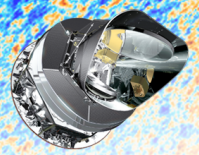
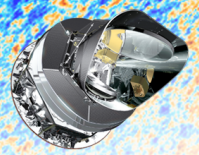


PLANCK 2015

OVERVIEW & SYSTEMATICS

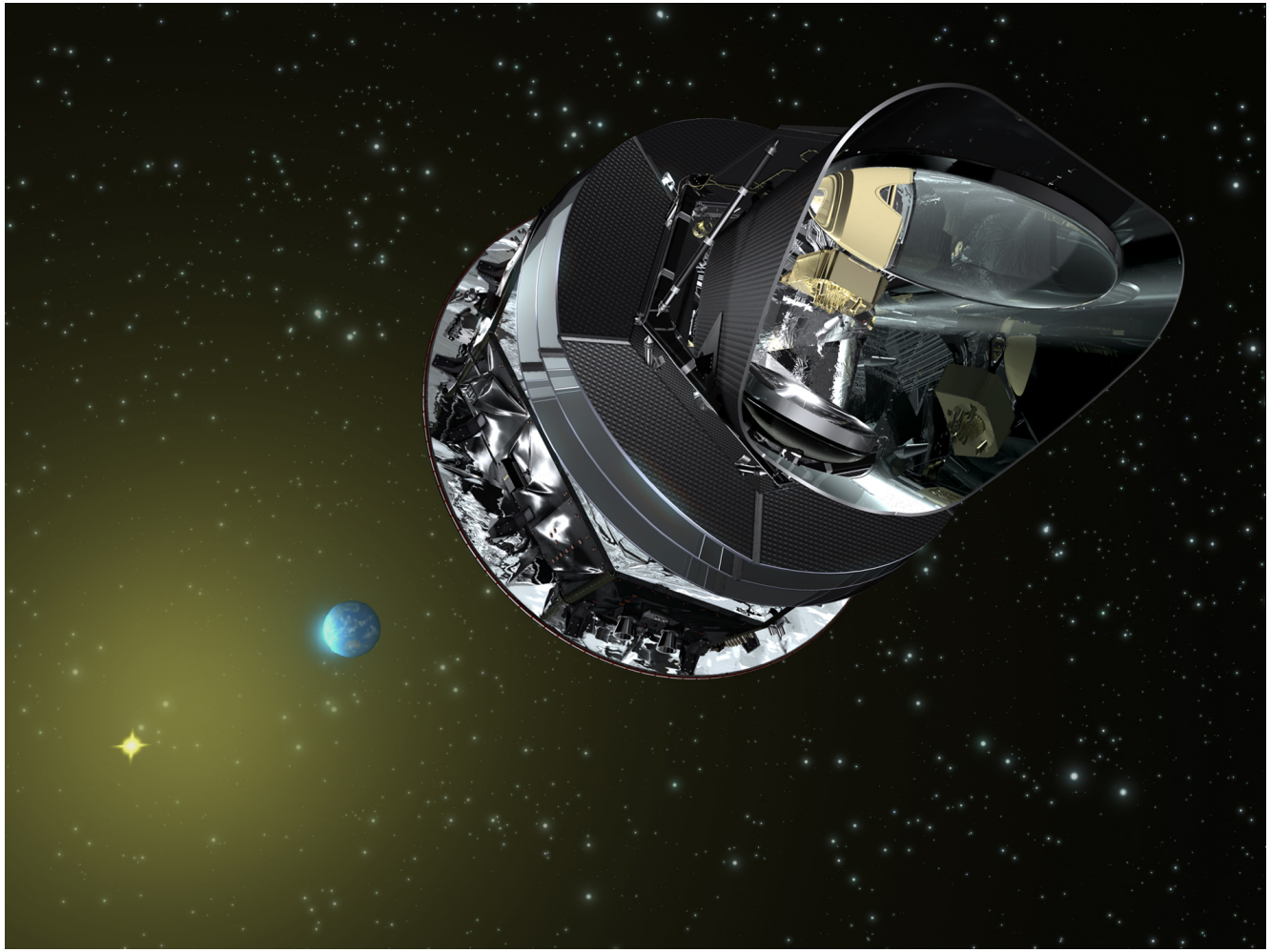
C. R. Lawrence, JPL
for the Planck Collaboration

Minneapolis
2015 January 14

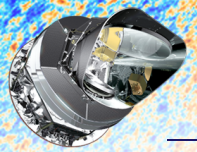


Planck, the 3rd Generation Space CMB Mission

- 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.

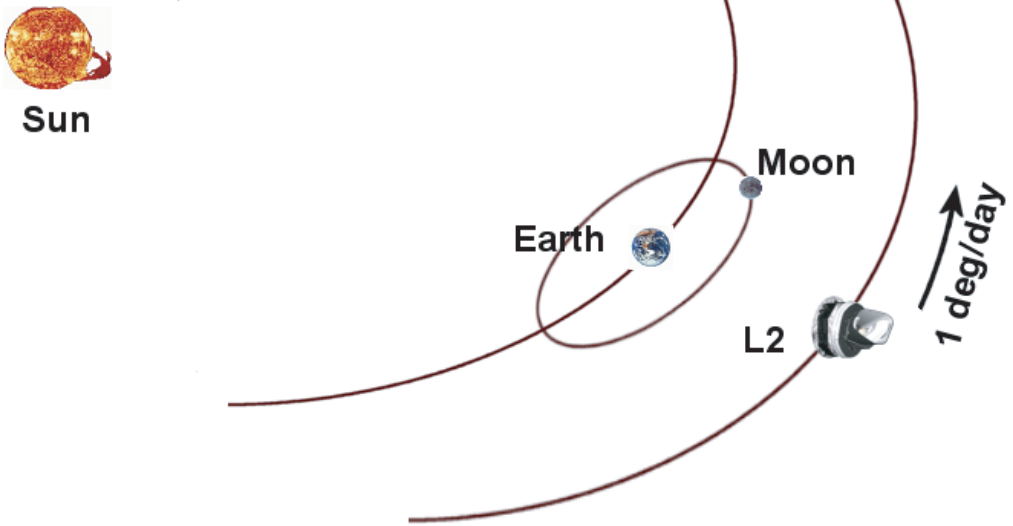


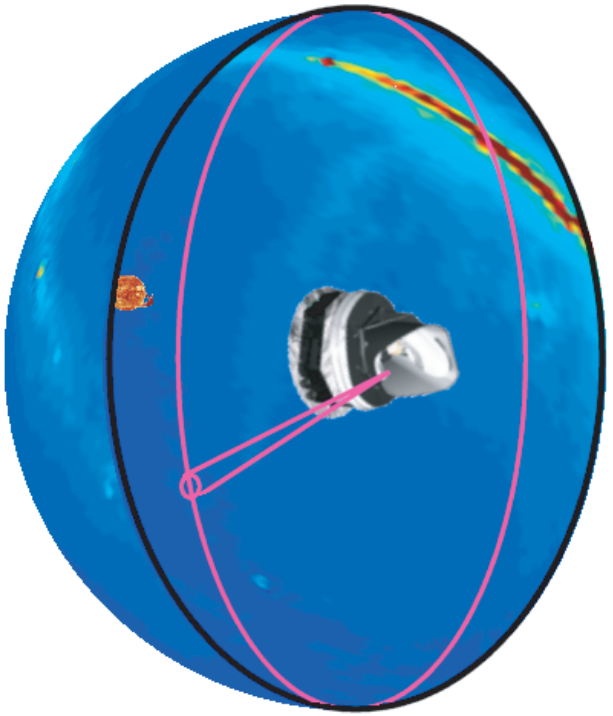
- First all-sky surveys at $143 \leq \nu \leq 857$ GHz that can detect individual sources

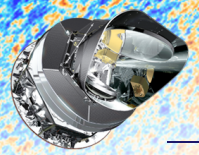


Orbit

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







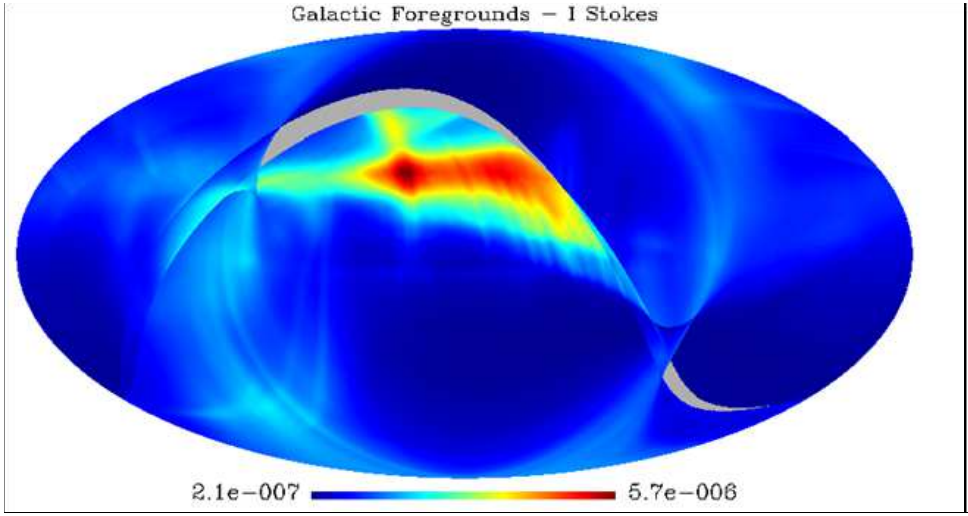
Time, "Surveys", & Years

SS1	SS2	SS3	SS4	SS5	SS6	SS7	SS8
yr1		yr2		yr3		yr4	
Nominal(2013)							
HFI							
LFI							

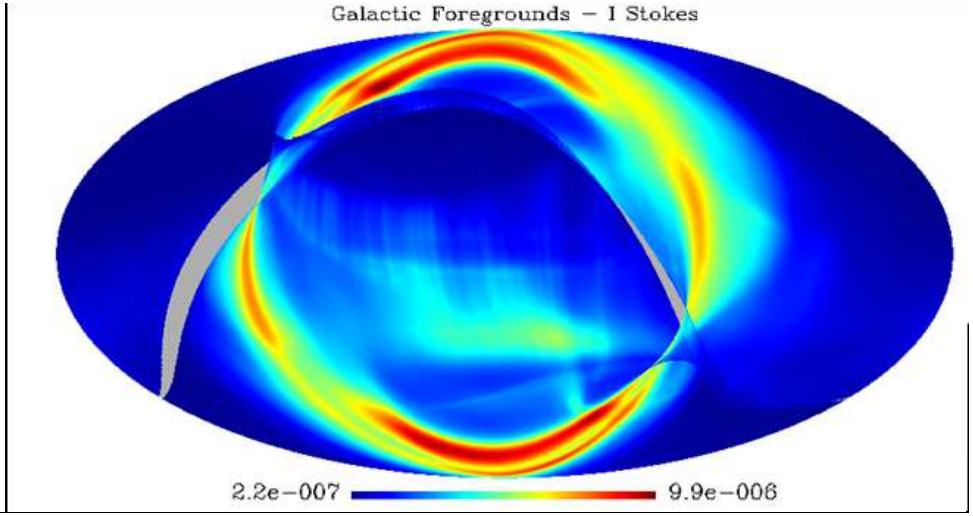
- Repeat observations provide multiple levels of null tests
- "Odd" and "Even" surveys, for example, have very different far sidelobe pickup

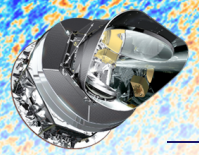
Galactic straylight simulation

Odd survey



Even survey



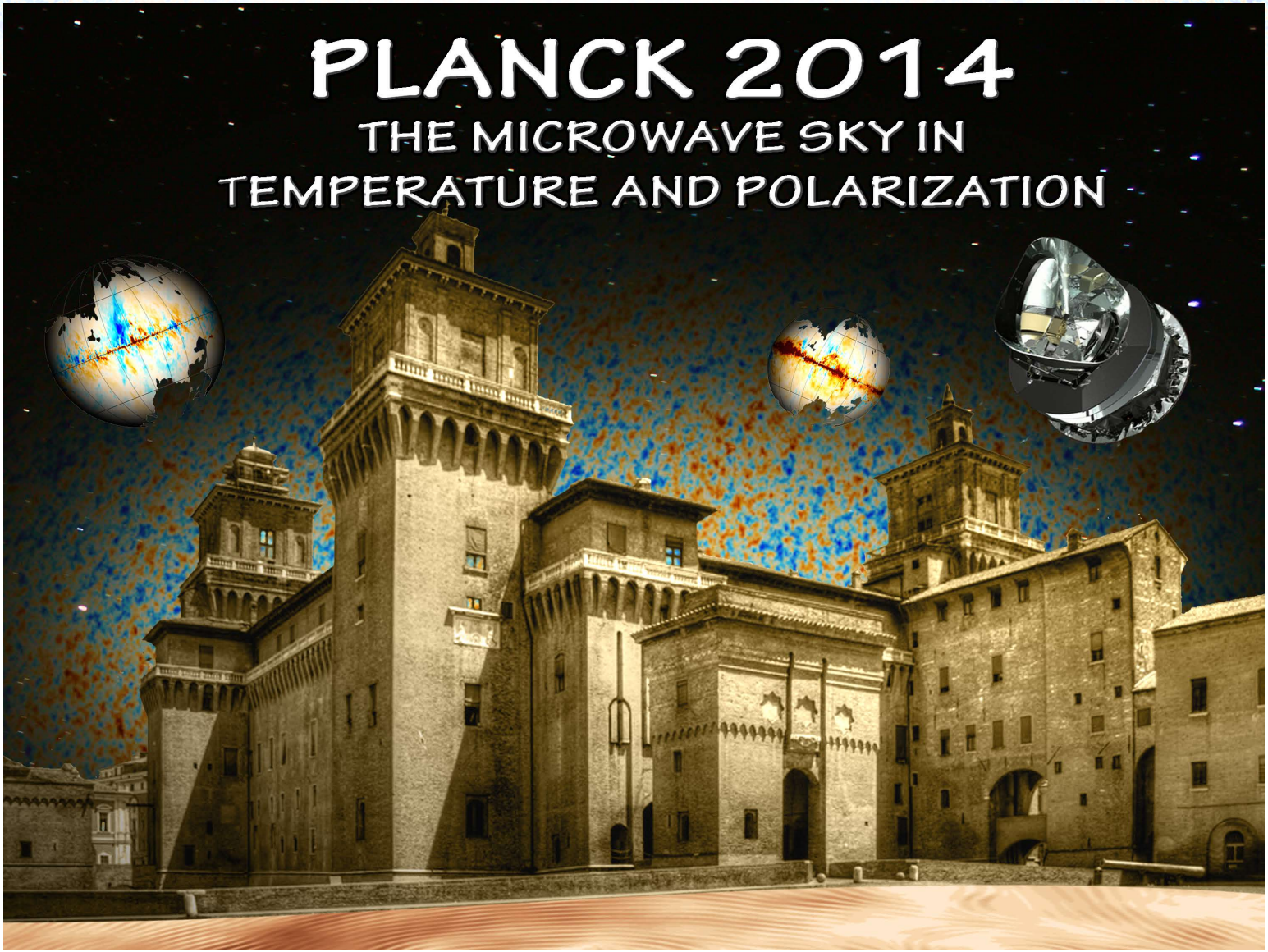


2013 and 2015 Data Releases

2013	2015
15.5 months, "nominal mission"	29 (HFI) & 48 (LFI) months, "full mission"
Temperature data only	Temperature and polarization
	Better calibration, beams, systematics, etc.
Maps, beams, etc., no time-ordered data	Time-ordered data, maps, beams, etc.
31 "2013 results" papers	∼20 "2015 results" papers, not all at once
FFP6 simulations	FFP8 simulations

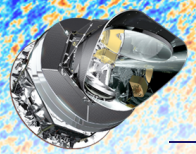
Release will be soon. Recognized but not yet fully characterized systematic errors affect large angular scales in polarization. CMB Q and U maps will be high-pass filtered.

Data will be available from ESA archive at ESAC and NASA archive at IPAC.
Simulations will be available at NERSC.



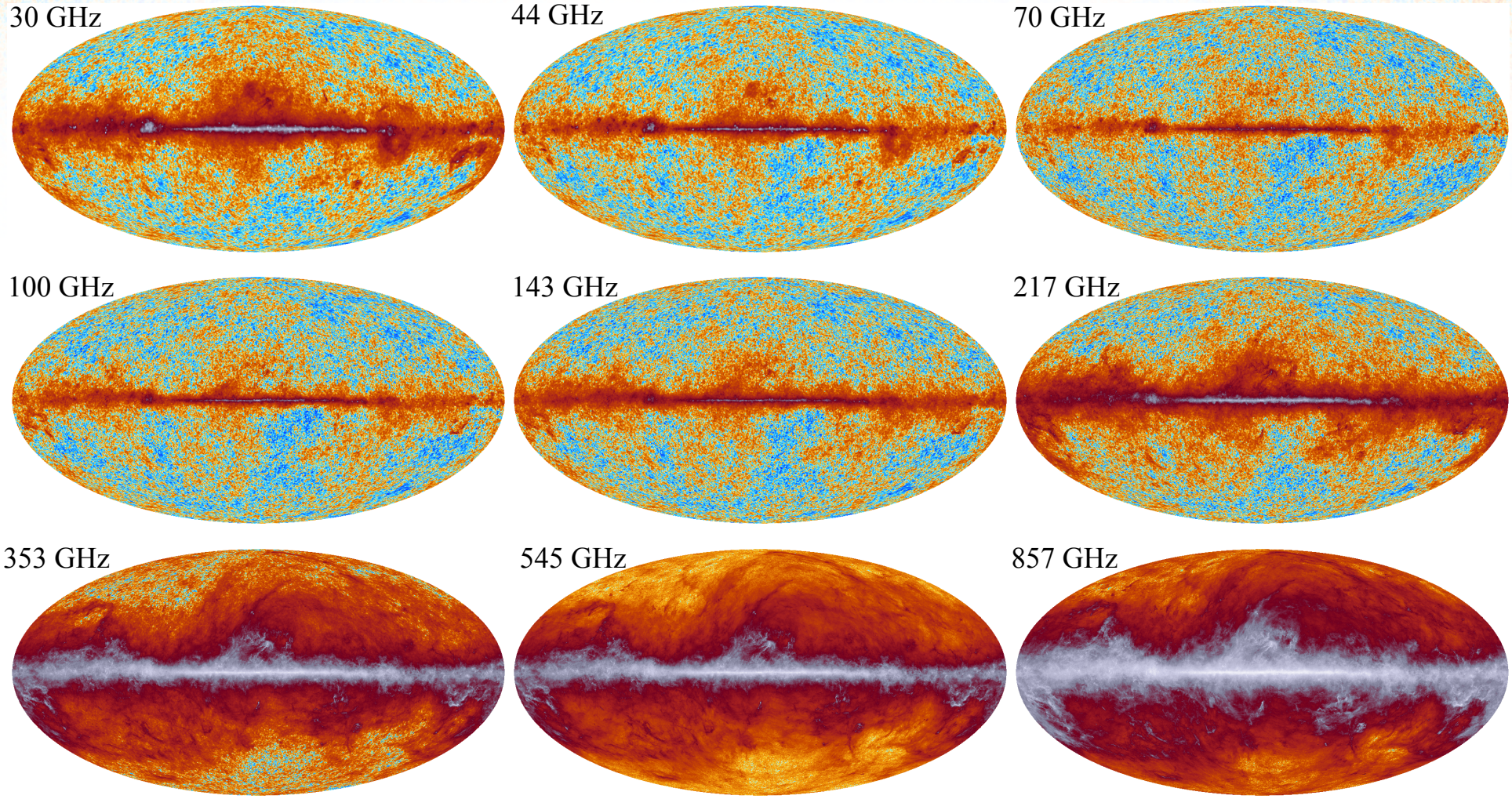
Slides from talks at Ferrara conference last month available at

http://www.cosmos.esa.int/web/planck/ferrara2014

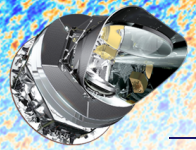


The Universe: Temperature, Nine Frequencies

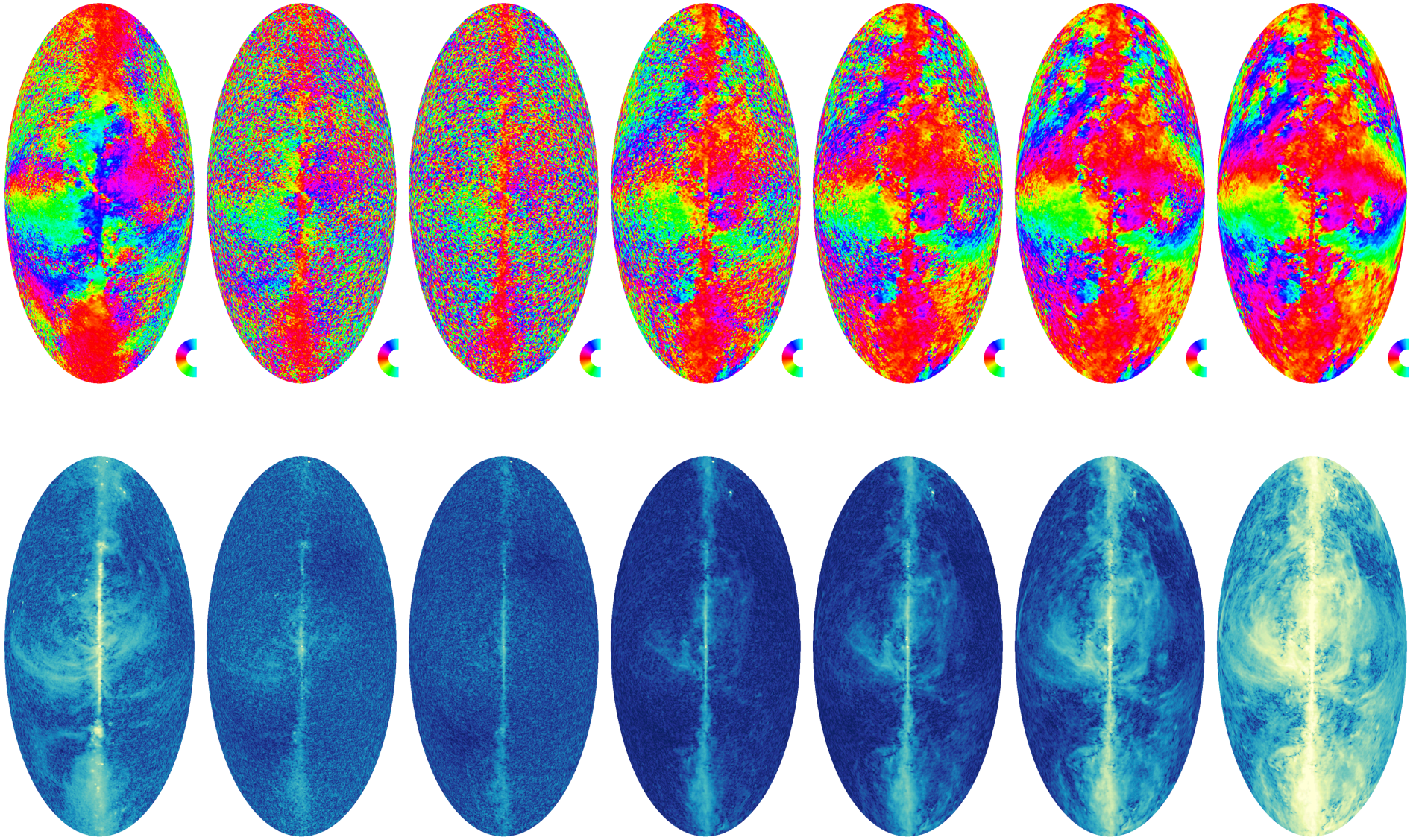
PLANCK



Preliminary



Planck Polarization, Seven Frequencies



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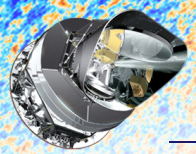
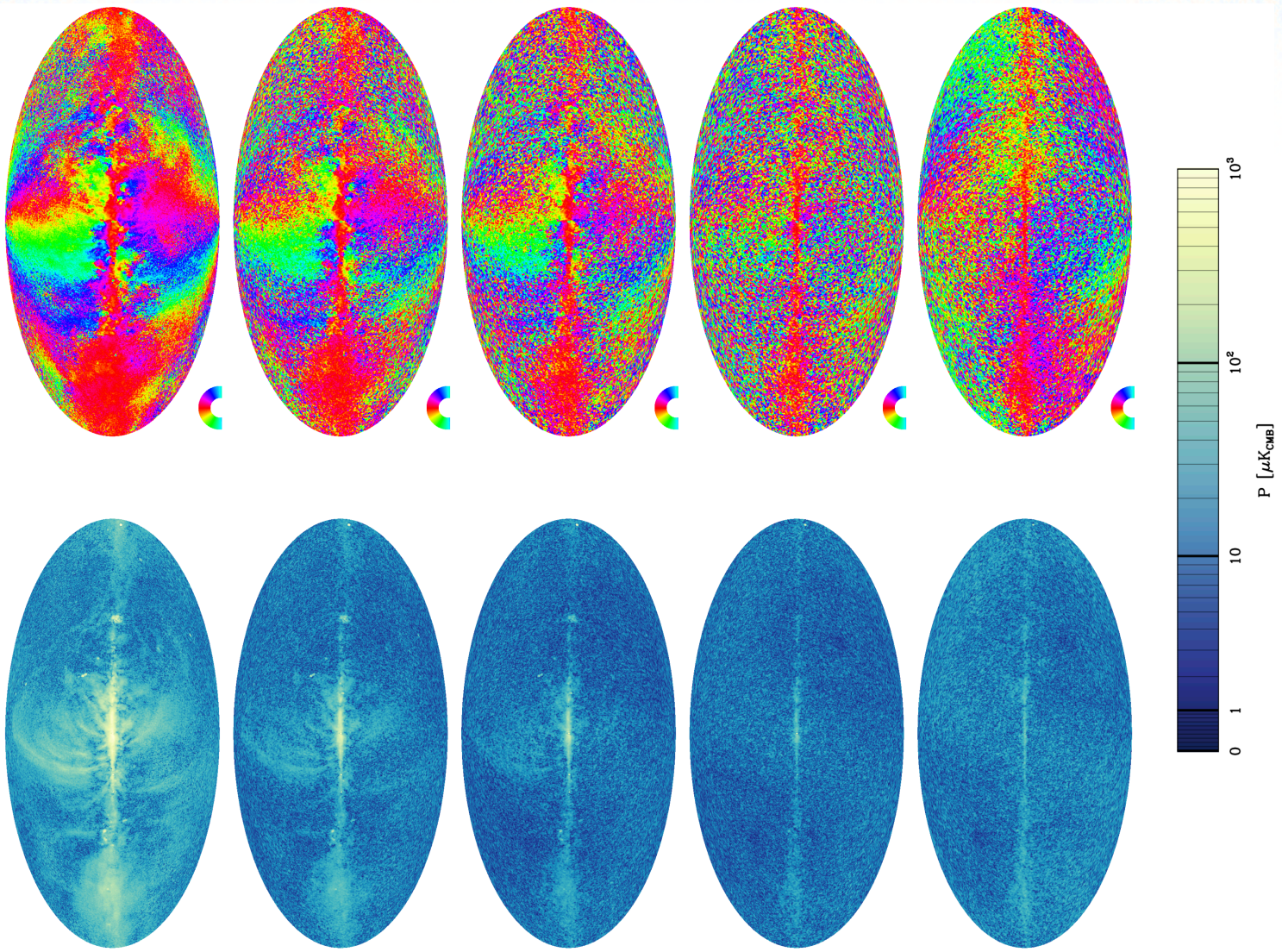
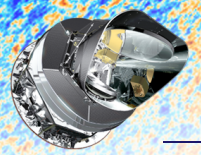


