

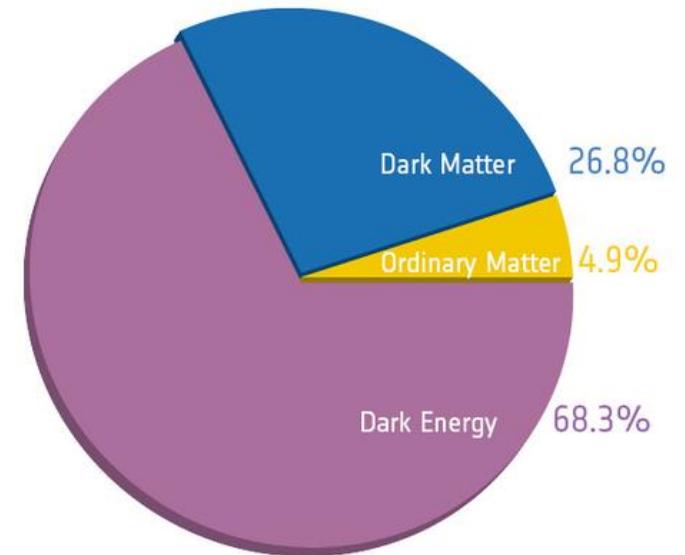
Planck: 2013 results and future prospects

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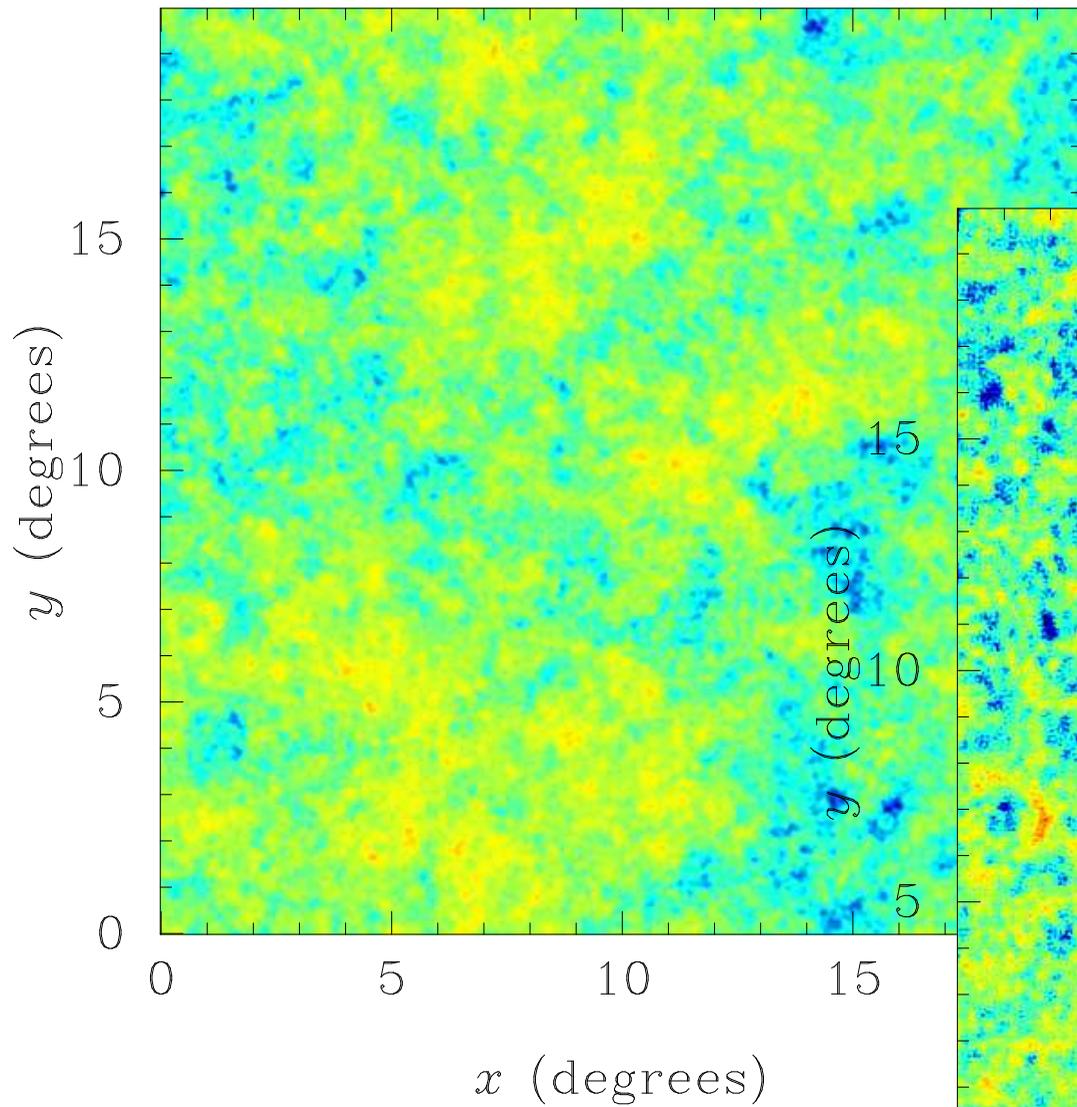
STANDARD COSMOLOGICAL MODEL

- Matter and geometry:
 - Flat universe (trivial topology)
 - SM baryons (inc. charged leptons)
 - Photons
 - 3 ν families (one massive state at 0.06 eV)
 - CDM (negligible velocity dispersion and interactions)
 - Cosmological constant (vacuum energy)
- Inflation-like primordial curvature perturbations
 - Adiabatic
 - Gaussian
 - Power-law spectrum

