HITO y RETOS

From “Precision Cosmology” to “Cosmology under revision”

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[CEFCA]

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Once upon a time ... not so long ago (from 1997 up to ~2018), there was, amongst cosmologists, a so-called *Concordance cosmological model* upon which low redshift and high redshift cosmological observations agreed ...
The Cosmic Microwave Background (CMB) provided an image of our universe at its childhood that was consistent with a \textit{flat} LCDM scenario, and which was also consistent with cosmological observations at recent epochs …
The Cosmic Microwave Background (CMB) provided an image of our universe at its childhood that was consistent with a **flat** LCDM scenario, and which was also consistent with cosmological observations at recent epochs ...
Ultimate “End-to-end” test for $\Lambda$CDM, Predict and Measure $H_0$

Standard Model: (Vanilla) $\Lambda$CDM, 6 parameters + ansatz (w, $N_{\text{eff}}$, $\Omega_K$, etc)

- Predict physical size fluctuations, $r_s$, $\Omega_B$
- Measure angular fluctuations (or $\Omega_B$)
- Calibrate $\Lambda$CDM...

Big Bang
Cosmic Microwave Background

Expansion history predicted
("guard rails", BAO, SNe)

Planck Predicted, $H_0=67.4+/-0.5$ km/s/Mpc

Silde from A. Riess (July 2019)
Cosmological "concordance" Model

Kowalski 2008
However, when observations at either side of the history of the universe increased their precision,
However, when observations at either side of the history of the universe increased their precision,
However, when observations at either side of the history of the universe increased their precision, **tensions** (and maybe *more* than tensions) have arisen:
Assess for $\Lambda$CDM, Predict and Measure $H_0$

- 6 parameters + ansatz (w, $N_{\text{eff}}$, $\Omega_K$, etc)

- Detect physical size fluctuations, $r_s$, $\Omega_B$
- Measure angular fluctuations (or $\Omega_B$)
- Calibrate $\Lambda$CDM ...

Big Bang

Cosmic Microwave Background

Expansion history predicted
("guard rails", BAO, SNe)

Planck Predicted, $H_0 = 67.4 \pm 0.5$ km/s/Mpc
The most significant sources of tension are:

- $H_0$ measurements at low and high redshifts:
  
  $(3 - 5 \sigma, \text{tension} \rightarrow \text{problem, crisis?})$

- The amplitude of CMB lensing
- The amplitude of density perturbations at low redshifts ($\sigma_8$)
  
  $(3 \sigma \text{ tension})$

- The non-flat curvature of the universe ($\Omega_k = -0.04$)
  
  $(3 \sigma \text{ tension})$
Measuring the universe expansion rate $H_0$

- Indirectly, using the angle projected by the sound horizon at recombination at $z \sim 1100$ via CMB observations, and at $z \sim 0.5$ via clustering measurements of the Large Scale Structure (LSS)

- Directly, by (1) using standard candles (SNIa), and calibrating their distance with Cepheids in LMC, Detached Eclipsing Binaries (DEB) in LMC, galactic parallaxes, the tip of the Red Giant Branch (TRGB), or (2) gravitational lensing at intermediate redshifts ($z \sim 0.5$)

V. Bonvin, for Verde, Tommaso, & Riess 2019
Measuring the universe expansion rate $H_0$

**Pros:**

- Weak dependence of sound horizon on (well known) cosmological parameters,
- Measurements based upon a model that is relatively *simple* (linear order in perturbation theory) for CMB, mildly-non linear for LSS measurements
- Different probes (CMB and LSS) having very different (potential) systematics yield $H_0$ estimates in excellent agreement

**Cons:**

- They are all *indirect* measurements of the expansion rate that are *model dependent*

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\[ r_s(\eta) = \int_0^\eta d\eta' c_s = \int_0^\eta d\eta' \frac{1}{\sqrt{3(1 + R)}} \]

\[ R = \frac{\rho_b + \rho_b}{\rho_c + \rho_c} \approx \frac{3\rho_b}{4\rho_c} \]
Measuring the universe expansion rate $H_0$

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**Pros:**

- These are, for SNIa and Surface Brightness Fluctuation-based estimates, *direct* measurements of $H_0$ that are **model independent**.
- Lensing measurements, maser-based $H_0$ measurements, and SNIa-based estimates, are all un-correlated, independent measurements of $H_0$.

**Cons:**

- Measurements based on complex, highly non-linear systems (Cepheids, SNIa, clusters of galaxies) **whose calibration are obtained empirically** (more room for systematics).
- Results from the CCHP collaboration on the TRGB significantly off from those of SH0ES: evidence for hidden systematics?
Measuring the universe expansion rate $H_0$

Possible solutions to this puzzle:

- **Systematics in CMB observations**: unlikely, provided different CMB experiments beyond *Planck* (like SPT, ACT) are providing very similar measurements of $H_0$.

