PLANCK

Analysis & Results 2013-2020

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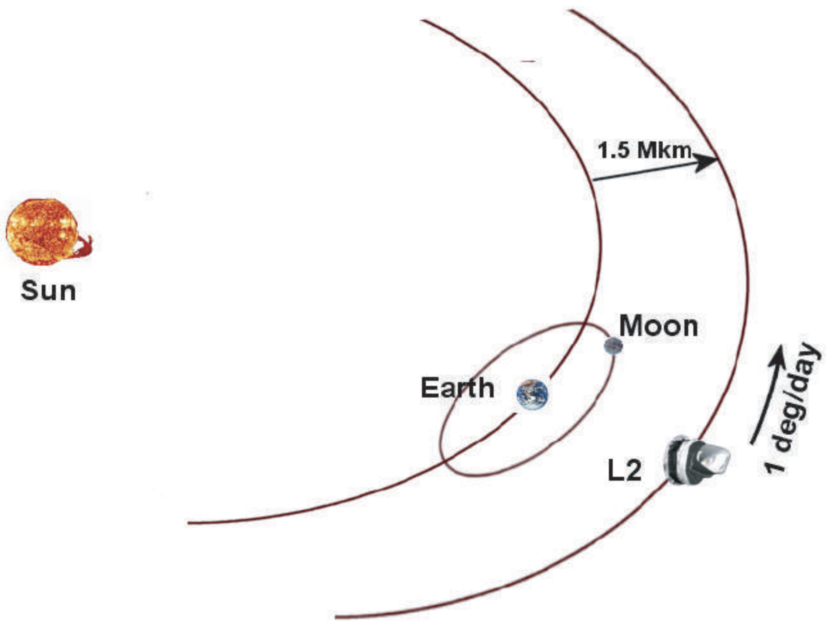
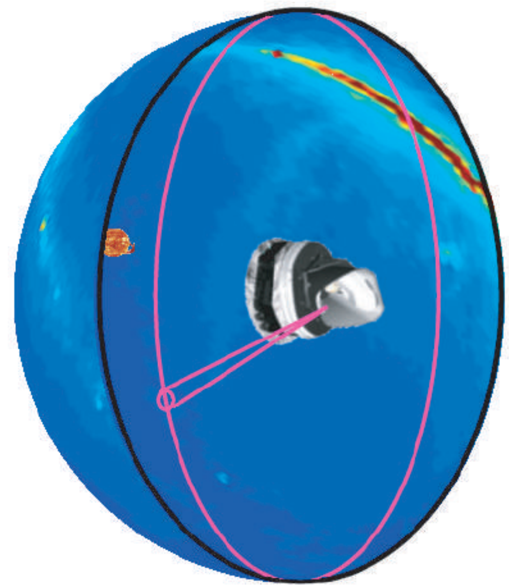
BeyondPLANCK Conference

2020 November 18

14 May 2009

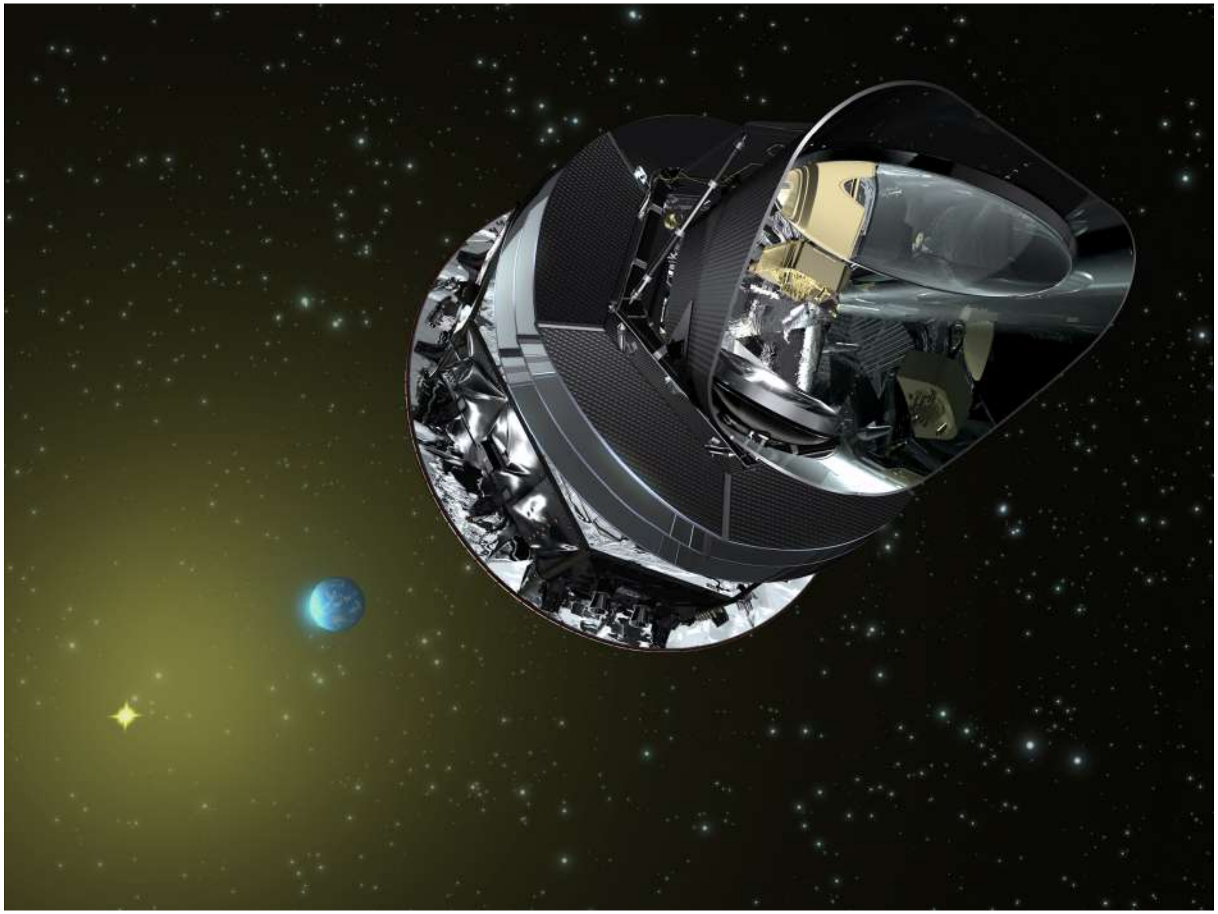
SUN-EARTH L_2





The 3rd-Generation Space CMB Mission

- Goal: measure the temperature anisotropies of the cosmic microwave background (CMB) to fundamental limits down to 5′, also measure polarization better than ever before
  - Two state-of-the-art cryogenic instruments
  - Nine bands, 30 GHz to 857 GHz. 30–353 GHz polarized.



Paper and Data Releases

Papers	Release	Data [Months] LFI	Data [Months] HFI	Data TOD	Data Maps	Stokes LFI	Stokes HFI	Calibration Solar	Calibration Orbital	Science
Early	...	10	10	no	yes	I	I	yes	...	astrophysics
2013	PR1	15.5	15.5	yes	yes	I	I	yes	...	astro+cosmo
2015	PR2	50.5	29	yes	yes	IQU	$I(QU)$[a]	...	yes	cosmology
2018	PR3	50.5	29	yes	yes	IQU	(I)[b]QU	...	yes	cosmology
NPIPE........	PR4	50.5	29	yes	yes	IQU	IQU	...	yes	limited

[a] Not usable at low ℓ.

[b] Not changed from 2015.

