OVERVIEW OF NEW CMB RESULTS

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for the Planck Collaboration

UCLA Dark Matter 2016
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Introduction

- Planck
  - First cosmological data release 2013 ("Planck 2013 results")
  - Second cosmological data release 2015 ("Planck 2015 results")
- BICEP and Keck/BICEP
- Future
  - Spider
  - Polar Bear
  - CLASS
  -

The Standard Model of Cosmology . . .

. . . is based on a

- Spatially flat, expanding Universe. . .
- . . .whose dynamics are governed by general relativity. . .
- . . .and dominated by cold dark matter and Λ.
- The seeds of structure have Gaussian statistics. . .
- . . .and form an almost scale-invariant spectrum of adiabatic fluctuations.

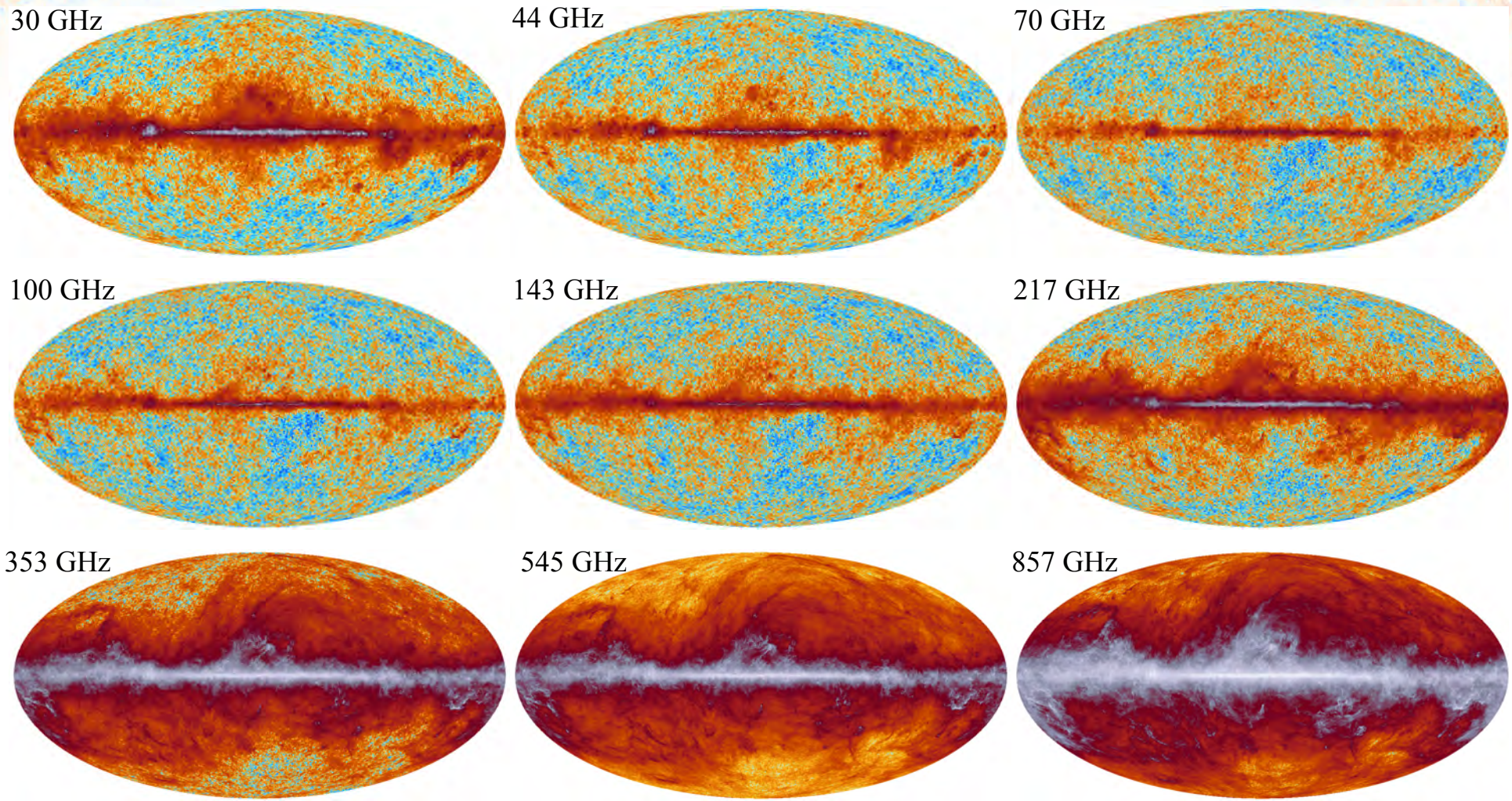
THE PLANCK 2015 DATA REMAIN IN EXCELLENT AGREEMENT WITH THIS PARADIGM, AND CONTINUE TO TIGHTEN THE CONSTRAINTS ON DEVIATIONS AND REDUCE THE UNCERTAINTIES ON THE KEY COSMOLOGICAL PARAMETERS.

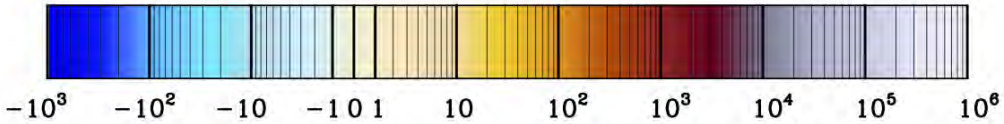
Analysis Changes for 2015

- Use of Planck polarization data instead of WMAP
- Improved calibration — "orbital" dipole rather than the "Solar"
- More data — full mission, 29 months HFI and 50 months LFI vs. 15 months
- Changes in foreground masks — use more sky
  many fewer point source "holes"
- Improvements in foreground separation
- Better control of systematic errors

