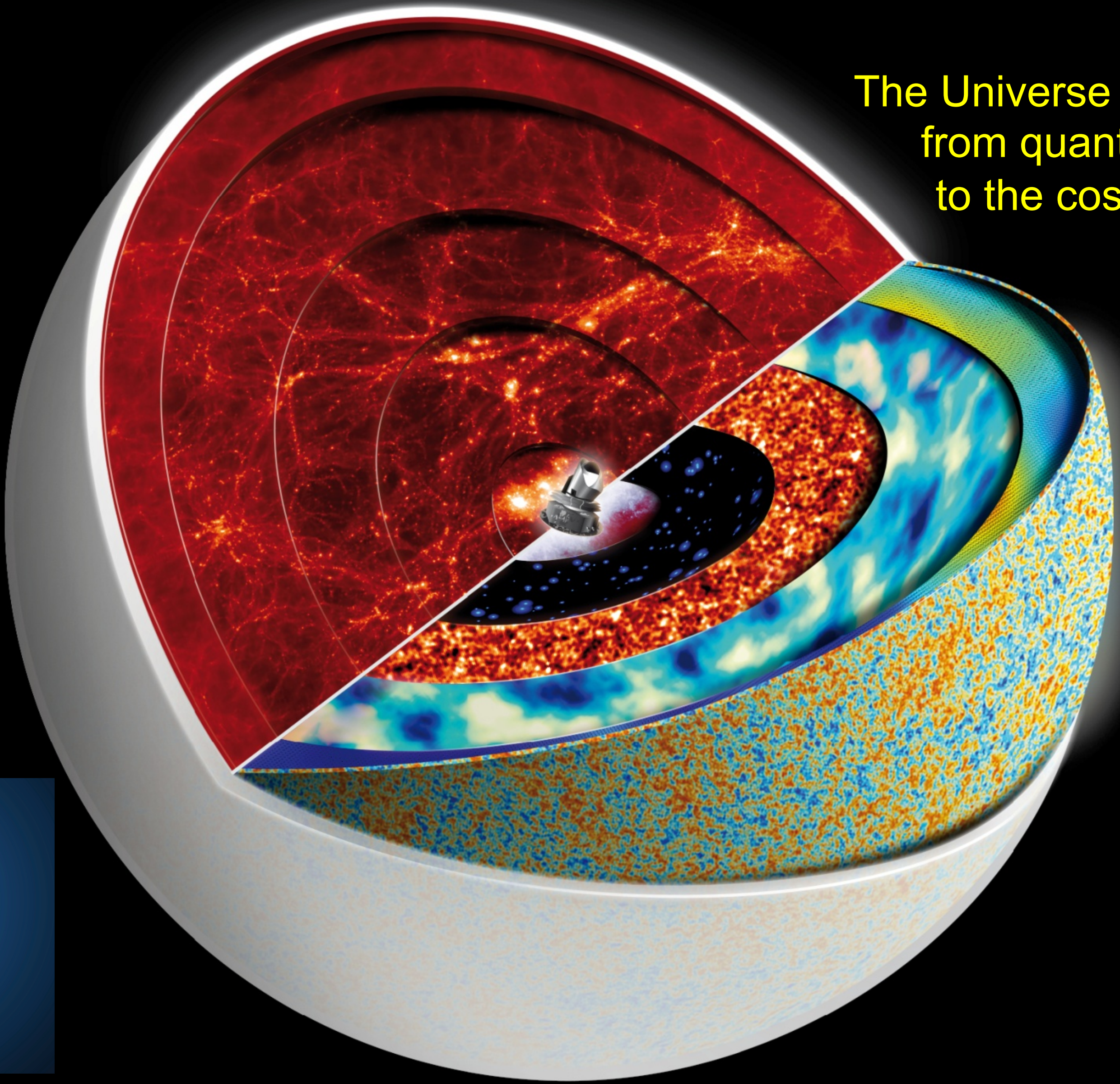
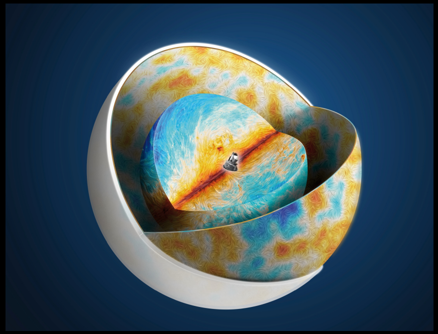
PLANCK 2015: CMB RESULTS

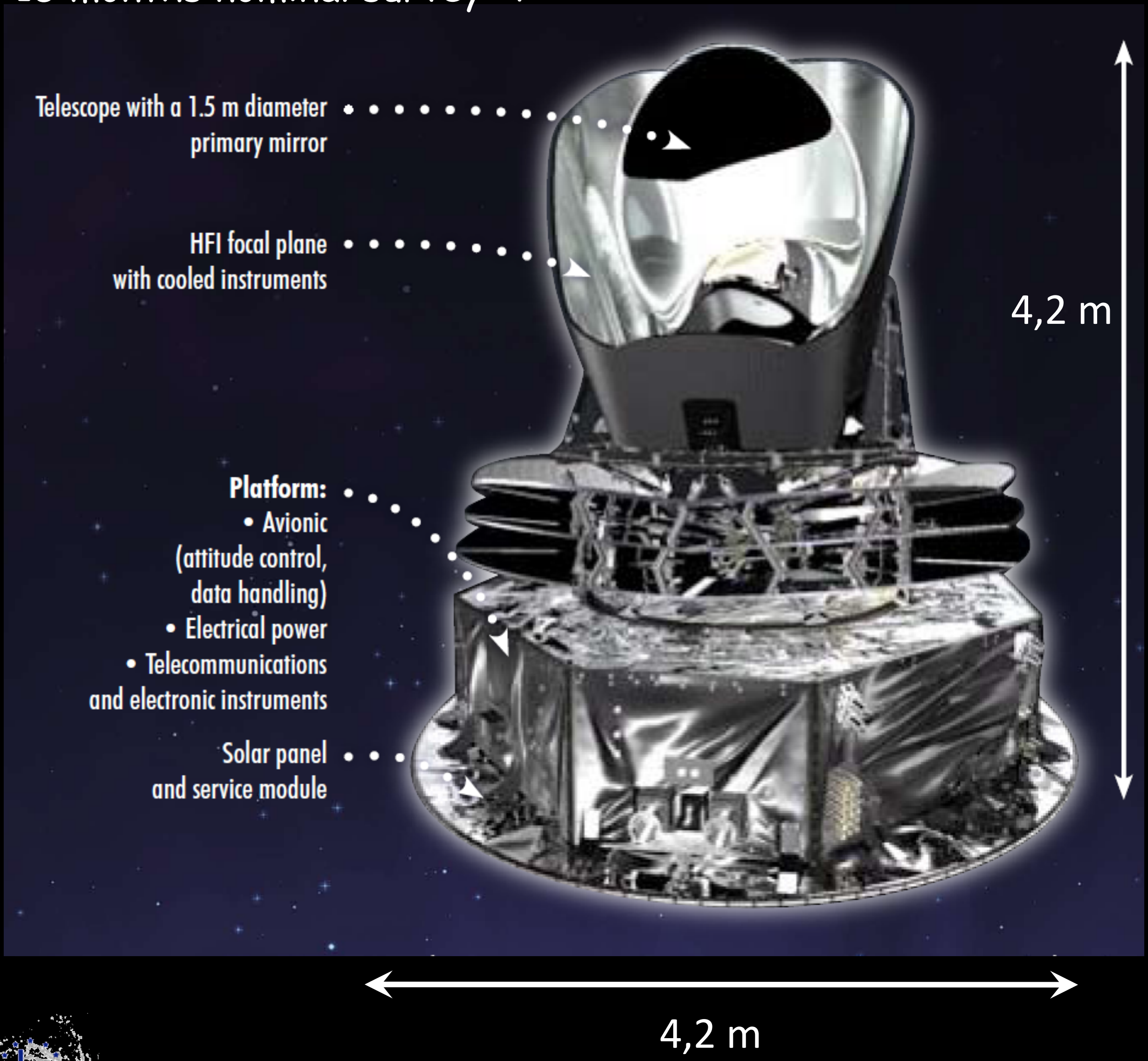


The Universe in a nutshell:
from quantum foam
to the cosmic web



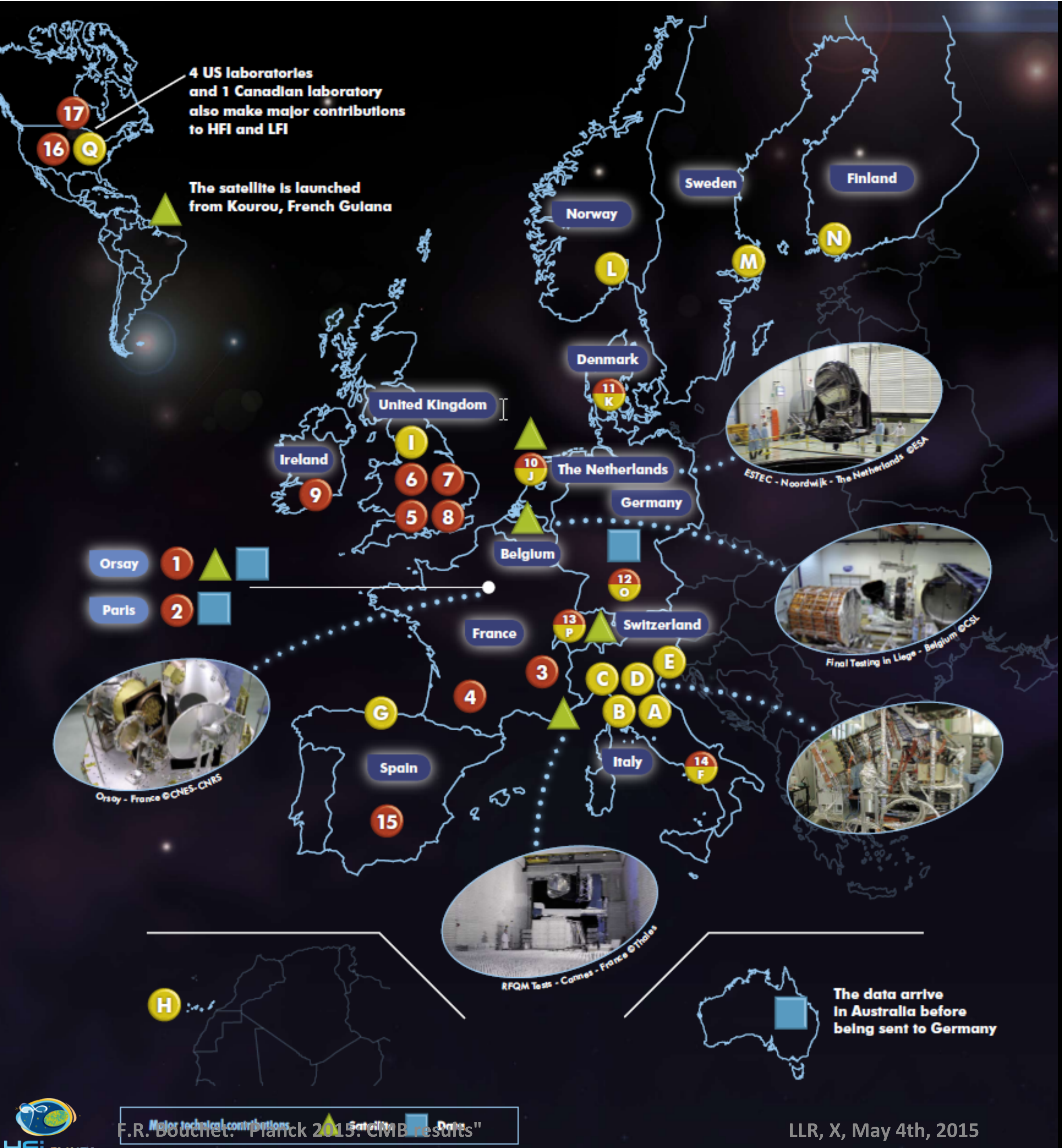
François R. Bouchet on behalf of the Planck Collaboration

2000 Kg
1600 W consumption
2 instruments - HFI & LFI
15 months nominal survey+4



50 000 electronic components
36 000 l ^{4}He
12 000 l ^{3}He
11 400 documents
20 years between the first project and first results (2013)

6c per European per year
16 countries
400 researchers among 1000



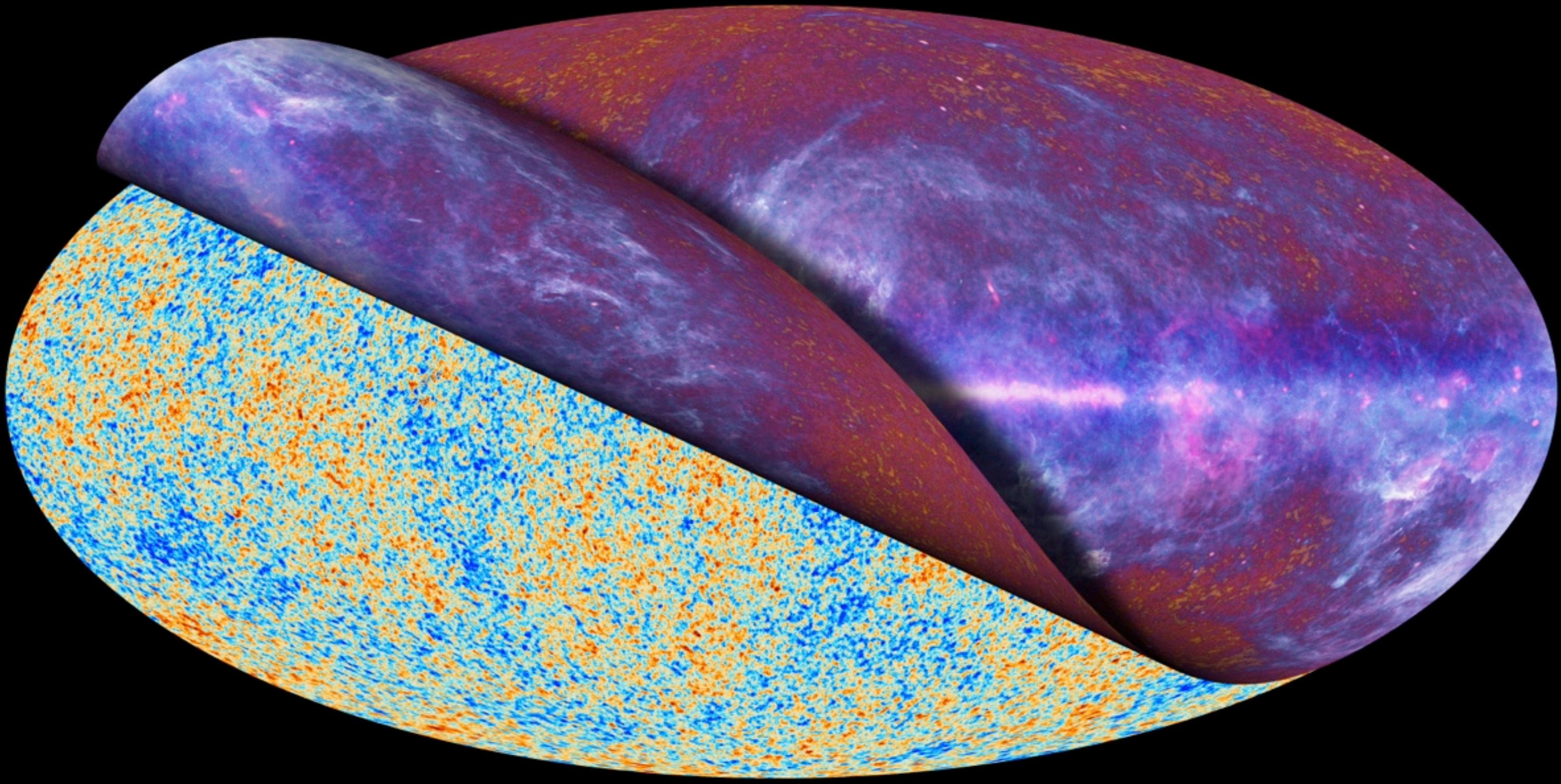
Research Laboratories in the HFI Collaboration

1 Institut d'Astrophysique Spatiale, Orsay (F)
1 Laboratoire de l'Accélérateur Linéaire, Orsay (F)
1 Commissariat à l'Énergie Atomique, Gif-sur-Yvette (F)
2 Institut d'Astrophysique de Paris, Paris (F)
2 Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique, Paris, (F)
2 AstroParticule et Cosmologie, Paris (F)
3 Laboratoire de Physique Subatomique et de Cosmologie, Grenoble (F)
3 Institut Louis Néel, Grenoble (F)
4 Centre d'Études Spatiales des Rayonnements, Toulouse (F)
5 Cardiff University, Cardiff (UK)
6 Rutherford Appleton Laboratory, Chilton (UK)
7 Institute of Astronomy, Cambridge (UK)
7 Mullard Radio Astronomy Observatory, Cambridge (UK)
8 Imperial College, London (UK)
9 National University of Ireland, Maynooth (IR)
10 Space Science Dpt of ESA, Noordwijk (NL)
11 Danish Space Research Institute, Copenhagen (DK)
12 Max-Planck-Institut fuer Astrophysik, Garching (D)
13 Université de Genève , Geneva (CH)
14 University La Sapienza, Rome (I)
15 Universidad de Granada, Granada (E)
16 California Institute of Technology, Pasadena (USA)
16 Jet Propulsion Laboratory, Pasadena (USA)
16 Stanford University, Stanford (USA)
17 Canadian Institute for Theoretical Astrophysics, Toronto (Canada)

Research Laboratories in the LFI Collaboration

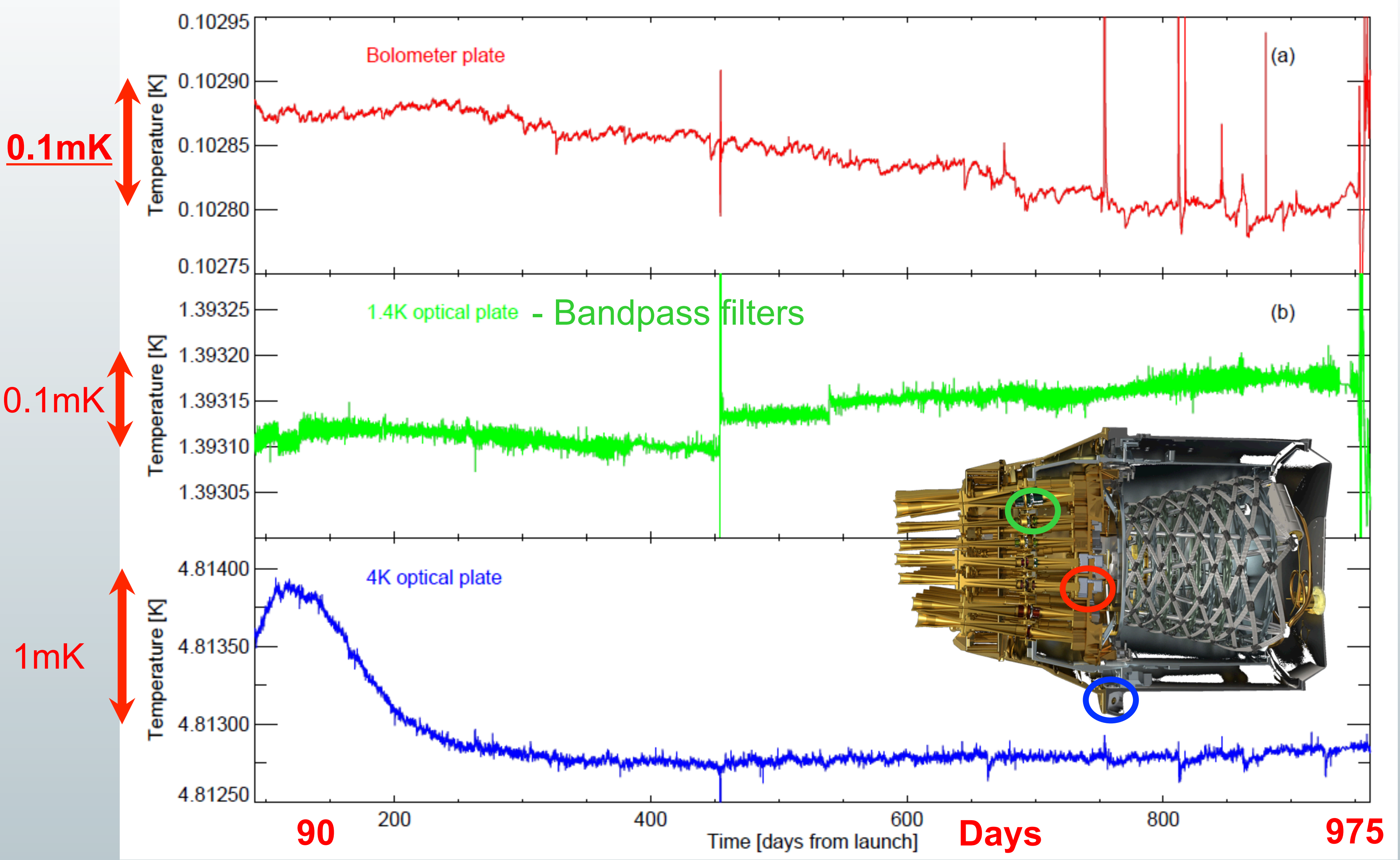
A Istituto Nazionale di Astrofisica Spaziale et Fisica Cosmica, Bologna (I)
B Istituto CAISMI, Firenze (I)
C Istituto IASF (CNR), Milano (I)
C Istituto di Fisica del Plasma IFP (CNR), Milano (I)
D Osservatorio Astronomico di Padova, Padova (I)
E Osservatorio Astronomico di Trieste, Trieste (I)
E SISSA, Trieste (I)
F Istituto IFSI, Roma (I)
F Universita Tor Vergata, Roma (I)
G Instituto de Fisica de Cantabria, Santander (E)
H Instituto de Astrofisica de Canarias, La Laguna (E)
I Jodrell Bank Observatory, Macclesfield (UK)
J Space Science Dpt of ESA , Noordwijk (NL)
K Danish Space Research Institute , Copenhagen (DK)
K Theoretical Astrophysics Center, Copenhagen (DK)
L University of Oslo, Oslo (N)
M Chalmers University of Technology, Goteborg (S)
N Millimetre Wave Laboratory, Espoo (FI)
O Max-Planck-Institut fuer Astrophysik, Garching (D)
P Université de Genève, Geneva (CH)
Q University of California (Berkeley), Berkeley (USA)
Q University of California (Santa Barbara), Santa Barbara (USA)
Q Jet Propulsion Laboratory, Pasadena (USA)

Paris, March 21st 2013

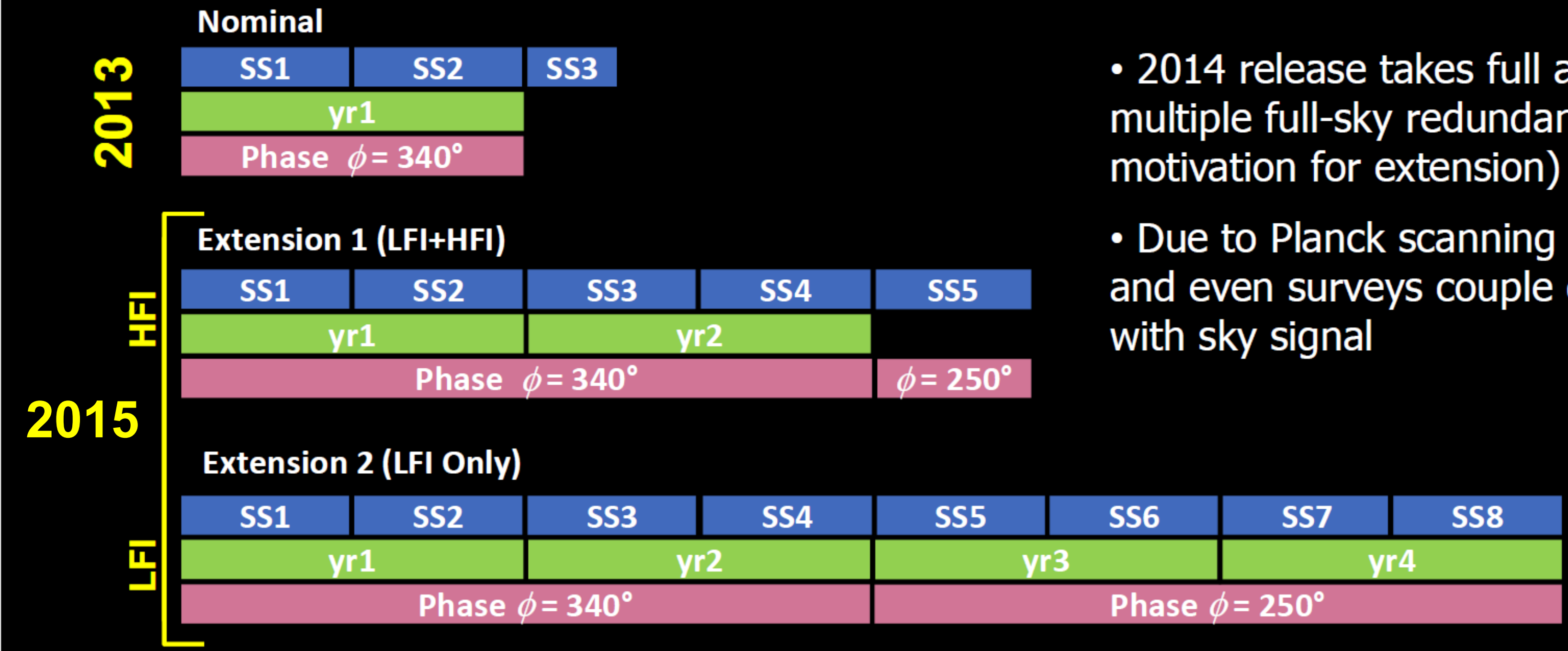


Planck unveils the Cosmic Microwave Background

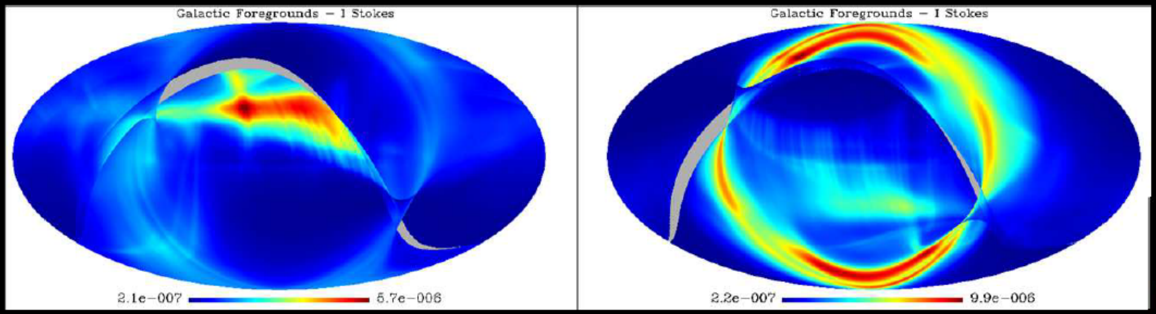
Quietly cool…



2015 release: Planck full mission data

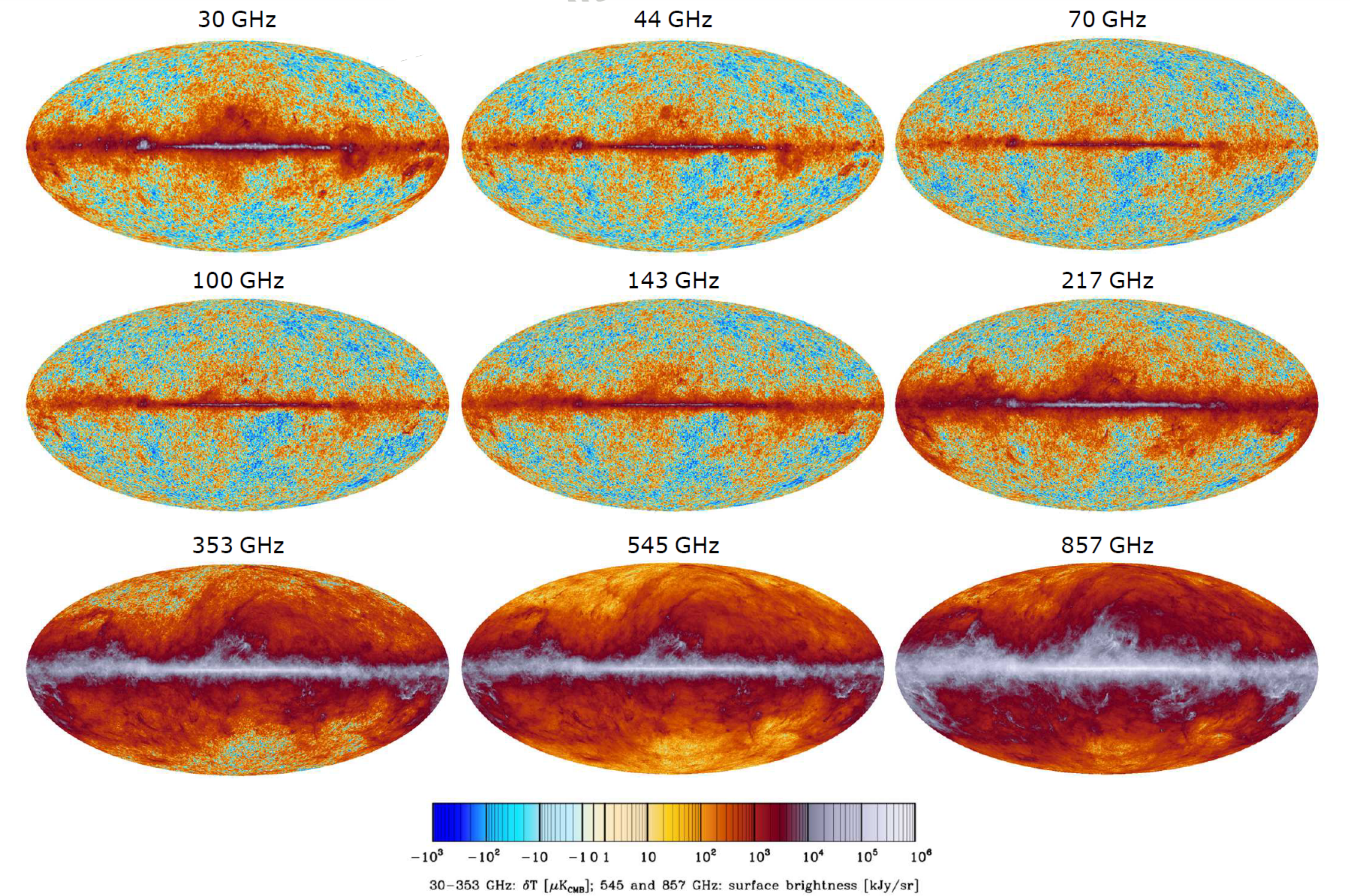


- 2014 release takes full advantage of multiple full-sky redundancies (main motivation for extension)
- Due to Planck scanning strategy, odd and even surveys couple differently with sky signal

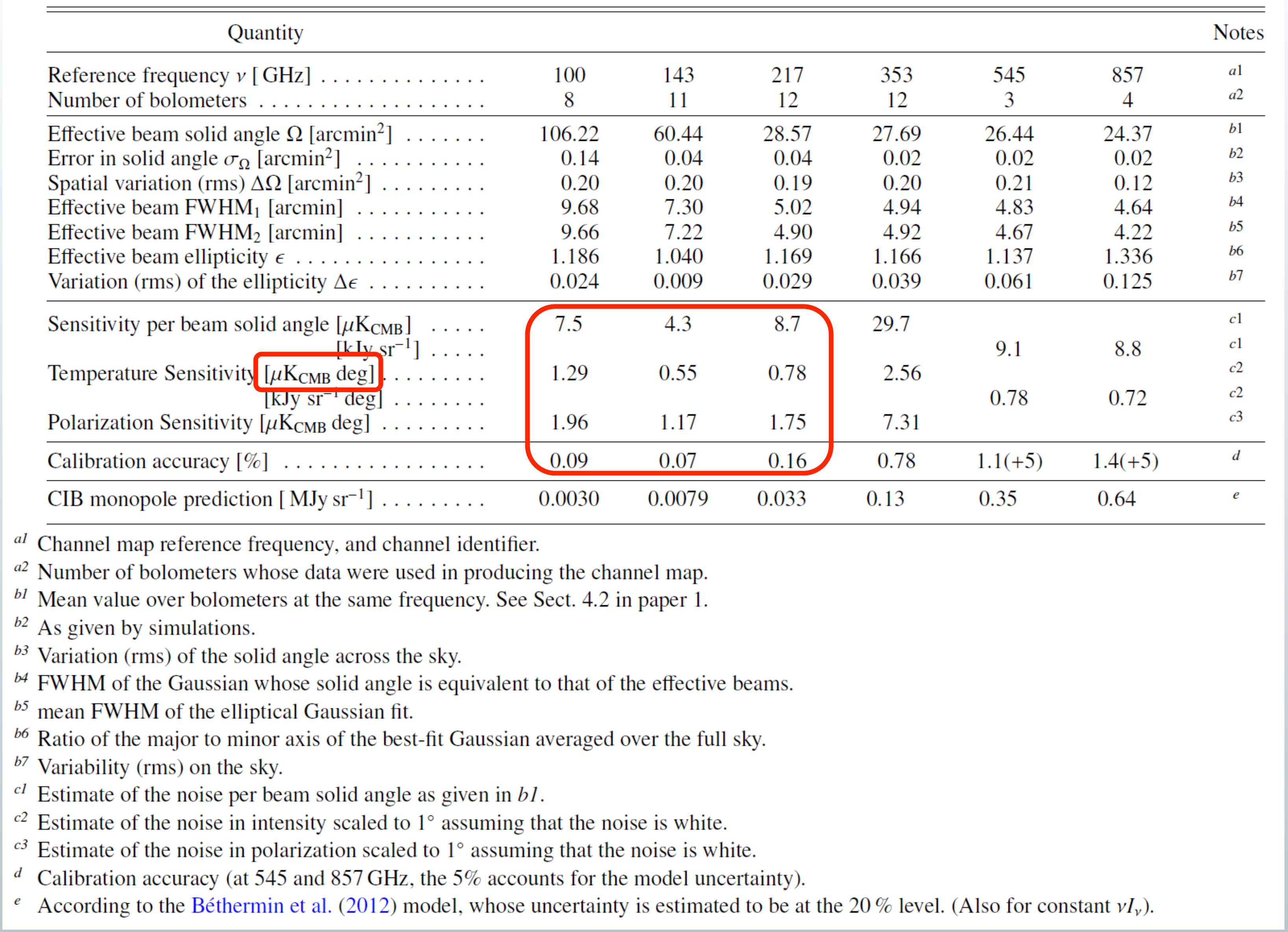

Galactic straylight (simulation)

Odd survey | Even survey

Planck 2015 temperature maps



Main characteristics of HFI full Mission maps



Quantity							Notes
Reference frequency ν [GHz]	100	143	217	353	545	857	*a*1
Number of bolometers	8	11	12	12	3	4	*a*2
Effective beam solid angle Ω [arcmin^2]	106.22	60.44	28.57	27.69	26.44	24.37	*b*1
Error in solid angle σ_Ω [arcmin^2]	0.14	0.04	0.04	0.02	0.02	0.02	*b*2
Spatial variation (rms) $\Delta\Omega$ [arcmin^2]	0.20	0.20	0.19	0.20	0.21	0.12	*b*3
Effective beam FWHM_1 [arcmin]	9.68	7.30	5.02	4.94	4.83	4.64	*b*4
Effective beam FWHM_2 [arcmin]	9.66	7.22	4.90	4.92	4.67	4.22	*b*5
Effective beam ellipticity ϵ	1.186	1.040	1.169	1.166	1.137	1.336	*b*6
Variation (rms) of the ellipticity $\Delta\epsilon$	0.024	0.009	0.029	0.039	0.061	0.125	*b*7
Sensitivity per beam solid angle [$\mu\mathrm{K_{CMB}}$]	7.5	4.3	8.7	29.7			*c*1
[$\mathrm{kJy\ sr^{-1}}$]					9.1	8.8	*c*1
Temperature Sensitivity [$\mu\mathrm{K_{CMB}}$ deg]	1.29	0.55	0.78	2.56			*c*2
[$\mathrm{kJy\ sr^{-1}}$ deg]					0.78	0.72	*c*2
Polarization Sensitivity [$\mu\mathrm{K_{CMB}}$ deg]	1.96	1.17	1.75	7.31			*c*3
Calibration accuracy [%]	0.09	0.07	0.16	0.78	1.1(+5)	1.4(+5)	*d*
CIB monopole prediction [$\mathrm{MJy\ sr^{-1}}$]	0.0030	0.0079	0.033	0.13	0.35	0.64	*e*

[a1] Channel map reference frequency, and channel identifier.

