Cosmology with Planck and beyond

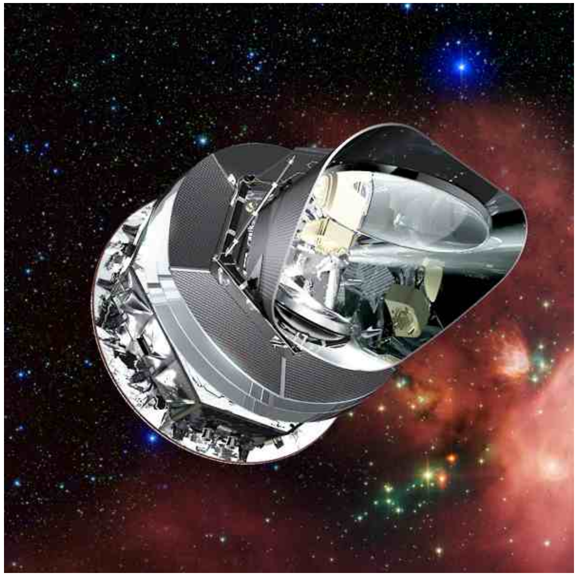
Paolo Natoli

Università di Ferrara and INFN

Les Rencontres de Physique de la Vallée d'Aoste

La Thuile– 6 March 2017

THE PLANCK SATELLITE



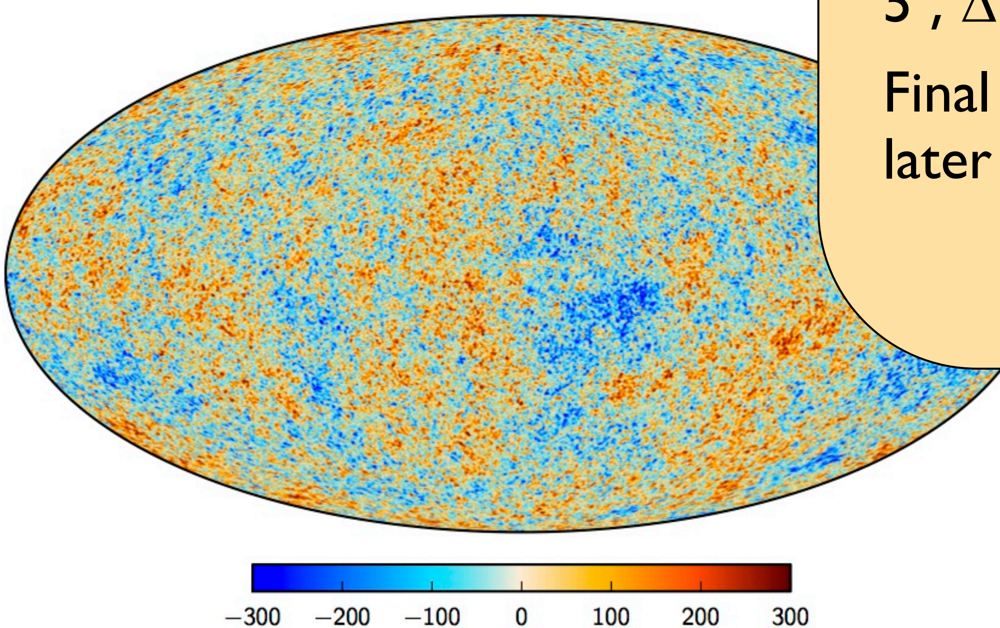
Planck is a 3rd generation ESA satellite devoted to CMB

Ultimate characterization of the temperature anisotropies

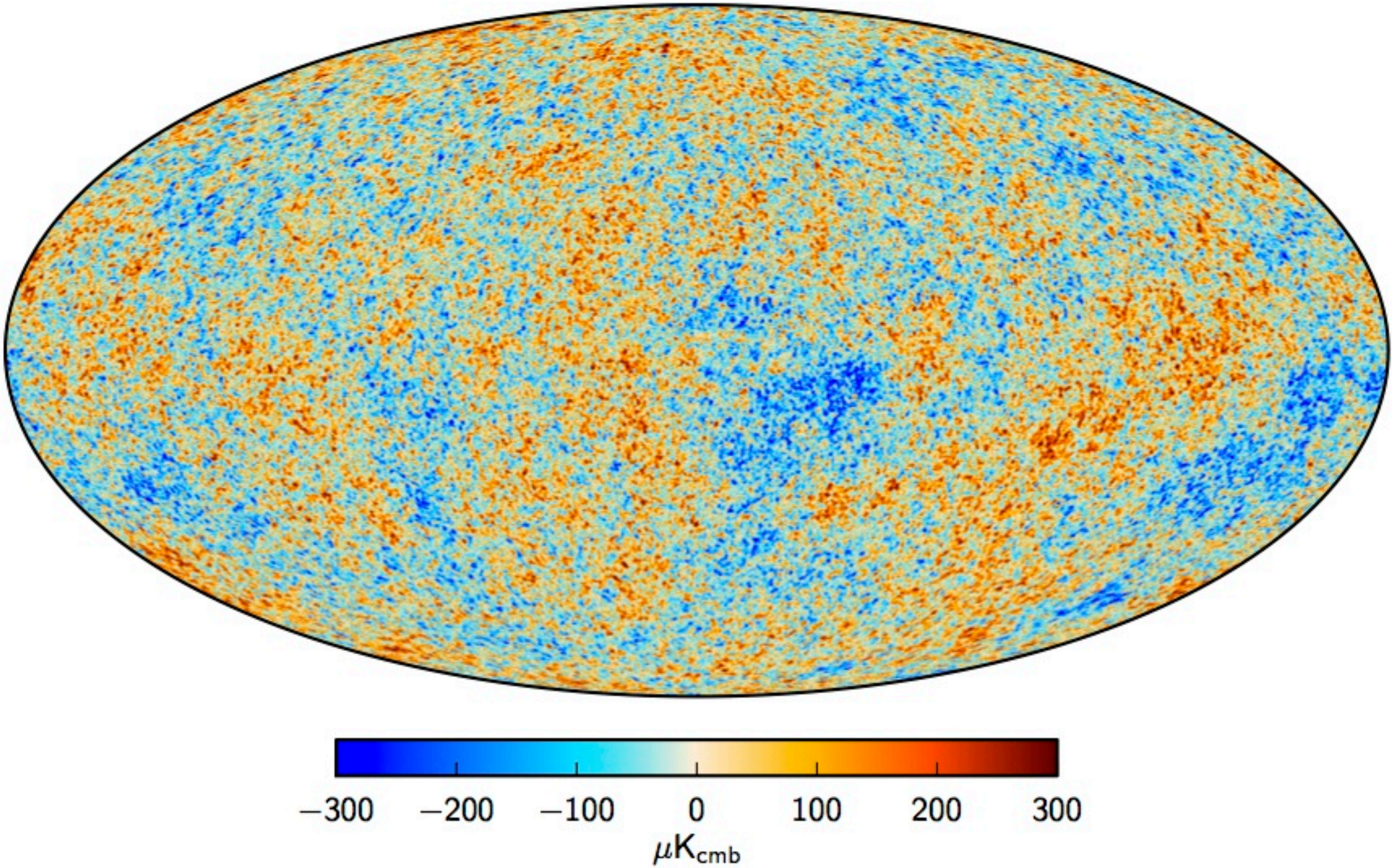
74 detectors (radiometers and bolometers) in 9 frequency bands from 30 to 857 GHz

angular resolution between 30’ and 5′, $\Delta T/T \sim 2 \times 10^{-6}$

Final (legacy) release expected later this year

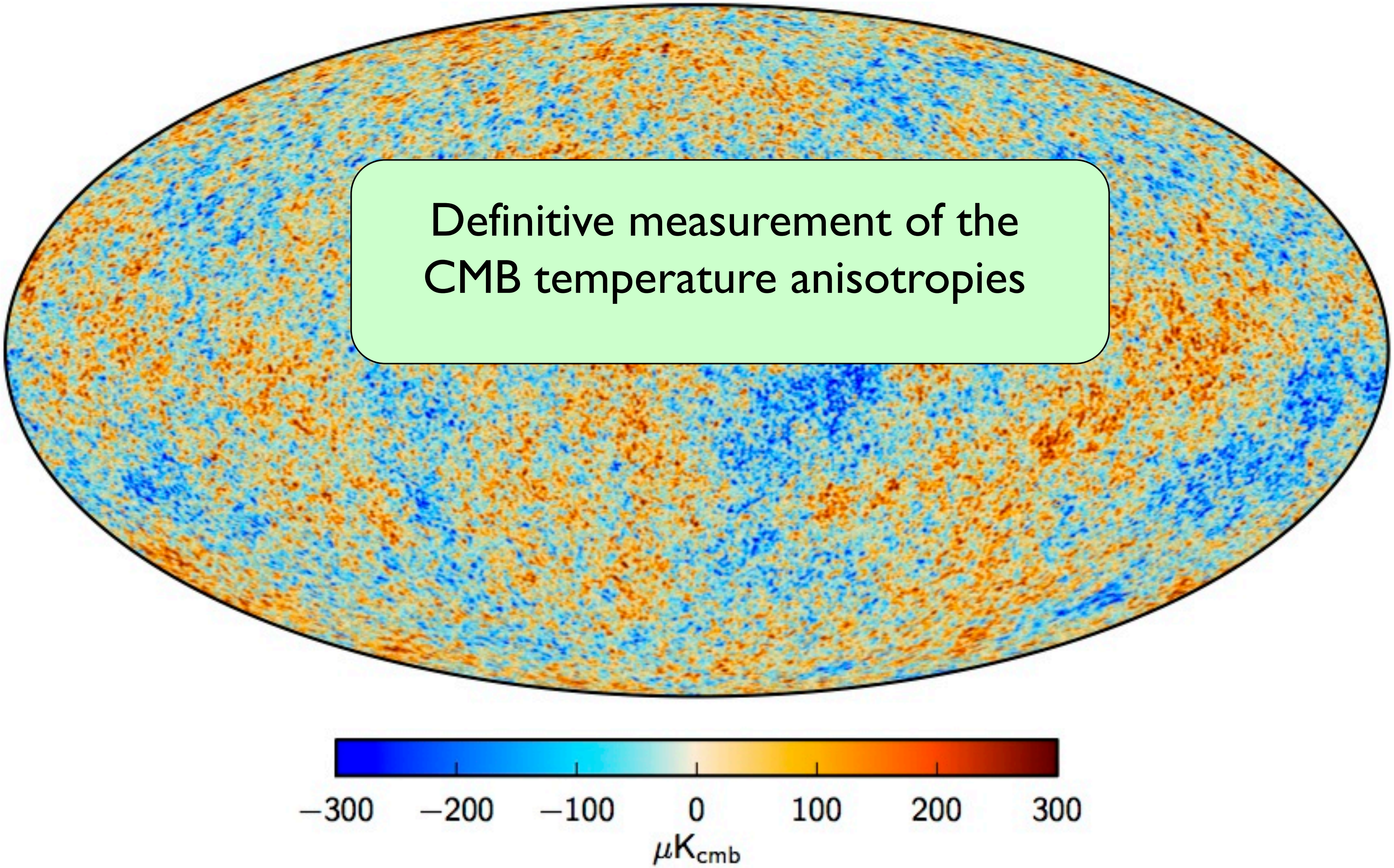


Planck: Temperature Anisotropies

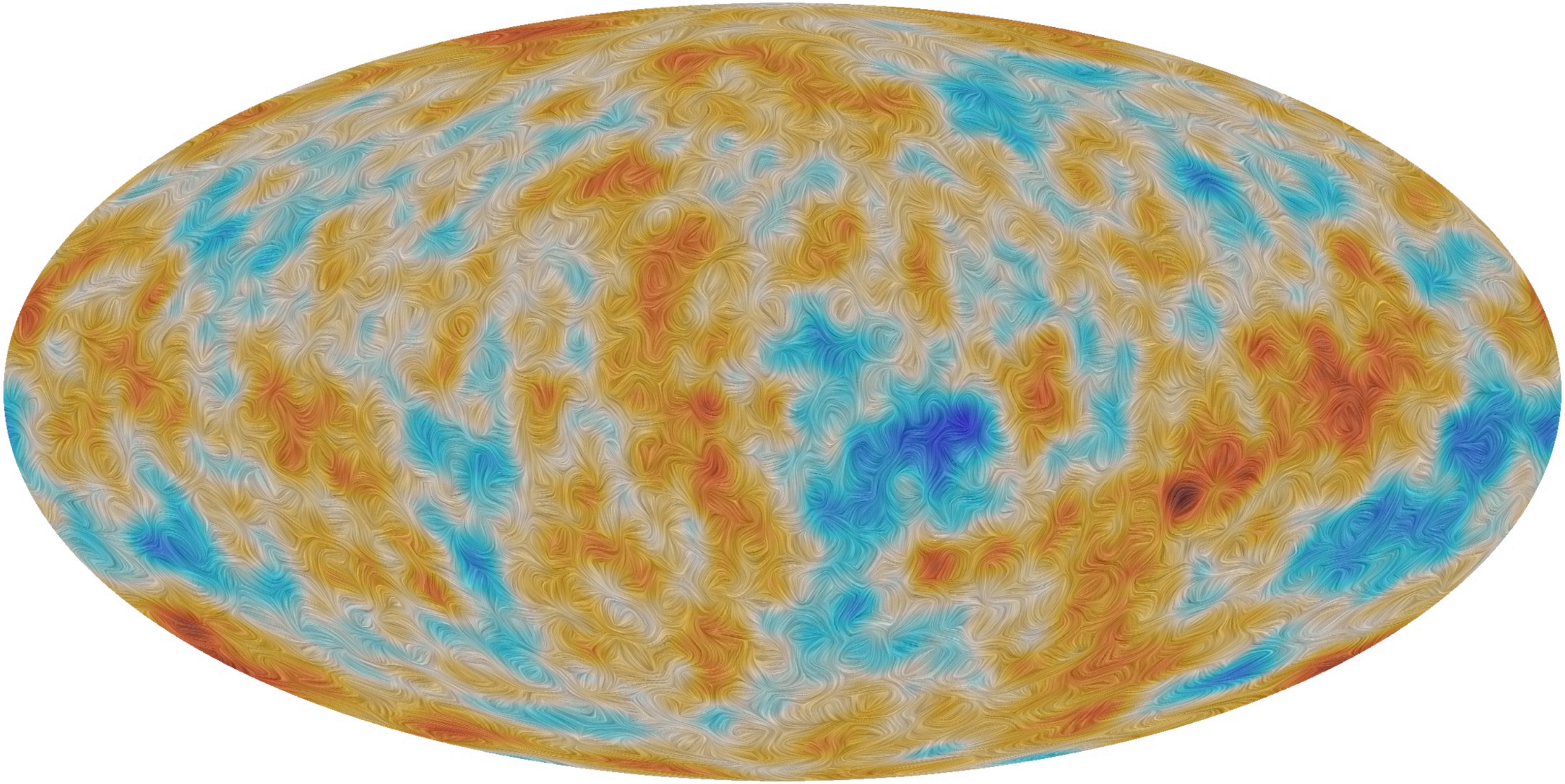


PLANCK: TEMPERATURE ANISOTROPIES

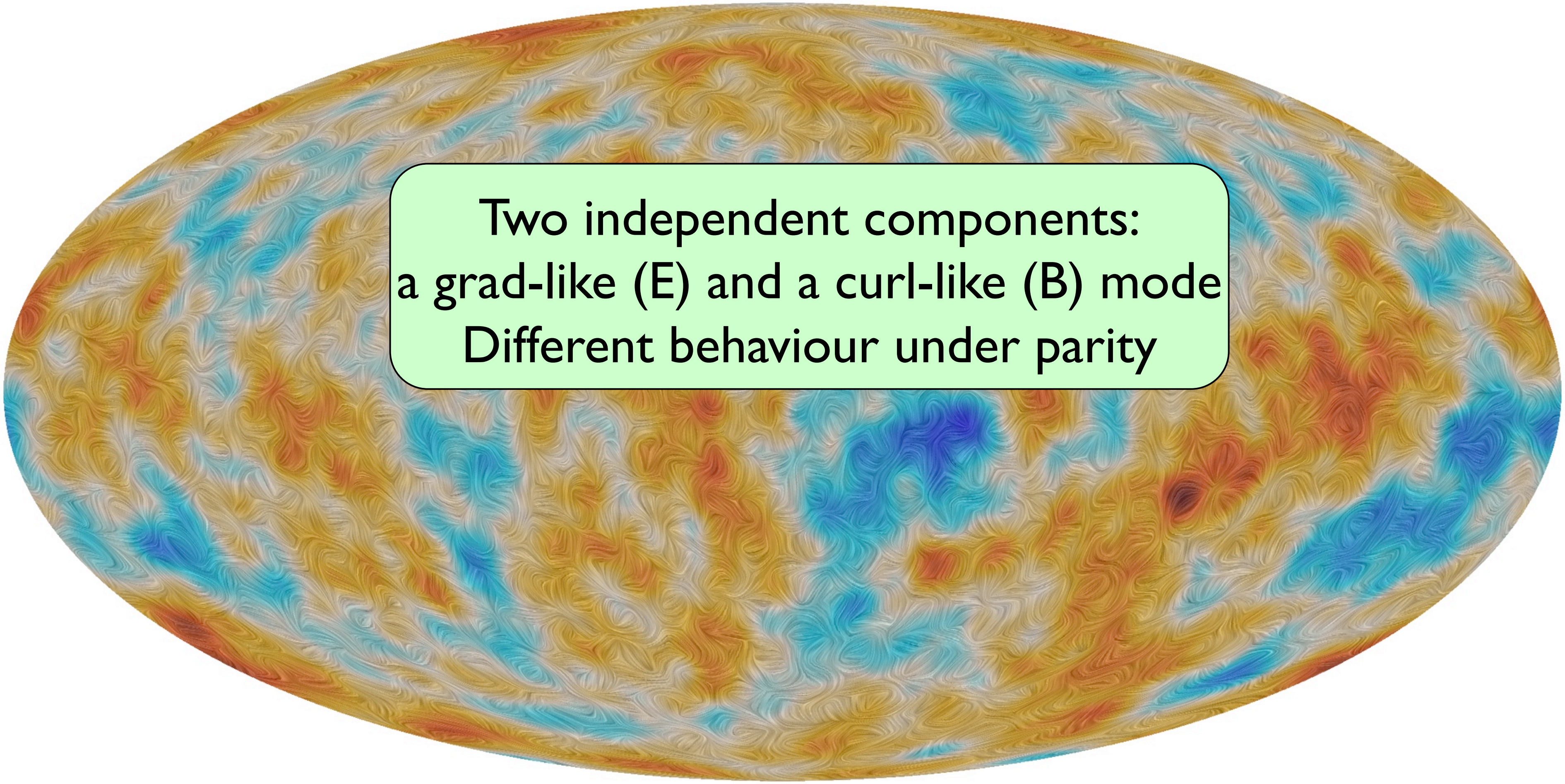
Definitive measurement of the CMB temperature anisotropies



