Planck

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For the Planck Collaboration

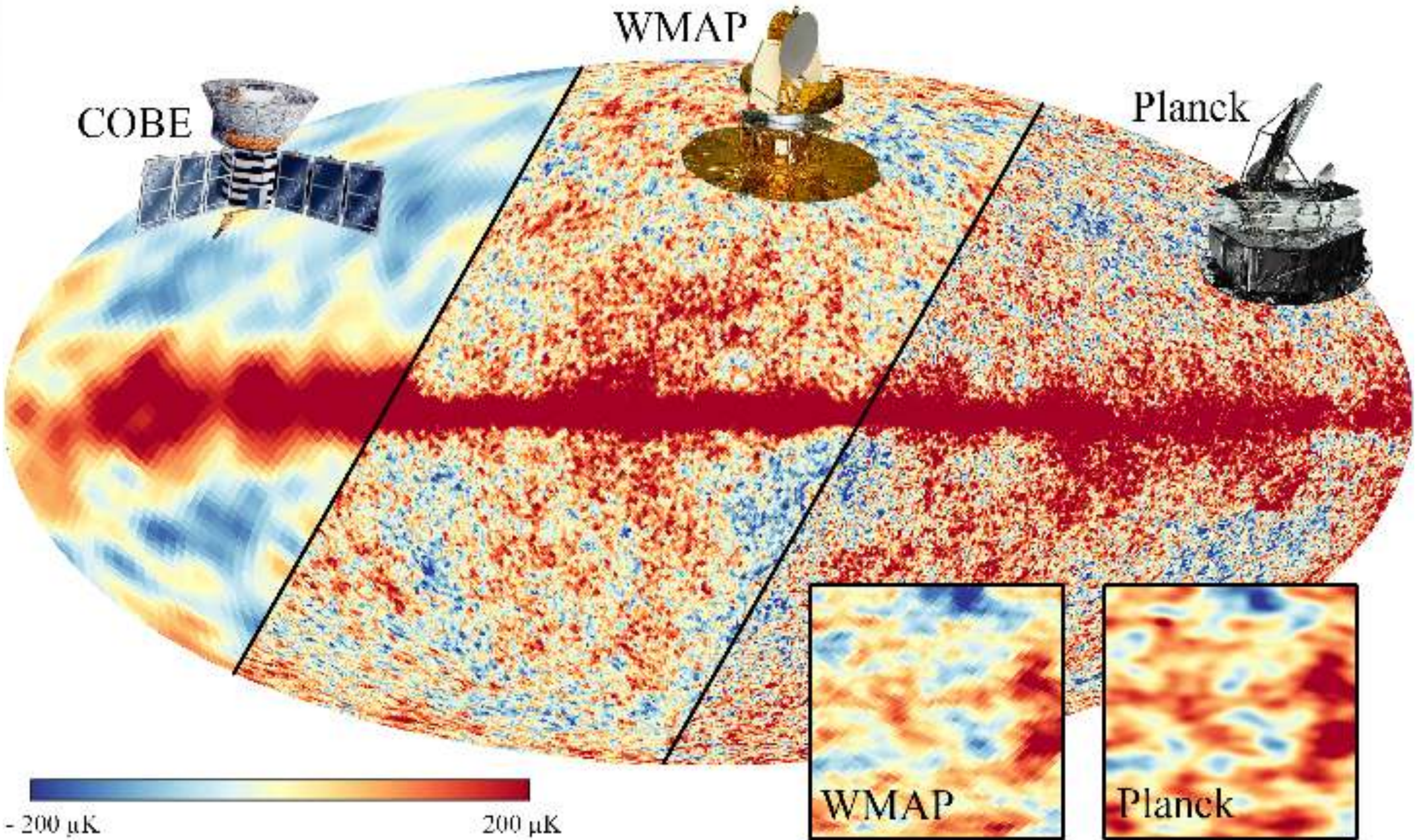
Planck 2015 Results

'2015: The Spacetime Odyssey Continues'
Nordita Institute, Stockholm, June 2015

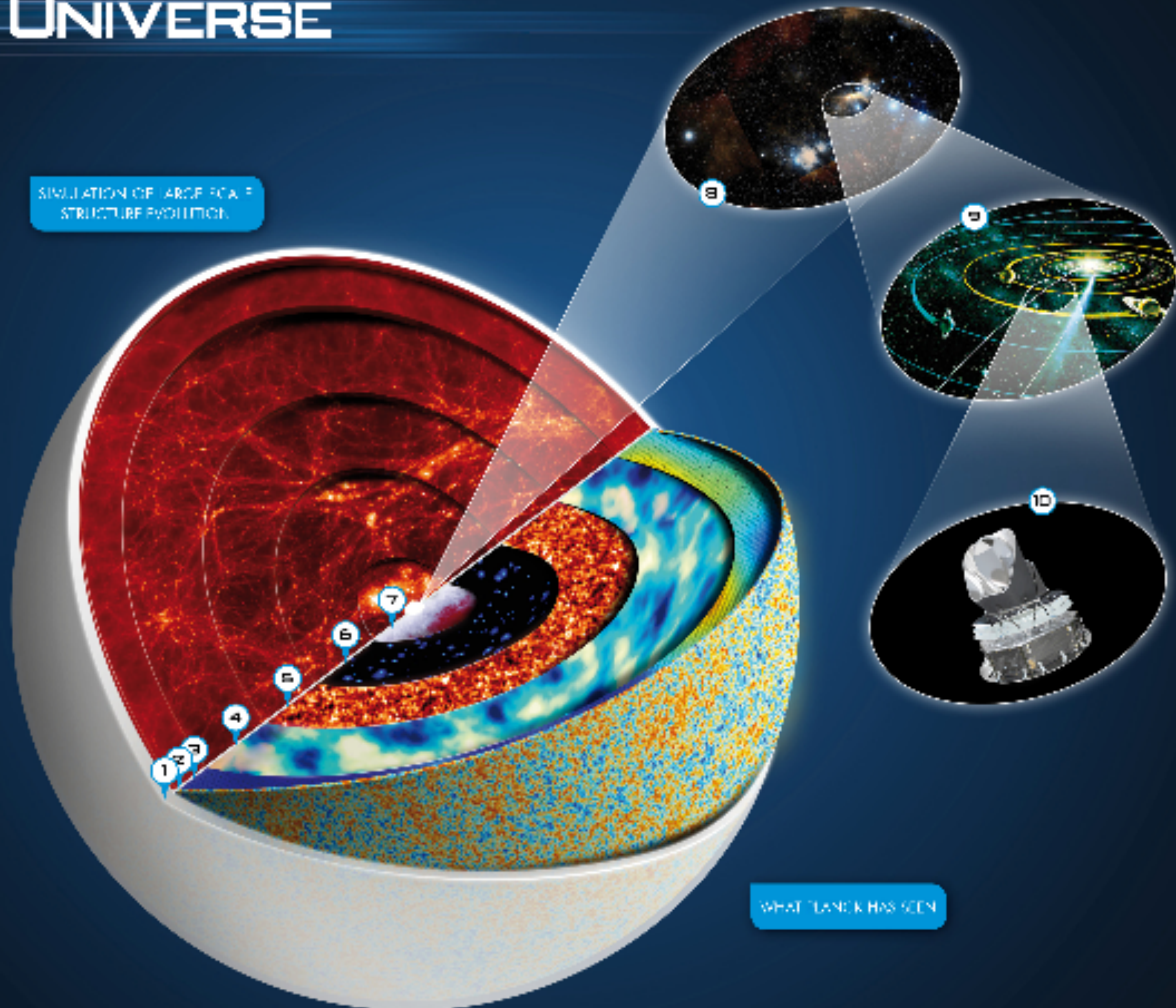
2015 is the *Jubilaeus Annus* for the discovery of the Cosmic Microwave Background.

We have been enormously privileged to have seen the success of 3 satellite missions and a number of remarkable suborbital experiments dedicated to exploration of the CMB sky.

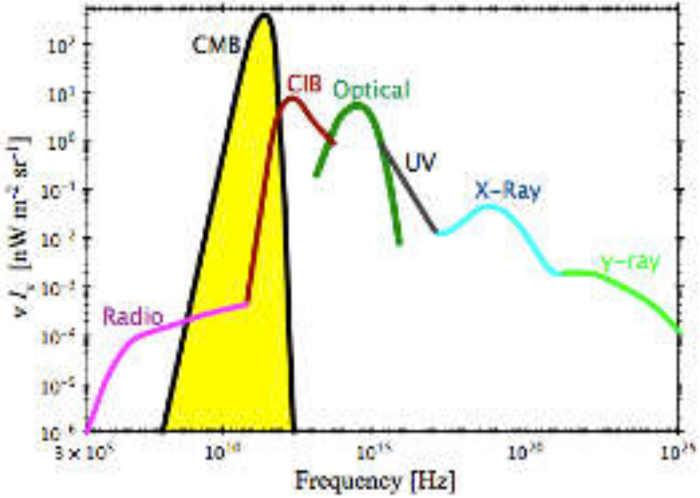
It is a good moment to reflect briefly on **why were we doing this?**



OUR UNIVERSE



1. Big-Bang
   t = 0
2. Relic radiation
   t ≈ 380 000 years
3. Reionization (simulation in 2013)
   t ≈ 500 million years
4. Dark and ordinary matters
   t ≈ 2 billion years
5. Dust
   t ≈ 4 billion years
6. Clusters of galaxies
   t ≈ 8 billion years
7. Our Galaxy
   t ≈ 13.8 billion years
8. Our Galaxy
9. Our solar system
10. The Planck satellite



~95% of the radiation content of the universe is in the CMB black body radiation

Why Is the CMB So Important?

- We see directly the Universe 370,000 years after the Big Bang
- The Universe then was very simple
  - No chemistry: p^+, n, e^-, D^+, T^+, $^3He^{++}$, $^4He^{++}$,Li^{+++}, plus "dark" matter
  - Well-understood physical conditions

    3000 K

    High vacuum (a few million nuclei per m^3)

    Extremely uniform (~ 1 part in 10^5)
  - Calculate how matter and radiation would behave as a function of things that we want to know. Compare with observations, and infer the parameters.

The "Standard ΛCDM" Model. . .

- . . .has been developed over many years:
  - General Relativity
  - Homogeneous, isotropic, and expanding

    "Λ", the cosmological "constant," is now generally referred to as "dark energy"
  - Early period of accelerated expansion, *cosmological inflation*, driven by "some physics"

    Quantum fluctuations seeded the present large-scale matter distribution via gravitational instability

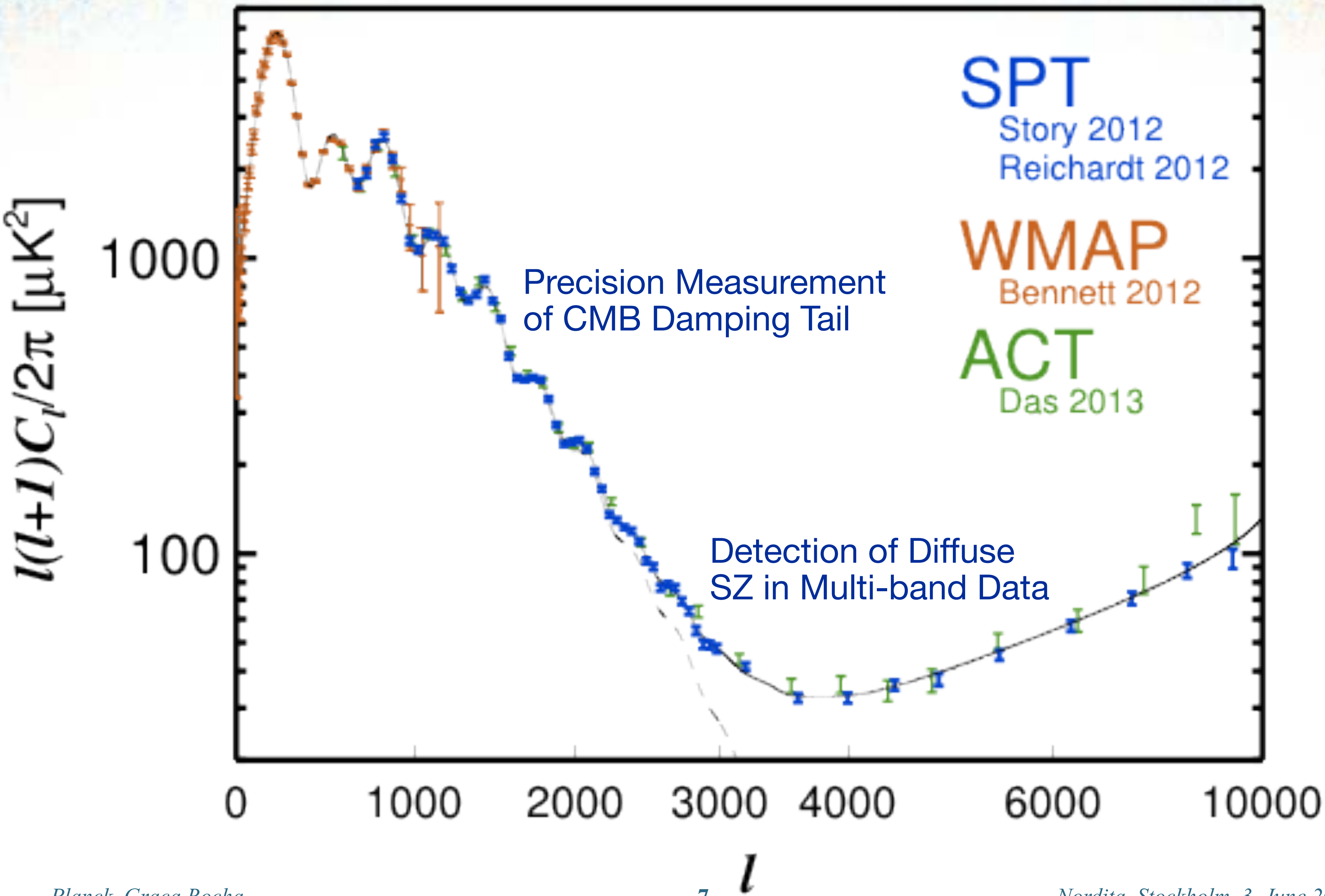
Perturbations were nearly scale-invariant, adiabatic, Gaussian distributed – all those properties to be determined from measurements

Parameters

- A_s, n_s — inflation fluctuations; 10^{-35} s;
  - scale invariance ruled out at σ
- $\Omega_b h^2$, $\Omega_c h^2$ — baryons and cold dark matter; first few minutes
  - 0.6% and 1.1% precision
- θ_{MC} — sound horizon; 370,000 years
  - 0.03% precision
- τ — reionization optical depth; 13.8 billion years

Dramatic improvements in the quality of CMB anisotropy measurements
since the discovery reported in 1992 by COBE-DMR
have put the term "precision cosmology" into a new category,
and allowed a continuing race for determination, with ever growing fidelity,
of those cosmological parameters.

SPT-SZ: *CMB Power Spectrum*



"Last" word
on pre-Planck
determination
of parameter
values
in the standard
Λ CDM model
(from early 2013,
temperature
measurements-
based, except
WMAP9-driven tau)

TABLE I. Standard ΛCDM parameters from the combination of WMAP9, ACT and SPT.

Parameter	WMAP9 +ACT	WMAP9 +SPT	WMAP9 +ACT+SPT[a]
$100\Omega_b h^2$	2.260 ± 0.041	2.231 ± 0.034	2.252 ± 0.033
$100\Omega_c h^2$	11.46 ± 0.43	11.16 ± 0.36	11.22 ± 0.36
$100\theta_A$	1.0396 ± 0.0019	1.0422 ± 0.0010	1.0424 ± 0.0010
τ	0.090 ± 0.014	0.082 ± 0.013	0.085 ± 0.013
n_s	0.973 ± 0.011	0.9650 ± 0.0093	0.9690 ± 0.0089
$10^9 \Delta^2_{\mathcal{R}}$	2.22 ± 0.10	2.15 ± 0.10	2.17 ± 0.10
Ω_Λ[b]	0.716 ± 0.024	0.737 ± 0.019	0.735 ± 0.019
σ_8	0.830 ± 0.021	0.808 ± 0.018	0.814 ± 0.018
t_0	13.752 ± 0.096	13.686 ± 0.065	13.665 ± 0.063
H_0	69.7 ± 2.0	71.5 ± 1.7	71.4 ± 1.6
$100 r_s/D_{V\,0.57}$	7.50 ± 0.17	7.65 ± 0.14	7.66 ± 0.14
$100 r_s/D_{V\,0.35}$	11.29 ± 0.31	11.56 ± 0.26	11.57 ± 0.26
best fit χ^2	7596.0	7617.1	7640.7

[a] The combination ACT+SPT uses ACT-E data only. We report errors at 68% confidence levels.

[b] Derived parameters: Dark energy density, the amplitude of matter fluctuations on 8 h^{-1}Mpc scales, the age of the Universe in Gyr, the Hubble constant in units of km/s/Mpc, and the galaxy correlation scales at redshifts 0.57 and 0.35.

ΛCDM Model Parameters

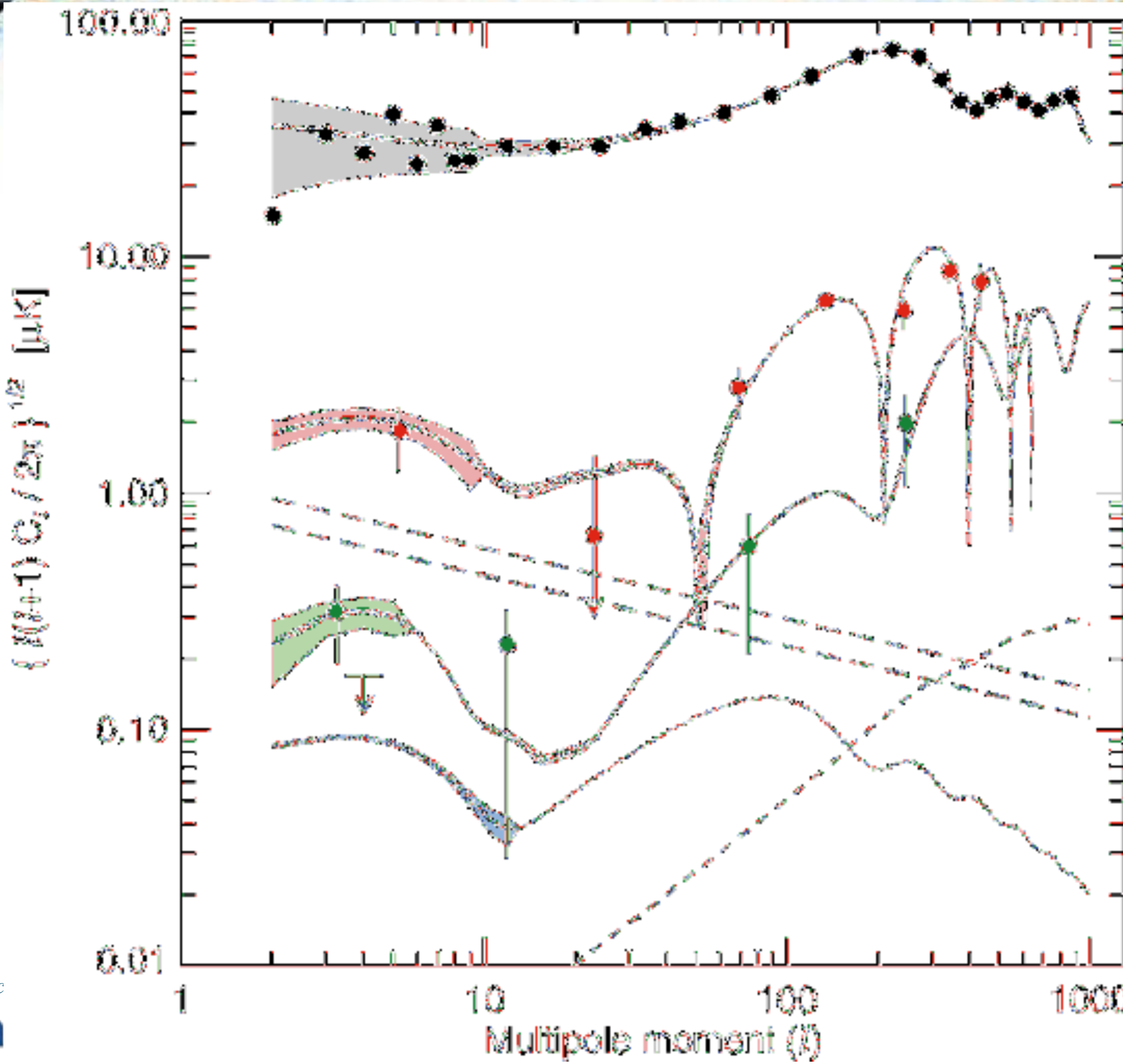
Planck 2015 – the latest suite of cosmological parameters (caveats notwithstanding, first time inclusion of TE&EE)

Parameter	TT	TT, TE, EE + lensing	N_σ
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00016	139
$\Omega_c h^2$	0.1197 ± 0.0022	0.1193 ± 0.0014	85
$100\theta_{MC}$	1.04085 ± 0.00047	1.04087 ± 0.00032	3250
τ	0.078 ± 0.019	0.063 ± 0.014	4.5
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.059 ± 0.025	122
n_s	0.9655 ± 0.0062	0.9653 ± 0.0048	(7.2)
H_0	67.31 ± 0.96	67.51 ± 0.64	105
Ω_m	0.315 ± 0.013	0.3121 ± 0.0087	36
σ_8	0.829 ± 0.014	0.8150 ± 0.0087	94
z_{re}	9.9 ± 1.9	8.5 ± 1.4	6
z_{recomb}	1090.09 ± 0.42	1090.00 ± 0.29	3750

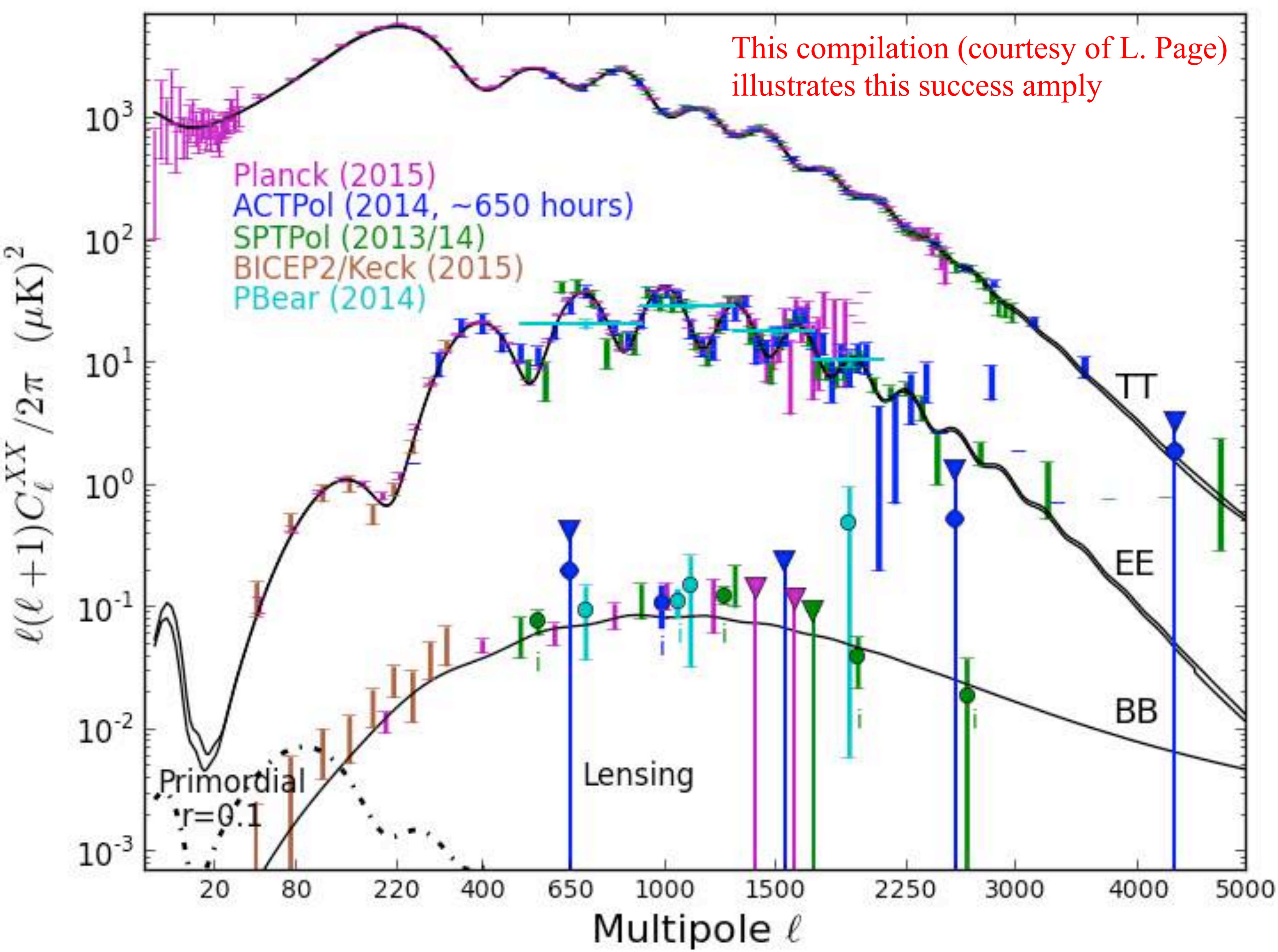
Conclusion

- 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.
  - No evidence for cosmological non-Gaussianity
  - “Simple” inflation favored
  - 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
- Full 2015 release starting soon, in three phases
- Final data release at the end of 2015/beginning of 2016
  - New analysis should improve data quality even more for the final release!