Planck Collaboration Papers

Set	# of Papers	# of Pages Total	per Paper	Mean
Early results	26	584	7–56	22.5
2013 results	32	992	20–66	31.0
2015 results	28	1067	17–99	38.1
2018 results	12	661	31–95	57.3
Intermediate	57	1311	12–88	23.0
Planck/Bicep	1	17		
Total	156	4632		29.7

- 48,779 citations as of 17 November 2020
- 8,962 citations for Parameters 2015
- Another >226 papers by Planck team members that are not Planck Collaboration papers

Calibration Example

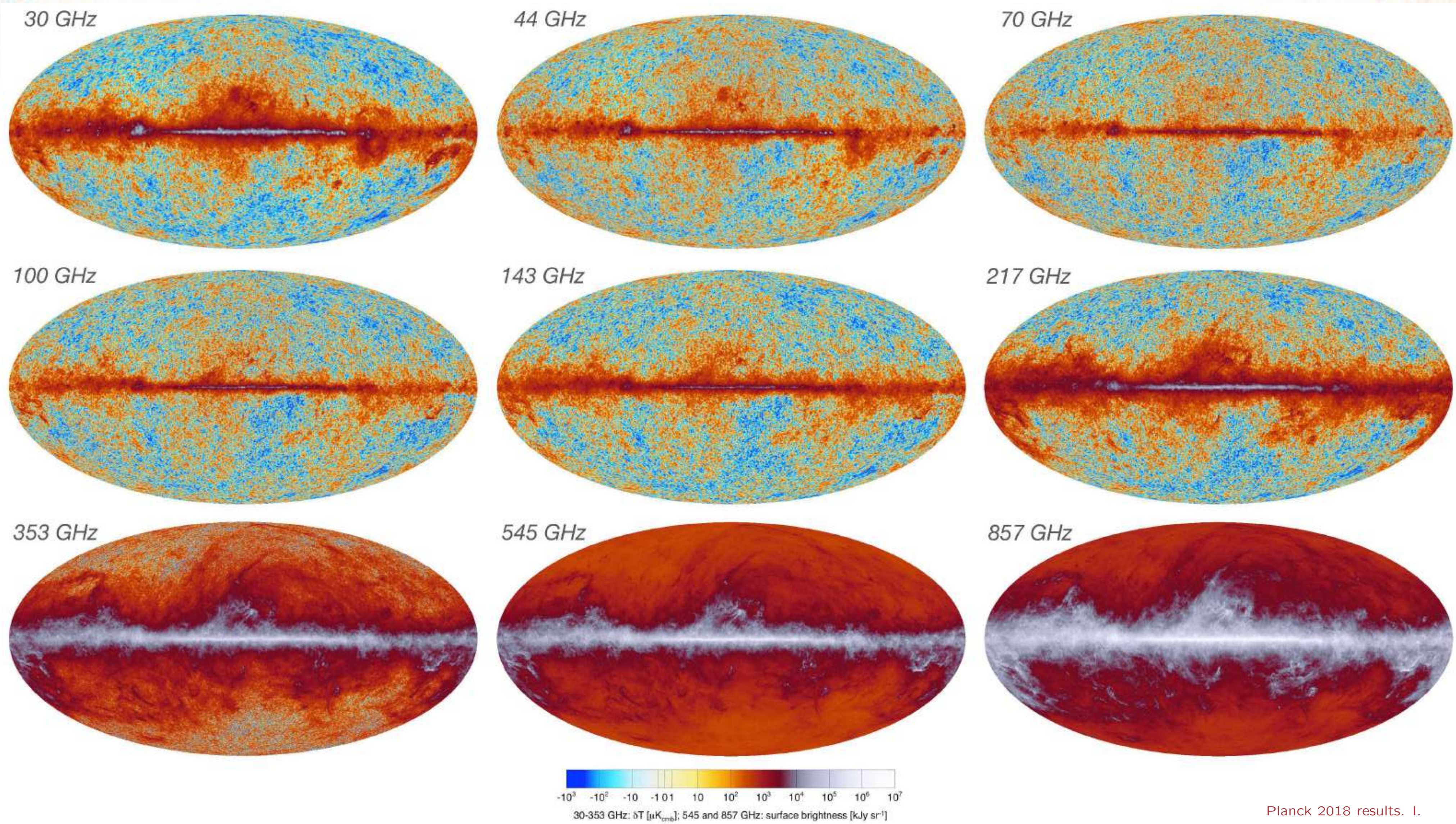
- For the 2013 results papers, the CMB power spectra produced by LFI and HFI agreed over the first peak extremely well
  - But disagreed with WMAP by about 2%, with concerning significance
  - This was a puzzle for a while
- *Planck* 2013 results. XXXI. Consistency of the *Planck* data started to sort it out
  - For LFI, the full 4π beam response used in the diipole calibration needed improvement (~ 0.2% in power spectra)
  - For HFI, near sidelobe estimates(from "main" beam out to 5°) needed improvement (beam window function corrections of 0.5–1.2%). Time constants were a factor.
  - Planck in 2013 was calibrated on the WMAP solar dipole, not the orbital dipole. WMAP, on the other hand, was calibrated on the orbital dipole WMAP solar dipole errors fed directly into Planck errors. Foreground errors in the WMAP solar dipole fed directly into Planck errors, but didn't affect WMAP.
  - Corrections for foregrounds, including unresolved sources, were necessary
  - LFI and HFI agreed well within uncertainties. Planck $-$ WMAP was a 1.5–2σ difference
- Overall 2013 Planck calibration errors were estimated at 0.62% for 70 GHz *maps* and 0.54% for 100 and 143 GHz *maps*
- Planck 2018 and NPIPE are better than 0.1%. Stay tuned for later talks.
  - The improvement was a result of many, many factors.

Systematic Errors

- This is the hard part, of course!
- Planck ultimately was not limited by systematics except at the lowest few multipoles
- The hardest to deal with was an HFI combination of
  - ADC non-linearities (not anticipated)
  - Way out-of-spec EMC from the 4-K-cooler drive electronics (known before launch)
  - Limited downlink bandwidth

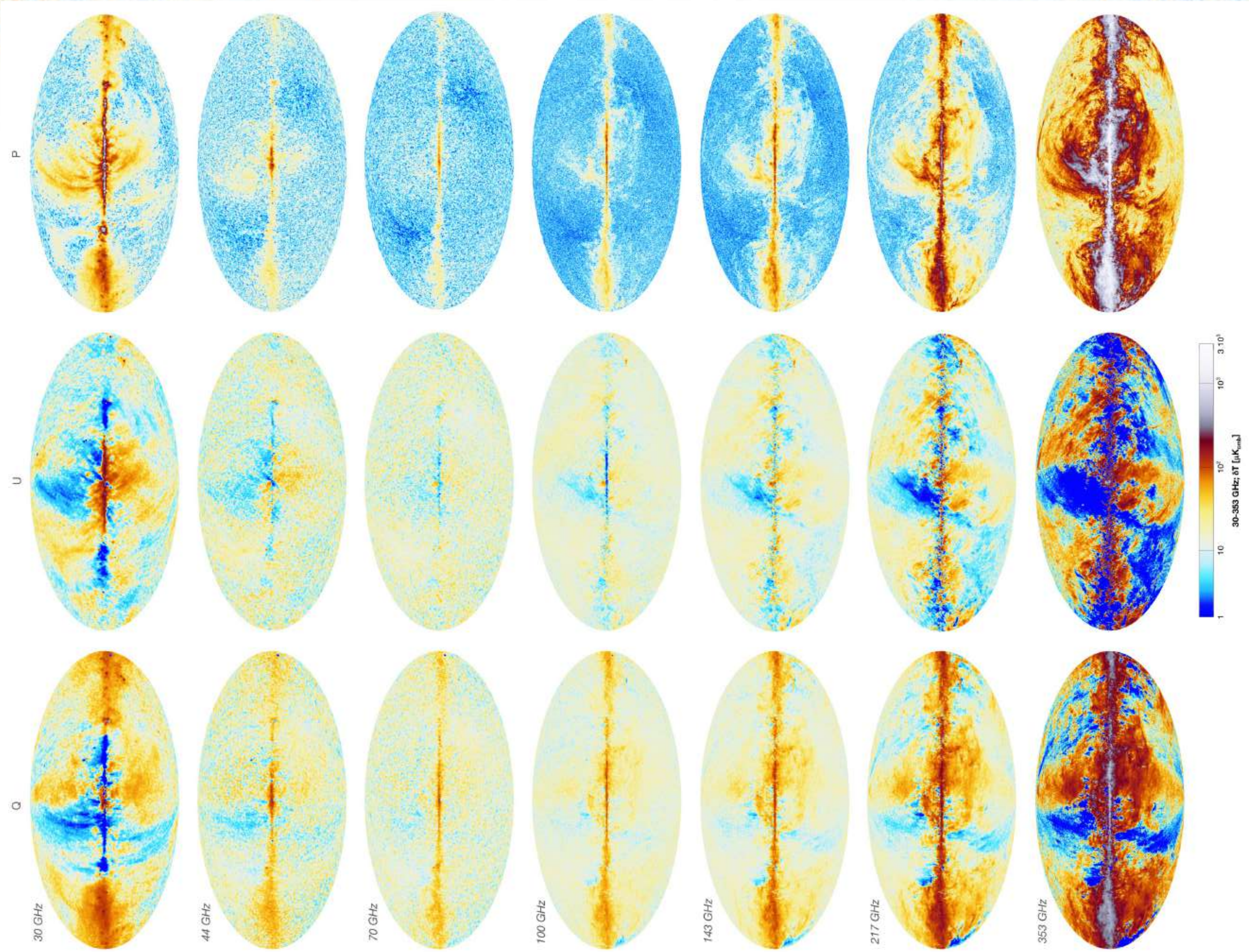
    40 successive readout samples were summed on board, so sample-by-sample correction was impossible
- Second-hardest was another HFI combination, of
  - Beams
  - Time constants
  - 'Long' cosmic rays
- There are no shortcuts in finding and mitigating systematic problems
  - Must connect any effect to its hardware cause
  - Must be able to reproduce it with simulations built on the real behavior of hardware
  - Sometimes valuable techniques such as blind analysis and machine learning don't help

