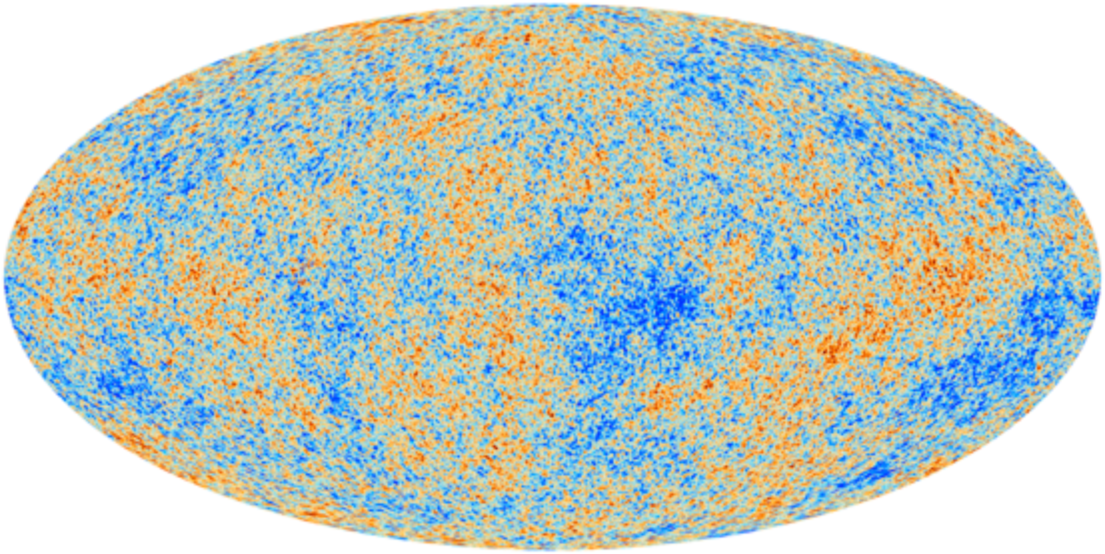
Cosmological Parameters from Planck



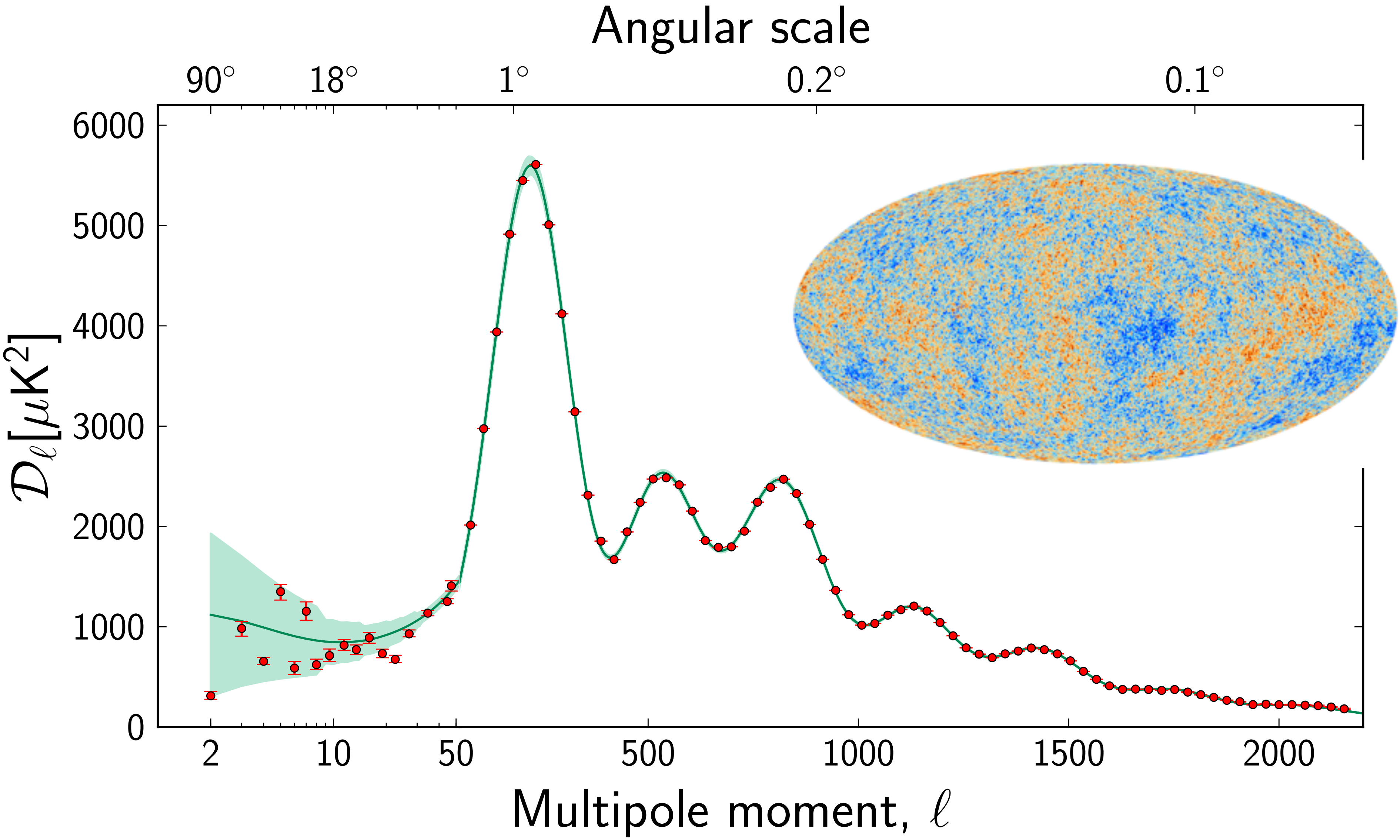
Jo Dunkley

Oxford Astrophysics

On behalf of the Planck collaboration

KITP, April 22

This talk focused on Paper XVI: Cosmological Parameters; paper lead G. Efstathiou


Angular scale
90°
18°
1°
0.2°
0.1°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
Multipole moment, ℓ

What questions can we ask of the data?

Does ΛCDM still work?

Is inflation the right paradigm?

Which inflation model?

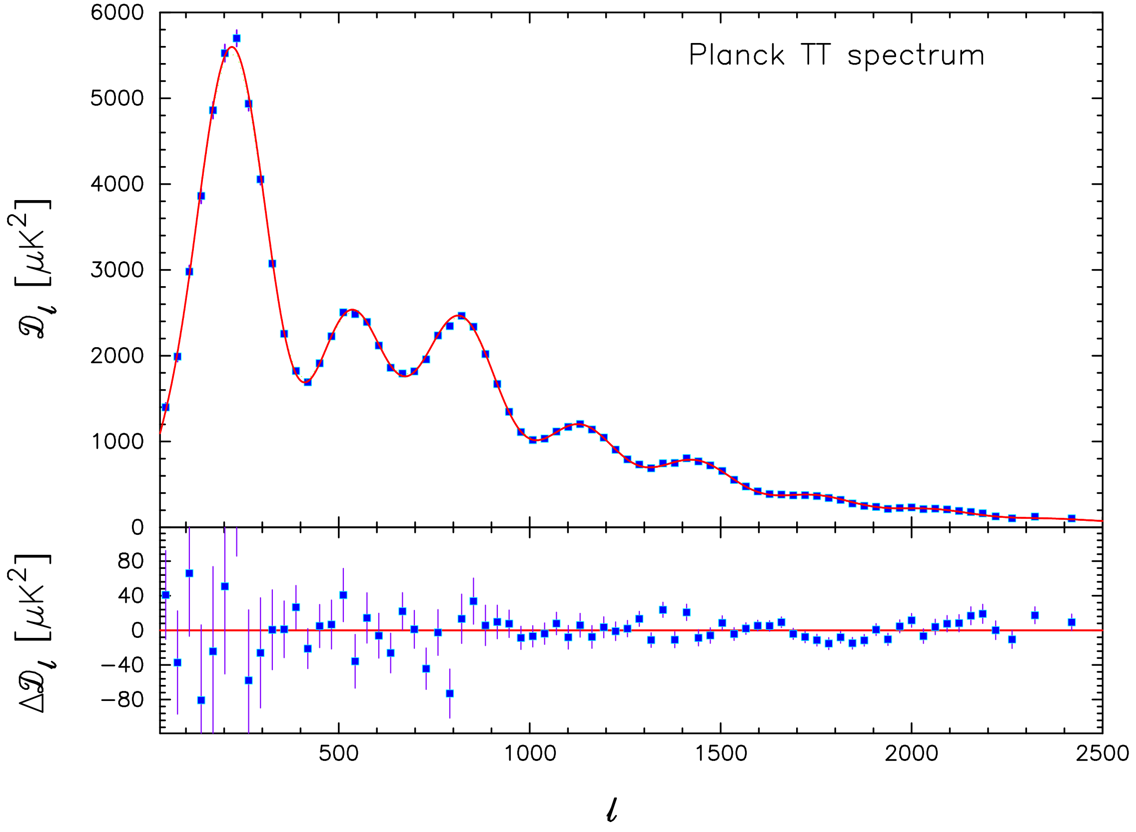
Is Dark Energy a constant, or a dynamical component?

