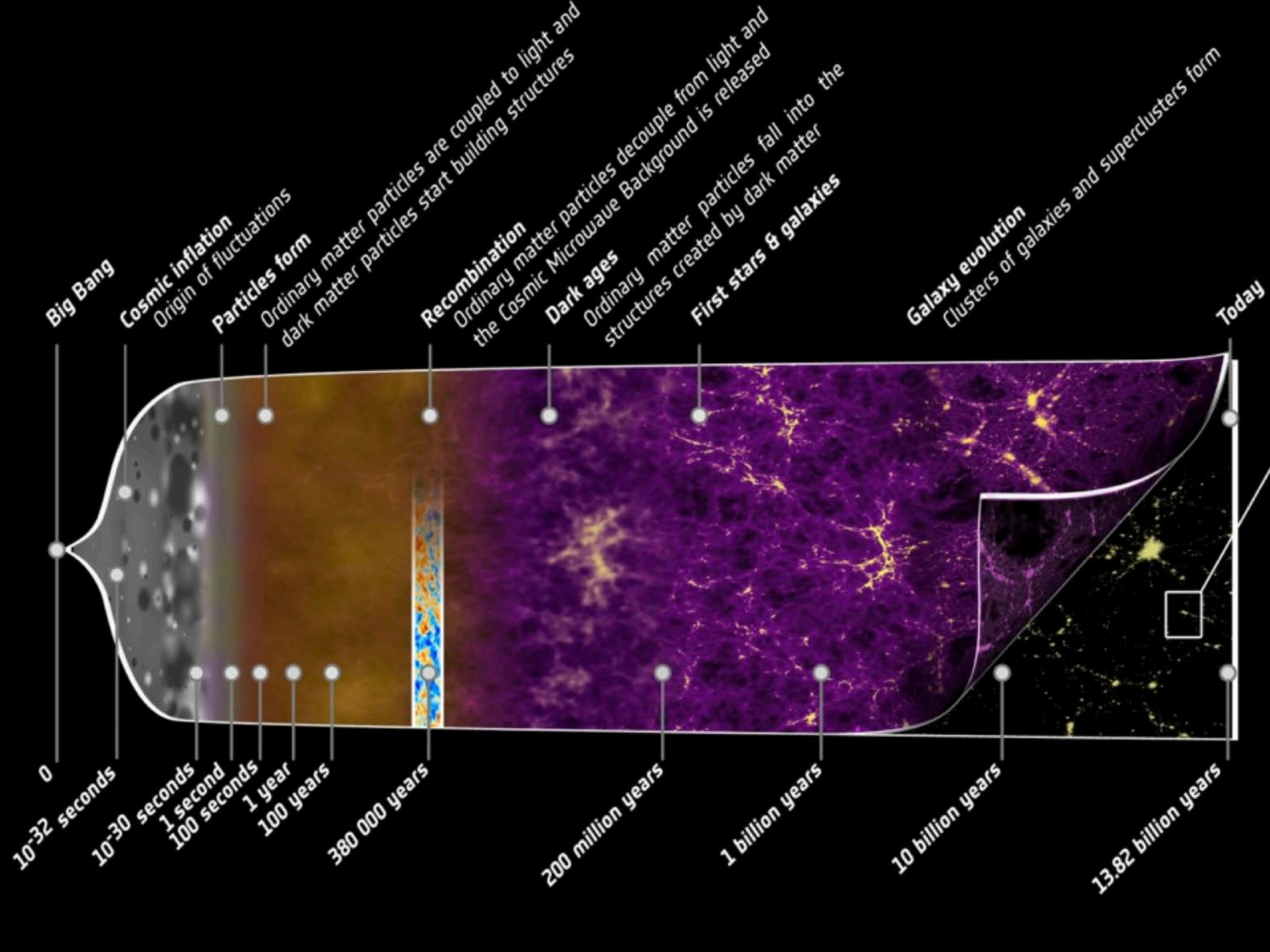
The Planck Legacy
and... beyond

Nazzareno Mandolesi

University of Ferrara & INAF

On behalf of the Planck Collaboration



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

CMB and Particle Physics

Temperature and polarization variations across the microwave sky include the fingerprints of quantum fluctuations in the early universe.

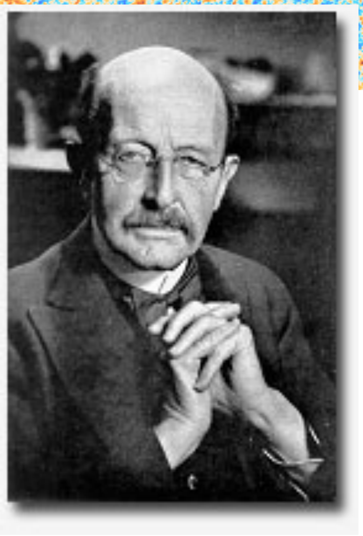
Will they reveal physics or new physics at unprecedented energy scales?

Outline

- ✓ Introduction
- ✓ Stability of main scientific results across the 2013, 2015 and intermediate product public deliveries, confirmed by the 2018 legacy release.
- ✓ 2018: Main Legacy results and improvements in understanding and correction of systematics in Polarization.
- ✓ Issues to be addressed:
  - Small remaining uncertainties of systematics in polarization
  - Some 2.0/2.5 σ “anomalies”: lack of power at low ell + minor “curiosities”
  - 3.8 σ tension with “distance ladder” measured H_0
- ✓ ………Beyond Planck

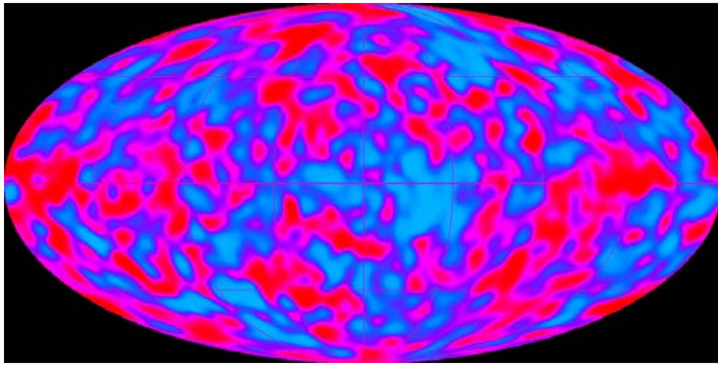
the cosmic microwave background from space

Penzias & Wilson 1965, Dicke, Peebles, Roll & Wilkinson 1965



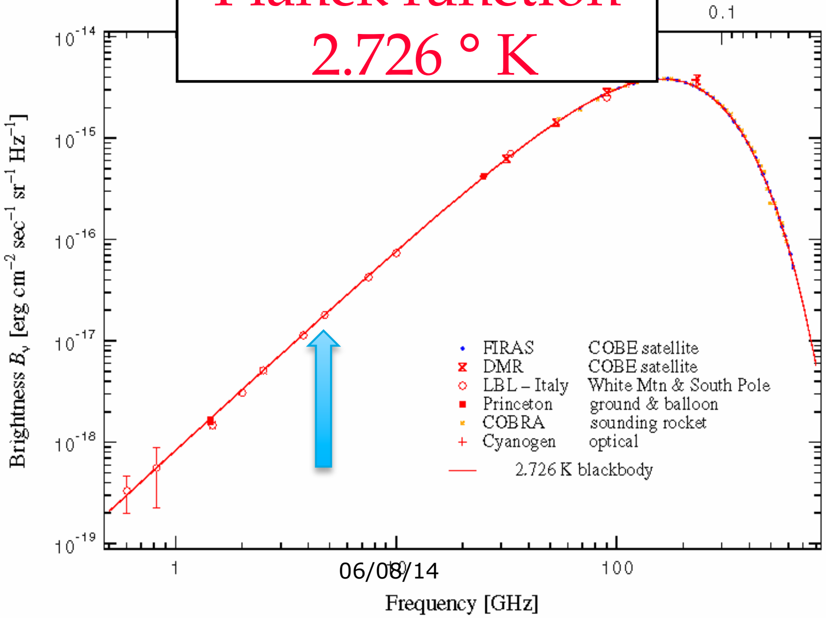
Cosmic Background predicted by Gamow in 1948, and by Ralph Alpher & Robert Herman in 1950. Serendipitously observed in 1965 par Arno Penzias and Robert Wilson at the Murray Hill Centre (NJ) of the Bell Telephone Laboratories as « A source of excess noise in a radio Receiver ». Joint interpretation article in Physical Review by Dicke, Peebles, Roll, Wilkinson…(Princeton).

Predictions of the temperature oscillated between 5K and tens of K
Discovery: 3.5 ±1 K



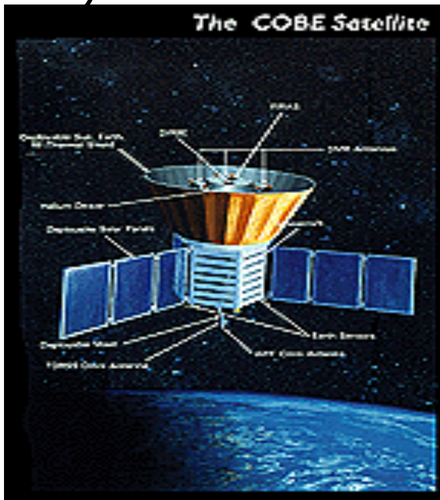
G. Smoot et al 1992
DMR experiment
(COBE)

Planck function
2.726 ° K



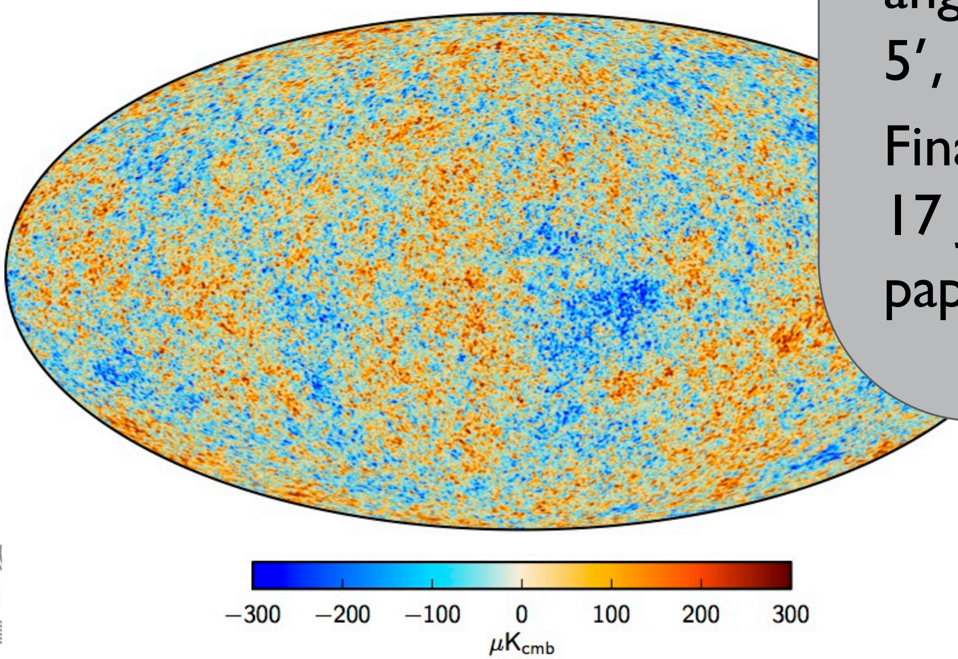
J. Mather et al
1990
FIRAS
experiment

M. Hauser et al
1998
DIRBE
experiment
(COBE)

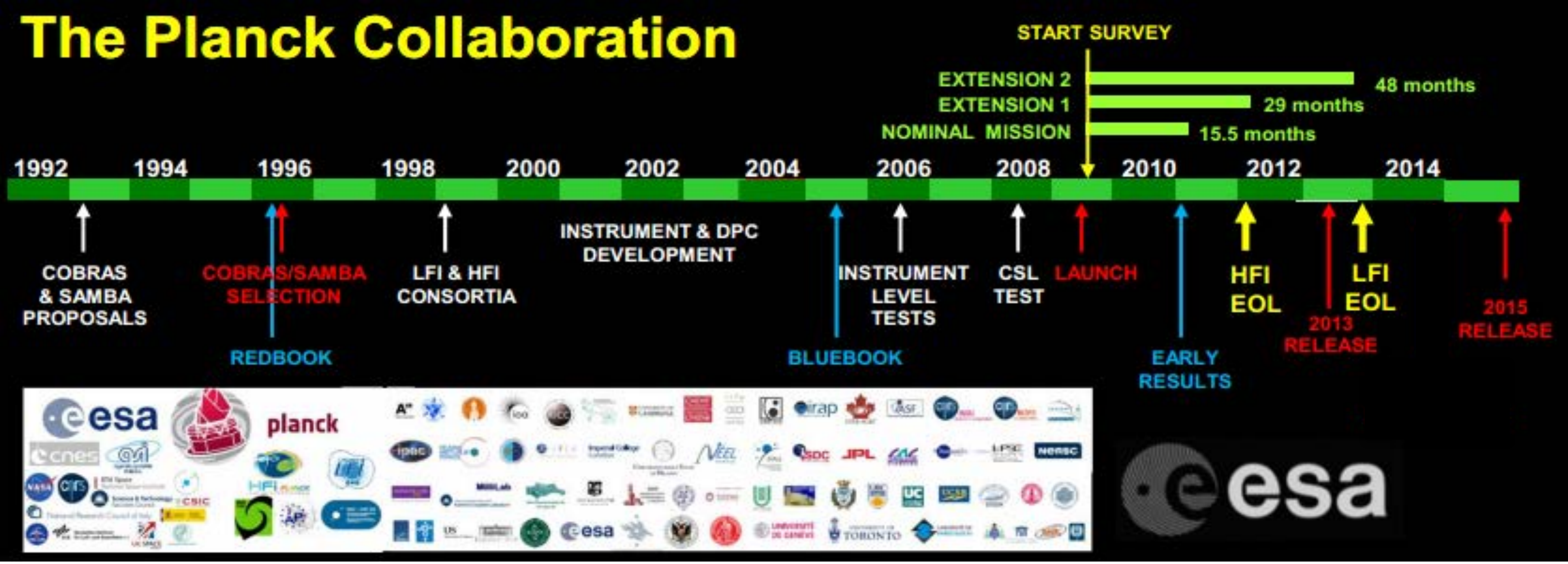


THE PLANCK SATELLITE

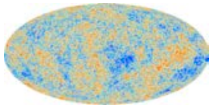
- Planck is the 3rd generation ESA satellite devoted to CMB
- Ultimate characterization of the temperature anisotropies
- 74 detectors (radiometers and bolometers) in 9 frequency bands from 30 to 857 GHz
- angular resolution between 30’ and 5′, $\Delta T/T \sim 2 \times 10^{-6}$
- Final (legacy) release took place on 17 July 2018, for data and (most) papers.



The Planck Collaboration



May 2009: Launched from Kourou

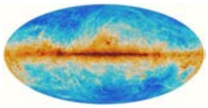


Mar 2013: Data Release and Cosmology Results
Nominal Mission Temperature data

32 papers

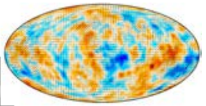
Oct 2013: Planck 'Shut Down'

52 papers / intermediate results



Feb 2015: Data Release and Cosmology Results
Full Mission Temperature and (preliminary) Polarization data

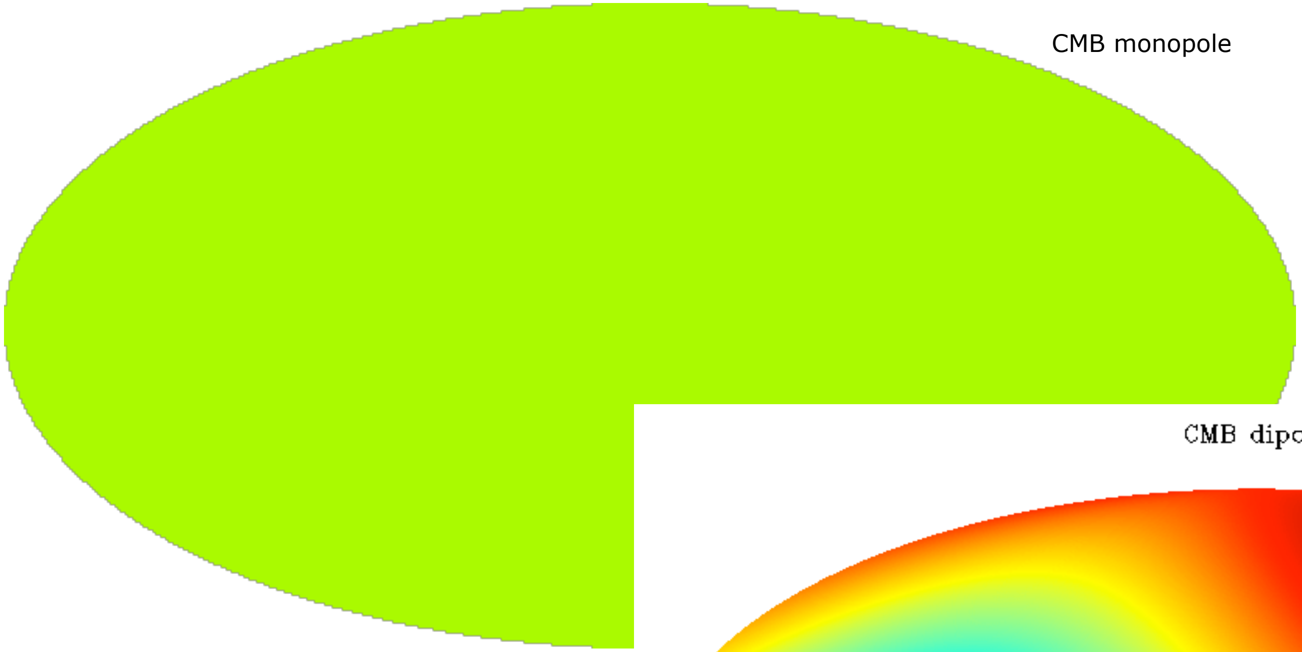
28 papers

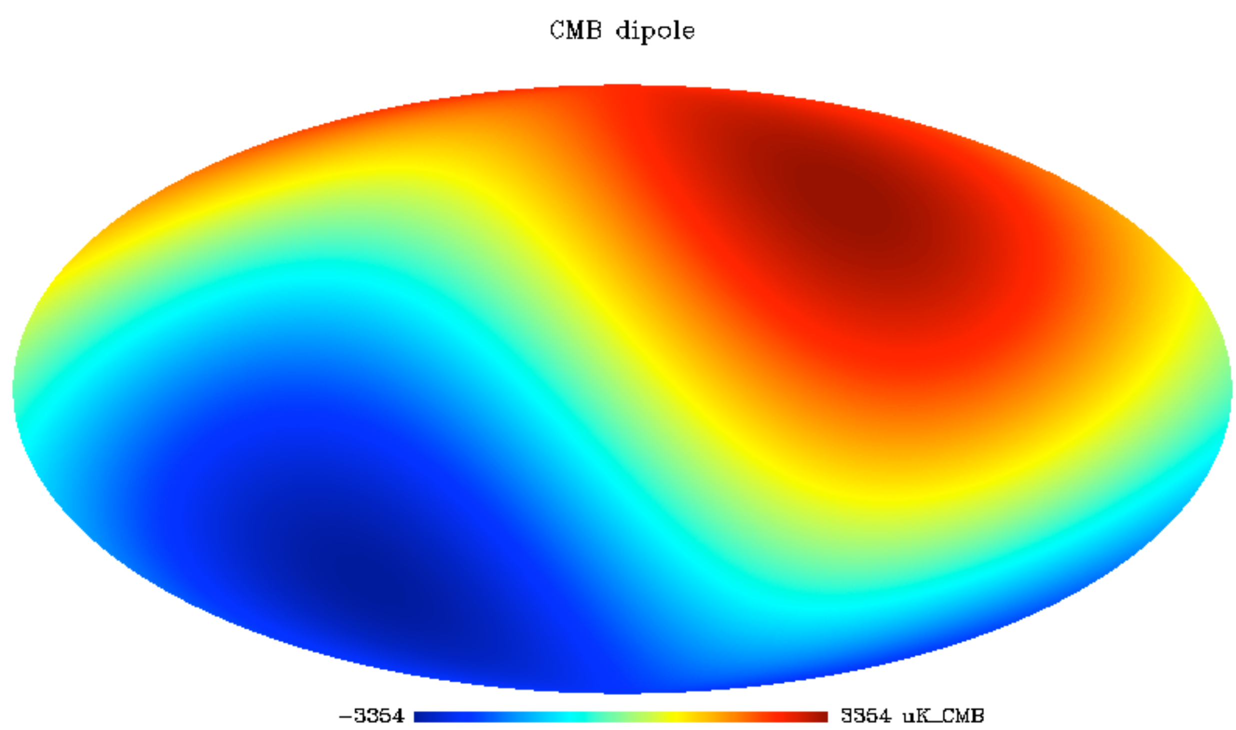


Jul 2018: Legacy Data & Paper Release

9 papers (+3 to appear soon)

