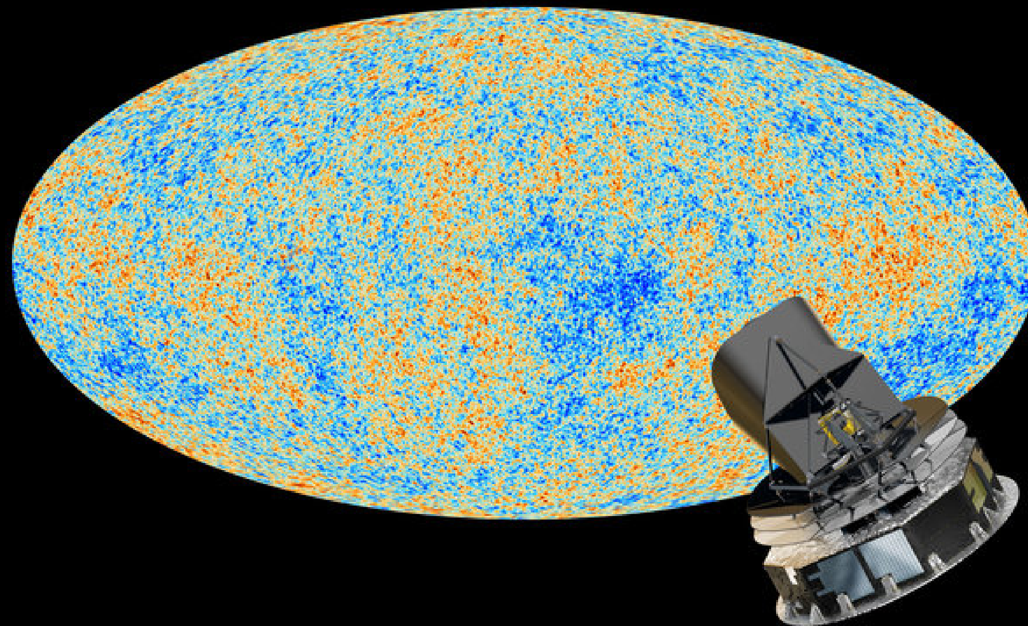

Cosmological parameters from the 2- and 4-point functions with Planck

Anthony Challinor

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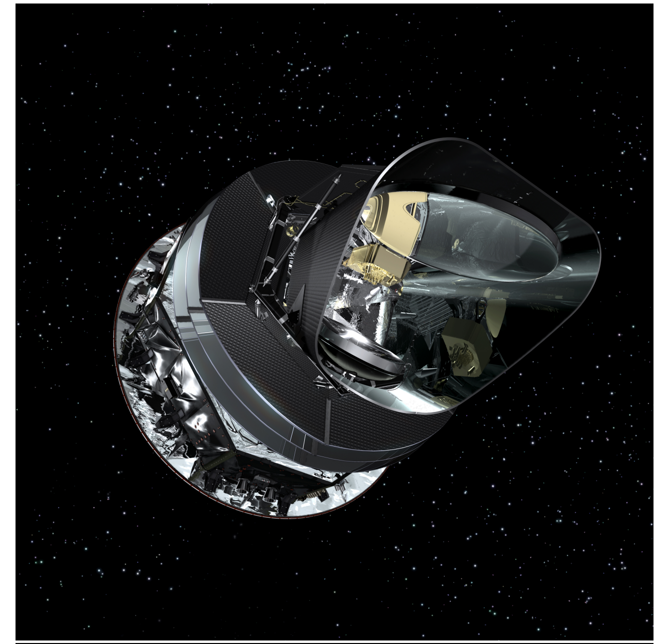
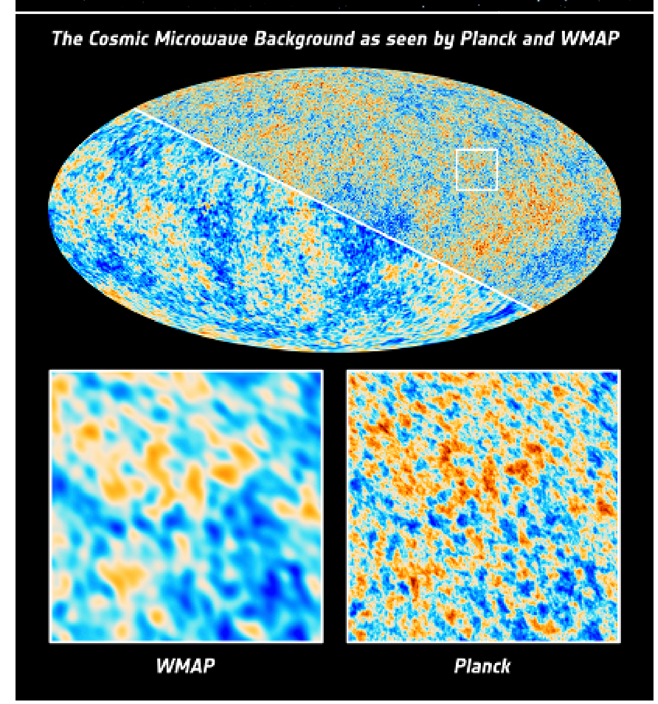
On behalf of the Planck collaboration

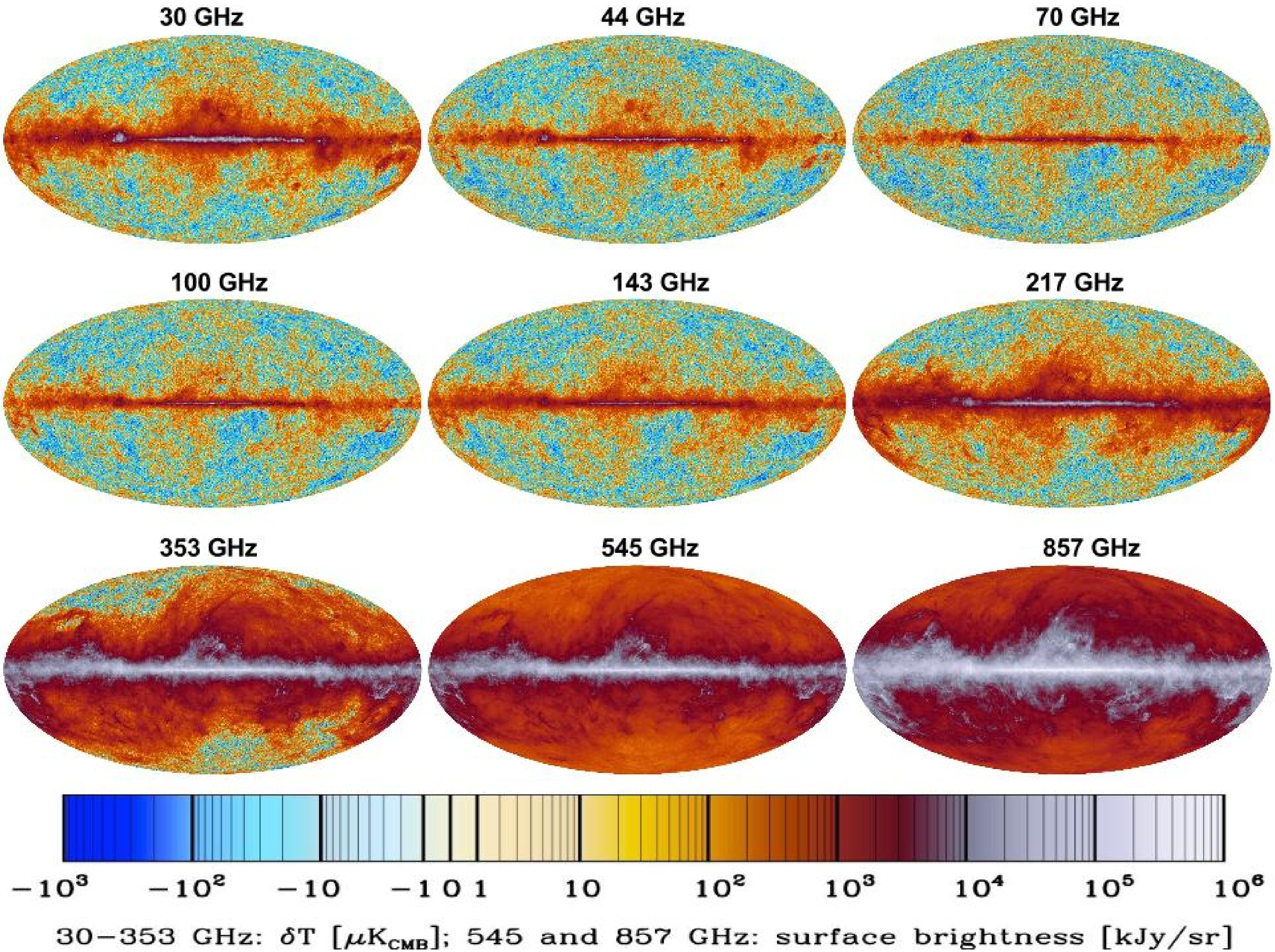
- Design goal: measure CMB ΔT to fundamental limits on scales $> 5\,\mathrm{arcmin}$
- Launched (with Herschel) 14 May 2009
- HFI operated to January 2012 completing > 4 sky surveys
- LFI still operational
- Nine frequencies covering 30–857 GHz
- $3\times$ resolution of WMAP
- $\sim 20\times$ instantaneous sensitivity
- Nominal Planck survey $7\times$ sensitivity of WMAP9

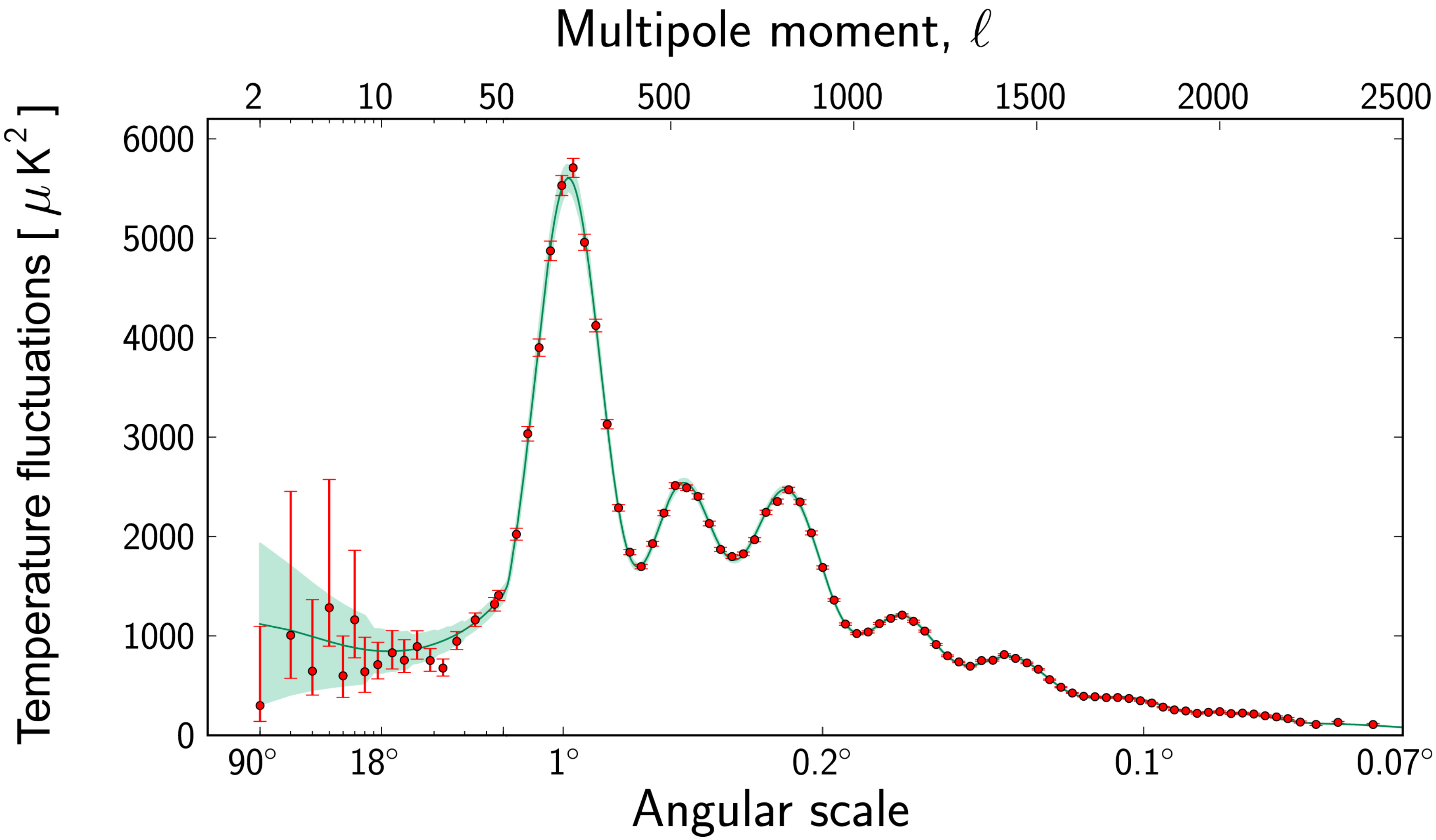




Planck collaboration

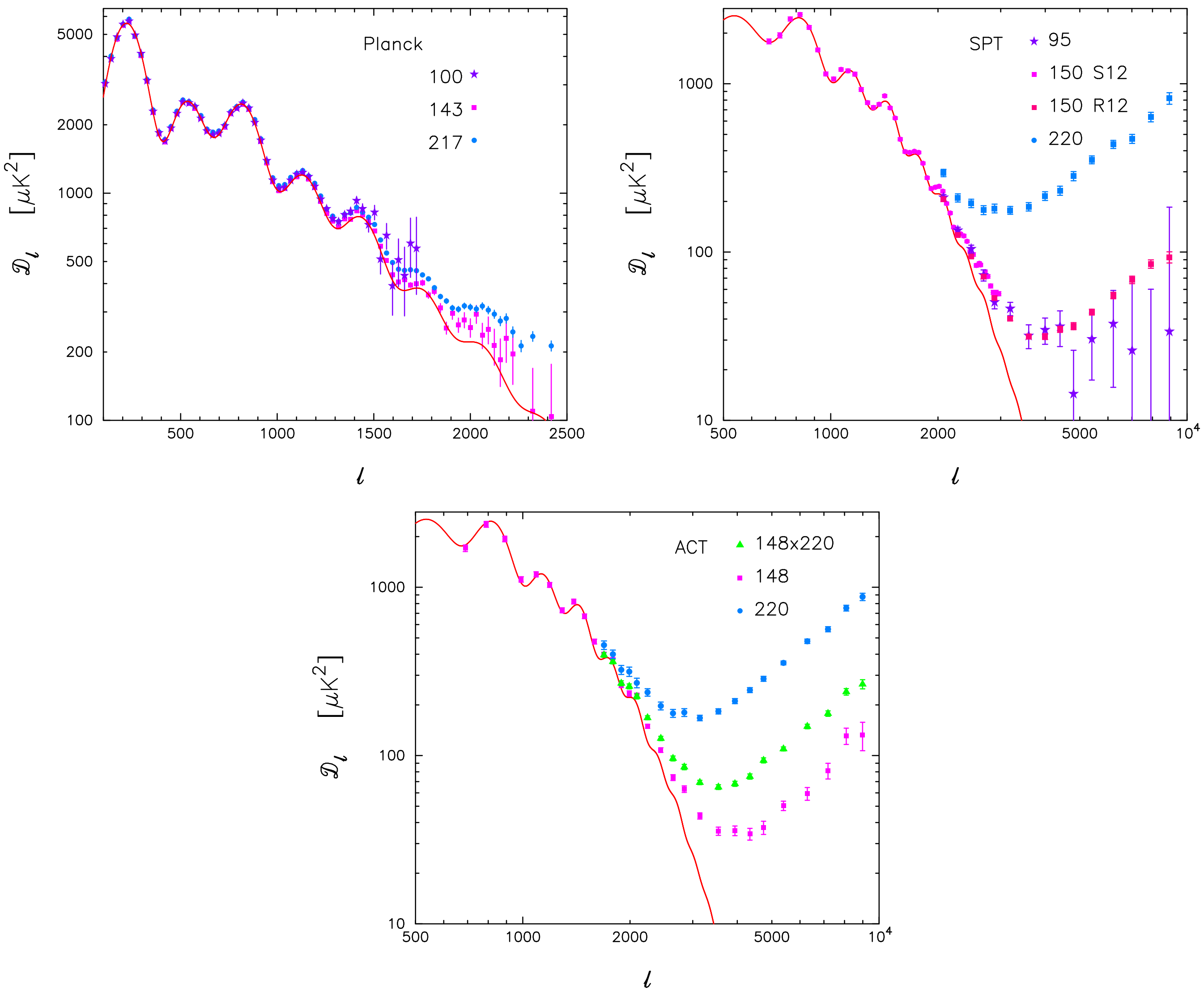
PLANCK MAPS


30 GHz
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]



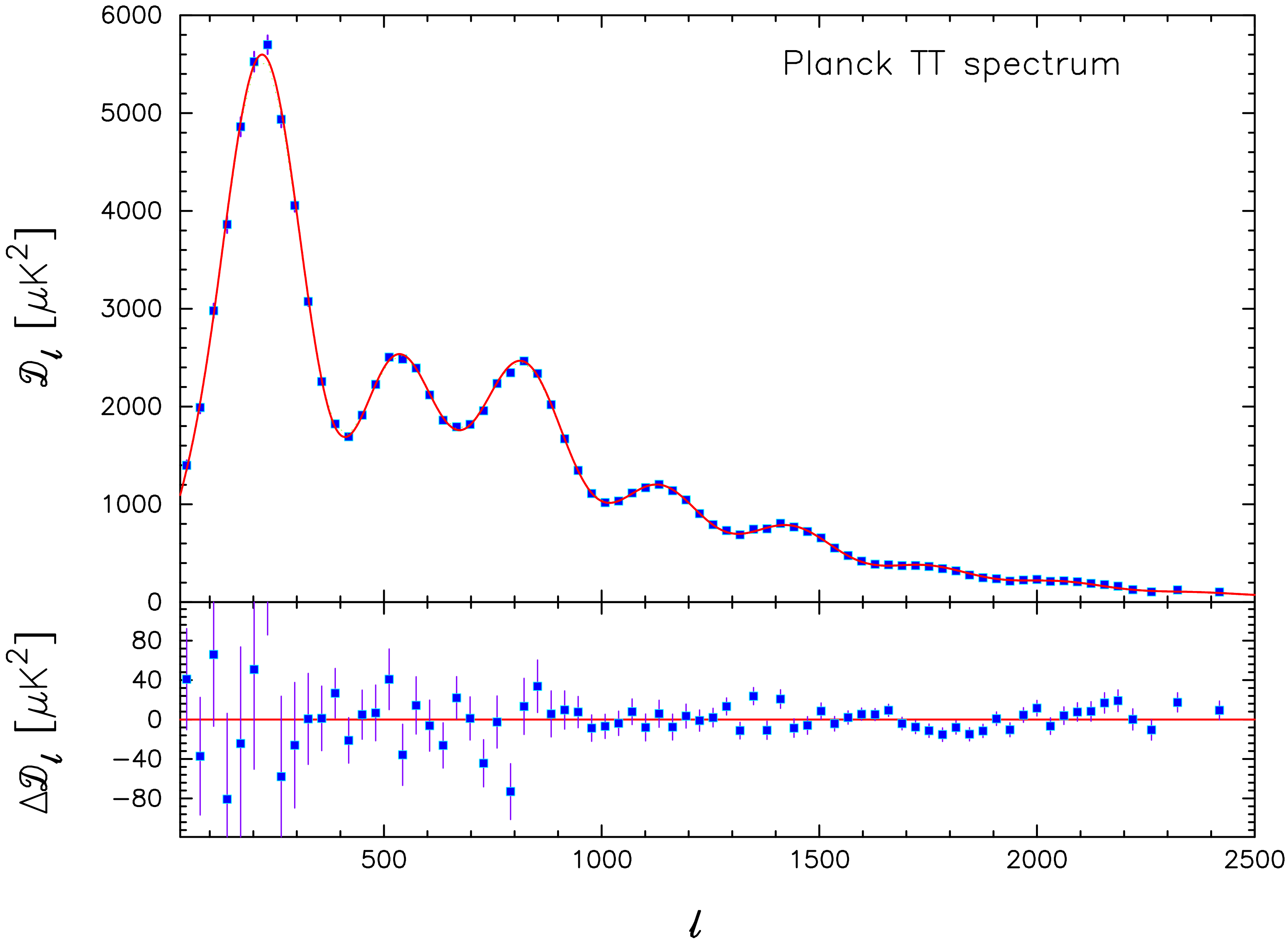
- $l < 50$: maximum-likelihood solution with parametric map-based foreground cleaning
- $l \geq 50$: best-fit C_l to all cross-spectra after fitting C_l-based foreground templates