What are the masses of the neutrinos?

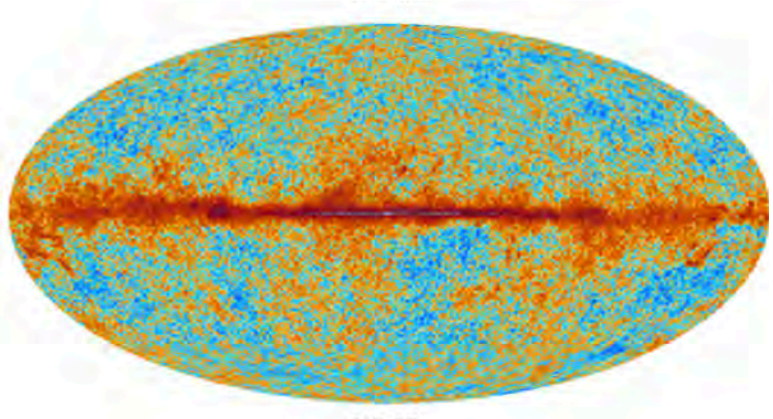
Are there extra relativistic species?

Are there other high energy signatures?

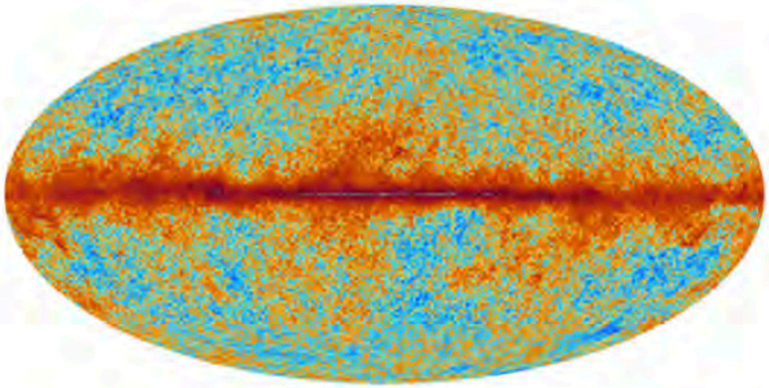
Are there ‘other’ signatures?



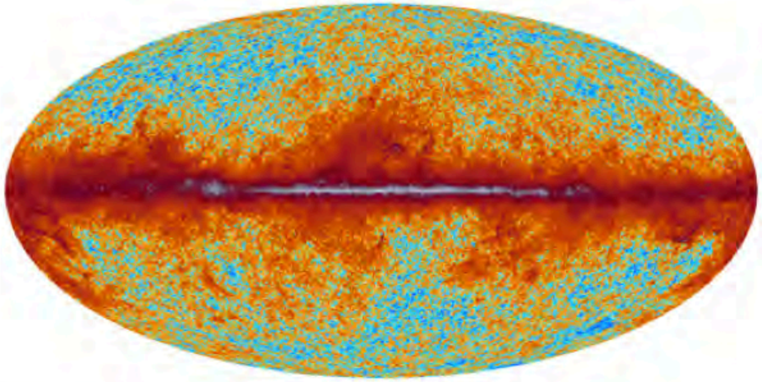
Planck spectra



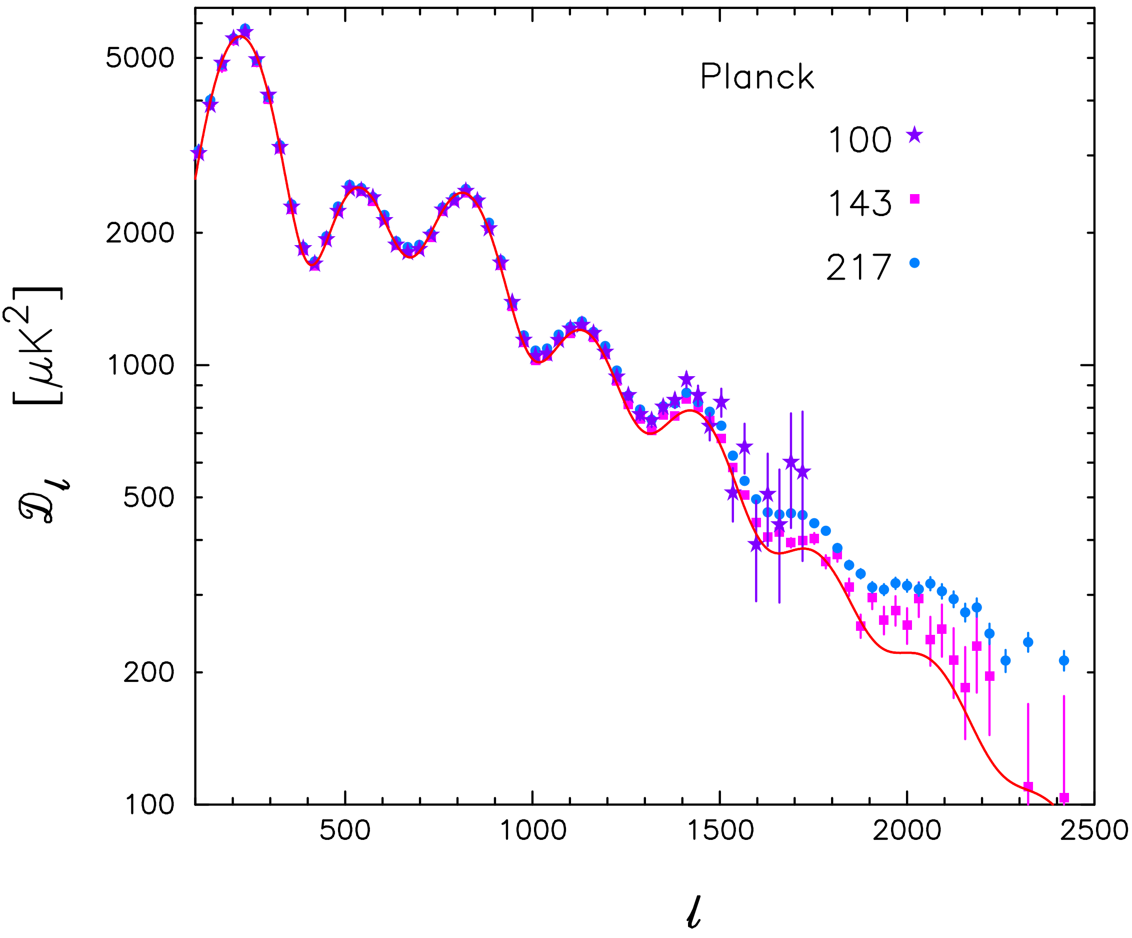
100 GHz 49%



143 GHz 31%

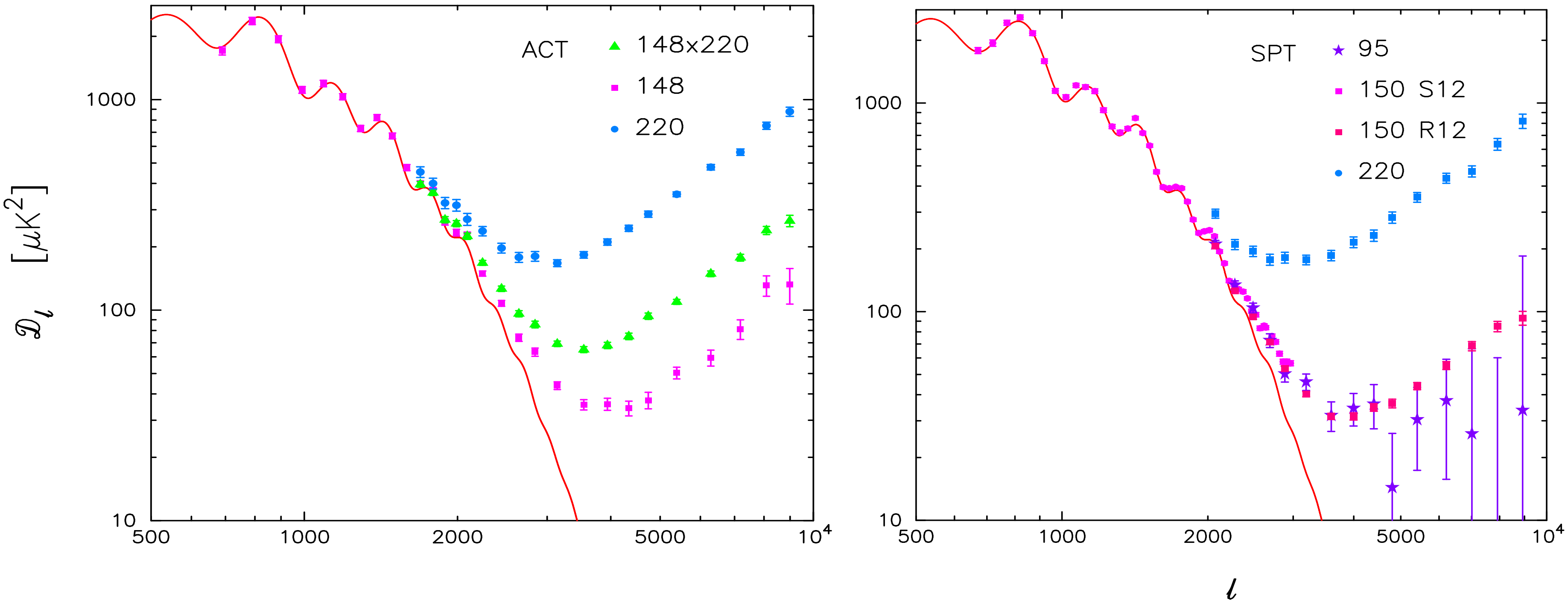


217 GHz 31%



Non-CMB spectra at small scales modeled with extra parameters

ACT and SPT at smaller scales



'Secondary' power from:

Extragalactic sources (radio and infrared)

Thermal and kinetic Sunyaev-Zel'dovich effects

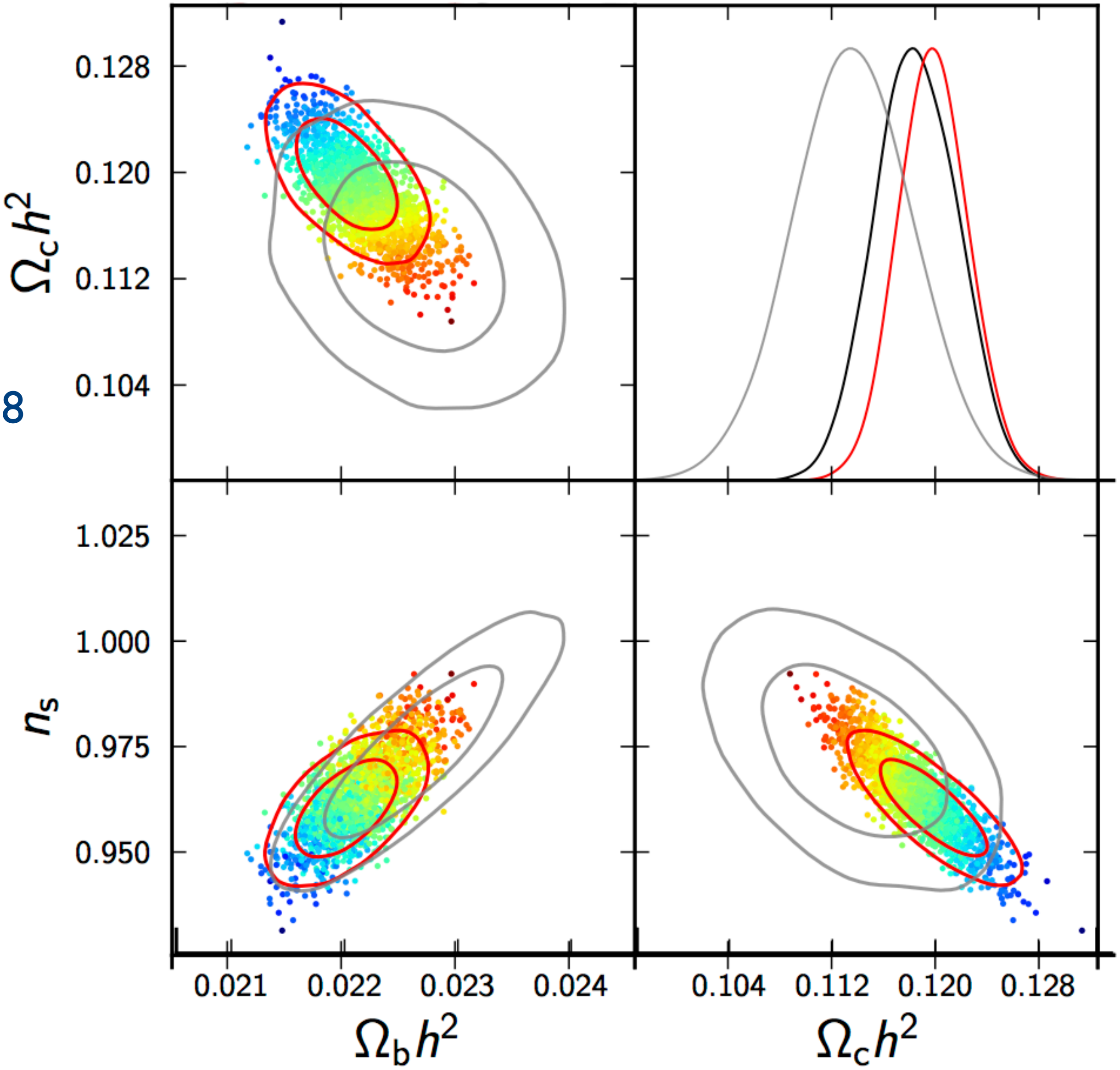
Galactic cirrus

ΛCDM

Planck +*WP*

$\Omega_b h^2$ = 0.02205 ± 0.00028
$\Omega_c h^2$ = 0.1199 ± 0.0027
n_s = 0.960 ± 0.007
τ = 0.089 ± 0.014
$10^9 A_s$ = 2.20 ± 0.06

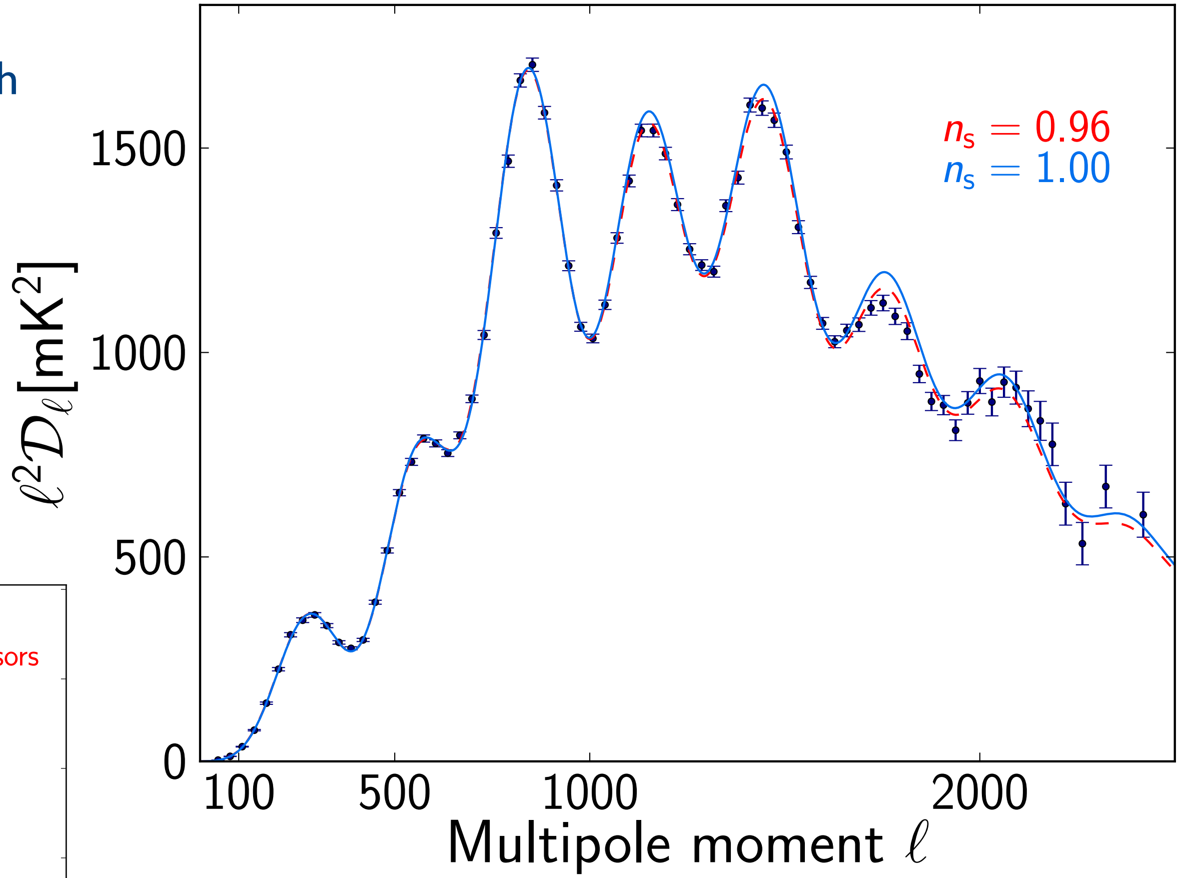
H_0 = 67.3 ± 1.2
Ω_Λ = 0.685 ± 0.017
σ_8 = 0.829 ± 0.012