GOOD AGREEMENT WITH 2013 RESULTS, WITH INCREASED PRECISION

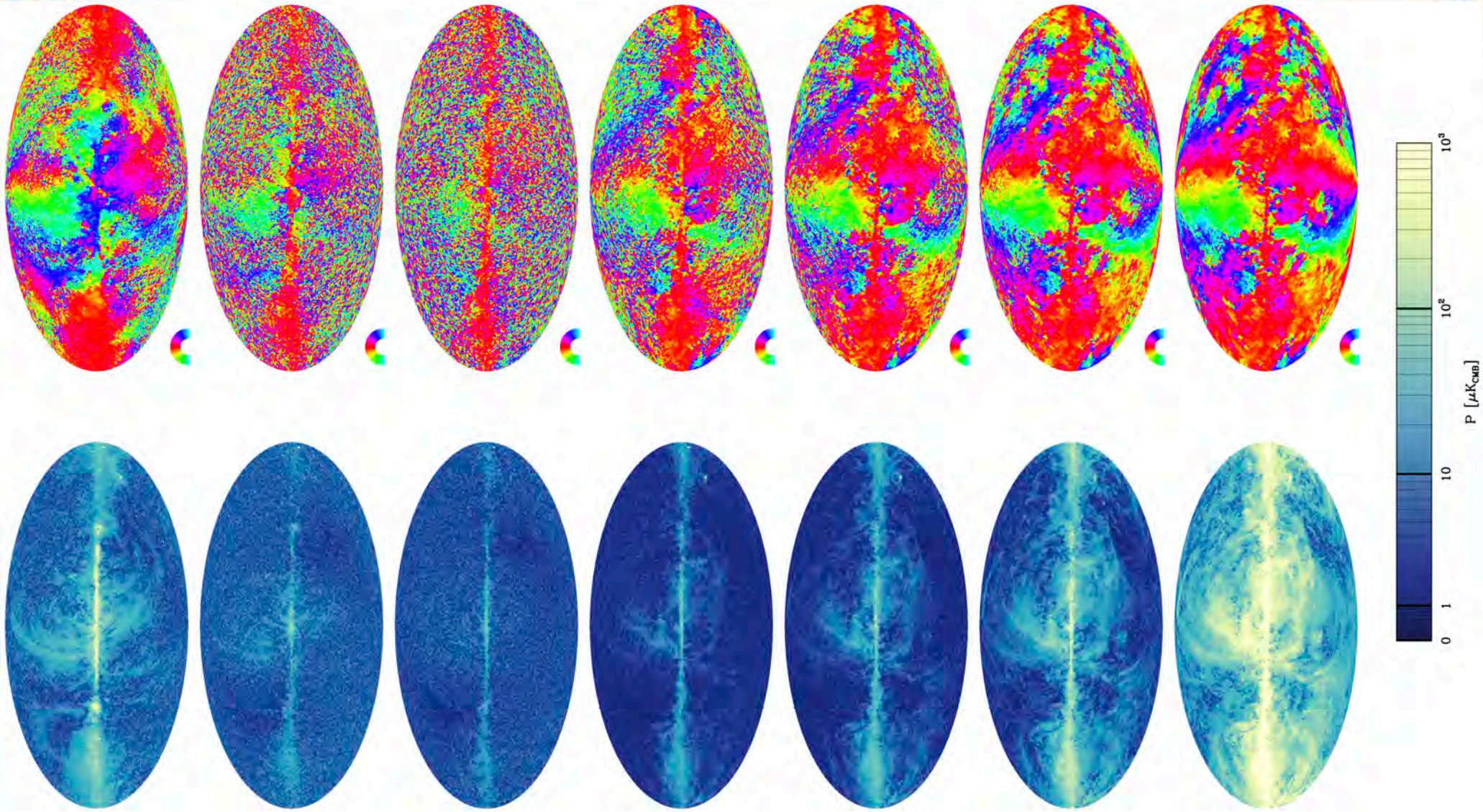
Temperature Maps



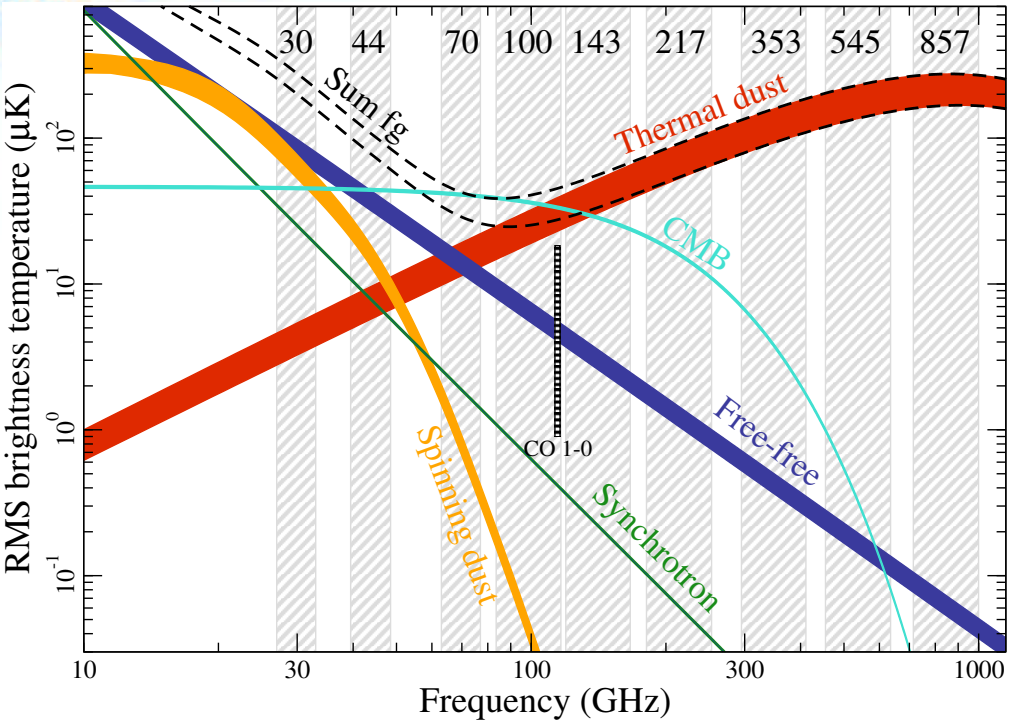


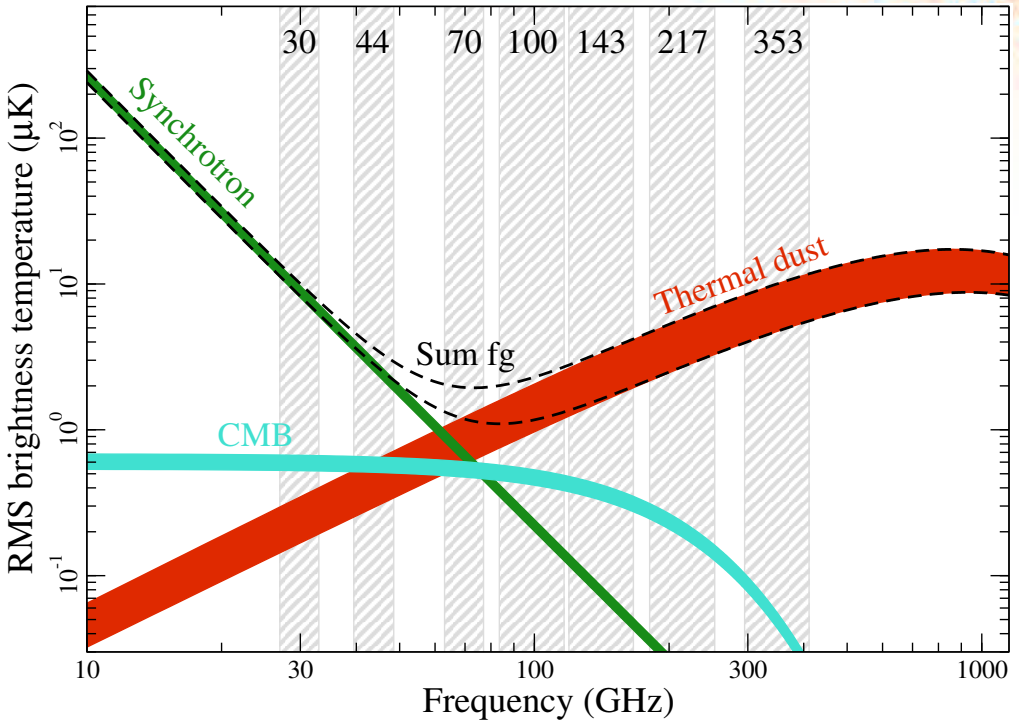
30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

Polarization Maps



Separation of 'Foregrounds' from the CMB





Planck 2015 results. X.

