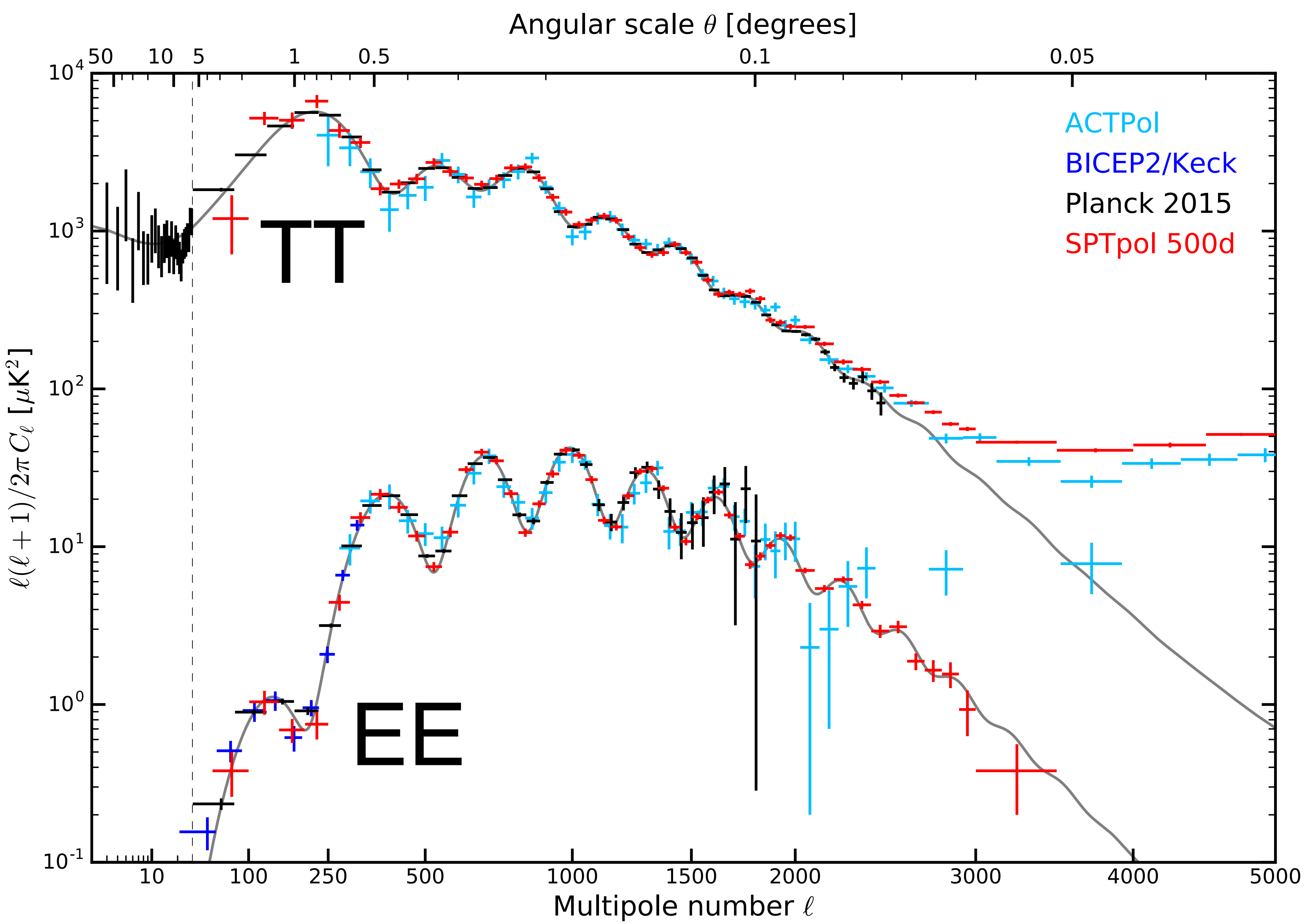
Constraining H_0 with the CMB

Jason W. Henning (KICP)

October 13, 2016

Compilation of TT and EE Measurements



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.

$$H^2(a) = H_0^2 \left[\Omega_\gamma a^{-4} + (\Omega_{\rm c} + \Omega_{\rm b})a^{-3} + \Omega_{\rm k} a^{-2} + \Omega_\Lambda\right]$$

Ratios of constituent densities to critical density

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

$$H^2(a) = H_0^2\left[\Omega_\gamma a^{-4} + (\Omega_\mathrm{c} + \Omega_\mathrm{b})a^{-3} + \Omega_\mathrm{k} a^{-2} + \Omega_\Lambda\right]$$