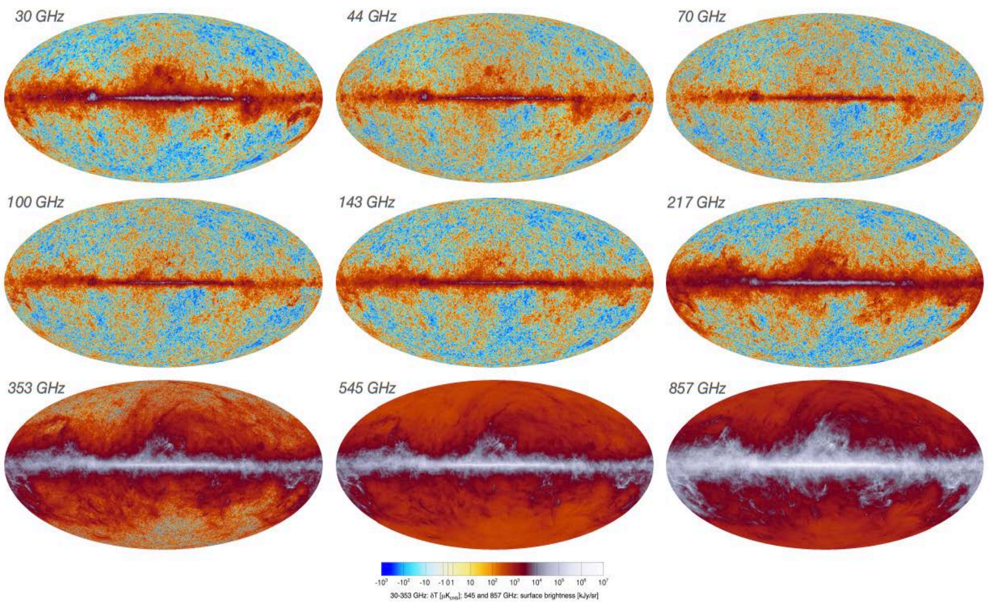
CMB monopole and dipole



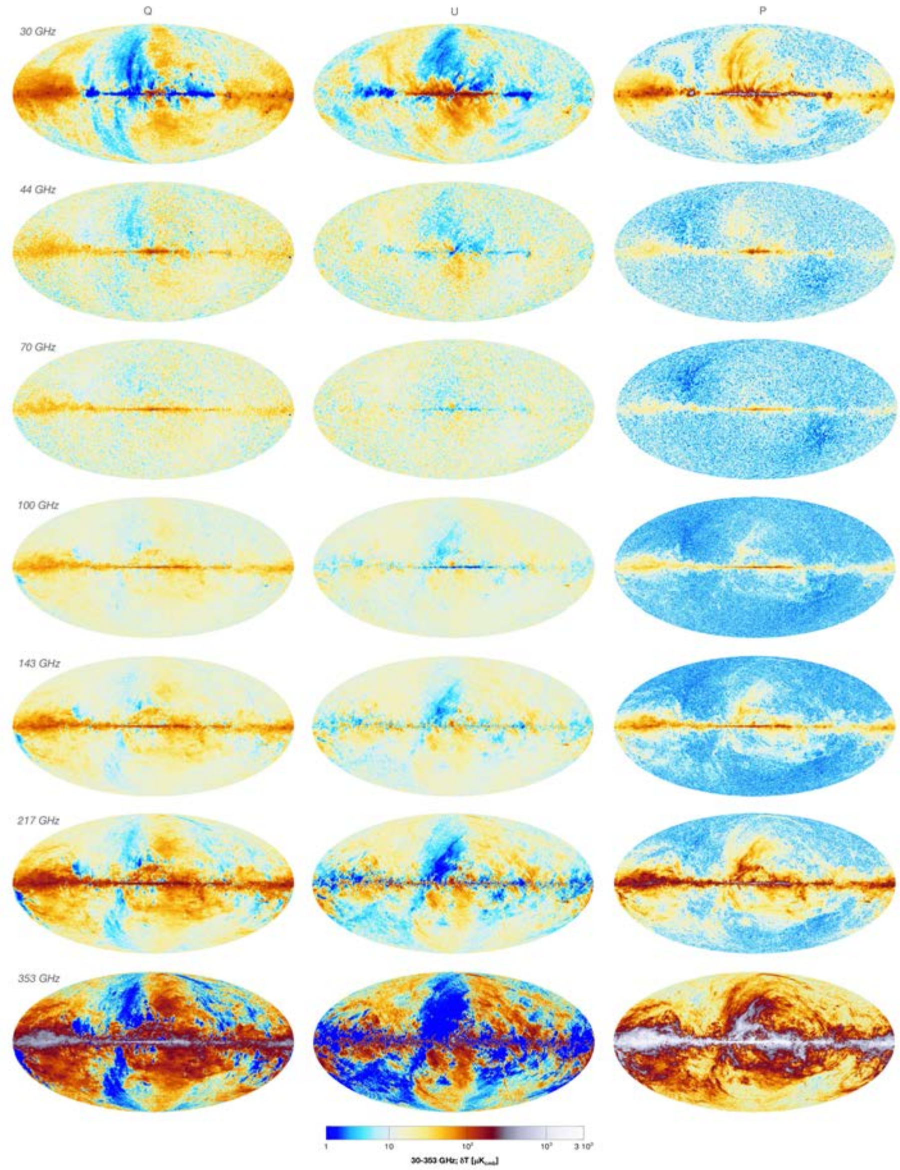


The 2018 maps

Intensity

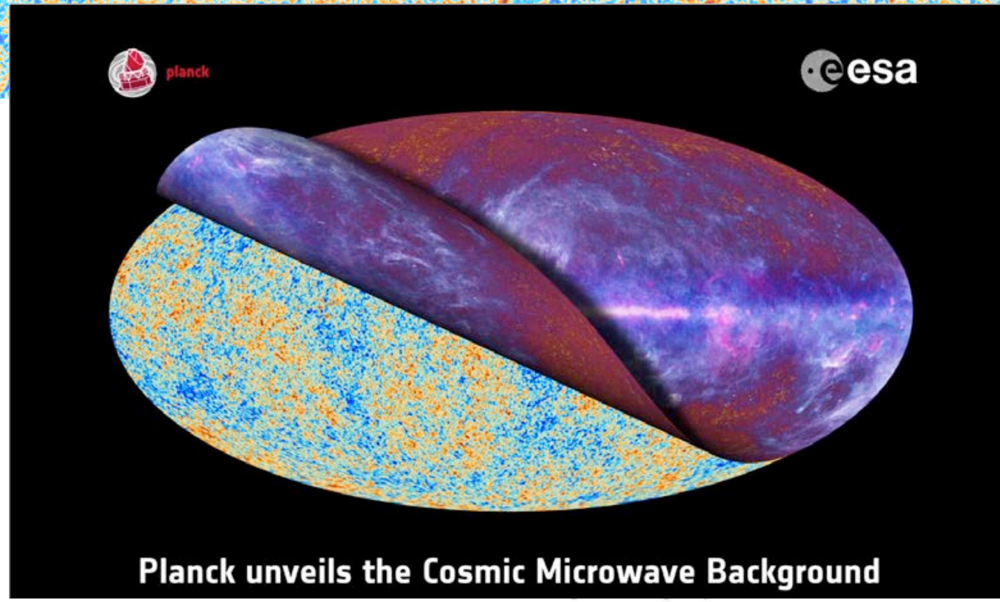


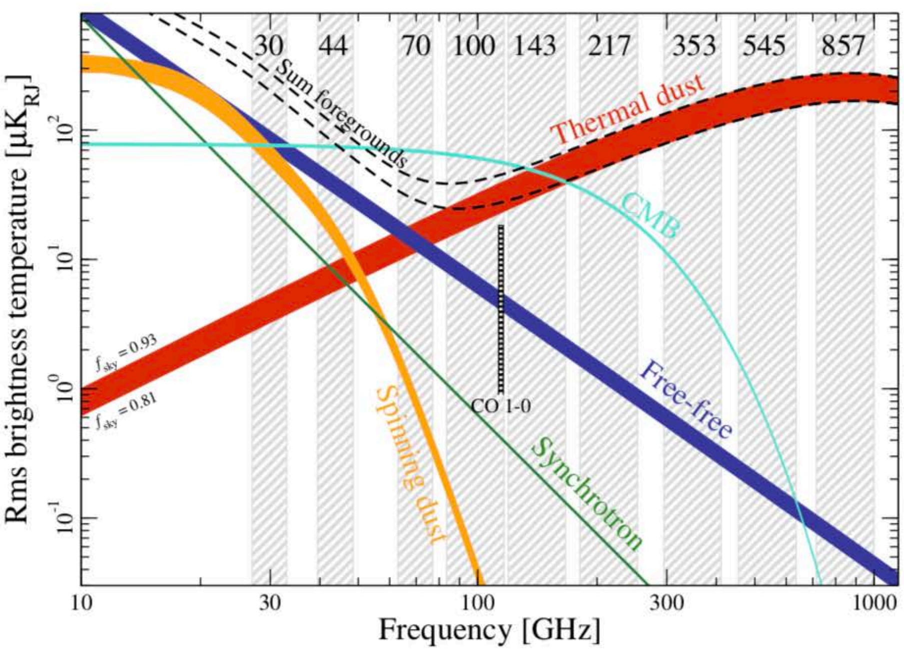
Polarization

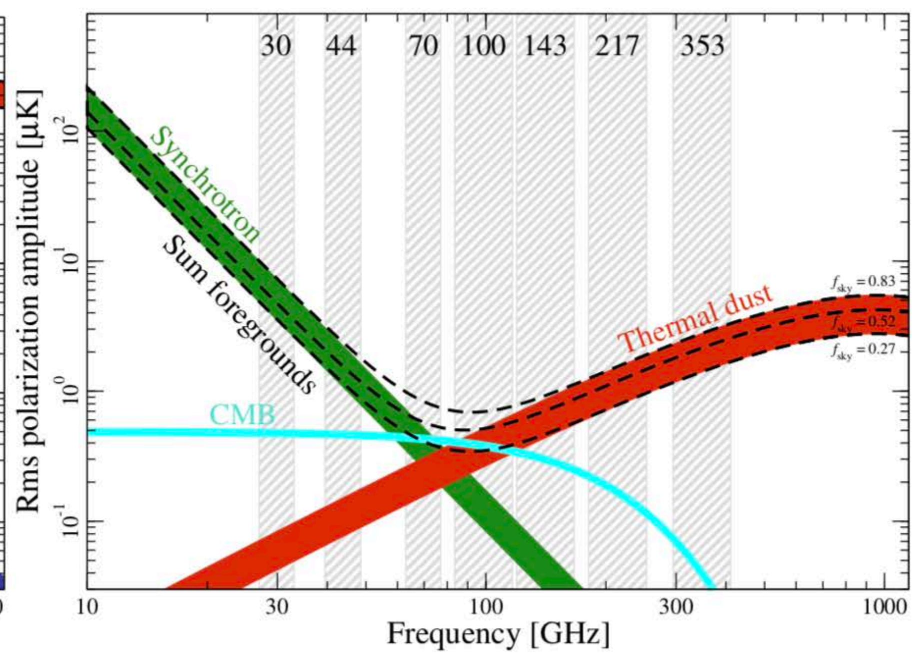


UNVEILING THE CMB SKY

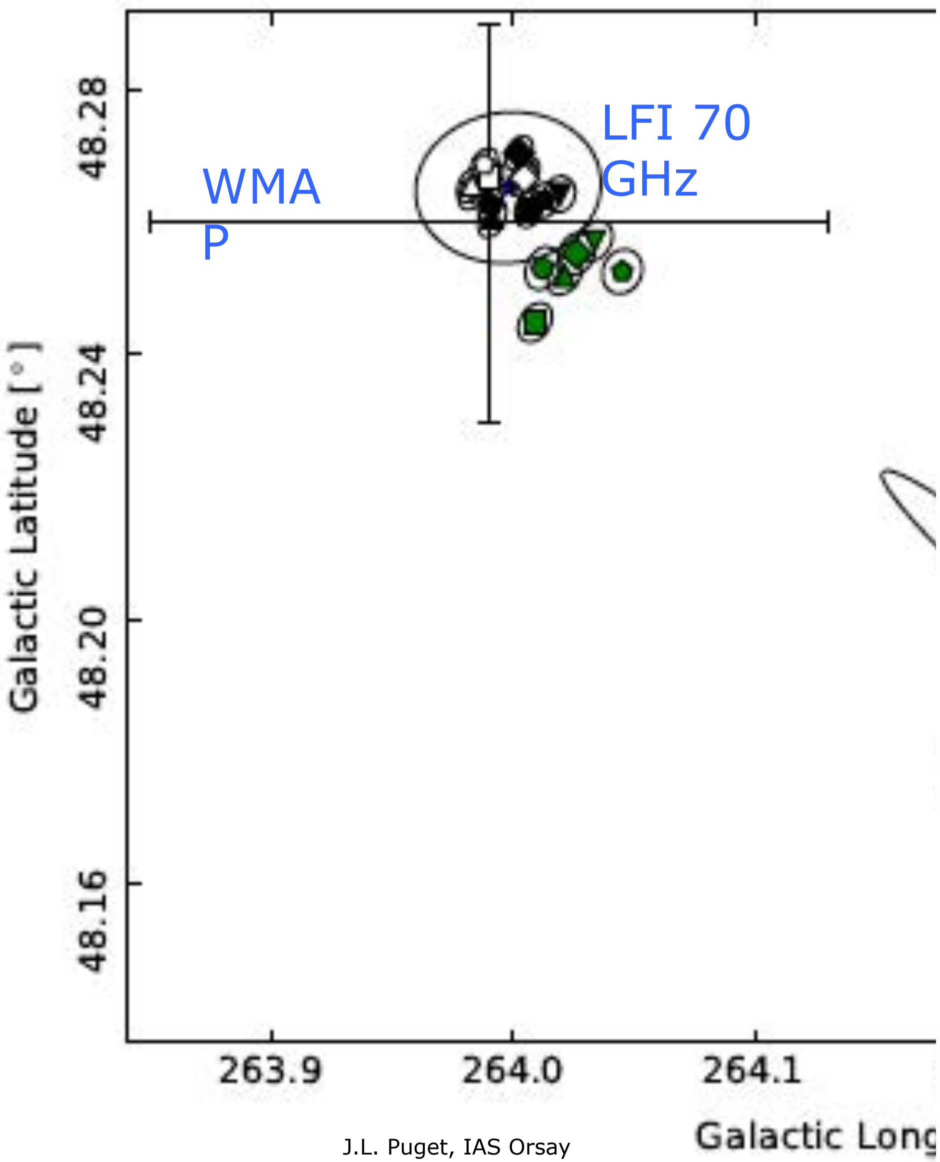
The *ultimate* measurement of the CMB temperature anisotropy field

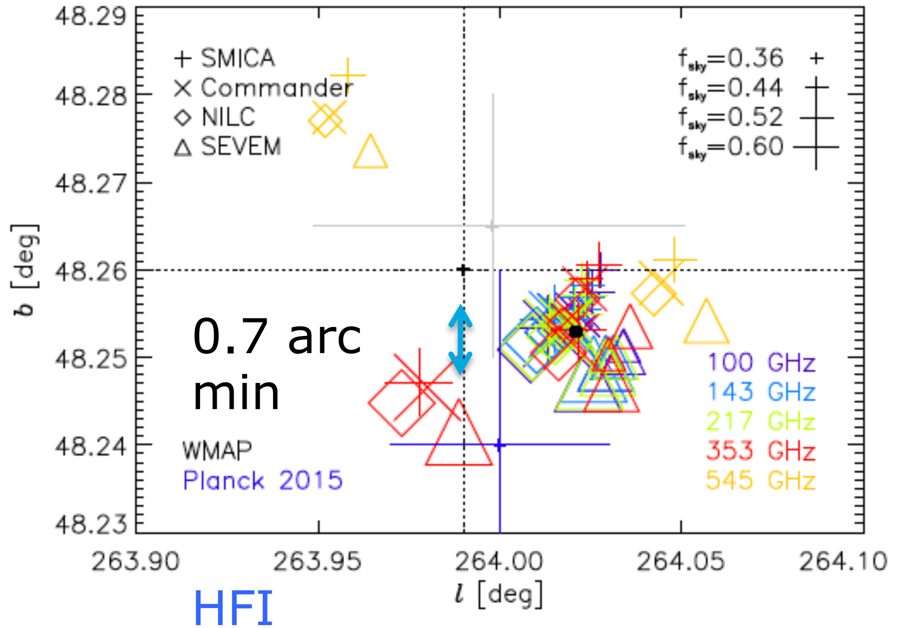


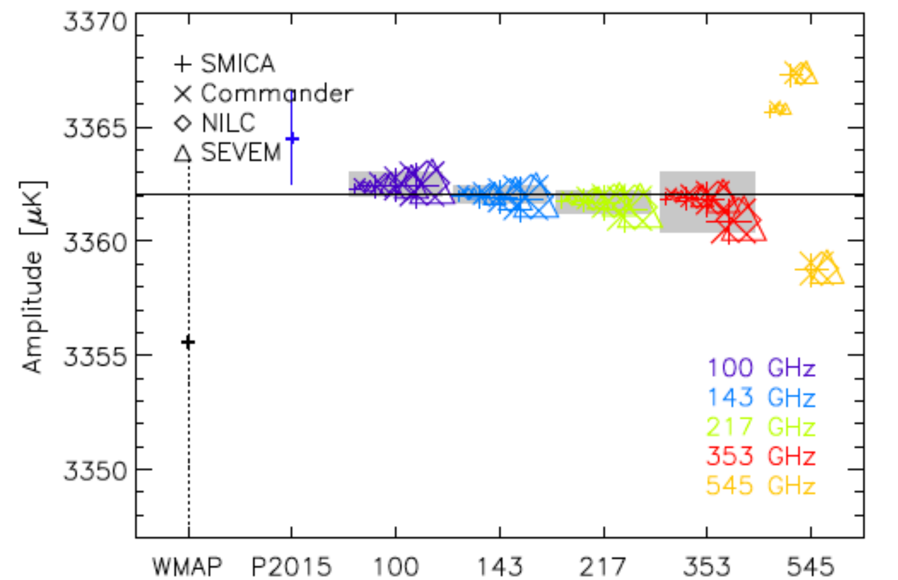




LFI and HFI Solar dipole direction and amplitude





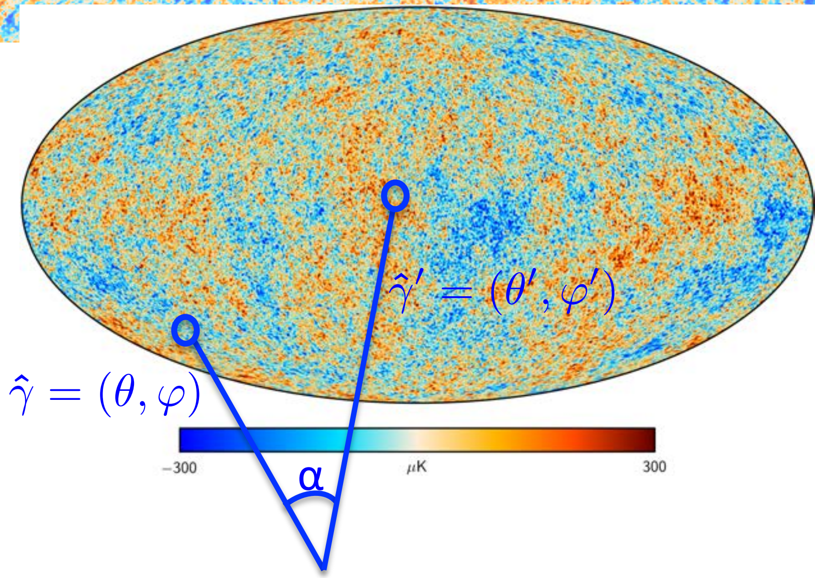


Calibration and solar dipole

1. the dipole due to the motion of the solar system w.r.t. the CMB has been measured with unprecedented accuracy
2. it is a very powerful tool for inter-calibration and testing
3. we remove the foregrounds and the CMB anisotropies with 4 different methods
4. the calibration of each detector is obtained from the orbital dipole (earth motion around the sun
5. we then measure the solar dipole (direction and amplitude) for a set of galactic sky cuts (20 to 90 %)
6. finally we compare the results between frequencies

$$
\begin{aligned}
v &= (369.8160 \pm 0.0010)\,\mathrm{km\,s^{-1}};\\
A &= [3362.08 \pm 0.09\,(\mathrm{stat.}) \pm 0.45\,(\mathrm{syst.}) \pm 0.45\,(\mathrm{cal.})]\;\mu\mathrm{K};\\
l &= 264^{\circ}\!.021 \pm 0^{\circ}\!.003\,(\mathrm{stat.}) \pm 0^{\circ}\!.008\,(\mathrm{syst.});\\
b &= 48^{\circ}\!.253 \pm 0^{\circ}\!.001\,(\mathrm{stat.}) \pm 0^{\circ}\!.004\,(\mathrm{syst.}).
\end{aligned}
$$

STATISTICAL DESCRIPTION



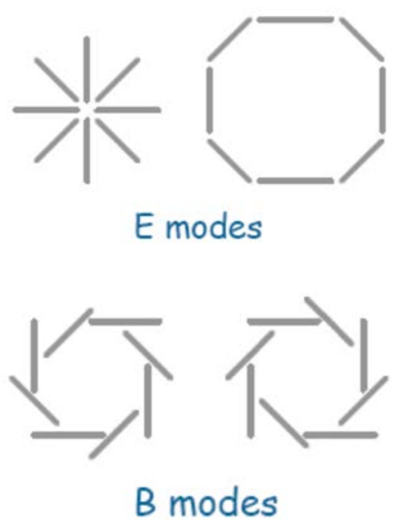
CORRELATION FUNCTIONS

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma})\frac{\Delta T}{T}(\vec{\gamma}')\right\rangle$$ ← from Inflation

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma})\frac{\Delta T}{T}(\vec{\gamma}')\frac{\Delta T}{T}(\vec{\gamma}'')\right\rangle$$

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma})\frac{\Delta T}{T}(\vec{\gamma}')\frac{\Delta T}{T}(\vec{\gamma}'')\frac{\Delta T}{T}(\vec{\gamma}''')\right\rangle$$

...



