What we have learnt from Planck
(organizer’s title!)

Wayne Hu
IAP, June 2019
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I learned
What we have learnt from Planck
(or how I learned to love tension)

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slim pickings

stop worrying and

anomalies

curiosities

ΛCDM?

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Paradigm of Precision Cosmology

- Precision measurements and maps
  - temperature
  - polarization
  - lensing
  - 9 frequencies
- Control over systematics
  - most recently polarization
- Accurate and precise theoretical predictions
  - Gaussian, adiabatic
  - $\Lambda$CDM
Near Perfection in 6 Numbers

- All this precision data described by 6 $\Lambda$CDM parameters
  - $\Omega_c h^2$: CDM
  - $\Omega_b h^2$: baryons
  - $\theta_s$: sound scale
  - $A_s$: amplitude
  - $n_s$: tilt
  - $\tau$: reionization
- Measured to sub percent precision (except $\tau$)
Predictive Power

- Small residuals from ΛCDM in various spectra
- Temp ↔ pol residuals in ΛCDM with reduced sample variance
- Largely consistent, but with high precision, moderately significant deviations
- ∼ 2σ outliers, expected but some also drive parameters

Planck (2018) I

TE glitch
Predictive Power

- Predicts all other observables, which direct measurements test

- Good agreement, even weak lensing, clusters, and yes $H_0 (< 10\%)$
Anchors Sink $\Lambda$CDM?

- When distance ladder calibrated by CMB sound horizon, $H_0$ discrepant with local measurements at $4.4\sigma$ (Riess et al. 2019)

- Relative distances forward/backwards by ladder: CMB to BAO to SN isolating discrepancy as anchors (e.g. Aylor et al. 2018)

- Relative distances $\sim$ $\Lambda$CDM: little room for any new physics at intermediate redshifts to resolve
Driving in the Anchor

- CMB anchor is sound horizon, must calibrate propagation time
- $H(z < 10^3)$: with radiation, baryons fixed only $\Omega_c h^2$ unknown

$\Omega_c h^2$ controls matter-radiation ratio and radiation driving from potential decay due to Jeans stability
Glitch and Oscillatory Residuals

- **Shifts** in CMB anchor between low & high $\ell$ (Addison et al 2015)

- **Low multipole** glitch – deficit of power – looks like peaks should be higher, **more driving**, less matter, higher $H_0$

- **High multipole** oscillatory residuals: **smoother acoustic peaks**, less driving, more matter, lower $H_0$
  - also drives “lensing tension”: Pavel Motloch’s talk

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**Figure:**

- $\ell < 2500$
- $\ell < 800$
- $\ell < 2500$ fixlens
- $30 < \ell < 2500$
- $30 < \ell < 800$

- $H_0 \sim 70$

**Graph:**

- $\Delta C_{\ell}^{TT}/\sigma$
- $-2\Delta \ln L_{TT}$
- $\Lambda CDM$ TT (all)
Glitch and Large Angle Features

- Exclude low $\ell < 30$ glitch (Planck Intermediate 2016 LI)
- $H_0$ falls, consistent with high multipoles within errors

- Alternately marginalize over possible features during inflation, mild $\Delta \chi^2 \sim 12$ improvement, but 5 params
- Likewise $H_0$ returns to low value (Obied et al 2017)
Driving and Oscillatory Residuals

- Oscillatory residuals indicate smoother peaks (and persist even in best fit $\Lambda$CDM)
- Driving sharpens the peaks
- Residuals indicate less driving, higher matter-radiation ratio
- Higher $\Omega_c h^2$, lower $H_0$
Driving and CDM

- **Signatures of CDM** $\Omega_c h^2$: TT amplitude and oscillatory residuals
- **Polarization** sharper test: projection effects for TT (Galli et al. 2014)

Obied et al (2017)
Polarization Signatures

- **Polarization sensitivity** provides independent calibration using $\ell < 1000$ TE Planck data

- **TE glitch at $\ell \sim 165$ enhances sensitivity**, since lowering $\Omega_c h^2$ (raising $H_0$) further raises predictions

\[ \Delta C_{\ell}^{TE} / \sigma_{\ell} \]

\[ -2 \Delta \ln \mathcal{L}_{\text{TT}} \]

