The Planck Legacy

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on behalf of the Italian CMB community

Planck legacy: Astrophysics and CMB intensity

1. Planck is mainly devoted to CMB but has done much astrophysics as well. I do not discuss it here, but :
    a. Full sky diffuse components of Galaxy emission (synchrotron, free-free, dust, spinning dust, CO…)
    b. Compact sources, both Galactic and extra Galactic on a frequency range never observed consistently so far: cold cores, SN remnants, radio galaxies, dusty galaxies (CIB), blazars, galaxy clusters with SZ…
2. **Planck brings the ultimate dataset for CMB anisotropy (temperature). Cosmic variance on all modes of interest. No experiment will ever do better!**
3. To do better, you must travel to a Galaxy far far away and observe another realization of CMB anisotropy
4. Why this was worth it
    a. Most precise Solar dipole ever (our motion in the Universe)
    b. Measure of cosmological parameters to cosmic variance precision
    c. Understanding big bang nucleosynthesis
    d. Understanding the dynamics of inflation
    e. Limits on primordial non Gaussianity
    f. Limits on neutrino masses and number of neutrino species
    g. Understanding the evolution of LSS through gravitational lensing

Planck Legacy: polarization

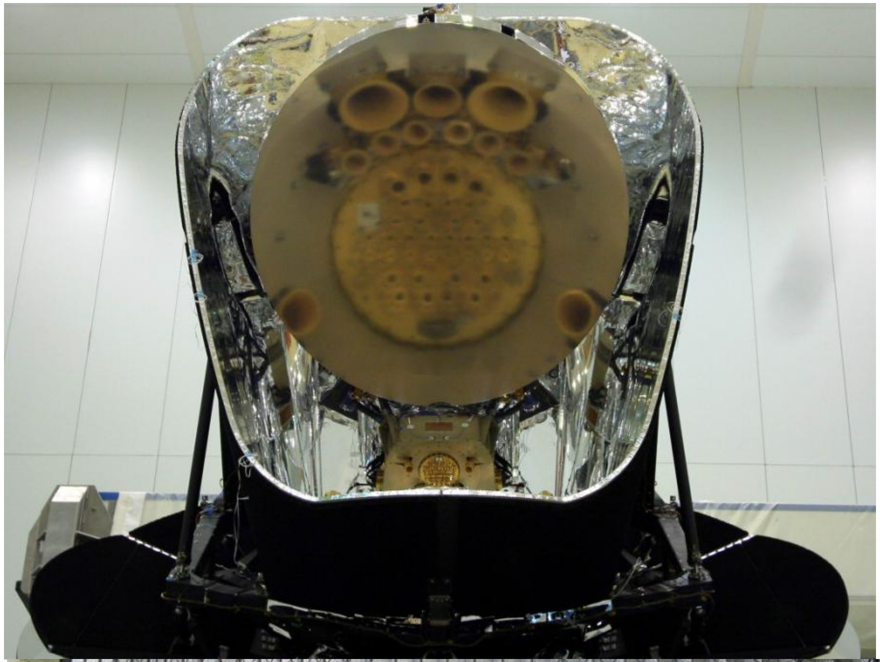
1. The polarized microwave sky was almost completely uncharted territory before Planck. Planck has opened a new observational channel for astrophysics and cosmology.
2. Astrophysics: Galactic polarization (e.g. understanding magnetic fields, foregrounds physics), polarized sources
3. From CMB polarization:
    1. Limits on fundamental physics beyond the standard model: modified electromagnetism, fundamental symmetry breaking…
    2. Limits on primordial gravitational waves – B modes
    3. Understanding the dark ages, reionization history of the Universe.
4. **Planck has opened a new era for polarization. Some other experiment will have to close it (Ground, balloons, space…)**

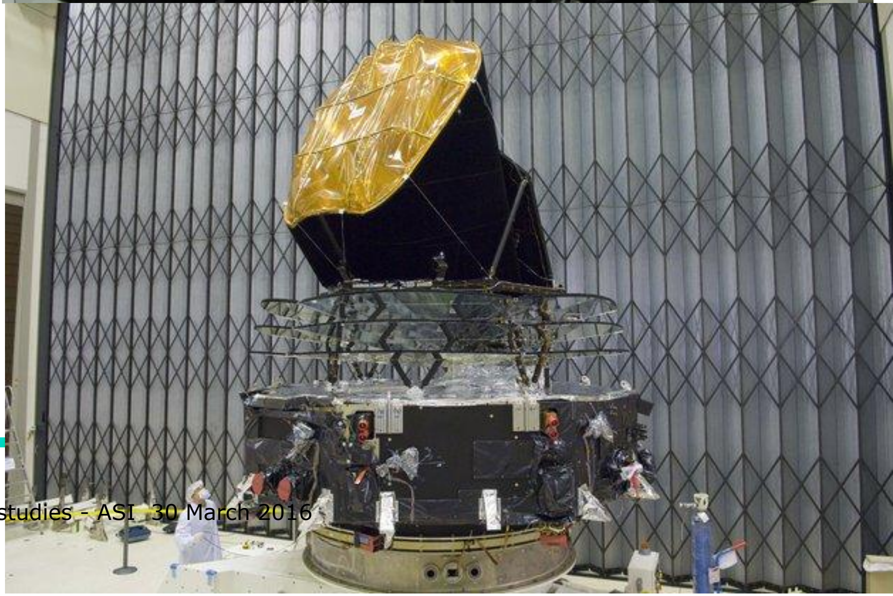
Value

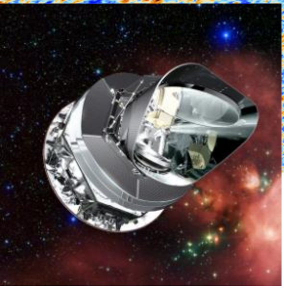
1. Physics/astrophysics experiments are often designed to have a single goal or a restricted set of targets.
2. Planck is a machine to measure many many things, from astrophysics to cosmology, to fundamental physics: best value from money!
3. Ended up in school text books: forced authors to rewrite the cosmology section
4. Too many results to discuss in less than 30 min. I will have to make selections…
5. 100 years after Einstein GR we have observed gravitational waves. Opens a new window on the universe. But primordial gravitational waves will not be observable with measurements for decades. Our only bet is to observe them in CMB polarization!