POLARIZATION

$$\mathbf{P}(\hat{\gamma}) = \nabla\mathbf{E} + \nabla\times\mathbf{B}$$

E-modes: even under parity

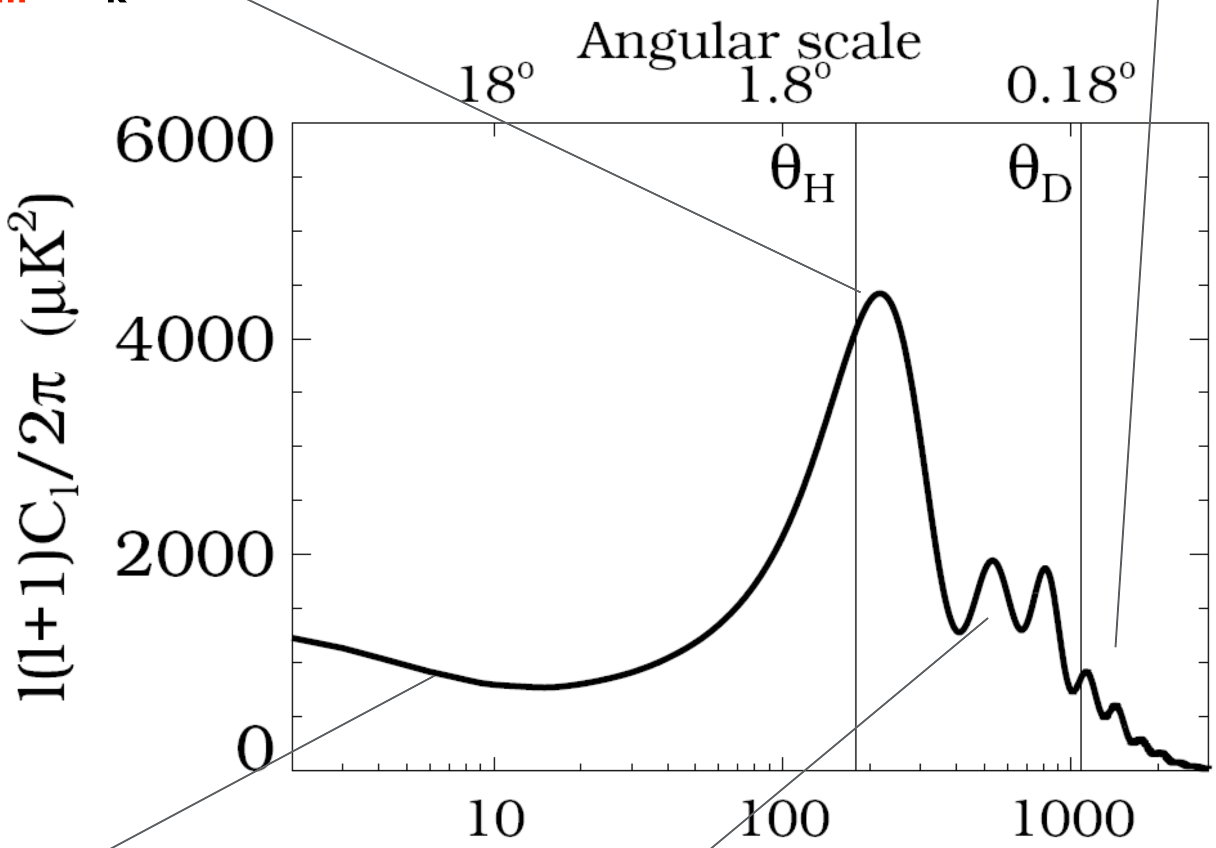
B-modes: odd under parity

Density perturbations -> E-modes

Gravitational Waves -> E- and B-modes

spatial curvature
relative abundance of matter and radiation
distance to the last scattering surface
H_0, Ω_m, Ω_k

Photon diffusion length at recombination
Slope of the primordial spectrum
N_{eff}, Ω_b, Y_p, n_s



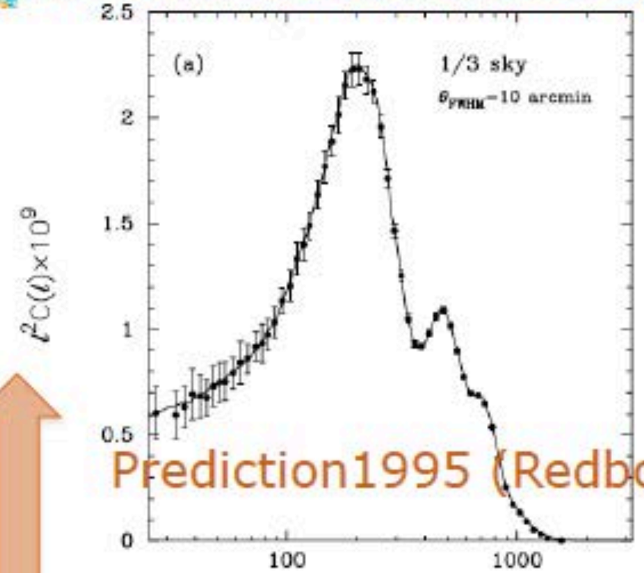
+ Overall power
$A_s\, e^{-2\tau}$

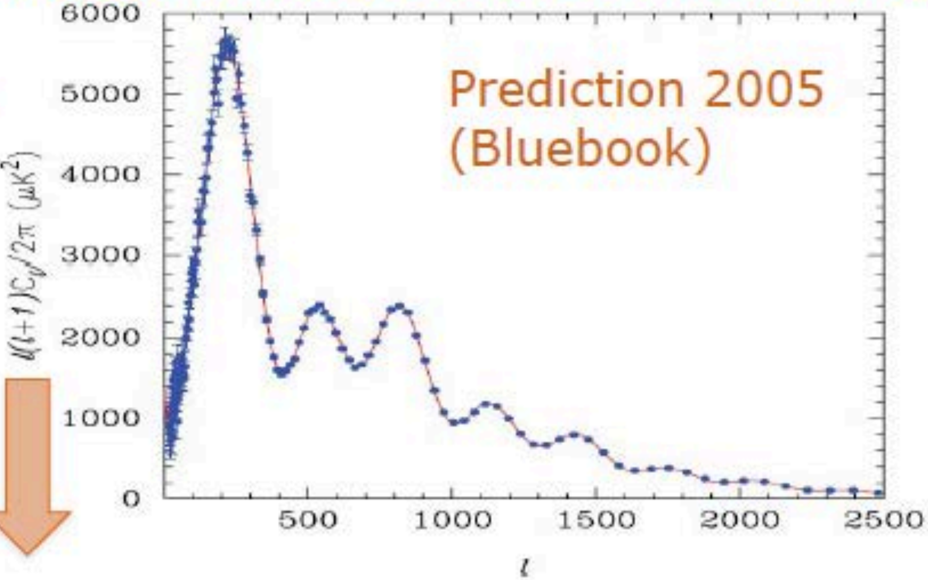
+ low-ell polarization (not shown)
Reionization history
τ

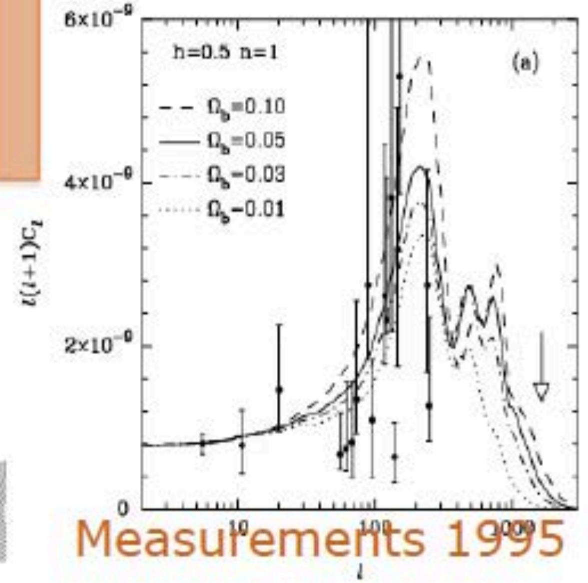
Primordial power spectrum
late time expansion
A_s, Ω_Λ

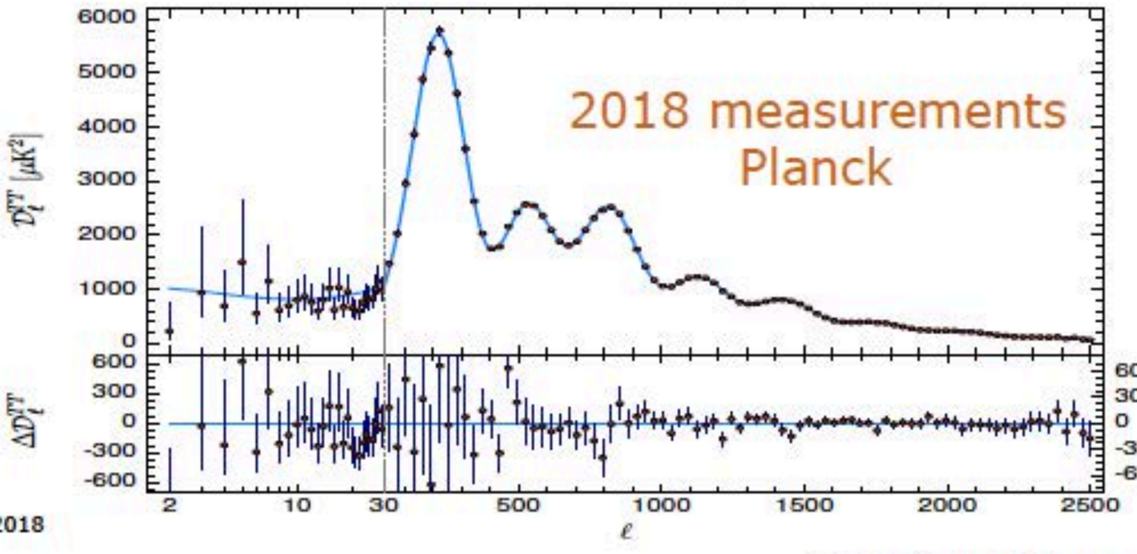
Baryon abundance
Ω_b

Expectations





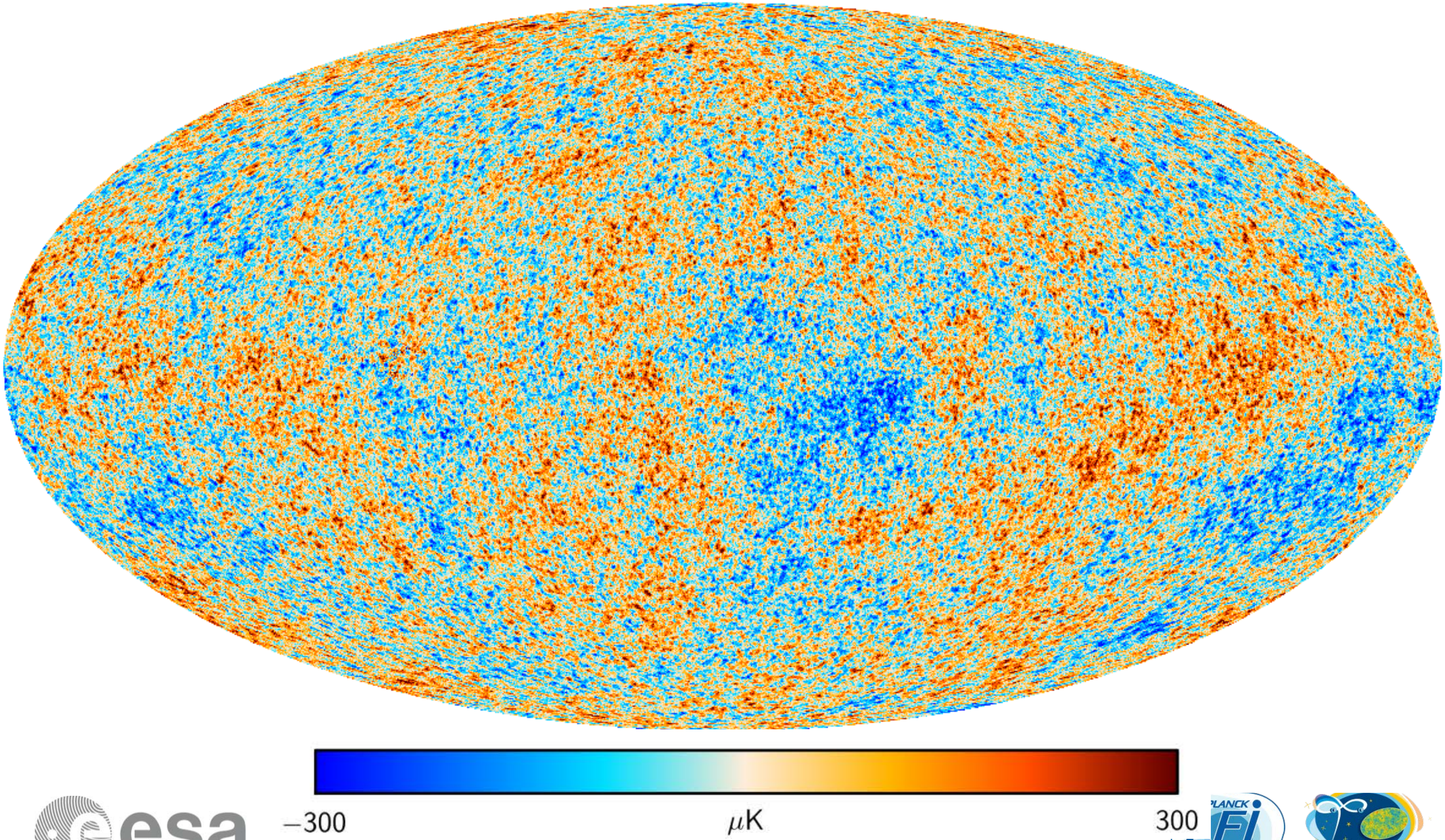




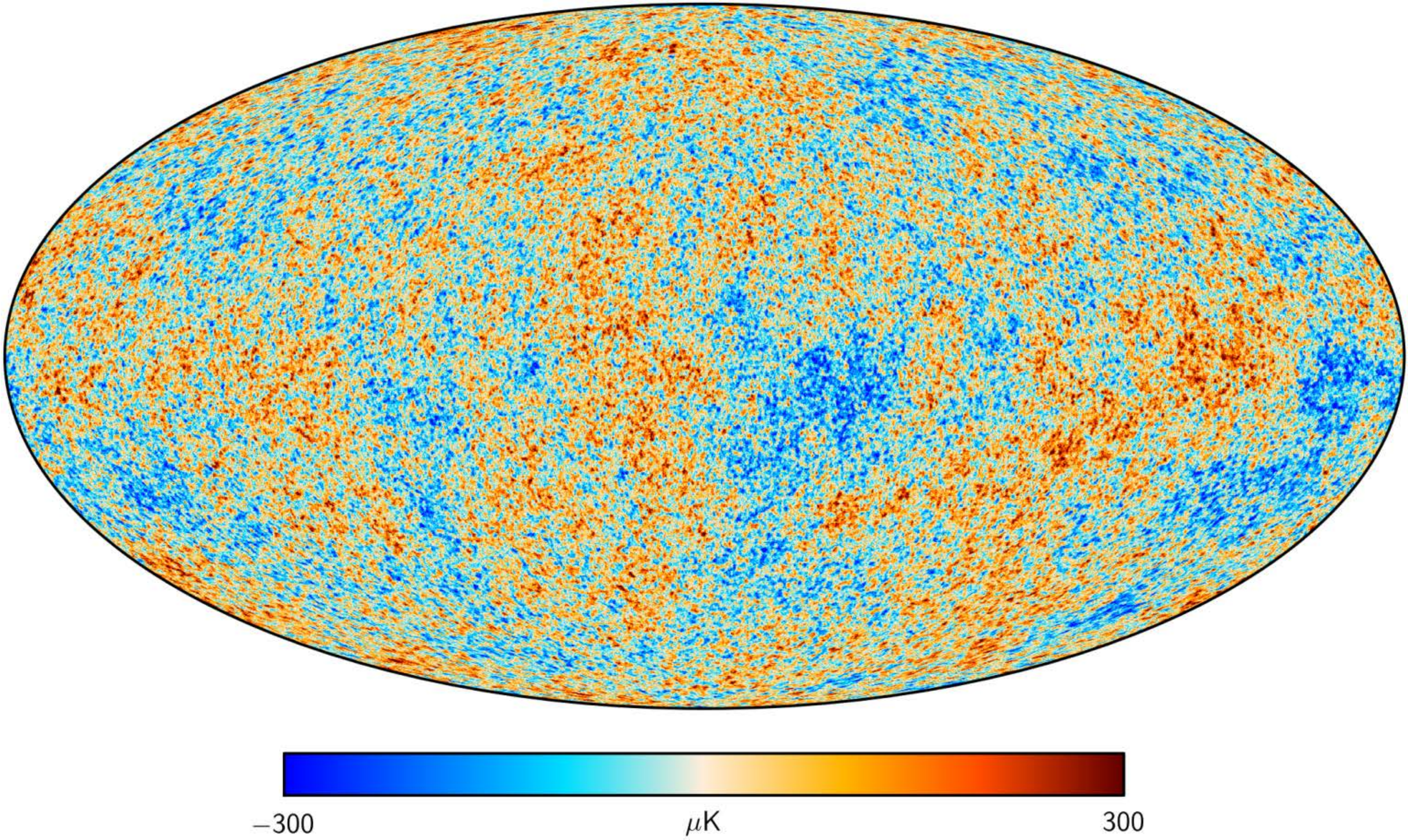
The Planck Legacy in a snapshot

- ✓ Ultimate Anisotropy Temperature maps at all CMB scales
- ✓ To date, unprecedented sensitivity Anisotropy Polarization full sky maps
- ✓ And much more……