[a2] Number of bolometers whose data were used in producing the channel map.

[b1] Mean value over bolometers at the same frequency. See Sect. 4.2 in paper 1.

[b2] As given by simulations.

[b3] Variation (rms) of the solid angle across the sky.

[b4] FWHM of the Gaussian whose solid angle is equivalent to that of the effective beams.

[b5] mean FWHM of the elliptical Gaussian fit.

[b6] Ratio of the major to minor axis of the best-fit Gaussian averaged over the full sky.

[b7] Variability (rms) on the sky.

[c1] Estimate of the noise per beam solid angle as given in *b1*.

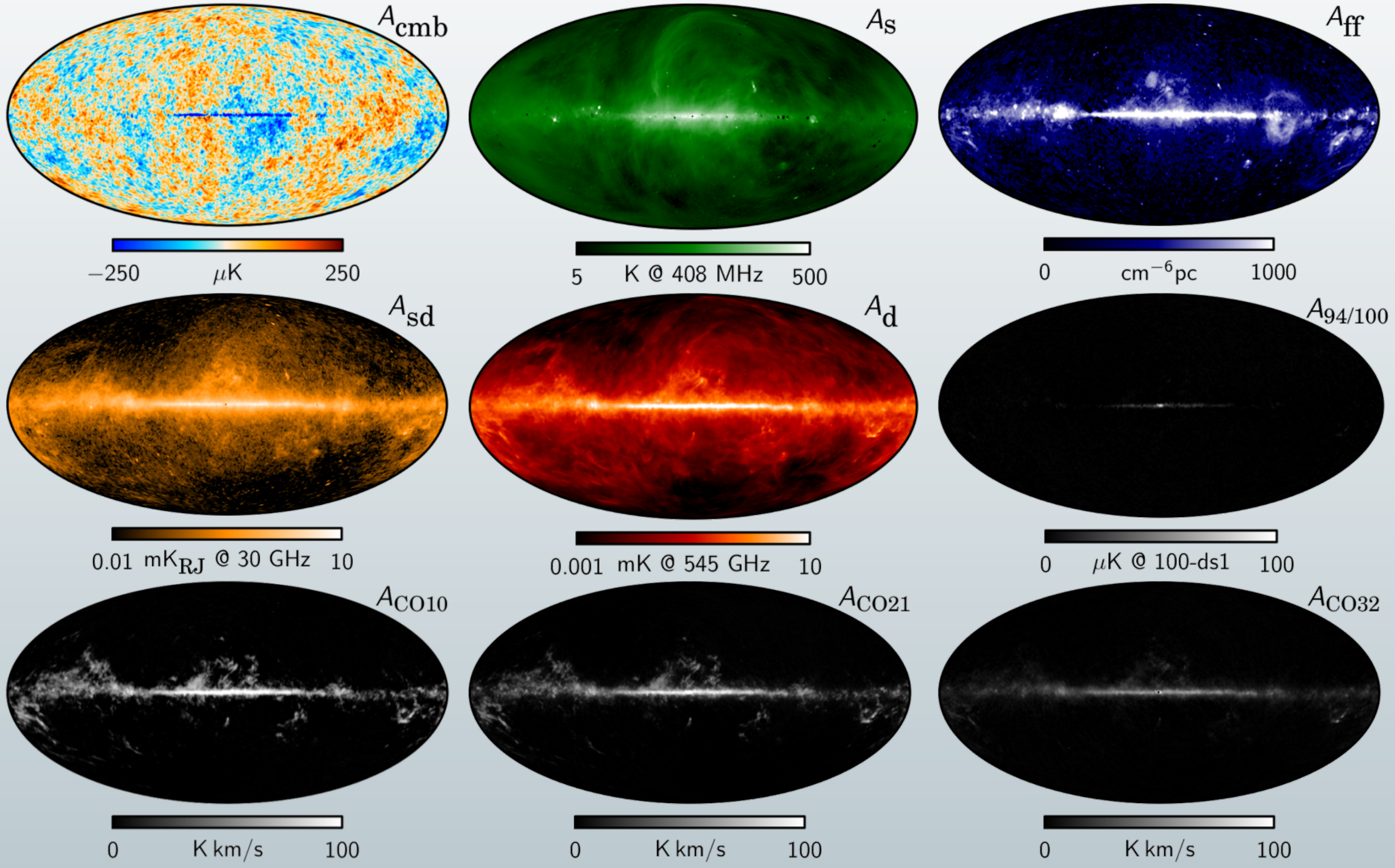
[c2] Estimate of the noise in intensity scaled to 1° assuming that the noise is white.

[c3] Estimate of the noise in polarization scaled to 1° assuming that the noise is white.

[d] Calibration accuracy (at 545 and 857 GHz, the 5% accounts for the model uncertainty).

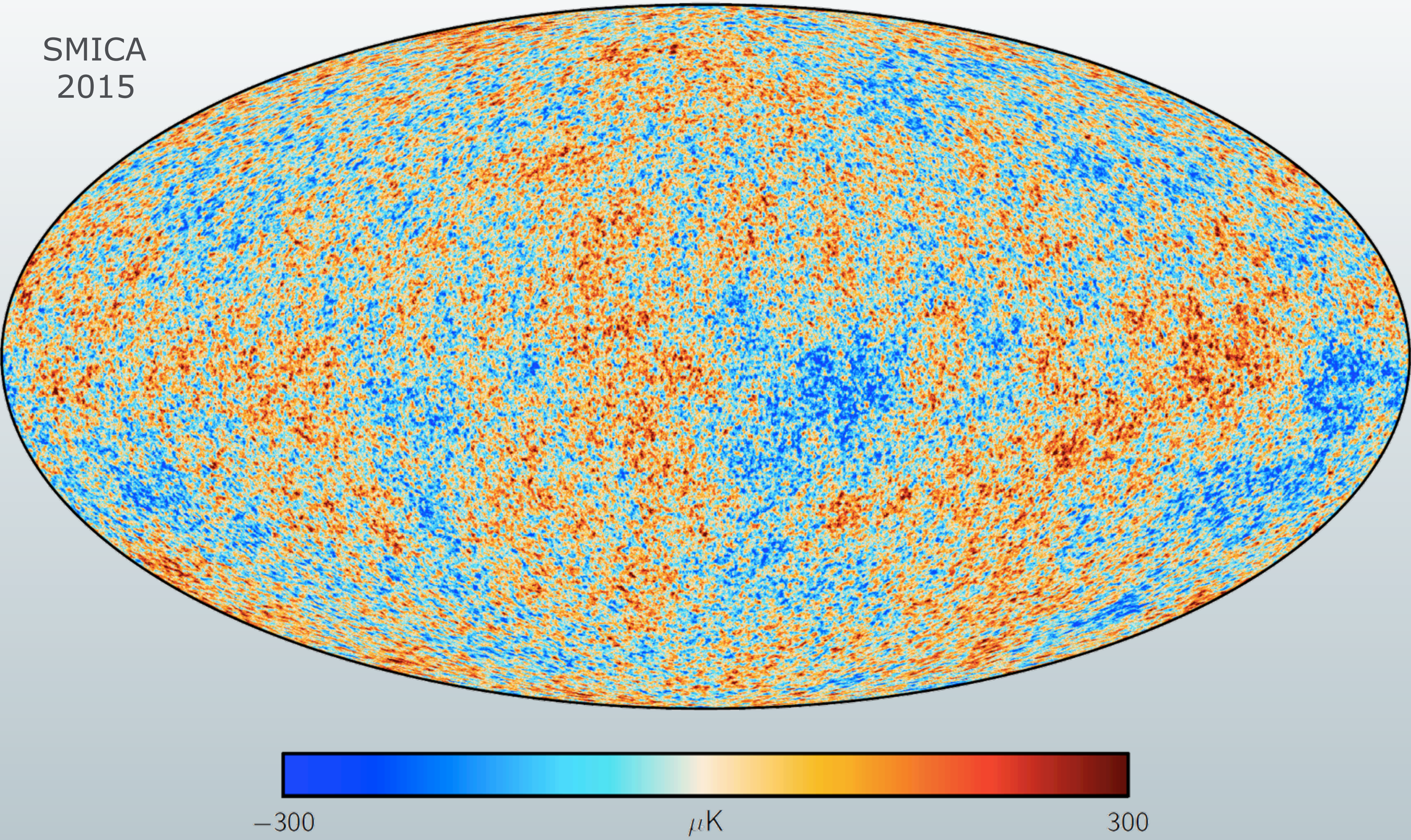
[e] According to the Béthermin et al. (2012) model, whose uncertainty is estimated to be at the 20 % level. (Also for constant νI_ν).

Temperature sky model



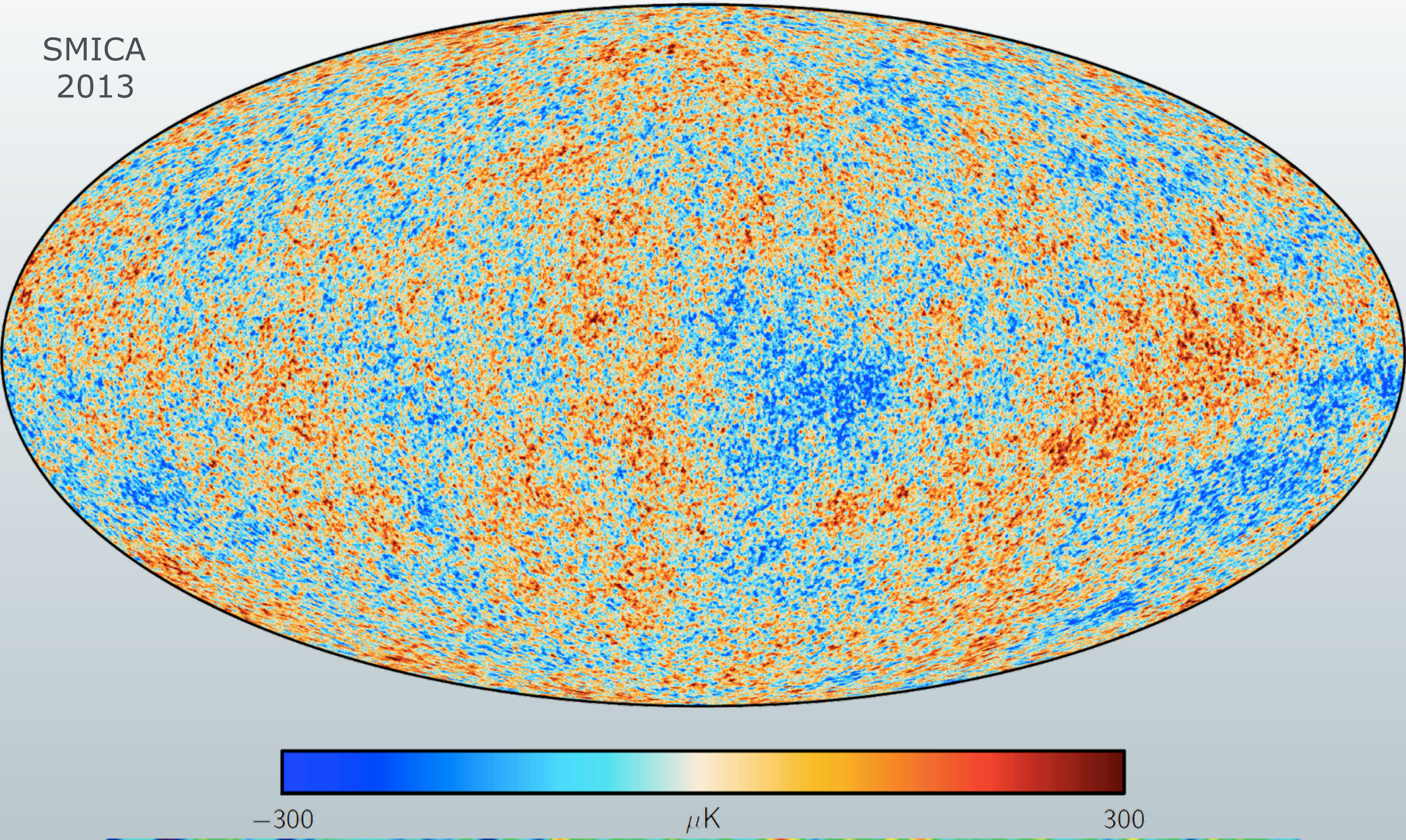
2013 vs 2015 temperature map

SMICA
2015



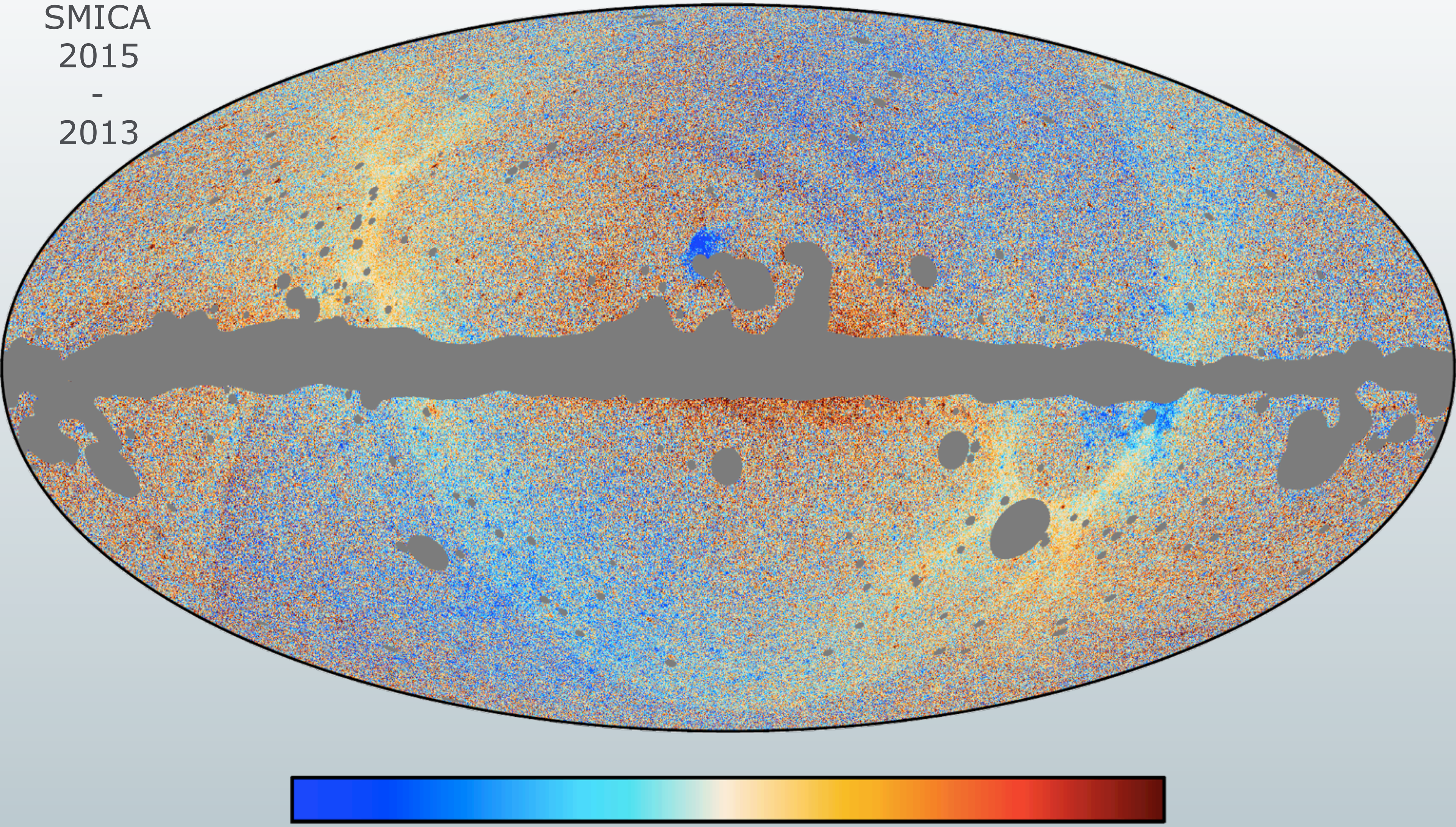
2013 vs 2015 temperature map

SMICA
2013

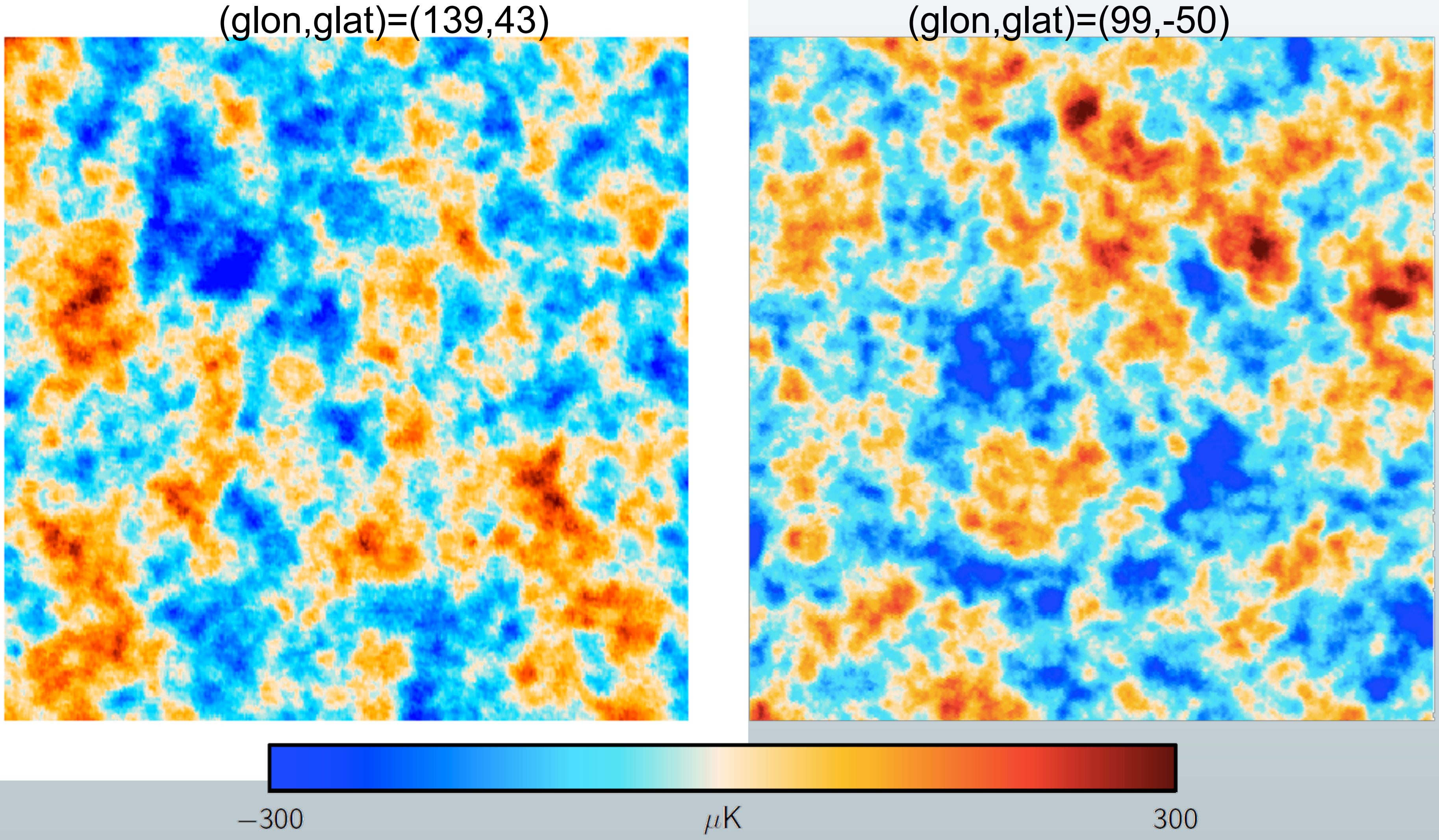


2013 vs 2015 temperature map

SMICA
2015
-
2013

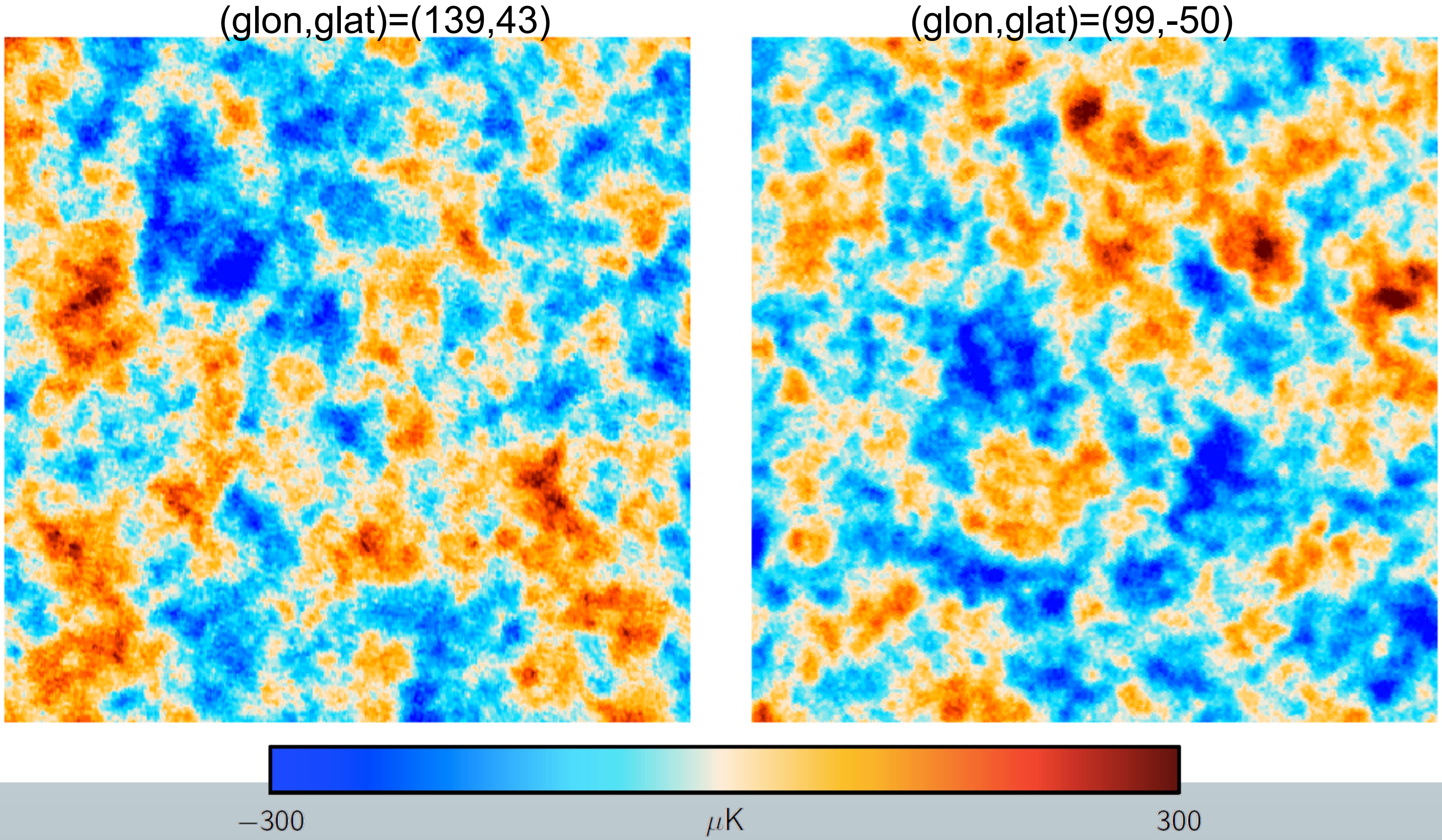


2015


(glon,glat)=(139,43)

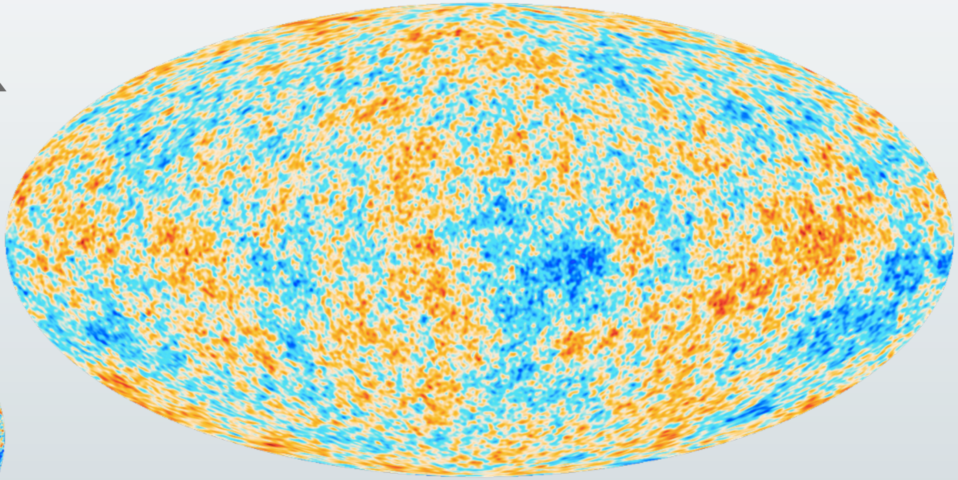
(glon,glat)=(99,-50)

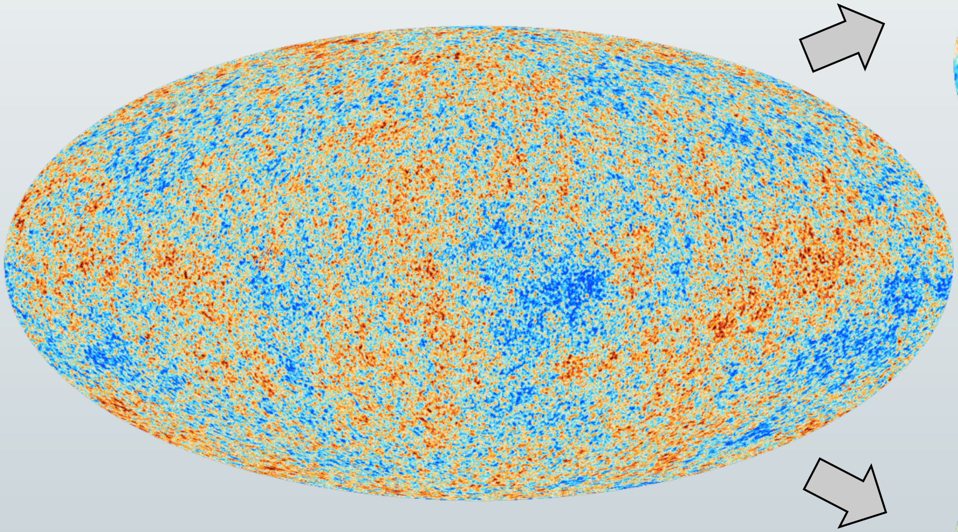
2013

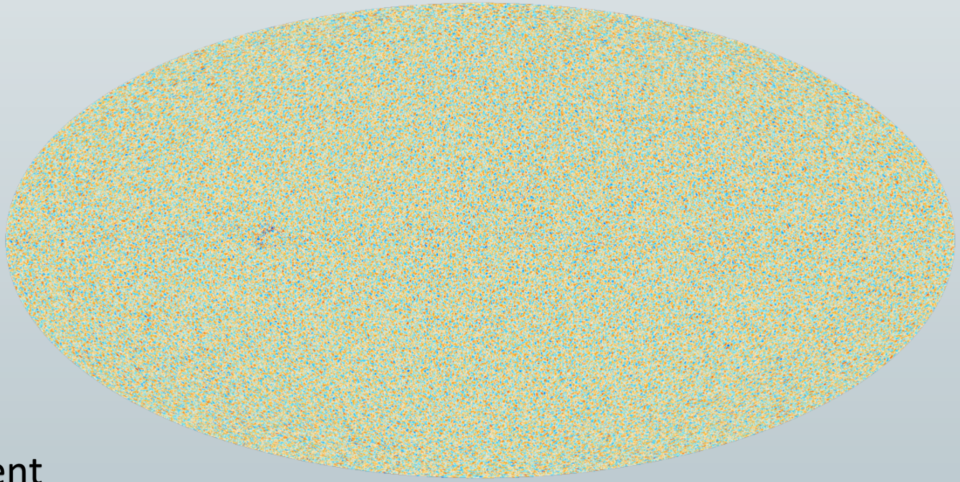


Our window

Smoothed map (suppressing scales θ < 1 deg) :
Quantum Fluctuations imprinted
When the age of the Universe was in the
interval [10^{-39}, 10^{-12}] seconds







Difference map (scales θ < 1 deg) :
Acoustic oscillations at small scales
< ct when t=380 000 years (~150 Mpc today).
Which allows to take a census of the Universe content

Power Spectrum estimation

Same methodology than in 2013. What's new:

- More data: 48/29 months of LFI/HFI observations respectively (instead of 15), enabling further checks.
- Improved data processing:

  systematics removal, calibration, beam reconstruction
- Improved foreground model

  → *Larger sky-fraction used for analysis*
- More robust to systematics:

  based on half-mission cross power spectra
- *The 2015 analysis allows using polarization*.

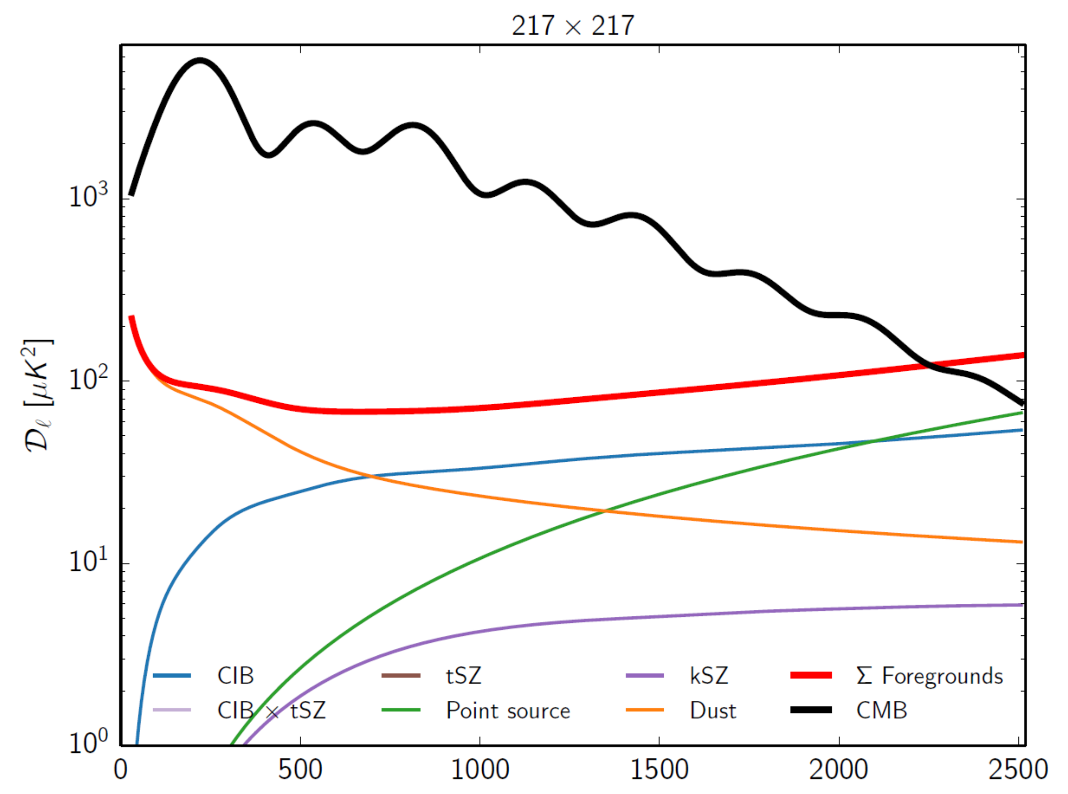
NB: we cross-checked with 4 different methods: Plik, camspec, mspec, hillipop (+Xfaster)

- At ell < 30: T from Commander (f_{sky}=93%), *polarisation from 70GHz* (-S2 & S4, 47%), *cleaned with 30 &* ***353GHz***.