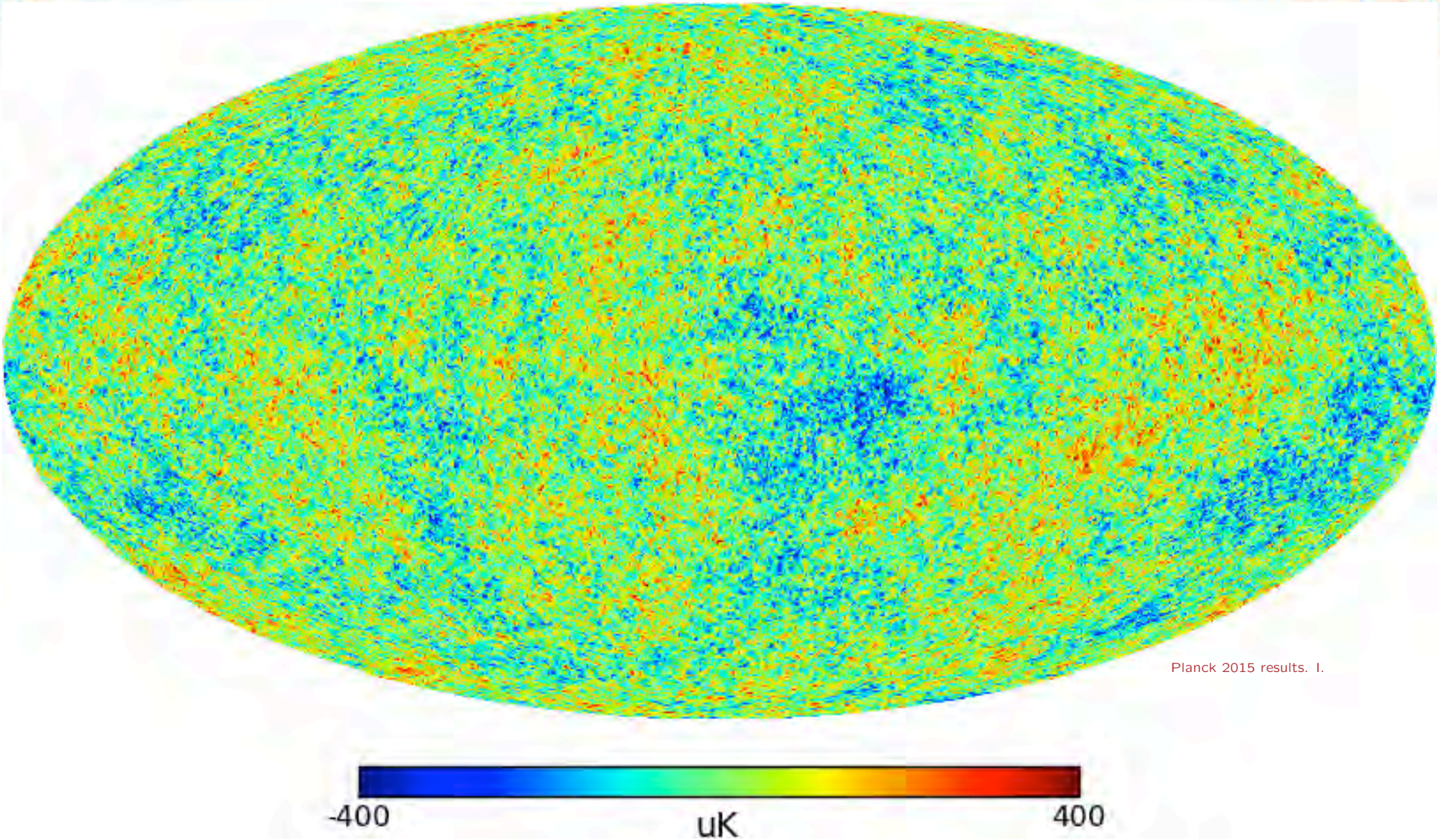
Temperature

- All components smoothed to 1°
- Sky fractions 81–93% of sky

Polarization

- All components smoothed to 40′
- Sky fractions 73–93% of sky

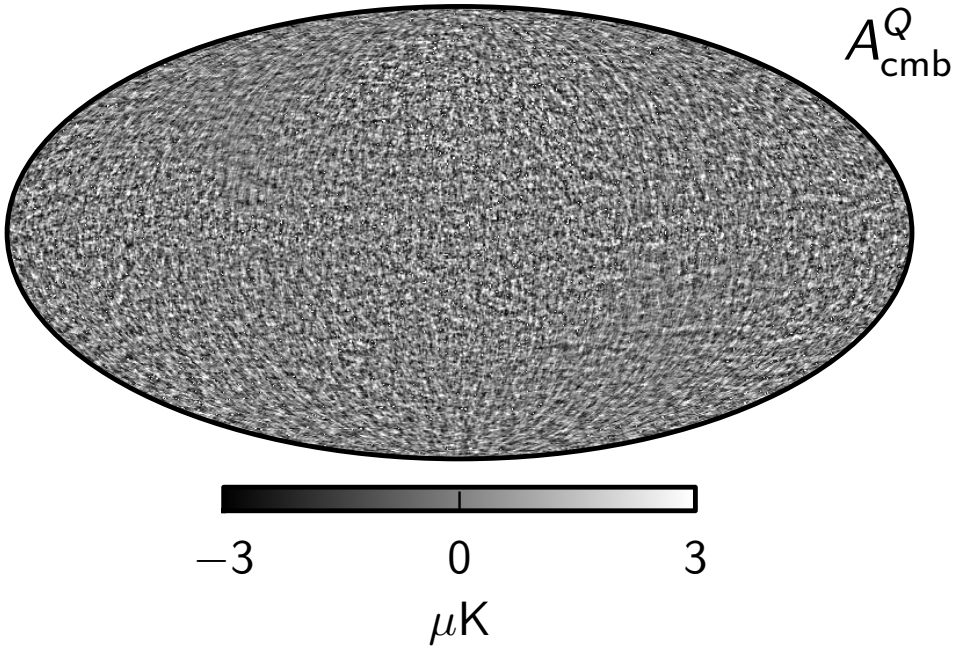
CMB *I*

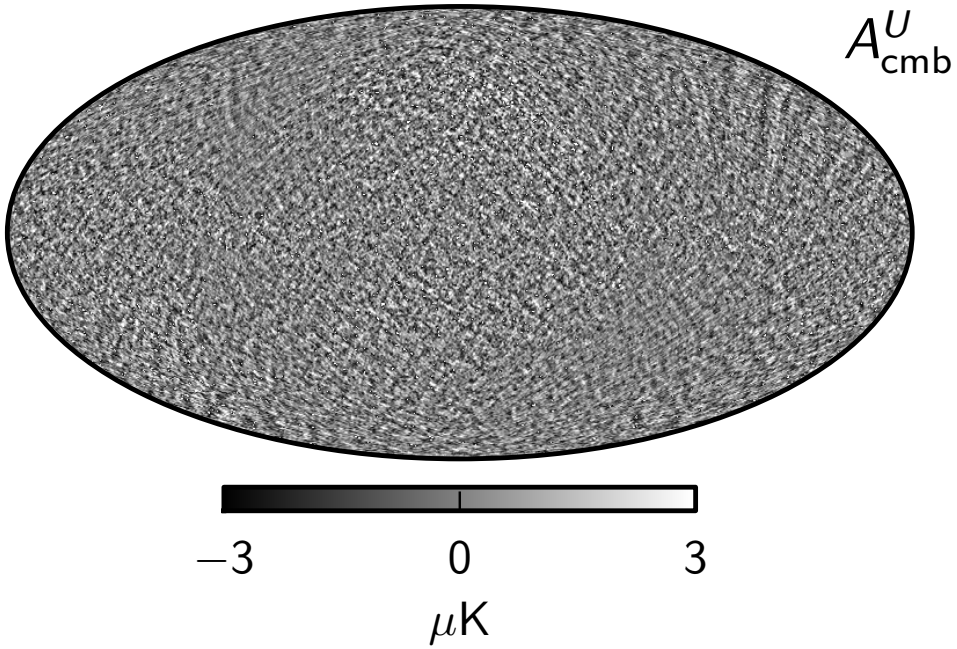


Planck 2015 results. I.

(A few % of the sky in the plane of the Milky Way is filled in with a "constrained realization".)

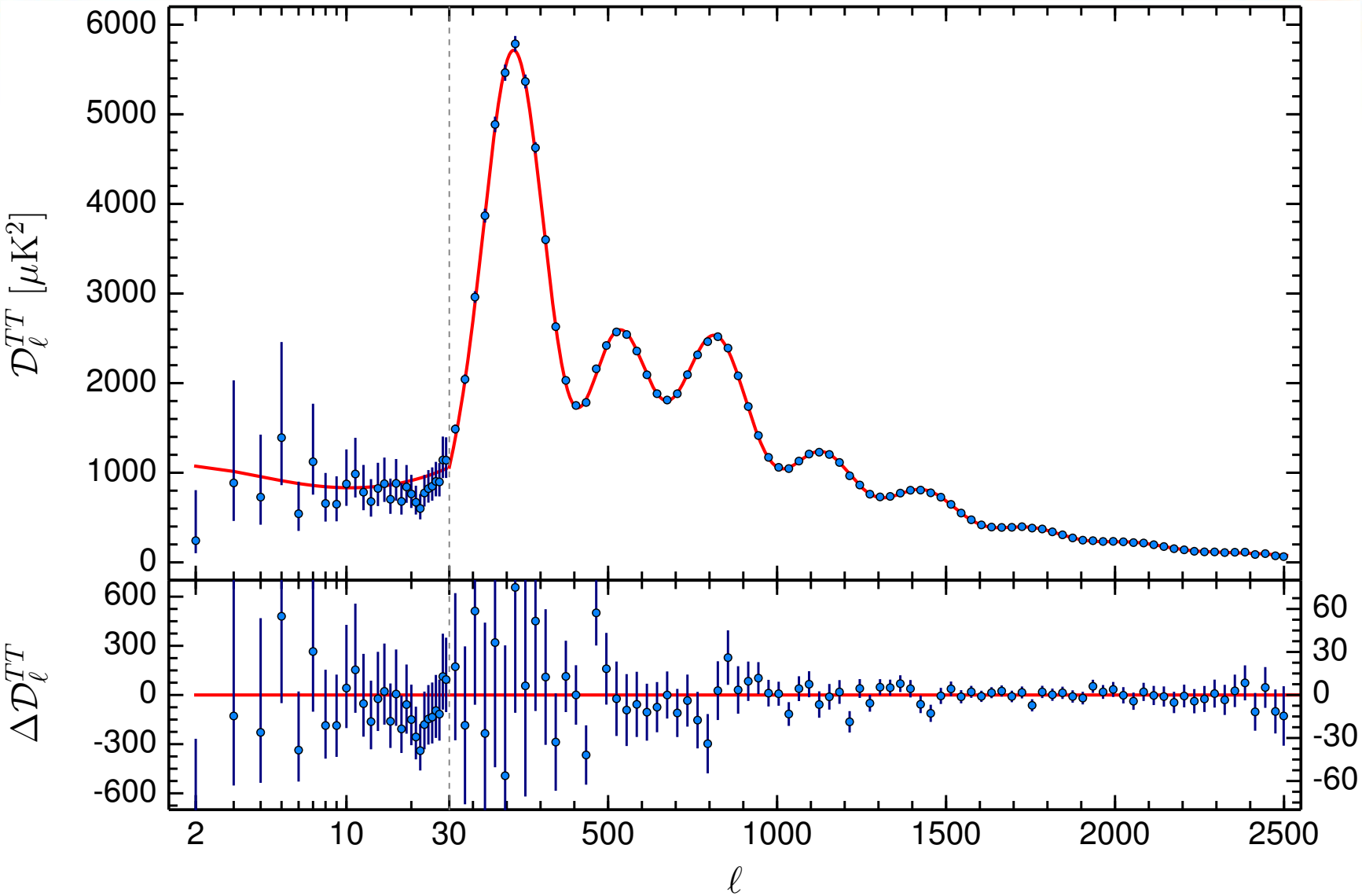
CMB Q and U





High-pass filtered, cosine apodization $20 \leq \ell \leq 40$, to avoid contamination from unremoved systematic errors in polarization on the largest angular scales.

