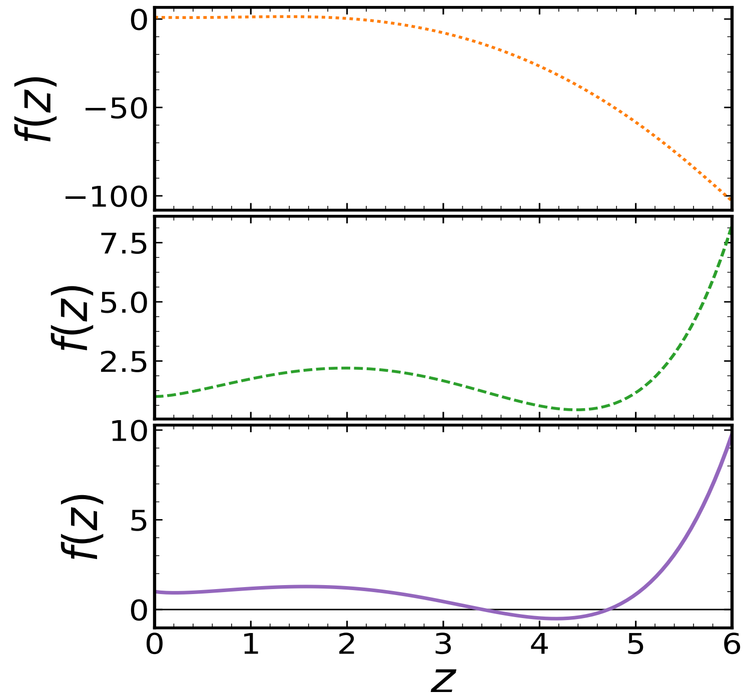


Left ones are for $\Omega_m^{(0)} = 0.3$ and right ones for $\Omega_m^{(0)} = 0.32$.

Generic features of $f(z)$:

- The overall shape for $f(z)$ is the same for different choices of $\Omega_m^{(0)}$ and the z_{match}:
  - It has always a minimum at some $z = z_{min}$, and
  - generically $f(z) < 0$ at this minimum.
- z_{min} and $f_{\mathrm{min}} = f(z_{min})$ depend on the value of $\Omega_m^{(0)}$ and z_{match}.
- For $\Omega_m^{(0)} > 0.29$, there is always a negative minimum for $f(z)$, and
- for $H(z)$ data from the Planck at higher redshift range, the negative minimum for $f(z)$ exists with a greater confidence level.

Reconstructed $f(z)$ for various data sets; mean $f(z)$ is plotted from the MCMC.



Top plot: ONLY low redshift data, without H_0 and Planck.

Middle plot: Low redshift +Planck, without H_0.

Bottom plot: Low redshift + H_0 + Planck for $H(z)$ for higher redshifts.

Planck points for $H(z)$ are for $z_{match} = 5$ and $\Omega_m^{(0)} = 0.3$ is assumed.

Discussions on general results

- $f(z)$ shows "time dependence" of the dark energy density $\rho_{\rm DE}(z)$.

- Tiime derivative of $\rho_{\rm DE}$ vanishes at z_{min}:

$$\dot{\rho}_{DE}(z)\Big|_{z=z_{min}} = 0 \quad \Longrightarrow (\rho_{\rm DE} + P_{\rm DE})_{z=z_{min}} = 0.$$

  At the minimum $\rho_{\rm DE}$ behaves like a cosmological constant.

- If this minimum value is negative, it can be modeled by a *negative cosmological constant* with $\Lambda = 3H_0^2(1 - \Omega_m^{(0)})f_{\rm min}$.