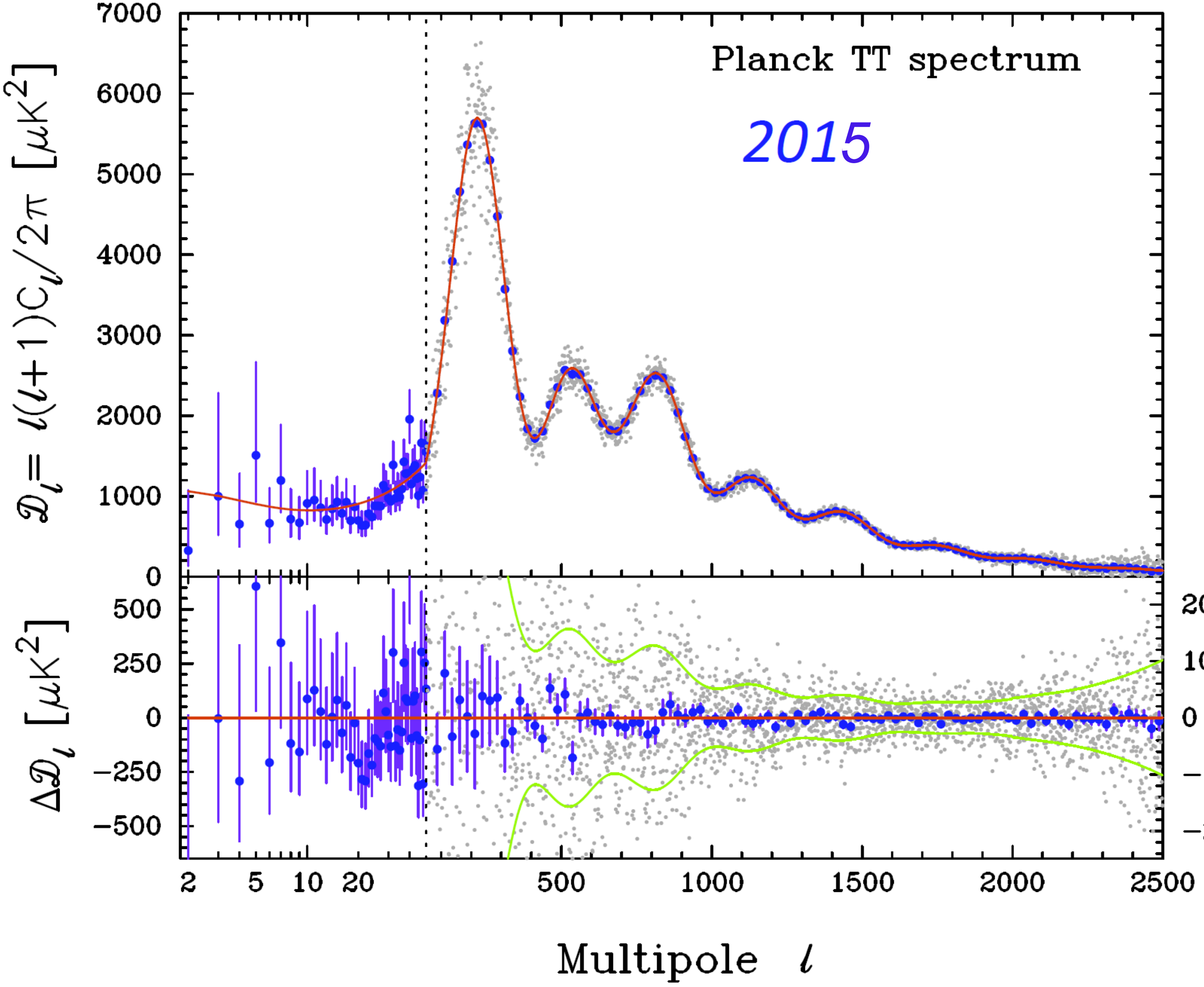
The high-ell likelihood (l>30)

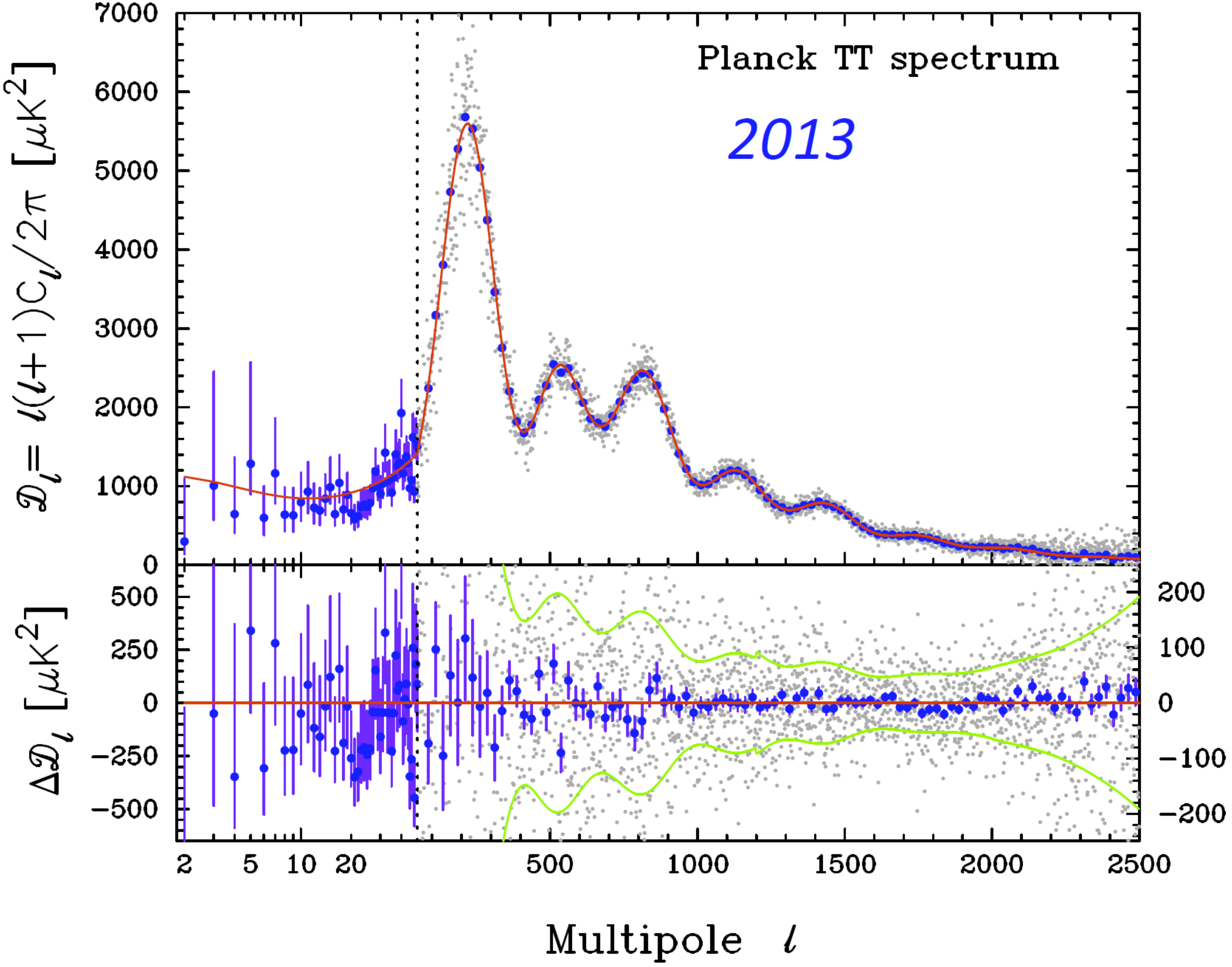
We construct a Gaussian likelihood, using

- A parameterised foreground model to marginalise over (12 parameters)
- a covariance matrix which includes signal, noise, FG, masks… Full TT, TE, EE reduces to 2300^2 elements when binned (Cond Num~ $O(10^{11})$)

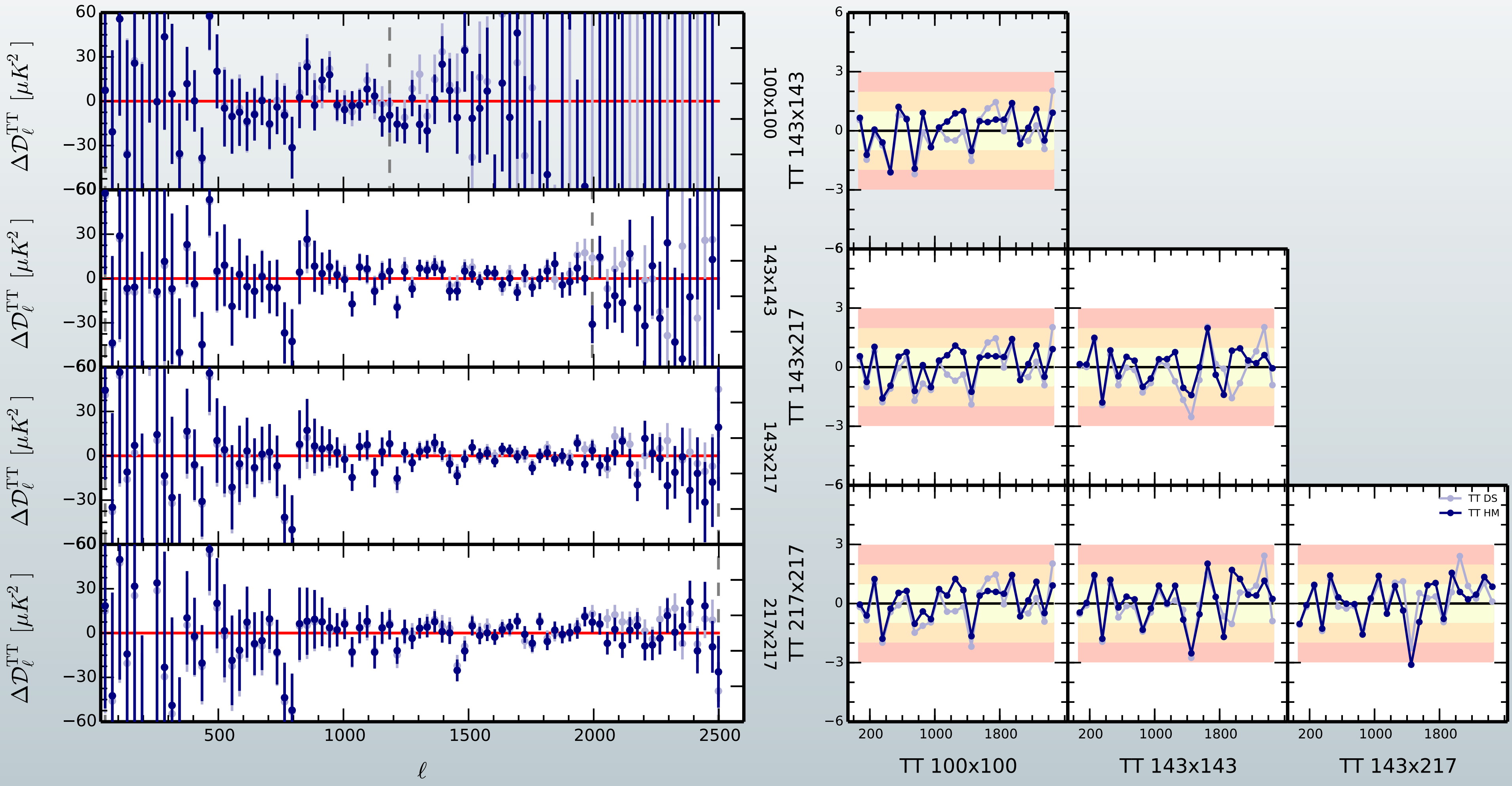


(Instead of 23000^2)

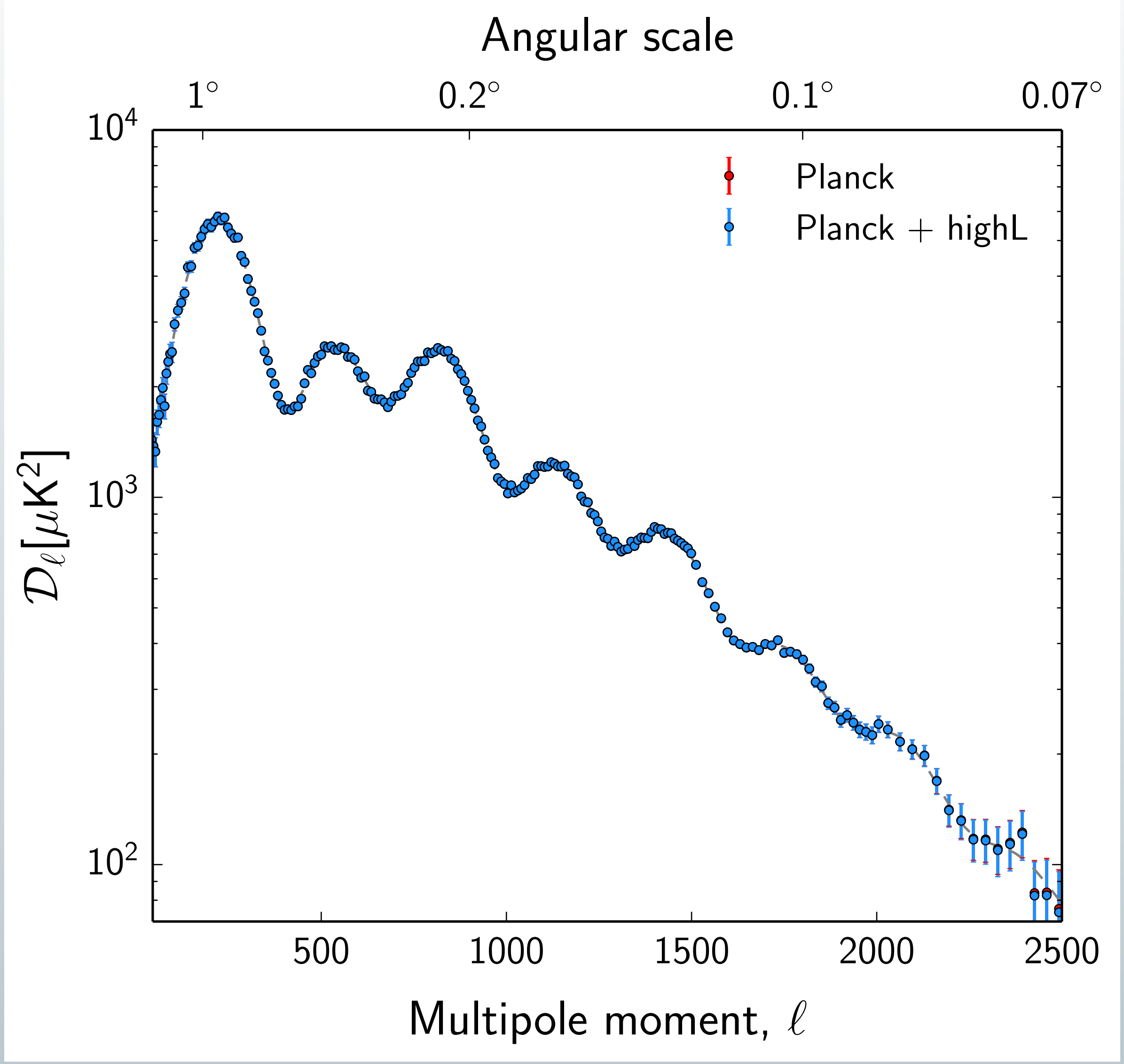

Planck TT spectrum
2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
7000
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500
Multipole ℓ


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

Consistency checks (freq, DS..)

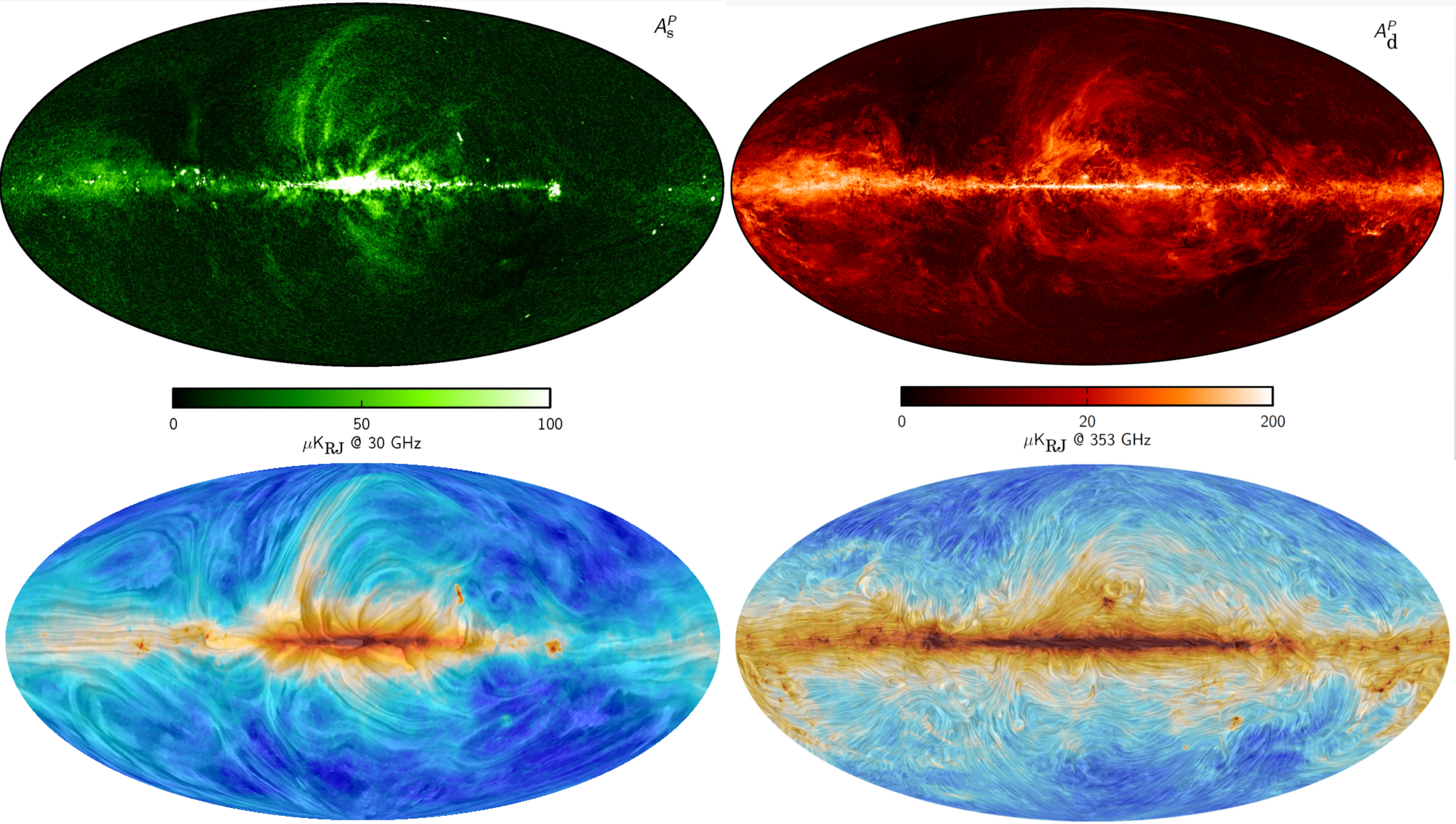


highL data (ACT&SPT) are consistent w. Planck



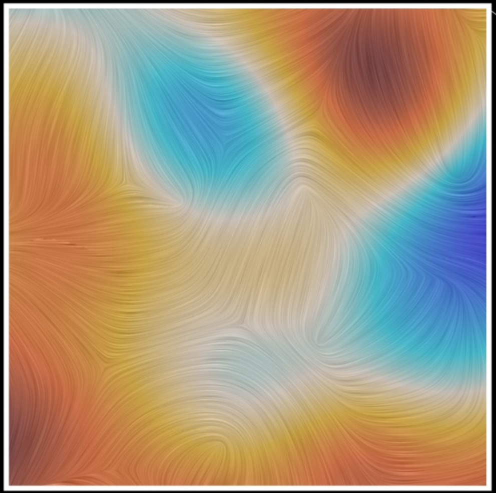
➔ Only used for consistency checks, not for cosmology (but SZ priors)

Synchrotron (30GHz) and Dust (353GHz)

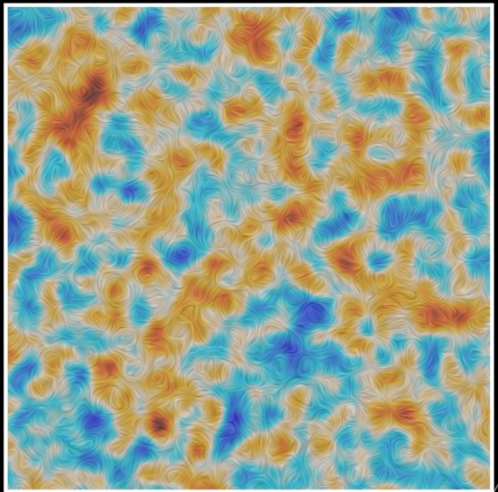


Top: Polarisation amplitude, Bottom: magnetic field direction and total intensity

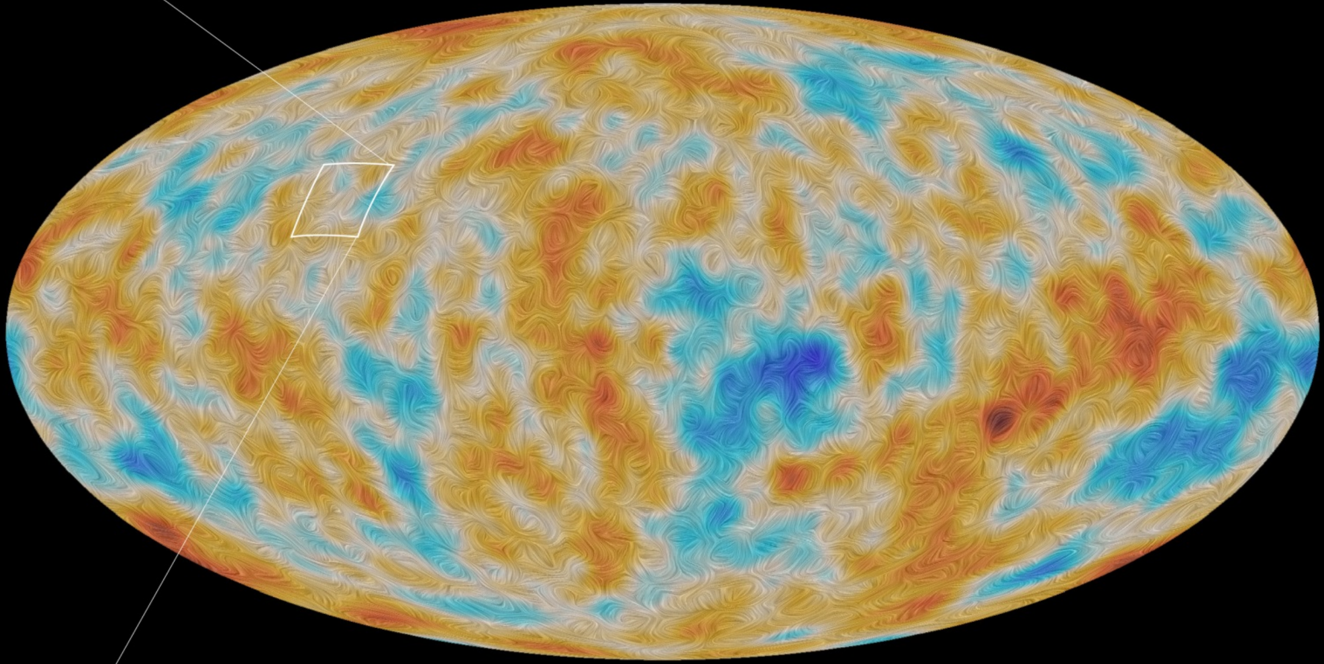
→ PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND



Filtered at 5 degrees



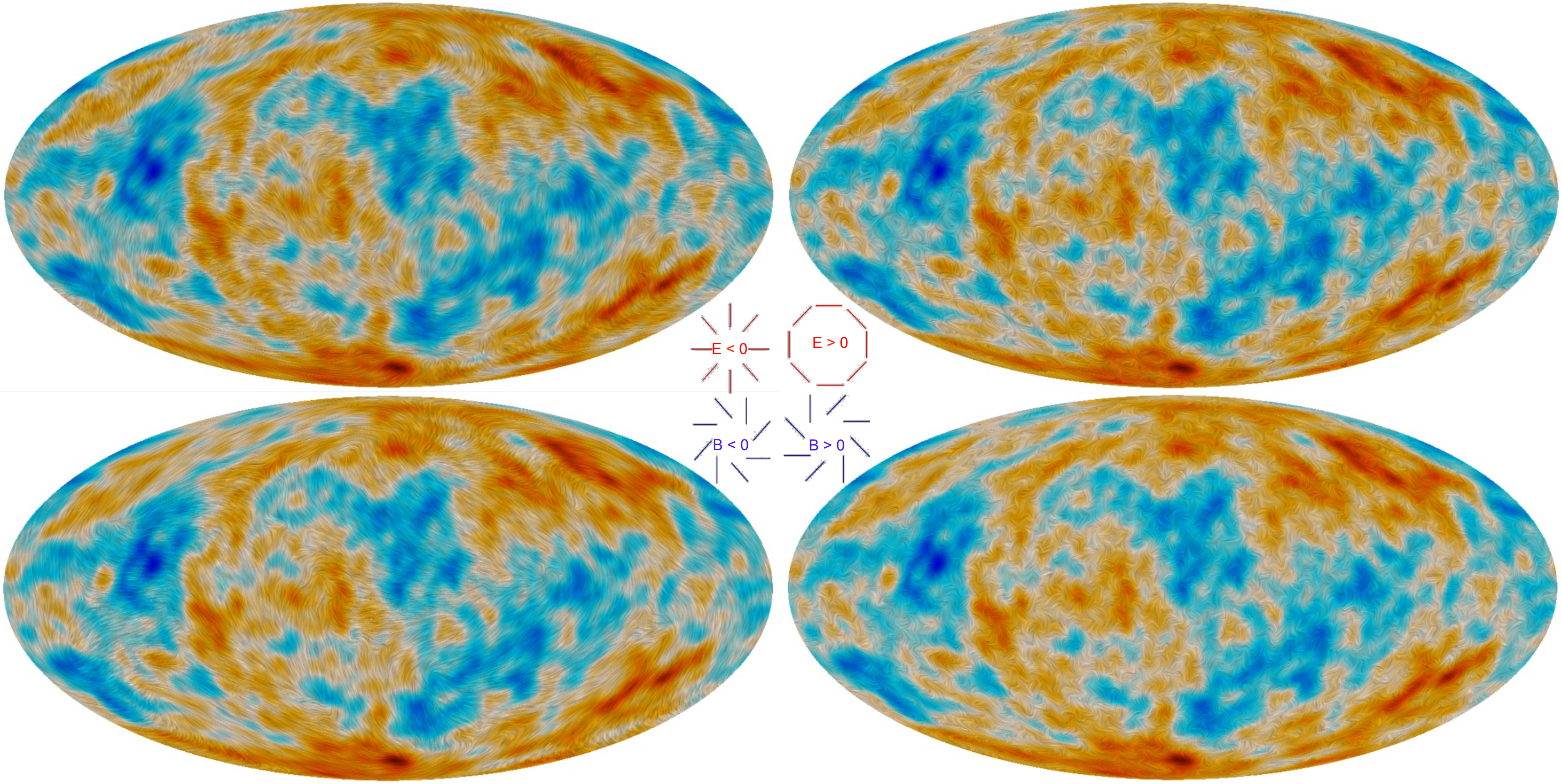
Filtered at 20 arcminutes



Full sky map
Filtered at 5 degrees

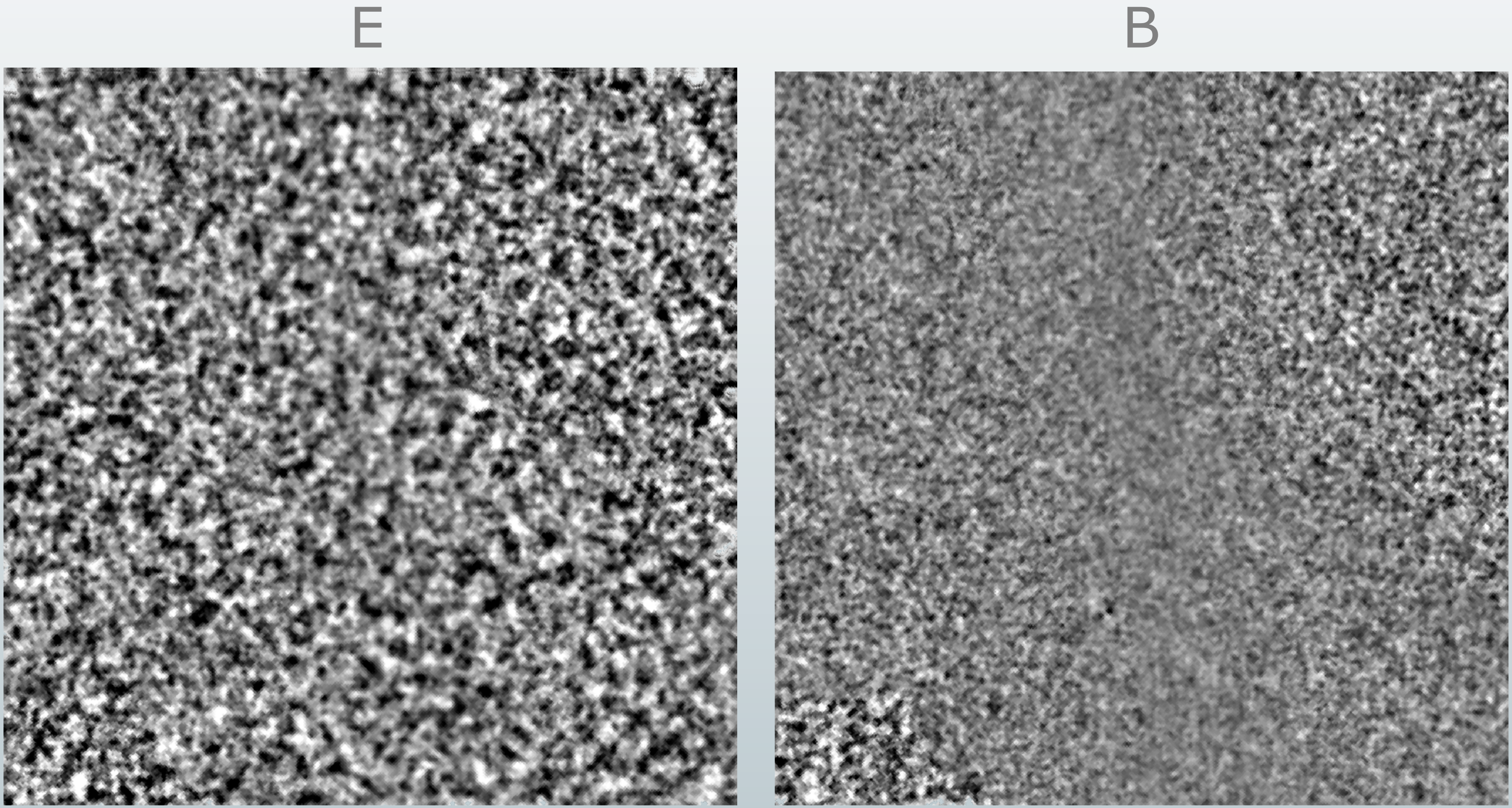
LCDM Polarisation realisations

E **E filtered (no large scales)**



B **B filtered (no large scales)**

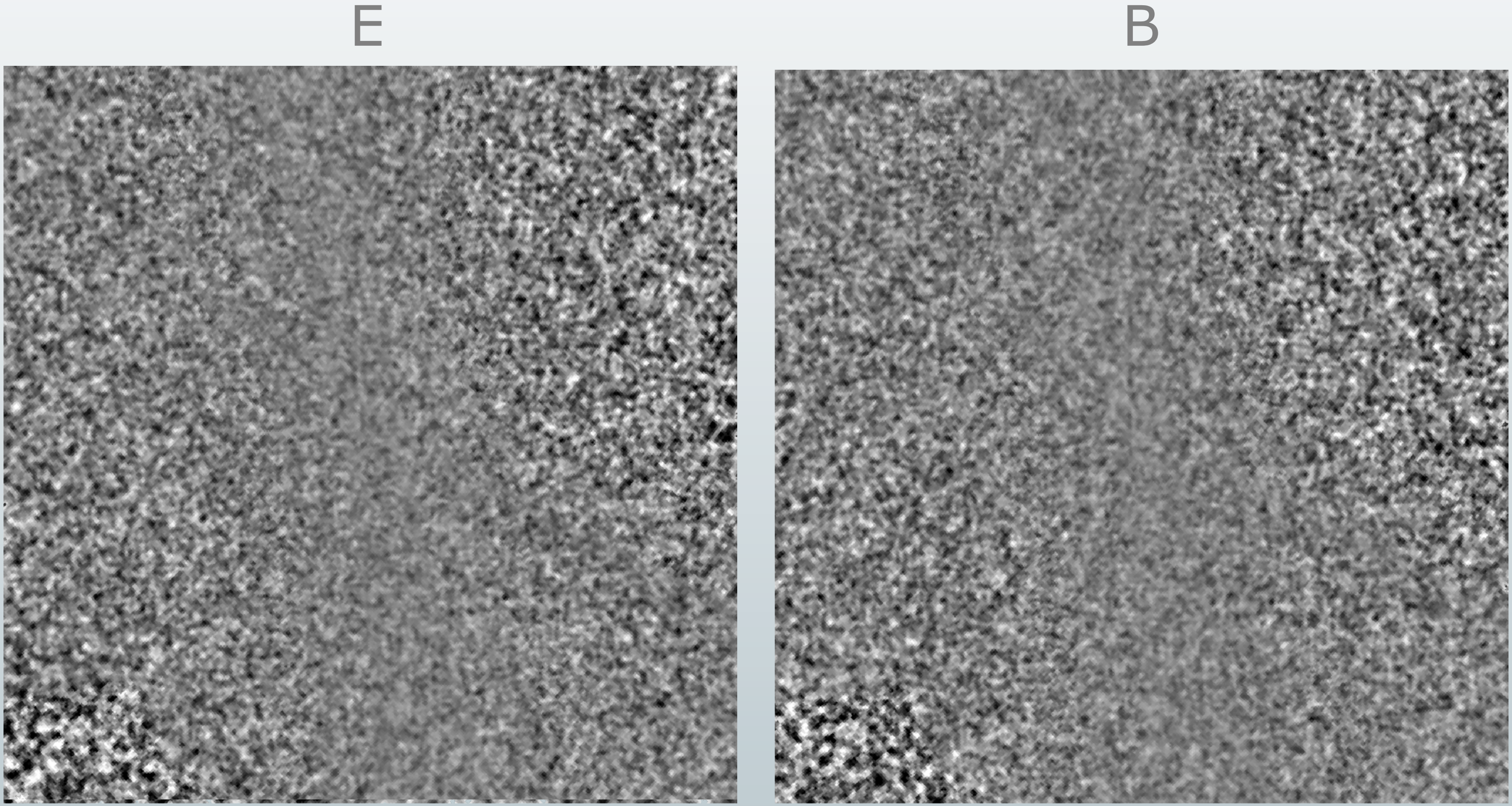
Polarisation maps @ 10 arcmin



10° x 10° zoom-in of North Ecliptic Pole

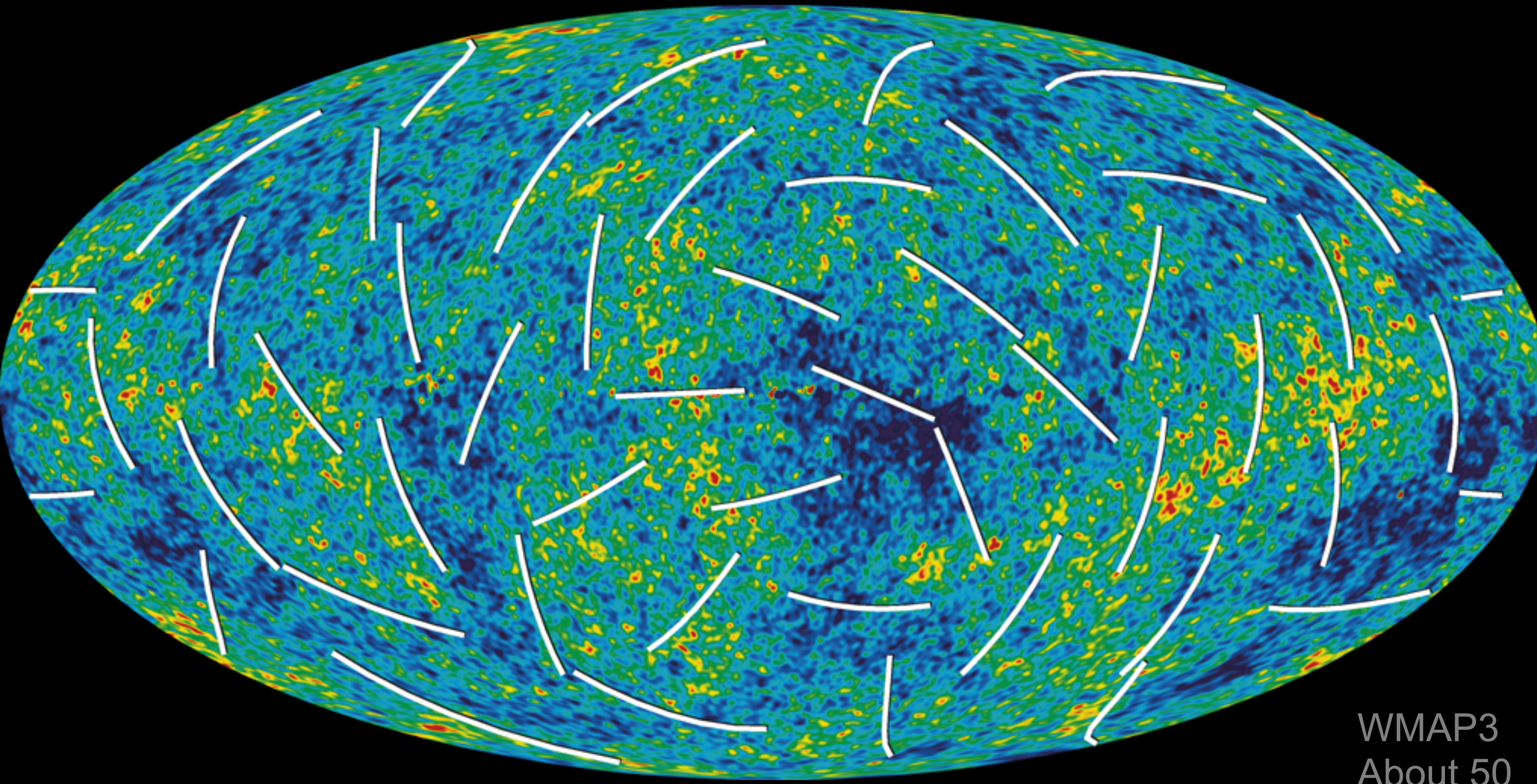
Half-difference half-ring pol. maps

@ 10 arcmin



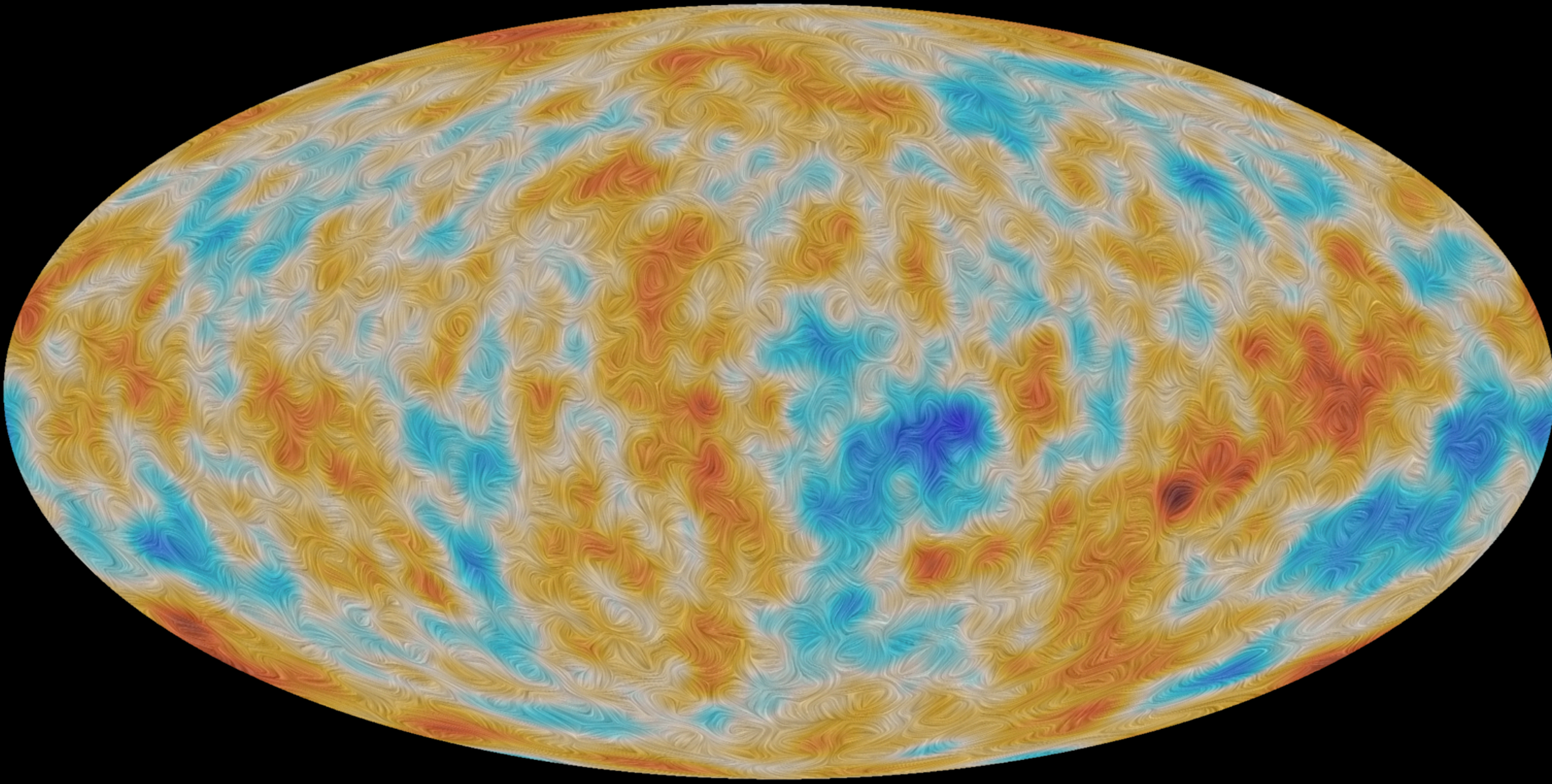
10° x 10° zoom-in of North Ecliptic Pole