UNRESOLVED FOREGROUNDS AND HIGH-l EXPERIMENTS



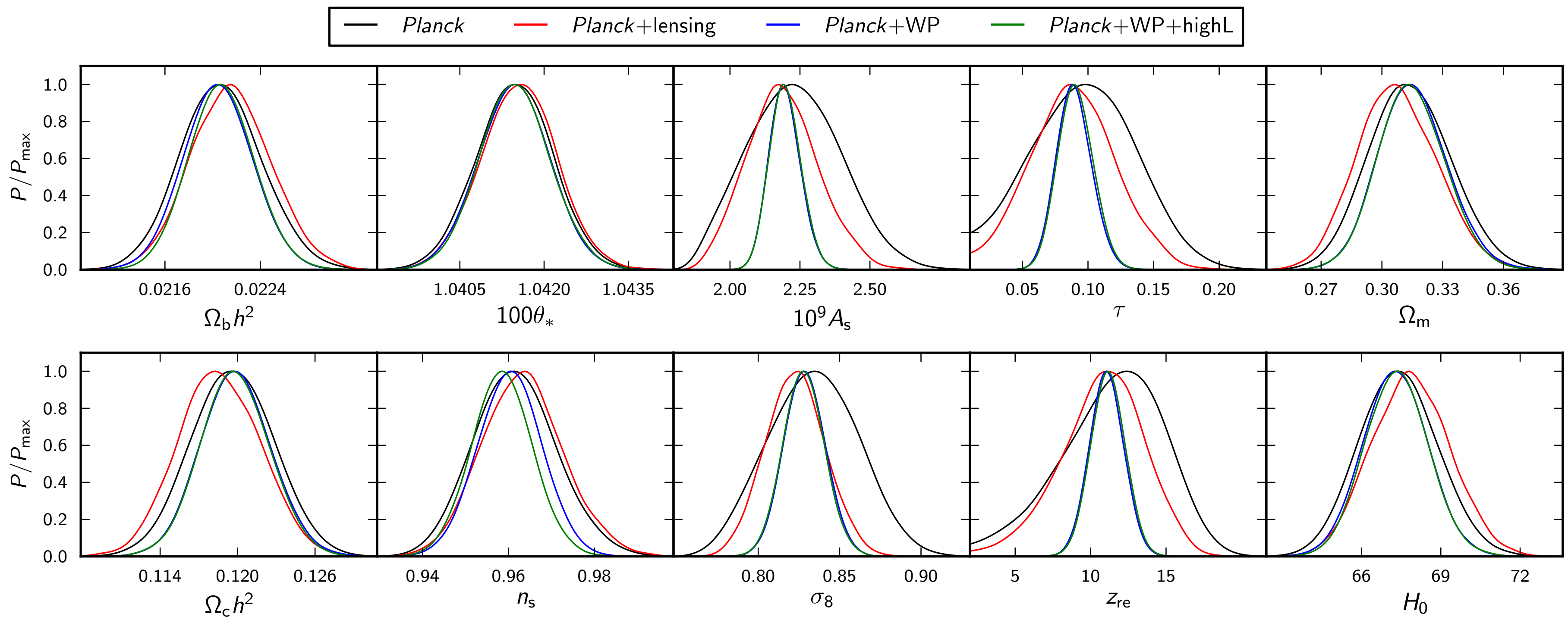
- Major unresolved extra-Galactic (isotropic) foregrounds: radio and dusty (CIB) galaxies and thermal SZ
- ACT and SPT spectra very helpful for constraining diffuse foreground contributions
- Beam uncertainties important for Planck at high-l

LCDM FIT

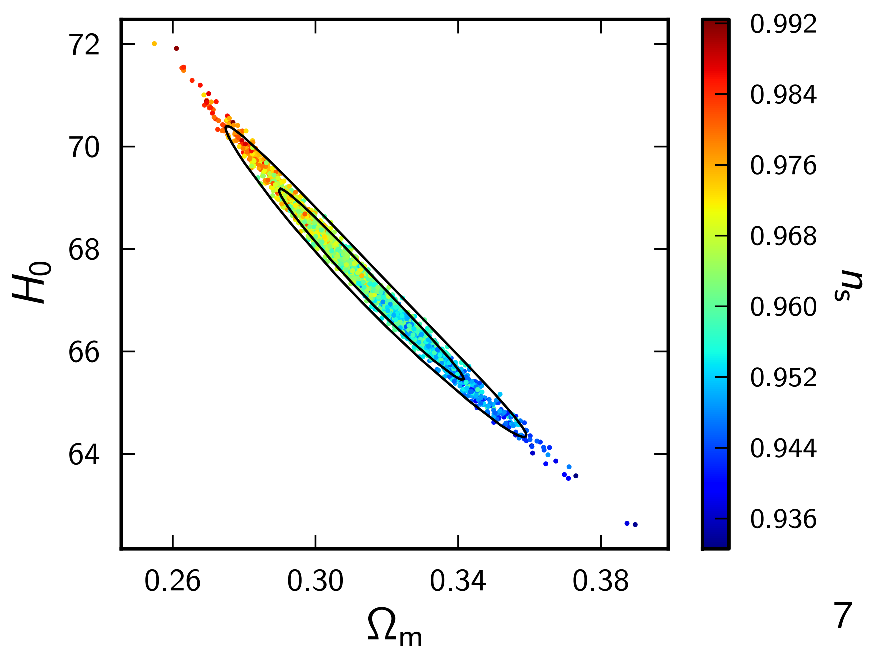


- Acceptable fit to channel spectra and composite spectrum: χ^2 compatible with LCDM to $1.6\,\sigma$

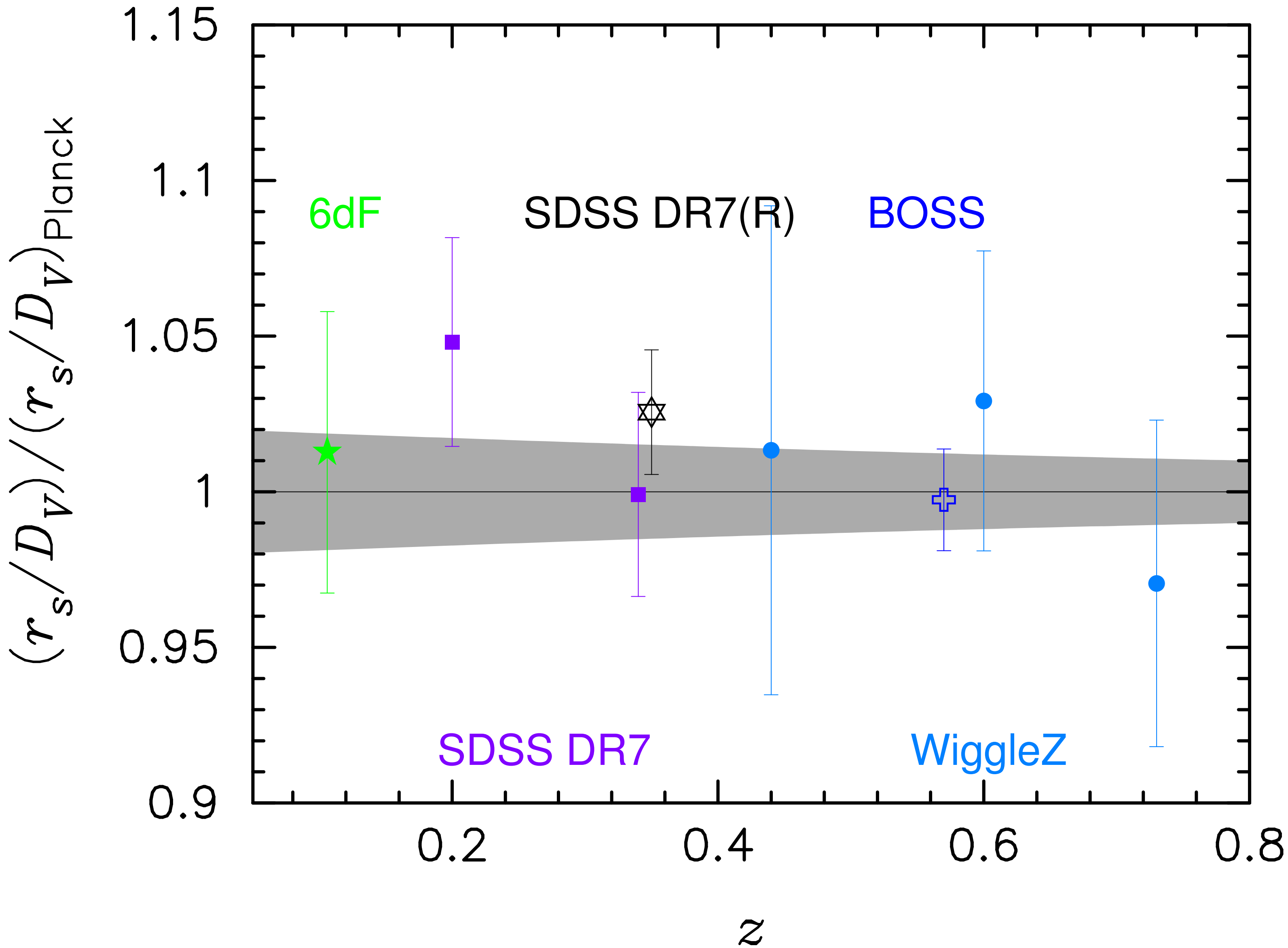
LCDM PARAMETERS



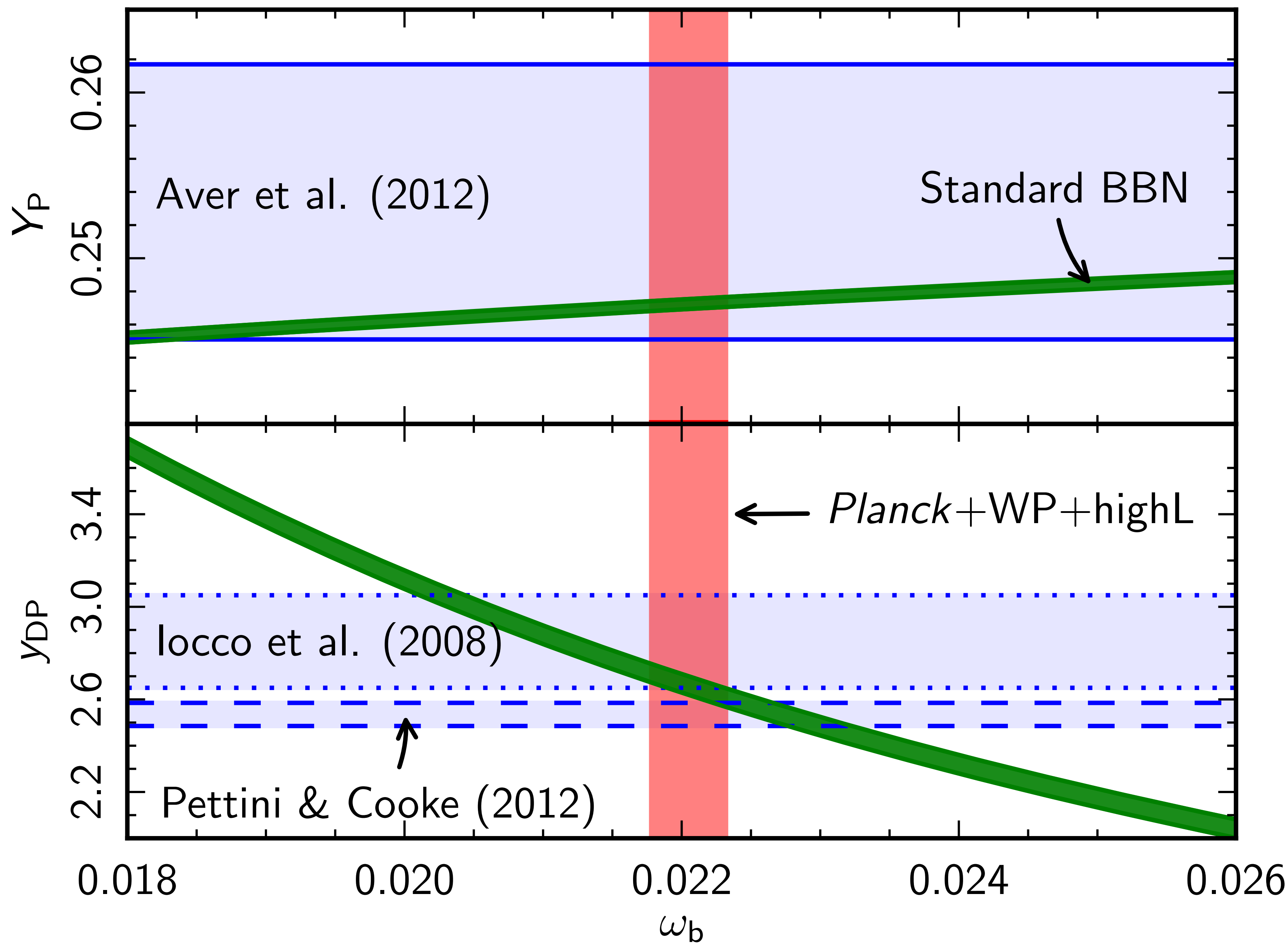
- Percent-level precision
- Not limited by foreground modelling
- Main degeneracy: $\Omega_m h^3 = \text{const.}$
  - 0.06% precision on θ_*
- τ from TT(+lensing) alone