WMAP <TT>, <TE>, & <EE> Spectra (schematically)

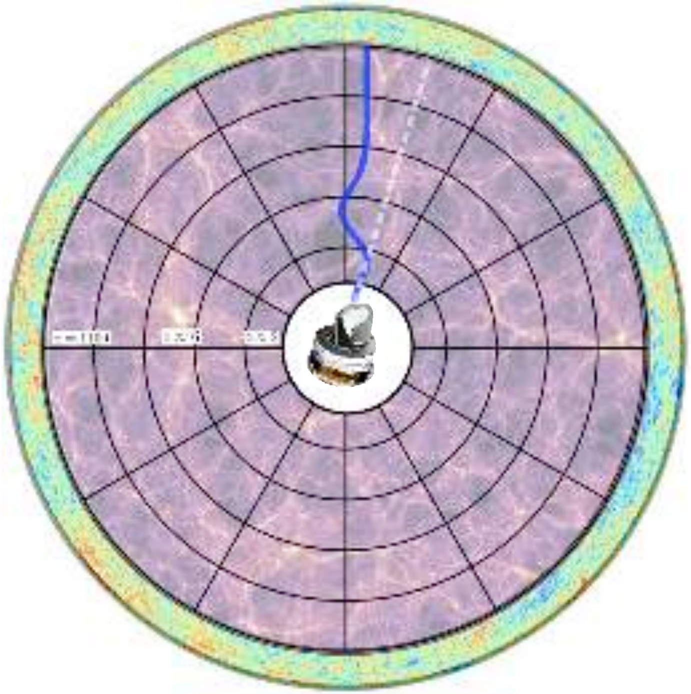


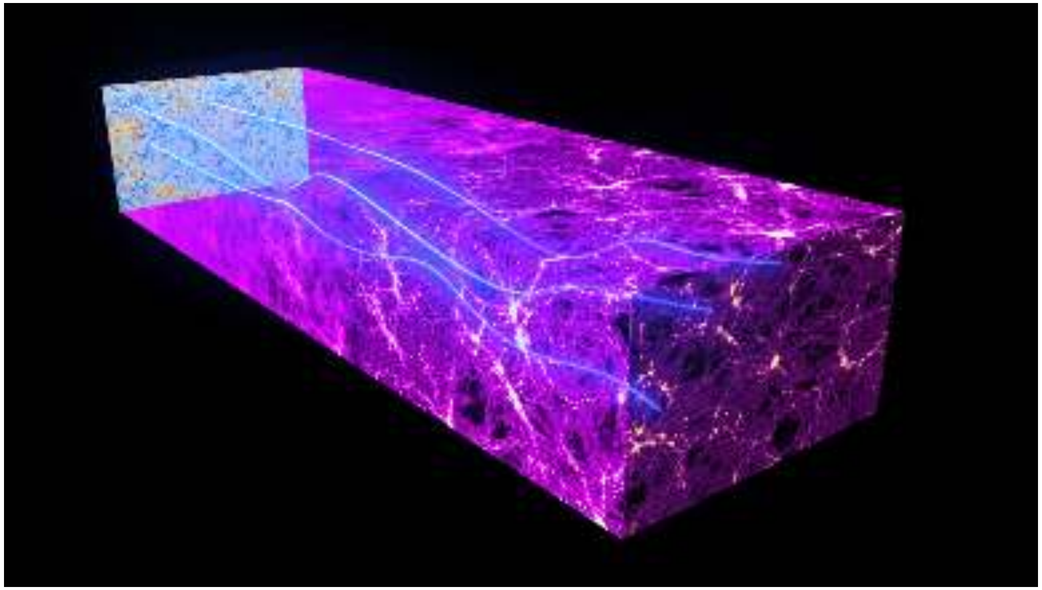
This compilation (courtesy of L. Page) illustrates this success amply



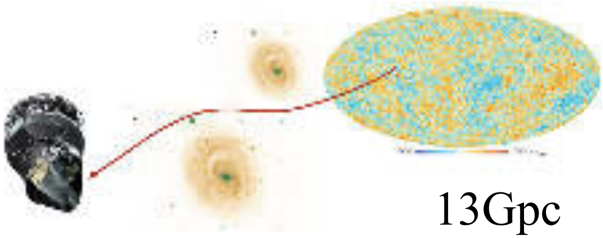
Why Is the CMB So Important? — cont'd

- As the light travels to us on its 13.8 billion year journey it is affected by the intervening parts of the Universe.





- Path bent by mass
- Spectrum changed by hot gas in galaxy clusters
- Photons scattered by reionized hydrogen



13Gpc

Lensing smoothes out the peaks and alters the statistics of the CMB

$$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n} + \nabla\phi)$$

lensed unlensed deflection

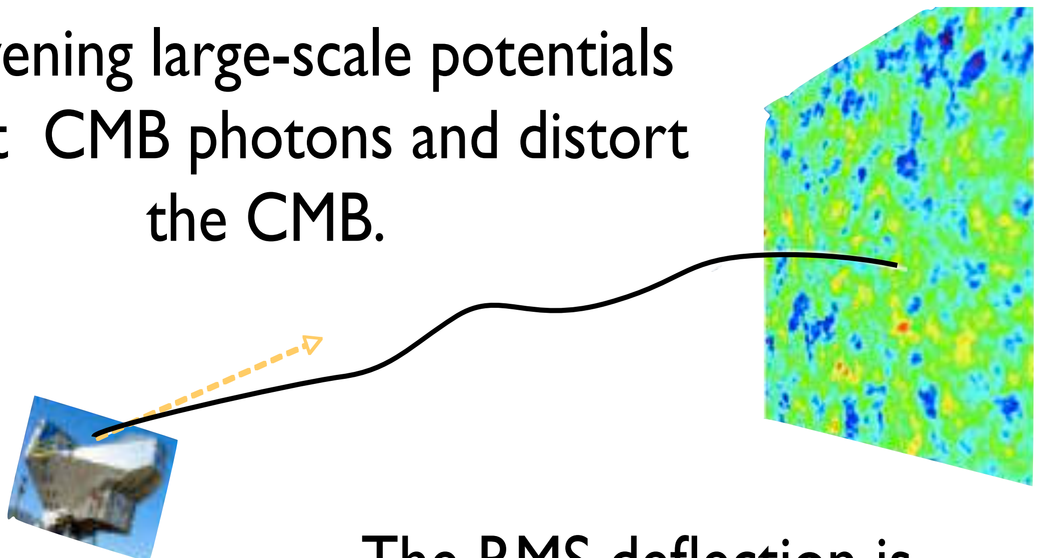
Lens-speak:

Lensing potential: ϕ

Deflection field: $\mathbf{d} = \nabla\phi$

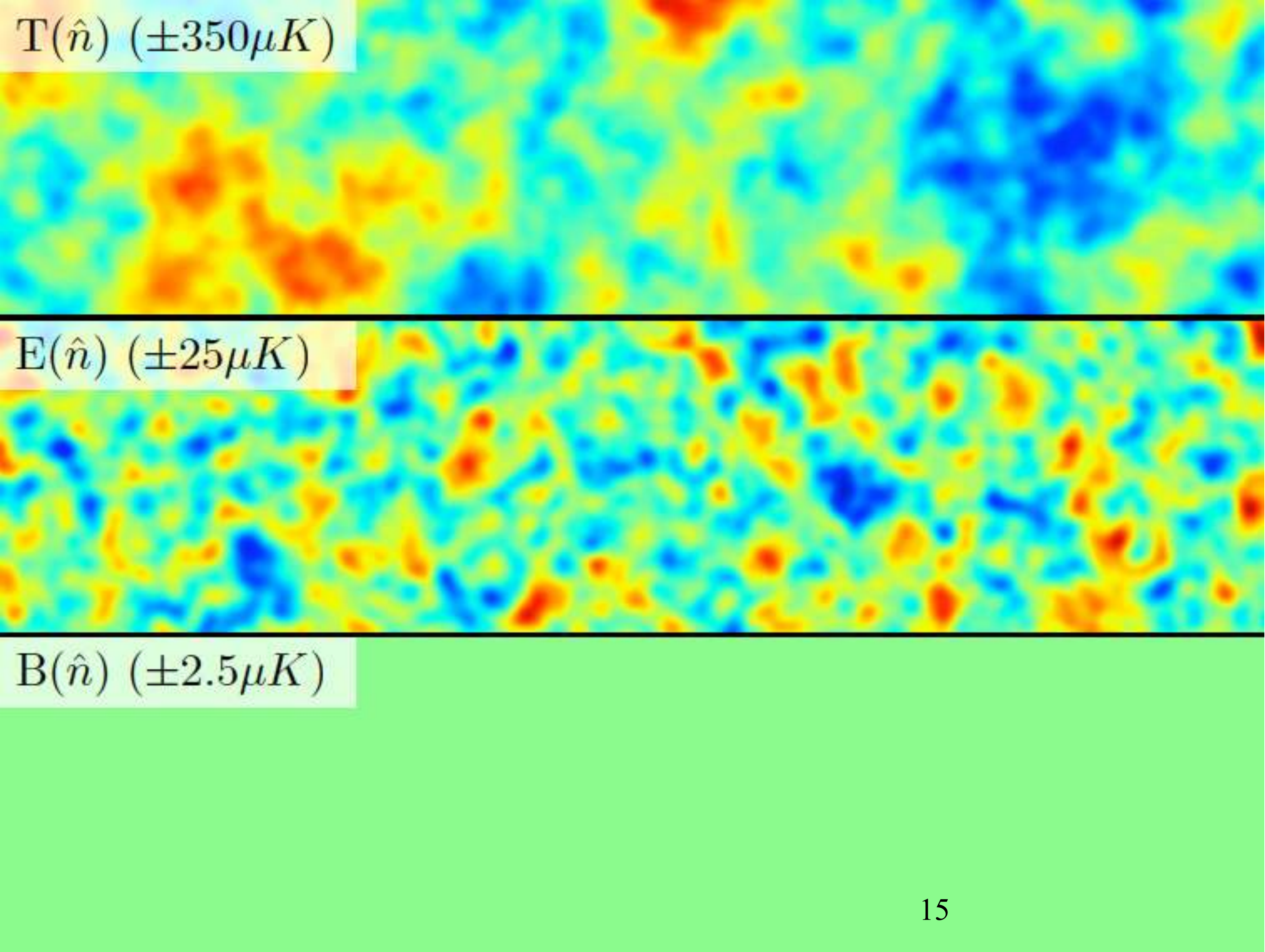
Convergence: $\kappa = \frac{1}{2}\nabla \cdot \mathbf{d}$

Intervening large-scale potentials deflect CMB photons and distort the CMB.

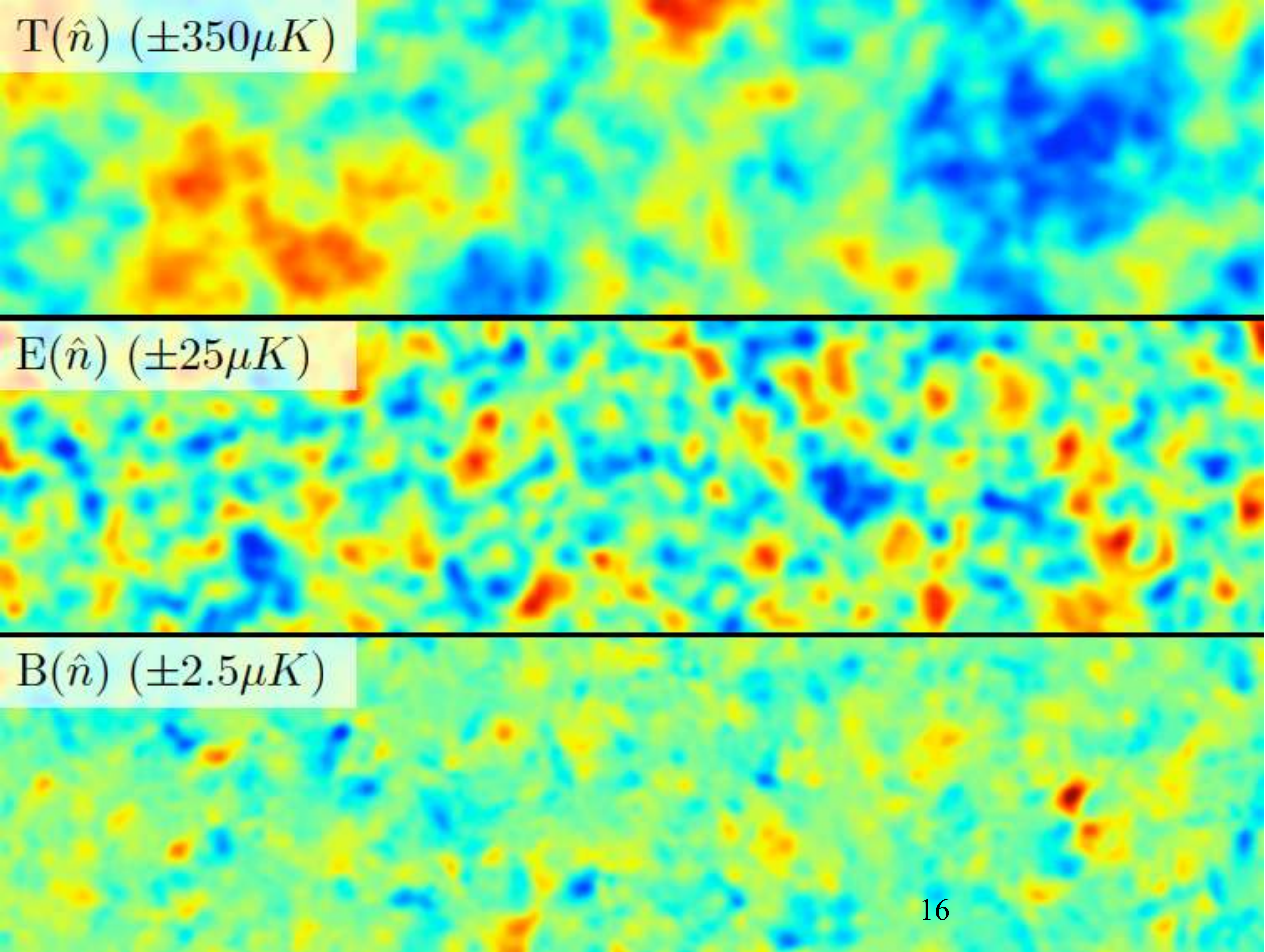


The RMS deflection is about 2.7 arcmins, but the deflections are coherent on degree scales.

From Sudeep Das



$T(\hat{n})$ ($\pm 350\mu K$)
$E(\hat{n})$ ($\pm 25\mu K$)
$B(\hat{n})$ ($\pm 2.5\mu K$)



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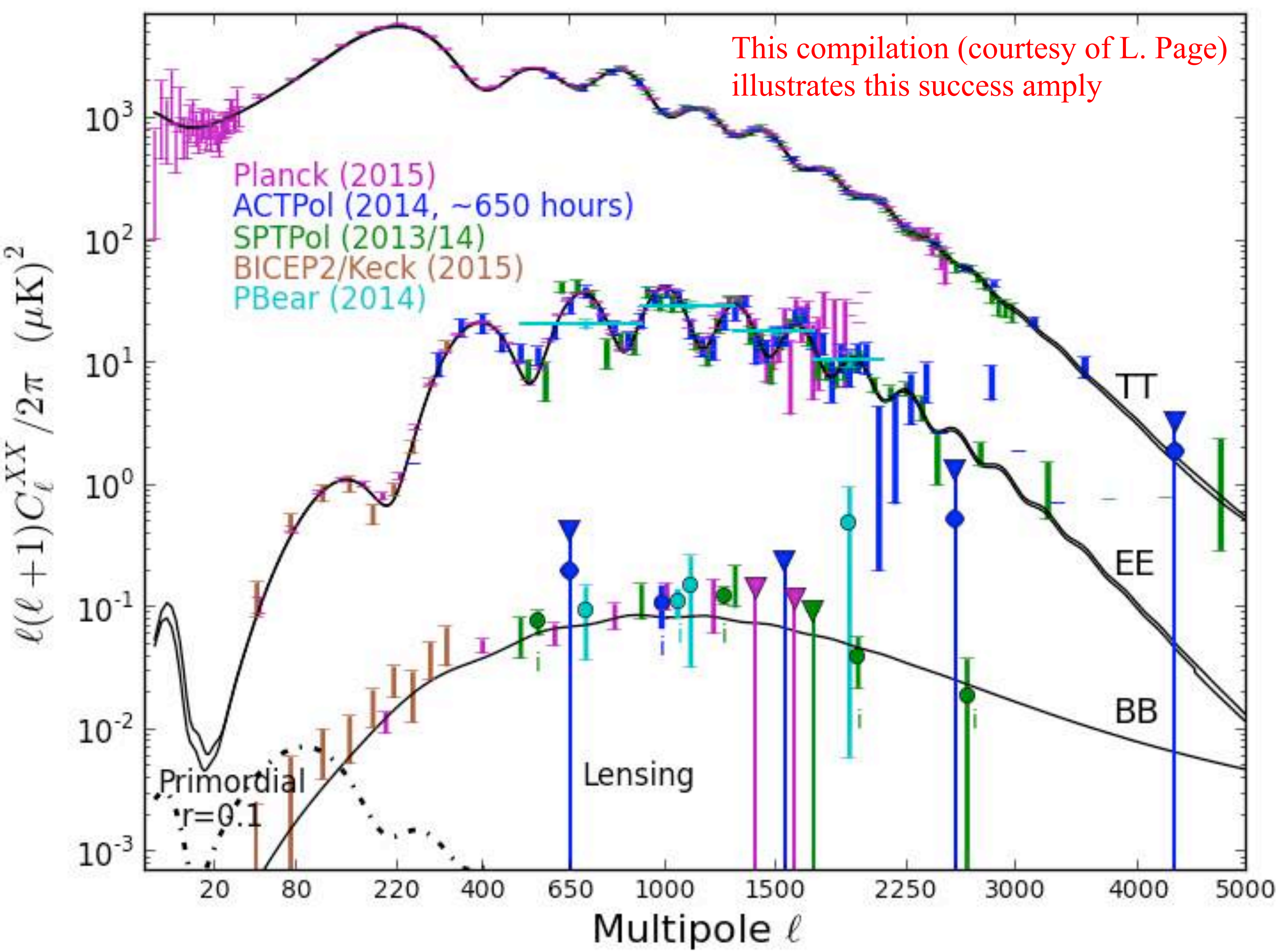


✧ Primary scientific goal:

To measure the temperature anisotropies of the CMB to fundamental limits down to angular resolution of 5arcmin;
also measure polarization better than ever before

✧ Fly at Sun-Earth **L**2 point

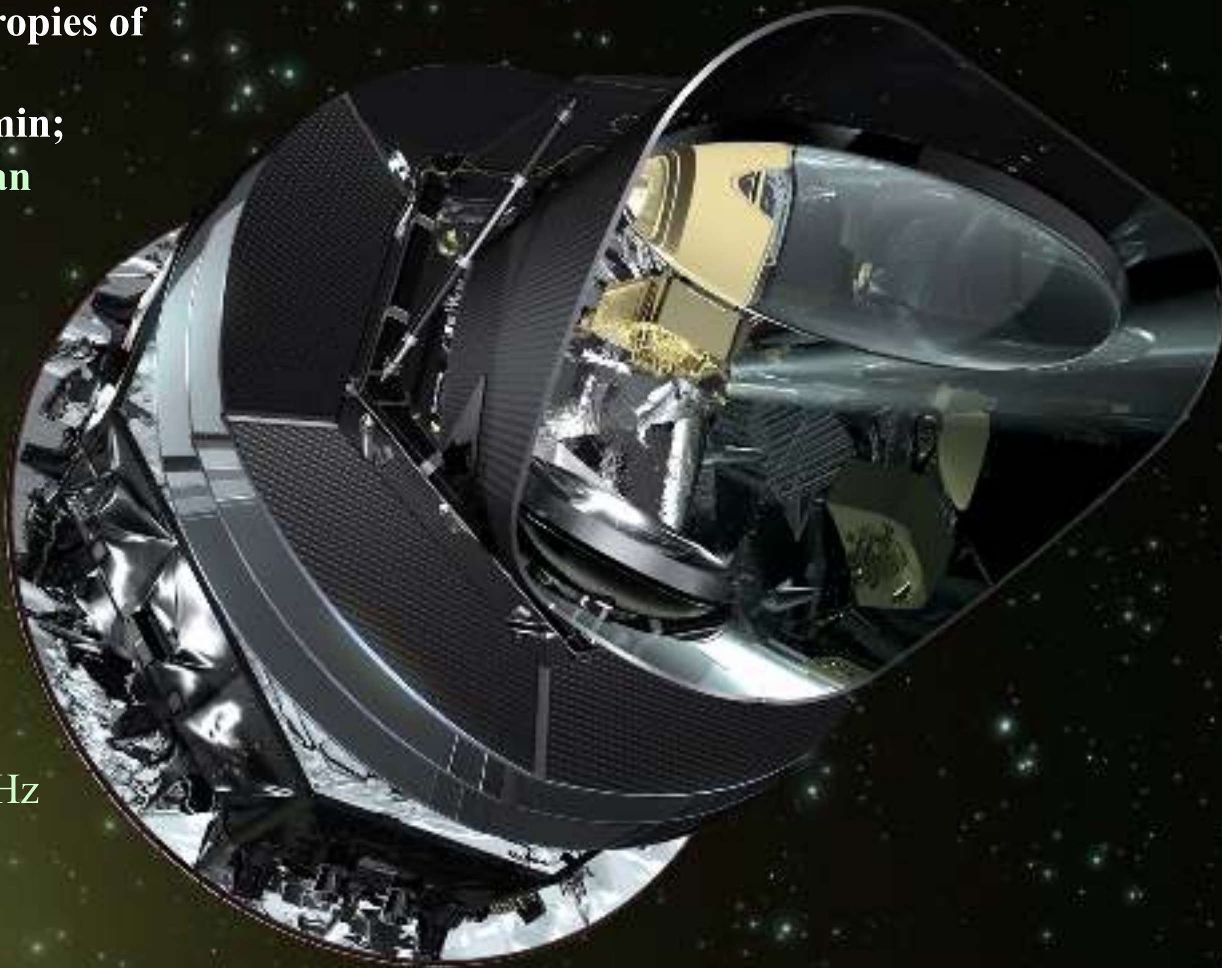
✧ Use 4-stage cooling system

✧ Carry two instruments:

- Low Frequency Instrument (LFI), 20-K cryogenic amplifiers
- High Frequency Instrument (HFI), 0.1-K bolometers

✧ Observe at 9 frequency channels:

LFI - 30, 44, 70 GHz, and
HFI - 100, 143, 217, 353, 545, 857 GHz
to deal with foregrounds



Planck is the 3rd Generation Space CMB Mission

- Formally: "ESA mission with significant participation of NASA"
- Translation: thermal design, sorption coolers, all bolometers, delivery of ERCSC, supercomputing support, expertise and participation in data analysis, and science

esa

PLANCK

Looking back to the dawn of time

Planck Telescope
1.5x1.9m off-axis
Gregorian
T = 50 K

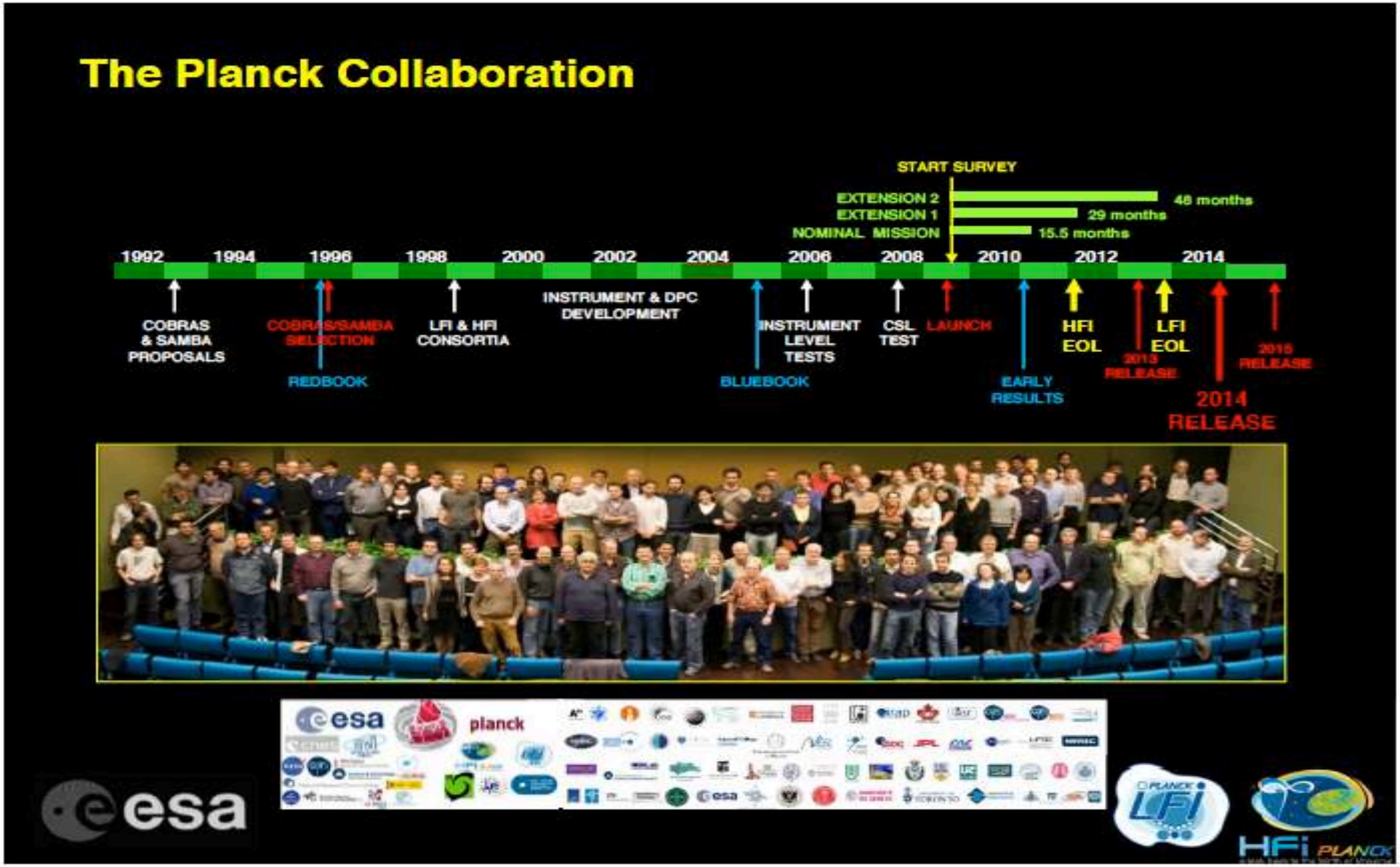
LFI Radiometers
30-70 GHz, T = 20 K

HFI Bolometers
100-857 GHz, T = 0.1 K

asi
agenzia spaziale italiana

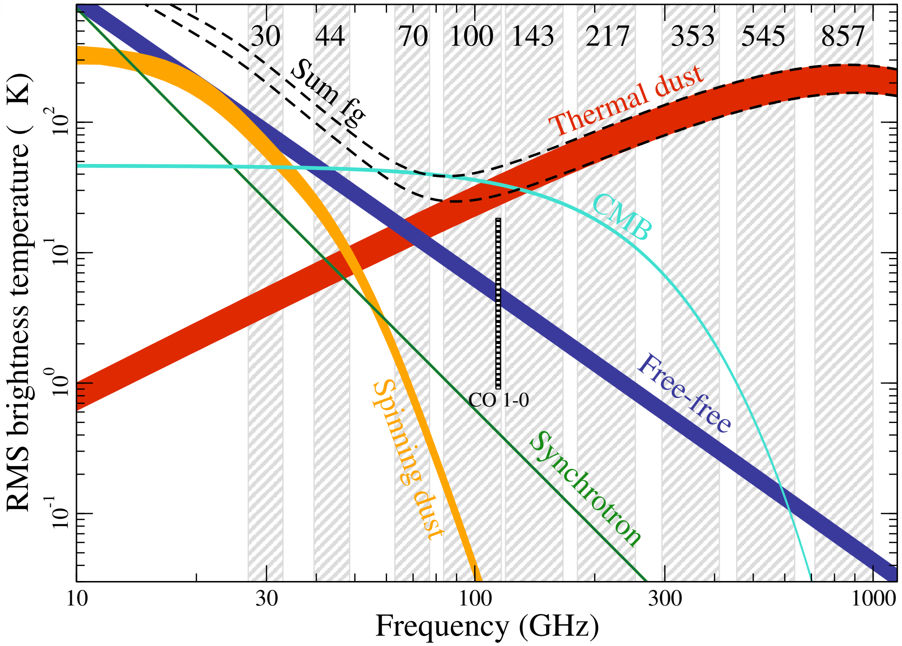
cnes
CENTRE NATIONAL D'ETUDES SPATIALES

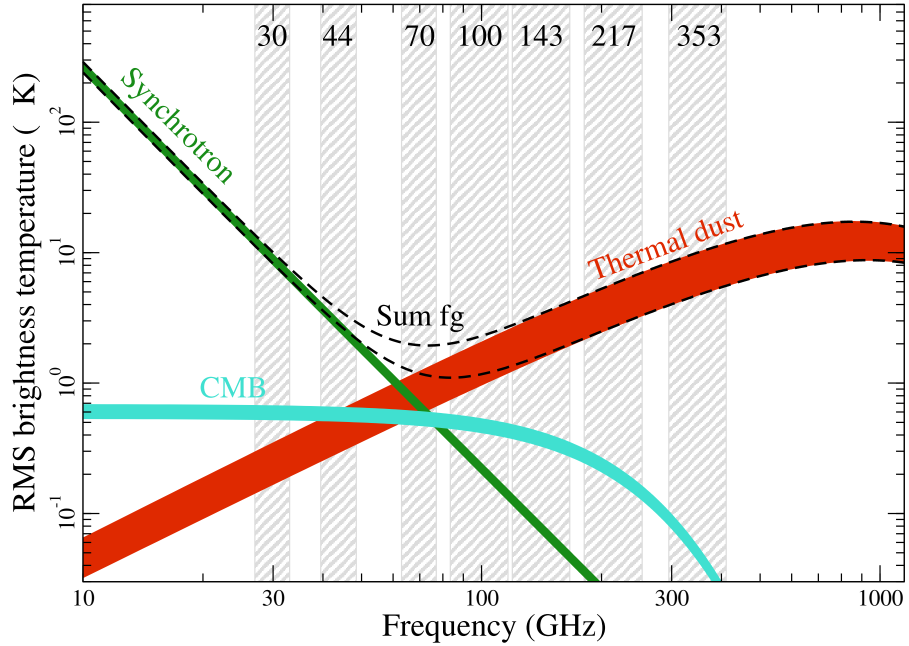
Planck Collaboration



Measuring the CMB

- CMB spectrum peaks between 100 and 200 GHz
- Everything else that radiates at the same frequencies will be seen as well.
  - Have to be able to separate the different sources.