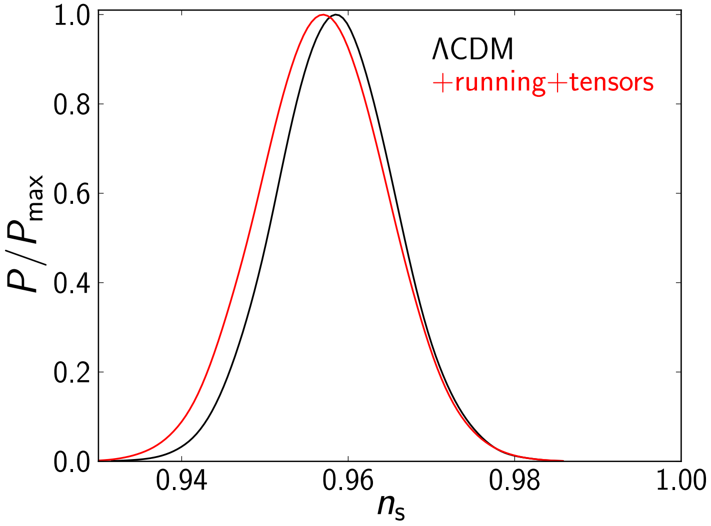


Scalar spectral index: n<1

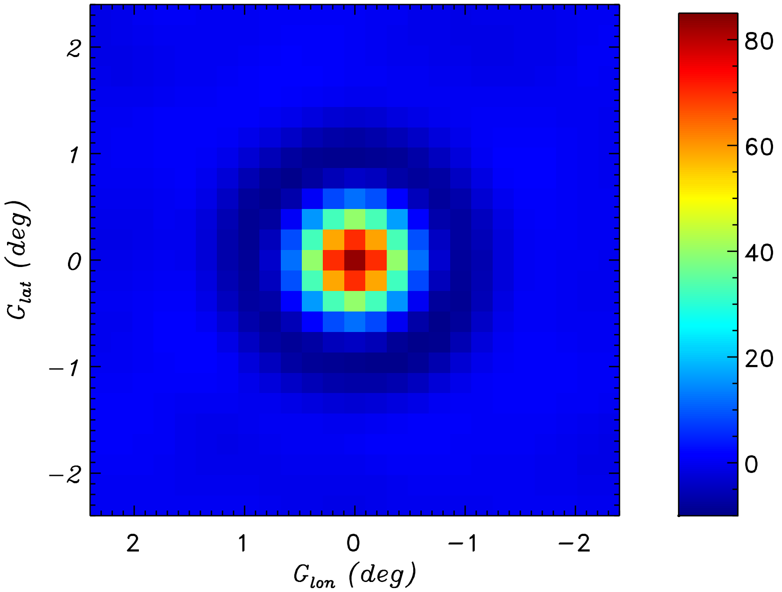
Harrison-Zel'dovich: too much power on small scales
Ruled out at >5σ

$n_s = 0.960 \pm 0.007$

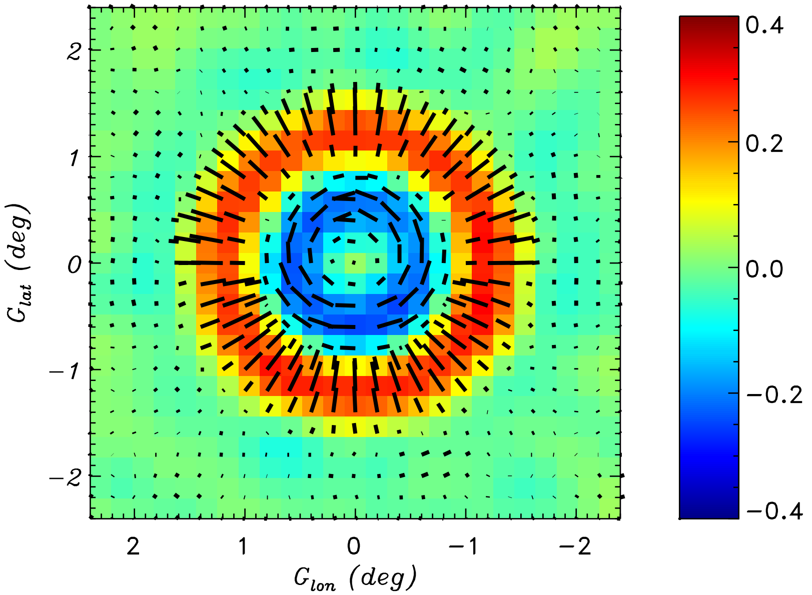




Consistency with polarization



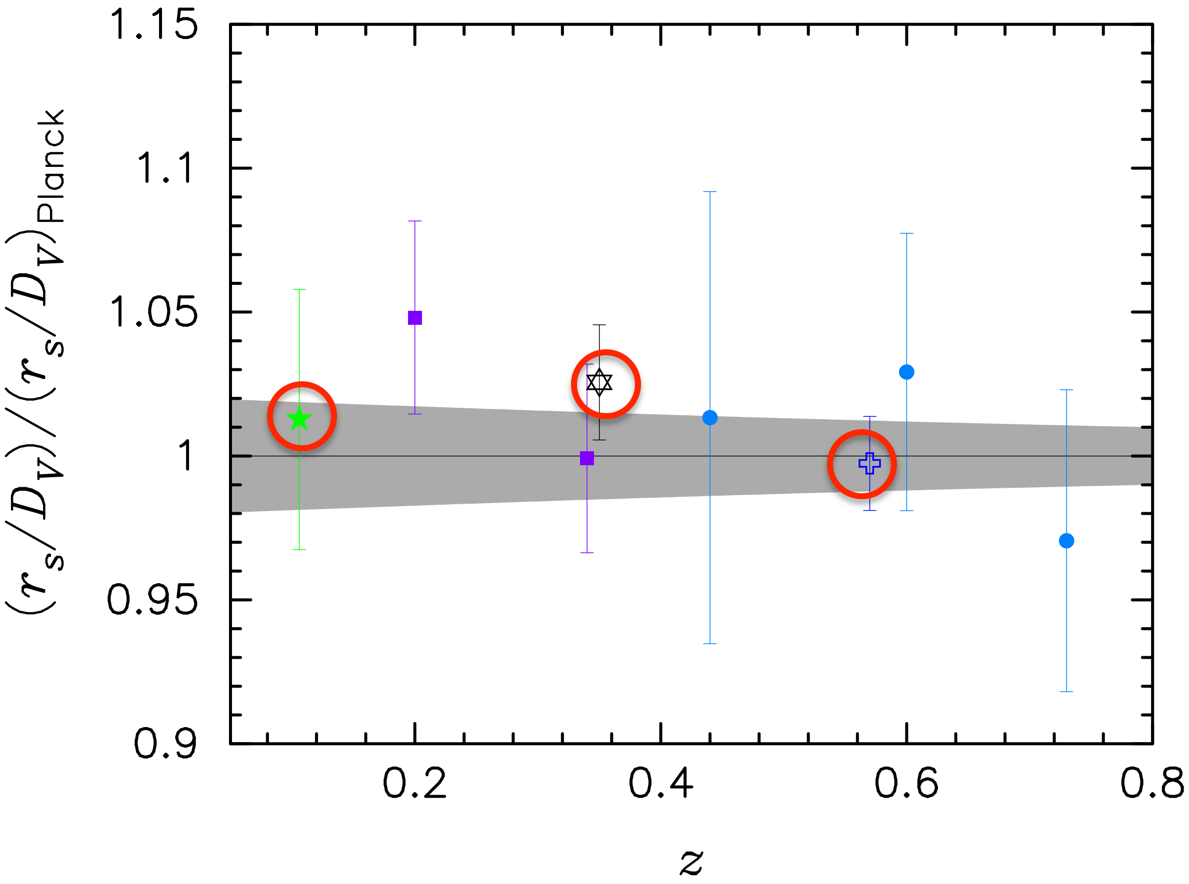
Intensity (hot spots)



Q_r (hot spots)

Polarization shows the dynamics of fluctuations at recombination
Flowing into potential well at one degree scales
Flowing out of well at half degree scales (high pressure causes reversal)