The Universe: Temperature, Nine Frequencies



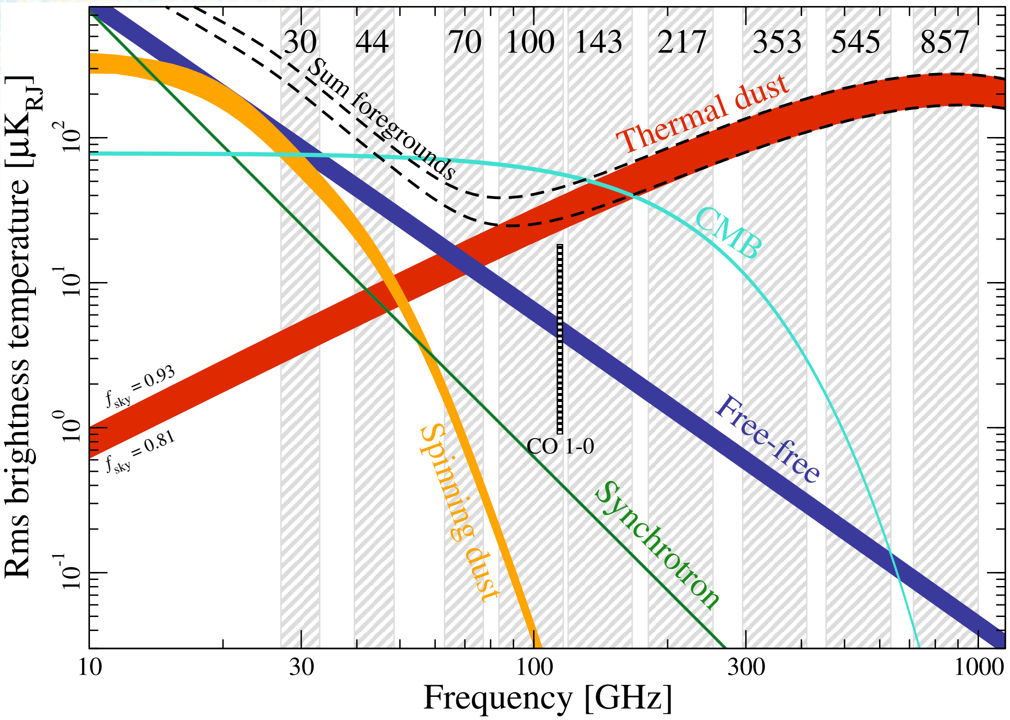
Planck 2018 results. I.

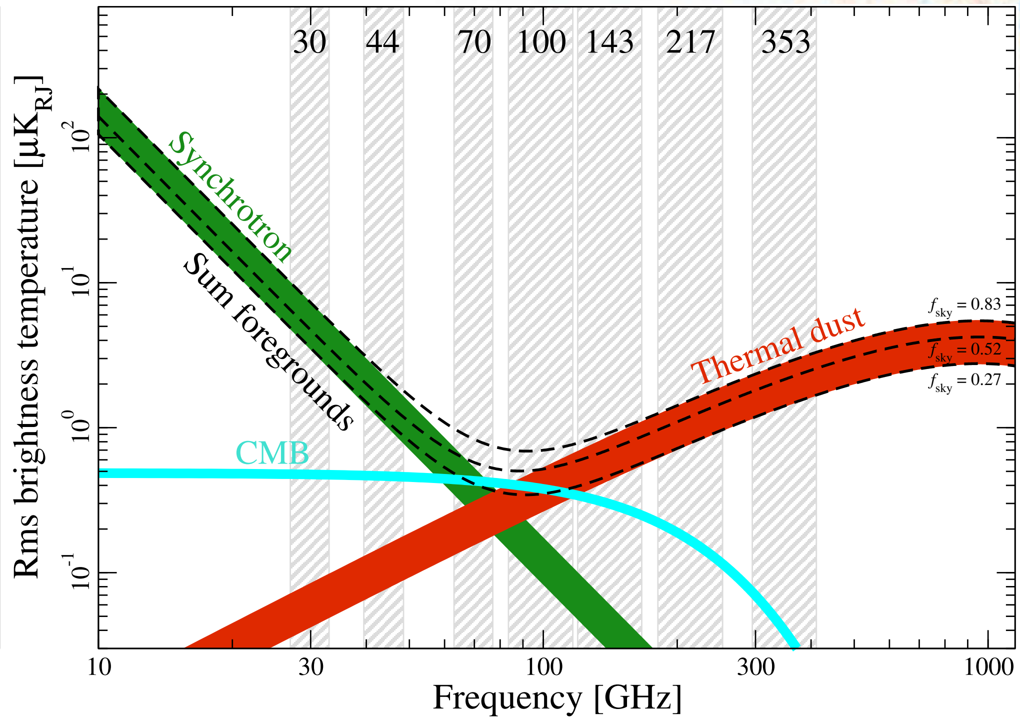
Planck Polarization, Seven Frequencies



Planck 2018 results. I.

Separation of 'Foregrounds' from the CMB





Planck 2018 results. I.