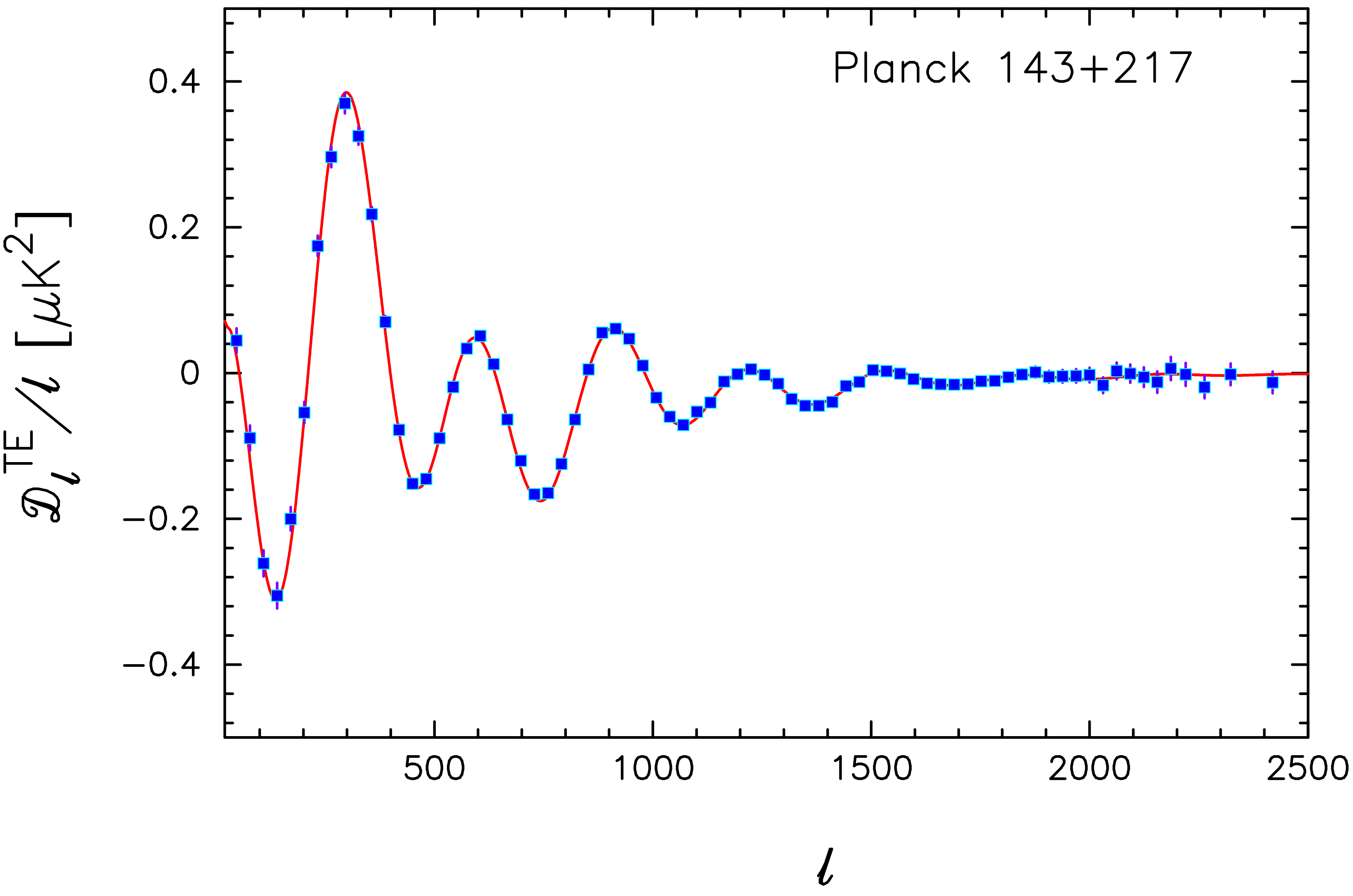
BAO CONSISTENCY

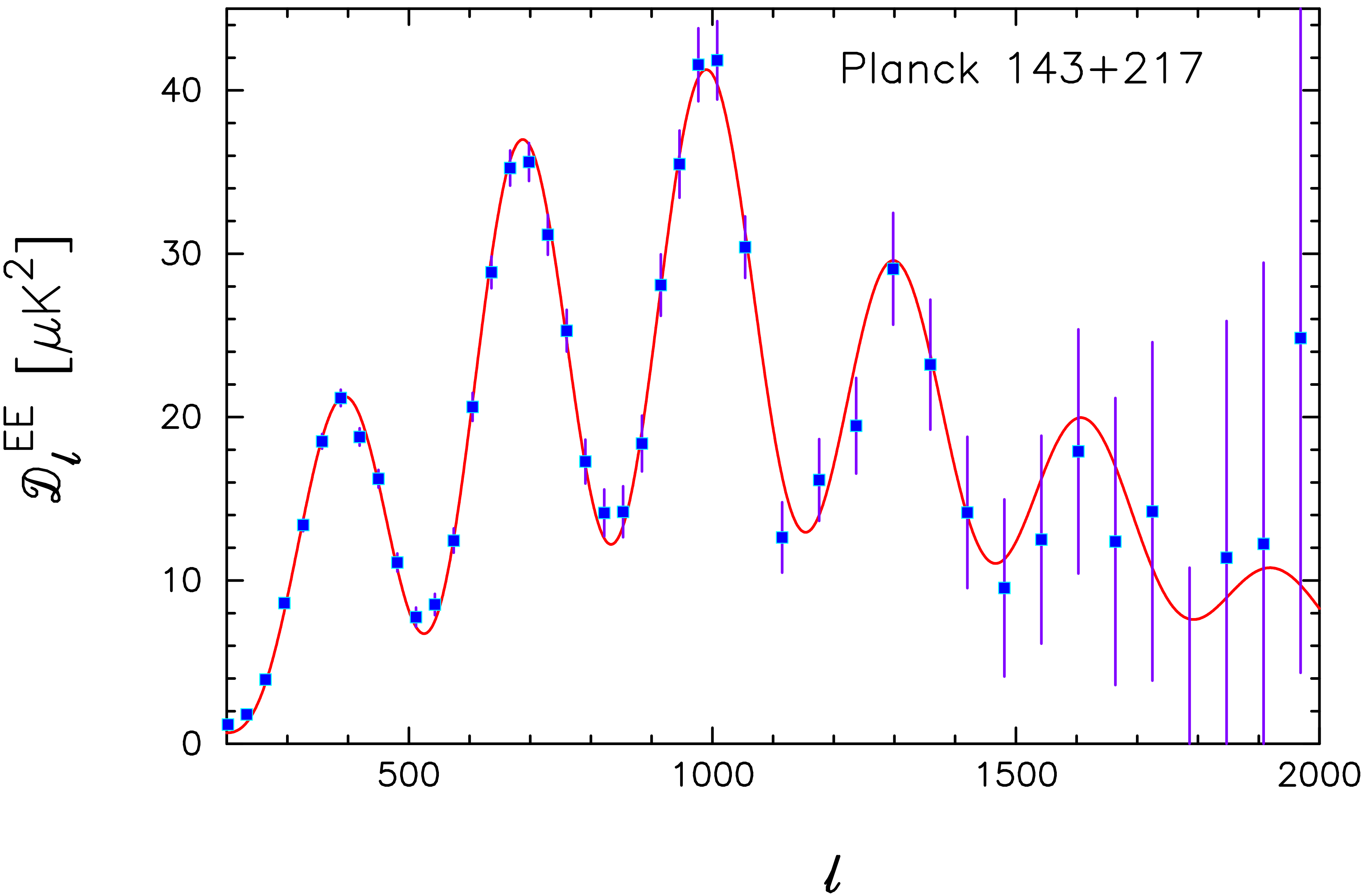


$$D_{\mathrm{V}}(z) = \left[(1+z)^2 D_{\mathrm{A}}^2(z) \frac{cz}{H(z)}\right]^{1/3}$$


Aver et al. (2012)
Standard BBN
Y_P
0.25
0.26
y_{DP}
Planck+WP+highL
Iocco et al. (2008)
Pettini & Cooke (2012)
2.2
2.6
3.0
3.4
0.018
0.020
0.022
0.024
0.026
ω_b

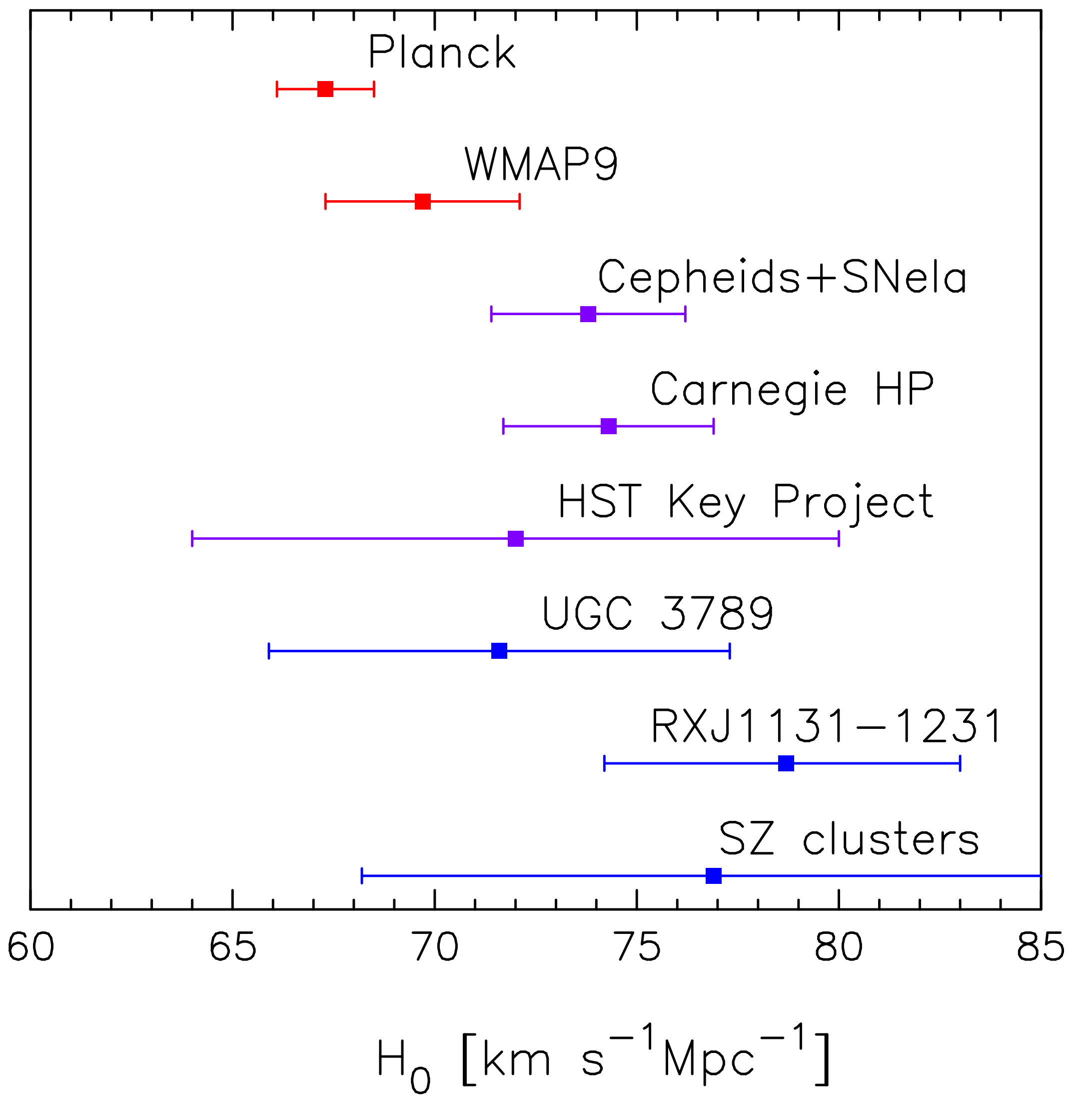
PLANCK POLARIZATION CONSISTENCY



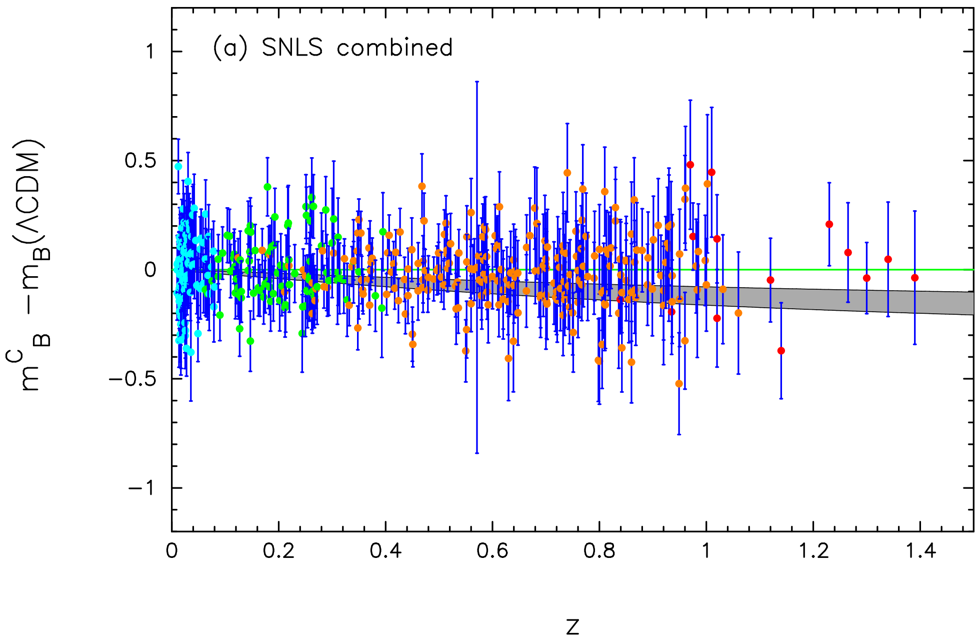

Planck 143+217
$\mathcal{D}_\ell^{EE}$ [μK^2]
ℓ
0
10
20
30
40
500
1000
1500
2000

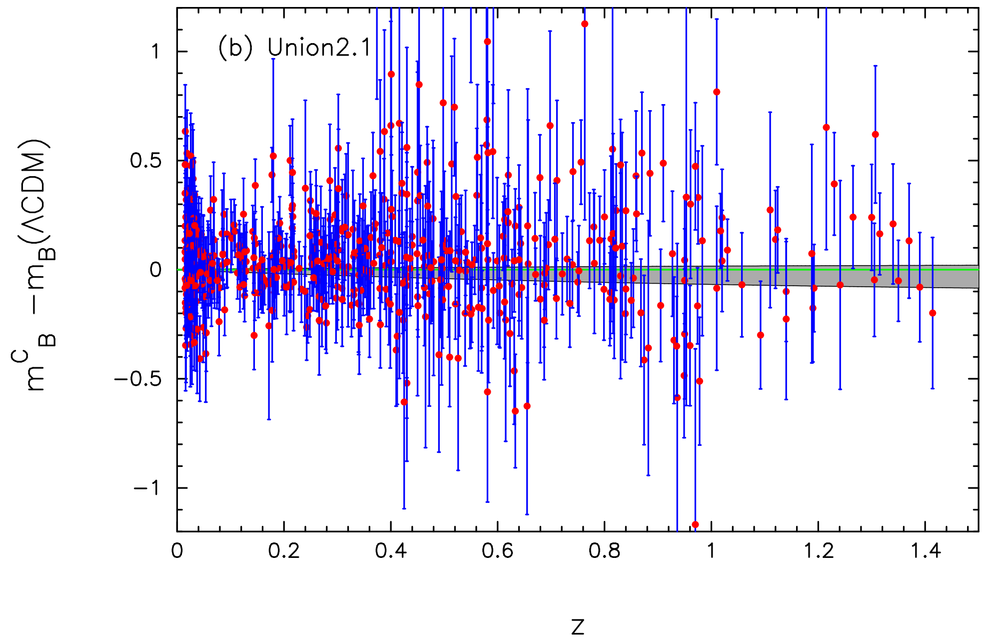
2.5 σ TENSION WITH HUBBLE CONSTANT

$H_0 = 67.3 \pm 1.2\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (68%; Planck+WP+highL; LCDM)

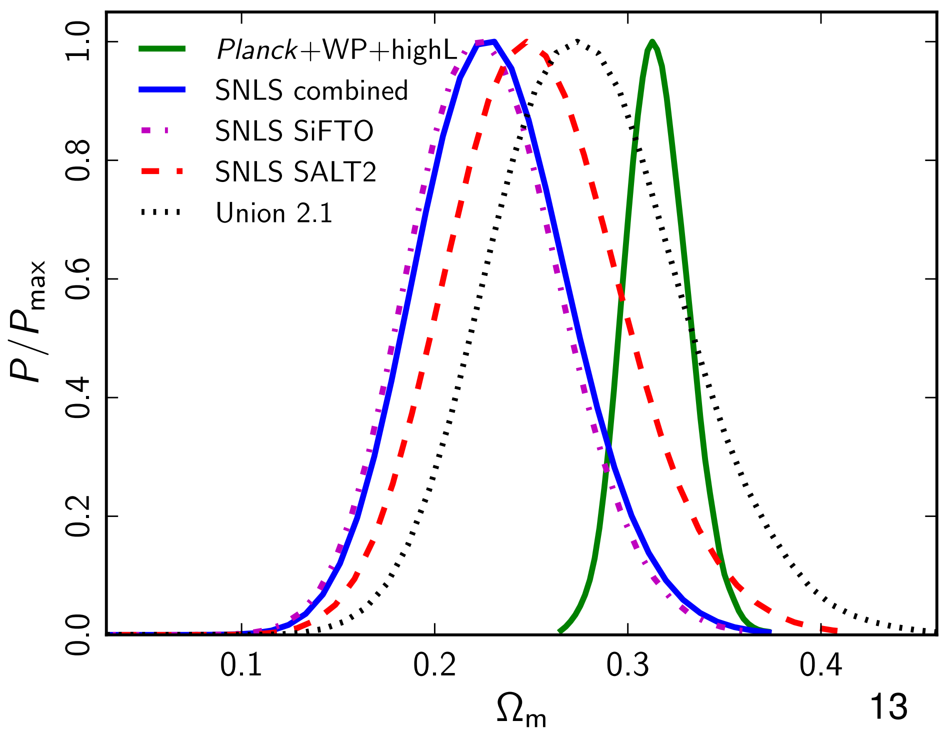


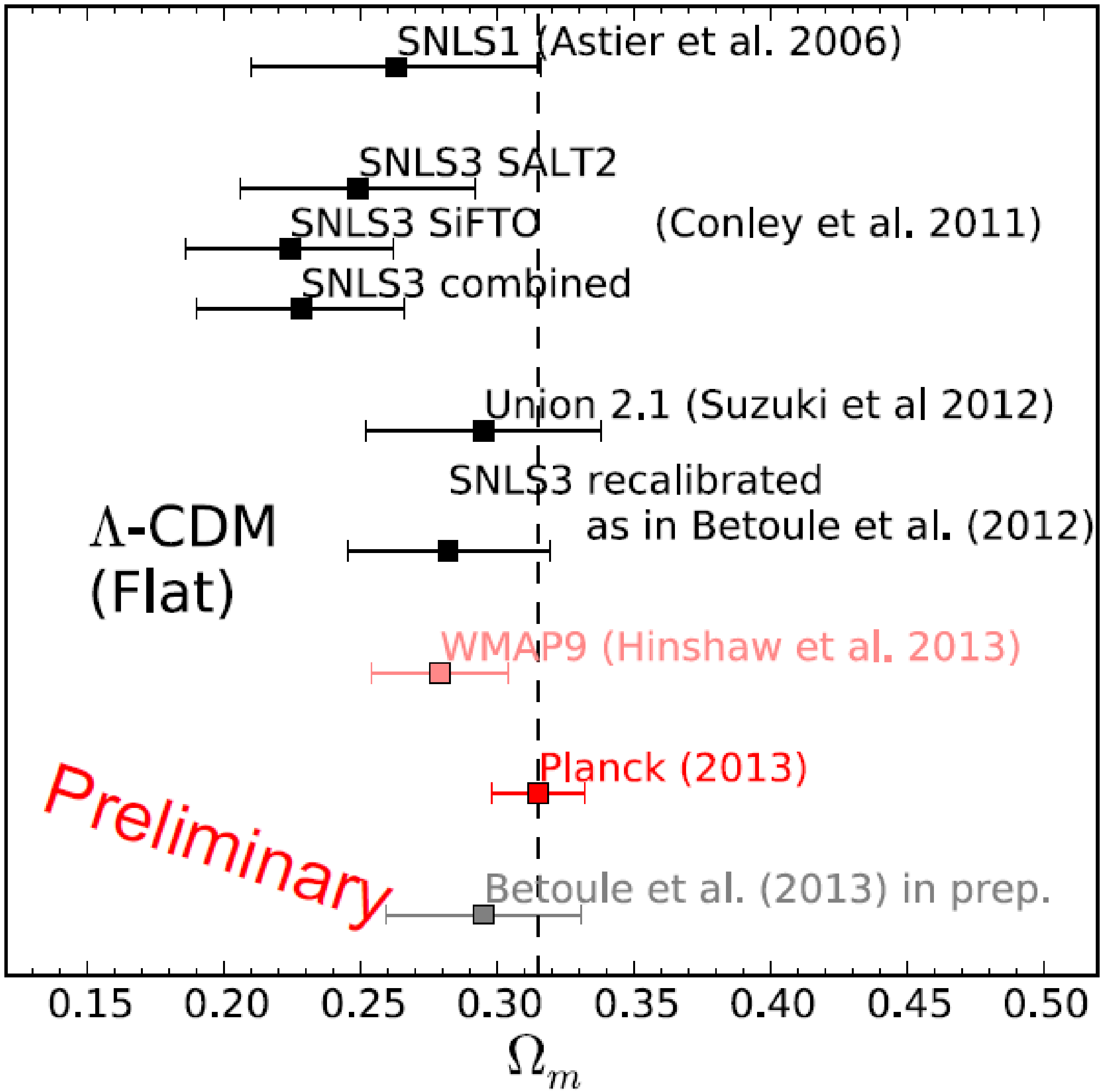
TENSION WITH SNE IA?