Consistency with BAO

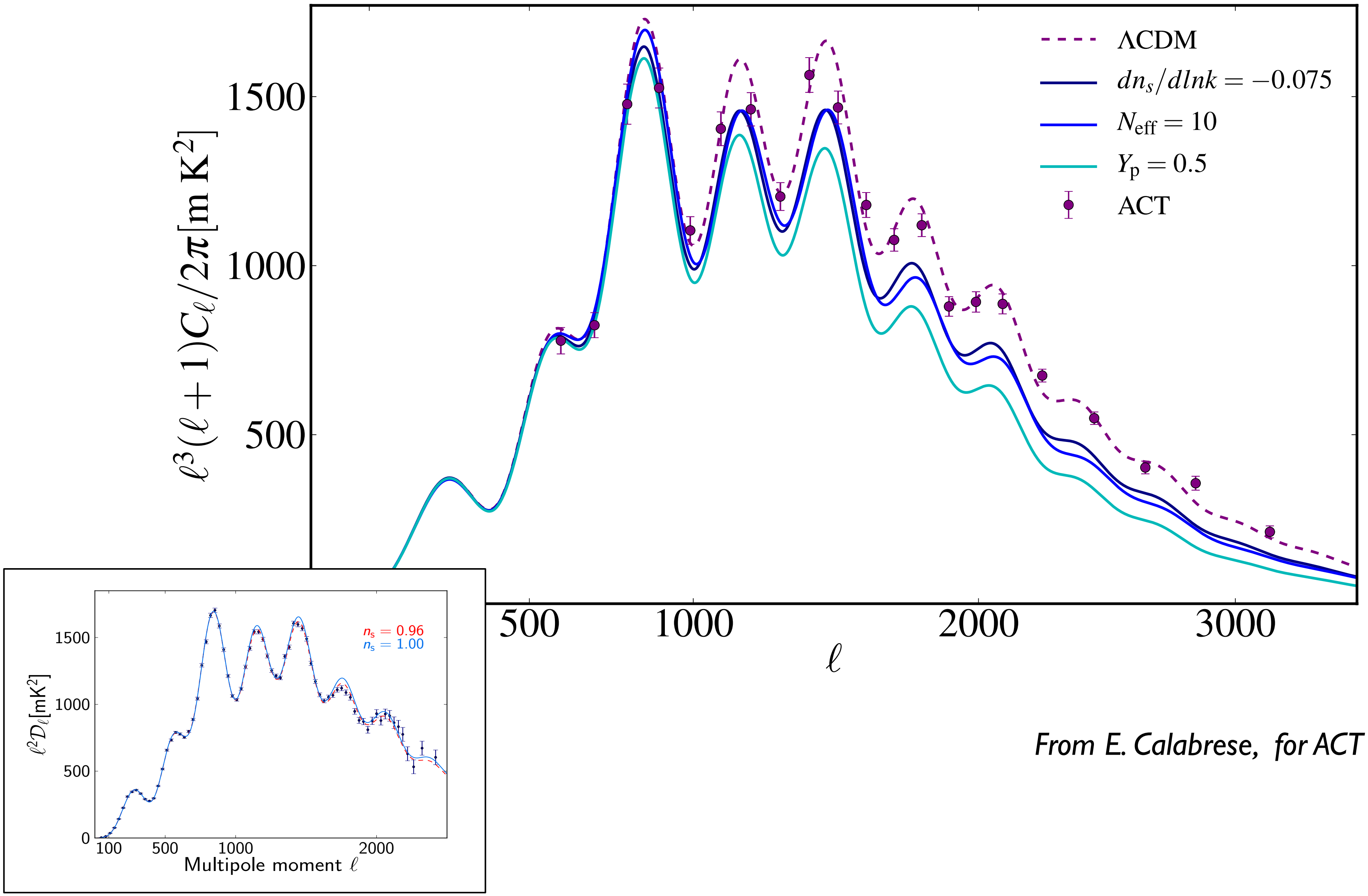


r_s is the comoving sound horizon at the baryon drag epoch

D_V combines the angular diameter distance and the Hubble parameter

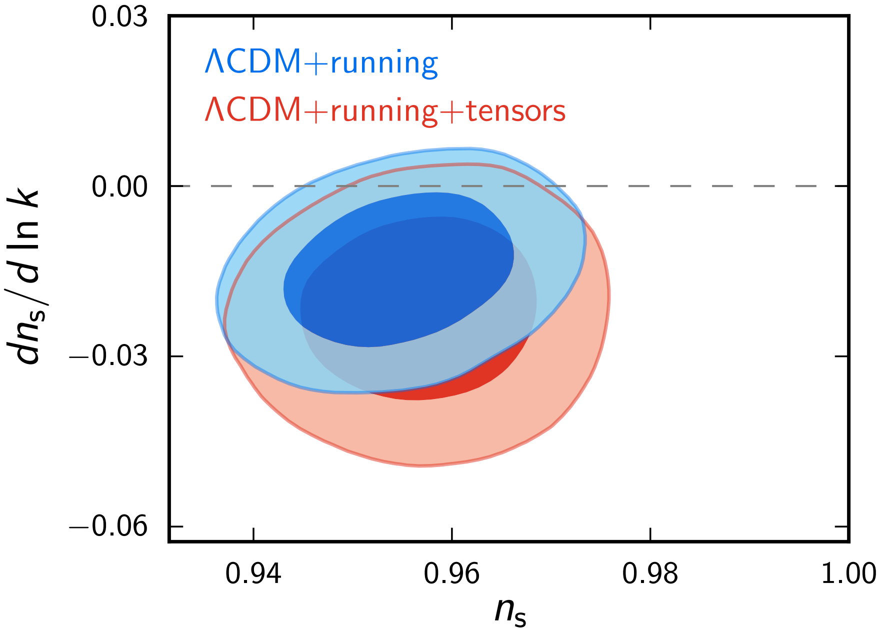
$$D_{\rm V}(z) = \left[(1+z)^2 D_{\rm A}^2(z)\frac{cz}{H(z)}\right]^{1/3}.$$

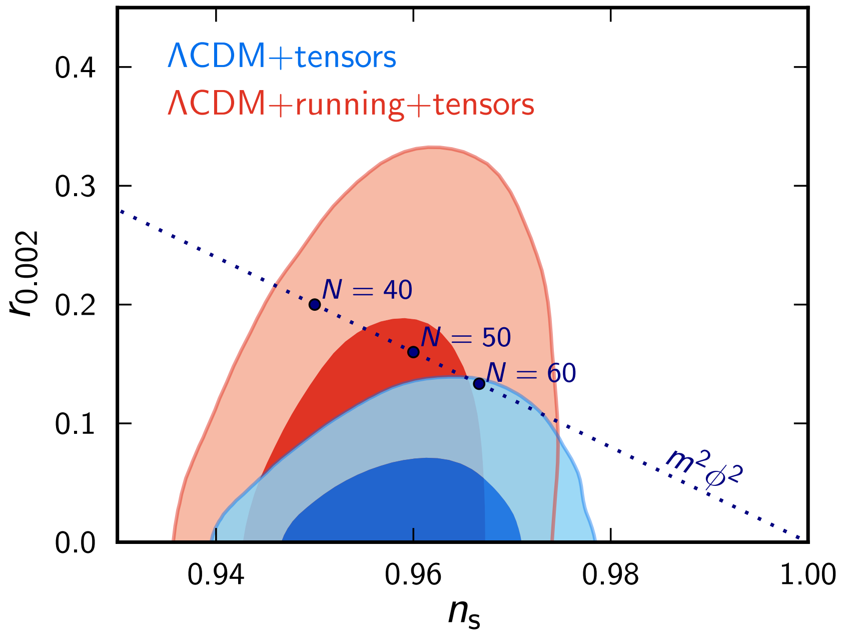
What do the small scales tell us?



From E. Calabrese, for ACT

Primordial fluctuations





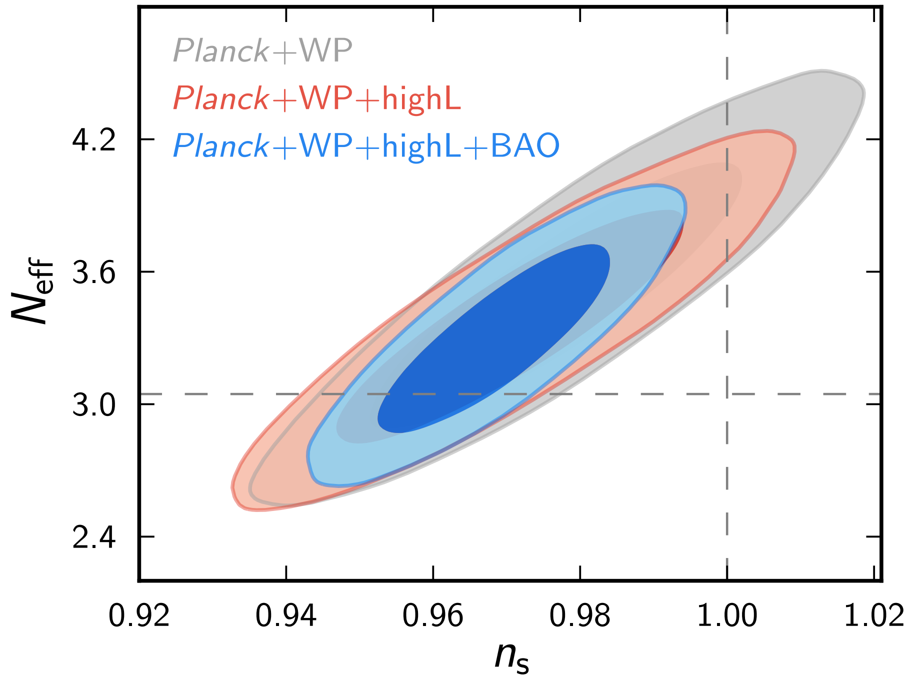
$dn_s/d\ln k = -0.015 \pm 0.009$ (68%, Planck+WP+highL)