WMAP Polarization, Five Frequencies





Component Separation

Two schemes

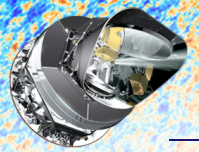
- For CMB and foreground maps
  - Used for higher-order statistics, foreground studies
  - Four methods for separating diffuse foregrounds

    Commander — parametric model fitting in pixel space

    NILC — needlet (wavelet) internal linear combination

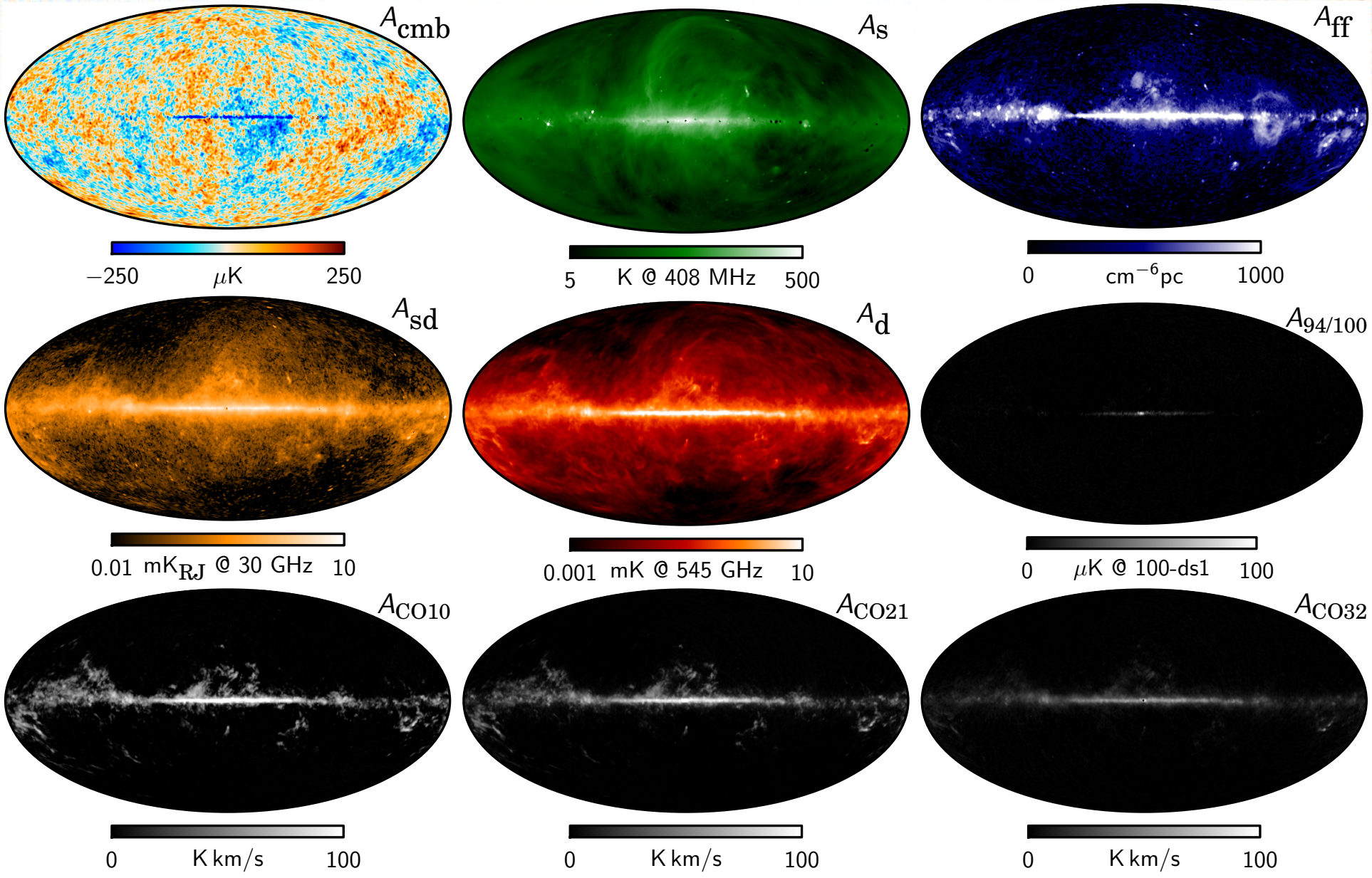
    SEVEM — template fitting in pixel space

    SMICA — non-parametric (low rank) spectral fitting and filtering
  - "Discrete" foregrounds handled various ways depending on use
- For likelihood and parameters (second-order statistics)
  - Modeling and subtraction at the power spectrum level

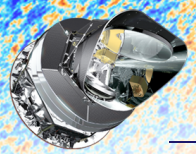


CMB and Foreground Stokes *I* Maps

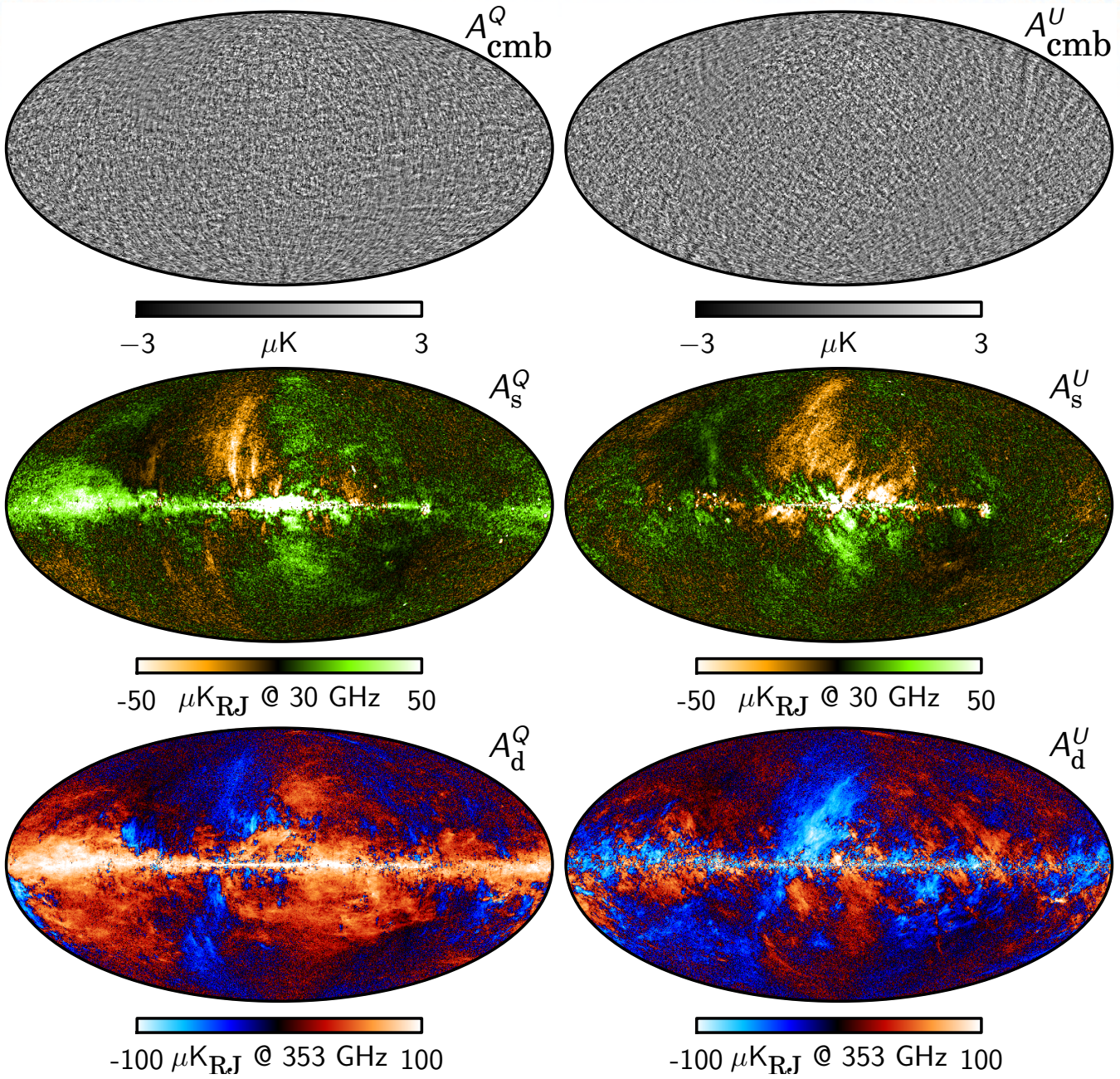
PLANCK



Preliminary



CMB and Foreground Stokes Q, U Maps



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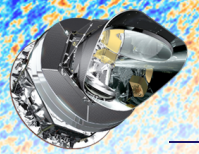
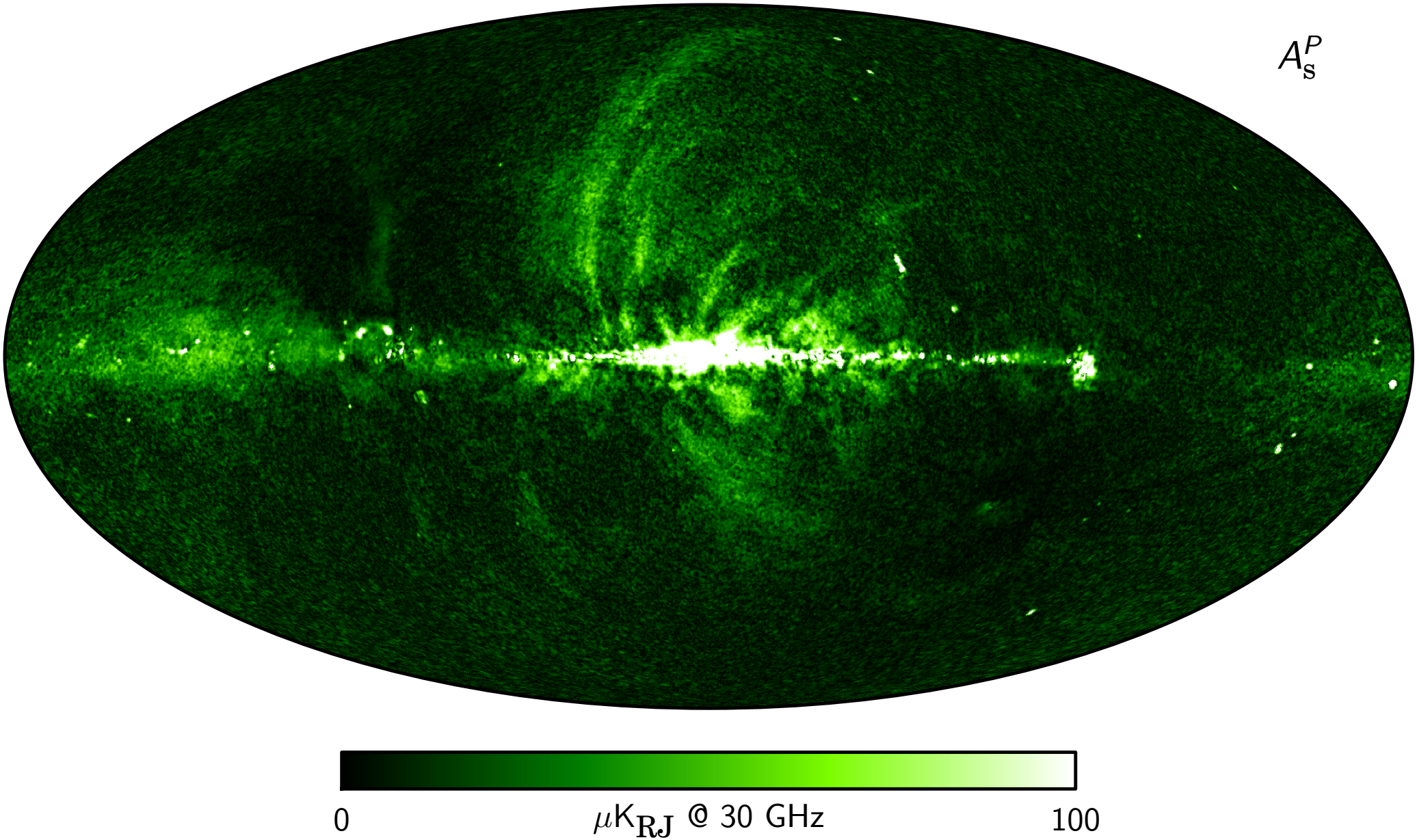
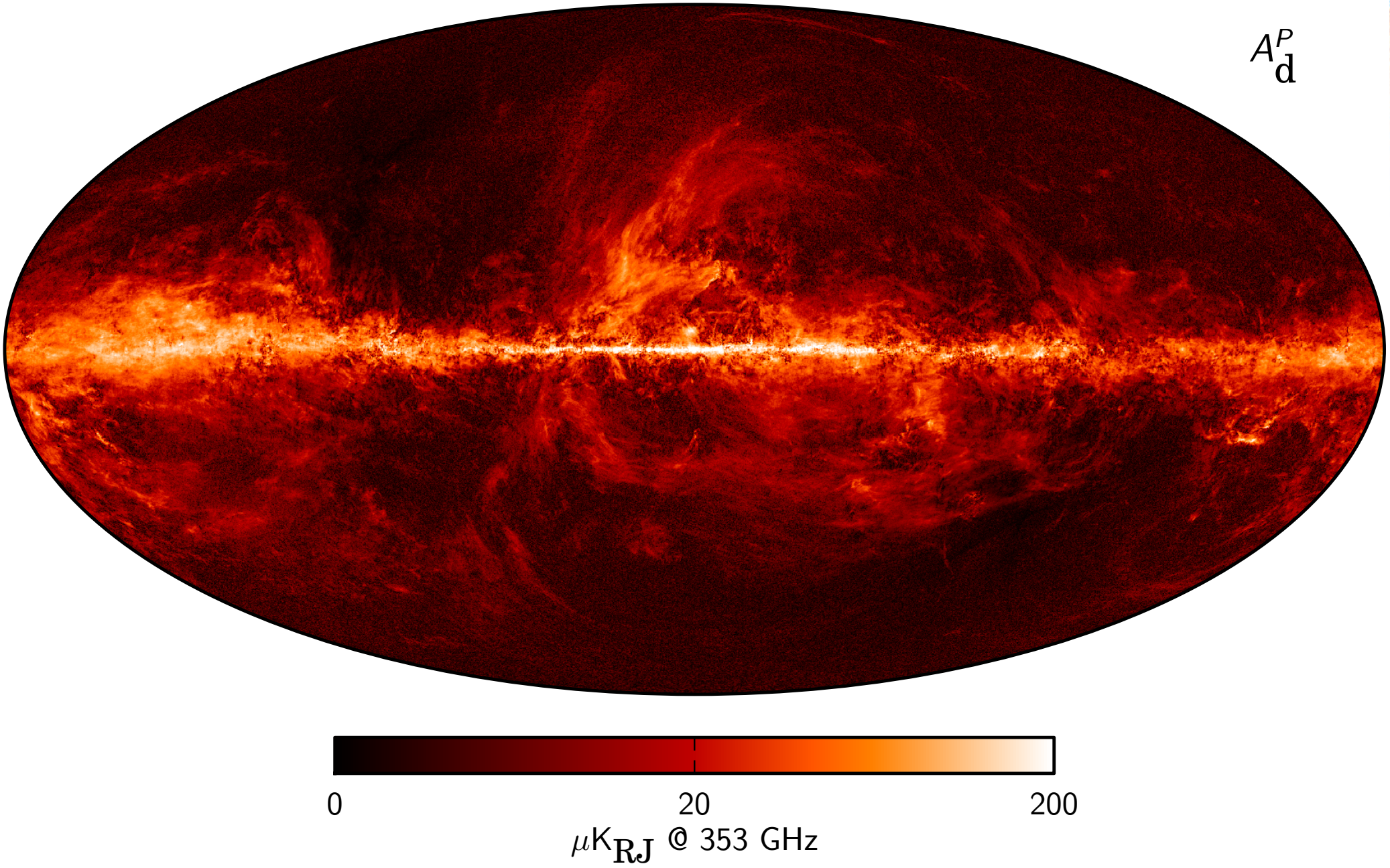


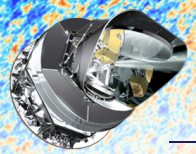
Synchrotron P Map at 30 GHz from Commander

PLANCK

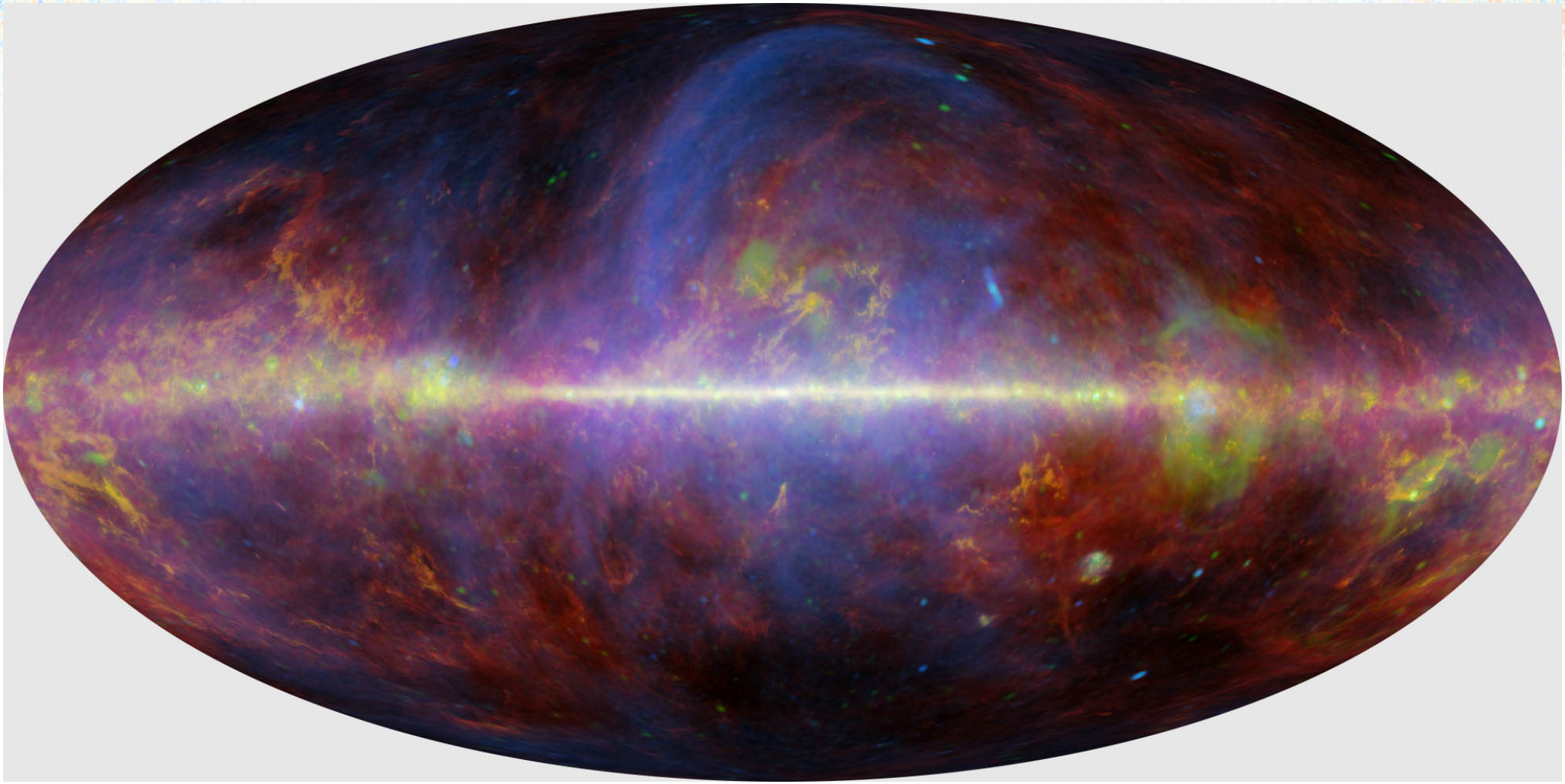


Dust P Map at 353 GHz from Commander

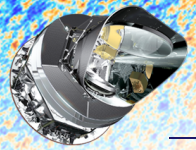




Color-Coded Foregrounds

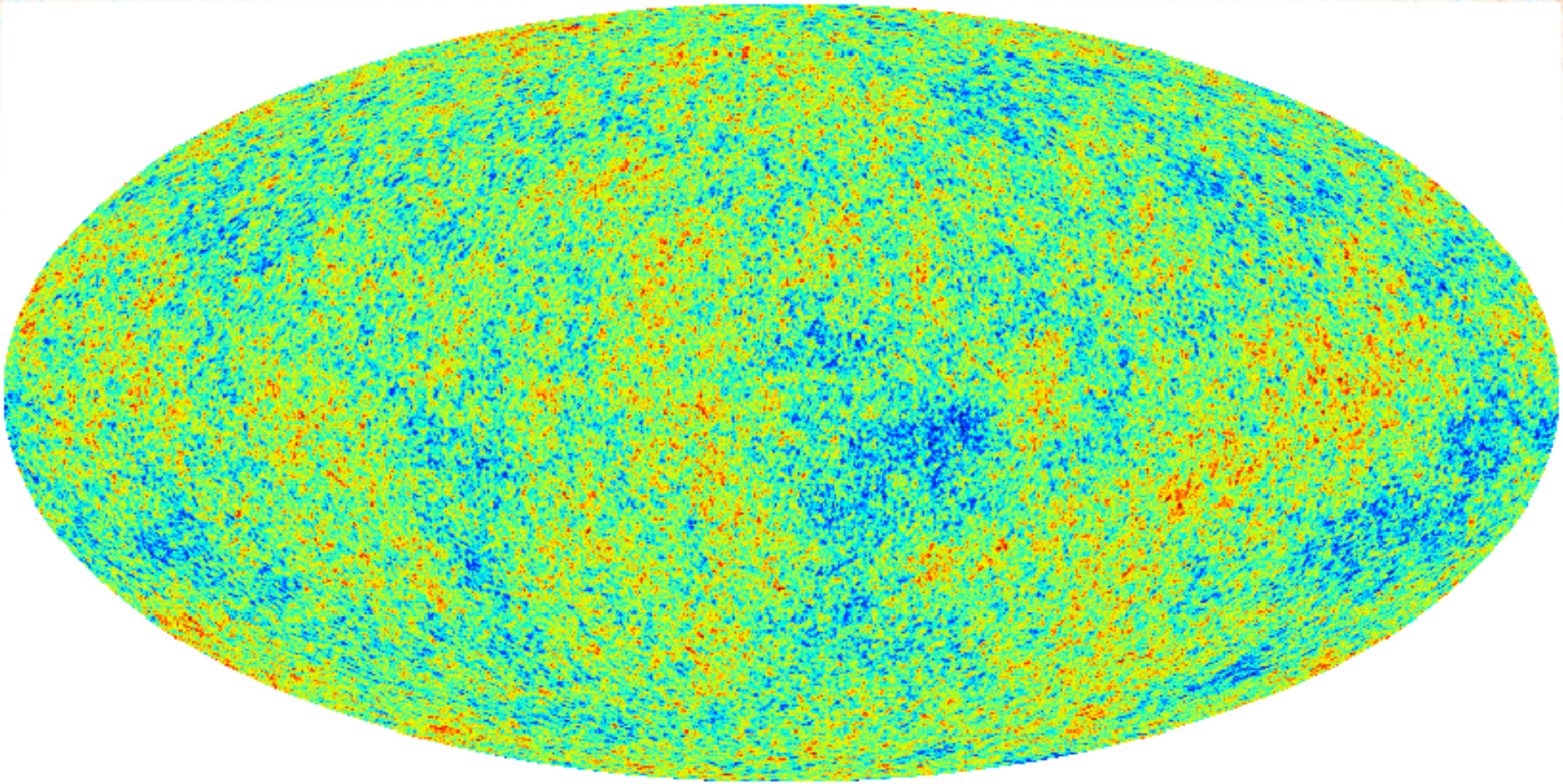


Blue—synchrotron; Green—free-free; Yellow—CO; Red—thermal dust

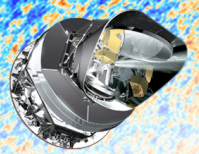


The Universe, Age 370,000 Years

PLANCK

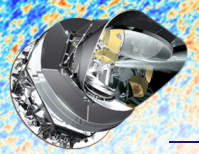


(The plane of the Milky Way is filled in with a "constrained realization".)