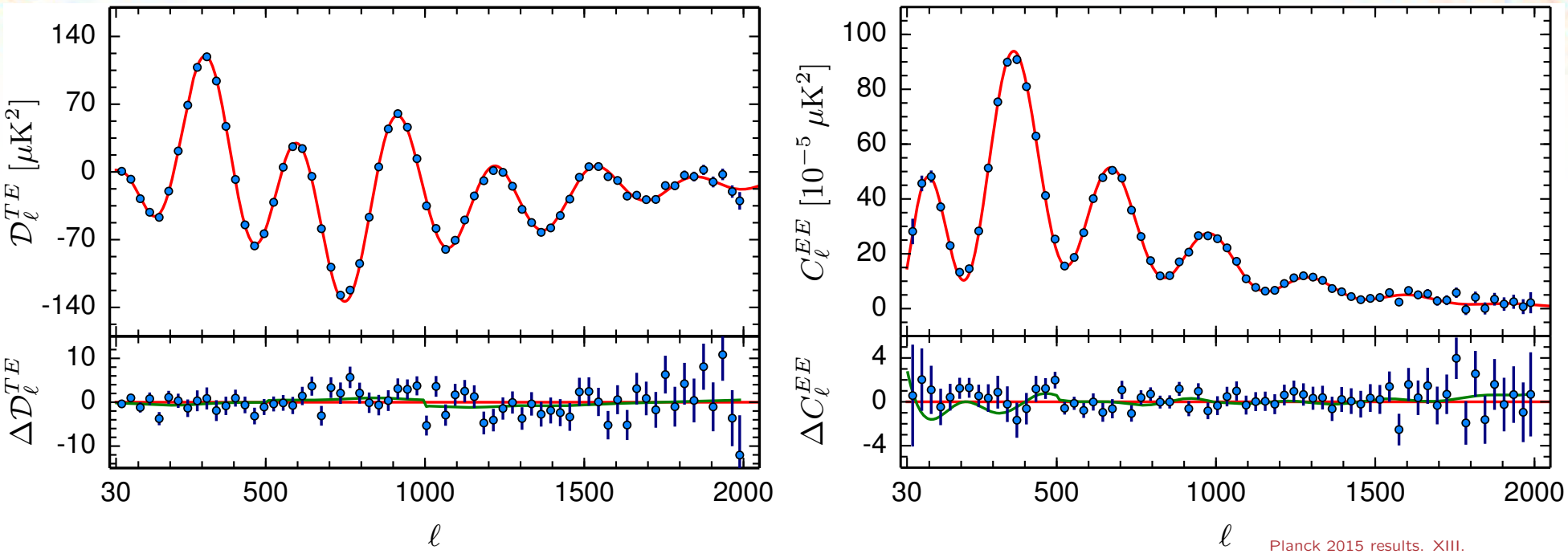
Angular Power Spectrum + Best-Fit Model



Planck 2015 results. XIII.

Red line is the "best-fit" model to the temperature data.

Polarization Spectra, Same Model



Planck 2015 results. XIII.

TE

Temperature-polarization cross-spectrum

EE

Polarization auto-spectrum

Red line is again the "best-fit" model to the temperature data.

- Spectacular agreement between inferences from temperature and polarization

Cosmological Parameters I

Parameter	$TT, TE, EE + \text{lowP} + \text{lensing} + \text{ext}$	N_σ
$\Omega_\mathrm{b} h^2 [18.79\,\mathrm{yg\,m^{-3}}]$	0.02230 ± 0.00014	159
$\Omega_\mathrm{c} h^2 [18.79\,\mathrm{yg\,m^{-3}}]$	0.1188 ± 0.0010	119
$100\theta_\mathrm{MC}$	1.04093 ± 0.00030	3470
τ	0.066 ± 0.012	5.5
$\ln(10^{10} A_\mathrm{s})$	3.064 ± 0.023	133
n_s	0.9667 ± 0.0040	242
$H_0 [\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	67.74 ± 0.46	
Ω_Λ	0.6911 ± 0.0062	
Ω_b	0.04860 ± 0.00051	
Ω_c	0.2589 ± 0.0057	
Ω_m	0.3089 ± 0.0062	
$z_\mathrm{reionization}$	8.8 ± 1.2	
$z_\mathrm{recombination}$	1089.90 ± 0.23	
Age[Gyr]	13.799 ± 0.021	

68% confidence limits

Planck 2015 results. XIII.

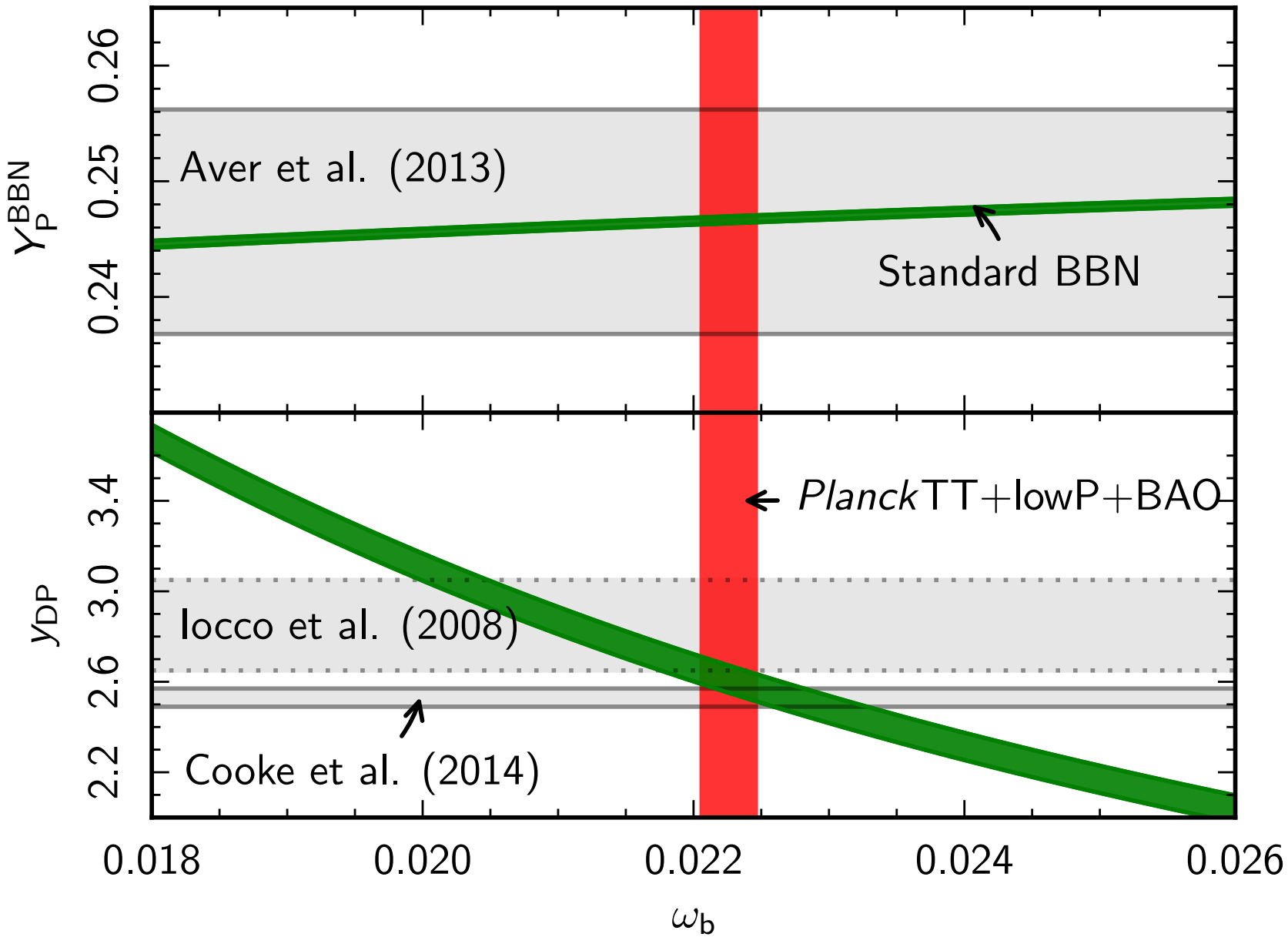
Cosmological Parameters II

- Changes from 2013
  - Amplitude of power spectrum up about 2% (orbital dipole and beams)
  - $n_{\rm s}$ increased by 0.7σ
  - $\Omega_{\rm b}h^2$ increased by 0.6σ

    } (correction of systematic error at $\ell \approx 1800$)
  - τ down by 0.85σ

    These shifts approximately cancel in the derived normalization of the matter power spectrum
  - Angular size of sound horizon, θ_* and CDM density $\Omega_{\rm c}$ are significantly better determined
- High ℓ data so precise, polarization data so constraining, that
  - See stong evidence for three species of light neutrinos
  - Can measure the effective viscosity of the neutrino "fluid" to be non-zero at 9σ
- Constraint on baryon density $\Omega_{\rm b}$ comparable with best errors from BBN
  - Possible to calibrate nuclear capture cross-sections from CMB observations?
- Addition of polarization improves upper limit on annihilation rate of DM by OoM

Cosmological Parameters III



Cosmological Parameters IV

- We've tried a wide range of extensions to the basic 6-parameter model
  - $\Omega_{\rm K}$ (curvature)
  - Σm_ν (neutrino mass) and $N_{\rm eff}$ (effective number of "neutrino" species)
  - $Y_{\rm P}$ (helium fraction)
  - $dn_{\rm s}/d\ln k$ (curvature in the input fluctuation spectrum)
  - $r_{0.002}$ (tensor-to-scalar ratio at $k_0 = 0.002\,{\rm Mpc}^{-1}$)
  - w (dark energy equation of state, constant)
  - Huge number of variations posted on the archive.