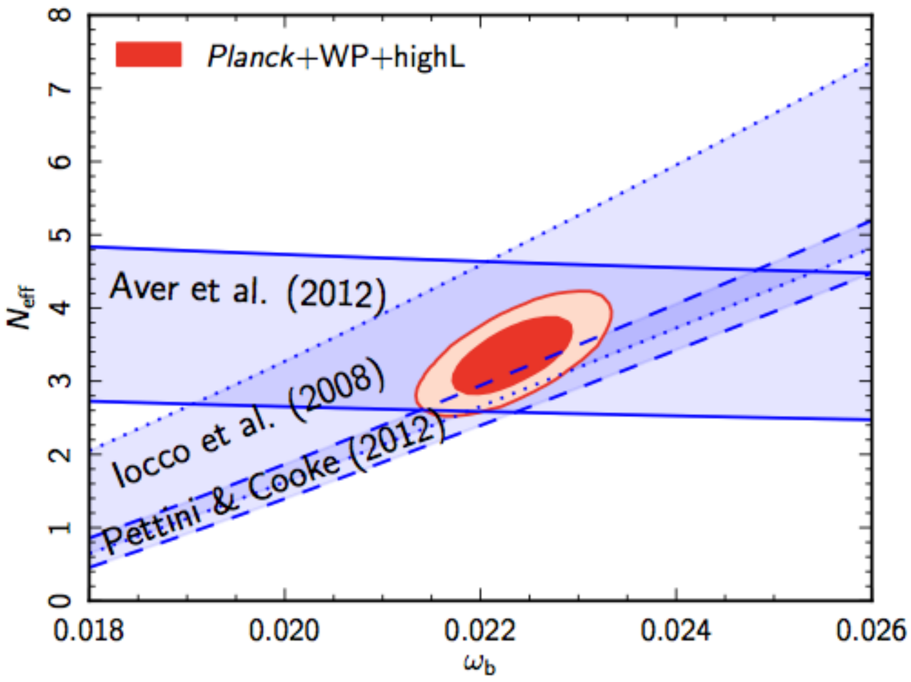
$r < 0.11$ (95%, Planck+WP+highL)

Constraint on r comes from large-scale TT; low-ell spectrum is ‘low’

Relativistic species

$$\rho_{rel} = \left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_{\gamma}$$

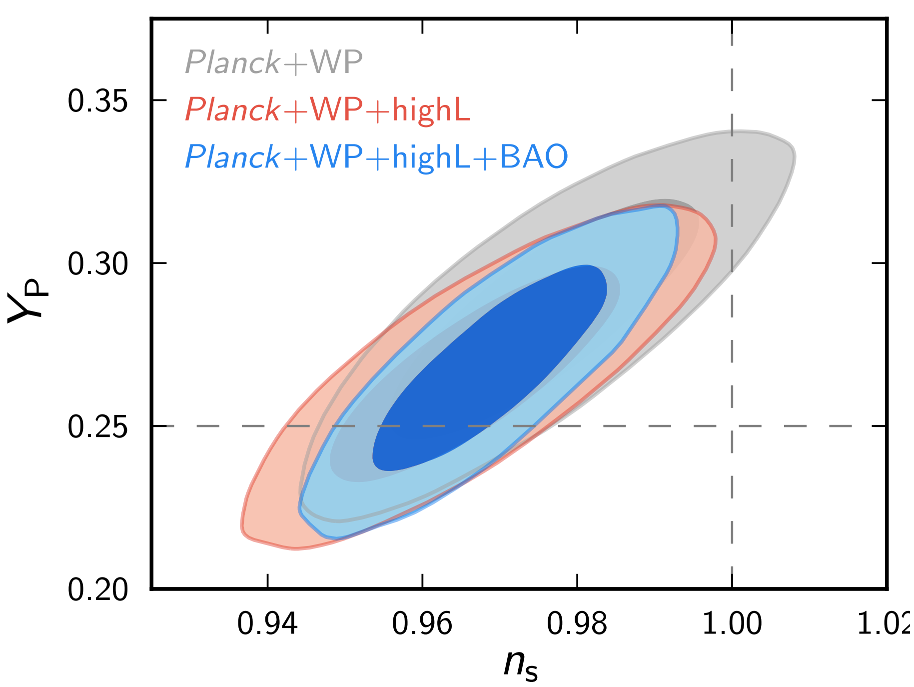


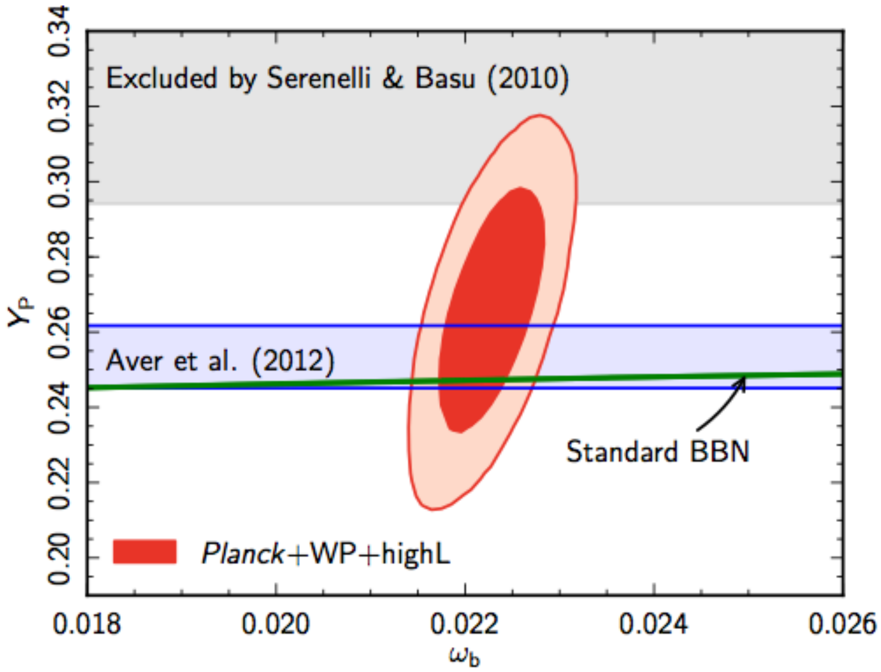


More species, longer radiation domination; suppress early acoustic oscillations in primary CMB; have anisotropic stress

N_{eff} = 3.36 ± 0.34 (68%, Planck+WP+highL)
N_{eff} = 3.30 ± 0.27 (+BAO)