PLANCK

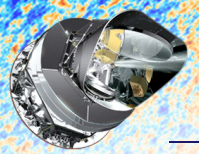
What have we learned?



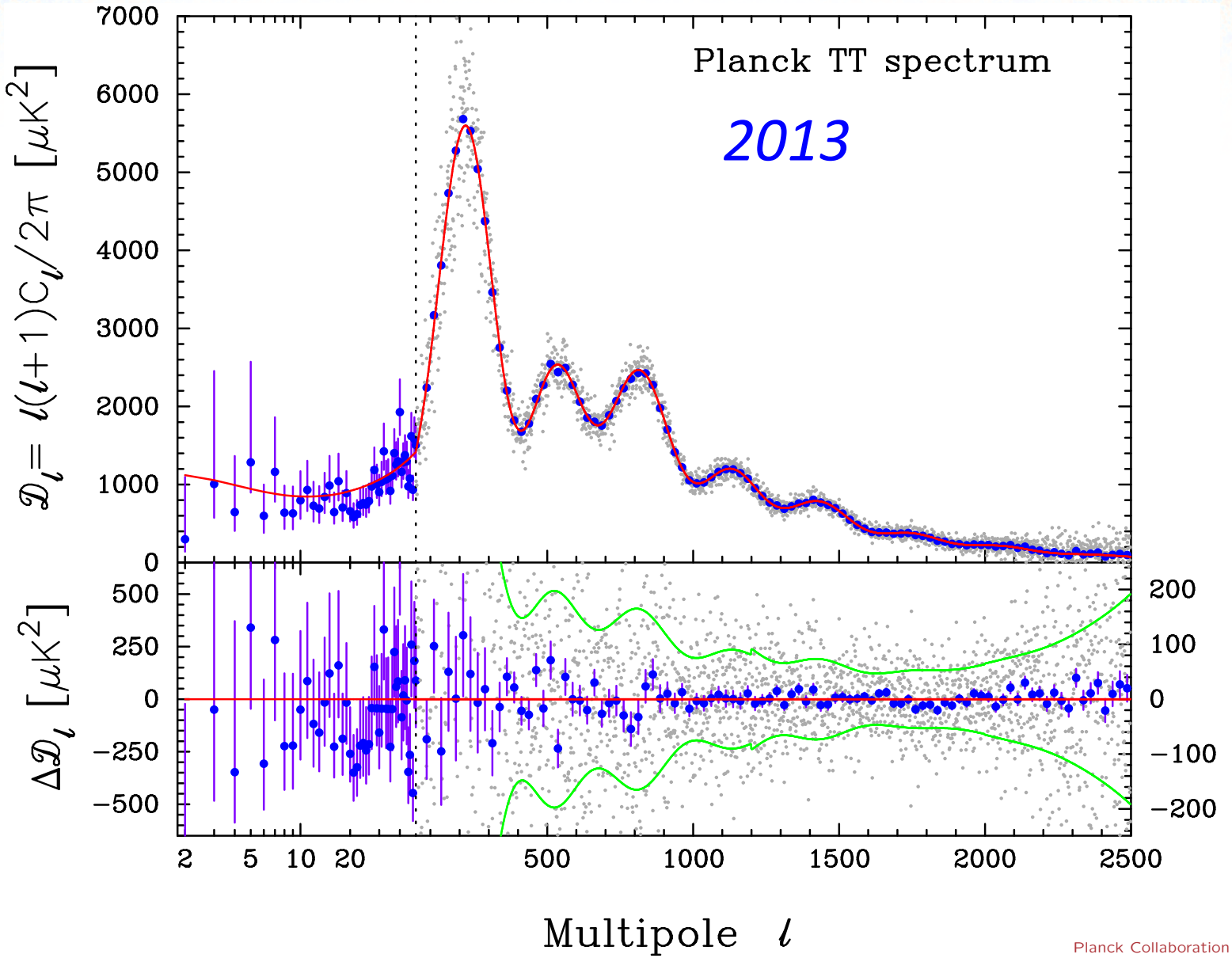
Six Parameters

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

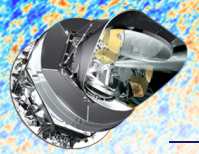
- $A_{\rm S}$, $n_{\rm S}$ — inflation fluctuations; 10^{-35} s;
  - scale invariance ruled out at 7σ
- $\Omega_{\rm b}h^2$, $\Omega_{\rm c}h^2$ — baryons and cold dark matter; first few minutes
  - 0.6% and 1.1% precision
- $\theta_{\rm MC}$ — sound horizon; 370,000 years
  - 0.03% precision
- τ — reionization optical depth; 13.8 billion years
  - 1σ lower than before



Angular Power Spectrum + Best-Fit Model, 2013

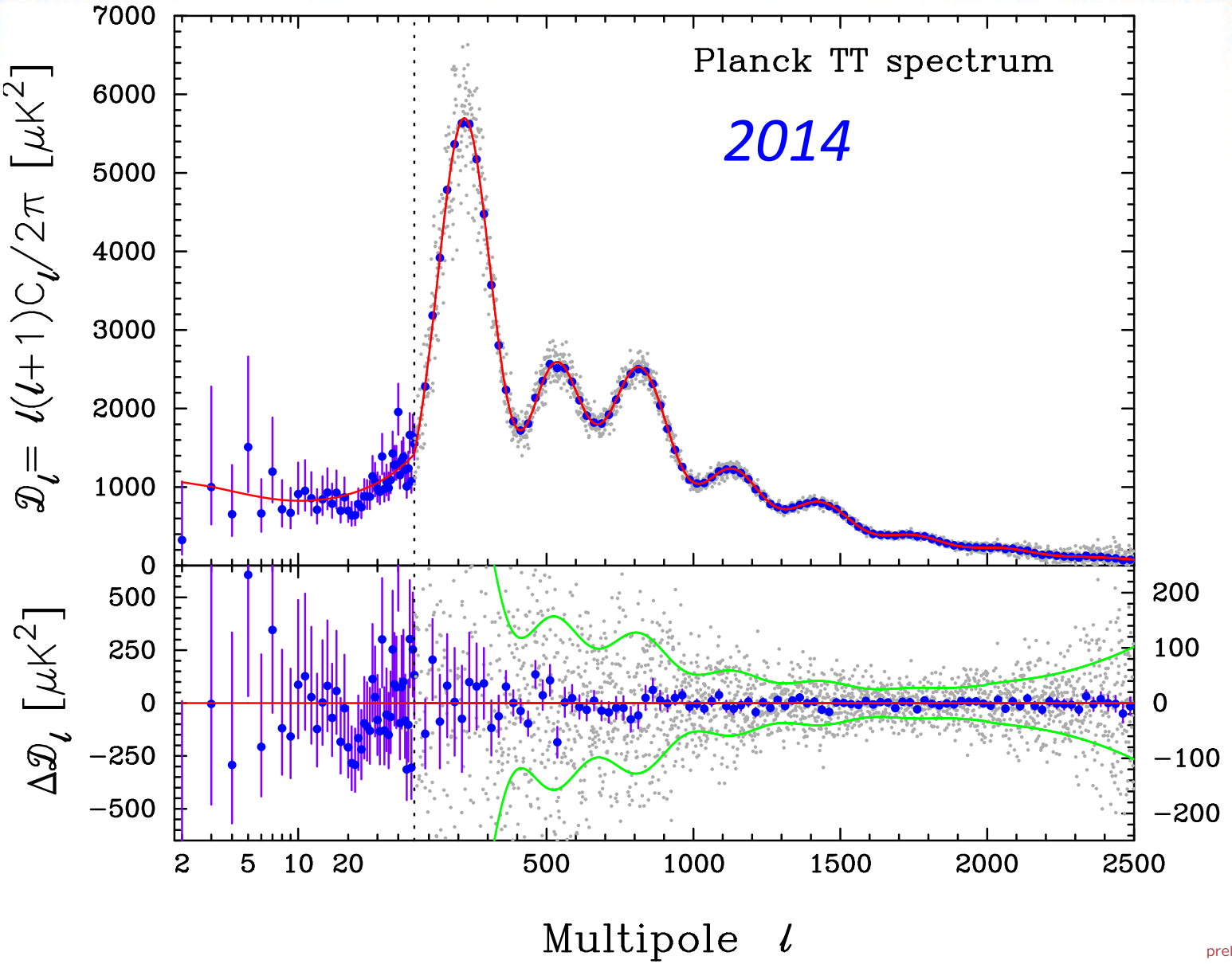


Planck Collaboration I 2013

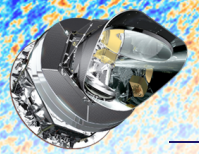


Angular Power Spectrum + Best-Fit Model, 2015

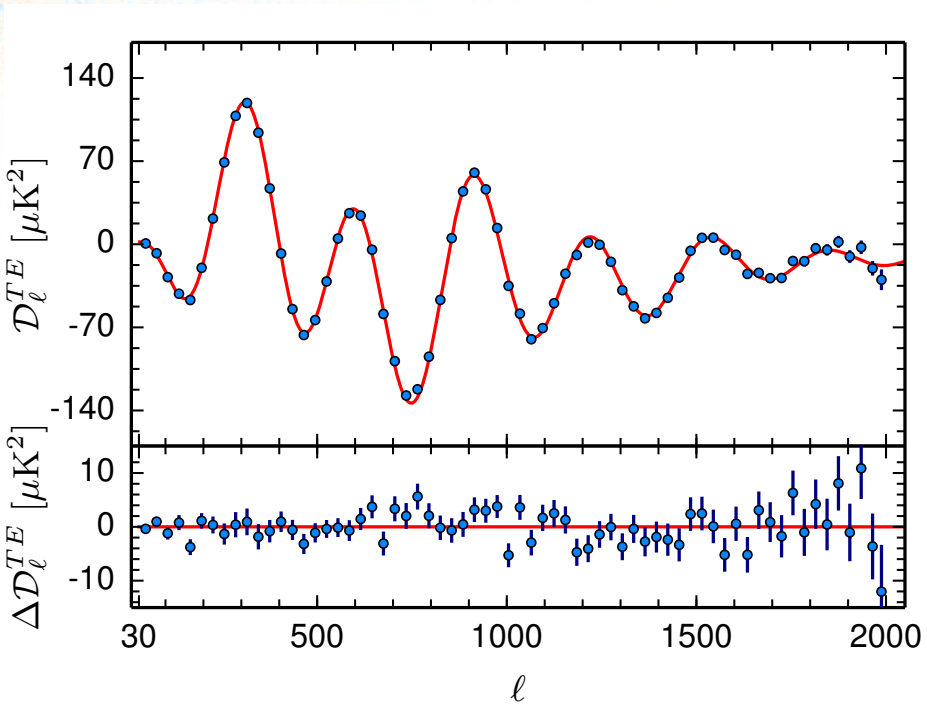
PLANCK

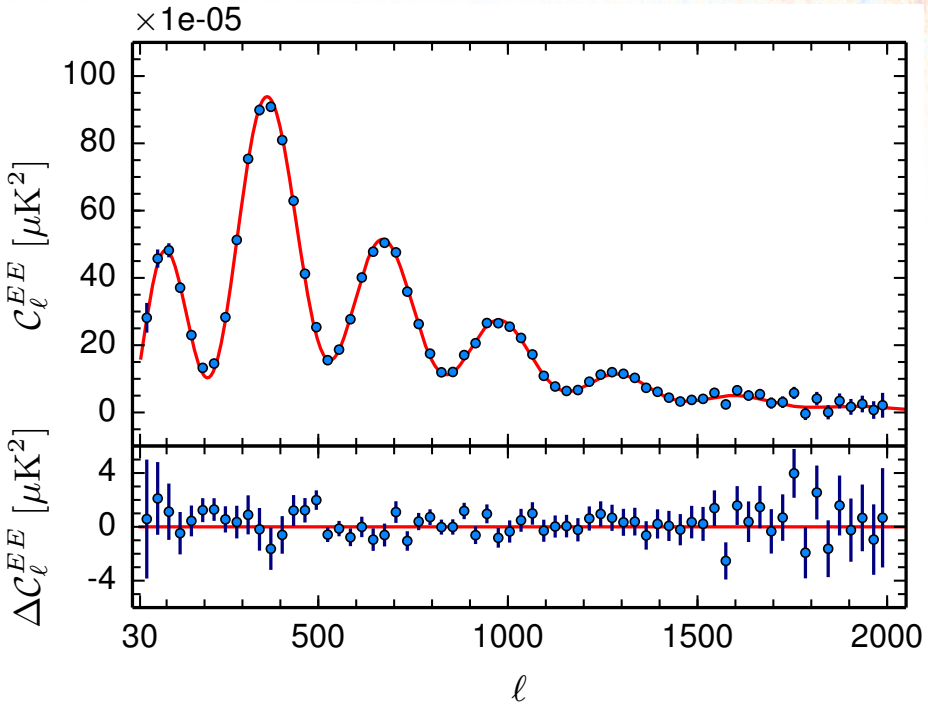


preliminary



Polarization Spectra, Same Model





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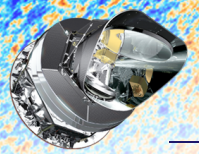
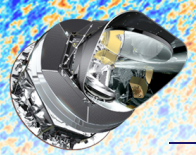


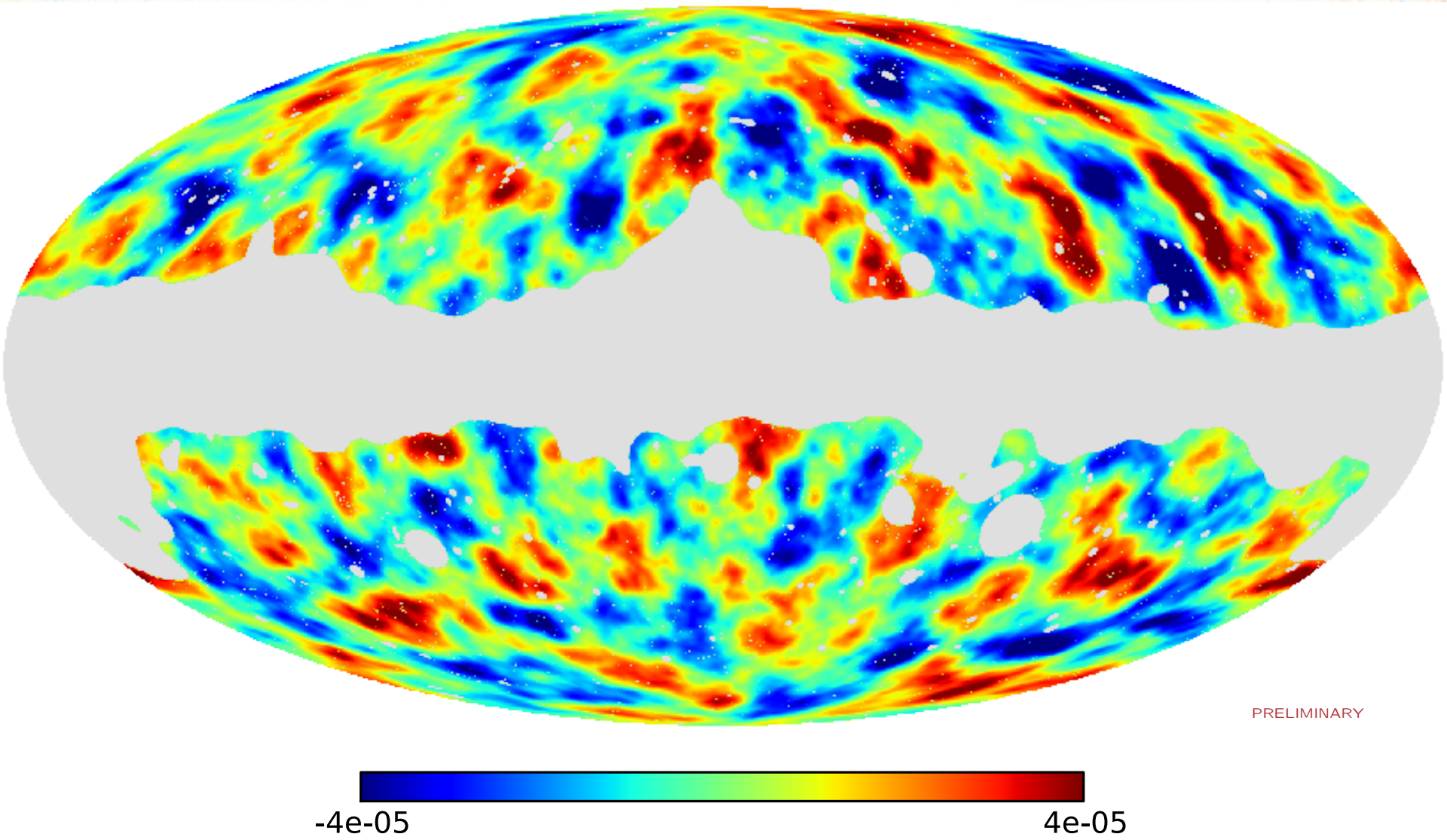
Changes in ΛCDM Model Parameters

- 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!
- Thomson τ lower by $\sim 1\sigma$ (so $z_{\rm re}$ decreased $\sim 1\sigma$)
  - But calibration increased power, so σ_8 hardly changed
- $n_{\rm s}$ increased by $\sim 0.7\sigma$
- $\omega_{\rm b}$ increased by $\sim 0.6\sigma$ and error decreased.
- Limits on isocurvature modes, $\Omega_{\rm K}$, m_ν, $\Delta N_{\rm eff}$, $f_{\rm NL}$, DM annihilation, etc., all tighter. No deviations detected.

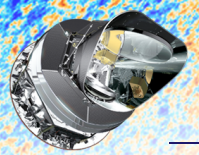
Preliminary



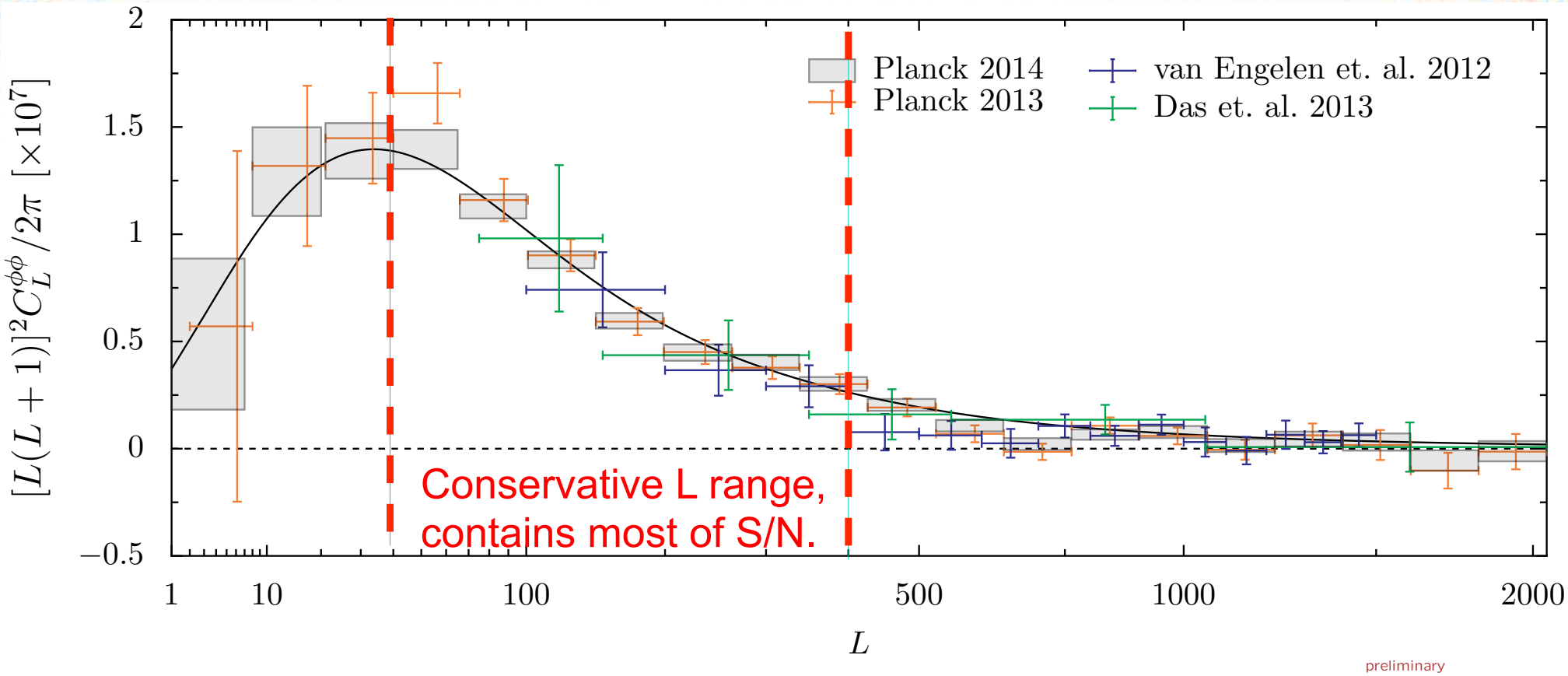
Lensing Potential



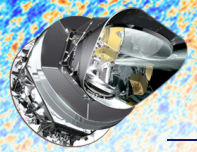
- Lensing now measured at 40σ. Better than predicted by anisotropy!