Ratios of constituent densities to critical density

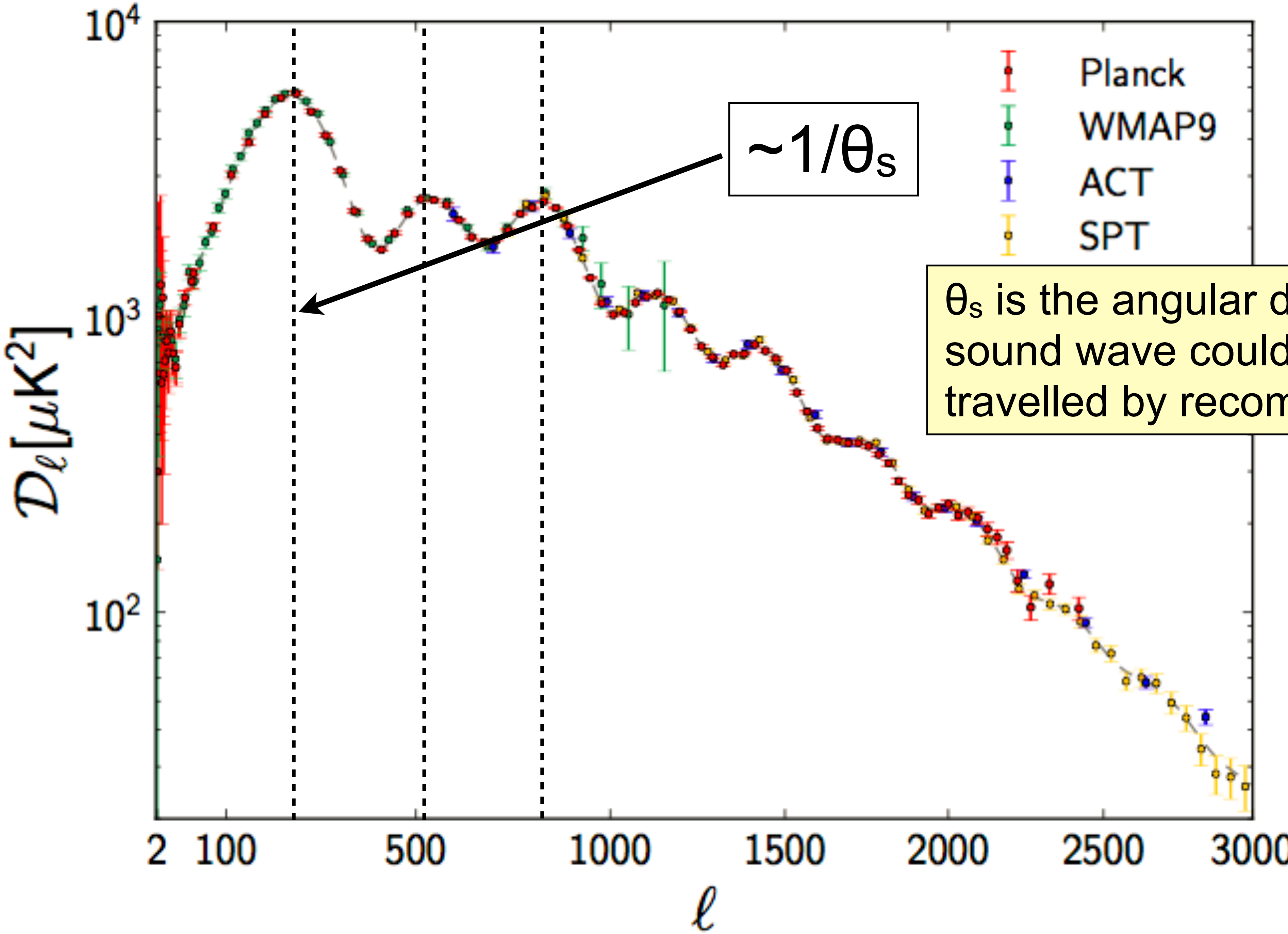
- Radiation content known from COBE.
- Relative heights of odd/even CMB peaks gives baryon content.
- Height of 2nd/3rd acoustic peaks helps constrain dark matter.
- … and much more phenomenology that provides additional measurements and consistency tests.

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, θ_s, & provides larger lever arm

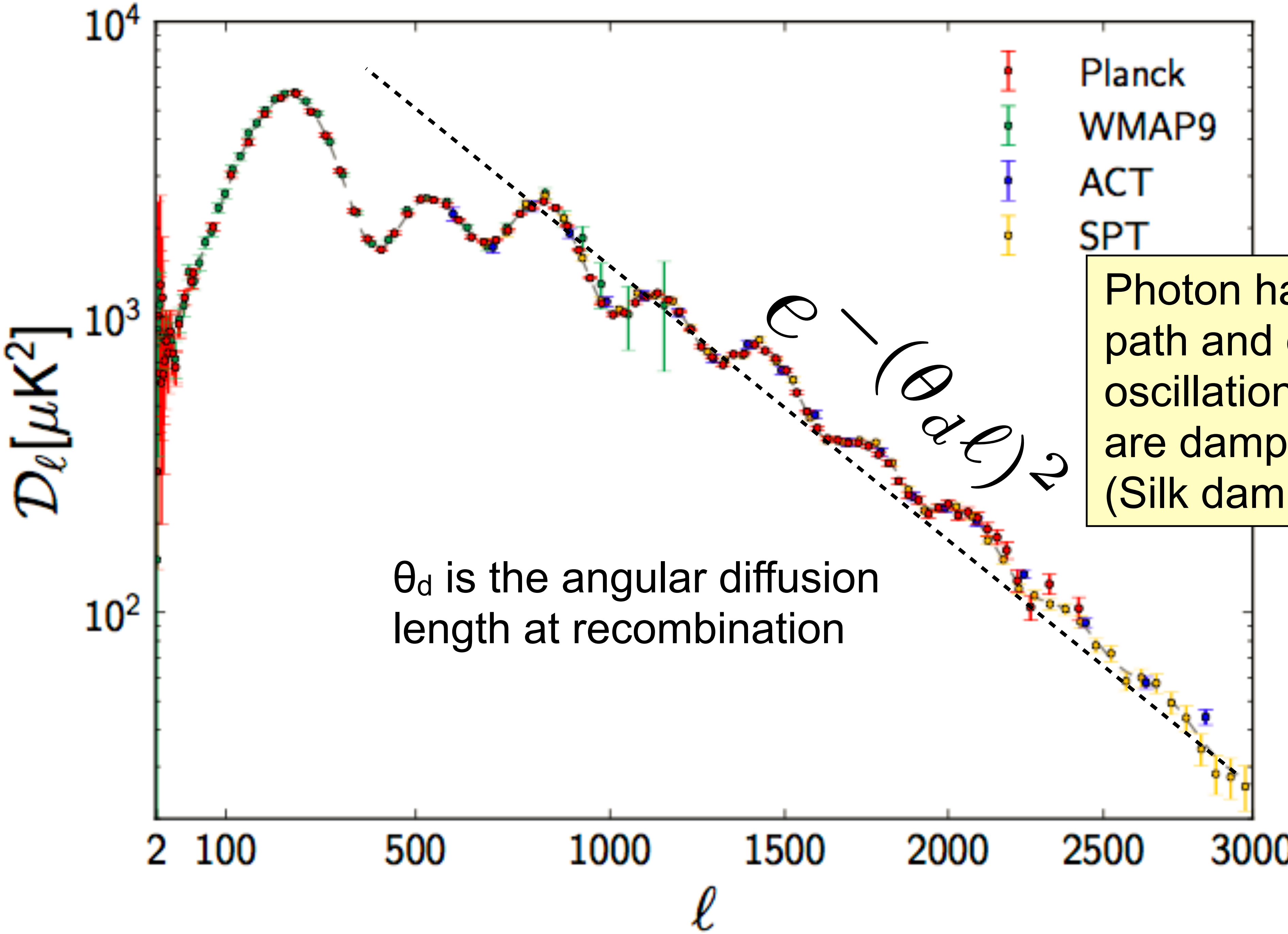


θ_s is the angular distance a sound wave could have travelled by recombination

Position (not height matters) = robust to systematics.