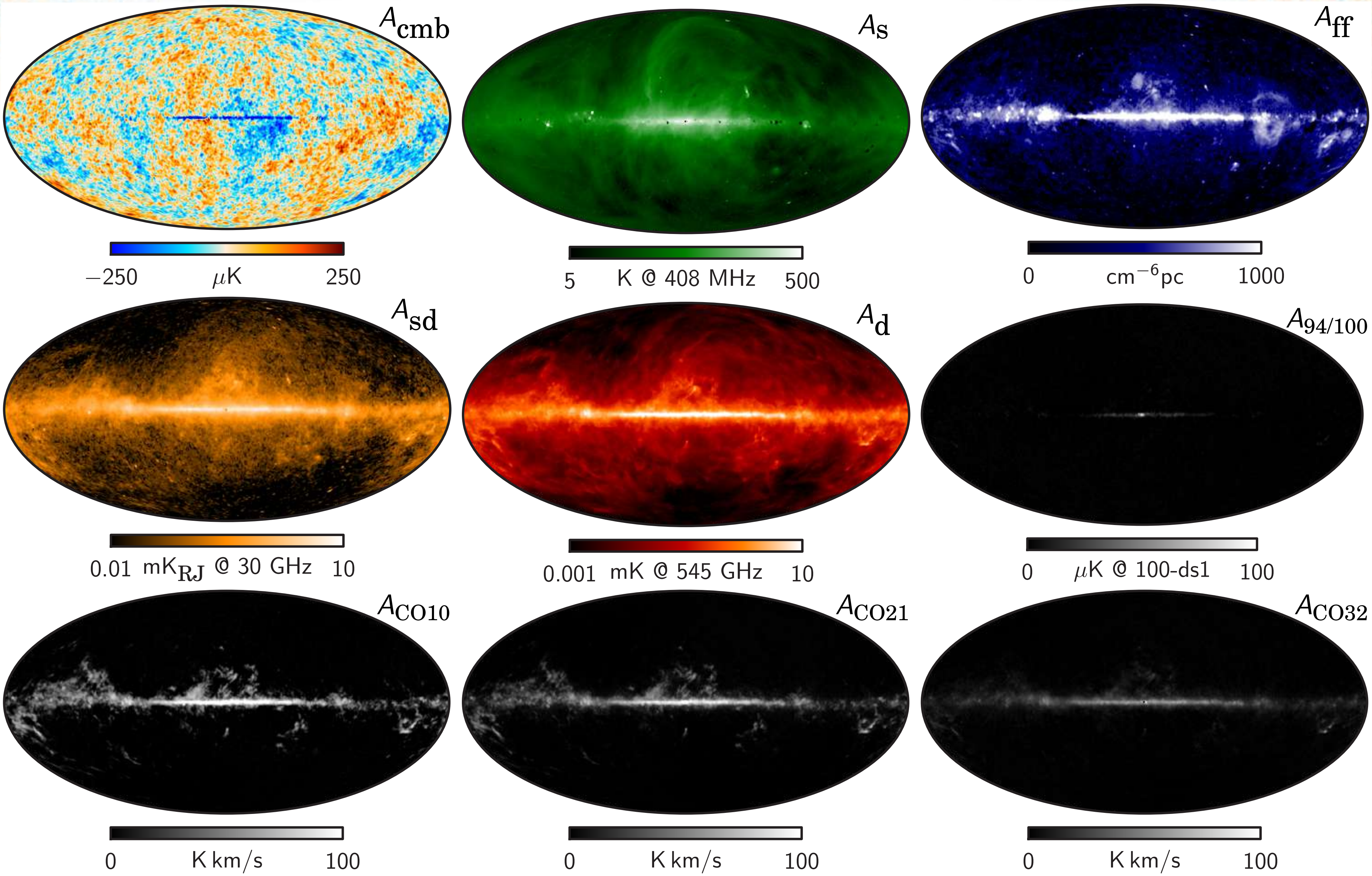
Temperature

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

Polarization

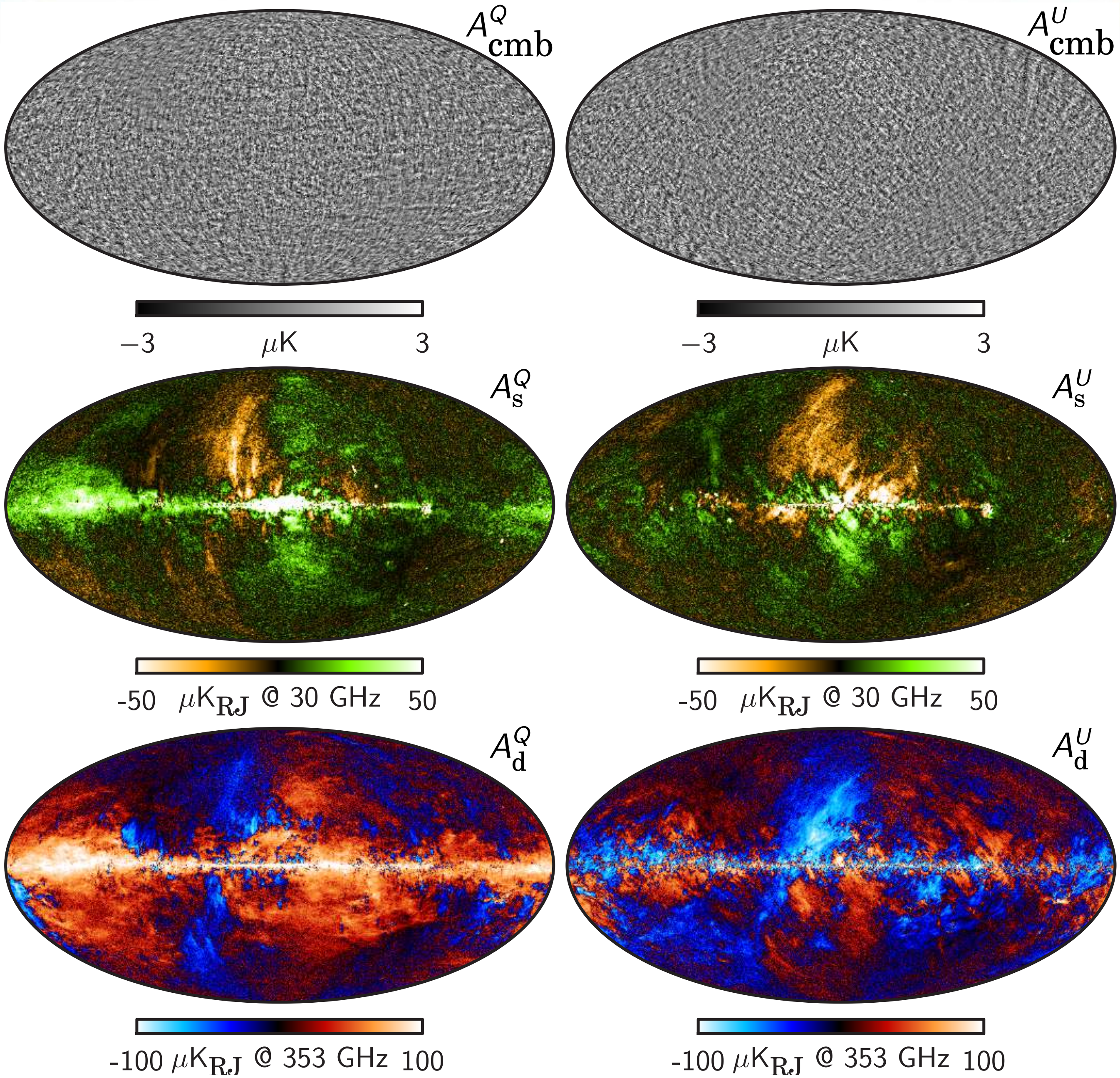
- All components smoothed to 40′
- Sky fractions 27–93% of sky

CMB and Foreground Stokes I Maps



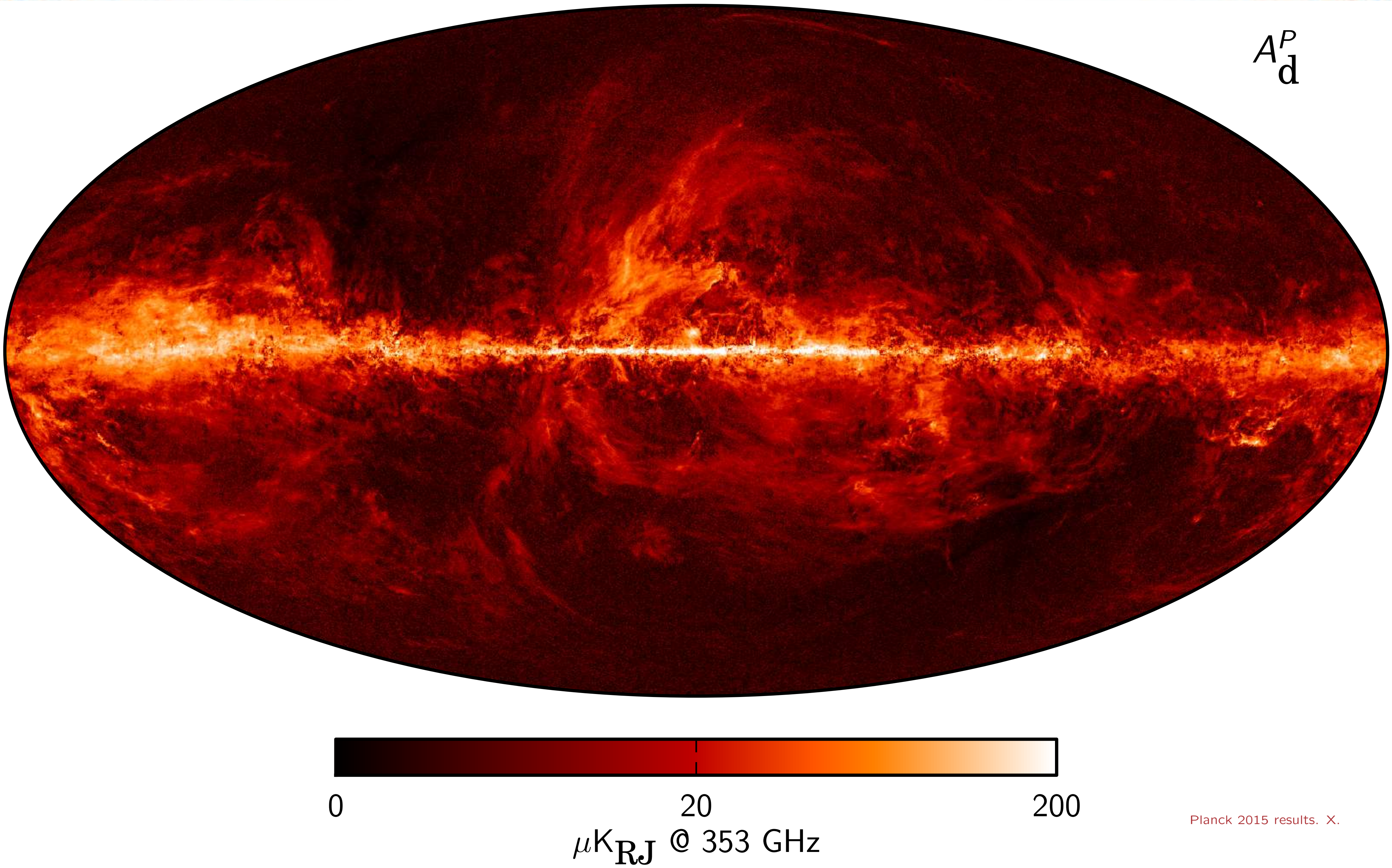
Planck 2015 results. X.

