PLANCK 2015 RESULTS

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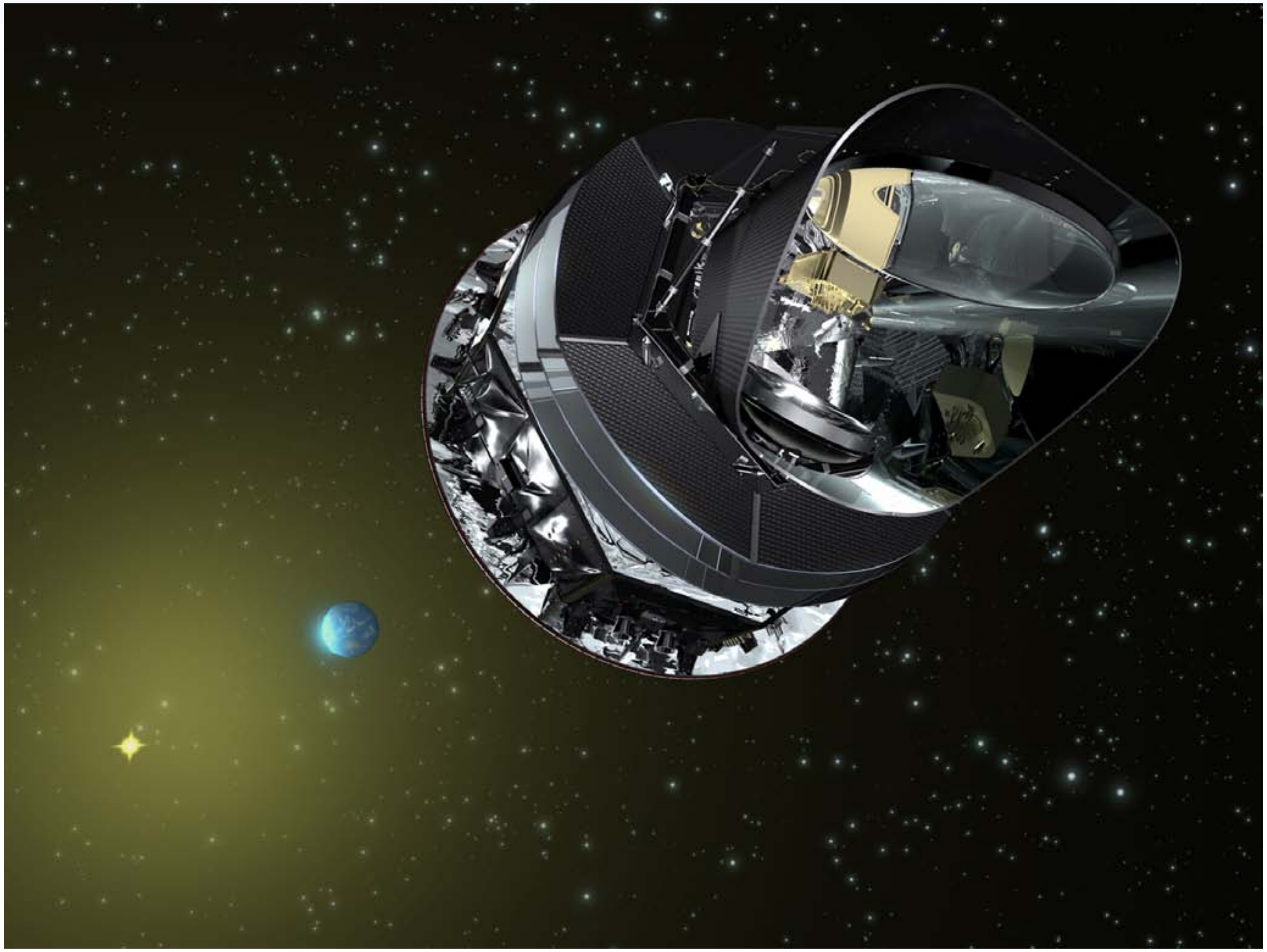
for the Planck Collaboration

Astrophysics Subcommittee
NASA HQ
2015 March 18

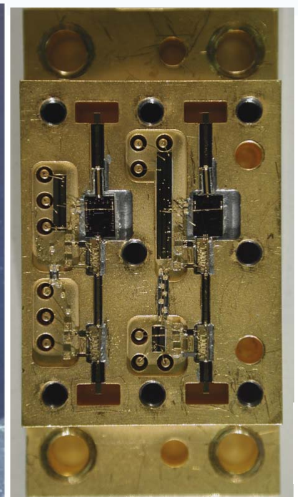
Planck, the 3rd Generation Space CMB Mission

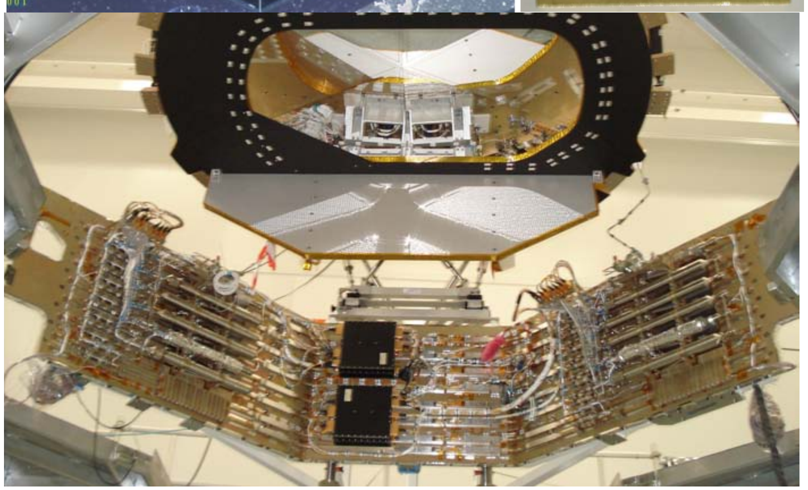
- Goal: measure the temperature anisotropies of the CMB to fundamental limits down to 5′, also measure polarization better than ever before
  - Two state-of-the-art cryogenic instruments
  - Nine bands, 30 GHz to 857 GHz. 30–353 GHz polarized.



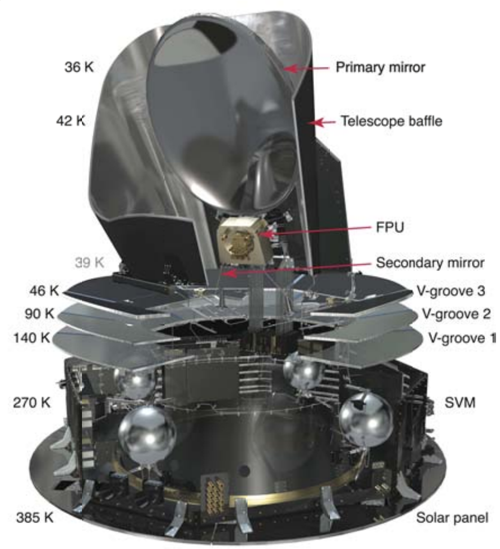
Enabling US Hardware Contributions to Planck

- Detectors for the High Frequency Instrument (JPL)
- Detector technology, receiver prototypes, and MICs and MMICs for the Low Frequency Instrument (JPL, TRW, UCSB)

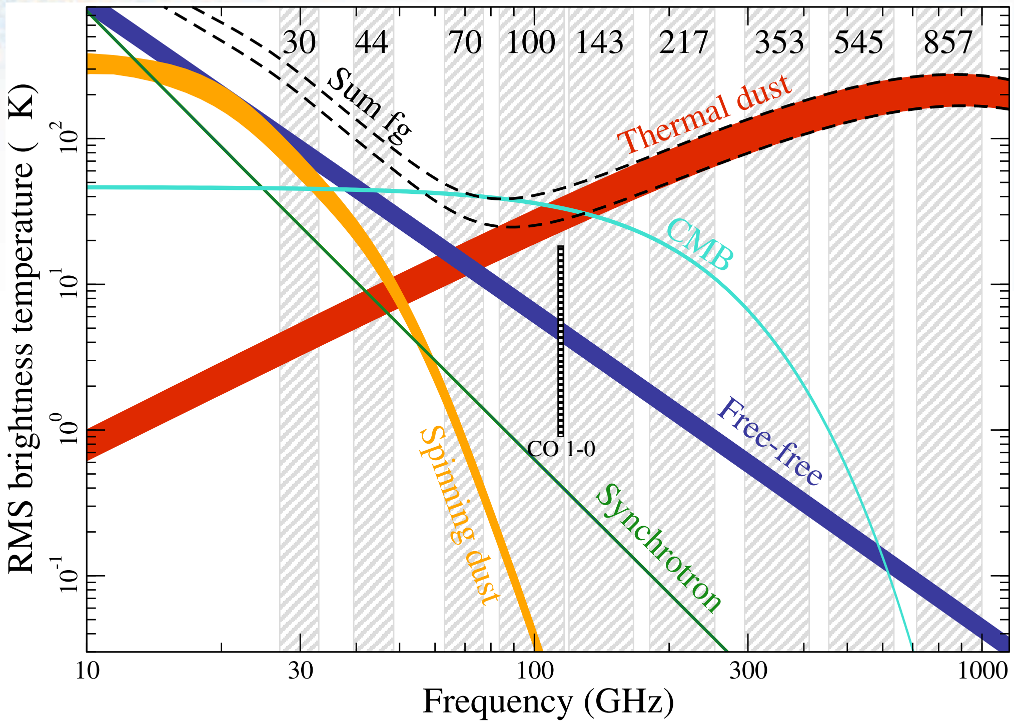


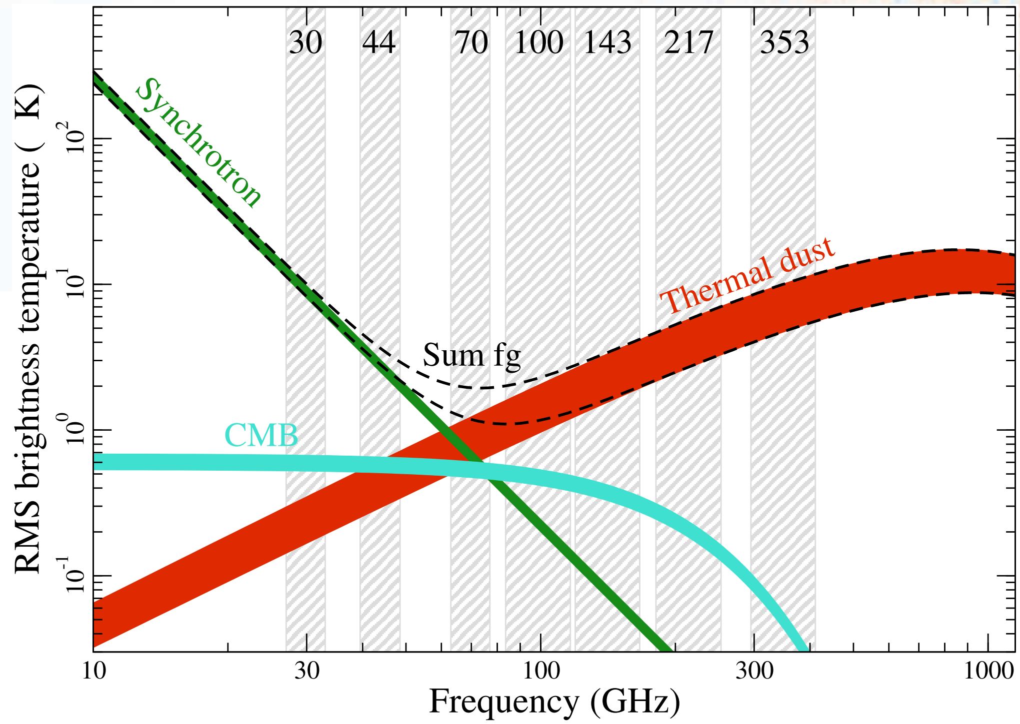


- 20-K hydrogen sorption coolers (JPL)
- Thermal design (JPL)
- Supercomputers (LBNL; National Energy Research Scientific Computing center)



The CMB and Foregrounds





Temperature

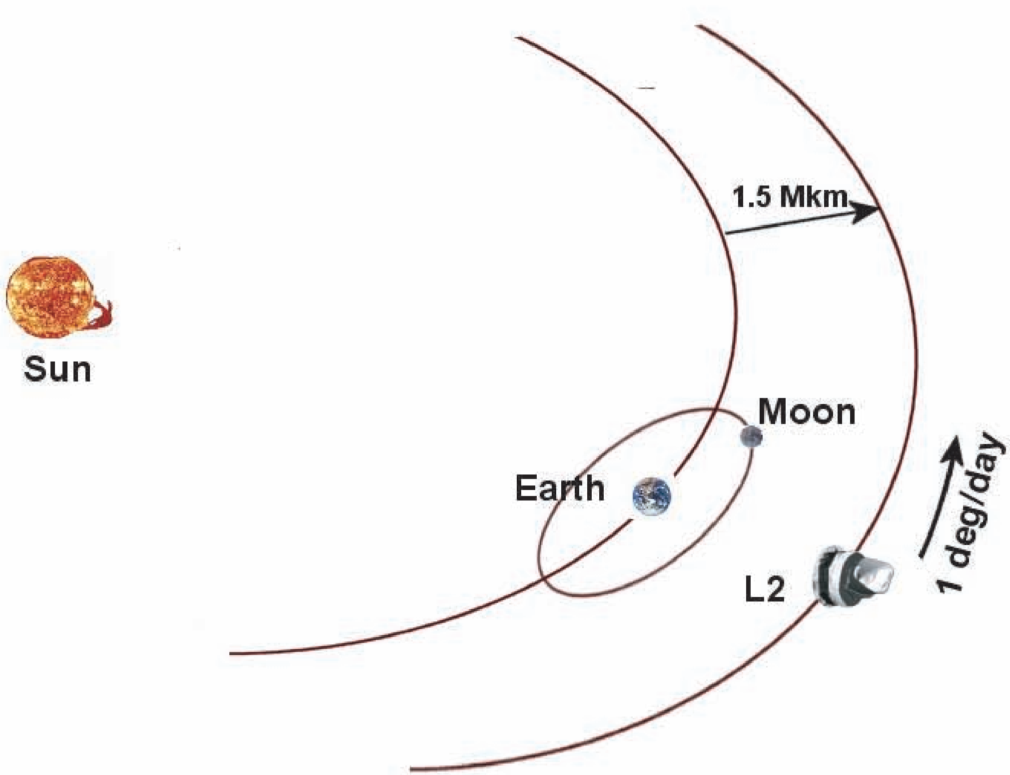
- All components smoothed to 1°
- Sky fractions 81–93% of sky

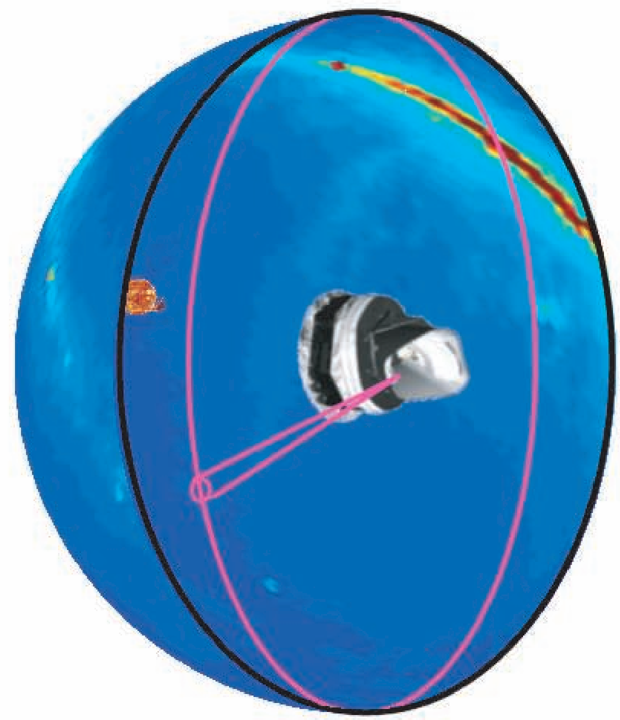
Polarization

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

L_2 Orbit

- Scanned nearly great circles at 1 rpm
- Mapped the sky approximately every six months





2013 and 2015 Data Releases

- 2013
  - "Nominal mission" data: 15.5 months
  - Temperature only
  - 31 papers
- 2015
  - Full mission data: 29 months HFI; 50 months LFI
  - Temperature and polarization
  - 20 (submitted) + 8 (on the way) papers

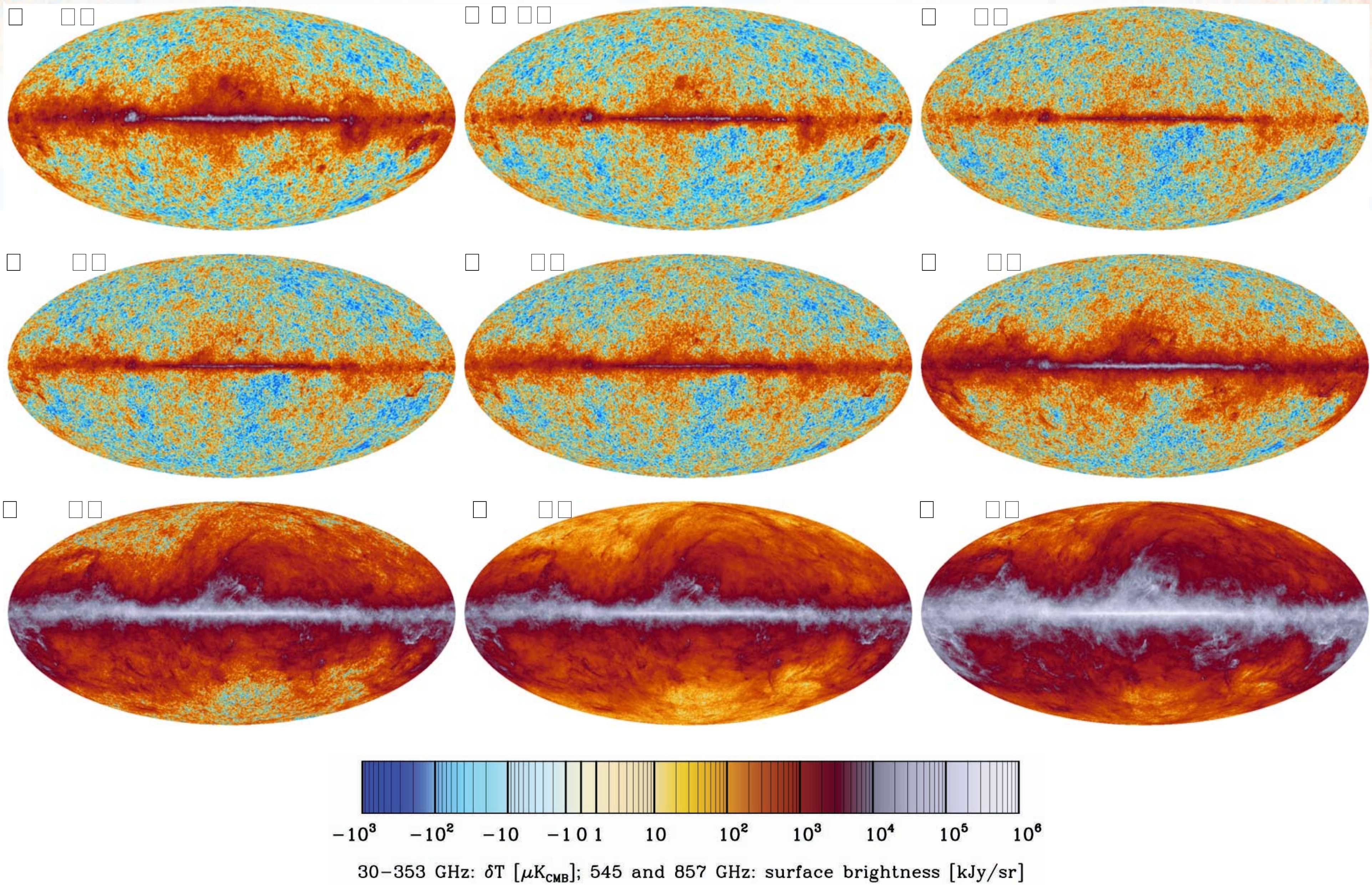
What's Changed?

- More data
  - Lower noise
  - More importantly, more checks on consistency and systematics
- Better beams
- Better calibration
  - Better beams
  - Could use "orbital dipole", rather than WMAP "Solar dipole"
- Polarization

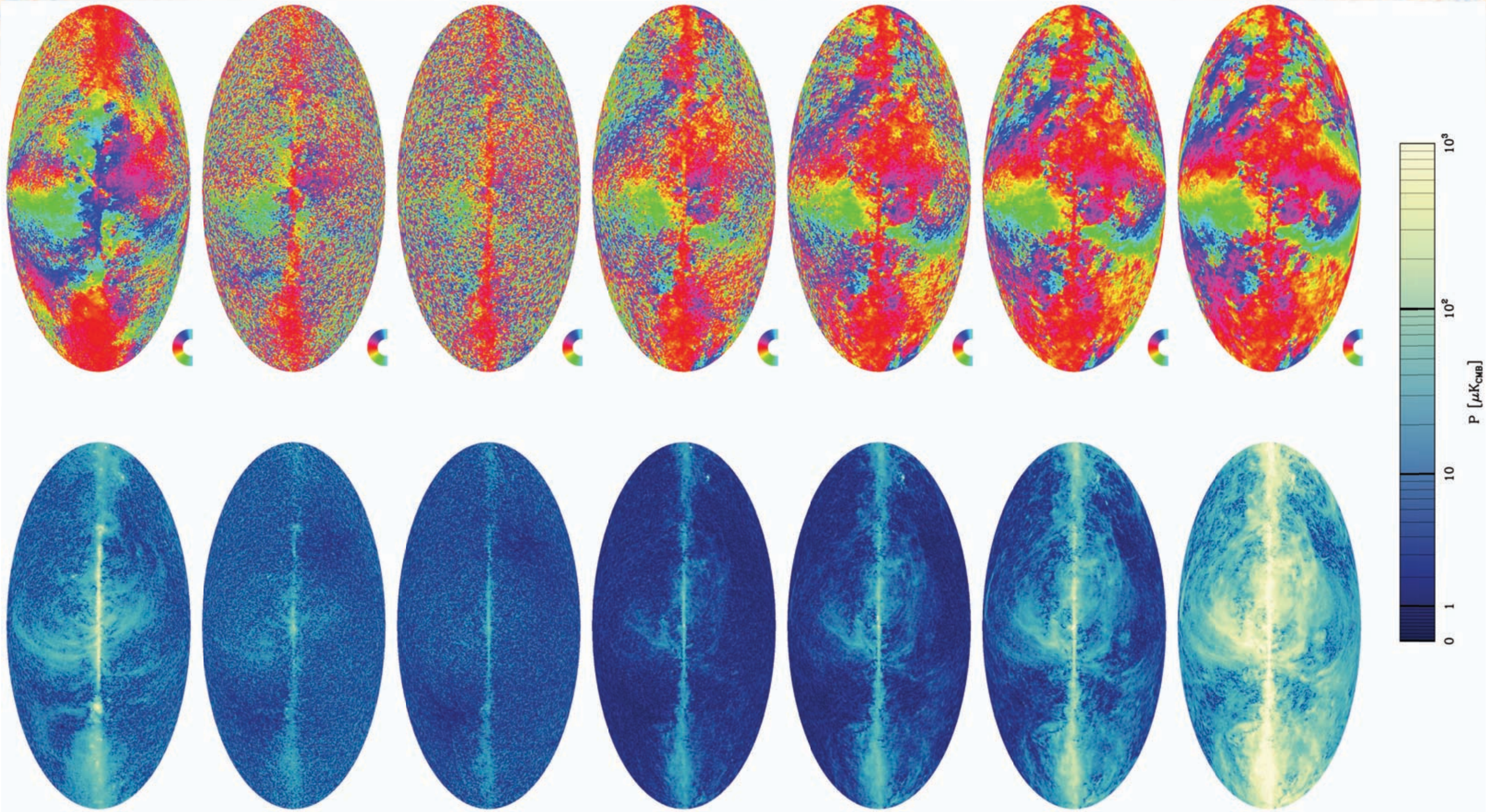
Important note: HFI polarization data on large angular scales still contain systematics that are not fully characterized. Sources known; fixes not completely and self-consistently applied.