From J. Carlstrom

And most importantly provides determination of the damping scale, θ_d



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

θ_d is the angular diffusion length at recombination

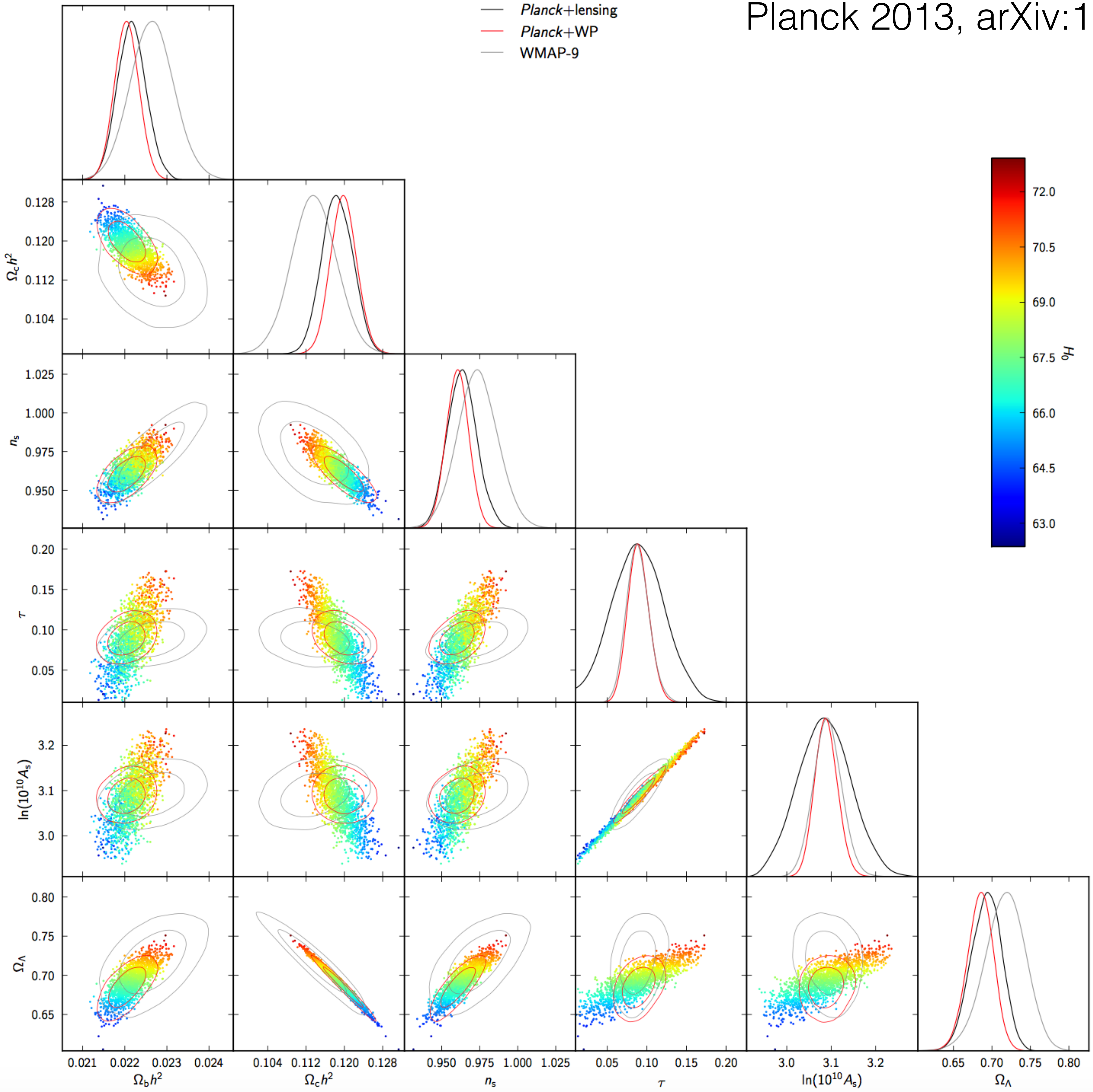
Note $\frac{r_d}{r_s} = \frac{\theta_d}{\theta_s} \propto H,^{0.5}$ so ratio is sensitive energy density.

