Constraining $H_0$ with the CMB

Jason W. Henning (KICP)
October 13, 2016
Compilation of TT and EE Measurements

Angular scale $\theta$ [degrees]

TT

$\ell(\ell+1)/(2\pi C_{\ell})$ [\mu K^2]

EE

Multipole number $\ell$

ACTPol
BICEP2/Keck
Planck 2015
SPTpol 500d
Expansion rate is defined as the change in time of the scale factor.

\[ H(a) \equiv \frac{1}{a} \frac{da}{dt} \]

Friedmann equation tells us how to relate expansion rate to content.

\[ H^2(a) = H_0^2 \left[ \Omega_K a^{-4} + (\Omega_c + \Omega_b) a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda \right] \]

Ratios of constituent densities to critical density
Friedmann equation tells us how to relate expansion rate to content.

\[ H^2(a) = H_0^2 \left[ \Omega_\gamma a^{-4} + (\Omega_c + \Omega_b) a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda \right] \]

Ratios of constituent densities to critical density

- Radiation content known from COBE.
- Relative heights of odd/even CMB peaks gives baryon content.
- Height of 2nd/3rd acoustic peaks helps constrain dark matter.
- … and much more phenomenology that provides additional measurements and consistency tests.

Still must constrain curvature, dark energy, and the expansion rate today…

… measure the angular scales of the sound horizon and diffusion length at recombination.
Primary CMB anisotropy - 9 harmonics
Improves precision of sound horizon, $\theta_s$, & provides larger lever arm

$\theta_s$ is the angular distance a sound wave could have travelled by recombination

$\sim 1/\theta_s$

Position (not height matters) = robust to systematics.

From J. Carlstrom
And most importantly provides determination of the damping scale, $\theta_d$

$\theta_d$ is the angular diffusion length at recombination.

Photon has a mean free path and diffuses. So, oscillations on small scales are damped exponentially. (Silk damping)

Note $\frac{r_d}{r_s} = \frac{\theta_d}{\theta_s} \propto H^{0.5}$ so ratio is sensitive energy density.

From J. Carlstrom
Assuming a flat universe…

...(H₀ is highly model-dependent)
Low-redshift information from lensing helps break degeneracies

CALABRESE ET AL, ASTRO-PH/0803.2309
CMB Lensing works:
Detecting Dark Energy using only the CMB

Detection of CMB lensing in TT power spectrum breaks geometric degeneracy between curvature and dark energy.

Slide from R. Keisler
$$\theta_* = \frac{r_*}{D_A} \quad \rightarrow \quad \text{High matter forces lower } H_0.$$ 

... assuming $\Lambda$CDM model.

**Fig. 17.** MCMC samples and contours in the $r_\ast$–$\Omega_m h^2$ plane (left) and the $D_A(z_\ast)$–$\Omega_m h^2$ plane (right) for $\Lambda$CDM models analysed with Planck+WP+highL. The lines in these plots show the expected degeneracy directions in the base $\Lambda$CDM cosmology. Samples are colour-coded by the values of $\Omega_b h^2$ (left) and $H_0$ (right).
Sources of Tension?

- NOT measurement of sound horizon (on full sky, anyway) but small surveys need to be careful.
  - Aberration
  - Super-sample CMB lensing

Effect of Aberration on ACTPol constraints

**Fig. 14.** Effect of aberration on the TT and EE CMB power spectra due to our proper motion with respect to the CMB. Our aberrated simulations agree with the analytical estimate of the expected effect.

**Fig. 17.** Effect of aberration, due to our proper motion with respect to the CMB, on the peak position parameter \( \theta \). The corrected power spectrum results in a 0.5\( \sigma \) decrease in the peak position.

Sources of Tension?

- Systematic affecting constraints on matter, etc?

Addison, et al. 2015, arXiv: 1511.00055v2
Sources of Tension?

- Use polarization for consistency checks
Sources of Tension?

- Use polarization for consistency checks

**Fig. 21.** $\Lambda$CDM parameters as measured by different ACTPol spectra, sampled directly (top) and derived (bottom). The TE spectrum now provides the strongest internal ACTPol constraint on the baryon density, peak position, and Hubble constant.

Sources of Tension?

- Assumption(s) in ΛCDM model are wrong?

Damping tail measurements inform us about neutrino and helium content, but these are also degenerate with $H_0$. 