Planck vs Early & Local Universe: Neutrinos and Dark Energy

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The 1%
ΔLocal Standards=New Physics

- $H_0$ and local structure: an end to end check of the standard cosmology when combined with the CMB
\( \Delta H_0 = \text{New Physics} \)

- Standard ruler \( D(z_*) \): sound horizon at recombination \( z_* \)
- In flat \( \Lambda \text{CDM} \), \( H_0 \) only remaining parameter in \( D(z_*) \) representing the density contributed by \( \Lambda \) - precisely predicted

![Graph showing \( D_\ell \) vs multipole \( \ell \)]

Planck 2013

sound horizon calibrated
[baryon/photon, matter/radiation]
$\Delta H_0 = \text{New Physics}$

- Compare precise predictions with $H_0$ measurements
- Any deviations indicate new physics during acceleration epoch or during recombination

\[ D(z_*) = \int_0^{z_*} \frac{dz}{H(z)} \]

sound horizon calibrated
[baryon/photon, matter/radiation]

Planck 2013
$\Delta H_0 = \text{New Physics}$

- Standard ruler $D(z_\ast)$: sound horizon at recombination $z_\ast$
- Diffusion scale provides consistency check on sound horizon calibration: new physics at recombination, while BAO on acceleration

Planck 2013
Falsifying ΛCDM

- CMB determination of matter density controls all determinations in the deceleration (matter dominated) epoch
- **Planck:** $\Omega_m h^2 = 0.1426 \pm 0.0025 \rightarrow 1.7\%$
- **Distance** to recombination $D_*$ determined to $\frac{1}{4} 1.7\% \approx 0.43\%$ ($\Lambda$CDM result $0.46\%; \Delta h/h \approx -\Delta \Omega_m h^2 / \Omega_m h^2$)
  [more general: $-0.11 \Delta w - 0.48 \Delta \ln h - 0.15 \Delta \ln \Omega_m - 1.4 \Delta \ln \Omega_{\text{tot}} = 0$]
- **Expansion rate** during any redshift in the deceleration epoch determined to $\frac{1}{2} 1.7\%$
- **Distance to any redshift** in the deceleration epoch determined as

$$D(z) = D_* - \int_{z}^{z_*} \frac{dz}{H(z)}$$

- **Volumes** determined by a combination $dV = D_A^2 d\Omega d\bar{z} / H(\bar{z})$
- **Structure** also determined by growth of fluctuations from $z_*$
Value of Local Measurements

- With high redshifts fixed, the largest deviations from the dark energy appear at low redshift $z \sim 0$
- By the Friedmann equation $H^2 \propto \rho$ and difference between $H(z)$ extrapolated from the CMB $H_0 = 38$ and 67 is entirely due to the dark energy density in a flat universe
- With the dark energy density fixed by $H_0$, the deviation from the CMB observed $D_*$ from the $\Lambda$CDM prediction measures the equation of state (or evolution of the dark energy density)

$$p_{\text{DE}} = w \rho_{\text{DE}}$$

- Likewise current amplitude of structure, e.g. local cluster abundance, tests the smooth dark energy paradigm
Forecasts for CMB+$H_0$

- To complement CMB observations with $\Omega_m h^2$ to 1%, an $H_0$ of ~1% enables constant $w$ measurement to ~2% in a flat universe.
New Physics?
**$H_0$ is for Hints**

- **Actual distance ladder measurements** prefer larger value
Quantifying Tension

- Predictions for $H_0$ and the amplitude of structure from Planck in flat $\Lambda$CDM is 2-3+ $\sigma$ in tension with measurements

Planck vs Local: $\Lambda$CDM

Wyman, Rudd, Vanderveld, Hu (2013)
Dark Energy

- Raising $H_0$ inferred from Planck CMB measurements with dark energy requires **phantom** equations of state.
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Dark Energy

- Predicts larger BAO (θ) angular and radial (z) scale; larger SN=H₀Dₐ relative luminosity distance; larger linear growth

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\Delta w = -0.23
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![Graph showing the fractional change in \( \Delta \ln H \) versus redshift (z) with a peak at \( z \approx 0.05 \) and a valley at \( z \approx 0.1 \)].
Dark Energy

- Predicts larger BAO ($\theta$) angular and radial ($z$) scale; larger SN=$H_0D_A$ relative luminosity distance; larger linear growth.