What we already knew

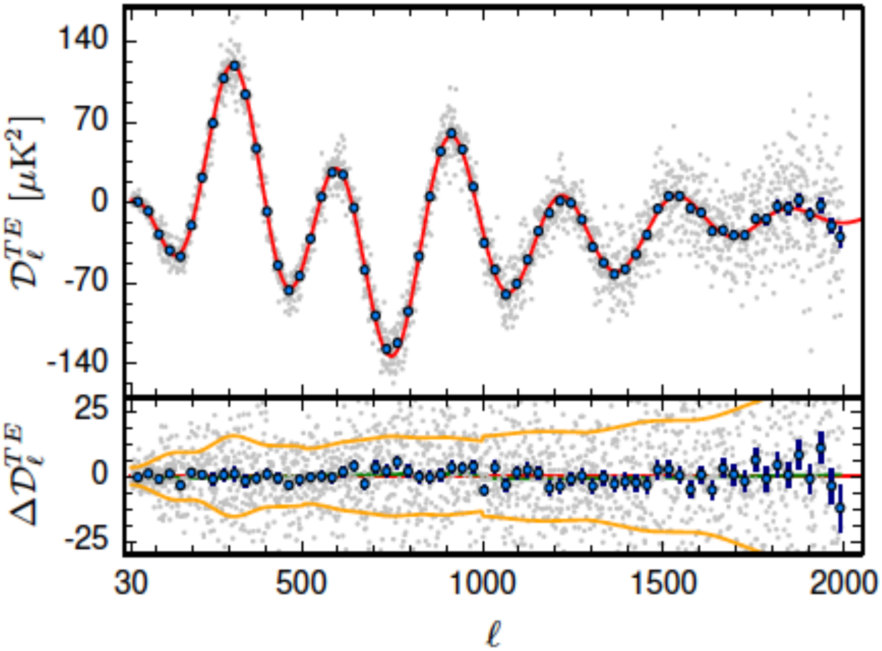


WMAP3
About 50
locations?

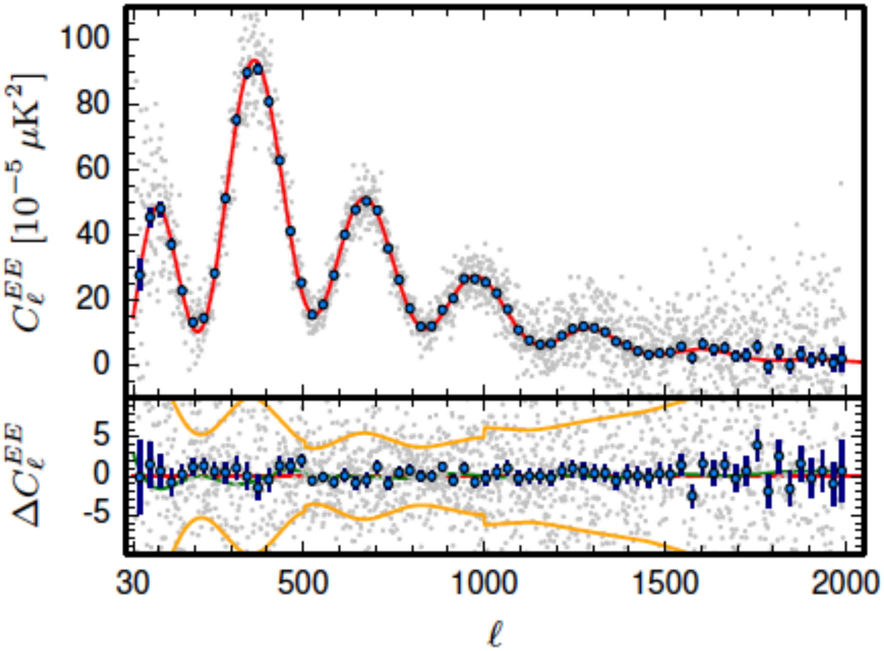
The Planck 2015 CMB polarisation sky



Planck 2015 - TE & EE spectra



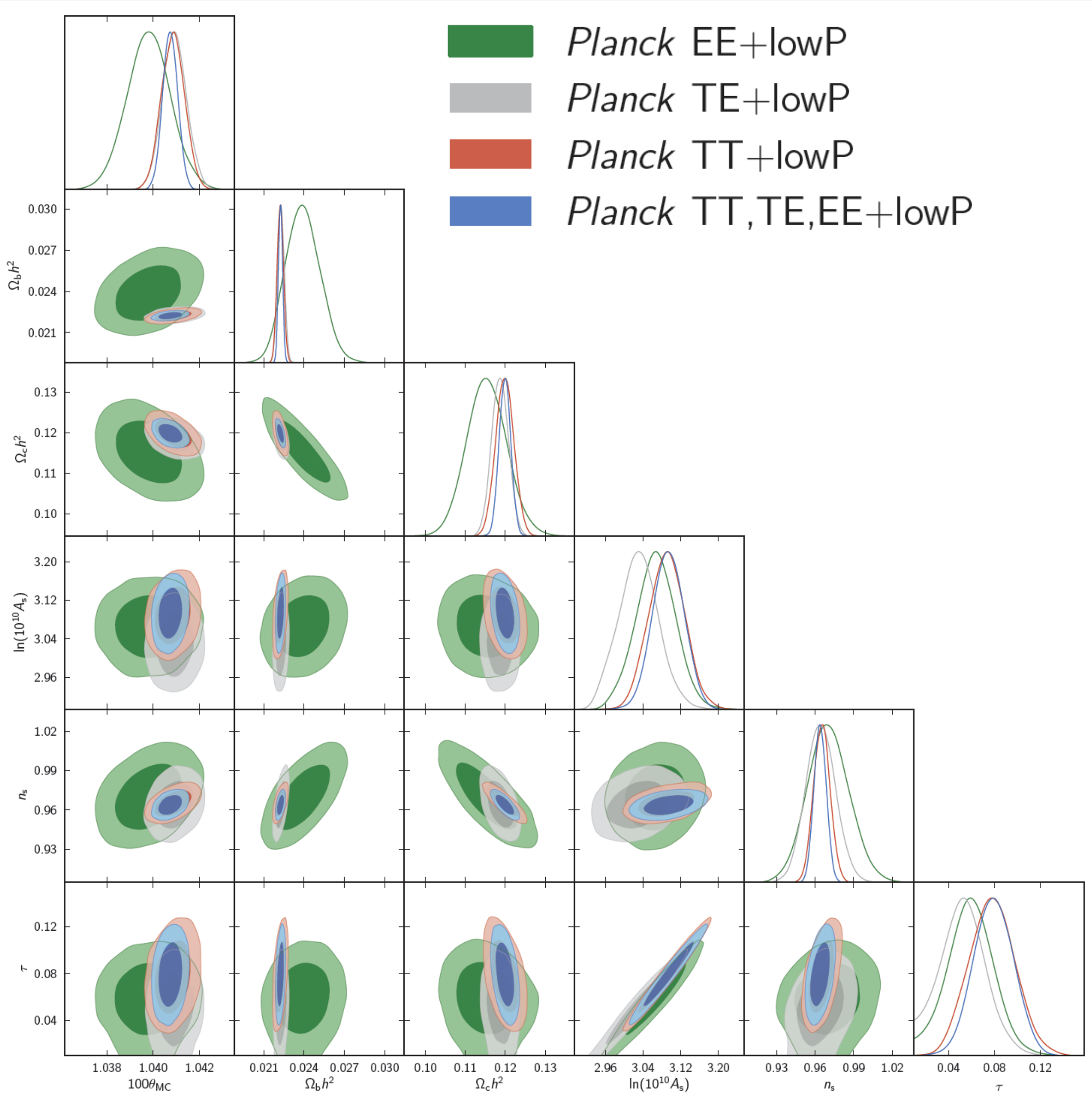
Frequency averaged spectrum reduced ^{2} = 1.04



Frequency averaged spectrum reduced ^{2} = 1.01

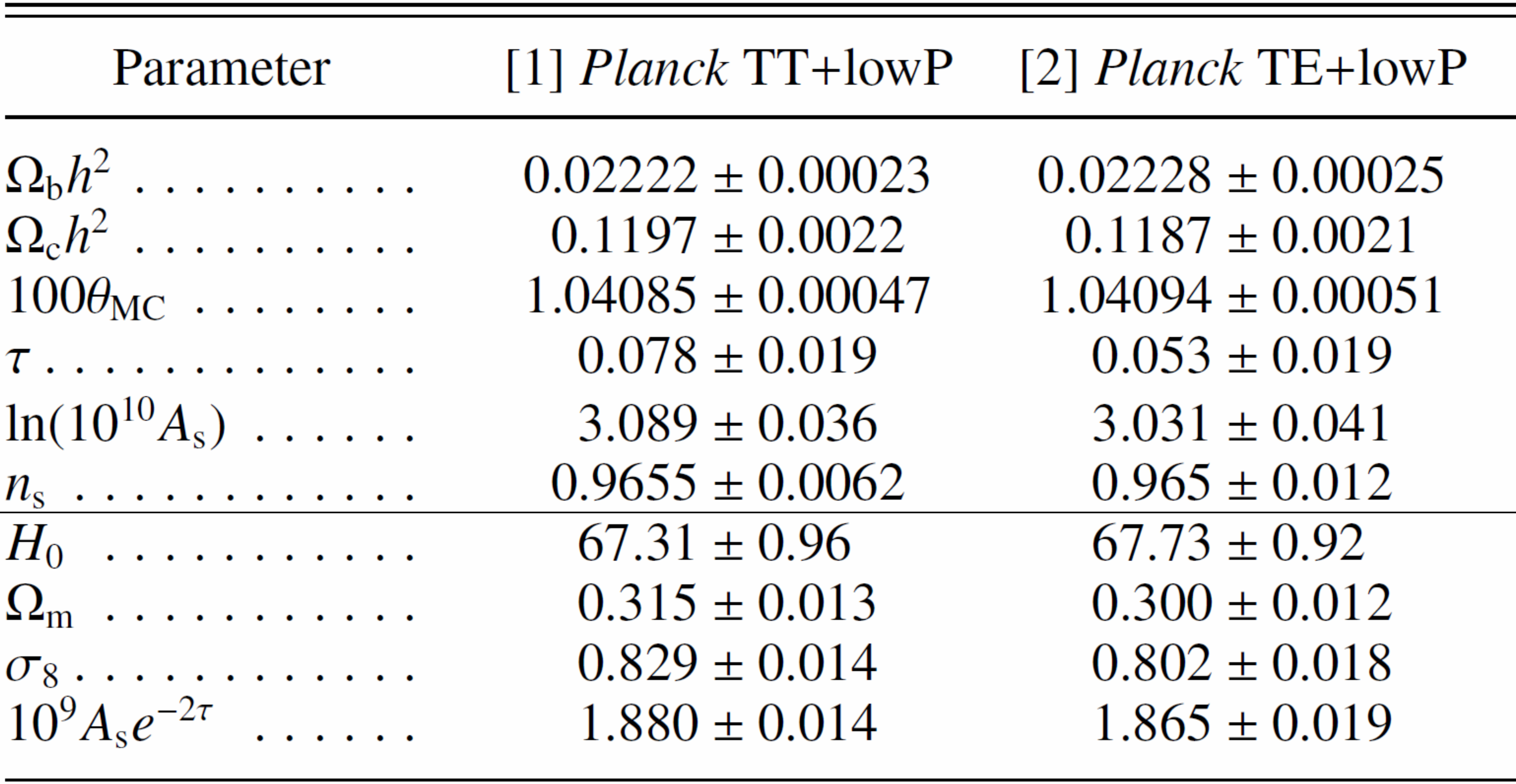
- Red curve is the prediction based on the best fit TT in base ΛCDM
- Albeit *magnificent*, 2014 polarisation data and results are *preliminary* because all systematic and foreground uncertainties have not been *exhaustively* characterised at O(1μK^2).

T & E – LCDM parameters



*Parameters from polarisation spectra are **highly consistent** with those from TT spectra.*

Base ΛCDM model

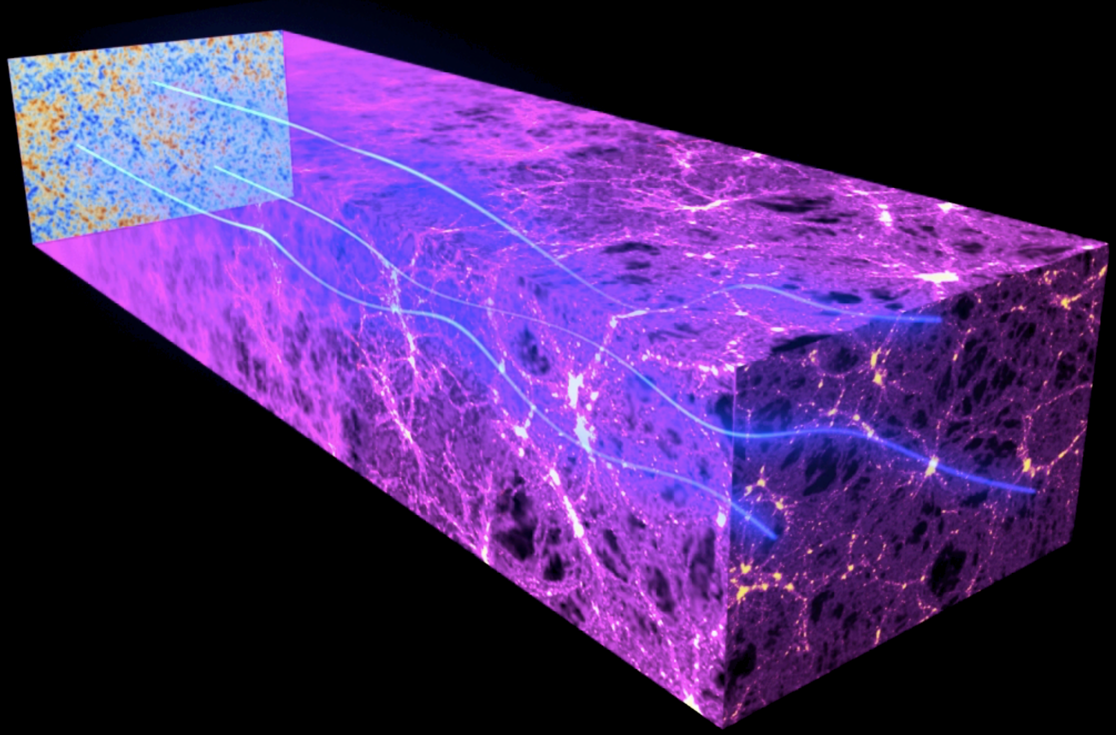


Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051
τ	0.078 ± 0.019	0.053 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041
n_s	0.9655 ± 0.0062	0.965 ± 0.012
H_0	67.31 ± 0.96	67.73 ± 0.92
Ω_m	0.315 ± 0.013	0.300 ± 0.012
σ_8	0.829 ± 0.014	0.802 ± 0.018
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019

TT & TE have quite similar uncertainties (but for n_s),
but beware that they are still some low level systematics in the polarisation data

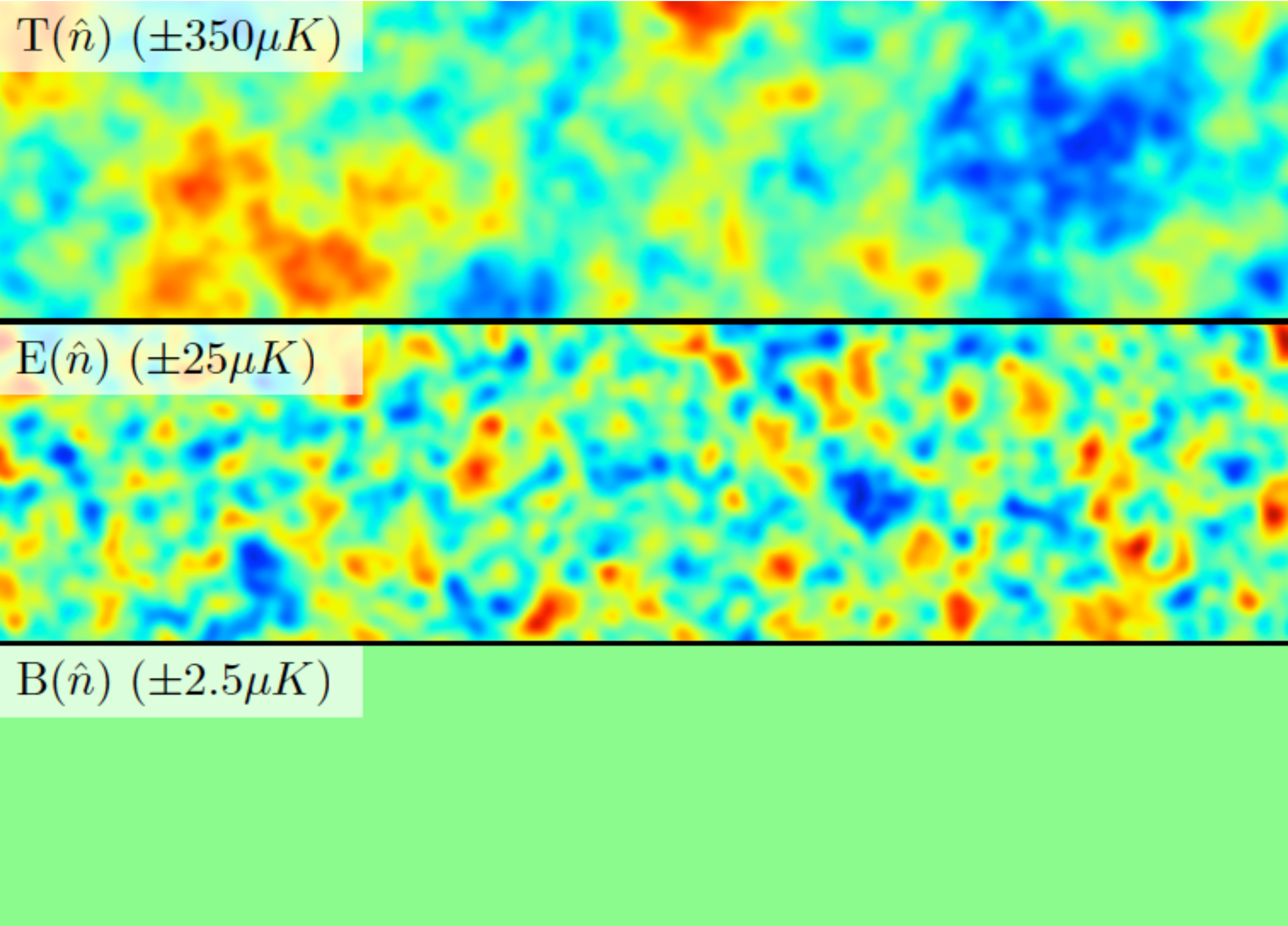
GRAVITATIONAL LENSING DISTORTS IMAGES

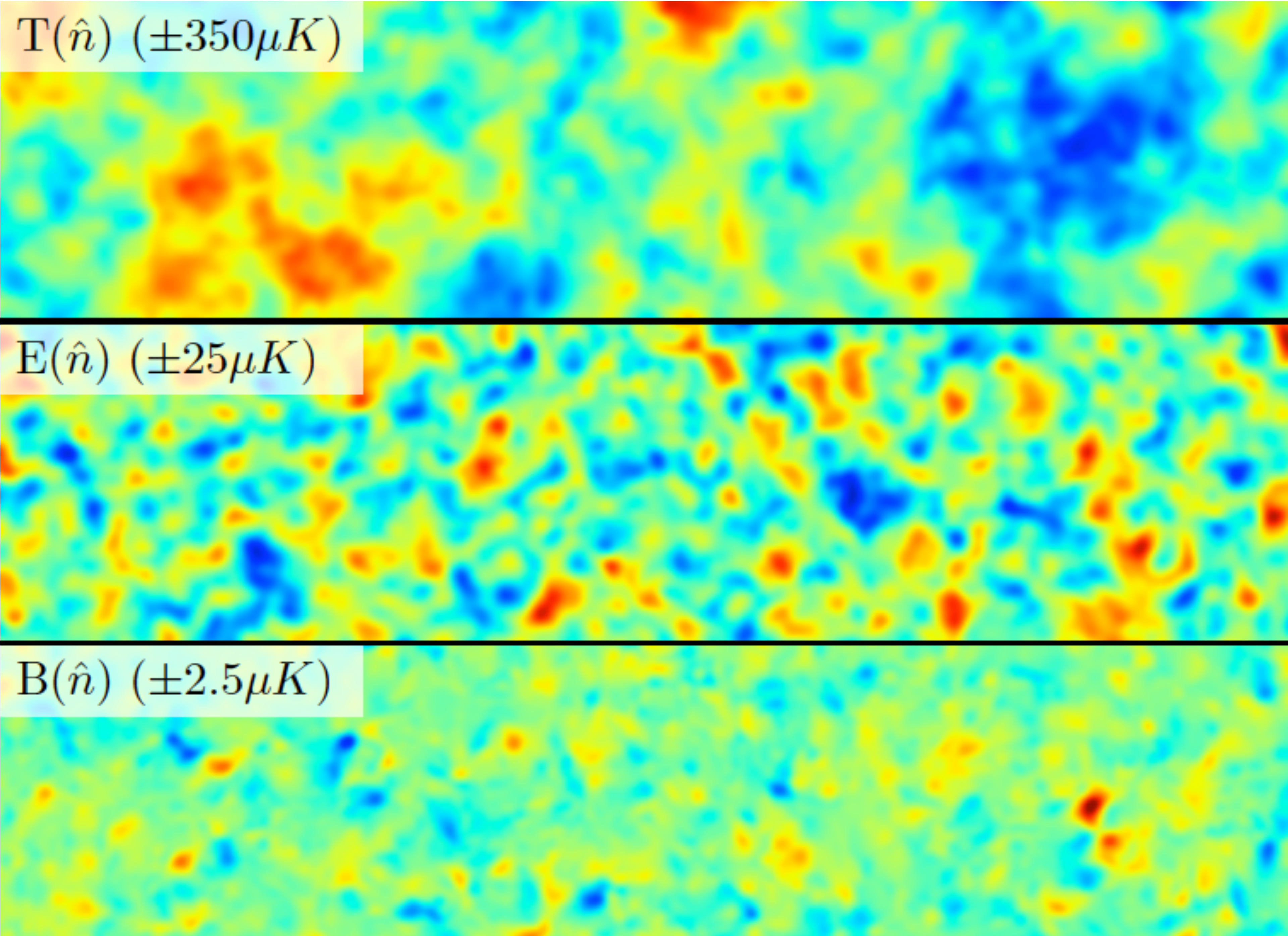
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



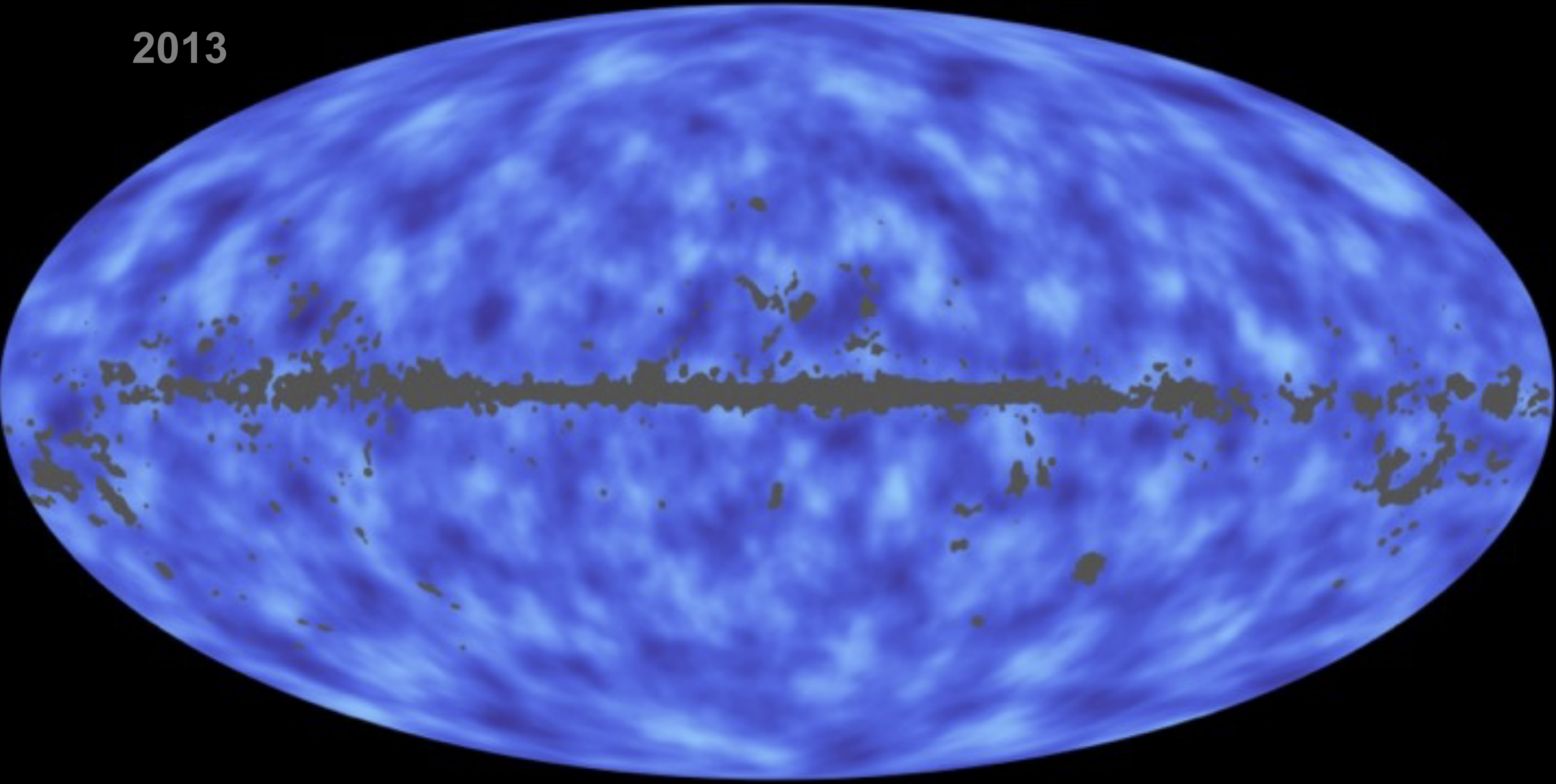
$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$

$$\bar{\phi} = \Delta^{-1}\vec{\nabla} \cdot [C^{-1}T\,\vec{\nabla}(C^{-1}T)]$$


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

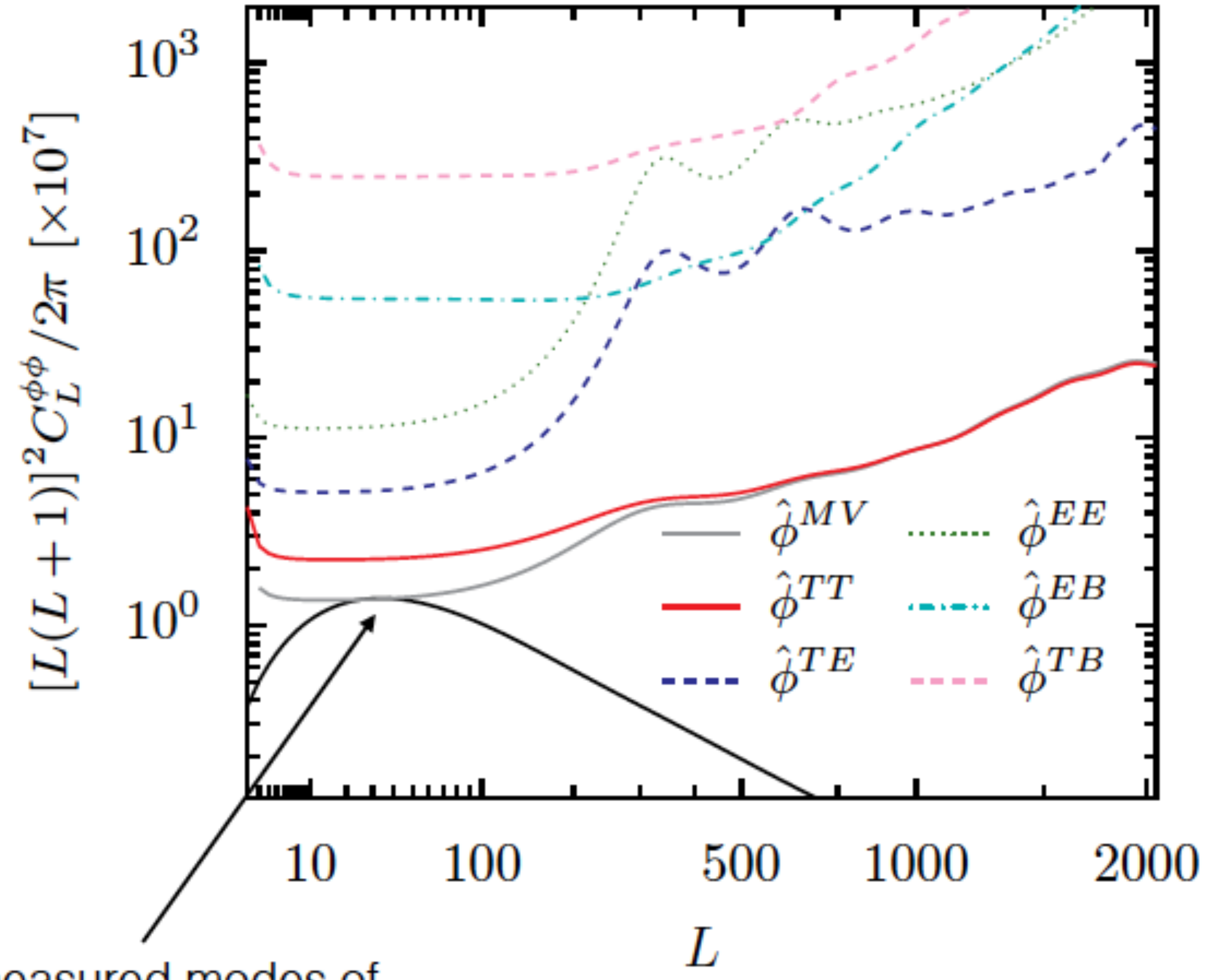

$\mathrm{T}(\hat{n})$ $(\pm 350\mu K)$
$\mathrm{E}(\hat{n})$ $(\pm 25\mu K)$
$\mathrm{B}(\hat{n})$ $(\pm 2.5\mu K)$

Projected mass map



The (grey) masked area is where foregrounds are too strong to allow an accurate reconstruction

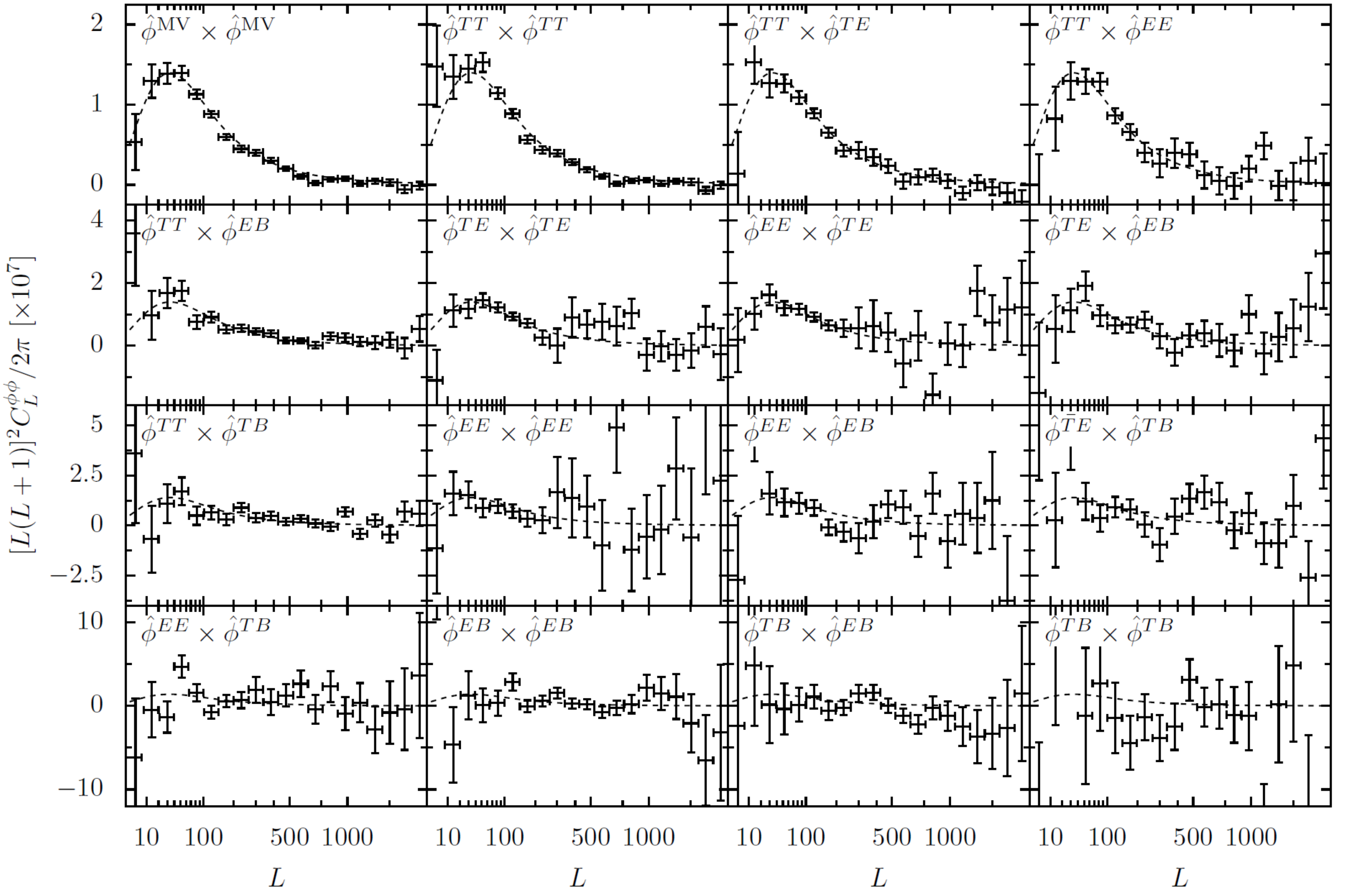
Noise power spectra for lensing estimators