Primordial helium fraction



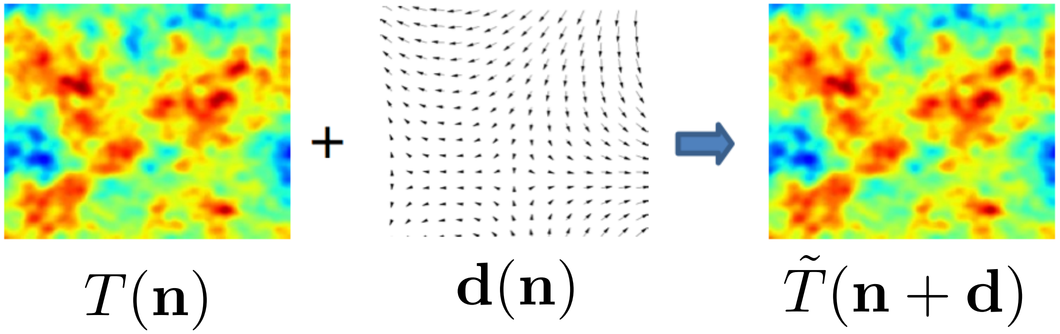


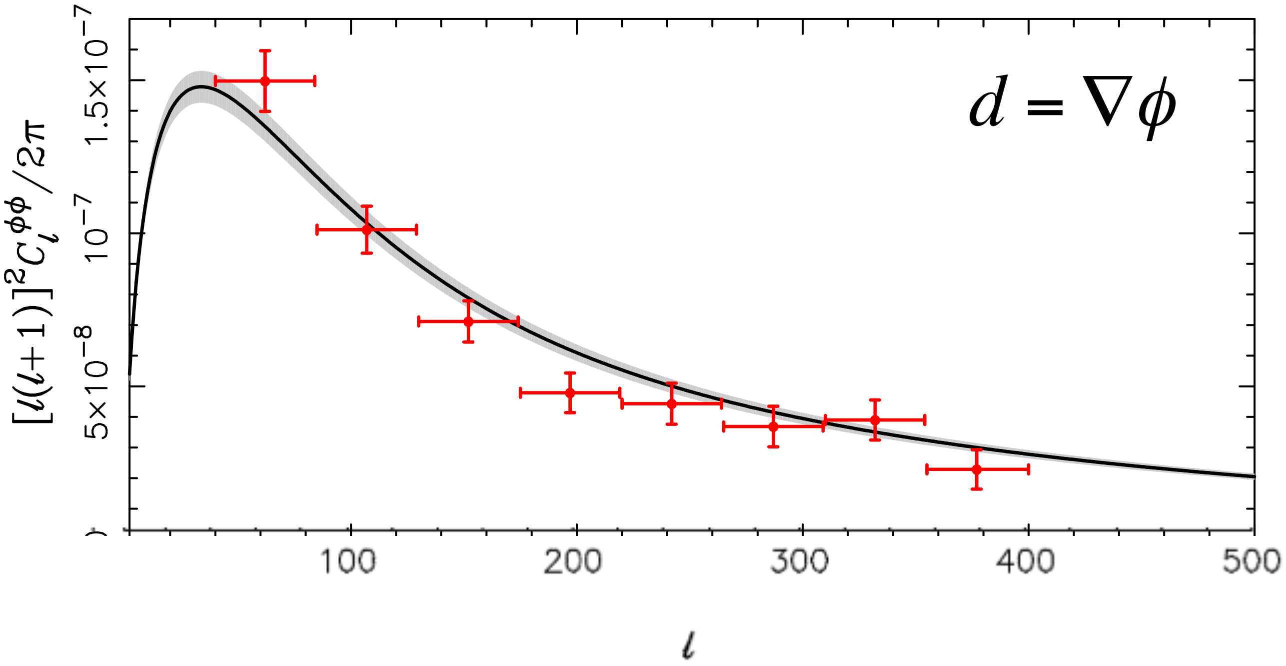
Increasing the Helium fraction increases mean free path of
Compton scattering: $n_e = n_b(1-Y_P)$

Previously hard to distinguish from changing Neff or running

$Y_P = 0.266 \pm 0.021$ (68%, Planck+WP+highL)

Planck lensing





$$\frac{\ell^2}{4}C_\ell{}^{dd} = \int_0^{\eta_*} \mathrm{d}\eta\, \underbrace{W^2(\eta)}_{\text{geometry}}\ \underbrace{P\left(k=\frac{\ell+1/2}{d_A(\eta)},\eta\right)}_{\text{matter}}$$

Spatial curvature

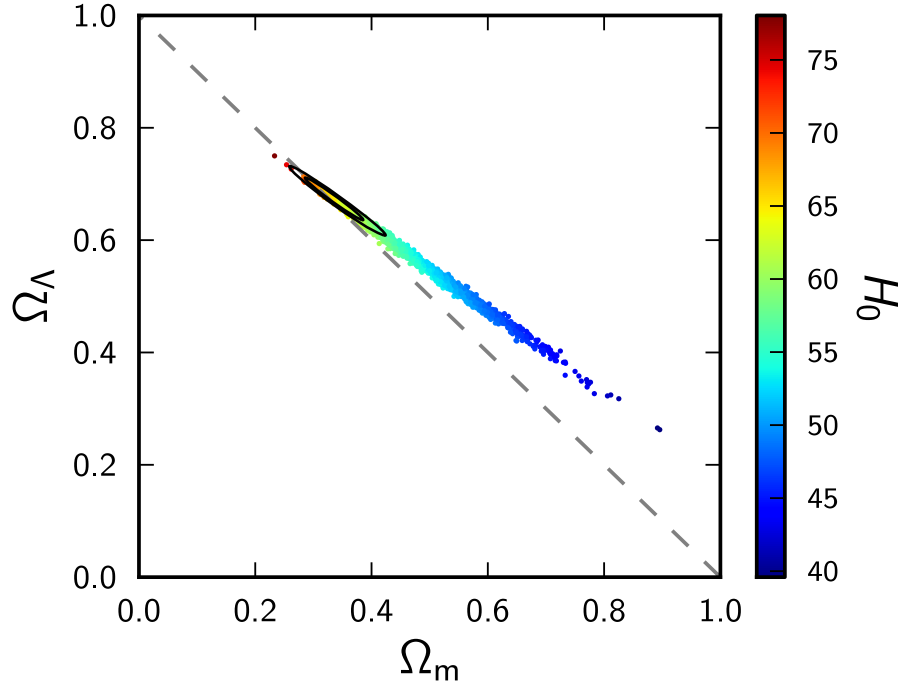
With primary CMB, cannot measure curvature.

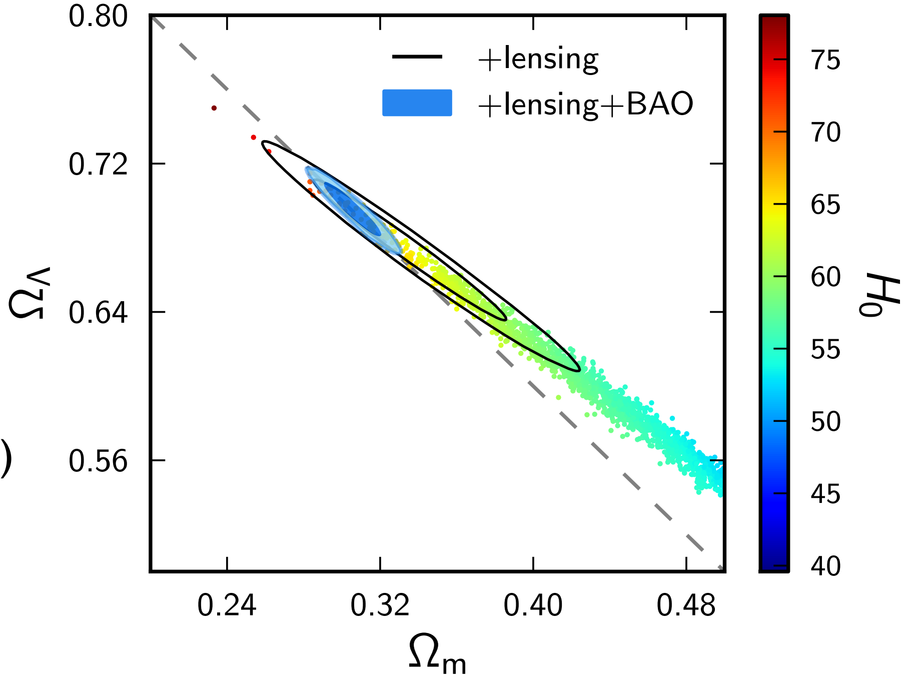
Planck measures curvature through lensing
(more closed, less dark energy → more lensing)

(i) smears out the small-scale TT peaks and moves power to small scales

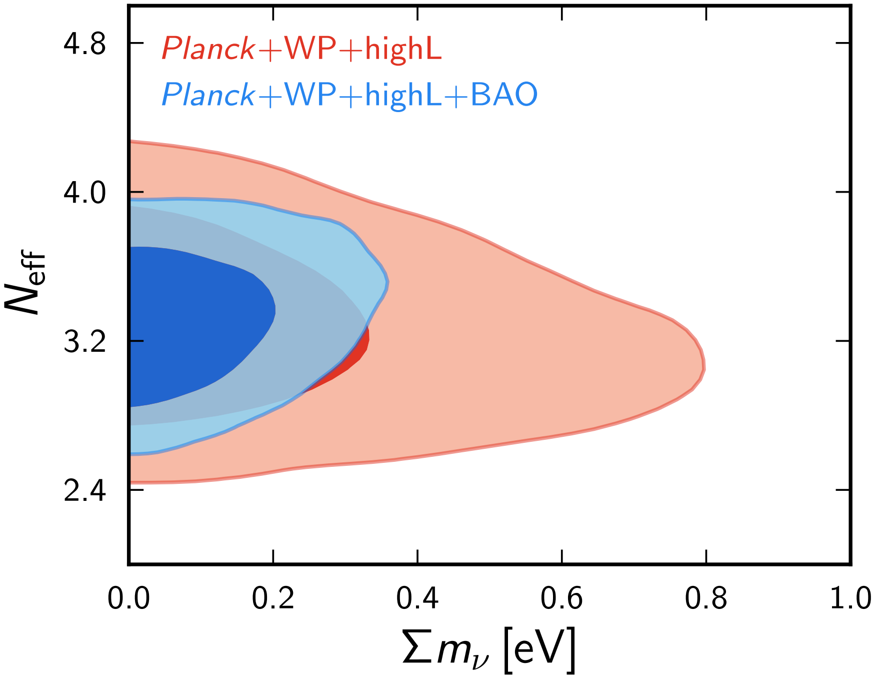
(ii) boosts the deflection power spectrum (about double at $\Omega_\Lambda = 0$)

Ω_k = -0.01 ± 0.009 (68%, Planck+WP+highL+lensing)
Ω_k = -0.001 ± 0.0032 (+BAO)





Sum of neutrino masses



- Still relativistic at recombination
- Improved limit from lensing in power spectrum: more mass = less lensing