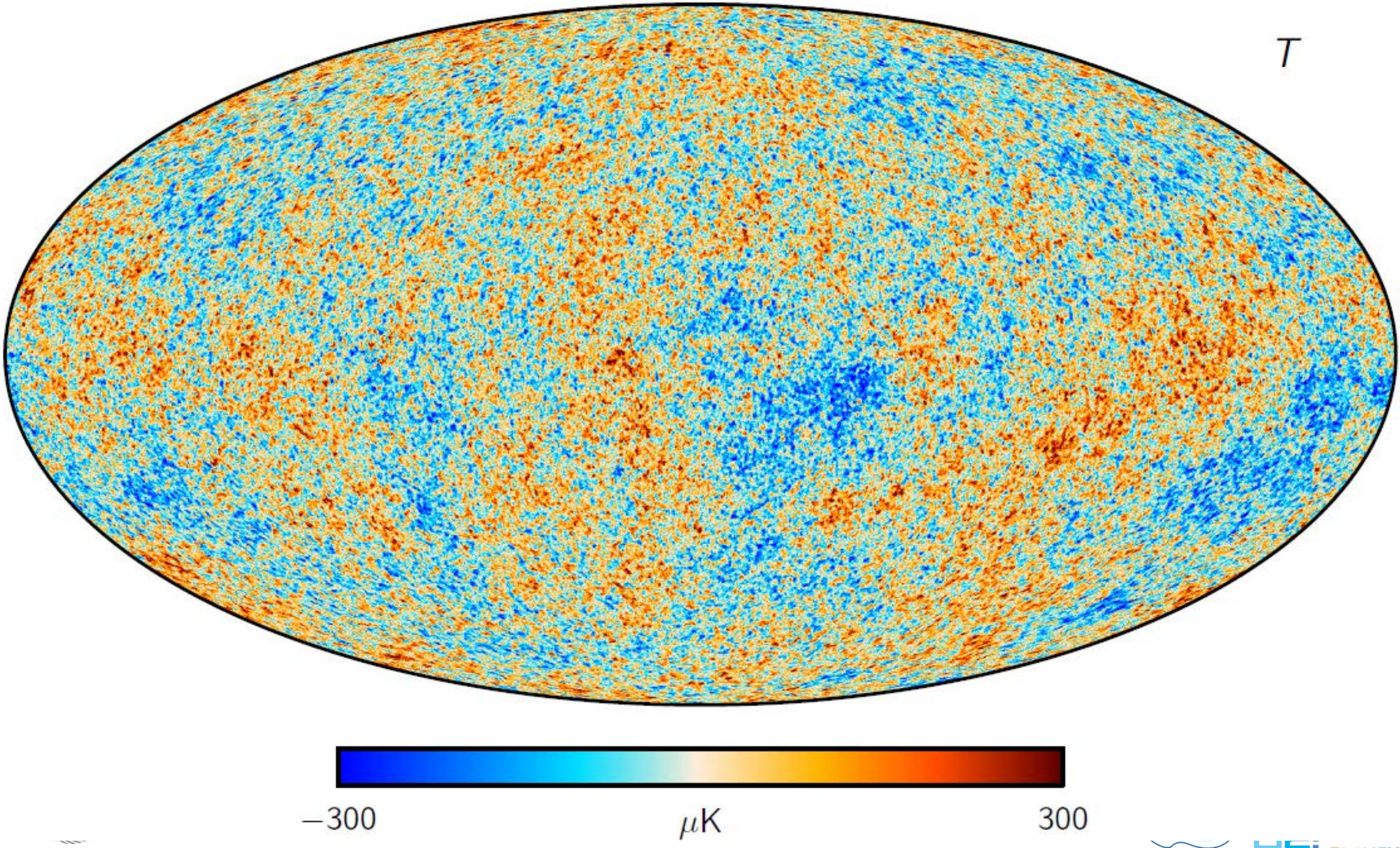
T map: 2013



T map: 2015



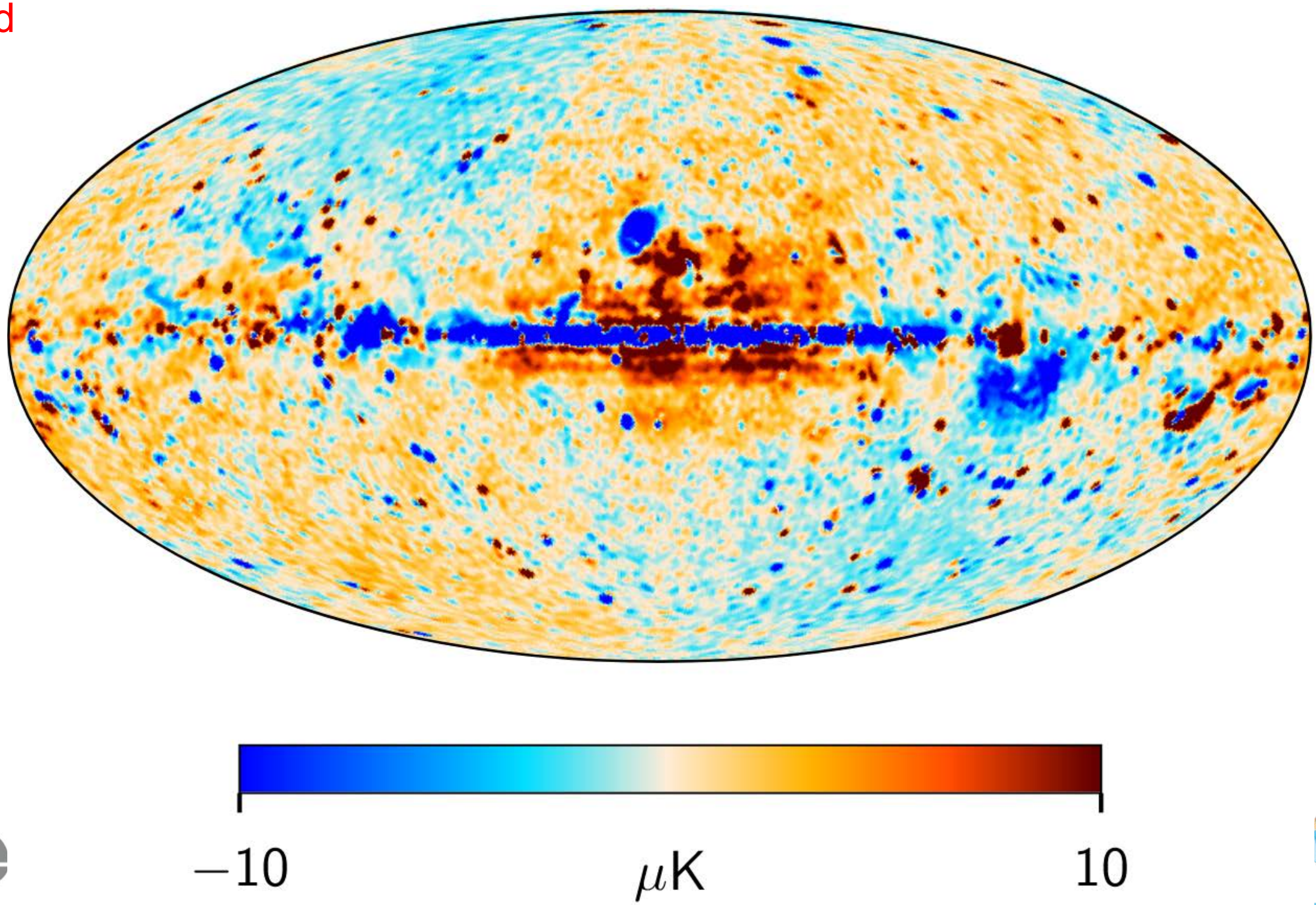
T map: 2018



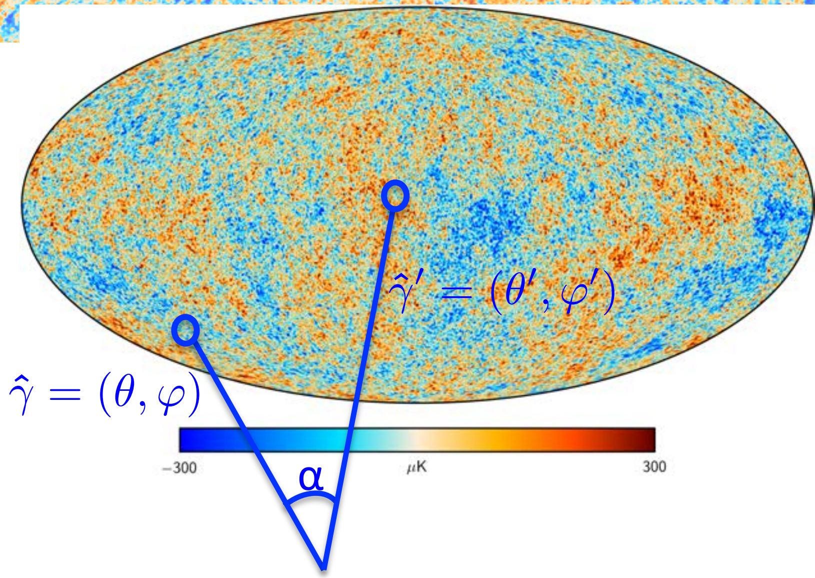
2015-2018 @ 80'

planck

In 2018 sources are removed



Statistical description



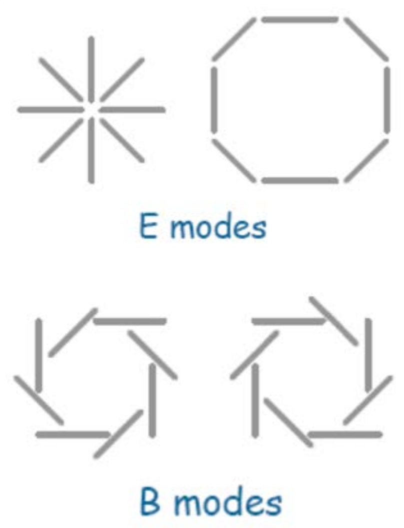
Correlation functions

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}) \frac{\Delta T}{T}(\vec{\gamma}') \right\rangle$$ ← from Inflation

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}) \frac{\Delta T}{T}(\vec{\gamma}') \frac{\Delta T}{T}(\vec{\gamma}'') \right\rangle$$

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}) \frac{\Delta T}{T}(\vec{\gamma}') \frac{\Delta T}{T}(\vec{\gamma}'') \frac{\Delta T}{T}(\vec{\gamma}''') \right\rangle$$

...



POLARIZATION

$$\mathbf{P}(\hat{\gamma}) = \nabla \mathbf{E} + \nabla \times \mathbf{B}$$

E-modes: even under parity

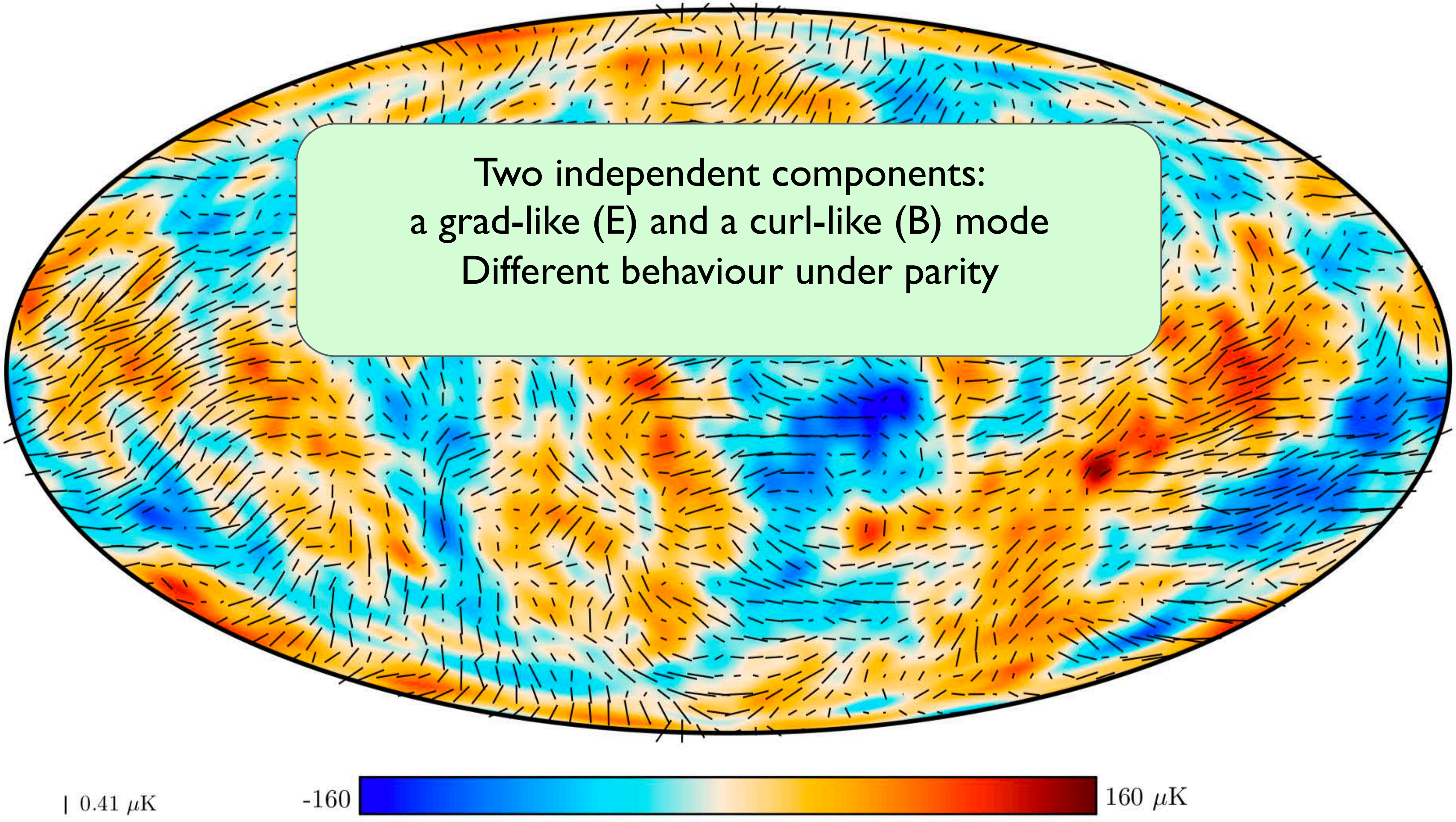
B-modes: odd under parity

Density perturbations -> E-modes

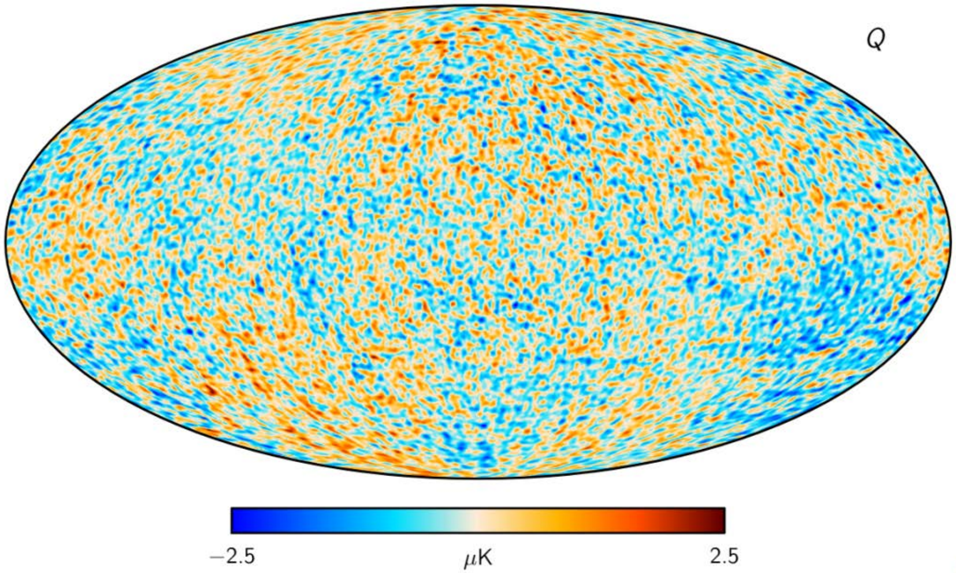
Gravitational Waves -> E- and B-modes

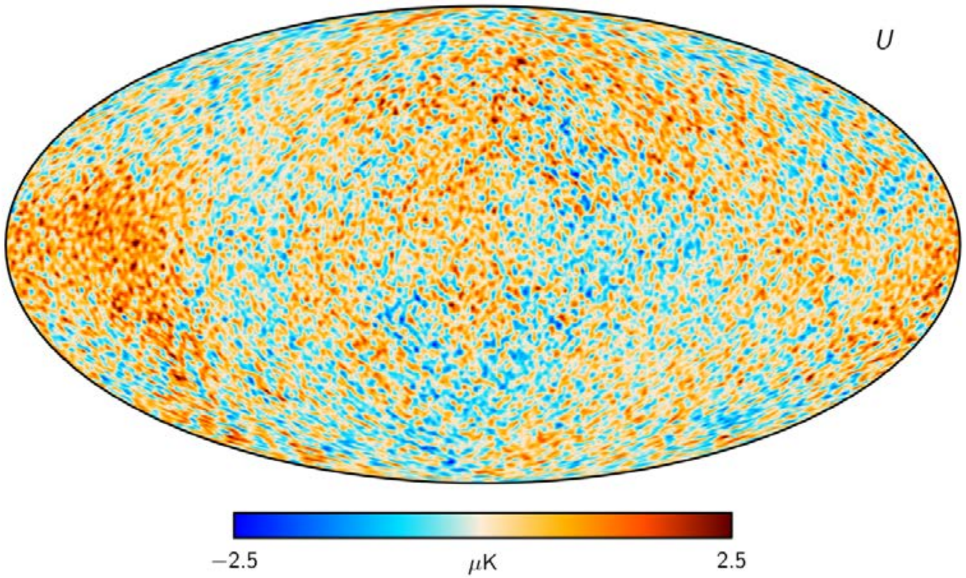
PLANCK: POLARIZATION ANISOTROPIES

Two independent components:
a grad-like (E) and a curl-like (B) mode
Different behaviour under parity

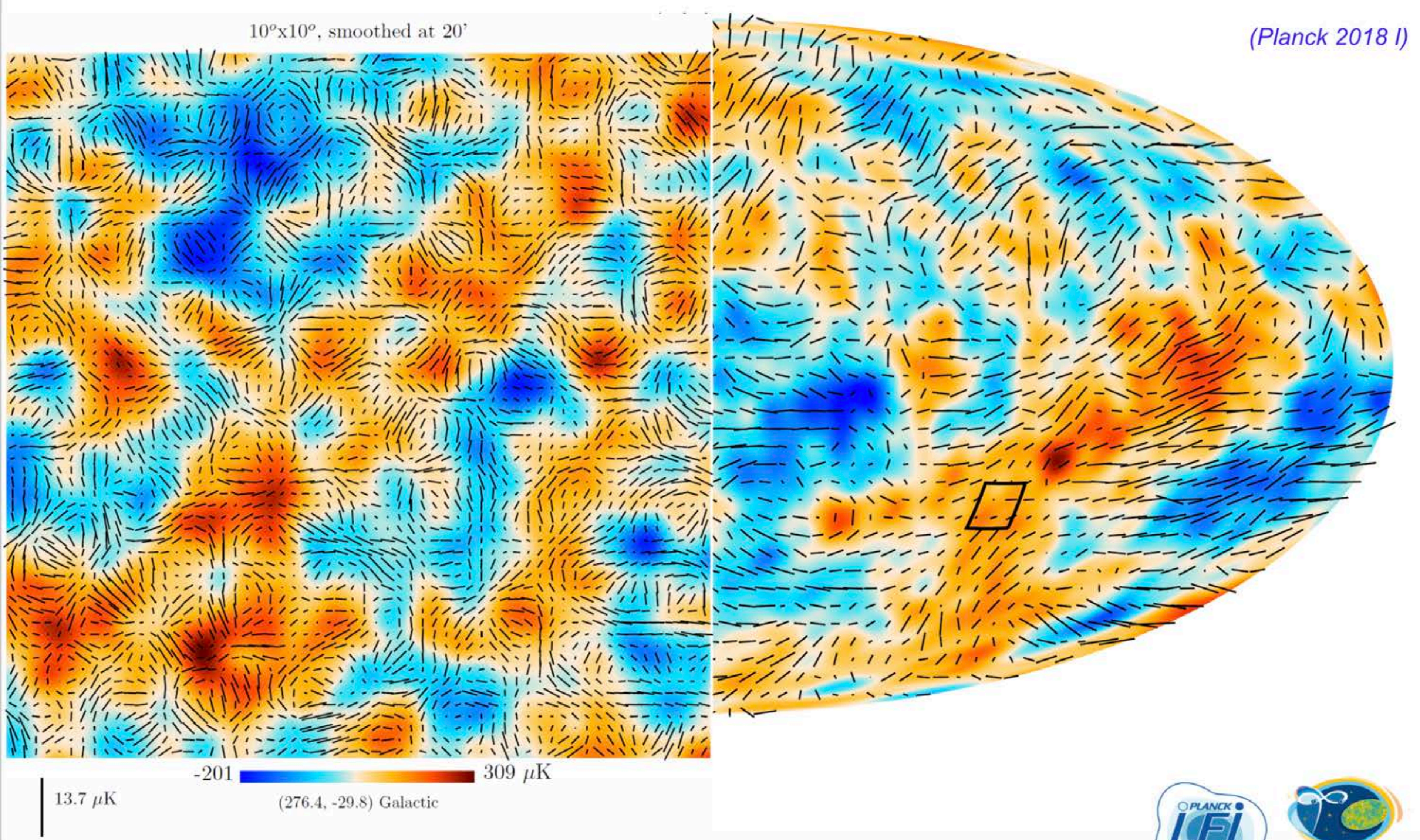


2018
Q and U @80’





PLANCK: POLARIZATION ANISOTROPIES



Planck-WMAP(V+W) comparison

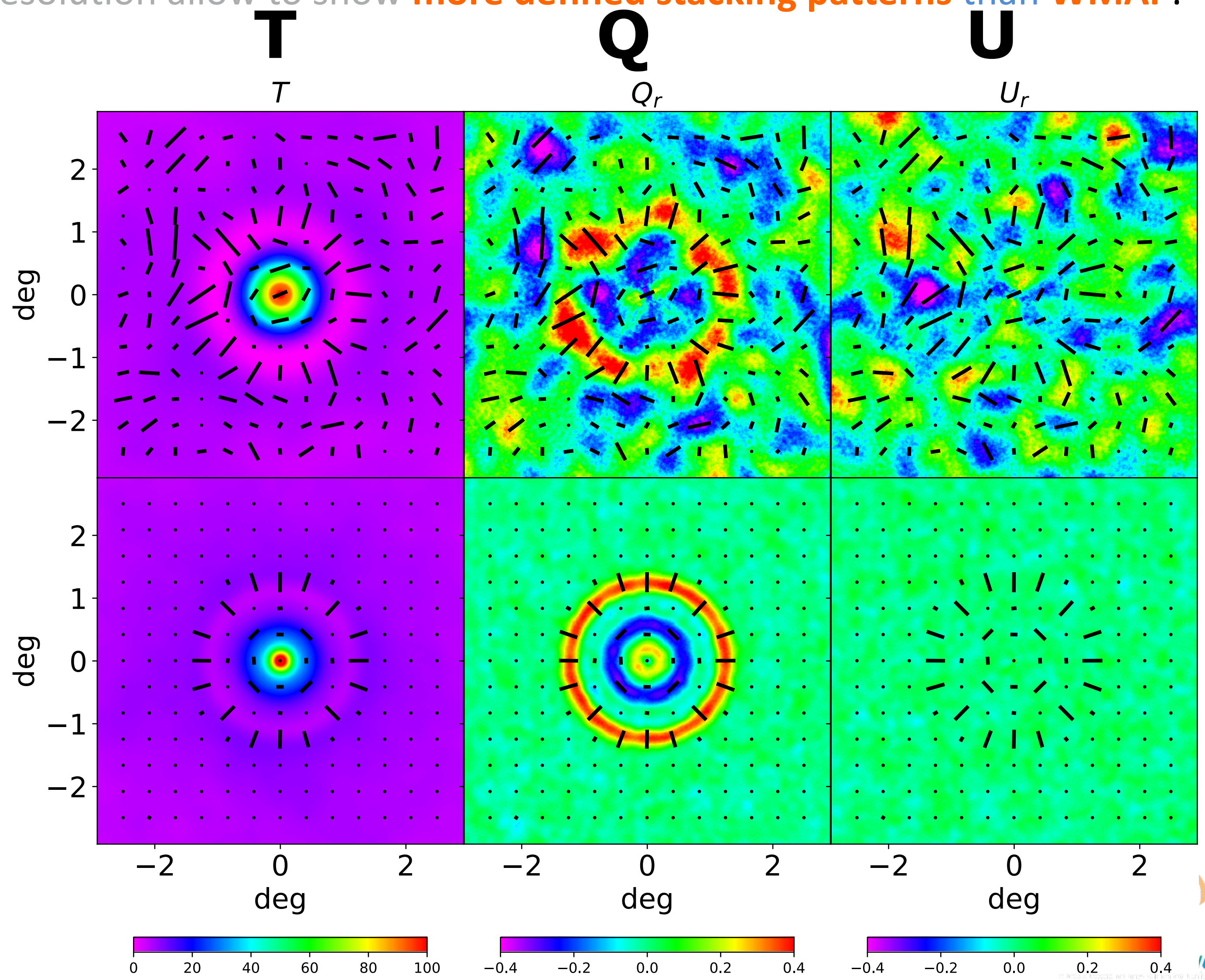
planck

Stacking of polarization maps on intensity peaks

Planck sensitivity and resolution allow to show **more defined stacking patterns** than **WMAP**.