FIND NO SIGNIFICANT EVIDENCE FOR A FAILURE OF THE MODEL

- Within each extension of the parameter space, the "default" parameter values remain a good fit
  - Continues to hold when we combine Planck data with other measurements, e.g., distance scale from BAO or Type Ia supernovae; growth of structure from redshift-space distortions

Cosmological Parameters V

- Little shift in cosmology since 2013, so we continue to see tensions with some astrophysical data sets
  - Abundance of clusters of galaxies
  - Weak lensing of galaxies or cosmic shear
  - BAO distances in the Ly α forest at high z
- These tensions cannot be resolved with standard single-parameters extensions of the base ΛCDM model

Constraints from Large Angular Scales

- Anisotropy at large angular scales, especially in polarization, places tight constraints on
  - τ — optical depth to Thomson scattering
  - r — tensor-to-scalar ratio
- τ
  - Temperature data + low-ℓ polarization from 70 GHz + CMB lensing

    $\Longrightarrow \tau = 0.066 \pm 0.016$
  - WMAP9 got $\tau \approx 0.089$, which we used as a prior in our 2013 analysis

    But, when we clean WMAP9 data of dust using our 353 GHz channel, WMAP polarization data are in good agreement with a lower optical depth of 0.07
  - $\tau = 0.066$ implies a lower redshift of reionization $z_{\rm re} = 8.8^{+1.7}_{-1.4}$
  - Get an independent constraint from CMB lensing

    $\Longrightarrow \tau = 0.071 \pm 0.016$

Constraints from Large Angular Scales II

- Downward shift in σ_8 implied by lower τ largely cancelled by the increase in CMB amplitude from better calibration

- r
  - Strongest Planck constraint still comes from temperature anisotropies at $\ell < 10^2$

    $r < 0.10$, limited by cosmic variance, and model-dependent
  - BICEP2 detected B mode polarization, but it was mostly (or all) dust
  - Combining Planck and Bicep2/Keck Array likelihoods leads to

    $r_{0.002} < 0.09$, 95%
  - Addition of 95 GHz Keck Array data gives BICEP2/Keck Array VI; arXiv:1510.09217

    $r_{0.05} < 0.09$, 95% (using Planck and WMAP to clean foregrounds)

    $r_{0.05} < 0.07$, 95% (joint analysis with Planck)

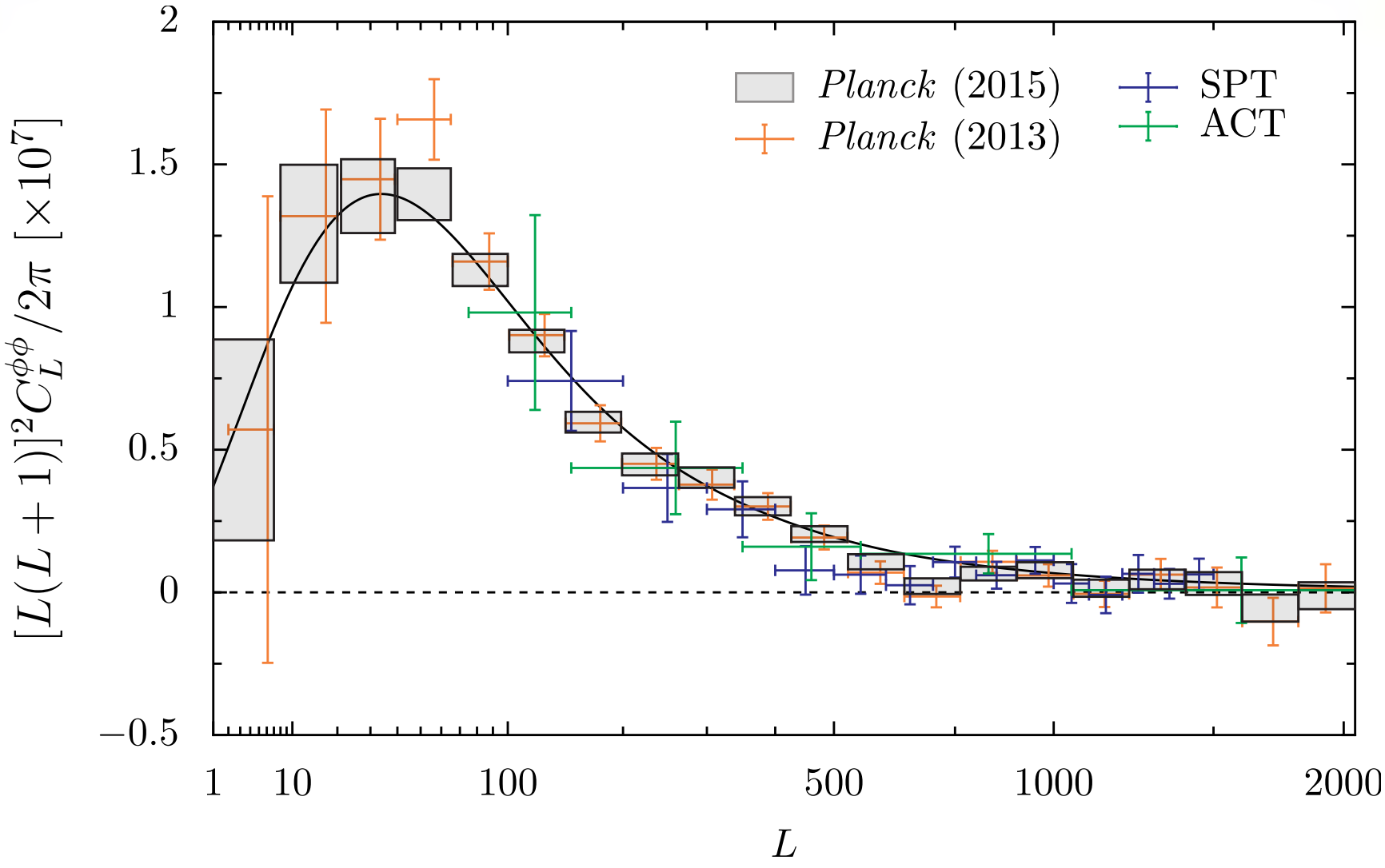
    $\Longrightarrow$ Disfavors inflationary models with a ϕ^2 potential

Dark Energy and Modified Gravity

- Results consistent with the simplest scenario, ΛCDM
- All constraints on DE models — minimally-coupled scalr field
  modified gravity (effective field theory, phenomenological, $f(R)$, coupled)
  are considerable improved wrt past analyses
- DE at early times is below 2% (95% confidence) of critical density
  - If DE present since recombination, $\Omega_{\rm e} < 0.0071$ for PlanckTT+lensing+BAO+SNe+H_0