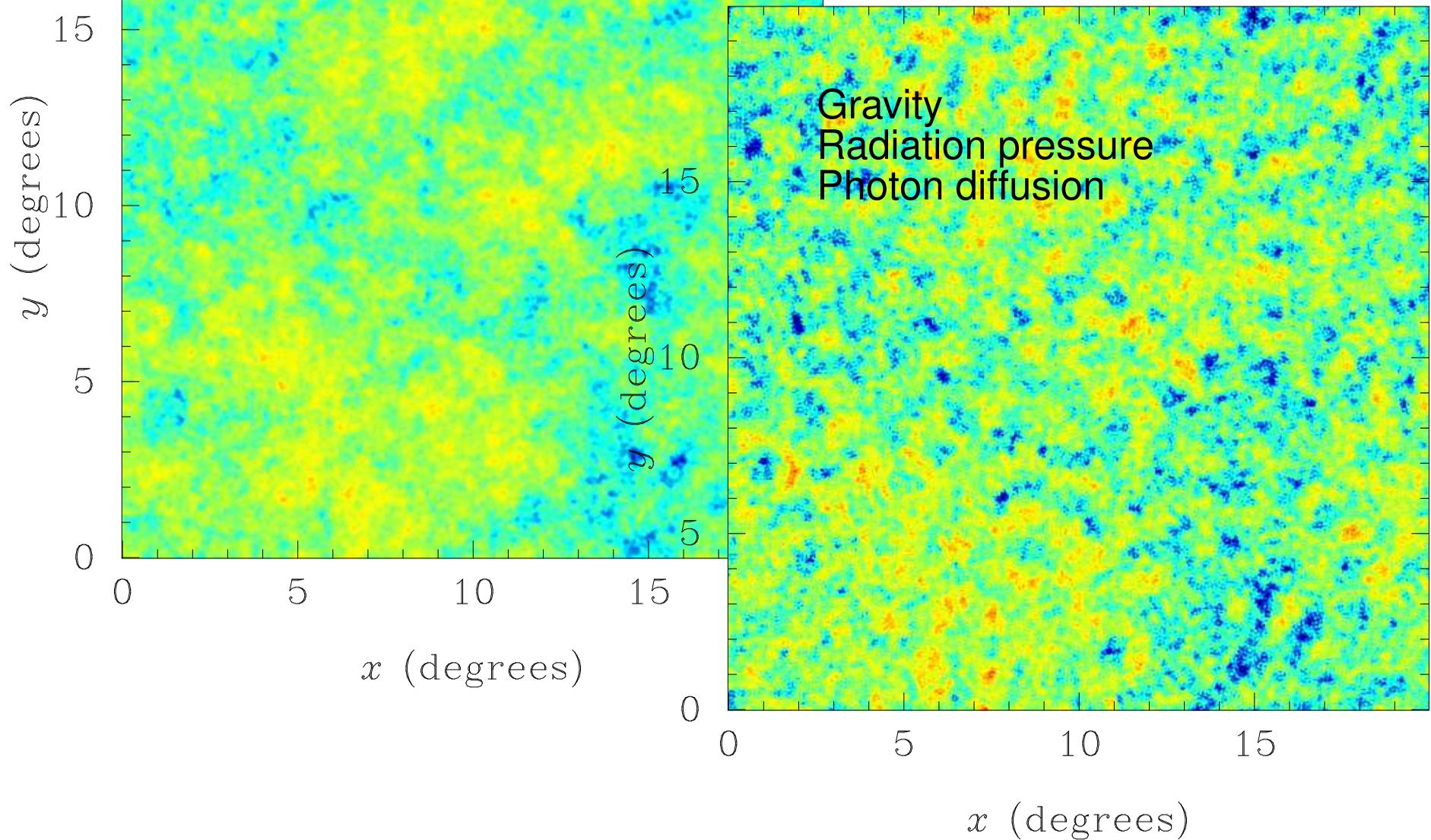


LINEAR PROCESSING OF PRIMORDIAL FLUCTUATIONS

Primordial

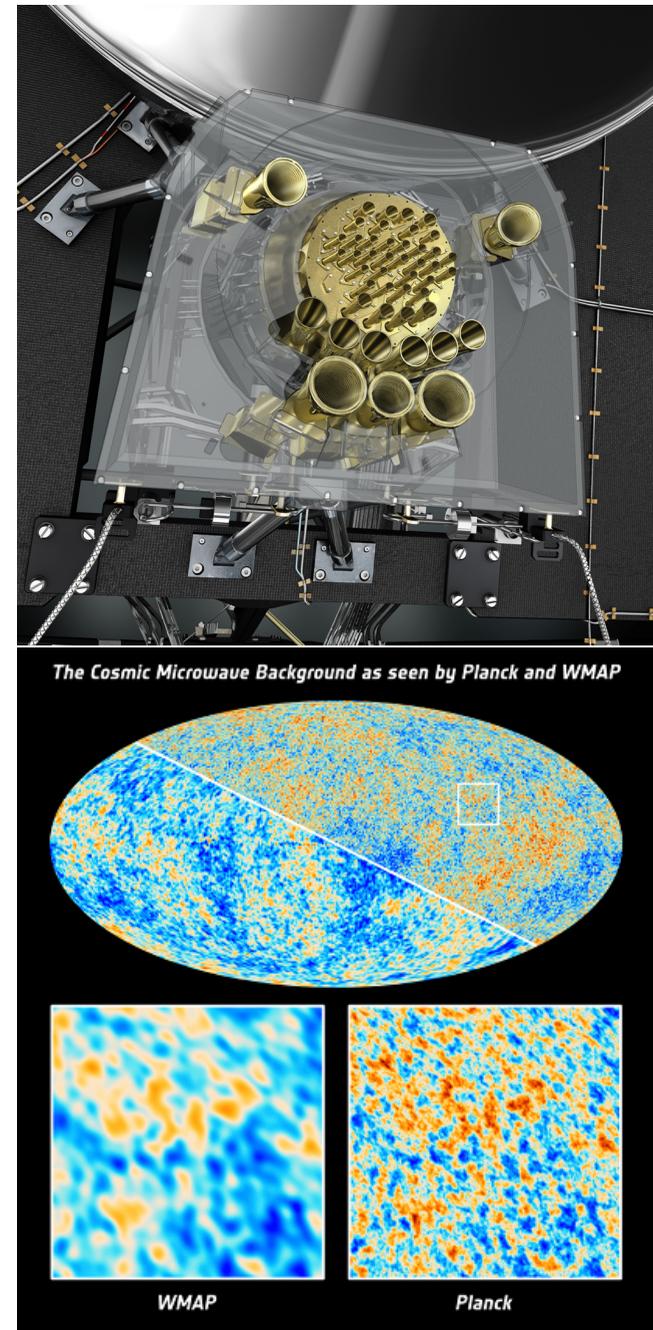


Processed

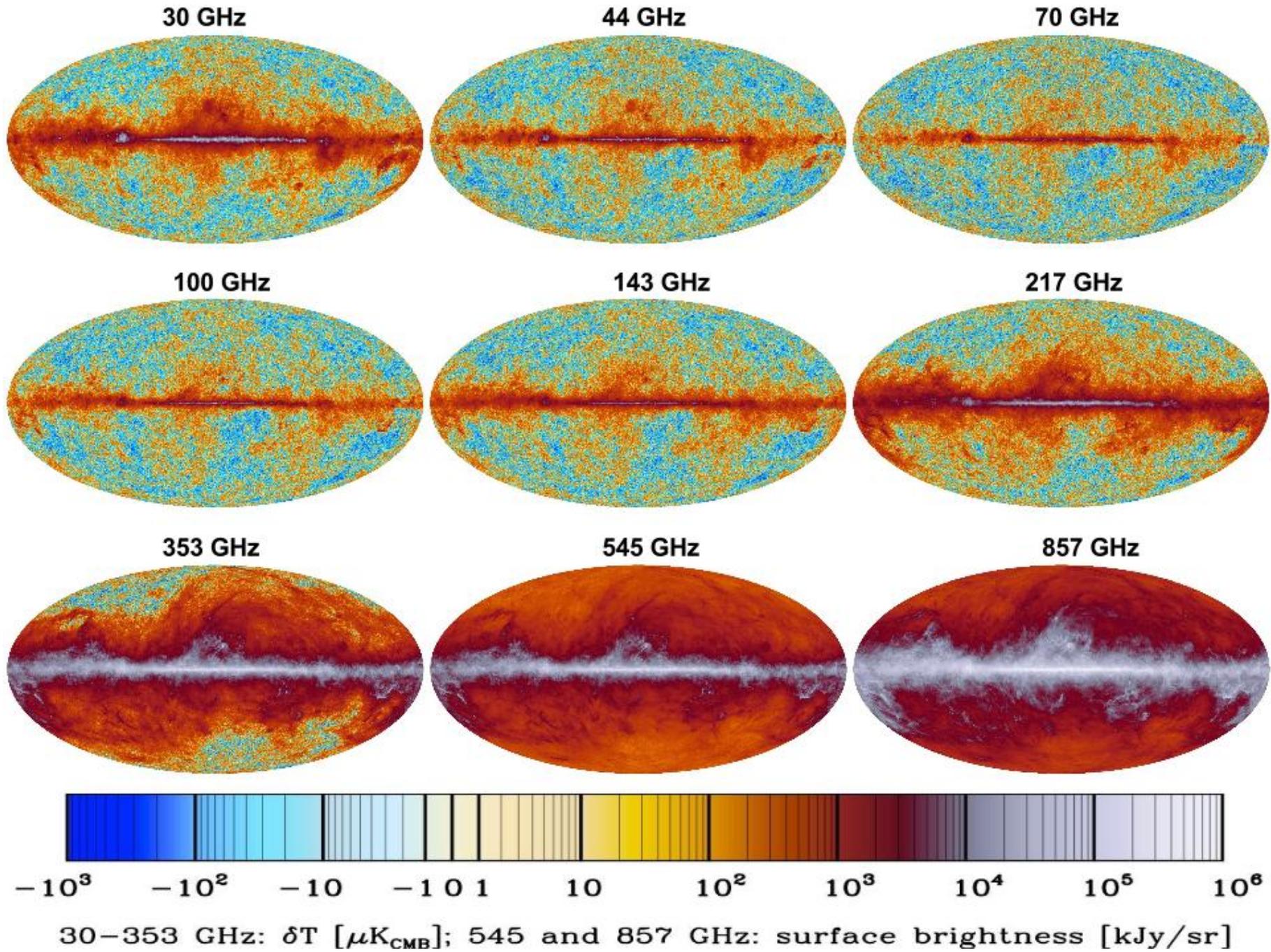


PLANCK MISSION

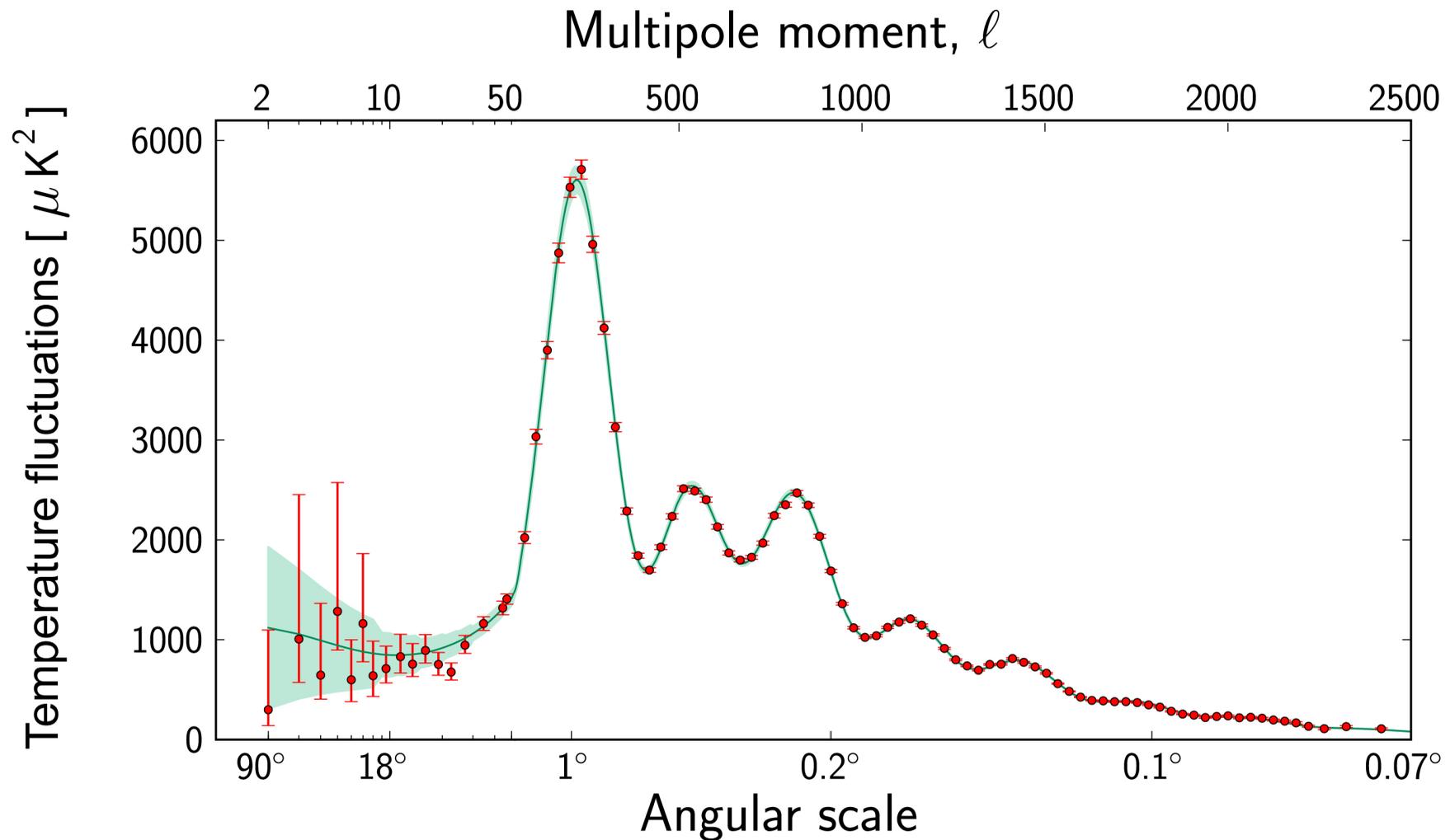
- Design goal: measure CMB ΔT to fundamental limits on scales > 5 arcmin
- Launched (with Herschel) 14 May 2009
- HFI operated to January 2012 completing 5 sky surveys
- LFI operated to October 2013
- Nine frequencies covering 30–857 GHz
- $3\times$ resolution of WMAP
- $\sim 20\times$ instantaneous sensitivity
- Nominal Planck survey $7\times$ sensitivity of WMAP9



PLANCK MAPS

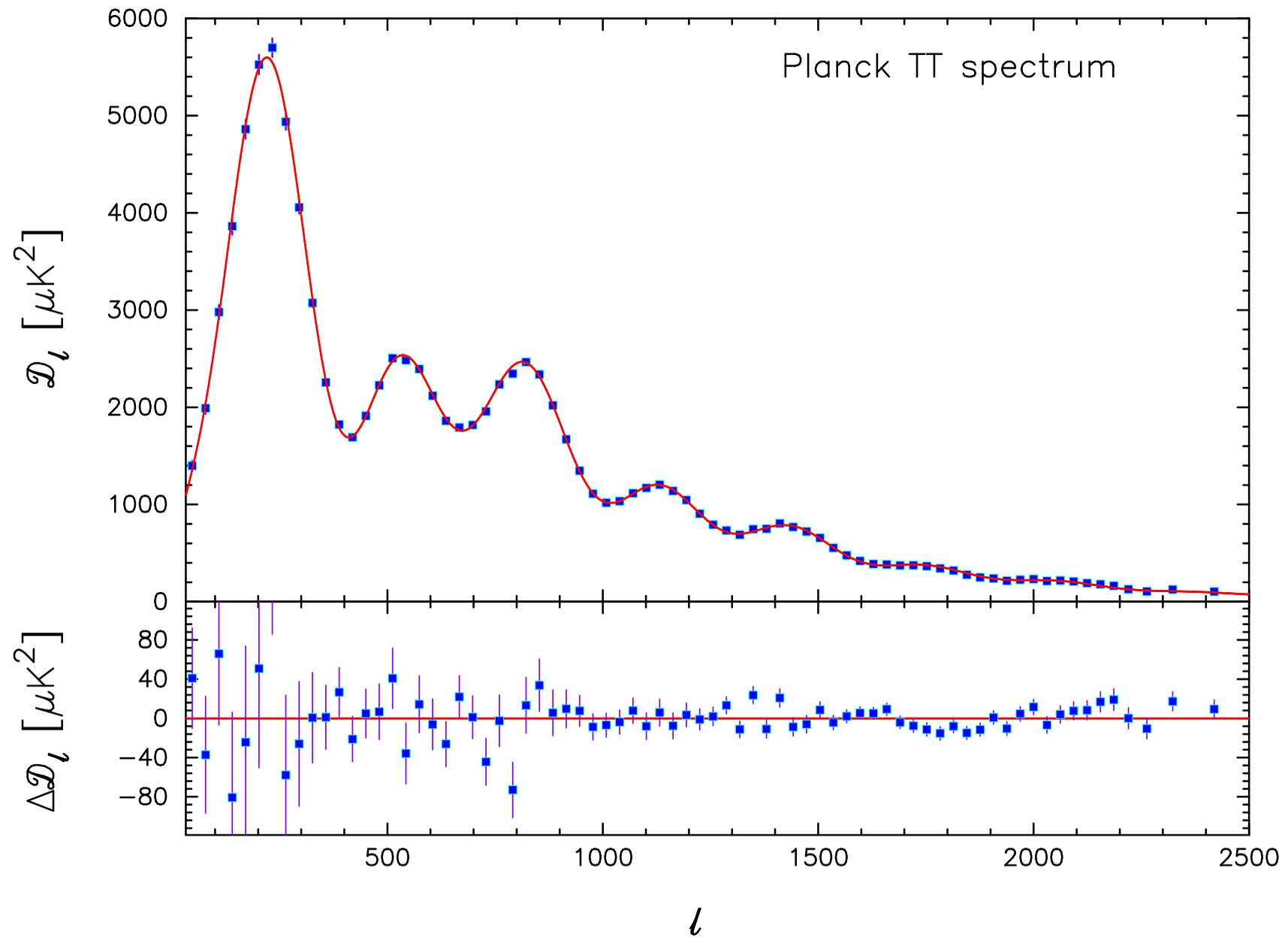


“PLANCK POWER SPECTRUM”



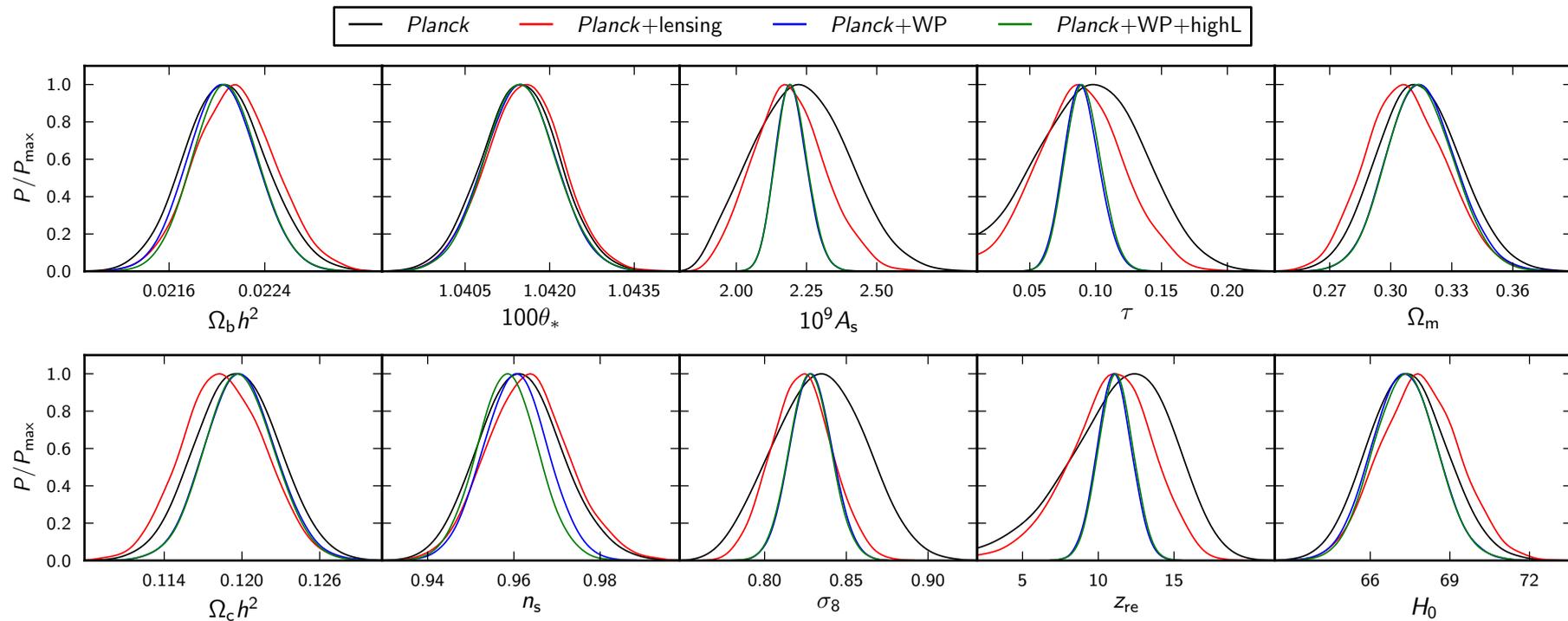
- $l < 50$: maximum-likelihood solution with parametric map-based foreground cleaning
- $l \geq 50$: best-fit C_l to all cross-spectra after fitting C_l -based foreground templates

LCDM FIT

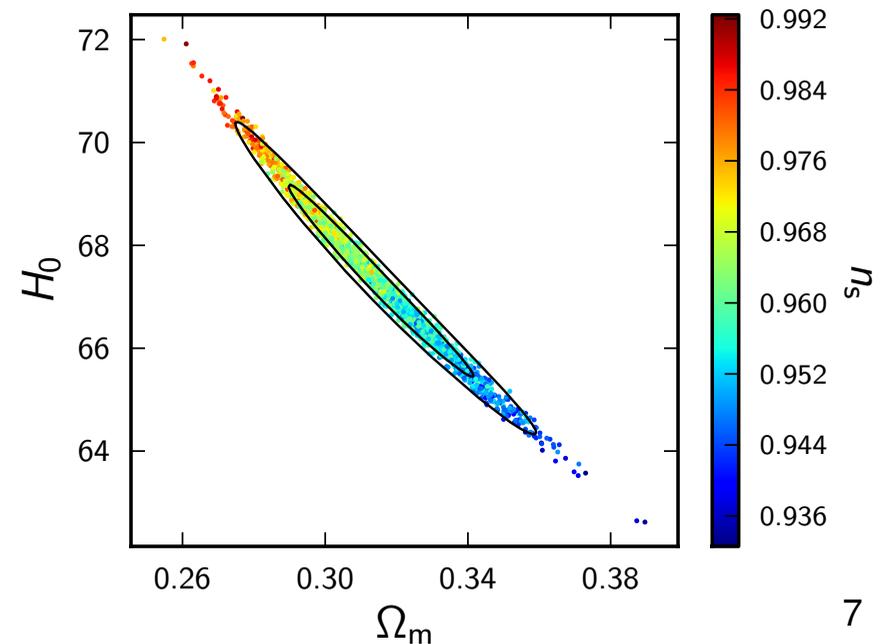


- Acceptable fit to channel spectra and composite spectrum: χ^2 compatible with LCDM to 1.6σ

LCDM PARAMETERS



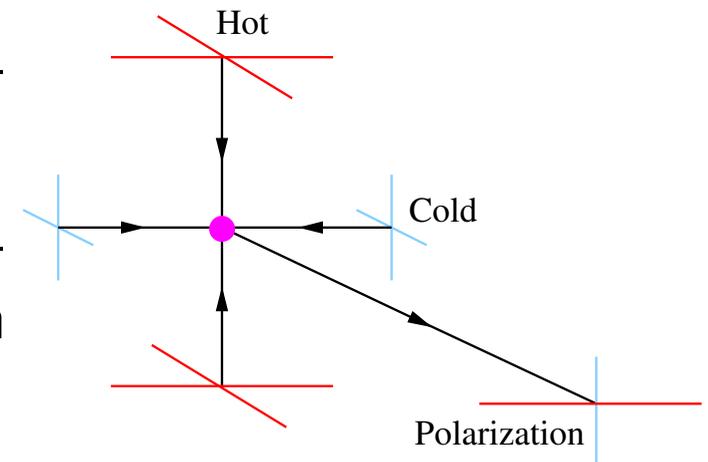
- Percent-level precision
- Not limited by foreground modelling
- Main degeneracy: $\Omega_m h^3 = \text{const.}$
 - 0.06% precision on θ_*
- τ from $TT(+\text{lensing})$ alone



Internal consistency

CMB POLARIZATION

- Photon diffusion around recombination → local temperature quadrupole
 - Subsequent Thomson scattering generates (partial) linear polarization with r.m.s. $\sim 5 \mu\text{K}$ from density perturbations

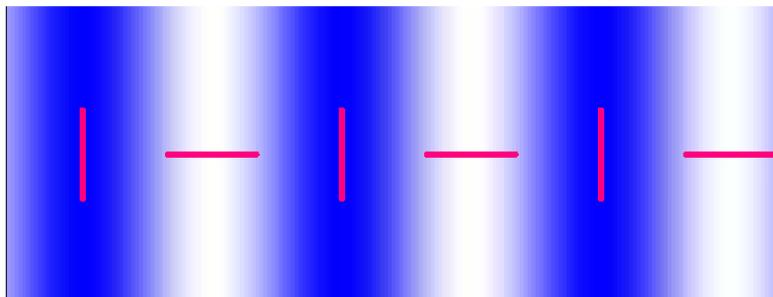


- Decomposition of polarization tensor into E and B modes:

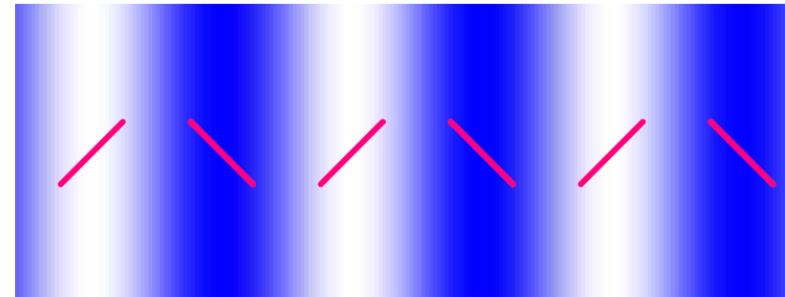
$$\mathcal{P}_{ab}(\hat{n}) \equiv \frac{1}{2} \begin{pmatrix} Q & U \\ U & -Q \end{pmatrix} = \nabla_{\langle a} \nabla_{b \rangle} P_E + \epsilon^c_{(a} \nabla_{b)} \nabla_c P_B$$

- Only three power spectra if parity respected in mean: C_l^E , C_l^B and C_l^{TE}