Planck: Polarization Anisotropies

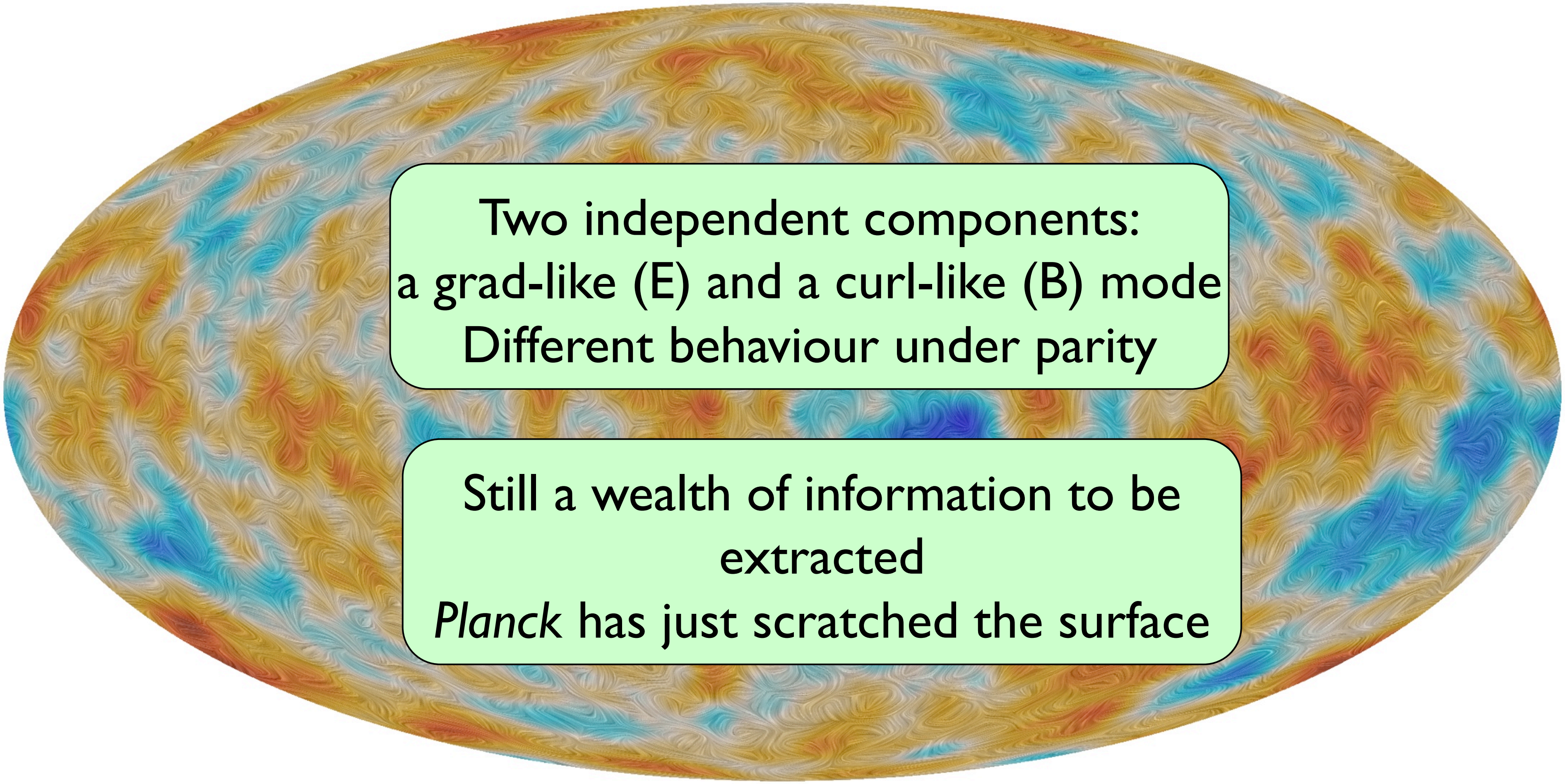


Planck: Polarization Anisotropies



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

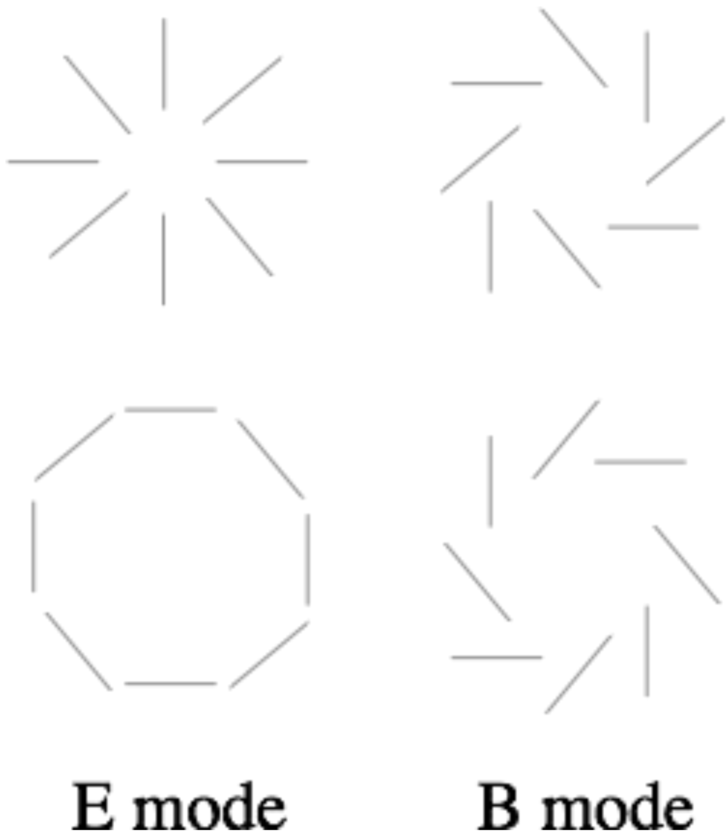
PLANCK: POLARIZATION ANISOTROPIES



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

Still a wealth of information to be extracted
Planck has just scratched the surface

E-mode and B-mode

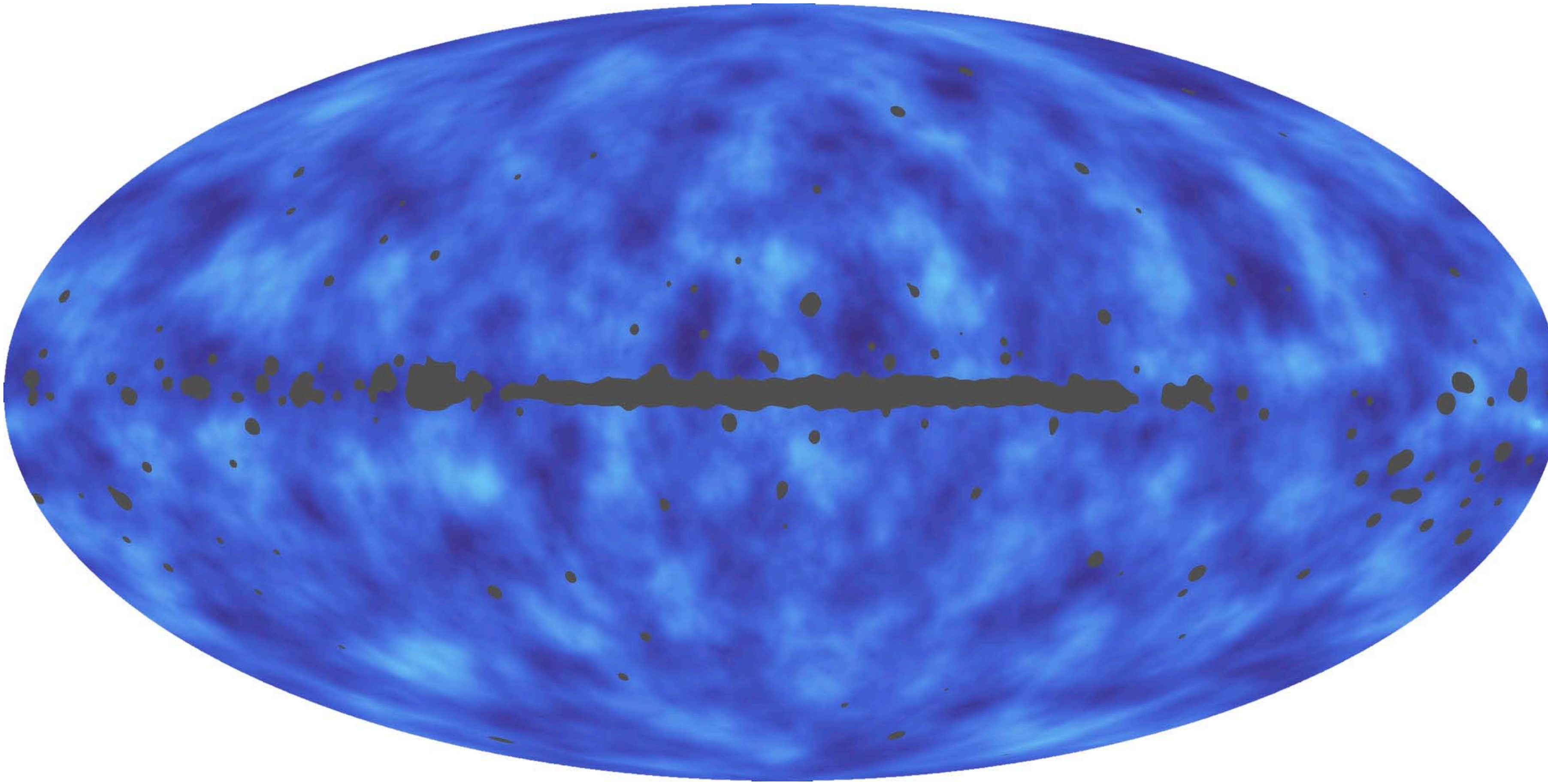


- Polarization is a spin 2 tensor, can be decomposed in parity even and parity odd component ("E" and "B")

- Gravitational potential (density perturbation, parity even) can generate the E-mode polarization, but not B-modes because CMB physics is electromagnetic (parity conserving)

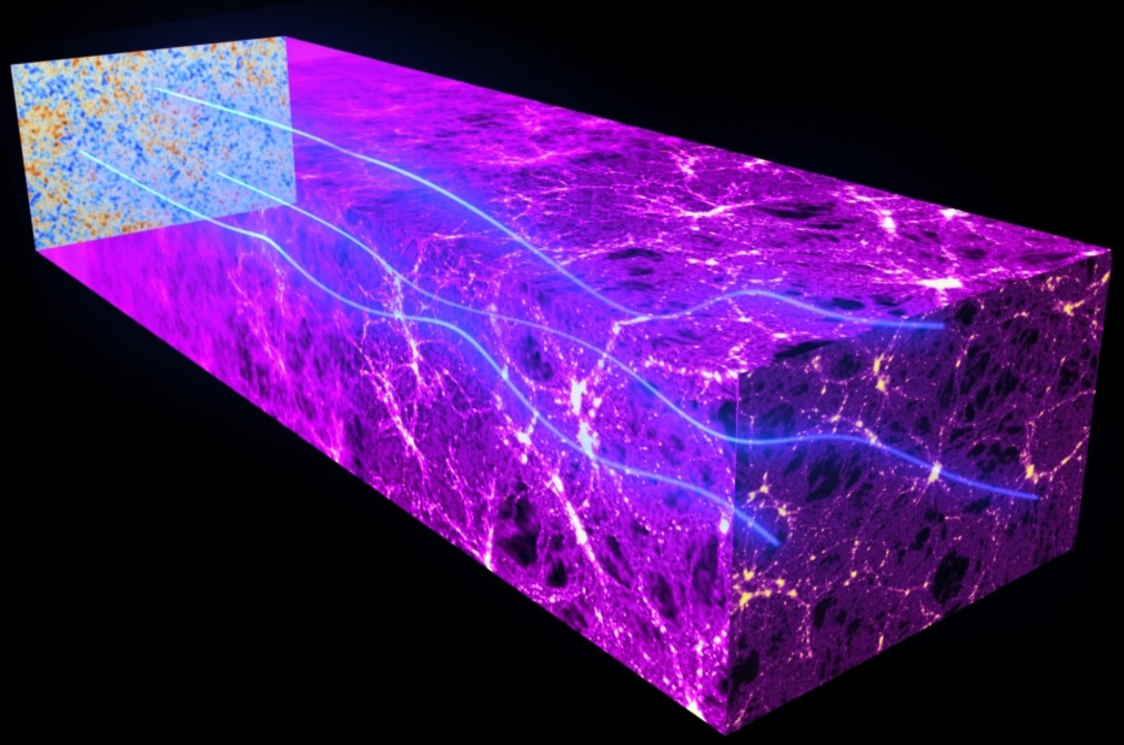
- **Primordial Gravitational waves** from inflation can generate both E- and B-modes!