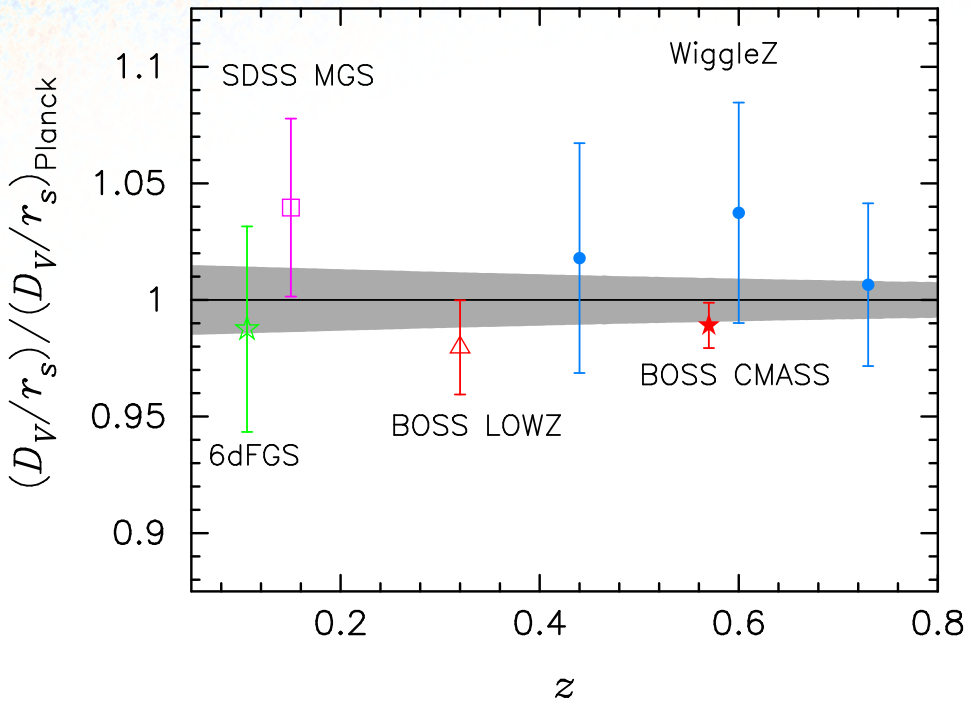
Lensing Spectrum

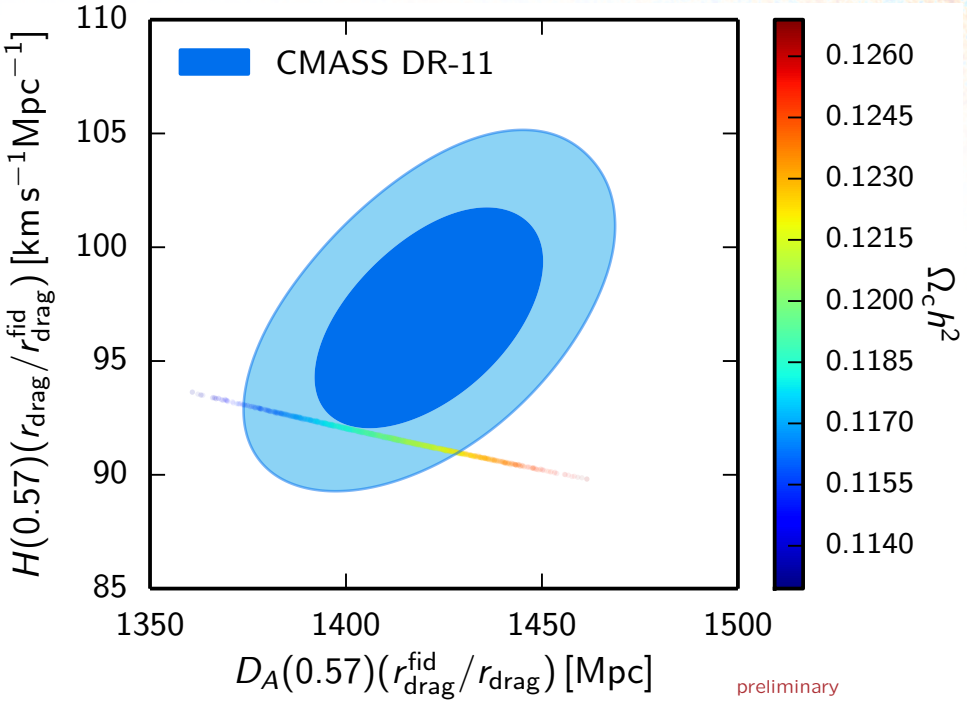


- Constrains $\sigma_8 \Omega_{\rm M}^{1/4}$ to 3.5%!



Baryon Acoustic Oscillations



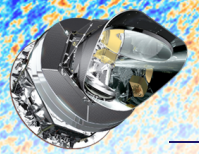


- Excellent agreement between Planck, BAO surveys. . .

$r_s =$ comoving sound horizon at end of baryon drag epoch

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

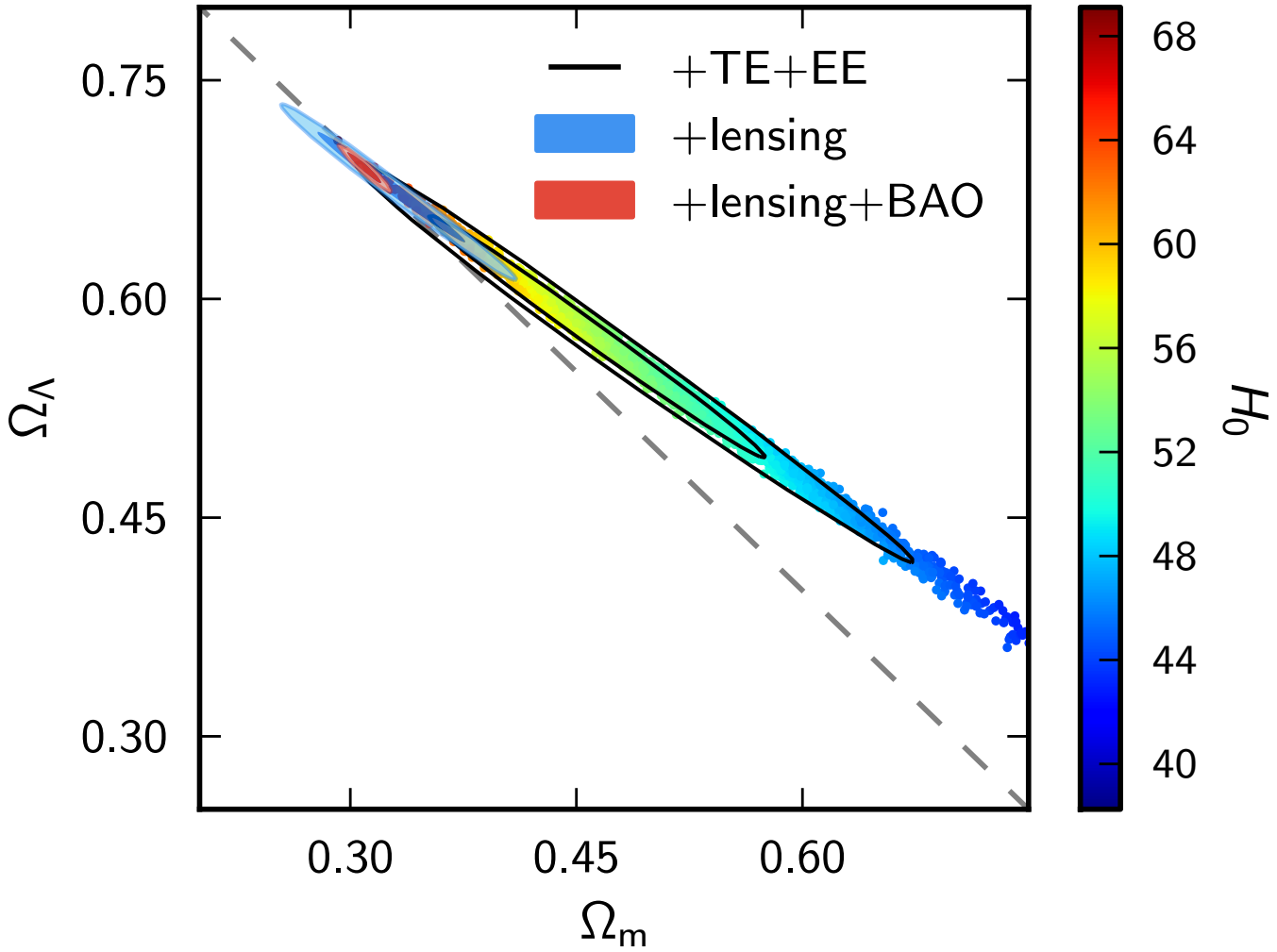
$D_{\rm A} =$ angular diameter distance



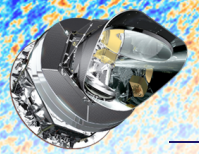
Spatial Curvature

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

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

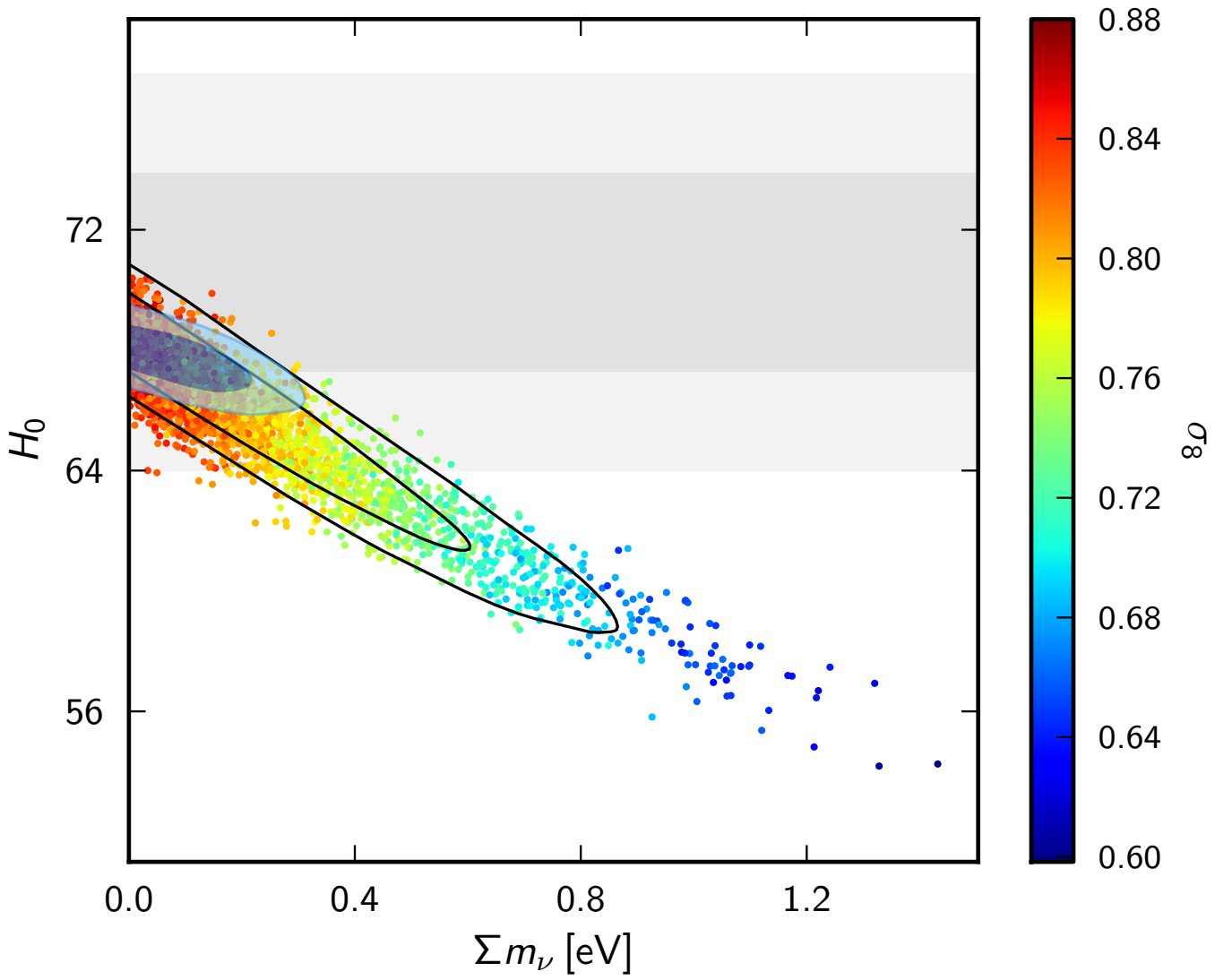


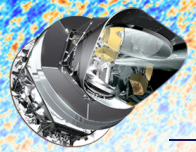
preliminary



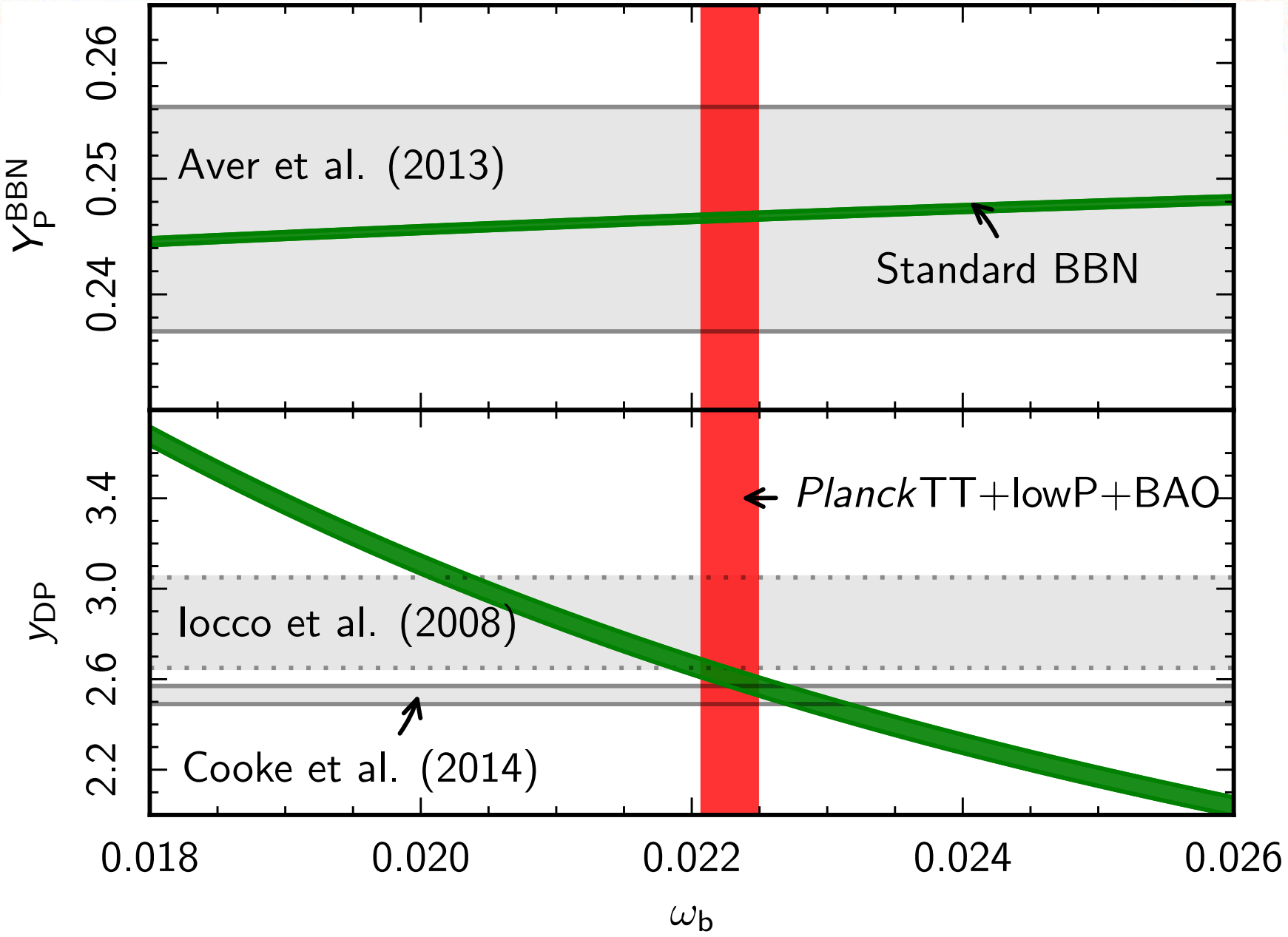
Neutrino Masses

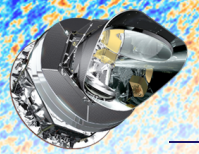
- . . . and on neutrino masses $\Sigma_\nu < 0.21\,\mathrm{eV}$ (95%)





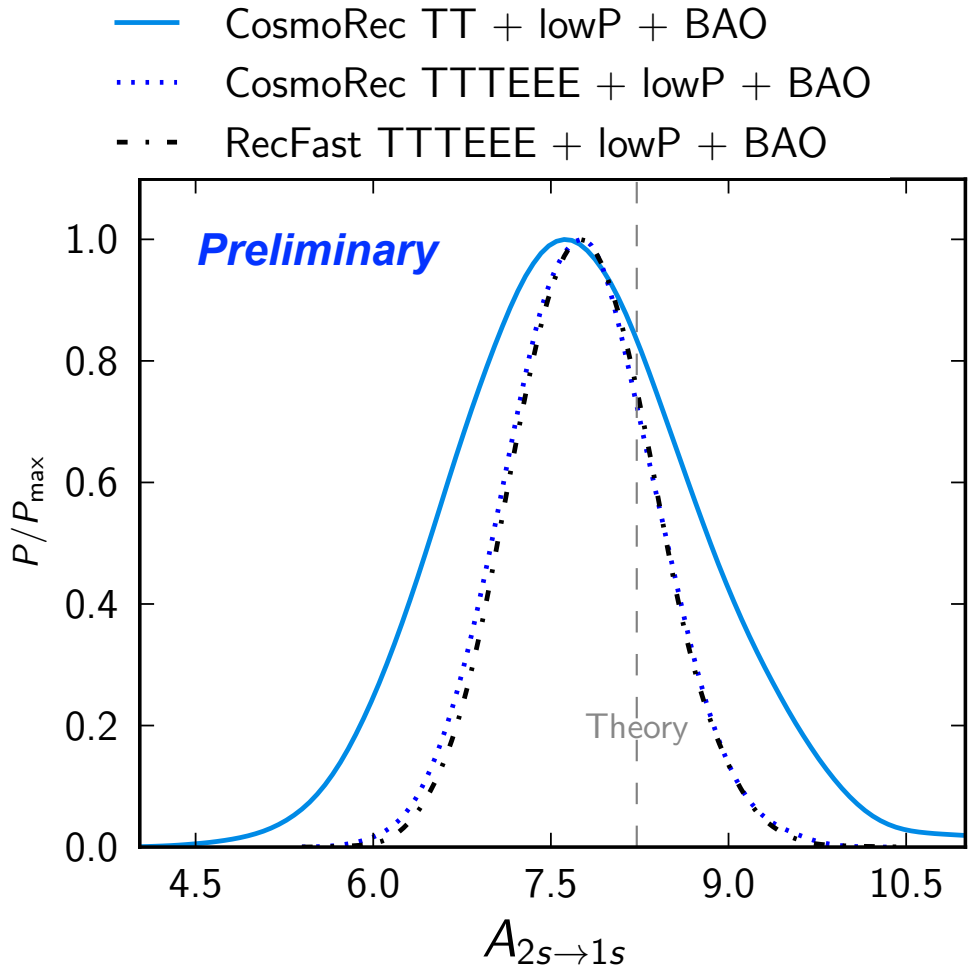
Big Bang Nucleosynthesis





Atomic Physics

- Hydrogen 2s→1s two-photon rate crucial for recombination dynamics
- Best lab measurement has 43% error (Labzowsky et al. 2005)
- Planck data directly constrain its value



- $A_{2s\to1s}^{\rm theory} = 8.2206\,{\rm s}^{-1}$
- $A_{2s\to1s} = 7.71 \pm 0.99\,{\rm s}^{-1}$

  Planck TT + lowP + BAO
- $A_{2s\to1s} = 7.75 \pm 0.61\,{\rm s}^{-1}$

  Planck TT, TE, EE + lowP + BAO
- Planck measurement in excellent agreement with theoretical value

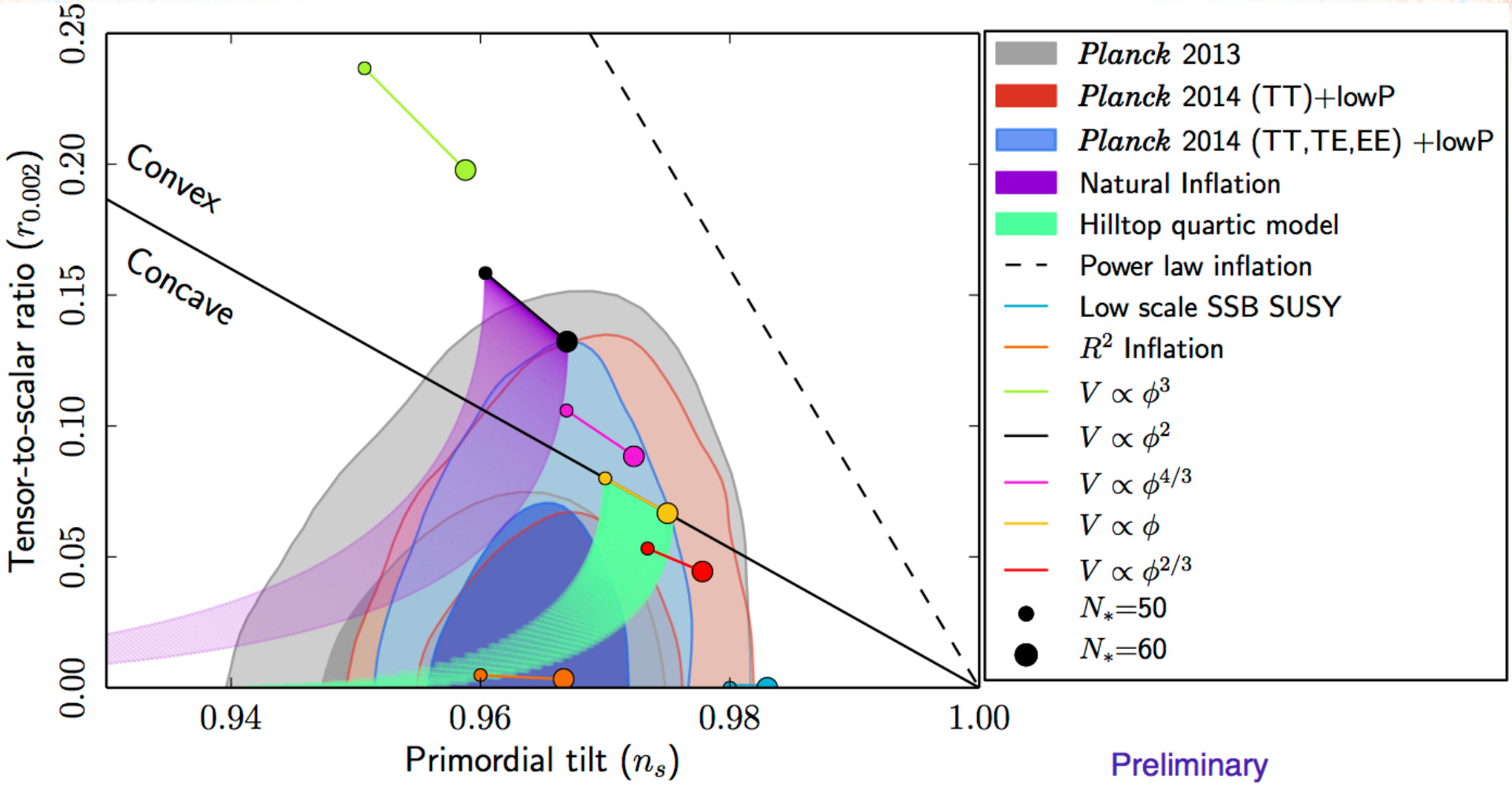
Planck 2014

Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	**1.8 ± 5.6**
Equilateral	−10 ± 69	**−9.2 ± 69**
Orthogonal	−43 ± 33	**−20 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.1	**0.71 ± 5.1**
Equilateral	−8.9 ± 44	**−9.5 ± 44**
Orthogonal	−35 ± 22	**−25 ± 22**

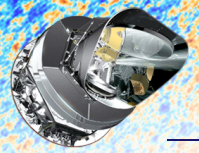
Planck 2013

	ISW-lensing subtracted		
	KSW	Binned	Modal
Local	**2.7 ± 5.8**	2.2 ± 5.9	1.6 ± 6.0
Equilateral	**−42 ± 75**	−25 ± 73	−20 ± 77
Orthogonal	**−25 ± 39**	−17 ± 41	−14 ± 42

Constraints on Inflation

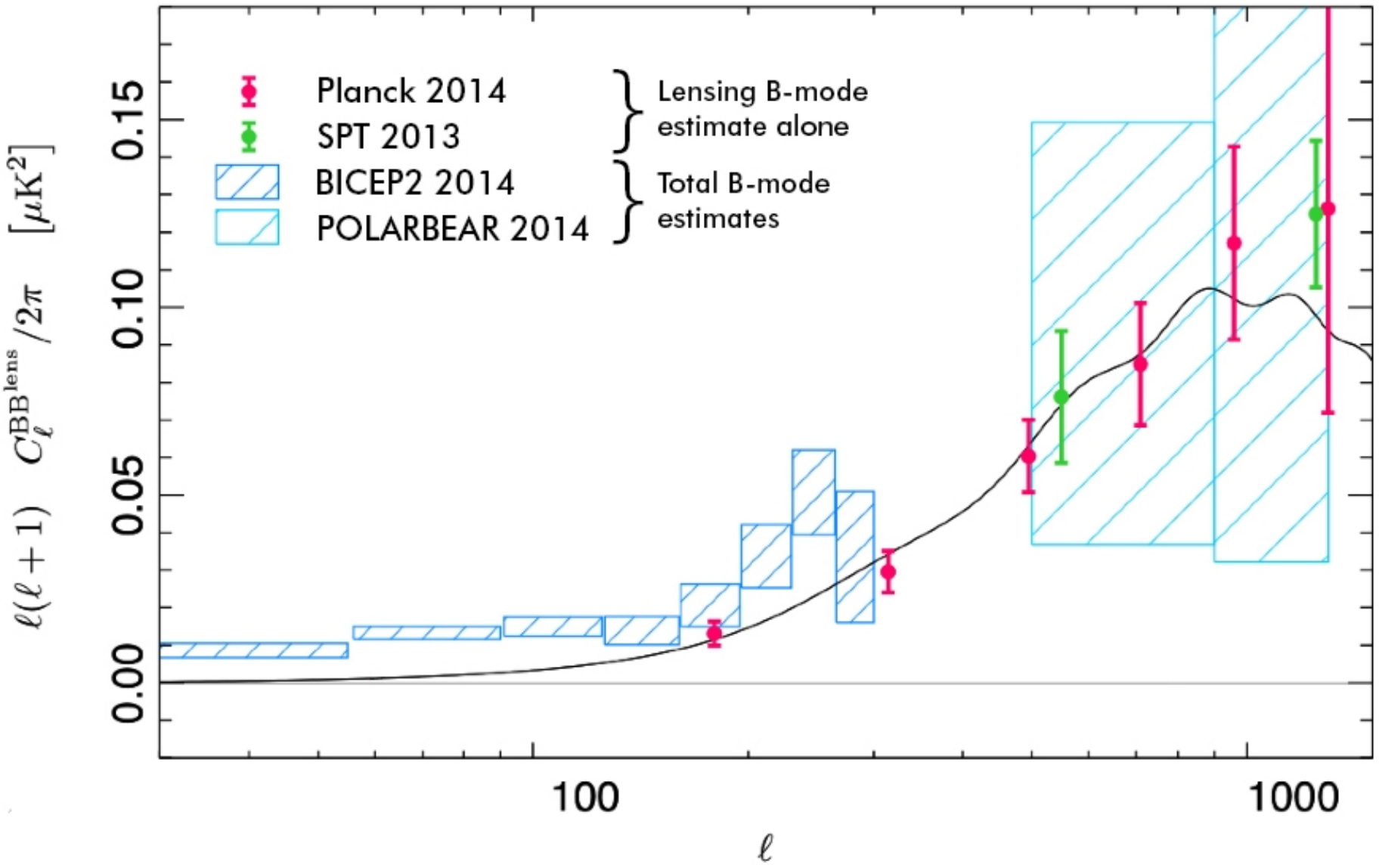


- Constraint on tensor-to-scalar ratio ($r_{0.002} < 0.10$ at 95% CL with no "running" with Planck TT and lowP is dominated by the temperature low-ℓ tail.
- Tighter constraints on inflationary models by Planck 2015 data.