CMB and Foreground Stokes Q, U Maps



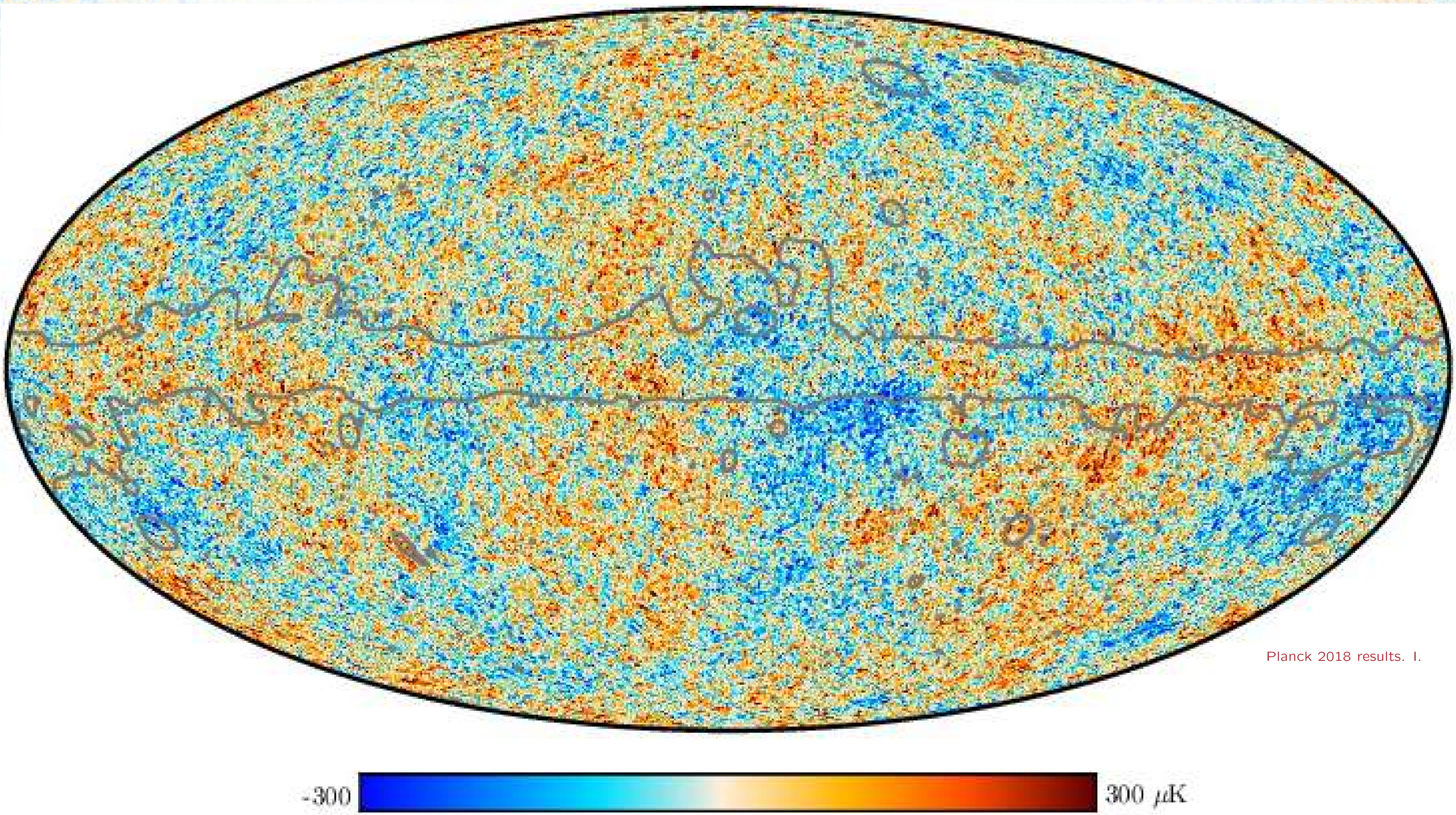
Planck 2015 results. X.

Polarized Dust Emission (353 GHz)



Planck 2015 results. X.

CMB I



(A few % of the sky in the plane of the Milky Way is filled in with a "constrained realization".)
(Regions inside the grey lines aren't used for cosmology, as residual foreground emission is too high.)

A "simple" 6-parameter ΛCDM model fits the Planck data extremely well!

The TT, TE, EE, and CMB lensing spectra are consistent with each other under the assumption of the base ΛCDM cosmology.

Assumptions Underlying ΛCDM

1 Physics is the same throughout the Universe

2 General Relativity is an adequate description of gravity

3 On large scales, the Universe is statistically the same everywhere

4 The Universe was once hot and dense, and has been expanding

5 Five basic cosmological constituents

- Dark energy that behaves like the energy density of the vacuum
- Dark matter that is pressureless, stable, and non-electromagnetically-interacting
- Regular "atomic" (baryonic) matter that behaves just like it does on Earth
- The photons we observe as the CMB
- Neutrinos that are almost massless, and stream like non-interacting, relativistic particles

6 The curvature of space is very small

7 Variations in density were created early, and are Gaussian, adiabatic, and nearly scale invariant, as predicted by inflation

- I.e., Proportional in all constituents, and with similar amplitudes as a function of scale

8 The Universe has "trivial" topology (in particular, it is not periodic or multiply connected)

The Six

1 Density of baryonic matter in the Universe $\Omega_b h^2$

2 Density of cold dark matter in the Universe $\Omega_c h^2$

3 Angle subtended by the distance sound travelled in the first 370,000 years after the Big Bang θ_{MC}

4 Fraction of CMB photons scattered on their 13.8 billion year journey by electrons and protons (hydrogen) reionized by stars, quasars, etc. τ

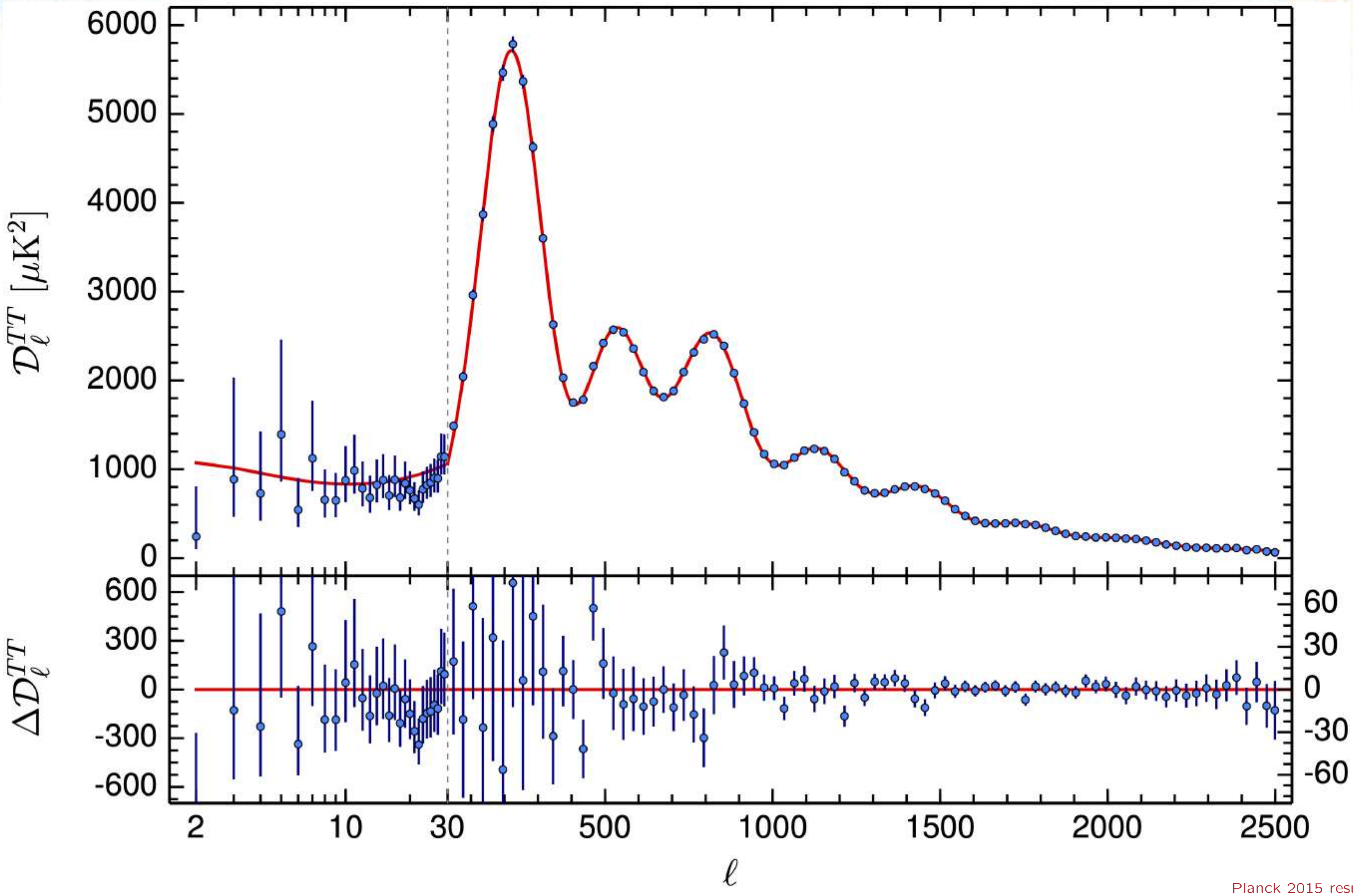
5 Amplitude of the initial fluctuation spectrum A_s