Temperature

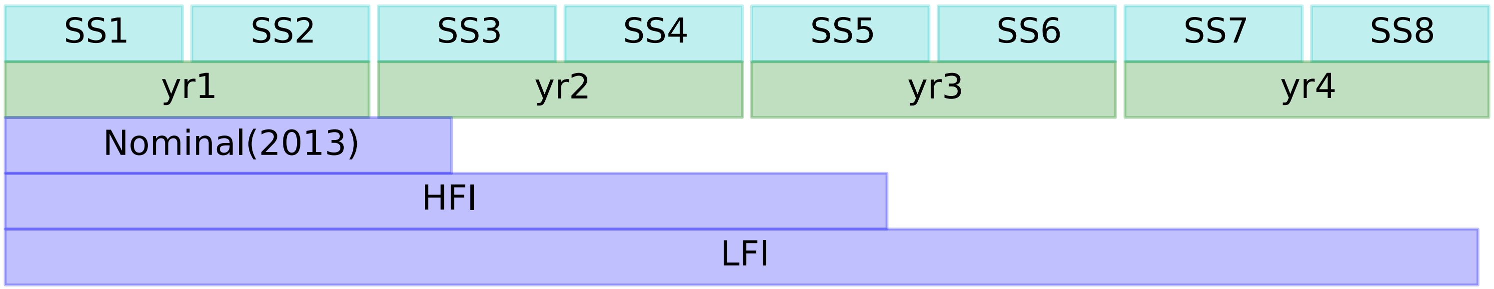
- All components smoothed to 1°
- Sky fractions 81–93% of sky

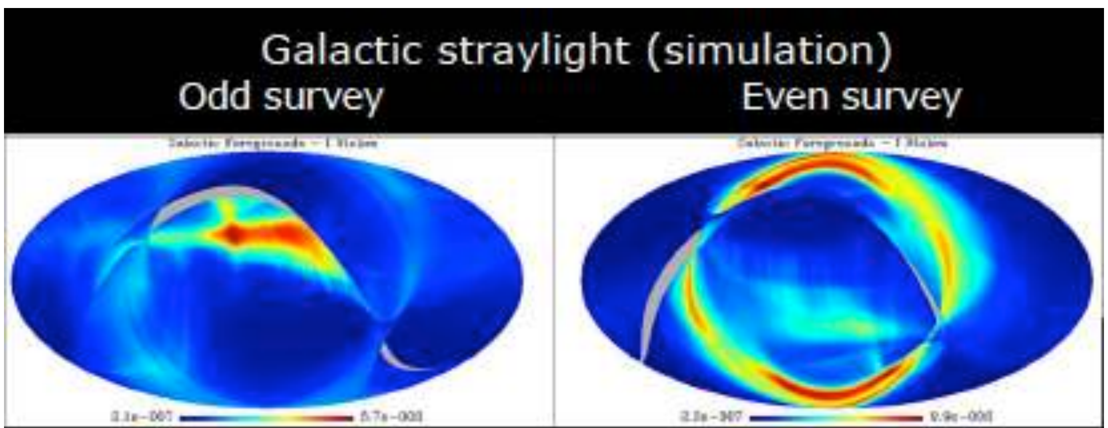
Polarization

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

2015: Planck full mission

- Second Planck data release: Full mission data (12 Aug 2009 – 23 Oct 2013)
- Planck 2015 release has better S/N and takes full advantage of multiple full-sky redundancies (main motivation for the extension) – *Surveys & Years*





Due to Planck scanning strategy, odd and even surveys couple differently with sky signal

Odd and even surveys have different far sidelobe pick up

2015: Planck data & products

- Frequency maps and CMB maps
- Angular power spectrum
- Likelihood
  - CMB+lensing Temperature+Polarisation;
  - Low-ell likelihood based on LFI 70 GHz (replaces WMAP)
- Foregrounds
  - Dust (temp and pol), Synchrotron (temp and pol), Free-Free, Spinning Dust, CO emission;
- Map of integrated lensing potential
- New catalogue of compact sources
- New catalogue of SZ sources
- Cosmological parameters
- Constraints on B-modes, Bicep2/Keck/Planck coll.
- Higher order statistics, etc.

http://wiki.cosmos.esa.int/planckpla

2015: Planck data & products:

- More data: 48/29 months of LFI/HFI observations, therefore further checks. ☺
- Improved data processing:
  - systematics removal, calibration, beam reconstruction
    - Changes to the filtering applied to remove "4-K" cooler lines from the time-ordered data (TOD); Changes to the deglitching algorithm used to correct the TOD for cosmic ray hits; Improved absolute calibration based on the spacecraft orbital dipole;more accurate models of the beams, accounting for the intermediate and far side-lobes, etc..
- Improved foreground model
  - Larger sky-fraction used for analysis
- More robust to systematics:
  - based on half-mission cross power spectra of frequency channels and half-mission auto-spectra of CMB maps
- The 2015 analysis includes polarization:
  - l<30: T from Commander (93%), Polarisation from 70GHz (-S2 & S4, 47%), cleaned with 30 & 353GHz
  - High-resolution High-Pass-Filtered CMB Q and U maps , analysis for 30<l<2000 for Commander, NILC, SEVEM and SMICA

2105: Cosmology from Planck: Standard model and beyond

Lets's start with what has not changed:

- **ΛCDM** still a good fit.
- The Universe is still **very flat**
- Parameters and major cosmological inferences from 2013.
- Power asymmetry at large angular scales
  - Features on 2015 full mission data are very similar to 2013 nominal mission data

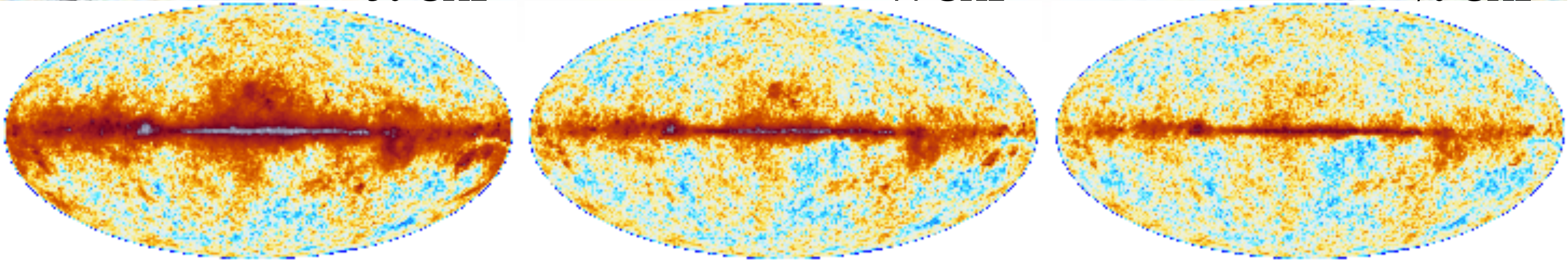
Now what's new:

- Typical uncertainty reduced by more than **25%**.
- Photometric calibration increased by **0.8%**.
  - Uncertainty now 0.05%. Excellent agreement on orbital dipole between WMAP, LFI & HFI! ☺
- Thomson $\boldsymbol{\tau}$ lower by ~**1σ (**so $\mathbf{z_{re}}$ decreased ~1σ**)**
  - but calibration increased power so $\boldsymbol{\sigma_8}$ hardly changed
- $\mathbf{n_s}$ increased by ~**0.7σ**
- $\boldsymbol{\omega_b}$ increased by ~**0.6σ** and error decreased**.**
- Limits on isocurvature modes, $\mathbf{\Omega_K}$**,** $\mathbf{m_\nu}$, $\mathbf{\Delta N_{eff}}$, $\mathbf{f_{nl}}$, **DM** annihilation etc. all tighter. No deviations detected

Planck 2015 Temperature Maps

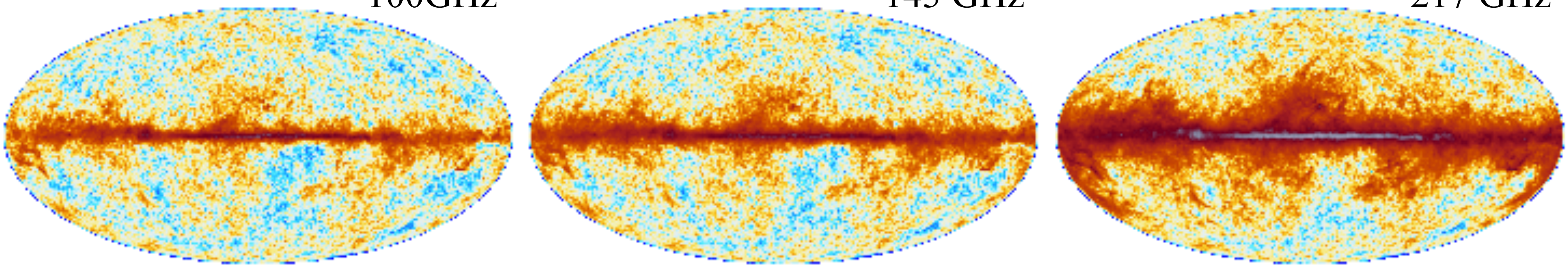
Low Frequency Instrument:

30 GHz | 44 GHz | 70 GHz

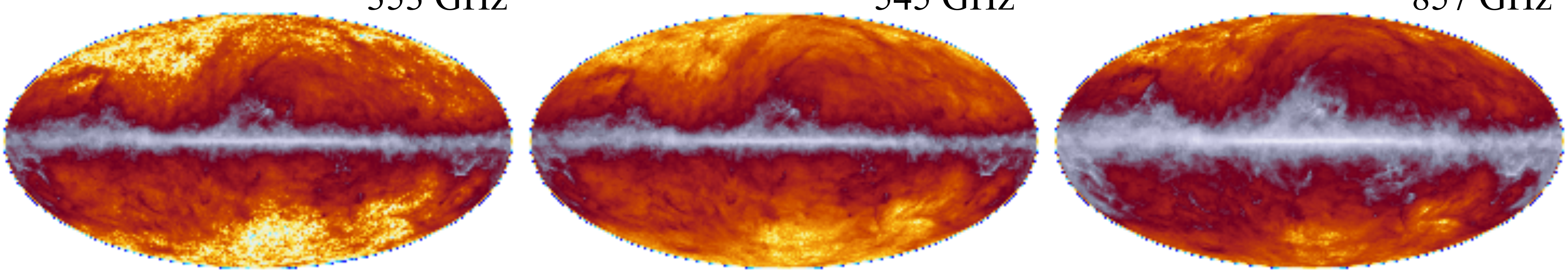


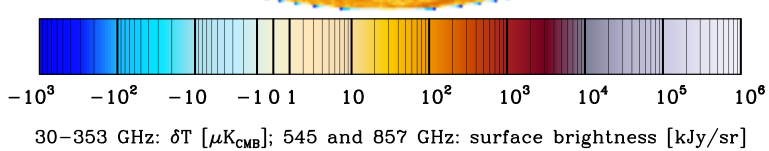
High Frequency Instrument:

100GHz | 143 GHz | 217 GHz

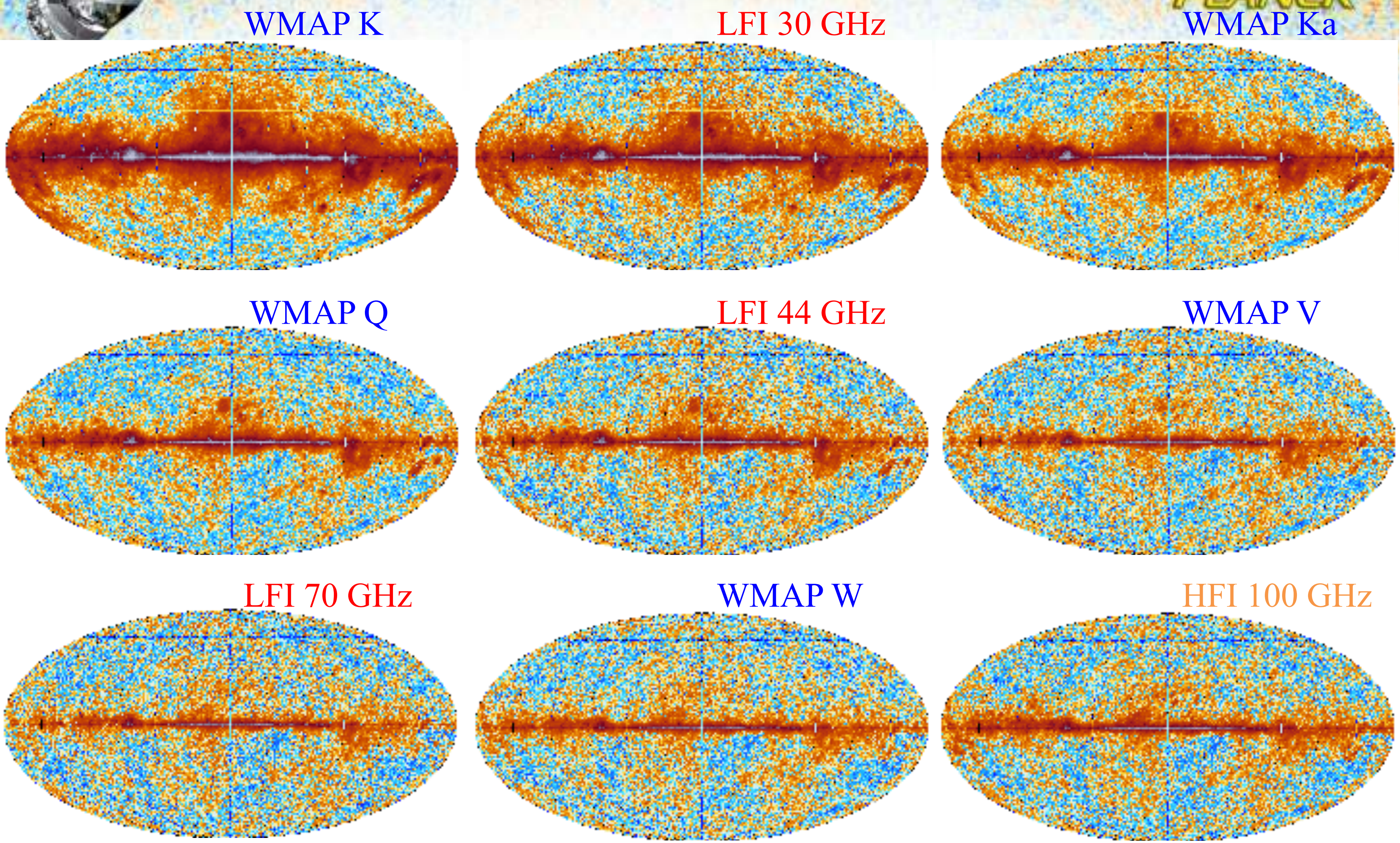


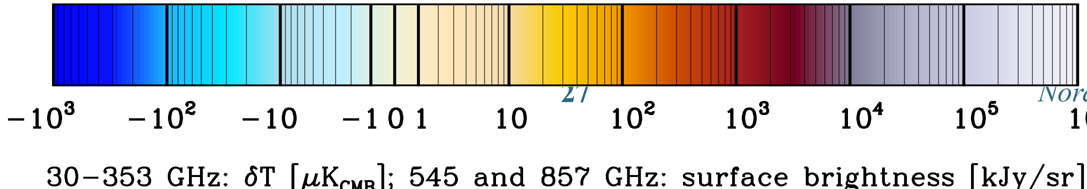
353 GHz | 545 GHz | 857 GHz



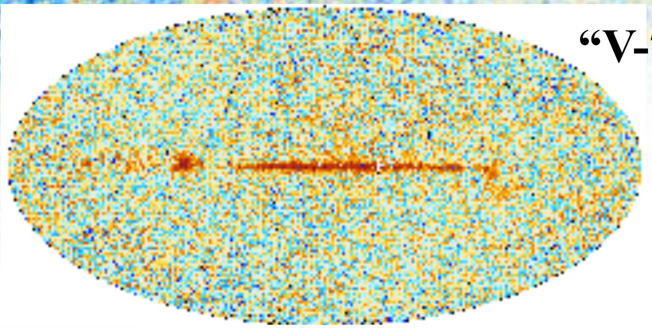


Planck and WMAP aggregate data set over 20 ÷ 100 GHz

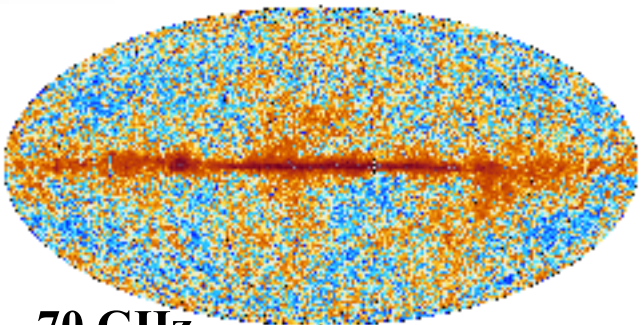




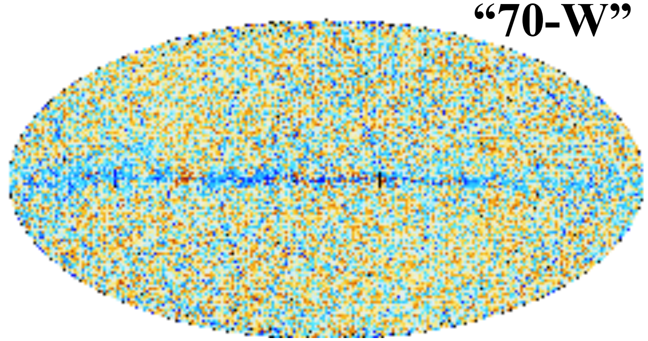
Poor man's component separation … and a bit more; Map differencing near the minimum of the foreground emission



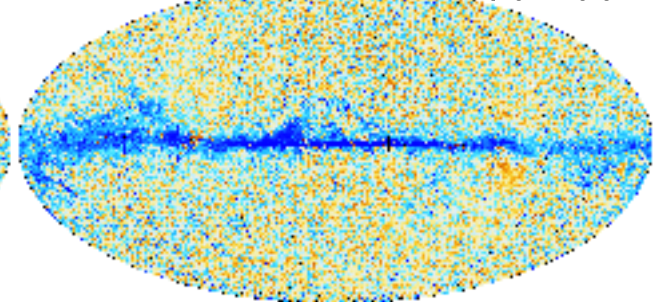
"V-70"



70 GHz

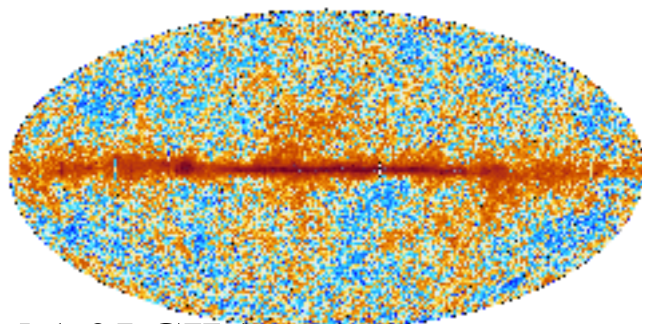


"70-W"

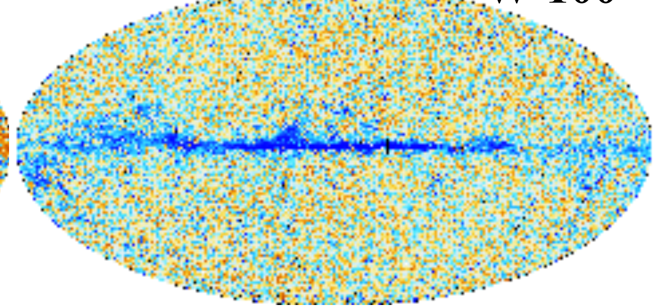


"70-100"

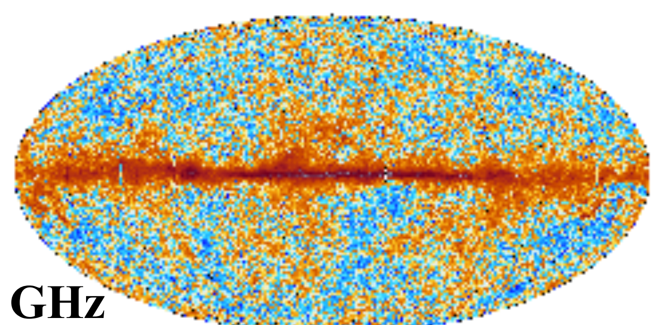
courtesy of K. Gorski



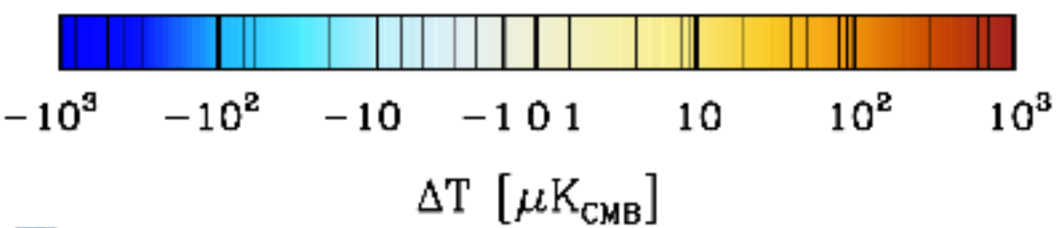
W-band (~95 GHz)



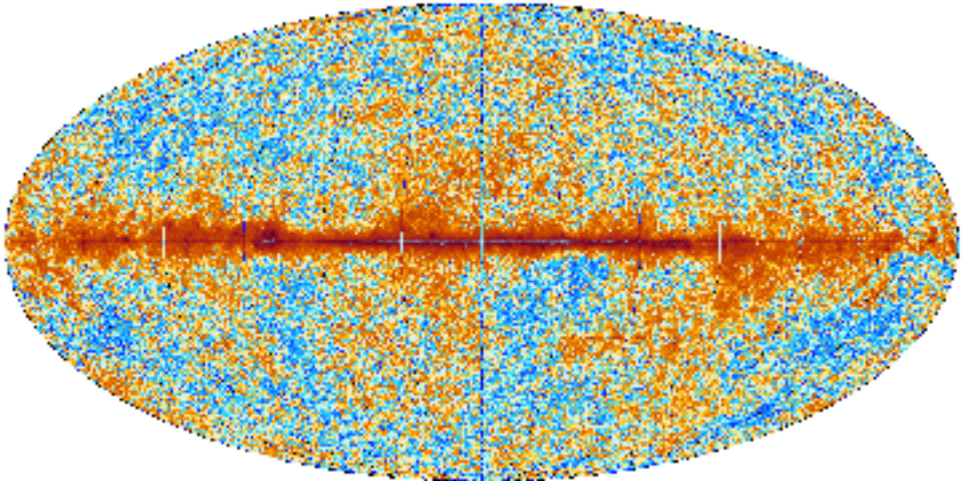
"W-100"



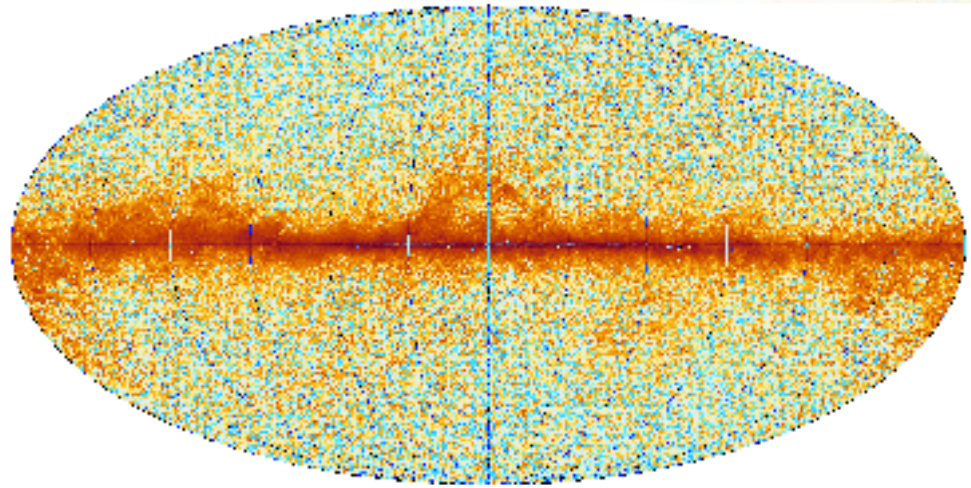
100 GHz



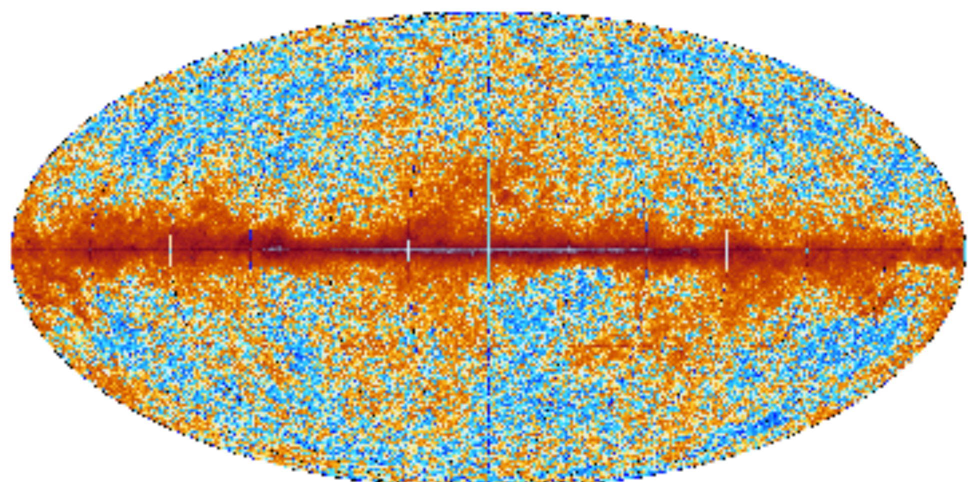
W-band (~95 GHz)