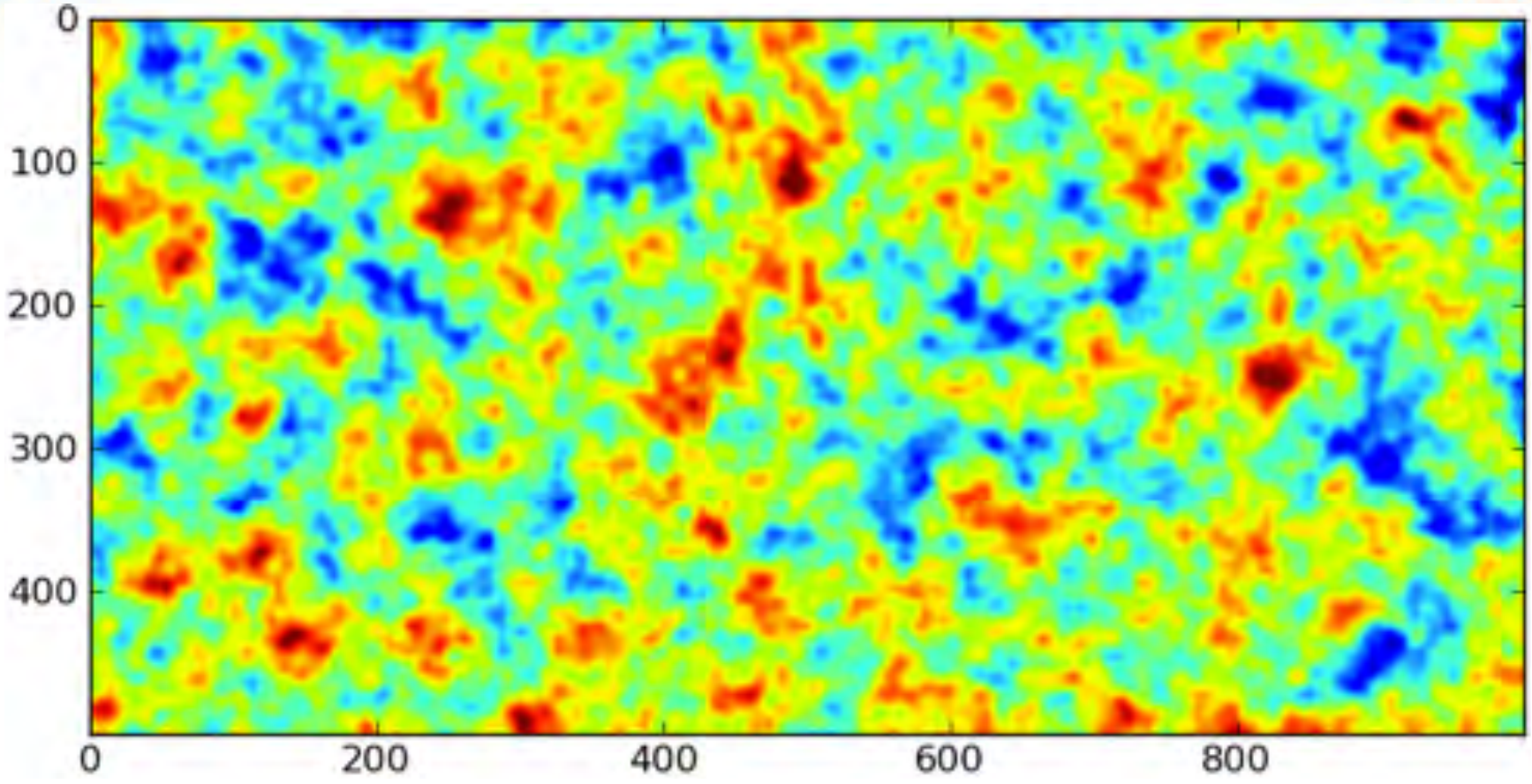
Lensing of the CMB

- Seen at high significance



Planck Collaboration I 2015

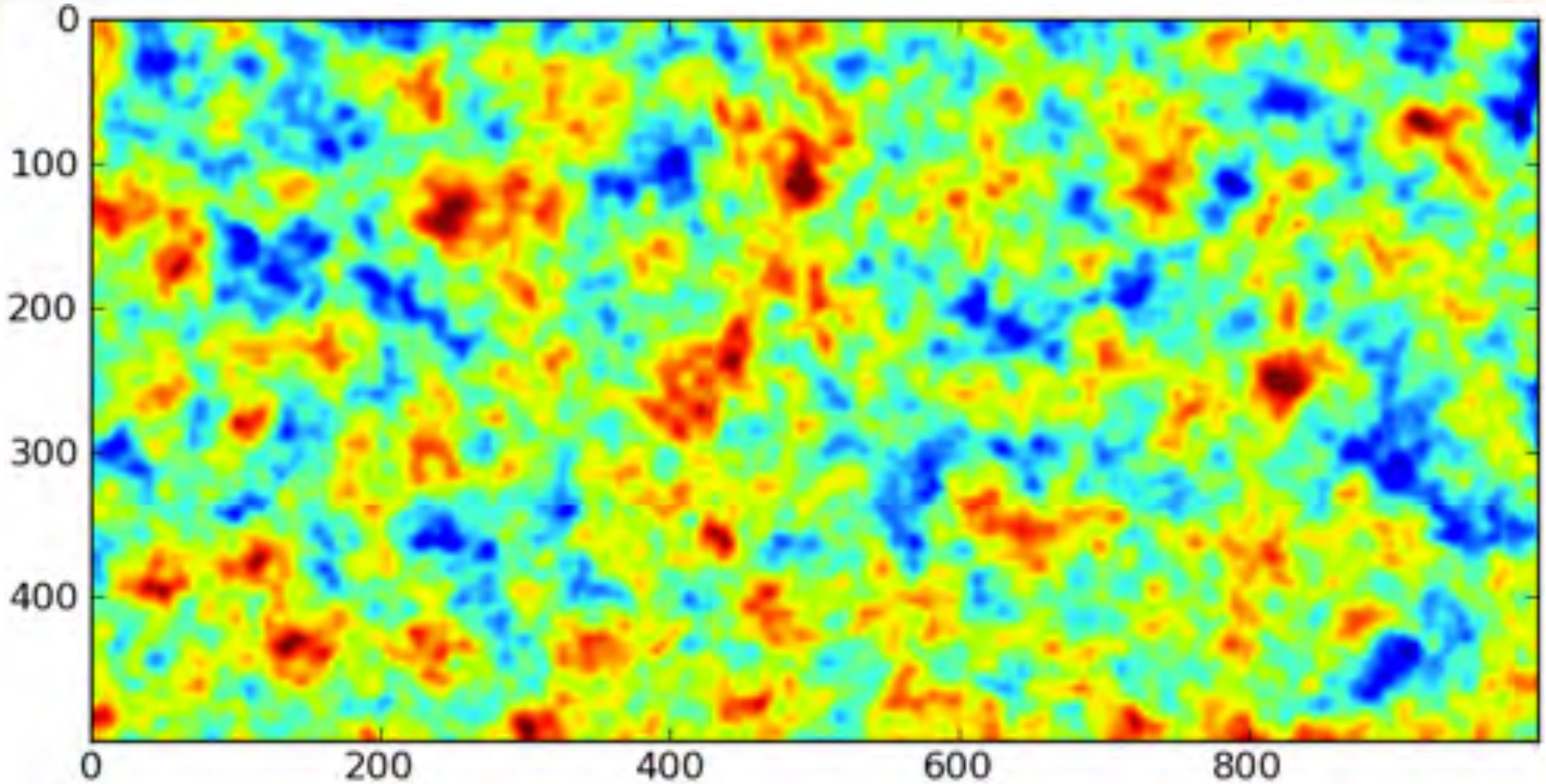
Simulation: Unlensed



Simulated patch 10° wide

- RMS of deflection angle is $\sim 2\farcm5$
- Coherent on degree scales

Simulation: Lensed



Simulated patch 10° wide

- RMS of deflection angle is $\sim 2\farcm5$
- Coherent on degree scales

Lensing of the CMB II

- Consistent with basic 6-parameter ΛCDM model

  $\Longrightarrow$ Strong consistency check on the gravitational instability paradigm and the growth of structure over more than two decades in expansion factor.

- Provides sensitivity to the growth of structure between the surface of last scattering and the present epoch

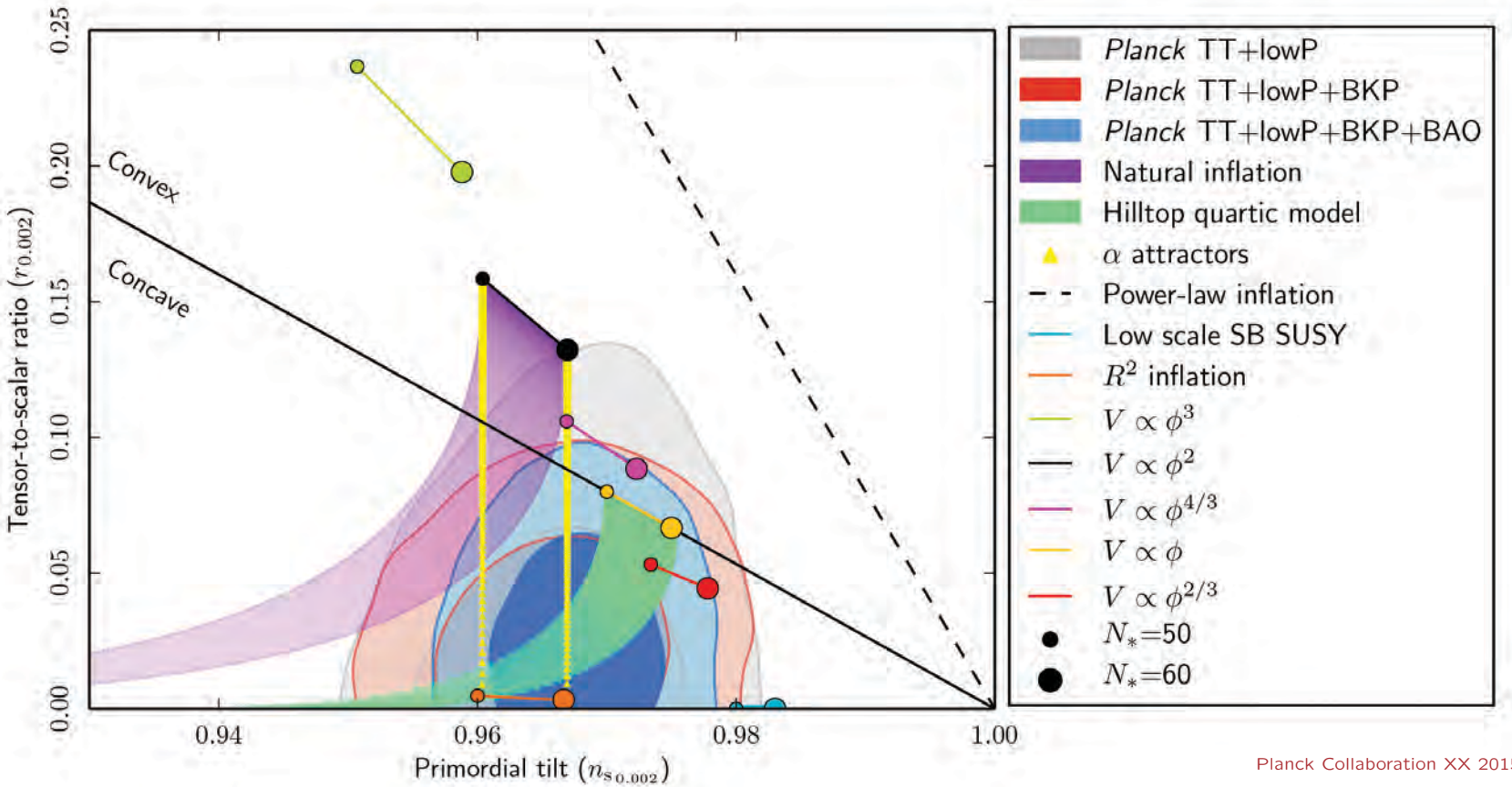
  $\Longrightarrow$ Breaks parameter degeneracies, allows measurement of important parameters.