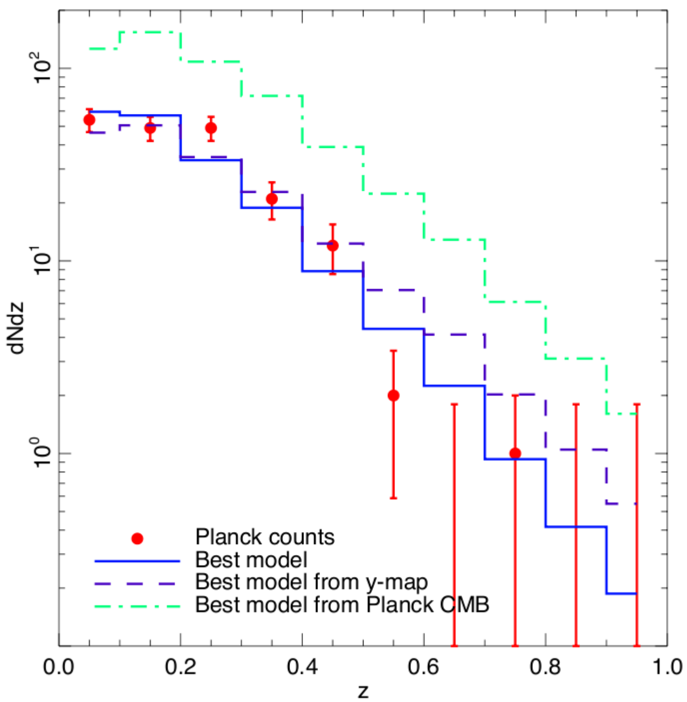


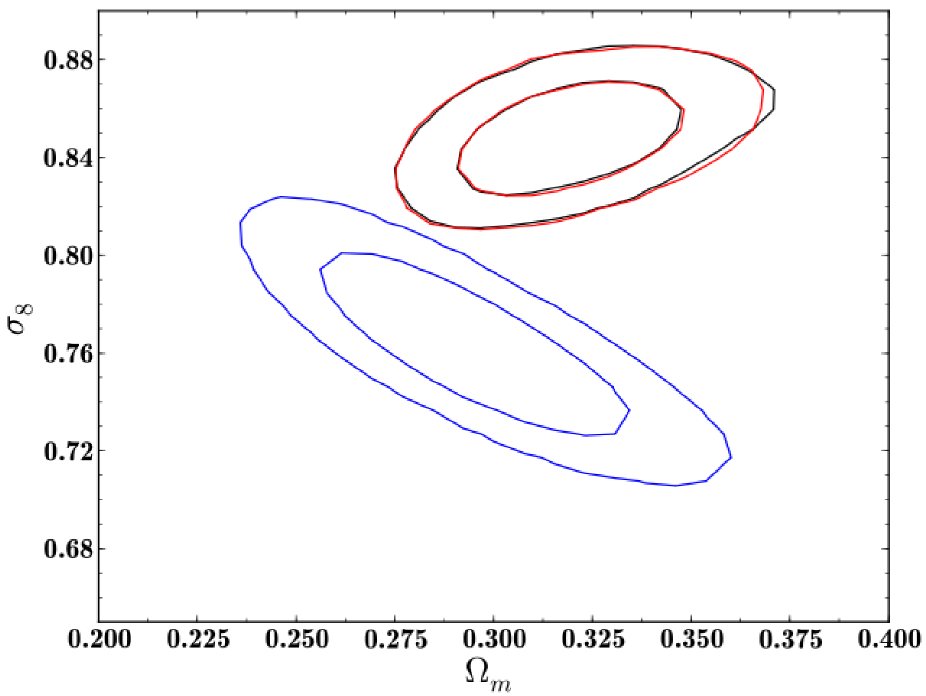
- SNLS cleaner sample, but wants $\Omega_m = 0.23$, $2\,\sigma$ discrepant with Planck
  - Degree of tension depends on lightcurve fitter





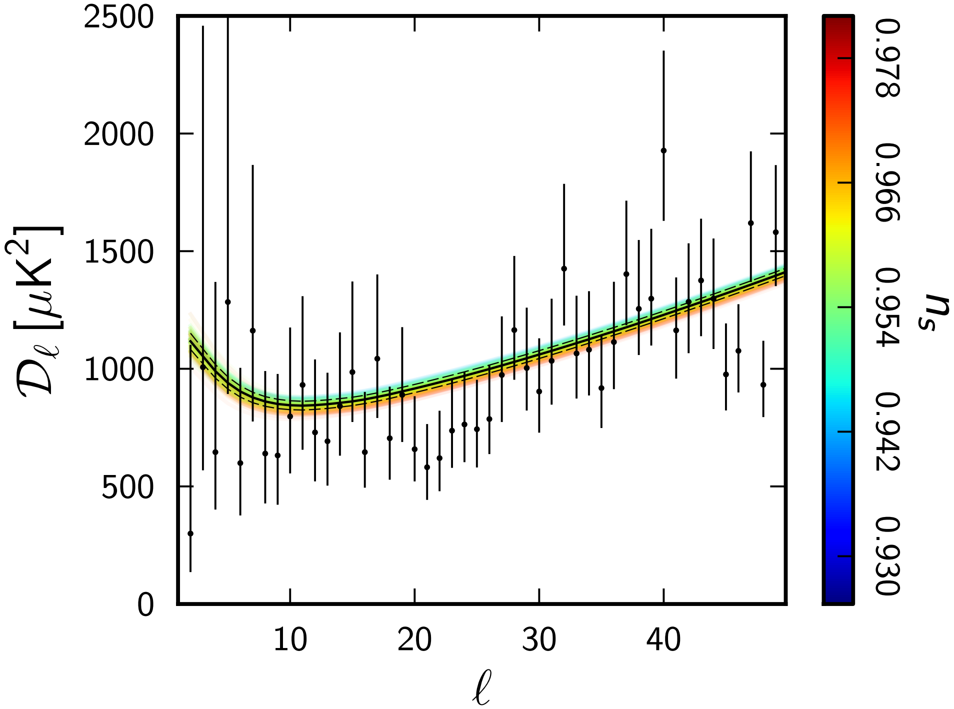
Reynald Pain, ESLAB April 2013

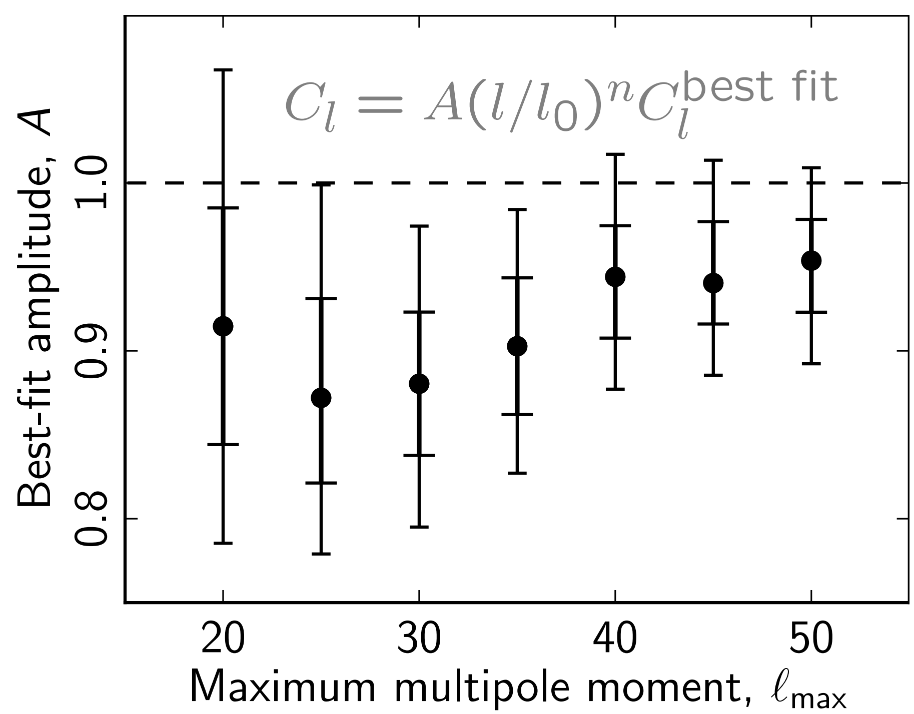




- Planck XX (2013) constrains $\sigma_8(\Omega_m/0.27)^{0.3} = 0.78 \pm 0.01$ from 189 $S/N > 7$ SZ (confirmed) clusters
- Planck TT best-fit LCDM model over-predicts number of clusters: $\sigma_8(\Omega_m/0.27)^{0.3} = 0.87 \pm 0.02$ (Planck+WP+highL)
  - Issues with modelling selection function, Y_{SZ}–mass calibration etc?
  - New physics?

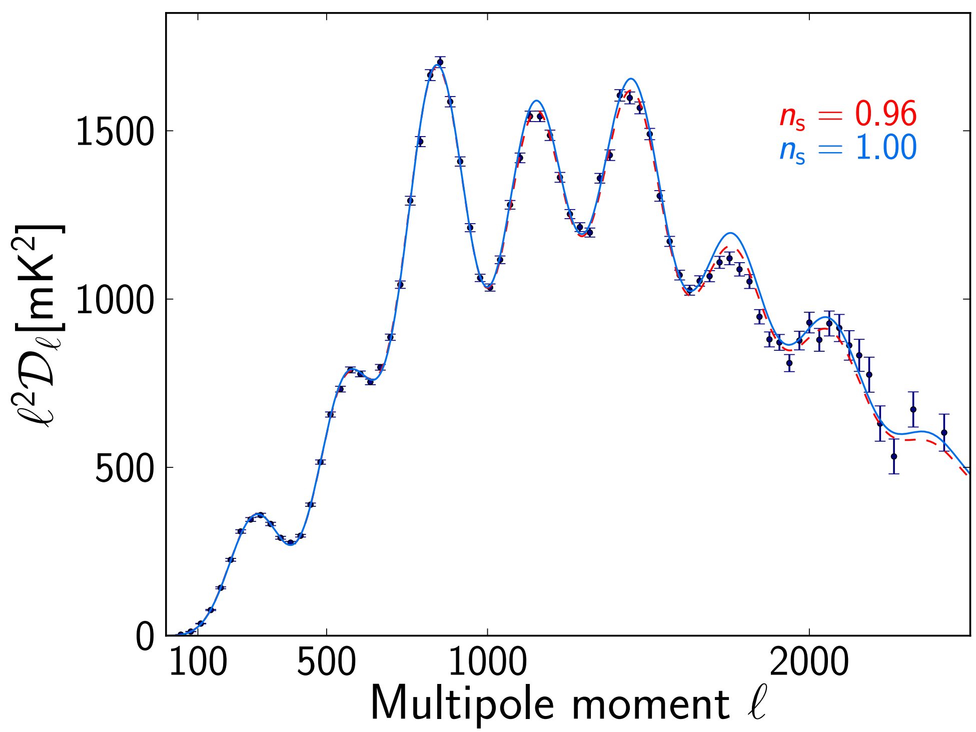
ANOMALOUS LOW-l POWER

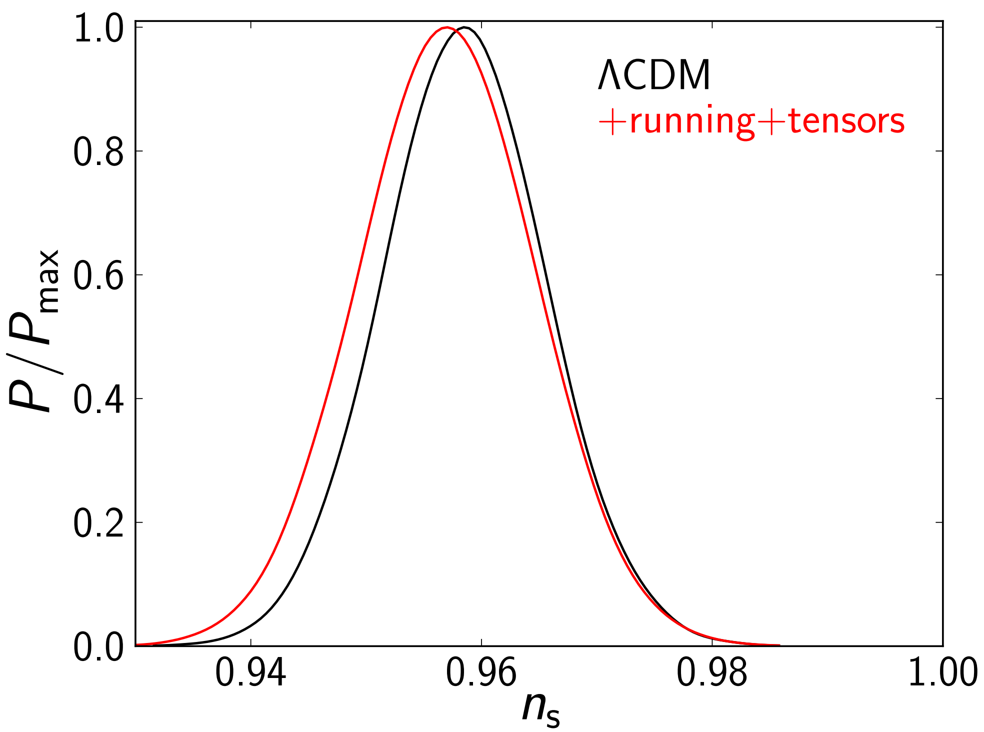




- 2–3 σ evidence for low power relative to LCDM best-fit on large scales
  - Internal tension that gives a number of $2\,\sigma$ results in extended models

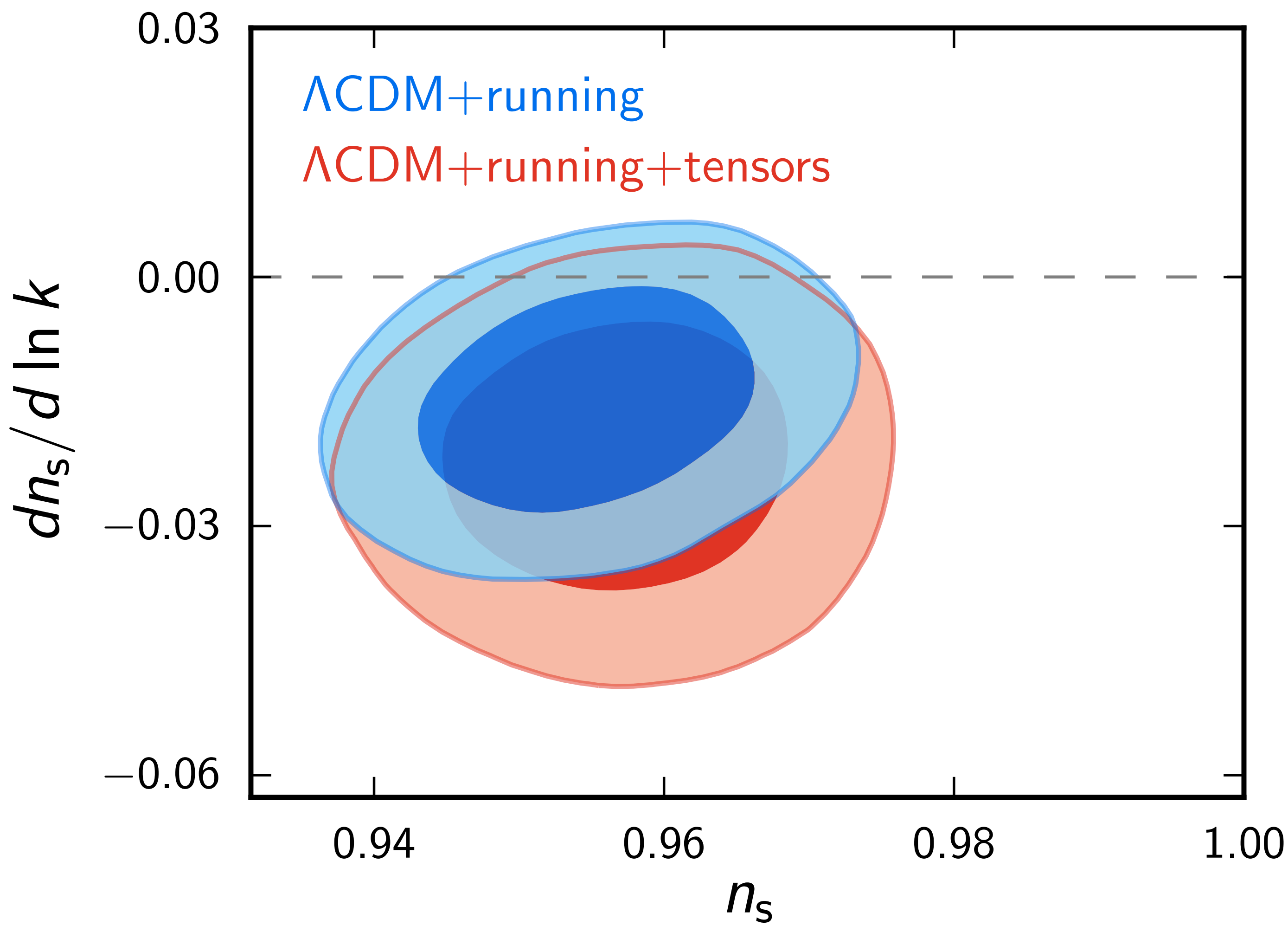
CONSTRAINTS ON INFLATION: n_s





$n_s = 0.958 \pm 0.007$ (68%; Planck+WP+highL; LCDM)