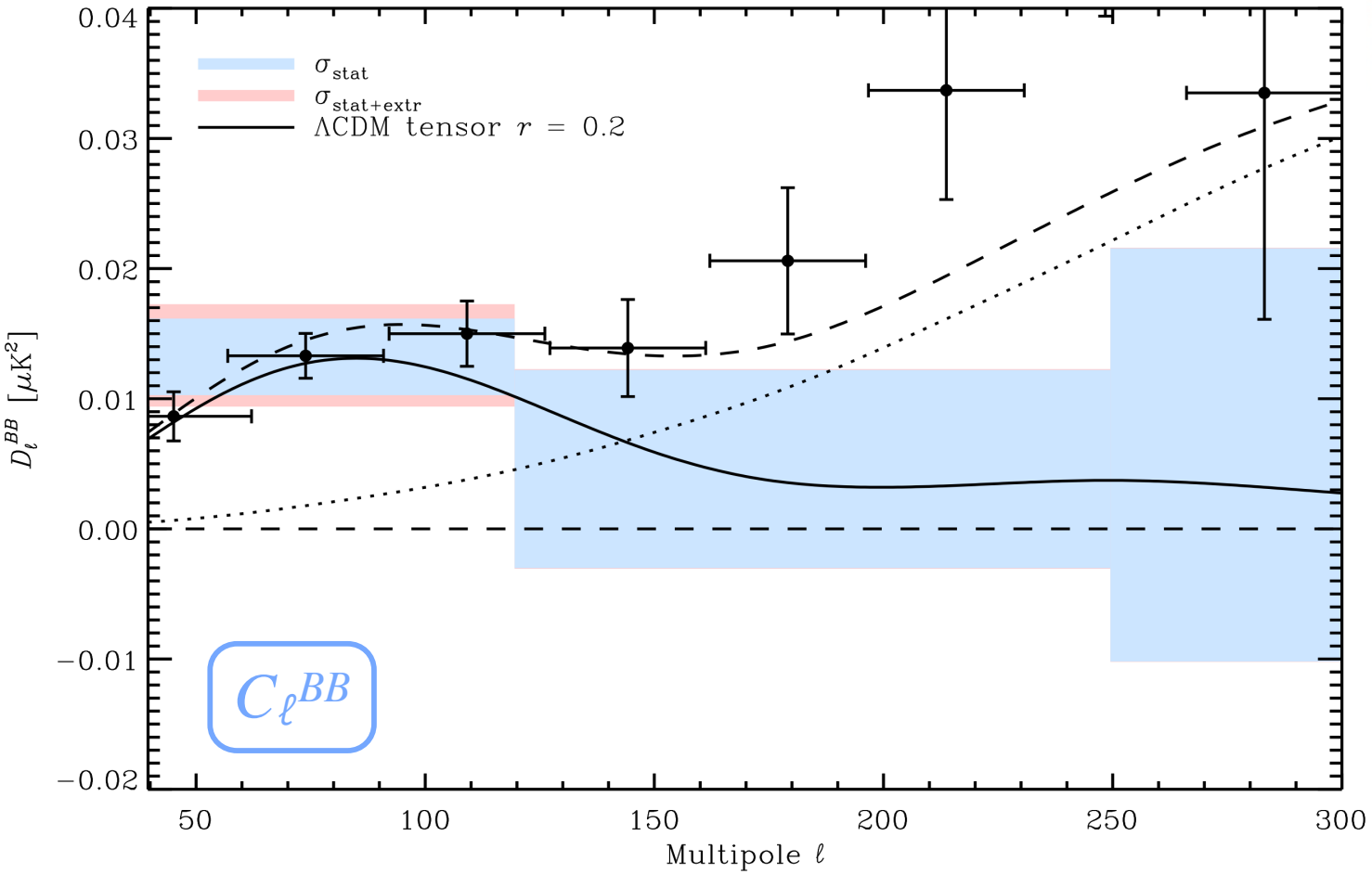
Lensing B-mode Spectrum

PLANCK

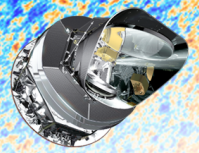


Planck and the BICEP2 Field

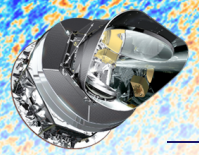
★ Computation of the *BB* spectrum at 353 GHz in the BICEP2 regio
★ Extrapolation to 150 GHz



★ 4.5σ detection of the dust at 353 GHz
★ 3.6σ prediction at 150 GHz
★ Prediction of the dust level similar to the *B*-modes measured by BICEP2



Systematics



Low Noise

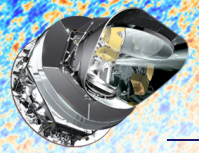
- Necessary. . .

Noise **measured in-flight**, full mission (CMB channels)

	30GHz	44GHz	70GHz	100GHz	143GHz	217GHz	353GHz
Angular resolution [arcmin]	33.2	28.1	13.1	9.7	7.3	5.0	4.9
Noise sensitivity [$\mu K_{CMB}\ s^{1/2}$]	148.5	173.2	151.9	41.3	17.4	23.8	78.8
NOISE/PIXEL							
From detector sensitivity [μK_{CMB}]	9.2	12.7	23.9	9.6	5.4	10.7	36.5
Measured from maps [μK_{CMB}]	9.2	12.5	23.2	11.2	6.6	12.0	43.2
Extended mission [months]	*48*	*48*	*48*	*29*	*29*	*29*	*29*
End-of-missioni [μK_{CMB}]	5.2	7.1	13.2	8.2	4.8	8.8	31.6
Measured End-of-Mission [$\Delta T/T$, $\mu K/K$]	**1.9**	**2.6**	**4.8**	**3.0**	**1.8**	**3.2**	**11.6**
2005: Blue book GOAL [$\Delta T/T$, $\mu K/K$]	**2.0**	**2.7**	**4.7**	**2.5**	**2.2**	**4.8**	**14.7**
1996: Red book GOAL [$\Delta T/T$, $\mu K/K$]				**~ 2**			

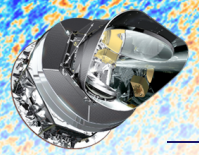
At end of mission, Planck fulfills completely the very ambitious sensitivity goals proposed in the design phase many years ago

- . . .But not nearly enough

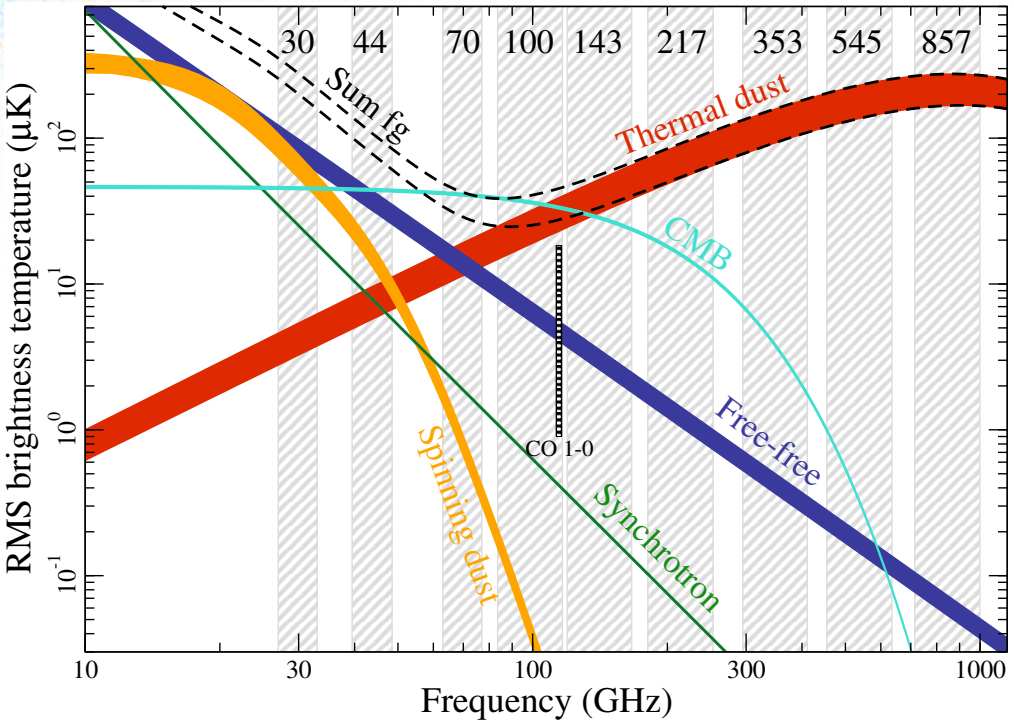


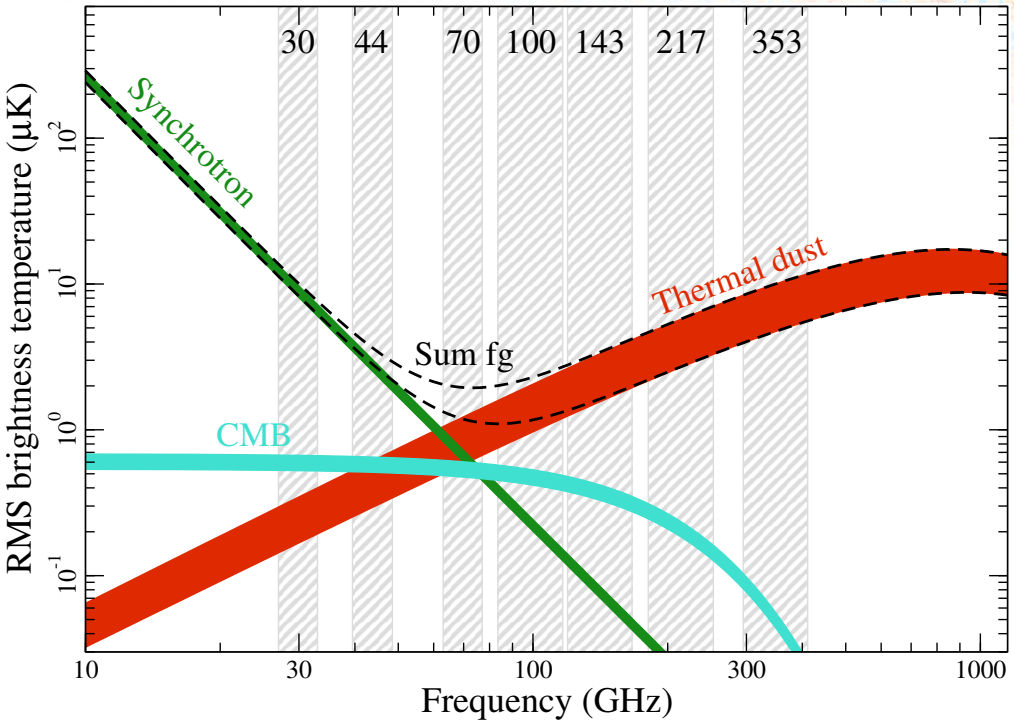
Ultimate Limits

- Foregrounds
- Systematics



Foregrounds



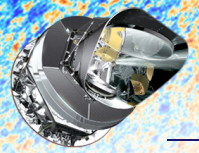


Temperature

- All components smoothed to 1°
- Sky fractions 81–93% of sky
- Foreground minimum 80 GHz (81%)
  90 GHz (93%)

Polarization

- All components smoothed to 40′
- Sky fractions 73–93% of sky
- Foreground minimum 70 GHz (73%)
  85 GHz (93%)

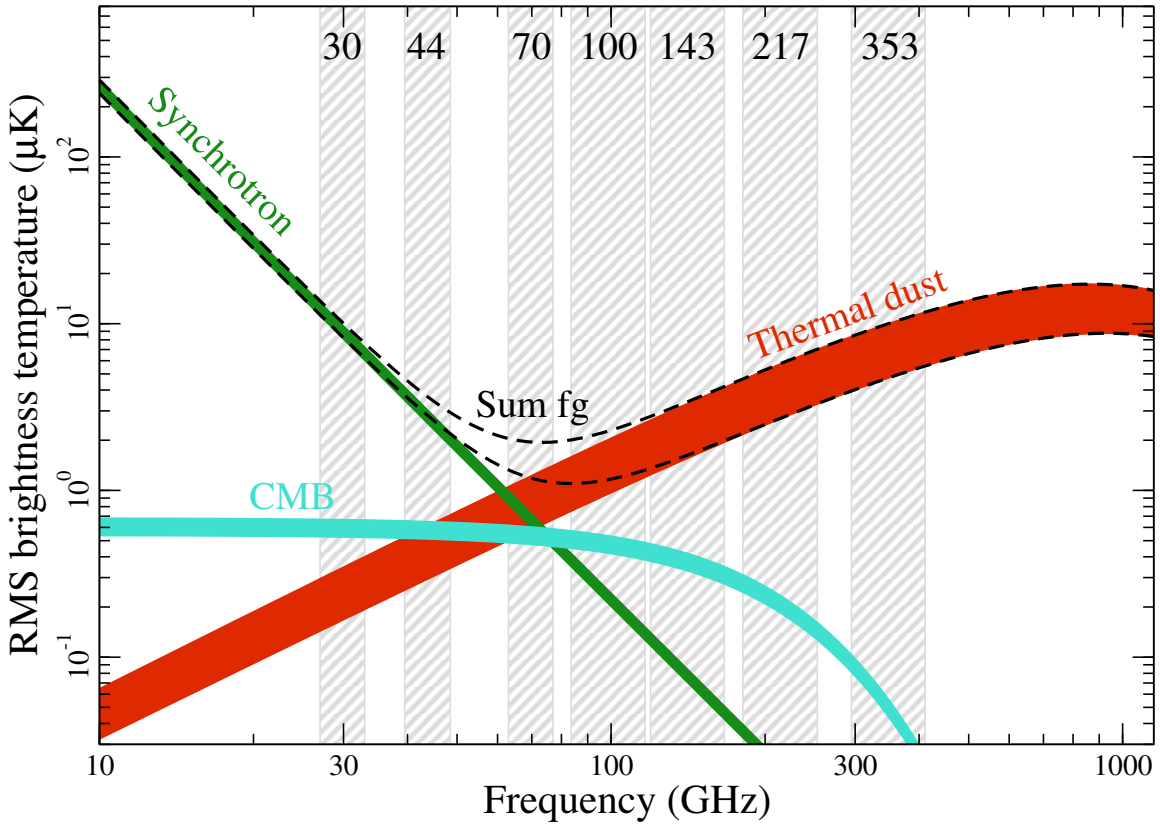


What About...?

- "Observe above (below) the minimum. Better to observe one foreground well than many."
- "Dust isn't highly polarized."
- "Observe in really clean patches of sky."

Foregrounds—cont'd

- "Observe above (below) the minimum. Better to observe one foreground well than many."



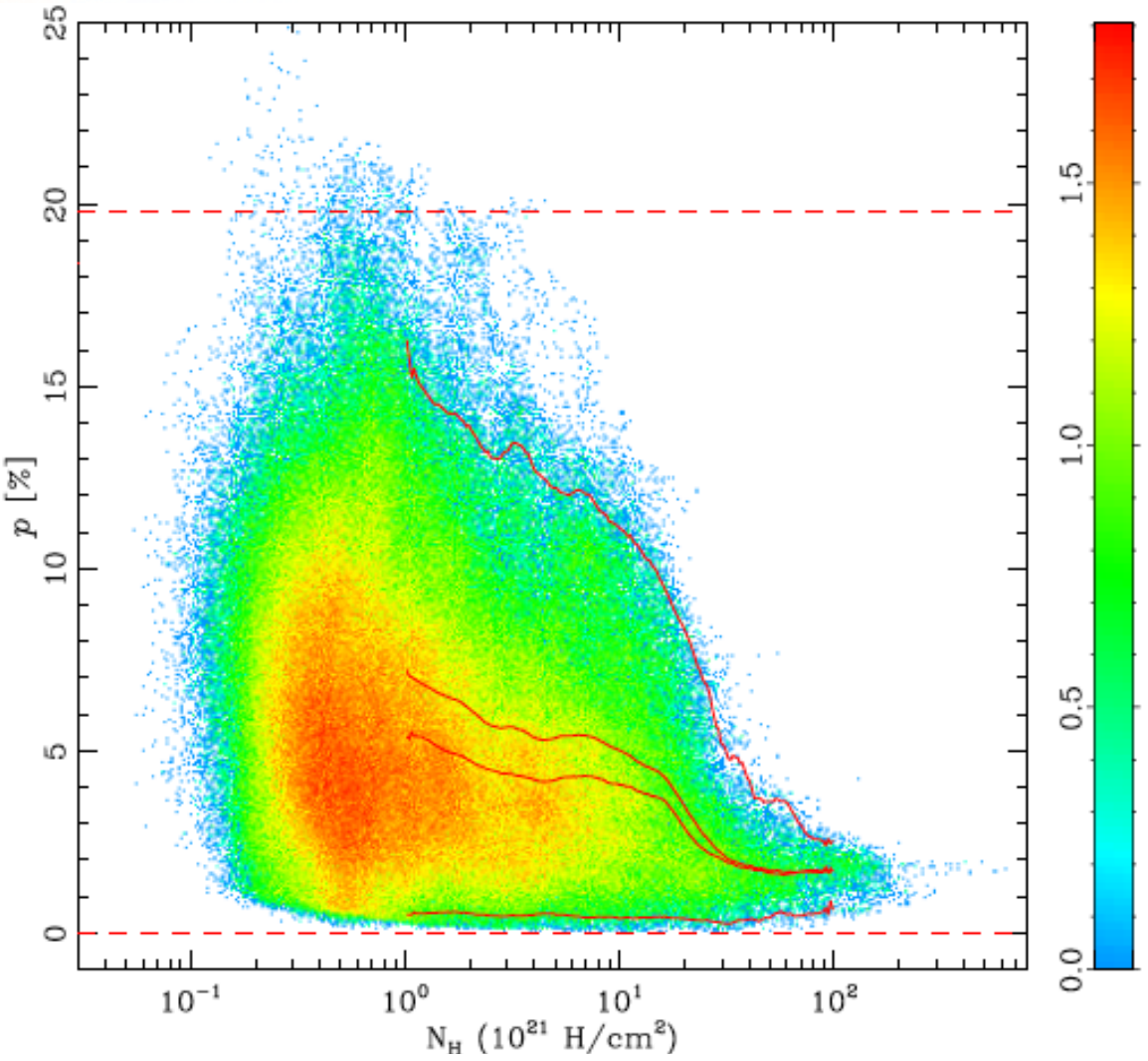
At 73% of sky: $\text{Dust}_{\text{pol}} > 0.1 \times \text{CMB}_{\text{pol}}$ above 13 GHz
$\text{Synch}_{\text{pol}} > 0.1 \times \text{CMB}_{\text{pol}}$ below 200 GHz

$\text{Dust}_{\text{pol}} > 10 \times \text{CMB}_{\text{pol}}$ above 200 GHz
$\text{Synch}_{\text{pol}} > 200 \times \text{CMB}_{\text{pol}}$ below 13 GHz

Doomed!

Foregrounds—cont'd

- "Dust isn't highly polarized."



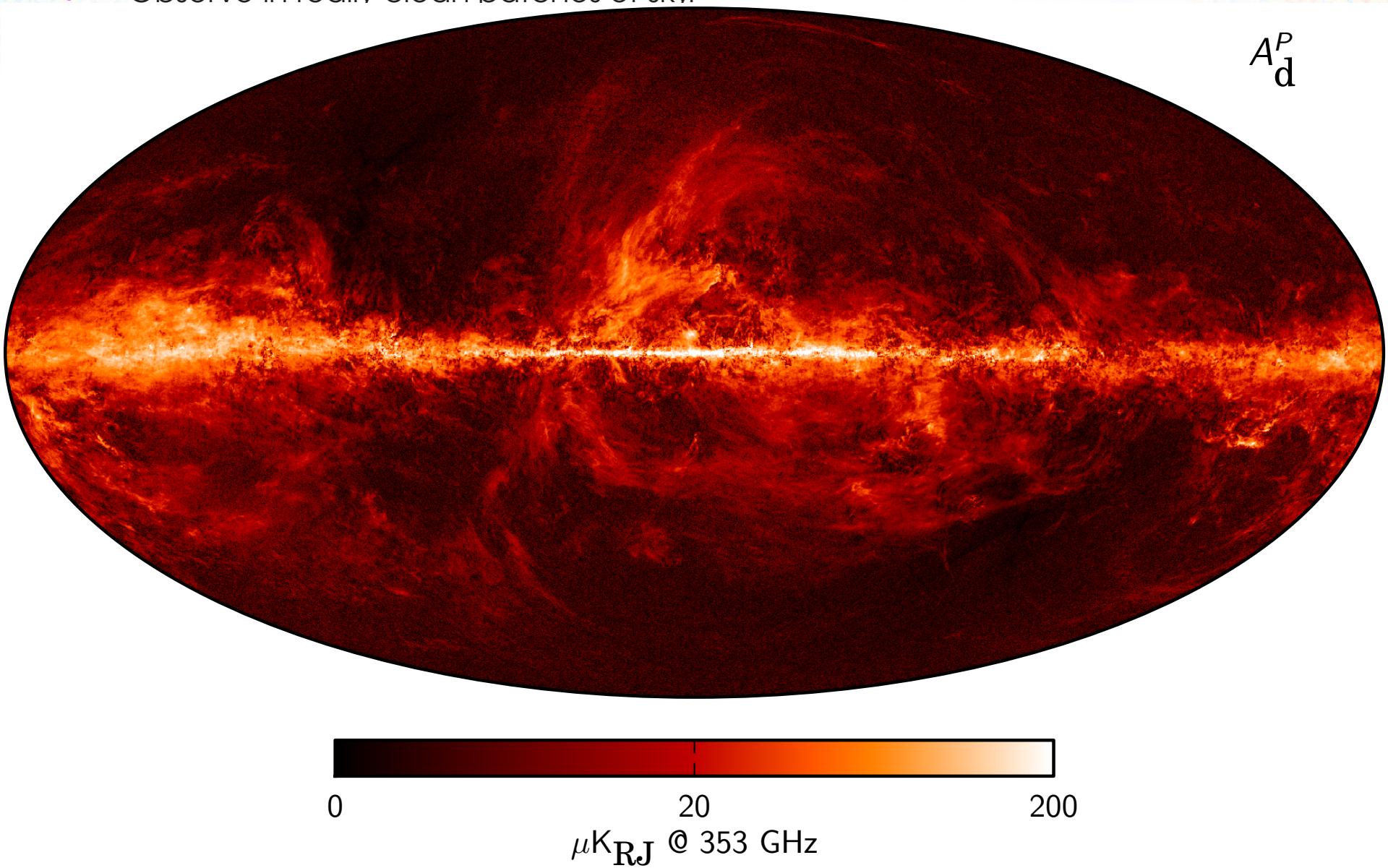
PIP XIX 2014

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

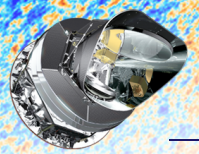
Doomed again!