Inflation

- Data consistent with a purely adiabatic, power-law spectrum of initial fluctuations

$$n_{\rm S} = 0.9677 \pm 0.06$$

- Isocurvature modes now constrained at the percent level
- No statistically significant evidence for departures from a power law



Planck Collaboration XX 2015

Marginalized joint 68% and 95% CL regions for $n_{\rm S}$ and $r_{0.002}$ from Planck in combination with other data sets, compared to the theoretical predictions of selected inflationary models. All monomial models $V(\phi) \propto \phi^{2p}$ with $p \geq 1$ are disfavored.

Primordial non-Gaussianity

- Addition of polarization information reduces the allowed model space
- $f_{\rm NL}^{\rm local} = 0.8 \pm 5.0$
  $f_{\rm NL}^{\rm equil} = 0.8 \pm 5.0$
  $f_{\rm NL}^{\rm ortho} = 0.8 \pm 5.0$
- Covers a greatly extended range of primordial 3-point and 4-point signals

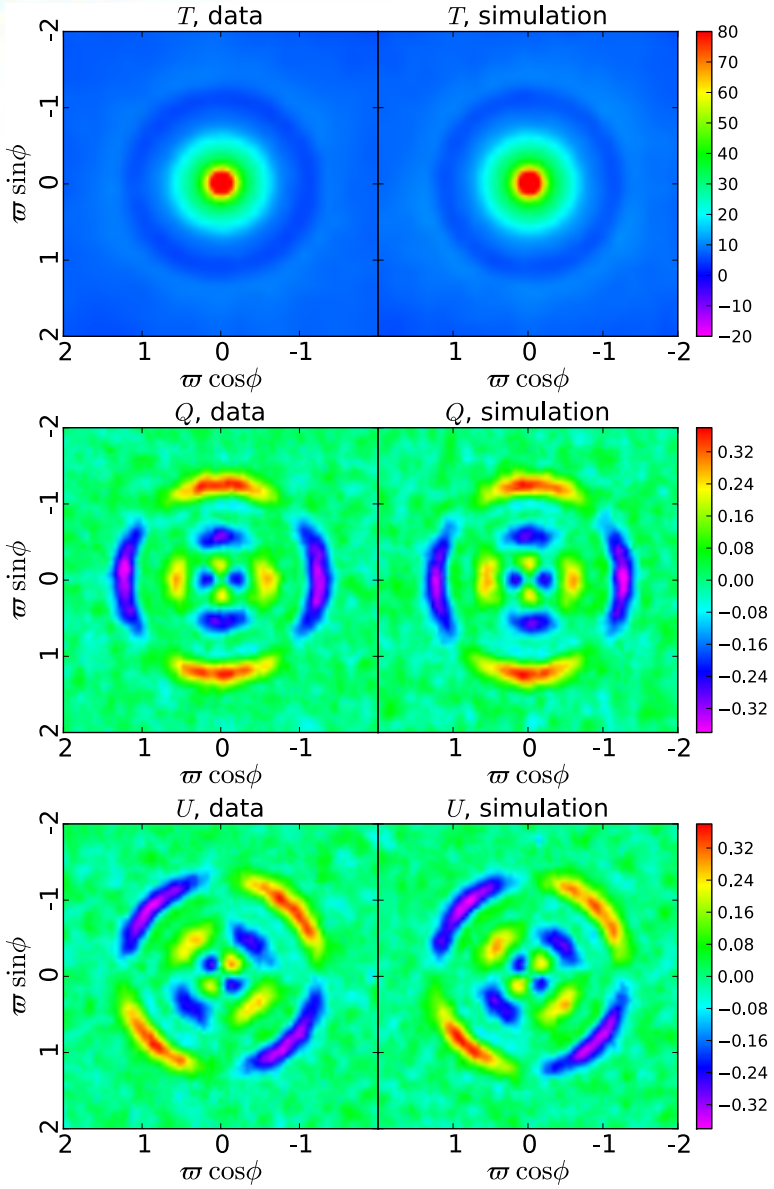
Consistent with the premises of ΛCDM cosmology, that the structure we observe today is the consequence of the passive evolution of adiabatic, Gaussian, nearly scale-invariant, primordial seed perturbations.

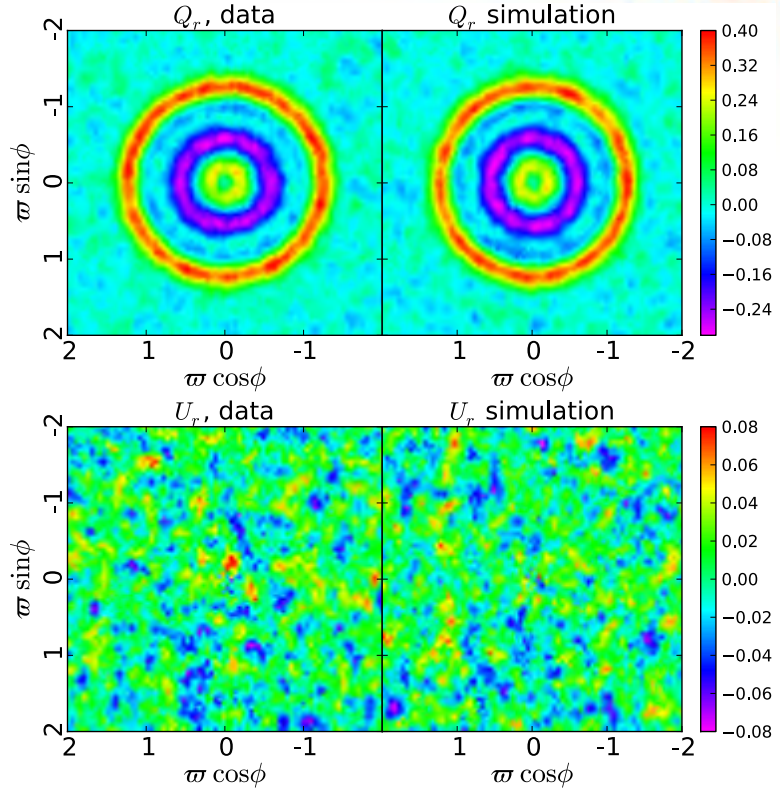
Isotropy and Statistics

- Planck 2013 found statistically anisotropic signals in the CMB
  - Confirm previous studies made using WMAP data

    $\Longrightarrow$ Real features of the microwave sky, potentially challenging fundamental assumptions of the standard cosmological model
- Planck 2015 extends these studies to full mission temperature data, and some polarization
  - Polarization limited to angular scales $< 10^\circ$ by large-scale systematics in HFI data
- First examination of polarization data by a stacking analysis
  - Morphology of stacked peaks is consistent with the expectations of statistically isotropic simulations

Isotropy and Statistics II





Planck Collaboration 2015 XVI

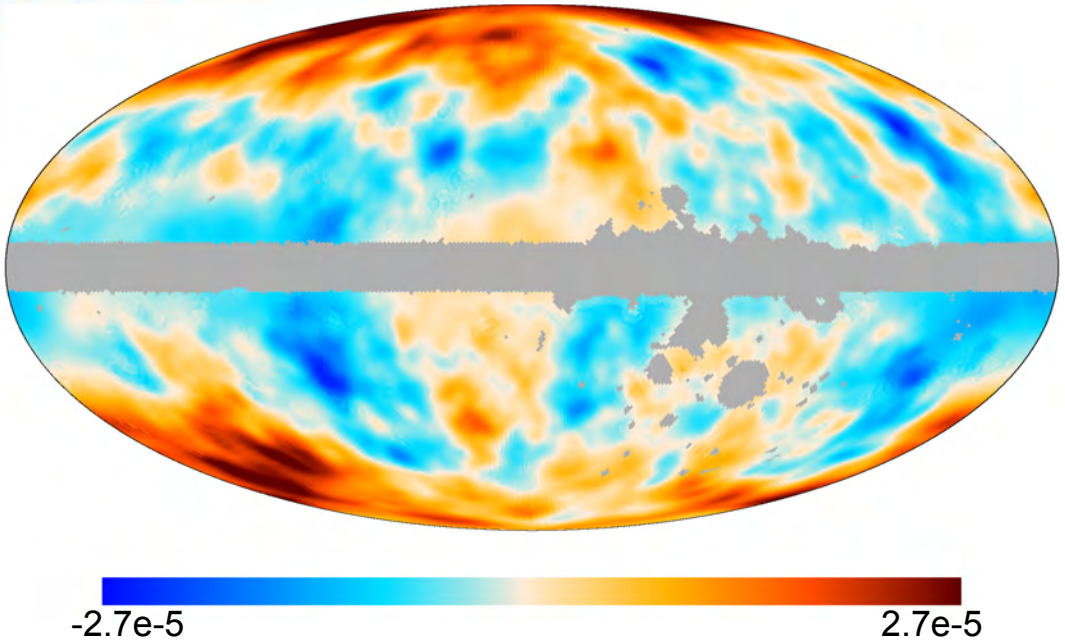
- $x = \varpi \cos\phi \;\; y = \varpi \sin\phi$; flat-sky coordinates

$$Q_{\rm r}\left(\vec{\hat{n}};\vec{\hat{n}}_0\right) = -Q\left(\vec{\hat{n}}\right)\cos\left(2\phi\right) - U\left(\vec{\hat{n}}\right)\sin\left(2\phi\right),$$
$$U_{\rm r}\left(\vec{\hat{n}};\vec{\hat{n}}_0\right) = Q\left(\vec{\hat{n}}\right)\sin\left(2\phi\right) - U\left(\vec{\hat{n}}\right)\cos\left(2\phi\right).$$