- Q and U CMB maps are high-pass filtered: $\ell > 20$, cosine apodization $20 < \ell < 40$
- Time-ordered data not yet released for 100–353 GHz. Summer 2015.
- Low ℓ polarization results, e.g., τ, are based on 70 GHz alone

The Universe: Temperature, Nine Frequencies



Planck Polarization, Seven Frequencies



Component Separation

Two schemes

- For CMB and foreground maps (Used for higher-order statistics, foreground studies)
  - Separate diffuse foregrounds at map level

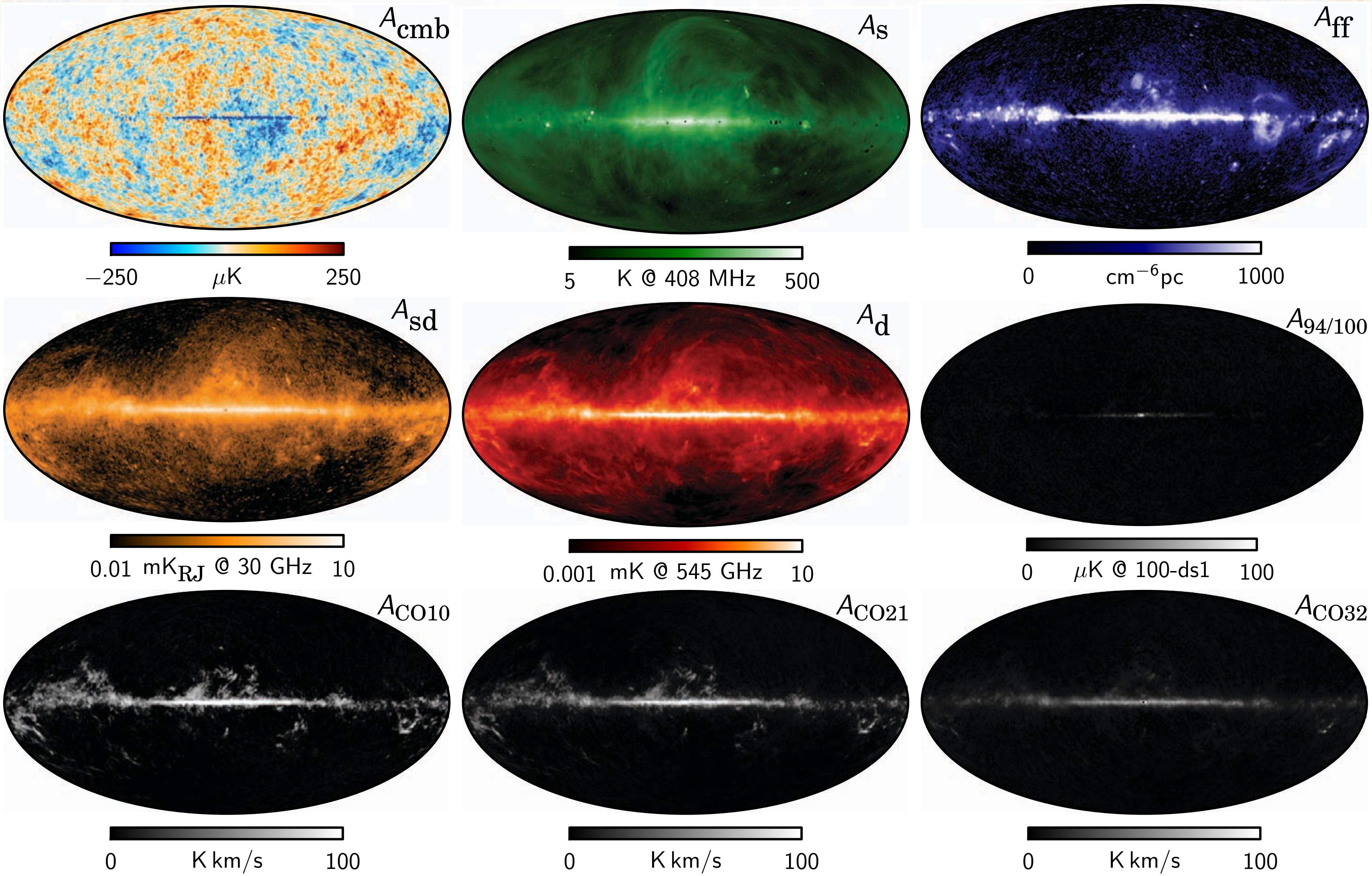
    Commander — parametric model fitting in pixel space

    NILC — needlet (wavelet) internal linear combination

    SEVEM — template fitting in pixel space

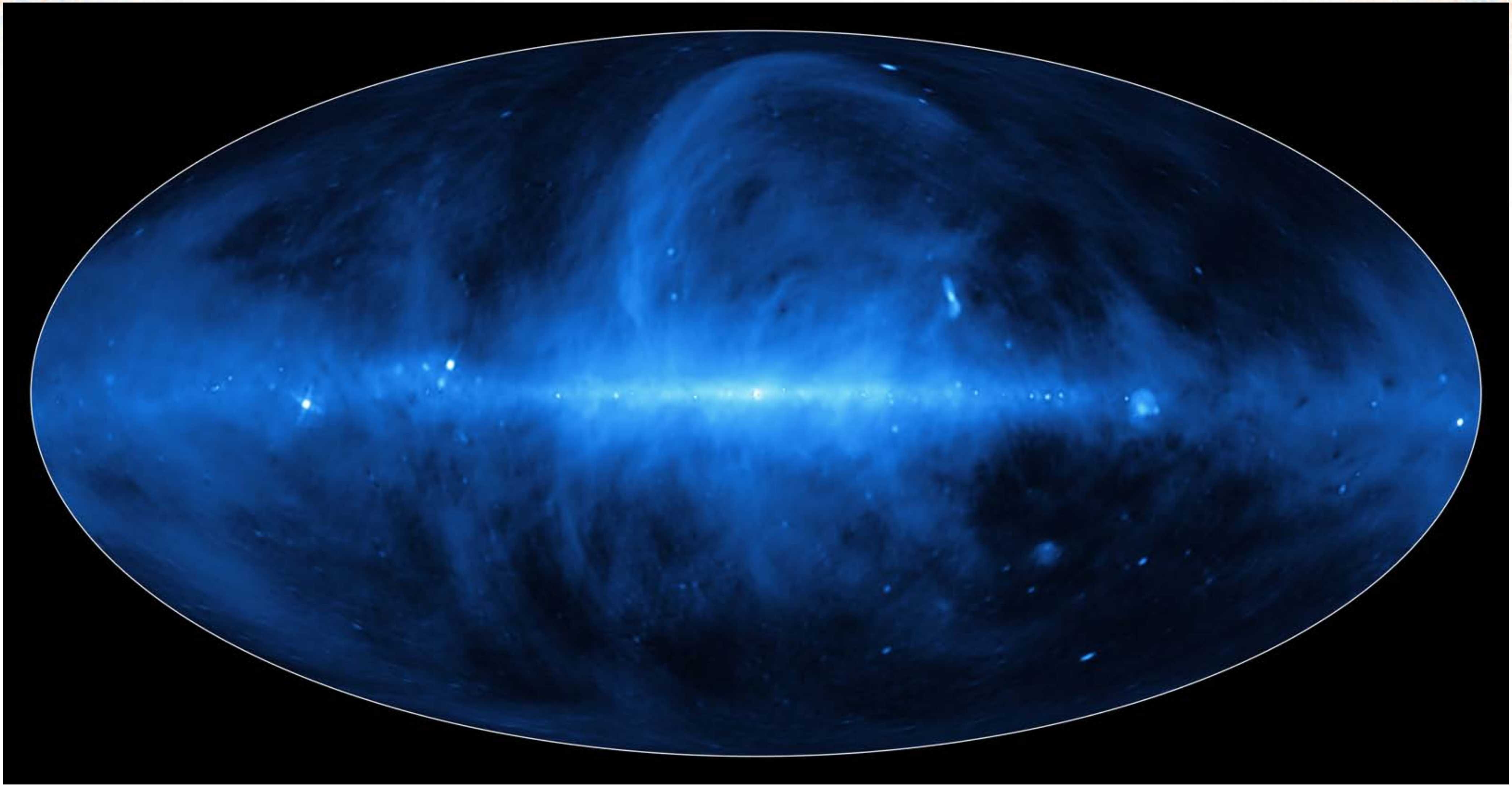
    SMICA — non-parametric (low rank) spectral fitting and filtering
  - Handle "discrete" foregrounds various ways depending on use
- For likelihood and parameters (second-order statistics)
  - Model and subtract both diffuse and discrete foregrounds at the power spectrum level

CMB and Foreground Stokes *I* Maps

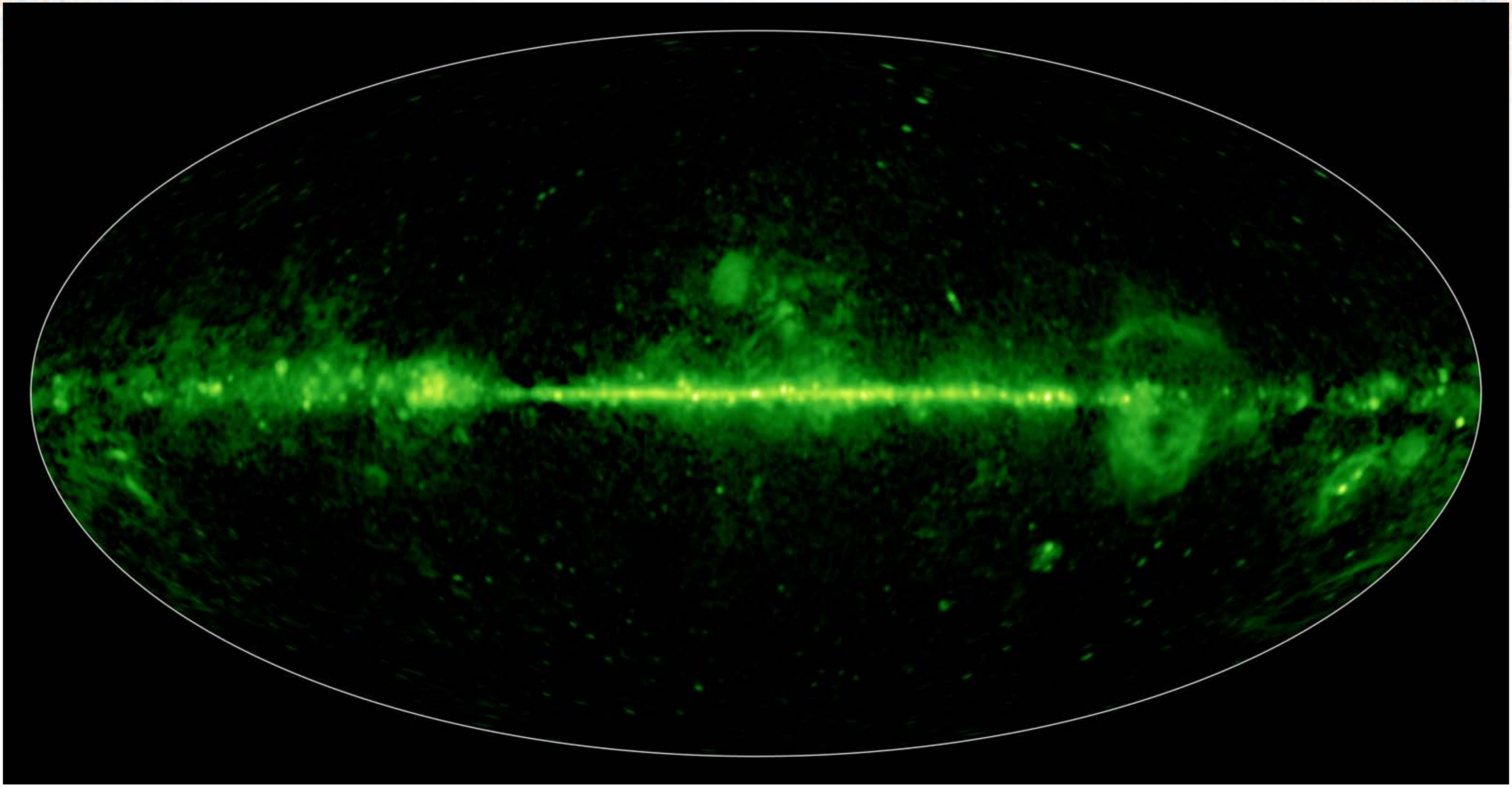


Planck 2015 results. X.