6 Slope of the initial fluctuation spectrum n_s

The Six Again

- A_s, n_s — inflation fluctuations; 10^{-35} s;
- $\Omega_b h^2$, $\Omega_c h^2$ — baryons and cold dark matter; first few minutes
  - 0.6% and 0.8% precision
- θ_{MC} — sound horizon; 370,000 years
  - 0.03% precision
- τ — reionization optical depth; 13.8 billion years

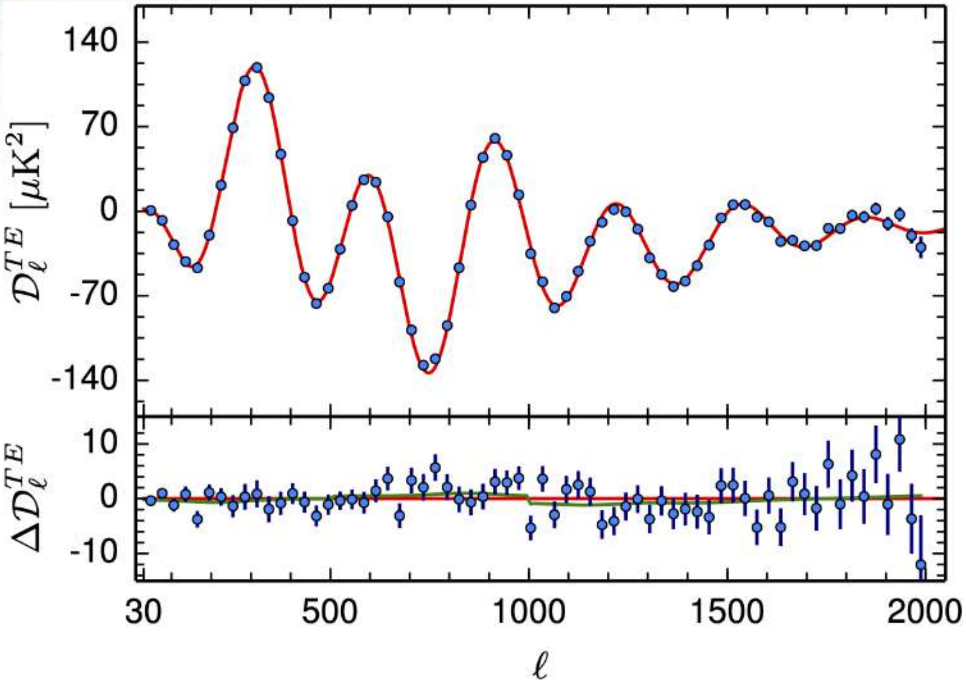
Angular Power Spectrum + Best-Fit Model

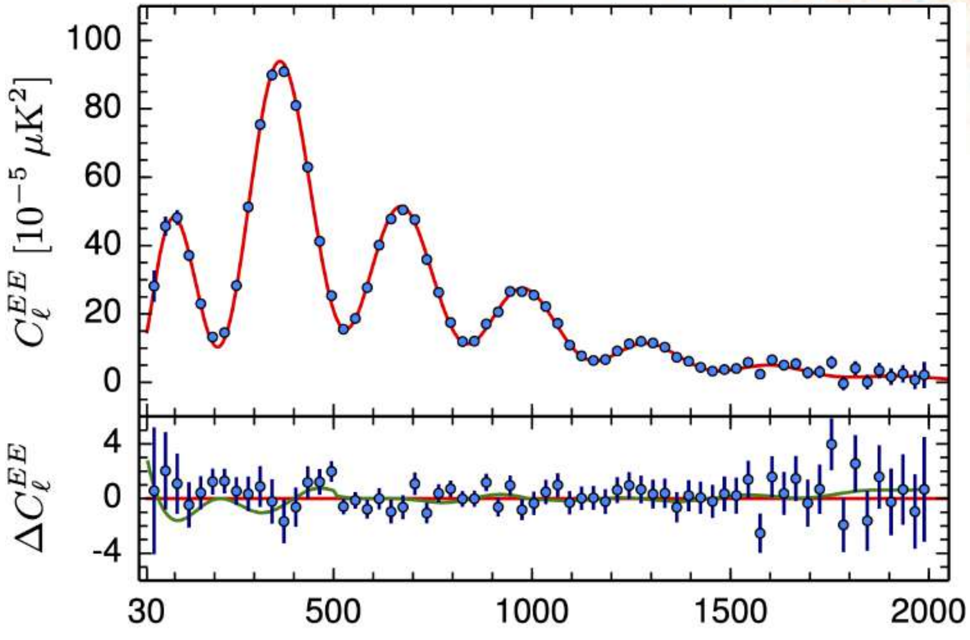


Planck 2015 results. XIII.

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

Polarization Spectra, Same Model





Planck 2015 results. XIII.

TE

Temperature-polarization cross-spectrum

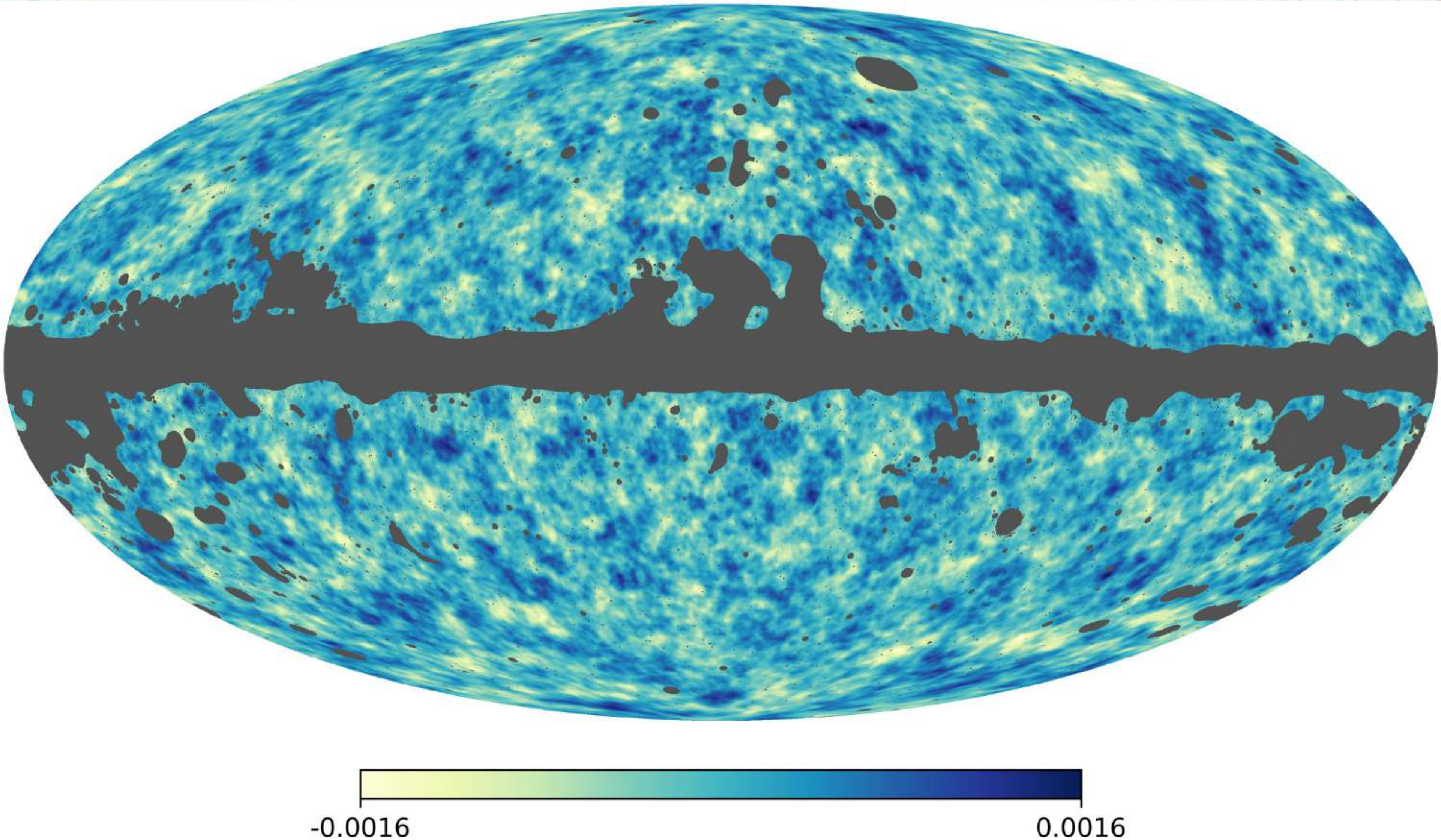
EE

Polarization auto-spectrum

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

- Spectacular agreement between inferences from temperature and polarization

Lensing Potential — All the Mass in the Universe



Planck 2018 results. I.