PLANCK: LENSING POTENTIAL

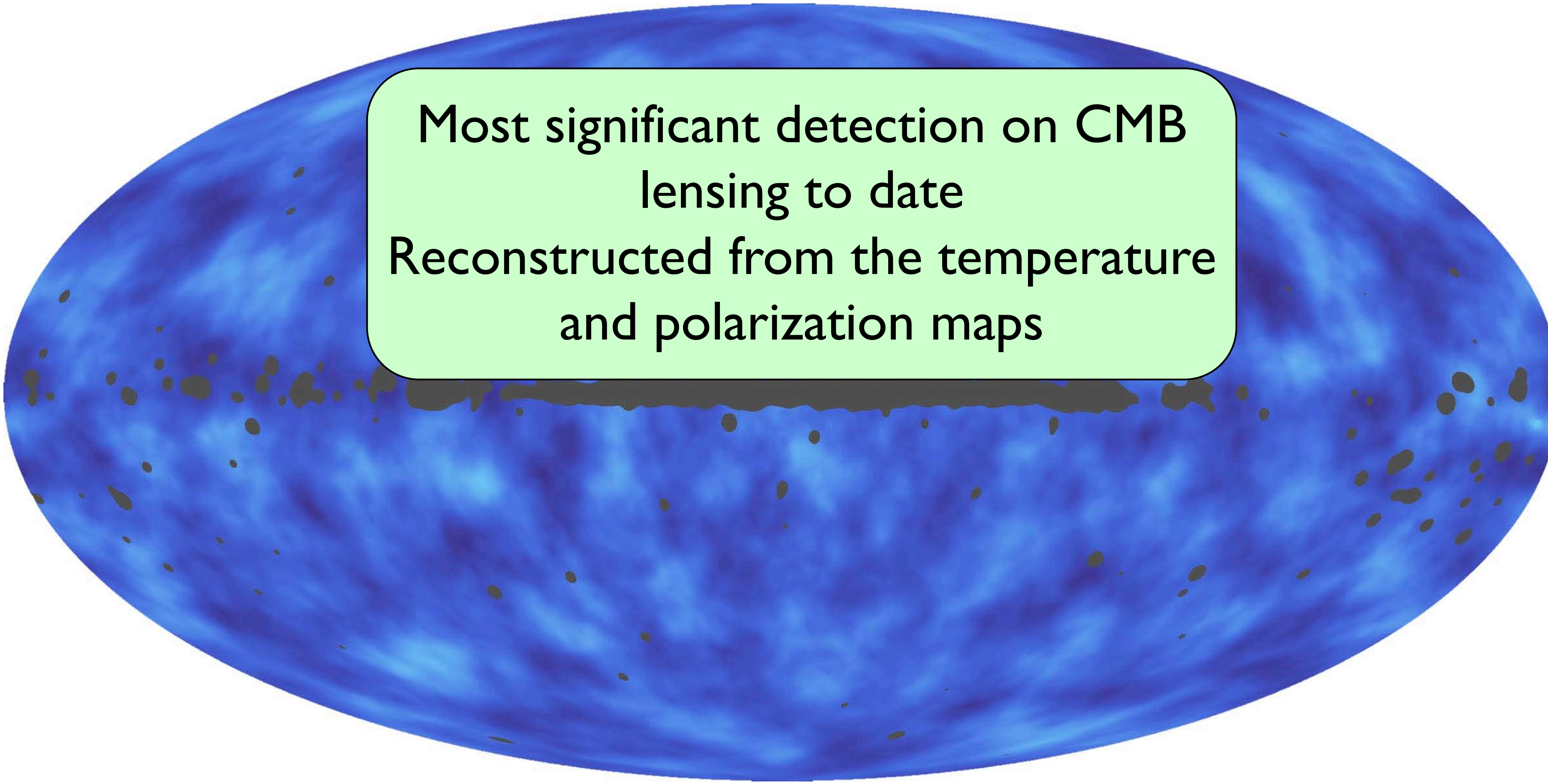


PLANCK PROBES AND EXPLOITS CMB LENSING

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

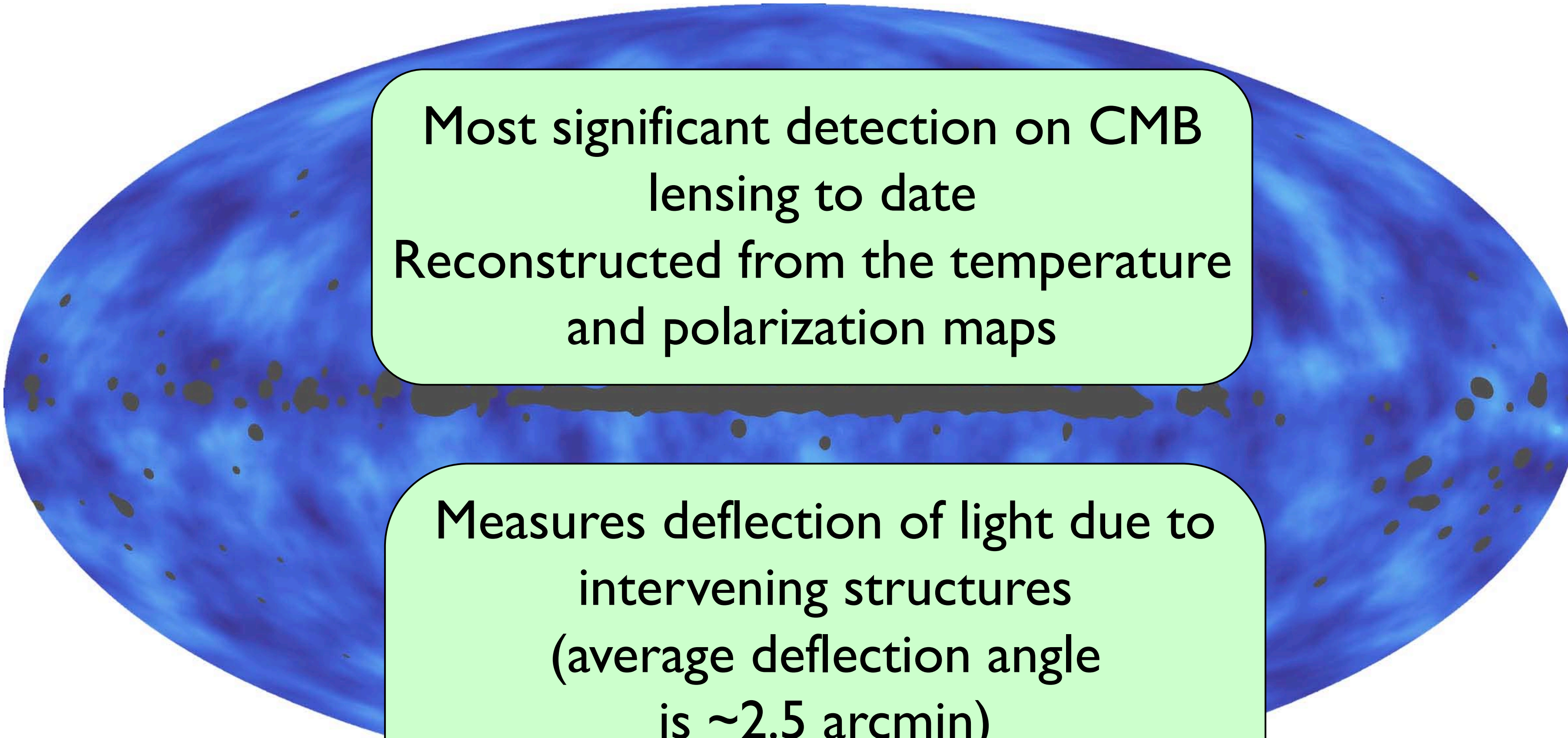


PLANCK: LENSING POTENTIAL



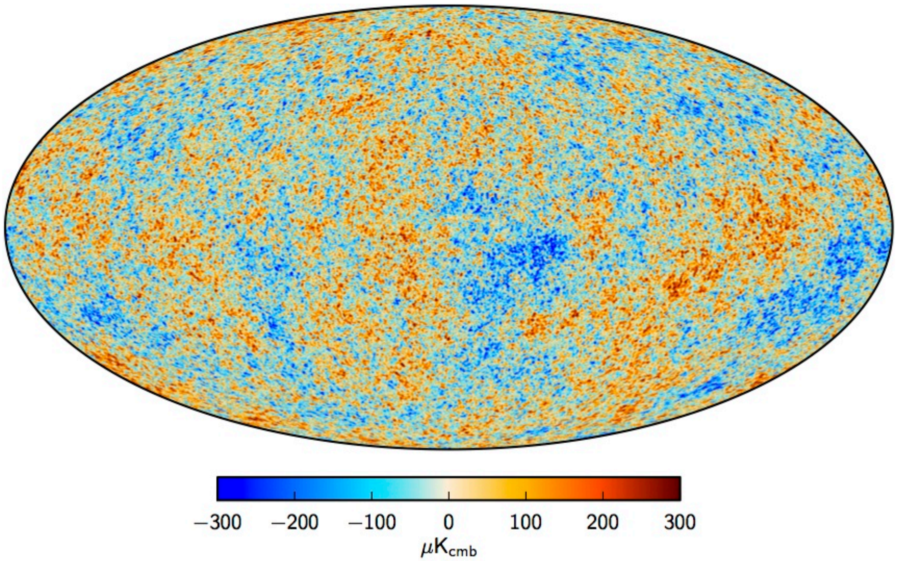
Most significant detection on CMB lensing to date
Reconstructed from the temperature and polarization maps

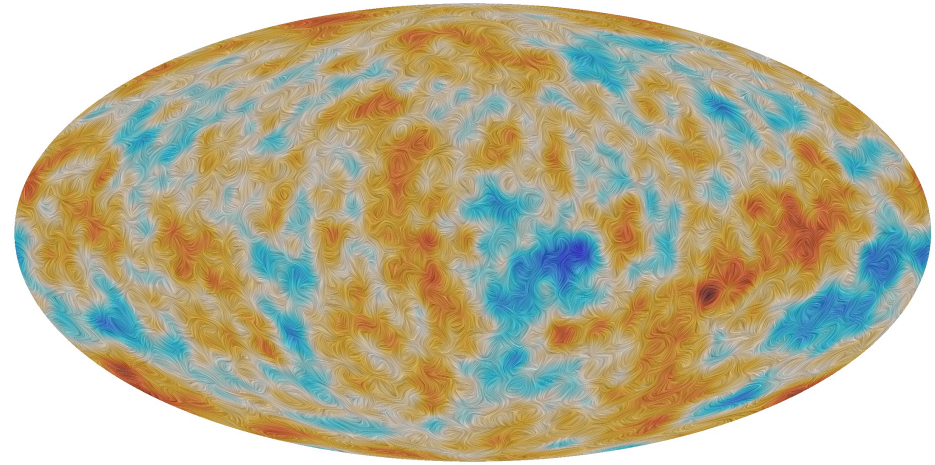
PLANCK: LENSING POTENTIAL

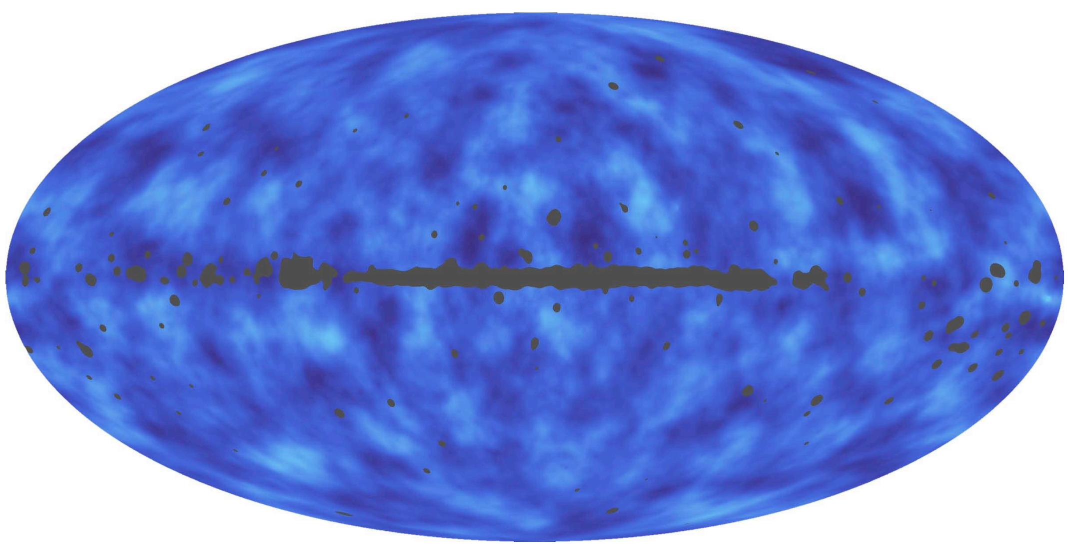


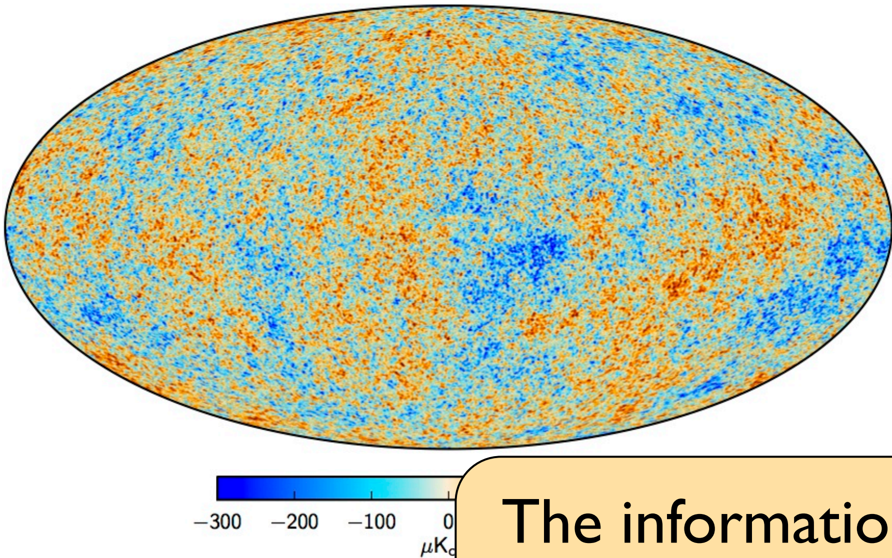
Most significant detection on CMB lensing to date
Reconstructed from the temperature and polarization maps

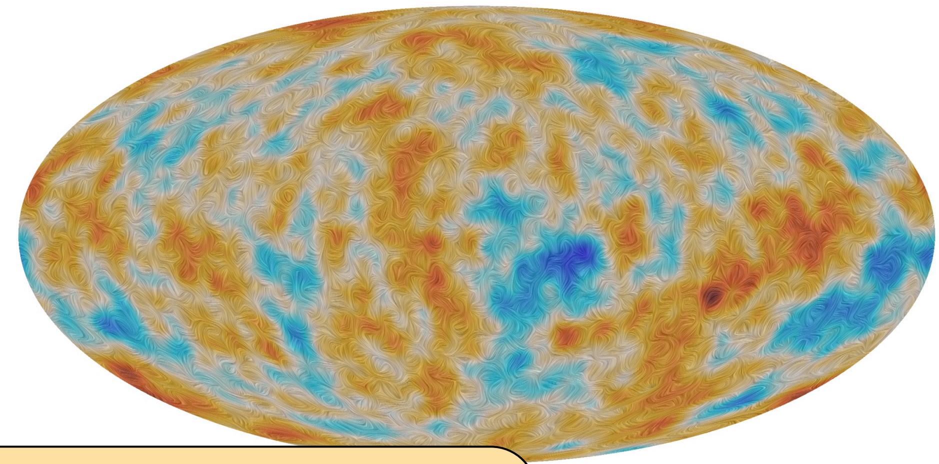
Measures deflection of light due to intervening structures
(average deflection angle is ~2.5 arcmin)
Gives integrated information about the matter distribution between us and the last scattering surface