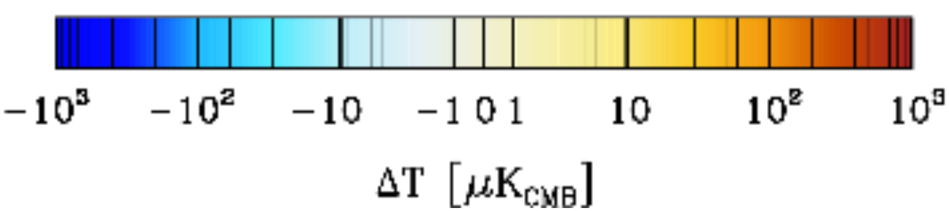
“W-143” (mostly dust emission)

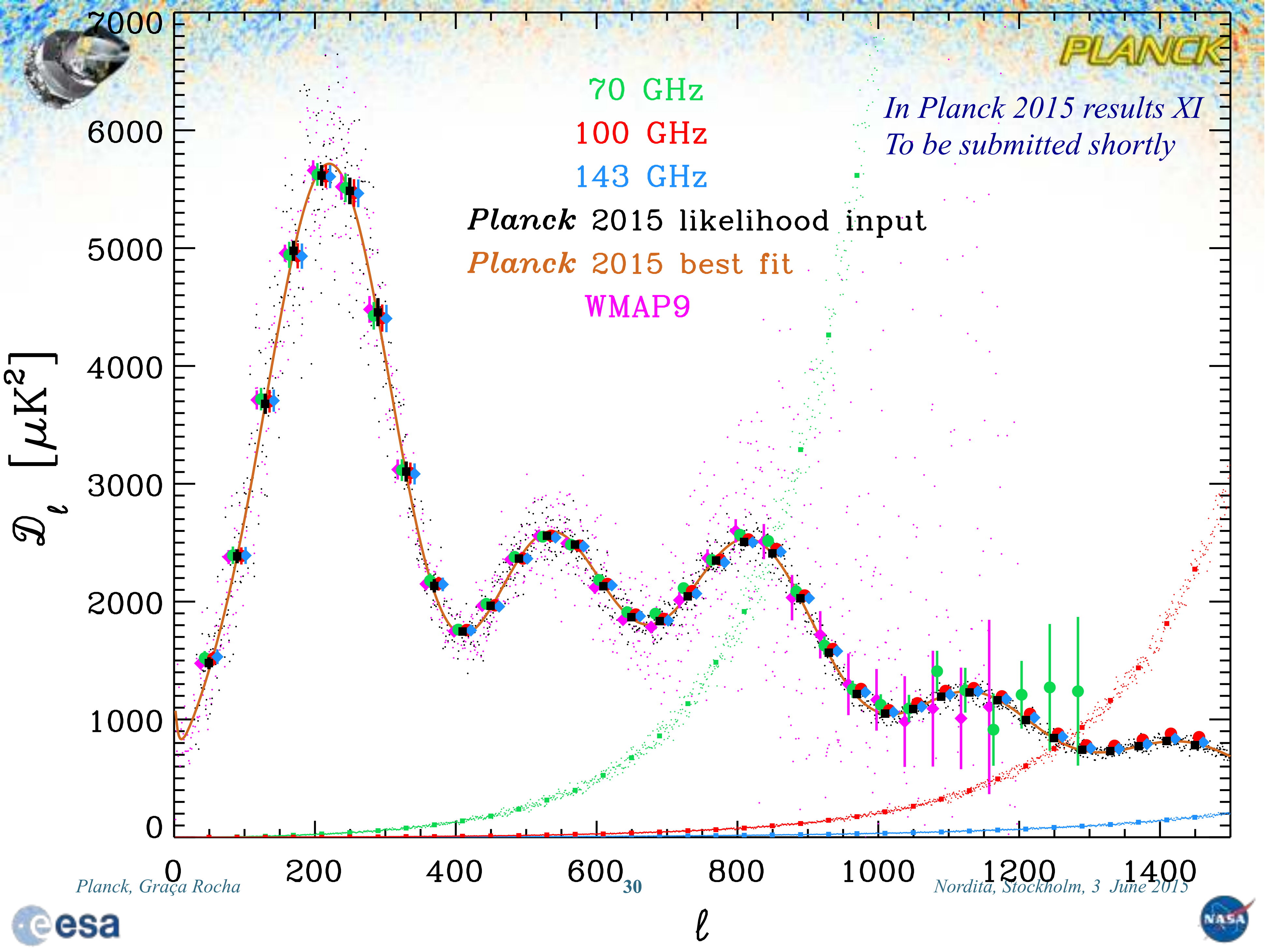


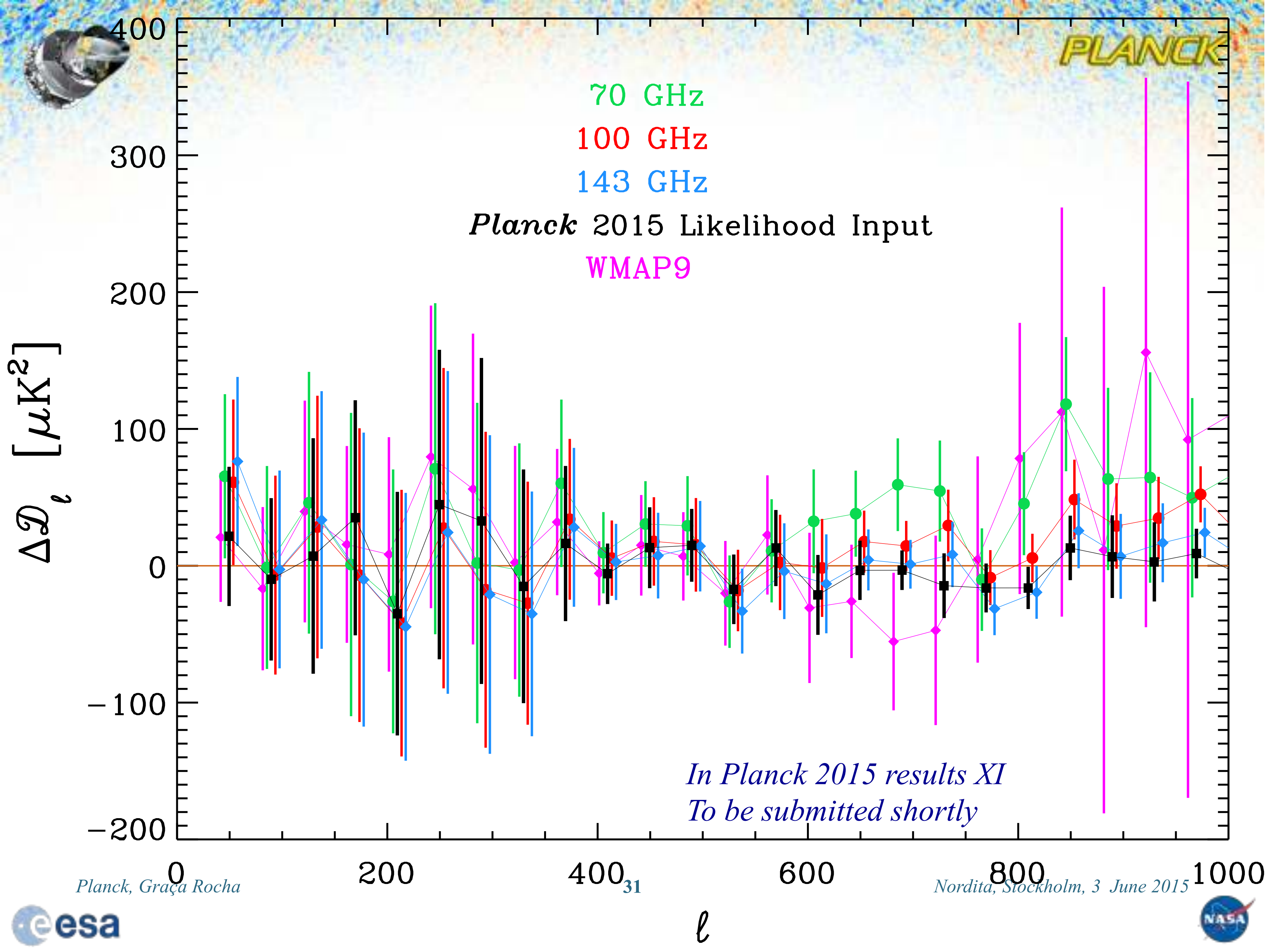
143 GHz



courtesy of K. Gorski




70 GHz
100 GHz
143 GHz
Planck 2015 likelihood input
Planck 2015 best fit
WMAP9
In Planck 2015 results XI
To be submitted shortly
PLANCK
7000
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400
$\mathcal{D}_\ell$ [μK^2]
ℓ


70 GHz
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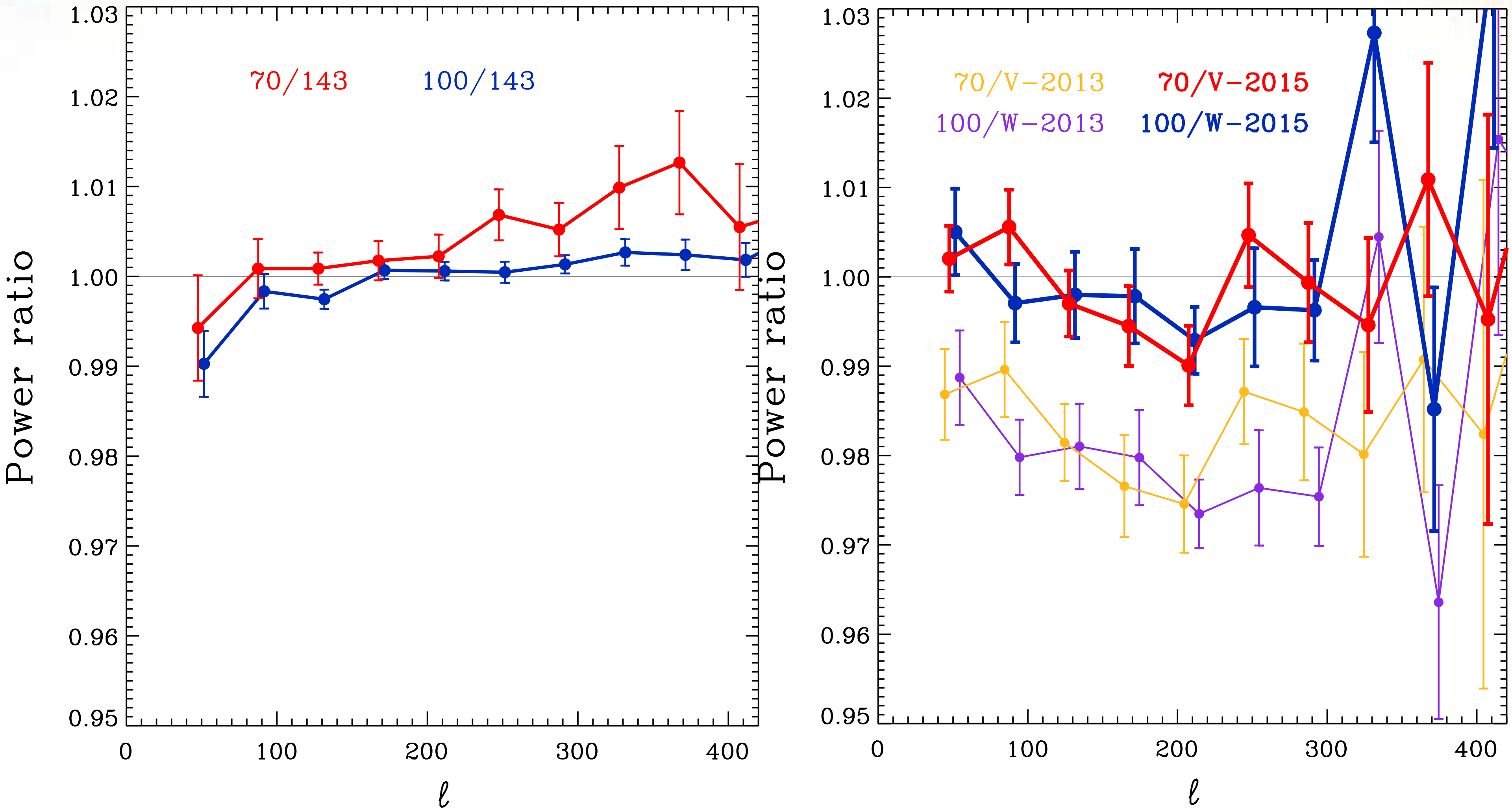
To be submitted shortly
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ
400
300
200
100
0
−100
−200
0
200
400
600
800
1000