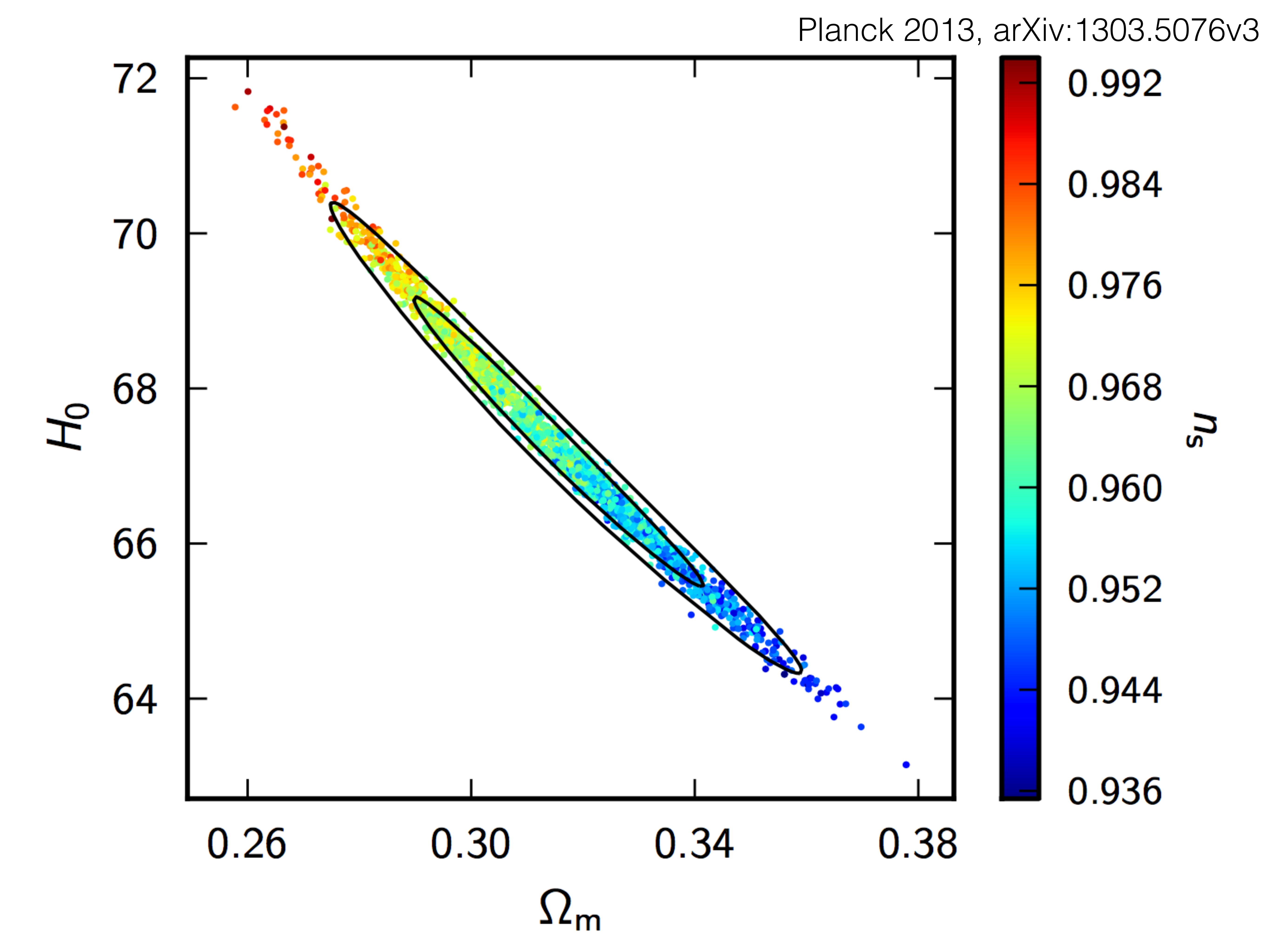
From J. Carlstrom

Assuming a flat universe…

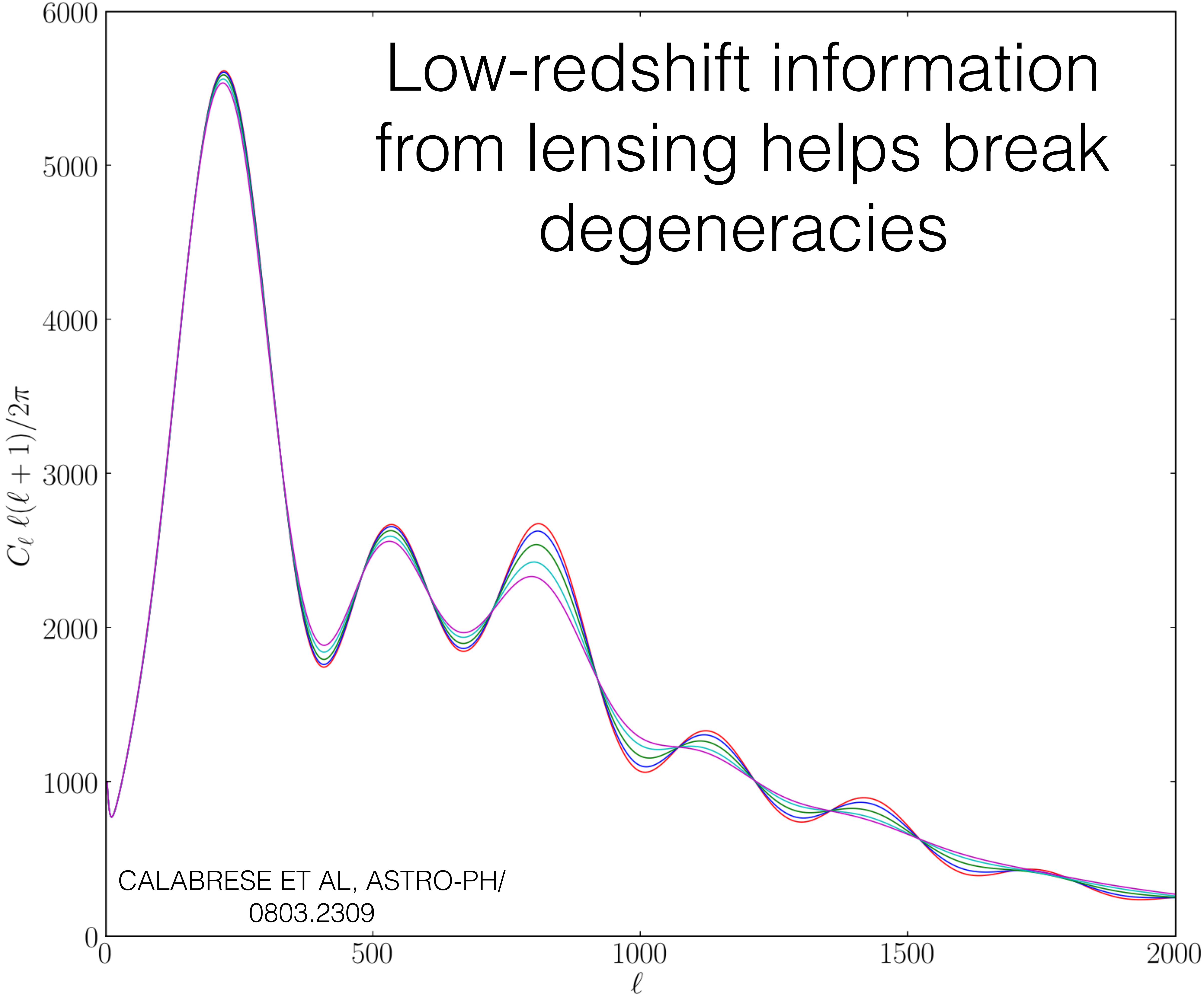
…(H_0 is highly model-dependent)