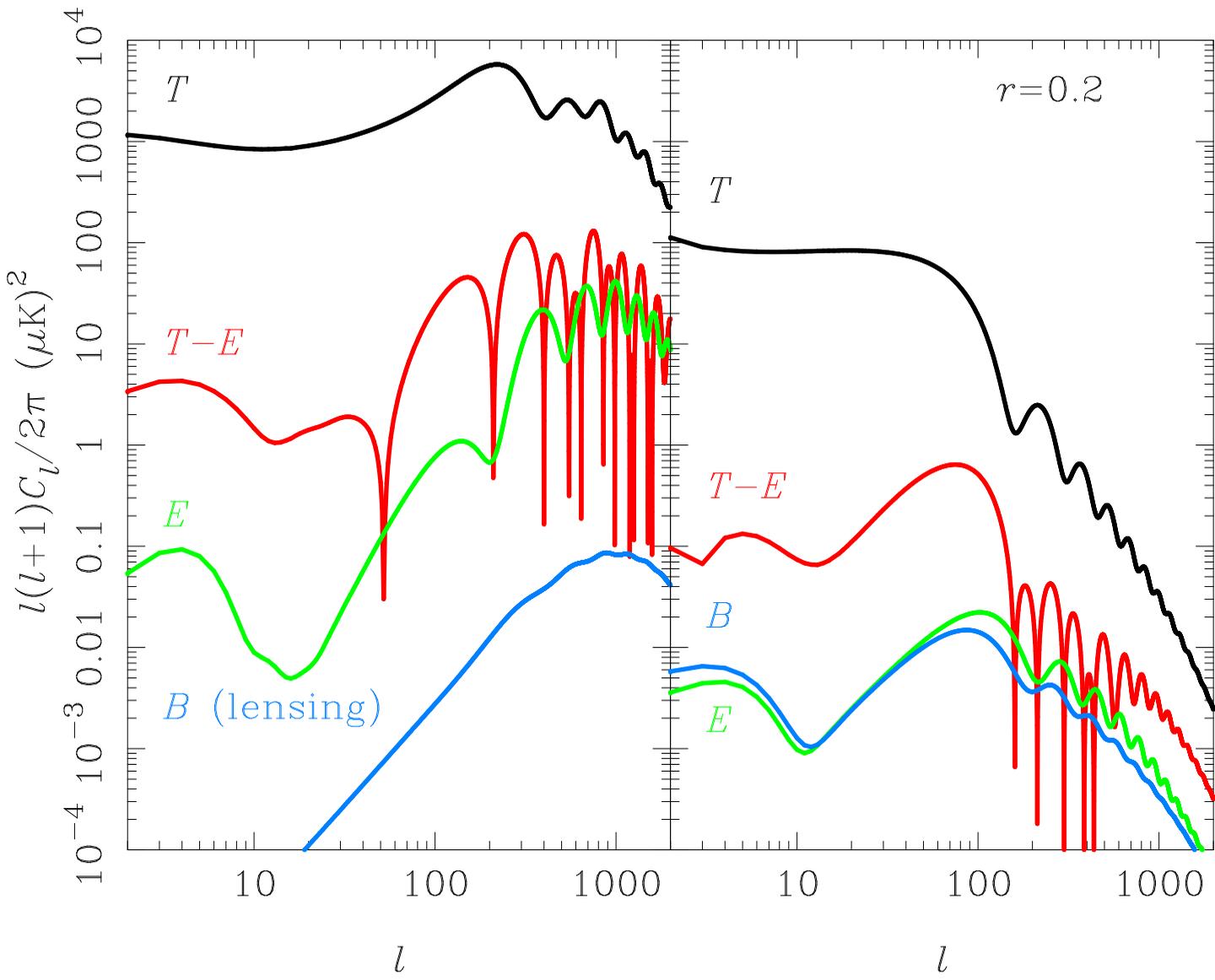
Pure E mode



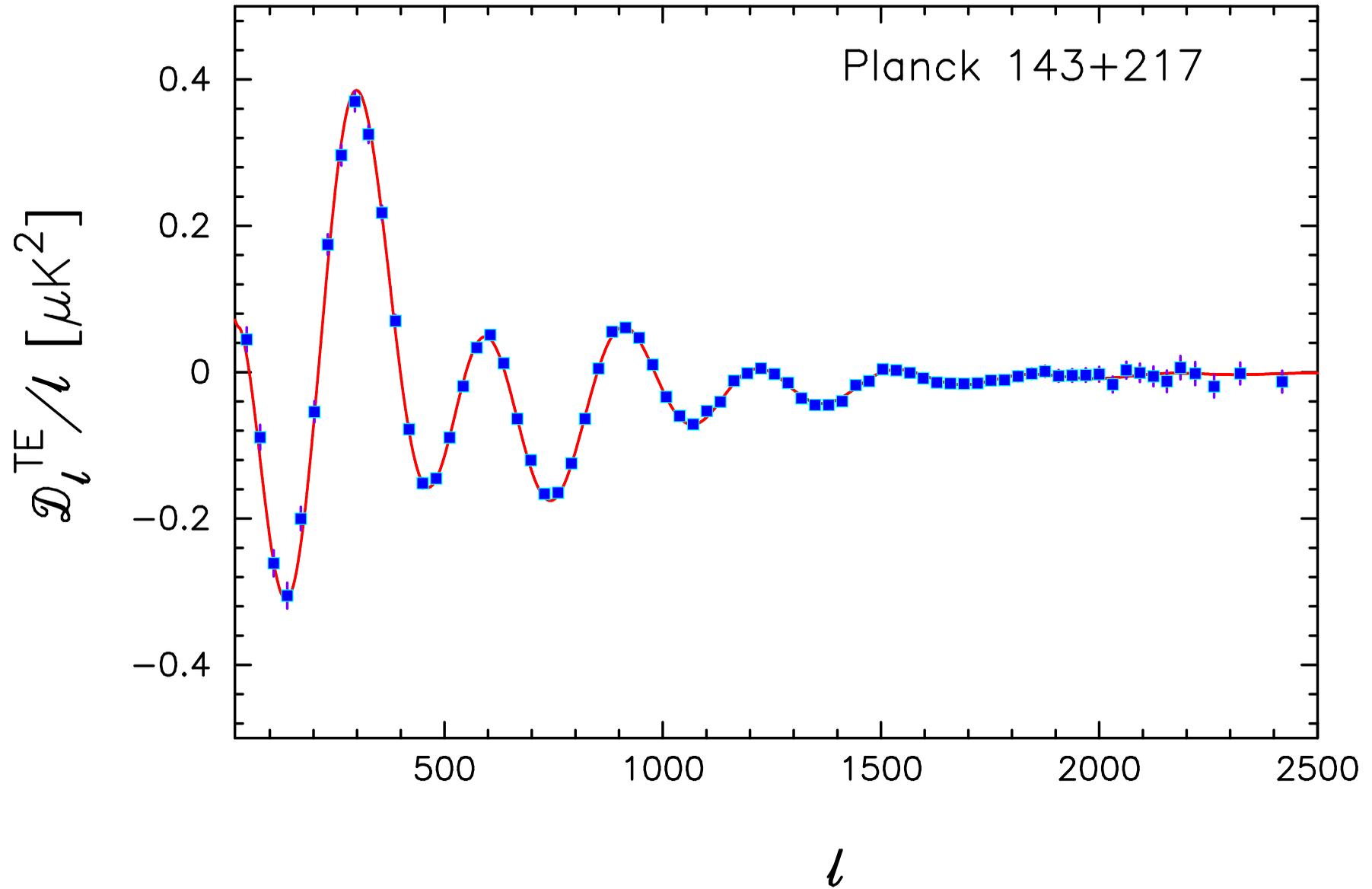
Pure B mode



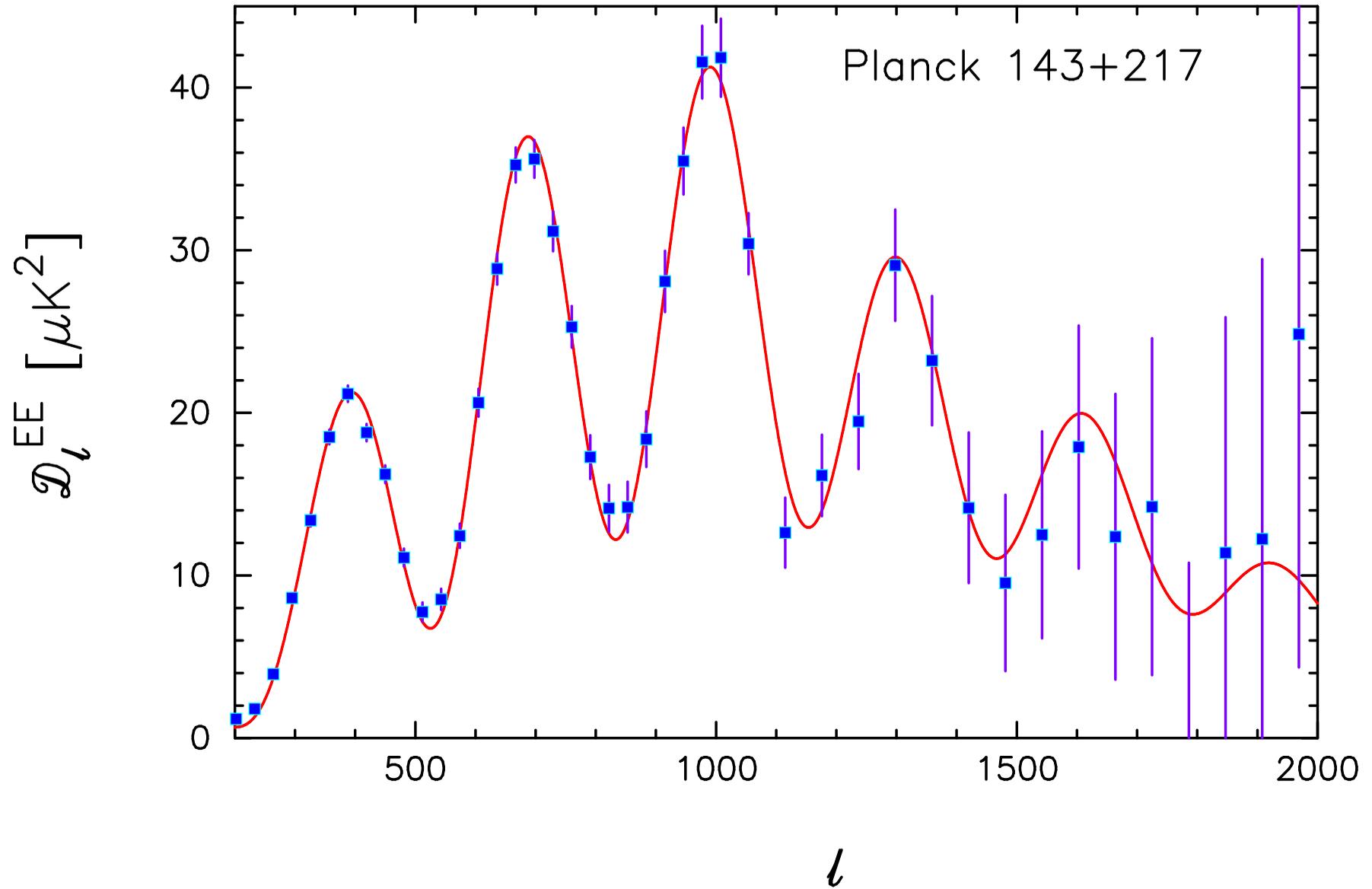
CMB OBSERVABLES



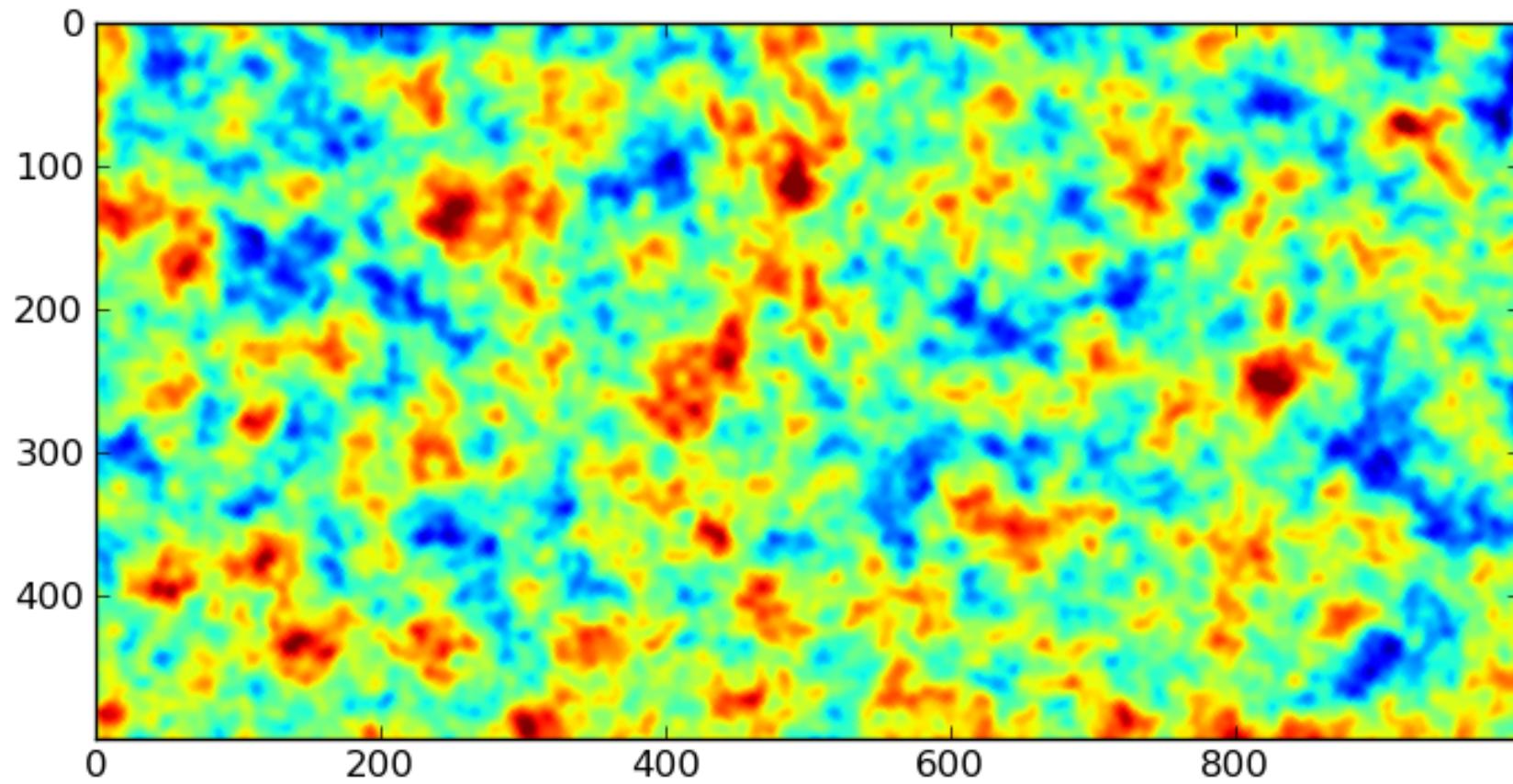
PLANCK POLARIZATION CONSISTENCY



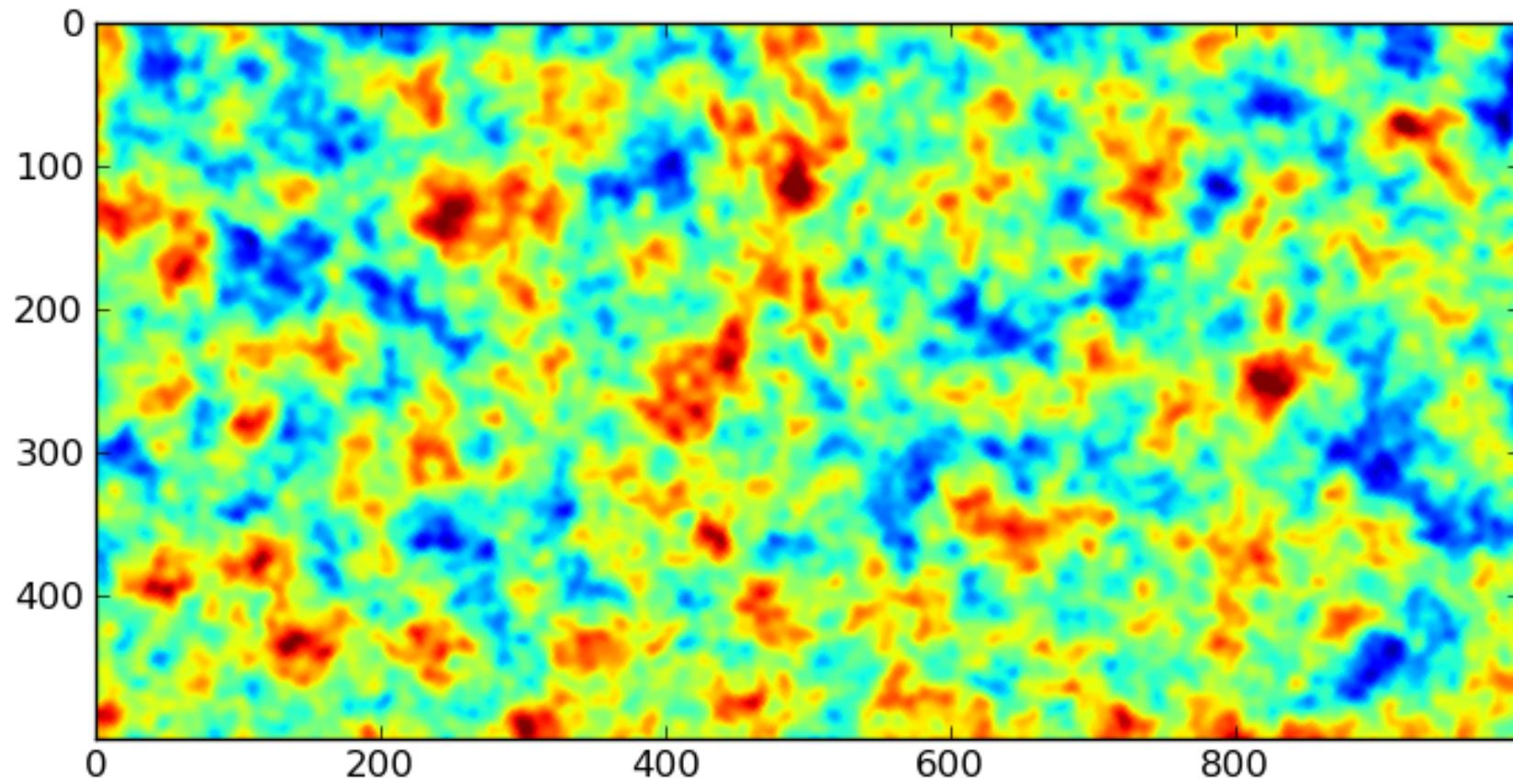
PLANCK POLARIZATION CONSISTENCY



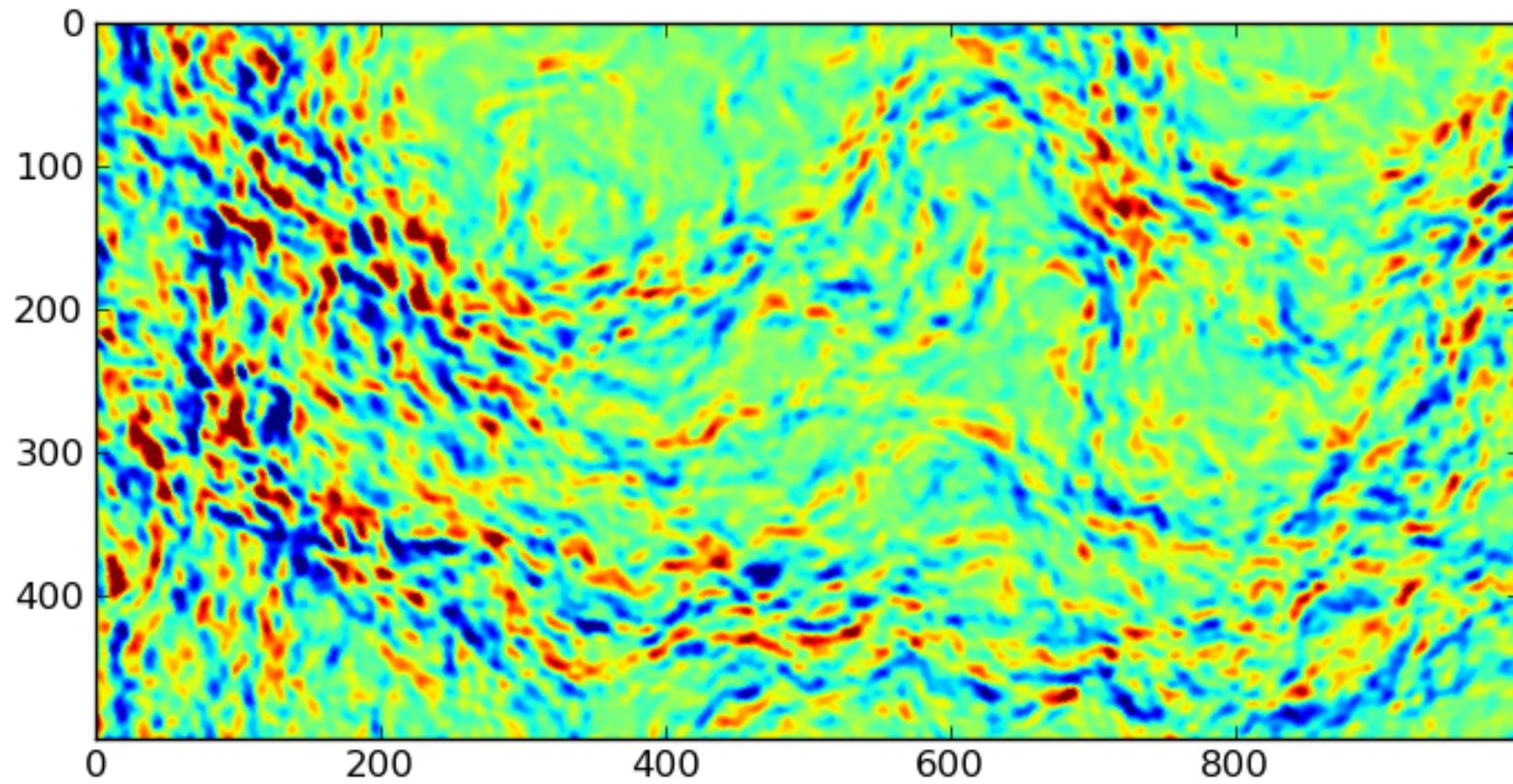
CMB LENSING: UNLENSED TEMPERATURE



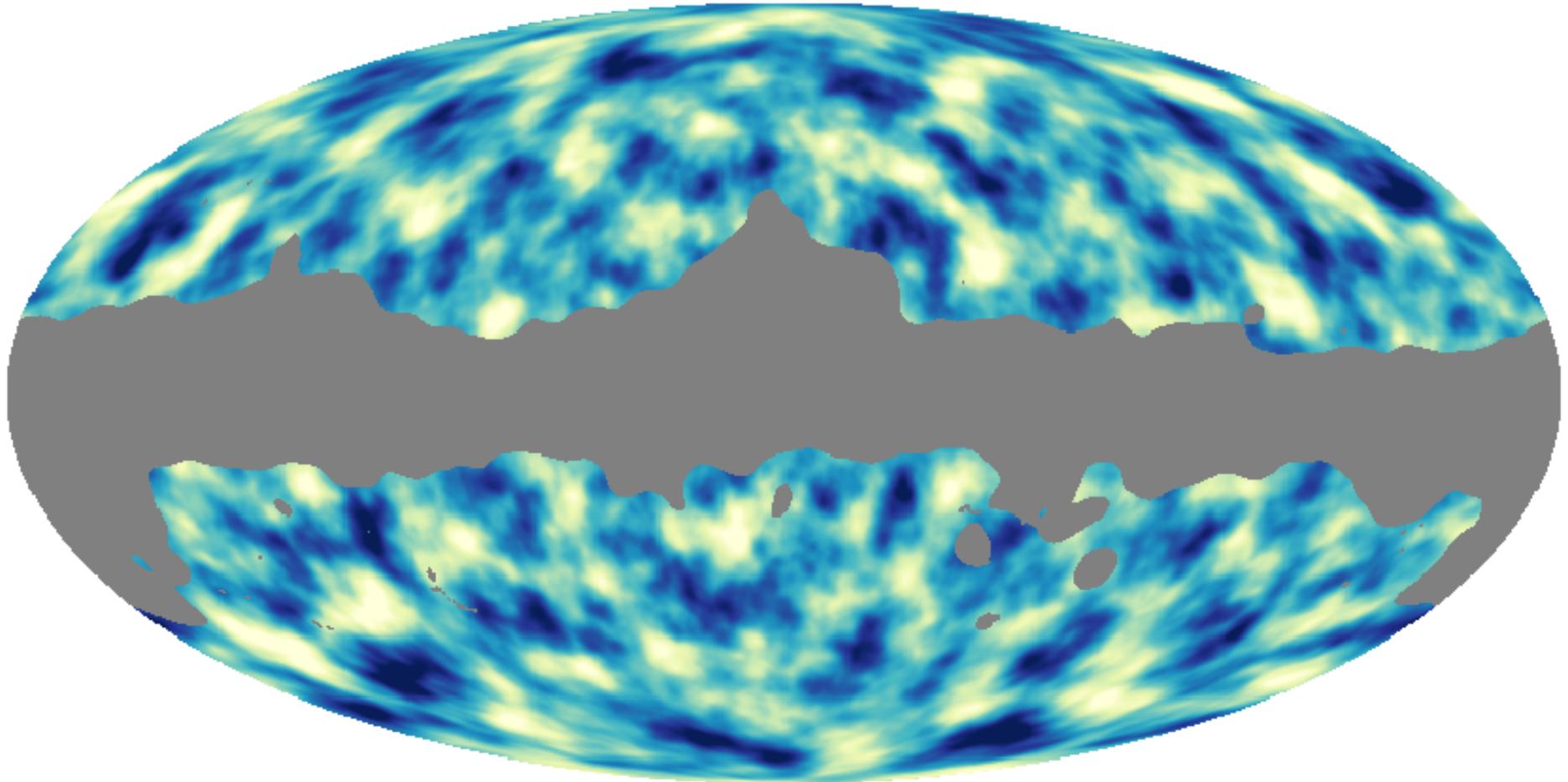
CMB LENSING: LENSED TEMPERATURE



CMB LENSING: LENSING DIFFERENCE

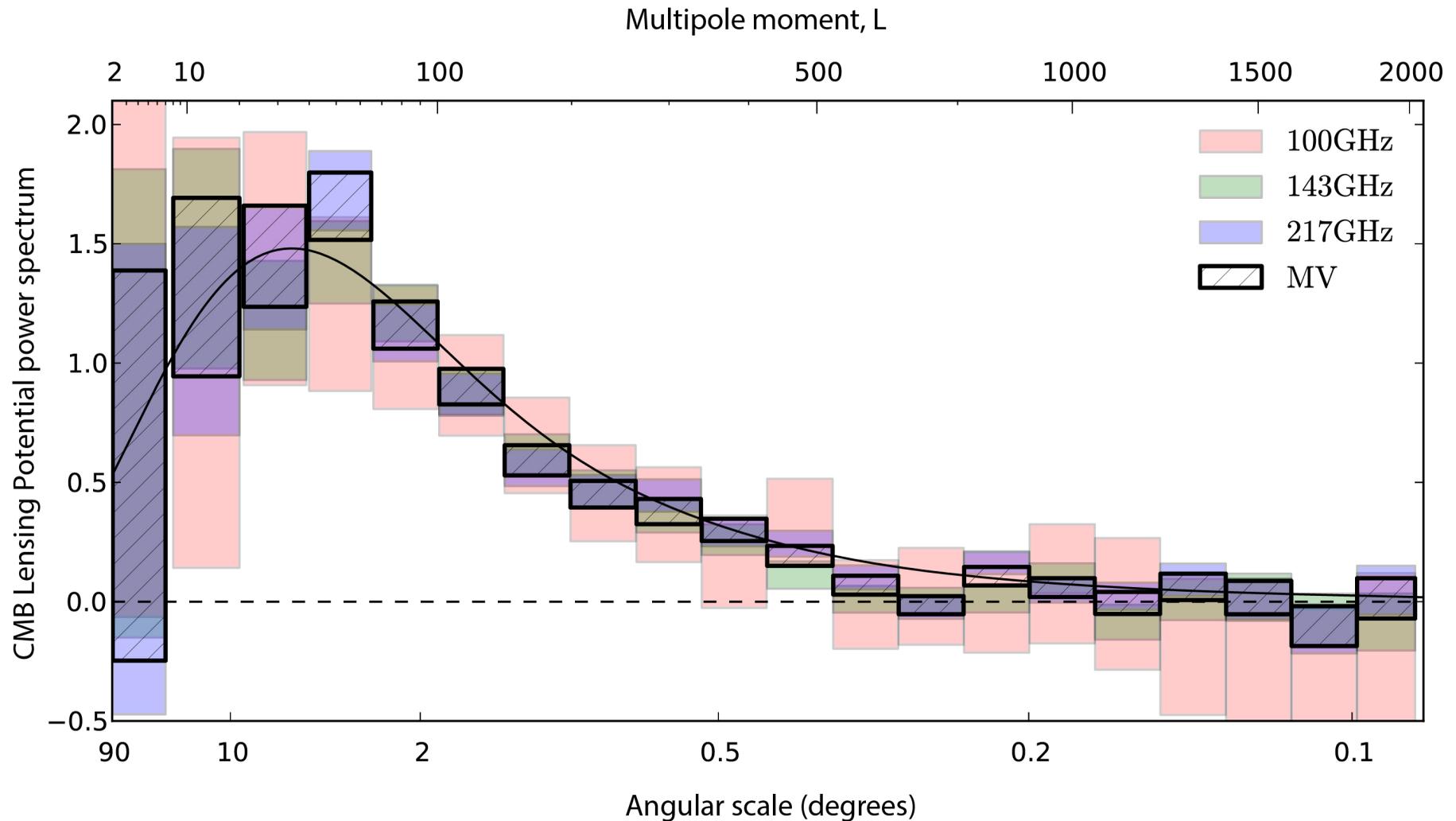


Mollweide view