The ISW Effect

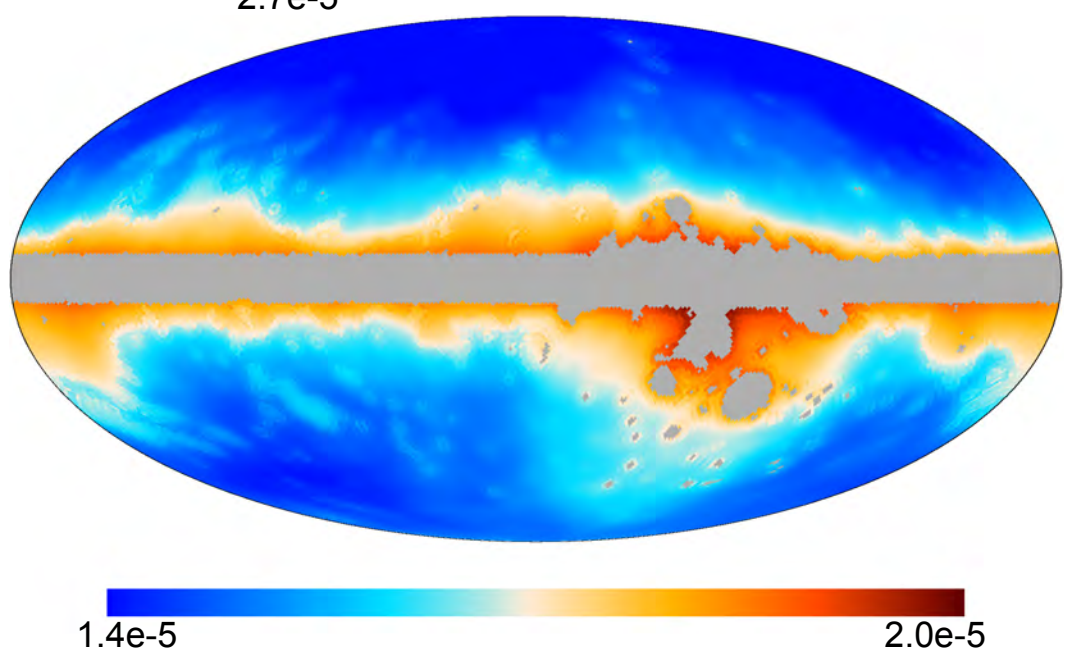
- 2013 results refined and extended
- Now detect ISW effect at 4σ by cross-correlating CMB temperature map with tracers of large-scale structure:
  - NRAO VLA Sky Survey (NVSS)
  - SDSS III BOSS luminous galaxy catalog
  - SDSS-DR8 galaxies
  - WISE galaxy and AGN catalogs
  - Planck lensing map

The ISW Effect II



ISW anisotropies, in kelvin

Per $\sim 1^\circ$ pixel uncertainty



Cosmology from Clusters

- 2015 cluster analysis has
  - 438 objects vs. 189 in 2013
  - Greater control of the selection function
  - Recent gravitational lensing determinations of mass bias (normalization of scaling relation between SZ signal and mass)

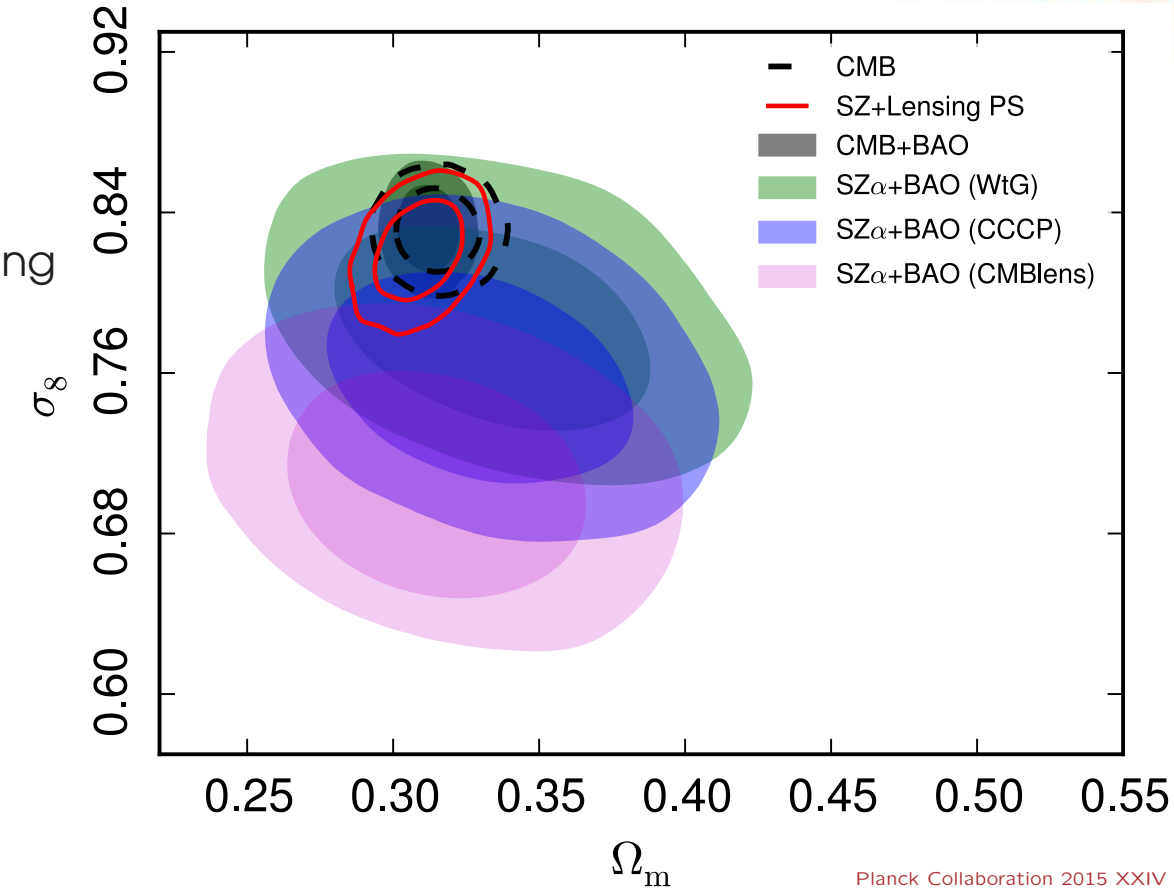
    Weighing the Giants (WtG; von der linden et al. 2014)

    Canadian Cluster Comparison Project (CCCP; Hoekstra et al., priv. comm.)

    CMB lensing (Melin & Bartlett 2014)

Cosmology from Clusters II

- 2015 constraints on σ_8 and $\Omega_{\rm m}$ are statistically identical to 2013 when adopting the same scaling relation and mass bias



Planck Collaboration 2015 XXIV

- WtG calibration reduces tension to $\sim 1\sigma$

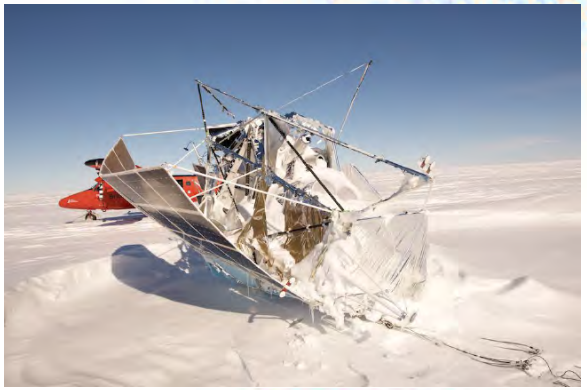
  CCCP between 1 and 2σ

  CMB lensing $> 2\sigma$

Red contours are from a joint analysis of cluster counts and the Planck lensing power spectrum. Fully independent of those from primary CMB, but in good agreement.

- Mass bias remains the main uncertainty in interpretation of the cluster counts

The Future



- Sub-orbital experiments underway
  - Spider: one flight completed (90, 150 GHz)
  - Bicep2–Keck Array–Bicep3 (95, 150 GHz)
  - CLASS, in Chile (38 GHz), (90, 150, 220 GHz) in future
  - POLARBEAR-2 (150, 220 GHz)

Johns Hopkins scientists have been building a telescope that will look into the early universe from the Chilean desert. The "Cosmology Large Angular Scale Surveyor" was packed and moved. (Amy Davis, Baltimore Sun video)

  - Etc.
- Space plans. . .
- Foregrounds and systematics are the key
  - Frequency coverage!!
  - Raw sensitivity is necessary, but not remotely sufficient
  - Space will be necessary to measure B-mode polarization $\ell < 10$

Summary

- The CMB continues to be a major contributor to cosmology and the establishment of a standard model
- Planck will have a third cosmological data release in 2016, and a final refinement to follow
- Foregrounds and instrumental systematics are the keys to the future, with primordial and "reionized" B mode polarization the prize
  - Many suborbital experiments and at least one space mission will be necessary

The Planck Collaboration