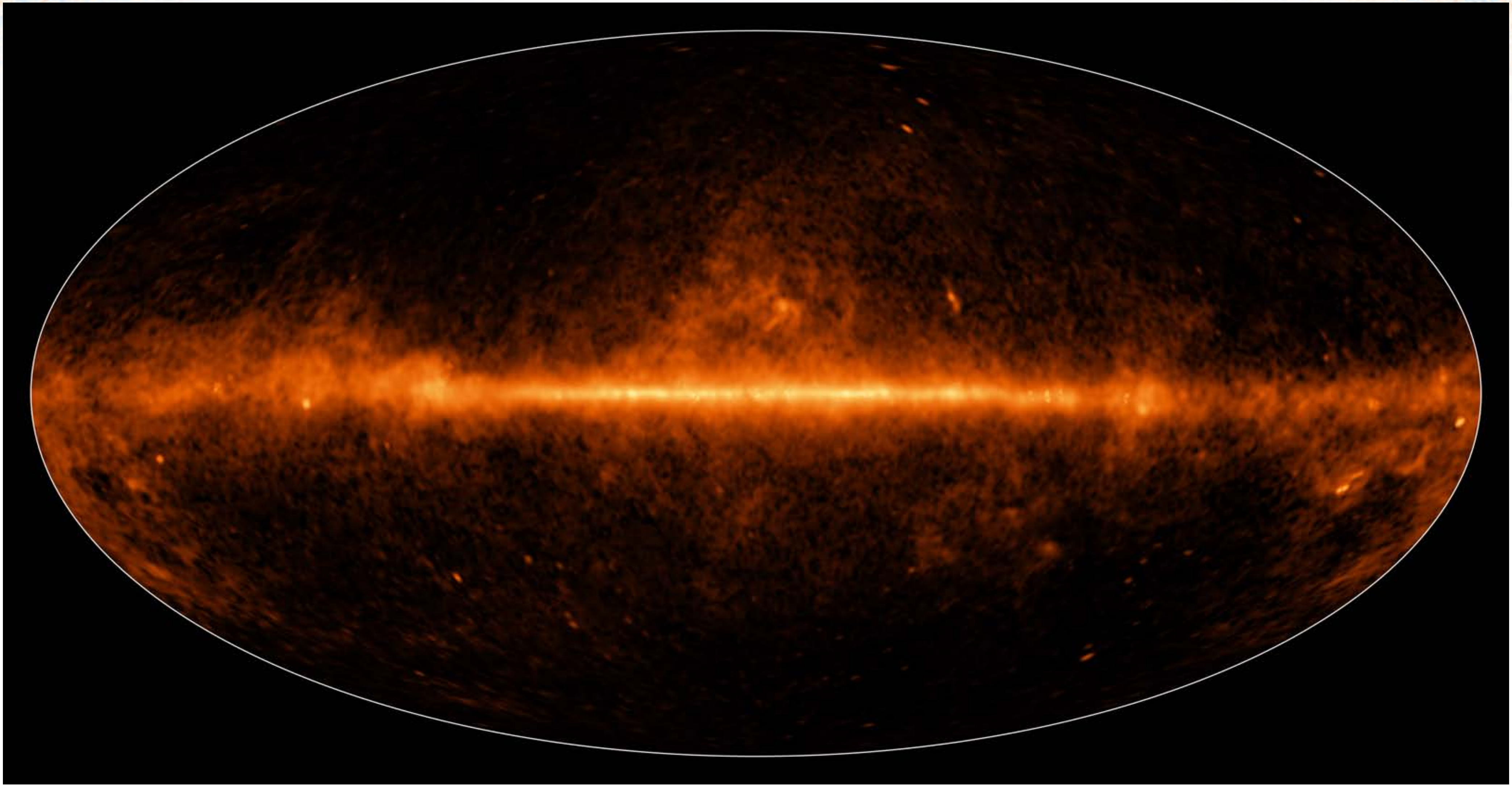
Synchrotron



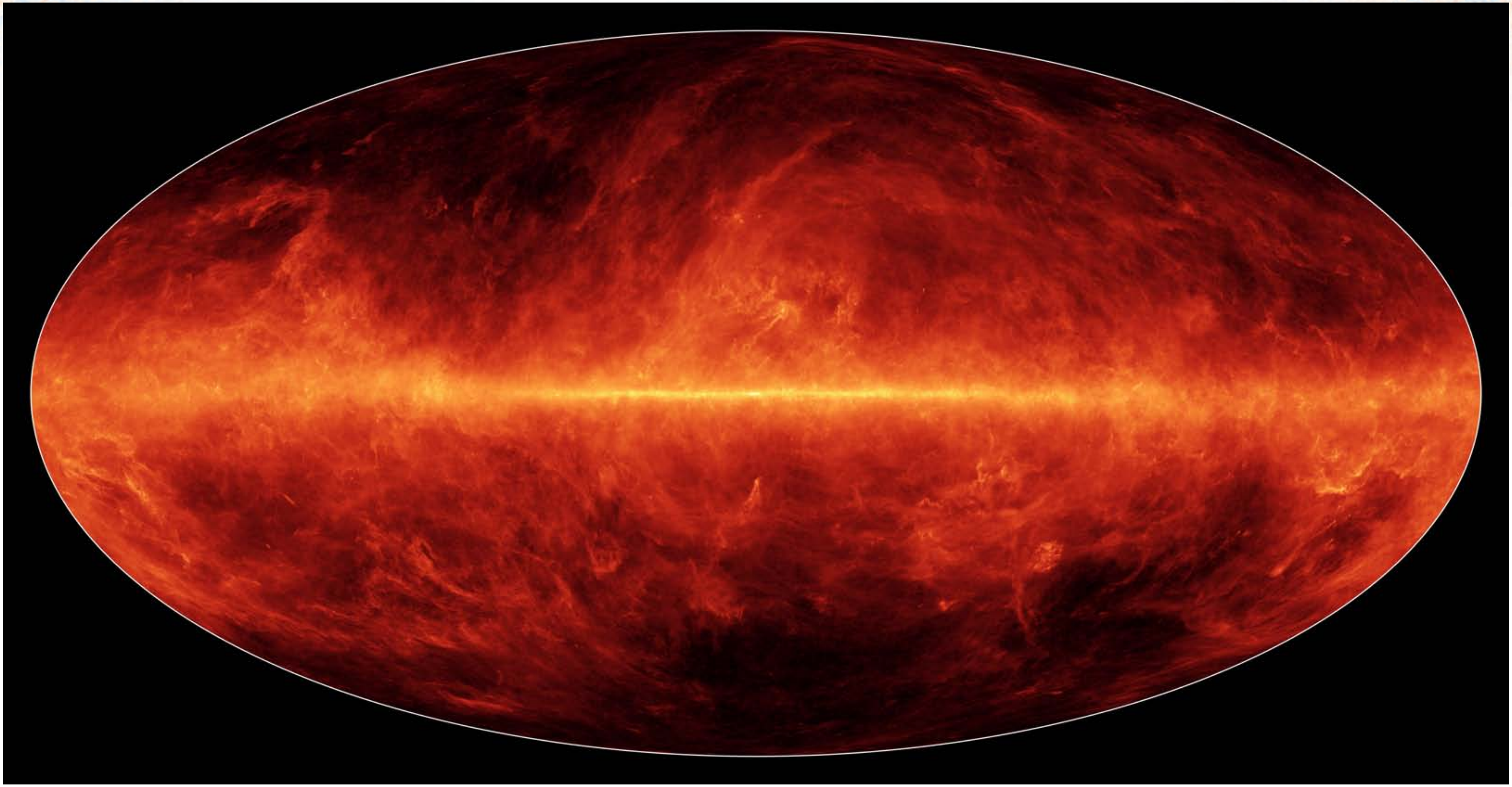
Free-Free



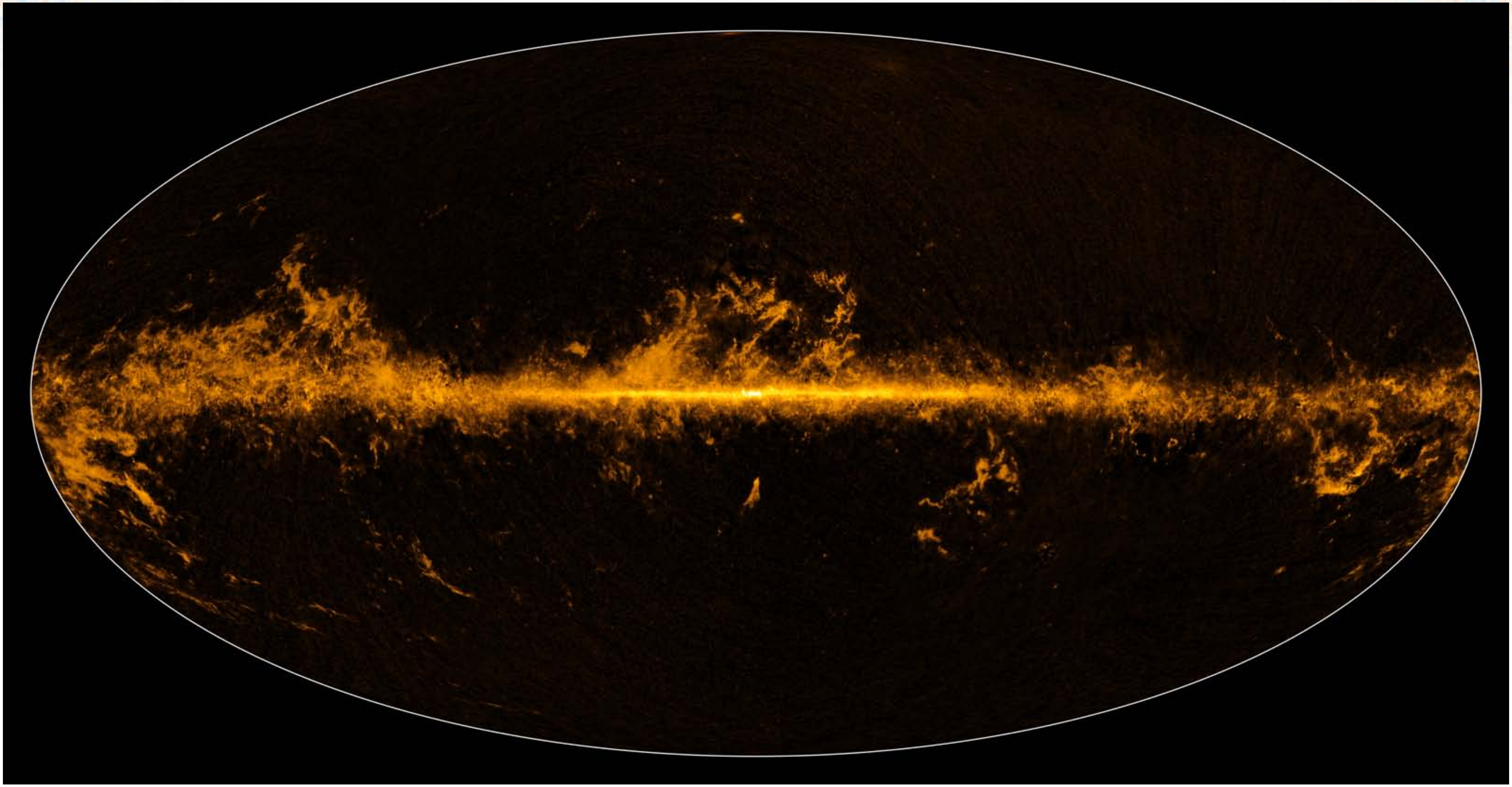
Spinning Dust



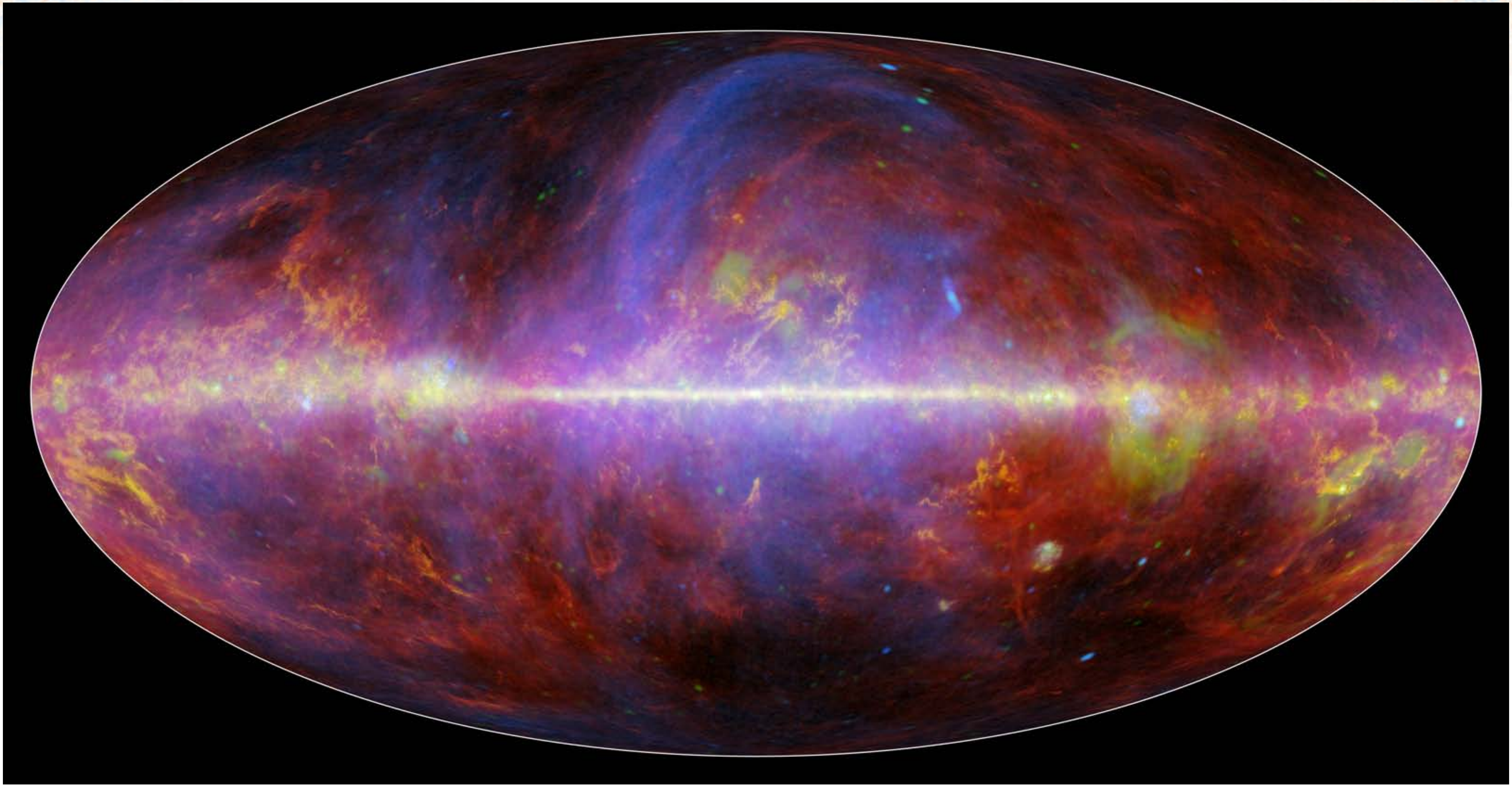
Thermal Dust



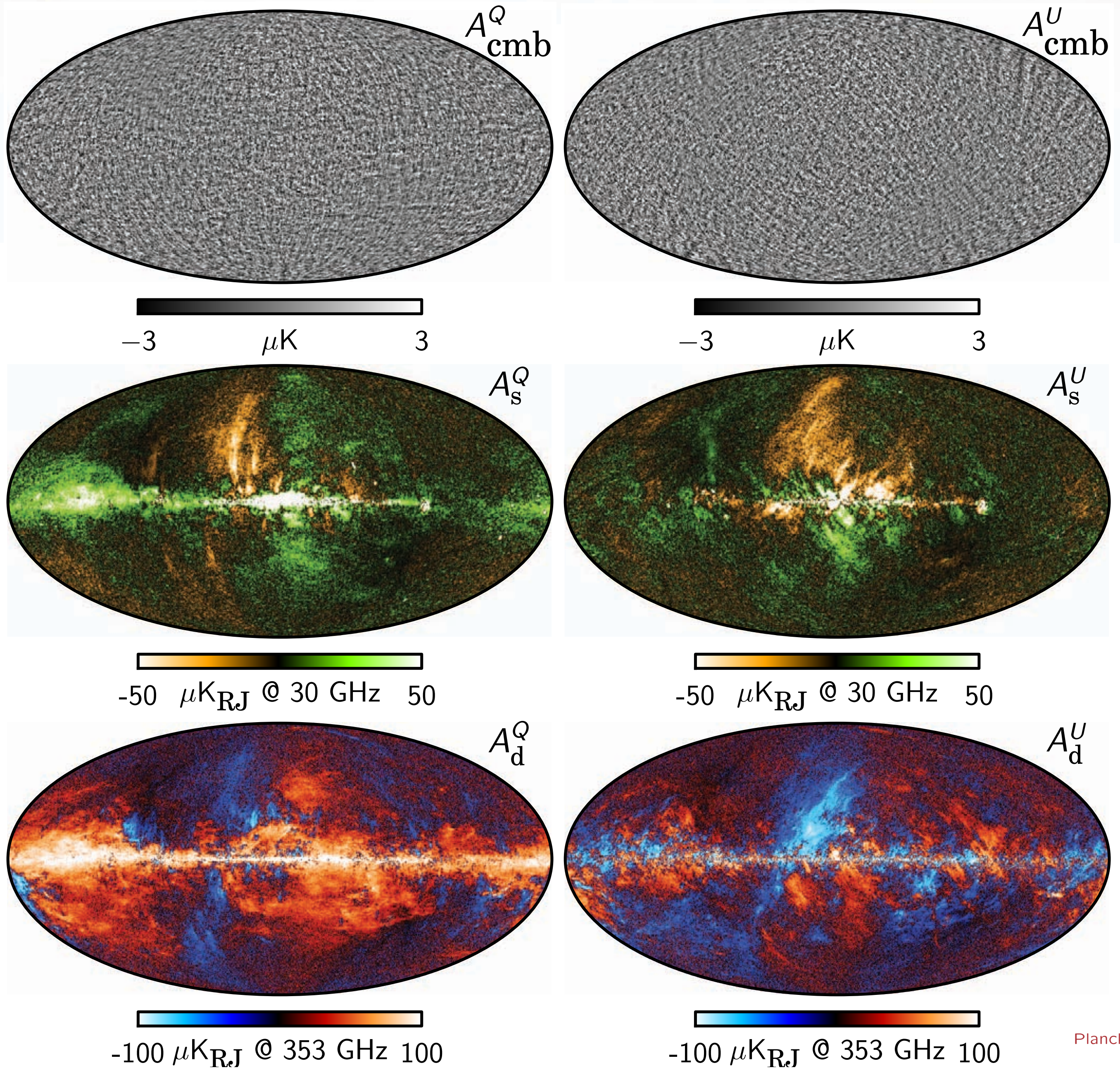
CO



All Together, Color-Coded

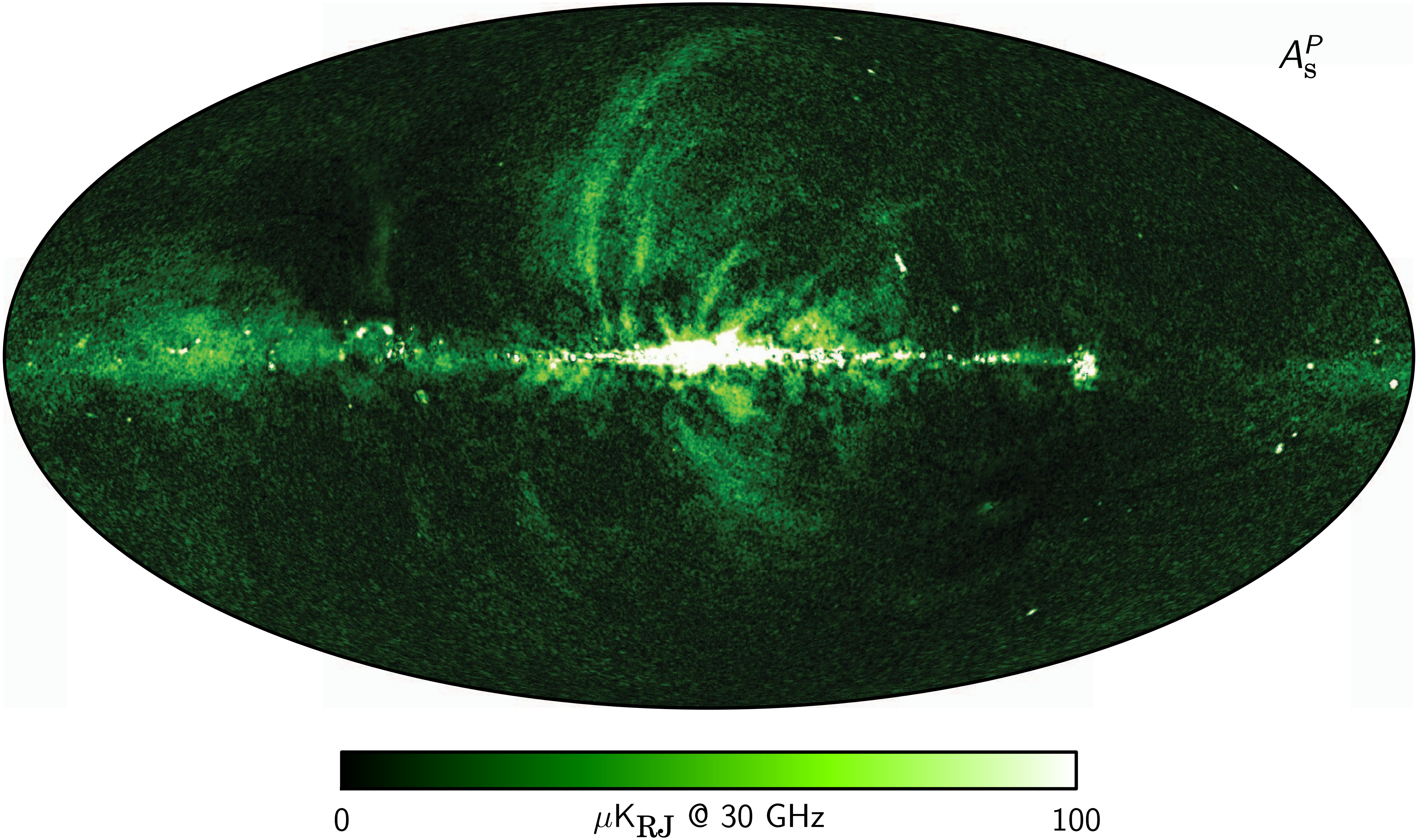


CMB and Foreground Stokes Q, U Maps

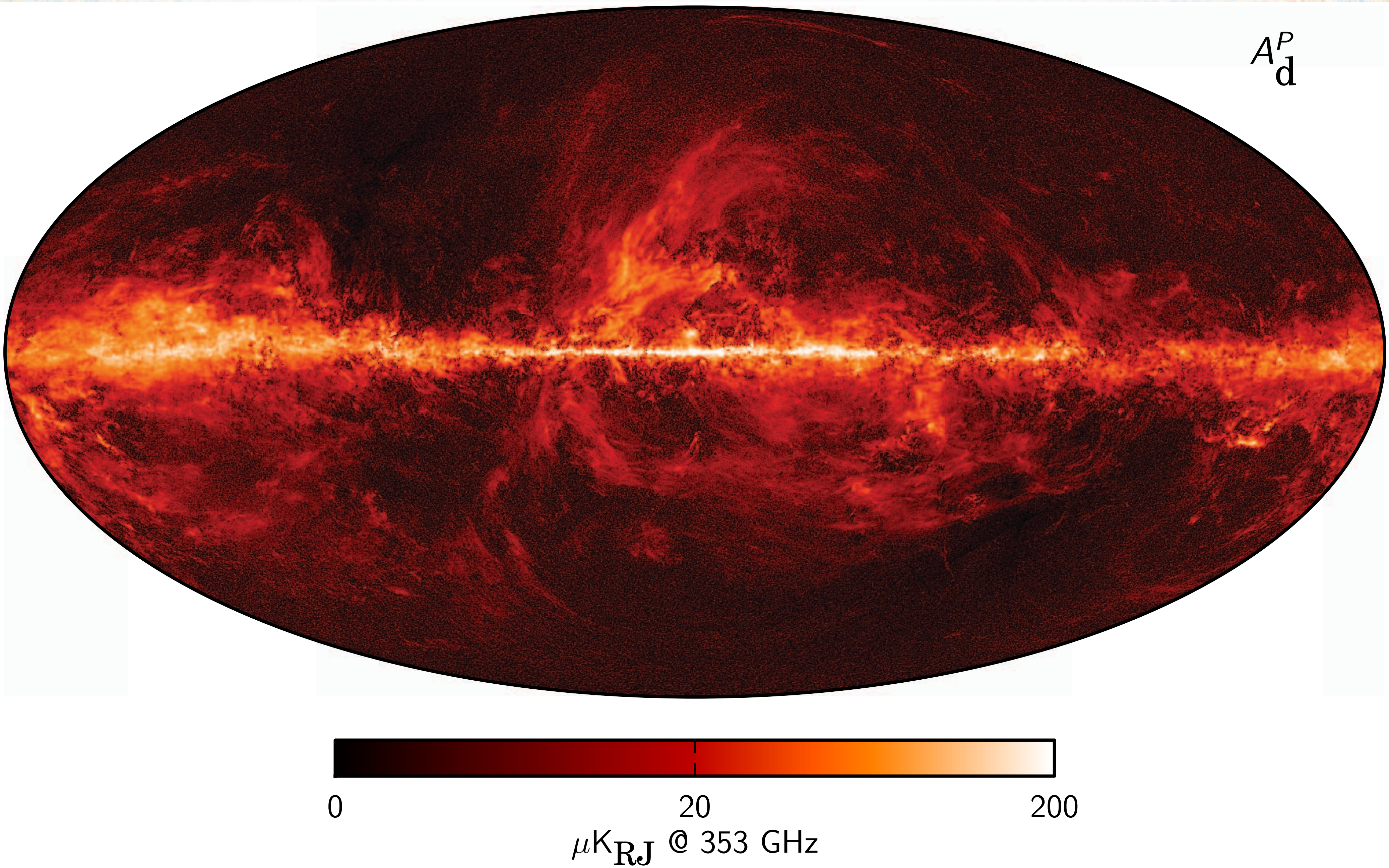


Planck 2015 results. X.

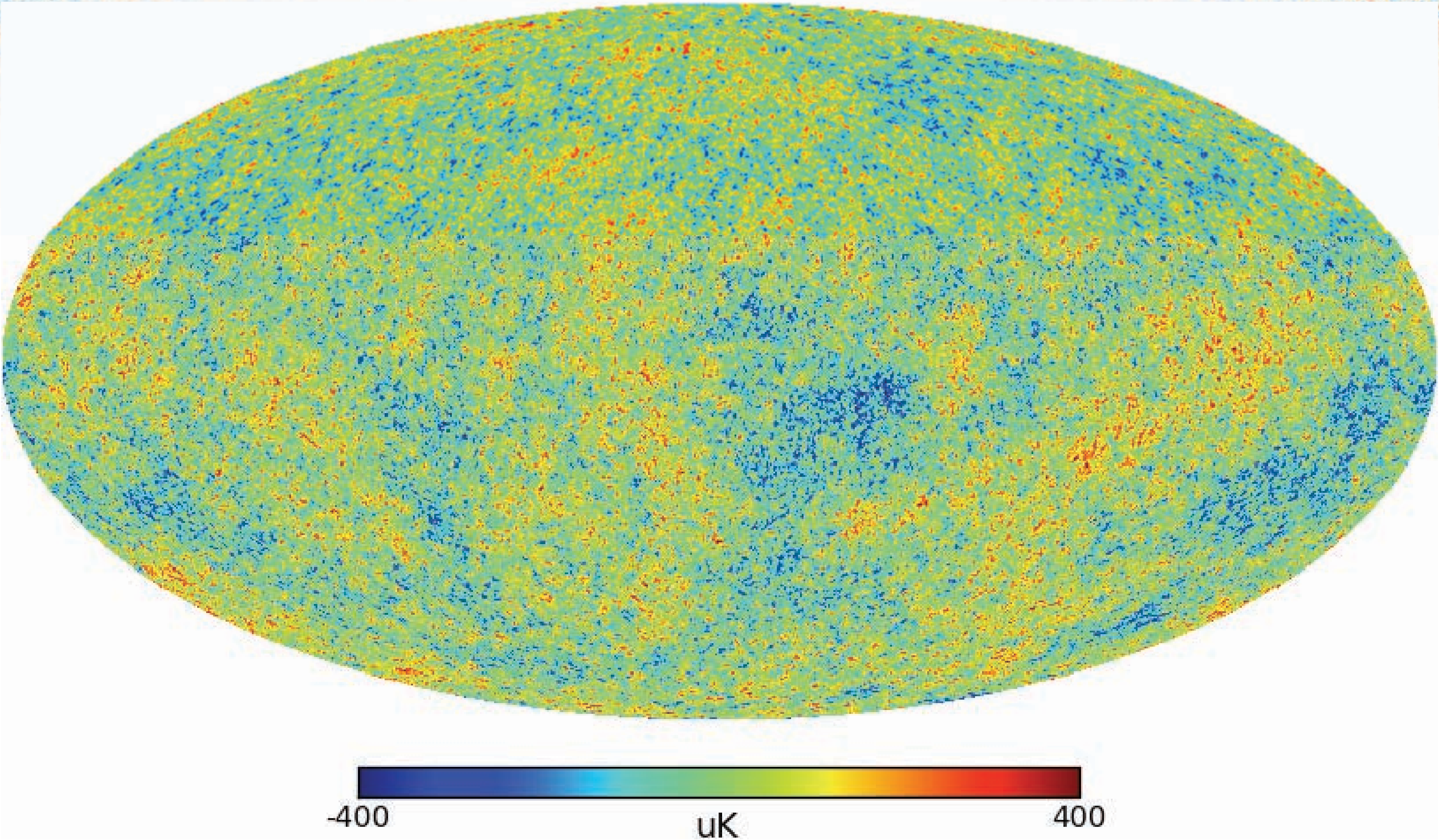
Polarized Synchrotron Emission (30 GHz)



Polarized Dust Emission (353 GHz)



CMB I



(The plane of the Milky Way is filled in with a "constrained realization".)

Six Parameters

A "SIMPLE" 6-PARAMETER ΛCDM MODEL STILL 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.