Planck 2013, arXiv:1303.5076v3



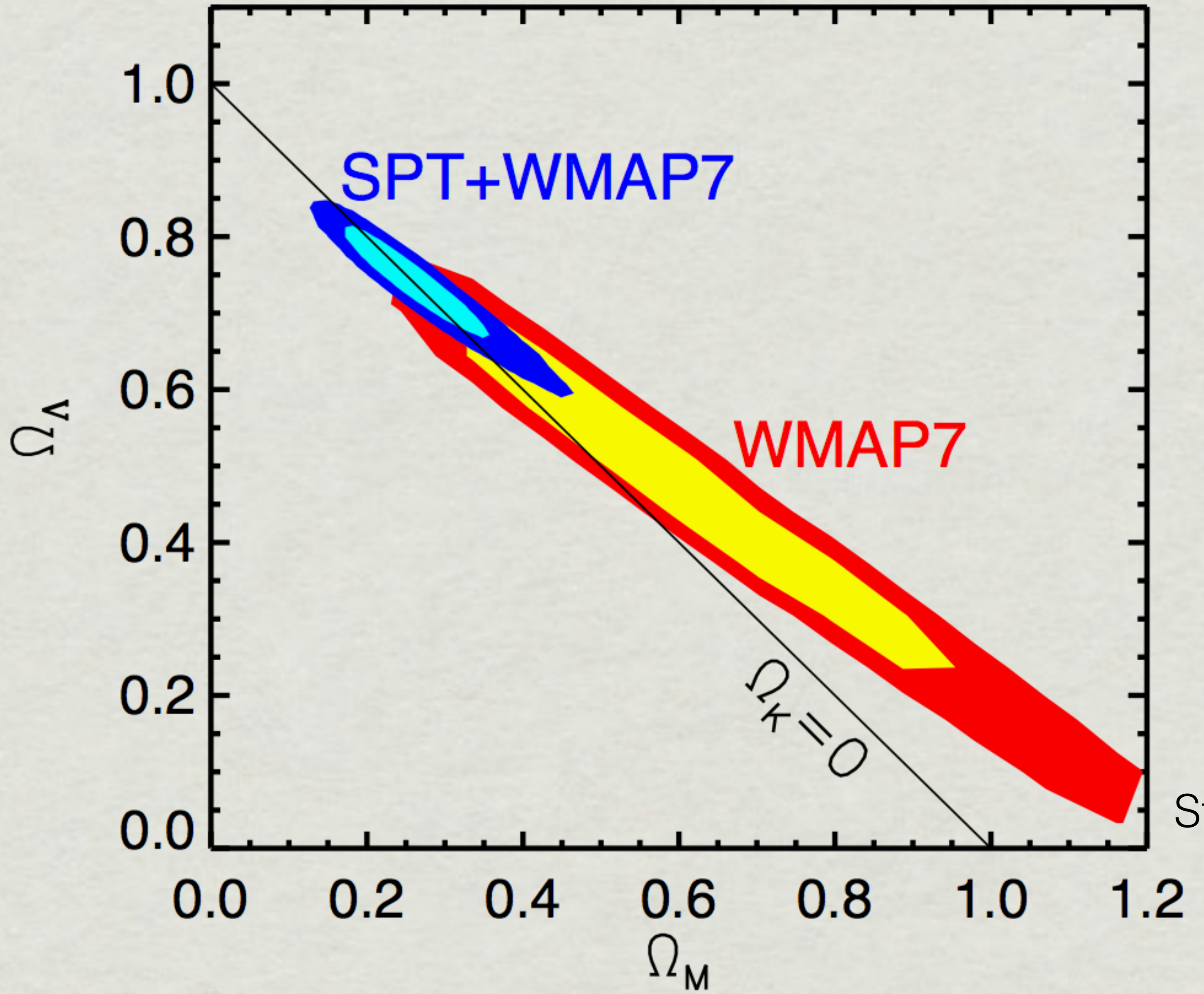

Planck 2013, arXiv:1303.5076v3
72
70
68
66
64
H_0
0.26
0.30
0.34
0.38
Ω_m
0.992
0.984
0.976
0.968
0.960
0.952
0.944
0.936
n_s

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



Story et al., arxiv:1210.7231

Slide from R. Keisler

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

Planck 2013, arXiv:1303.5076v3

$$\theta_* = \frac{r_*}{D_A}$$ → High matter forces lower H_0.

… assuming ΛCDM model.

Planck Collaboration: Cosmological parameters

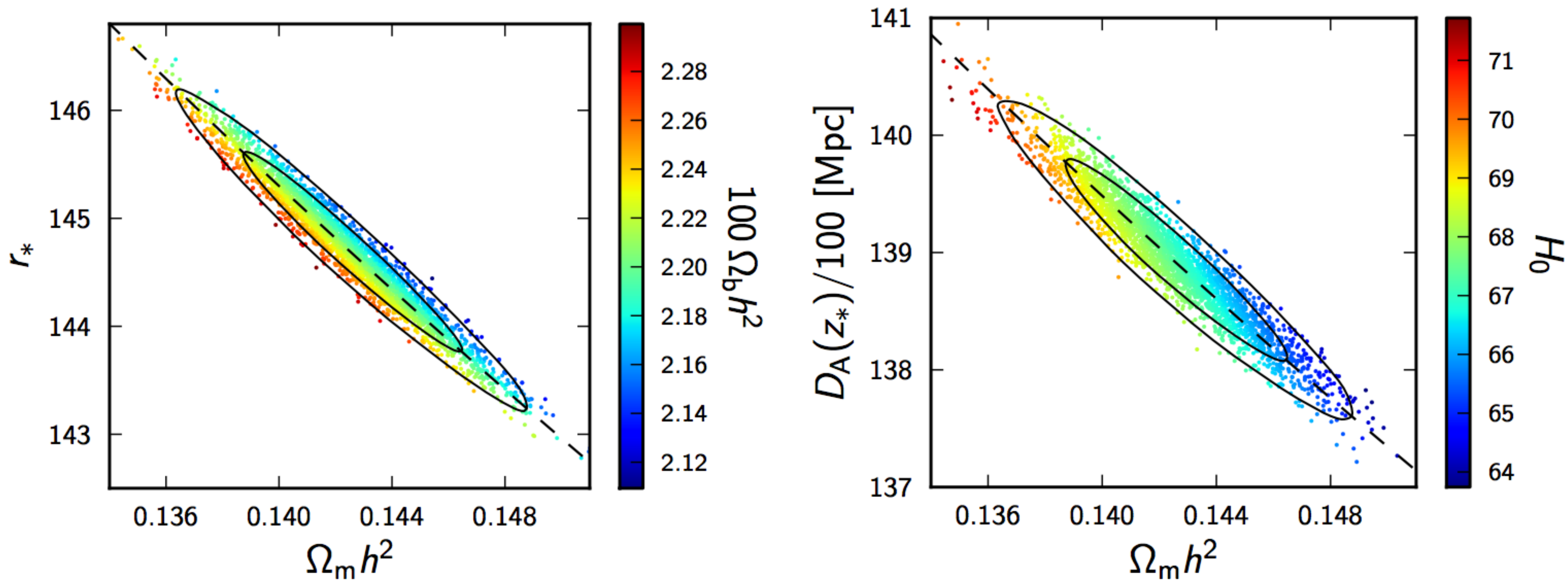


Fig. 17. MCMC samples and contours in the r_*–$\Omega_m h^2$ plane (left) and the $D_A(z_*)$–$\Omega_m h^2$ plane (right) for ΛCDM models analysed with *Planck*+WP+highL. The lines in these plots show the expected degeneracy directions in the base ΛCDM cosmology. Samples are colour-coded by the values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