−300
−200
−100
0
100
200
300
μK_{cmb}

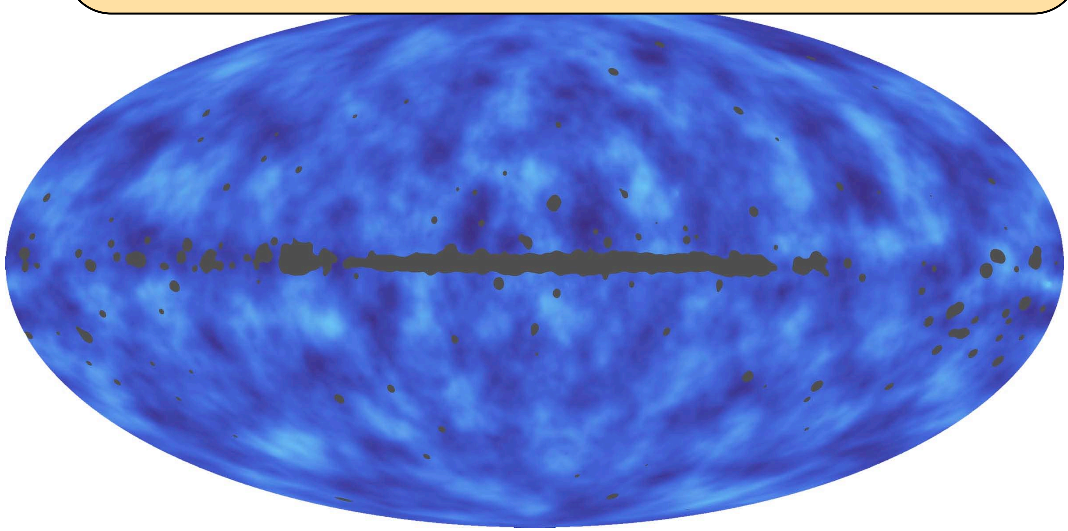


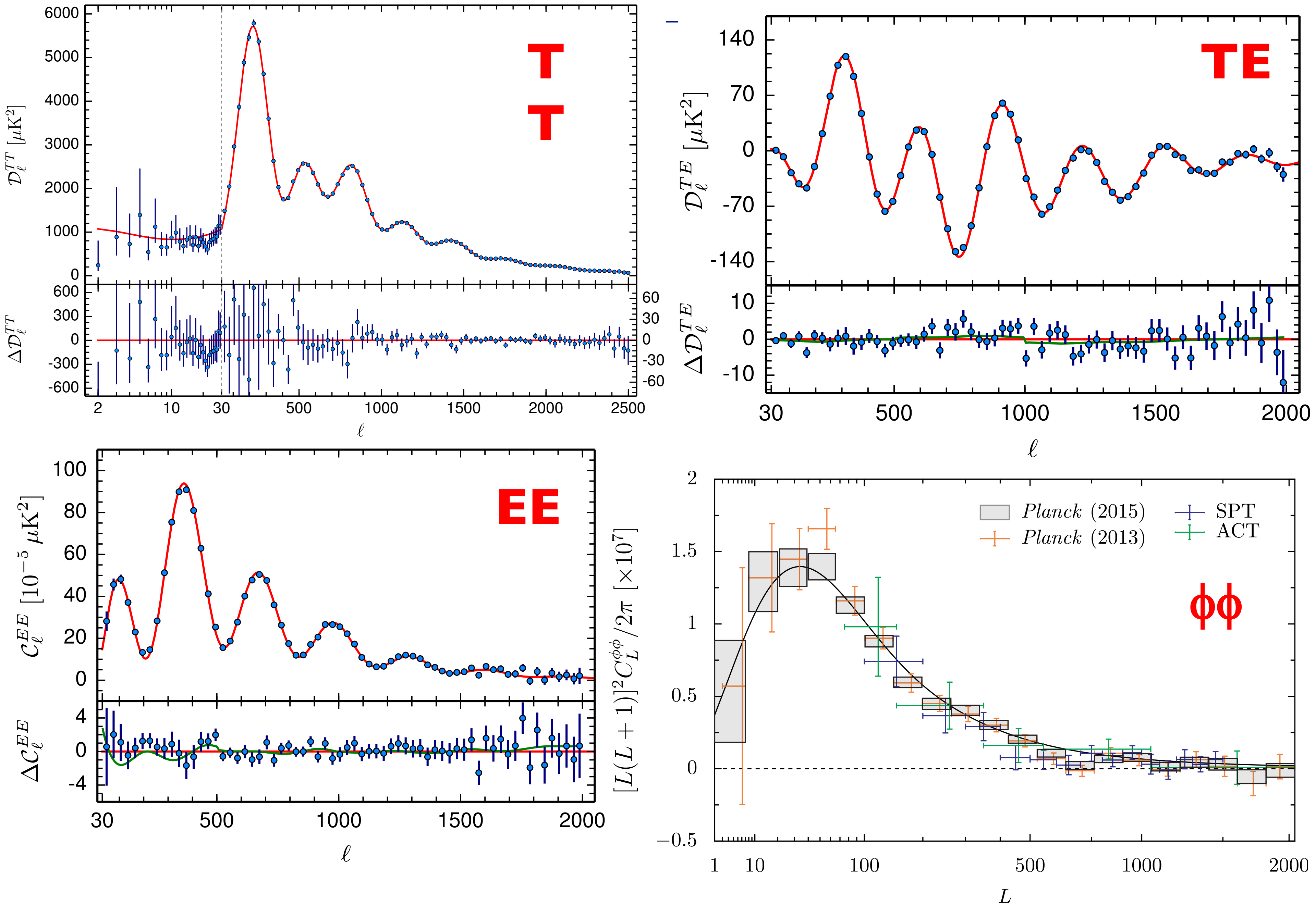




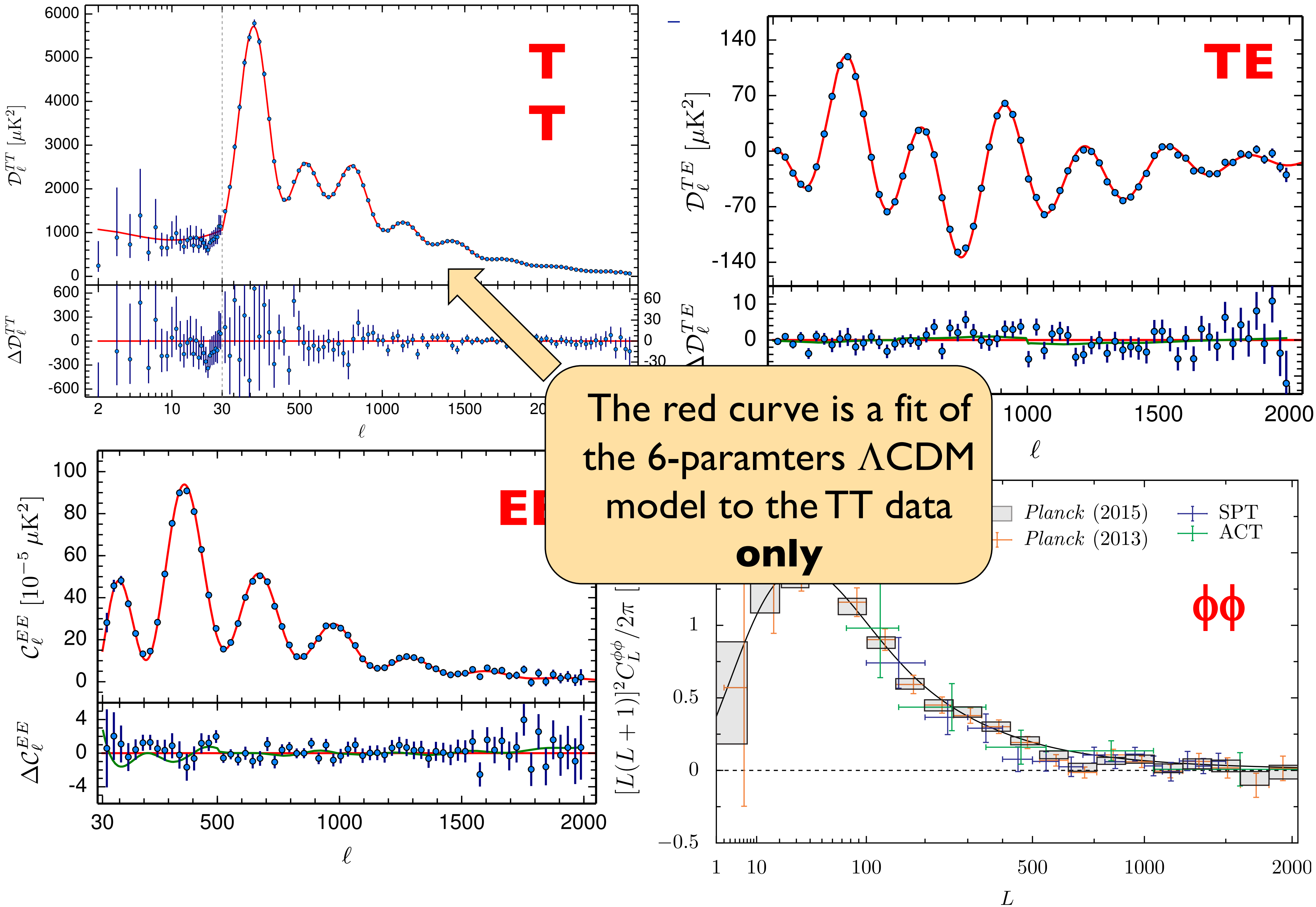


The information in the maps can be compressed by computing the 2-point correlation functions (i.e., spectra)

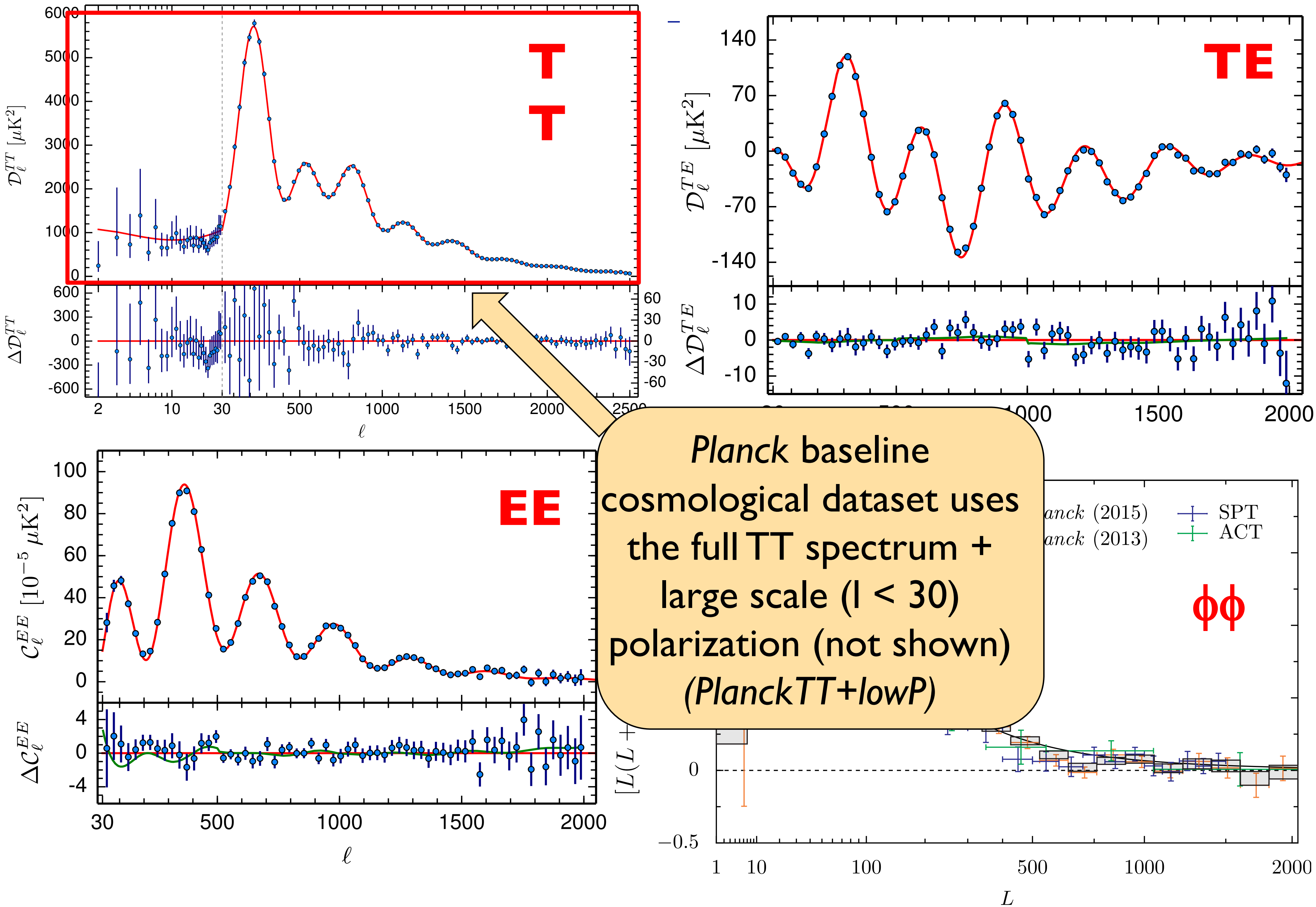




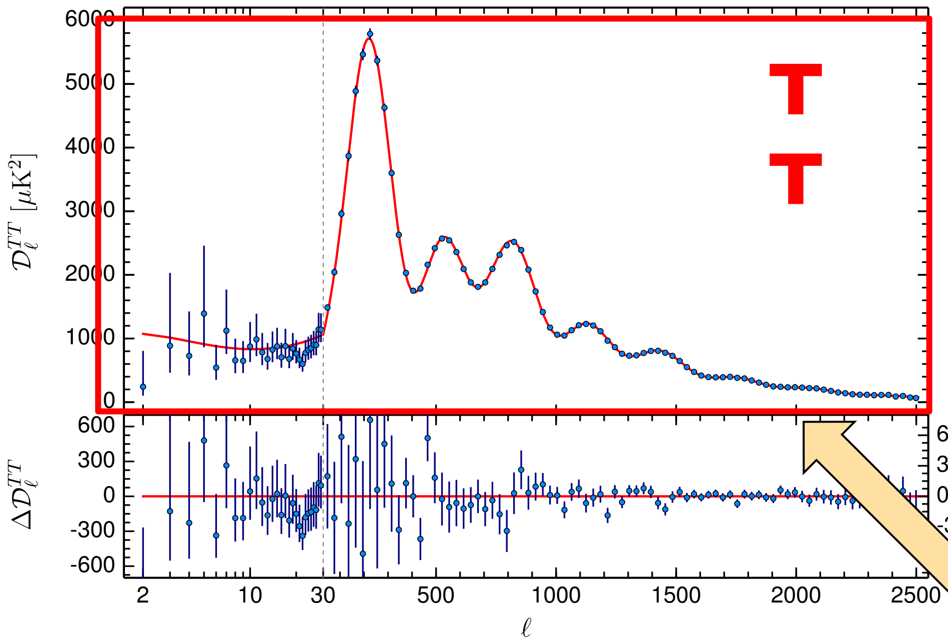
TT
$\mathcal{D}_\ell^{TT}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TT}$
6000
5000
4000
3000
2000
1000
0
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ
TE
$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$
140
70
0
-70
-140
10
0
-10
30
500
1000
1500
2000
ℓ
EE
$\mathcal{C}_\ell^{EE}$ [$10^{-5}\,\mu$K^2]
$\Delta\mathcal{C}_\ell^{EE}$
100
80
60
40
20
0
4
0
-4
30
500
1000
1500
2000
ℓ
φφ
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi$ [$\times 10^7$]
Planck (2015)
Planck (2013)
SPT
ACT
2
1.5
1
0.5
0
−0.5
1
10
100
500
1000
2000
L

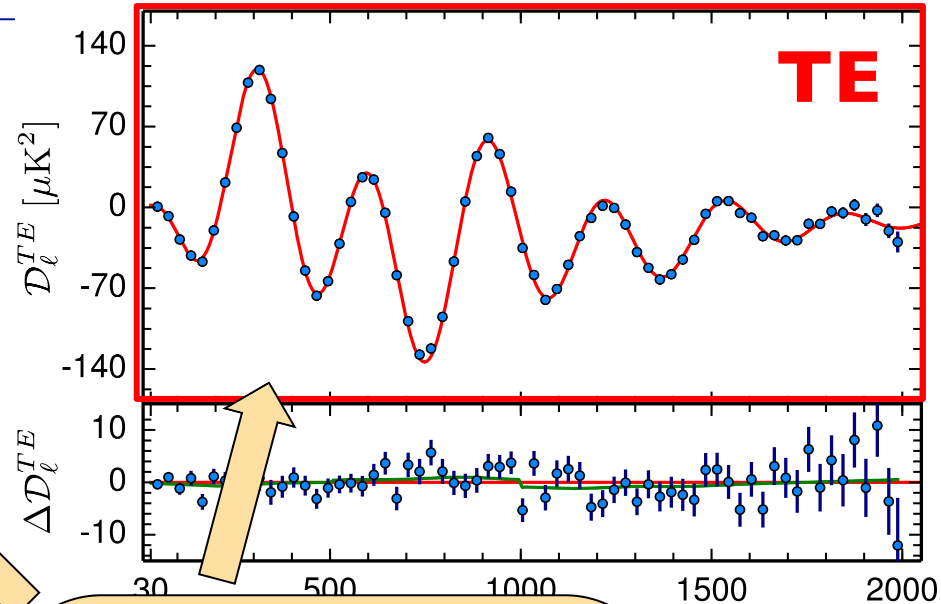


The red curve is a fit of the 6-paramters ΛCDM model to the TT data **only**

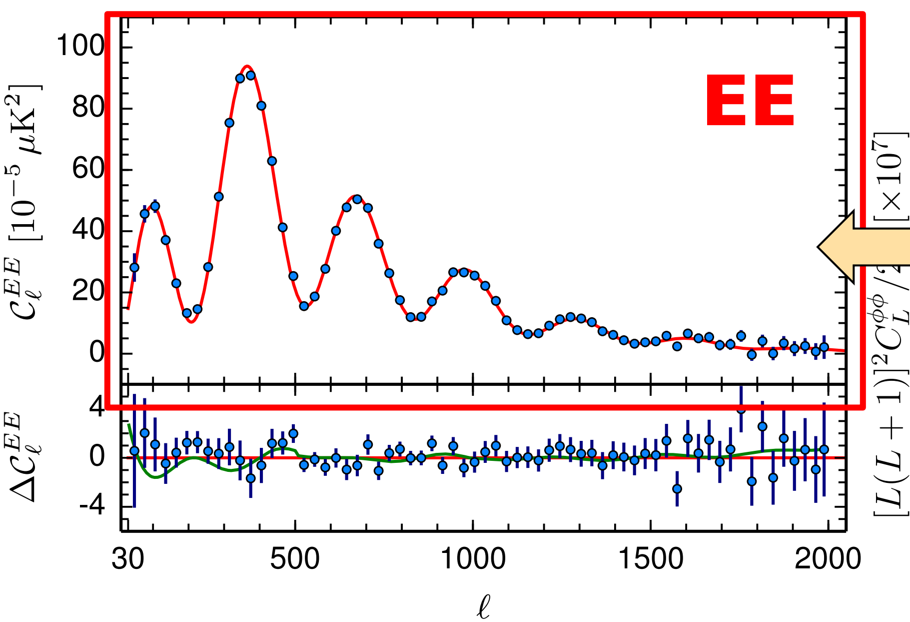


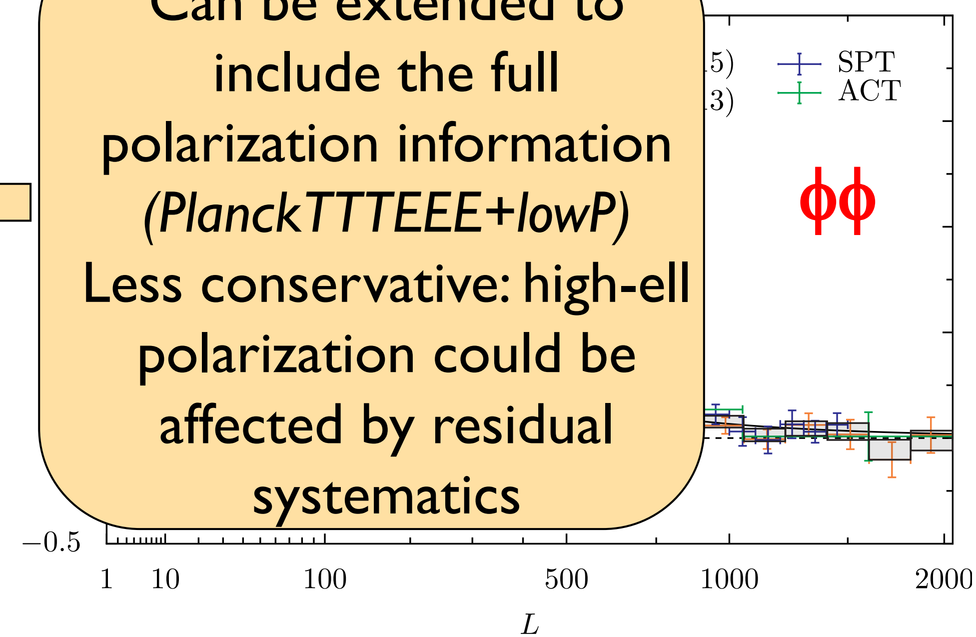
T
T
TE
EE
ϕϕ
Planck (2015)
Planck (2013)
SPT
ACT
ℓ
L
Planck baseline cosmological dataset uses the full TT spectrum + large scale (l < 30) polarization (not shown)
(PlanckTT+lowP)

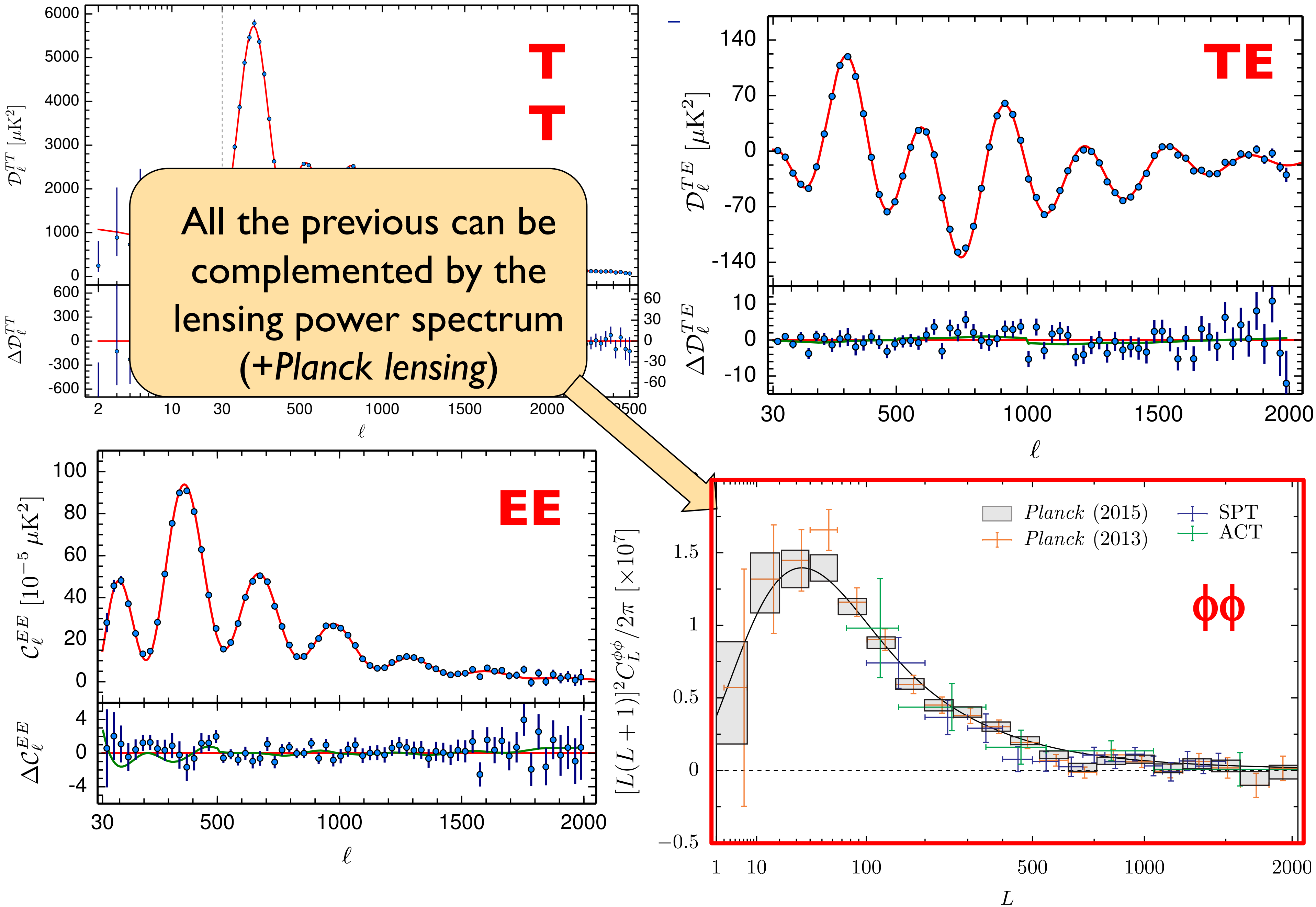




Can be extended to include the full polarization information *(PlanckTTTEEE+lowP)*
Less conservative: high-ell polarization could be affected by residual systematics