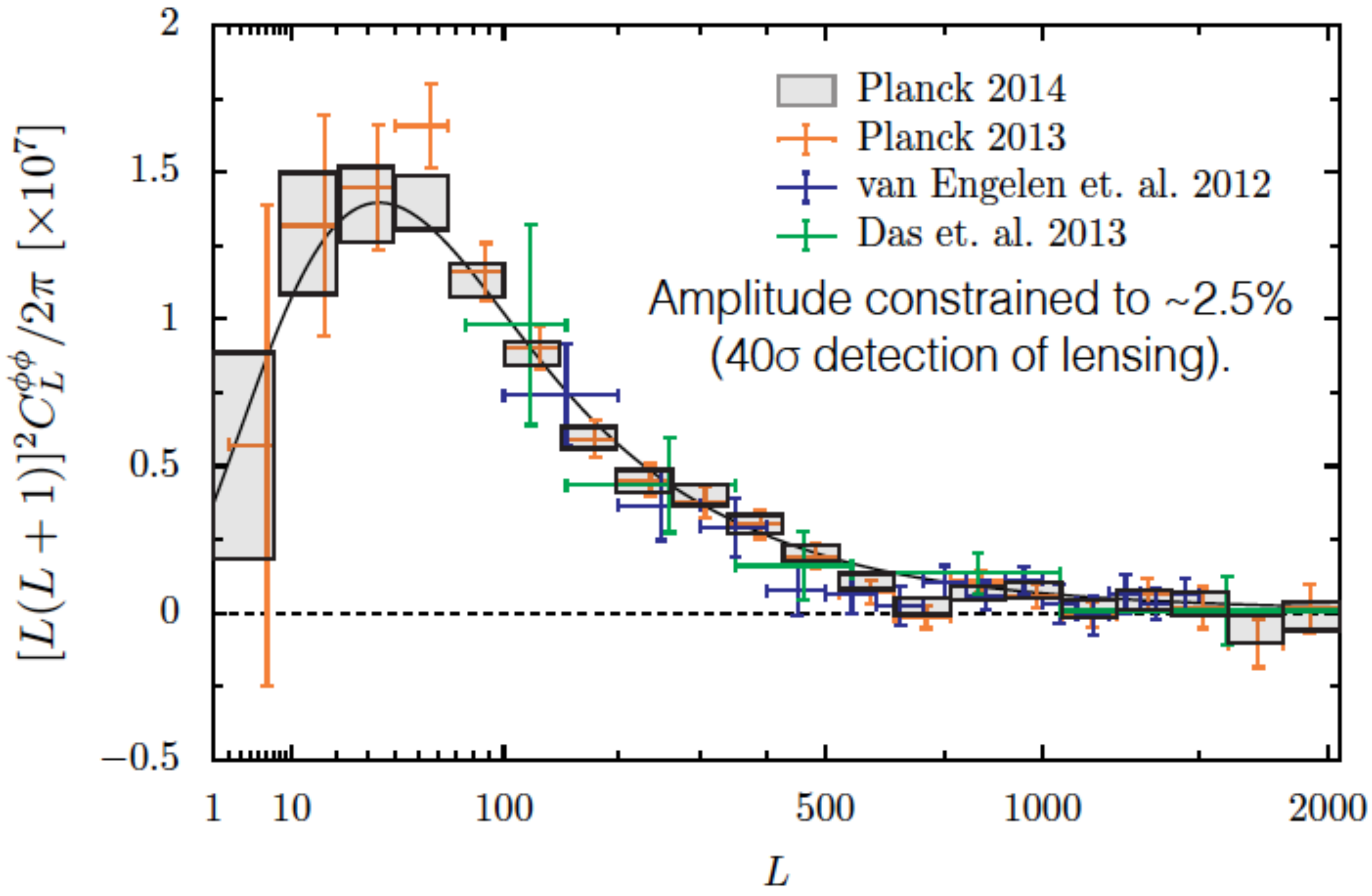
Best measured modes of
MV estimator have S/N=1.

Preliminary

Individual lensing cross-spectra

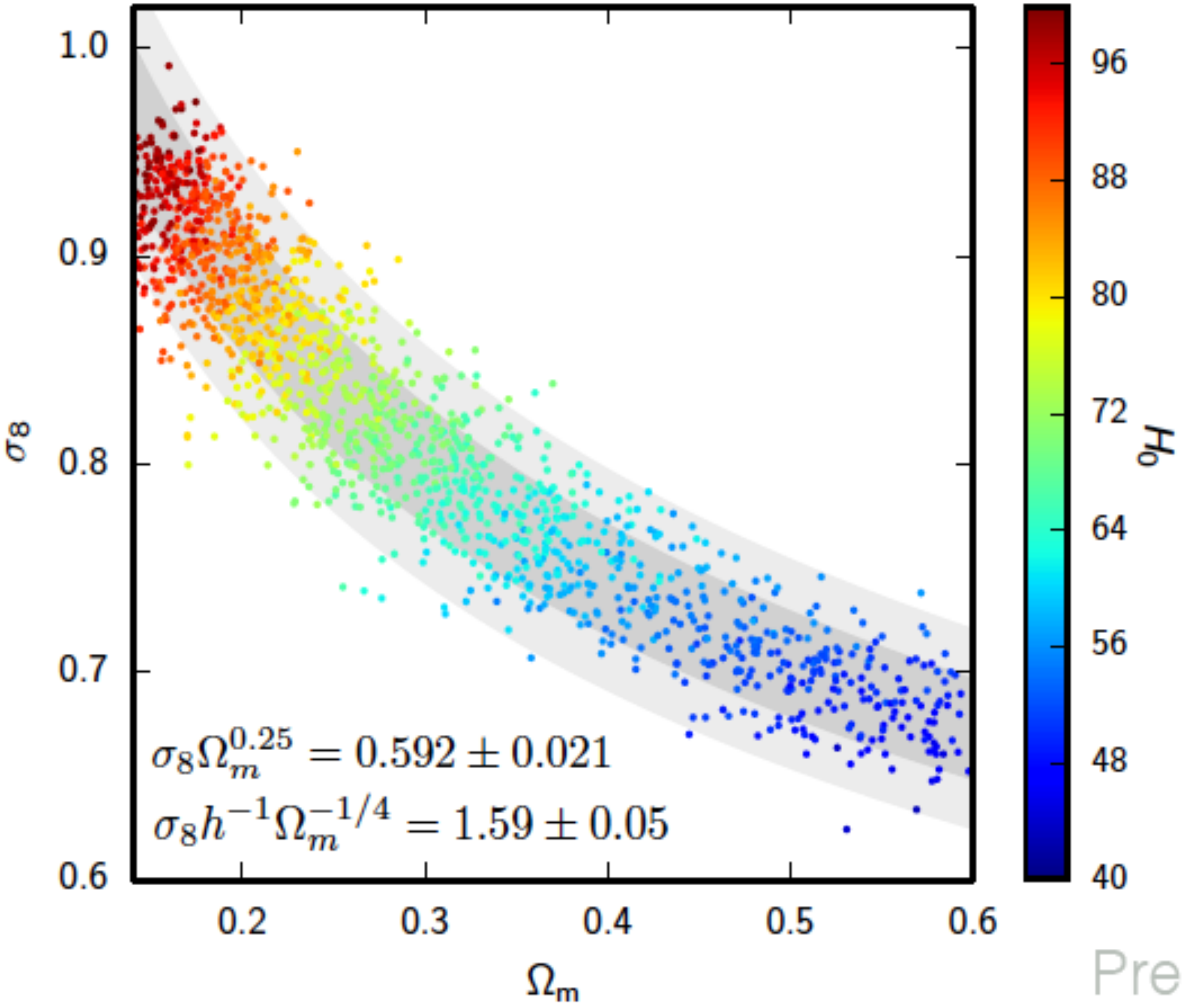


Lensing power spectrum



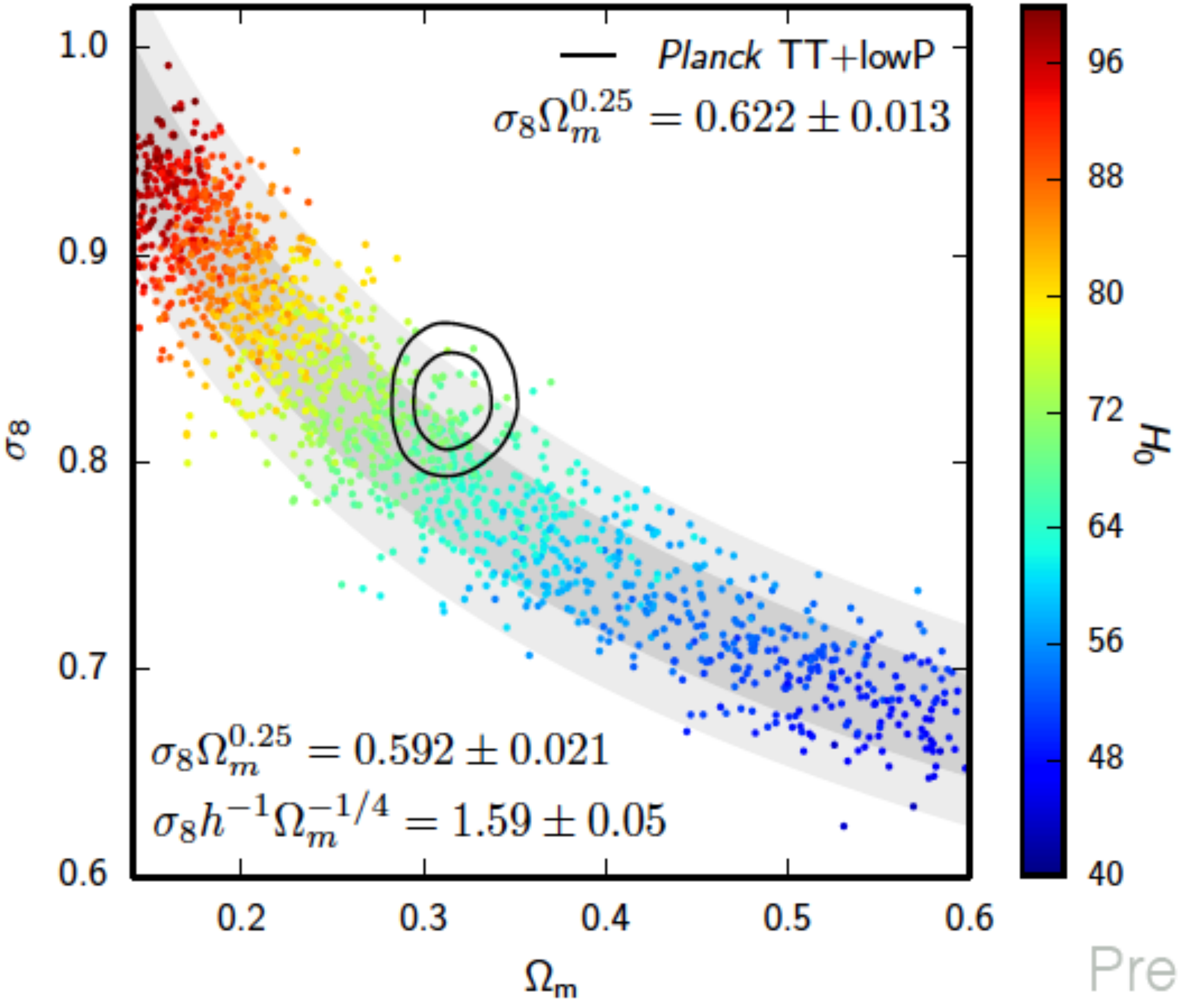
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

ΛCDM constraint from CMB Lensing only



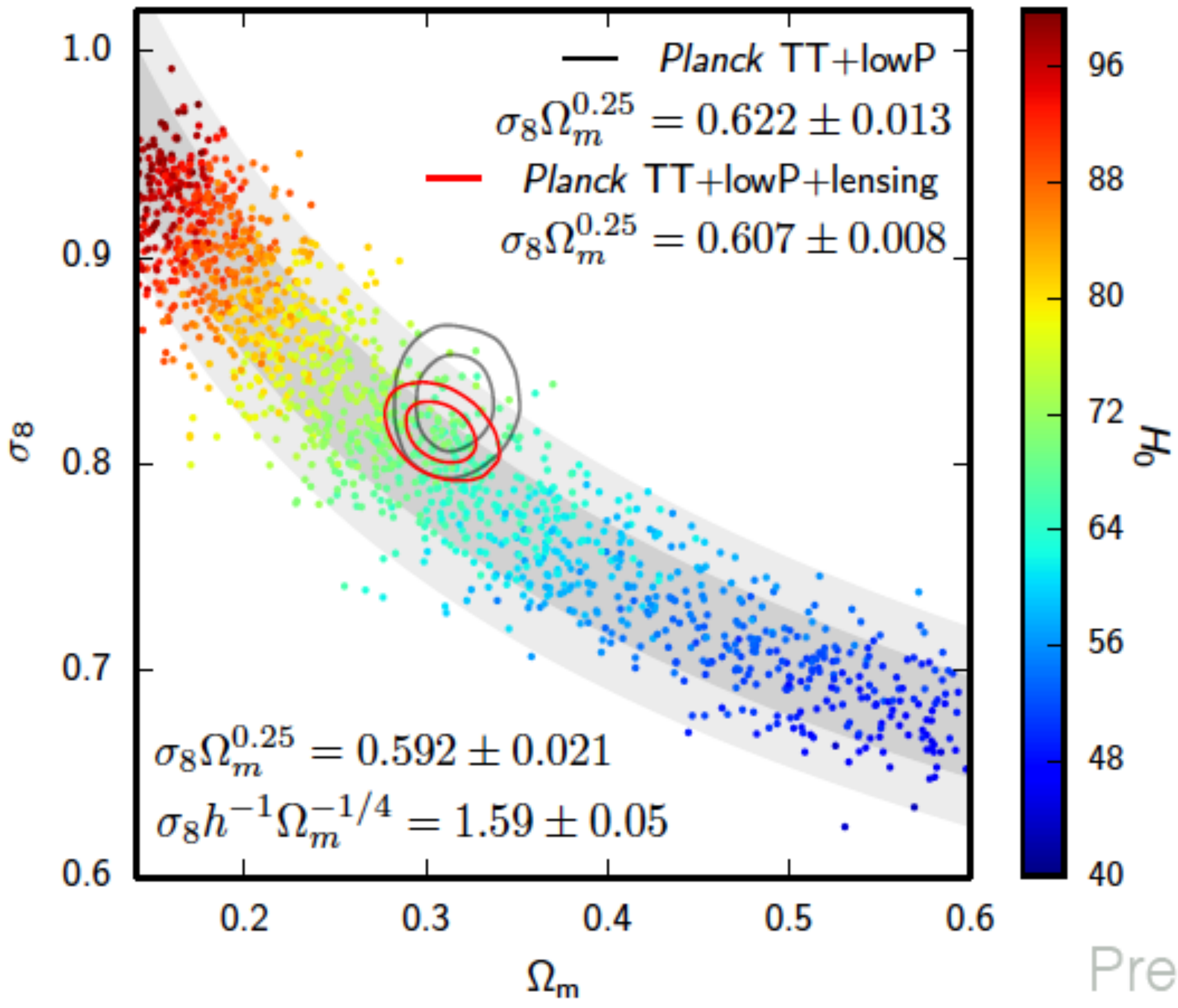
Preliminary

ΛCDM constraint from CMB Lensing only



Preliminary

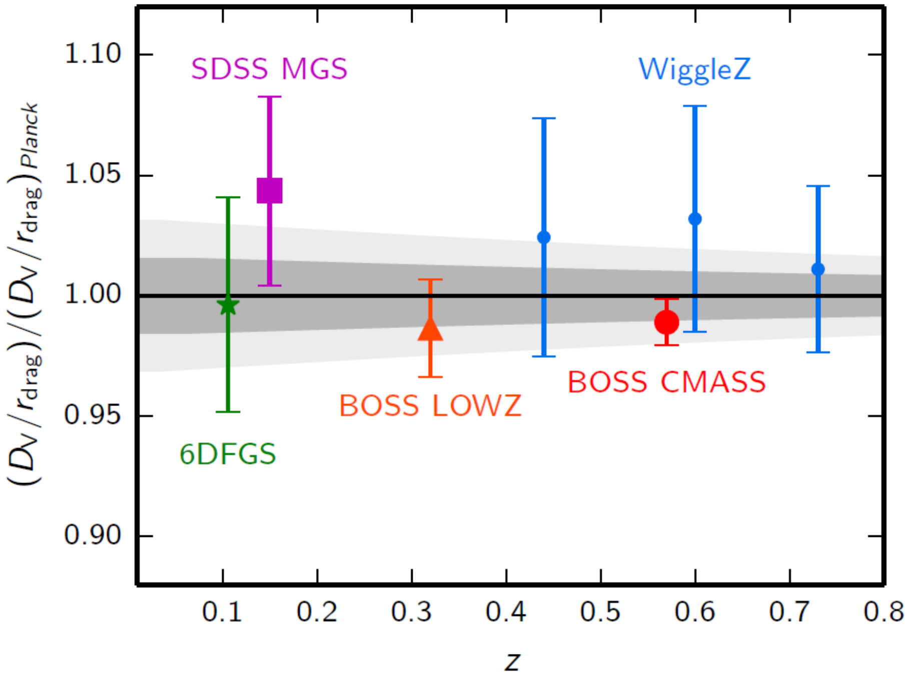
ΛCDM constraint from CMB Lensing only

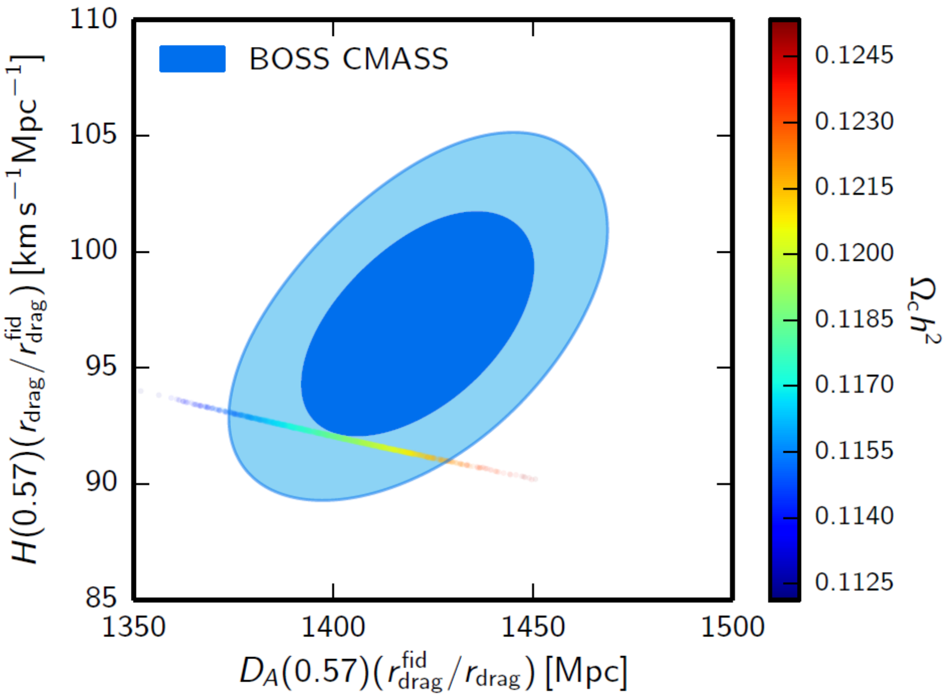


Preliminary

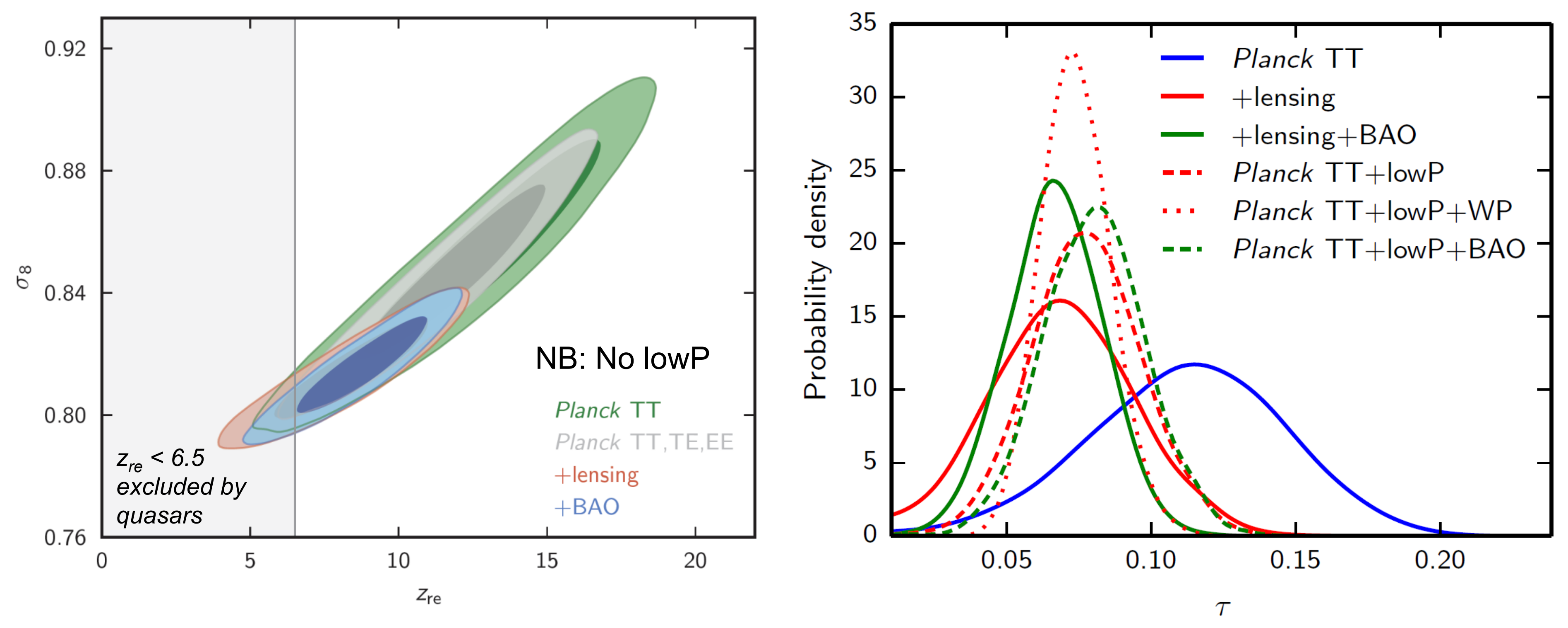
BAO

Grey band is Planck TT+LowP 1(2) sigma range





Optical depth constraints



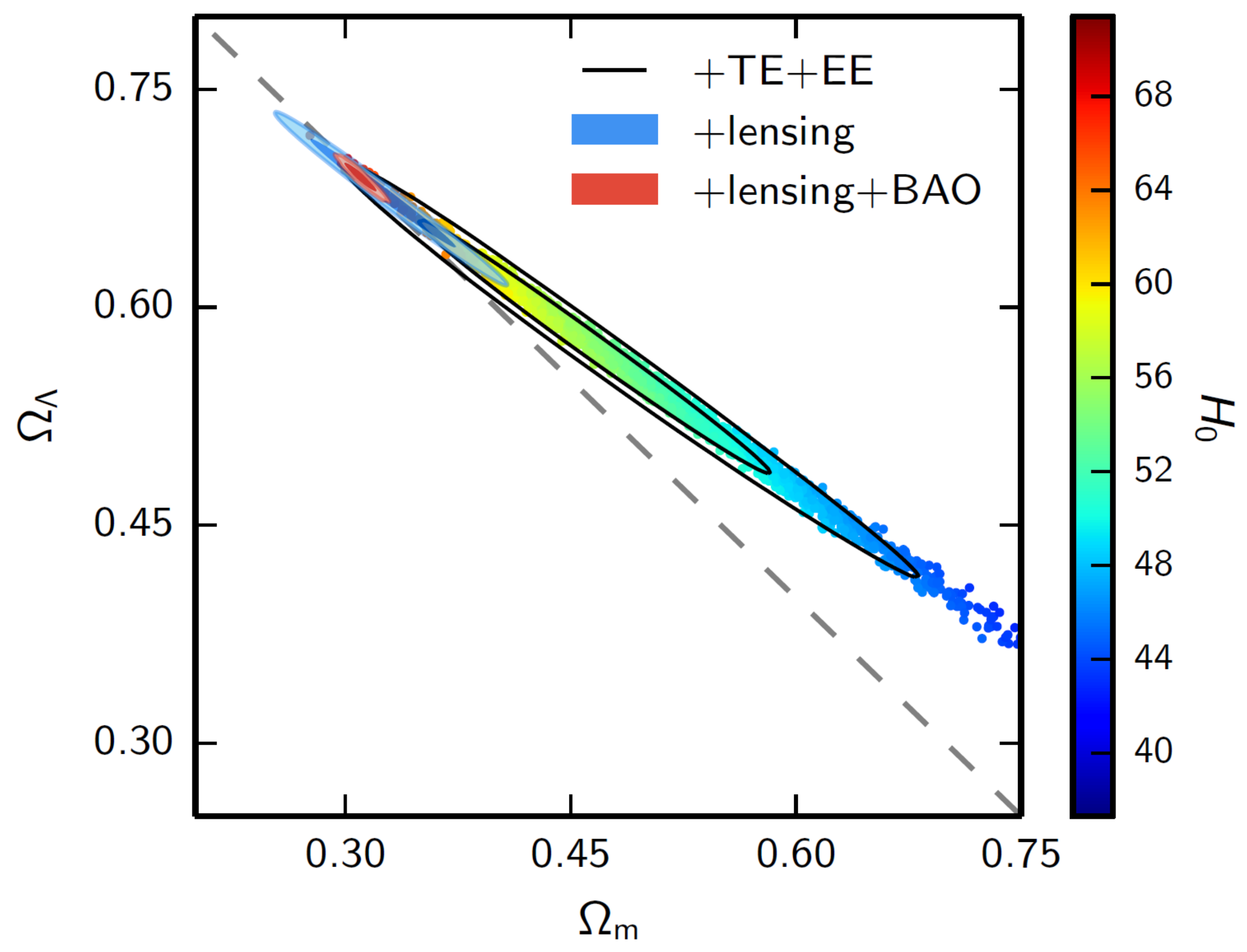
A new, independent, way to look at τ

➔Consistency of lensing versus LowP constraints on τ

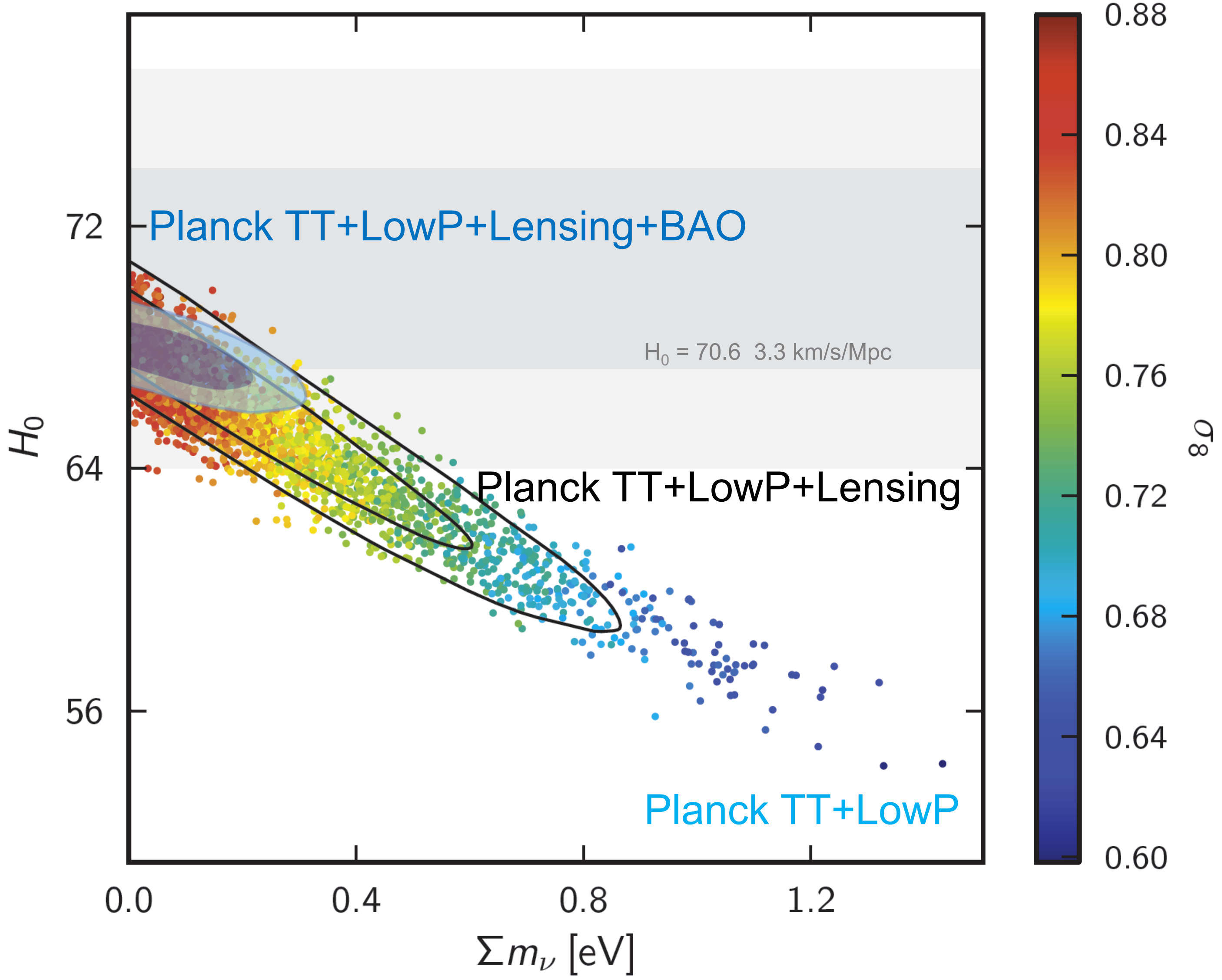
Pointing to lower values than previous WMAP based values

Spatial curvature constraint

$\Omega k = 0.000 \pm 0.005$ $(95\%\ CL)$!



Neutrinos masses $\sum m\nu < 0.23$ eV (95%)

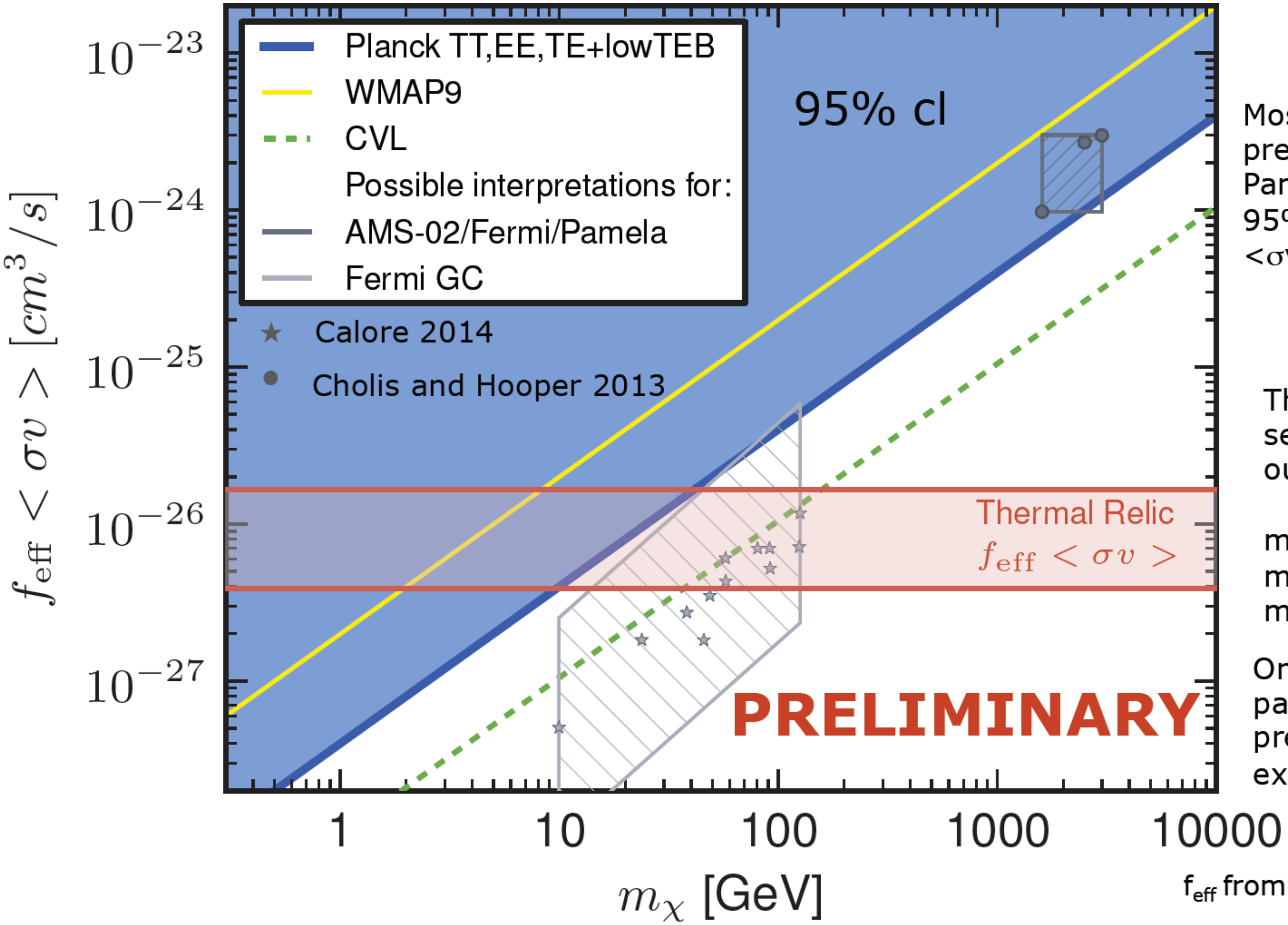


0.23eV is from TT+lowP +lensing +ext

➔ $\Omega\nu h^2 < 0.0025$

(slight tightening with TE & EE)

Planck 2014 Constraints



Most of parameter space preferred by AMS-02/ Pamela/Fermi ruled out at 95%, under the assumption <σv>(z=100)=<σv>(z=0)

Thermal Relic cross sections at z~1000 ruled out for:

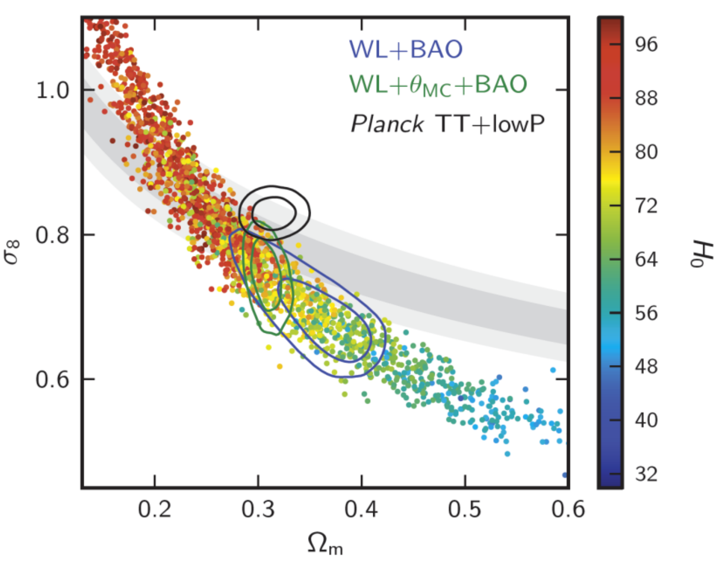
m~<40GeV (e^-e^+)
m~<20GeV ($\mu^+\mu^-$)
m~<10 GeV ($\tau^+\tau^-$).