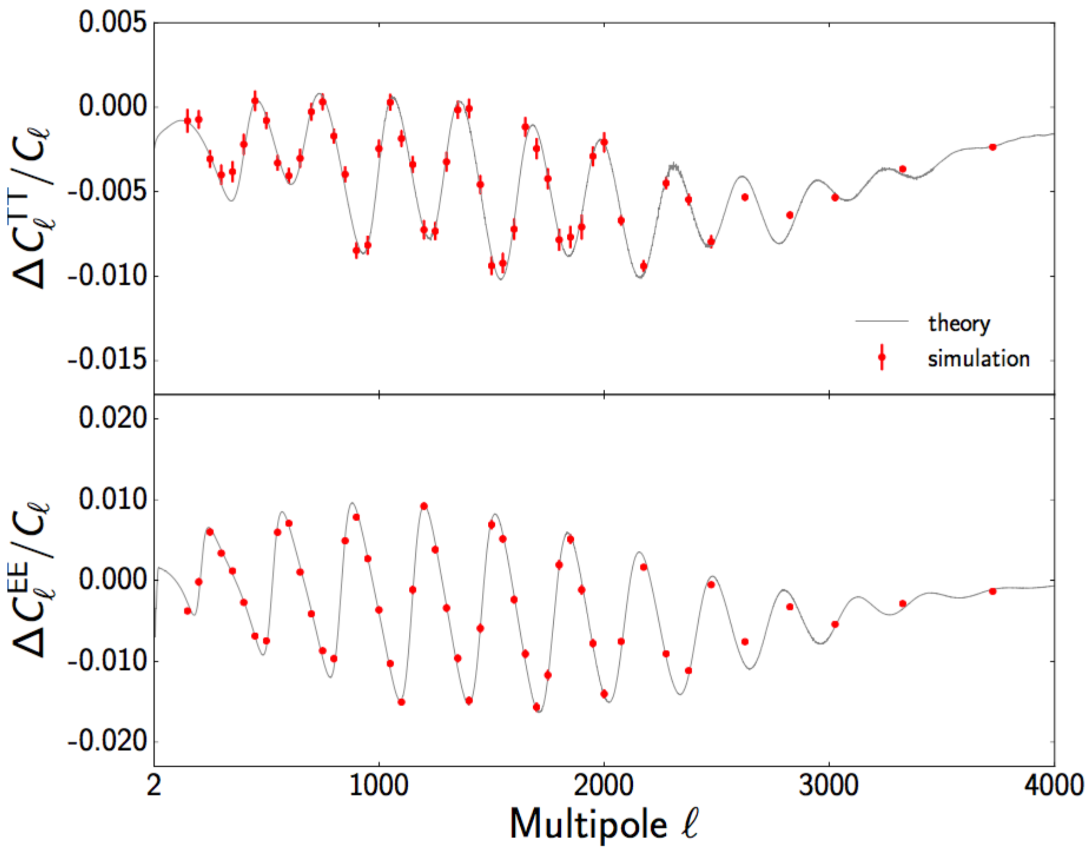


FIG. 14.— Effect of aberration on the TT and EE CMB power spectra due to our proper motion with respect to the CMB. Our aberrated simulations agree with the analytical estimate of the expected effect.

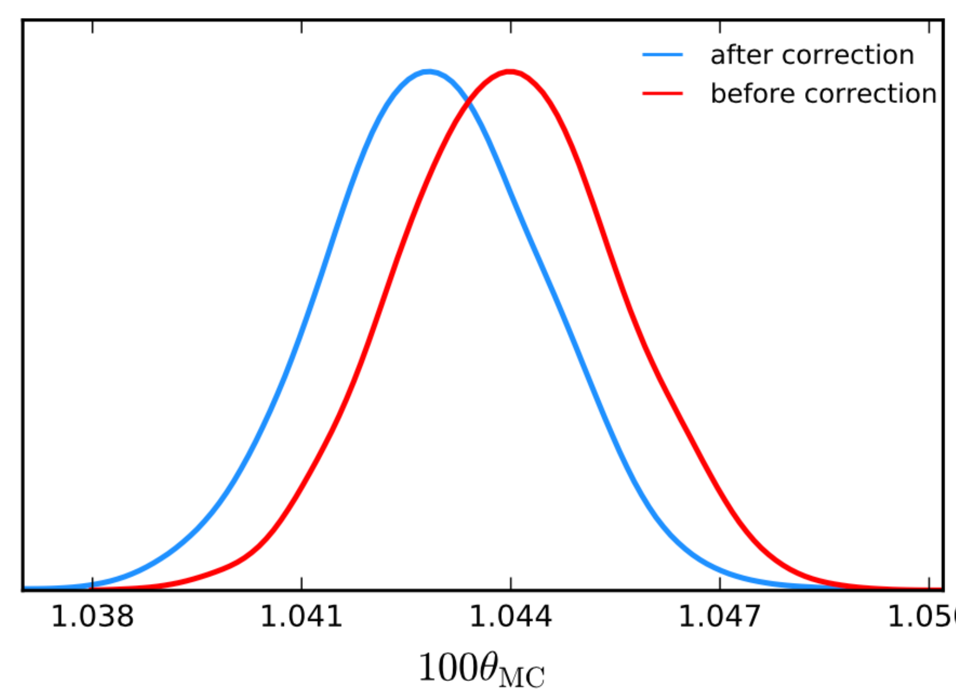
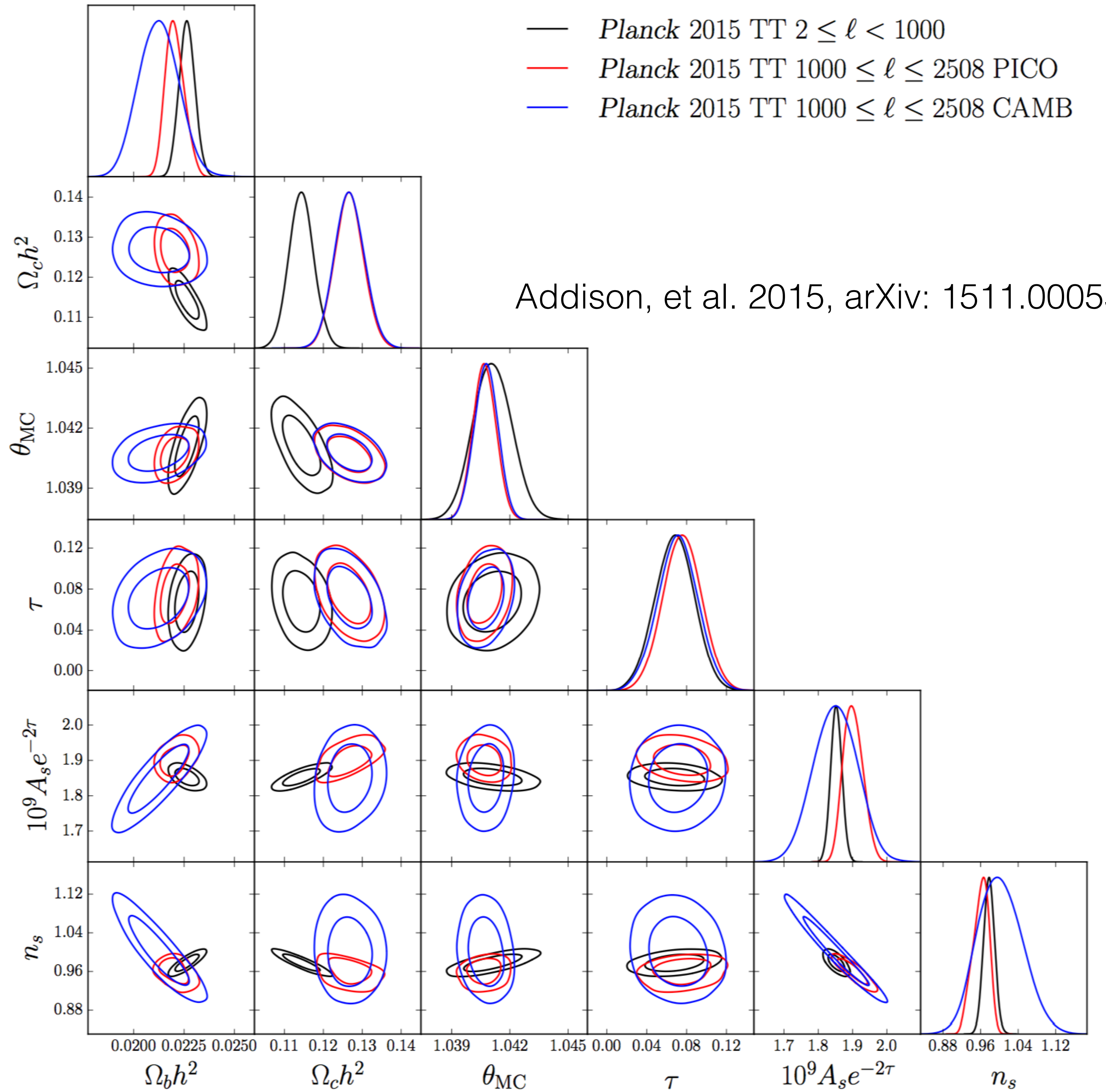