$\Delta w = -0.23$
Dark Energy

- Predicts larger BAO ($\theta$) angular and radial ($z$) scale; larger $SN/H_0D_A$ relative luminosity distance; larger linear growth

$$\Delta w = -0.23$$

fractional change

tension with data!
Dark Energy

- Predicts larger BAO ($\theta$) angular and radial ($z$) scale; larger $SN=H_0D_A$ relative luminosity distance; larger linear growth

$\Delta w = -0.23$
Curvature

- Predicts larger BAO ($\theta$) angular and radial ($z$) scale; larger $SN=H_0D_A$ relative luminosity distance; smaller linear growth.

![Graph showing the fractional change in various parameters as a function of redshift ($z$).](image)

- $\Delta \ln \theta$ BAO $\theta$
- $\Delta \ln H$
- $\Delta \ln BAO_z$
- $\Delta \ln (SN)$
- $\Delta \ln Grow$

$\Delta \Omega_K = 0.012$

Tension with data! Alleviate tension!
Neutrinos?
Neutrinos

• Hints of extra **sterile neutrino** species (~eV) in long-baseline and reactor anomalies

• Potentially **populated** (partially?) in early universe

• Changes expansion at recombination: age, **sound horizon**
Neutrinos

- Predicts same **BAO** ($\theta$) angular and **radial** ($z$) scale;
- same **SN**=$H_0D_A$ relative luminosity distance;
- same **linear growth** - change the **ruler** not the distance

$\Delta N_{\text{eff}} = 1$, fixed matter/radiation
Neutrinos

- Predicts more damping of the CMB: sound horizon scales as conformal time $\eta$, random walk diffusion scale $\eta^{1/2}$
Gravitational Wave Excess

- BICEP2 B-polarization inflationary gravitational waves \((r=0.2)\) imply low multipole temperature excess that is not observed \((r<0.1)\)
Gravitational Wave Excess

- BICEP2 B-polarization inflationary gravitational waves ($r=0.2$) imply low multipole temperature excess that is not observed ($r<0.1$)
• In $\Lambda$CDM with power law scalar power spectra, Planck temperature power spectrum in tension with BICEP2 polarization detection
• Extra neutrino requires a blue-ward change in tilt, suppressing excess power at low multipoles
• Adding neutrinos relaxes the tension by allowing a blueward change in tilt, suppressing the excess large angle power.
Quantifying Tension

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Wyman, Rudd, Vanderveld, Hu (2013)
Neu(trino)r Concordance

- Partially populated sterile, massive neutrinos change both the acoustic standard ruler and suppress structure and fixes $H_0$, clusters and tensor excess

$\nu r \Lambda$CDM: CMB predictions

Dvorkin, Wyman, Rudd, Hu (2014) [Zhang, Li, Zhang 2014]
Neutrino Concordance

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$\nu r\Lambda\text{CDM}: \text{CMB predictions}$

Dvorkin, Wyman, Rudd, Hu (2014) [Zhang, Li, Zhang 2014]
Neu(trino)r Concordance

- Allows a fully populated extra sterile neutrino of 0.5eV

Sterile Neutrinos: >3σ stat

oscillation populated mass=$m_s/\Delta N_{\text{eff}}$ (eV)

$\Delta N_{\text{eff}}=1$, 1 fully populated species

Dvorkin, Wyman, Rudd, Hu (2014) [Zhang, Li, Zhang 2014]
Summary

- $\Delta H_0$ from flat $\Lambda$CDM prediction indicates new physics
- Predictions from CMB are as precise as standard ruler calibration
  \[|\Delta h/h| \approx |\Delta \Omega_m h^2/\Omega_m h^2| \approx 1.7\% \text{ currently}\]
- To test predictions require direct measurements at this precision
- New physics either additions to $\Lambda$CDM at recombination (standard ruler) or during acceleration (distance-redshift)
- Consistency with damping tail, BAO distinguishes cases
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- Current mismatch between $H_0 \approx 67$ prediction and $H_0 \approx 74$ measurements may indicate extra relativistic species at recombination
- Simultaneously alleviates tension with BICEP2 inflationary tensor detection
- If massive neutrino, also alleviates tension with cluster abundance
Big Bang Nucleosynthesis

- Extra radiation density during Big Bang Nucleosynthesis predicts higher helium abundance