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

PLANCK LENSING POWER SPECTRUM



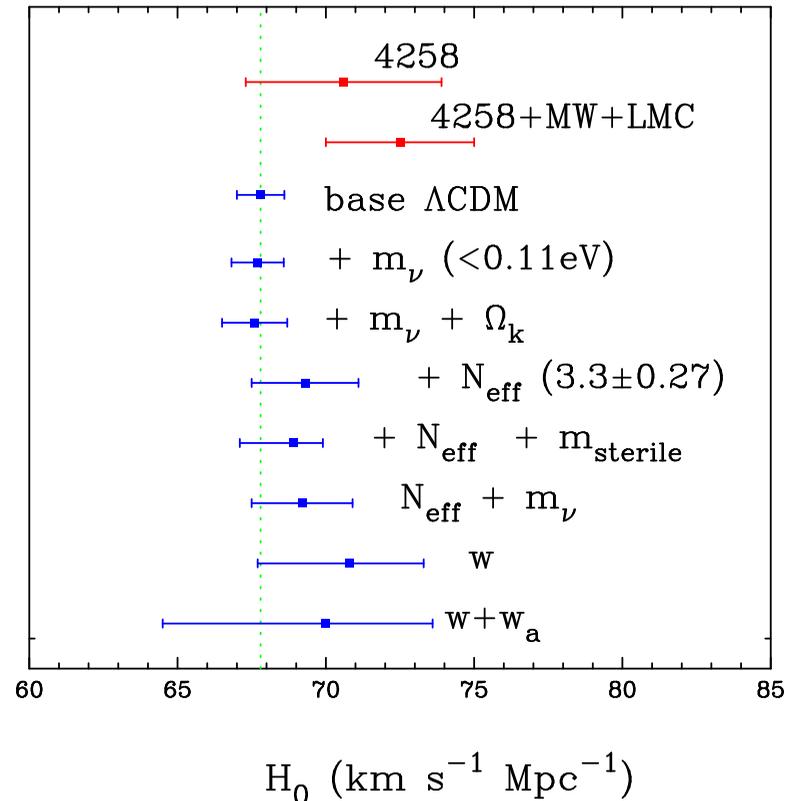
- $> 25\sigma$ detection of non-zero power (via CMB 4-point function)
- Consistent with predicted C_L^ϕ in Λ CDM from Planck TT
 - $\chi^2 = 10.9$ (8 d.o.f.) for $40 \leq L \leq 400$; PTE of 21%

Tensions in Λ CDM

- Hubble constant
- Supernovae
- High- z BAO ($\text{Ly-}\alpha$)
- Clustering (cluster counts, lensing etc.)
- Low- l temperature

HUBBLE CONSTANT

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



Efstathiou (2014)