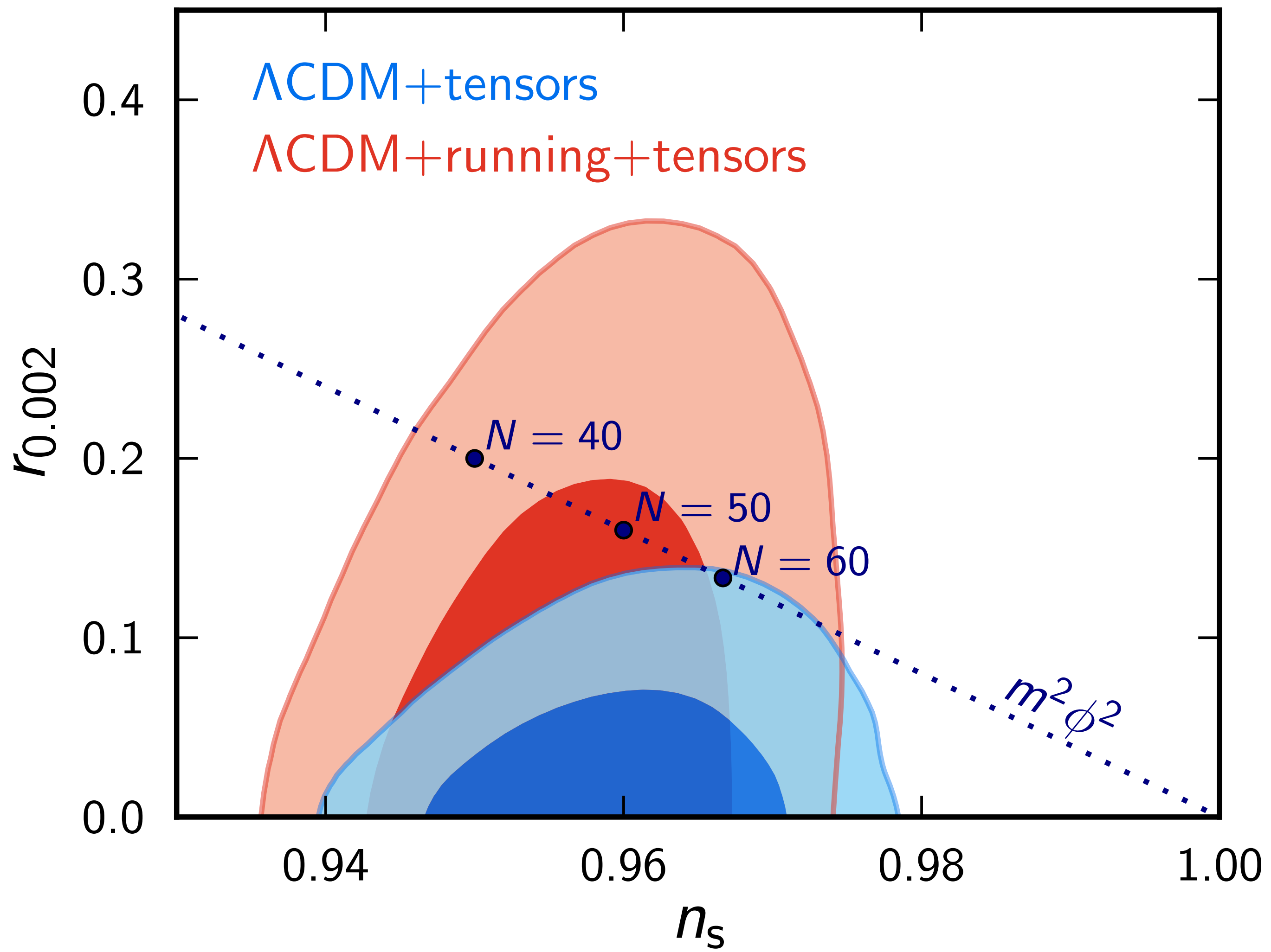
- $n_s < 1$ robust to addition of running and tensors
- Robust to matter content (e.g. N_{eff} and Helium) combining Planck with BAO



$dn_s/d\ln k = -0.013 \pm 0.009$ (68%; Planck+WP)

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

- Any preference for running is from low-l only

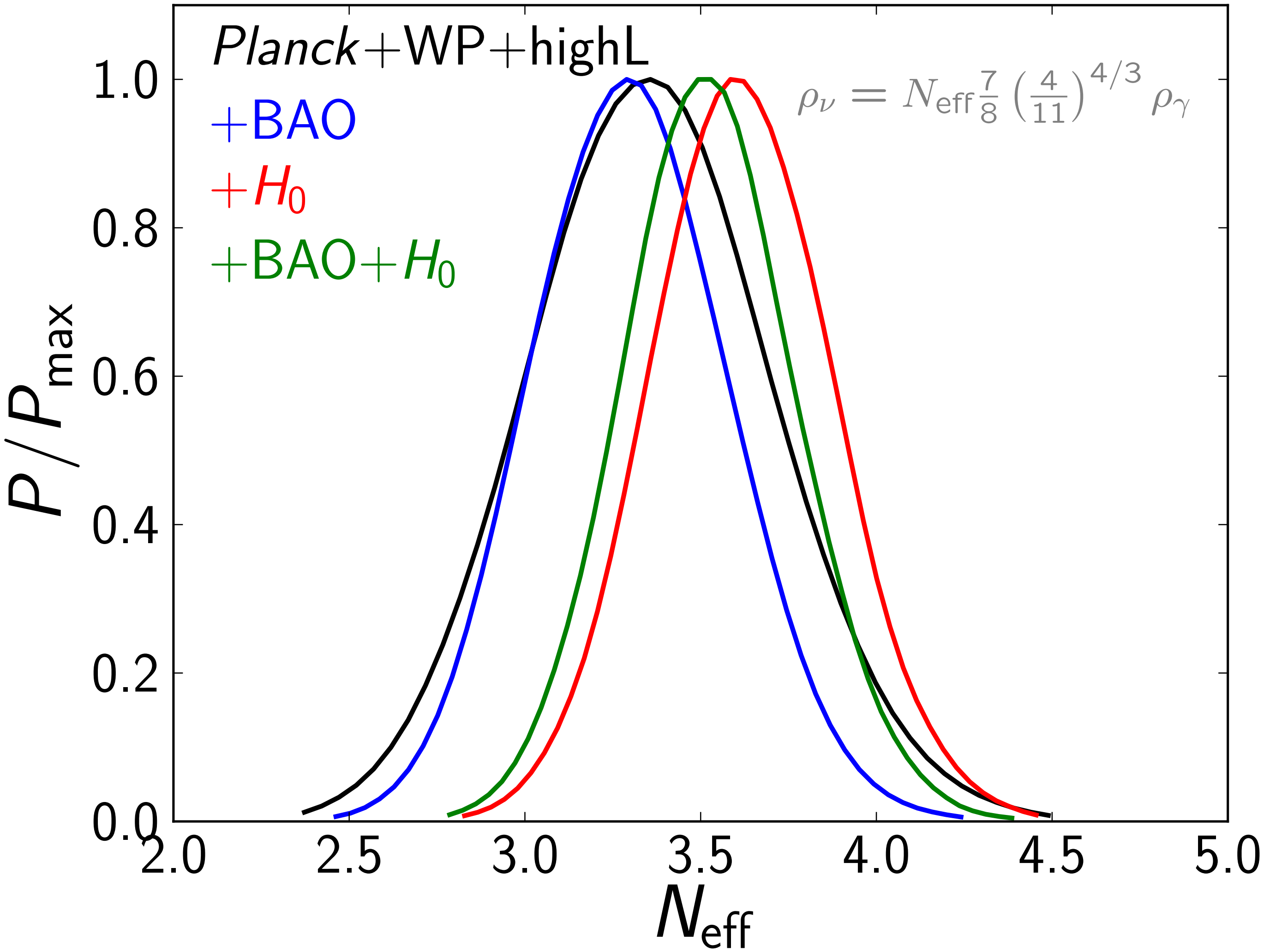


$r_{0.002} < 0.11$ (95%; Planck+WP+highL; no running)

$r_{0.002} < 0.26$ (95%; Planck+WP+highL; running)

- As good as you can do with TT (without running)

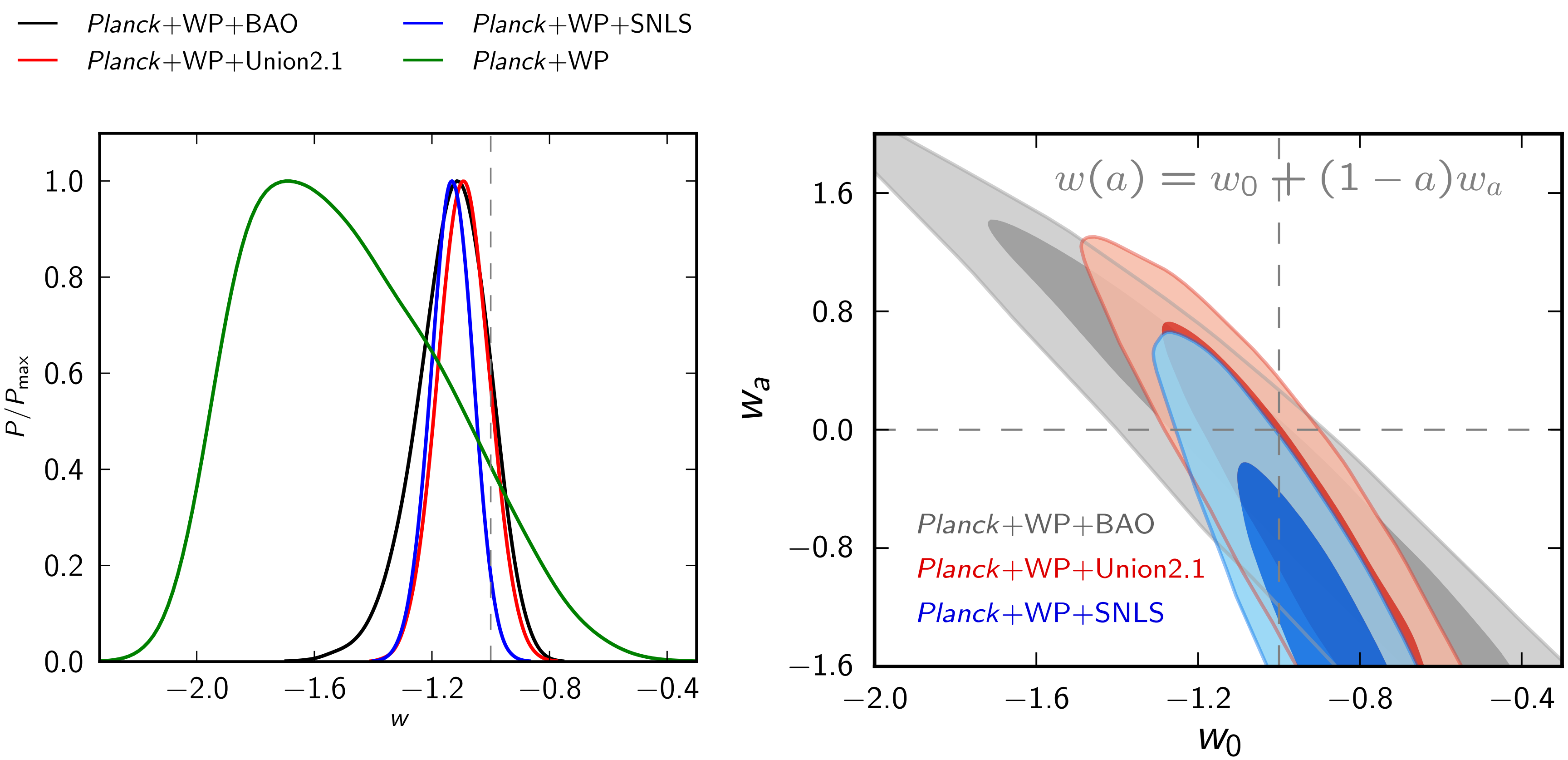
Extra relativistic degrees of freedom



$N_{\rm eff} = 3.36^{+0.68}_{-0.64}$ (95%; Planck+WP+highL)

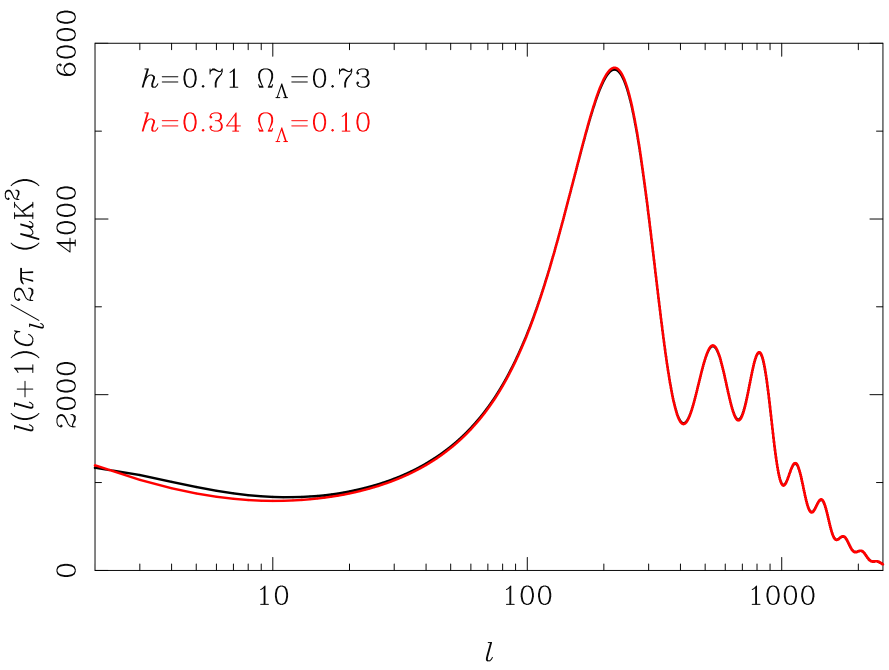
- Increasing $N_{\rm eff}$ at fixed θ_* reduces power in damping tail
  - Necessarily increases expansion rate at low redshifts

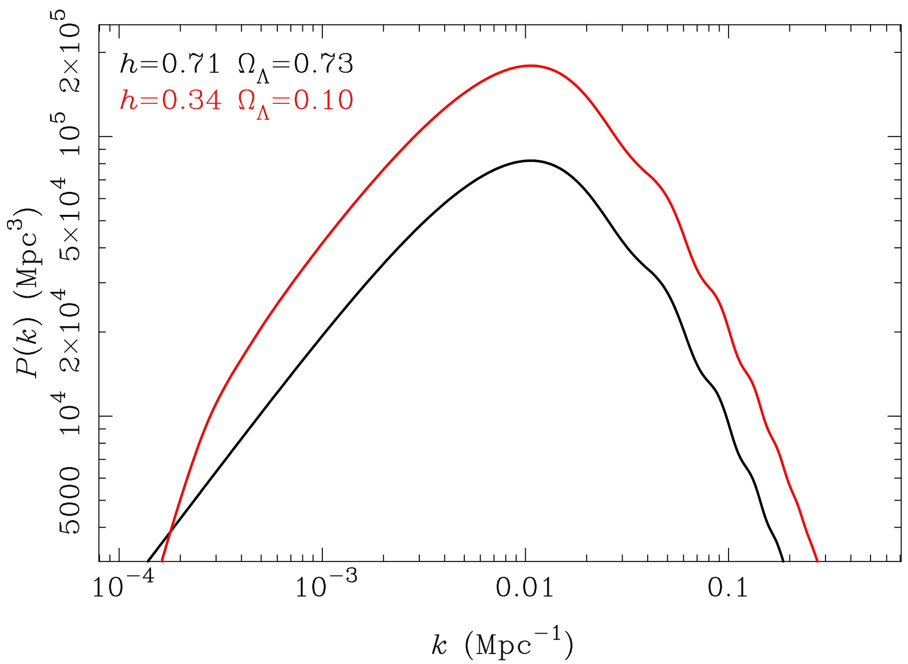
DYNAMICAL DARK ENERGY



- No evidence for dynamical dark energy with Planck+BAO
  - E.g. $w = -1.13 \pm 0.25$ (95%; Planck+WP+BAO; w const.)
- Tension with SNLS or H_0 pulls towards phantom dark energy ($2\,\sigma$)
  - E.g. SNLS want lower $d\ln H/dz$ – lower Ω_m or $w < -1$

- Dark parameters (Ω_Λ, Ω_K, $\sum m_\nu$, w etc.) affect *primary anisotropies* only through $D_A(z_*)$
- Break degeneracy with:
  - Geometric probes – BAO, SNe, H_0 etc.
  - Probes of LSS – galaxy clustering, lensing, Lyα etc.