All the previous can be complemented by the lensing power spectrum (+*Planck lensing*)
T
T
TE
EE
ϕϕ
Planck (2015)
Planck (2013)
SPT
ACT
$\mathcal{D}_\ell^{TT}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TT}$
$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$
$\mathcal{C}_\ell^{EE}$ [$10^{-5}\,\mu$K^2]
$\Delta\mathcal{C}_\ell^{EE}$
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi$ [$\times 10^7$]
ℓ
L

Parameters of the base ΛCDM cosmology

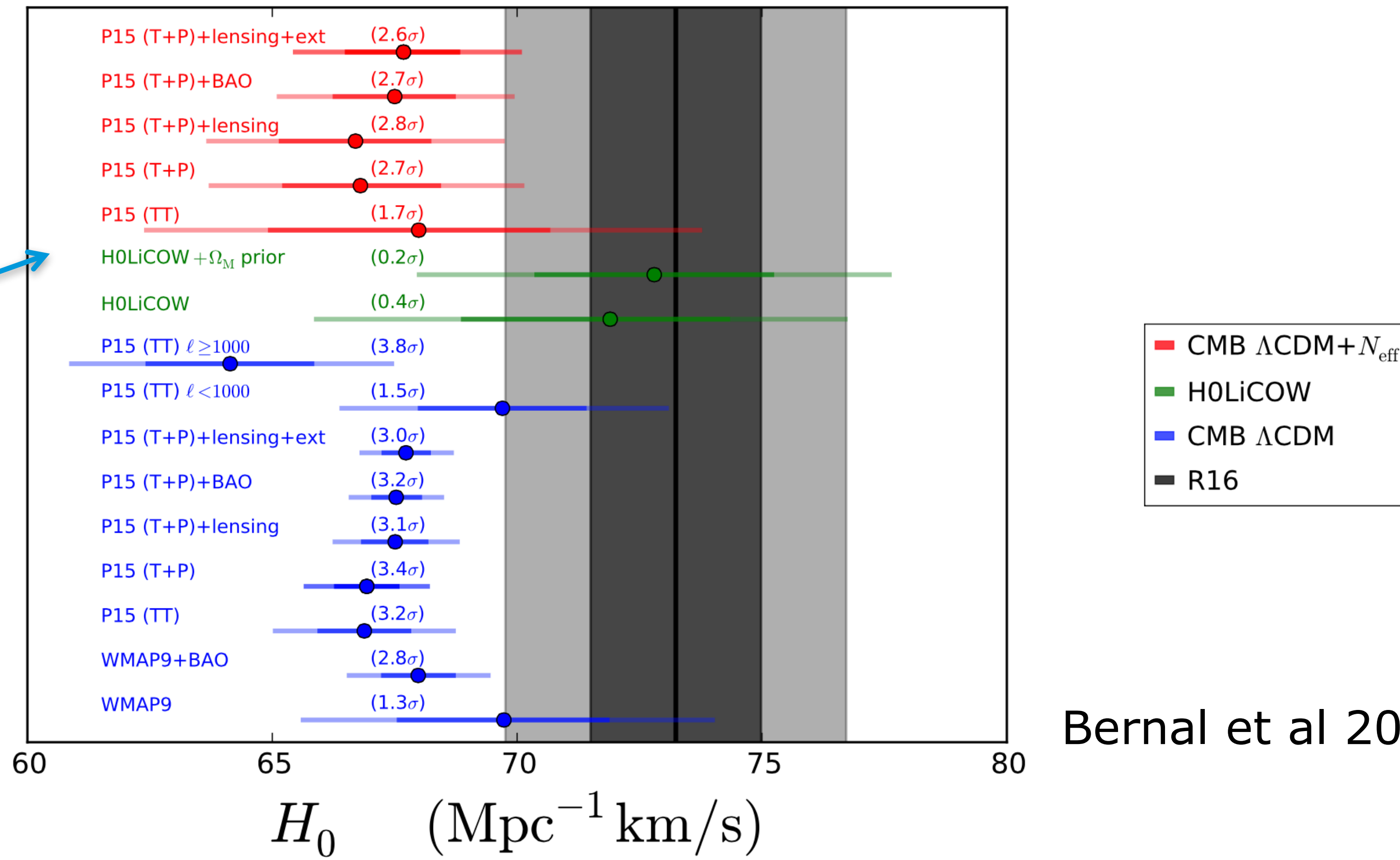
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	-0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	-0.1
$\ln(10^{10}A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	-0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	-0.1

All uncertainties are 68% CL

Parameters of the base ΛCDM cosmology

Parameter
$\Omega_b h^2$ . . . .
$\Omega_c h^2$ . . . .
$100\theta_{MC}$ . . . .
τ . . . .
$\ln(10^{10} A_s)$ . . . . .
n_s . . . .
H_0 . . . .
Ω_m . . . .
σ_8 . . . .
$10^9 A_s e^{-2\tau}$ . . . . .

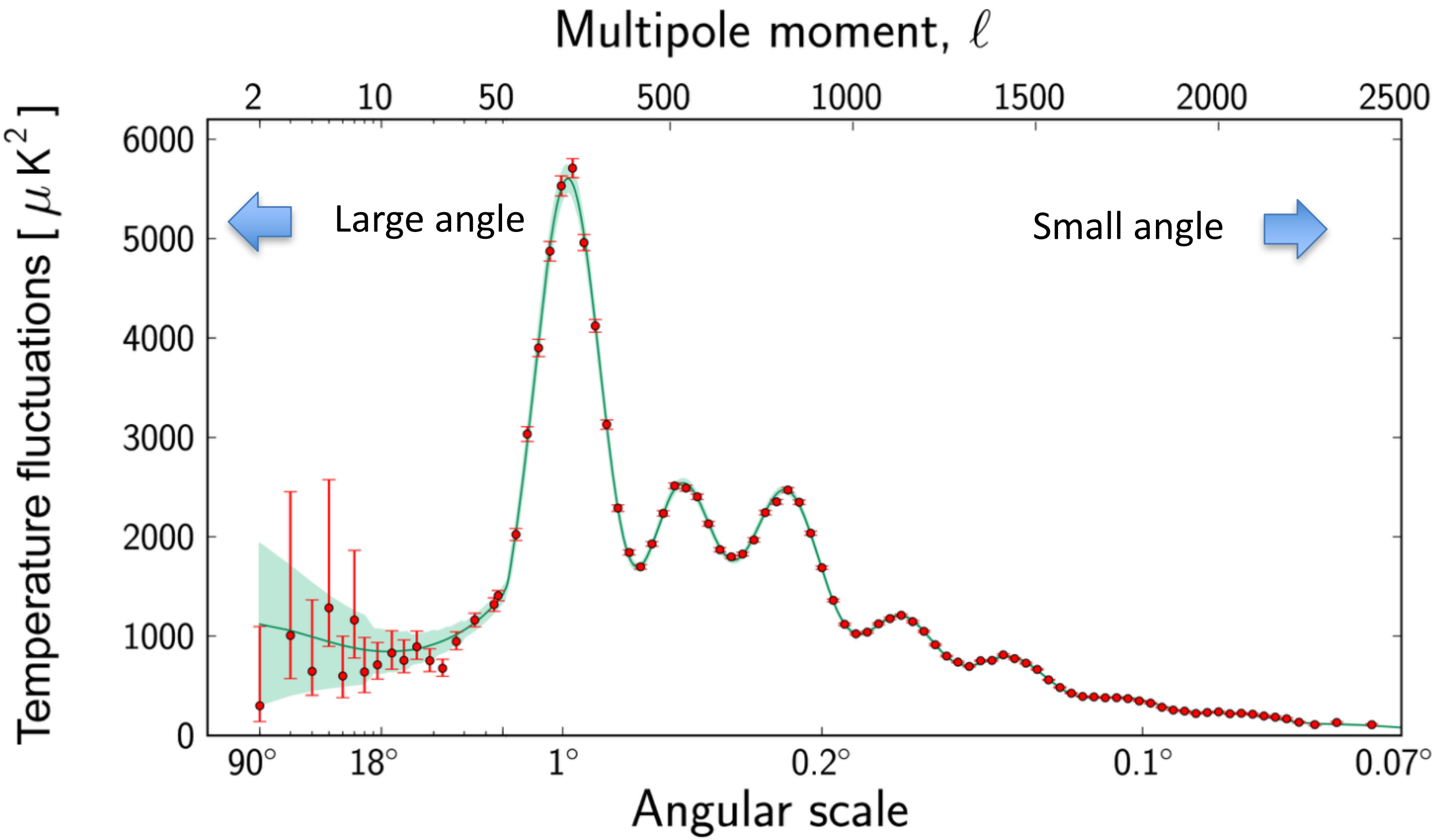
All unc



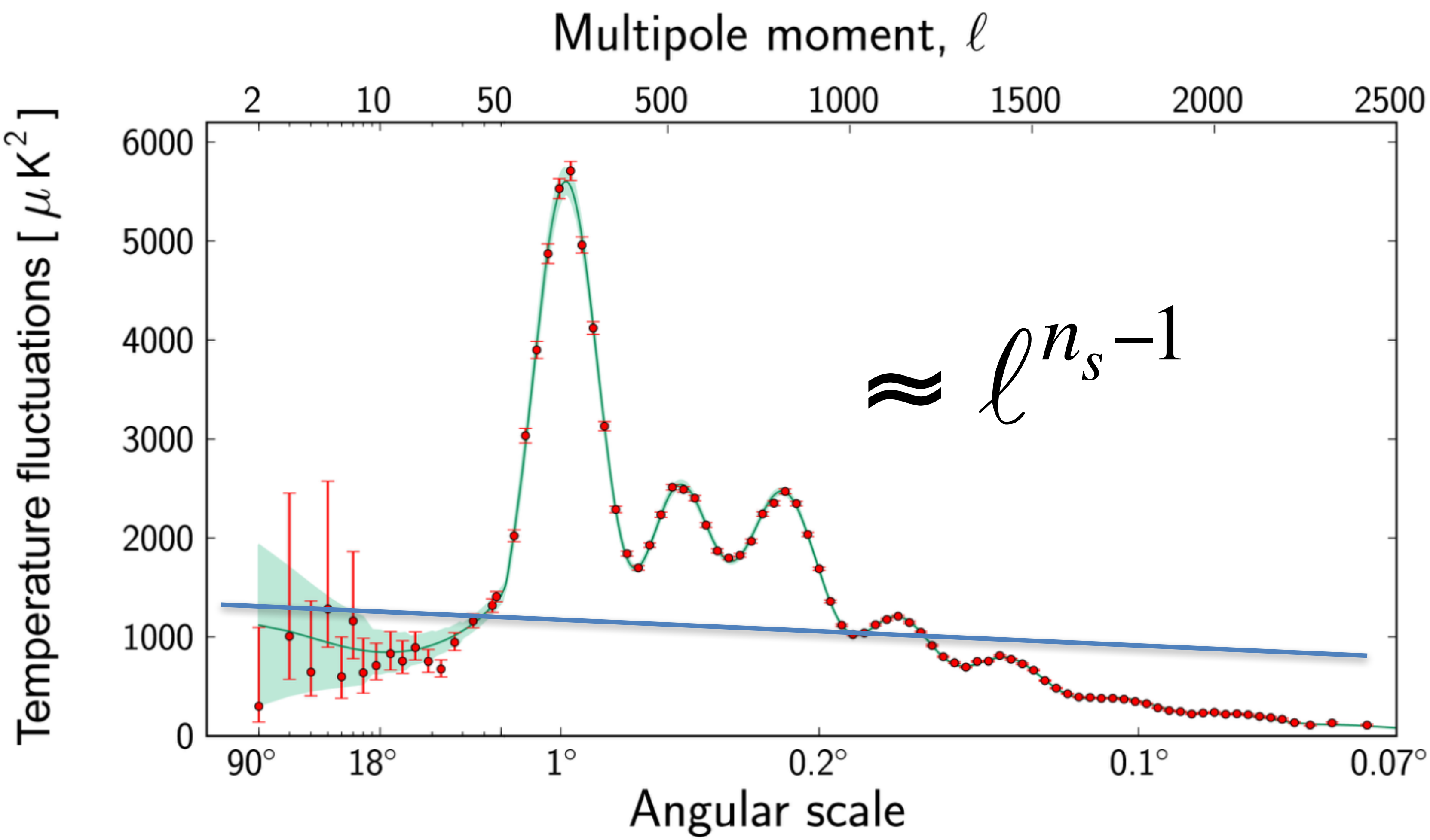
Bernal et al 2016

esa planck LFI HFI PLANCK

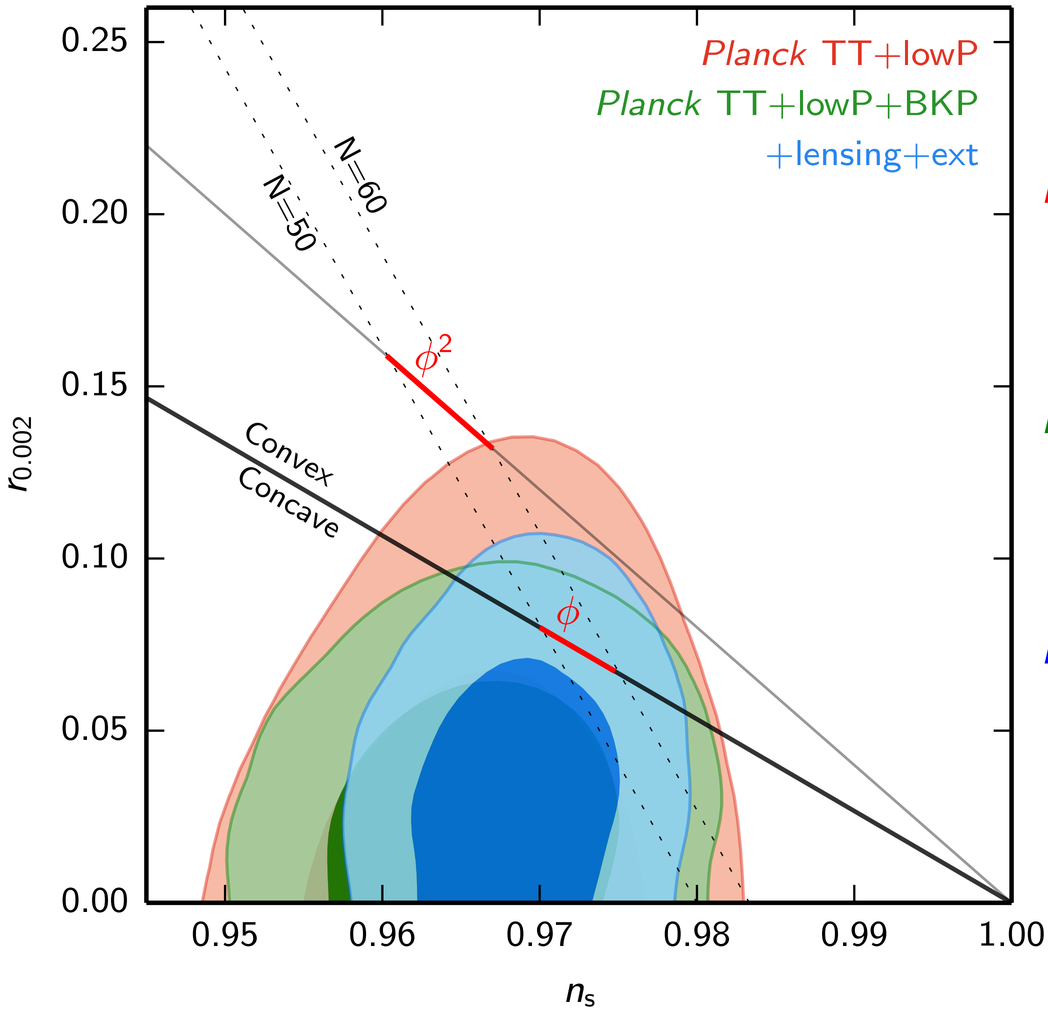
Measured TT spectrum



“Primordial” power spectrum



Scalar spectral index and tensor fluctuations



Planck TT + lowP

$r_{0.002} < 0.10$

Planck TT + lowP+BKP

$r_{0.002} < 0.08$

+ lensing + ext

$r_{0.002} < 0.09$

The Cosmic Neutrino Background

The presence of a background of relic neutrinos (***CνB***) is a basic prediction of the standard cosmological model