- Lensing now measured at 40σ.

ΛCDM Model Parameters

Parameter	*Planck + BAO*	N_σ
$\Omega_b h^2 [18.79\,\mathrm{yg\,m^{-3}}]$..........	0.02242 ± 0.00014	160
$\Omega_c h^2 [18.79\,\mathrm{yg\,m^{-3}}]$..........	0.11933 ± 0.00091	131
$100\theta_{\mathrm{MC}}$..........................	1.04101 ± 0.00029	3590
τ..................................	0.0561 ± 0.0071	7.9
τ (NPIPE)	0.051 ± 0.006	8.5
$\ln(10^{10} A_s)$	3.047 ± 0.014	218
n_s	0.9665 ± 0.0038	254
$H_0[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	67.66 ± 0.42	161
Ω_m................................	0.3111 ± 0.0056	55
$z_{\mathrm{reionization}}$........................	7.82 ± 0.71	11
$z_{\mathrm{recombination}}$	1059.94 ± 0.30	3533
Age[Gyr].......................	13.787 ± 0.020	689

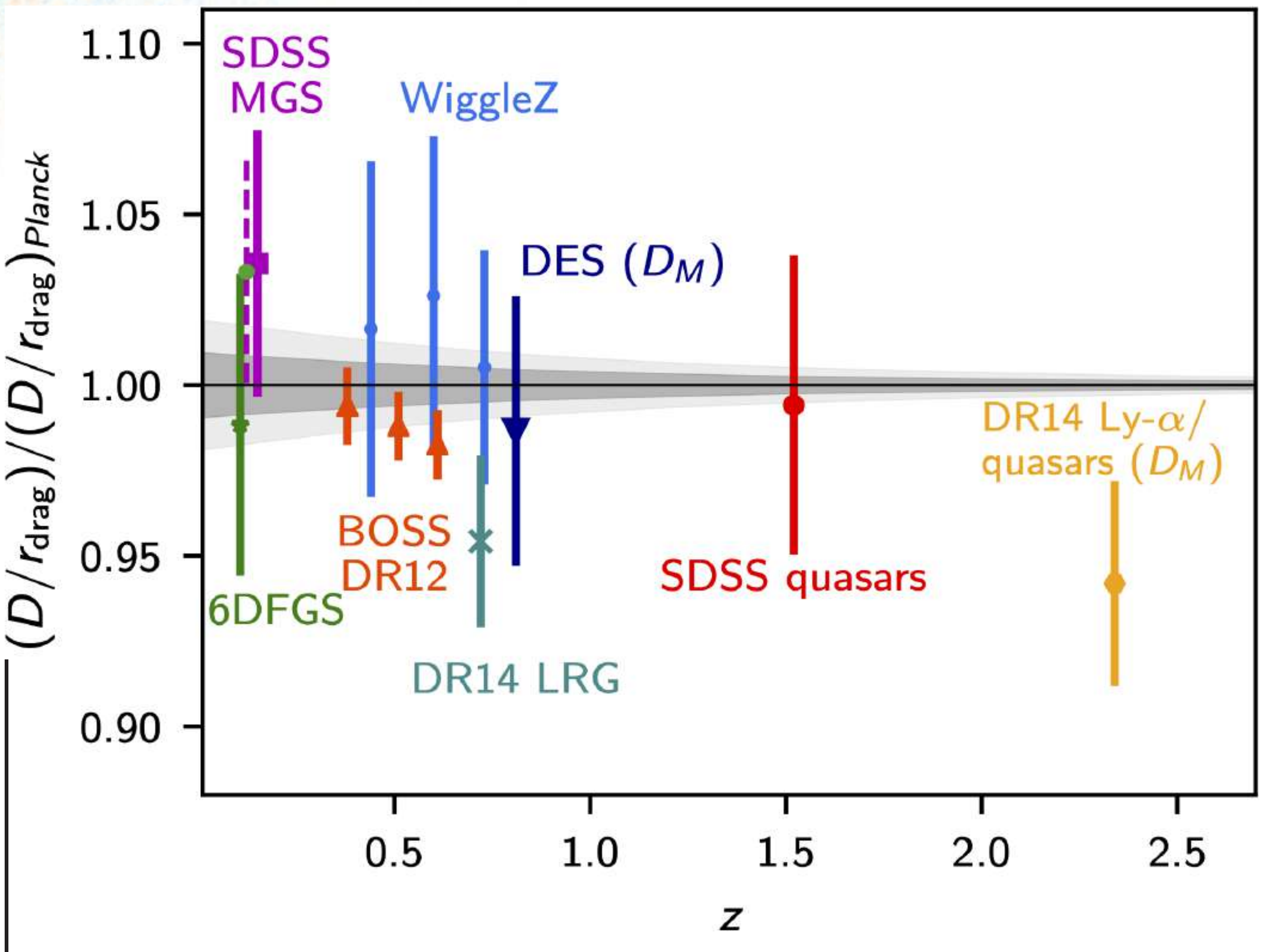
Planck 2018 results. I.

68% confidence limits

Consistency with Other Data

- Baryon Acoustic Oscillations (BAO; distance scale)
- Primordial nucleosynthesis
- Type Ia supernovae
- Direct measures of H_0
- Redshift-space distortions
- Rich clusters of galaxies

BARYON ACOUSTIC OSCILLATIONS (Distance Scale Comparison)



- Acoustic oscillations at $z \sim 1100$ and $z < 2.5$ tell the same story about the distance scale: ΛCDM!

Planck 2018 results. I.

Vertical axis is the ratio of the acoustic-scale distance as determined by the experiments plotted to that determined by Planck.

$D_V(z)/r_{\rm drag}$ is the acoustic-scale distance ratio

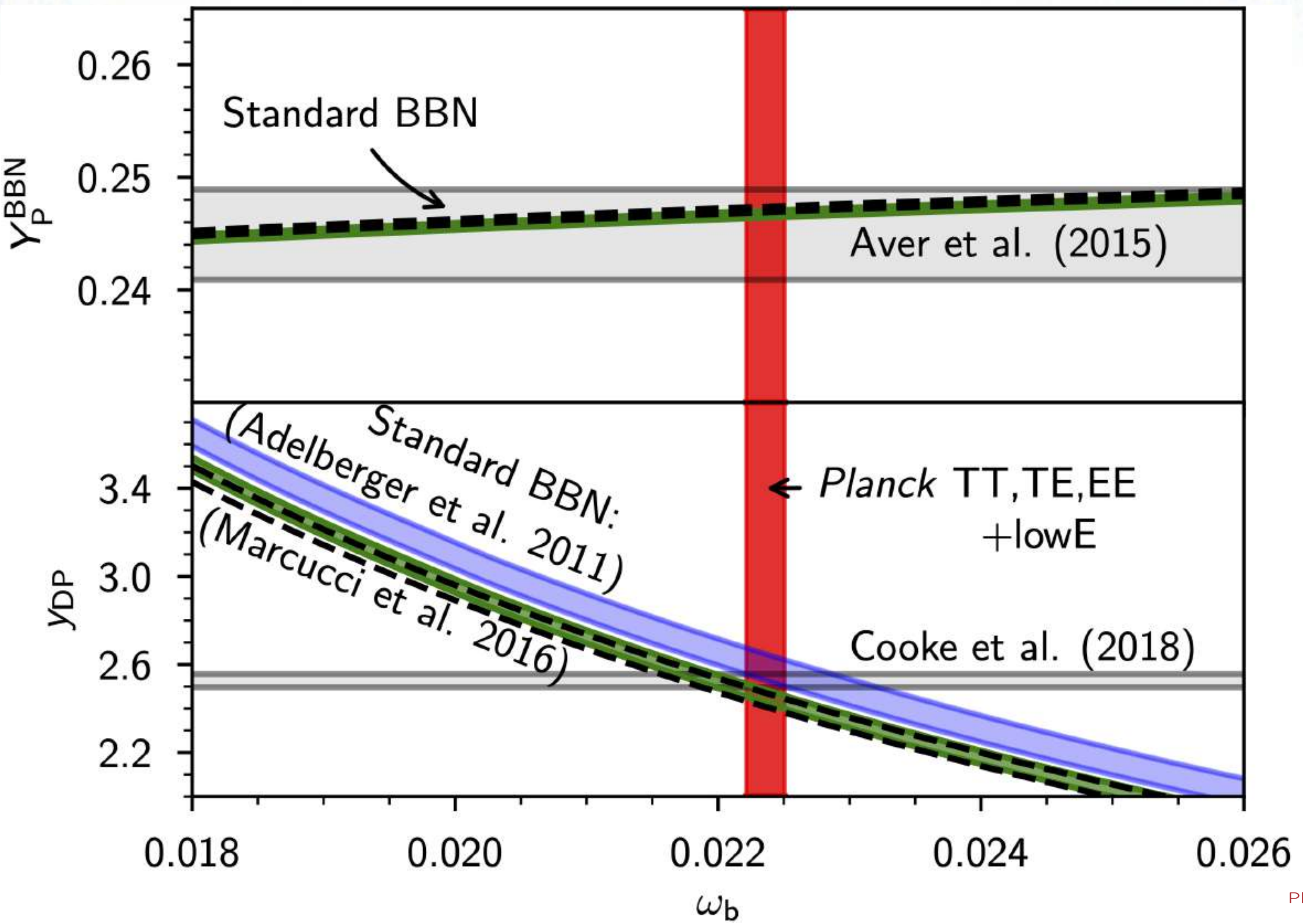
$r_{\rm drag}$ = comoving sound horizon at end of baryon drag epoch