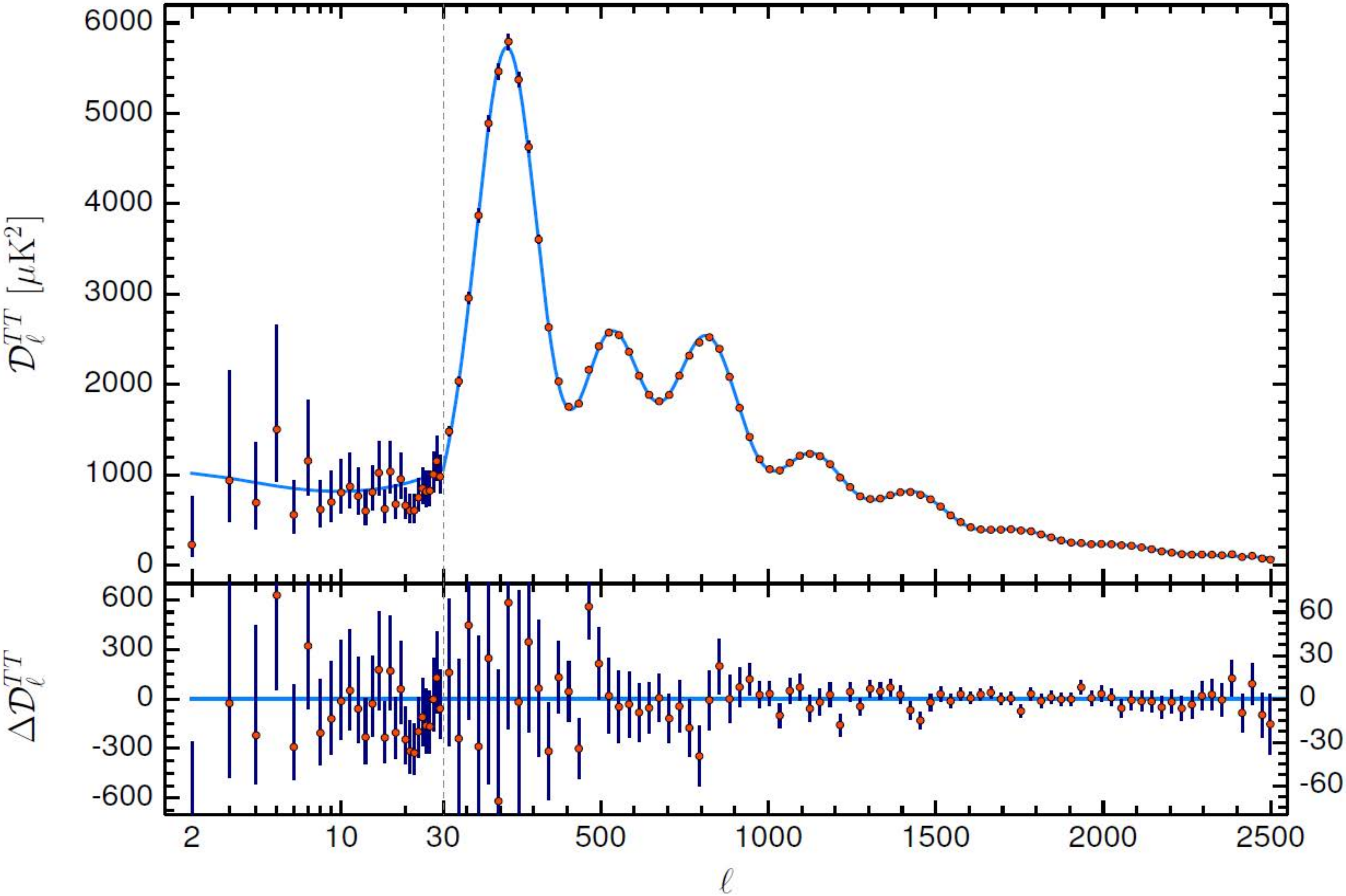
top: **WMAP**: V+W band
at N_{side} = 512 (30′)

Bottom: **Planck**:
at N_{side} = 1024 (10′)

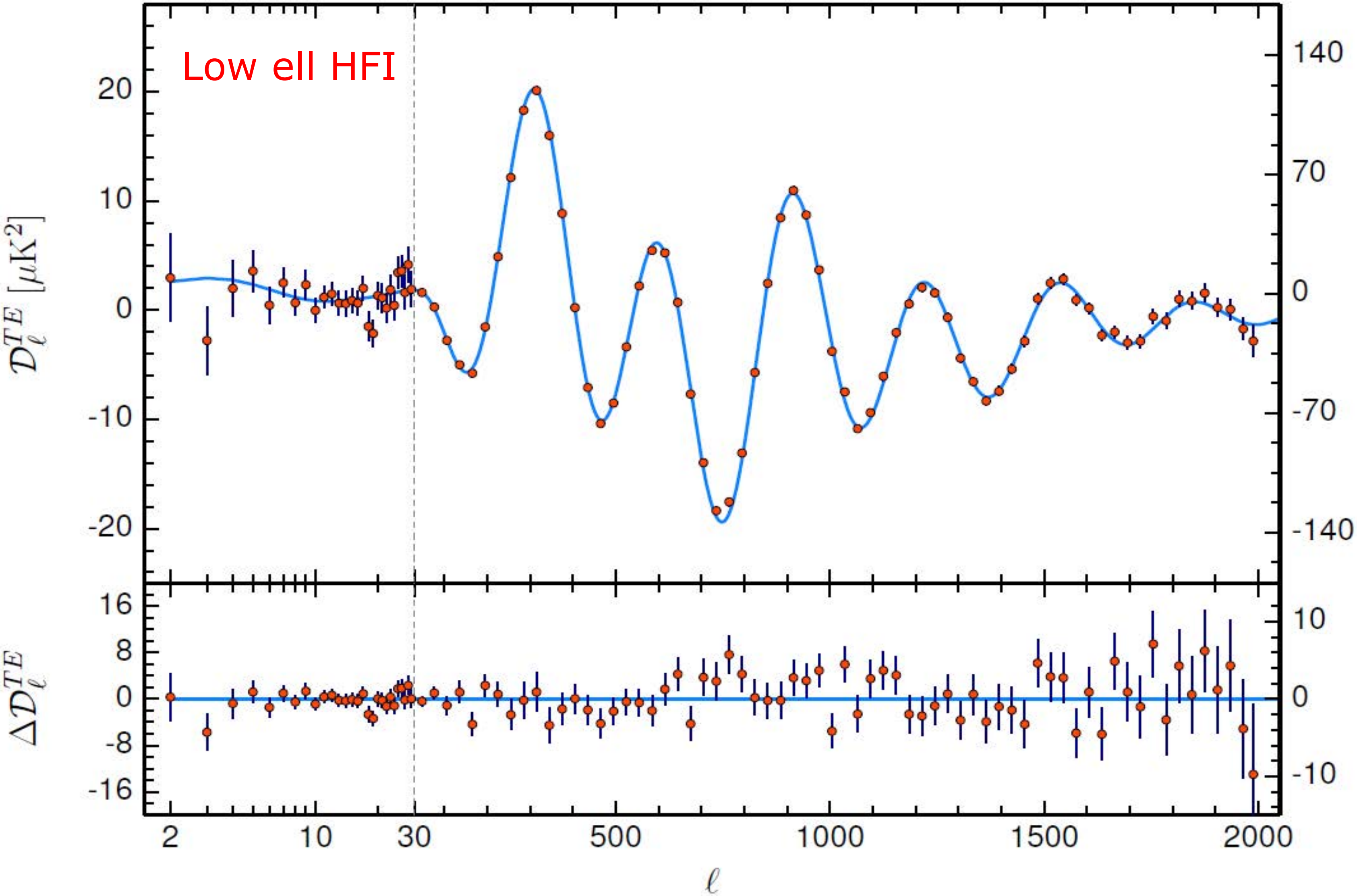


esa

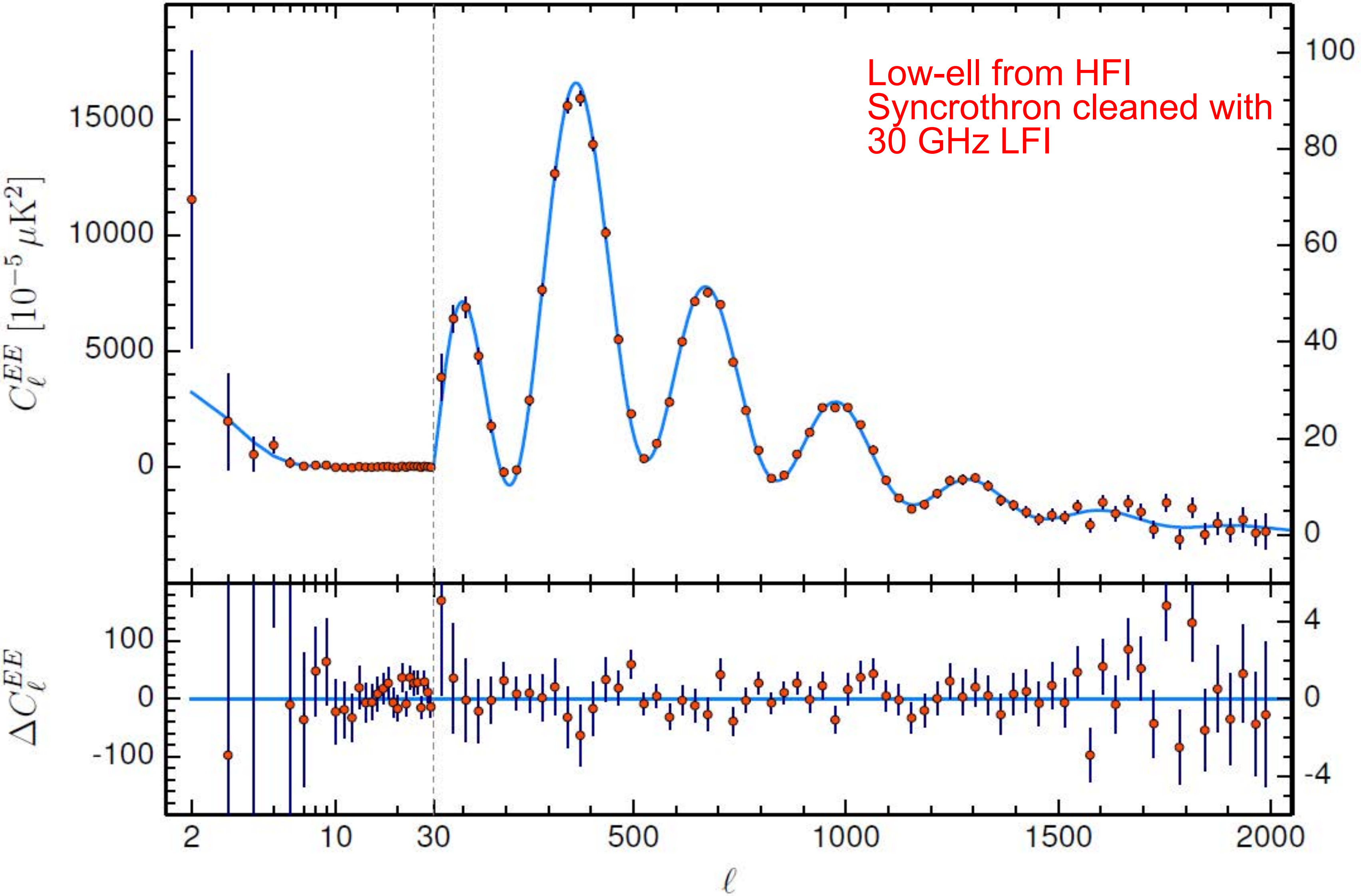
2018 Planck TT



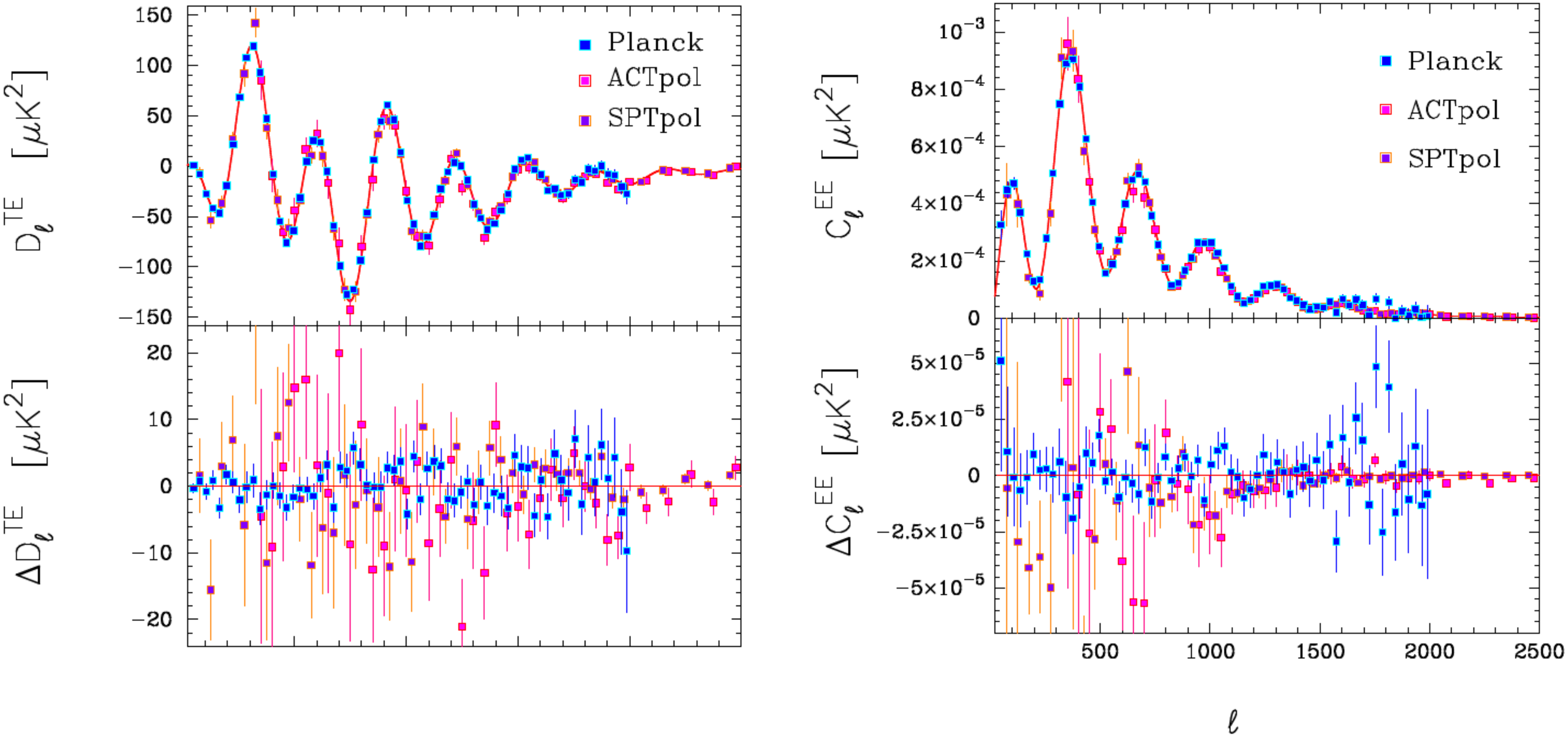
2018 Planck TE



2018 Planck EE



Comparison with ground-based experiments



ΛCDM results 2018 (T+Pol+lensing)

	Mean	σ	[%]
$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.7
$\Omega_c h^2$ DM density	0.1200	0.0012	1
100θ Acoustic scale	1.04092	0.00031	0.03
τ Reion. Optical depth	0.0544	0.0073	13
$\ln(A_s\, 10^{10})$ Power Spectrum amplitude	3.044	0.014	0.7
n_s Scalar spectral index	0.9649	0.0042	0.4
H_0 Hubble	67.36	0.54	0.8
Ω_m Matter density	0.3153	0.0073	2.3
σ_8 Matter perturbation amplitude	0.8111	0.0060	0.7

Robust against changes of likelihood, $<0.5\sigma$ (σ is small!)

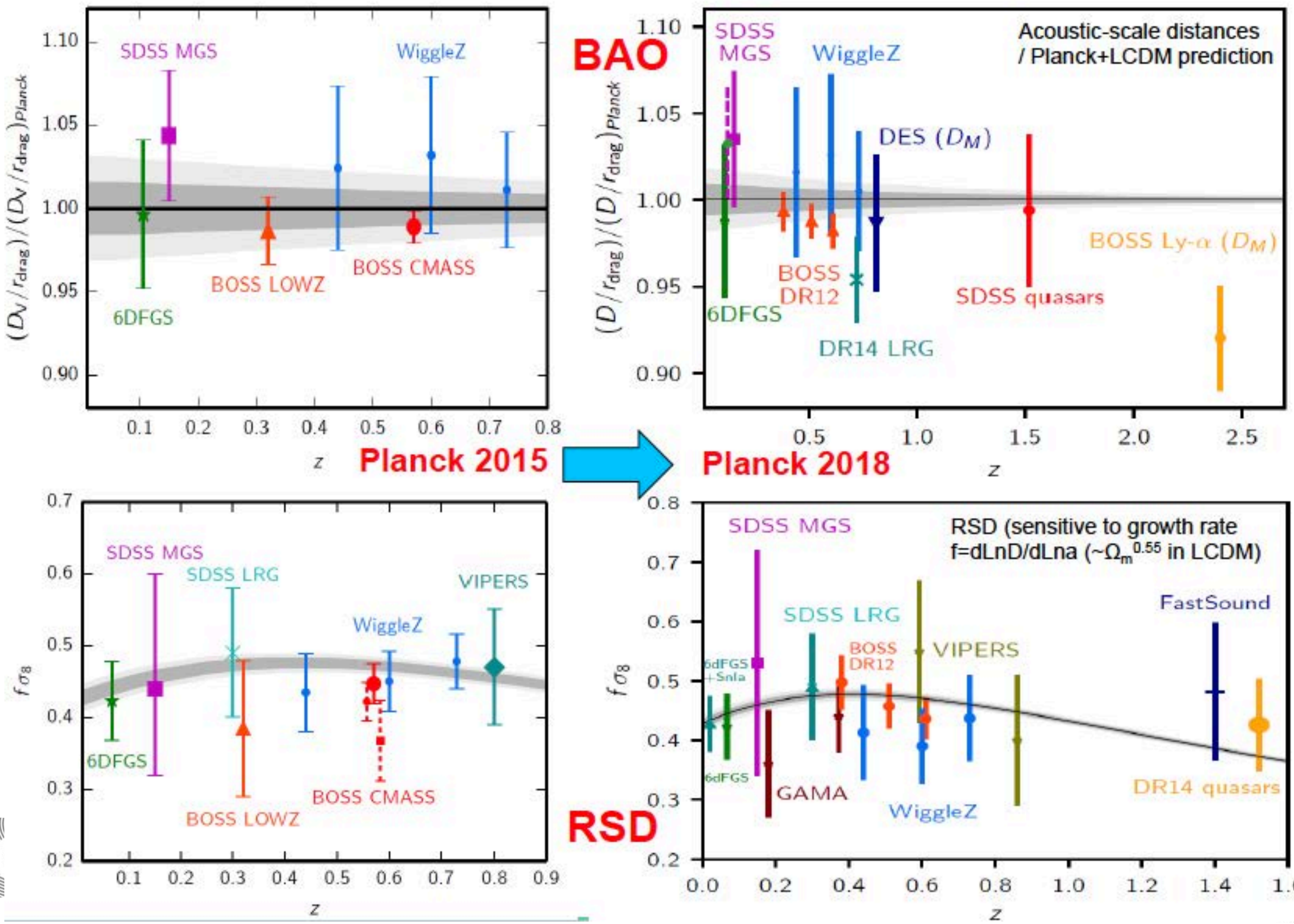
- Most of parameters determined at (sub-) percent level!
- Best determined parameter is the angular scale of sound horizon θ to 0.03%.
- n_s is 8σ away from scale invariance (even in extended models, always $>3\sigma$)
- Best **(0.8%)** determination of the Hubble constant to date.