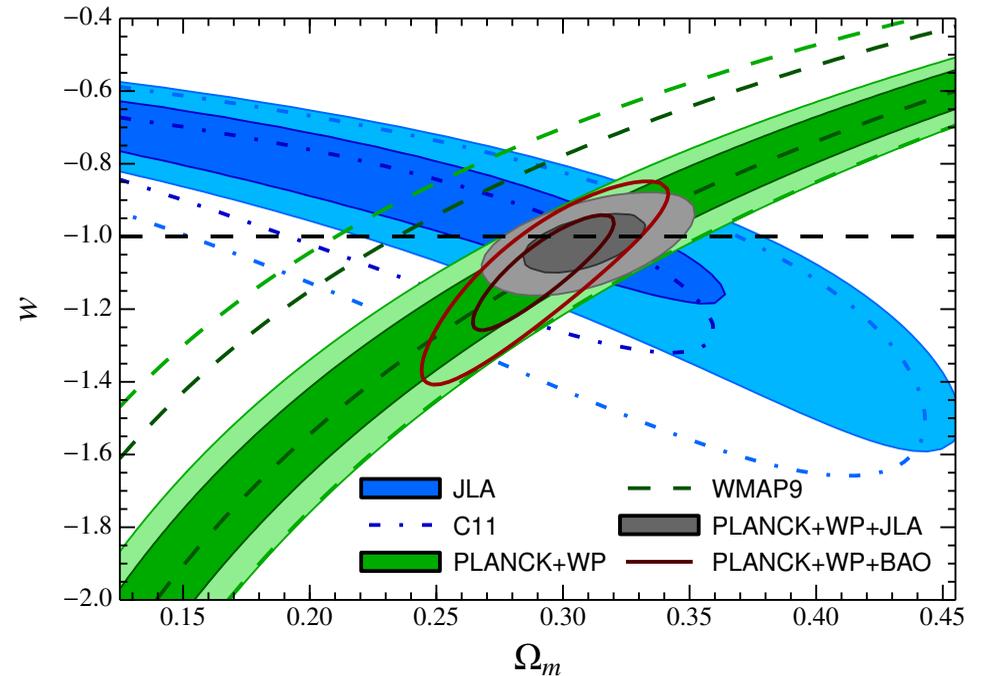
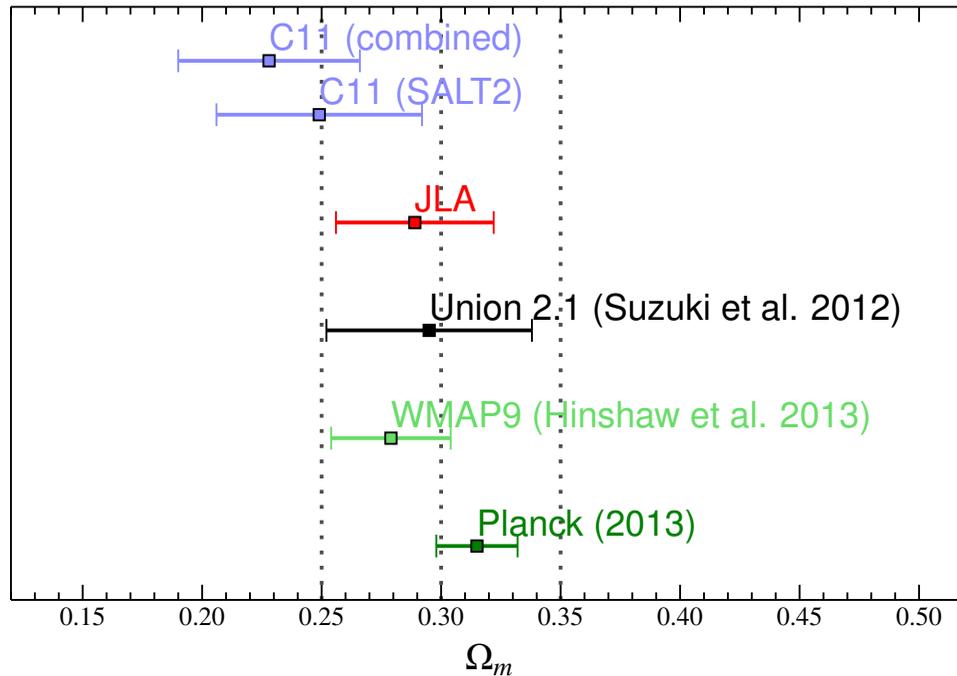
- Tension with Riess+ (2011) Cepheid-SNe Ia determination:

$$H_0 = 73.8 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

- Reduced with Humphreys+ (2013) revised maser distance to NGC4258

SNE IA: JLA UPDATE

$$\Omega_m = 0.315 \pm 0.017 \quad (68\%; \text{Planck+WP+highL}; \text{LCDM})$$



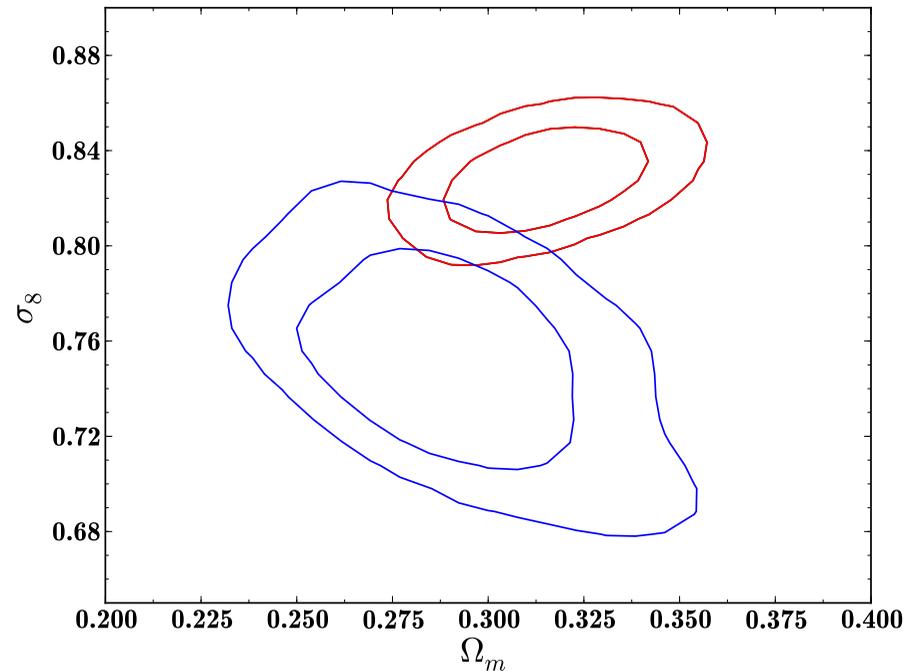
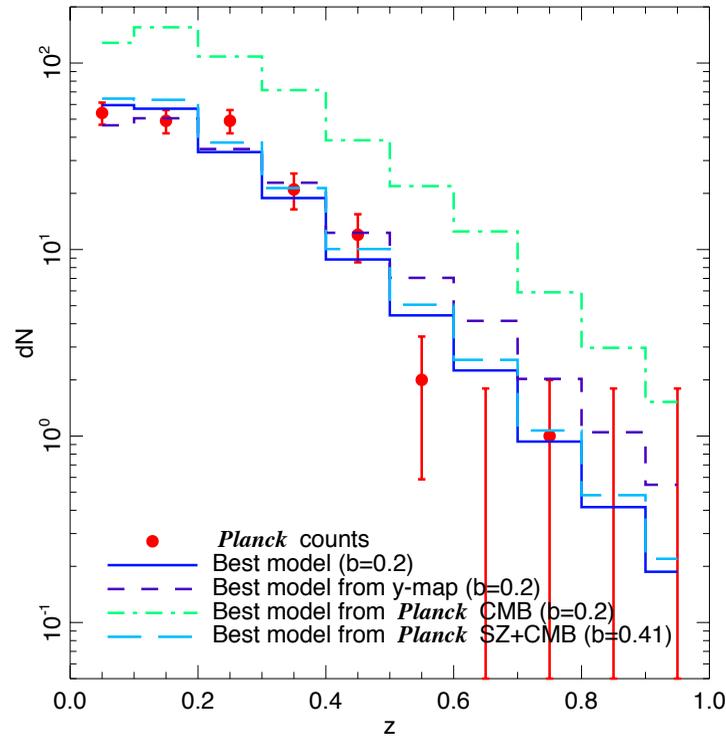
Betoule+ (2014)

- Original tension with SNLSS (Conley+ 2011) reduced with JLA analysis of SDSS-II and SNLS (better photometric calibration etc.):

$$\Omega_m = 0.295 \pm 0.034 \quad (68\%; \text{JLA}; \text{LCDM})$$

- Pull to phantom dark energy ($w < -1$) now gone

PLANCK CLUSTER COUNTS



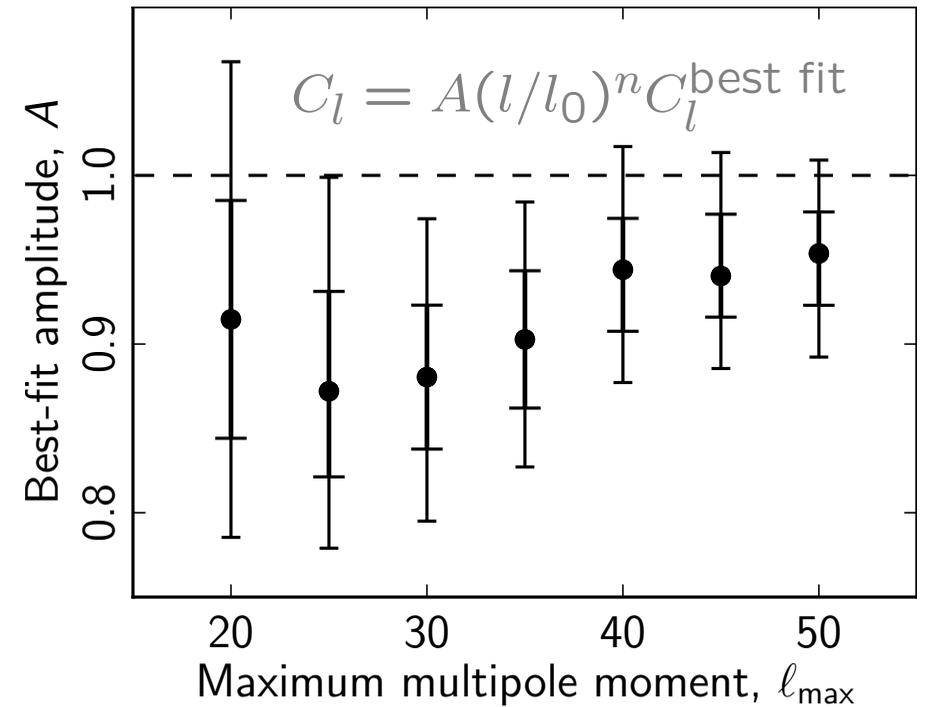
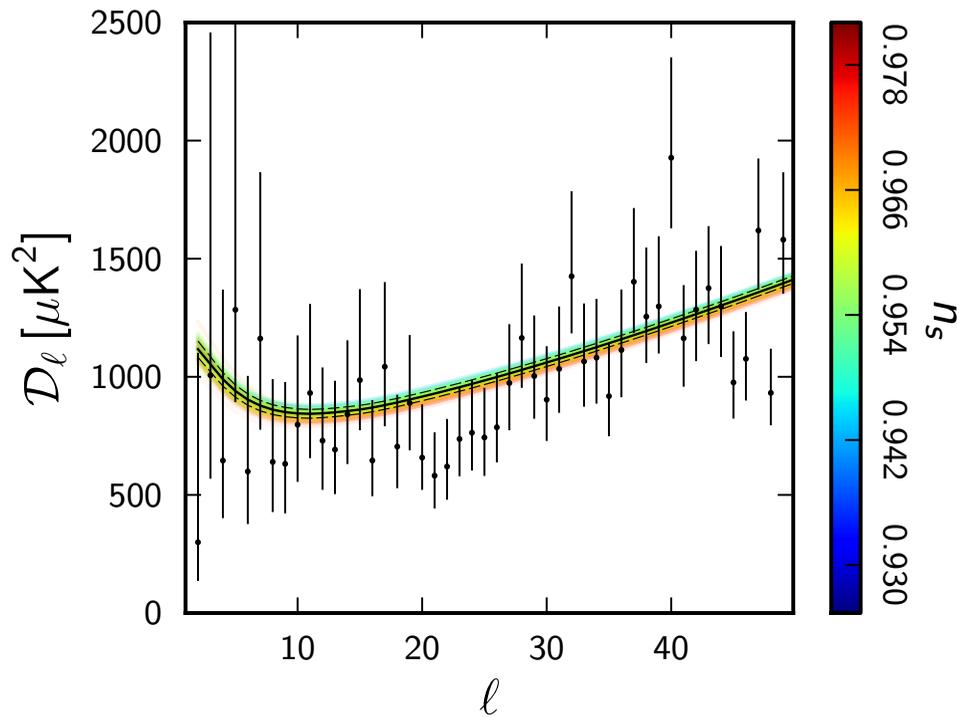
$\sigma_8(\Omega_m/0.27)^{0.3} = 0.76 \pm 0.03$ from 189 $S/N > 7$ SZ (confirmed) clusters

- Planck TT best-fit LCDM model over-predicts number of clusters:

$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.87 \pm 0.02 \quad (68\%; \text{Planck+WP+highL})$$

- 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 σ results in extended models

Constraints on inflation

KEY INFLATIONARY PREDICTIONS (SIMPLE MODELS)

- Spatially-flat universe
- Small curvature fluctuations with almost scale-invariant, power-law spectrum

$$\mathcal{P}_{\mathcal{R}}(k) \approx A_s (k/k_0)^{n_s-1}, \quad A_s = \frac{H^2}{8\pi^2 \epsilon_V M_{\text{Pl}}^2}, \quad n_s - 1 = -6\epsilon_V + 2\eta_V$$

– Negligible running: $dn_s/d \ln k = O(n_s - 1)^2$

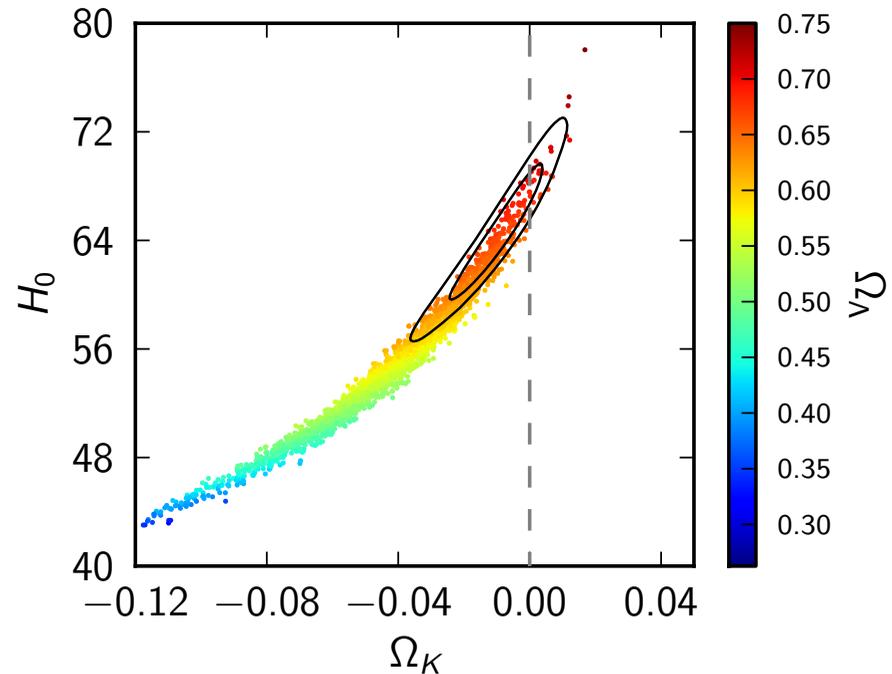
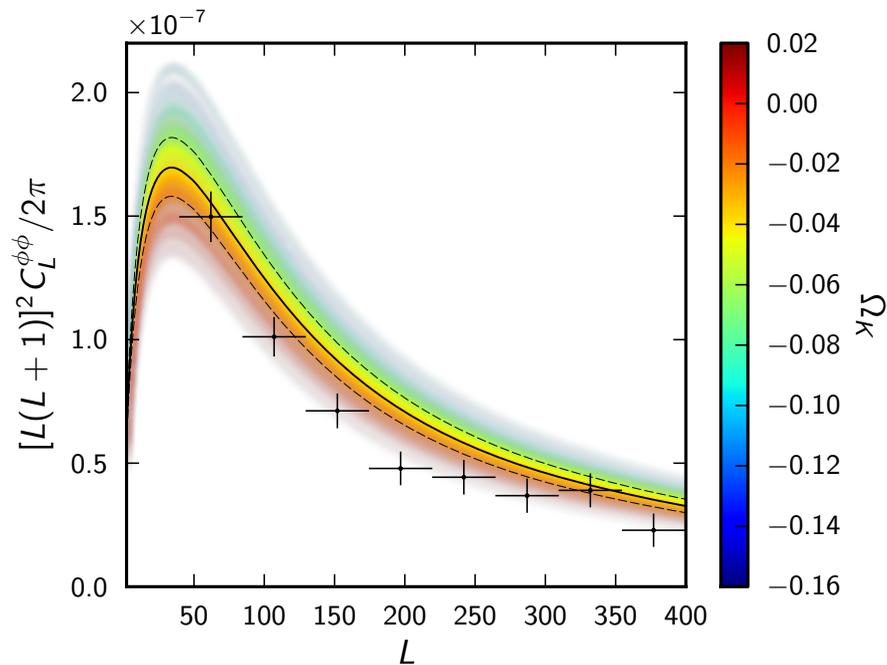
- Adiabatic initial conditions ✓
- Primordial fluctuations should be Gaussian (to observational accuracy) ✓
- Primordial gravitational waves with almost scale-invariant (not blue), power-law spectrum:

$$\mathcal{P}_h(k) \approx A_t (k/k_0)^{n_t}, \quad A_t \equiv r A_s = \frac{2H^2}{\pi^2 M_{\text{Pl}}^2}, \quad n_t = -2\epsilon_V \leq 0$$

– Consistency relation

$$r = -8n_t$$

CURVATURE/DARK ENERGY FROM THE CMB ALONE



$$\Omega_K = -0.0096^{+0.010}_{-0.0082}$$

(68%; Planck+lensing+WP+highL)