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

$D_{\rm A}$ = angular diameter distance

Helium

Deuterium



Planck 2018 results. I.

The width of the green stripes corresponds to 68% uncertainties in nuclear reaction rates and on the neutron lifetime. The horizontal bands show observational bounds on primordial element abundances compiled by various authors, and the red vertical band shows the Planck TT+lowP+BAO bound on $\Omega_b h^2$ (all with 68% errors). The BBN predictions and CMB results shown here assume $N_{\rm eff} = 3.046$ and no significant lepton asymmetry.

Do More Complicated Models Fit Better?

The standard ΛCDM model fits really well. Do models with more parameters fit better?

- $\Omega_{\rm K}$ (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.

No compelling evidence for any of these extensions

Curvature

- CMB + later-time data from lensing and BAO lead to remarkable constraints on spatial curvature...

$$\Omega_k = 0.0007 \pm 0.0019 (95\%)$$

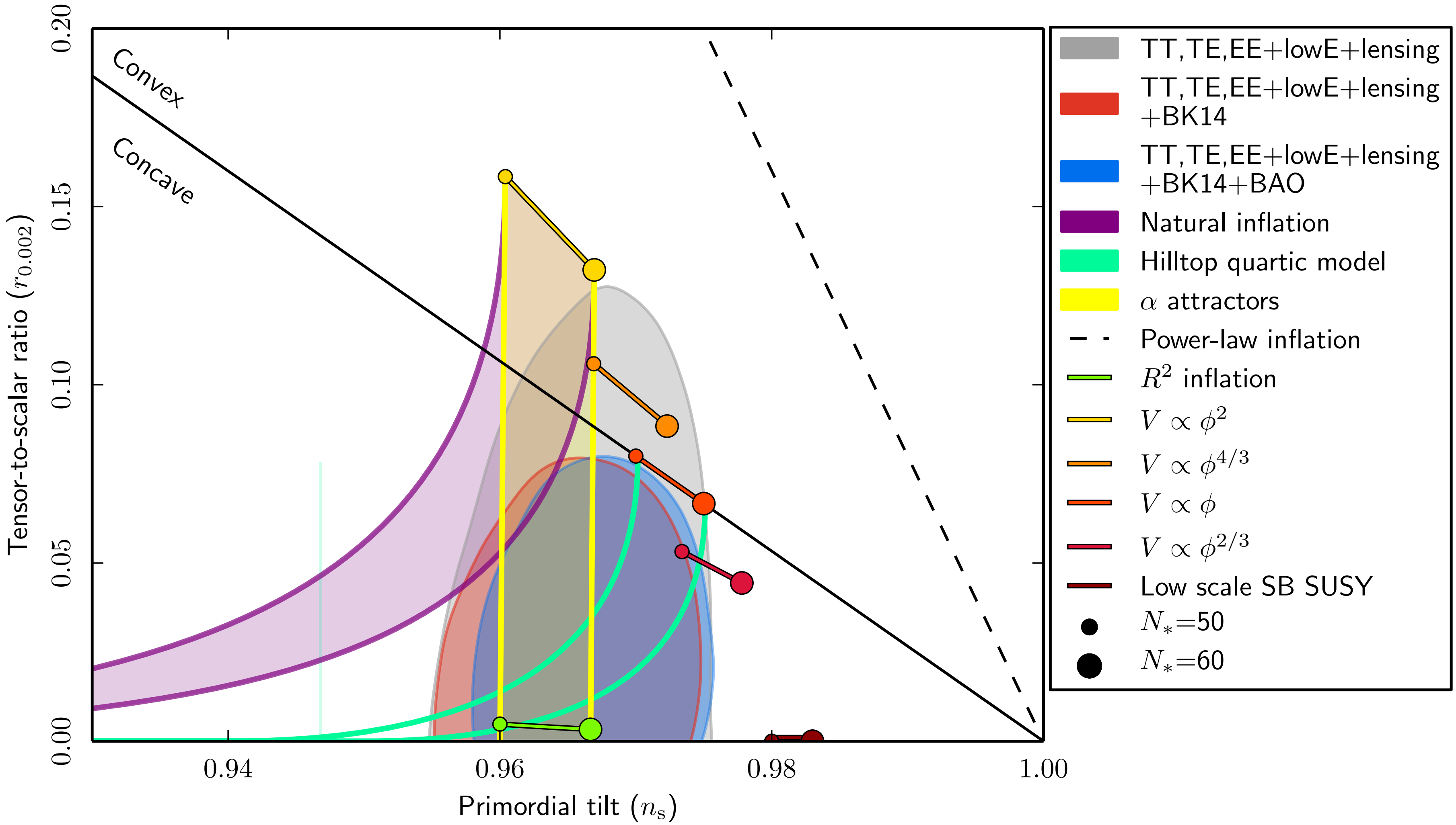
Planck 2018 results. I.

Non-Gaussianity

- $f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$
- $f_{\rm NL}^{\rm equil} = -26 \pm 47$
- $f_{\rm NL}^{\rm ortho} = -38 \pm 24$

Planck 2018 results. I.

Inflation Constraints from Planck + BAO



Planck 2018 results. I.

- $V(\phi) \propto m^2\phi^2$ and $\lambda\phi^4$ excluded. Models with $r \sim (1 - n_s)^2$ (concave potentials) are consistent with data.
- $\Rightarrow$ Energy scale of inflation $\quad V_* = (1.94 \times 10^{16}\,\text{GeV})^4\, r_{0.002}/0.12)$

Tensor-to-Scalar Ratio r

- From Planck 2018 VI, combining Planck data with BICEP-Keck 2015 data (BICEP2 Collaboration 2018), we get

$$r_{0.002} < 0.06, \quad 95\%$$

- From a new paper under review at A&A, combining NPIPE-processed Planck data with BICEP-Keck 2015 data, we get

$$r_{0.002} < 0.044, \quad 95\%$$

Astronomy & Astrophysics manuscript no. planck_tensor
November 17, 2020

Planck constraints on the tensor-to-scalar ratio

M. Tristram[1], A. J. Banday[2,3], K. M. Górski[4,5], R. Keskitalo[6,7], C. R. Lawrence[4], K. J. Andersen[8], R. B. Barreiro[9], J. Borrill[6,7], H. K. Eriksen[8], R. Fernandez-Cobos[9], T. S. Kisner[6,7], E. Martínez-González[9], B. Partridge[10], D. Scott[11], T. L. Svalheim[8], H. Thommesen[8], and I. K. Wehus[8]

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[11] Department of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, British Columbia, Canada

November 17, 2020

arXiv:2010.01139

Summary of Results

- 6-parameter ΛCDM fits!
- CMB and large-scale structure (BAO) provide a consistent picture
- Extensions of the model have been tested. They are not required, and provide many limits
- Primordial fluctuations are to good approximation
  - Isotropic (but not completely)
  - Gaussian
  - Nearly scale invariant ($n_{\rm s} = 1$ is excluded at 9σ)
- Space is flat
- Matter is mostly dark and cold
- Baryon density, helium and deuterium abundances, are consistent with BBN
- There are no gravitational waves at the $< 10\%$ level

However...

- We don't know what dark matter is.
- We don't have any idea at all what dark energy (Λ) is.
- The physics of inflation are largely unknown

Conclusion

- Planck met its goals
- The Planck data releases and papers are a major and wonderful contribution to our knowledge of the Universe
- There is much left to do with the Planck data. . .
- . . .and a lot left to squeeze out of the CMB

The Planck Collaboration