The Six

1 Density of baryonic matter in the Universe $\Omega_{\rm b}h^2$

2 Density of cold dark matter in the Universe $\Omega_{\rm c}h^2$

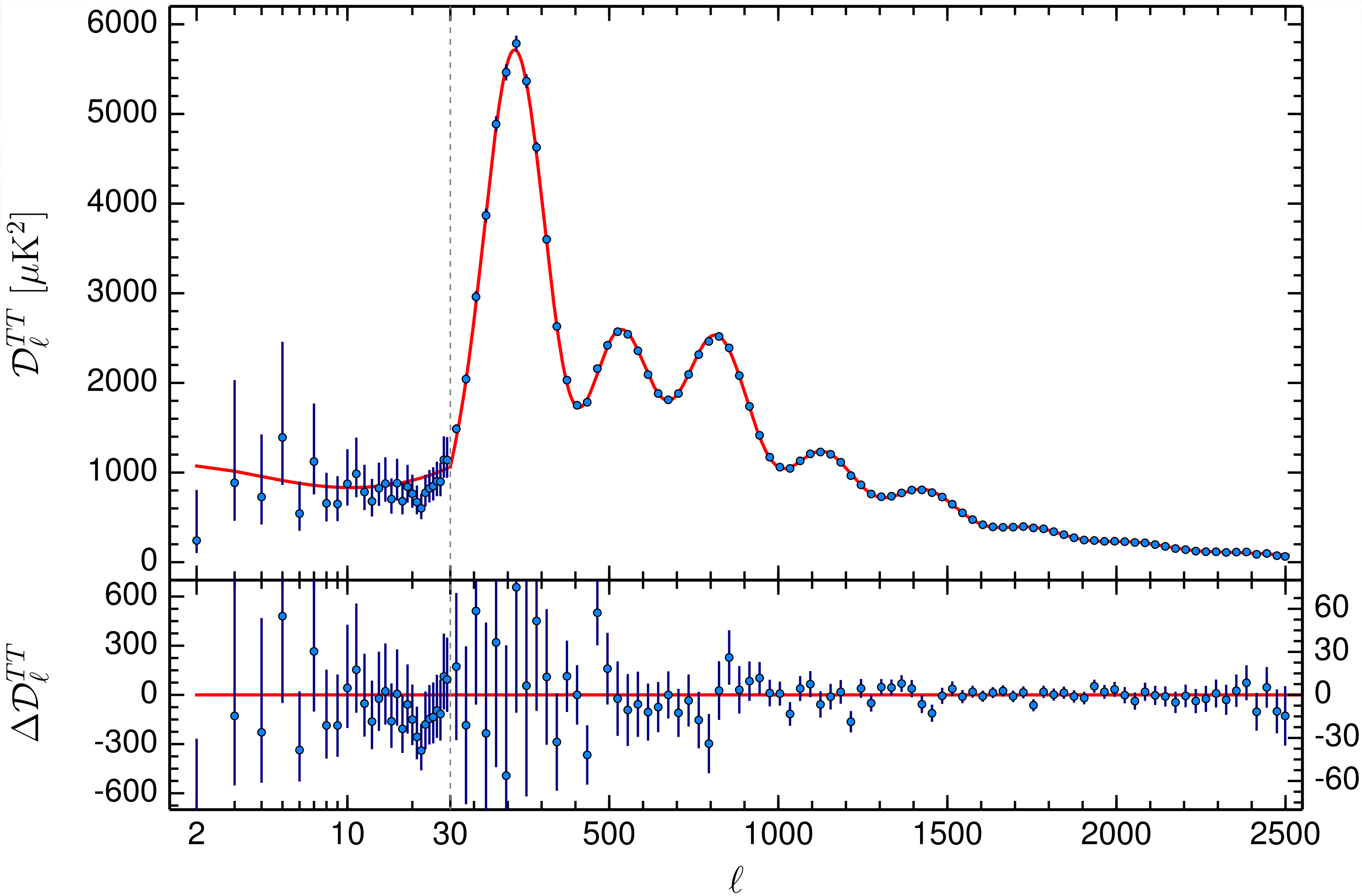
3 Angle subtended by the distance sound travelled in the first 370,000 years after the Big Bang $\theta_{\rm MC}$

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 $A_{\rm s}$

6 Slope of the initial fluctuation spectrum $n_{\rm s}$

Angular Power Spectrum + Best-Fit Model



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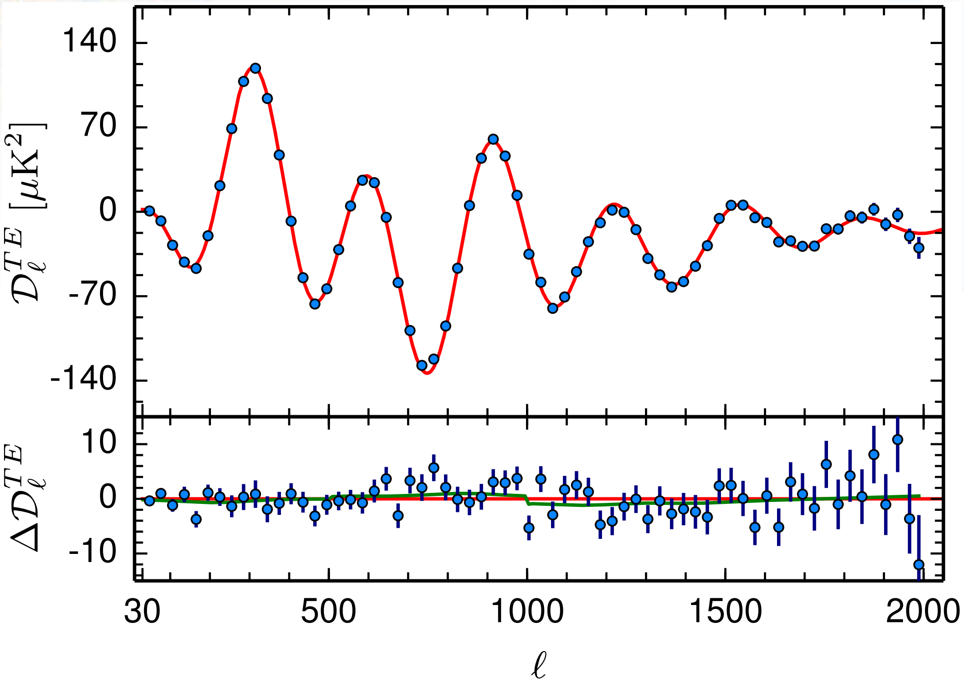
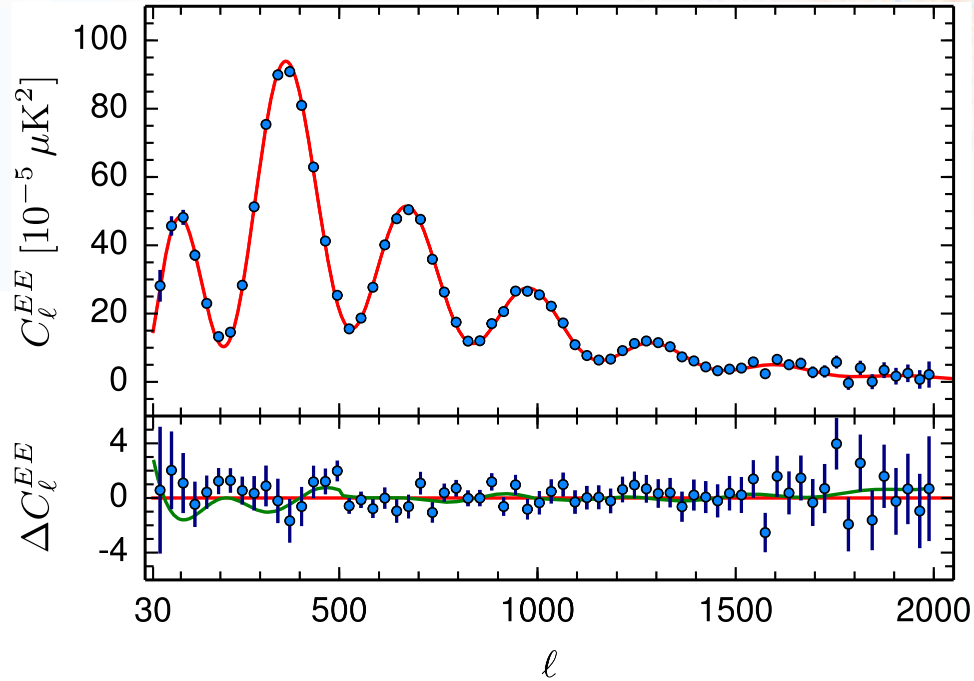
Polarization Spectra, Same Model





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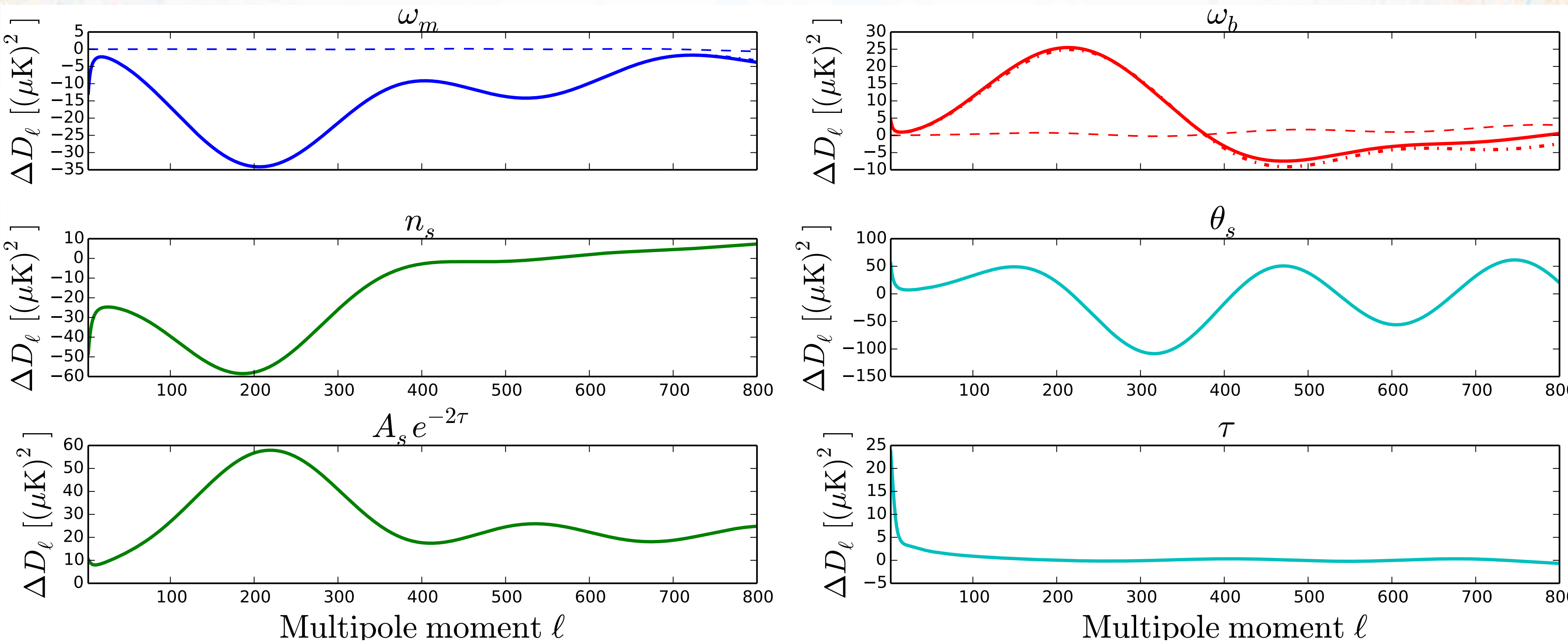
TE

Temperature-polarization cross-spectrum

EE

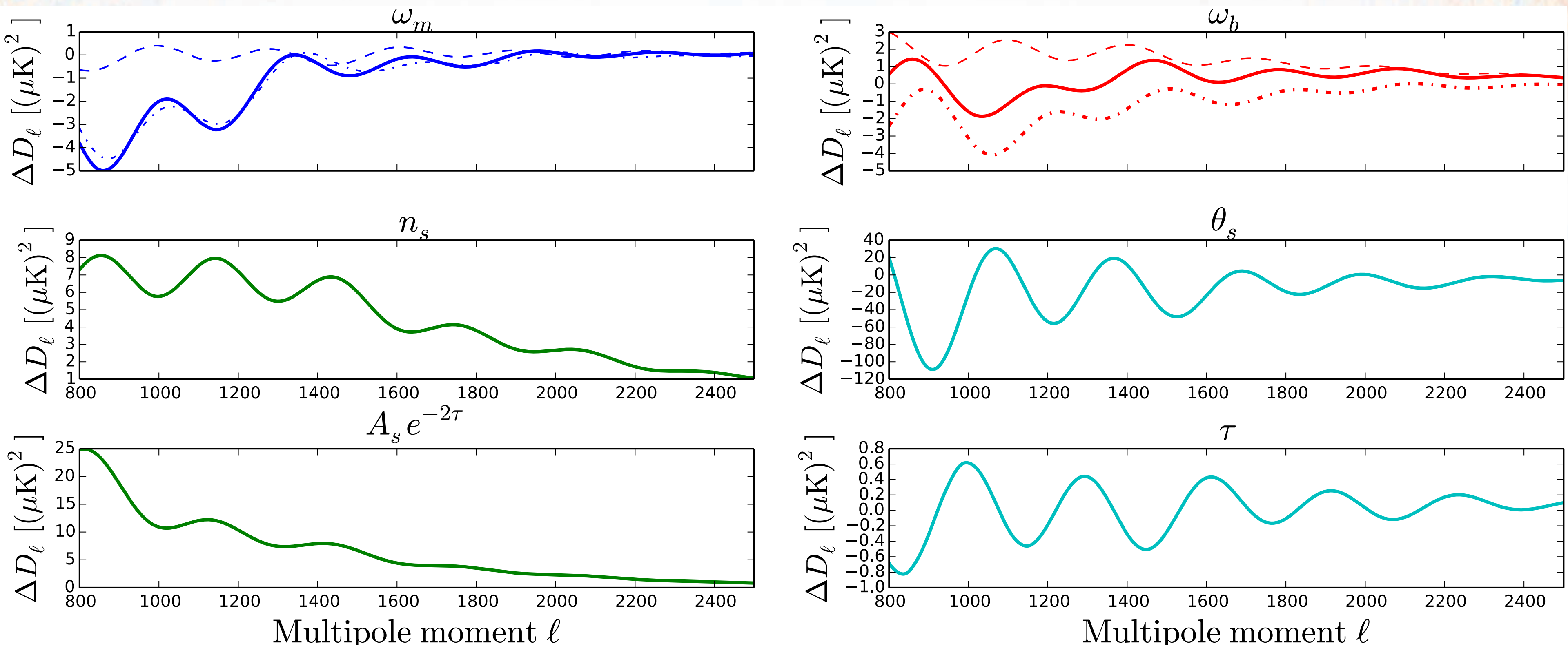
Polarization auto-spectrum

How Parameter Changes Affect the Power Spectrum — I



Response of $\mathcal{D}_\ell^{\mathrm{TT}}$ to 1% increases in ω_{m}, $A_s e^{-2\tau}$, θ_S and ω_{b}, and changes of 0.01 to τ and n_s. All changes are made with the other parameters held fixed. For the matter density, the dashed line shows the contribution of gravitational lensing to the power spectrum change resulting from a 1% increase in ω_{m}. The dot-dashed line is the change that would occur in the absence of lensing. For the baryon density, the dashed line shows the contribution of diffusion damping to the power spectrum change resulting from a 1% increase in ω_{b}. The dot-dashed line is the change that would occur in the absence of diffusion damping.

How Parameter Changes Affect the Power Spectrum — II



Response of $\mathcal{D}_\ell^{\mathrm{TT}}$ to 1% increases in ω_{m}, $A_s e^{-2\tau}$, θ_S and ω_{b}, and changes of 0.01 to τ and n_s. All changes are made with the other parameters held fixed. For the matter density, the dashed line shows the contribution of gravitational lensing to the power spectrum change resulting from a 1% increase in ω_{m}. The dot-dashed line is the change that would occur in the absence of lensing. For the baryon density, the dashed line shows the contribution of diffusion damping to the power spectrum change resulting from a 1% increase in ω_{b}. The dot-dashed line is the change that would occur in the absence of diffusion damping.

Changes in ΛCDM Model Parameters, 2013 $\longrightarrow$ 2015

- Typical uncertainty reduced by more than 25%.
- Photometric calibration, now on orbital dipole, increased by 0.8%.
  - Uncertainty 0.05%. Excellent agreement between WMAP, LFI, & HFI!
- τ (reionization optical depth) lower by $\sim 1\sigma$ (so z_{re} decreased $\sim 1\sigma$)
  - $\tau = 0.066 \pm 0.016$; $\quad z_{\mathrm{re}} = 8.8^{+1.7}_{-1.4}$
  - In good agreement with those inferred from WMAP9 polarization data cleaned for polarized dust emission with 353 GHz maps.
  - But calibration increased power, so σ_8 hardly changed
- n_{s} increased by $\sim 0.7\sigma$
- $\Omega_{\mathrm{b}}h^2$ increased by $\sim 0.6\sigma$ and error decreased.
- Limits on isocurvature modes, Ω_{K}, m_ν, ΔN_{eff}, f_{NL}, DM annihilation, etc., all tighter. No deviations detected.

ΛCDM Model Parameters

Parameter	TT, TE, EE + lowP + lensing + ext	N_σ
$\Omega_b h^2 [18.79\,\mathrm{yg\,m^{-3}}]$	0.02230 ± 0.00014	159
$\Omega_c h^2 [18.79\,\mathrm{yg\,m^{-3}}]$	0.1188 ± 0.0010	119
$100\theta_{\mathrm{MC}}$	1.04093 ± 0.00030	3470
τ	0.066 ± 0.012	5.5
$\ln(10^{10} A_s)$	3.064 ± 0.023	133
n_s	0.9667 ± 0.0040	242
$H_0 [\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	67.74 ± 0.46	147
Ω_m	0.3089 ± 0.0062	50
$z_{\mathrm{reionization}}$	8.8 ± 1.2	7
$z_{\mathrm{recombination}}$	1089.90 ± 0.23	4740
Age[Gyr]......................	13.799 ± 0.021	657

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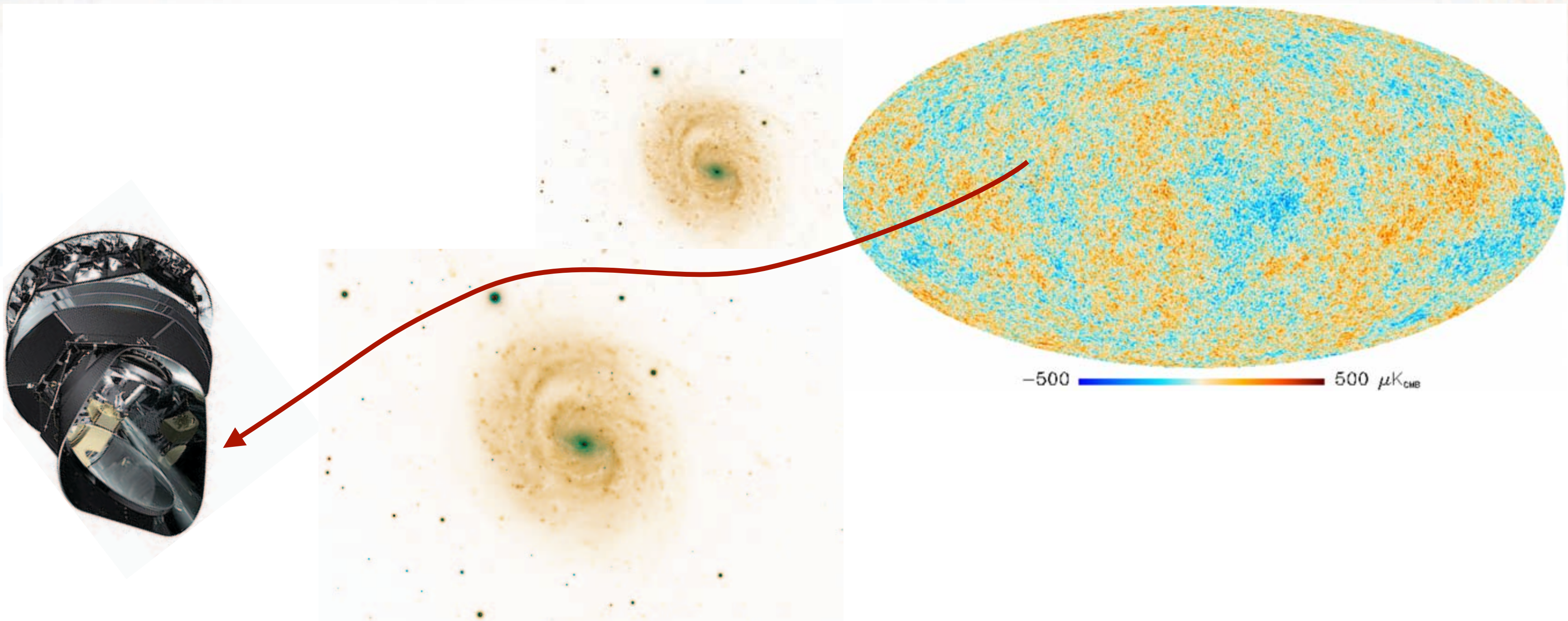
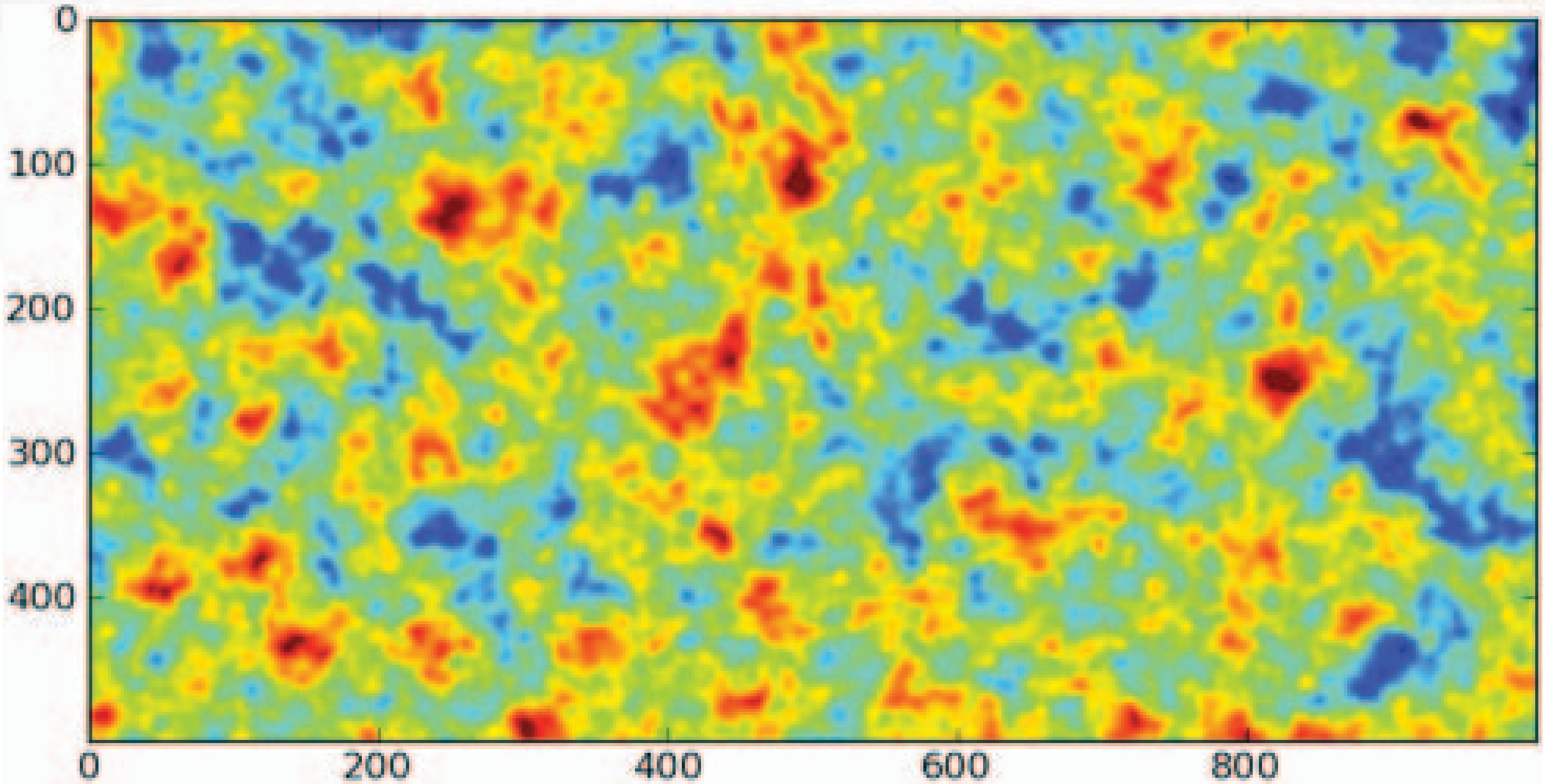
68% confidence limits