Only a small part of the parameter space preferred by Fermi GC is excluded

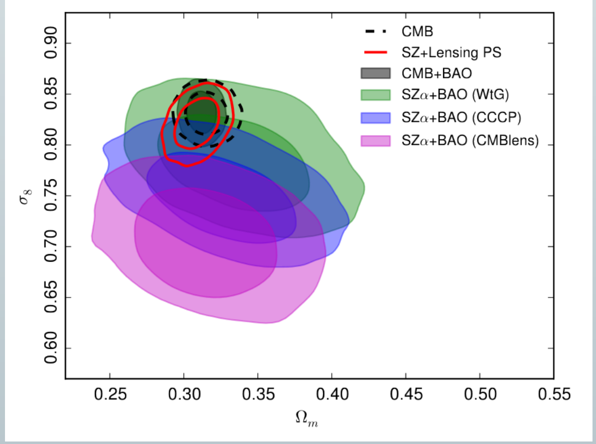
$f_{\rm eff}$ from T. Slatyer (Madhavacheril 2013

Some tensions

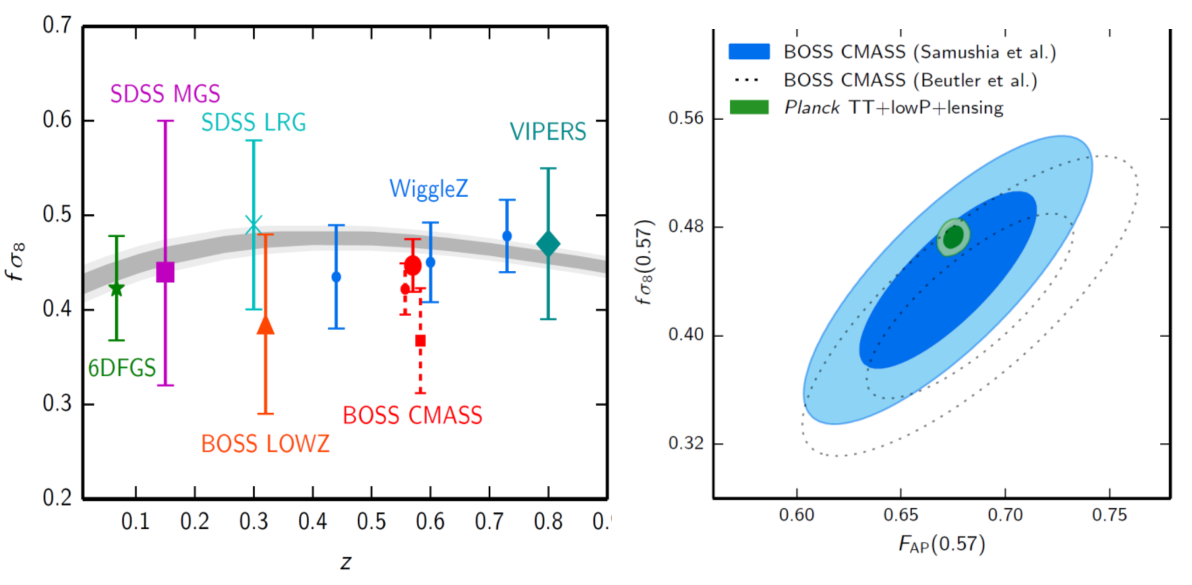
WL from CFHTLens



Number counts
of SZ clusters



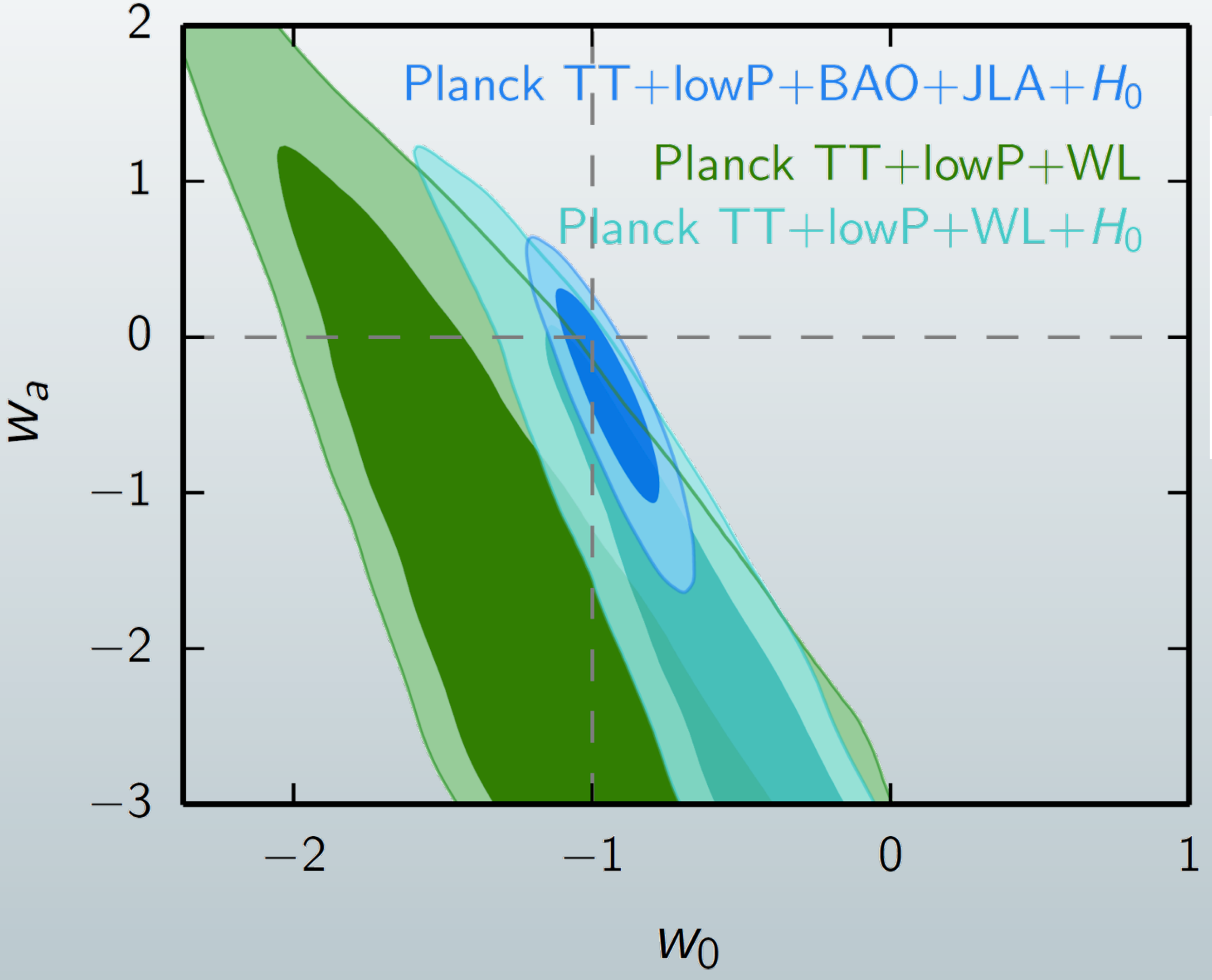
Growth rate of fluctuations from redshift space distortions



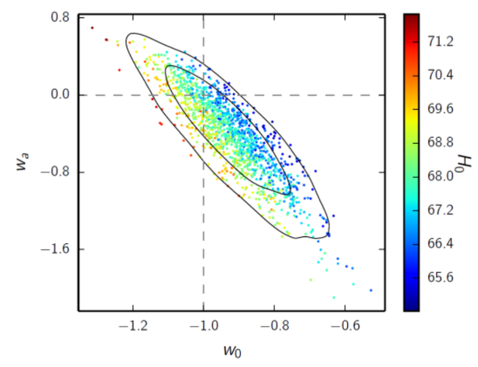
i.e. some tensions with astrophysical measurements of the amplitude of matter fluctuations (at low z)

What these tensions can do…

$$W(a) = w_0 + (1-a)\, w_a$$



Ref.



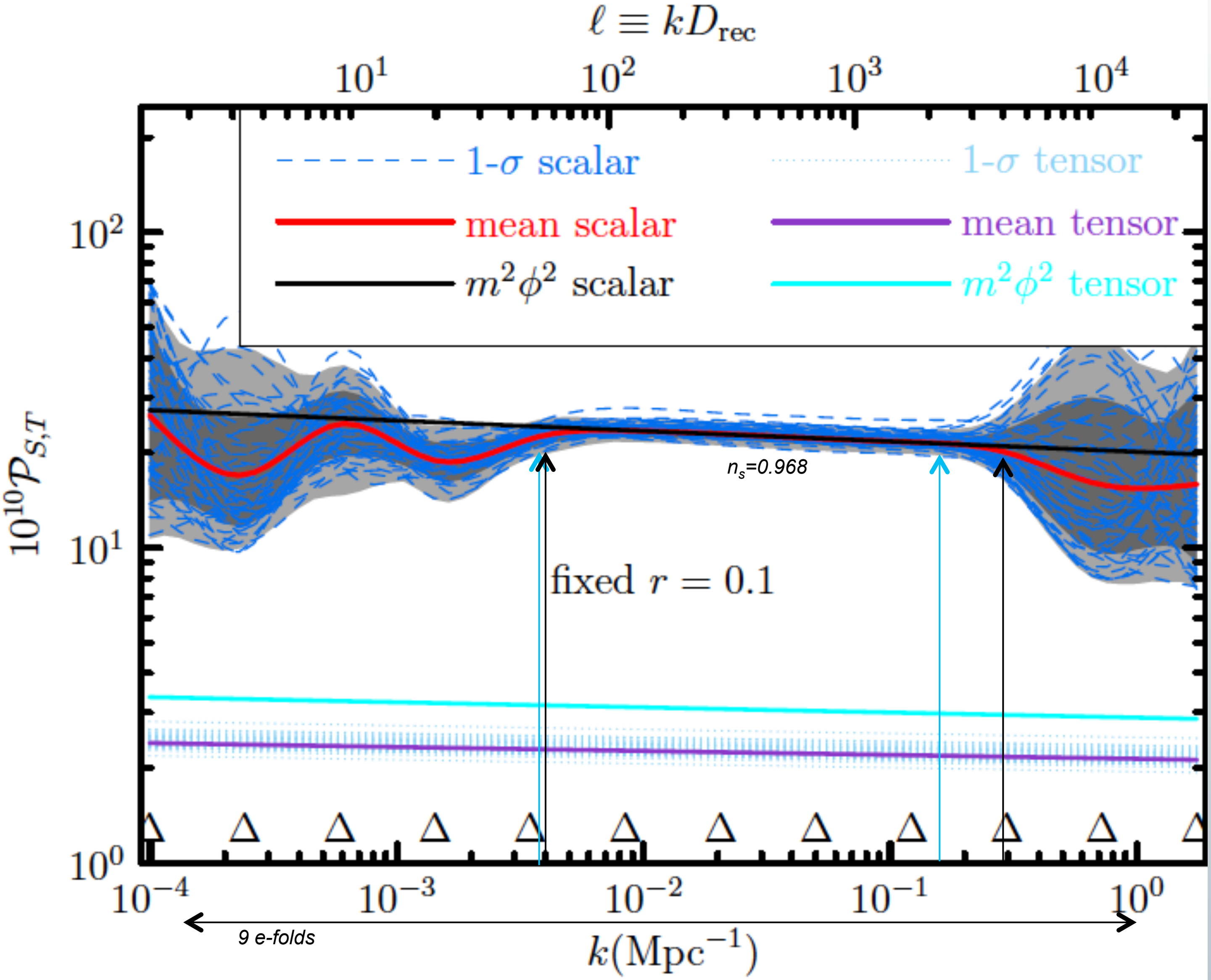
Power spectra reconstruction

2015

TT+lowP

+BAO+JLA

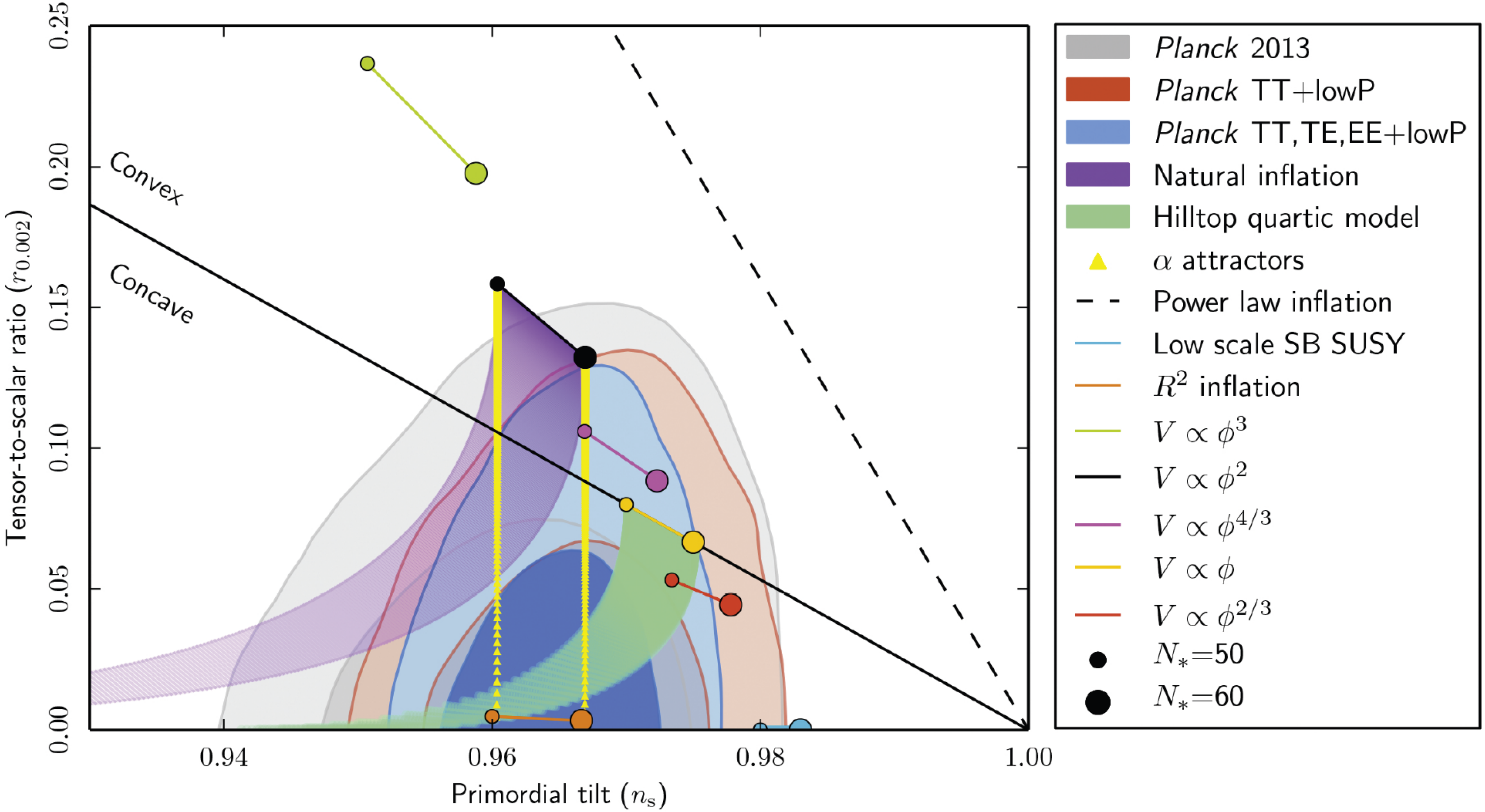
+Hlow



12-knot power spectra

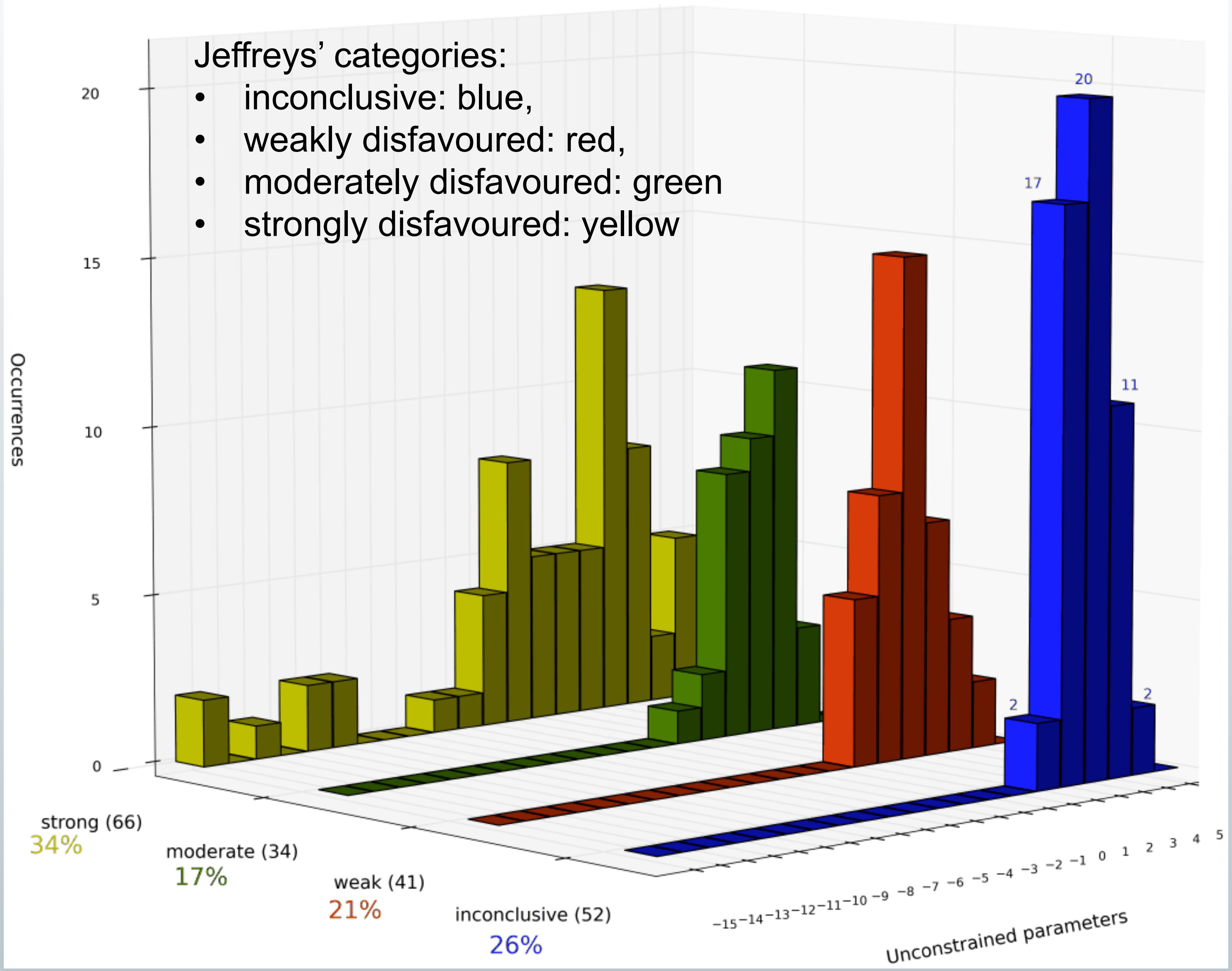
Data sets in common: lowP + BAO + SN + HST + zre > 6 prior.

Planck 2015: n_s vs r



Similar (indirect) r constraint than with 2013 release ($r_{0.002} < 0.10$ @ 95% CL vs 0.11)

Single field slow-roll models


Jeffreys' categories:

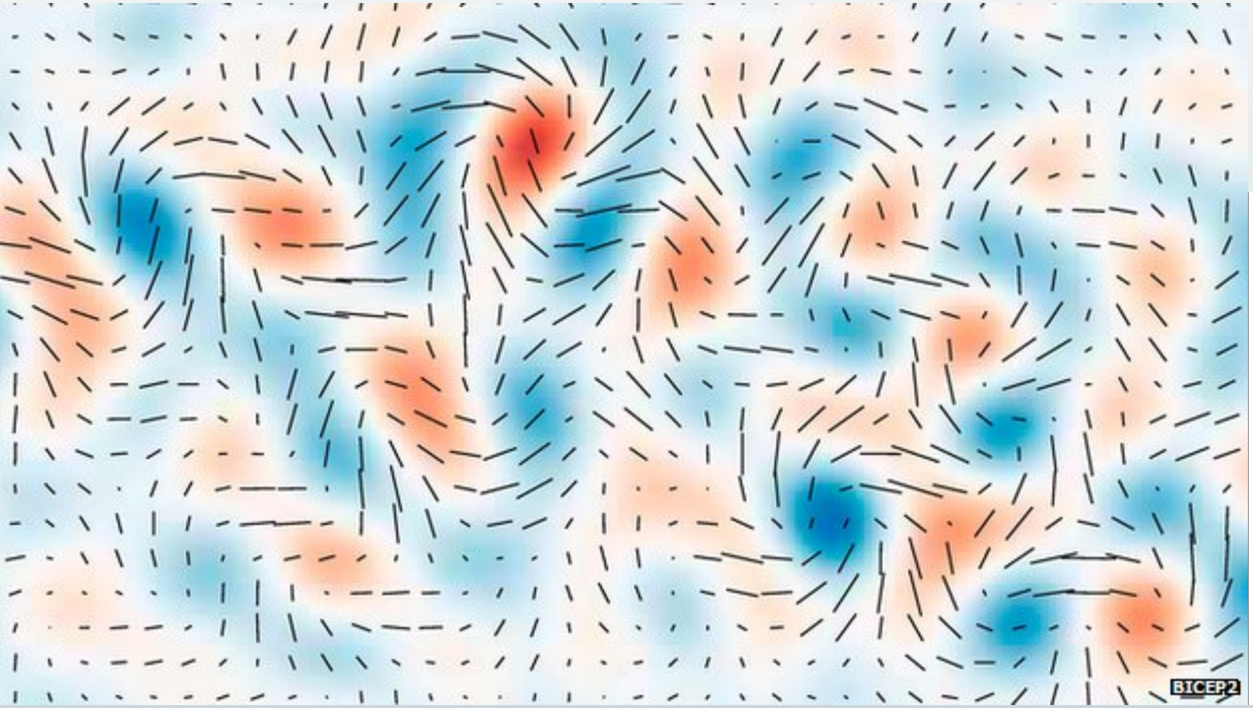
- inconclusive: blue,
- weakly disfavoured: red,
- moderately disfavoured: green
- strongly disfavoured: yellow

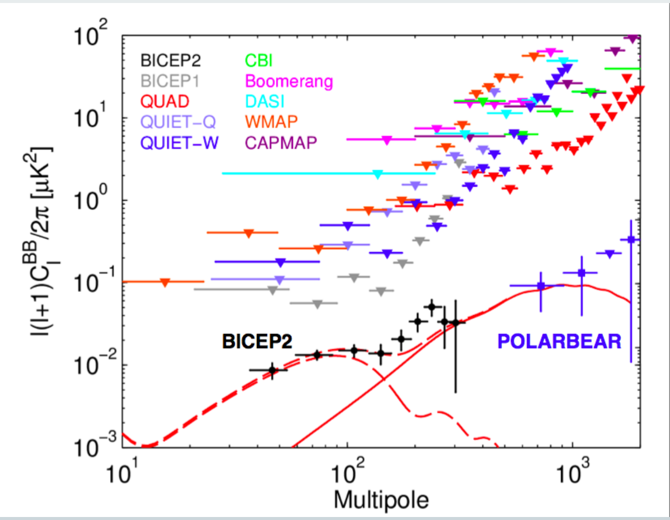
archiv/1303.3787

"models" include different priors

BICEP2

March 17th 2014

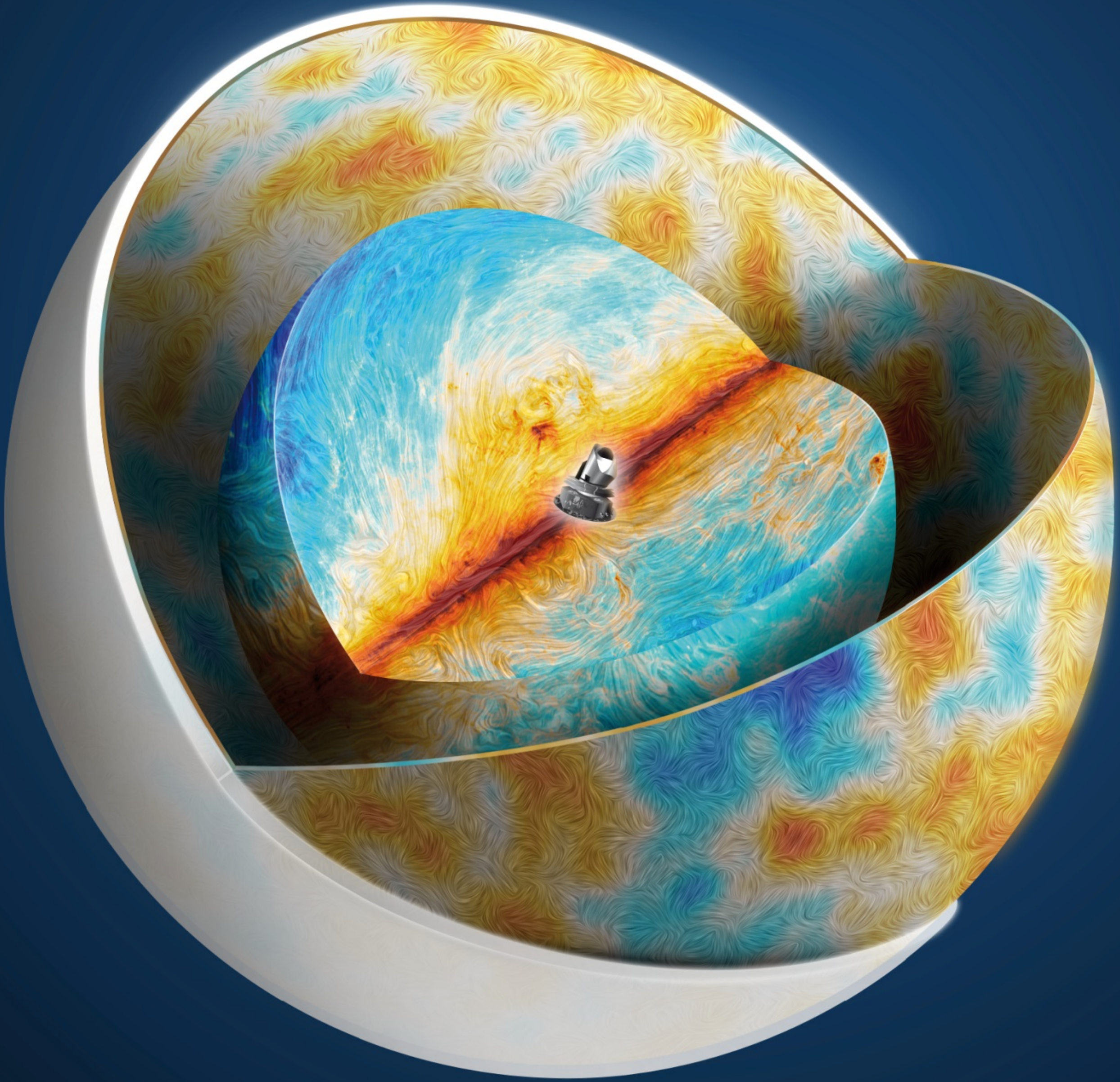




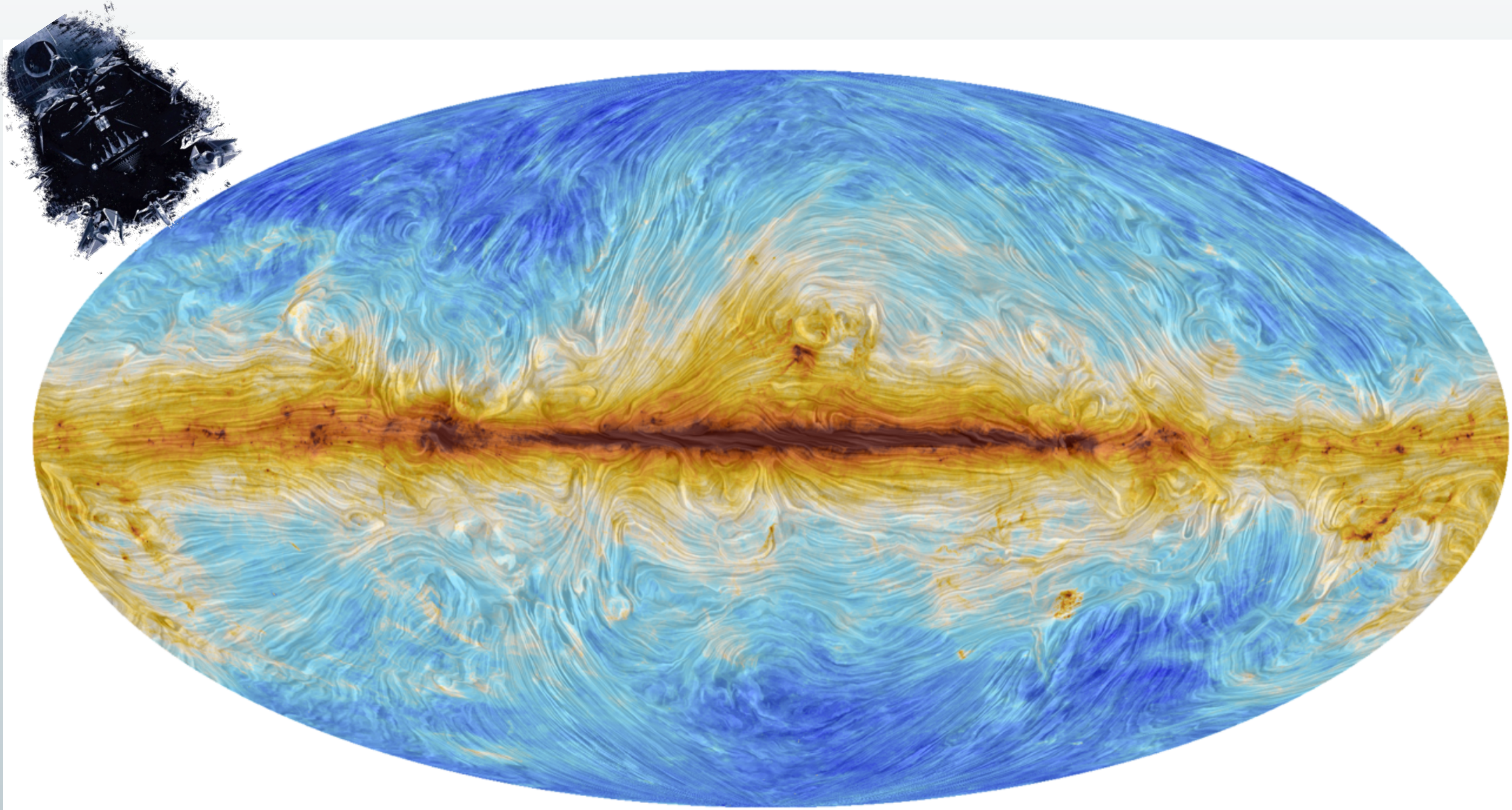
The world of physics is taken aback by an extraordinary result from a beautiful experiment:

The search for primordial gravitationnal waves is over.

It is r=0.2 and it is 5 sigma!