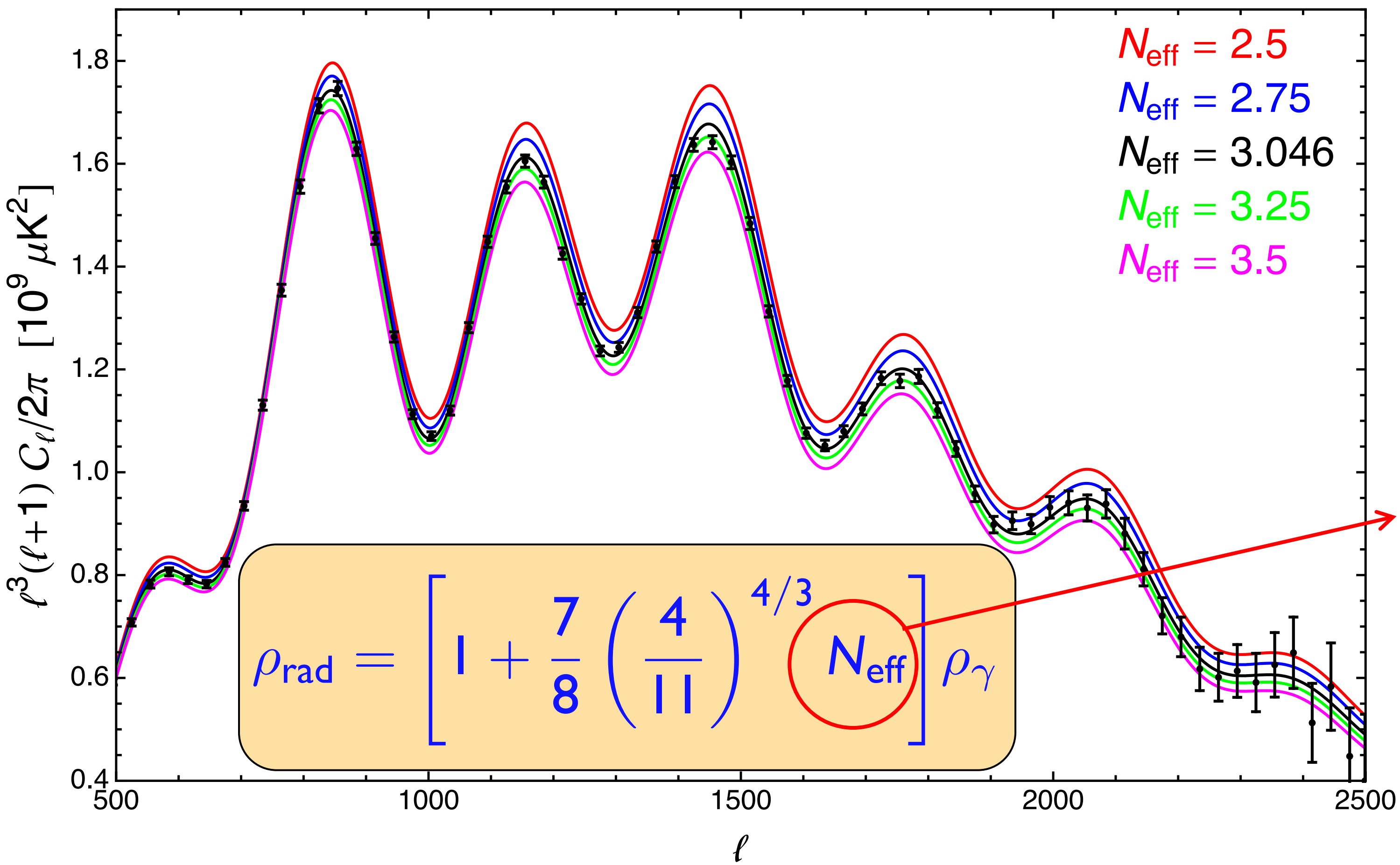
- Neutrinos are kept in thermal equilibrium with the cosmological plasma by weak interactions until T ~ 1 MeV (z ~ 10^{10});
- Below T ~ 1 MeV, neutrino free stream keeping an equilibrium spectrum:

$$f_\nu(p) = \frac{1}{e^{p/T} + 1}$$

- Today T_ν = 1.9 K and n_ν = 113 part/cm^3 per species

The Cosmic Neutrino Background

This picture is consistent with current CMB observations:



$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

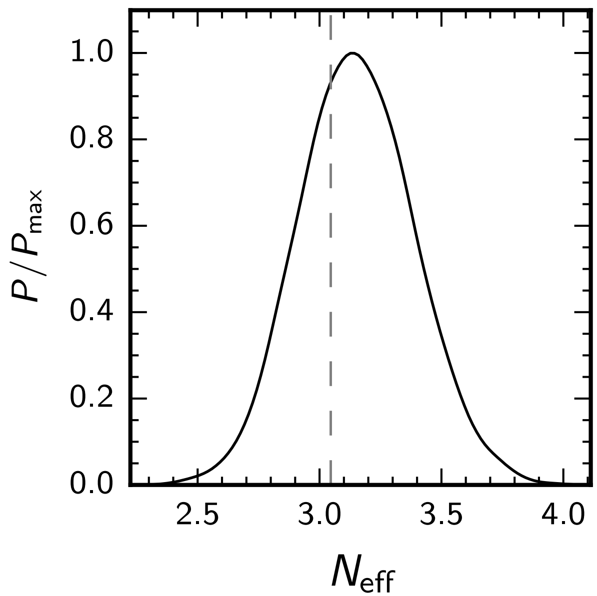
Energy density in units of "standard" neutrino density (thermally distributed with T=1.9 K)

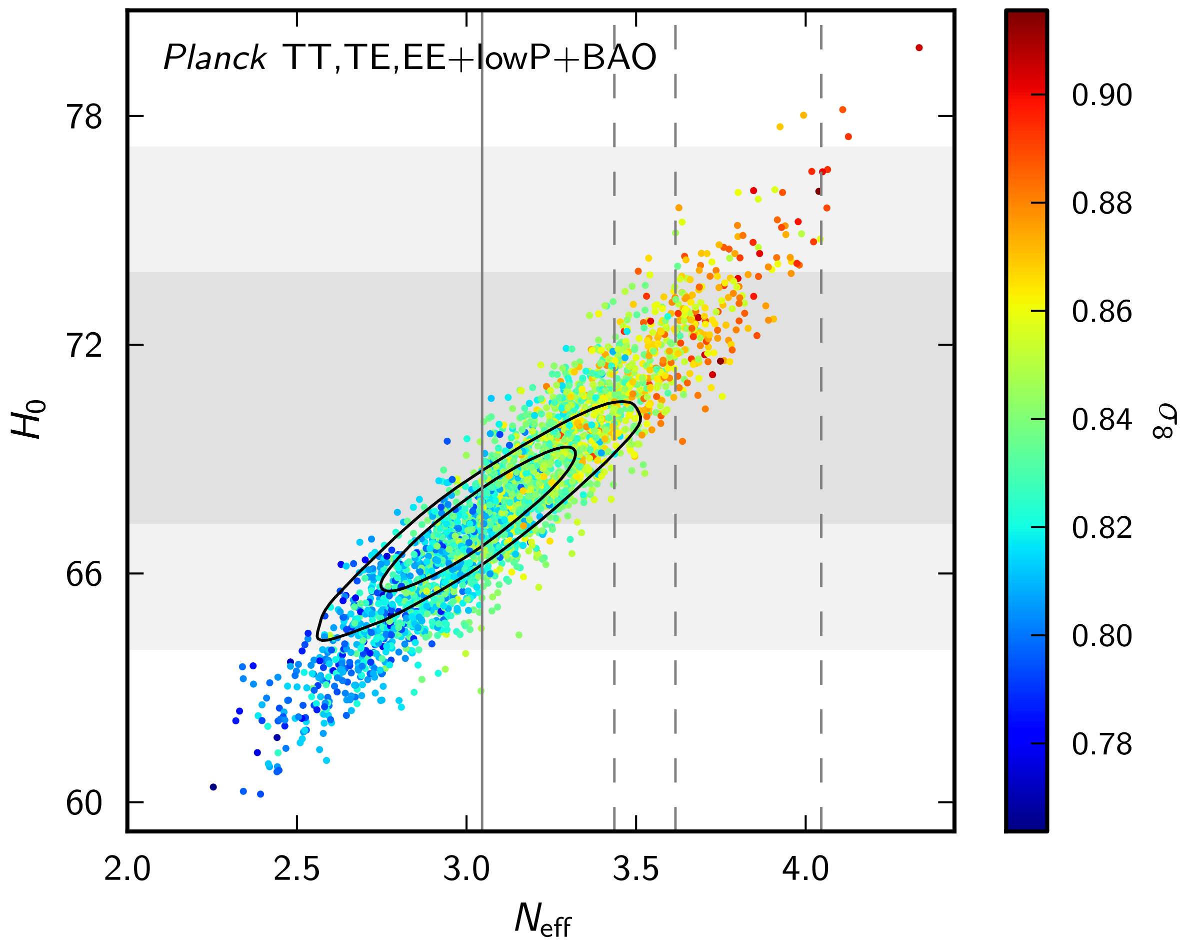
Due to non-instantaneous decoupling, the standard expectation is $\mathbf{N_{eff} = 3.046}$

(note I am showing ~ $l^4\,C_l$, not $l^2\,C_l$)

The Cosmic Neutrino Background

This picture is consistent with current CMB observations:





$N_{\rm eff}$ = 3.15 ± 0.23
(PlanckTT+lowP+BAO)

(Planck 2015 XIII)

Effective number of neutrino families

$N_{\mathrm{eff}} = 3.13 \pm 0.32$ (PlanckTT+lowP)

$N_{\mathrm{eff}} = 3.15 \pm 0.23$ (PlanckTT+lowP+BAO)

$N_{\mathrm{eff}} = 2.99 \pm 0.20$ (PlanckTT,TE,EE+lowP)

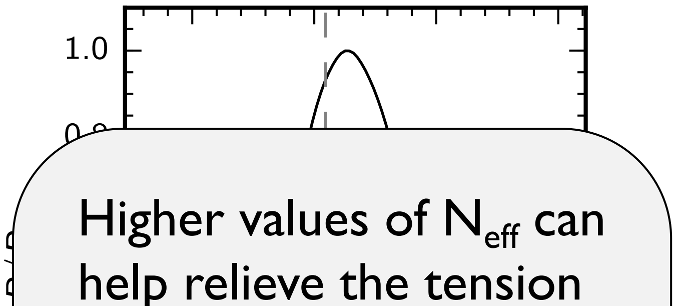
$N_{\mathrm{eff}} = 3.04 \pm 0.18$ (PlanckTT,TE,EE+lowP+BAO)

(uncertainties are 68% CL)

$N_{\mathrm{eff}} = 4$ (i.e., one extra thermalized massless neutrino)
is excluded at between ~ 3 and 5 sigma.

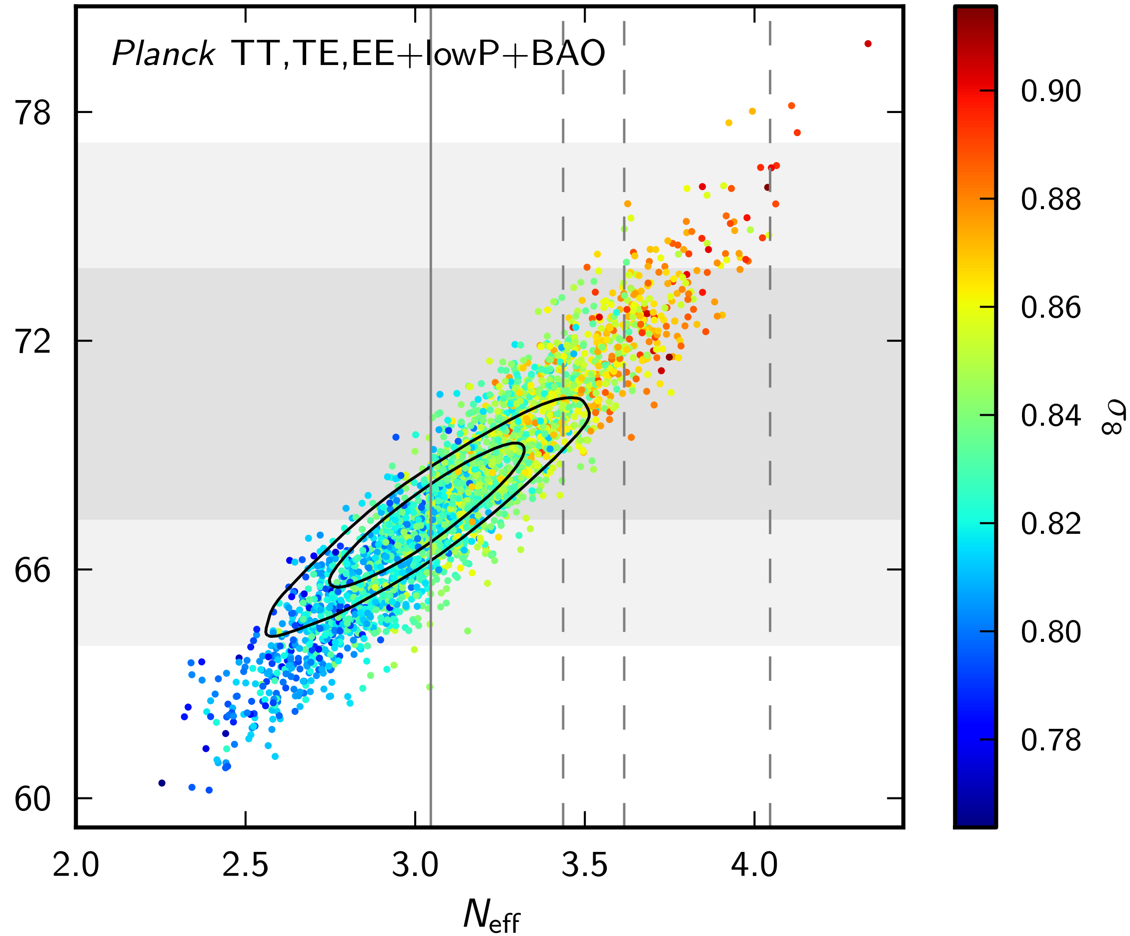
THE COSMIC NEUTRINO BACKGROUND

This picture is consistent with current CMB observations:



Higher values of N_{eff} can help relieve the tension with astrophysical measurements of H_0

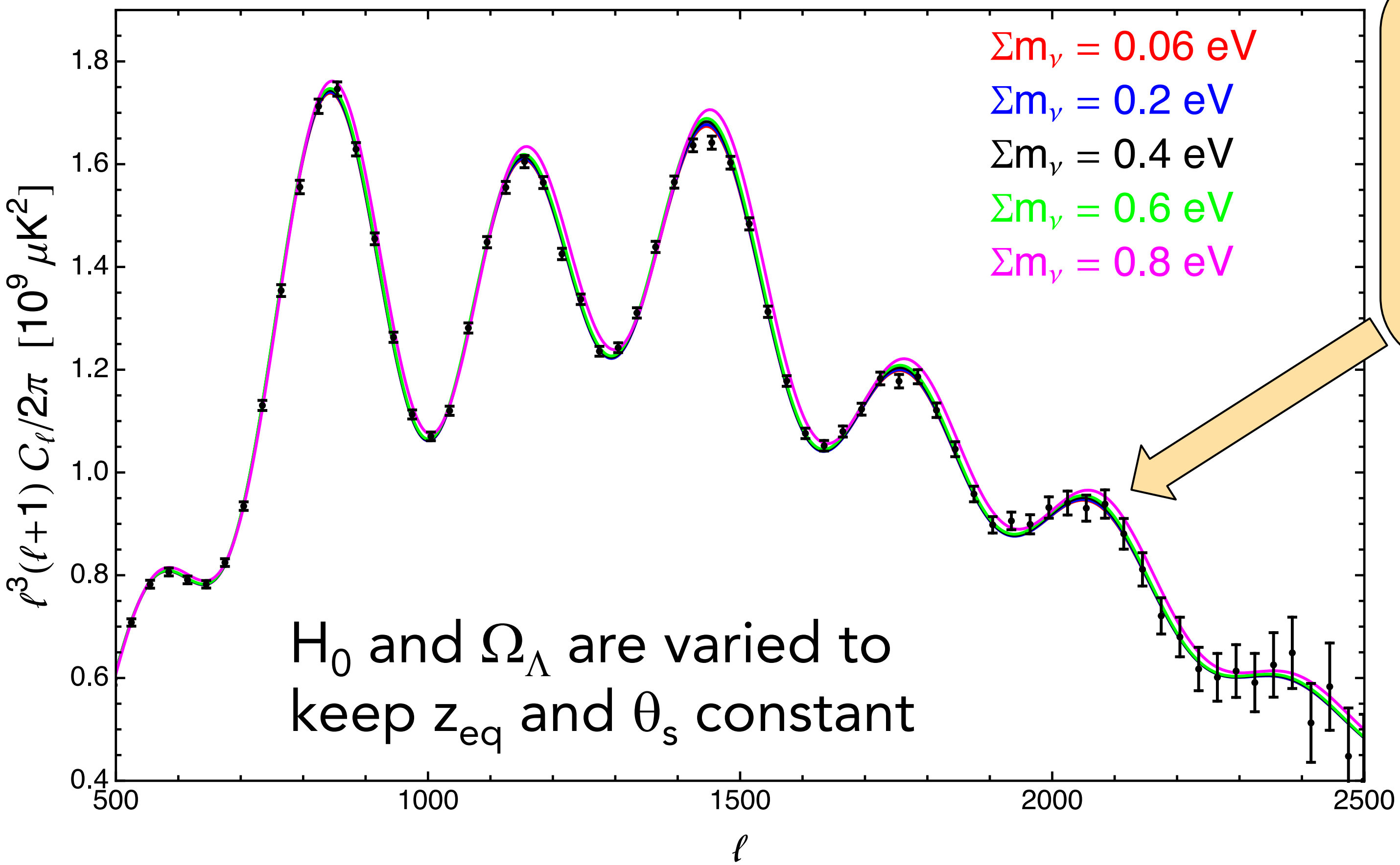
However, they imply a larger σ_8 and thus worsen the tension with LSS probes.