CMB Lensing 1



- Deflection of light by matter is well-observed in astronomy
- CMB is the most distant "source," with a precisely known redshift

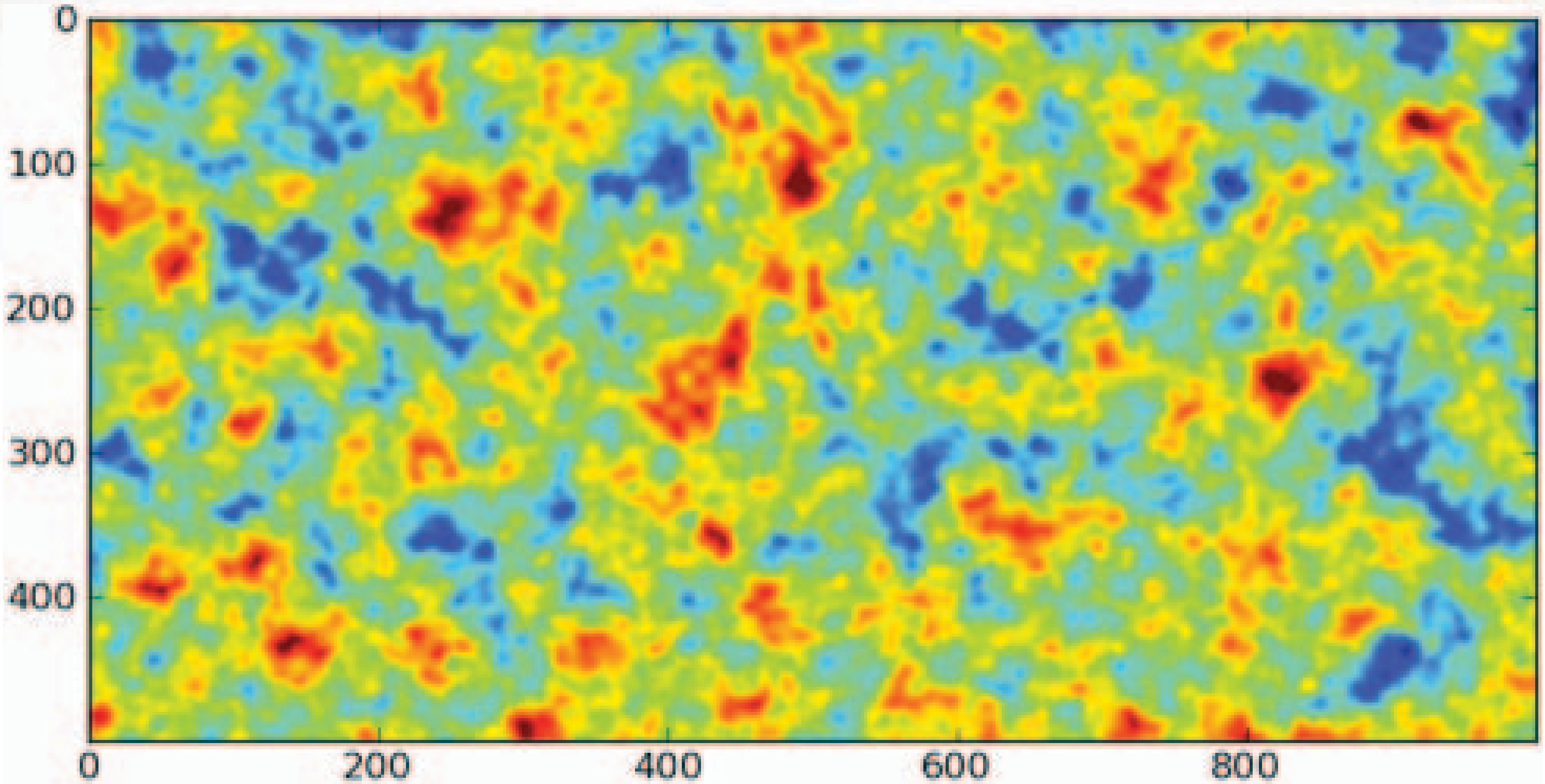
Simulation: Unlensed



Simulated patch 10° wide

- RMS of deflection angle is $\sim 2\overset{\prime}{.}5$
- Coherent on degree scales

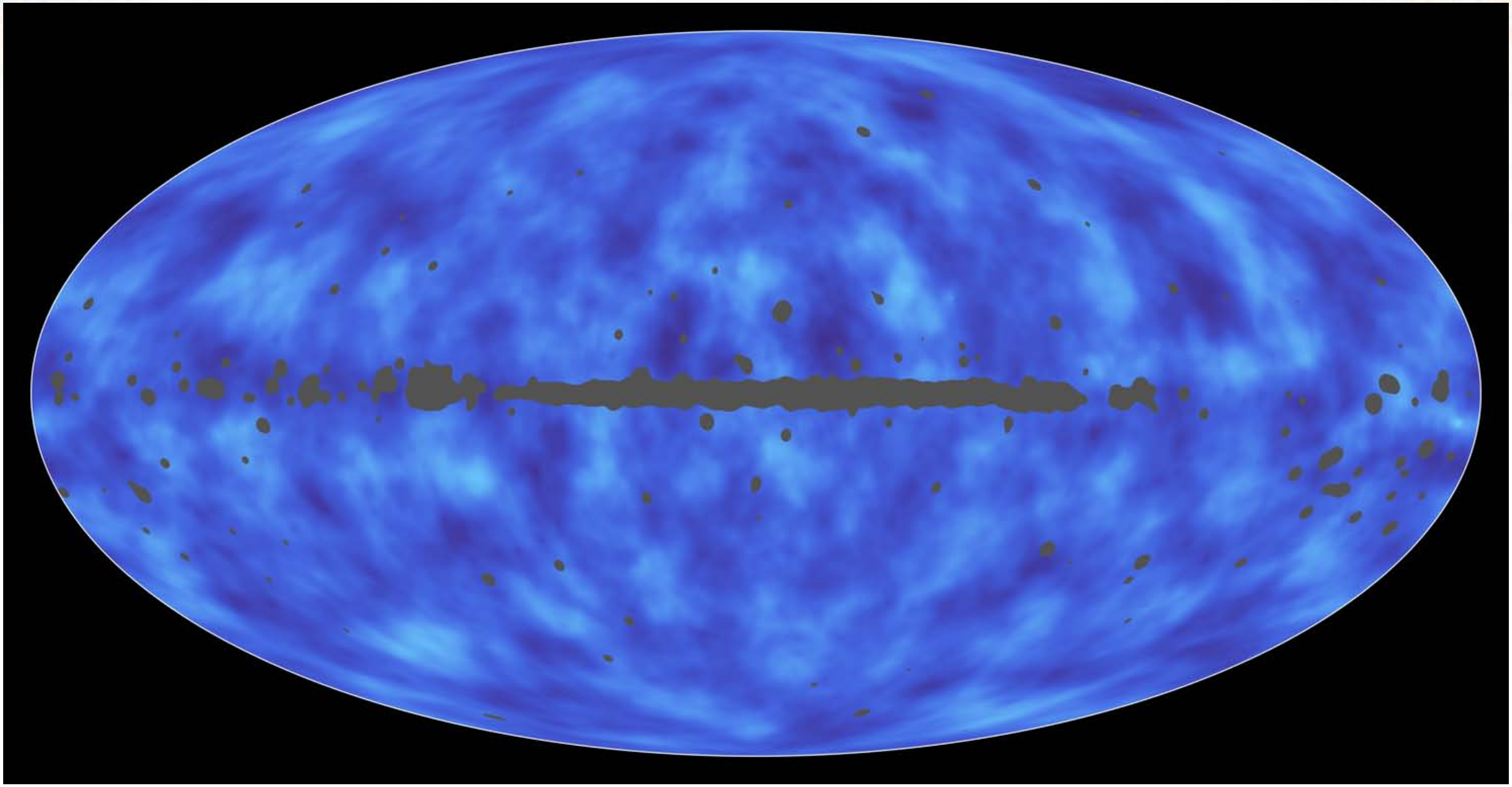
Simulation: Lensed



Simulated patch 10° wide

- RMS of deflection angle is $\sim 2\overset{\prime}{.}5$
- Coherent on degree scales

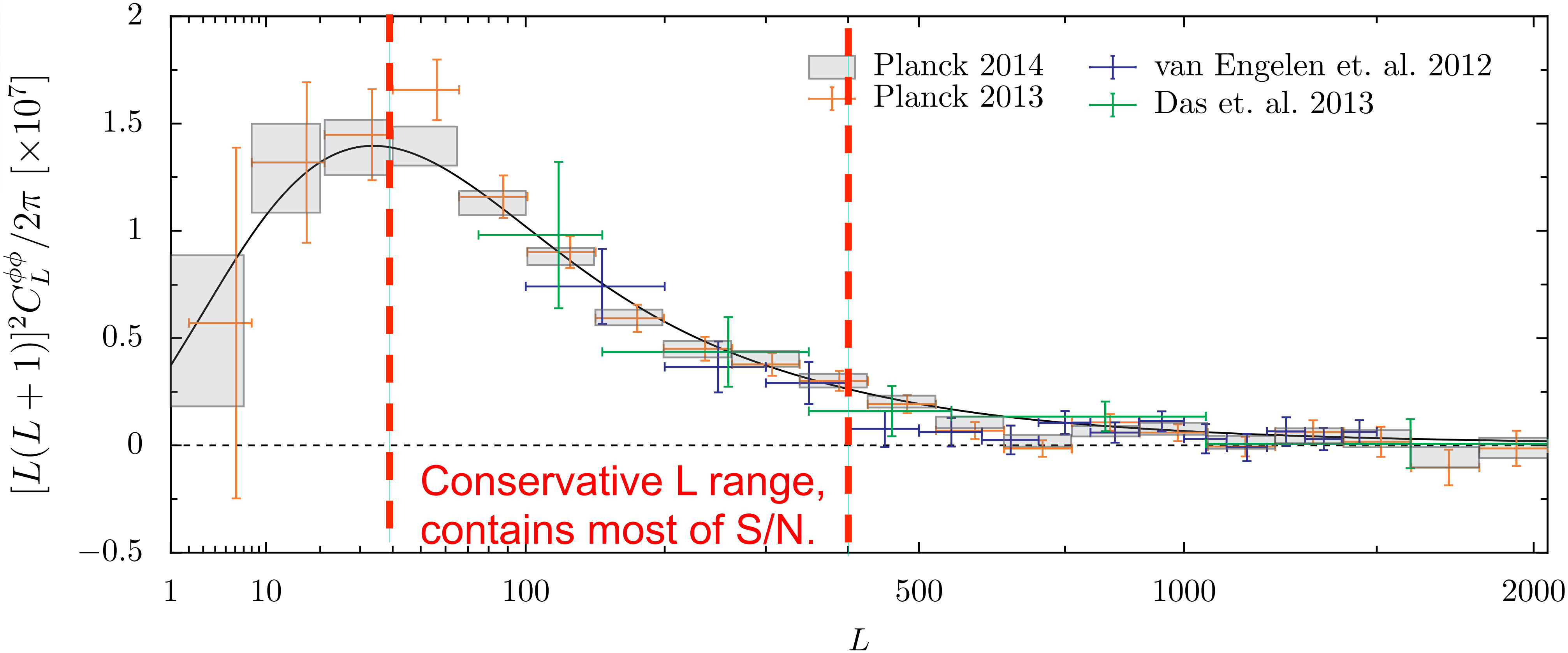
Lensing Potential — All the Mass in the Universe



Planck 2015 results. XV.

- Lensing now measured at 40σ. Better than predicted by anisotropy!

Lensing Spectrum



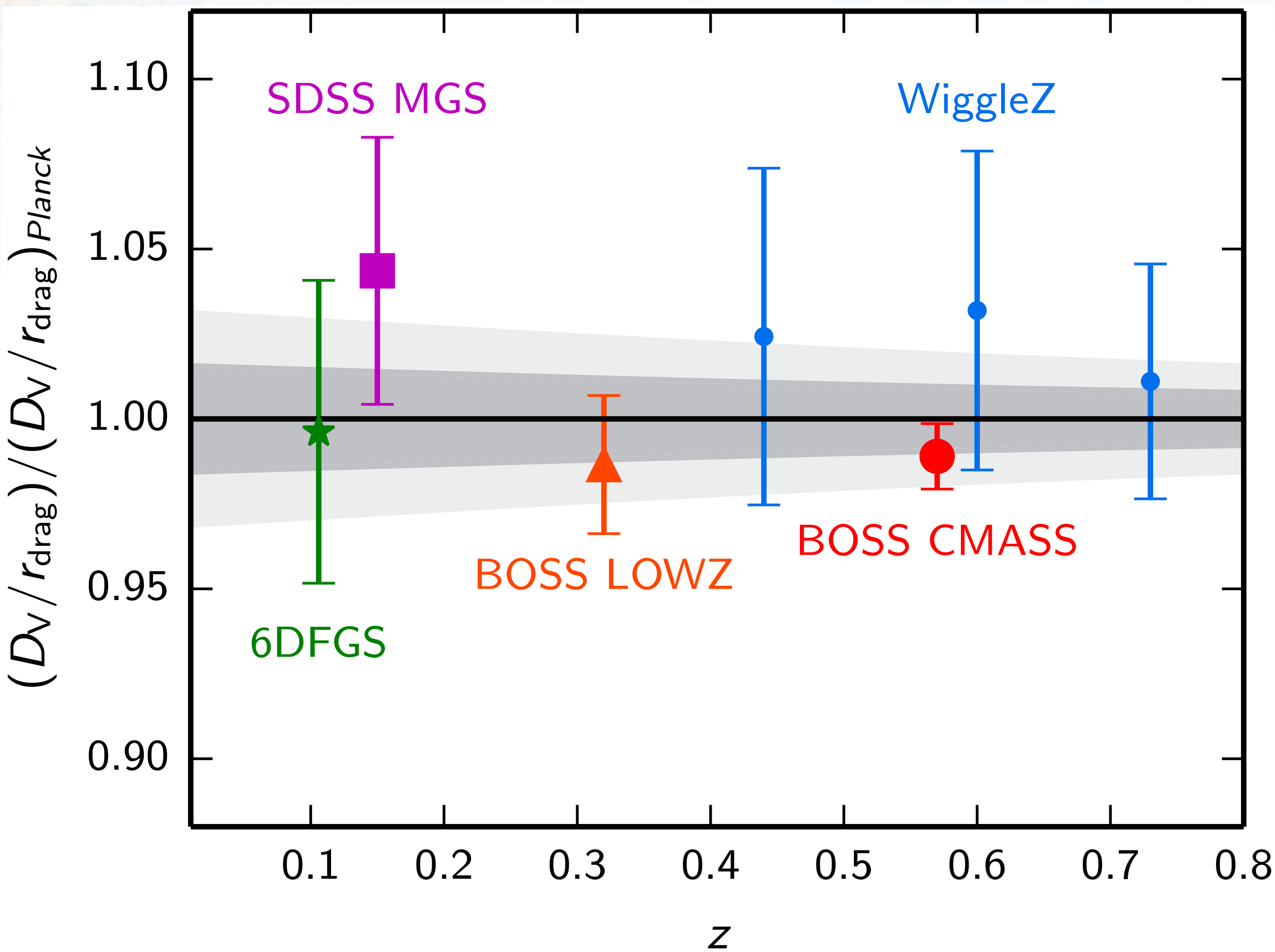
Planck 2015 results. XV.

- Constrains $\sigma_8 \Omega_{\mathrm{M}}^{1/4}$ to 3.5%!

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

Distance Scale Comparison: Baryon Acoustic Oscillations



- Acoustic oscillations at $z \sim 1100$ and $z < 1$ tell the same story about the distance scale: ΛCDM!

$D_V(z)/r_s$ is the acoustic-scale distance ratio

$r_s =$ 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

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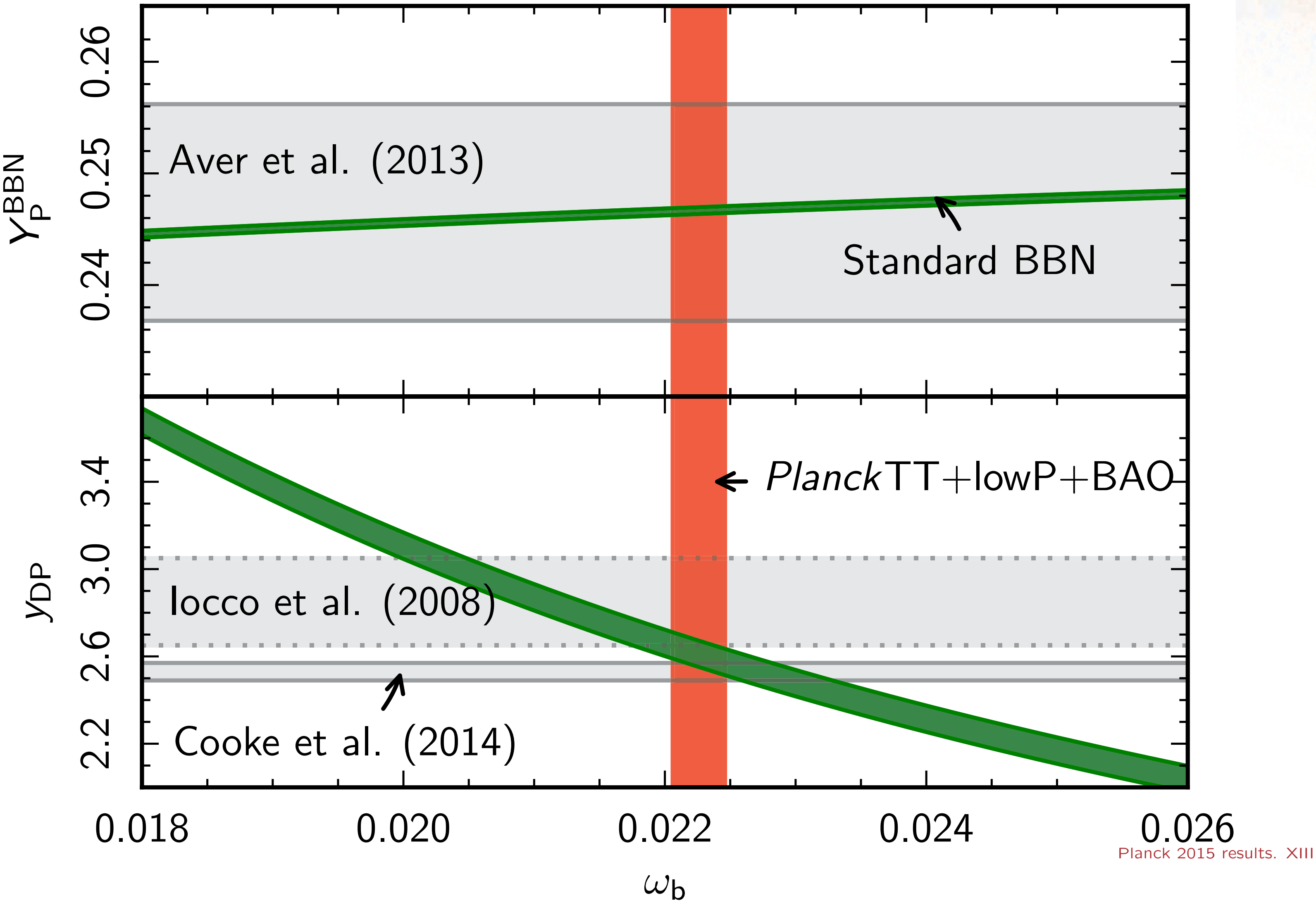
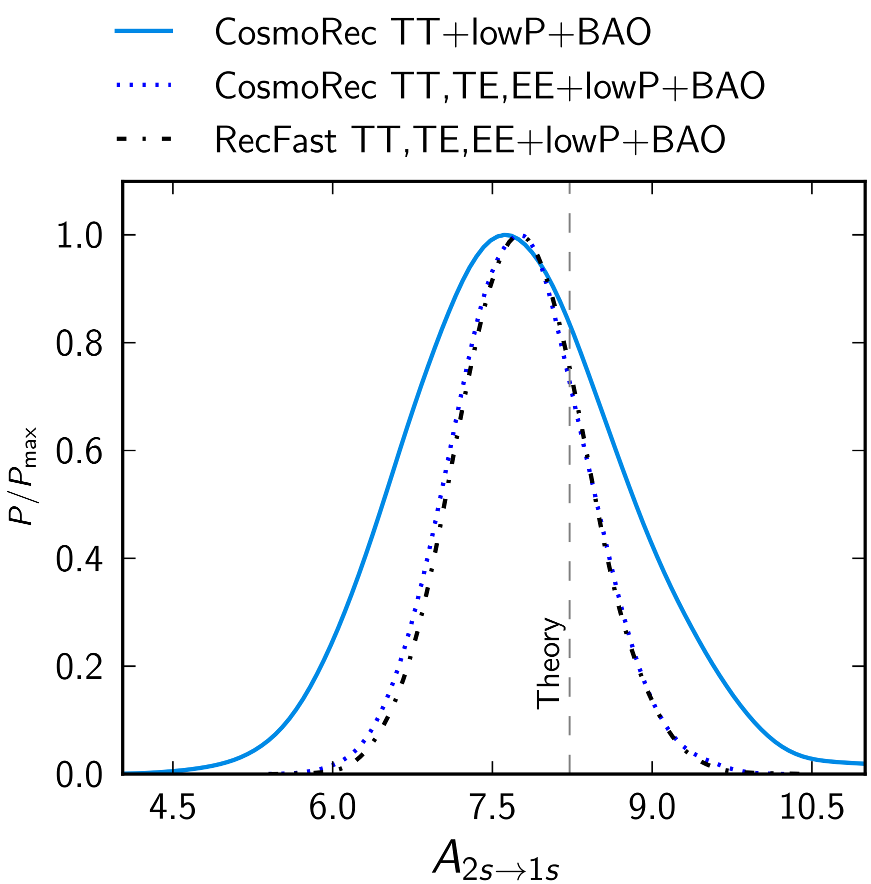
Big Bang Nucleosynthesis



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 significan lepton asymmetry.