FIG. 17.— Effect of aberration, due to our proper motion with respect to the CMB, on the peak position parameter θ. The corrected power spectrum results in a 0.5σ decrease in the peak position.

Louis, et al. 2016, arXiv: 1610.02360v1

Sources of Tension?

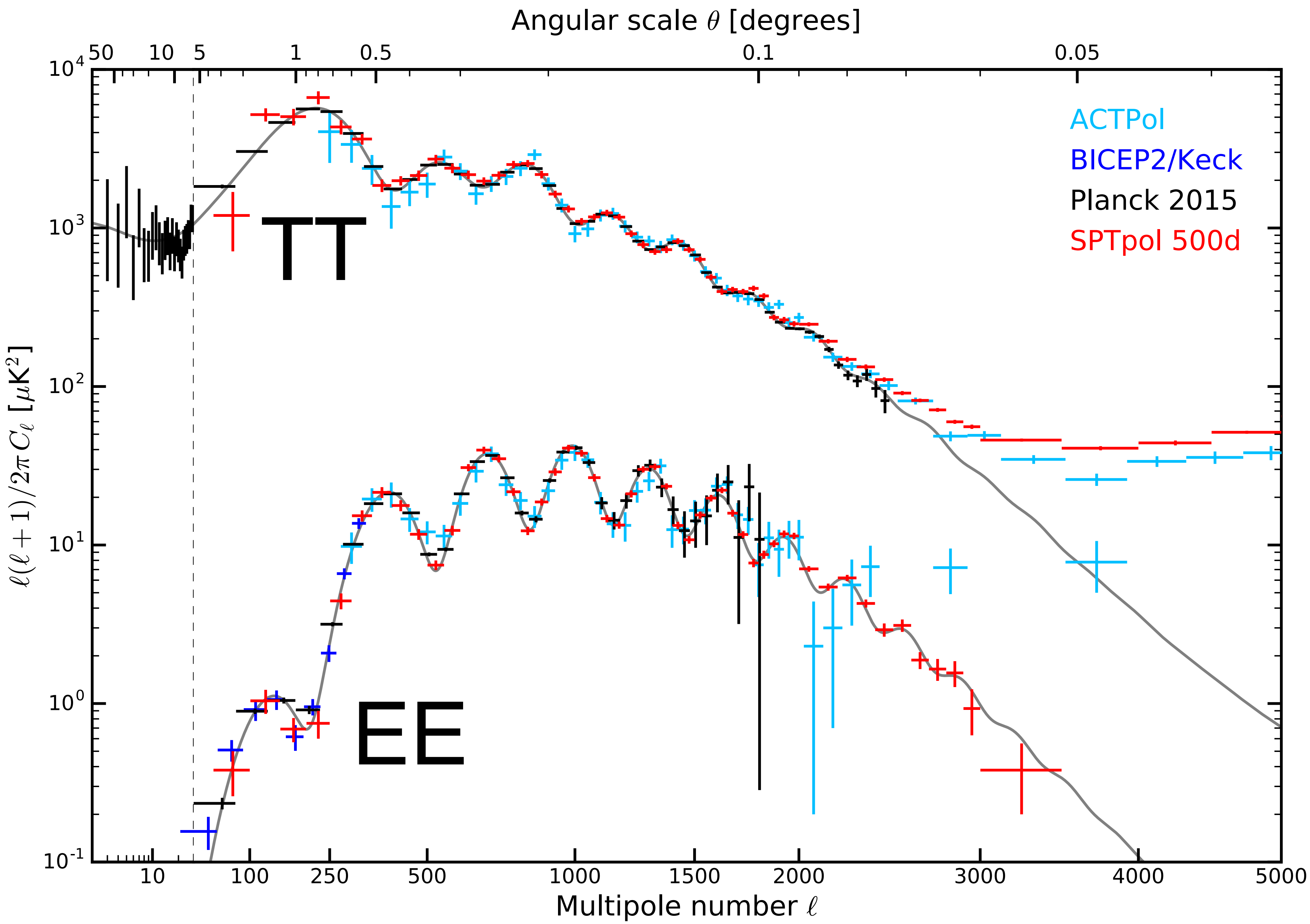
- Systematic affecting constraints on matter, etc?