Foregrounds—cont'd

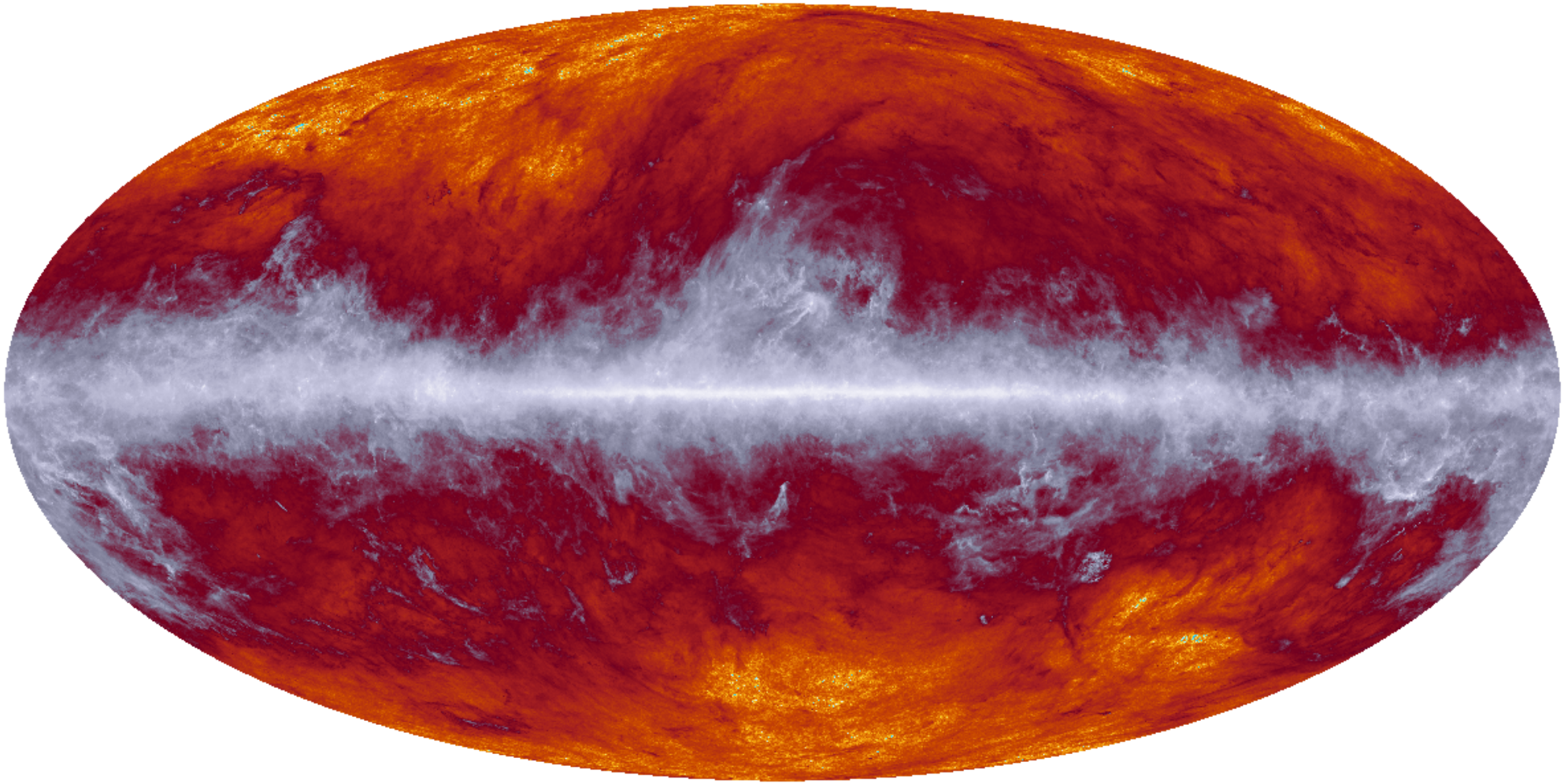
- "Observe in really clean patches of sky."



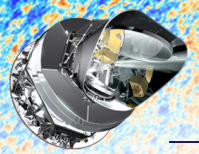
A space B-mode polarization mission must measure the reionization scales, and that requires a lot of sky.



857 GHz

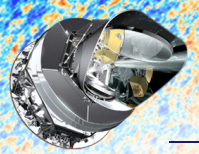


Foregrounds — cont'd



Foregrounds — end

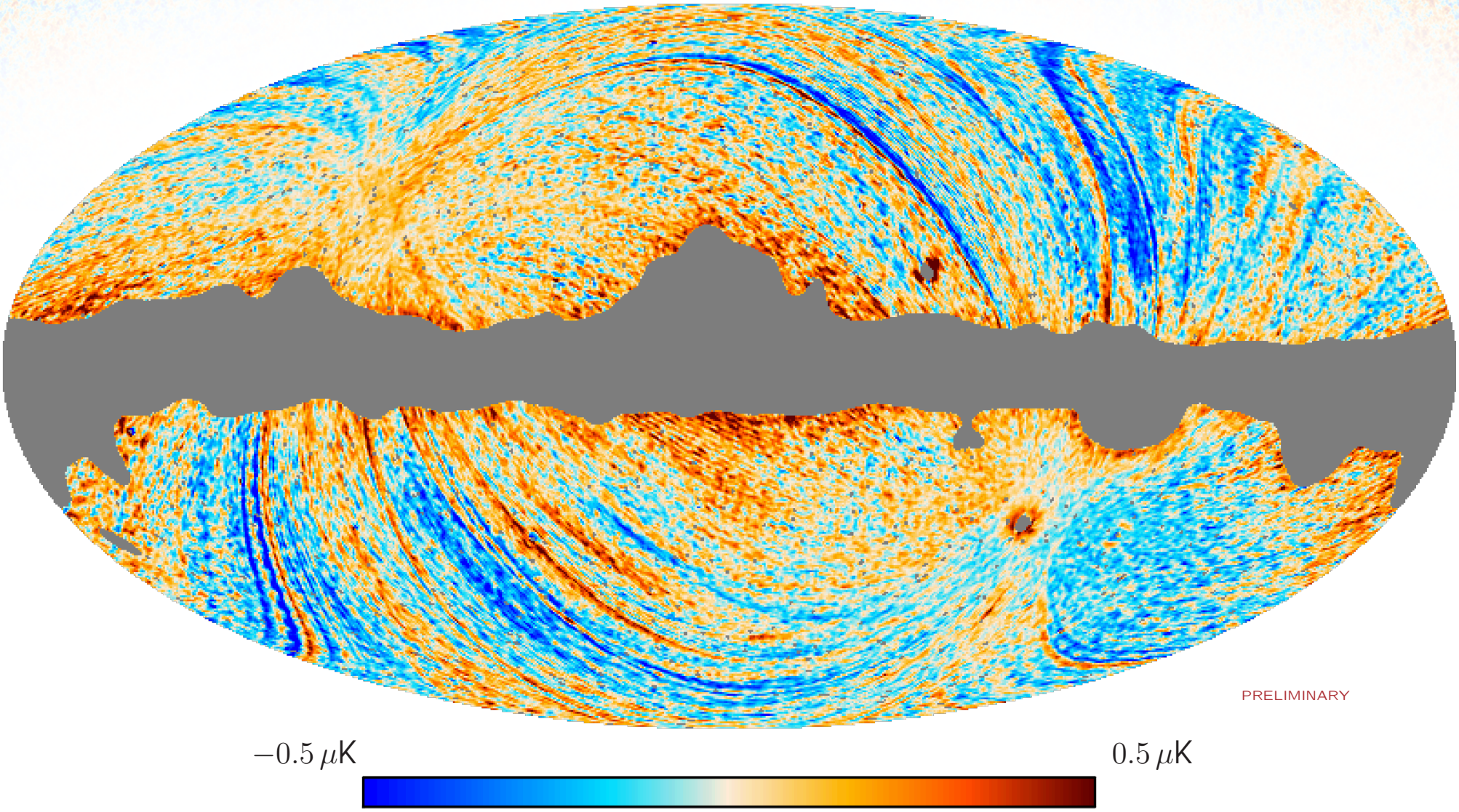
There is no escape from foregrounds in polarization!!!



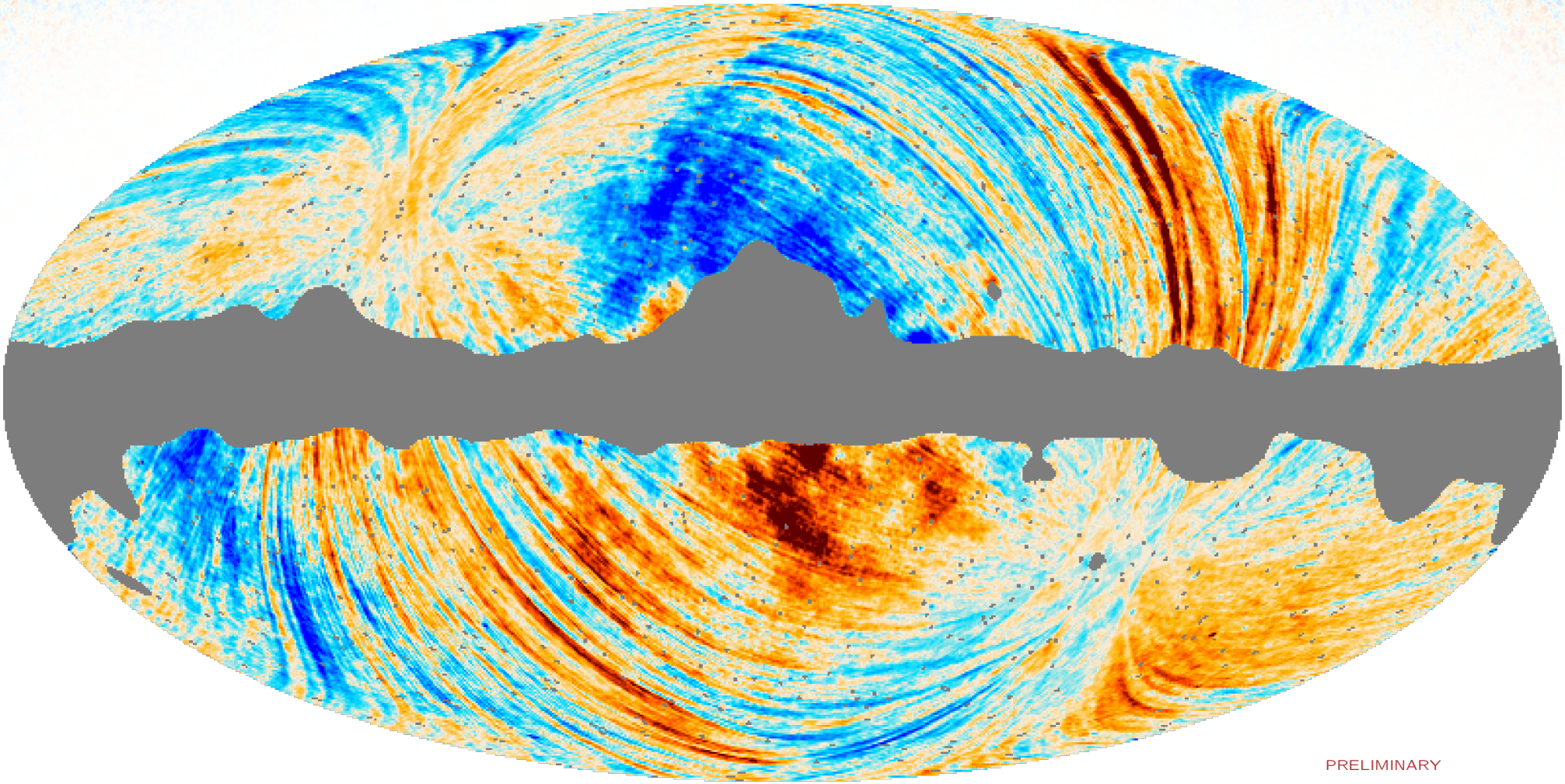
Systematics — LFI

- ADC non-linearity (0.31 μK in T at 70 GHz)
- Bias fluctuations (0.13 μK)
- Pointing uncertainty 0.12 μK)
- 20-K temperature fluctuations (0.08 μK)
- 1-Hz spikes (0.08 μK)
- 4-K temperature fluctuations (temp of 4-K loads) (0.07 μK)
- Intermediate sidelobes (0.07 μK)
- Polarization angle uncertainty (0.003 μK)
- 300-K temperature fluctuations ($< 10^{-3}$ μK)