Hydrogen $2s \rightarrow 1s$ Transition Rate

- Hydrogen $2s \rightarrow 1s$ two-photon rate crucial for recombination dynamics
- Best lab measurement has 43% uncertainty
- Planck data directly constrain its value



- $A_{2s\rightarrow 1s} = 7.75 \pm 0.61\,\mathrm{s}^{-1}$

  Planck TT, TE, EE + lowP + BAO

  8% uncertainty

- Planck measurement in excellent agreement with theoretical value

  $A^{\mathrm{theory}}_{2s\rightarrow 1s} = 8.2206\,\mathrm{s}^{-1}$

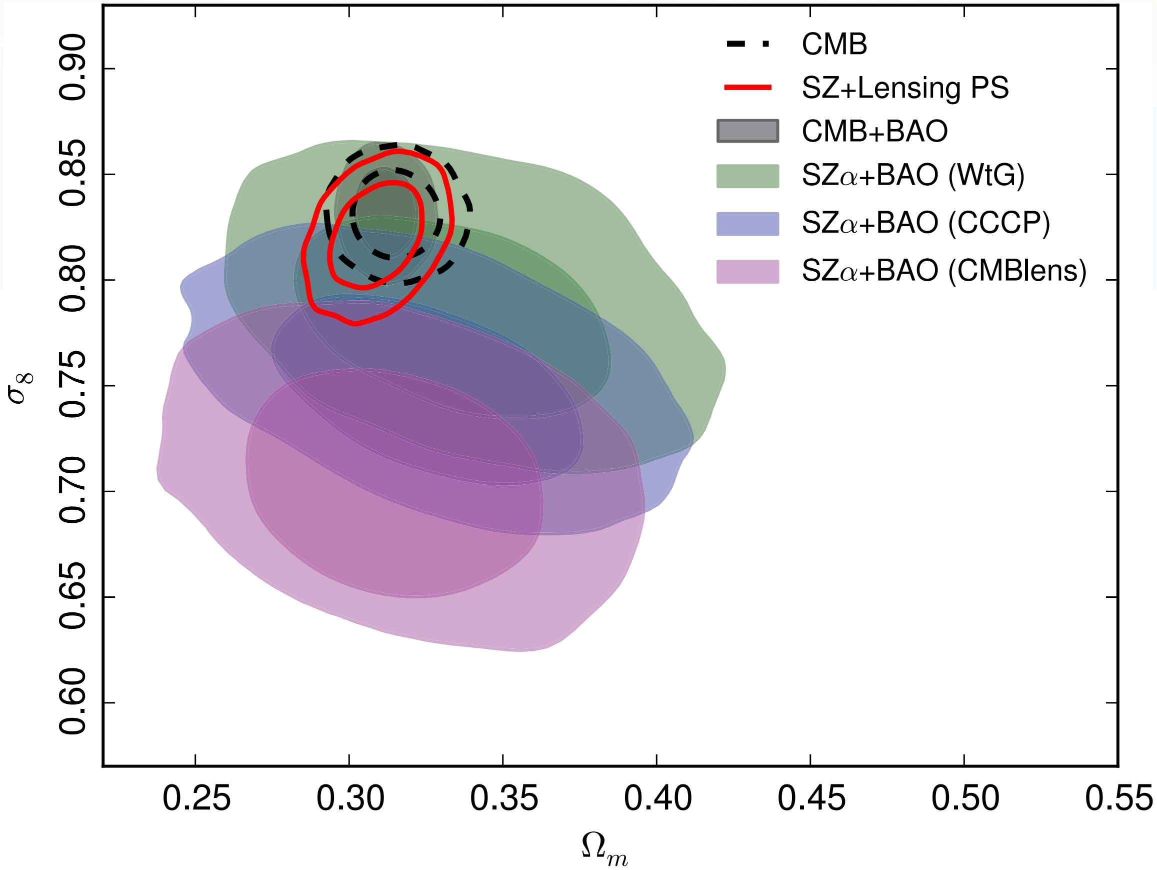
Type Ia Supernovae

- In 2013 compared with two SN samples
  - SNLS (Conley et al. 2011)
  - Union2.1 (Suzuki et al. 2012)
- SNLS was about 2σ from Planck in $\Omega_{\rm m}$, 0.23 vs. 0.315 ± 0.017
- Betoule et al. (2013) worked on relative calibrations between SNLS and SDSS SN surveys $\Rightarrow$ "Joint Light-curve Analysis" (JLA)
  - $\Omega_{\rm m} = 0.295 \pm 0.034$
  - Relieves tension between SNLS and Planck

Direct Measures of H_0

- CMB determination of H_0 is model-dependent
  - Planck TT+lowP: $H_0 = 67.3 \pm 1.0$ km s^{-1} Mpc^{-1}
    $\Omega_\mathrm{m} = 0.315 \pm 0.013$
  - Planck TT+lowP+lensing: $H_0 = 67.8 \pm 0.9$
    $\Omega_\mathrm{m} = 0.308 \pm 0.012$
  - WMAP9: $H_0 = 69.7 \pm 2.1$
  - WMAP9+BAO: 68.0 ± 0.7
- Direct measures are higher
  - Reiss et al. (2011): 73.8 ± 2.4
  - Freedman et al. (2012): 74.3 ± 2.6
  - Efstathiou (2014) reanalysis of Reiss et al. (2011) Cepheid data (Cepheids in SNe host galaxies compared to those in NGC 4258) using the more recent Humphreys et al. (2013) geometric maser distance to NGC 4258: 70.6 ± 3.3
- Planck estimates are consistent with small errors. If a persuasive case can be made that direct measurements of H_0 conflict, it will be strong evidence for physics beyond the base ΛCDM model

Clusters of Galaxies



Comparison of constraints from the CMB to those from the cluster counts in the $(\Omega_{\rm m}, \sigma_8)$-plane. The green, blue, and violet contours give the cluster constraints (two-dimensional likelihood) at 1 and 2σ for the WtG, CCCP, and CMB lensing mass calibrations, respectively, as listed in Table 2. These constraints are obtained from the MMF3 catalogue with the SZ+BAO+BBN data set and α free. Constraints from the Planck TT,TE,EE+lowP CMB likelihood (hereafter, Planck primary CMB) are shown as the dashed contours enclosing 1 and 2σ confidence regions (Planck Collaboration XIII 2015), while the grey shaded region also includes BAO. The red contours give results from a joint analysis of the cluster counts, primary CMB, and the Planck lensing power spectrum (Planck Collaboration XV 2015), leaving the mass bias parameter free and α constrained by the X-ray prior.

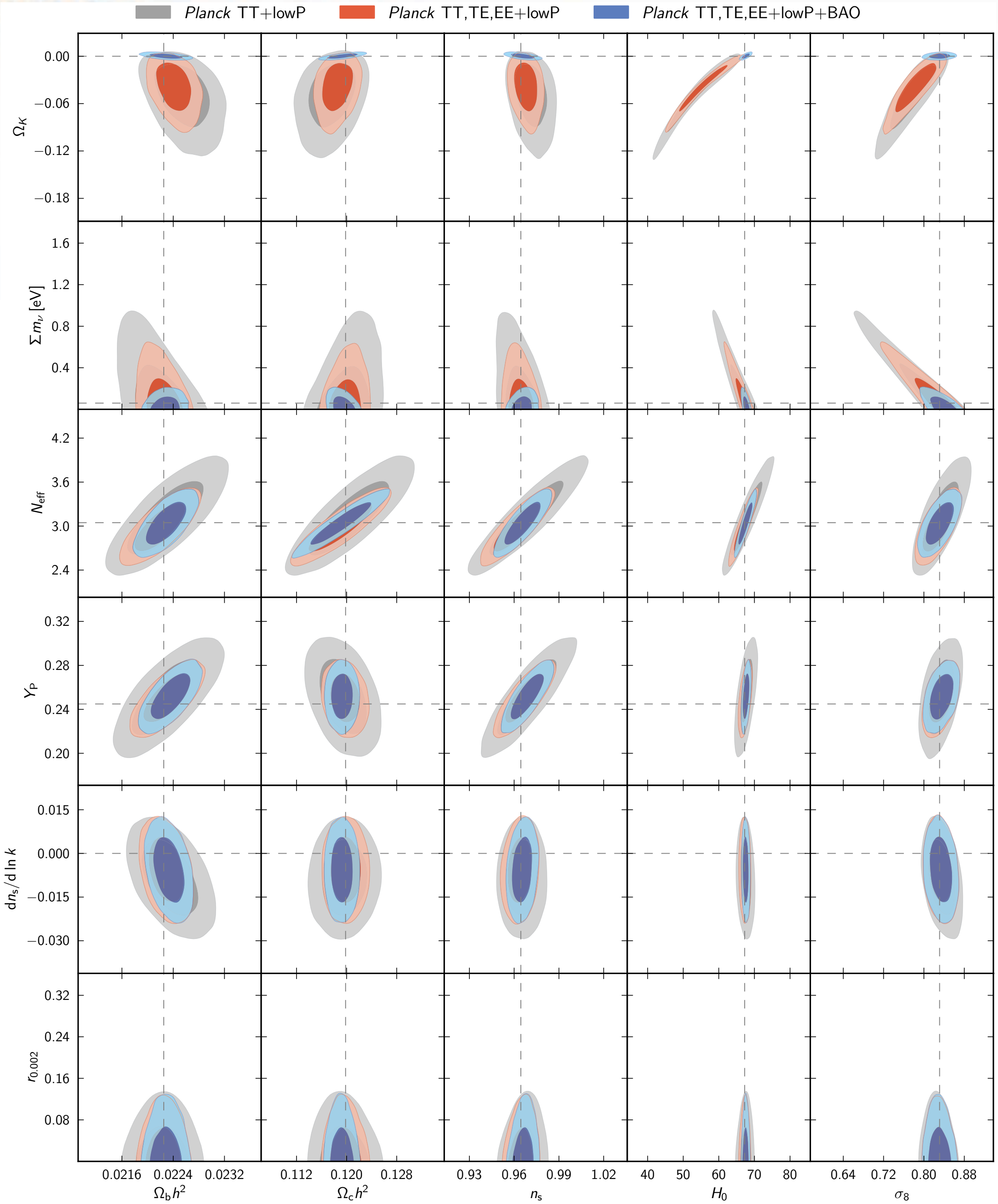
- “The situation is still murky.” Mass estimates and bias factors are the key.

Extensions To the Base ΛCDM Model

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

- $\Omega_{\rm K}$ (curvature)
- Σm_ν (neutrino mass), $N_{\rm eff}$ (effective number of "neutrino" species)
- Isocurvature modes
- $Y_{\rm P}$ (helium fraction)
- $dn_{\rm s}/d\ln k$ ("running" of the input fluctuation spectral index)
- Tensor modes
- w (dark energy equation of state, constant)

1-Parameter Extensions



68% and 95% confidence regions

Horizontal dashed lines correspondto the parameter values assumed in the base ΛCDM cosmology. Vertical dashed lines show the mean posterior values in the base model for Planck TT,TE,EE+lowP+BAO.

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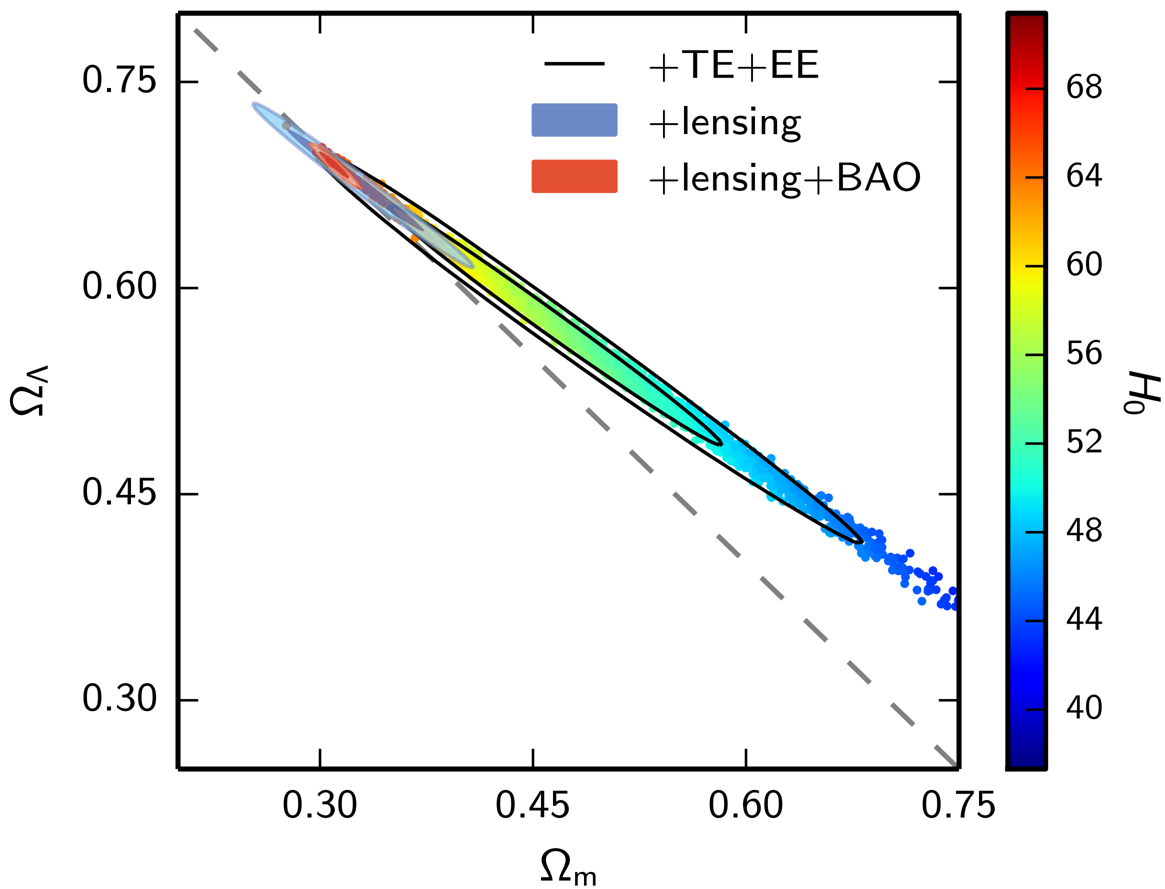
Curvature

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

$$\Omega_k = 0.000 \pm 0.005 (95\%)$$



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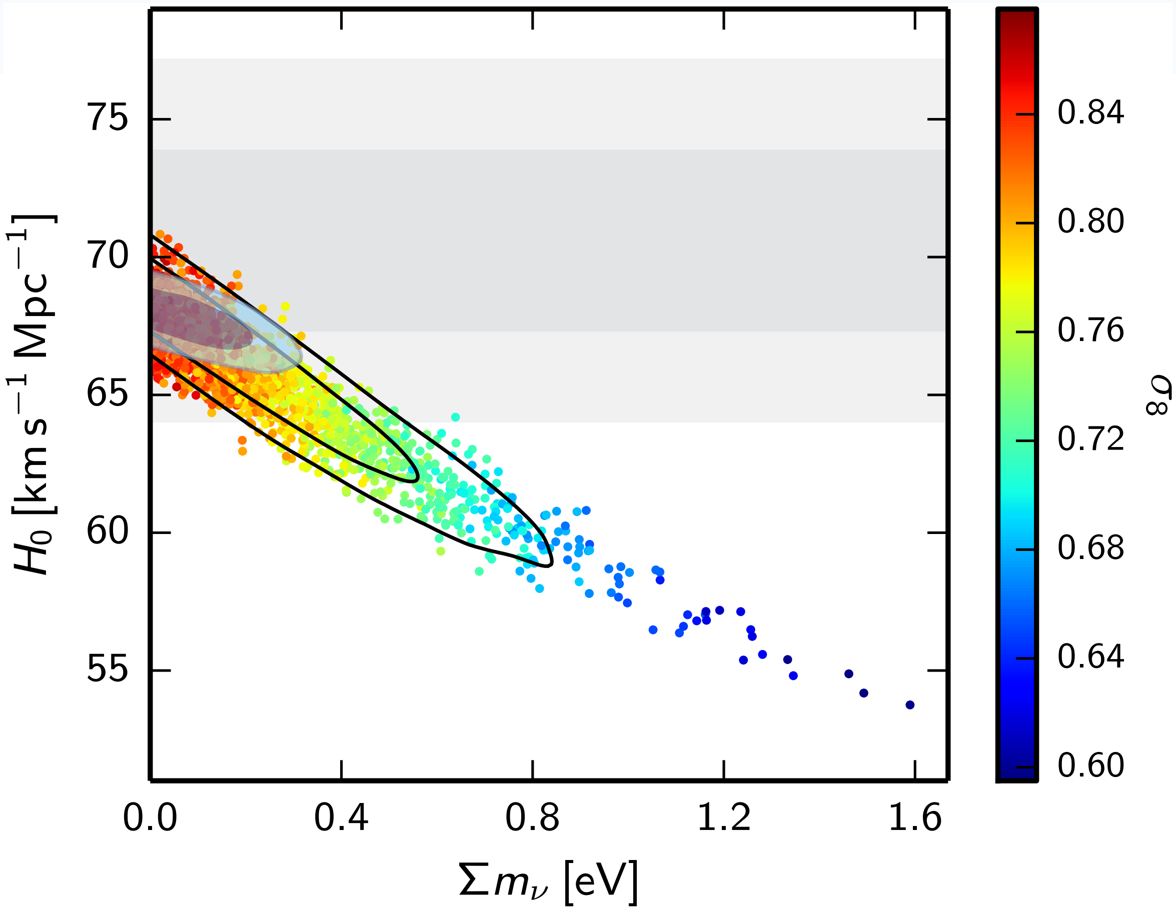
Tighter Constraints on Neutrino Masses. . .

- $\Sigma_\nu < 0.17\,\mathrm{eV}$ (95%) Planck TT,TE,EE+lowP+BAO

  $\Omega_\nu h^2 < 0.0018$



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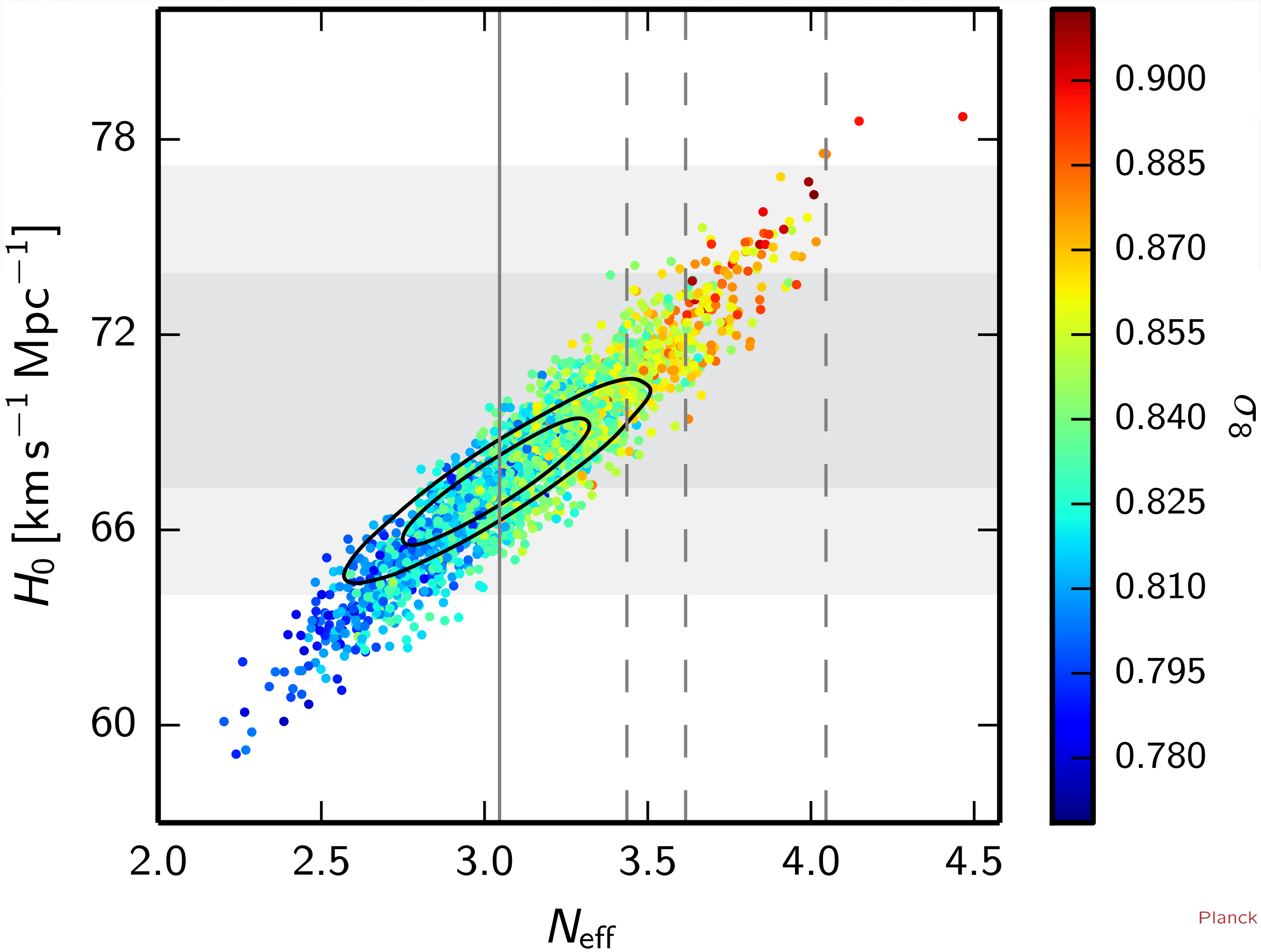
Samples from the Planck TT+lowP posterior in the $\sum m_\nu$–H_0 plane, colour-coded by σ_8. Higher $\sum m_\nu$ damps the matter fluctuation amplitude σ_8, but also decreases H_0 (grey bands show the direct measurement $H_0 = (70.6 \pm 3.3)\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, Eq. 30). Solid black contours show the constraint from Planck TT+lowP+lensing (which mildly prefers larger masses), and filled contours show the constraints from Planck TT+lowP+lensing+BAO.