Addison, et al. 2015, arXiv: 1511.00055v2

Sources of Tension?

- Use polarization for consistency checks



Sources of Tension?

- Use polarization for consistency checks

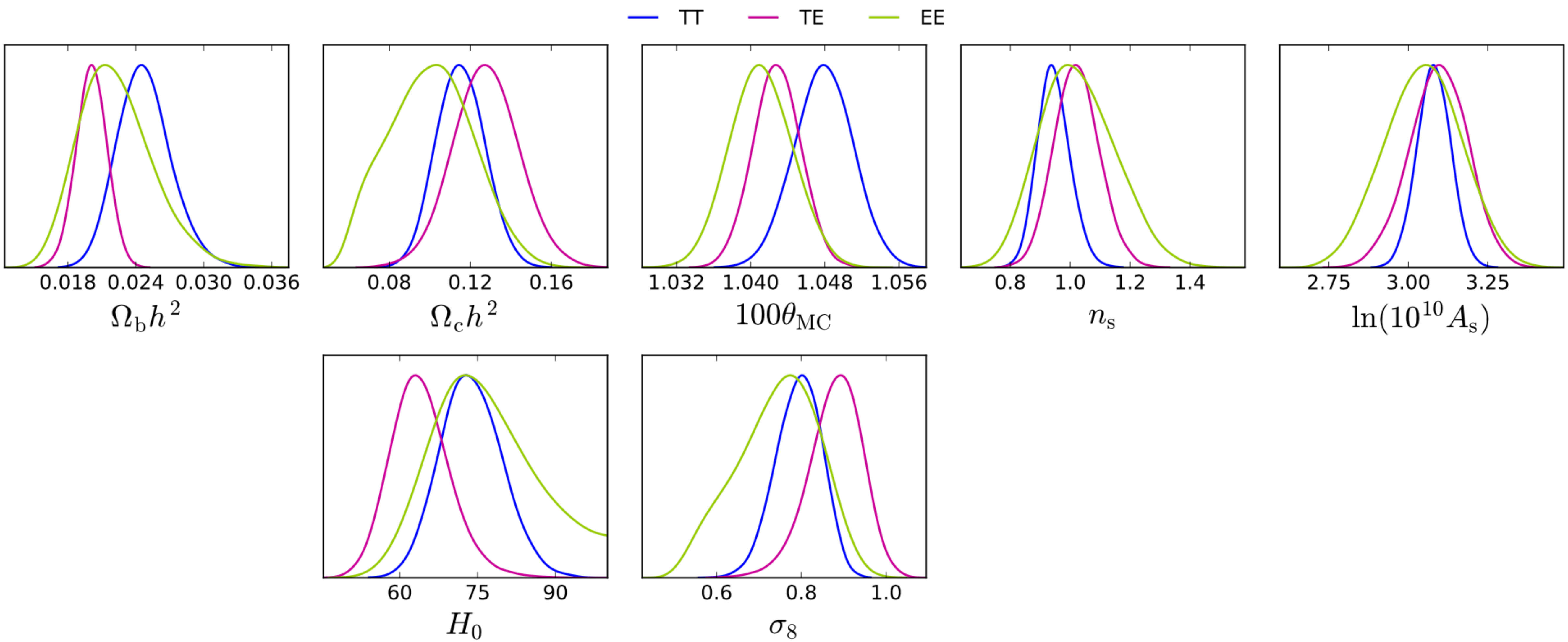
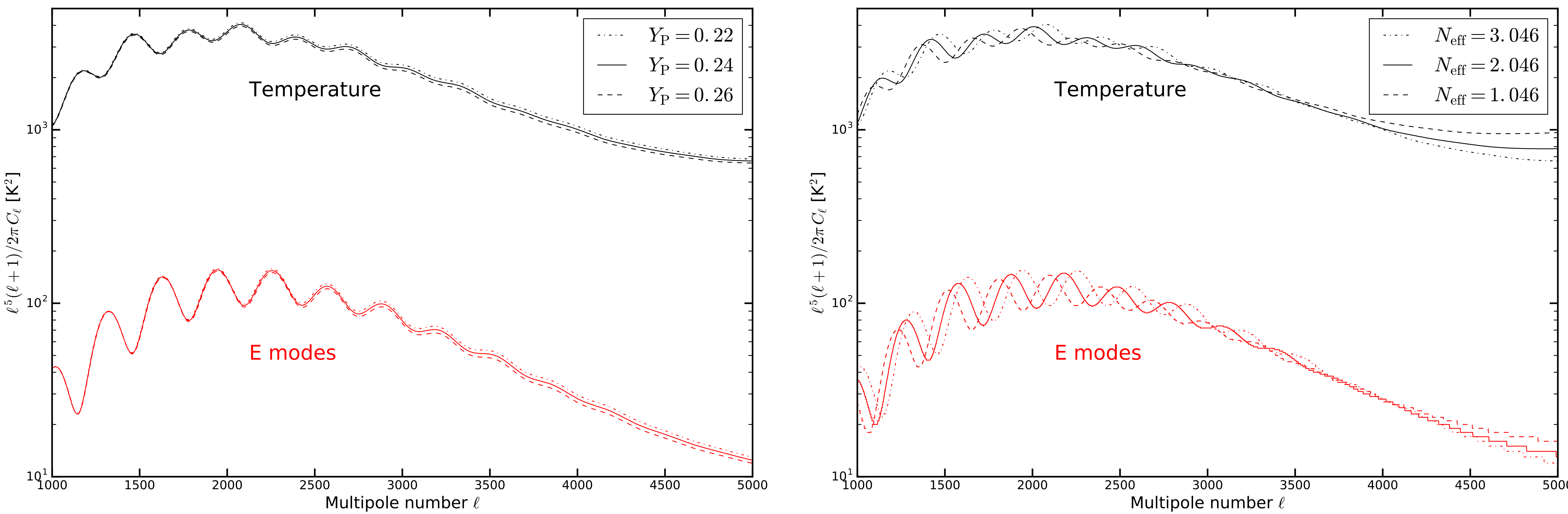


FIG. 21.— ΛCDM parameters as measured by different ACTPol spectra, sampled directly (top) and derived (bottom). The TE spectrum now provides the strongest internal ACTPol constraint on the baryon density, peak position, and Hubble constant.

Louis, et al. 2016, arXiv: 1610.02360v1

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.