ΛCDM results 2018

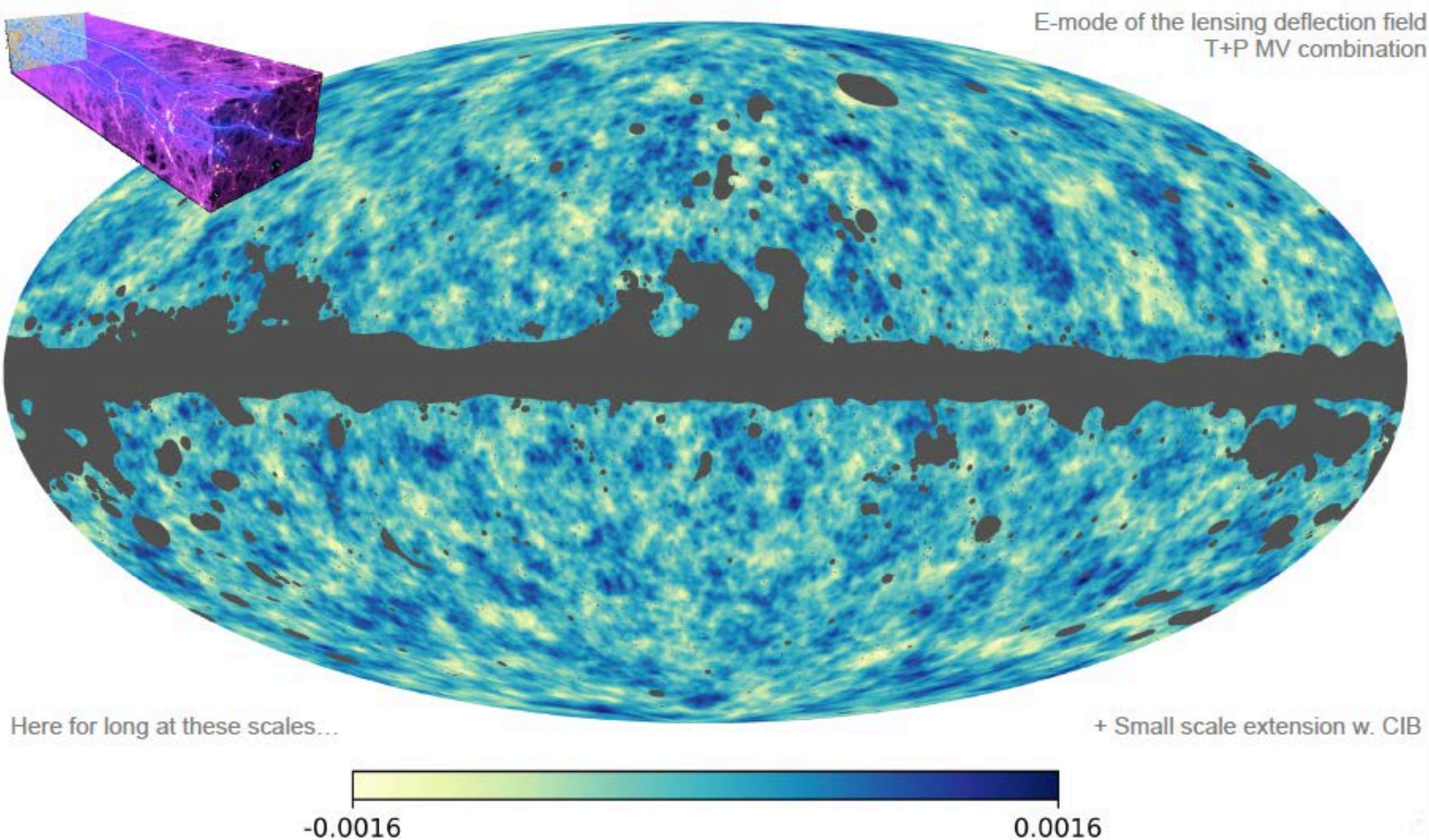
From a joint fit to Planck temperature, polarisation and lensing data

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
$k_{eq}[\mathrm{Mpc}^{-1}]$	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

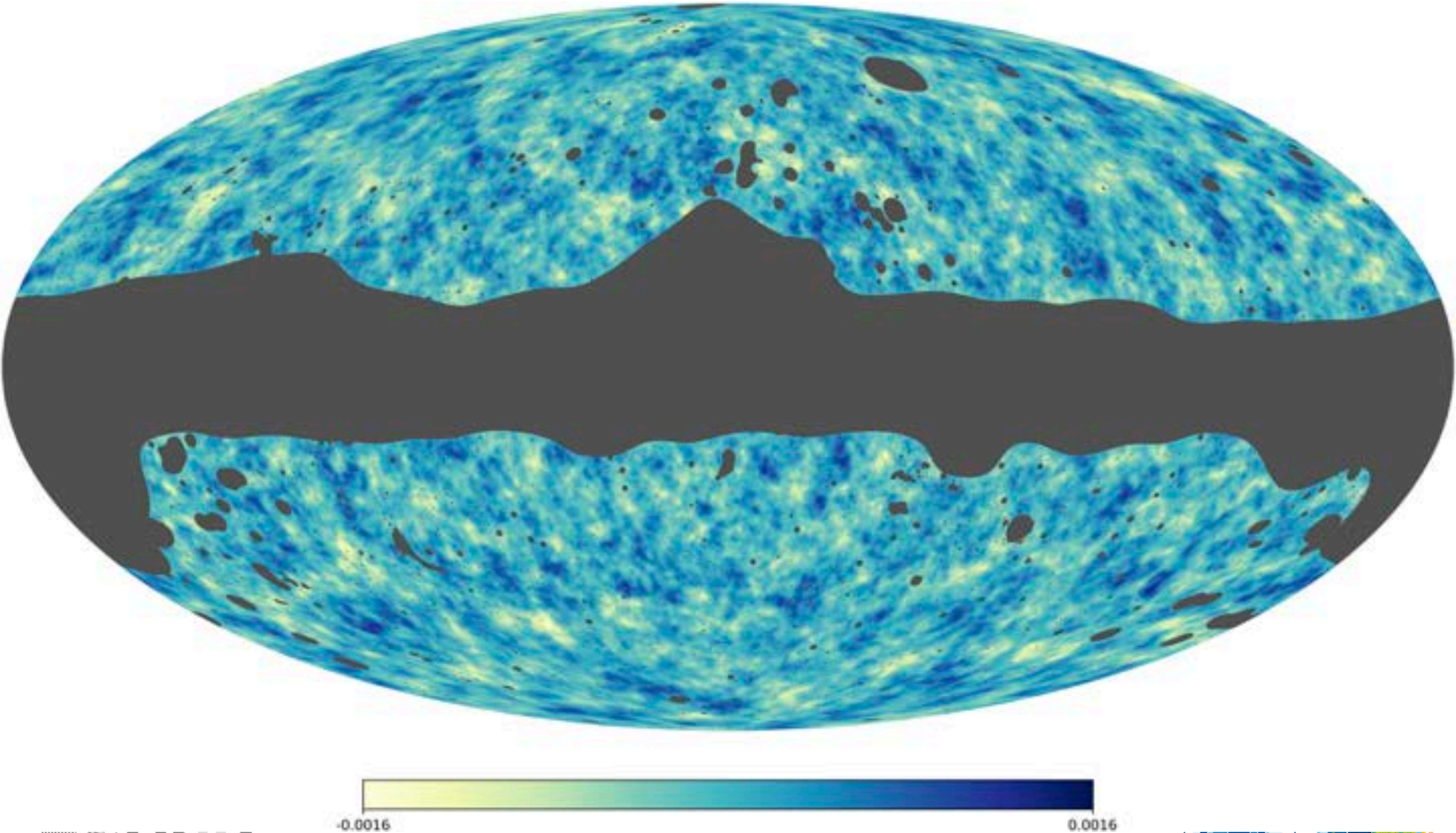
Improved consistency with BAO and RSD



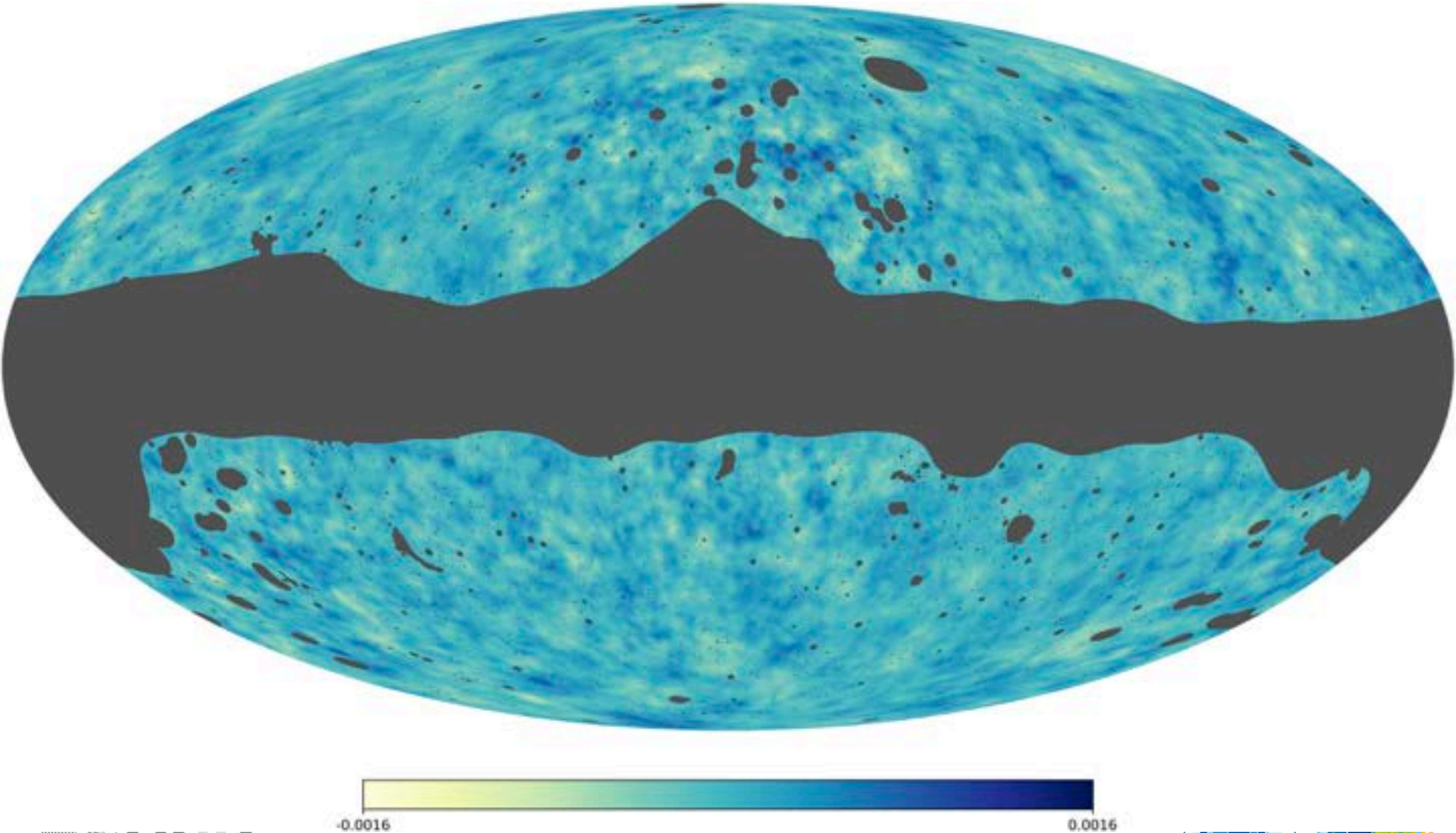
2018 lensing map - MV

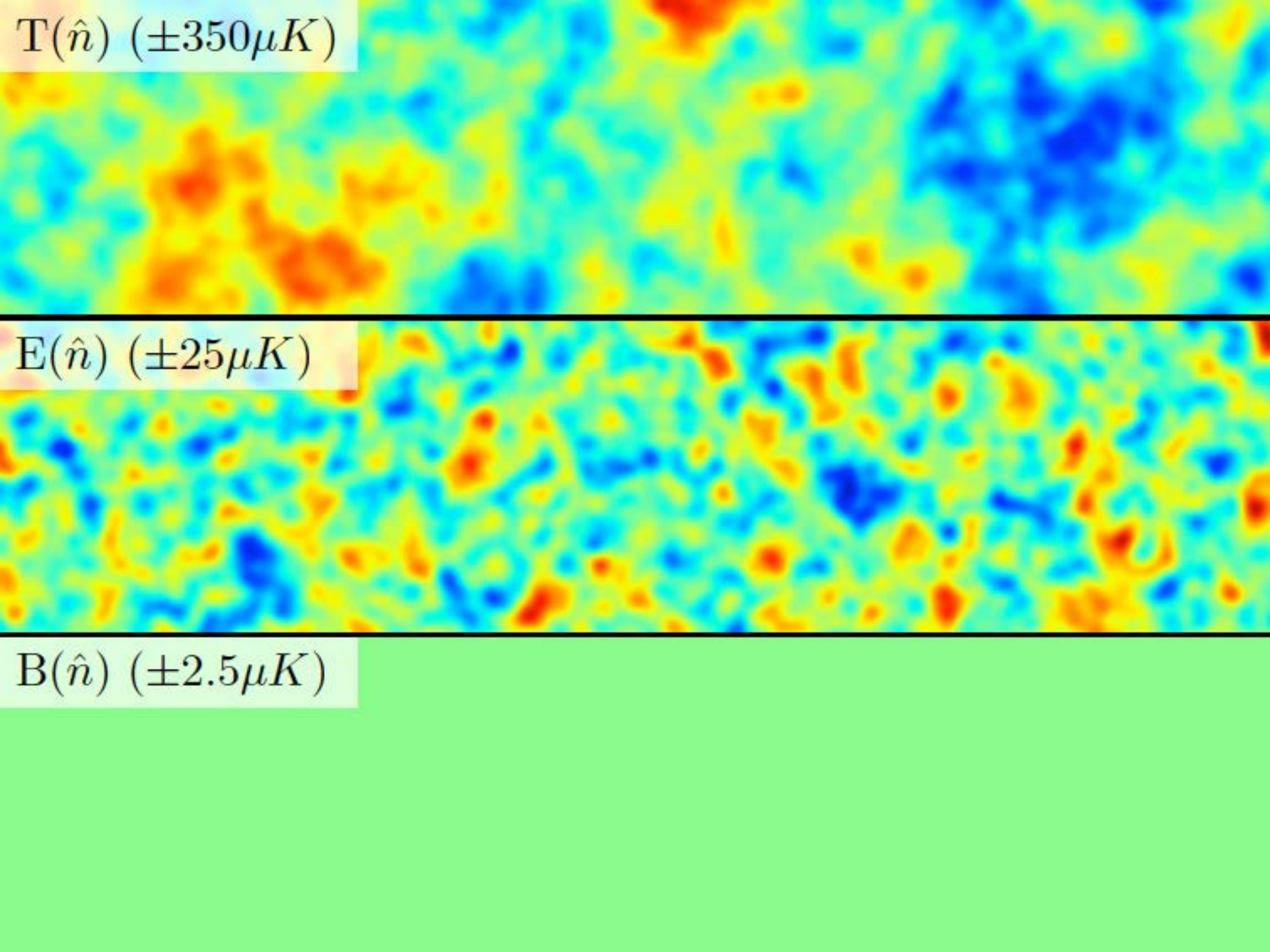


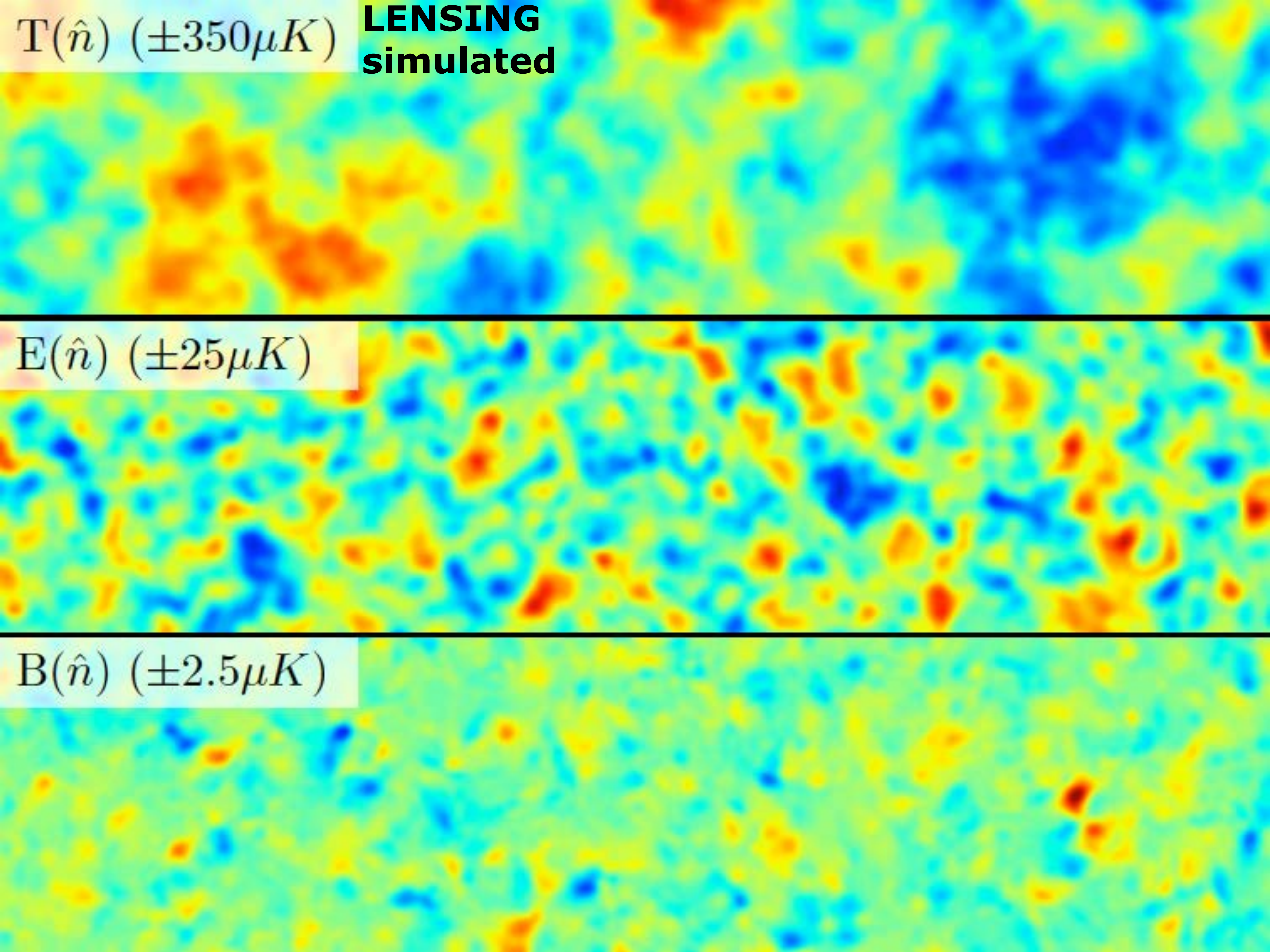
2018 lensing map - TT

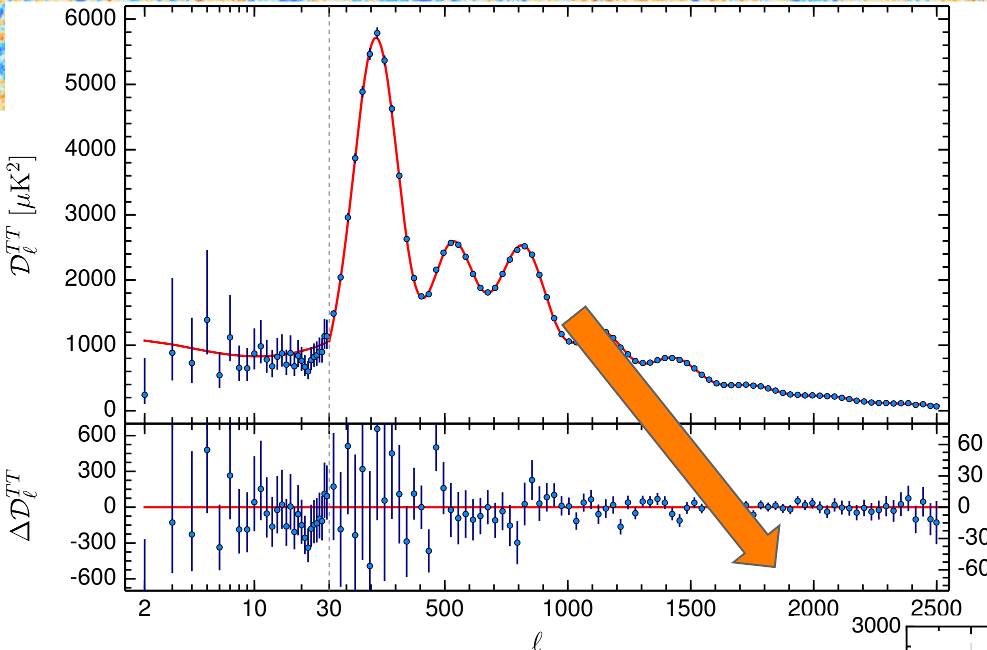


2018 lensing map - Pol..