- **New physics!**: Emerging Dark Energy (EDE), Interacting Dark Energy, Übergravity, decaying Dark Matter, Rock 'n Roll models (RnR), Vacuum Dynamics, *what not!* – yet to be seen whether they can satisfy, some of them (EDE, RnR) already discarded …

- **Systematics in the direct $H_0$ measurements** …

V. Bonvin, for Verde, Tommaso, & Riess 2019
Measuring the universe expansion rate $H_0$
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Breaking news from last week!!

V. Bonvin, for Verde, Tommaso, & Riess 2019
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But even if we drop cluster lensing ...

V. Bonvin, for Verde, Tommaso, & Riess 2019
Measuring the universe expansion rate $H_0$

But even if we drop cluster lensing ...
Other (weaker) sources of tension ... (at $2 - 3 \sigma$)
CMB photons are deflected in their journey to the observer. This effect can be accessed in two ways:

**(Approach 1)** Looking at non-Gaussianities induced by lensing on the smallest scales, using a 4-point function $<T(n_1)T(n_2)T(n_3)T(n_4)>$

**(Approach 2)** Looking at the 2-point function ($<T(n_1)T(n_2)>$) or angular power spectra $C_i = <a_{l,m}(a_{l,m})^*>$: the impact of lensing-induced ray deflection smears/softens the acousting peaks
CMB 2-point function $<a_{l,m} a_{l,m}^*> = C_l$ (angular power spectrum)

$A_L = 0 \rightarrow 8$

$A_L = 1$ is what our theory predicts …
Problem: The amplitude of lensing inferred from Approach 2 is about 15% higher than for Approach 1, at \(\sim 3\sigma\) level. It's like if lensing was more efficient at smearing CMB acoustic peaks than predicted.

CMB photons are deflected in their journey to the observer. This effect can be accessed in two ways:

(Assumption 1) Looking at non-Gaussiananities induced by lensing on the smallest scales, using a 4-point function \(\langle T(n_1)T(n_2)T(n_3)T(n_4)\rangle\).

(Assumption 2) Looking at the 2-point function \(\langle T(n_1)T(n_2)\rangle\) or angular power spectra \(C_l = \langle a_{l,m}(a_{l,m})^* \rangle\): the impact of lensing-induced ray deflection smears/softens the acoustic peaks.
Problem: The amplitude of lensing inferred from Approach 2 is about 15% higher than for Approach 1, at ~3σ level) – It's like if lensing was more efficient at smearing CMB acoustic peaks than predicted.
CMB gravitational lensing + lensing shear from KiDs & CFHTLenS

Problem: The amplitude of lensing inferred from Approach 2 is about 15% higher than for Approach 1, at ~3σ level) – It's like if lensing was more efficient at smearing CMB acoustic peaks than predicted

If CMB lensing were more efficient than what we predict, the 3σ tension with galaxy lensing shear would be alleviated
And finally, if we look at *Planck 2018* only ...
The universe does not seem flat, but has strong preference (~2σ) for being \textit{closed} instead of flat!
The universe does not seem flat, but has strong preference (~2σ) for being **closed instead of flat**!

This would **solve the problem with the lensing amplitude/efficiency and other internal anomalies in Planck data** (low quadrupole, alignment of low / multipoles, etc)
The universe does not seem flat, but has strong preference ($\sim 2\sigma$) for being **closed** instead of flat!

But it falls apart with **all** other cosmological observations at lower redshifts!
The universe does not seem flat, but has strong preference (~2σ) for being closed instead of flat!

Can this be a fluke/result of chance??
Cosmic Discordance: Planck and luminosity distance data exclude LCDM.

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(Dated: March 12, 2020)

We show that a combined analysis of CMB anisotropy power spectra obtained by the Planck satellite and luminosity distance data simultaneously excludes a flat universe and a cosmological constant at 99% C.L.. These results hold separately when combining Planck with three different datasets: the two determinations of the Hubble constant from Riess et al. 2019 and Freedman et al. 2020, and the Pantheon catalog of high redshift supernovae type-Ia. We conclude that either LCDM needs to be replaced by a drastically different model, or else there are significant but still undetected systematics. Our result calls for new observations and stimulates the investigation of alternative theoretical models and solutions.

Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics Beyond ΛCDM

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(Accepted ApJ, March 26, 2019)
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  \[(3 \sigma \text{ tension})\]

- The non-flat curvature of the universe ($\Omega_k = -0.04$)

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Looking at the future …

CMB:
ACTPol
SPTPol
LiteBird
Future ESA space CMB mission (?)

LSS:
Euclid
DESI
Vera Rubin
J-PAS
SphereX
SKA

GWs
Looking at the future ... 

CMB:
- ACTPol
- SPTEPol
- LiteBird
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LSS:
- Euclid
- DESI
- Vera Rubin
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- SKA

¡MUCHAS GRACIAS!