Obied et al (2017)
Dark Radiation

- Extra dark species whose energy density redshifts faster than matter change sound horizon calibration
- Raise $H(z < 10^3)$, lower sound horizon, raise $H_0$ at fixed $\theta_s$
- Additional driving from Jeans stable $\Delta N_{\text{eff}}$ radiation compensated by raising matter $\Omega_c h^2$
Driving and Damping

- But damping provides second standard ruler in diffusion scale
- Random walk distance of photon scales as harmonic mean between horizon and mean free path
- Consistency check that $\Lambda$CDM passes and constrains any additional radiation $\Delta N_{\text{eff}}$
Dark Exotica

- Decreasing additional dark components during radiation domination changes damping vs sound horizon
- Reconcile ratio if timed exactly right

![Graph showing fraction of total density vs parameter a](image)


- Poulin et al (2018): specific anharmonic, periodic scalar potential
General Mechanism

- Must compensate effect of raising $\Omega_c h^2$ which reduces decay of potential

\[ \Delta (\Psi + \Phi) = 0.04/\text{Mpc} \]
General Mechanism

- **Dark exotica** with relativistic sound speed, acoustic oscillations, enhances decay

\[ \Delta (\Psi + \Phi) = 0.04 / \text{Mpc} \]

\[ a_{\text{eq}} \]

\[ k = 0.04 / \text{Mpc} \]
4 Parameter Tuning

- Tune the impact with sound speed (first dark acoustic peak) and equation of state (redshifts away faster)

\[
\Delta(\Psi + \Phi) = k = 0.04/\text{Mpc}
\]
Reducing Tuning

- **Poulin et al (2018)** 4 parameters, amplitude, time scale, $c_s^2$ and $w$ must be carefully tuned (top of oscillatory potential $c_s^2 \downarrow$)

- Data favor something both more specific and generic: $c_s^2 = w$, transition to **kinetic energy domination** (Lin et al 2019)

![Graph showing fraction of total density vs. $a$ with acoustic DE and locally $m^2\phi^2$ curves.](chart.png)
Potential to Kinetic

- With $c_s^2 = w = 1$ leaves 2 parameters: amplitude and slope of potential and requires kinetic energy redshift away (not oscillate)

- Amplitude $\sim 0.08\rho_{eq}$ and slope must be large enough to release from Hubble drag

![Graph showing acoustic DE and locally $m^2\phi^2$](image-url)
Fit and Predictive Signatures

- Fits joint data better by $\Delta \chi^2 \sim 12 - 14$ for 2-3 parameters
- Fits CMB itself better, largely TE
- TE glitch $\ell \sim 165$ highly sensitive
- Dark component redshifts away by recombination leaving nearly bare $\Omega_c h^2$ signature

Lin et al (2019)
Potential Conversion of $H_0$ Tension

- Raises $H_0$ to bring CMB and local anchors into better agreement
- Minor further improvements with additional parameters
- Posterior depends on parameter volume near $\Lambda$CDM, maximum likelihood (ML) more reflective

- But mainly converts $H_0$ question to “why this, why then”!
Potential Conversion of $H_0$ Tension

- Raises $H_0$ to bring CMB and local anchors into better agreement
- Minor further improvements with additional parameters
- Posterior depends on parameter volume near $\Lambda$CDM, maximum likelihood (ML) more reflective

- Already limited by Planck TE polarization, distinguishing details

![Graph showing $H_0$ distributions](Lin et al (2019))
Potential Conversion of $H_0$ Tension

- Raises $H_0$ to bring CMB and local anchors into better agreement
- Minor further improvements with additional parameters
- Posterior depends on parameter volume near $\Lambda$CDM, maximum likelihood (ML) more reflective
- EE residuals are $\sim 0.3$ vs cosmic variance per multipole

- Opportunity for testing ideas based on changing CMB anchor!
Summary

- Planck and other precision CMB experiments have firmly established $\Lambda$CDM as the standard model.

- $\Lambda$CDM unreasonably effective and efficient in describing suite of cosmological observables.

- 6 numbers, mostly measured to sub percent precision, mostly consistent at this level with everything.

- Tensions, anomalies and curiosities: imperfection is more interesting than perfection.

- $H_0$ at 4.4$\sigma$, can only be explained by changing one of the anchors.

- CMB anchor is sound horizon and cross checked by damping scale.

- Potential conversion illustrates designer difficulties, one or more parameters per effect:
  - look for predictive power of any explanation.