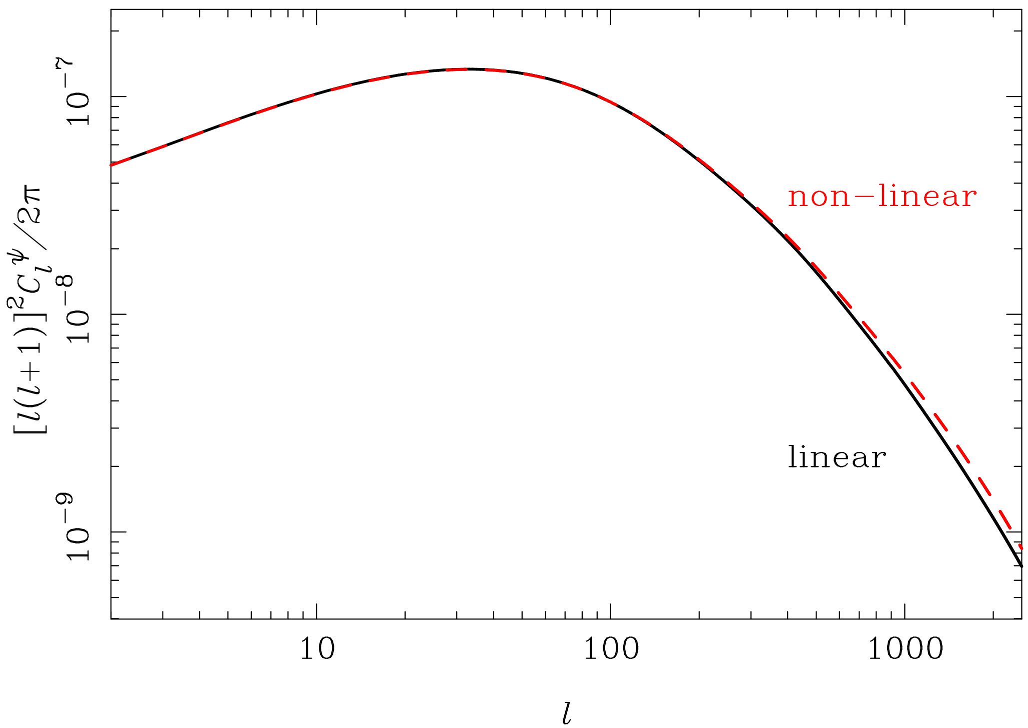
- Lensing preserves brightness; simply re-maps temperature from recombination

$$\tilde{T}(\hat{\boldsymbol{n}}) = T(\hat{\boldsymbol{n}} + \boldsymbol{\alpha})$$

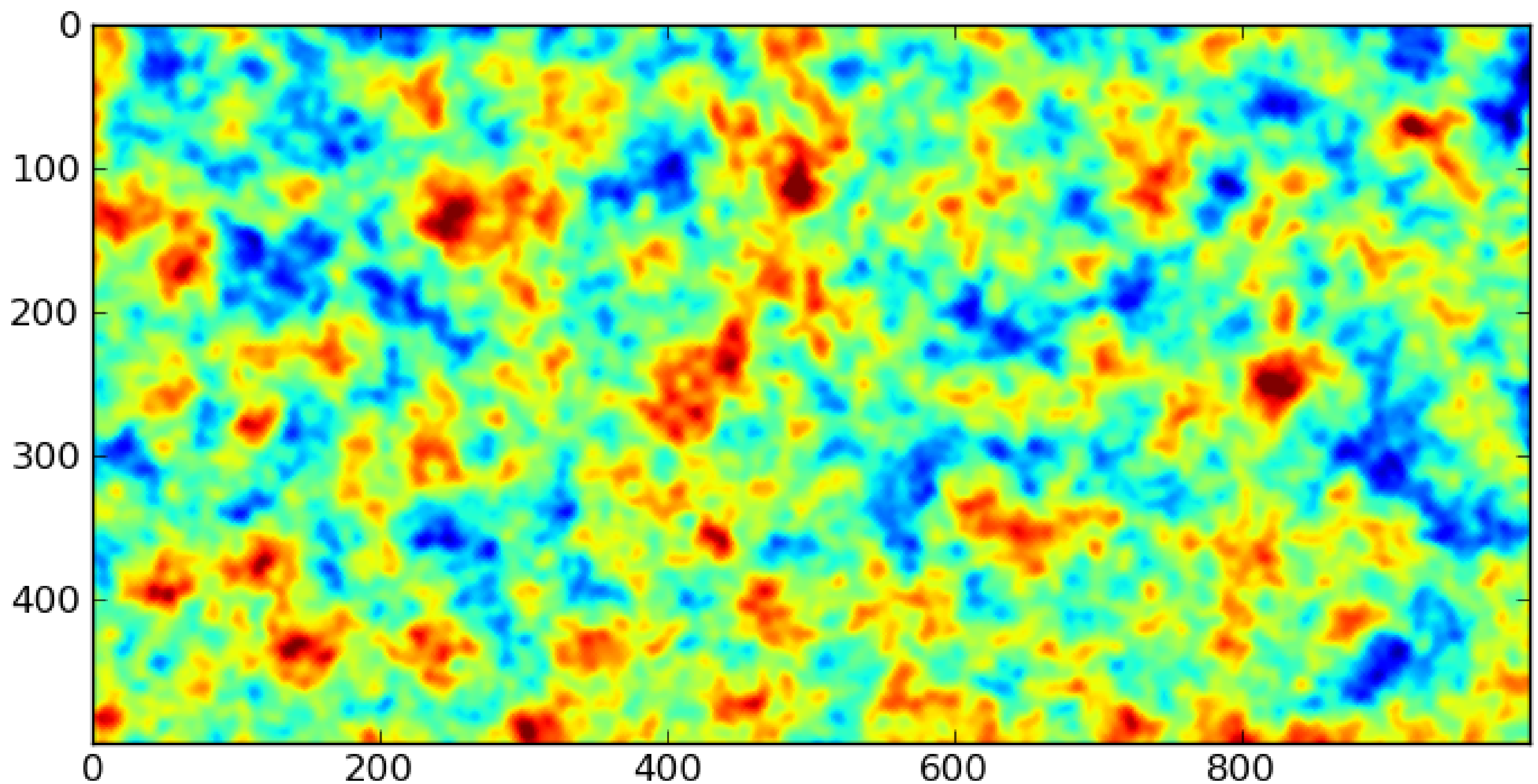
- Deflection is gradient, $\boldsymbol{\alpha} = \boldsymbol{\nabla}\phi$, in Born approximation:

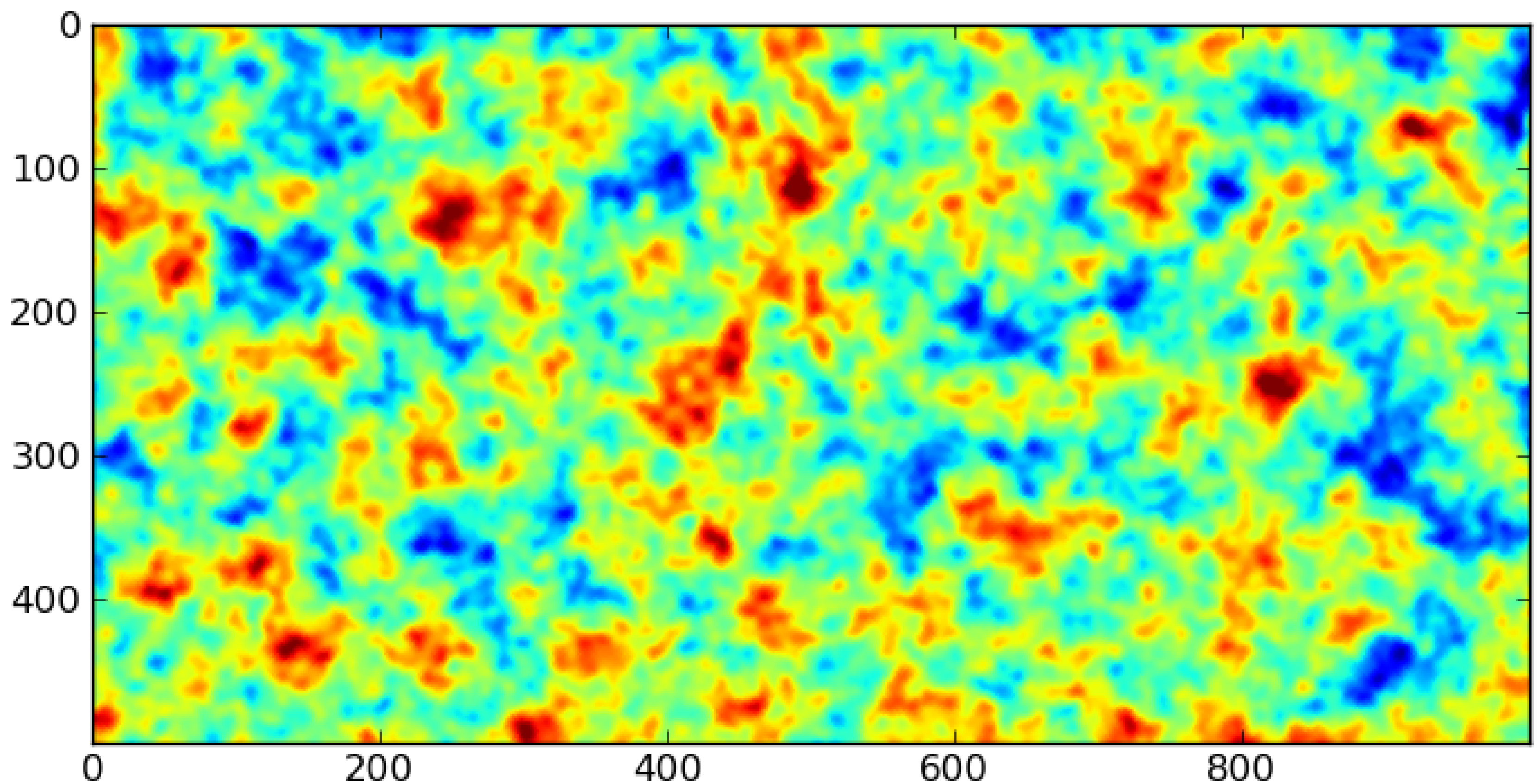
$$\phi(\hat{\boldsymbol{n}}) = -\int_0^{\chi_*} \mathrm{d}\chi (\Phi + \Psi)(\chi\hat{\boldsymbol{n}}; \eta_0 - \chi) \frac{\chi_* - \chi}{\chi\chi_*}$$

  - R.m.s. deflection $\langle \boldsymbol{\alpha}^2 \rangle^{1/2} = 2.4\,\mathrm{arcmin}$
  - Coherent over several degrees



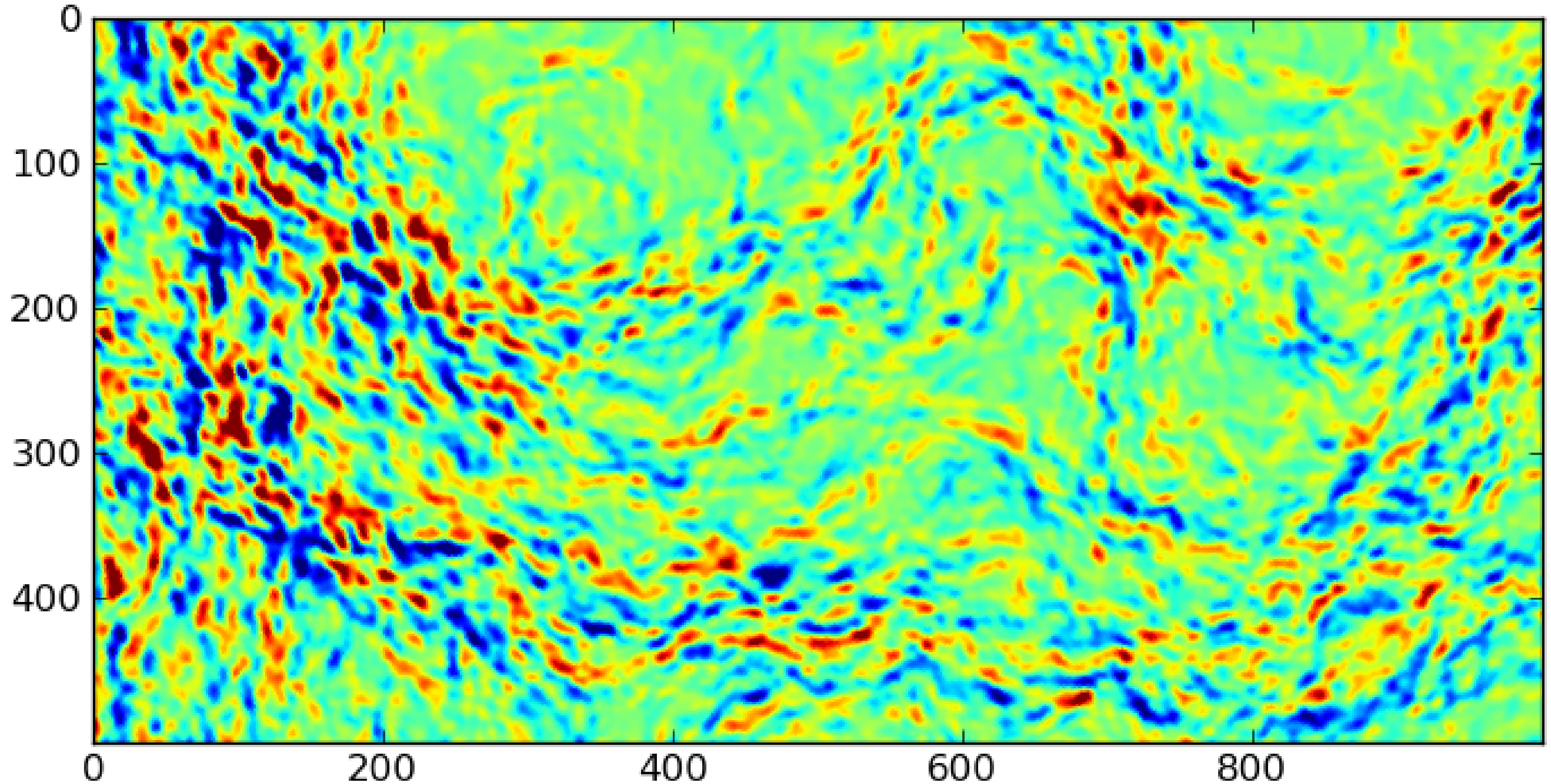
Unlensed temperature



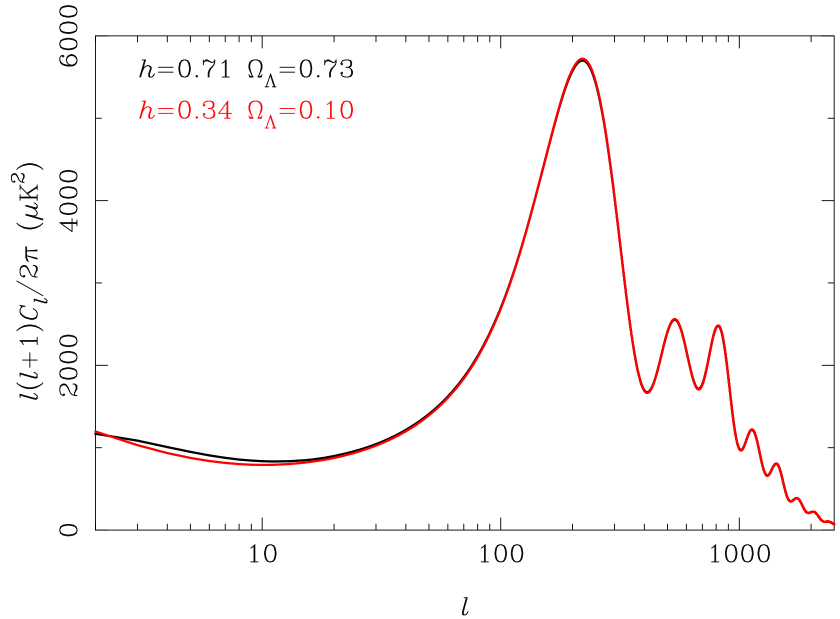

0
100
200
300
400
0
200
400
600
800

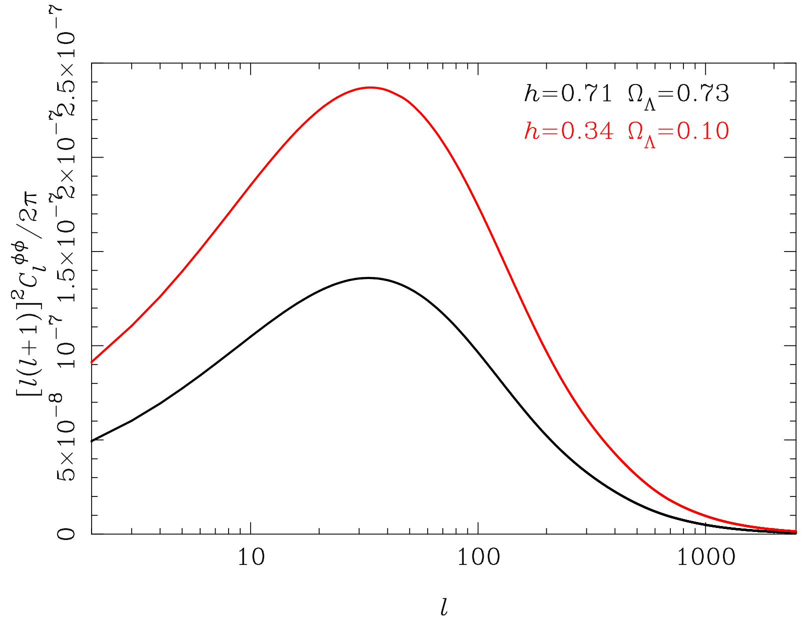
Lensing difference

$$\Delta\tilde{T}(\hat{\boldsymbol{n}}) = \boldsymbol{\alpha} \cdot \nabla T + \cdots$$