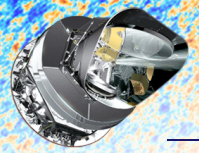
Sum of Systematics, 30 GHz *I*



Sum of Systematics, 30 GHz Q

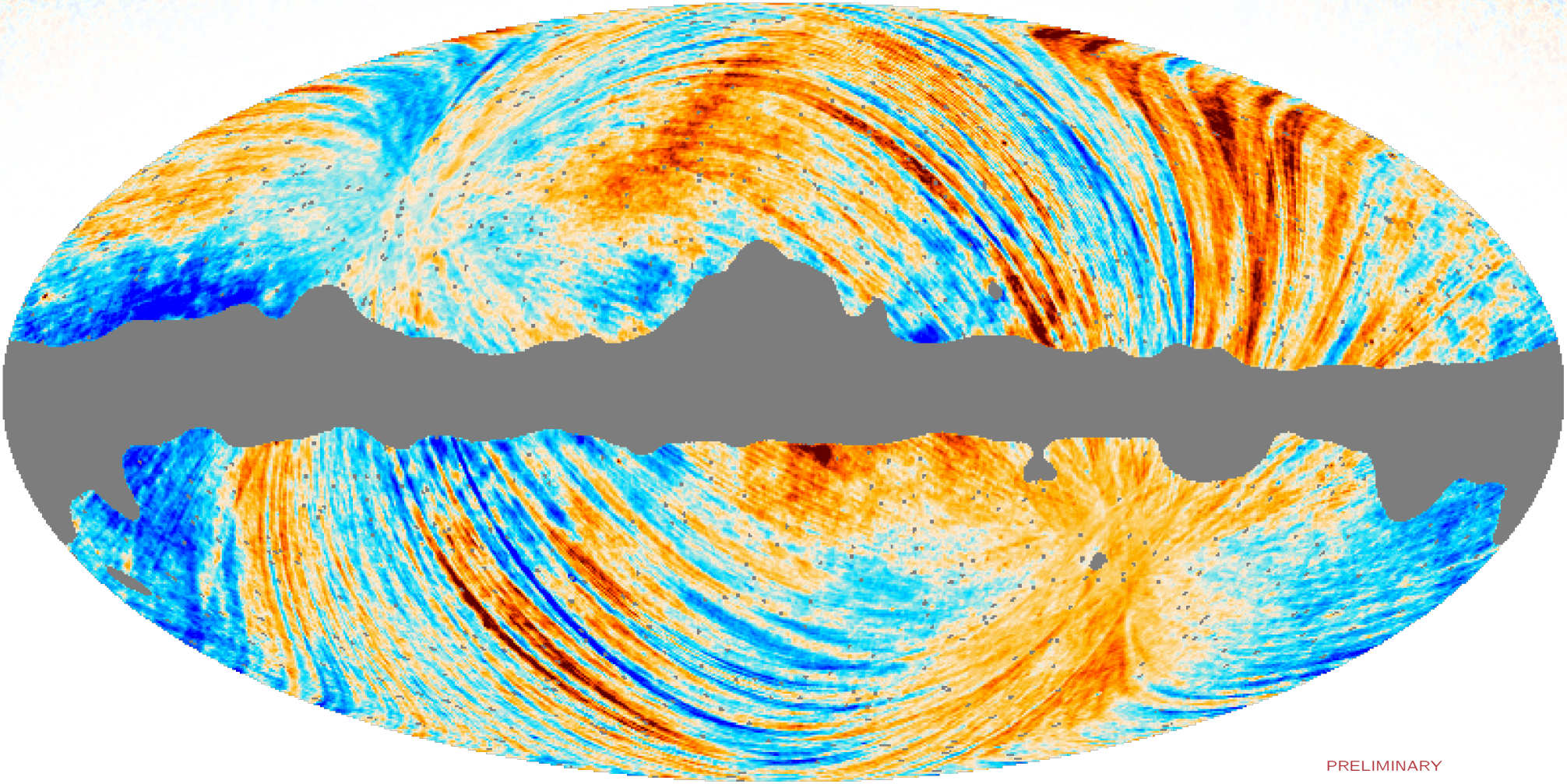


$-0.7\,\mu$K $0.7\,\mu$K

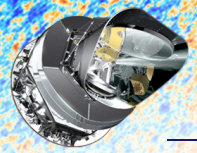


Sum of Systematics, 30 GHz U

PLANCK

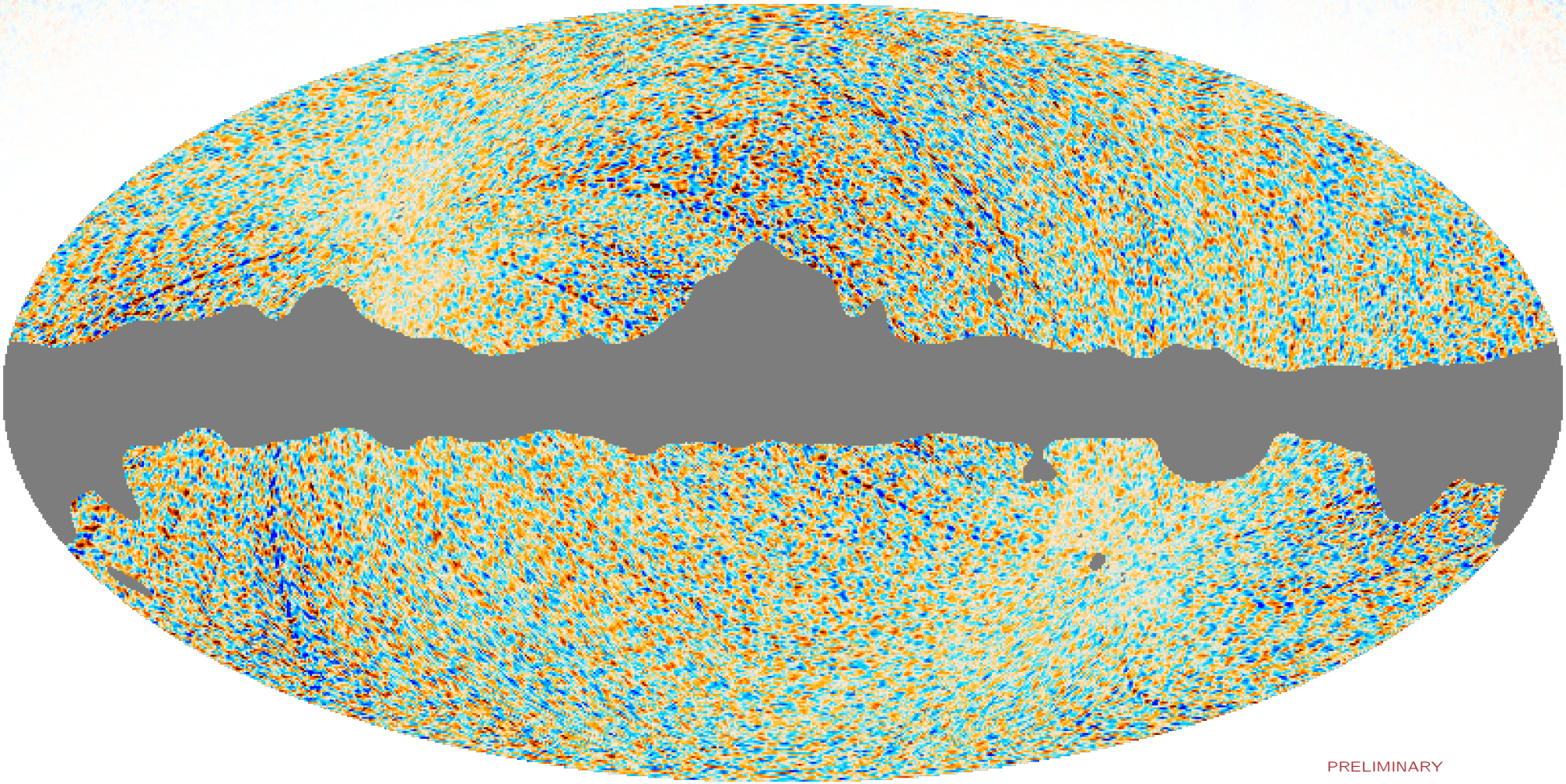


$-0.6\,\mu$K $0.6\,\mu$K

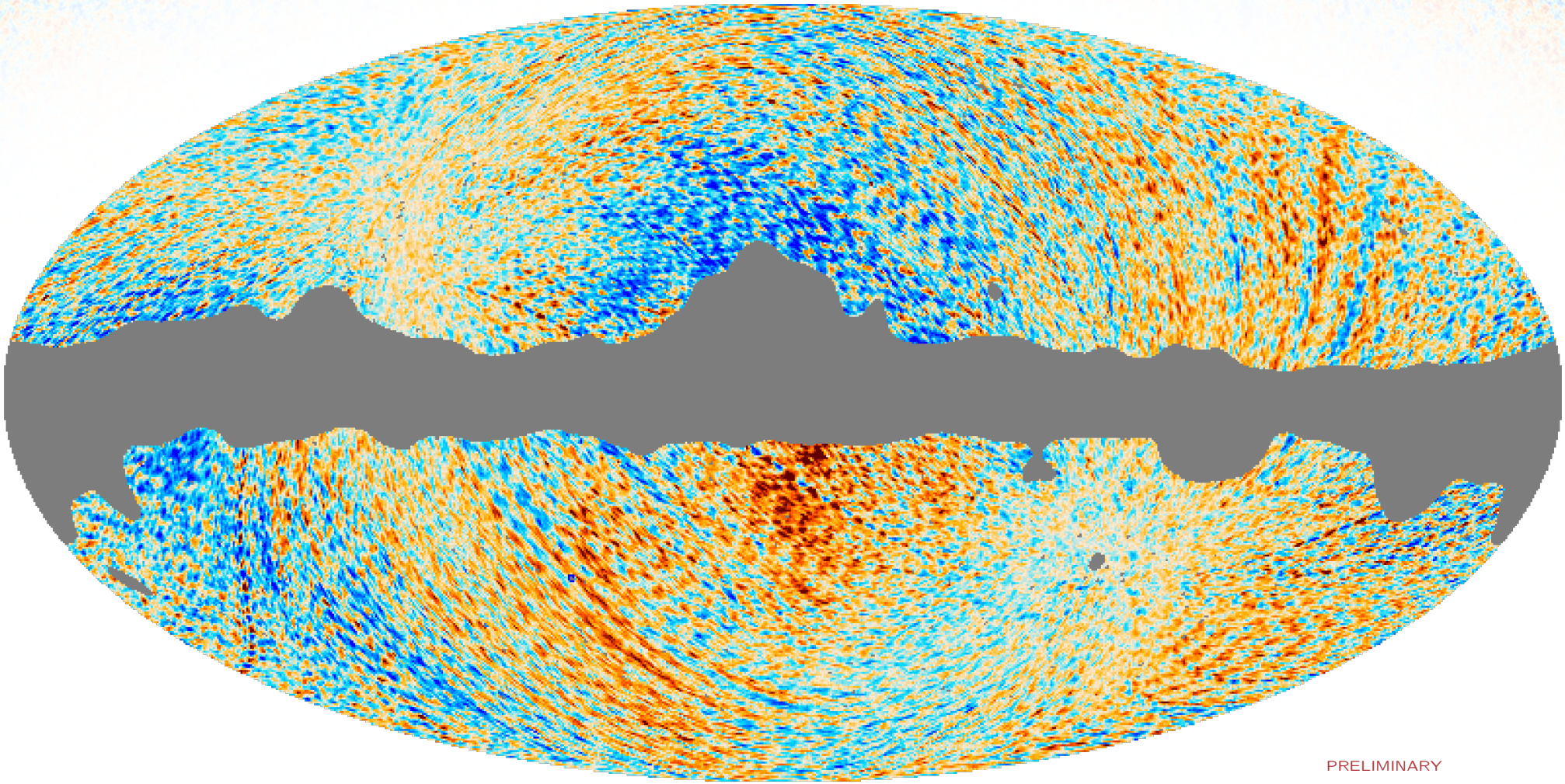


Sum of Systematics, 44 GHz *I*

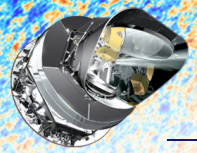
PLANCK



Sum of Systematics, 44 GHz Q

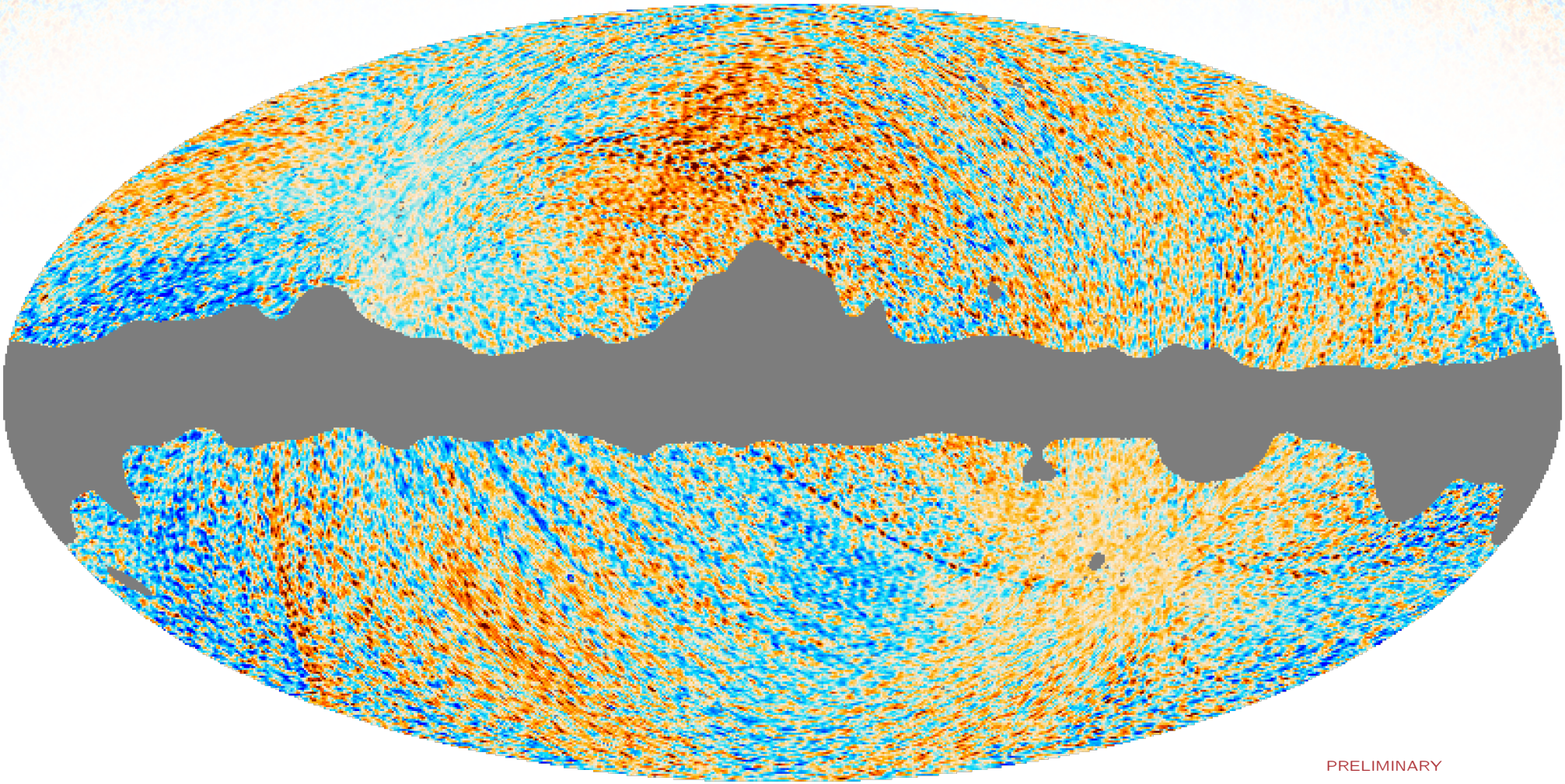


$-0.6\,\mu$K $0.6\,\mu$K

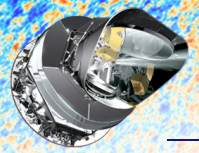


Sum of Systematics, 44 GHz U

PLANCK

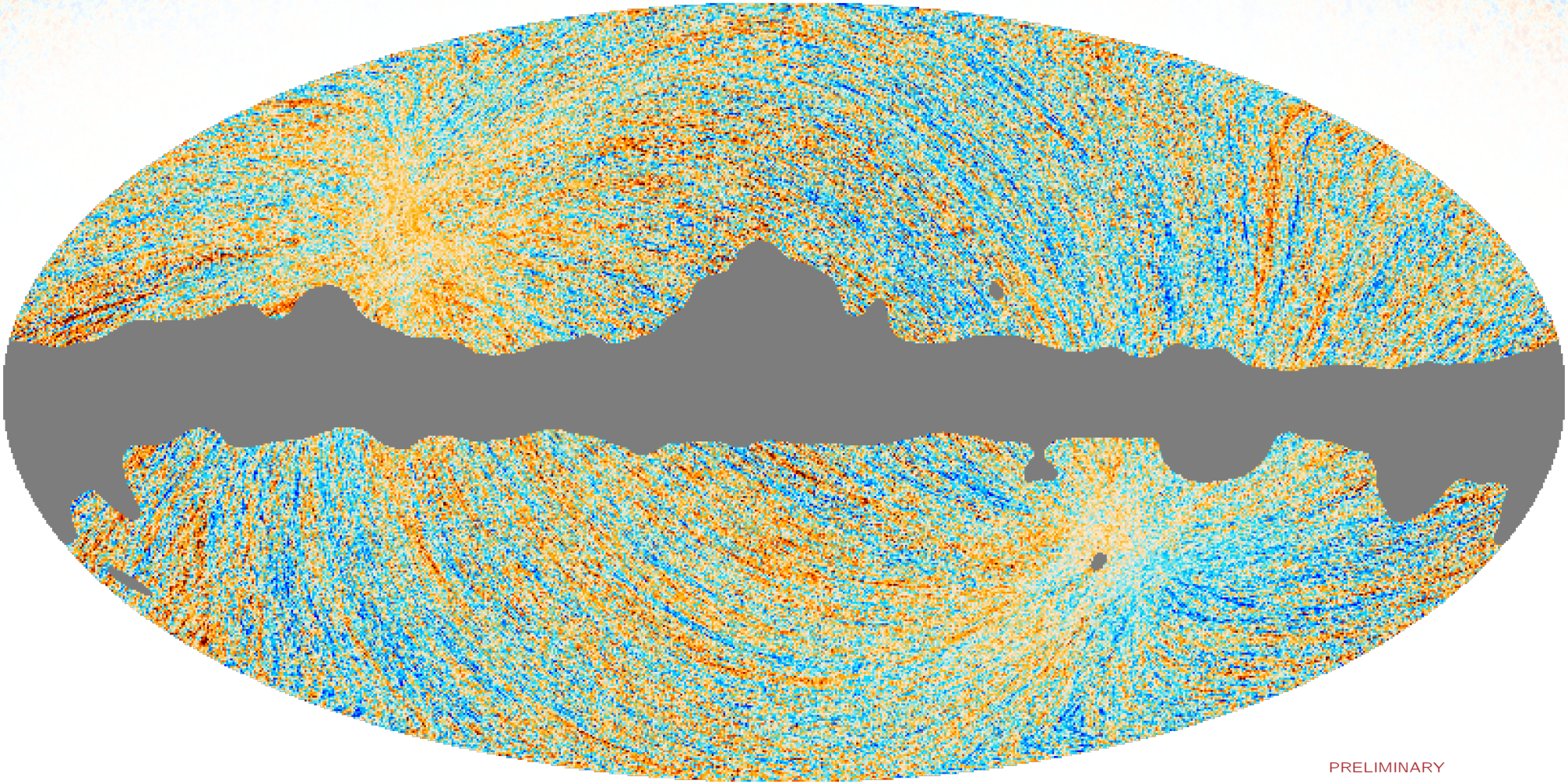


$-0.6\,\mu$K $0.6\,\mu$K



Sum of Systematics, 70 GHz *I*

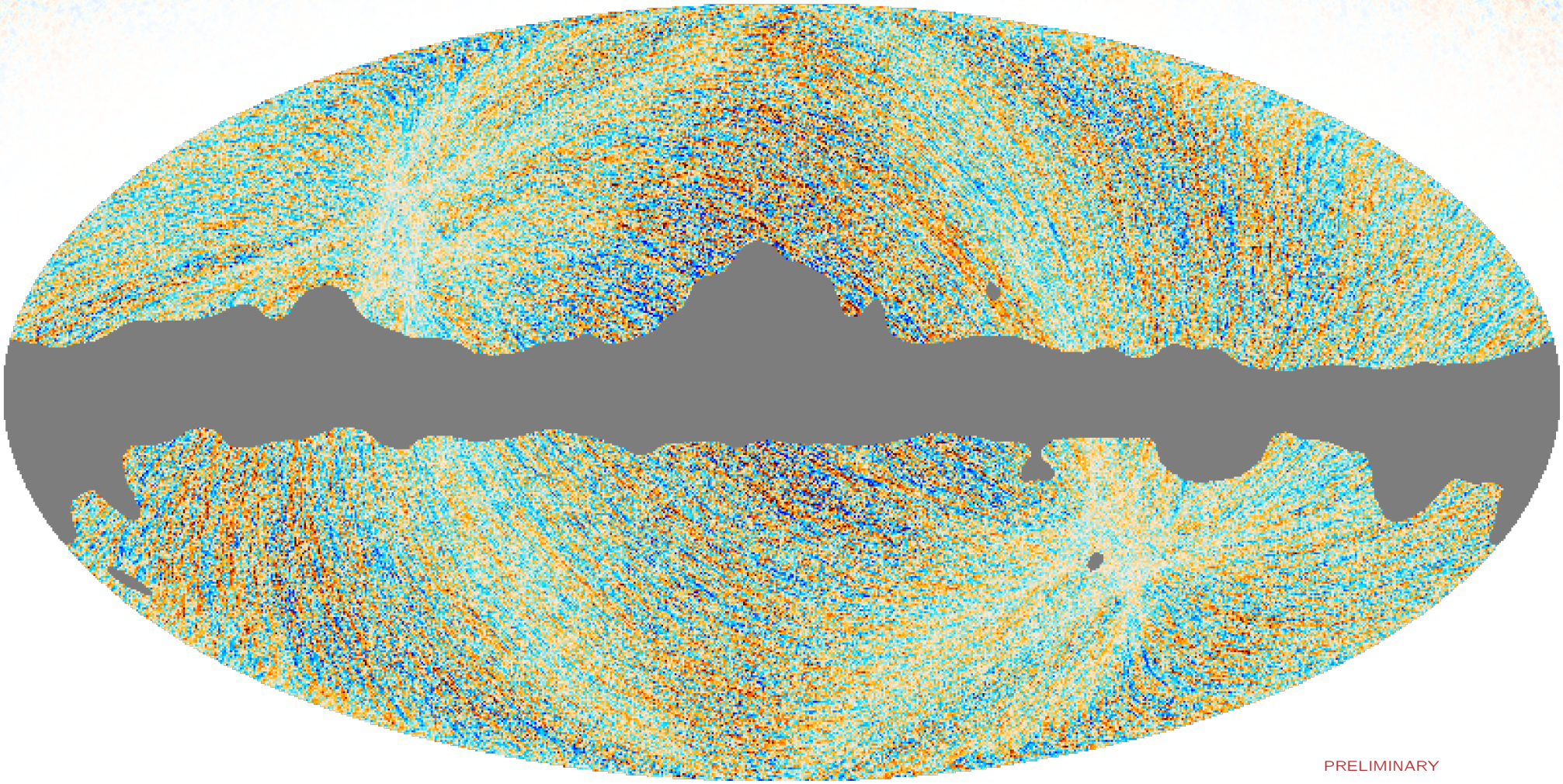
PLANCK



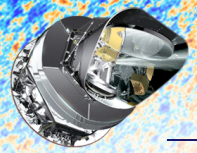
PRELIMINARY

$-0.9\,\mu$K  $0.9\,\mu$K

Sum of Systematics, 70 GHz Q

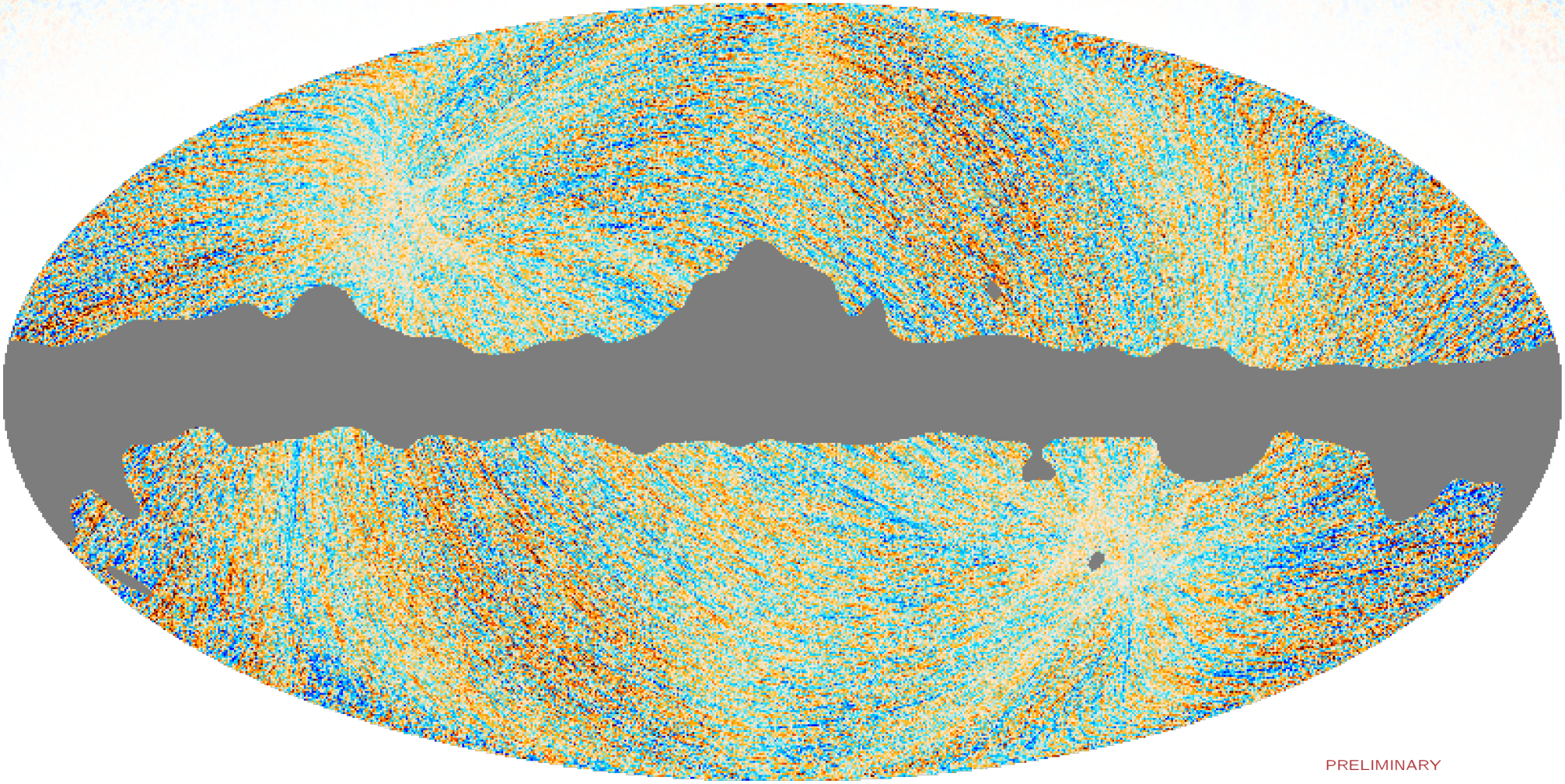


$-1.1\,\mu$K $1.1\,\mu$K

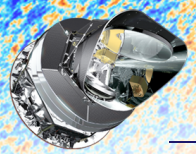


Sum of Systematics, 70 GHz U

PLANCK

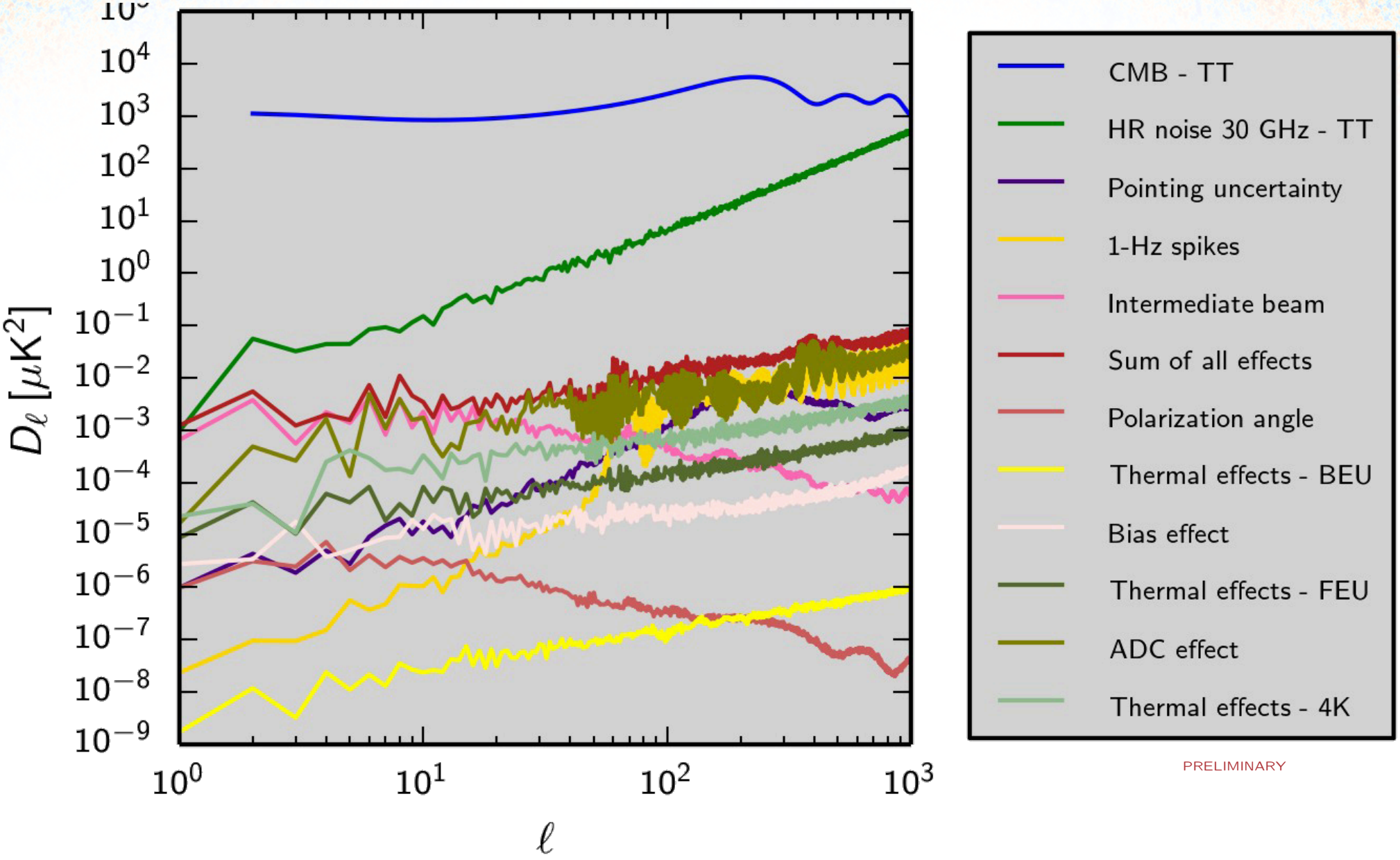


$-1.1\,\mu$K $1.1\,\mu$K

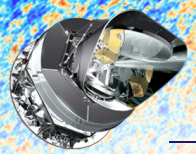


Power Spectrum Uncertainties, 30 GHz *TT*

PLANCK

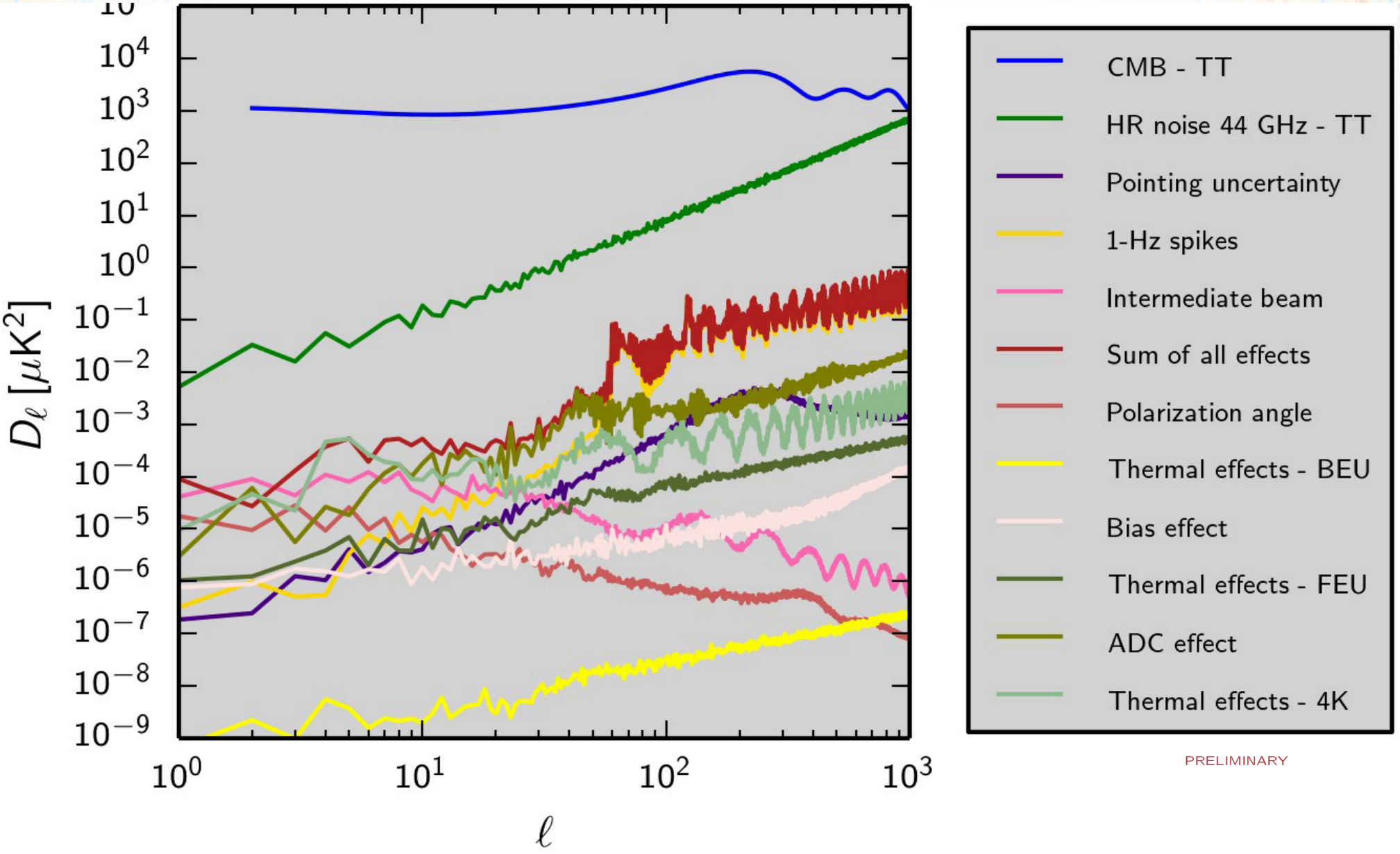


PRELIMINARY

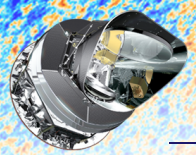


Power Spectrum Uncertainties, 44 GHz *TT*

PLANCK

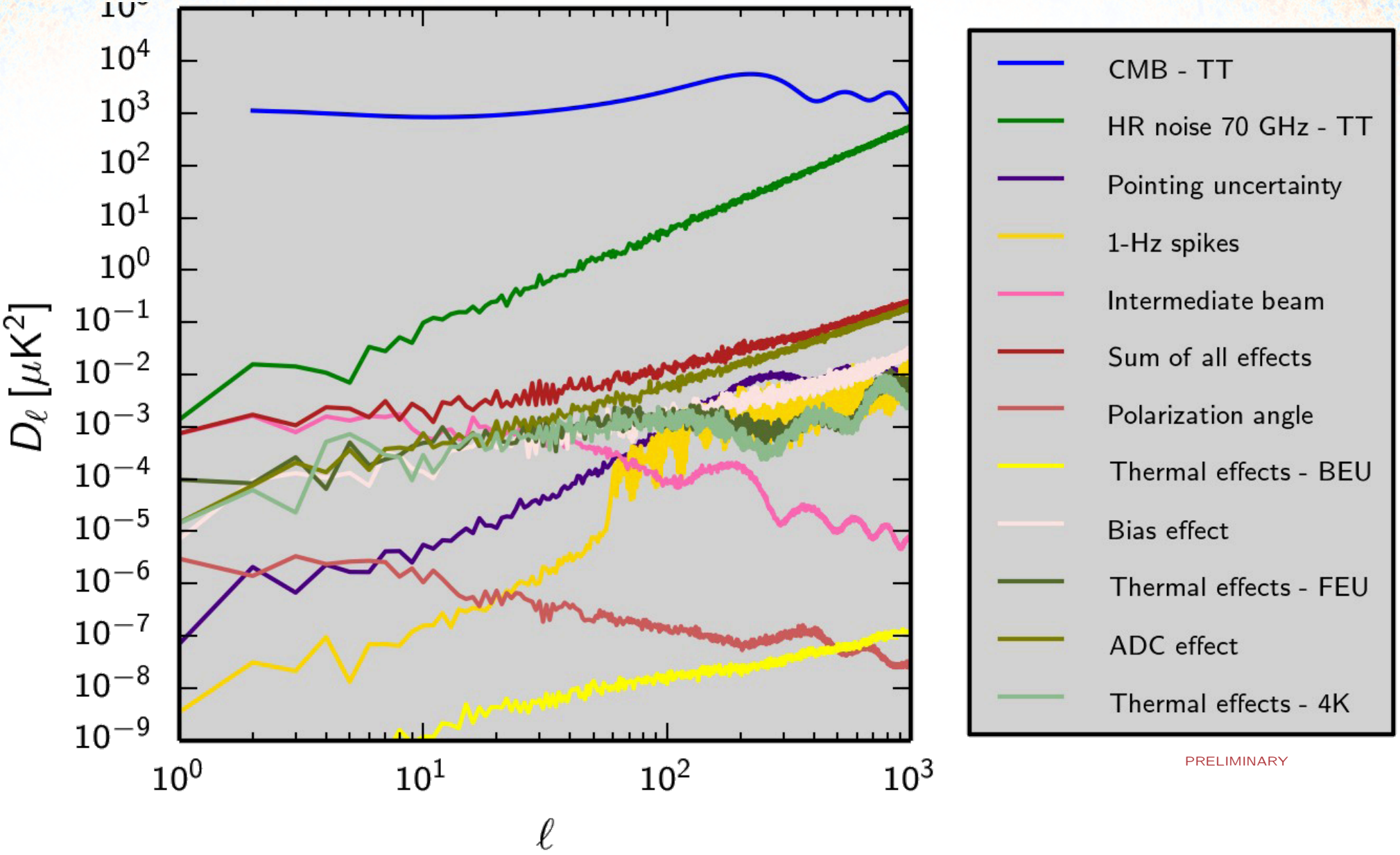


PRELIMINARY

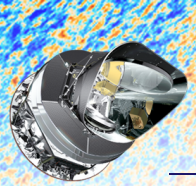


Power Spectrum Uncertainties, 70 GHz *TT*

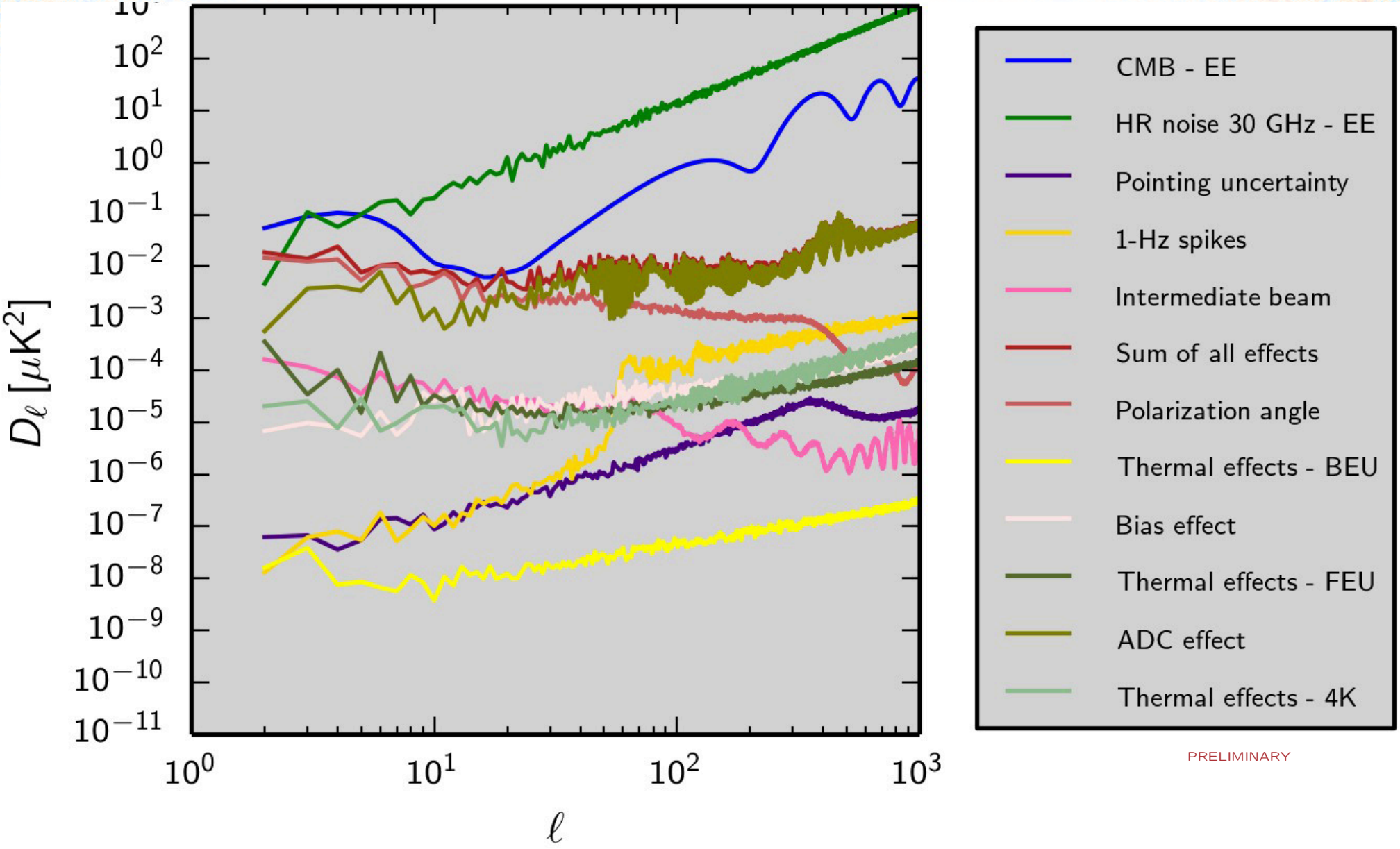
PLANCK



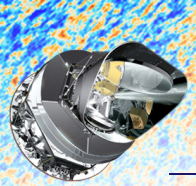
PRELIMINARY



Power Spectrum Uncertainties, 30 GHz EE

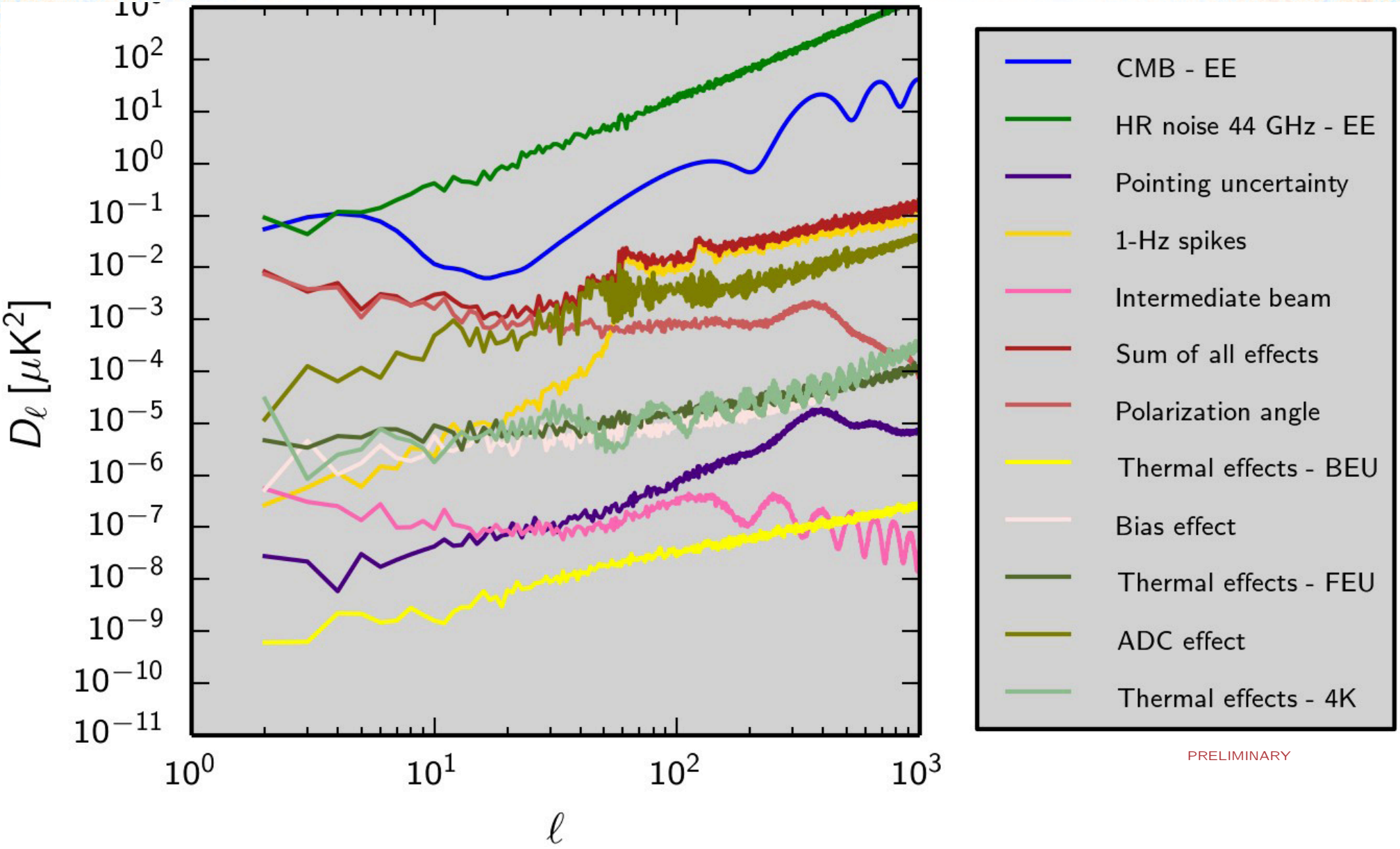


PRELIMINARY

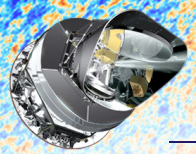


Power Spectrum Uncertainties, 44 GHz *EE*

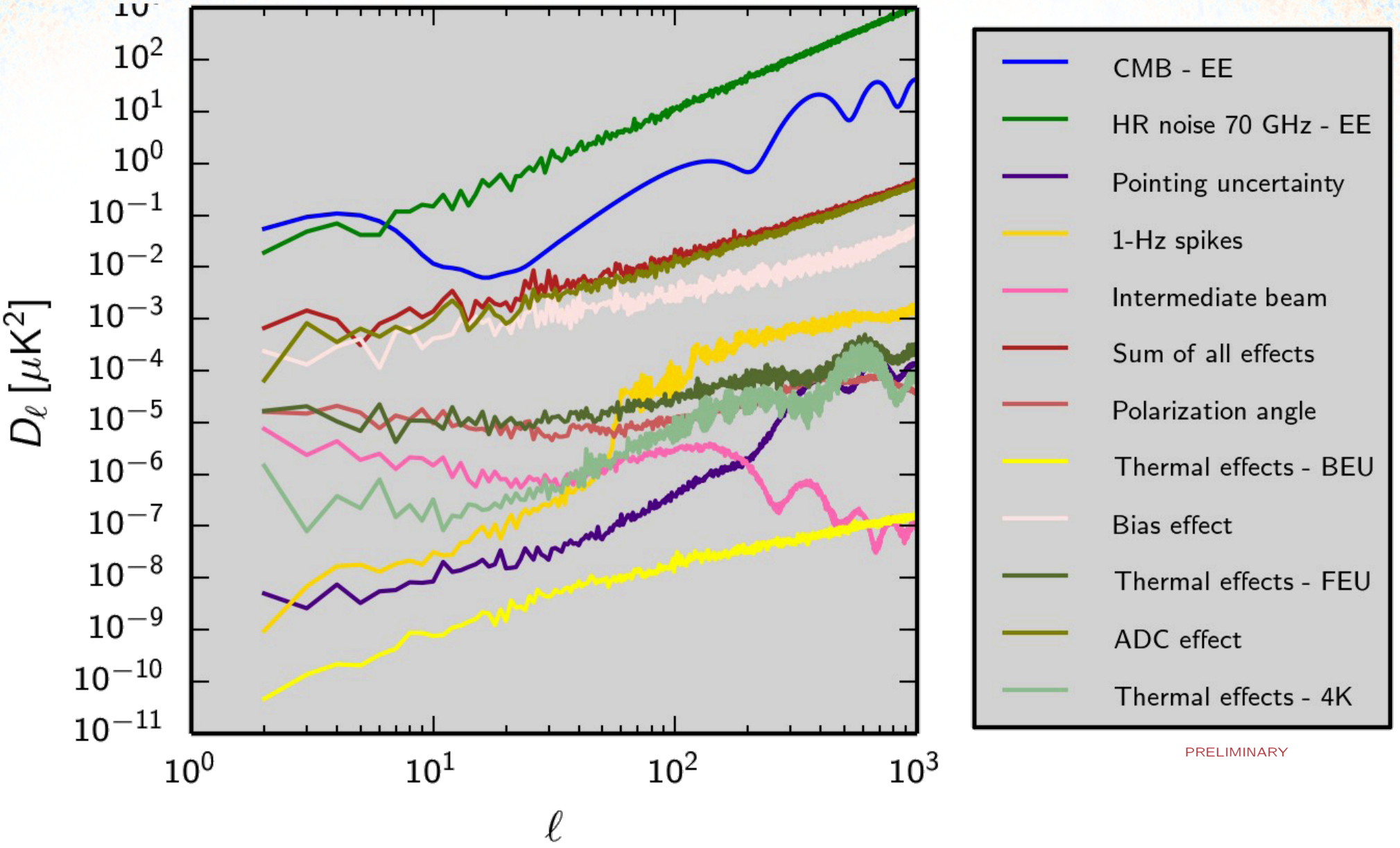
PLANCK



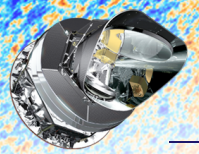
PRELIMINARY



Power Spectrum Uncertainties, 70 GHz EE



PRELIMINARY



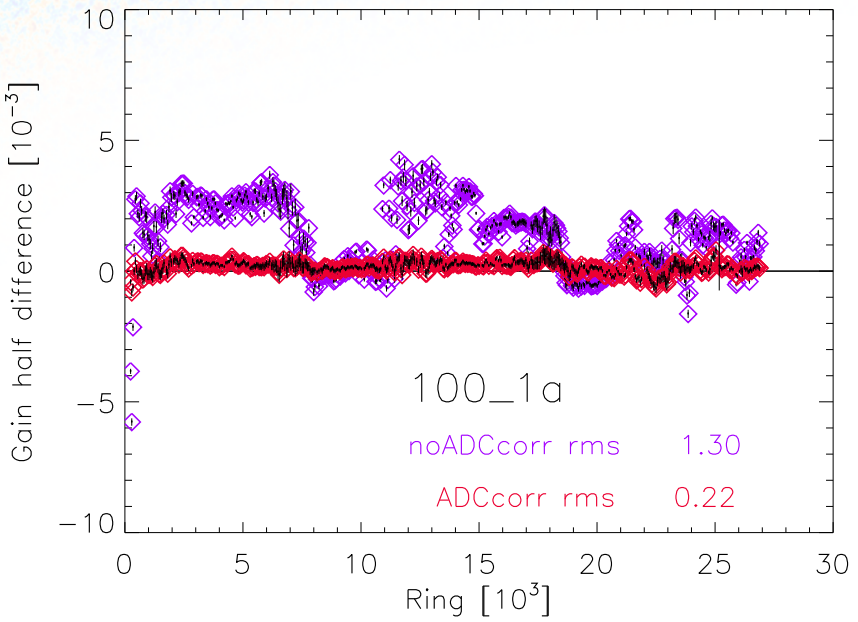
Systematics — HFI

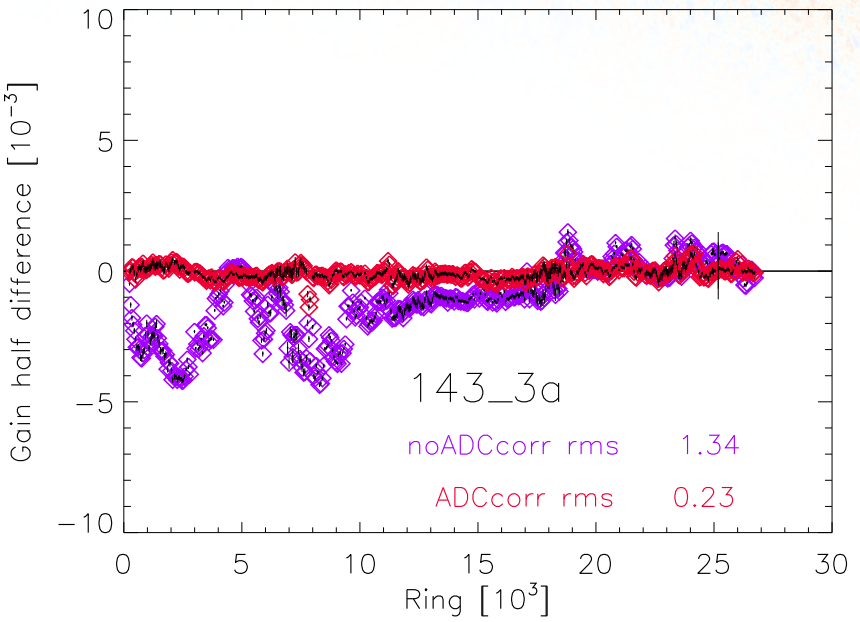
- ADC non-linearity
- Cosmic ray residuals
- 4-K cooler EMI $\Rightarrow$ lines at specific frequencies in the temporal power spectrum
- Long-time-constant detector response
- Sidelobes and beams
- $I \rightarrow Q,U$ leakage

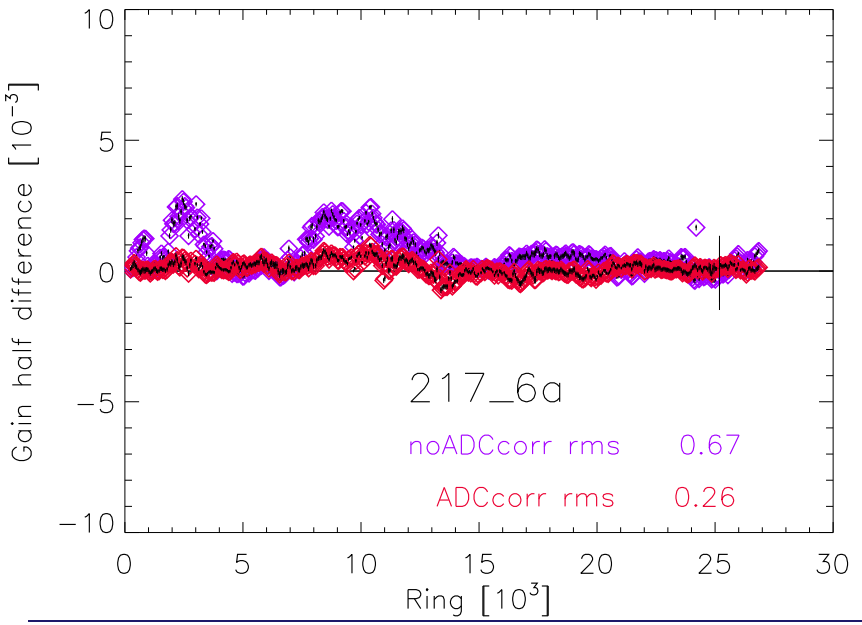
  Gain mismatch

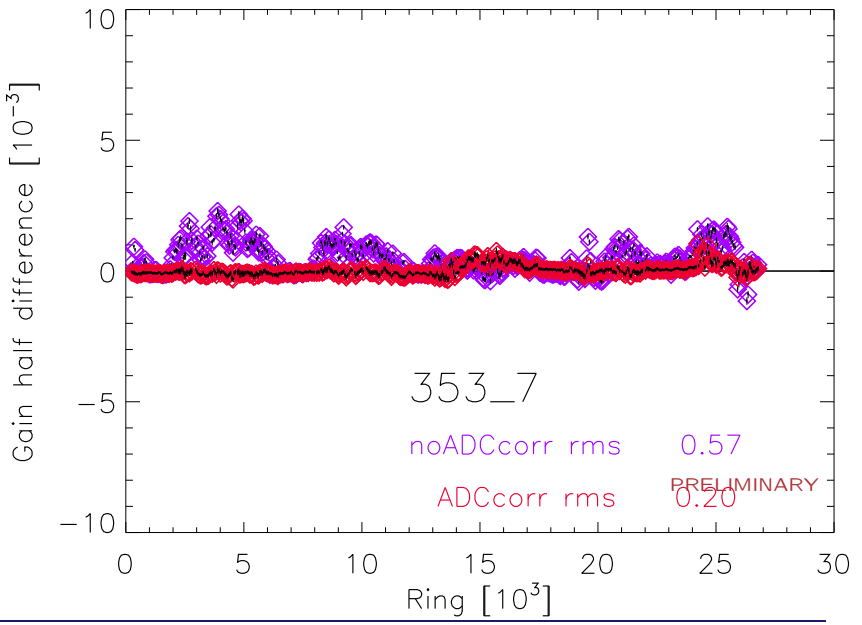