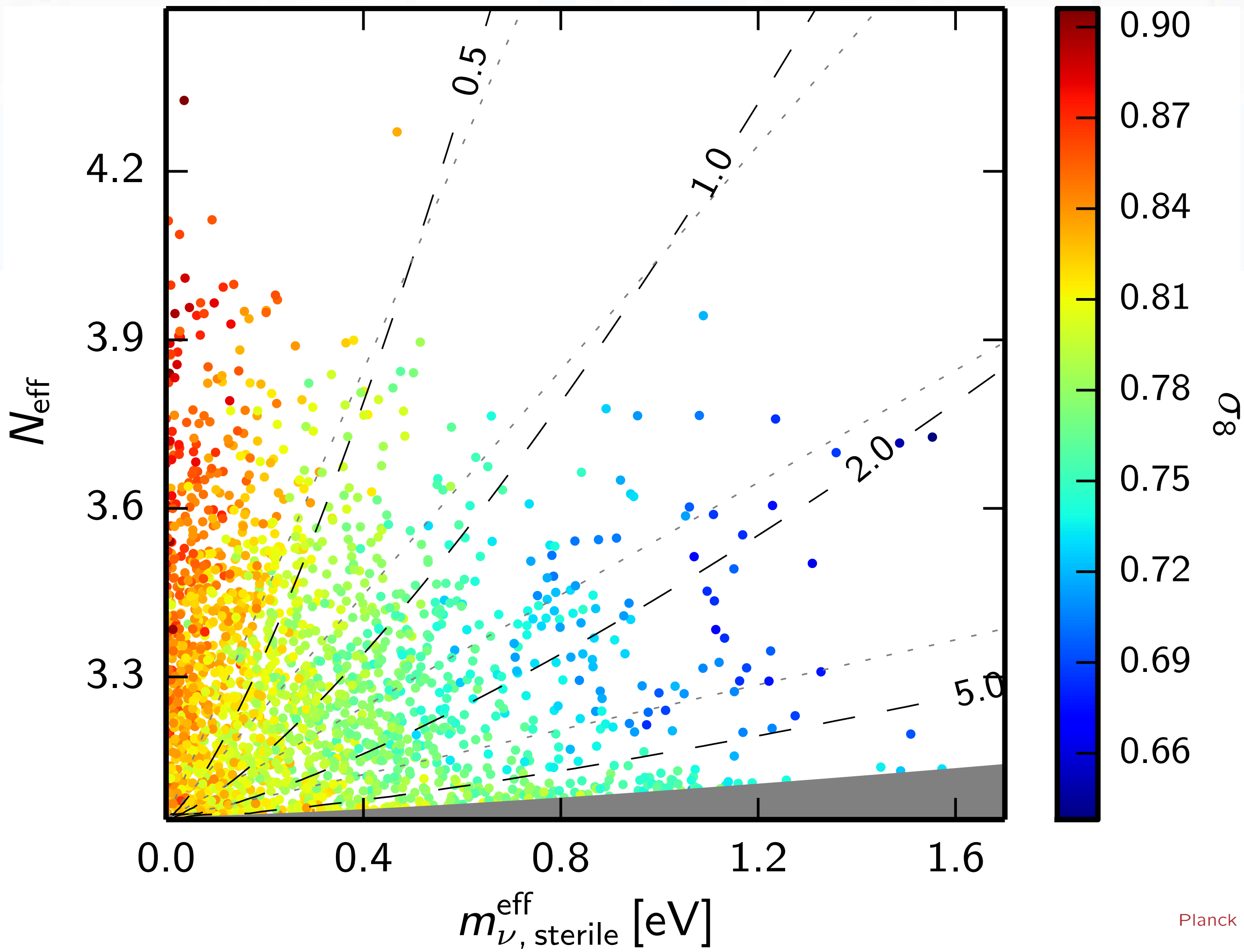
. . . Neutrino Number . . .



Planck 2015 results. XIII.

Samples from Planck TT+lowP chains in the $N_{\rm eff}$–H_0 plane, colour-coded by σ_8. The grey bands show the constraint $H_0 = (70.6 \pm 3.3)\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ of Eq. 30. Note that higher $N_{\rm eff}$ brings H_0 into better consistency with direct measurements, but increases σ_8. Solid black contours show the constraints from Planck TT,TE,EE+lowP+BAO. Models with $N_{\rm eff} < 3.046$ (left of the solid vertical line) require photon heating after neutrino decoupling or incomplete thermalization. Dashed vertical lines correspond to specific fully-thermalized particle models, for example one additional massless boson that decoupled around the same time as the neutrinos ($\Delta N_{\rm eff} \approx 0.57$), or before muon annihilation ($\Delta N_{\rm eff} \approx 0.39$), or an additional sterile neutrino that decoupled around the same time as the active neutrinos ($\Delta N_{\rm eff} \approx 1$).

. . . and $N_{\rm eff}$ + Neutrino Mass

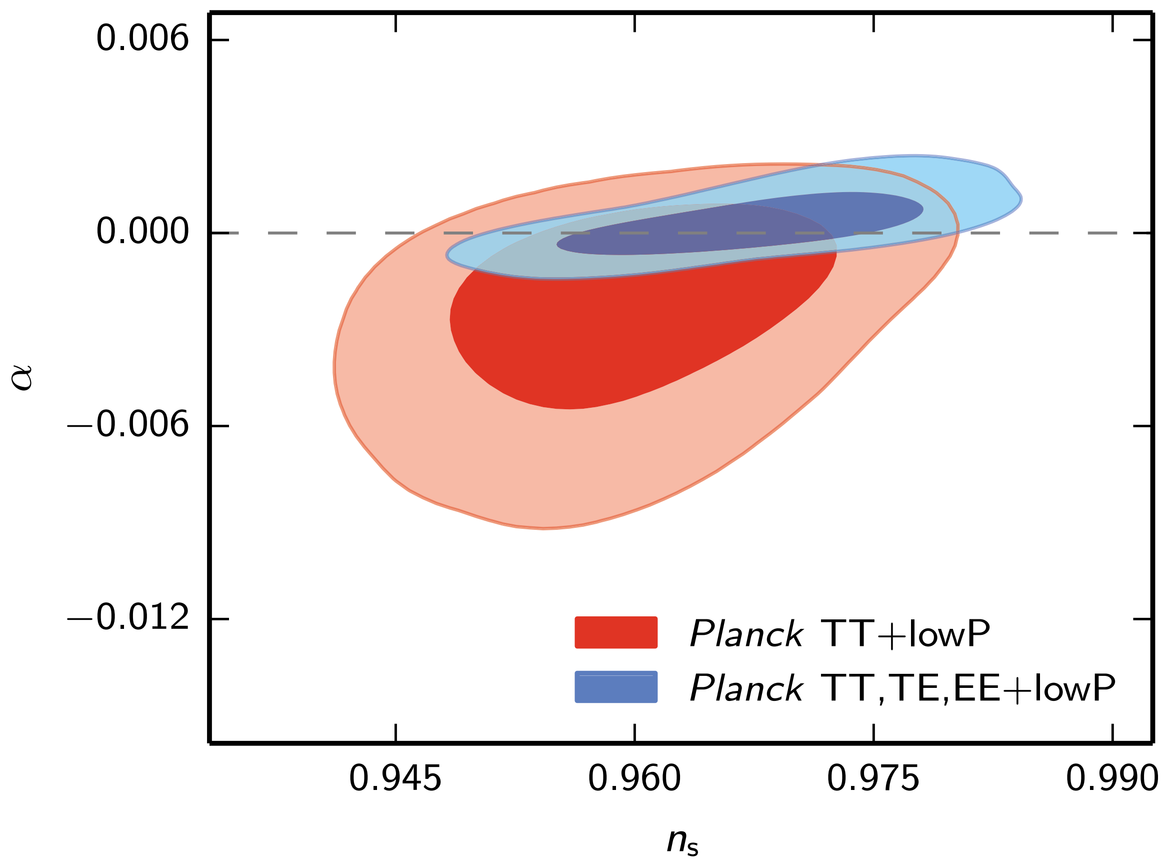


Planck 2015 results. XIII.

Samples from Planck TT+lowP in the $N_{\rm eff}$–$m^{\rm eff}_{\nu,\,\rm sterile}$ plane, colour-coded by σ_8, in models with one massive sterile neutrino family, with effective mass $m^{\rm eff}_{\nu,\,\rm sterile}$, and the three active neutrinos as in the base ΛCDM model. The physical mass of the sterile neutrino in the thermal scenario, $m^{\rm thermal}_{\rm sterile}$, is constant along the grey dashed lines, with the indicated mass in eV; the grey region shows the region excluded by our prior $m^{\rm thermal}_{\rm sterile} < 10\,\rm eV$, which excludes most of the area where the neutrinos behave nearly like dark matter. The physical mass in the Dodelson-Widrow scenario, $m^{\rm DW}_{\rm sterile}$, is constant along the dotted lines (with the value indicated on the adjacent dashed lines).

Isocurvature Modes

- Strong constraint from high-ℓ polarization
  - $\alpha = -0.0025^{+0.0035}_{-0.0047}$ (95%) Planck TT+lowP
  - $\alpha = 0.0003^{+0.0016}_{-0.0012}$ (95%) Planck TT,TE,EE+lowP
- Perturbations we see are almost fully adiabatic ($\delta \mathrm{p} \sim \delta\rho$).



Planck 2015 results. XIII.

Tensor Modes

- Planck: $r_{0.002} < 0.10 \quad (95)\%$ Planck TT+lowP

  ($r_{0.002} \equiv$ tensor-to-scalar ratio at $k_0 = 0.002\,$Mpc^{-1})

  - Strongest Planck constraint still from CMB temperature at $\ell < 100$, limited by cosmic variance

- Bicep2/Keck dust-cleaned with Planck: $r_{0.05} < 0.12 \quad (95\%)$

  - Constraint from B-mode polarization

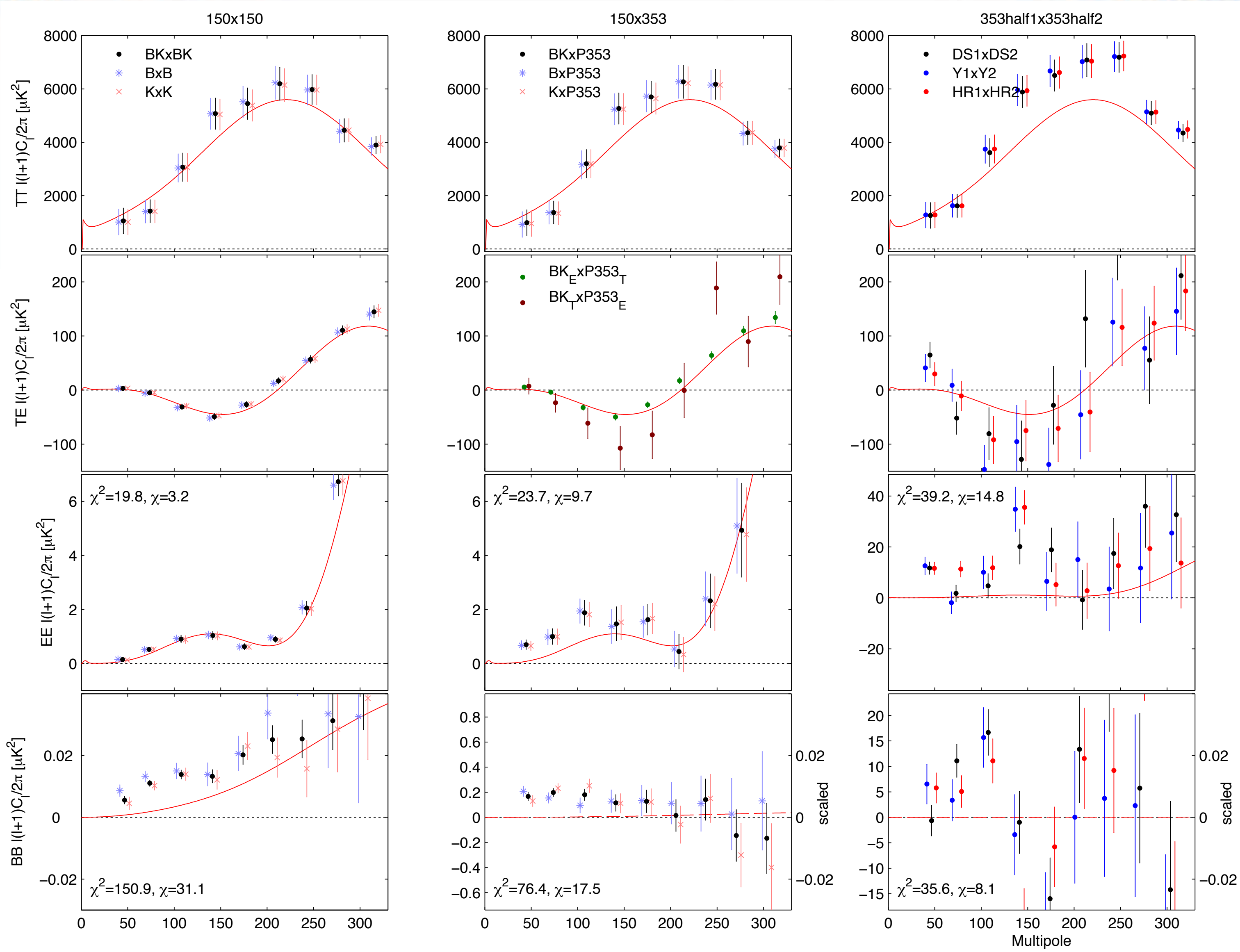
- Joint Planck+BKP likelihood analysis: $r_{0.002} < 0.08 \quad (95\%)$

- The only way of improving these limits or detecting gravitational waves is through direct B-mode detection

B-mode Polarization

- Three different sources:
  - Primordial tensor fluctuations, as produced by gravitational waves
  - Remapping of the CMB E-mode polarisation by gravitational lensing from intervening matter
  - Foregrounds — dust and synchrotron — in the Milky Way

Joint Bicep2/Keck Array/Planck Analysis



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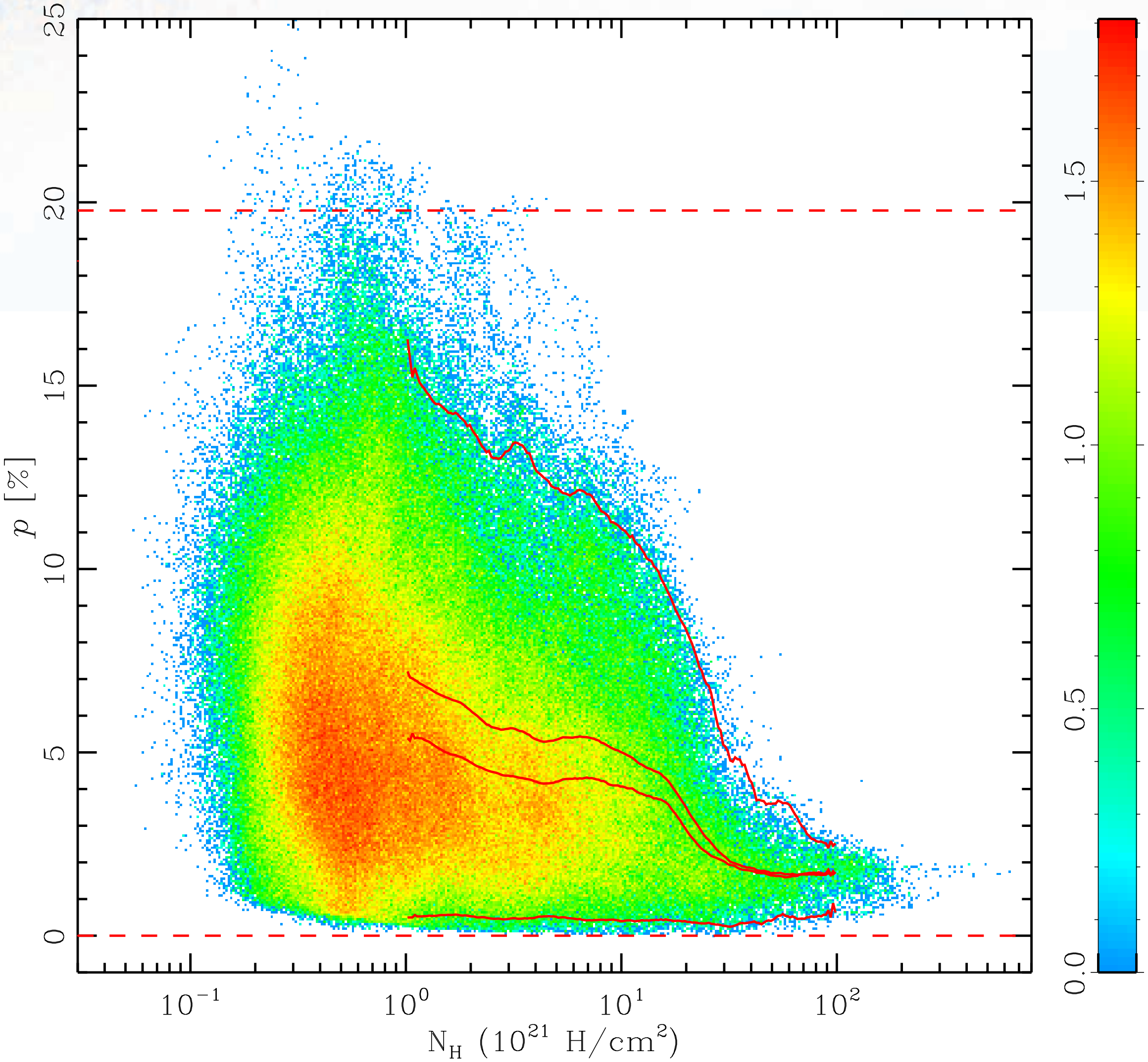
We see from the significant excess apparent in the bottom center panel that a substantial amount of the signal detected at 150 GHz by BICEP2 and Keck Array indeed appears to be due to dust.

Dust Polarization



- Polarization fraction up to 20%
- Large dispersion of p at all N_{H}, tracing changes in B-field orientation and depolarization within the beam
- Sharp decrease of p for $N_{\mathrm{H}} > 10^{22}\,\mathrm{cm}^{-2}$. Interpreted as loss of grain alignment in the shielded interiors of clouds.

Planck intermediate results. XIX.

Distribution of the polarization fraction (p) as a function of gas column density over the whole sky used in PIP XIX. The values of p were computed at 1° resolution. The gas column density is derived from the dust optical depth at 353 GHz. The colour scale shows the pixel density in $\log_{10}$ scale. The curves show, from top to bottom, the evolution of the upper 1 percentile, mean, median, and lowest 1 percentile of p for pixels with $N_{\mathrm{H}} > 10^{21}\,\mathrm{cm}^{-2}$. Horizontal dashed lines show the location of $p = 0$ and $p_{\max} = 19.8\%$.

Constraints on Inflation

- Planck 2013 had a huge impact on inflationary model building
- With Planck 2015
  - Constraints on non-Gaussianity are tighter, and new different types are considered explicitly
  - Constraints on isocurvature modes are tighter
  - Running of $n_{\rm s}$ is zero within 1σ
  - Further, there are tighter constraints on features in the primordial power spectrum
- Planck/BICEP2/Keck joint analysis gives tighter constraints on r

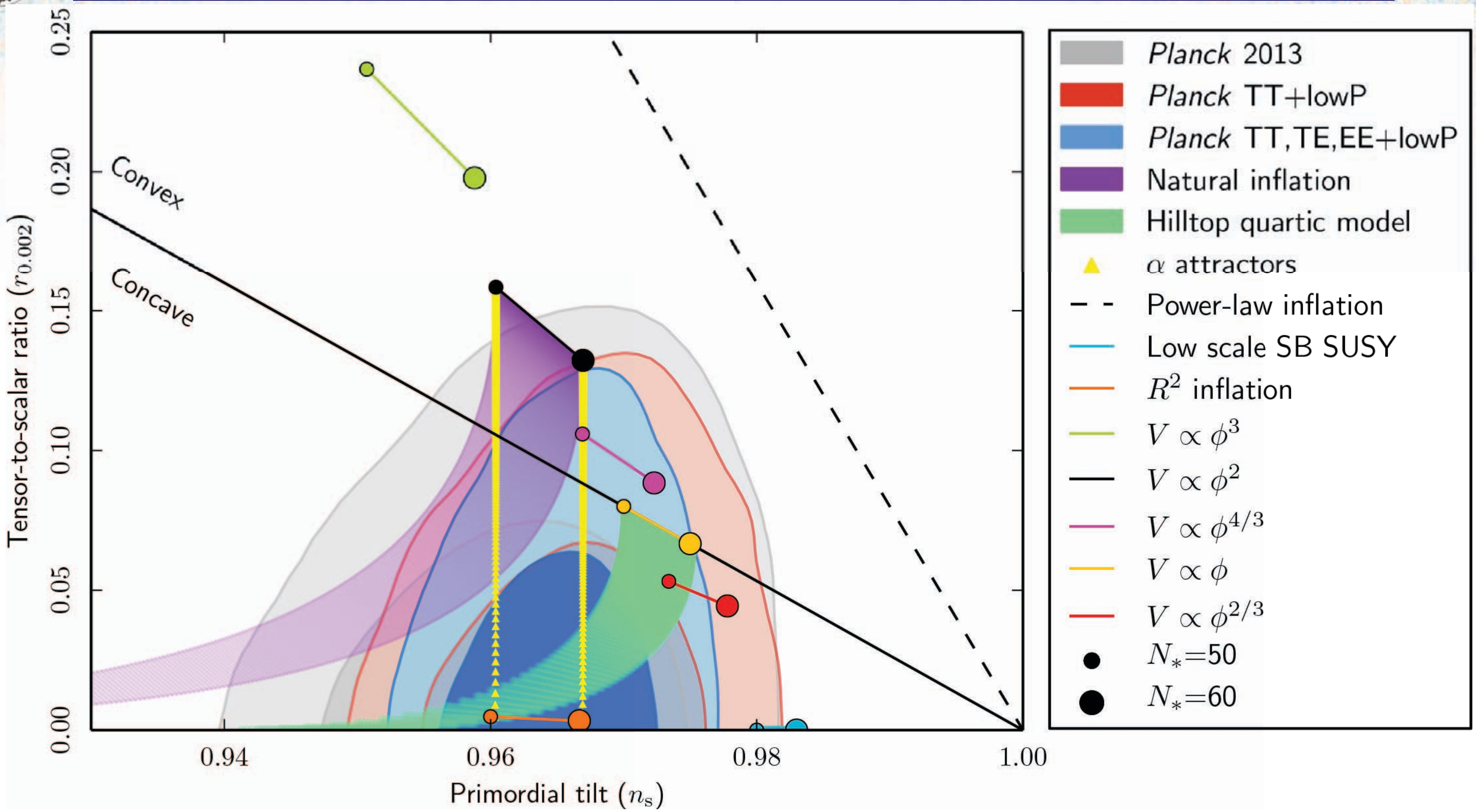
Non-Gaussianity: f_{NL}

Type	2013	2014	Generated by…
Local	2.7±5.8	0.7±5.1	Curvaton, reheating, multifield, …
Equilateral	-42±75	-9.5±44	Non-canonical kinetic term or higher derivative (e.g. K-flation, DBI, ghost inflation, with c_s<<1).
Orthogonal	-25±39	-25±22	Non-canonical kinetic term or higher derivative (c_s<<1).