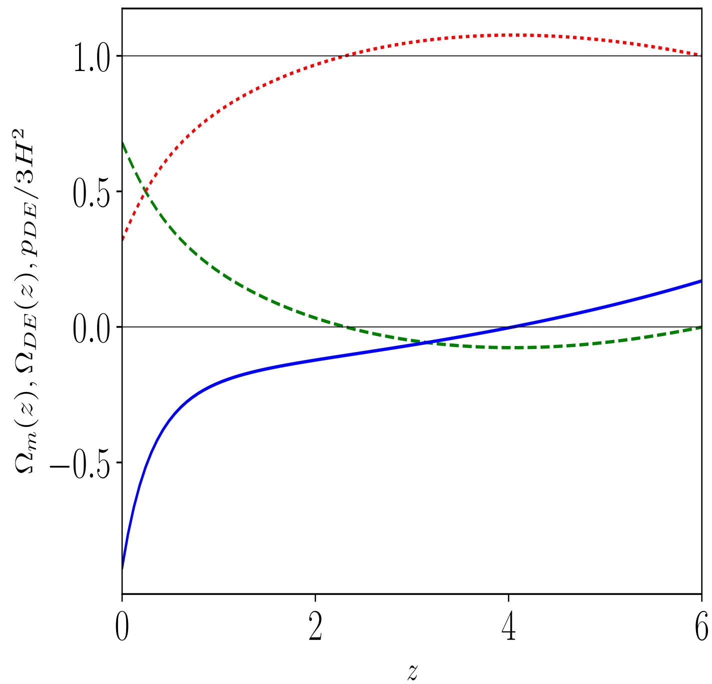
- From $\rho_{DE}(z)$ we can read dark energy pressure:

$$P_{\rm DE} = -\rho_{\rm DE} + \frac{(1+z)^2}{3}\frac{d}{dz}\rho_{\rm DE}$$

  where I used $a(t)/a_0 = 1/(1+z)$.

- Therefore, the dark energy EoS $\omega(z) = P_{\mathrm{DE}}/\rho_{\mathrm{DE}}$,

$$\omega(z) \gtreqless -1 \quad \text{if} \quad \frac{d}{dz}\rho_{\mathrm{DE}} \gtreqless 0$$



Dotted red line: $\Omega_{\mathrm{m}}(z)$, dashed green line $\Omega_{\mathrm{DE}}(z)$ and solid blue line is for $P_{\mathrm{DE}}/(3H^2)$.

This is for Planck $H(z)$ with $z_{match} = 5$ and $\Omega_m^{(0)} = 0.32$.

- Negative ρ_{DE} without any minimum for higher redshifts is an outcome of low redshift data ONLY.

- Inclusion of the Planck's constraints on $H(z)$ for higher redshifts, yields the minimum.

- It was expected that z_{min} should be around $2-3$ due to Lyman-α measurement of BAO.

- One may model ρ_{DE} with a two component dark energy fluid:
  - a NEGATIVE cosmological constant $\Lambda = 3H_0^2(1-\Omega_m^{(0)})f_{min}$
  - A "phantom dark energy field" with $\rho_{\text{DE}}^{Phantom} > 0$.

Concluding Remarks and Outlook

⊛ We reanalyzed low redshift cosmological data to resolve the H_0-tension in favor of Riess et al while keeping ΛCDM as the best fit for Planck data at higher redshifts.

⊛ We reconstructed $H(z)$ and subsequently $\rho_{\text{DE}}(z)$ and found three generic results:

- ρ_{DE} has a minimum;
- at this minimum $\rho_{\text{DE}} < 0$
- for $z < z_{min}$ we have a phantom behavior, while for $z > z_{min}$, $\omega_{\text{DE}} > -1$.

⊛ We proposed to model this by a two-component dark energy fluid: a negative Cosmological Constant and a phantom crossing scalar field.

Robustness of our results:

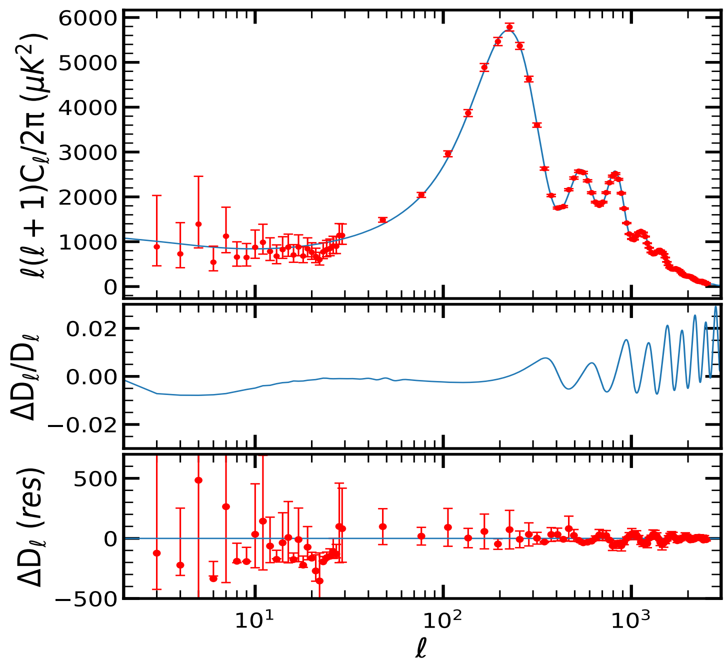
- We have tested different z_{match} and overall behavior of our results remain the same.