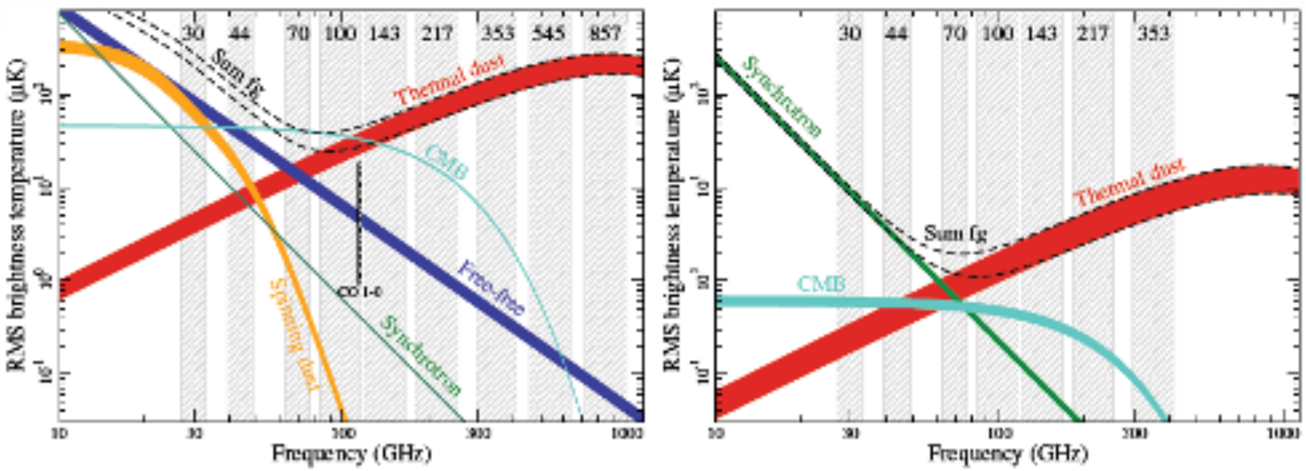
Calibration Update



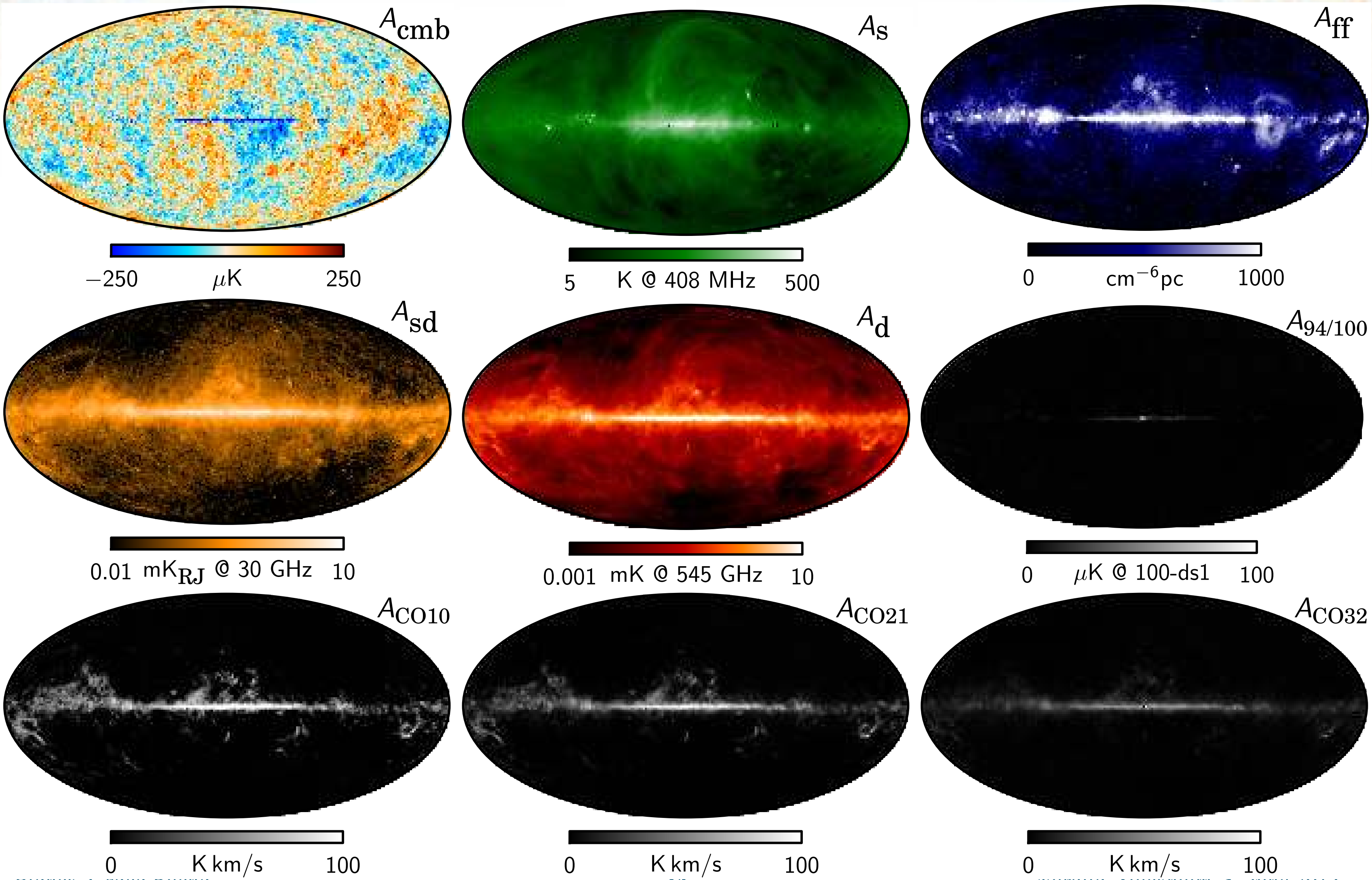
Component Separation

Two schemes

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

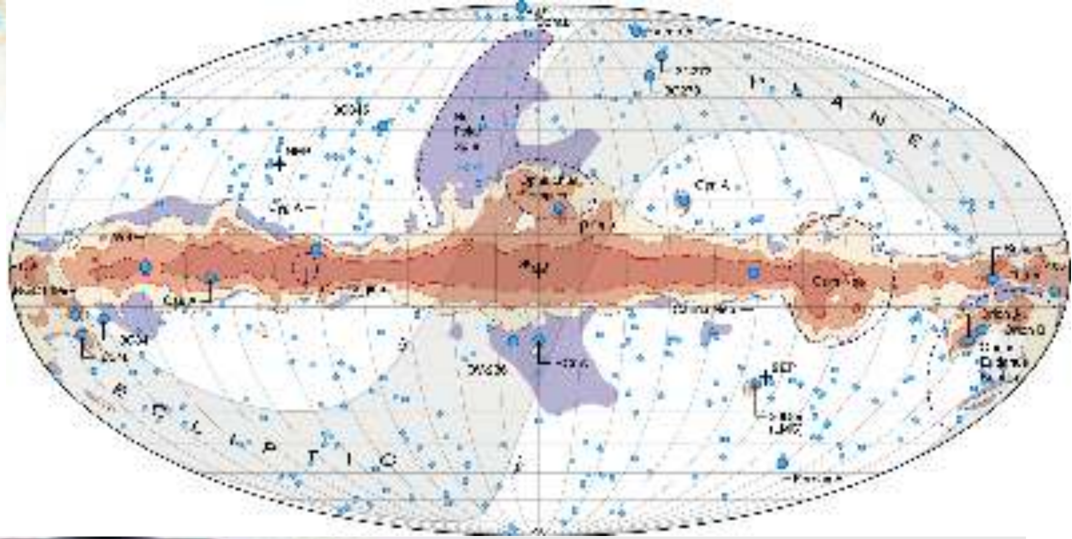


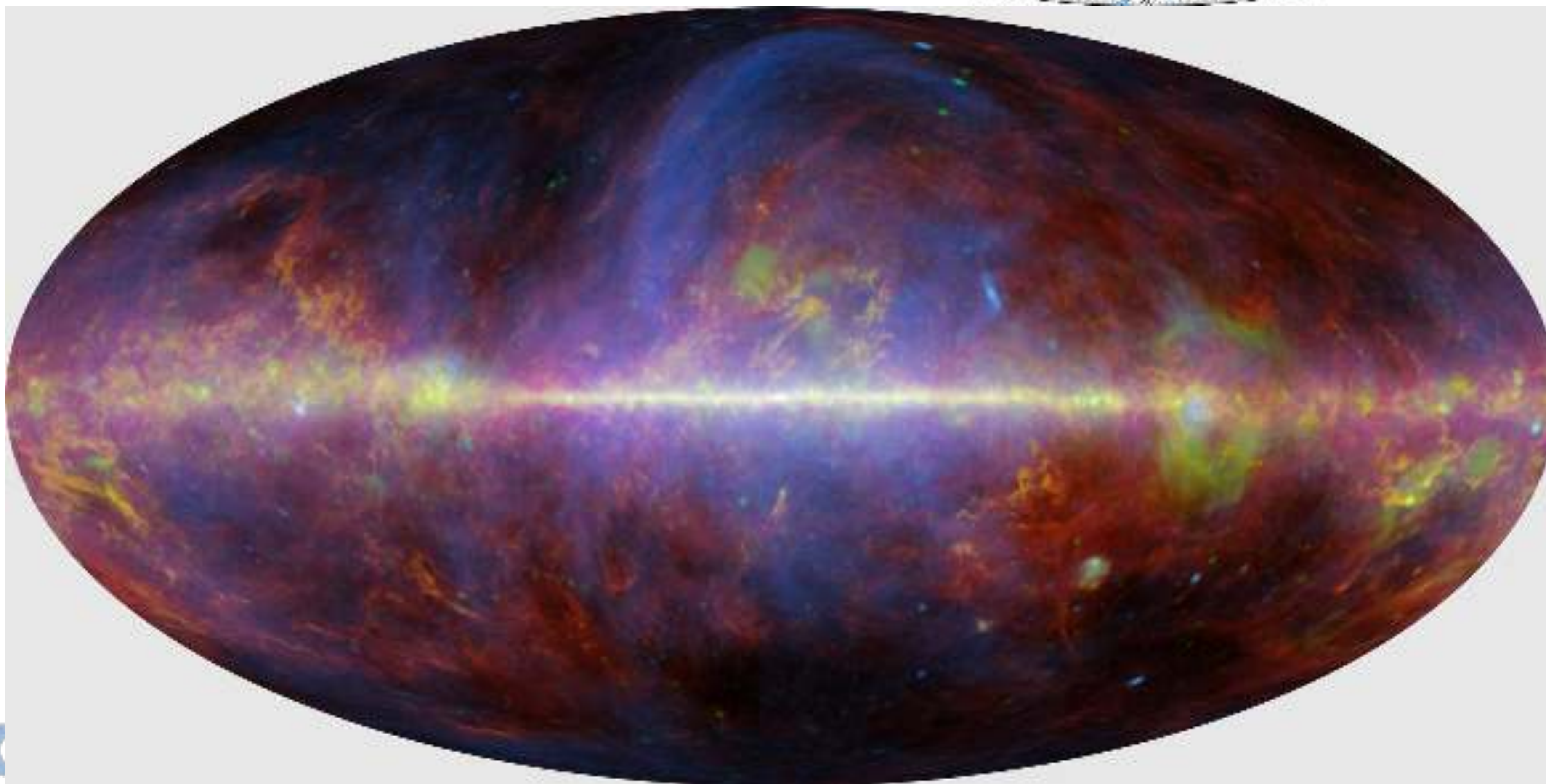
CMB and Foreground Stokes I Maps



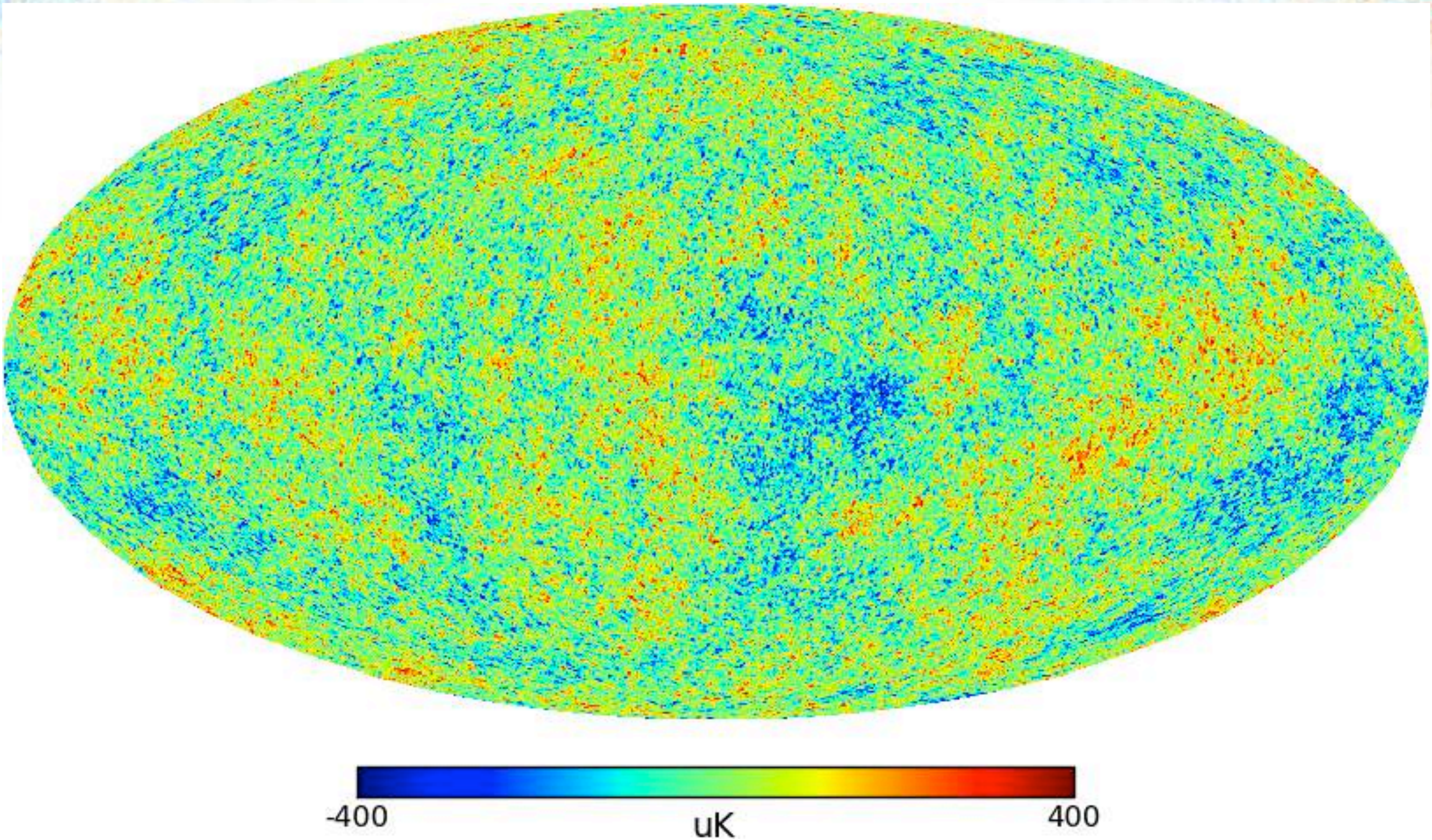
Preliminary

Four Color Composite Image of the Foreground Sky

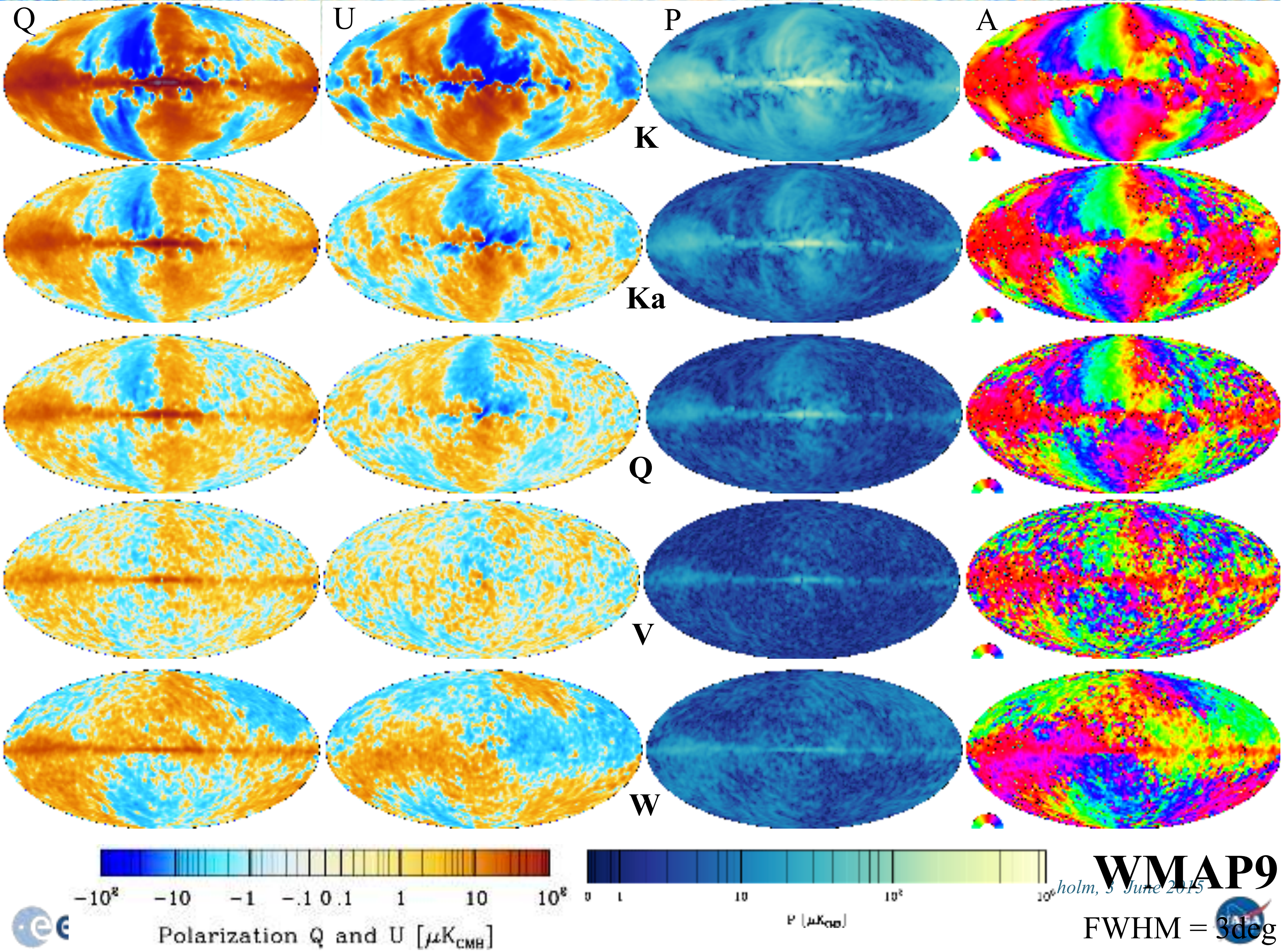


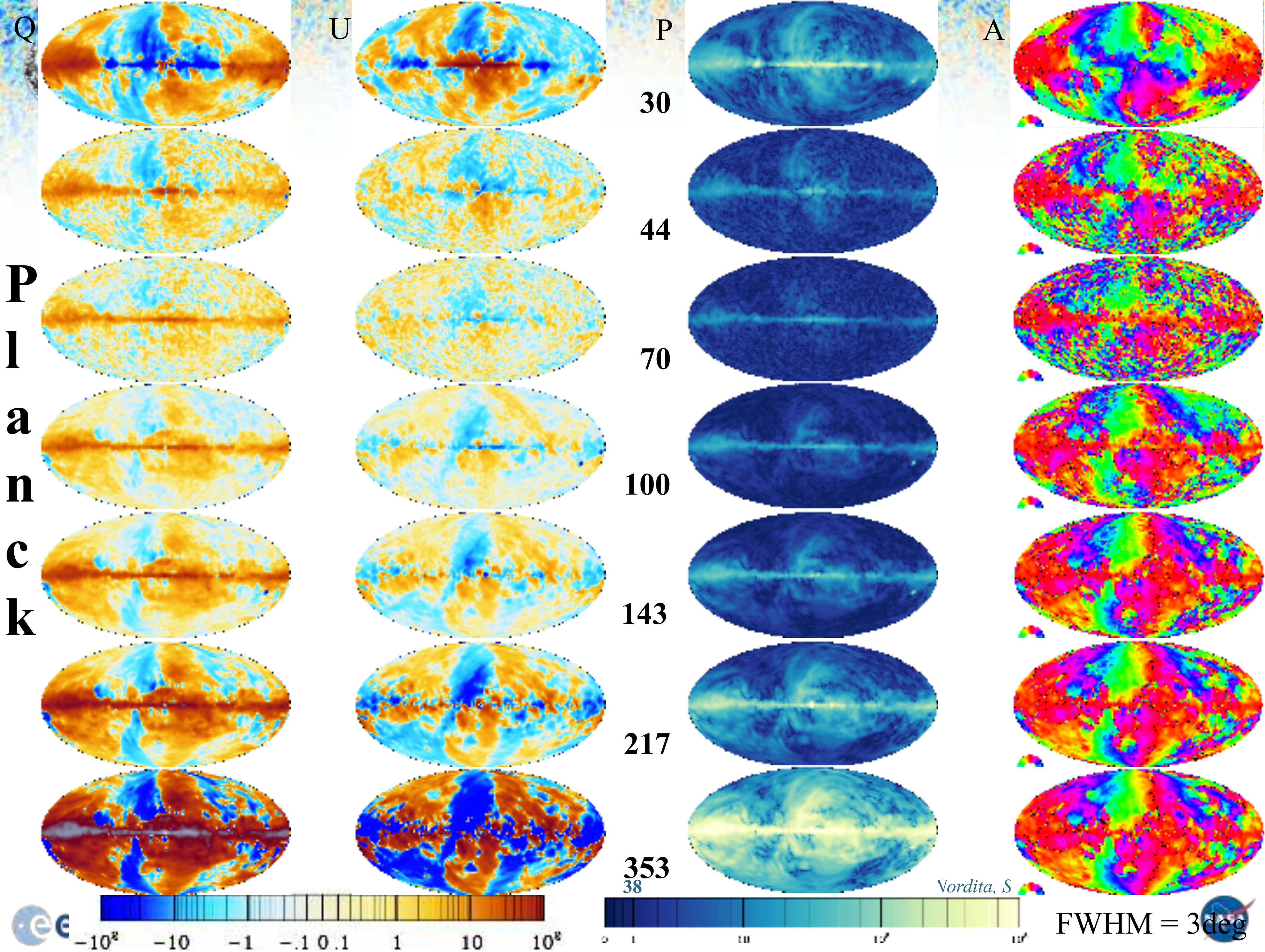


The Universe, Age 370,000 Years

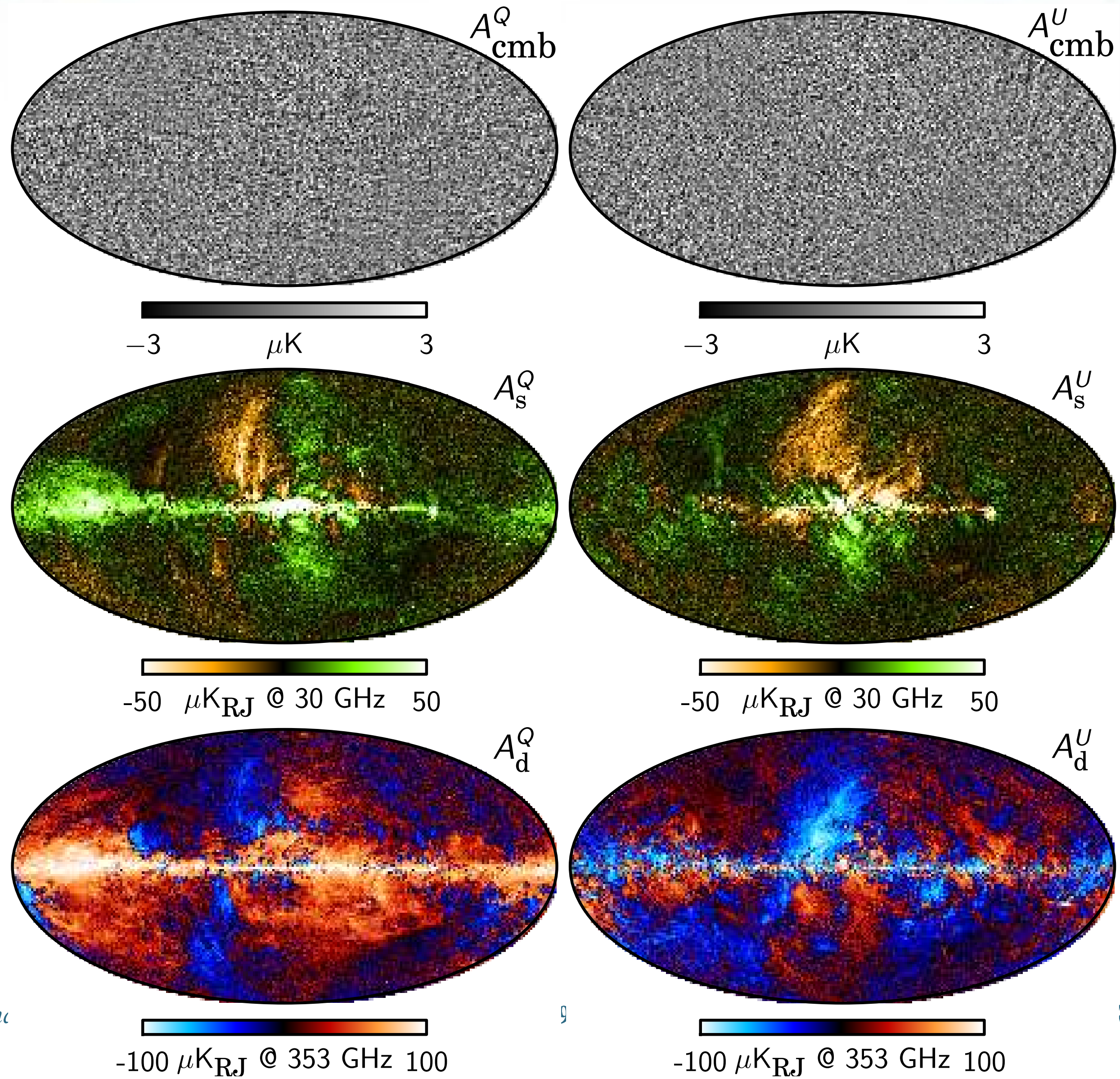


(The plane of the Milky Way is filled in with a "constrained realization".)


Q
U
P
A
K
Ka
Q
V
W
−10^8 −10 −1 −.1 0.1 1 10 10^8
Polarization Q and U [μK_CMB]
0 1 10 10^2 10^6
P [μK_CMB]
WMAP9
FWHM = 3deg

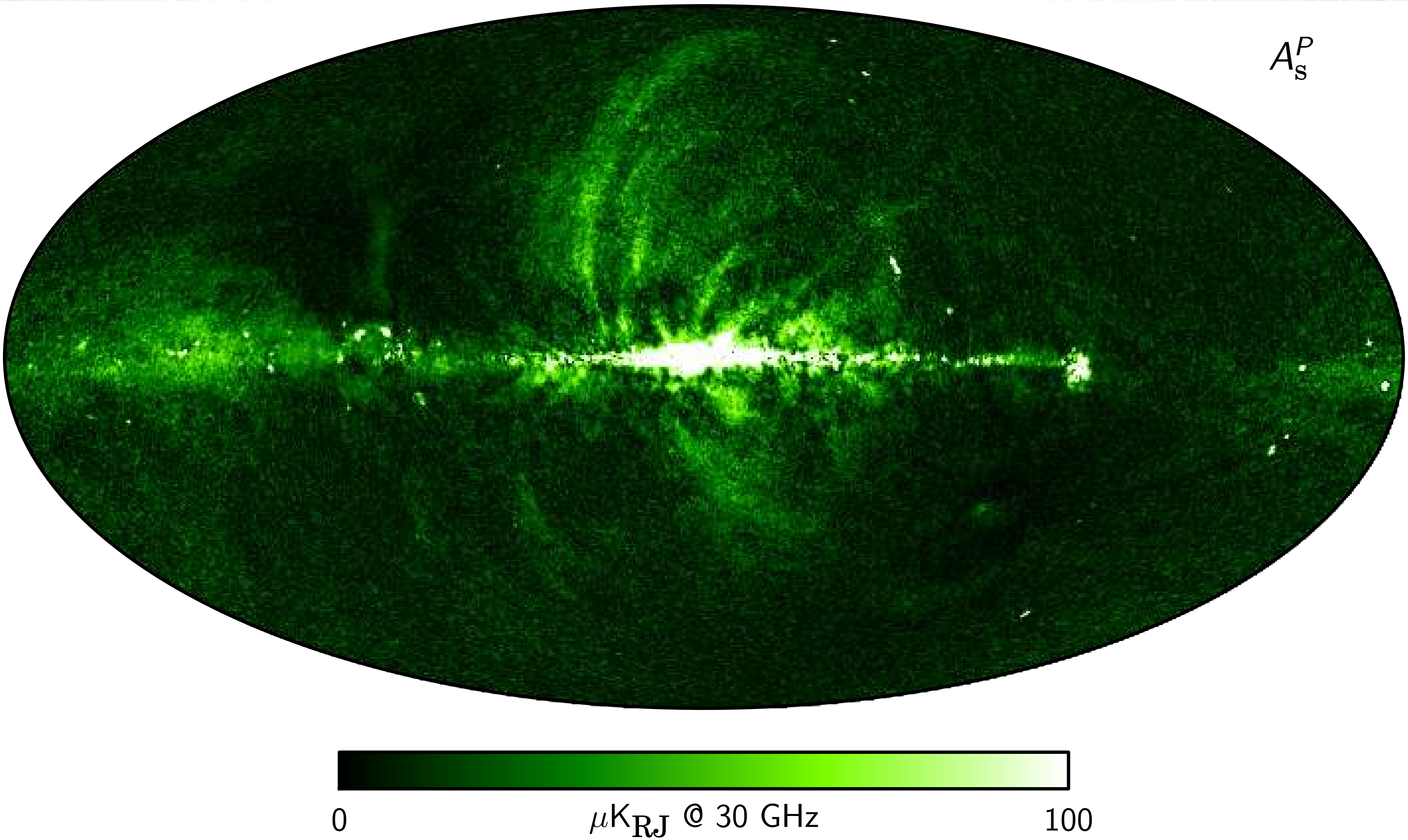

Q
U
P
A
P
l
a
n
c
k
30
44
70
100
143
217
353
−10^8
−10
−1
−.1 0 .1
1
10
10^8
Vordita, S
FWHM = 3deg

CMB and Foreground Stokes Q, U Maps

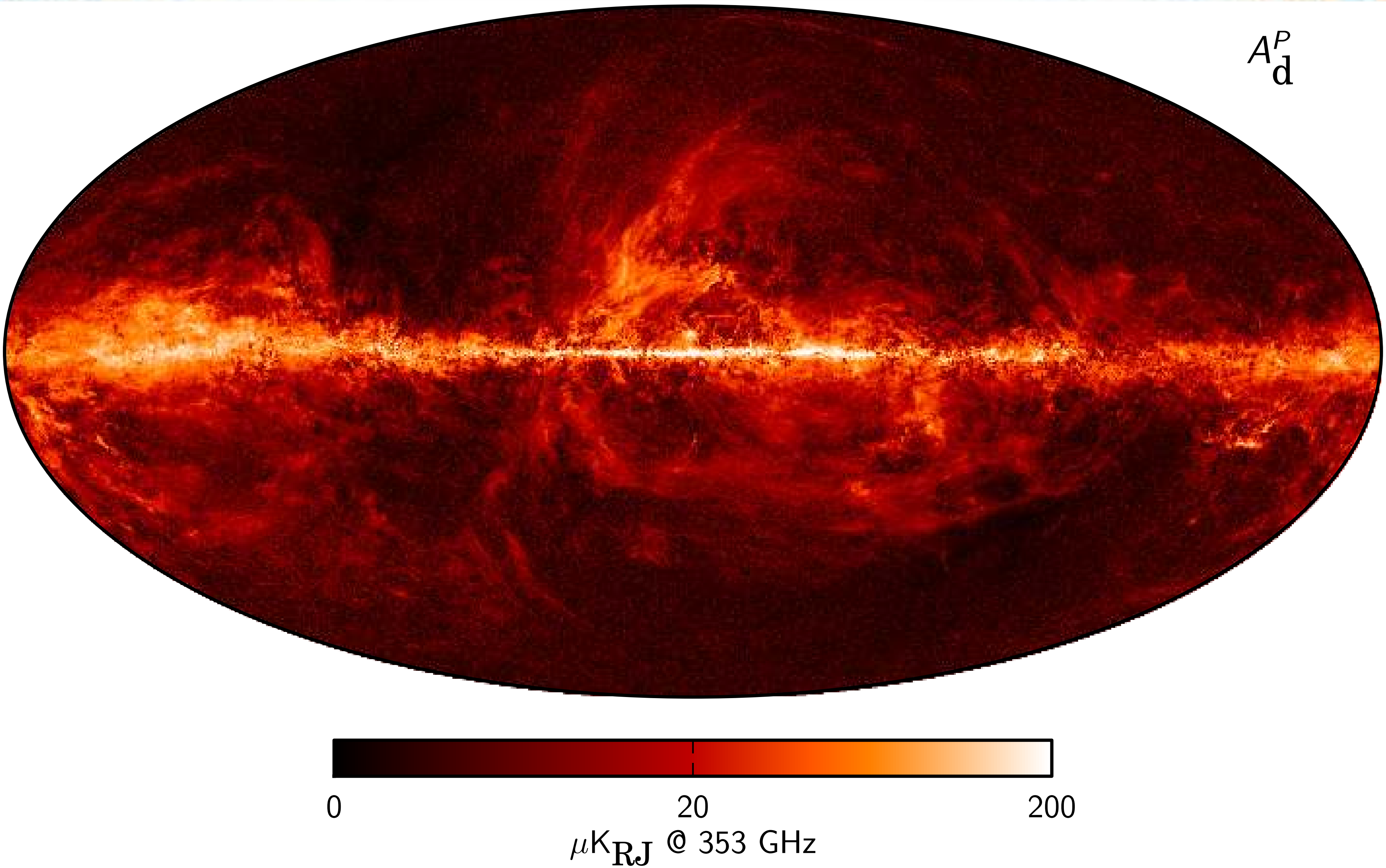


Preliminary

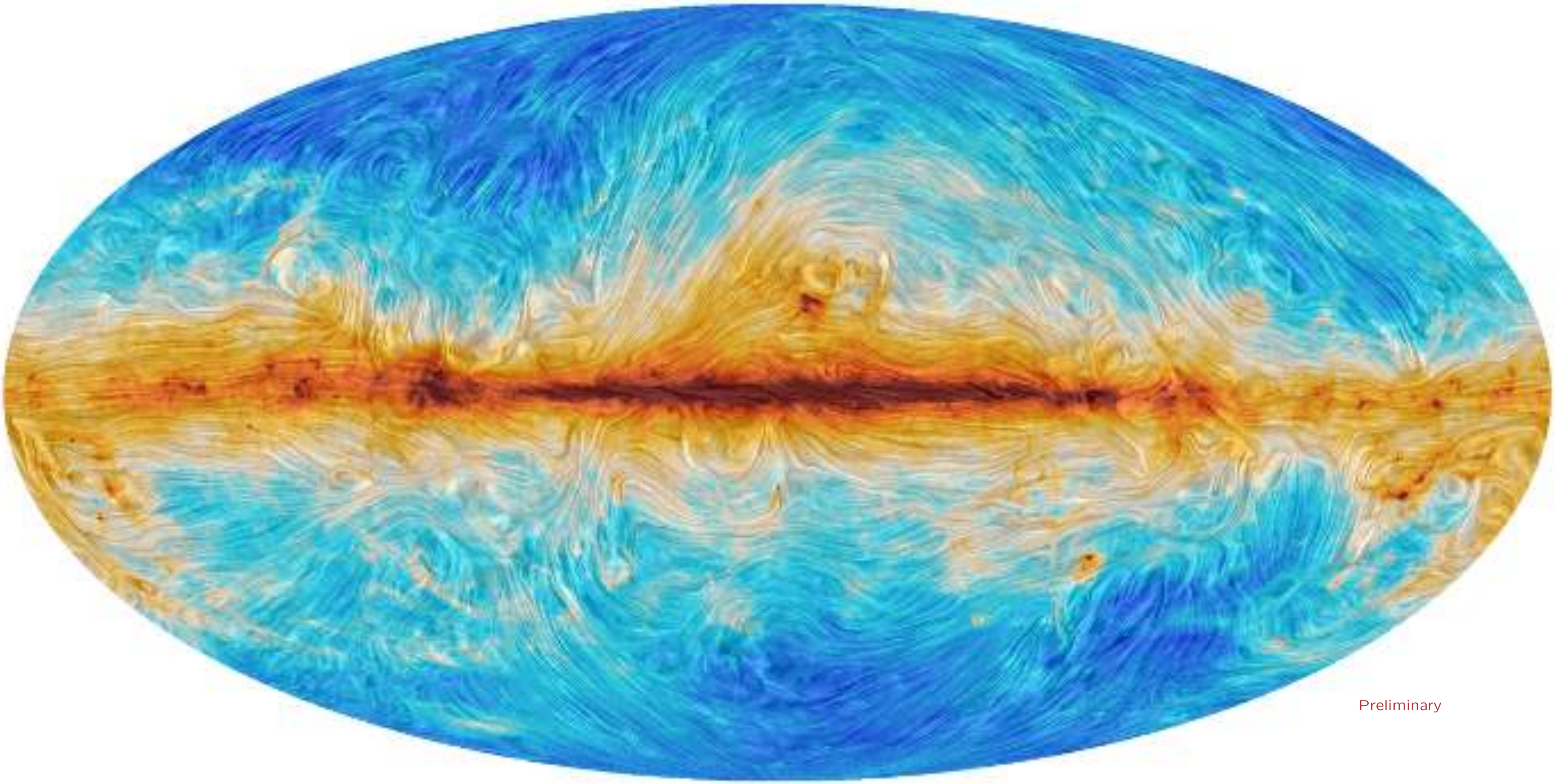
Synchrotron P Map at 30 GHz from Commander



Dust P Map at 353 GHz from Commander



Dust Temperature and Polarization at 353 GHz



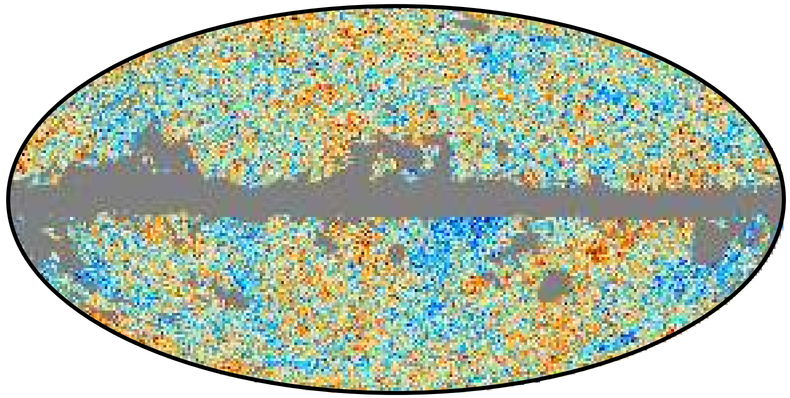
Total intensity encoded in colours

Polarization encoded in shaded striations.

Polarization orientation is at 90° from the striations, which indicate the direction of the magnetic field projected on the sky.

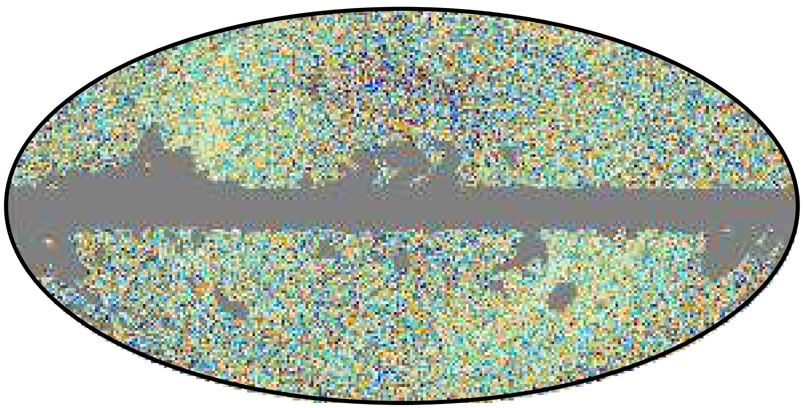
Planck 2105 CMB maps (T,Q,U)

T

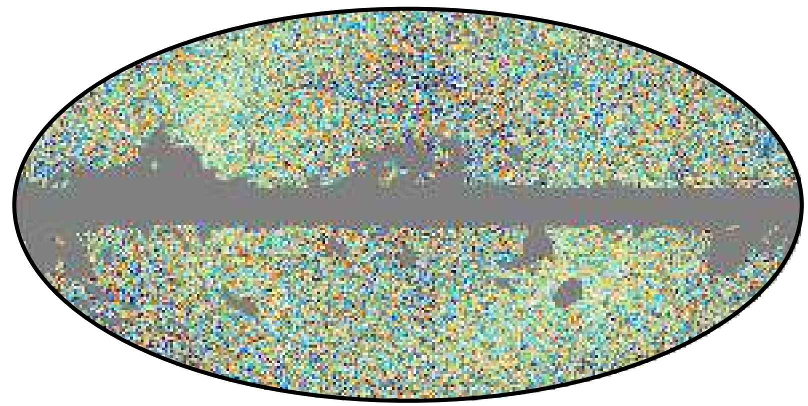


Commander

Q



U



	Commander	NILC	SEVEM	SMICA
HMHD RMS @ 60’	0.64	0.76	0.76	0.70

Summary

- The Planck mission has been very 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 next release!
  - Expect even better polarization measurements.