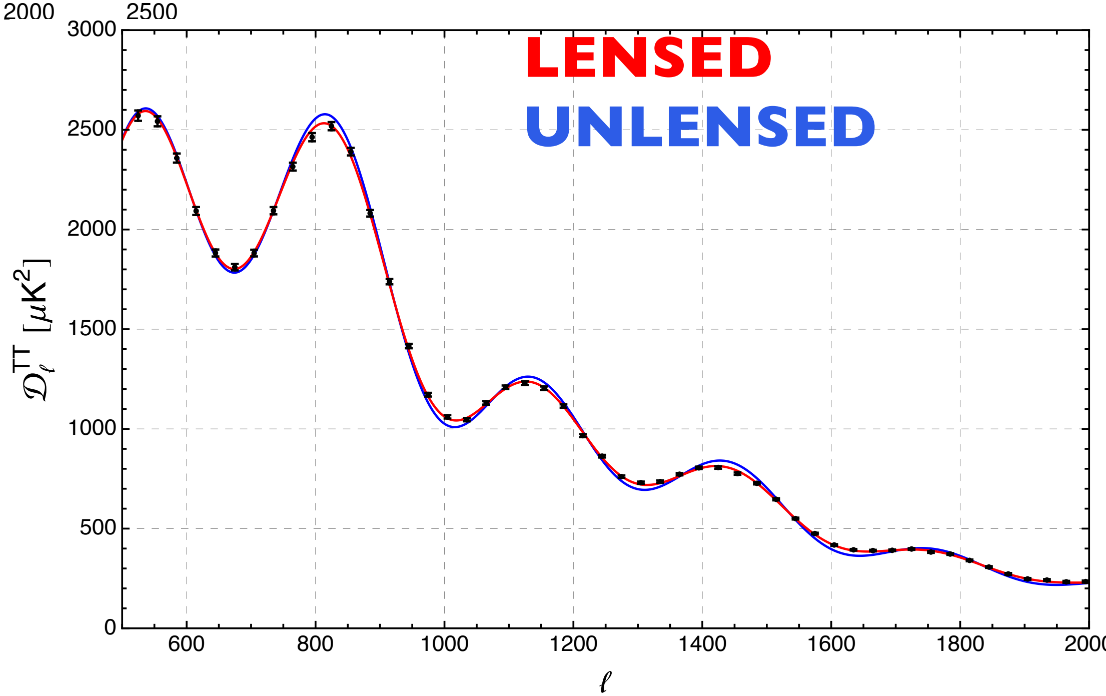

T($\hat{n}$) ($\pm 350\mu K$)
E($\hat{n}$) ($\pm 25\mu K$)
B($\hat{n}$) ($\pm 2.5\mu K$)


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

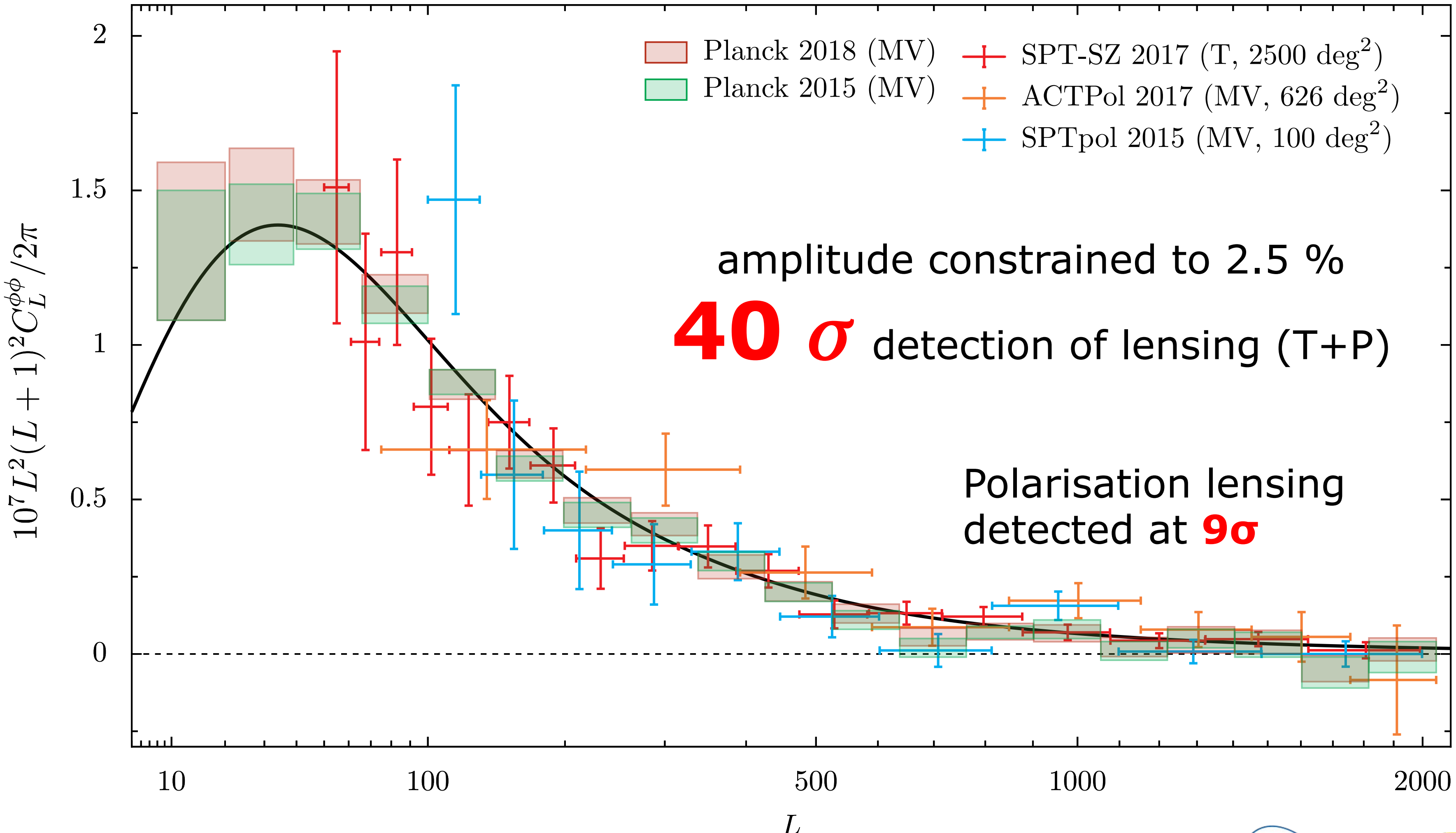


Lensing smooths the peaks of the CMB power spectrum…

… and introduces non-gaussianities in the map (nonzero 4-point c.f.)

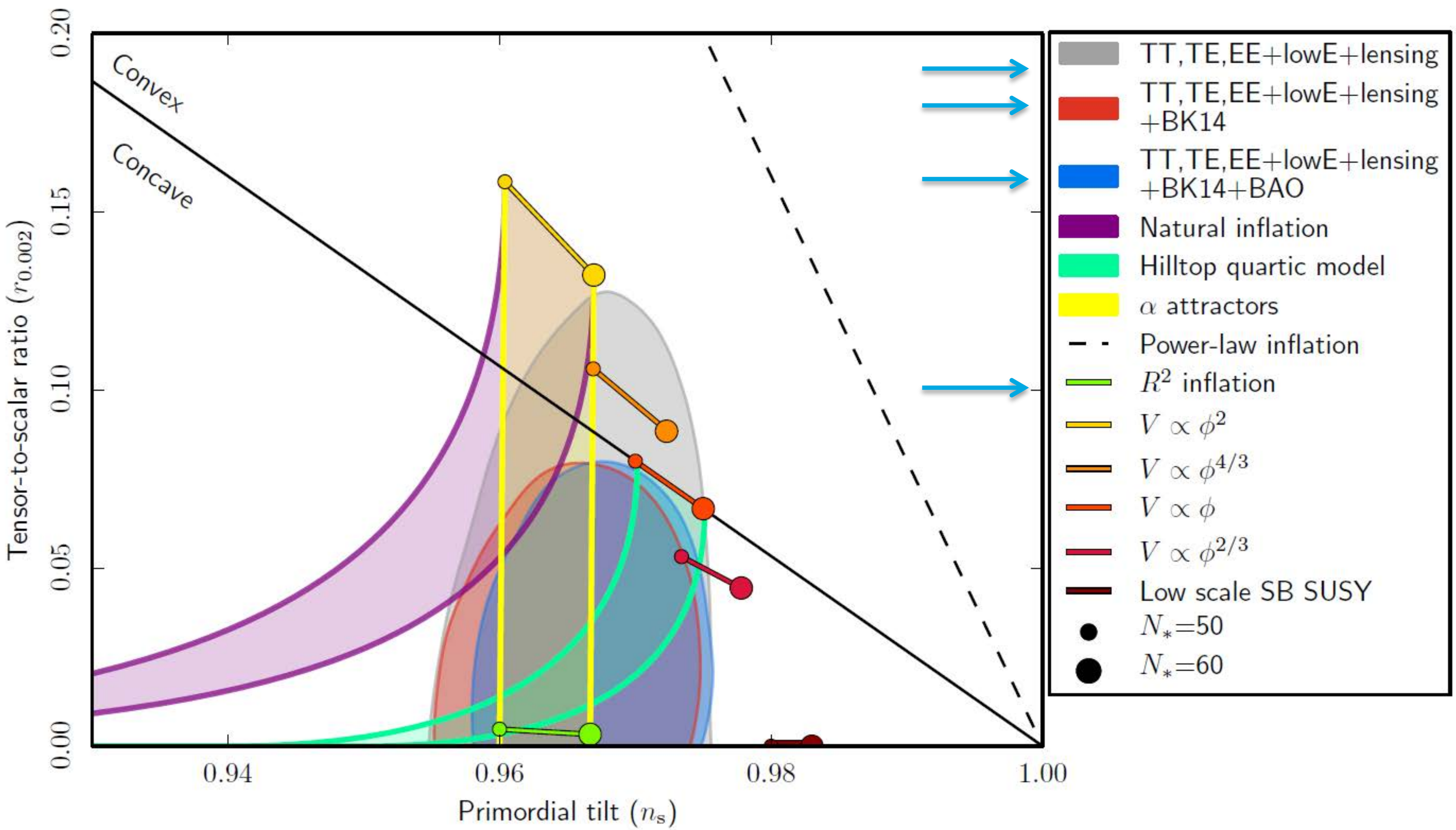


Lensing Potential Power Spectrum



Shifts from 2015 explained from different masks and SMICA weights

Inflation Physics



Are tensor modes required?

planck

Primary parameter r the tensor-to-scalar ratios at k =0.002 Mpc^{-1} (approximately ell<100) with theoretical prior $n_t = -r/8$

Planck 2018 + BK14 $r_{0.002} < 0.064$ $n_t = -r/8$ (95%CL)

A stochastic background of gravitational waves (GW) with a blue tensor tilt can be further constrained at much shorter wavelength as those probed by ground-based interferometers dedicated to the direct detection of GWs. The LIGO/VIRGO upper bound (Abbott et al. 2016) on the GW energy density translates in an upper bound on r on short scales.

$$\Omega_{\rm GW}(f) \leq 1.7 \times 10^{-7} \quad (95\%{\rm CL}) \quad \text{at } f = 20\,{\rm Hz}$$

$$\Omega_{\rm GW}(k) = \frac{k}{\rho_{\rm critical}} \frac{d\rho_{\rm GW}}{dk} = \frac{A_{\rm t1}(k/k_1)^{n_{\rm t}}}{24 z_{\rm eq}}$$

$$r \leq 2.6 \times 10^{7} \quad (95\%{\rm CL}) \quad \text{at } k = 1.3 \times 10^{16}\,{\rm Mpc}^{-1}$$

Planck 2018 + BK14 + LIGO/VIRGO and relaxing $n_t = -r/8$ $r_{0.002} < 0.069$ $-0.62 < n_t < 0.53$ (95%CL)

esa

PLANCK LFI

HFI PLANCK

Beyond Planck
The OPEN (?) questions

- ✓ Anomalies at large angular scales
- ✓ Omega-k and Alens
- ✓ Tensions between large and small scales
- ✓ Tensions between low and high redshift probes

↓

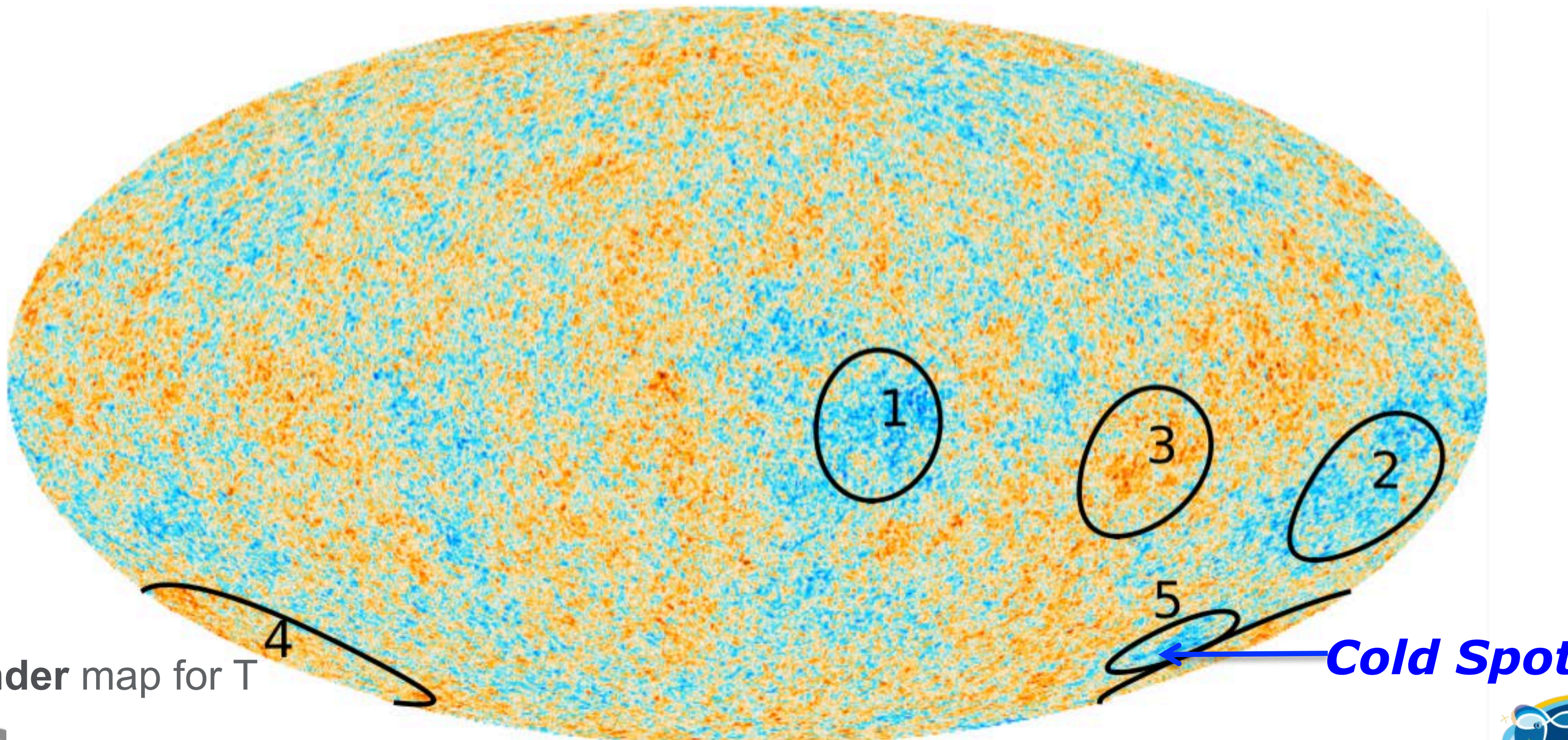
Need for high precision (goal: cosmic variance limited) full sky polarization maps

Anomalies in the CMB field

- At large angles, the CMB field is known to exhibit anomalies:
  - Lack of power
  - Hemispherical asymmetry
  - Even-odd asymmetry
  - And others…
- For temperature, Planck has reached cosmic variance. For polarization, there is much room for improvement.

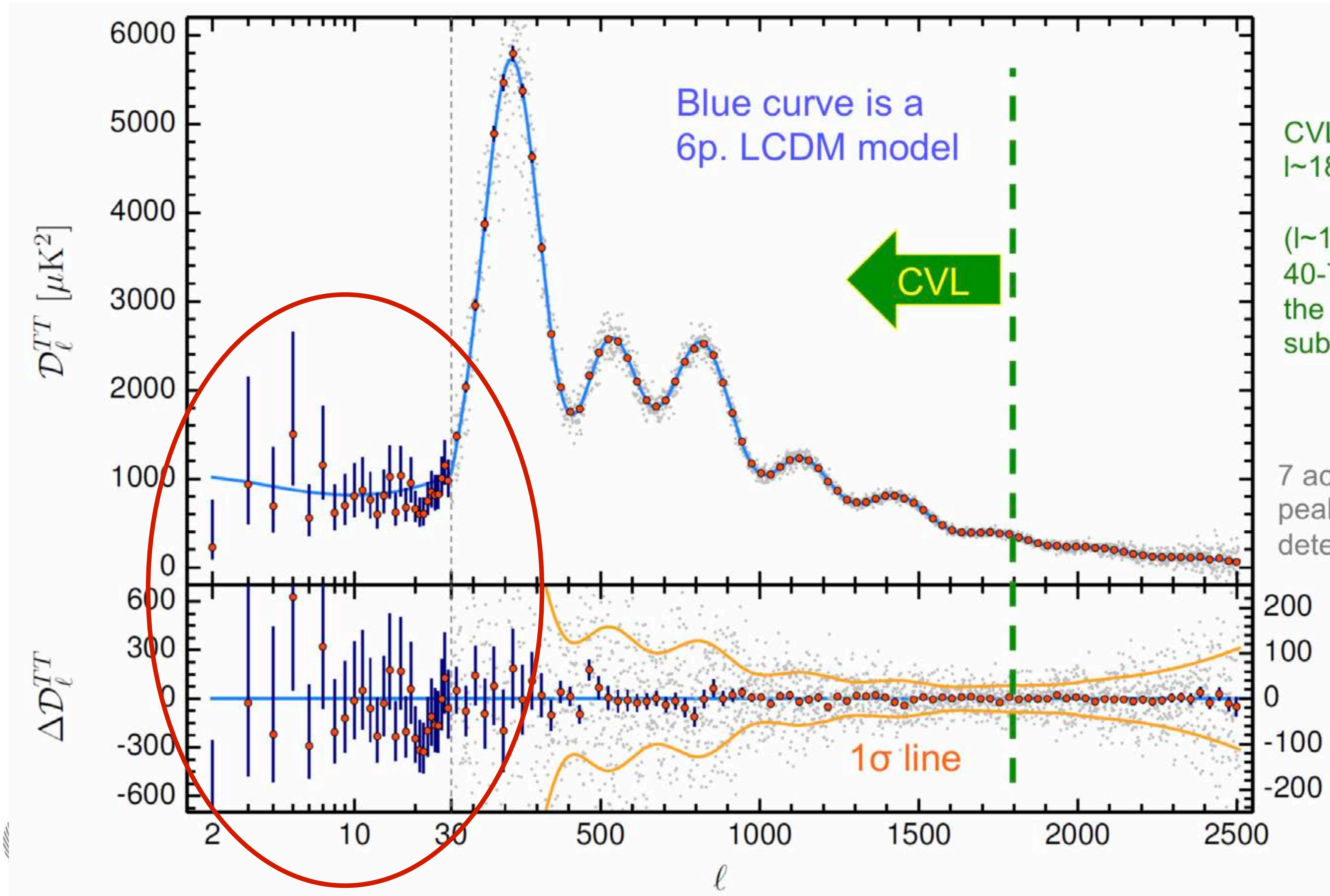
The *Cold Spot* and other large-scale peaks

The ***Cold Spot*** is an **anomalous** CMB feature of **large area** and a **very negative amplitude**, and a **large kurtosis** at scales of around **5 deg**.
Besides the ***Cold Spot*** we are also investigating the multipolar profiles of **four more large-scale peaks**, which have been previously identified anomalous features at very large scales (at 10 deg).



Commander map for T

Planck 2018 TT power spectrum



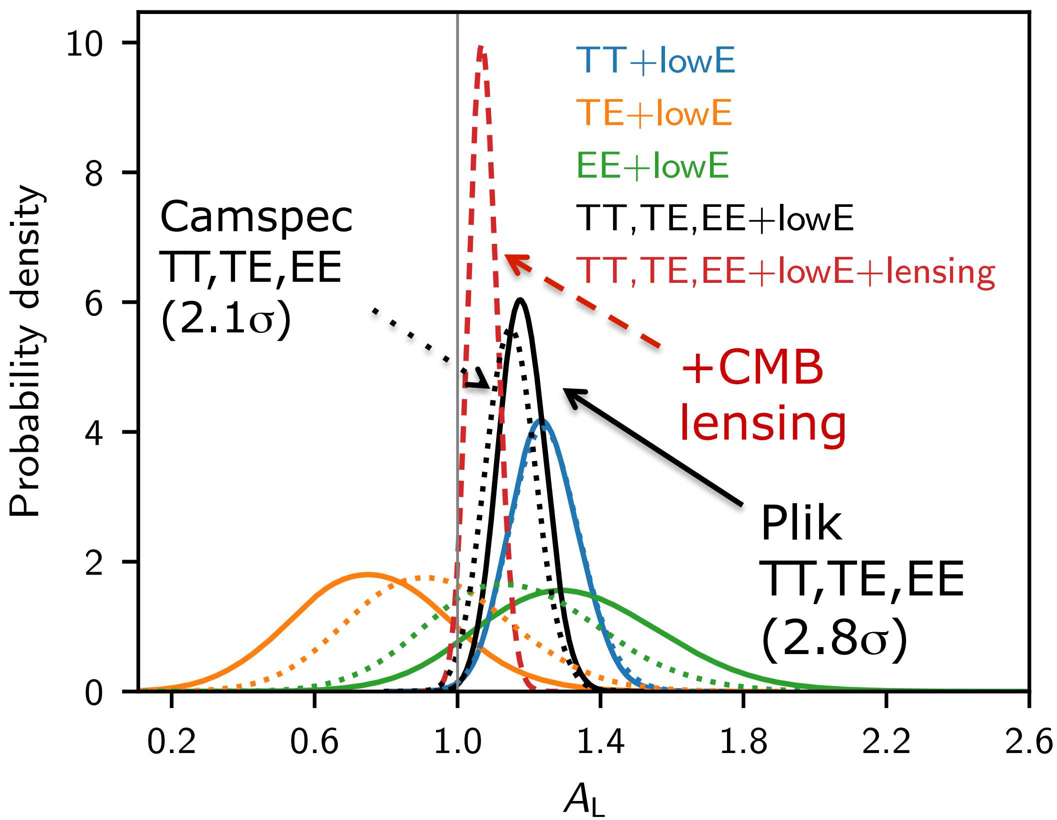
CVL
l~18

(l~16
40-7
the s
subs

7 acc
peak
detecoustic
ks well
cted

A_{Lens} issue: a statistical fluke?