- To determine z_{match}, one needs to do a full analysis using all the low redshift data together with Planck Likelihood assuming that for $z \leq z_{match}$, $H(z)$ is given by our Pade parametrization and for $z > z_{match}$, $H(z)$ is given by ΛCDM

Consistency with Planck's measurement of the CMB anisotropy:

- we use CLASS code to compute C_l^{TT} for CMB anisotropy spectra assuming $H(z)$ for $z \leq 6$ is given by best fit of our reconstructed $H(z)$ and for $z > 6$ by Planck best fit ΛCDM

- Note that at $z = 6$, ΛCDM model is well within matter dominated era.



Top plot: the model discussed here together with Planck data and error bars for TT spectra.
Middle plot: the difference in TT spectra for our model and Planck best fit ΛCDM model.
Bottom plot: Residual for our model with the Planck data.

Around $z = 6$, $\Omega_m = 1$ and $\Omega_{DE} = 0$, allowing us to match our reconstructed $H(z)$ with a matter dominated era.

Implications for Structure Formation:

- Ω_m is slightly greater than 1 for a certain redshift range depending on z_{match}.

- Therefore, we expect an enhancement in growth of structures at higher redshifts and the nonlinear regime may start earlier than in ΛCDM model.

- This may result in the presence of more massive galaxies at higher redshifts compared to ΛCDM model, effects on reionization process as well as on lensing.

■ Modeling the $\rho_{\text{DE}}(z)$?!

- Within our data analysis framework, we have a clear indication that cosmological constant cannot be "the dark energy".

- $\rho_{\text{DE}}, P_{\text{DE}}$ cannot be obtained from a minimally coupled scalar field (with any potential);

- quintessence models are hence inconsistent in our setup.

- Taking a CC $\Lambda = \rho_{\text{min}}$ and one may model $\rho = \rho_{\text{DE}} - \rho_{\text{min}}$ within a non-minimally coupled scalar theory with a positive definite potential. This latter should be such that it provides crossing to phantom region ($\rho_{\text{DE}} + P_{\text{DE}} < 0$) for $z < z_{min}$.

- Such models can be constructed, e.g. within Brans-Dicke theory [Wang et al, 2018].

Theoretical implications of our dark energy model:

- Positive cosmological constant which is assumed to drive the current accelerated expansion of the Universe is a theoretical challenge:
  - Getting a consistent and stable vacuum solution with a positive cosmological constant within string theory compactifications has been a daunting task.
  - String theory clearly prefers AdS background to de Sitter, consistent AdS backgrounds are ubiquitous in string theory settings.
  - Formulating quantum field theory on the background of a de Sitter space has its own challenges, from the choice of the vacuum state to non-existence of a well-defined S-matrix (on global de Sitter space).

- Our findings lifts all those questions by simply removing the need for a positive cosmological constant.

Implications for anthropic reasoning.

- In mid 1980's Weinberg argued that the value of cosmological constant, if positive, should not be much bigger than H_0^2.

- A negative value of the cosmological constant, too, is bounded by similar anthropic reasoning [Barrow-Tipler, 1984].

- The negative cosmological constant in our model which is within 1% of the current total energy density of the Universe is certainly consistent with these bounds.

Evidence seems to be indicating that ΛCDM is not compatible with the data and need modifications.

Our reconstructed dark energy density has definite observational signatures in large scale structure formation in the Universe and can be tested with present and future experiments.

Thank You For Your Attention