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

esa

planck

cnes

agenzia spaziale italiana

DTU Space
National Space Institute

Science & Technology Facilities Council

CSIC

National Research Council of Italy

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

CITA–ICAT

IN2P3 Les deux infinis

Imperial College London

Università degli Studi di Milano

NÉEL institut

ISDC

JPL

Université de Genève

University of Toronto

Université de Paris-Sud XI

holm, 3 June 2015

Appendix

Additional slides

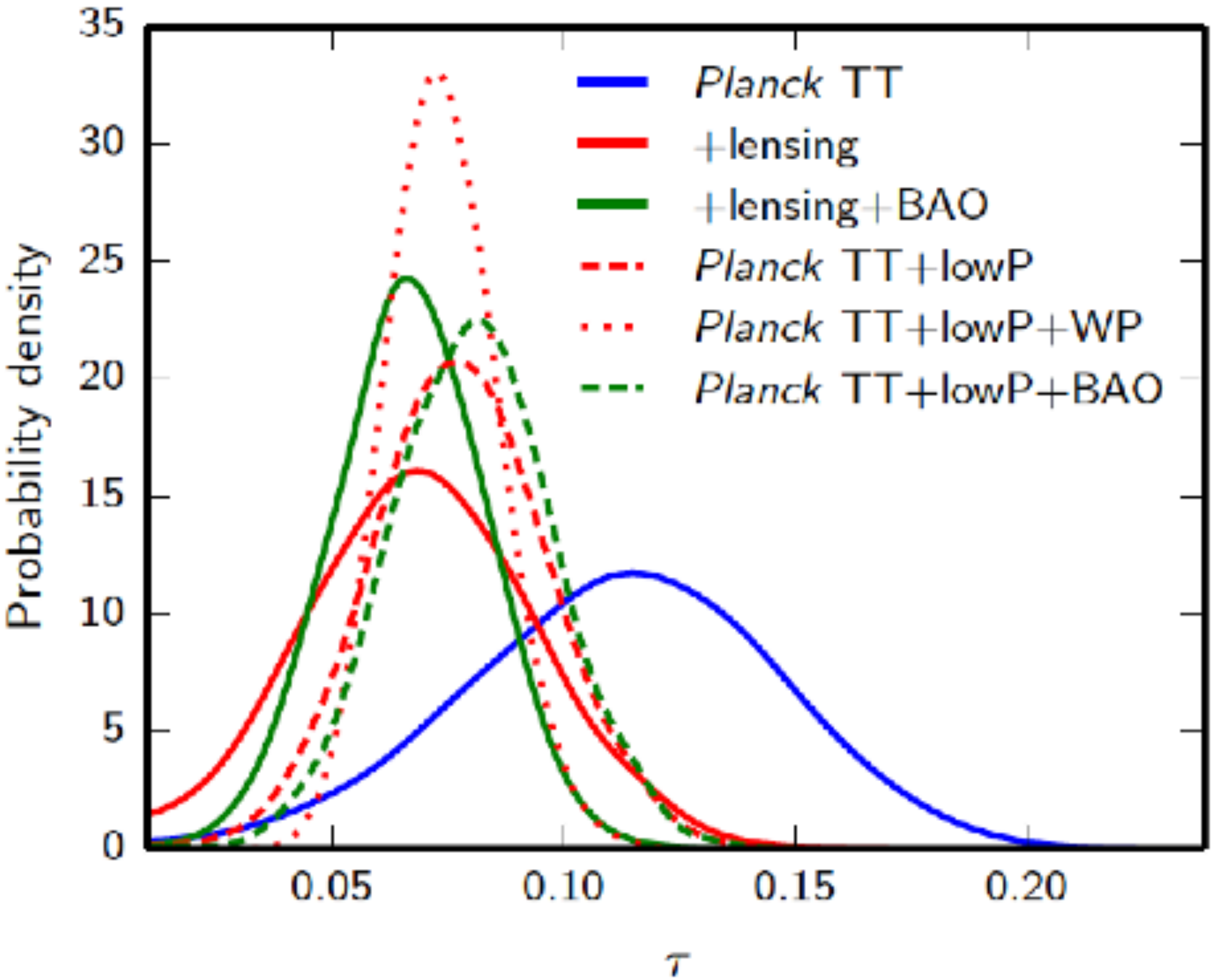


Fig. 8. Marginalized constraints on the reionization optical depth in the base ΛCDM model for various data combinations. Solid lines do not include low multipole polarization; in these cases the optical depth is constrained by *Planck* lensing. The dashed/dotted lines include LFI polarization (+lowP), or the combination of LFI and WMAP polarization cleaned using 353 GHz as a dust template (+lowP+WP).

PLANCK

τ shifts towards a lower value

Better FG (dust) cleaning with Planck 353GHz channel

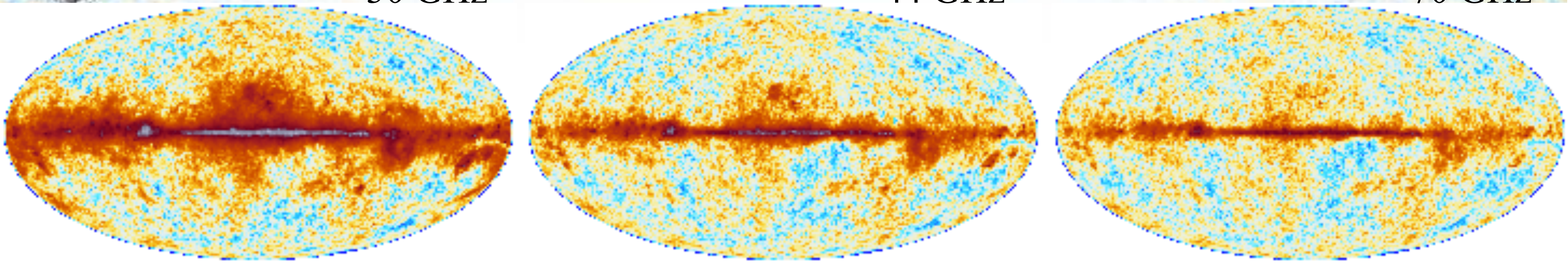
WMAP9 cleaned with Planck 353GHz exhibits a similar shift

The τ measurement from CMB is difficult because it is a small signal, confined to low multipoles, requiring accurate control of instrumental systematics and polarized foreground emission.

Planck 2015 Temperature Maps

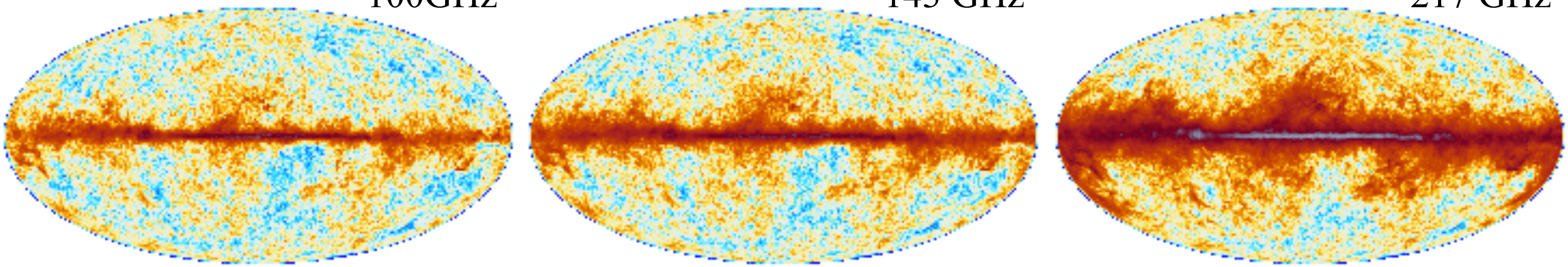
Low Frequency Instrument:

30 GHz 44 GHz 70 GHz

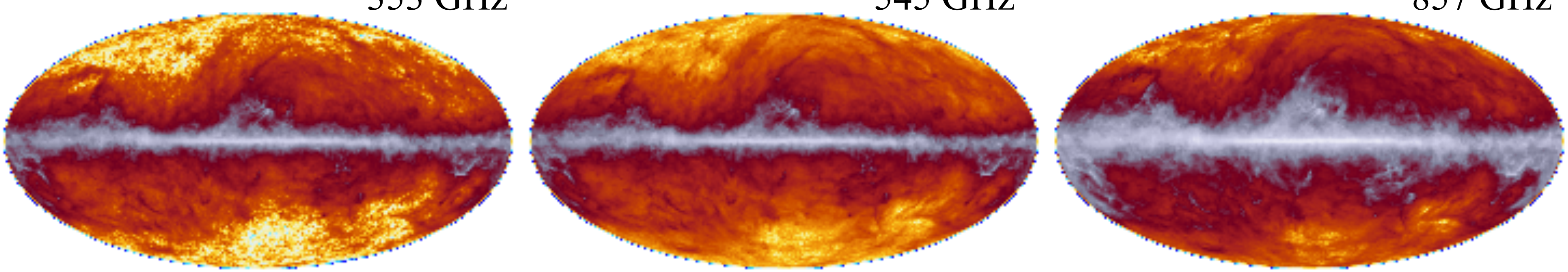


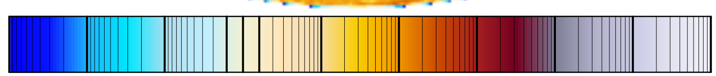
High Frequency Instrument:

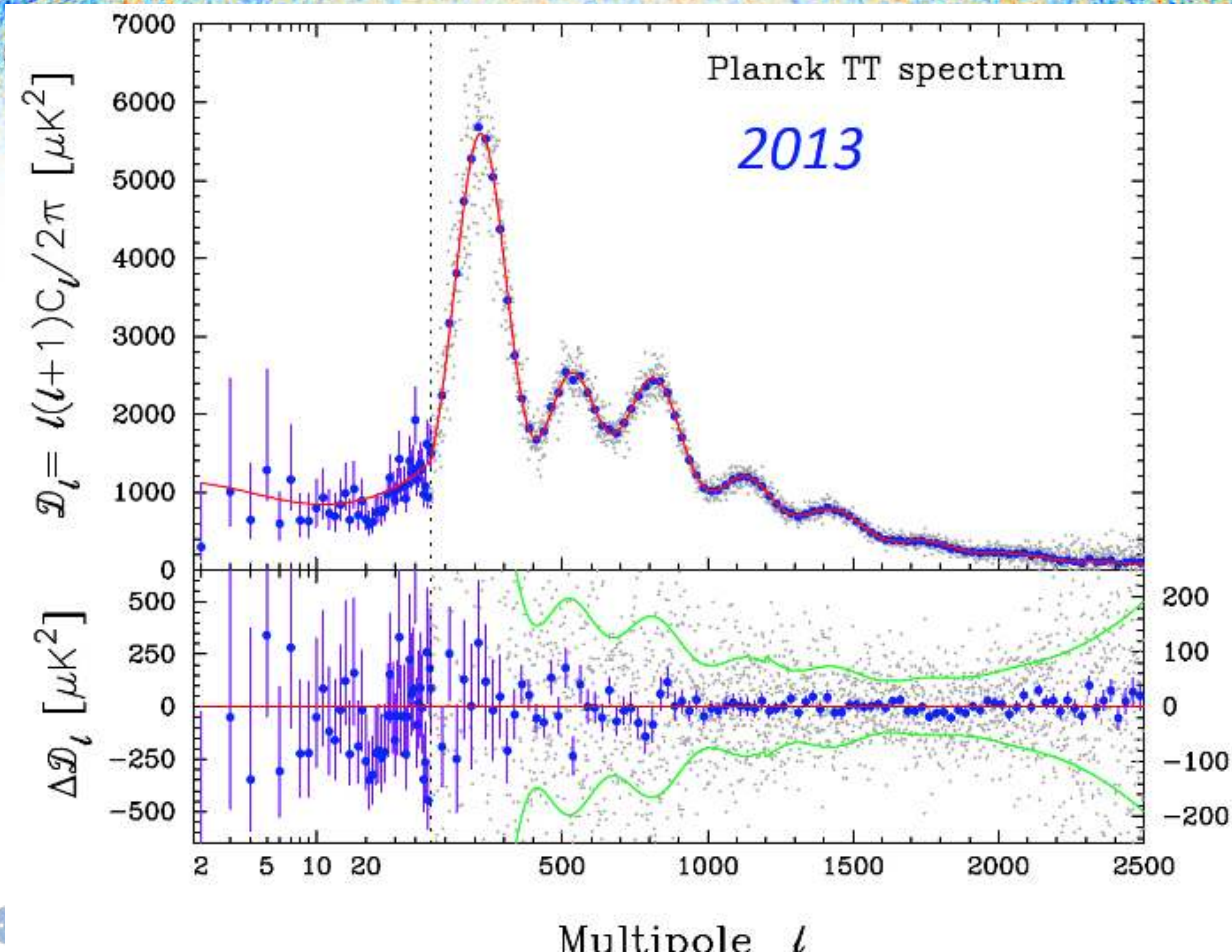
100GHz 143 GHz 217 GHz



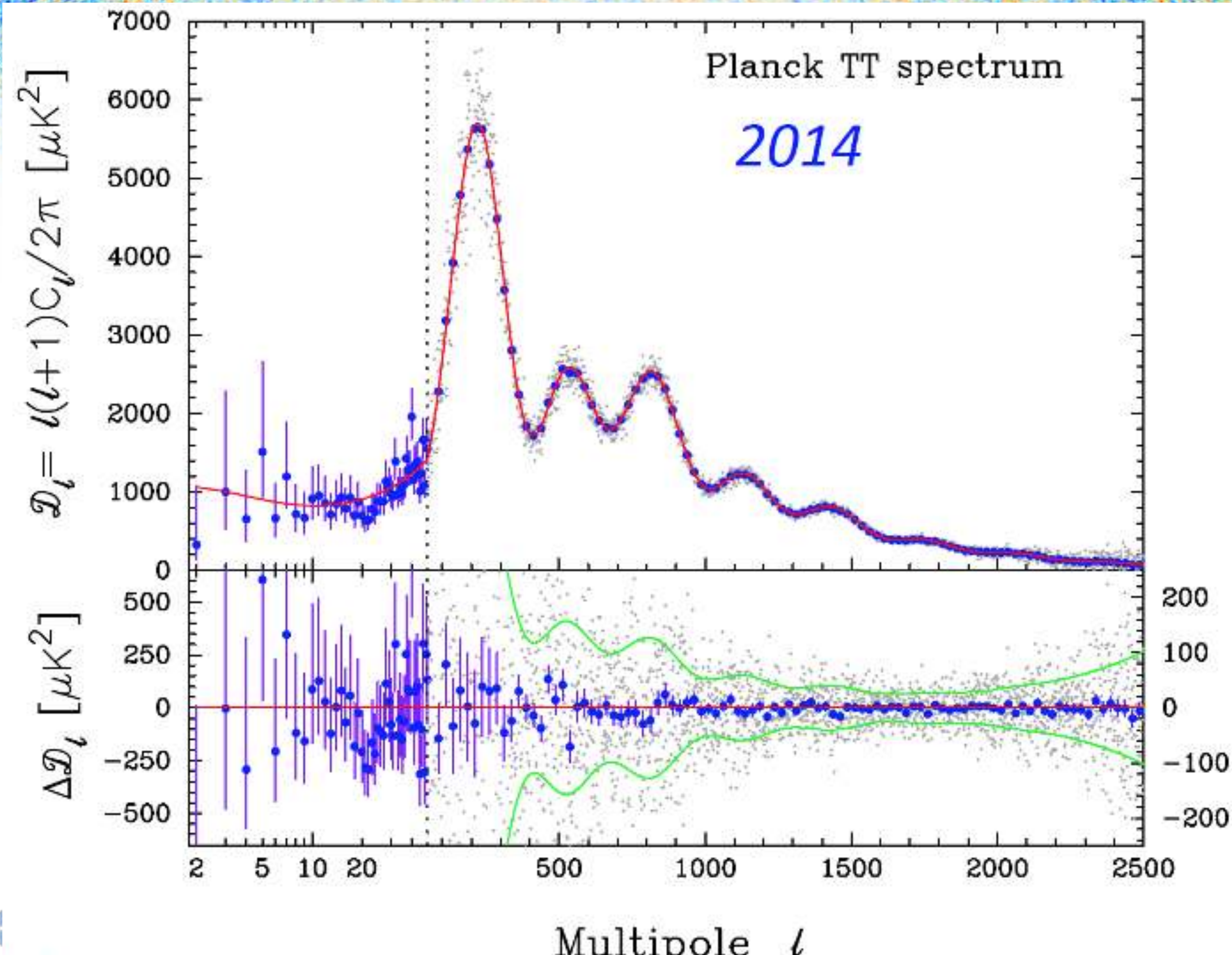
353 GHz 545 GHz 857 GHz





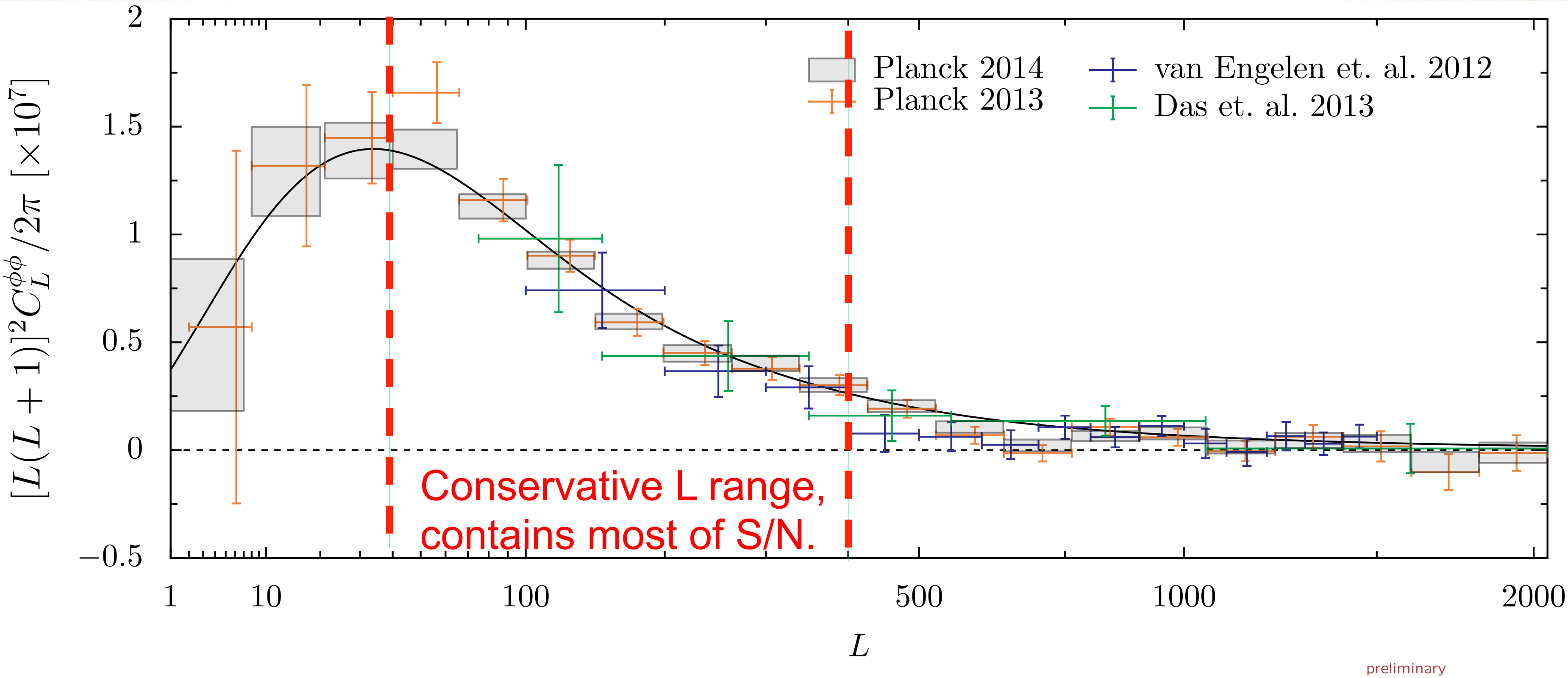


Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
-250
-500
200
100
0
-100
-200
2
5
10
20
500
1000
1500
2000
2500
Multipole ℓ



Planck TT spectrum
2014
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
-250
-500
200
100
0
-100
-200
2
5
10
20
500
1000
1500
2000
2500
Multipole ℓ

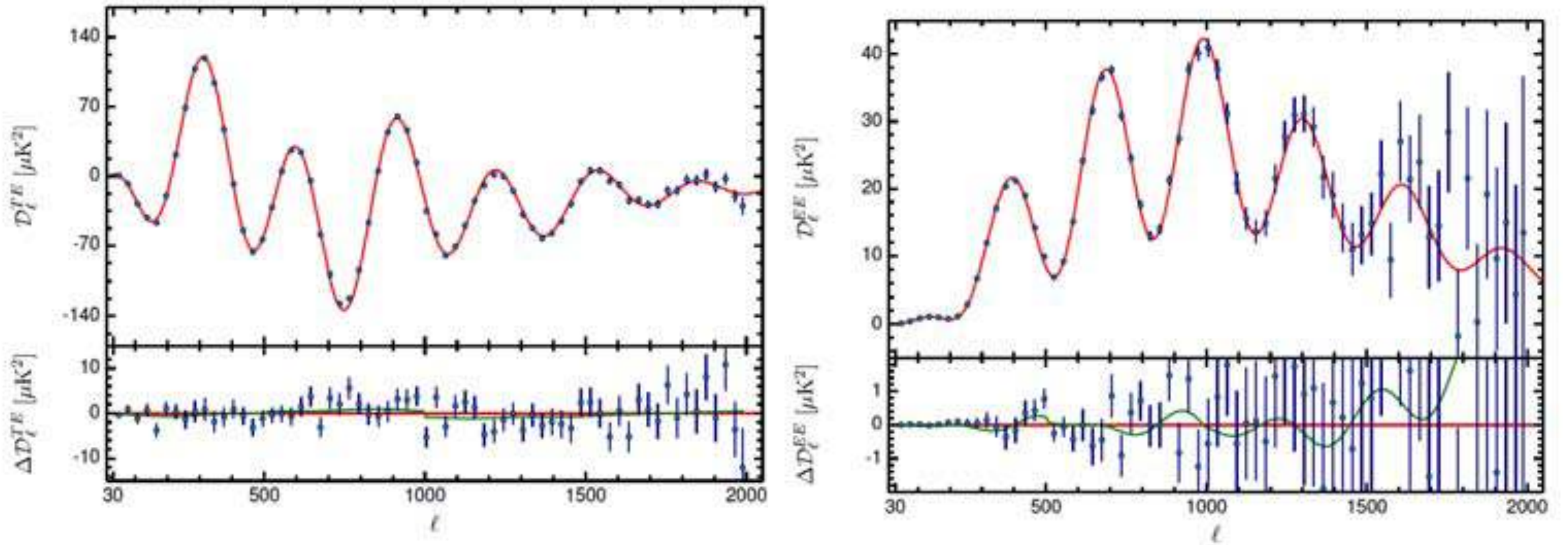
Lensing Spectrum



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

Polarization Spectra, Same Model

TE EE



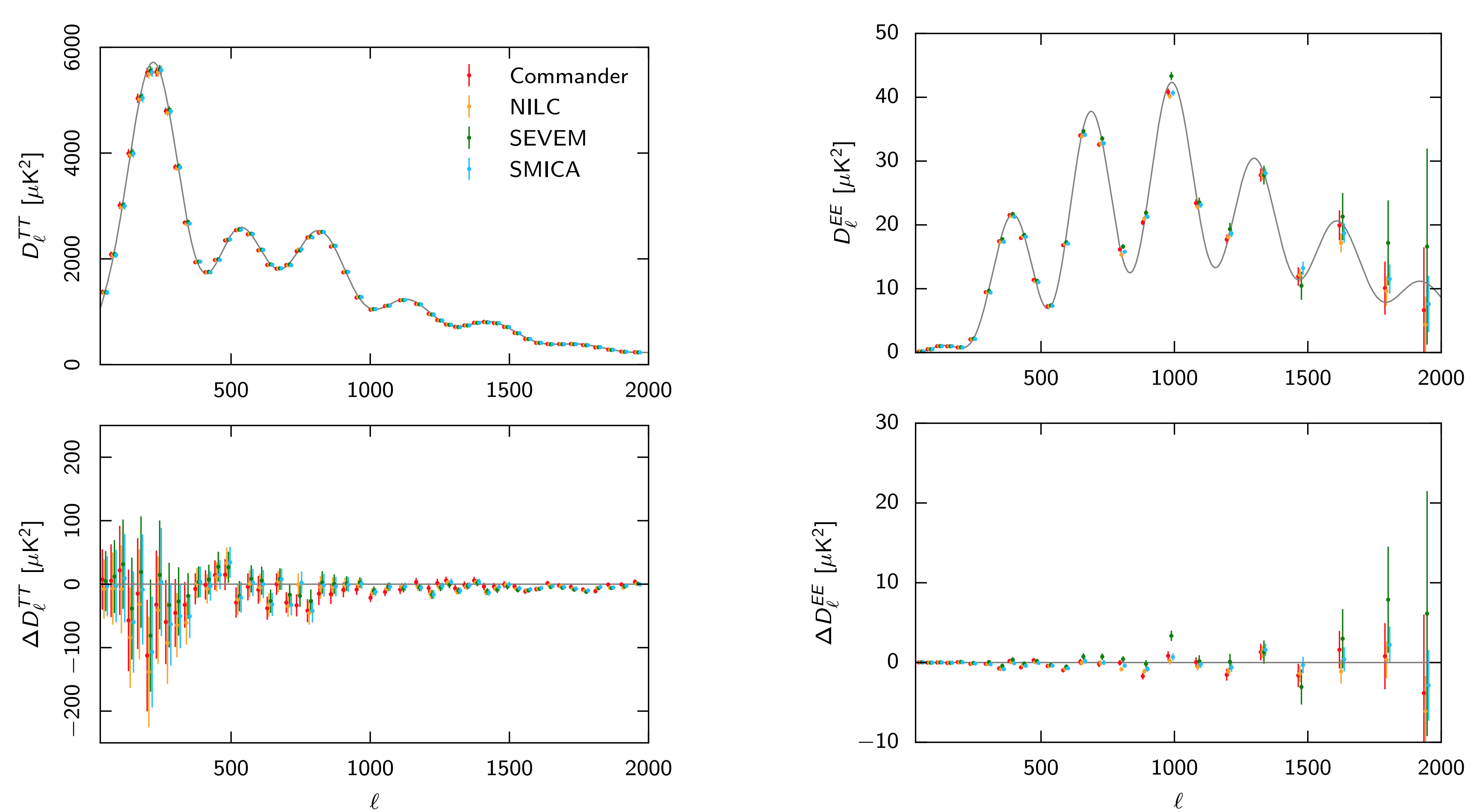
- Red curve is the prediction based on the best fit TT in base ΛCDM
    - 2015 polarisation data and results are preliminary because all systematic and foreground uncertainties have not been exhaustively characterised – we are looking at a precision level of

O(1) μK² level

green line - estimate of the (uncorrected) beam mismatch systematic effect, possibly the largest one at high-ell: results depending on this level of precision, O(1) μK² level, may therefore be subject to revision.