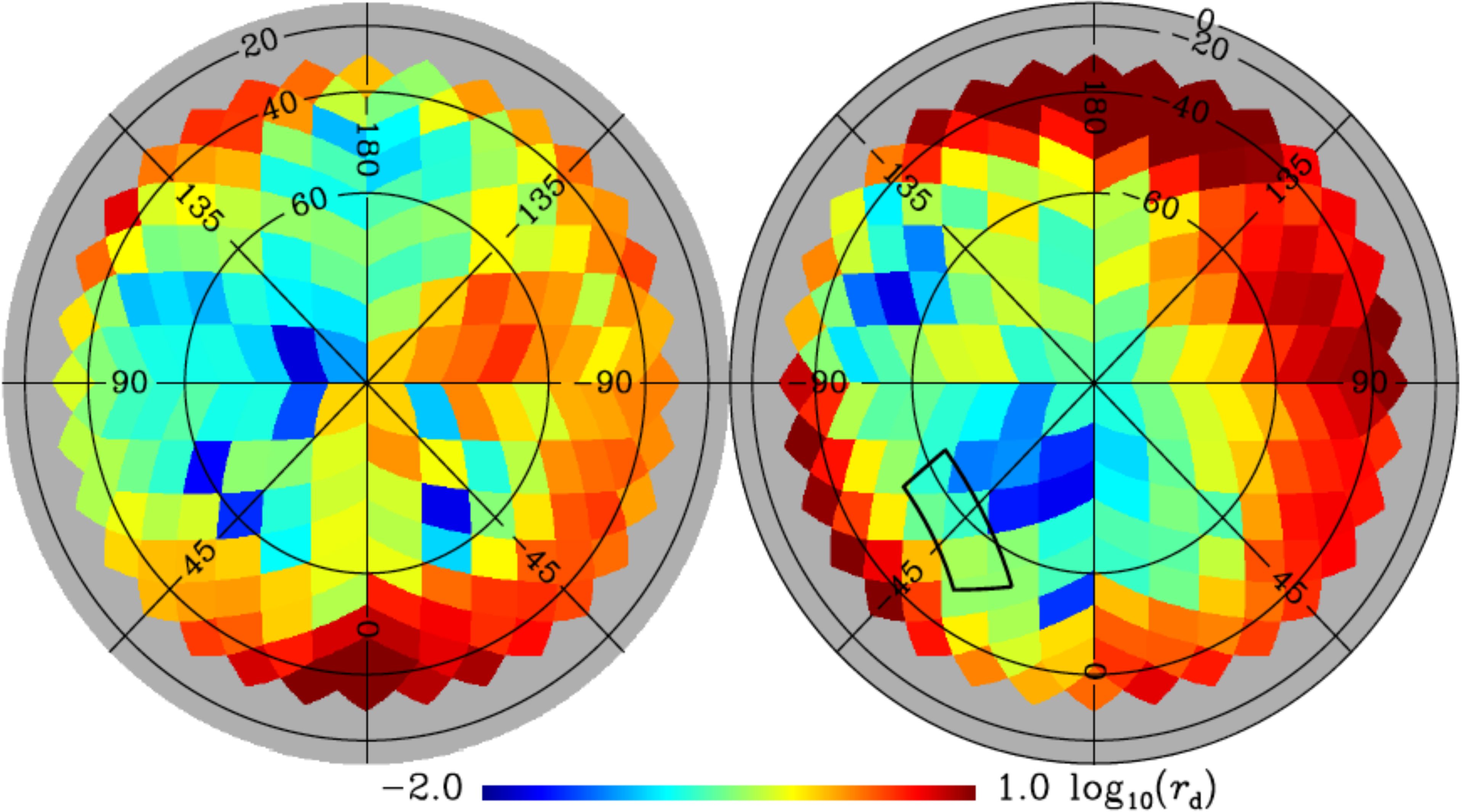


353GHz reveals the Galactic magnetic field



Dust extrapolation at 150GHz in unit of r

Sept 2015

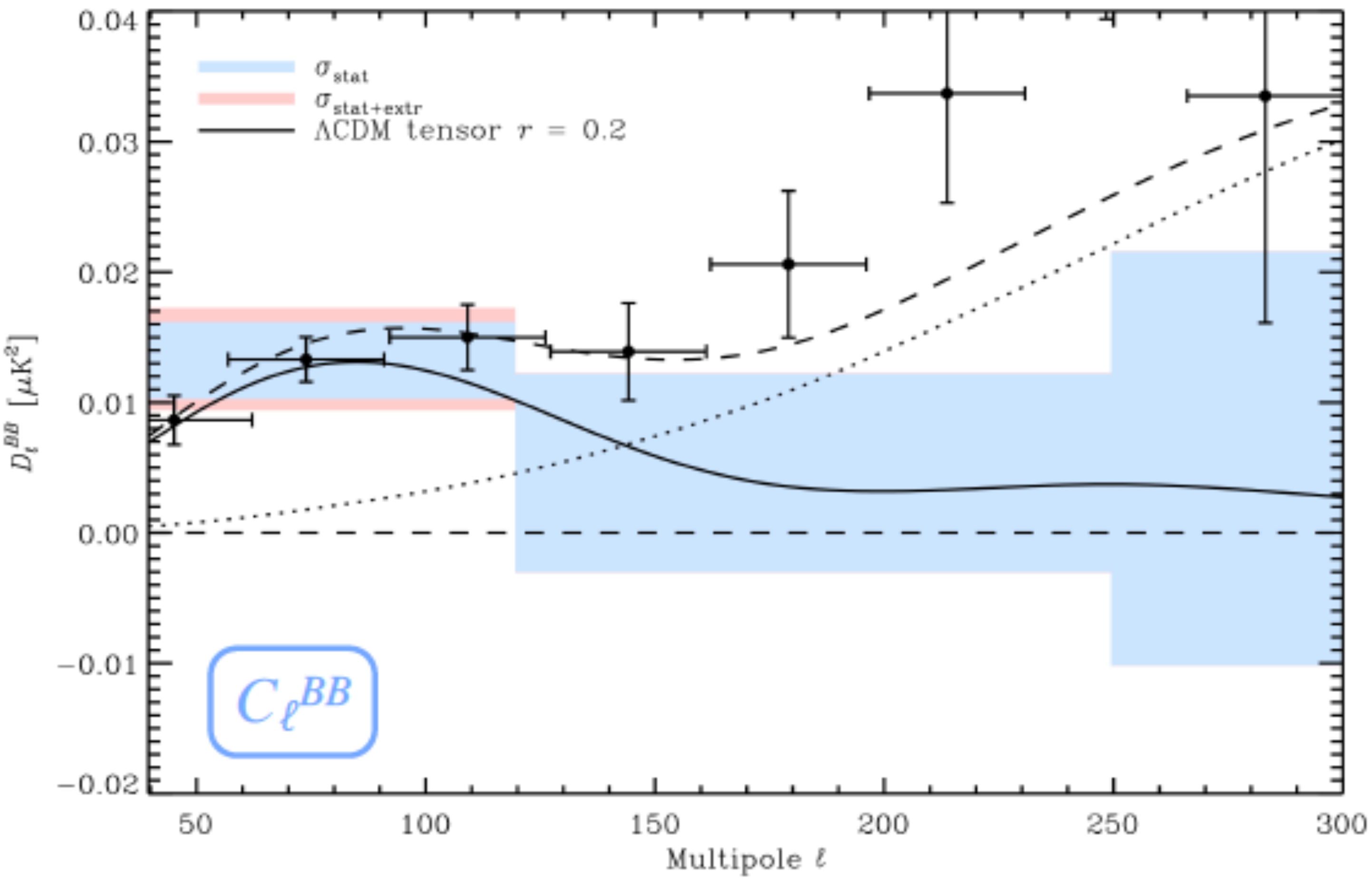


Measurement of the dust in the BICEP2 field

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

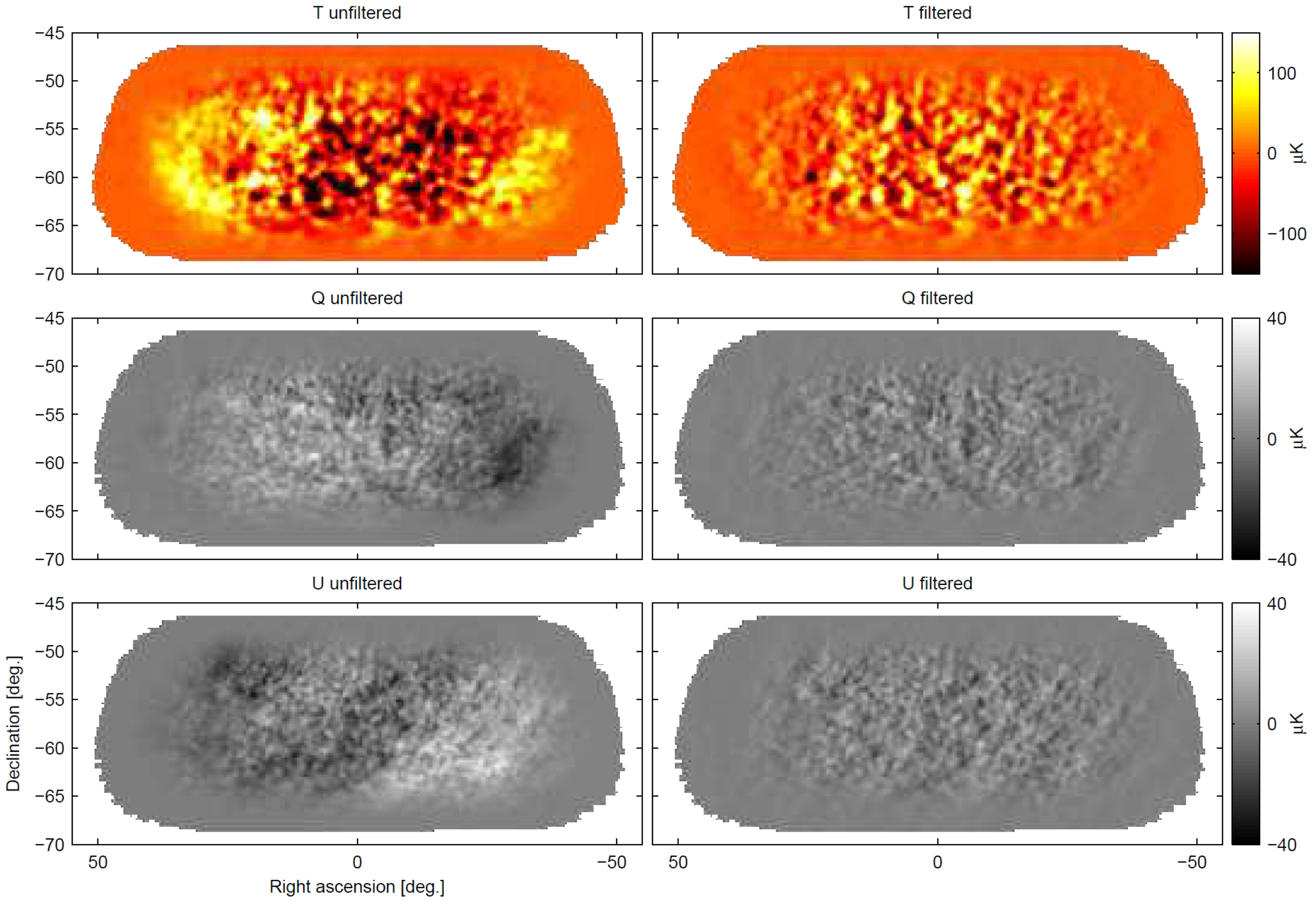
[Planck Intermediate XXX 2014, arXiv 1409.5738]

[BICEP2 Collaboration 2014]



- ★ 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

Planck-HFI 353GHz “a la Bicep2”



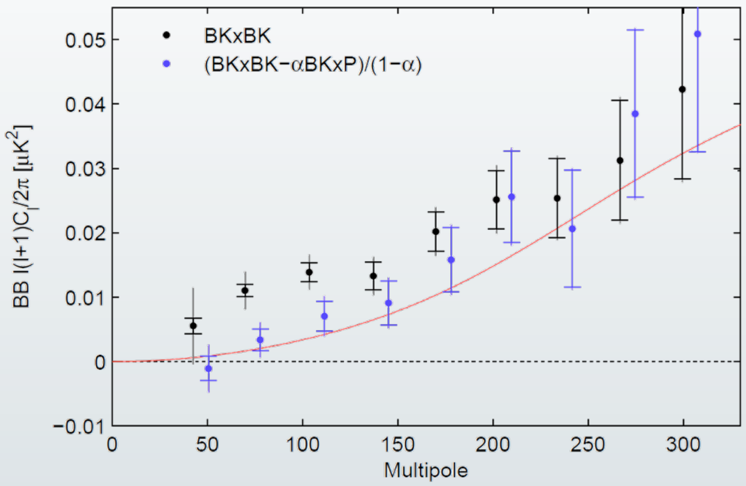
Planck X (Bicep2 & Keck)

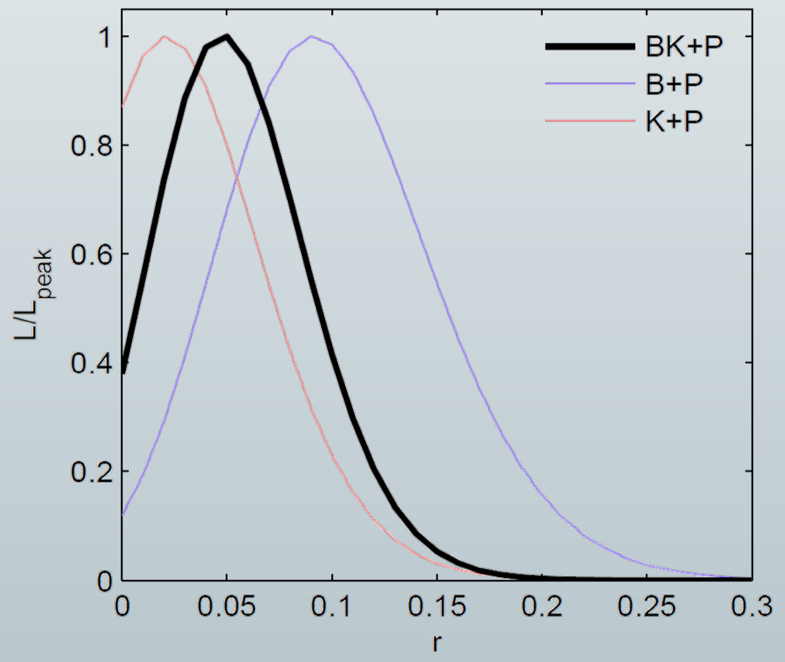
- Since January 30th 2015, the **direct** constraints on r (Planck X Bicep2 & Keck) have reached the level of the previous best **indirect constraints** (from Planck alone T), i.e.

- r < 0.11 @ 95%CL

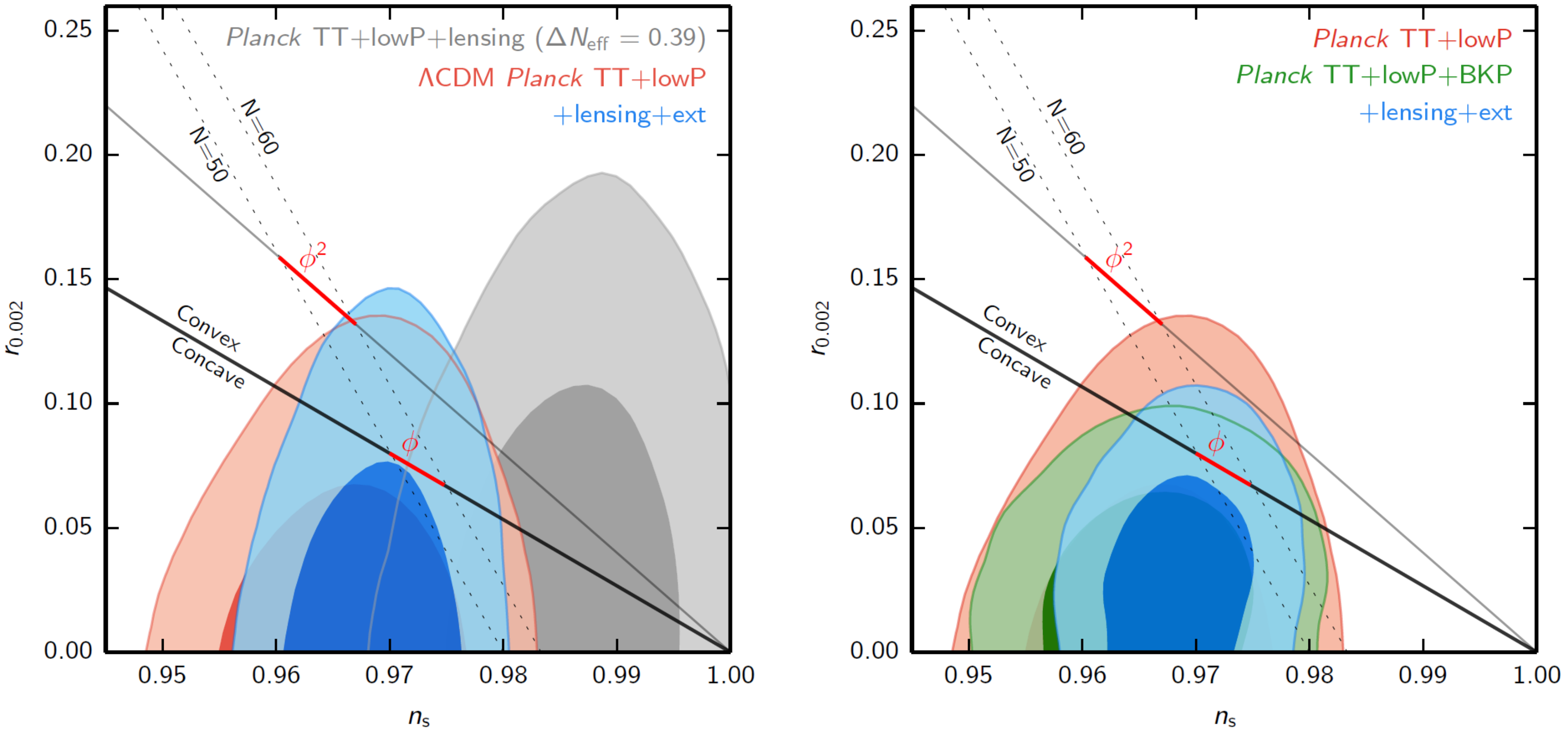
  (r =A_s/A_T à, e.g., k=0.05Mpc^{-1})

- A new era began…





Tensor to scalar ratio, r & BKP

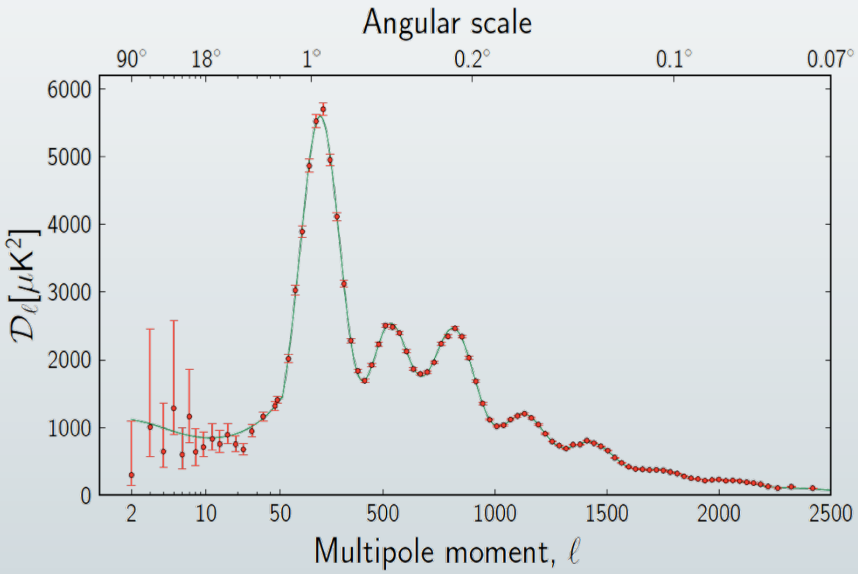


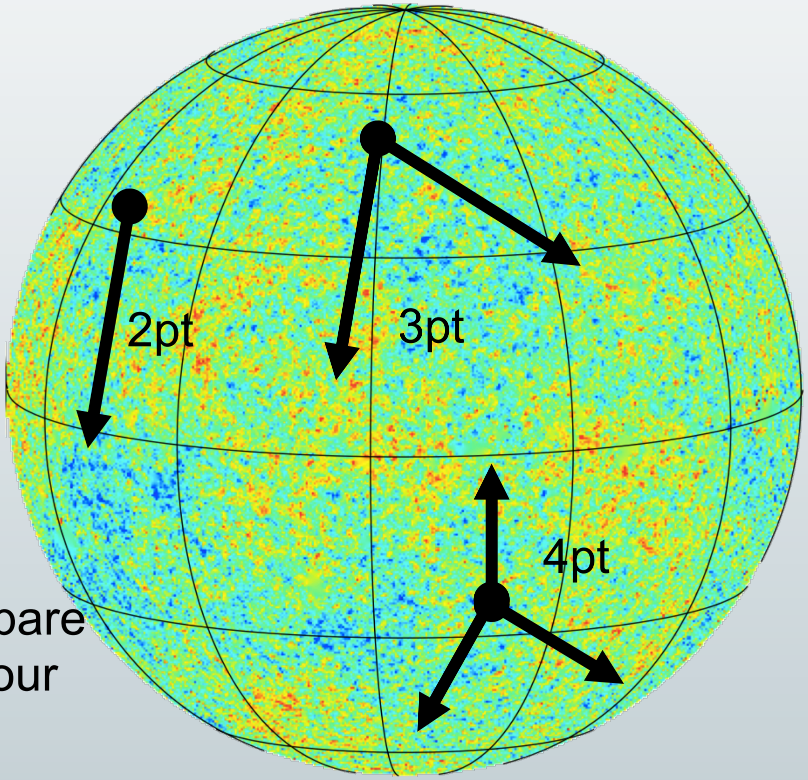
$r_{0.002} < 0.10$ @ 95%CL,
Planck TT+lowP+lensing+ext
NB: $\Delta N_{\rm eff}$=0.39 is disfavoured, but not excluded by Planck

$r_{0.002} < 0.09$ @ 95%CL,
Planck TT+lowP+lensing+ext+BKP
NB: $r_{0.002} < 0.11$ in Planck 2013
$\Leftrightarrow r_{0.05} < 0.12$ BKP 2015

Random field characterisation

The angular power spectrum compares two points separated by **one** angle





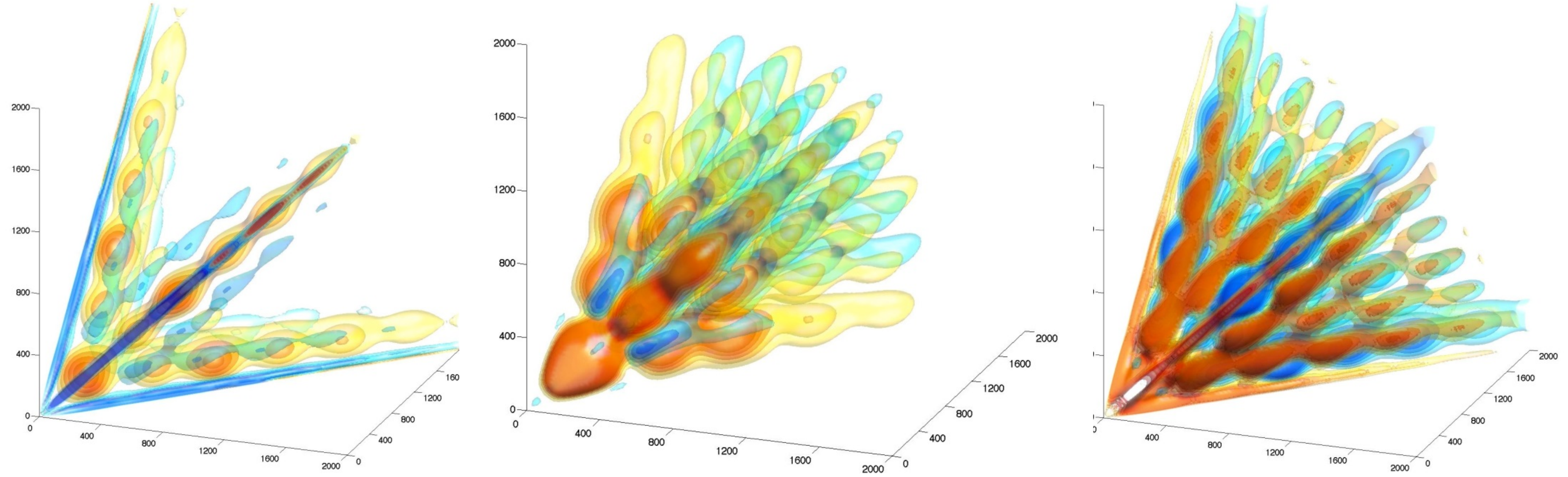
To assess non Gaussianity, one must compare fluctuations in three points (bi-spectrum), four point (tri-spectrum), etc.

Need **three** numbers to characterize a triangle

One origin of four point signal comes from lensing by Large Scale Structures.

CMB bispectrum fingerprinting with Planck

LEO (Local, Equilateral, Orthogonal) are common outputs



NG of ***local*** type ($k_1 \;\; k_2 \sim k_3$):

- Multi-field models
- Curvaton
- Ekpyrotic/cyclic models

(Also NG of **Folded** type

- Non Bunch-Davis
- Higher derivative)

NG of ***equilateral*** type ($k_1 \sim k_2 \sim k_3$):

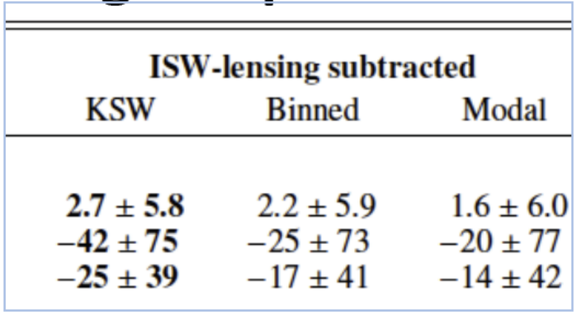
- Non-canonical kinetic term
  - K-inflation
  - DBI inflation
- Higher-derivate terms in Lagrangian
  - Ghost inflation
- Effective field theory

NG of ***orthogonal*** type ($k_1 \sim 2k_2 \sim 2k_3$) :

- Distinguishes between different variants of
  - Non-canonical kinetic term
  - Higher derivative interactions
- Galileon inflation

Planck 2013 headlines

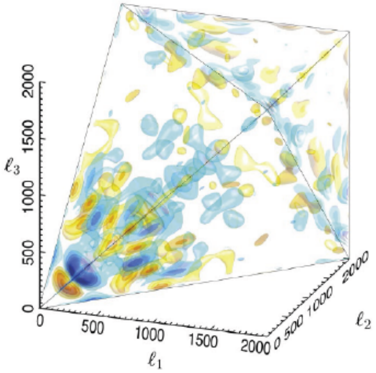
- **Tightest constraints on primordial non-Gaussianity so far: the highest precision test on the origin of cosmic structure**

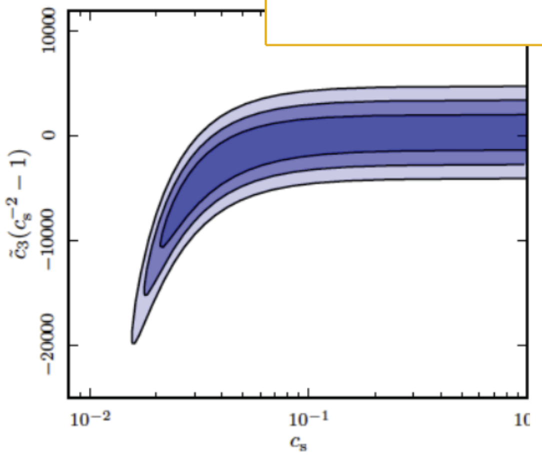


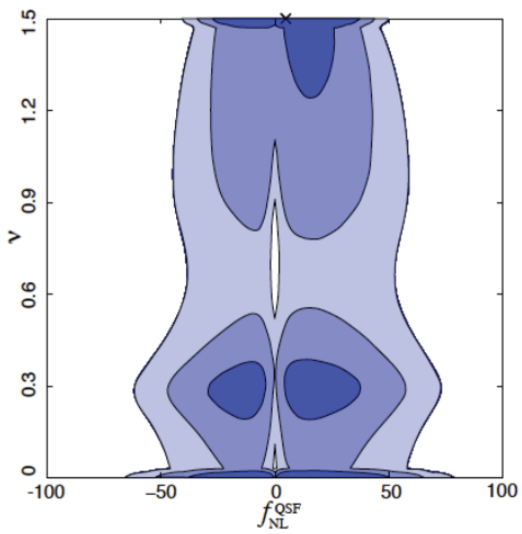
ISW-lensing subtracted		
KSW	Binned	Modal
2.7 ± 5.8	2.2 ± 5.9	1.6 ± 6.0
−42 ± 75	−25 ± 73	−20 ± 77
−25 ± 39	−17 ± 41	−14 ± 42

$$S = \int d^4x \sqrt{-g}\Big[-\frac{M_{\rm Pl}^2 \dot{H}}{c_s^2}\Big(\dot{\pi}^2 - c_s^2\frac{(\partial_i\pi)^2}{a^2}\Big) - M_{\rm Pl}^2\dot{H}(1-c_s^{-2})\dot{\pi}\frac{(\partial_i\pi)^2}{a^2} + \Big(M_{\rm Pl}^2\dot{H}(1-c_s^{-2}) - \frac{4}{3}M_3^4\Big)\dot{\pi}^3\Big]$$

- **Consistent with a Gaussian Universe**
- Some hints of oscillatory features

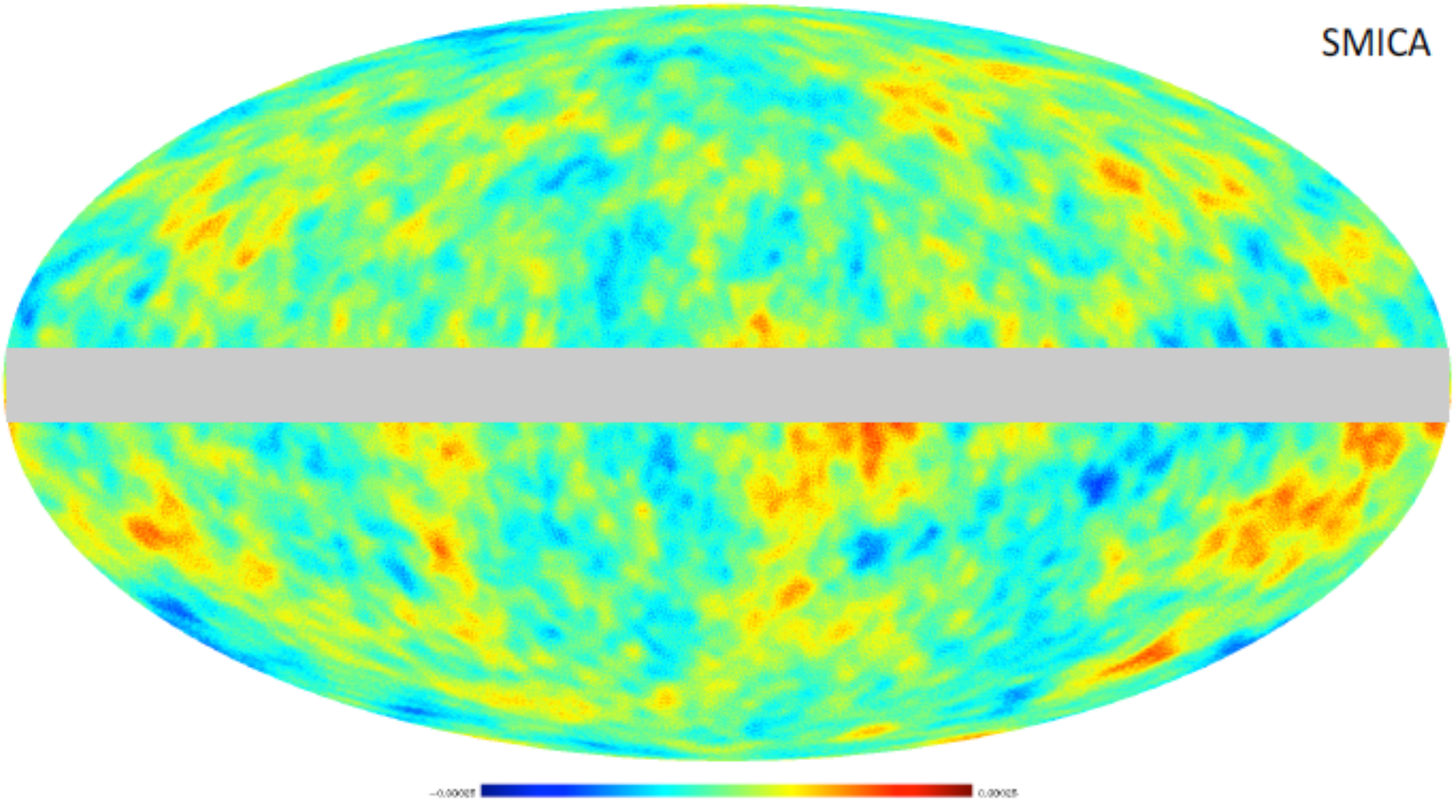






Primordial curvature fluctuations at $r=\eta_{CMB}$

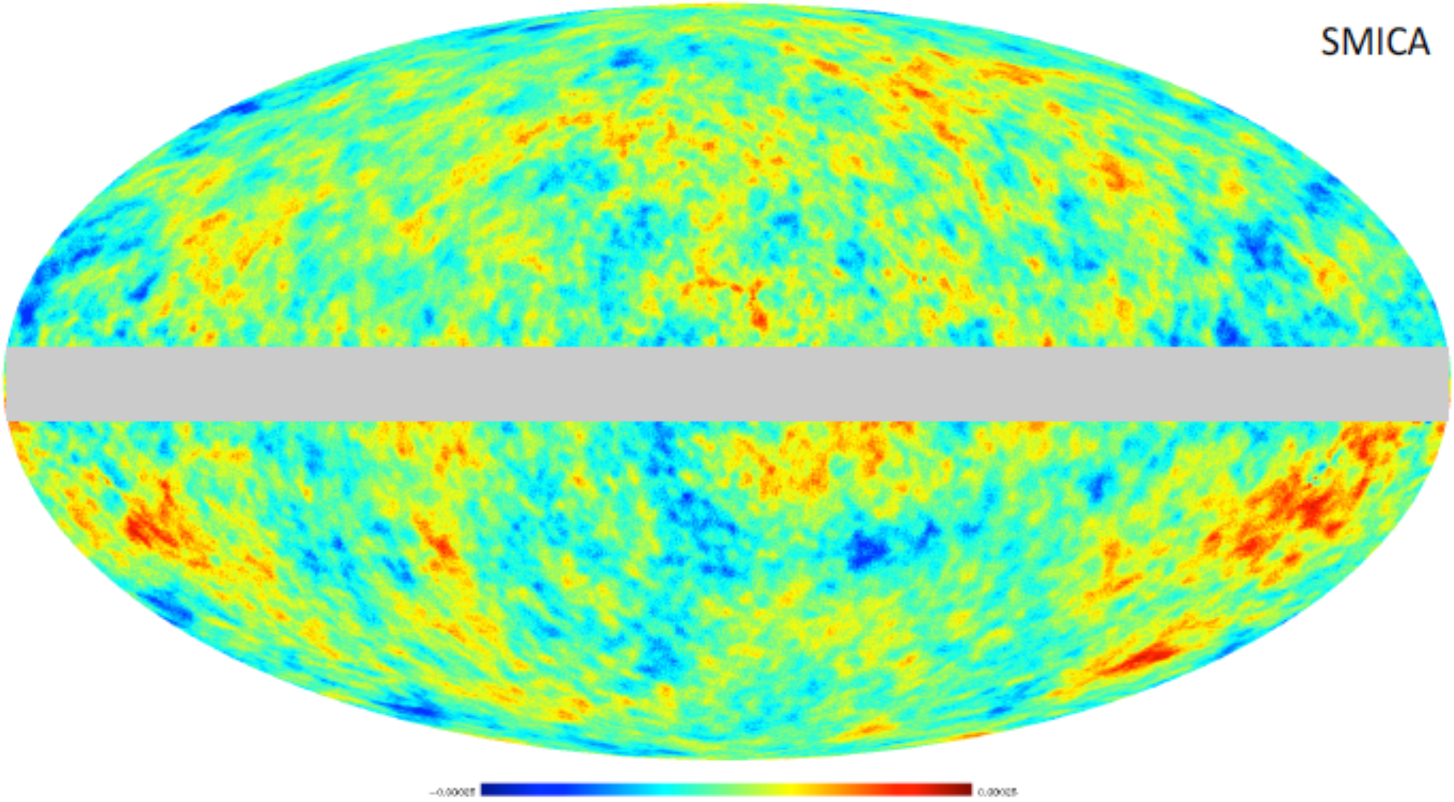
Planck T data



Preliminary

Primordial curvature fluctuations at r=η_{CMB}

Planck T & E data



Preliminary

2015: First NG constraints with CMB polarisation

- Developed a set of cross-validated optimal or nearly-optimal estimators for **T, E** and **T+E**:
  - *Komatsu, Spergel & Wandelt for local, equilateral, and orthogonal (LEO) and other factorizable templates*
  - *Binned bispectrum*
  - *2 modal bispectrum estimators*

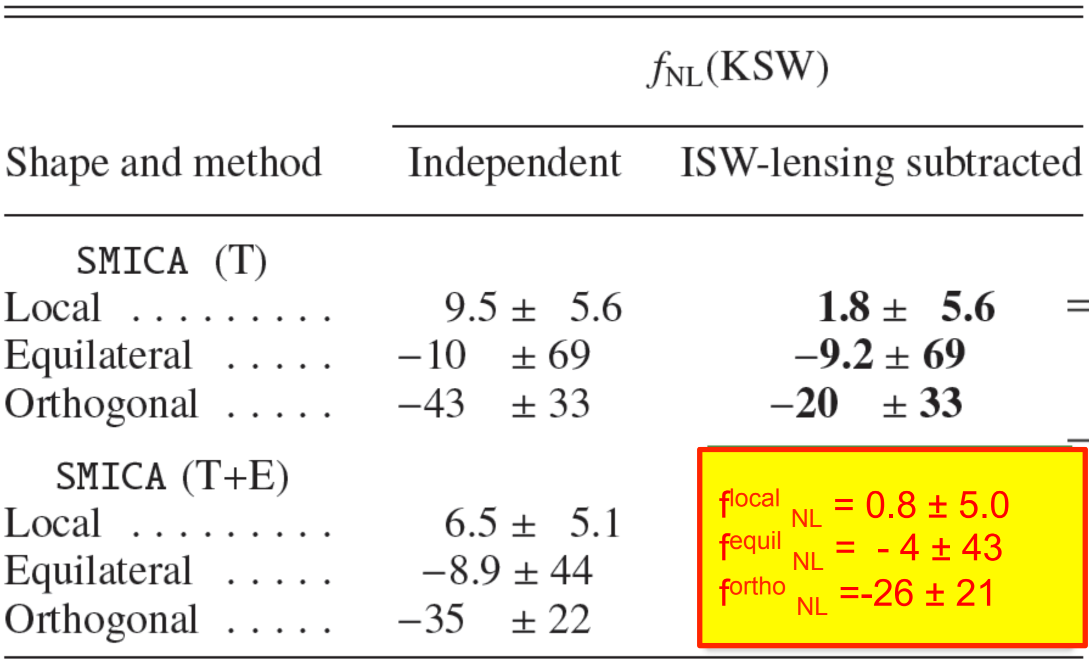
- An improved estimator based on Minkowski Functionals for **T**, **E** and **T+E**