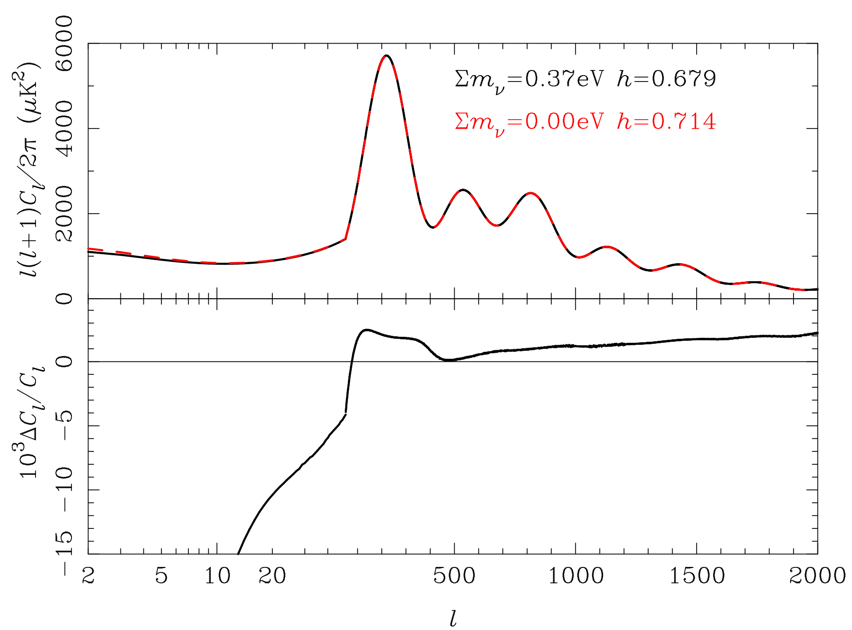


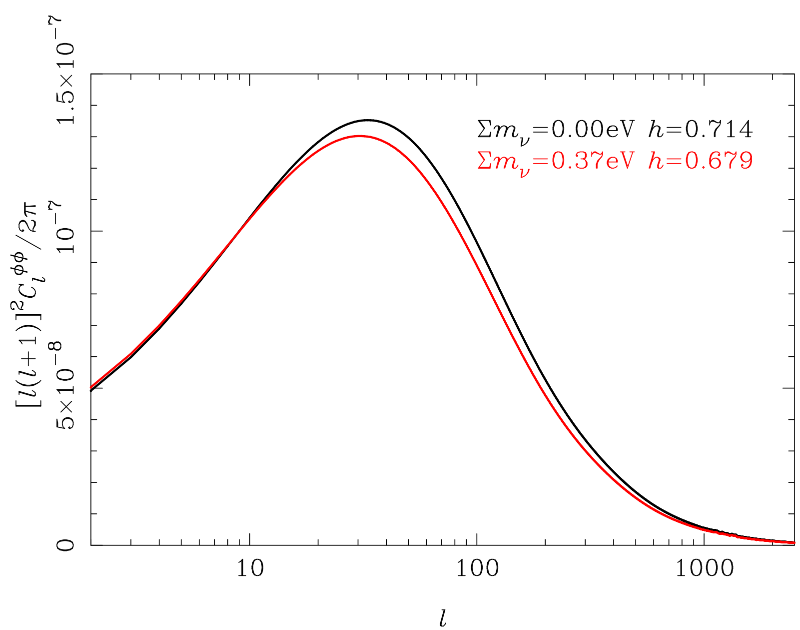
- Lensing sensitive to geometry and late-time growth of structure: curvature



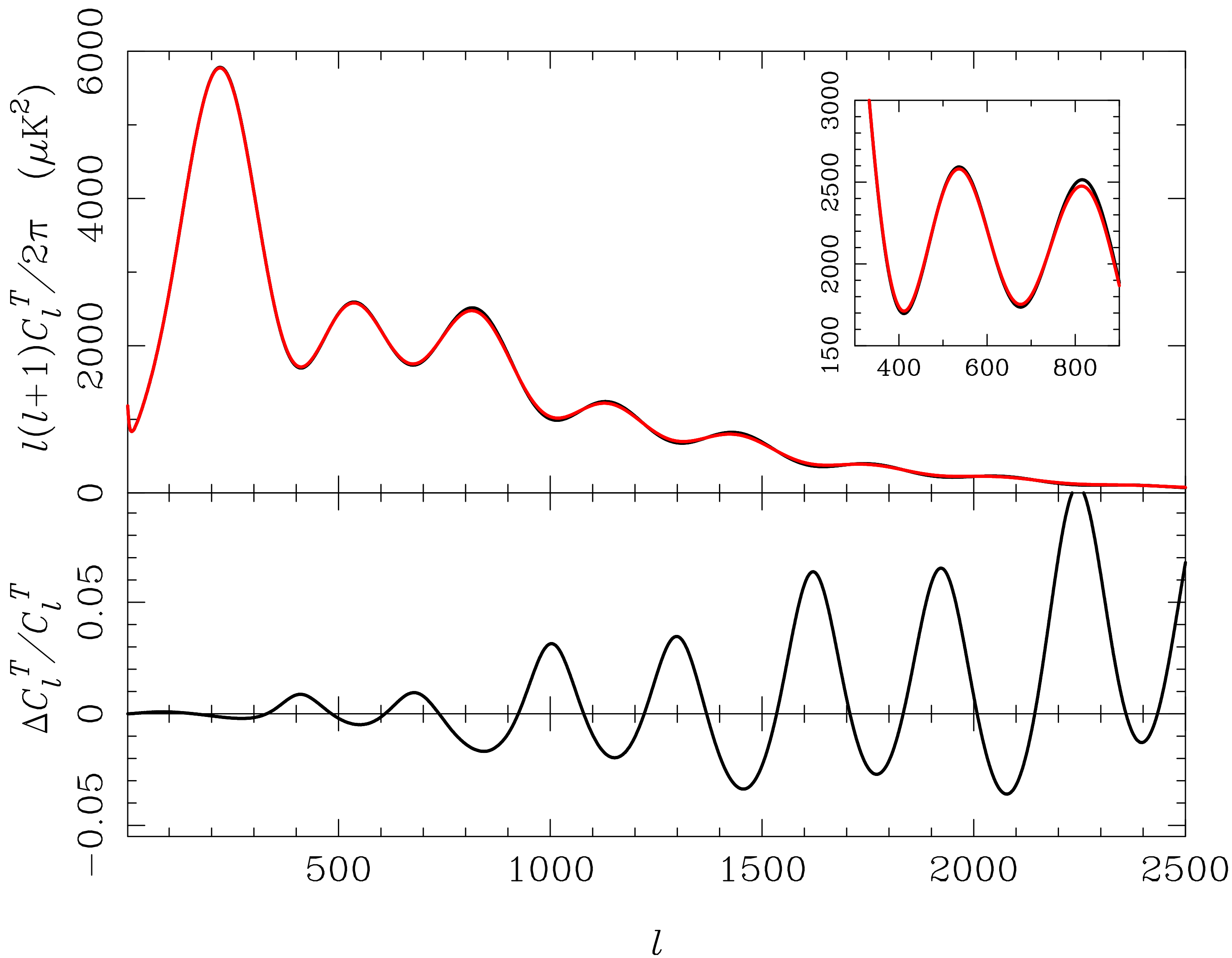


- Neutrino masses (non-relativistic at recombination for $m_\nu < 0.5\,\mathrm{eV}$):



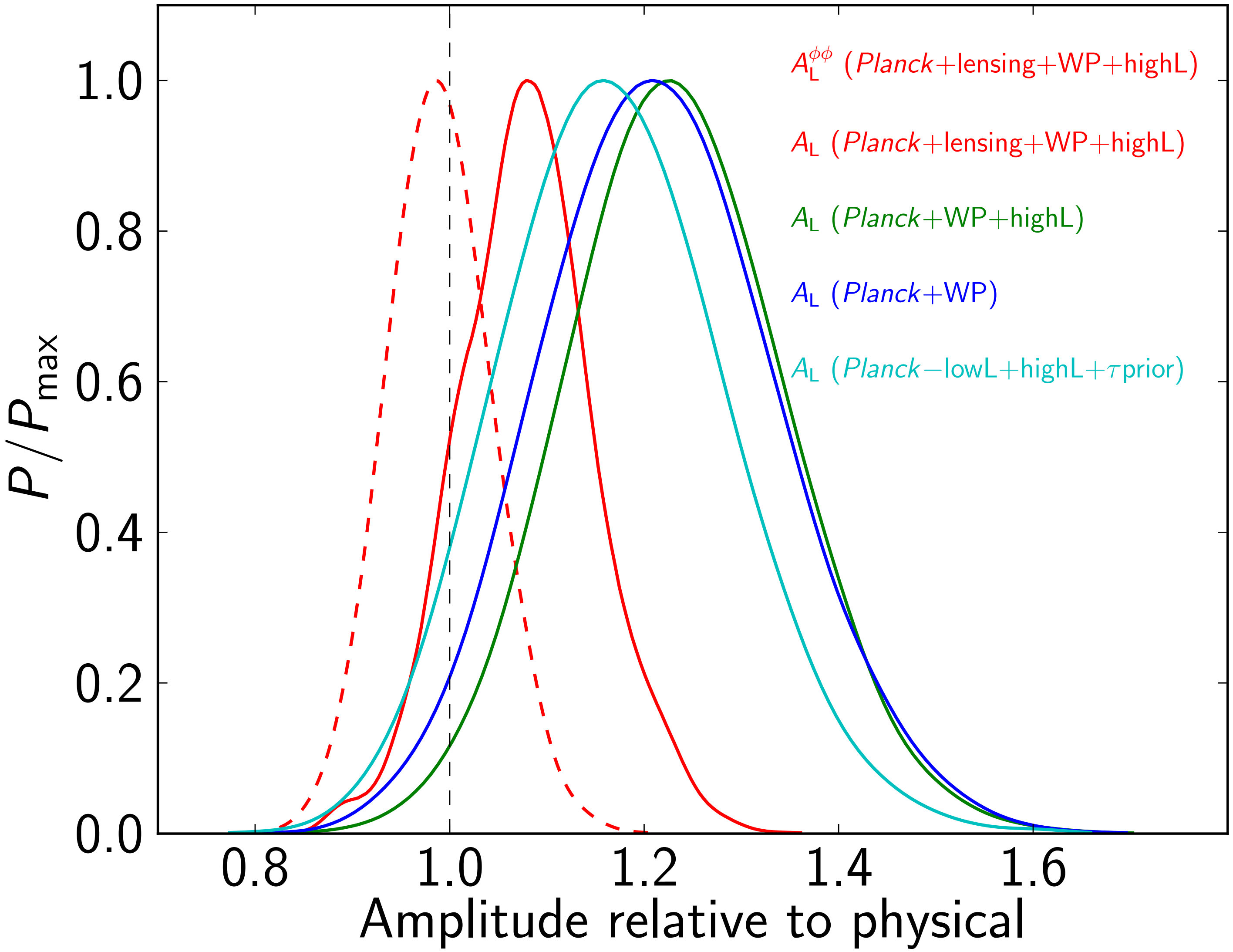


- Smooths acoustic peaks and generates small-scale power in damping tail



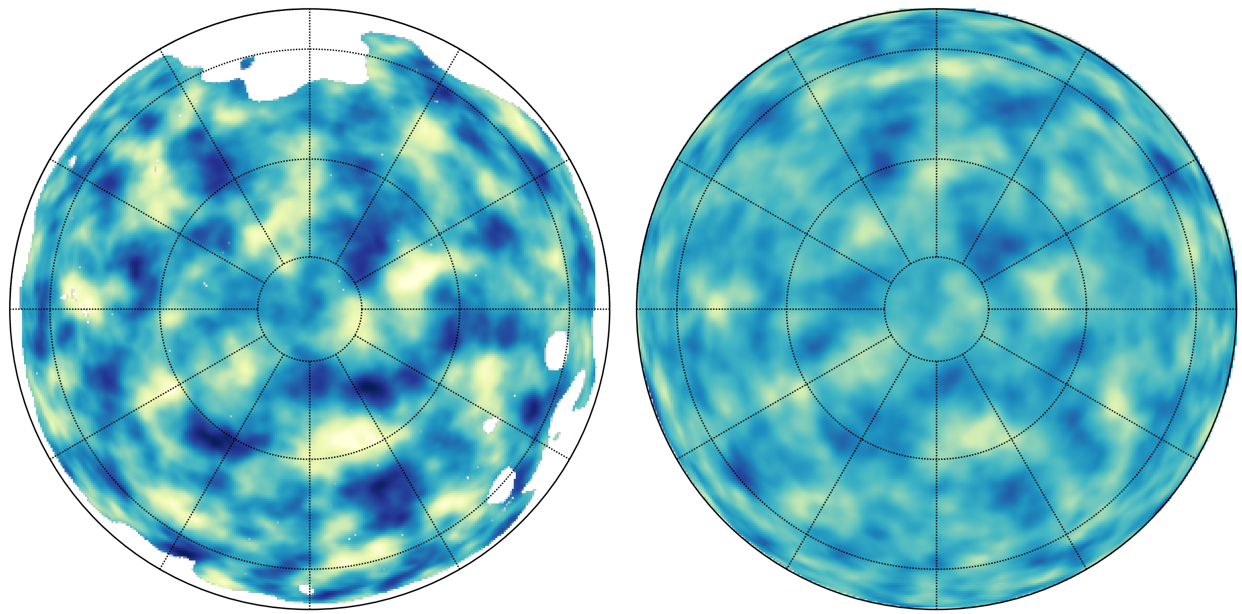
Lensing detected at 10σ in Planck TT

$$C_l^{\phi} \rightarrow A_L C_l^{\phi}$$



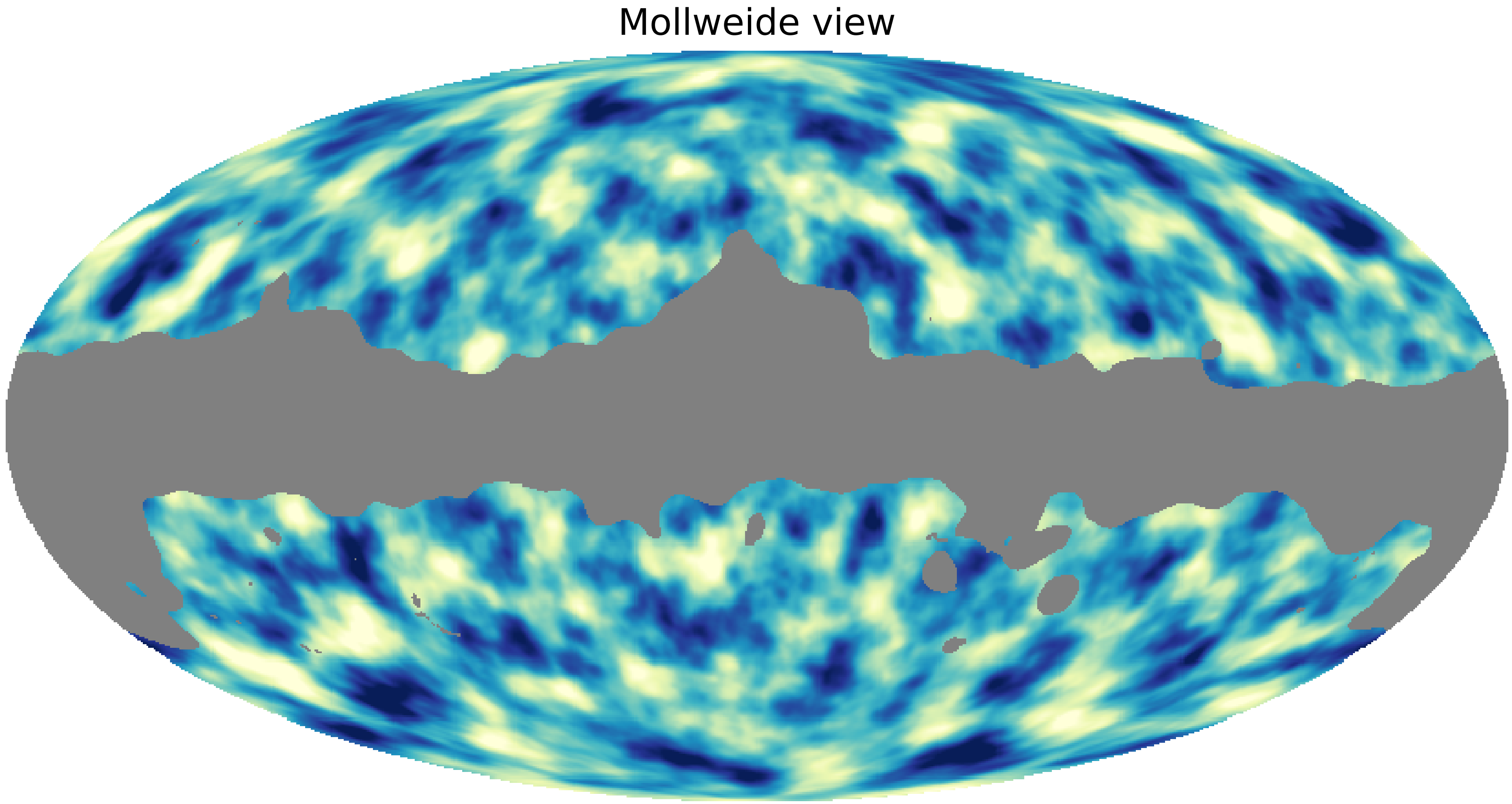
$$\tilde{T}(\hat{\boldsymbol{n}}) = T(\hat{\boldsymbol{n}}) + \alpha_i \nabla^i T + \cdots$$

- Basic idea: (fixed) lenses introduce anisotropic correlations in CMB
  - Estimate α_i with quadratic estimators $\sim \tilde{T}\nabla_i\tilde{T}$



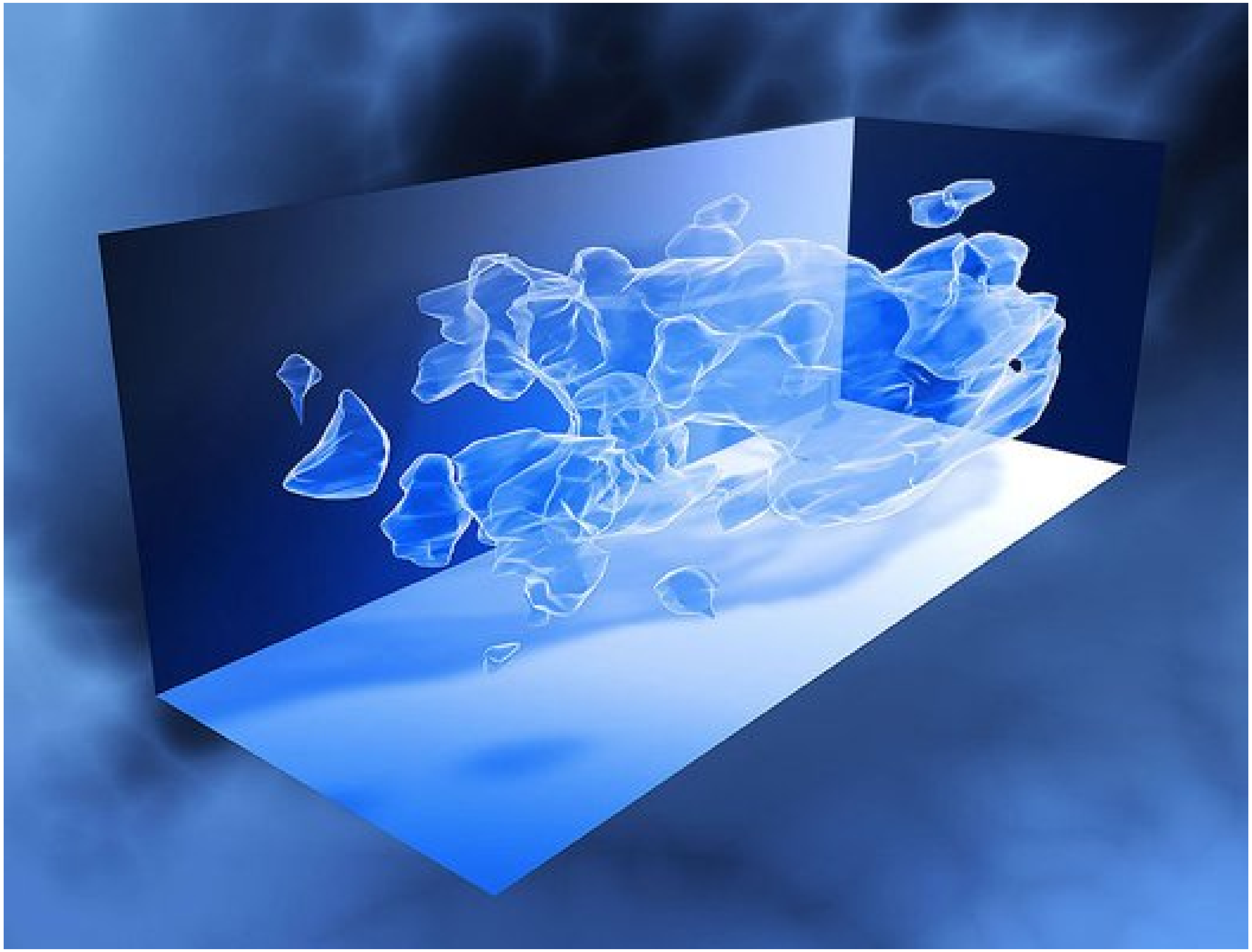
Simulation *Input*

- Reconstruct projected distribution of dark matter over full sky to $z = 1100$
  - Constrain dark parameters from power spectrum of reconstruction *retaining full shape information*
  - Cross-correlate with other LSS tracers (Smith et al. 2007; Bleem et al. 2012; Sherwin et al. 2012) to probe bias etc.