  Bandpass mismatch

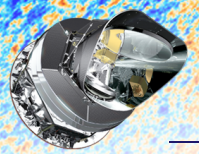
HFI Systematics — ADC Non-Linearity



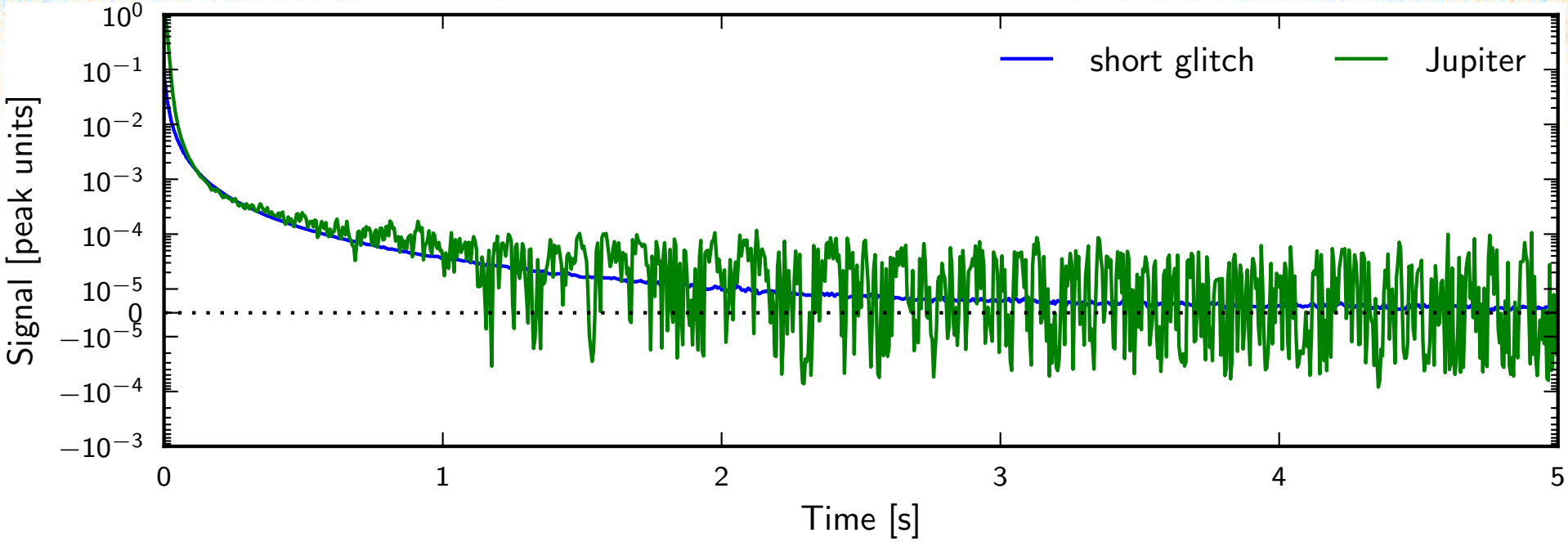








HFI Systematics — Cosmic Rays



PRELIMINARY

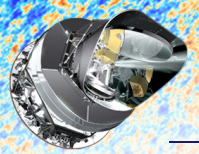
- "Short" glitches are due to particles hitting bolometer grid or thermistor
  - Time response of heat dissipation the same for short glitches and photons
  - Have a long tail, observed to be the same as on Jupiter scans

$\Rightarrow$ Stacked short glitches give high SNR measurement of photon time response

- Current bolometer time transfer function: sum of five single-pole low-pass functions

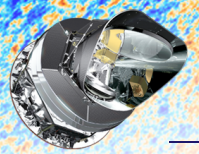
$$F(\omega) = \sum_{i=1,5} \frac{a_i}{1 + i\omega\tau_i}$$

  - Values of τ_i range from a few milliseconds to a few seconds



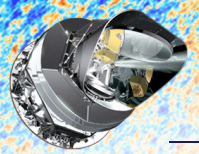
Systematics in the Future

- Over most of the multipole range, Planck is not limited by systematics
- For both LFI and HFI, calibration and control of systematics will improve in 2015
- At present, systematics are the limiting factor for HFI at large angular scales
  - All the important systematics have been identified and understood at some level, but have not been characterized well enough in the "2015 results" for release of the data
  - This is changing
  - They interact. Simultaneous, self-consistent removal required, and better simulations of instrument effects to support that removal.
  - That will happen in 2015



Commentary for Future Space Missions

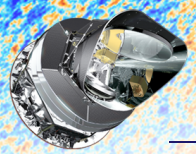
- It seems likely that in the end Planck will not be systematics-limited on any angular scale
- It was a huge effort, but well, OK. . .
- But, if the noise level were a factor of 10 or 20 lower, that would not be the case
- Space missions should not be planned with untested technologies and techniques, hoping for the best
- Test and demonstrate EVERYTHING sub-orbitally first



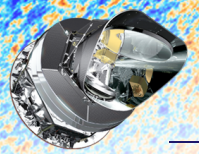
Conclusion

- 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.
  - Some indications of internal and external tensions, but with only modest statistical significance.
- New analysis should improve data quality even more for the final release!
  - Hope for even better polarization measurements.
  - Joint Planck+Keck+BICEP analysis coming soon.

frequencies



The Planck Collaboration



WMAP9, for Comparison