- A KSW estimator of high-frequency linearly oscillatory features for **T, E** and **T+E**

- And greatly extended analyses of template families…

Bispectrum constraints w. full mission data

Planck 2015



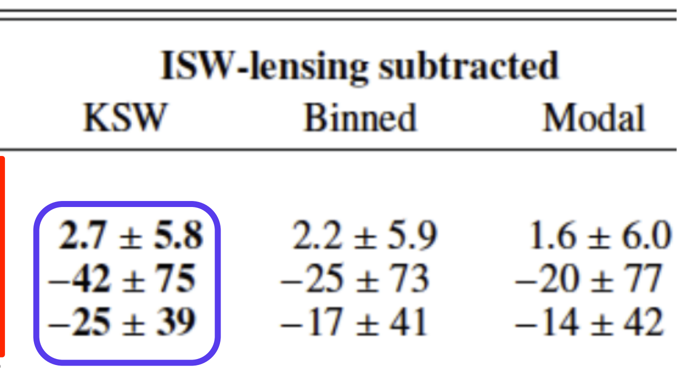
Shape and method	$f_{\rm NL}$(KSW) Independent	$f_{\rm NL}$(KSW) ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	**1.8 ± 5.6**
Equilateral	−10 ± 69	**−9.2 ± 69**
Orthogonal	−43 ± 33	**−20 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.1	
Equilateral	−8.9 ± 44	
Orthogonal	−35 ± 22	

$f^{\rm local}_{\rm NL} = 0.8 \pm 5.0$

$f^{\rm equil}_{\rm NL} = -4 \pm 43$

$f^{\rm ortho}_{\rm NL} = -26 \pm 21$

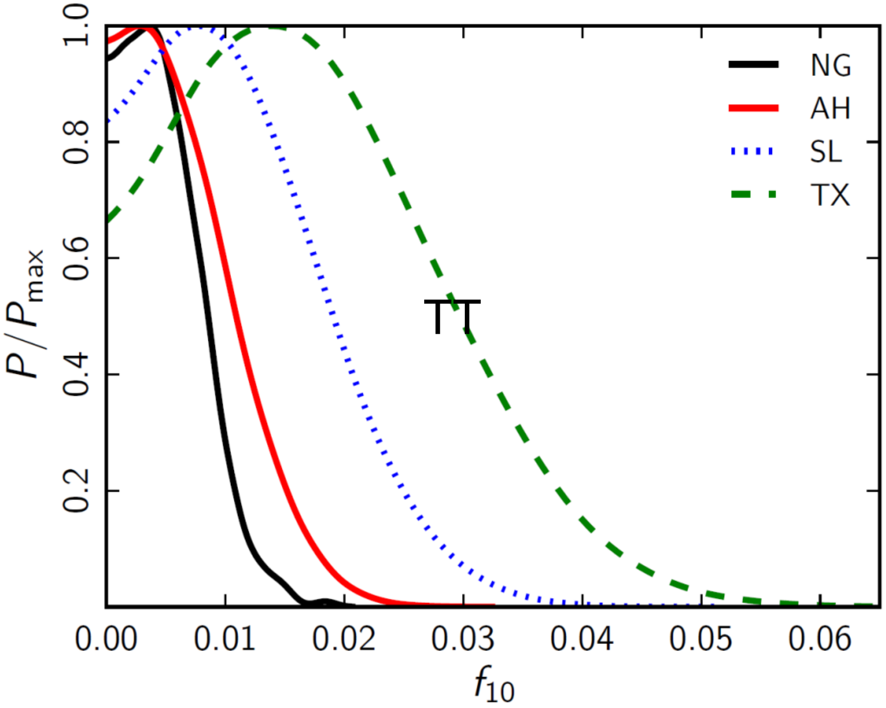
Planck 2013



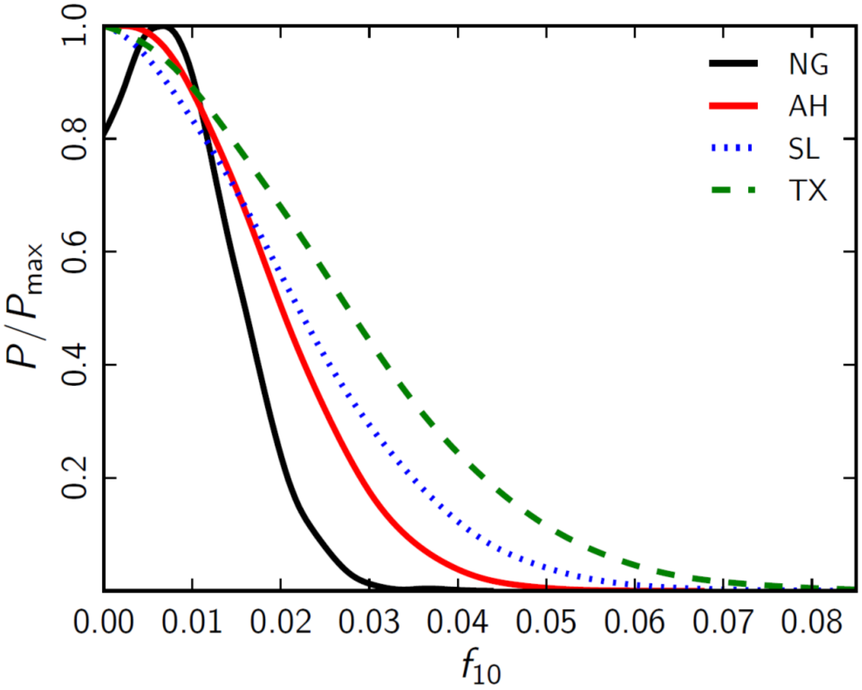
ISW-lensing subtracted KSW	ISW-lensing subtracted Binned	ISW-lensing subtracted Modal
2.7 ± 5.8	2.2 ± 5.9	1.6 ± 6.0
−42 ± 75	−25 ± 73	−20 ± 77
−25 ± 39	−17 ± 41	−14 ± 42

Constraint volume in LEO space shrunk by factor of 3.

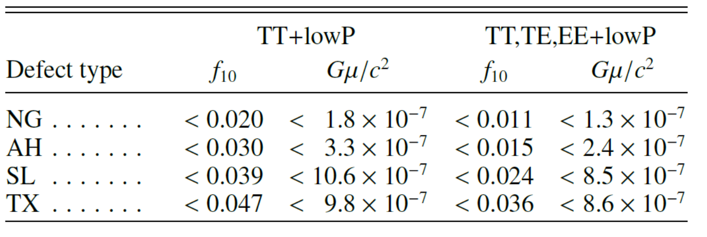
Constraints on Defects



Nambu-Goto
Abelian-Higgs
Semi-local
Textures (global)



95%CL

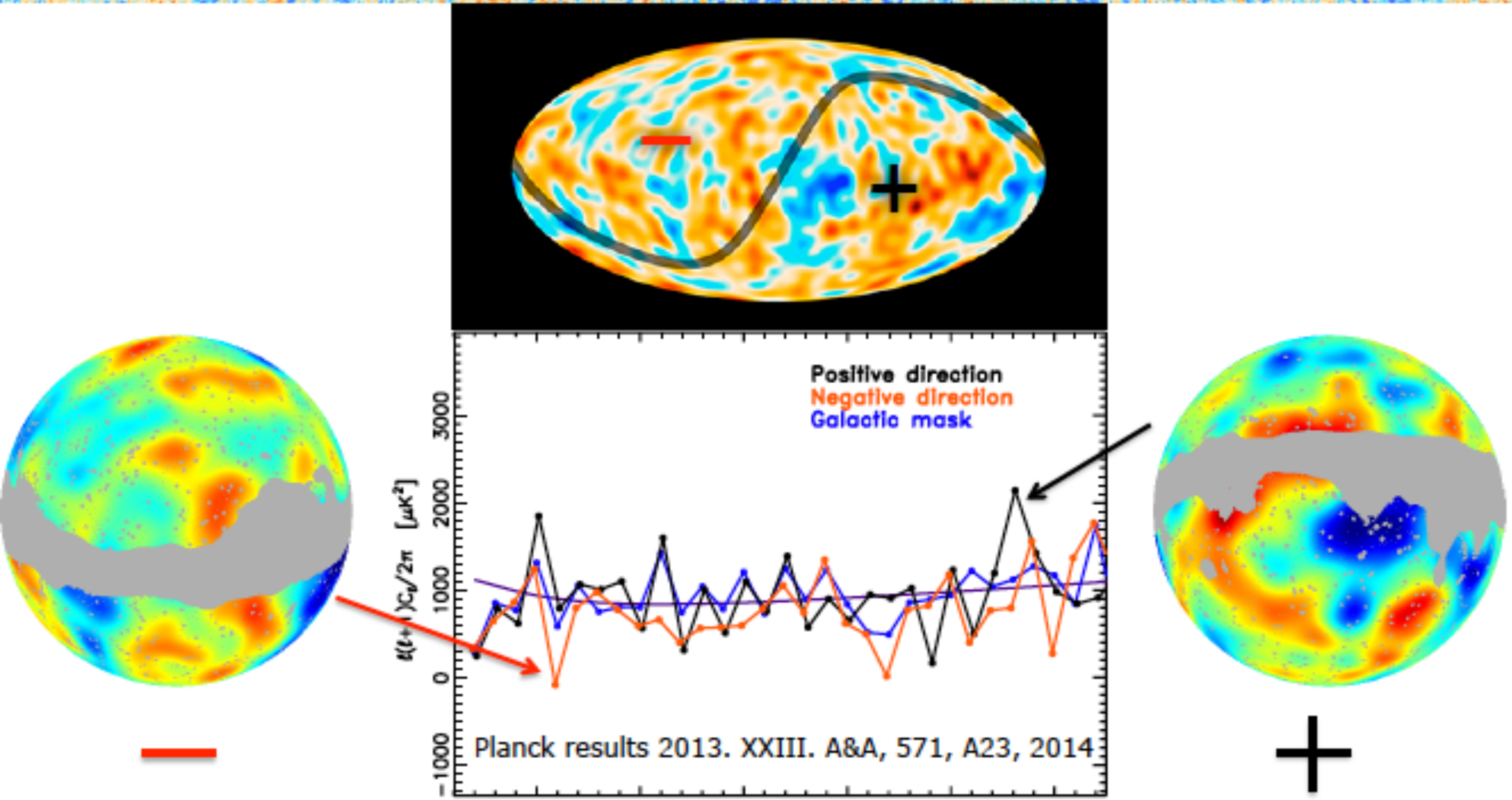


	TT+lowP		TT,TE,EE+lowP	
Defect type	f_{10}	$G\mu/c^2$	f_{10}	$G\mu/c^2$
NG	< 0.020	$< 1.8 \times 10^{-7}$	< 0.011	$< 1.3 \times 10^{-7}$
AH	< 0.030	$< 3.3 \times 10^{-7}$	< 0.015	$< 2.4 \times 10^{-7}$
SL	< 0.039	$< 10.6 \times 10^{-7}$	< 0.024	$< 8.5 \times 10^{-7}$
TX	< 0.047	$< 9.8 \times 10^{-7}$	< 0.036	$< 8.6 \times 10^{-7}$

NG summary

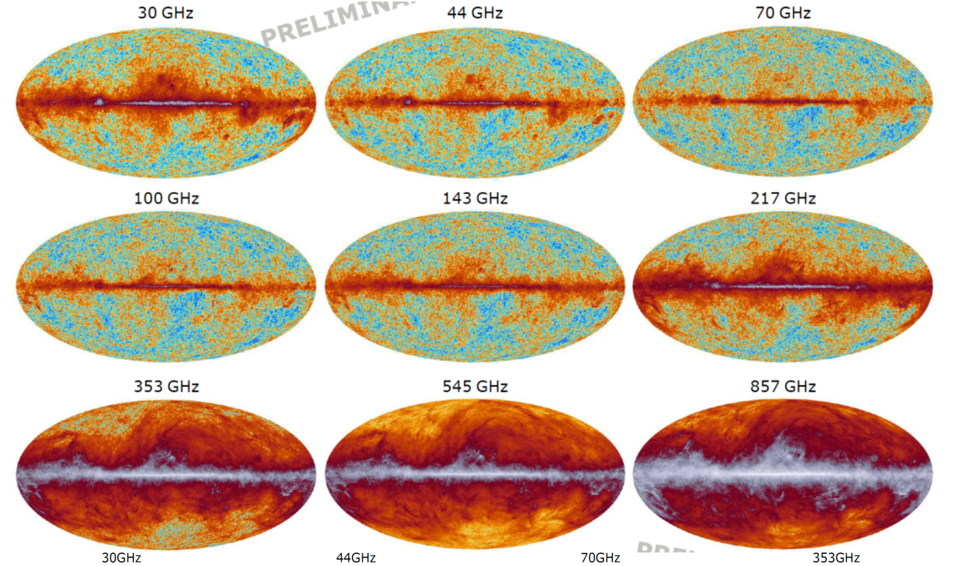
- Constraints on local, equilateral, orthogonal bispectra improved by up to 15% w.r.t. 2013
- First non-Gaussianity analysis using polarization data – fill in *blind modes* in the curvature perturbation
- Constraints based on T+E (2015) confirm temperature results and reduce error bars significantly
- 2013 "hints“ of non-Gaussianity in oscillatory feature models remain in temperature, but decrease in significance when polarization is included; new estimator for high oscillation frequencies covering 10 times more parameter space
- New constraints on
  - *Isocurvature non---Gaussianity, with polarization improving constraints significantly*
  - *Tensor non-Gaussianities analyzed: the parity---odd temperature limit consistent with the WMAP one (and consistent with 0)*
  - *Tri-spectrum due to cubic non-Gaussianity **(gNL)***
- The 2015 analysis contains greatly extended analysis of template families

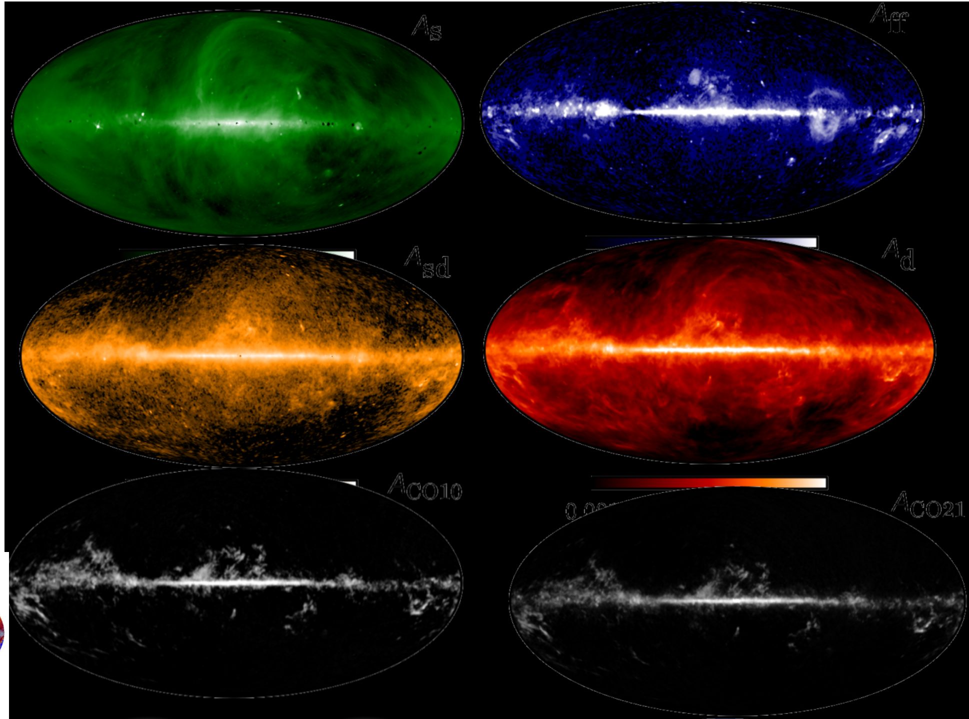
Power asymmetry in *Planck* 2013 nominal mission data

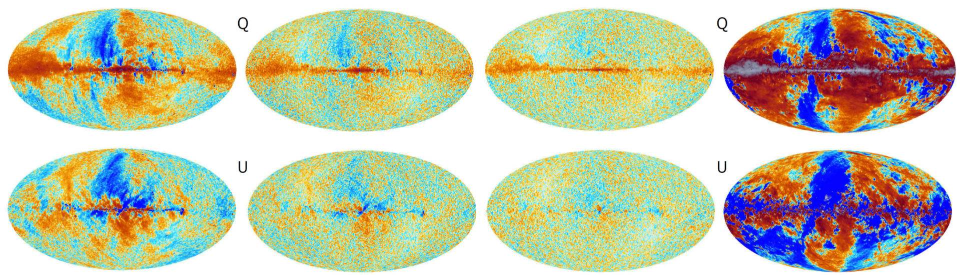


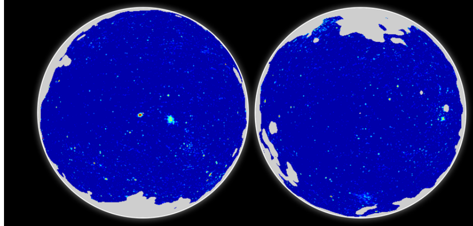
Planck results 2013. XXIII. A&A, 571, A23, 2014

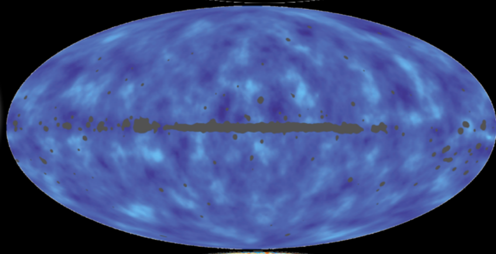
Large scale feature in 2015 full mission data are very similar to those in 2013 nominal mission data

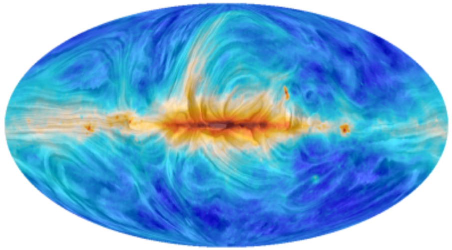


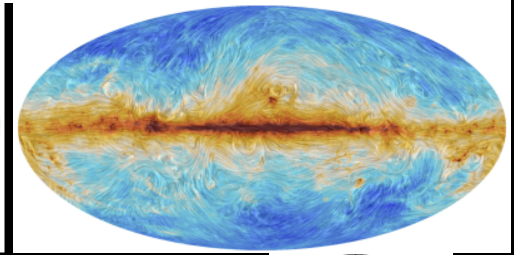


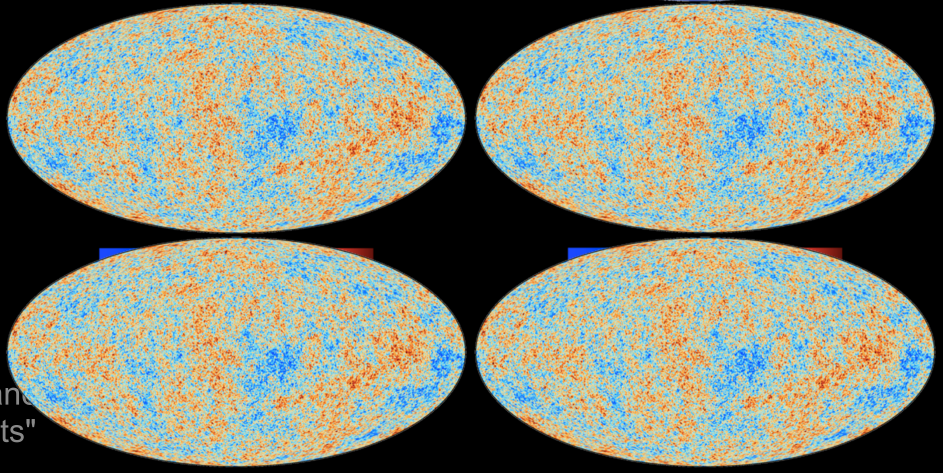


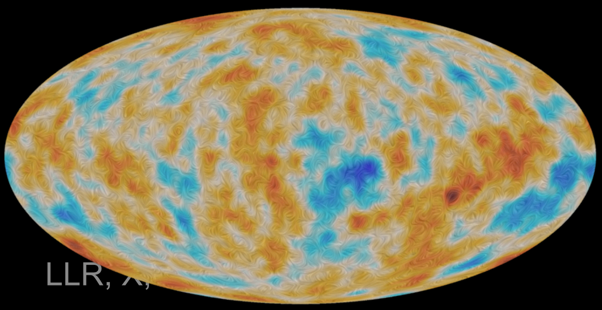


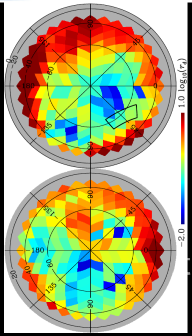












LLR, X,

: "Plan
results"

2015 Data products

February 2015

- Cleaned and calibrated timelines of the data for each detector at 30, 44, 70, 353, 545 and 857 GHz, and for the (unpolarized) spider-web bolometers at 100, 143, and 217 GHz.
- Maps of the sky at nine frequencies in temperature, and at 30, 44, 70, and 353 GHz in polarization. Additional products serve to quantify the characteristics of the maps to a level adequate for the science results being presented, such as noise maps, masks, and instrument characteristics.
- Four high-resolution maps of the CMB sky in temperature and polarization, and accompanying characterization products.
- Four high-pass-filtered maps of the CMB sky in polarization, and accompanying characterization products.
- A low-resolution CMB temperature map used in the low-ell likelihood code, with an associated set of foreground temperature maps produced in the process of separating the low-resolution CMB from foregrounds, with accompanying characterization products.
- Maps of thermal dust and residual cosmic infrared background (CIB), carbon monoxide (CO), synchrotron, freefree, and spinning dust temperature emission, plus maps of dust temperature and opacity.
- Maps of synchrotron and dust polarized emission.
- A map of the estimated CMB lensing potential over 70% of the sky.
- A map of the Sunyaev-Zeldovich effect Compton parameter.
- Monte Carlo chains used in determining cosmological parameters from the Planck data.
- The Second Planck Catalogue of Sunyaev-Zeldovich Sources (PSZ2), comprising a list of sources detected by their SZ distortion of the CMB spectrum. The PSZ2 supersedes the previous Early Sunyaev-Zeldovich Catalogue (Planck Collaboration XXIX 2014) and the PSZ1 (Planck Collaboration XXIX 2014).
- The Planck catalogue of Galactic Cold Clumps (PGCC, Planck Collaboration XXVIII 2015), providing a list of Galactic cold sources over the whole sky. The PGCC supersedes the previous Early Cold Core Catalogue (ECC), part of the Early Release Compact Source Catalogue (ERCSC, Planck Collaboration VII 2011).

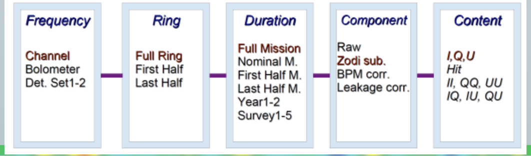
March 2015

- A likelihood code and data package used for testing cosmological models against the Planck data, including both the CMB and CMB lensing.
- The Second Planck Catalogue of Compact Sources (PCCS2), comprising lists of compact sources over the entire sky at the nine Planck frequencies. The PCCS2 includes polarization information, and supersedes the previous Early Release Compact Source Catalogue (Planck Collaboration XIV 2011) and the PCCS1 (Planck Collaboration XXVIII 2014).
- A full set of simulations, including Monte Carlo realizations.

Late spring/early summer 2015

- Cleaned and calibrated timelines of the data for all polarization-sensitive bolometers at 100, 143, and 217 GHz.
- Maps of the sky at 100, 143, and 217 GHz in polarization. Additional products serve to quantify the characteristics of the maps to a level adequate for the science results being presented, such as noise maps, masks, and instrument characteristics.

The release of 2015 products will be completed in the early summer of 2015. In parallel, the Planck Collaboration is developing the next generation of data products, which will be delivered in the early part of 2016.



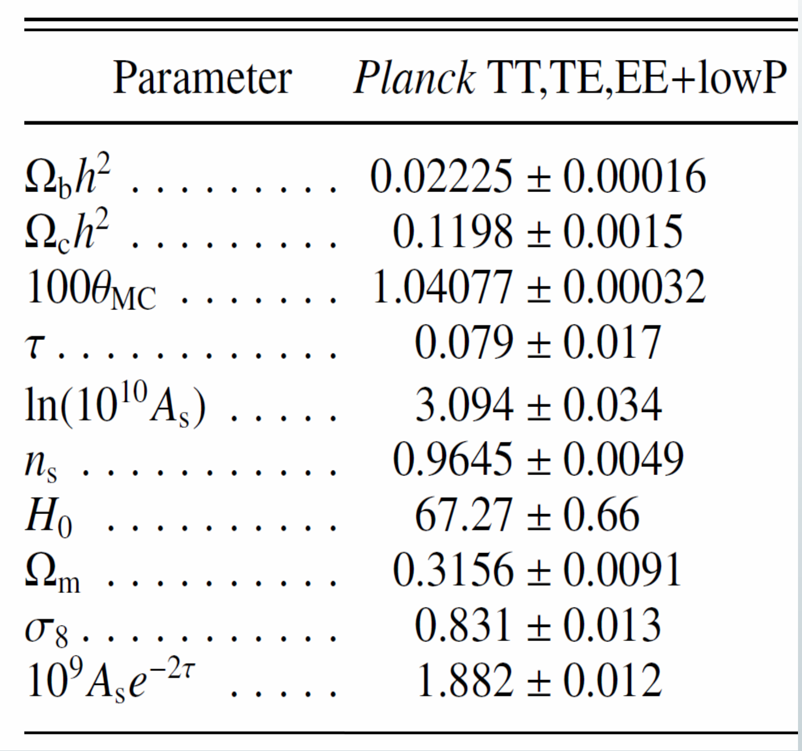
Frequency	*Ring*	*Duration*	*Component*	*Content*
Channel Bolometer Det. Set1-2	Full Ring First Half Last Half	Full Mission Nominal M. First Half M. Last Half M. Year1-2 Survey1-5	Raw Zodi sub. BPM corr. Leakage corr.	*I,Q,U* *Hit* *II, QQ, UU* *IQ, IU, QU*

2015 papers

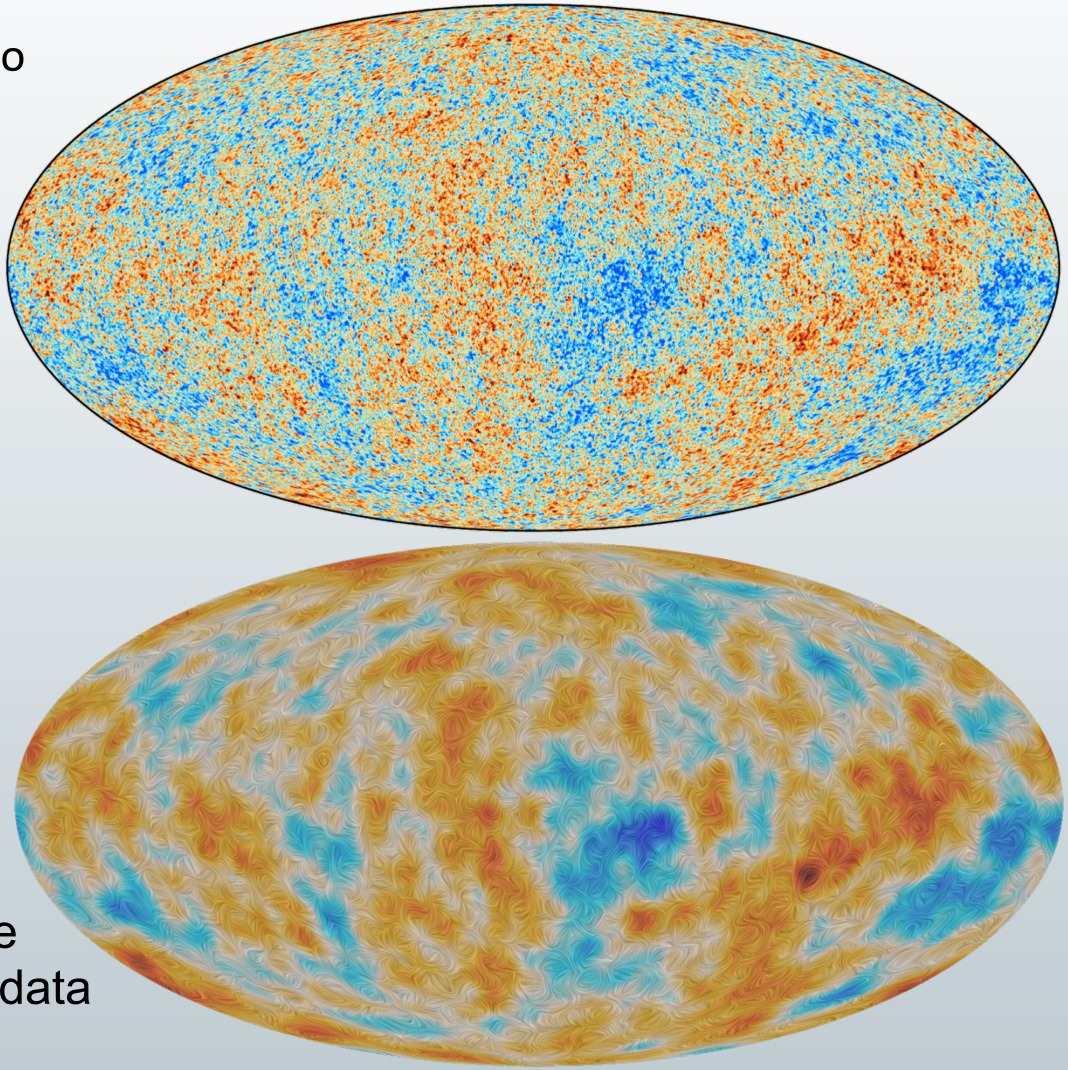
- I. Overview of products and results
- II. Low Frequency Instrument data processing
- III. LFI systematic uncertainties
- IV. LFI beams and window functions
- V. LFI calibration
- VI. LFI maps
- VII. High Frequency Instrument data processing: Time-ordered
- information and beam processing
- VIII. High Frequency Instrument data processing: Calibration
- and maps
- IX. Diffuse component separation: CMB maps
- X. Diffuse component separation: Foreground maps
- XI. CMB power spectra, likelihood, and consistency of cosmological parameters
- XII. Simulations
- XIII. Cosmological parameters
- XIV. Dark energy and modified gravity
- XV. Gravitational lensing
- XVI. Isotropy and statistics of the CMB
- XVII. Primordial non-Gaussianity
- XVIII. Background geometry and topology of the Universe
- XIX. Constraints on primordial magnetic fields
- XX. Constraints on inflation
- XXI. The integrated Sachs-Wolfe effect
- XXII. A map of the thermal Sunyaev-Zeldovich effect
- XXIII. The thermal Sunyaev-Zeldovich effect–cosmic infrared
- background correlation
- XXIV. Cosmology from Sunyaev-Zeldovich cluster counts
- XXV. Diffuse, low-frequency Galactic foregrounds
- XXVI. The Second Planck Catalogue of Compact Sources
- XXVII. The Second Planck Catalogue of Sunyaev-Zeldovich
- Sources
- XXVIII. The Planck Catalogue of Galactic Cold Clumps

Conclusions

➔ base ΛCDM continues to be a good fit to the Planck data, *including polarisation*.

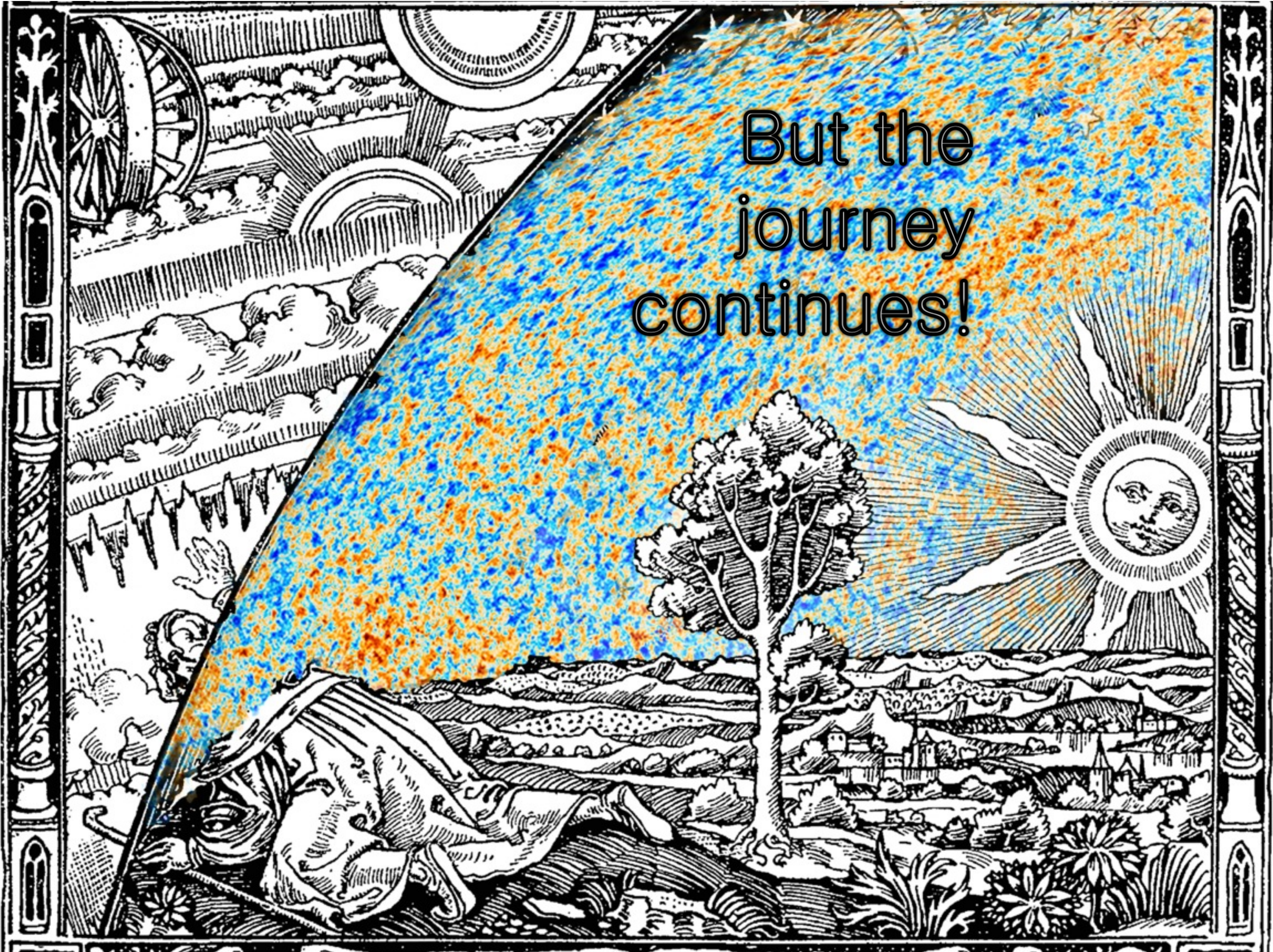


Parameter	*Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02225 ± 0.00016
$\Omega_c h^2$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04077 ± 0.00032
τ	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.094 ± 0.034
n_s	0.9645 ± 0.0049
H_0	67.27 ± 0.66
Ω_m	0.3156 ± 0.0091
σ_8	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.882 ± 0.012



➔powerful evidence in favour of simple inflationary models, that match Planck data to very high precision.

➔If there is new physics beyond base ΛCDM, then the corresponding observational signatures in the CMB are weak and difficult to detect.



But the journey continues!

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.

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.

Thank you