N_{eff} = 3.15 ± 0.23
(PlanckTT+lowP+BAO)

(Planck 2015 XIII)

HOW HEAVY?



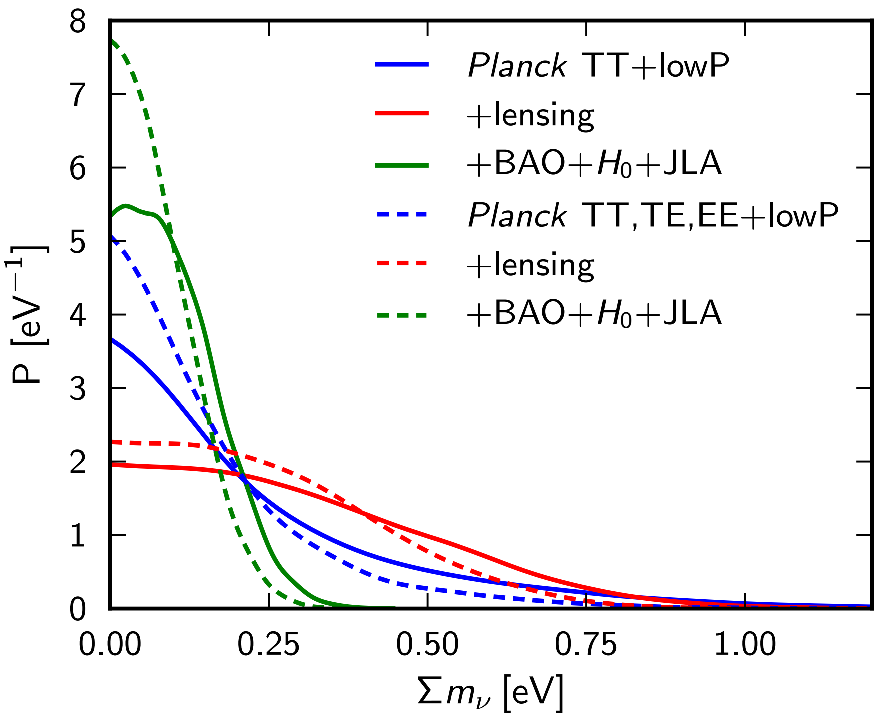
Net effect is to decrease lensing

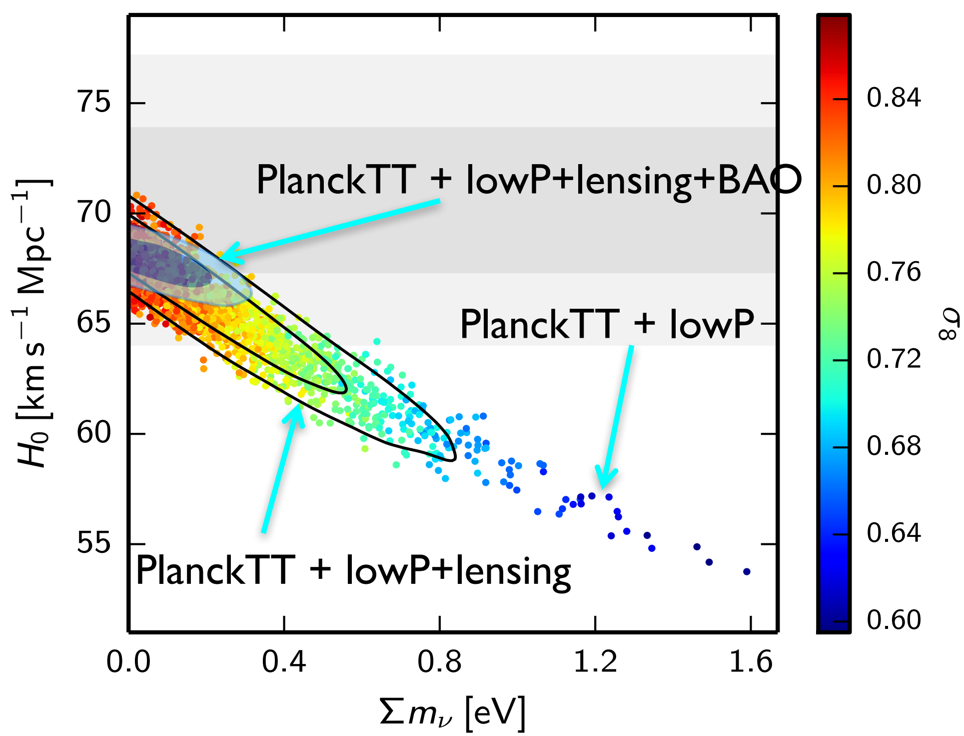
Perturbations: free streaming, damping of small-scale perturbations

- proportional to the neutrino energy density
- the effect is larger for larger masses

How heavy?

95% constraints on total mass	*PlanckTT*	*PlanckTTTEEE*
+lowP	<0.72 eV	<0.49 eV
+lowP+lensing	<0.68 eV	<0.59 eV
+lowP+BAO	<0.21 eV	<0.17 eV
+lowP+ext	<0.20 eV	<0.15 eV
+lowP+lensing+ext	<0.23 eV	<0.19 eV

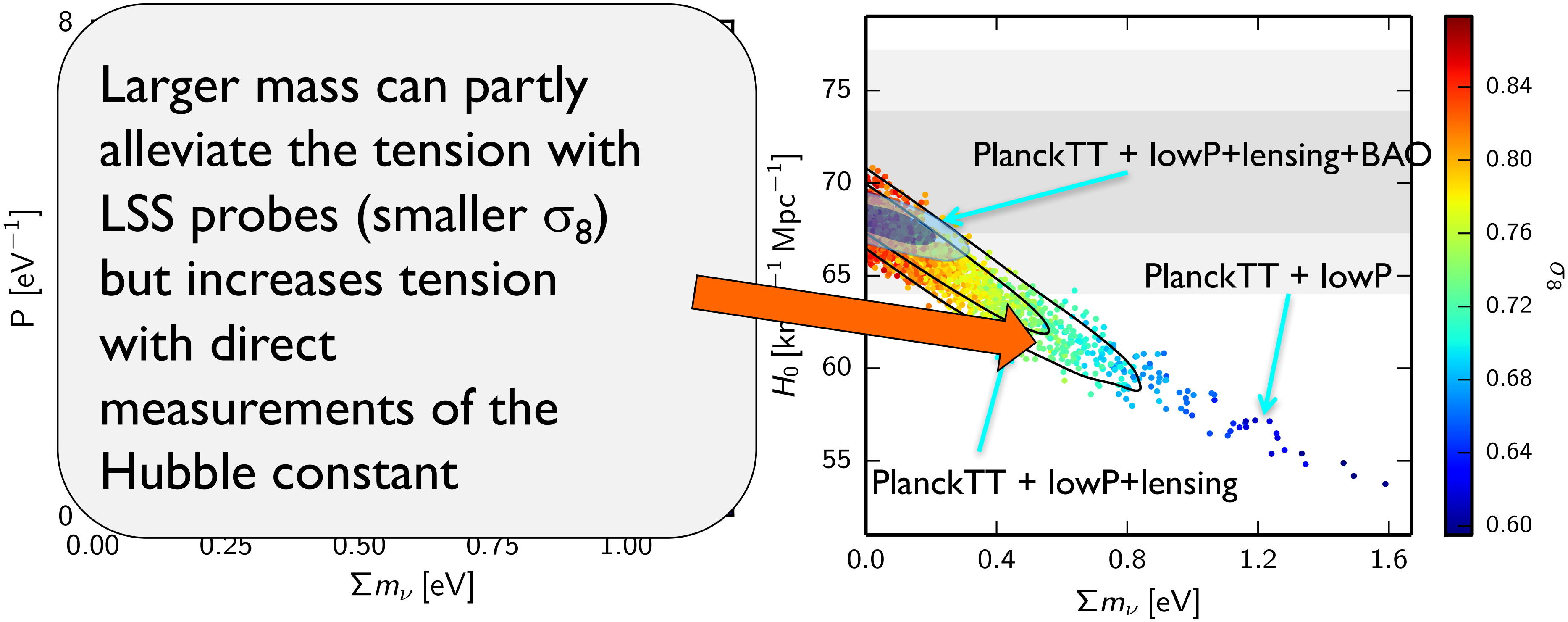




How heavy?

95% constraints on total mass	*PlanckTT*	*PlanckTTTEEE*
+lowP	<0.72 eV	<0.49 eV
+lowP+lensing	<0.68 eV	<0.59 eV
+lowP+BAO	<0.21 eV	<0.17 eV
+lowP+ext	<0.20 eV	<0.15 eV
+lowP+lensing+ext	<0.23 eV	<0.19 eV

Larger mass can partly alleviate the tension with LSS probes (smaller σ_8) but increases tension with direct measurements of the Hubble constant



How heavy?

95% constraints on total mass	*PlanckTT*	*PlanckTTTEEE*
+lowP	<0.72 eV	<0.49 eV
+lowP+lensing	<0.68 eV	<0.59 eV
+lowP+BAO	<0.21 eV	<0.17 eV
+lowP+ext	<0.20 eV	<0.15 eV
+lowP+lensing+ext	<0.23 eV	<0.19 eV

Planck 2015 + BOSS Lyman-α:

$\Sigma m_\nu < 0.12$ eV (@95%)

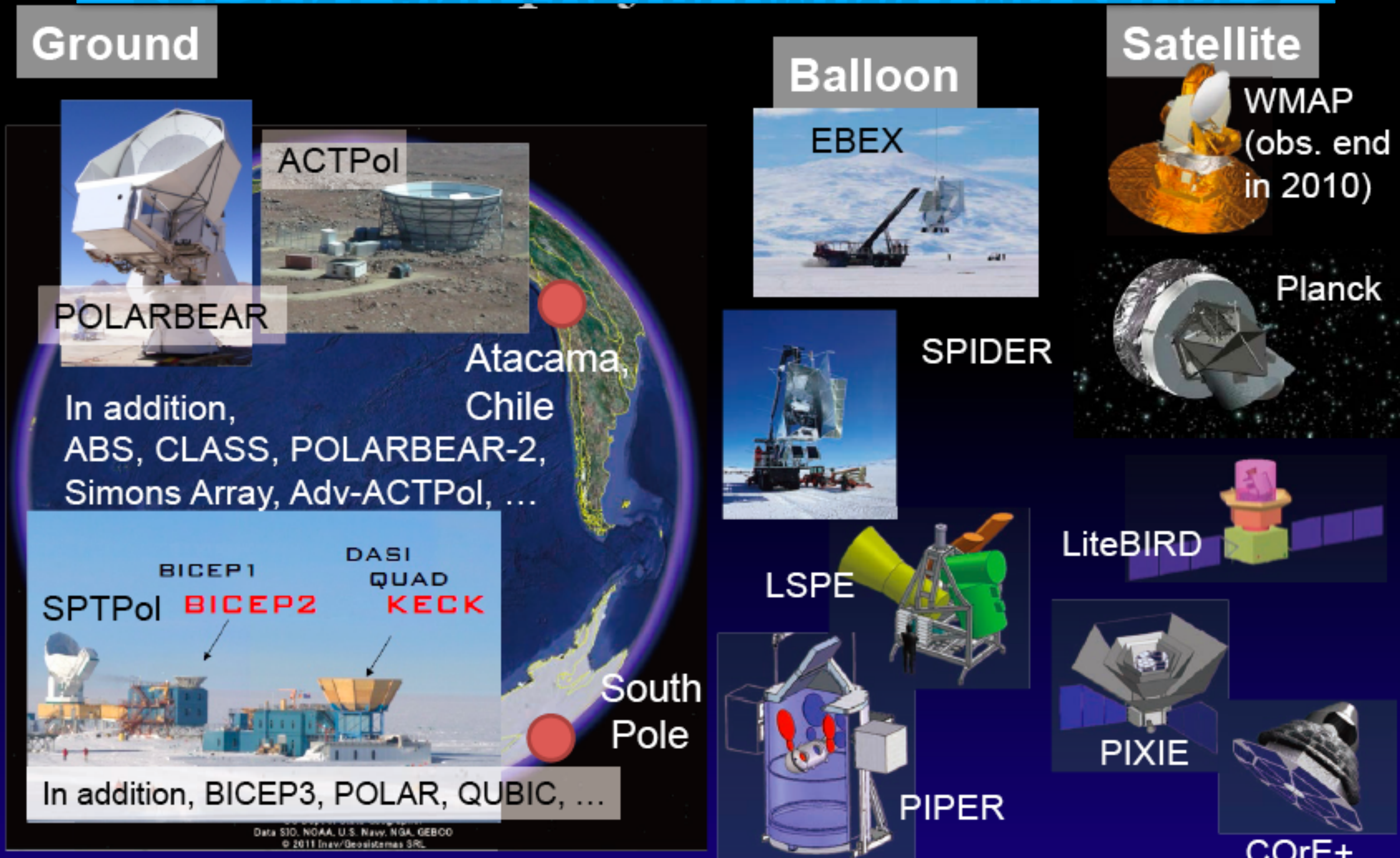
(Palanque-Delabrouille et al. 2015)

Planck 2015 + BOSS DR12 (BAO+shape):

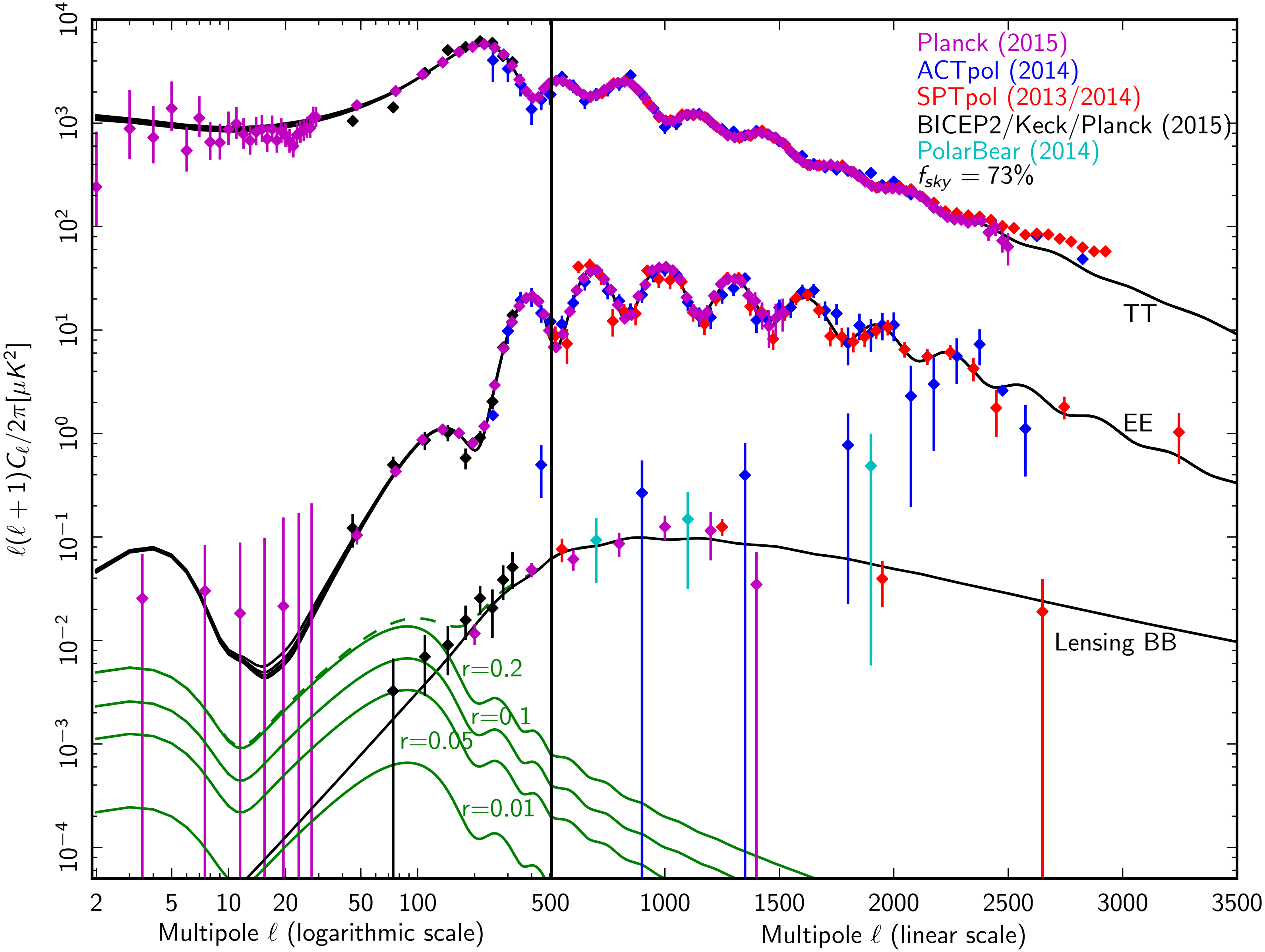
$\Sigma m_\nu < 0.16$ eV (@95%)

(BOSS collab., arXiv:1607.03155)