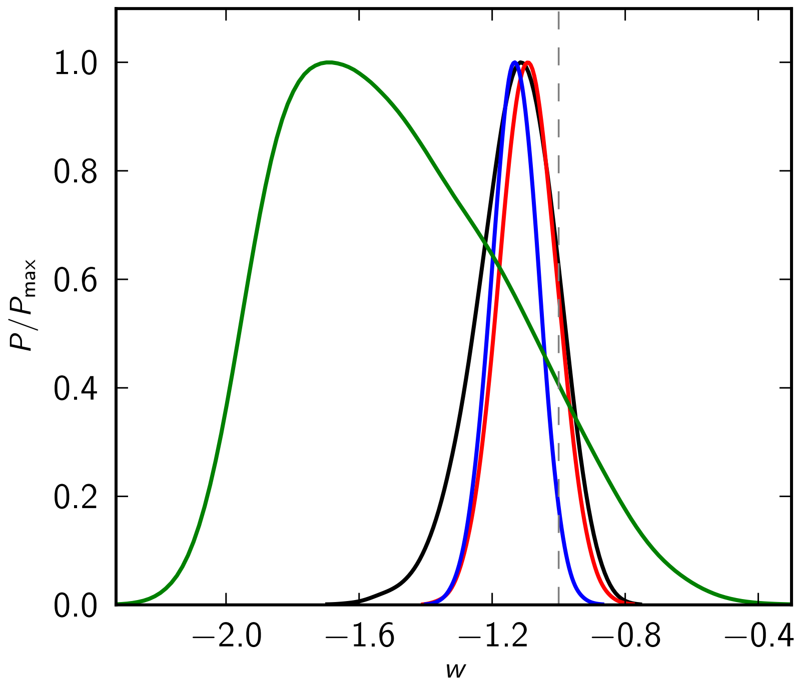
$\Sigma m_\nu < 0.66$ eV (95%, Planck+WP+highL)
$\Sigma m_\nu < 0.23$ eV (+BAO)

- But, adding Planck lensing spectrum increases limit to <0.85 eV.

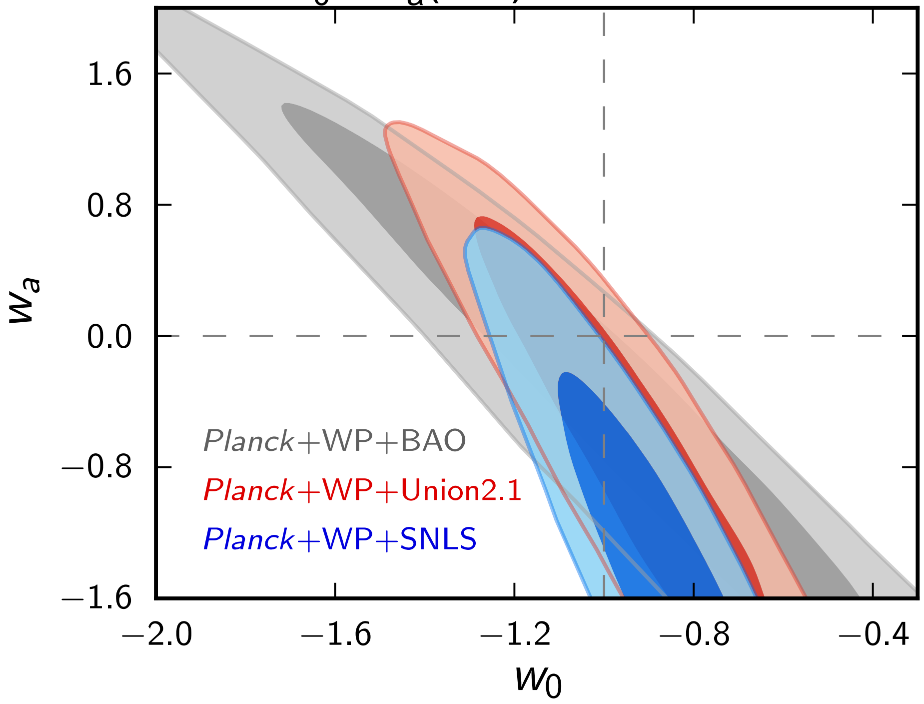
- With nominal cluster mass bias, SZ cluster counts prefer non-zero neutrino mass (~0.5 eV).

Dark energy

1: w=const



2: $w=w_0 + w_a(1-a)$



w = -1.13 ± 0.12 (68%, Planck+WP+BAO)

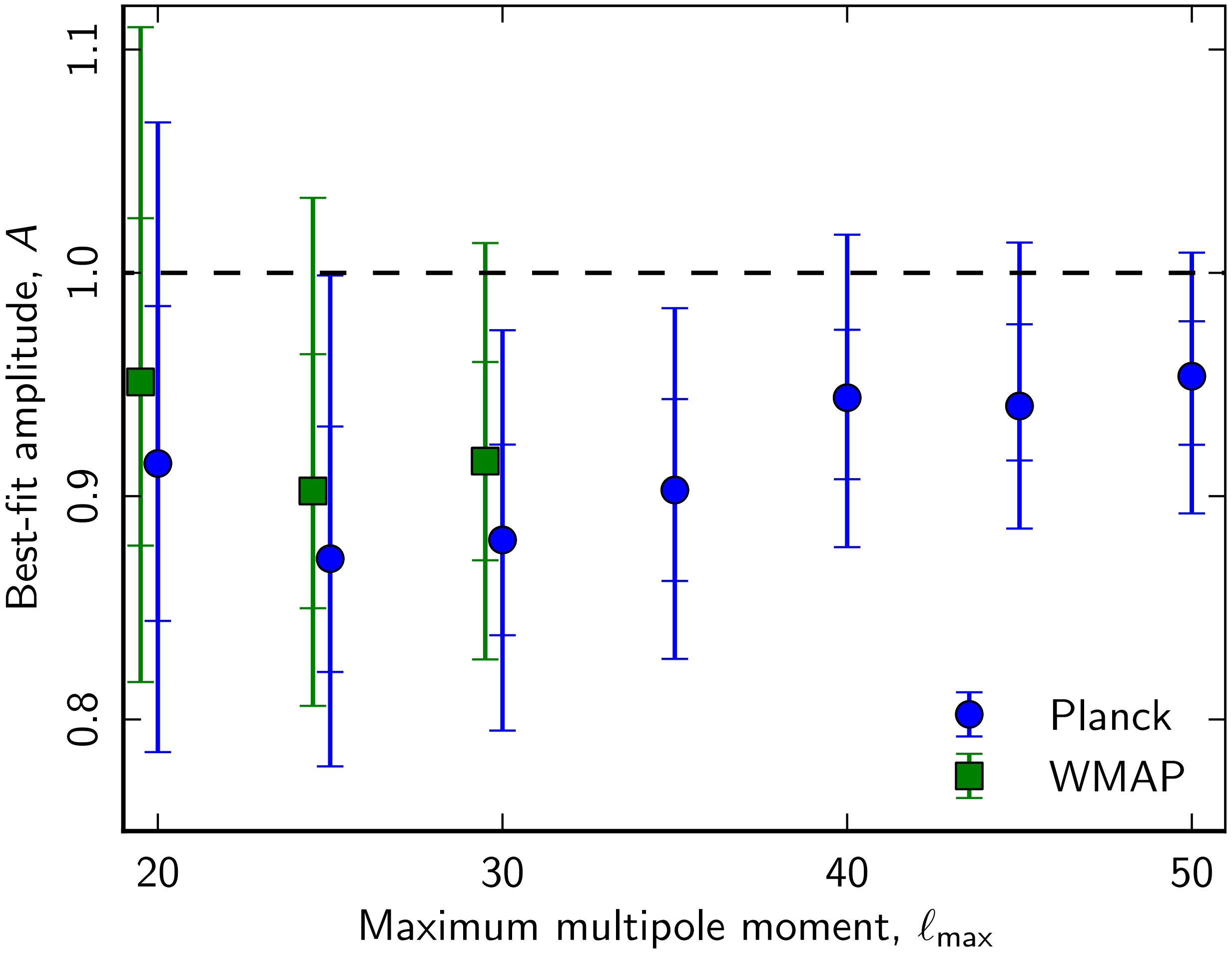
SNLS (blue) favours phantom dark energy, w<-1

3: Early dark energy

$$\Omega_{\rm de}(a) = \frac{\Omega^0_{\rm de} - \Omega_{\rm e}(1 - a^{-3w_0})}{\Omega^0_{\rm de} + \Omega^0_{\rm m} a^{3w_0}} + \Omega_{\rm e}(1 - a^{-3w_0}) \ .$$

$\Omega_{\rm e} < 0.009$ (95%; *Planck*+WP+highL).

Low-ell ‘anomaly’: 2-3σ low



Summary

- Planck has measured 7 acoustic peaks of the CMB power spectrum, and the lensing power spectrum

- Places strong (percent-level) constraints on ΛCDM model; in excellent agreement with data.
- Detection of n<1 at ~ 5 sigma; robust to extensions

- Some tension with direct H_0 and SN measurements, and with SZ cluster counts, within ΛCDM. Excellent consistency with BAO data.
- No model extensions are favoured, with significantly improved limits.

- The largest-scale power is low; anomalous at almost 3 sigma level