Planck 2015 results. XII.

The initial fluctuations were random to a high degree

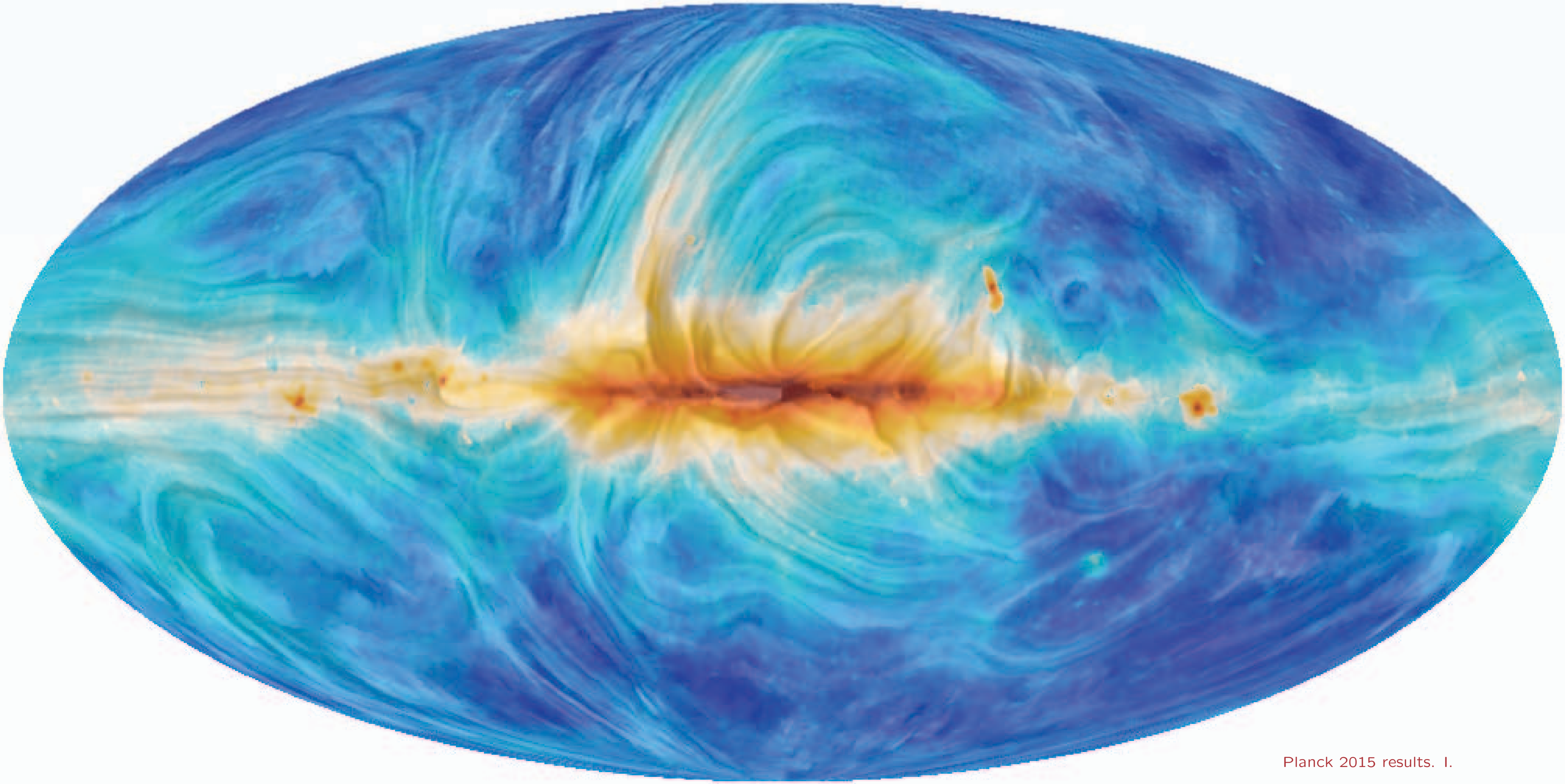
Inflation



Planck 2015 results. XX.

- $V(\phi) \propto \phi^2$ and natural inflation now disfavored compared to models predicting smaller r such as R^2

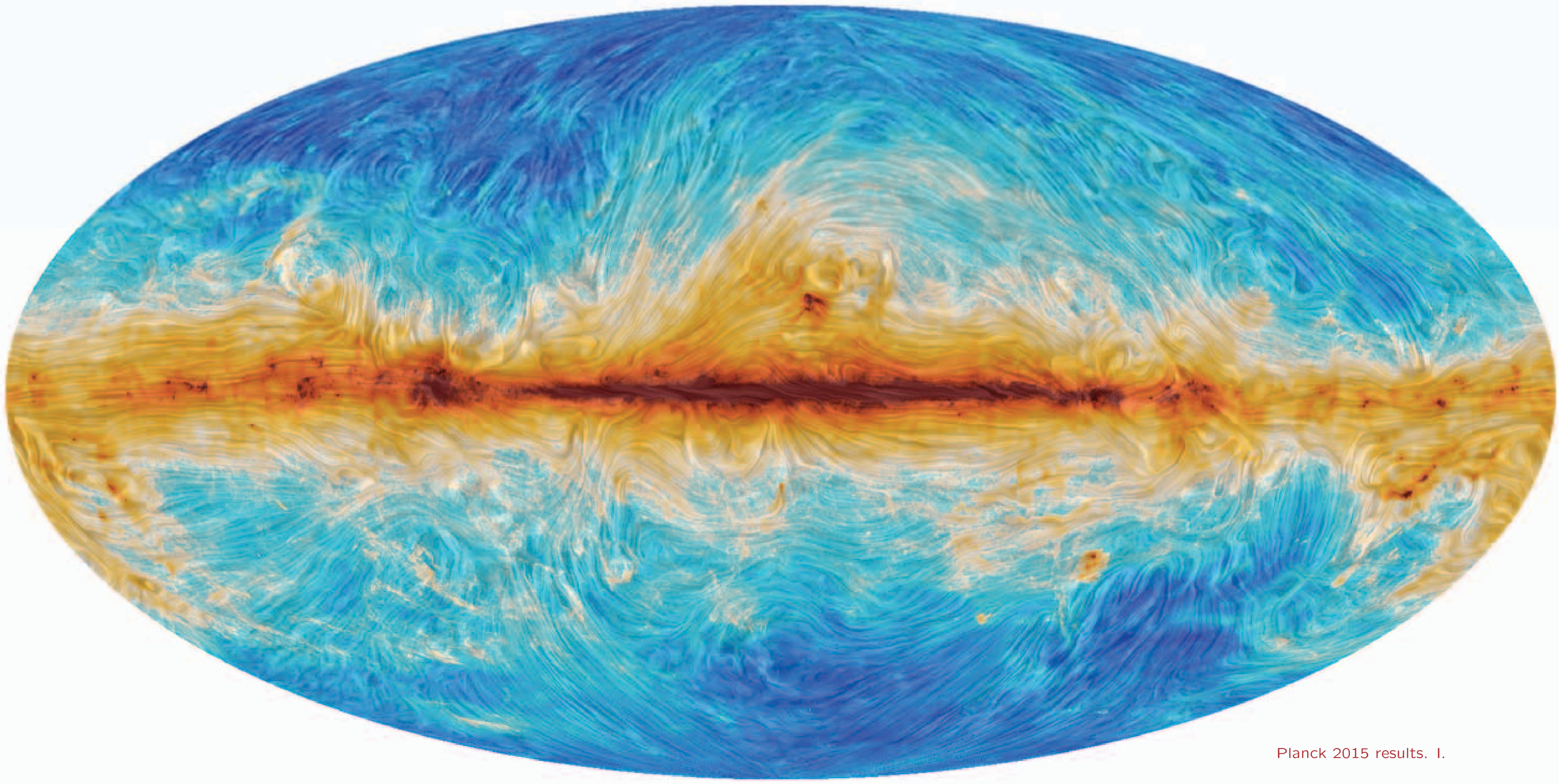
Synchrotron Temperature and Magnetic Field Orientation at 30 GHz



Planck 2015 results. I.

Total intensity shown by colours
Magnetic field orientation shown by striations (line integral convolution method (Cabral 1993))
Polarization orientation is 90° from the striations.

Dust Temperature and Magnetic Field Orientation at 353 GHz



Planck 2015 results. I.

Total intensity shown by colours
Magnetic field orientation shown by striations (line integral convolution method (Cabral 1993))
Polarization orientation is 90° from the striations.

The CMB "Prior"

- We now have precise knowledge of the universe at $z = 1090$
- We have tightly constrained
  - The physical densities of matter and baryons
  - The amplitude of the fluctuations
  - The shape of the primordial ("input") power spectrum.
- Our knowledge of physical conditions and large-scale structure at $z = 1090$ is better than our knowledge of such quantities at $z \sim 0$!

Conclusion

- The Planck mission has been stunningly successful.
- Impressive confirmation of the standard cosmological model.
  - Precise constraints on model and parameters.
  - Tight limits on deviations from base model.
  - No evidence for cosmological non-Gaussianity
  - Powerful evidence in favor of simple inflationary models, which provide an attractive mechanism for generating the slightly tilted spectrum of (nearly) Gaussian adiabatic pertubations that match the Planck data to high precision
  - Ties together many things: Distribution of matter (lensing), clusters, neutrinos, helium and deuterium abundances, hydrogen transitions
  - Plus a lot of astrophysics from all-sky surveys at nine frequencies
- Final data release at the beginning of 2016
  - Continued analysis will improve data quality even more for the final release!

Moreover. . .

- Planck is a brilliant example of an international mission
  - Could not have been done as it was in either the US or Europe
  - There are overheads. . .
  - . . .but we know how to do this. . .
  - . . .and the results are unprecedented!
- The US Planck team pioneered an agreement between NASA and DoE on supercomputing
  - Guaranteed Planck access to NERSC supercomputers
  - NASA contributed 2.3 FTE at LBL Computational Research Division
  - Last year (2014), e.g., US Planck team used 130 million CPU hours
  - All of the biggest computational tasks in Planck were done in the US
- Hardware/data analysis cost split for US was 48.4% / 51.6%.

Citations

- The “Planck 2013 results” papers have been out for almost exactly 2 years
  - 31 papers (992 pages)
  - 7143 citations in NASA ADS database
  - Eleven papers with more than 100 citations
  - Most-cited paper has 2864 citations

    The most cited paper with “Hubble” in the title is from 2004, with 2831 citations
- The “Planck 2015 results” papers have been out for 5 weeks
  - 19 papers so far, 9 more on the way
  - Already 80 citations
- No paper on cosmology or related subjects can be written without referencing Planck papers
- Planck results will be in textbooks for decades.

The Planck Collaboration

What's Next — The Third Release

- Improve calibration and control of systematics, especially low-ℓ polarization

  LFI

  Gain calibration. Optimal smoothing without including real jumps.

  Beams, far sidelobes in particular.

  Bandpass mismatch, $T \rightarrow P$ leakage

  HFI

  ADC non-linearity

  Cosmic ray removal

  $T \rightarrow P$ leakage

  Cooler electronics EMC

  Beams

  Accurate simulation of instrument behavior possible now for the first time. Major simulation effort of end-to-end analysis has the potential to improve corrections dramatically

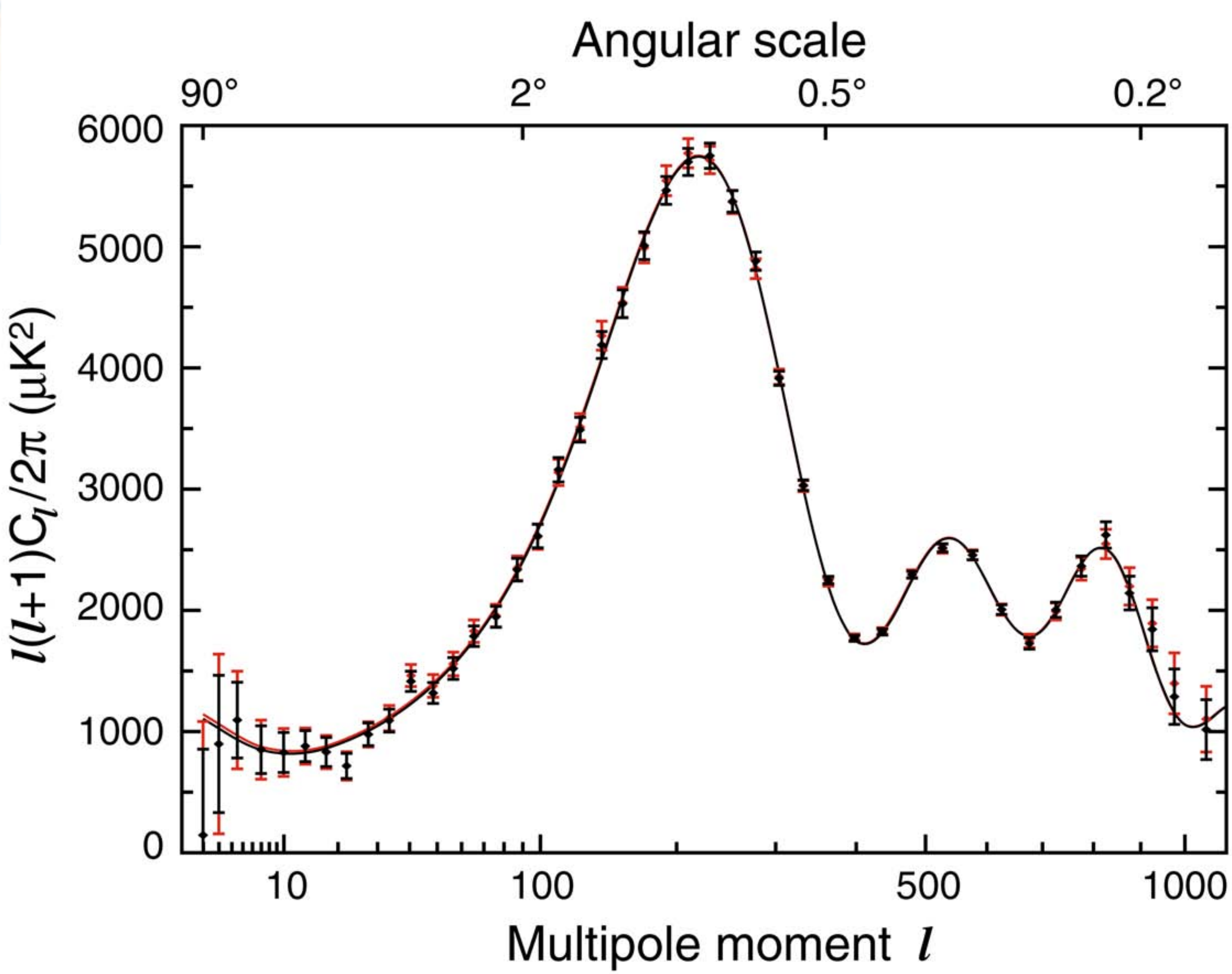
  - Simulations from instrument to science are demanding, huge, and an essential tool

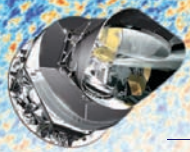
- US team working flat out on the above, racing against the clock

- Expect absolute calibration of both instruments to better than 0.05%

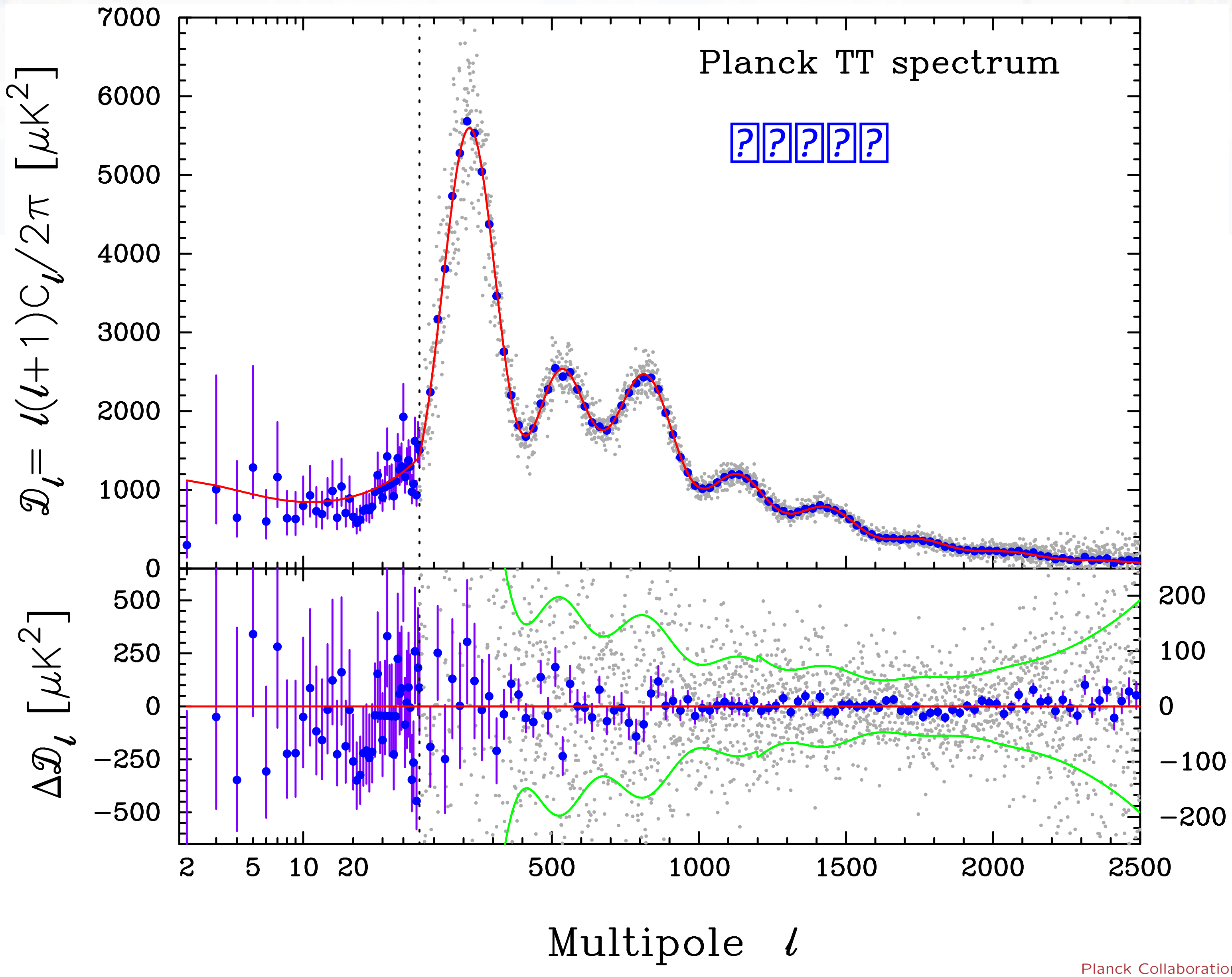
- Uncertainty on τ should go down by a factor of three

WMAP9, for Comparison



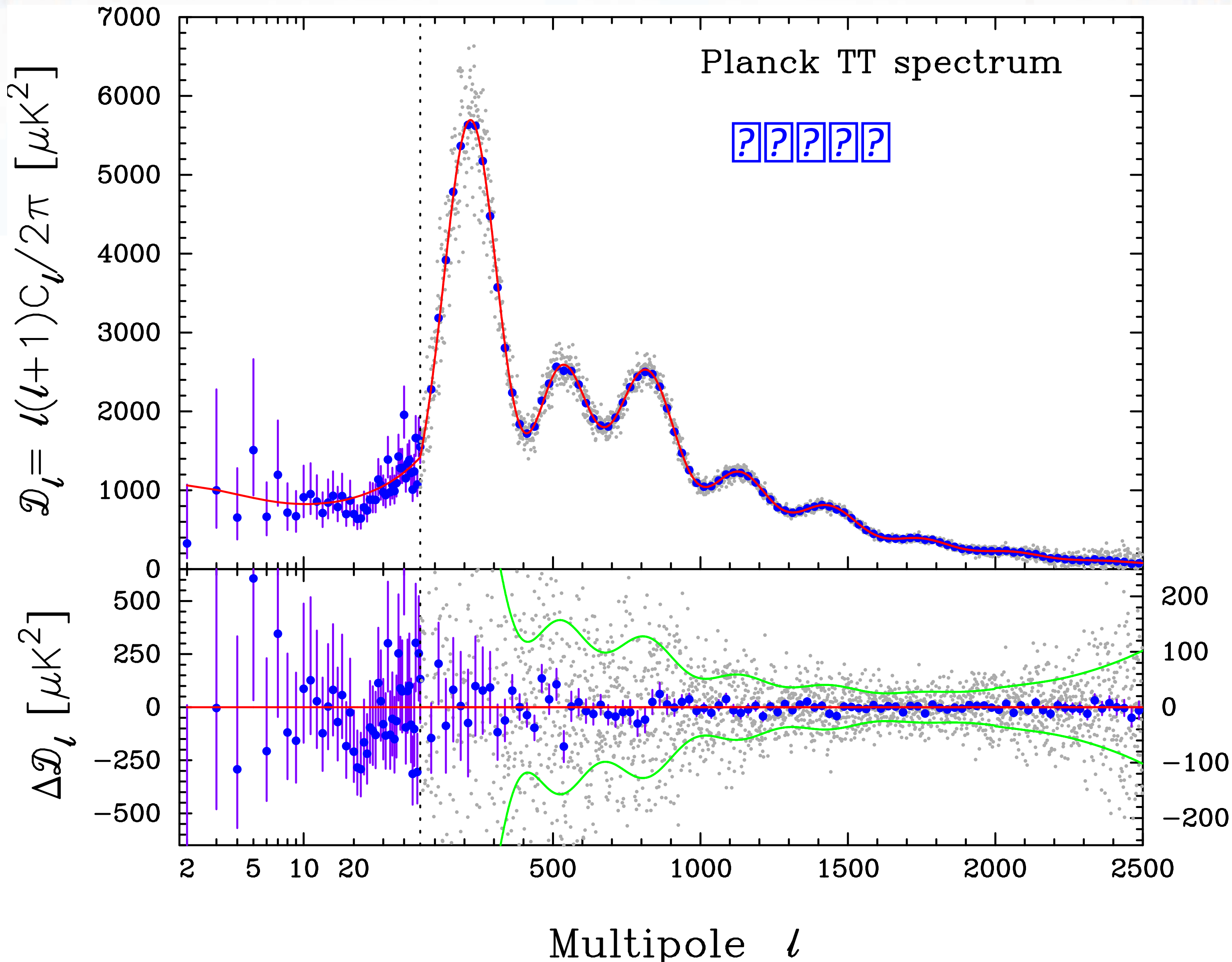


Angular Power Spectrum + Best-Fit Model, 2013



Planck Collaboration I 2013

Angular Power Spectrum + Best-Fit Model, 2015



preliminary