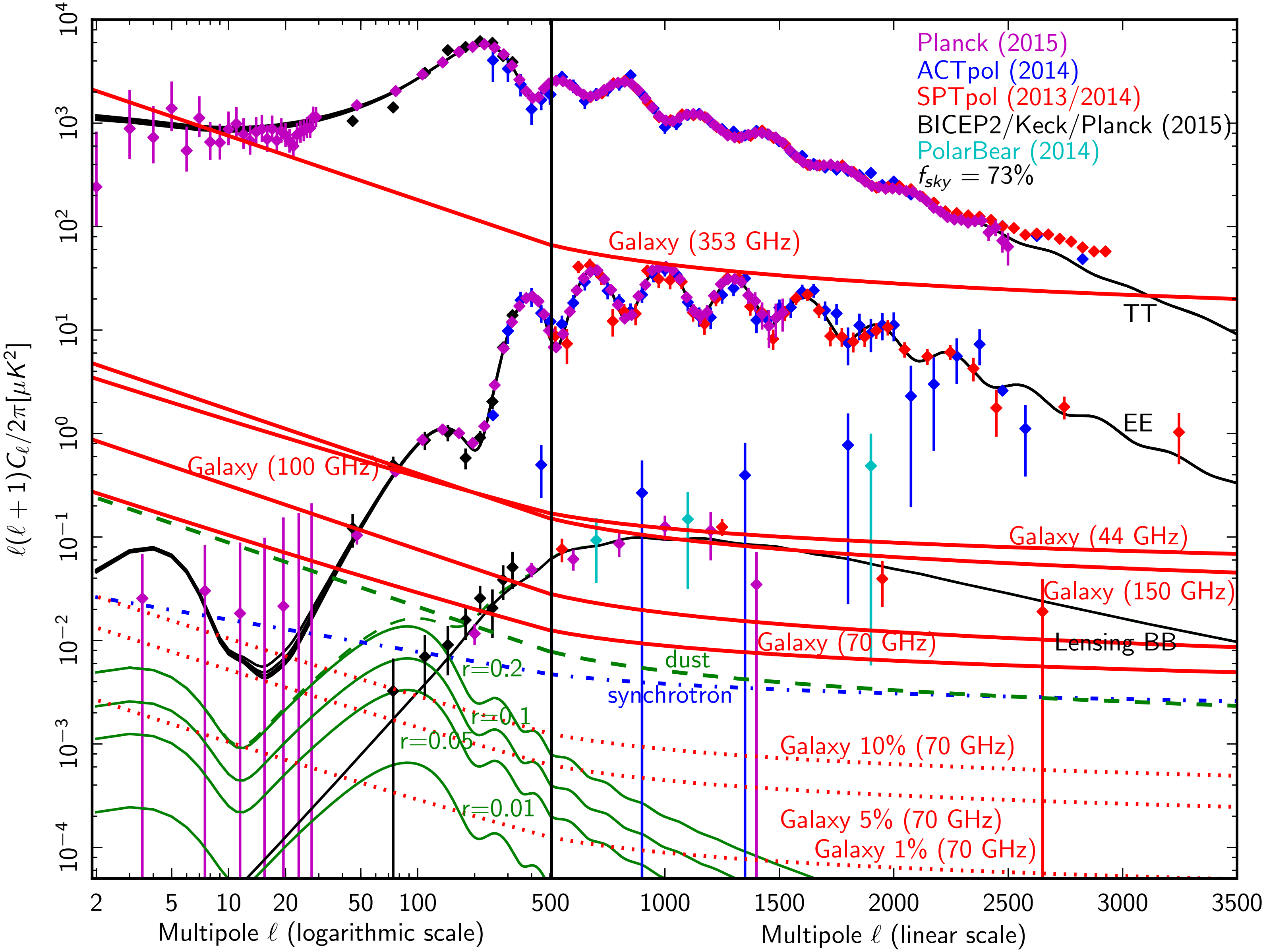
PRESENT AND FORTHCOMING CMB PROBES

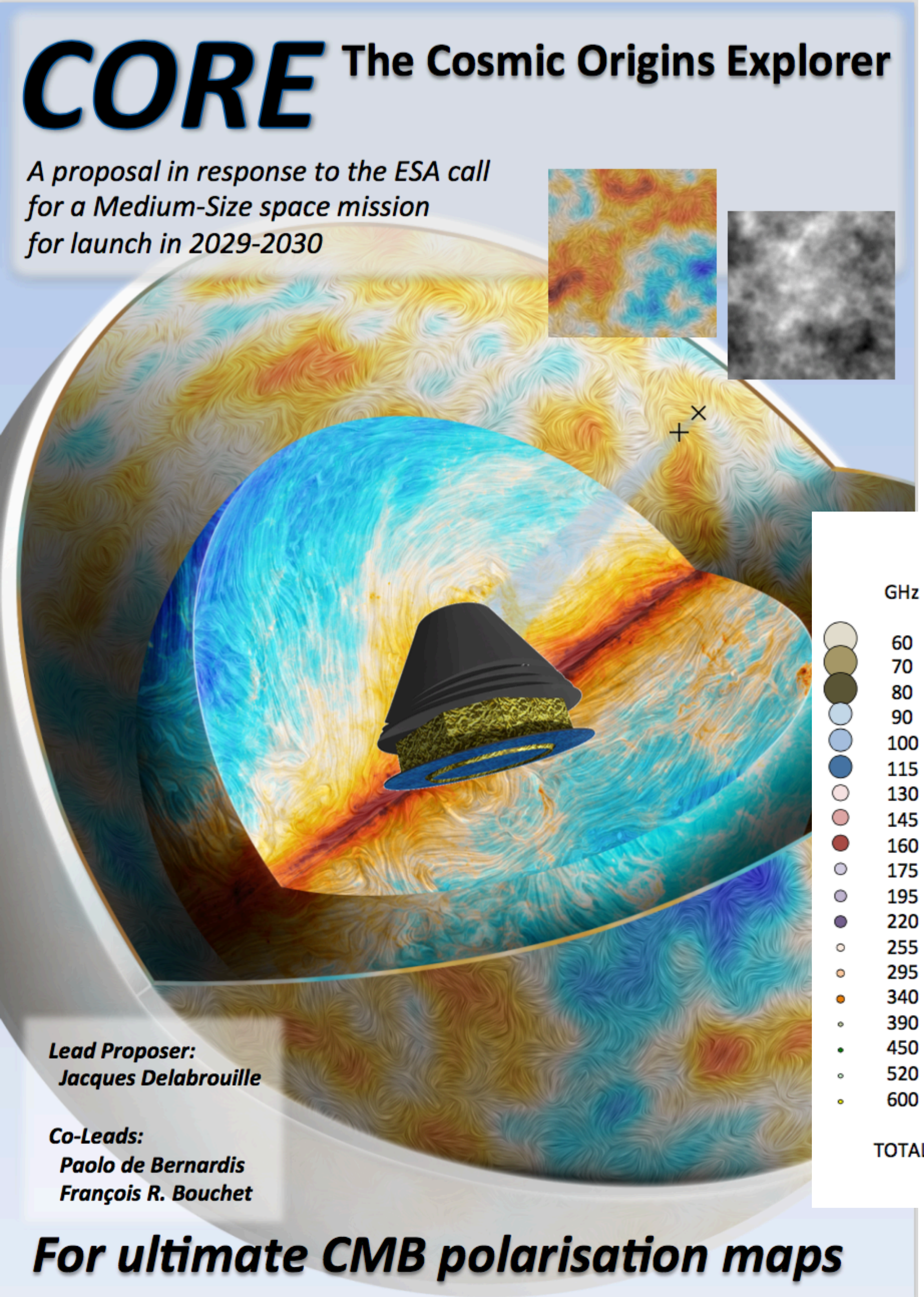


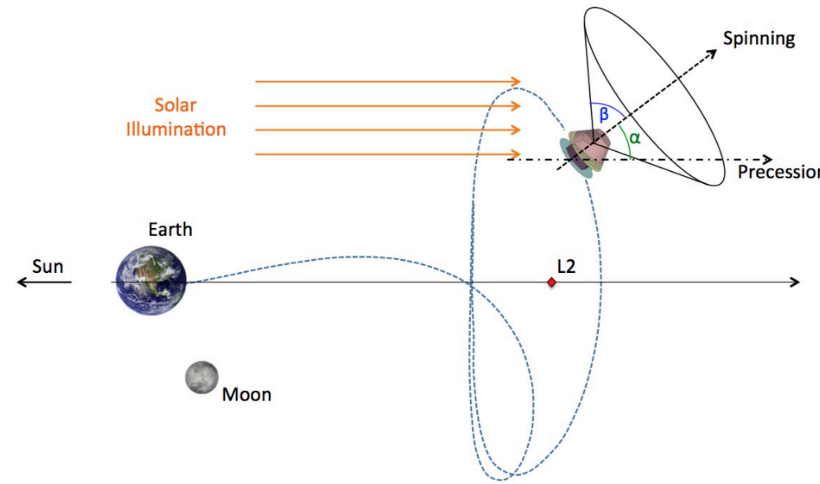
In addition, QUIJOTE in Canary island, AMiBA in Hawaii



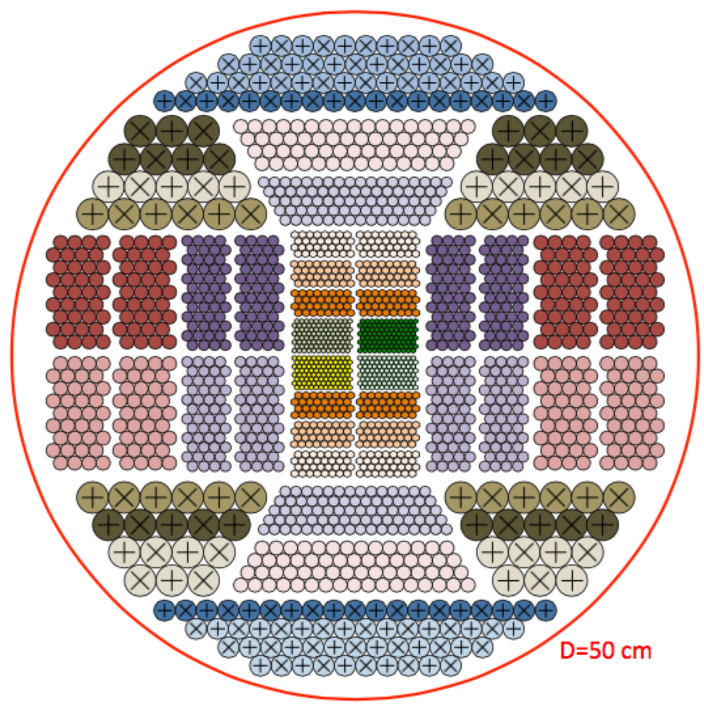
Planck (2015)
ACTpol (2014)
SPTpol (2013/2014)
BICEP2/Keck/Planck (2015)
PolarBear (2014)
$f_{sky} = 73\%$
TT
EE
Lensing BB
r=0.2
r=0.1
r=0.05
r=0.01
$\ell(\ell+1)C_\ell/2\pi[\mu K^2]$
Multipole ℓ (logarithmic scale)
Multipole ℓ (linear scale)


Planck (2015)
ACTpol (2014)
SPTpol (2013/2014)
BICEP2/Keck/Planck (2015)
PolarBear (2014)
$f_{sky} = 73\%$
Galaxy (353 GHz)
TT
EE
Galaxy (100 GHz)
Galaxy (44 GHz)
Galaxy (150 GHz)
Galaxy (70 GHz)
Lensing BB
dust
synchrotron
r=0.2
r=0.1
r=0.05
r=0.01
Galaxy 10% (70 GHz)
Galaxy 5% (70 GHz)
Galaxy 1% (70 GHz)
$\ell(\ell+1)C_\ell/2\pi[\mu K^2]$
Multipole ℓ (logarithmic scale)
Multipole ℓ (linear scale)

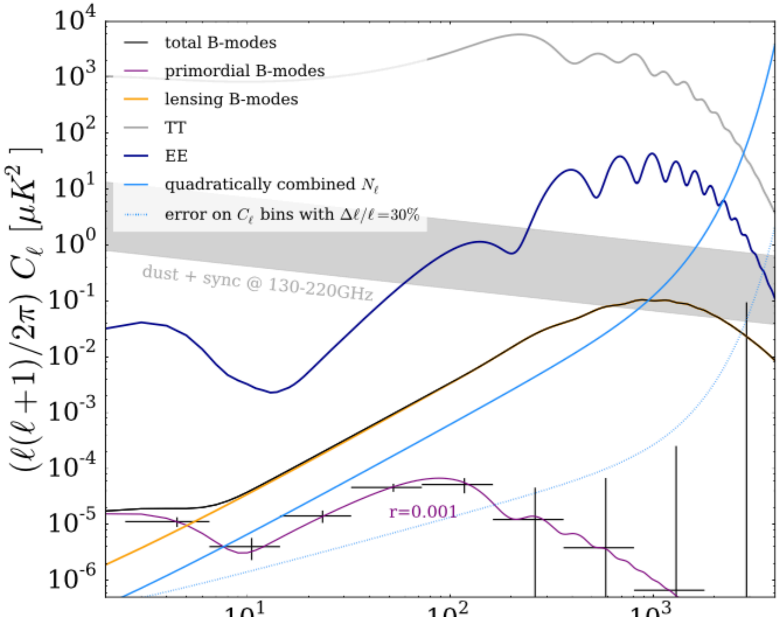


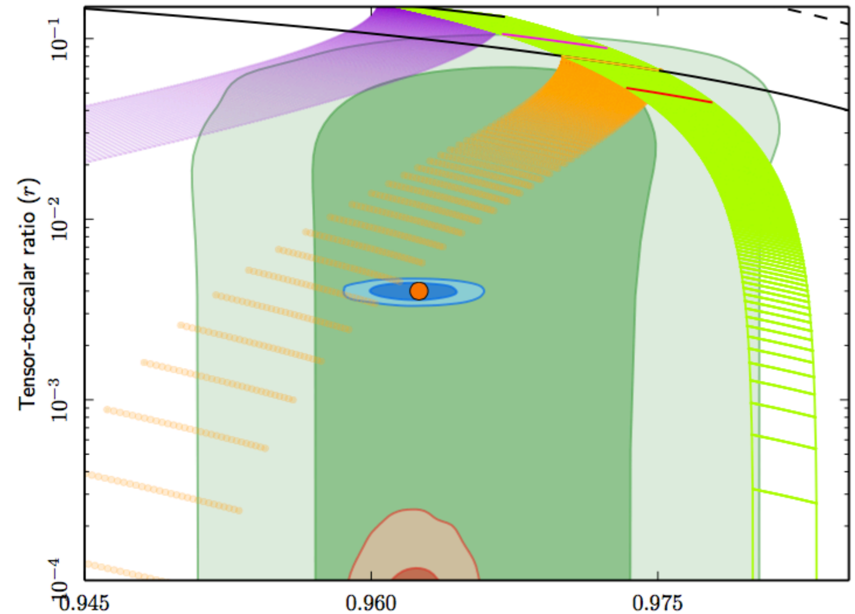


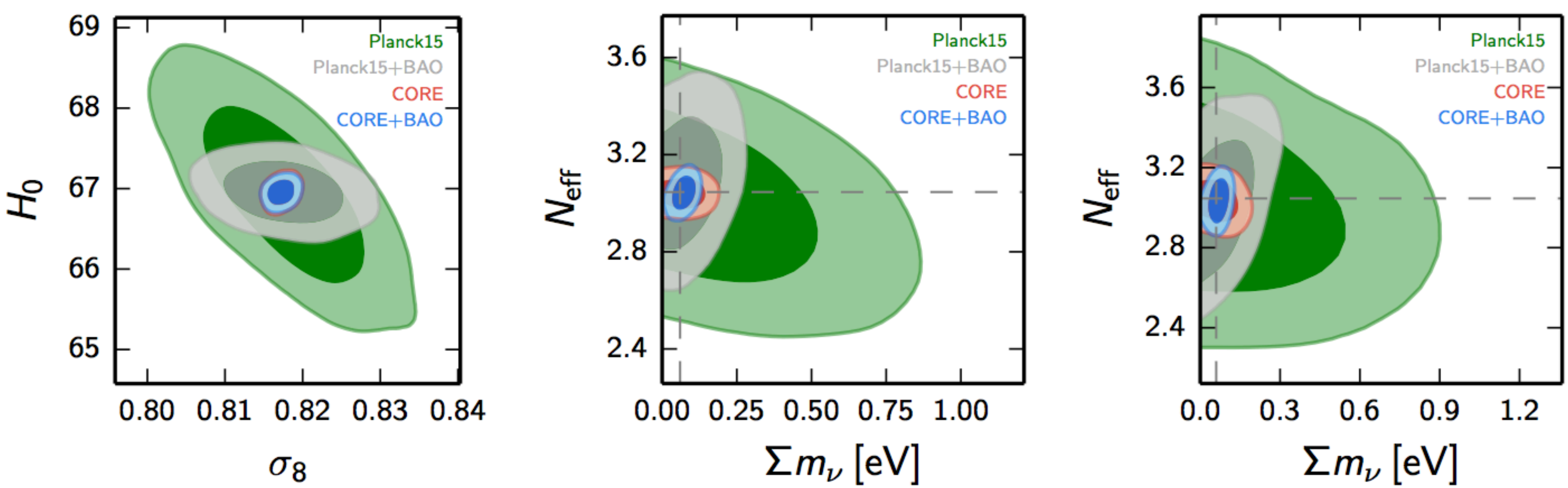
GHz	N_{det}
60	24×2
70	24×2
80	24×2
90	39×2
100	39×2
115	38×2
130	124
145	144
160	144
175	160
195	192
220	192
255	128
295	128
340	128
390	96
450	96
520	96
600	96
TOTAL	2100



CORE forecasts







Conclusions

- Planck is quickly approaching its final (legacy) release
- It has provided the ultimate (cosmic variance limited) measurement of CMB anisotropy
- … But just opened the door of CMB polarization (which was never designed to measure, by the way)
- It has already fulfilled its promise of measuring the fundamental cosmological parameters to percent accuracy
- And brought remarkable constraints on particle physics parameters as well, excluding a fourth fully thermalized neutrino and constraining the total neutrino masses in the range of 0.2 eV
- Has measured well one relevant inflationary parameter, the primordial spectral index, allowing constraints on the inflationary paridigm
- Yet has uncovered several tensions with astrophysical measurements, which may or may not hint at new physics.
- Primordial gravitational waves remain unseen.
- To exploit the wealth of information that still is in the CMB, we need to cope with the extraordinary complexity of the sky. This can be credibly done only with a space mission.