- Unphysical parameter used for consistency check.
- Preference for high A_L from Planck since 2013 (A_L expected to be 1)
- Not due to lensing: Predicted 4 points correlation function (lensing) is exactly what Planck measures
- Due to contrast on high ell acoustic peaks
- **It could be a statistical fluctuation/new physics/ systematics (but no evidence so far)**

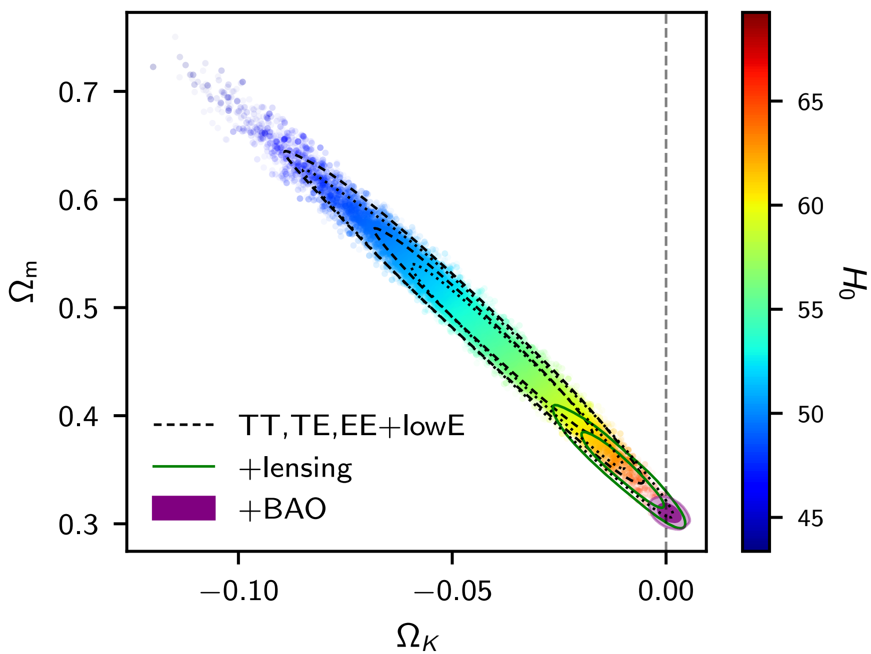


Amplitude of the lensing potential power spectrum. In ΛCDM=1

Different treatment of systematics in polarization (as done in our two likelihoods Camspec and Plik) can impact extensions of ΛCDM at ~0.5σ level.

Curvature and Dark Energy

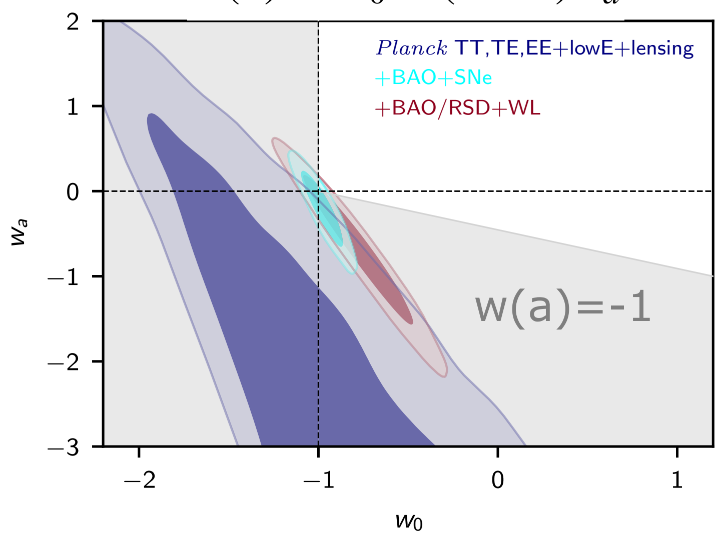
- Both curvature $\Omega_k<1$ and phantom dark energy w<-1 can provide larger lensing amplitude, thus preferred by TTTEEE
- Results between Plik and CAMspec differ at **~<0.5σ level.**
- When adding CMB lensing reconstruction, less preference for deviations, further tightened by BAO.



Curvature

$$\Omega_K = 0.0007 \pm 0.0019 \quad (68\,\%, \text{TT,TE,EE+lowE+lensing+BAO}).$$

$$w(a) = w_0 + (1-a)w_a$$

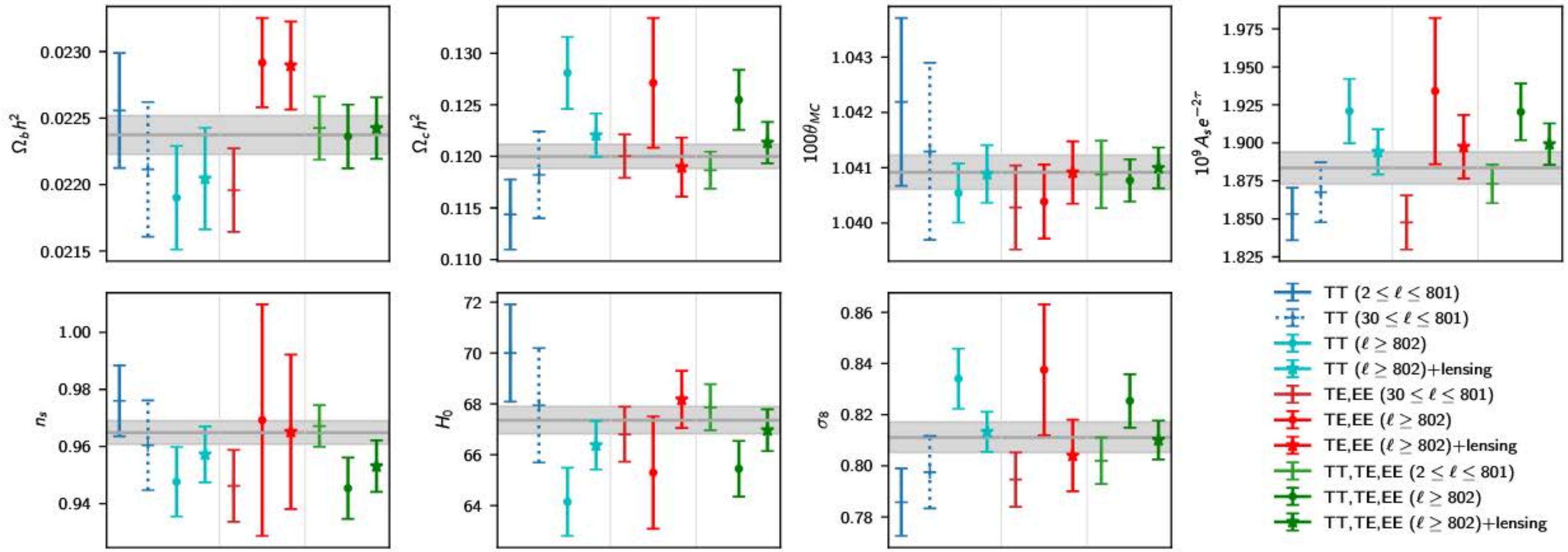


Dark energy equation of state

$$w_a = 0,$$

$$w_0 = -1.028 \pm 0.032 \quad (68\,\%, \textit{Planck}\ \text{TT,TE,EE+lowE+lensing+SNe+BAO}),$$

Tensions low-high ell ?



The results of Planck analysis comparing parameters measured from ell=30-1000 with those measured from 1000-2500 agree with what published in the Planck papers but are cleaner because taking into account of reduced foregrounds. Therefore there is nothing anomalous -- the parameters shifts are consistent with expectations. There is, however (see previous slides), some tension when we add the low ells from ell=2-30 (LFI).

This might be just a consequence of the low amplitudes at ell<30 that we have known about since WMAP. It's possible that there is new physics that suppresses the low ell multipoles -- but the statistical significance is not high.

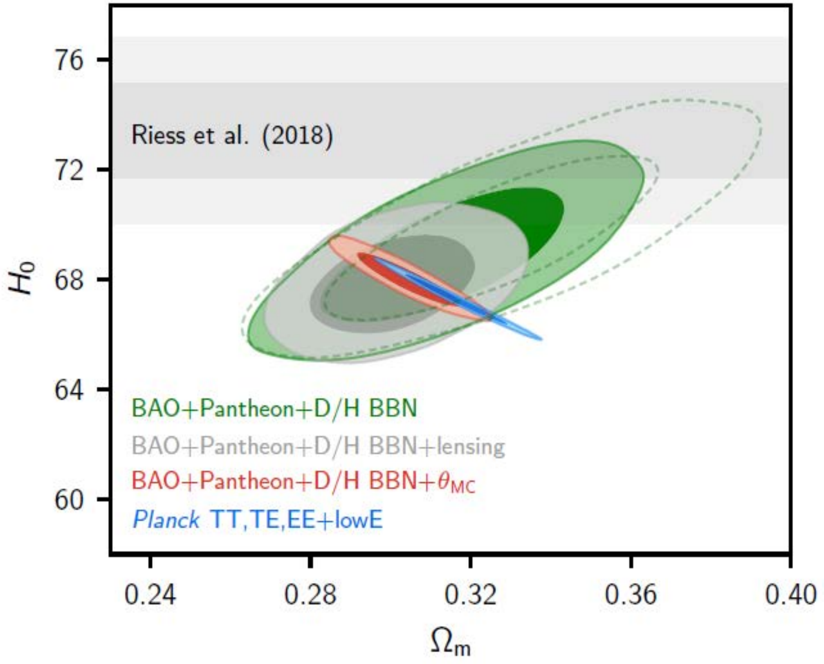
Tension: H_0 (3.8 sigma)

planck

Low-High redshift evolution?

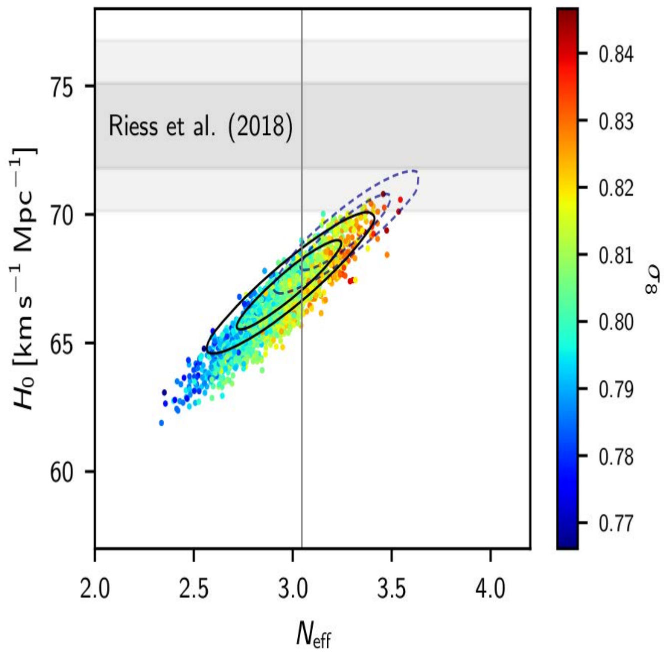
New physics or systematics?

Primordial deuterium abundances allow to constrain the sound horizon and this gives constraints that agree with the base LCDM model. So, if we want to resolve the tension between CMB and H_0, we have to change the sound horizon while preserving BBN and the acoustic peak structure of the CMB!!!!!!



esa

The neutrino legacy of Planck (1)



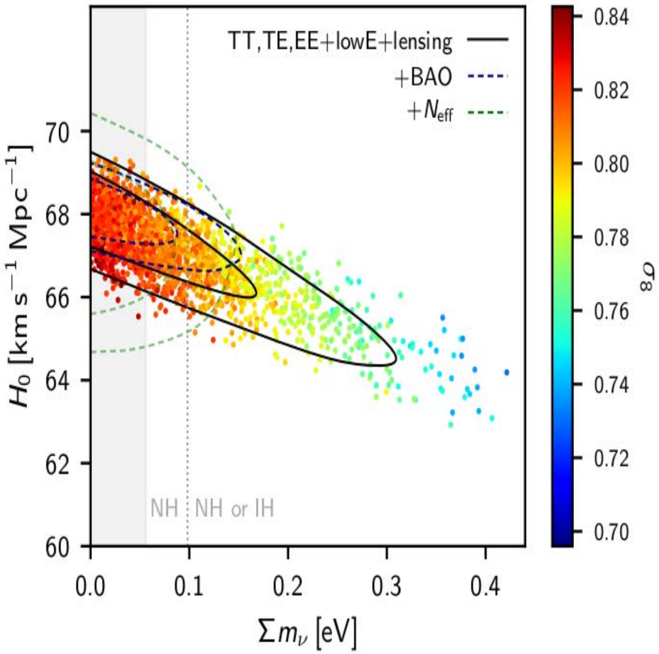
$$N_{eff} = 3.00^{+0.57}_{-0.53}$$ (95% CL, TT+lowE)

$$N_{eff} = 3.11^{+0.44}_{-0.43}$$ (95% CL, TT+lowE+lensing +BAO)

- Effective number of relativistic species is consistent with the standard expectation $N_{eff} = 3.046$
- Data are consistent with these relativistic species behaving as free-streaming neutrinos – a strong indication that they are indeed the SM neutrinos!
- A fourth thermalized species ($N_{eff}=4$) is excluded at 3.5 to 6 σ, depending on the dataset
- A light sterile neutrino species is allowed if not thermalized. Still, the sterile neutrino interpretation of the short-baseline anomalies is excluded by Planck

The neutrino legacy of Planck (2)

planck



$M_\nu < 0.44$ eV (95%CL, TT + lowE + lensing)

$M_\nu < 0.13$ eV (95%CL,TT+lowE+lensing+BAO)

- Tightest constraint from a single experiment
- First constraint exploiting the information encoded in the CMB weak lensing
- One order of magnitude better than present kinematic constraints, already at the same level than future expectations for KATRIN
- The combined limits from Planck and large scale structure probes are starting to corner the inverted hierarchy scenario

esa

PLANCK LFI

HFI PLANCK

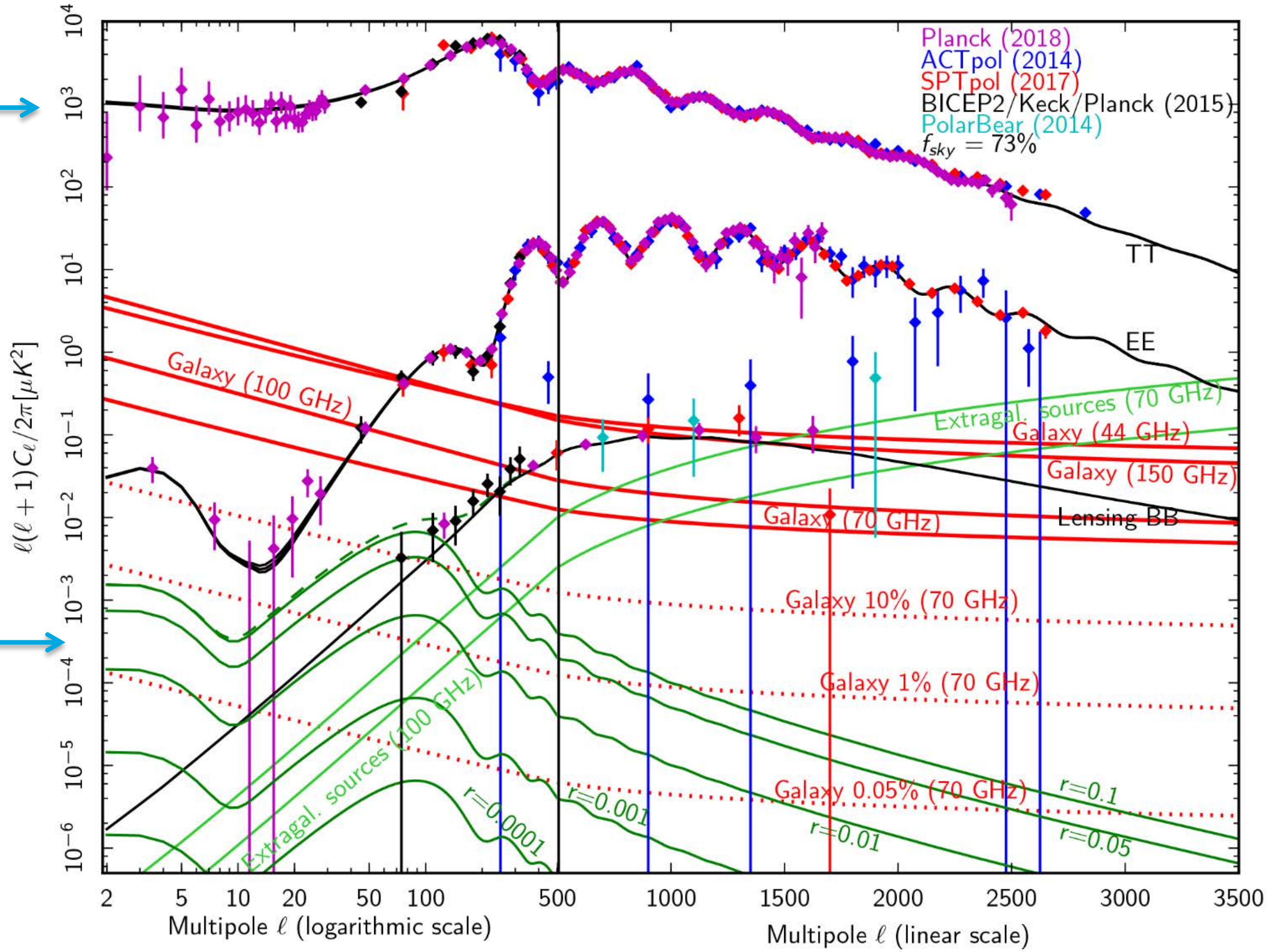
Planck exhausted the temperature
Polarization is the future

- The quest for B-modes
- Full sky E-modes cosmic variance limited

- Lack of power
- Reionization History
- Primordial Universe
- Neutrinos

Beyond Planck: Deal with the foregrounds and lensing

Courtesy of Molinari, Mandolesi, Burigana



10^8

Planck Legacy: main points

- ✓ Planck results stable across releases
- ✓ Polarization now better understood (~0.5 σ systematic uncertainty)
- ✓ Consistency with BAO, SN, RSD, DES lensing (in ΛCDM)
- ✓ Strong 3.8 σ tension with H_0 from distance ladder results
- ✓ Planck value in agreement with inverse distance ladder independent of CMB *(BAO+D/H+CMB lensing).*
- ✓ Some « anomalies » (low ell lack of power, A_L, low-high features, etc.), but not more than $2\sigma - 3\sigma$, no evidence for extensions of ΛCDM. Further investigations are needed.
- ✓ New Physics: ?????

WHAT'S NEXT IN ONE WORD

The legacy of Planck not only represents the status of the art of full sky microwave observations but the path to the future of CMB is:

POLARIZATION

"Foregrounds in polarization" are still very poorly known and this require a deep investigation. You will never be sure of a B-mode as long as foregrounds are not perfectly known beyond any doubt

TO PERFORM THE BEST POSSIBLE SEPARATION OF THE SKY COMPONENTS AS "**MANY FREQUENCY CHANNELS**" AS POSSIBLE ARE REQUIRED .
AND THE WIDEST FREQUENCY RANGE IN ORDER TO DISENTANGLE LOW FREQUENCY FOREGROUND COMPLEXITY

"Delensing". On small angular scales B-modes signal are dominated by the lensing. The only hope are delensing algorithms which need high resolution to be performant

THE FUTURE OF THE CMB MIGHT BE PROMISING
BUT
"COMPLEXITY WILL BE ORDERS OF MAGNITUDE HIGHER"

Experiments Beyond Planck

- Ground
- Balloon
- Space

Planck Legacy: Conclusions

Prediction	Measurement
A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$ 100
with a *nearly* scale-invariant (red)	
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$ 100
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$
dominated by scalar perturbations,	$r_{0.002} < 0.07$
which are Gaussian	$f_{NL} = 2.5 \pm 5.7$ 100
and adiabatic,	$\alpha_{-1} = 0.00013 \pm 0.00037$
with negligible topological defects	$f < 0.01$

100 This pictorial denotes a hundred fold improvement in precision since (at most) COBE

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