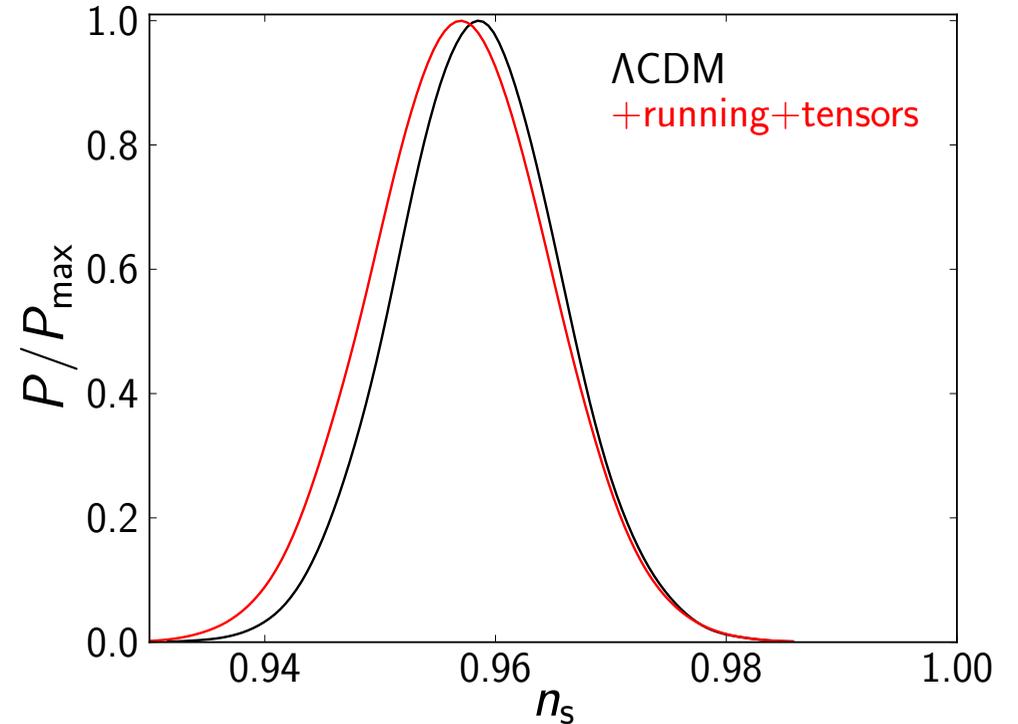
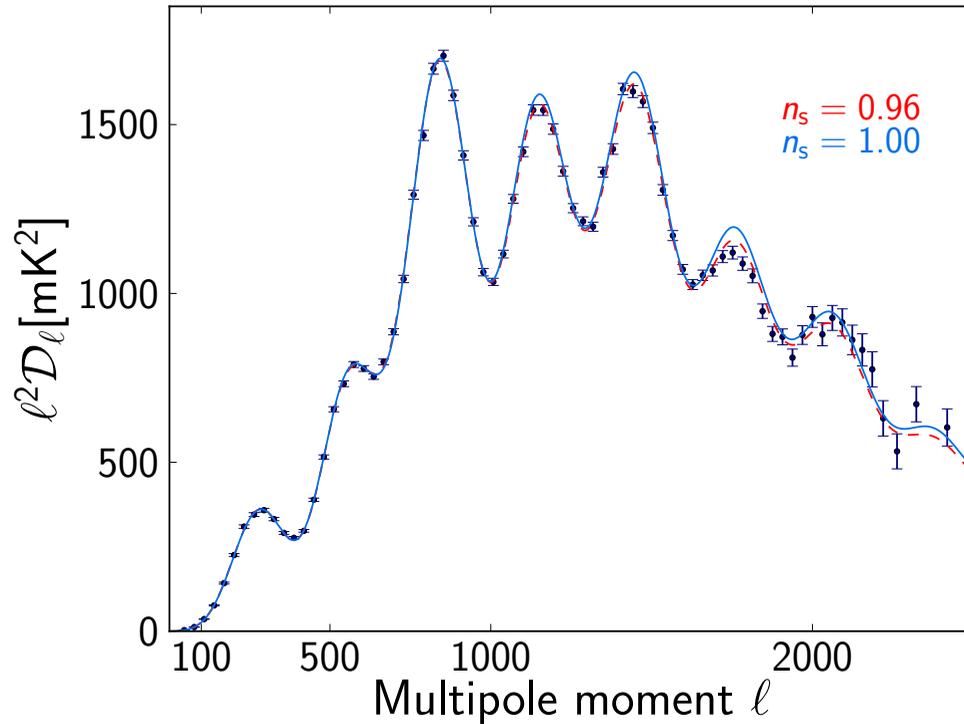
$$\Omega_\Lambda = 0.67^{+0.027}_{-0.023}$$

(68%; Planck+lensing+WP+highL)

- Spatial flatness to 1% from CMB alone

- Improves to $\Omega_K = -0.0005 \pm 0.0033$ including BAO

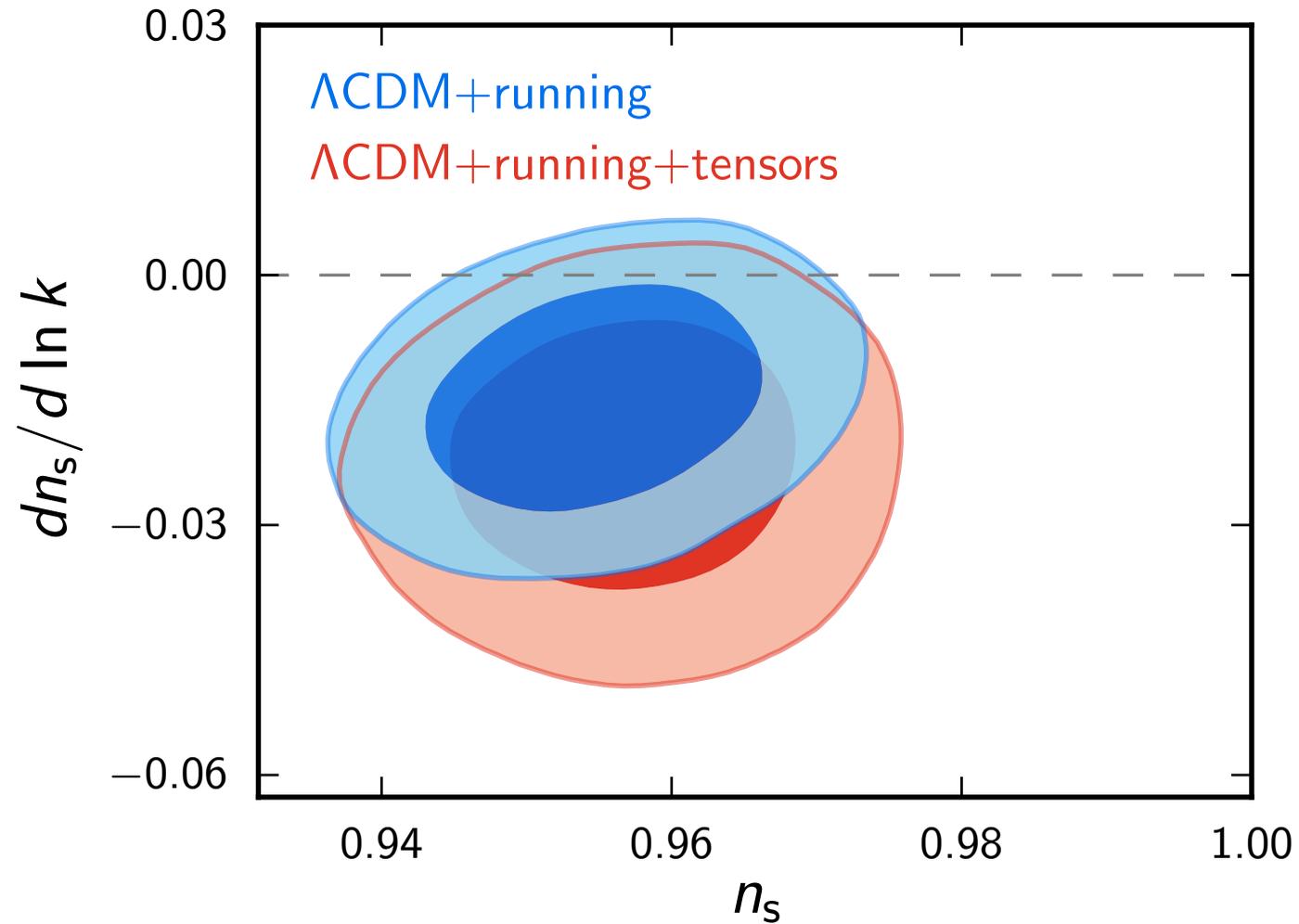
CONSTRAINTS ON INFLATION: n_s



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

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

CONSTRAINTS ON INFLATION: RUNNING



$$dn_s/d \ln k = -0.013 \pm 0.009$$

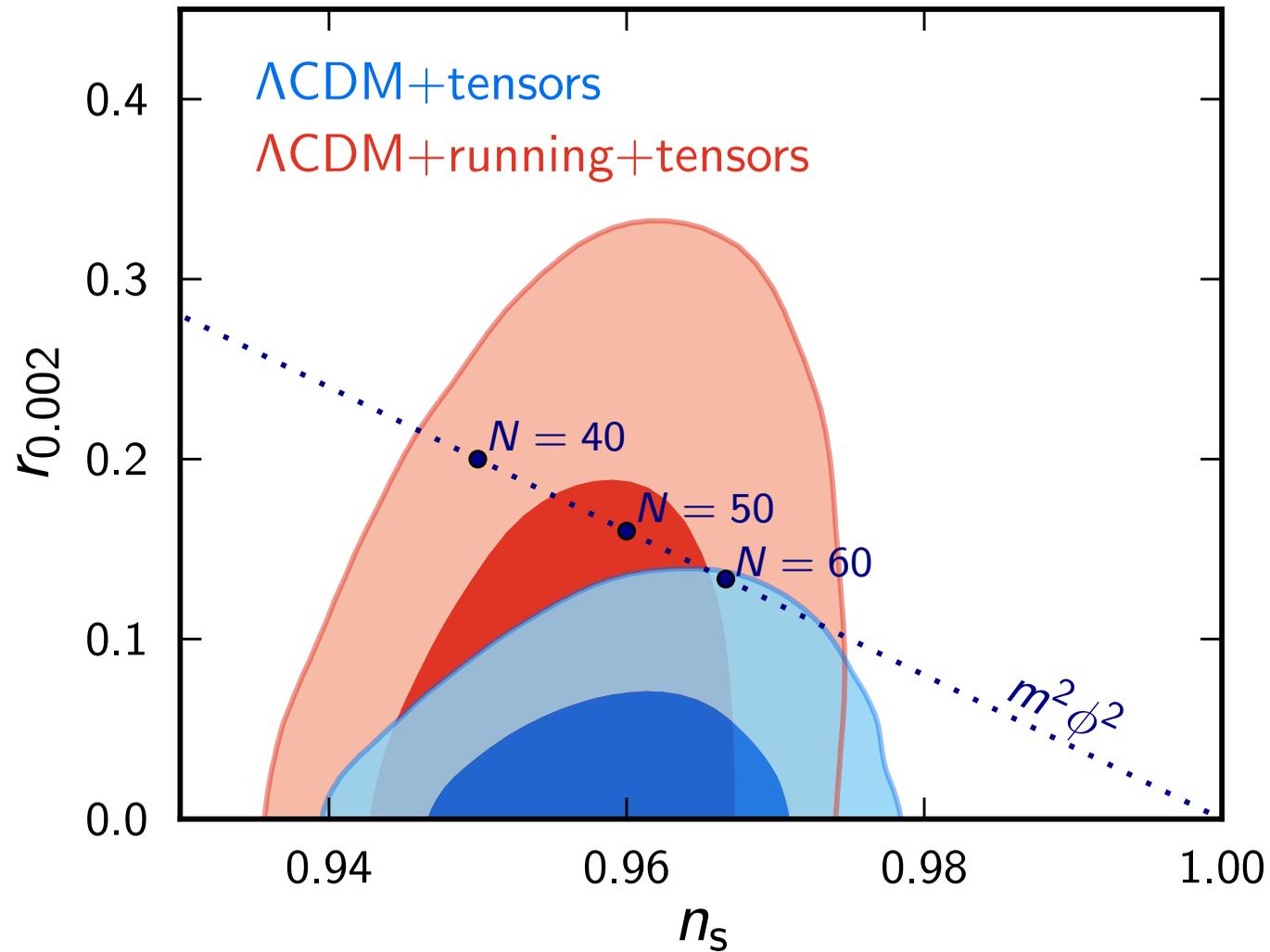
(68%; Planck+WP)

$$dn_s/d \ln k = -0.015 \pm 0.009$$

(68%; Planck+WP+highL)

- Any preference for running is from low- l only

CONSTRAINTS ON INFLATION: TENSORS



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

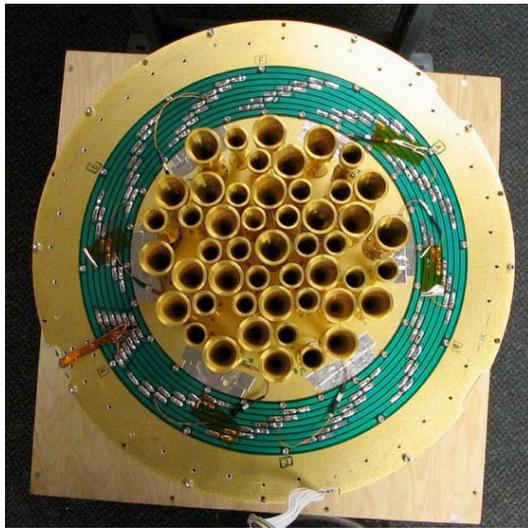
$r_{0.002} < 0.26$ (95%; Planck+WP+highL; running)

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

BICEP

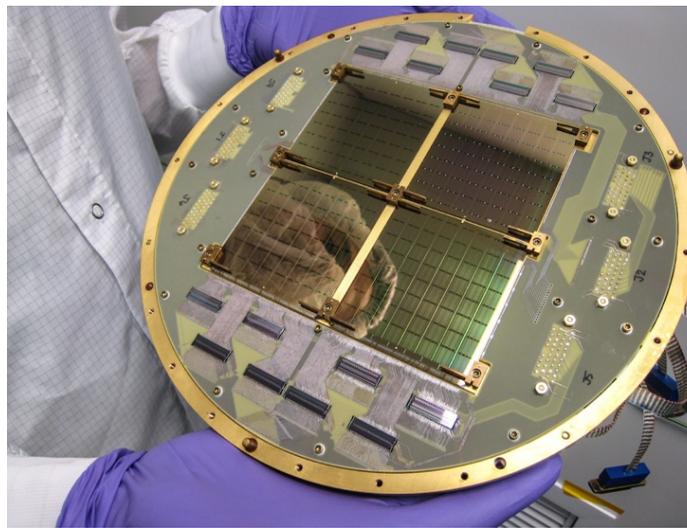
BICEP GENERATIONS

BICEP1



49 dual-pol pixels
100 & 150 GHz
2006–2008

BICEP2



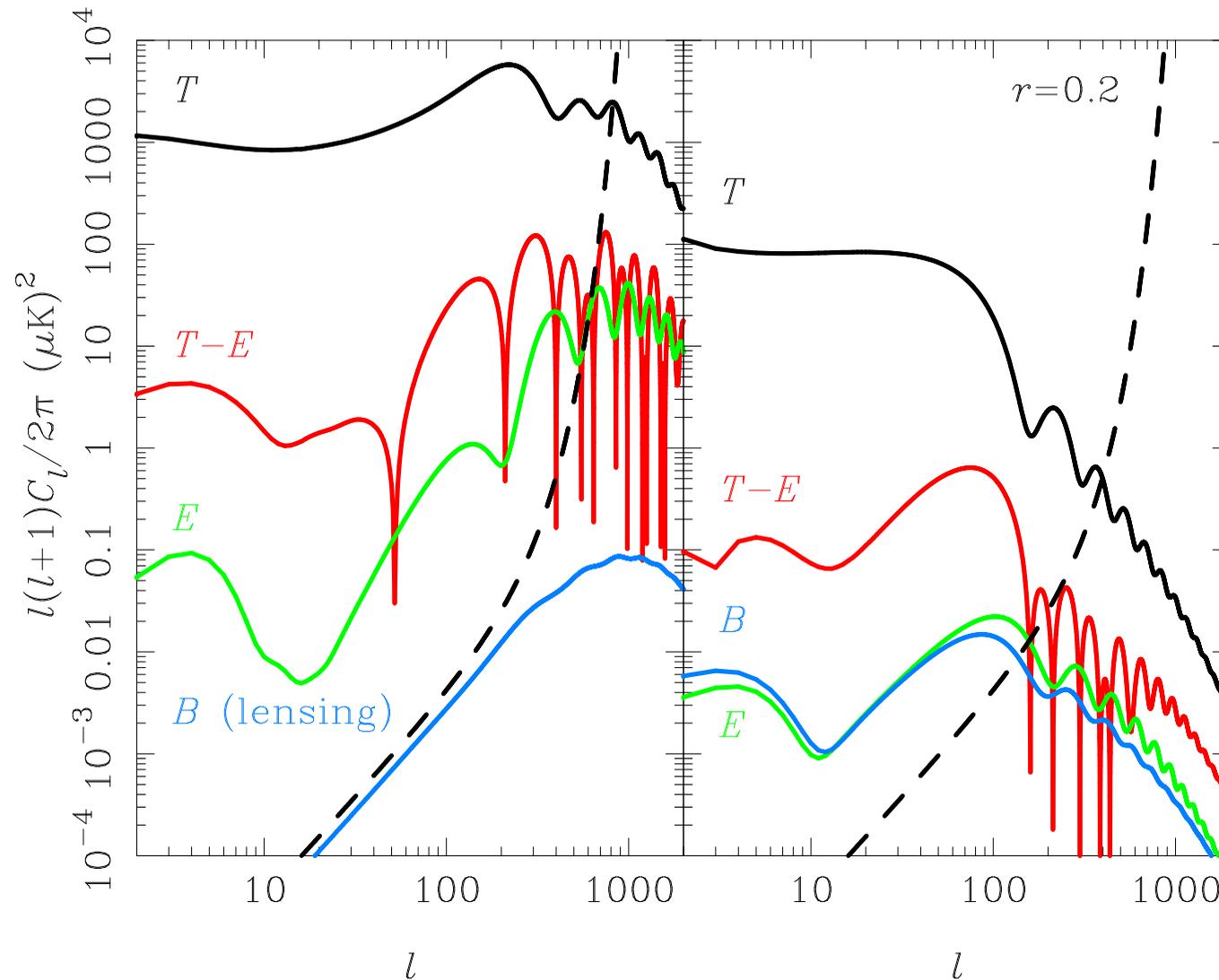
256 dual-pol pixels
150 GHz only
2010–2012