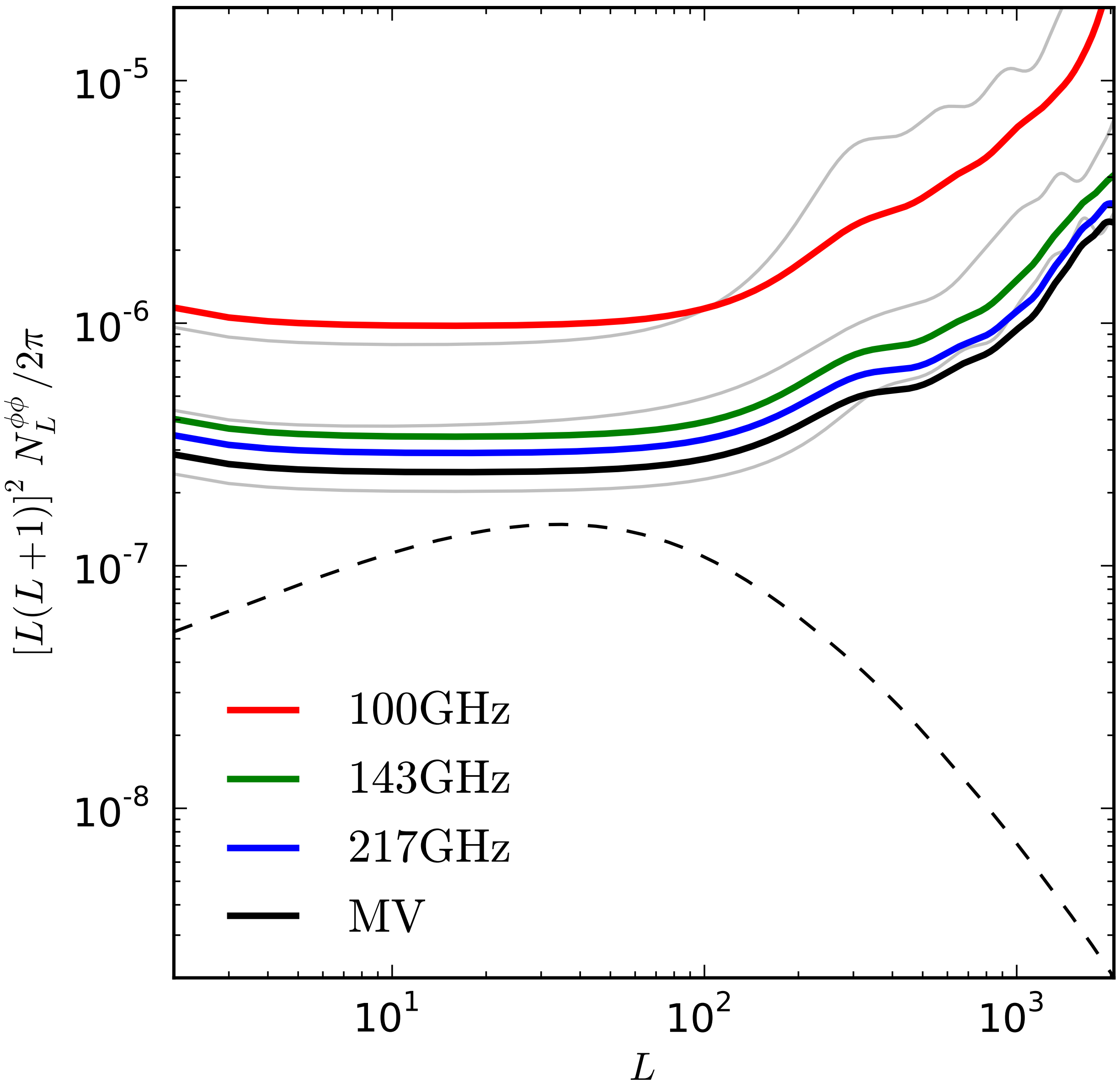
- Weiner-filtered reconstruction based on 143+217 GHz map

COSMOS SHEAR TOMOGRAPHY MAP

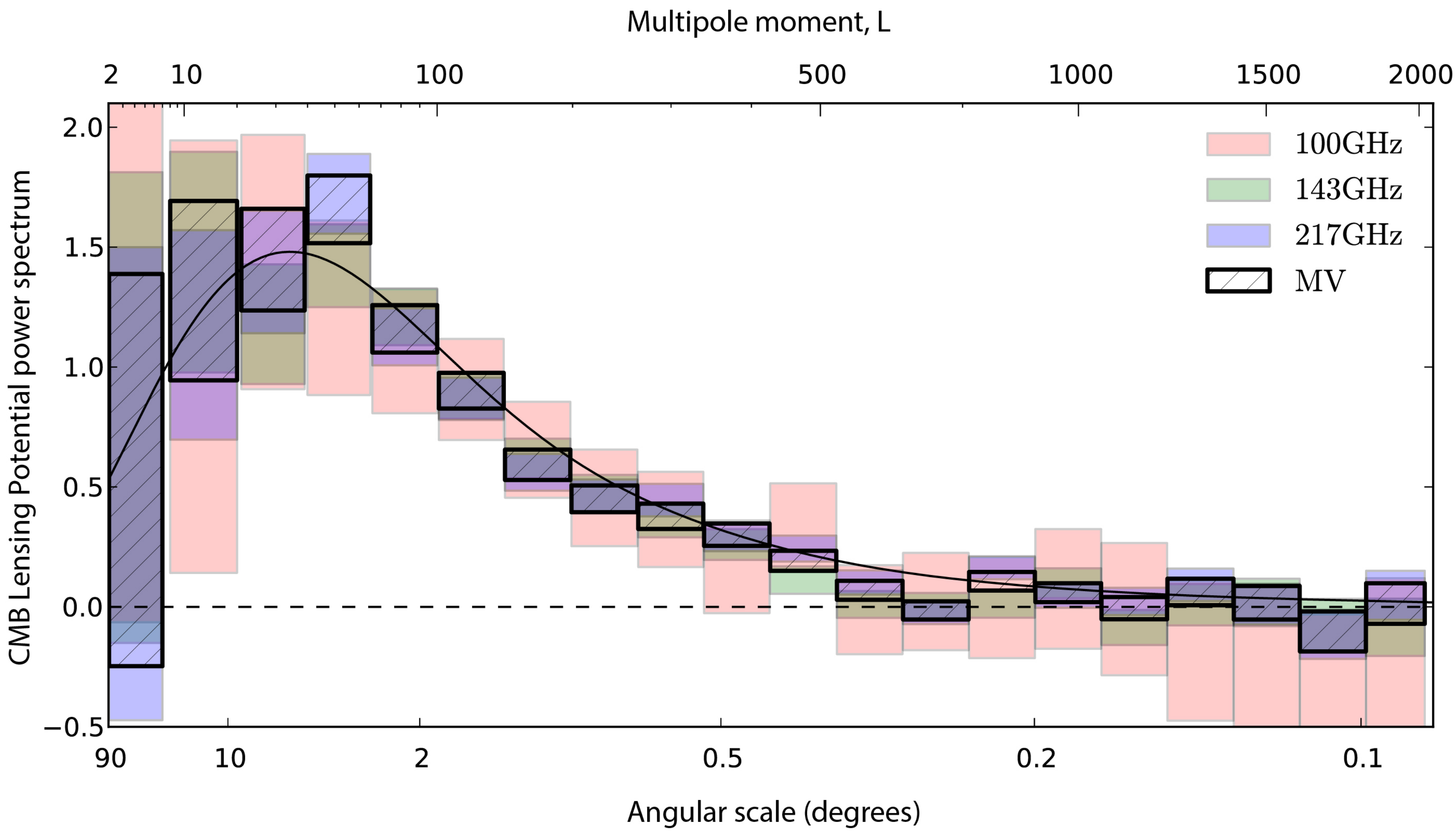


Massey et al (COSMOS)

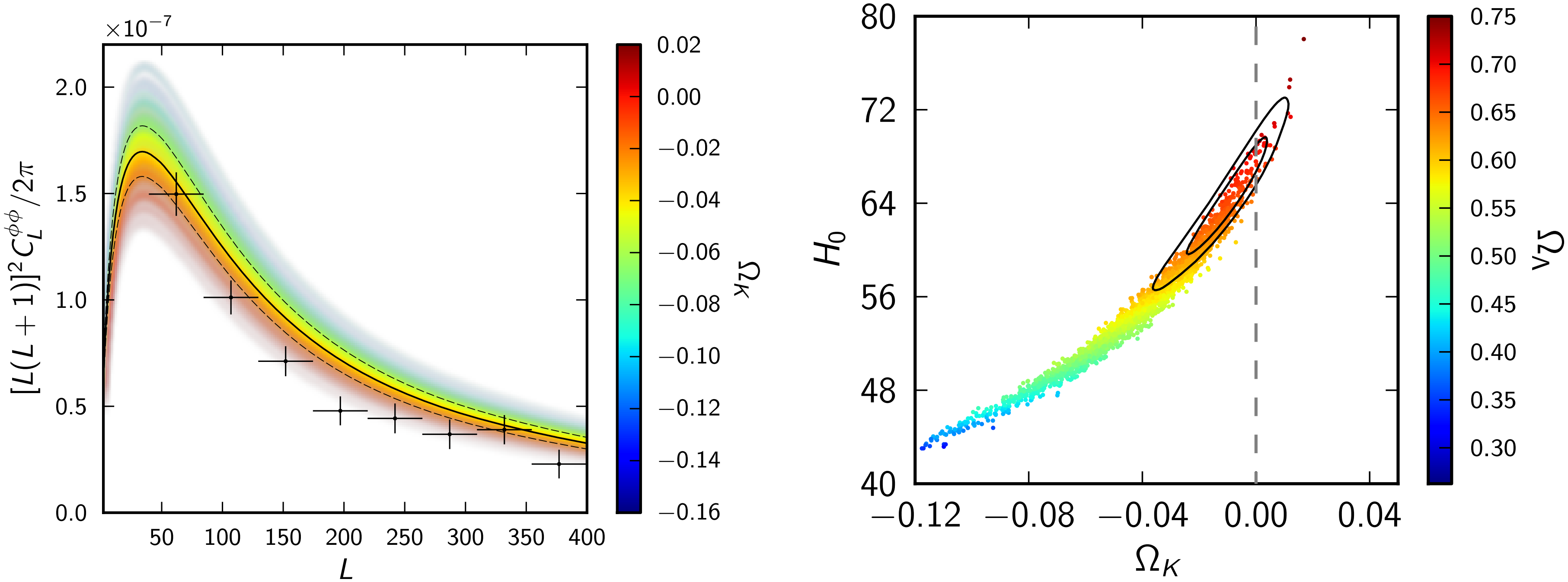
Statistical noise levels



PLANCK LENSING POWER SPECTRUM



- $> 25\sigma$ detection of non-zero power (via CMB 4-point function)
- Consistent with predicted C_L^ϕ in LCDM from Planck TT
  - $\chi^2 = 10.9$ (8 d.o.f.) for $40 \leq L \leq 400$; PTE of 21%

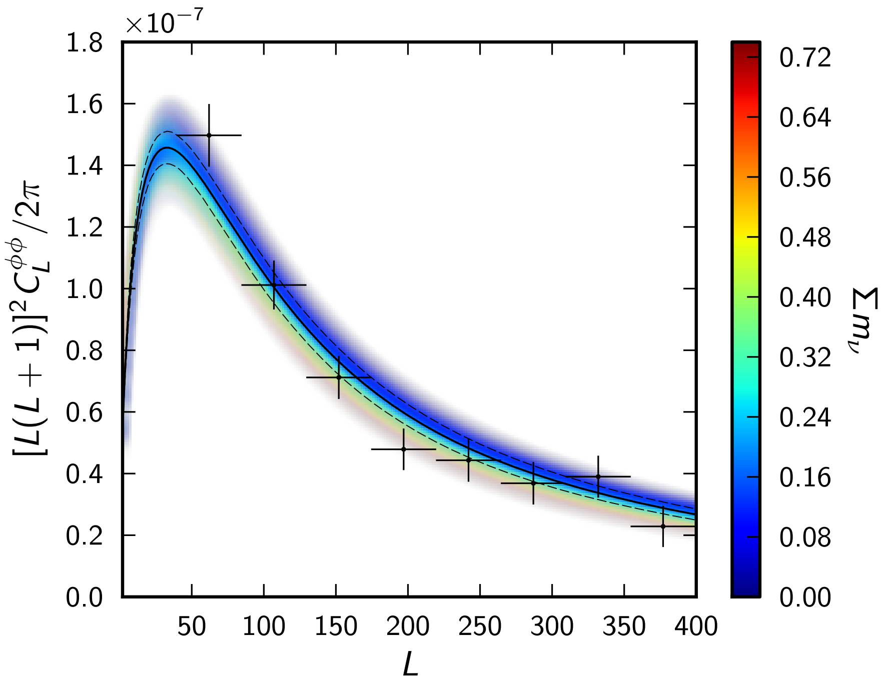


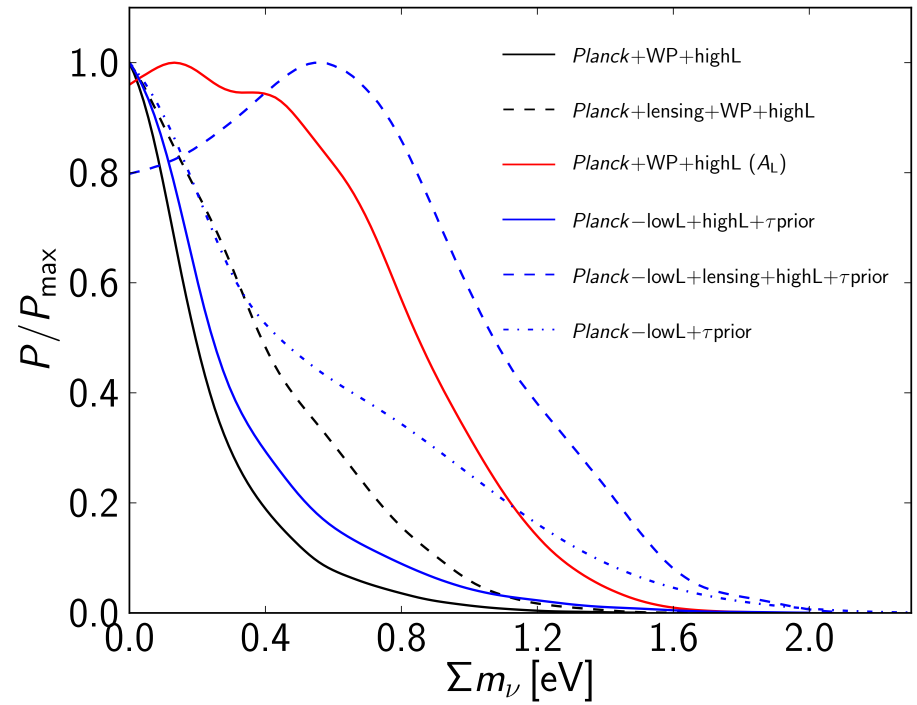
$\Omega_K = -0.0096^{+0.010}_{-0.0082}$ (68%; Planck+lensing+WP+highL)

$\Omega_\Lambda = 0.67^{+0.027}_{-0.023}$ (68%; Planck+lensing+WP+highL)

- Spatial flatness to 1% from CMB alone
  - Improves to $\Omega_K = -0.0005 \pm 0.0033$ including BAO

Neutrino masses





$$\sum m_\nu < \begin{cases} 0.66\,\text{eV} & \text{(95%; Planck+WP+highL)} \\ 1.08\,\text{eV} & \text{(95%; Planck+WP+highL } A_L\text{)} \\ 0.85\,\text{eV} & \text{(95%; Planck+lensing+WP+highL)} \\ 0.23\,\text{eV} & \text{(95%; Planck+WP+highL+BAO)} \end{cases}$$

- Planck TT constraint driven by lens smoothing
- Constraints degrade allowing for curvature [e.g. $\sum m_\nu < 0.32$ eV (95%; Planck+WP+highL+BAO)]

- Seven acoustic peaks measured in TT spectrum
- Lensing deflection spectrum measured at $25\,\sigma$
- Excellent consistency on intermediate and small scales with LCDM
  - But lack of power on large scales “drives” several marginal ($2\,\sigma$) results: A_{L} and $dn_{\mathrm{s}}/d\ln k$
- Also some tensions with SNe Ia and direct H_0 measurements
  - Relieved with new physics (e.g. N_{eff}) *but not favoured significantly by Planck*
- Expect better polarization, lensing etc. in future releases