Power spectra and (CMB, FG) Best Fit Model
TT & EE, higher-order stats

TT EE



We cannot tell the methods apart within the spectral uncertainties

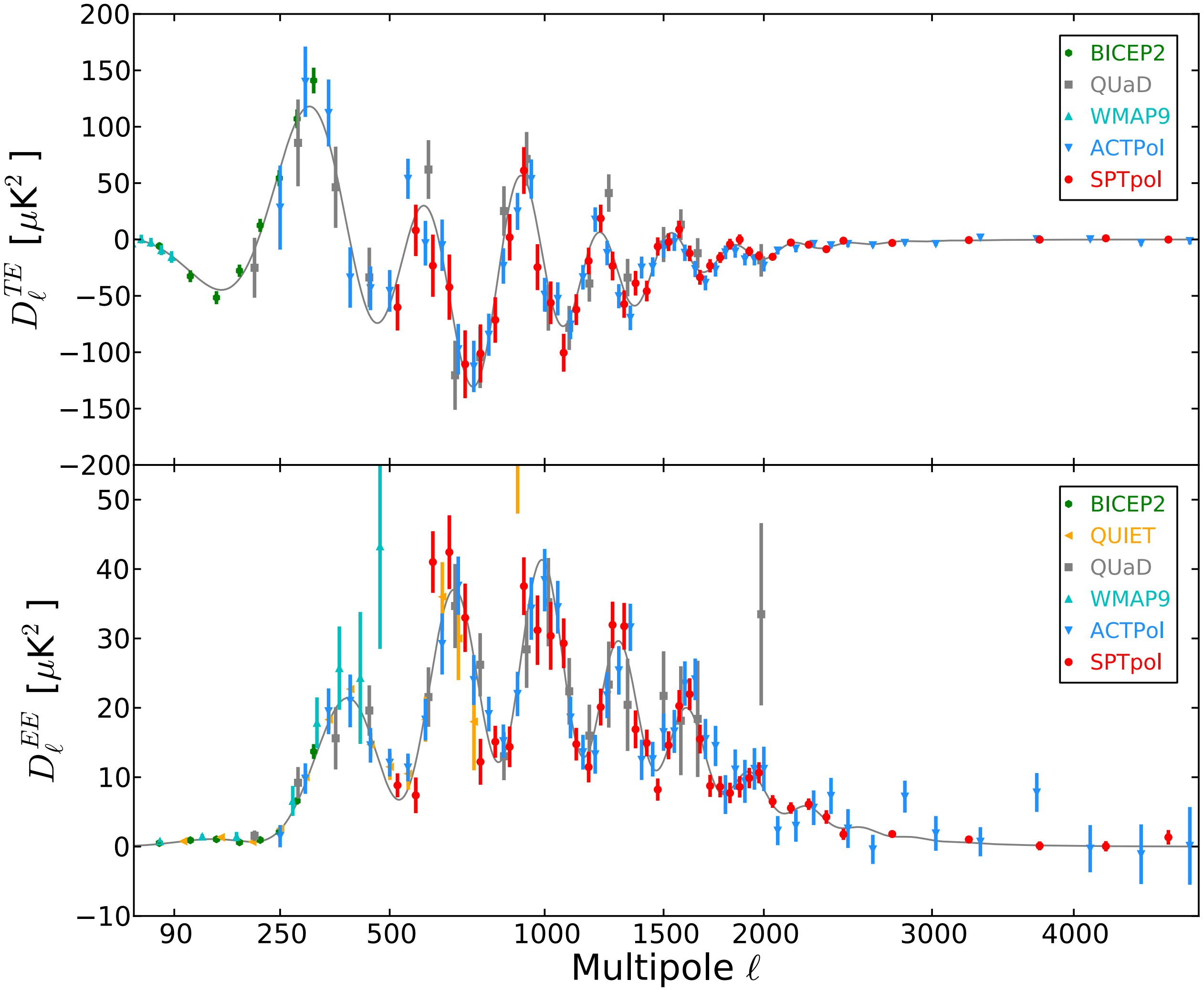
Higher order statistics - consistency with Gaussianity

In Planck 2015 results. IX, XII

No major surprises !

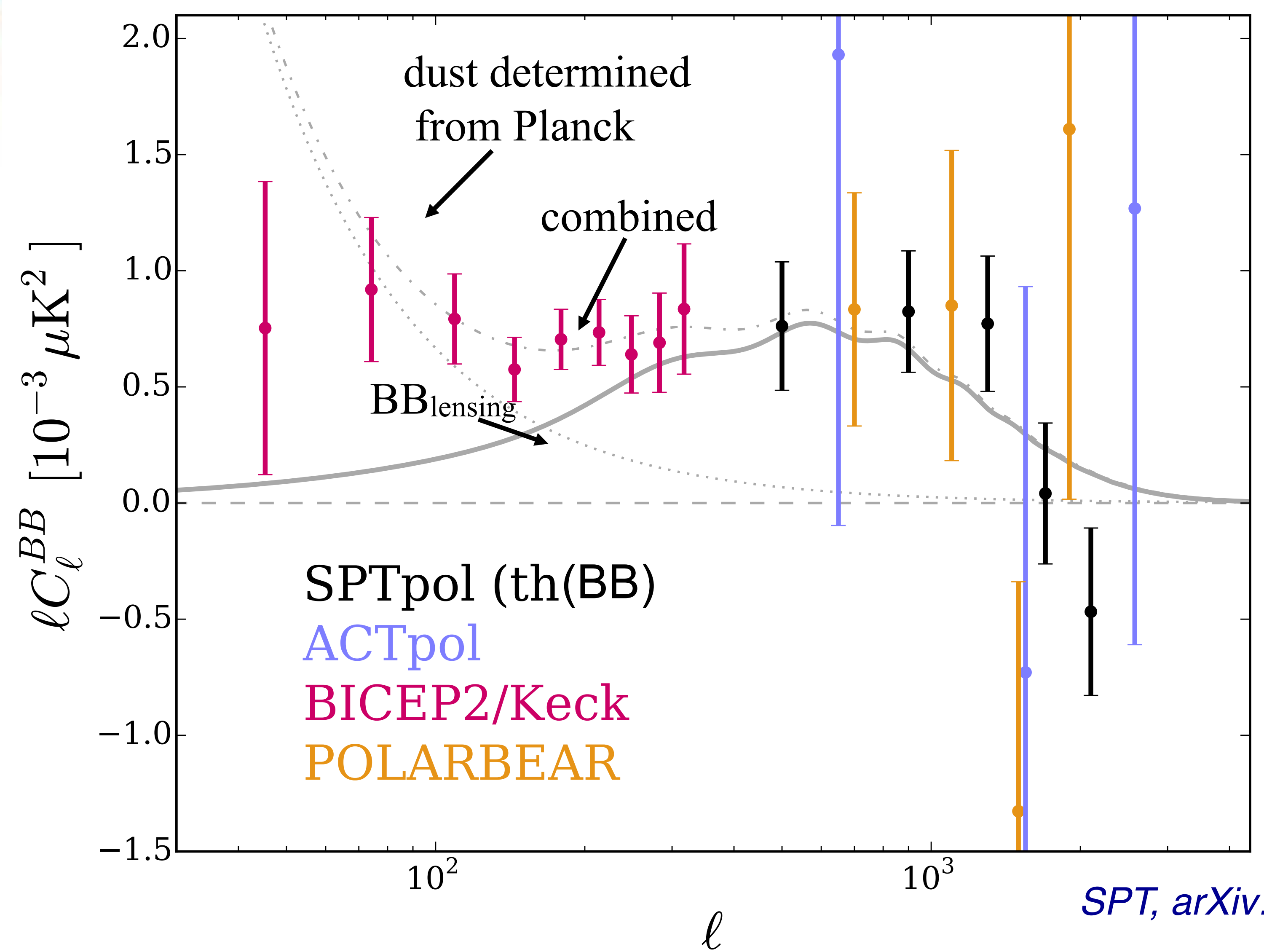
TE, EE Compilation Power Spectrum

Polarization measurements consistent with Planck
Planck ΛCDM model shown as solid line



SPT arXiv:1411.1042

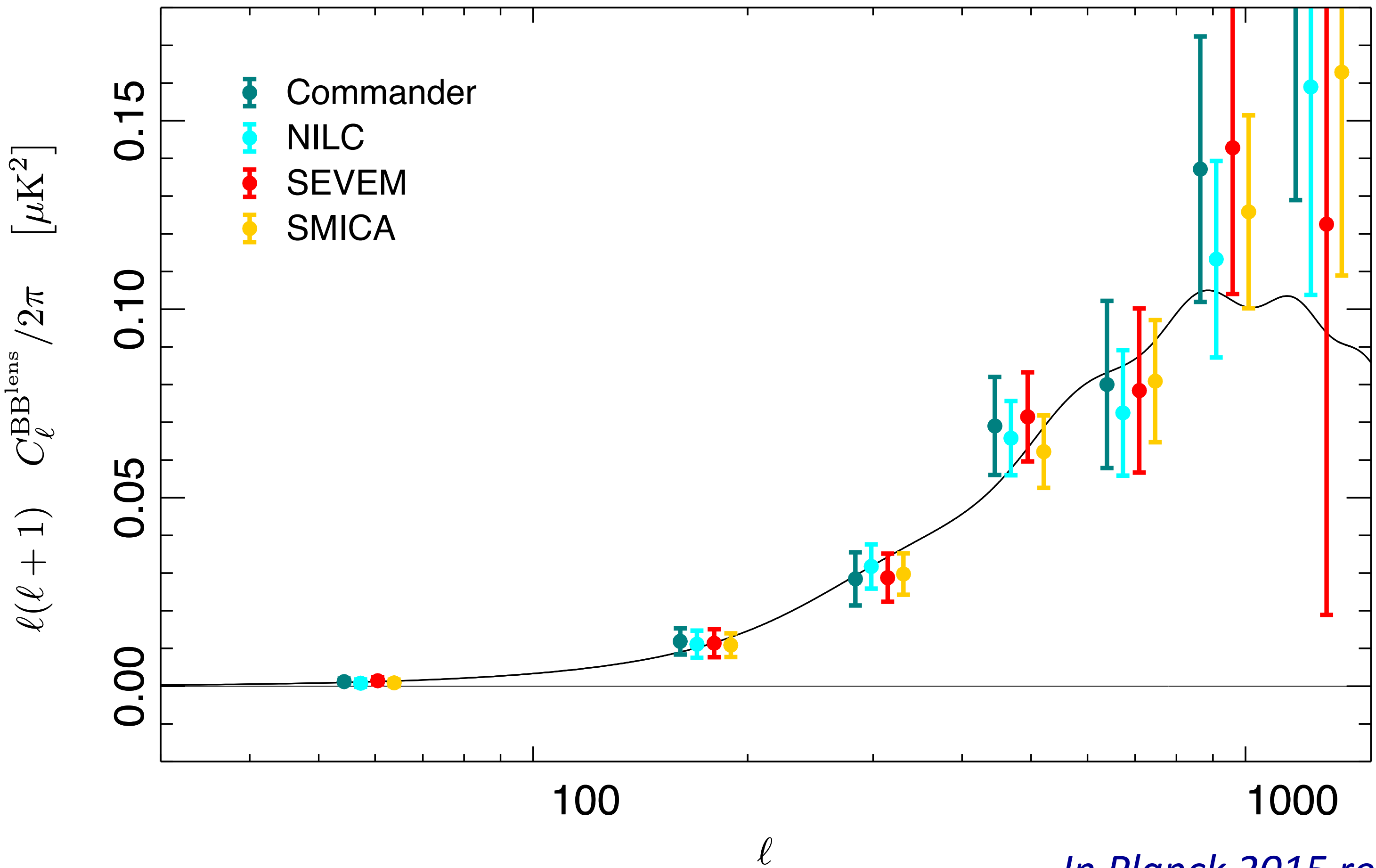
BB Compilation



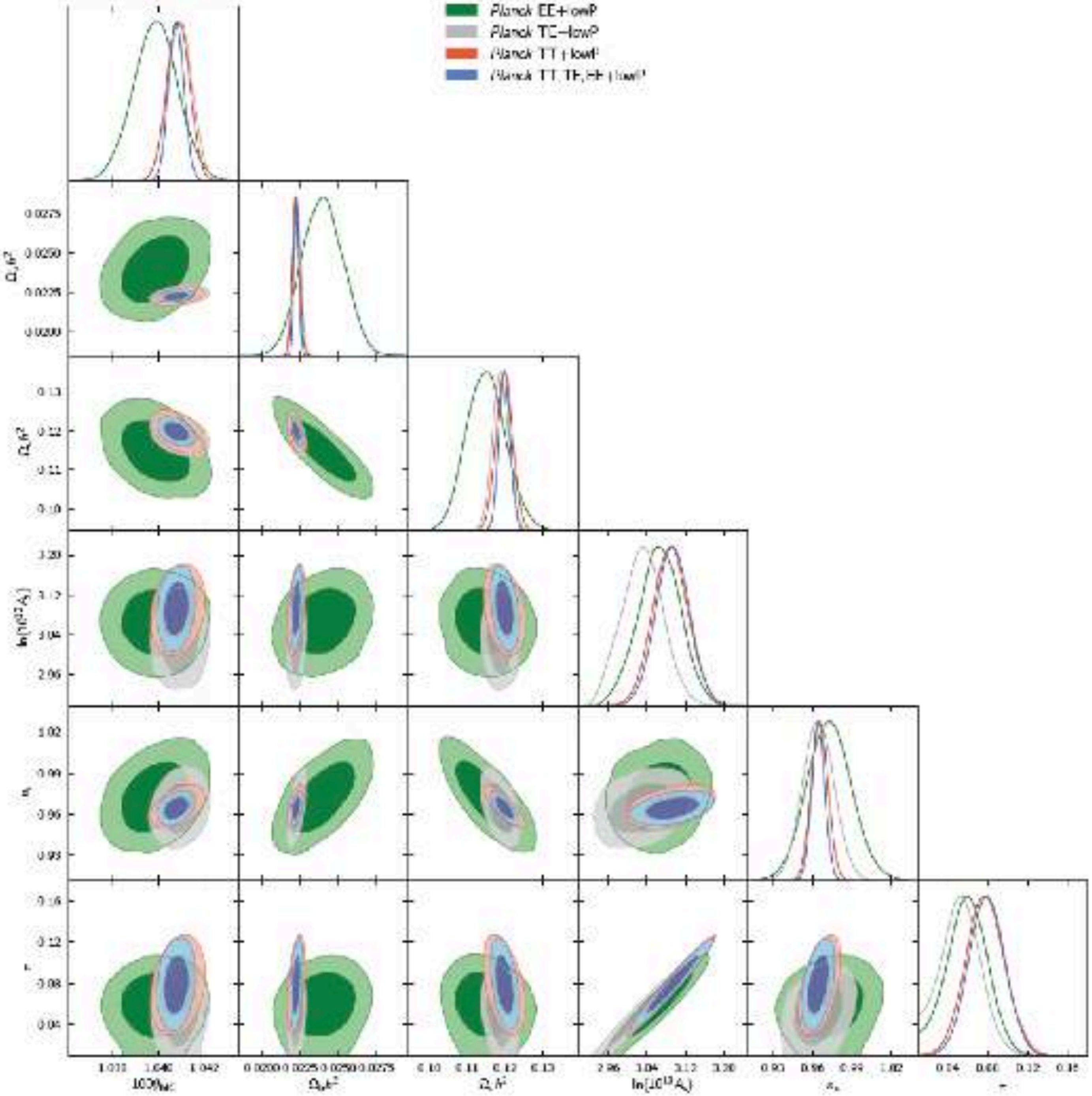
SPT, arXiv: 1503.02315

Gravitational lensing by large scale structure
Lensing B modes

Predicted lensing B modes of CMB polarization



In Planck 2015 results. IX

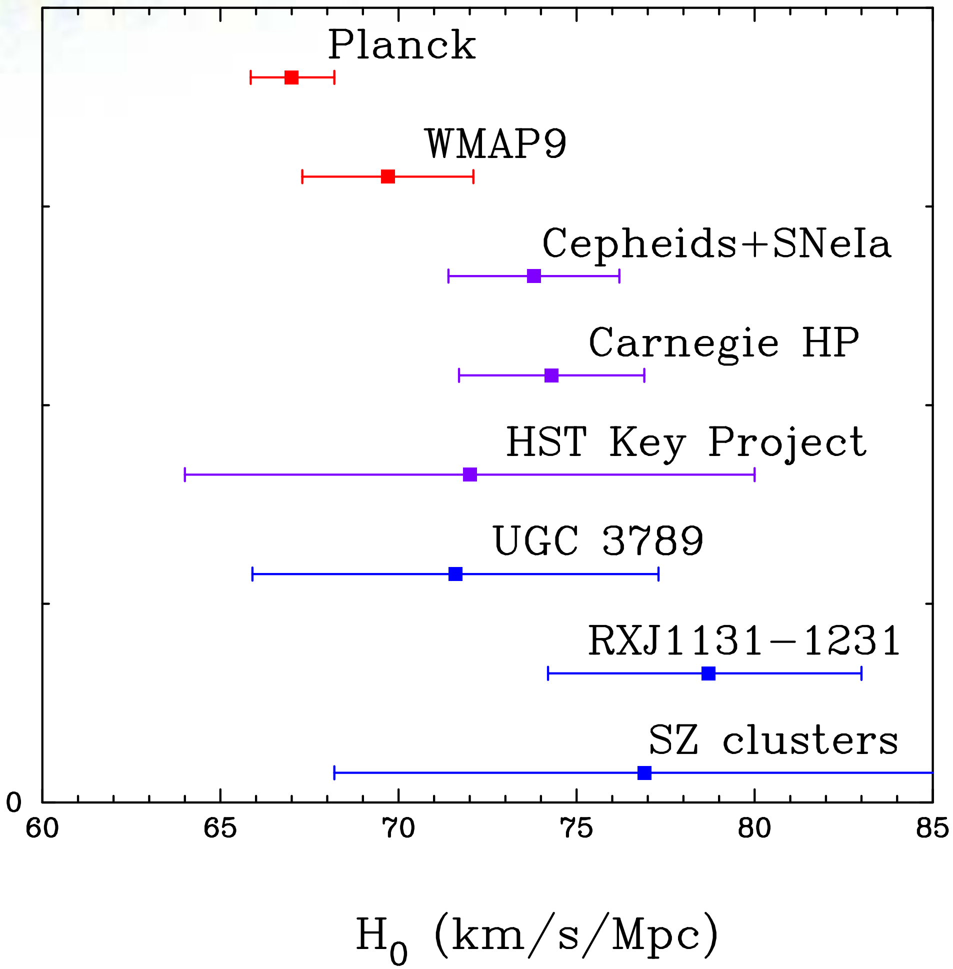


Planck, Gra … 3 June 2015

Fig. 6. Comparison of the base ΛCDM model parameter constraints from *Planck* temperature and polarization data.

ΛCDM model parameters "Tensions" – H_0

2013



Independent local cosmological probes:

Non-geometric and Geometric determination of H_0 were discordant with Planck 2013 value at 2.5σ level

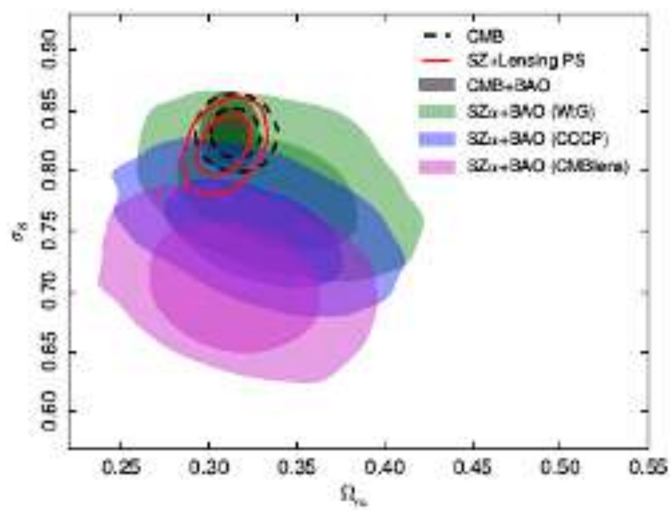
CMB estimation of H_0 is model dependent

In Planck 2013 results. XIII

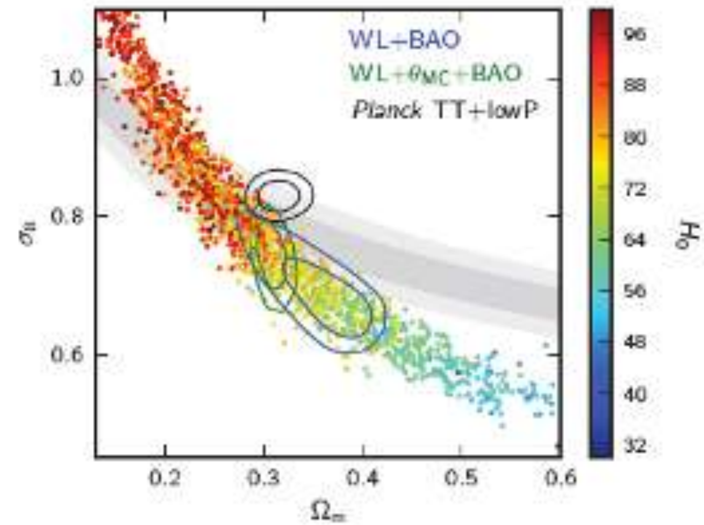
$WMAP9 + BAO -> H_0 = 68.0 \pm 0.7 kms^{-1} Mpc^{-1}$ -> driven towards the Planck value

ΛCDM model parameters
“Tensions” σ_8

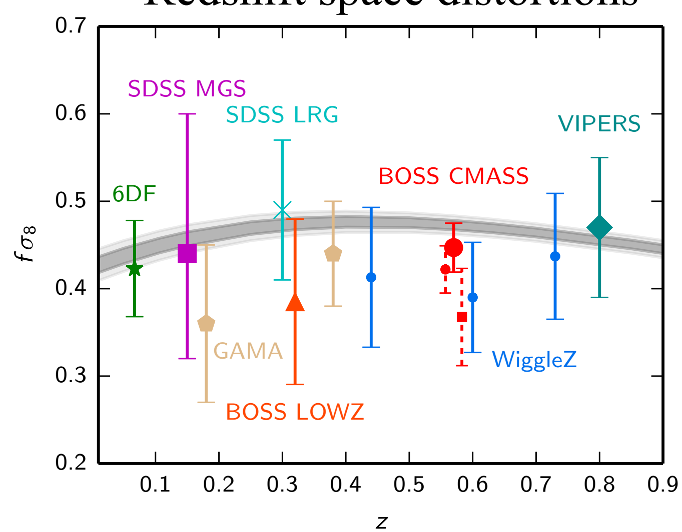
Cosmology from Planck SZ clusters



Weak-Lensing: H13 CFHTLenS

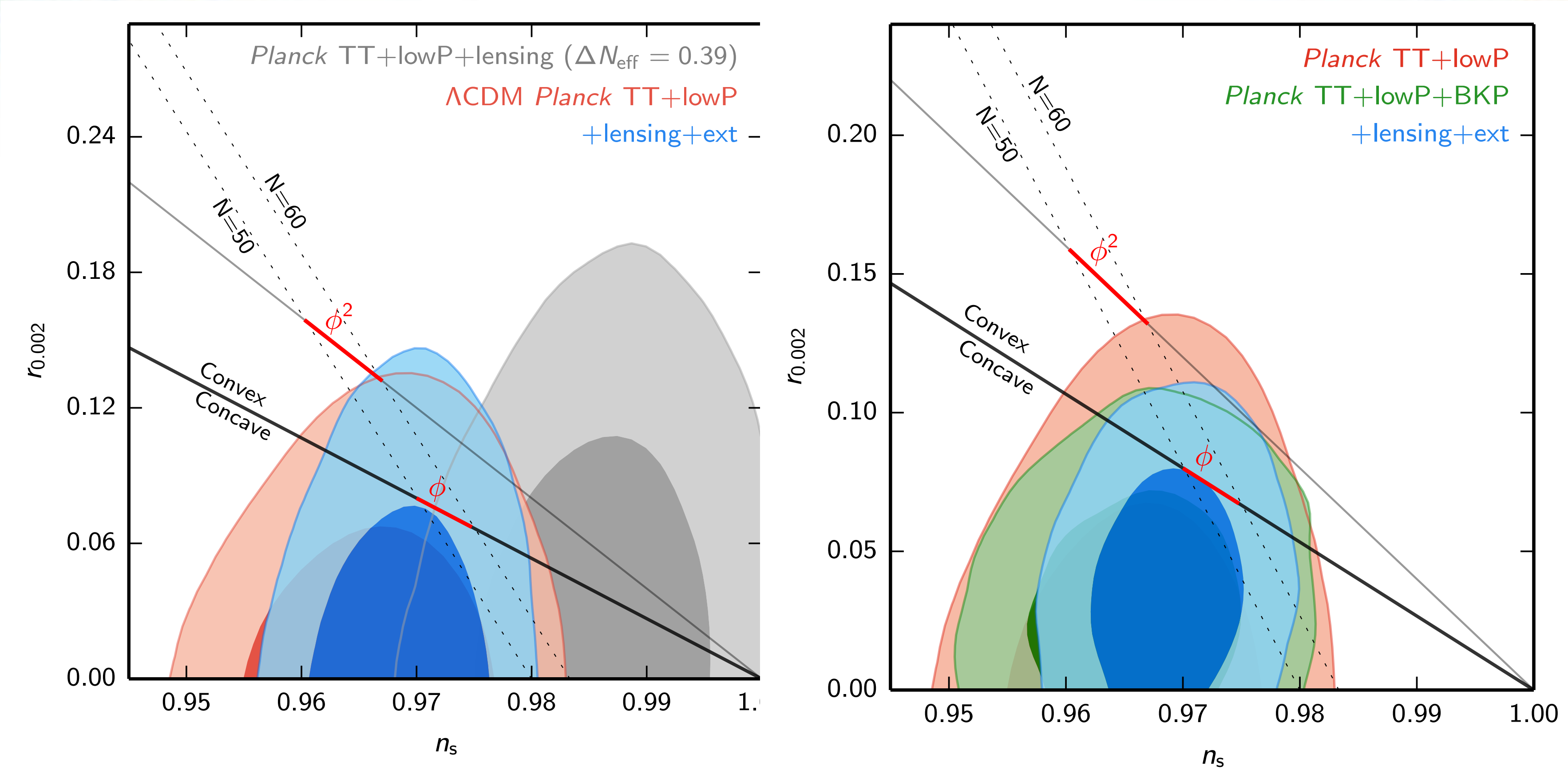


Redshift space distortions



In Planck 2015 results. XIII
In Planck 2015 results. XXIV

r vs n_s



$n_s = 0.9655 \pm 0.0062$

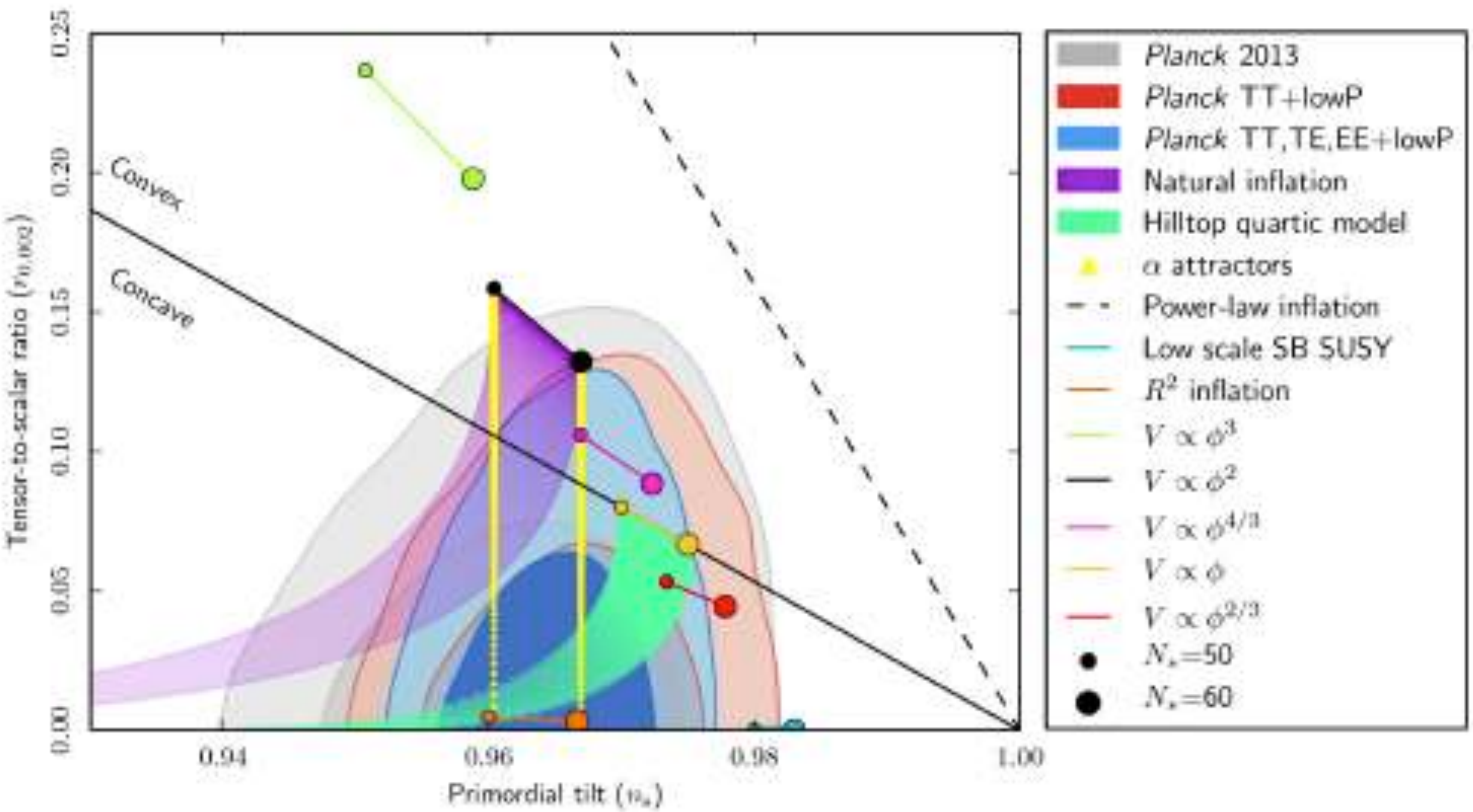
n_s shifts by 0.7σ between Planck 2013 and 2105 partly due to the l≈1800 systematic in the nominal 217 x 217 spectrum (*Planck 2013 results. XIII*)