Keck Array



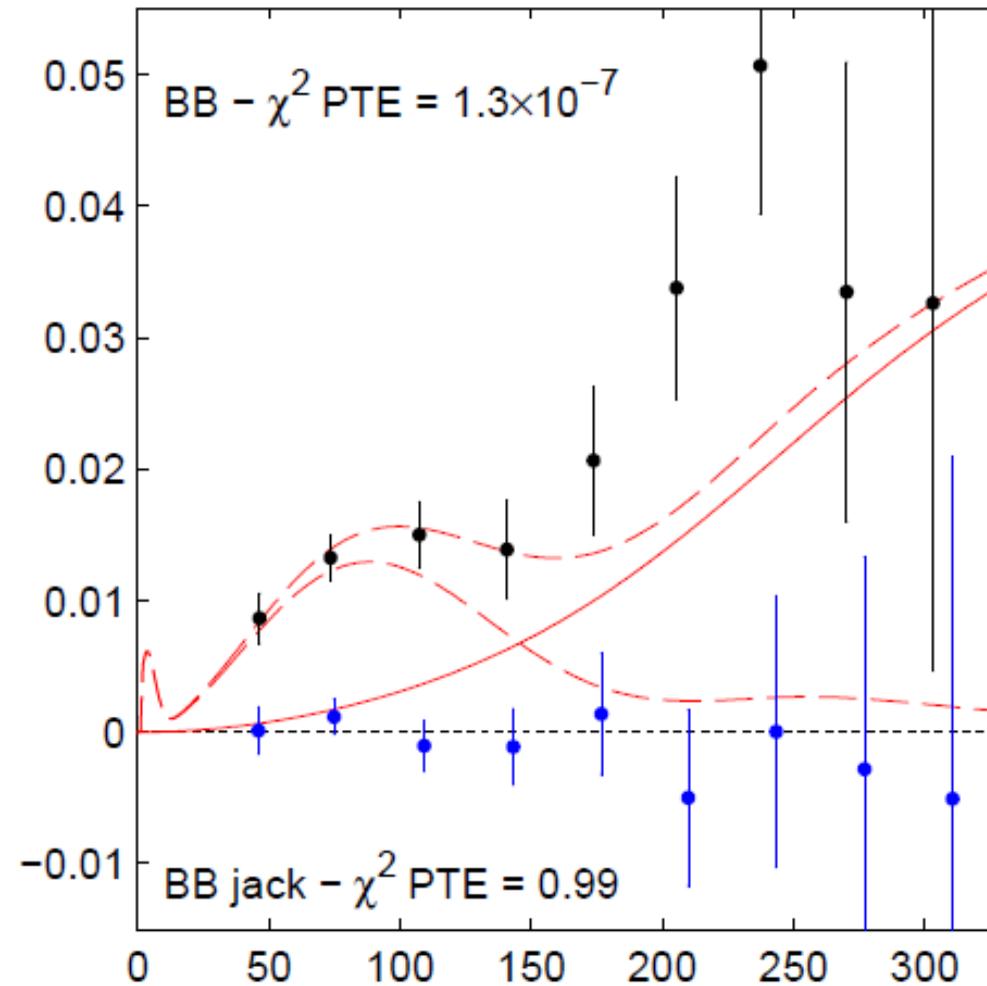
256x5 dual-pol pixels
2012–2013 150 GHz
2014– 2@100 GHz

GRAVITY WAVES IN THE CMB



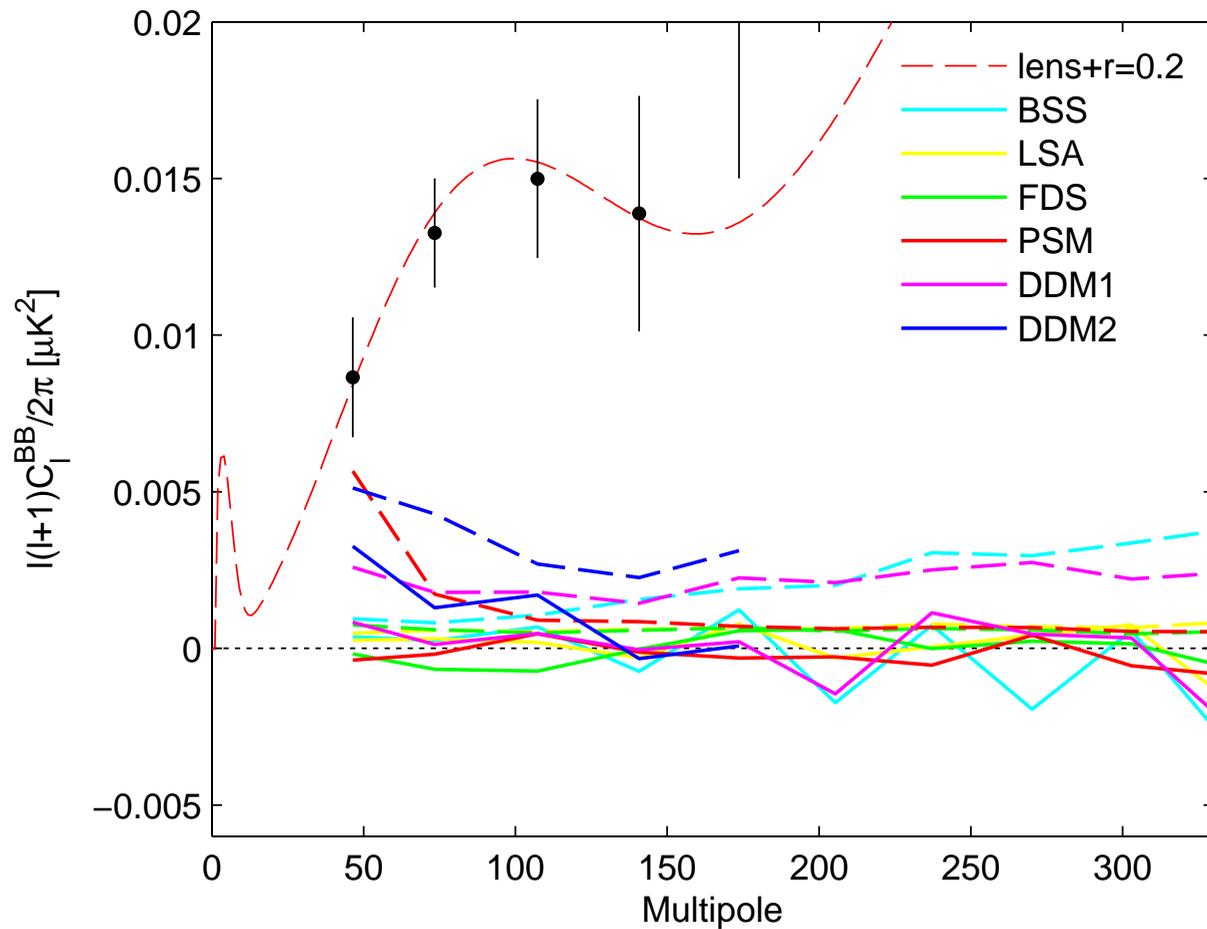
- B -modes: less confusion from curvature fluctuations and less model dependence
- But tiny signal: r.m.s. = $170(r/0.2)^{1/2}$ nK

BICEP2 B -MODE POWER SPECTRUM



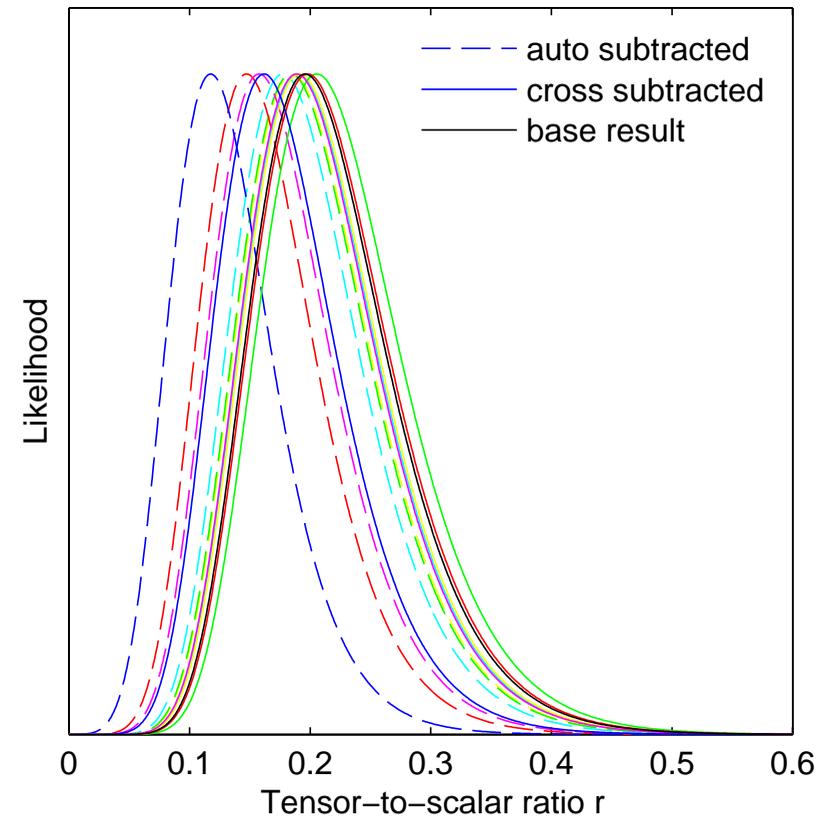
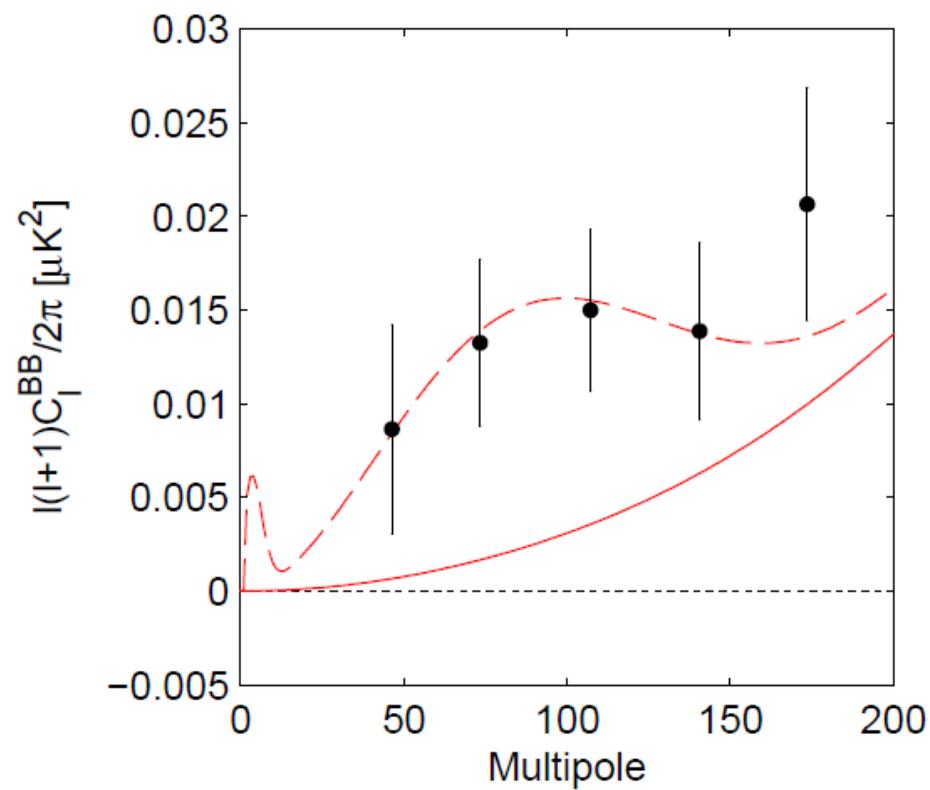
- 5.2σ detection of BB power in excess of lensing ($l < 200$)
- Temporal jackknife suggests noise bias under control (but high PTE)

FOREGROUNDS



- Dust modelled awaiting Planck 353 GHz polarization
- Synchrotron $r < 0.003$ from WMAP 23 GHz
- Extragalactic sources: $r \sim 0.001$

IMPLICATIONS FOR TENSOR-TO-SCALAR RATIO



$$r = 0.20^{+0.07}_{-0.05} \quad (68\%; \text{ no foreground correction})$$

- Large spread in max. likelihood $0.12 < r < 0.21$ with foreground models

IMPLICATIONS IF r REALLY 0.2

- Further strong support for inflation
- Gravity is quantized
- Energy scale of inflation

$$E_{\text{inf}} = 2.2 \times 10^{16} \text{ GeV} \left(\frac{r}{0.2} \right)^{1/4}$$

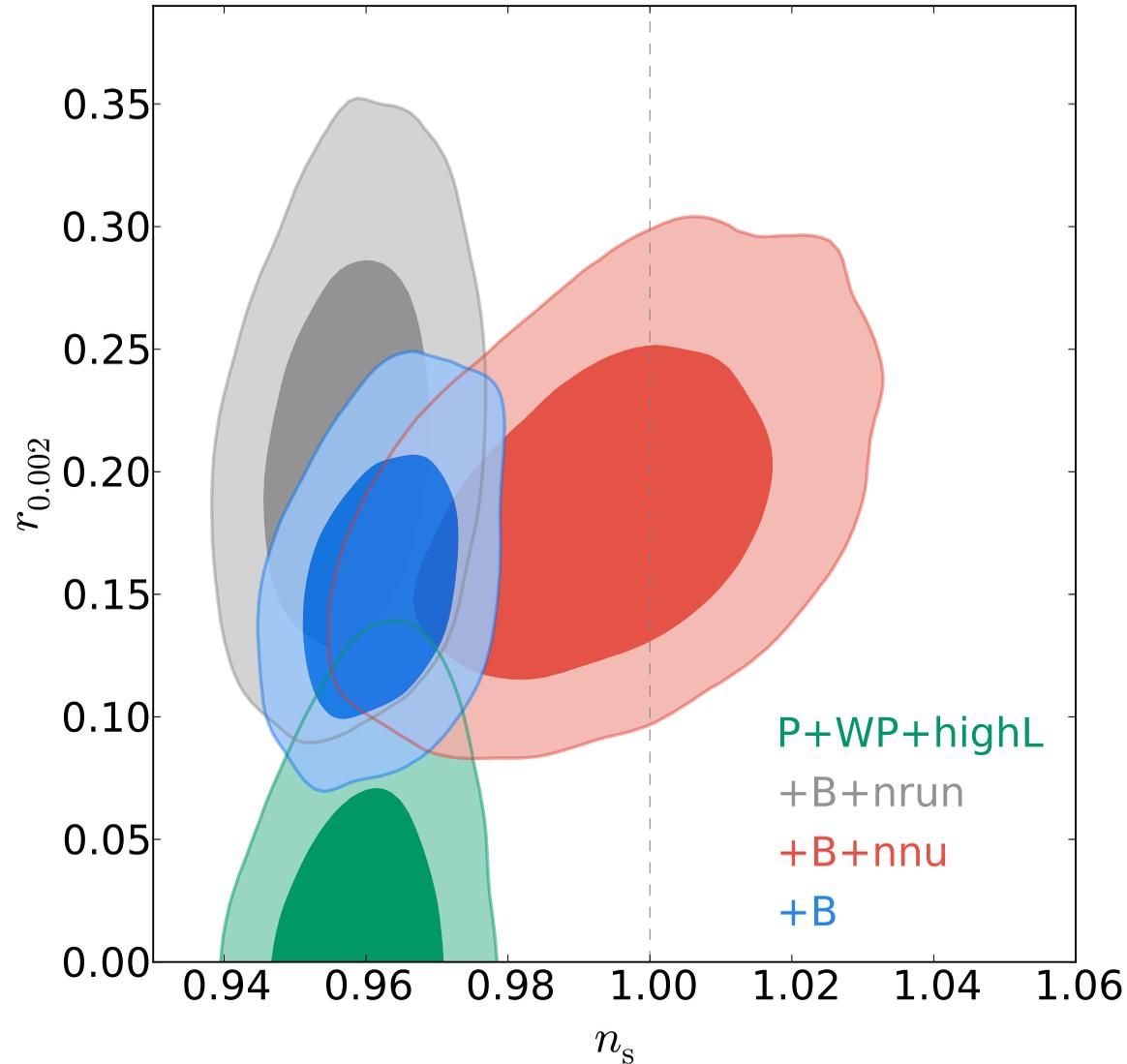
- Super-Planckian field excursion

$$\frac{\Delta\phi}{M_{\text{Pl}}} \geq N \sqrt{\frac{r}{8}} \sim 10 \sqrt{\frac{r}{0.2}}$$

- Shift symmetry mandatory for underlying theory
- Many (small-field) models are ruled out
- Direct detection may be possible with space-based interferometry

$$\Omega_{\text{gwh}} h^2 = 6 \times 10^{-16} \quad \text{at } f = 0.1 \text{ Hz if } r = -8n_t$$

“TENSION” BETWEEN PLANCK AND BICEP2



Antony Lewis

- Little pull on other parameters in Λ CDM + r

- Resolve tension with

- Large running

$$dn_s/d \ln k \sim -0.03$$

- Broken scale-invariance

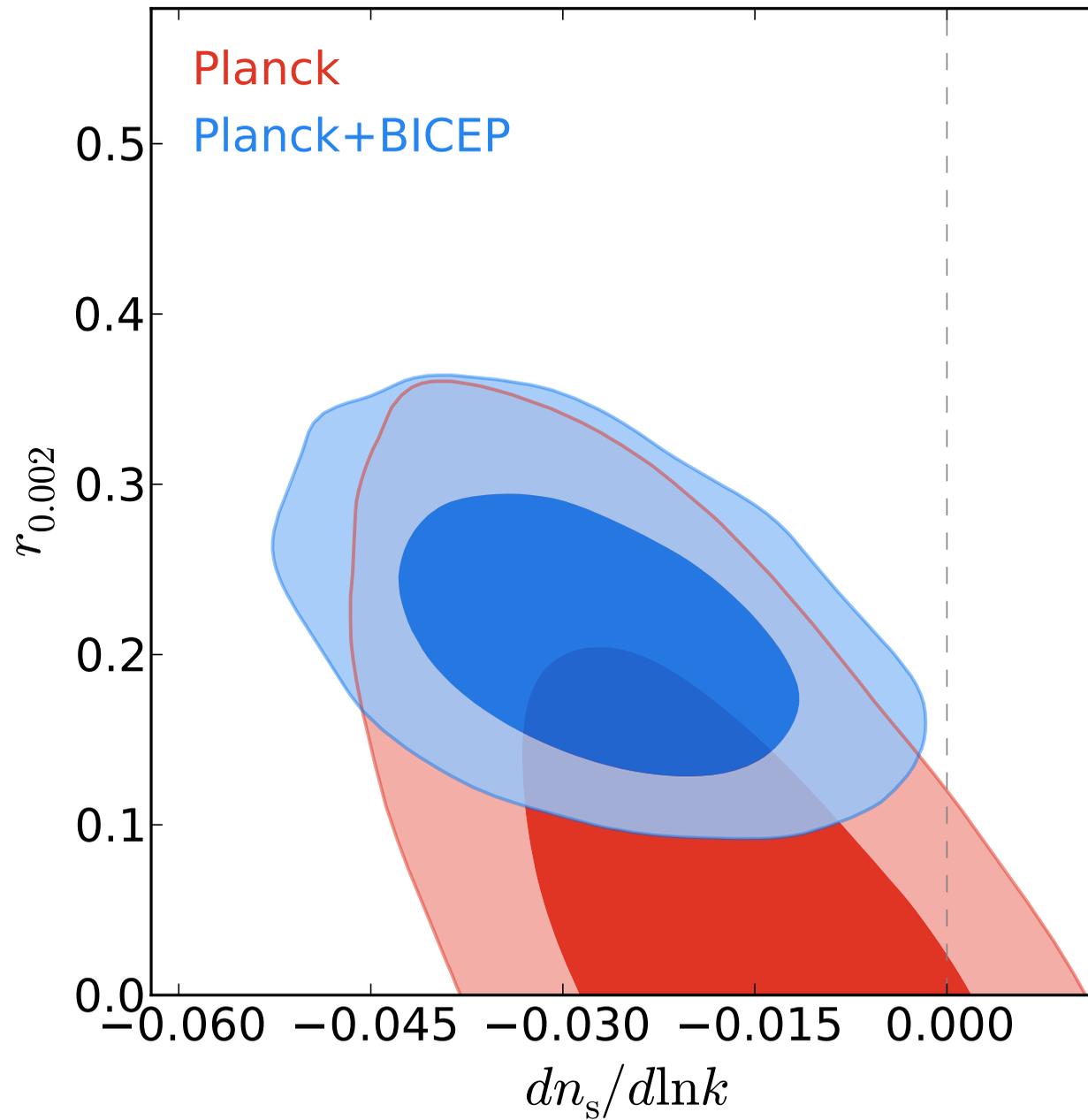
- Sterile neutrinos

- Anti-correlated isocurvature modes

- Strongly blue tensor tilt

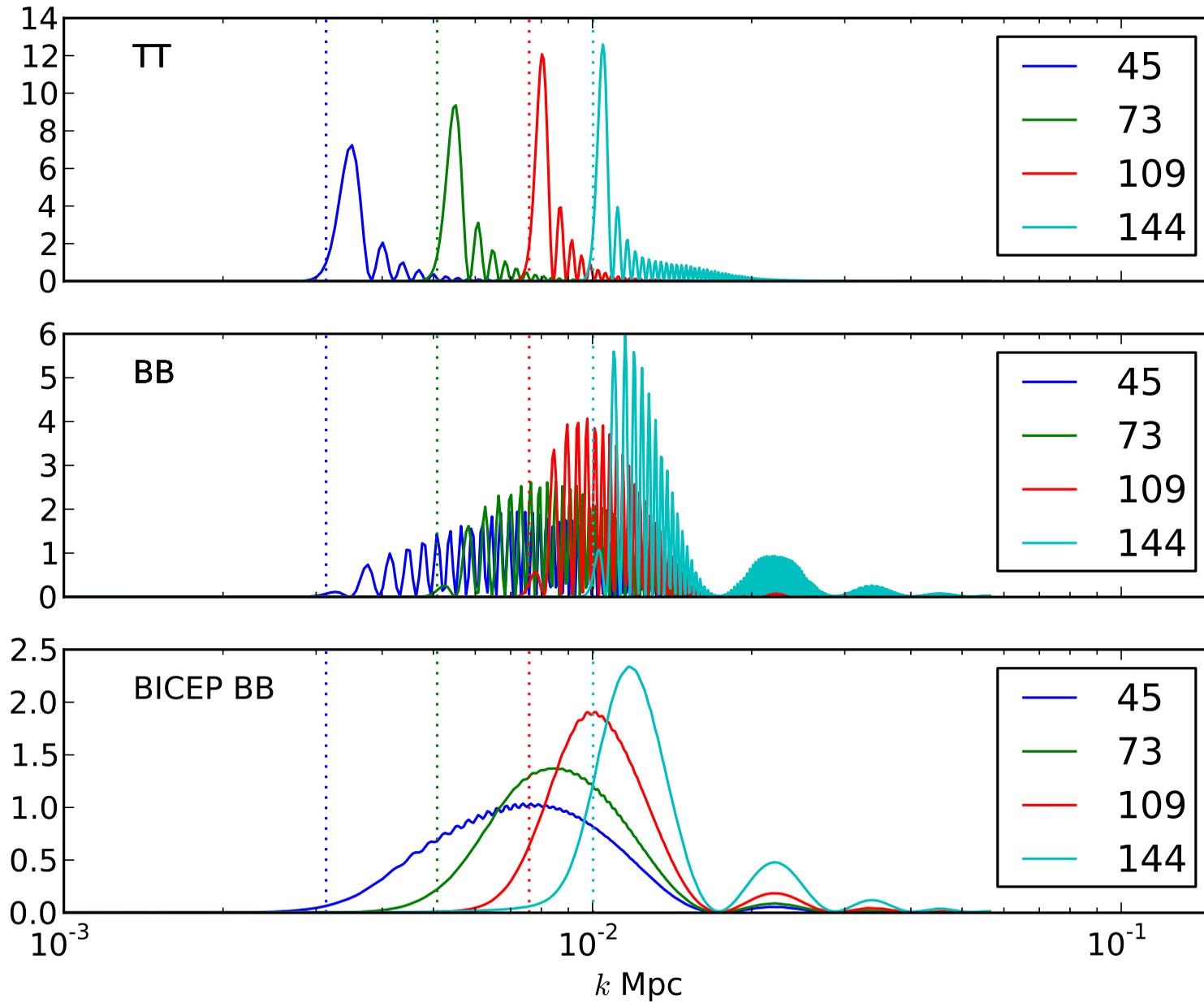
- ...

RUNNING OF THE SCALAR PRIMORDIAL POWER SPECTRUM



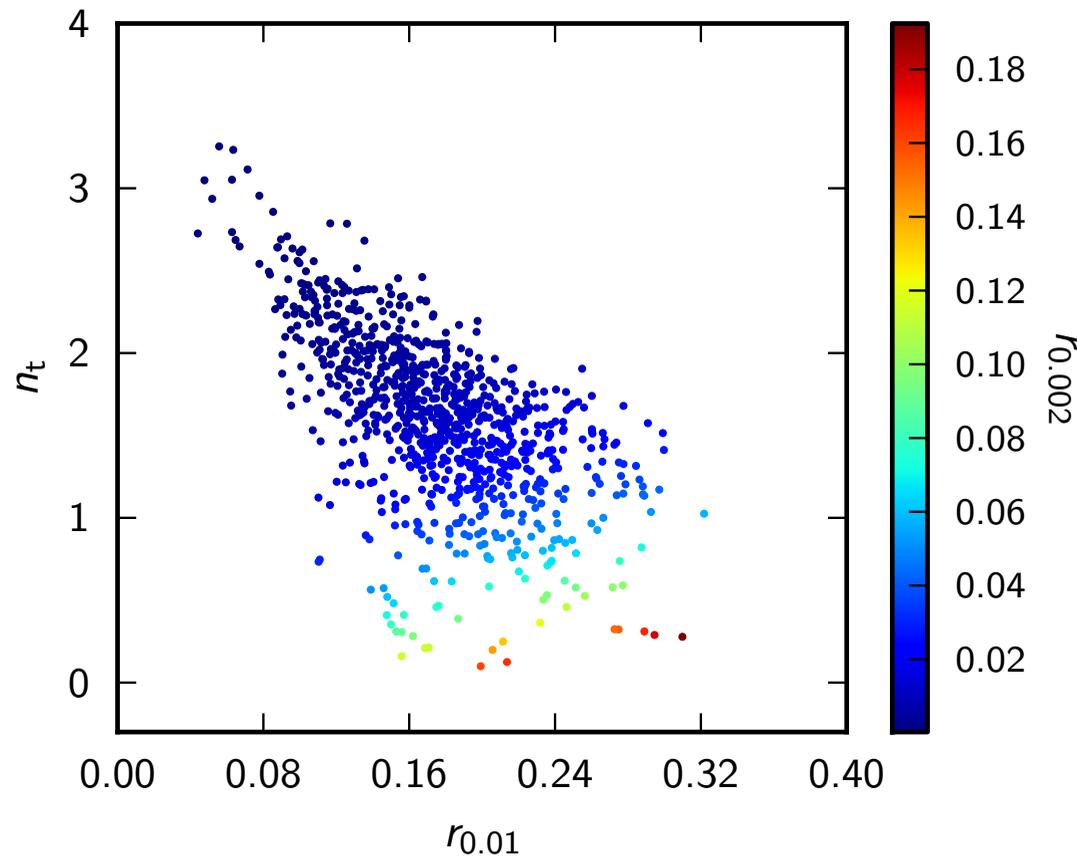
Antony Lewis

WHAT SCALES DOES BICEP PROBE?



Lewis & AC

BLUE TENSOR TILT?

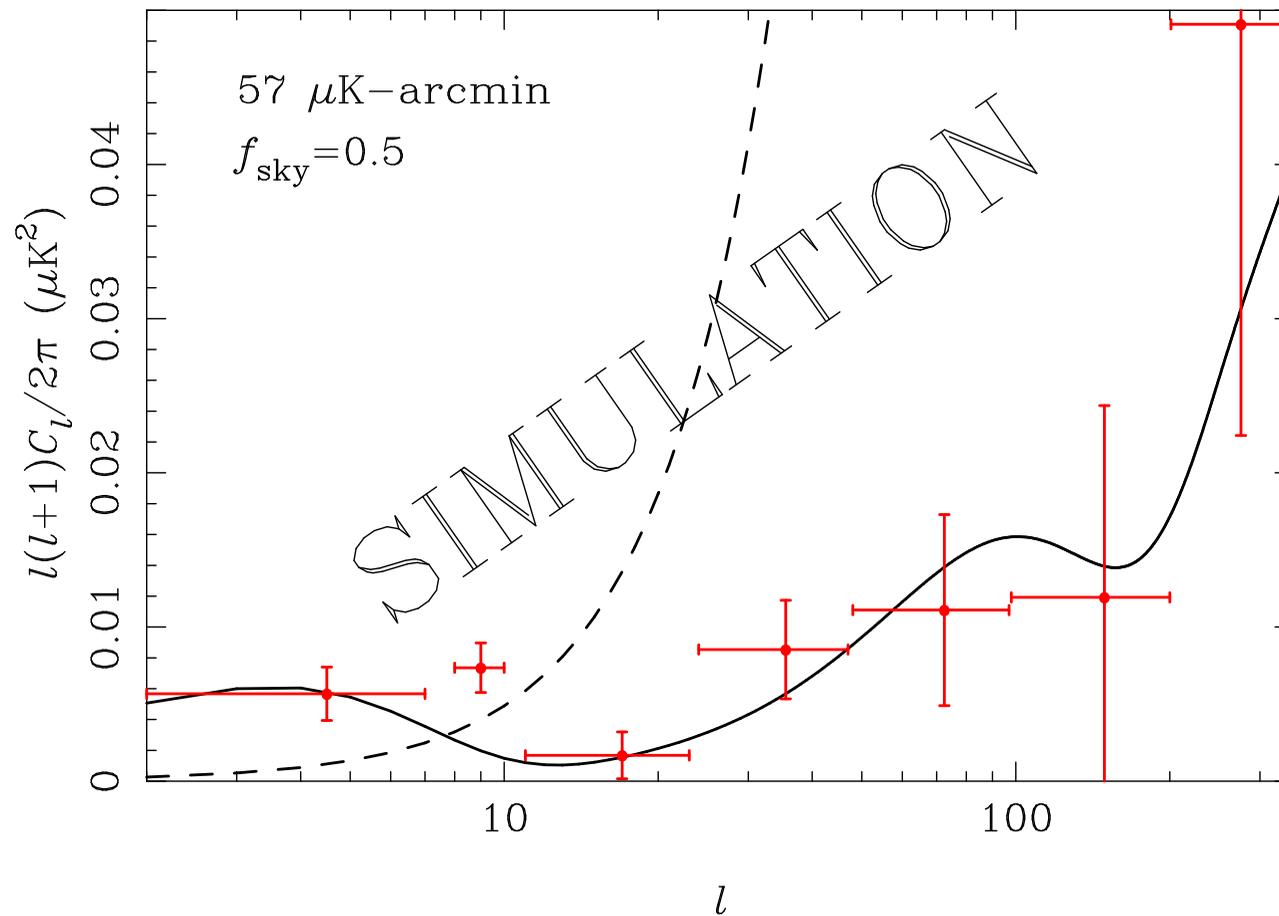


$$n_t = \frac{2\dot{H}}{H^2 + \ddot{H}}$$

Antony Lewis

- Driven by tension with low- l TT
- If inflation, requires violation of NEC (or non-BD vacuum etc.)
- Large blue tilt ruled out by BBN, pulsar timing etc.

CONFIRMATION WITH PLANCK?



- 353 GHz polarization should settle issue of foregrounds
- If $r \approx 0.2$ holds up:
 - Planck has sensitivity to detect B -modes in principle
 - Depends critically on ability to control systematic effects and foregrounds

- Full-mission data
 - HFI: 2 full-sky surveys → 5 full-sky surveys
 - LFI: 2 full-sky surveys → 8 full-sky surveys
- Polarization
- Improved beam modelling
 - Mars observations → Saturn + Jupiter + physical optics
- Improved calibration
 - Orbital dipole rather than solar dipole
- Less conservative masking in cosmological analyses
- ...

PLANCK COLLABORATION



SUMMARY

- Seven acoustic peaks measured in TT spectrum by Planck
- Lensing deflection spectrum measured at 25σ
- Excellent consistency on intermediate and small scales with Λ CDM
 - Lack of power on large scales “drives” several marginal (2σ) results
- Some relief of Λ CDM tensions with H_0 and SNe Ia updates
- BICEP2 surprise: $r = 0.2_{-0.05}^{+0.07}$ (68%; no foreground correction)
 - In tension with Planck TT at large scales – foregrounds, systematics, new physics?
- Expect polarization, better lensing ($\sim 40 \sigma$) etc. for Planck2014

END