$r < 0.11$ PlanckTT+lowP+lensing+ext

$r < 0.10$ PlanckTT+lowP

Model dependent

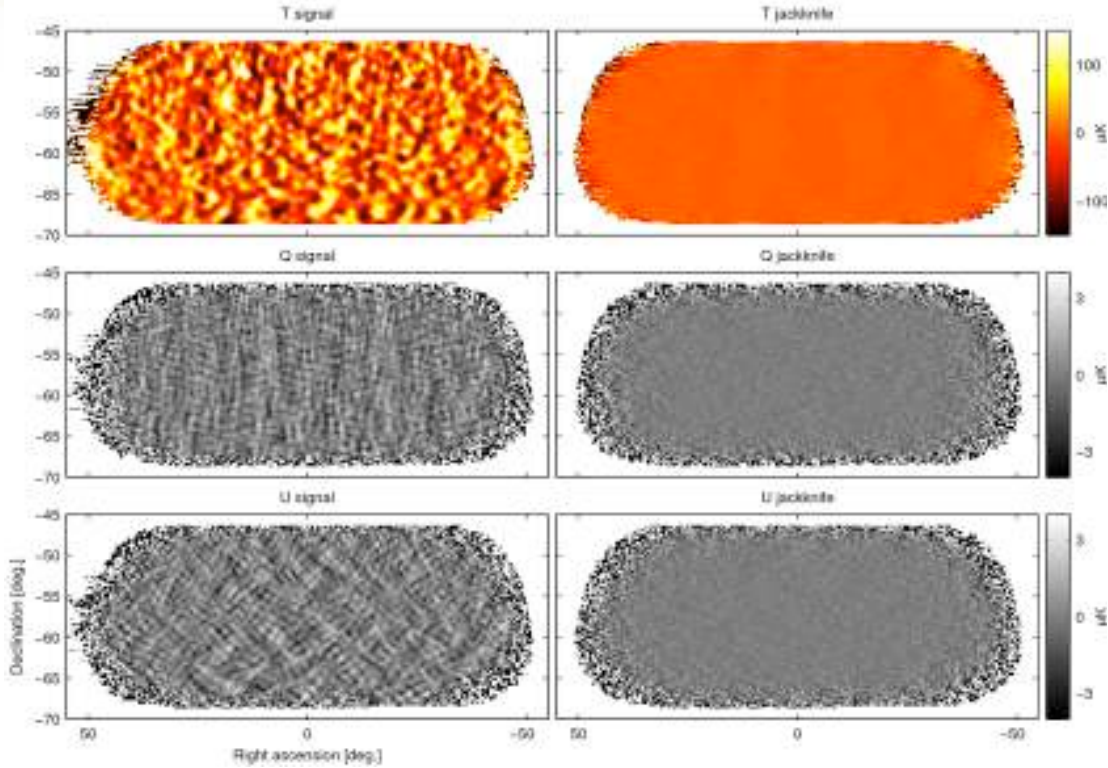
Planck 2015: Inflationary Scenarios



BICEP2 and Keck Array

Keck Array 2011-...

x5



Compact cold refractive optics optimized for the angular scales of the inflationary signal

Superconducting phased antenna arrays

Observation at 150 GHz (Keck 2014 also at 95 GHz)

Focus on ~**400 deg²** patch = 1% of the sky

3yrs of BICEP2 + Keck 2012/13

→ **Final map depth: 3.4 μK arcmin / 57 nk deg**

(RMS noise in sq-deg pixels)

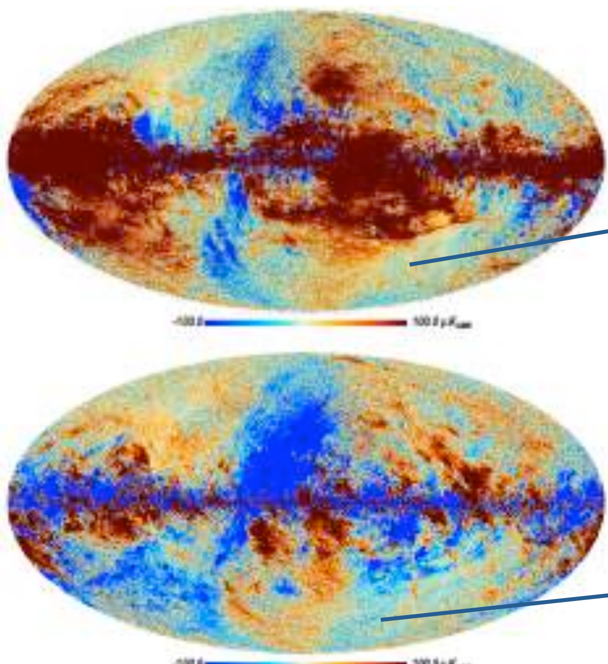
Deepest map of the CMB polarization ever made!

Planck 353 GHz

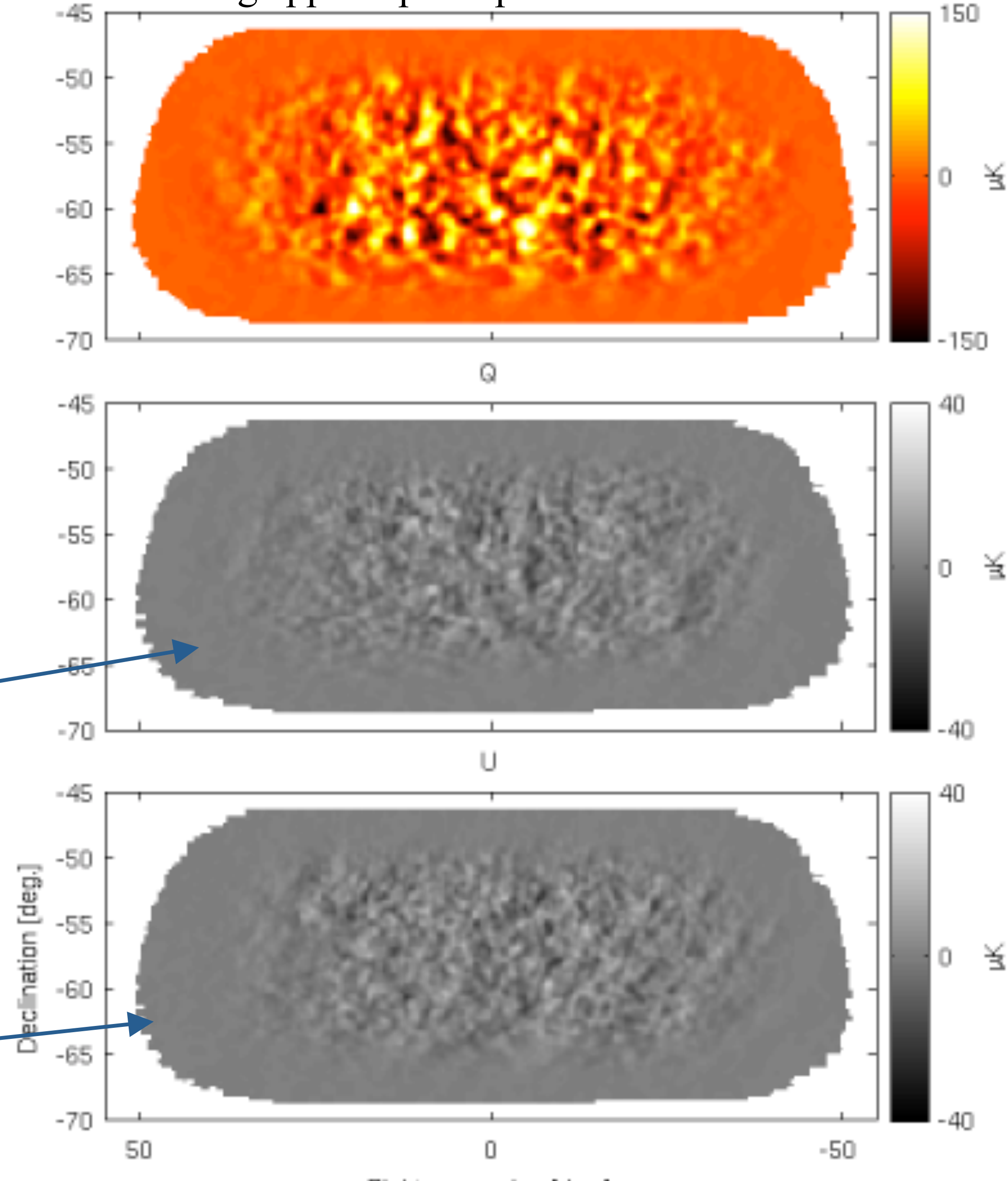
- Planck is the third generation space mission to observe the CMB: observes the full sky at 9 bands in intensity; 7 in linear polarization
- Full sky measurement, but in any given sky patch much less deep than BICEP2-Keck
- 353 GHz band is very sensitive to polarized dust emission

Q

U



Planck 353GHz maps in BICEP2/Keck sky region with full simulation of observation and filtering applied plus apodization



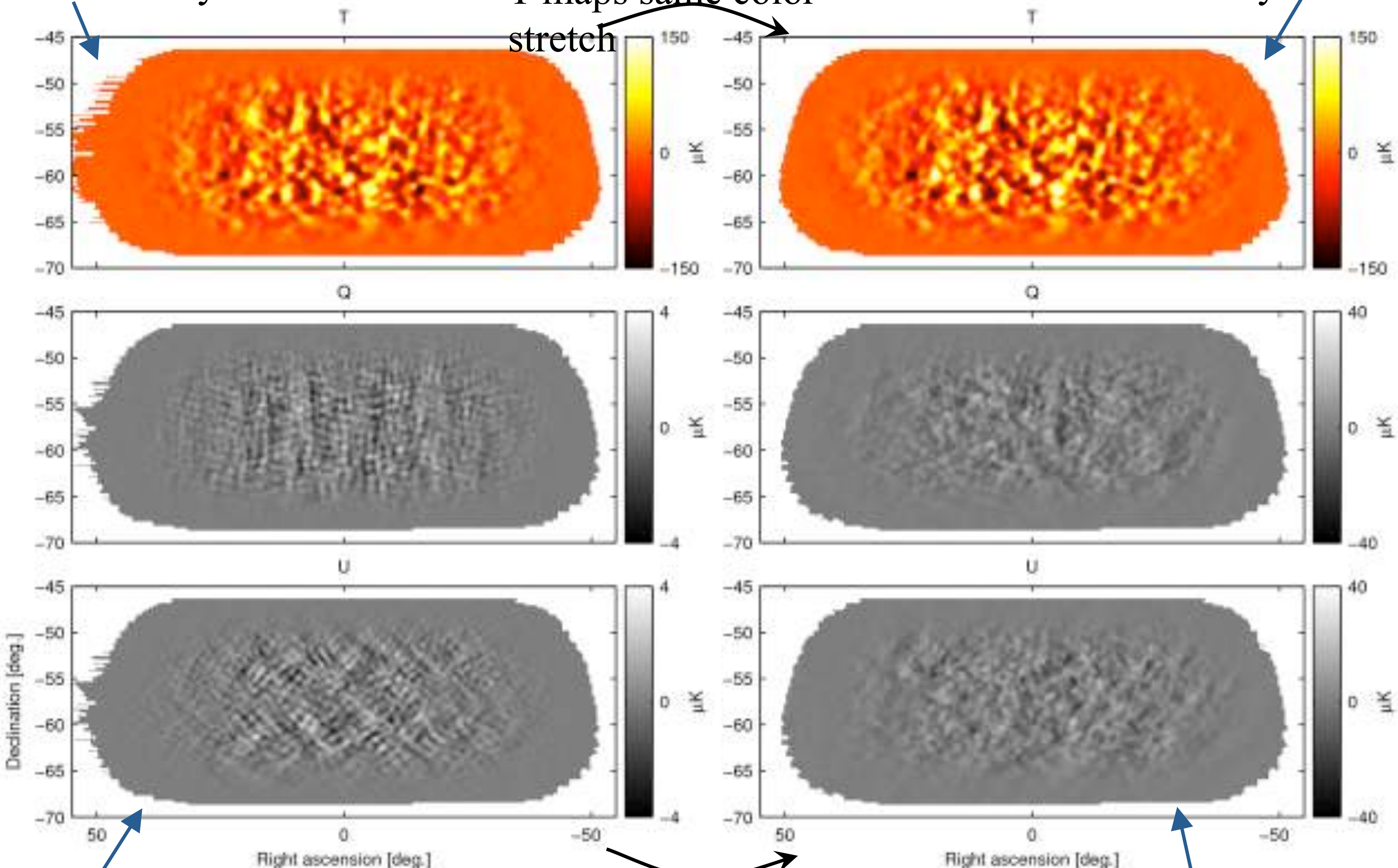
Pla

Compare BK 150 GHz (left) with Planck 353 GHz (right)

Dominated by LCDM T

T maps same color stretch

Dominated by LCDM T

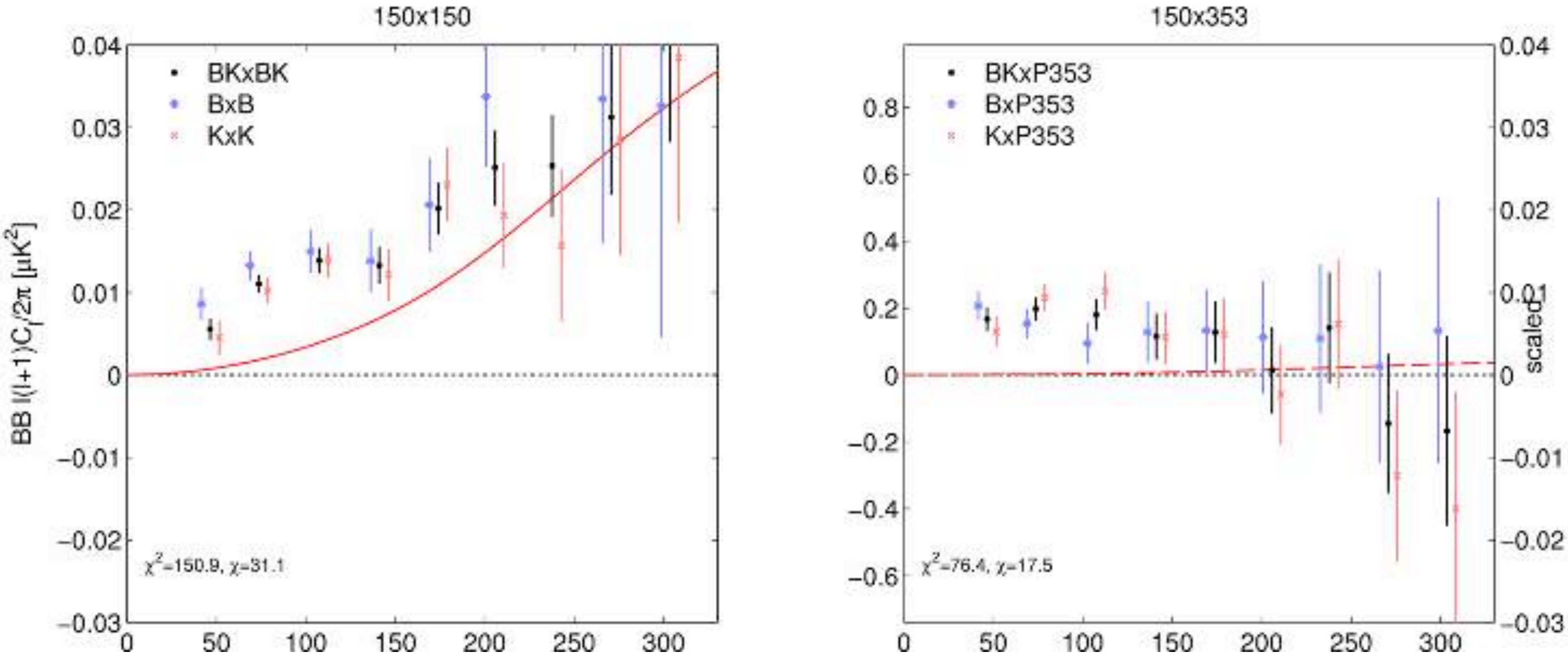


Dominated by LCDM E-modes

Q/U maps x10 color stretch

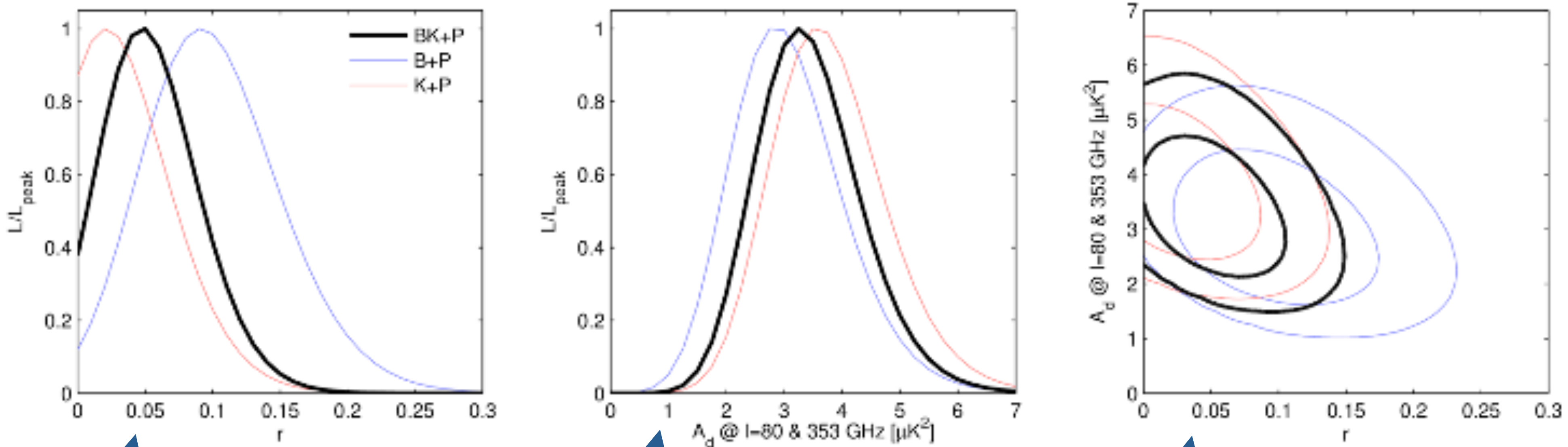
Dominated by noise & dust

BB Spectra



- ➢ Correlation of 150 GHz and 353 GHz B-modes is detected with high signal-to-noise.
- ➢ Scaling the cross-frequency spectrum by the expected brightness ratio (x25) of dust (right y-axis) indicates that dust contribution is comparable in magnitude to BICEP2/Keck excess over LCDM.
  - ○ Shape looks consistent with $\ell^{-0.42}$ power law expectation

Multi-component multi-spectral likelihood analysis



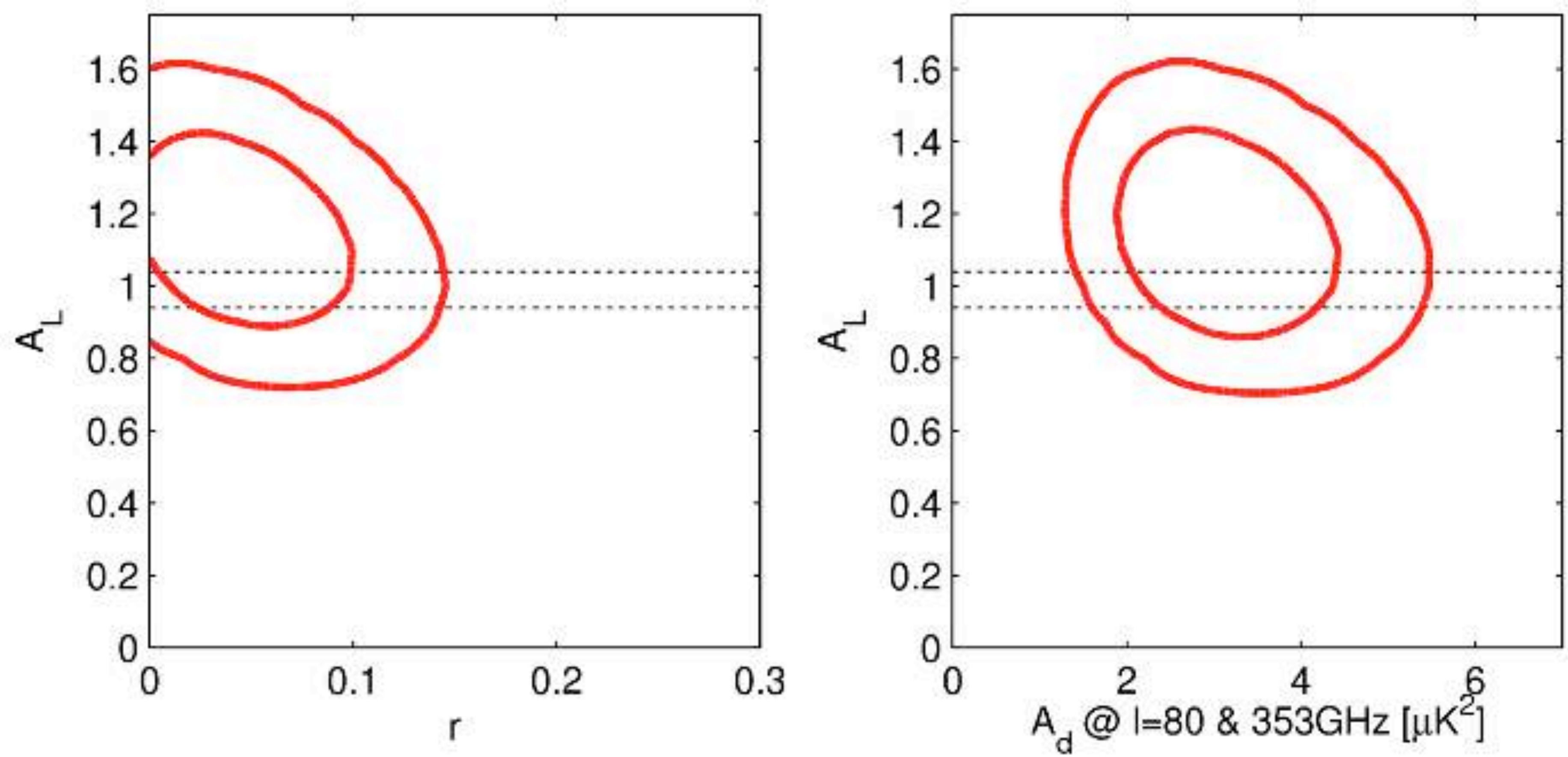
r constraint consistent with zero (For BK+P L_0/L_{peak} ratio is 0.4 which happens 8% of the time in a dust only model.)

Dust is detected with 5.1 σ significance

As expected dust and *r* are partially degenerate - reducing dust means more of the 150x150 signal needs to be *r*

- use single- and cross-frequency spectra between BK 150 GHz and Planck 217&353 GHz channels
- As addition to basic LCDM lensing signal include gravity wave signal (with amp *r*) and dust signal with
- amplitude A_d (specified at ℓ =80 and 353 GHz)
  - For dust SED use modified blackbody model and marginalize over range β_d=1.59±0.11
- Use 5 lowest BB bandpowers only (20<ℓ <200)

Constraints on lensing B-modes



- ➢ We next allow the amplitude of the lensing signal to vary while also extending the ℓ range up to 330
- ➢ We find that the lensing and dust components can be cleanly separated
  - ○ And detect lensing at 7.0 σ significance