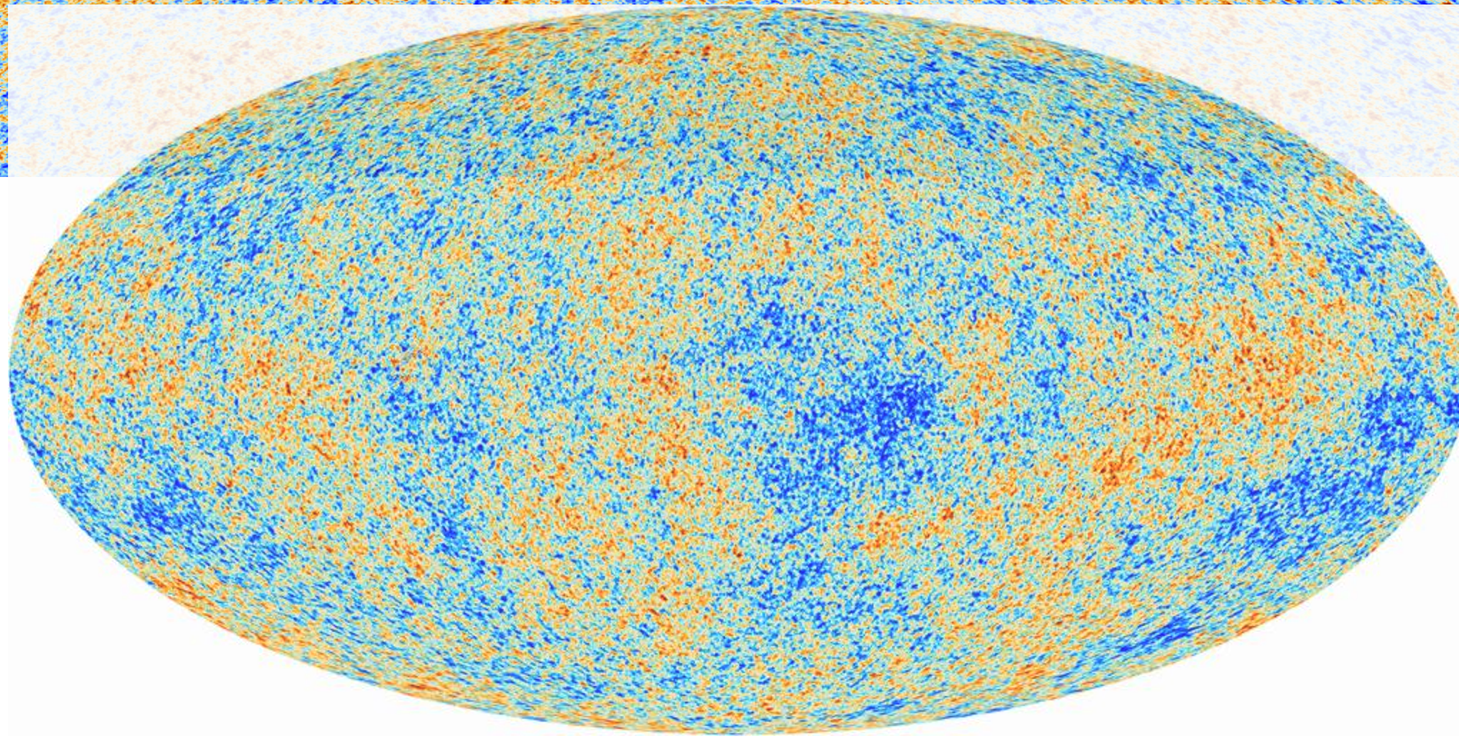
The Planck Satellite

- Third-generation satellite, launched and operated by ESA, dedicated to the CMB
- Observed the sky continuously from 12 August 2009 to 23 October 2013
- Focal plane hosts 74 detectors between 30 GHz and 1 THz (9 bands) with angular resolution between 30' and 5', $\Delta T/T_{CMB} \sim 2 \times 10^{-6}$
- Optics: 1.5 m class
- Low Frequency Instrument (LFI): pseudo-correlation radiometers observing at 30, 44, 70 GHz
- High Frequency Instrument (HFI): bolometers observing at 100, 143, 217, 353, 545 and 857 GHz
- Observed the microwave sky for ~ 30 (HFI) and 48 (LFI) months
- First cosmological release in May 2013, using the "nominal mission" temperature data (15.5 months of observations)
- Second cosmological release in Feb 2015: full mission temperature and polarization
- Third and final (legacy) release in 2016/2017







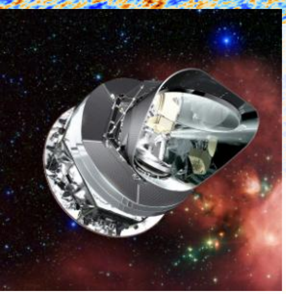


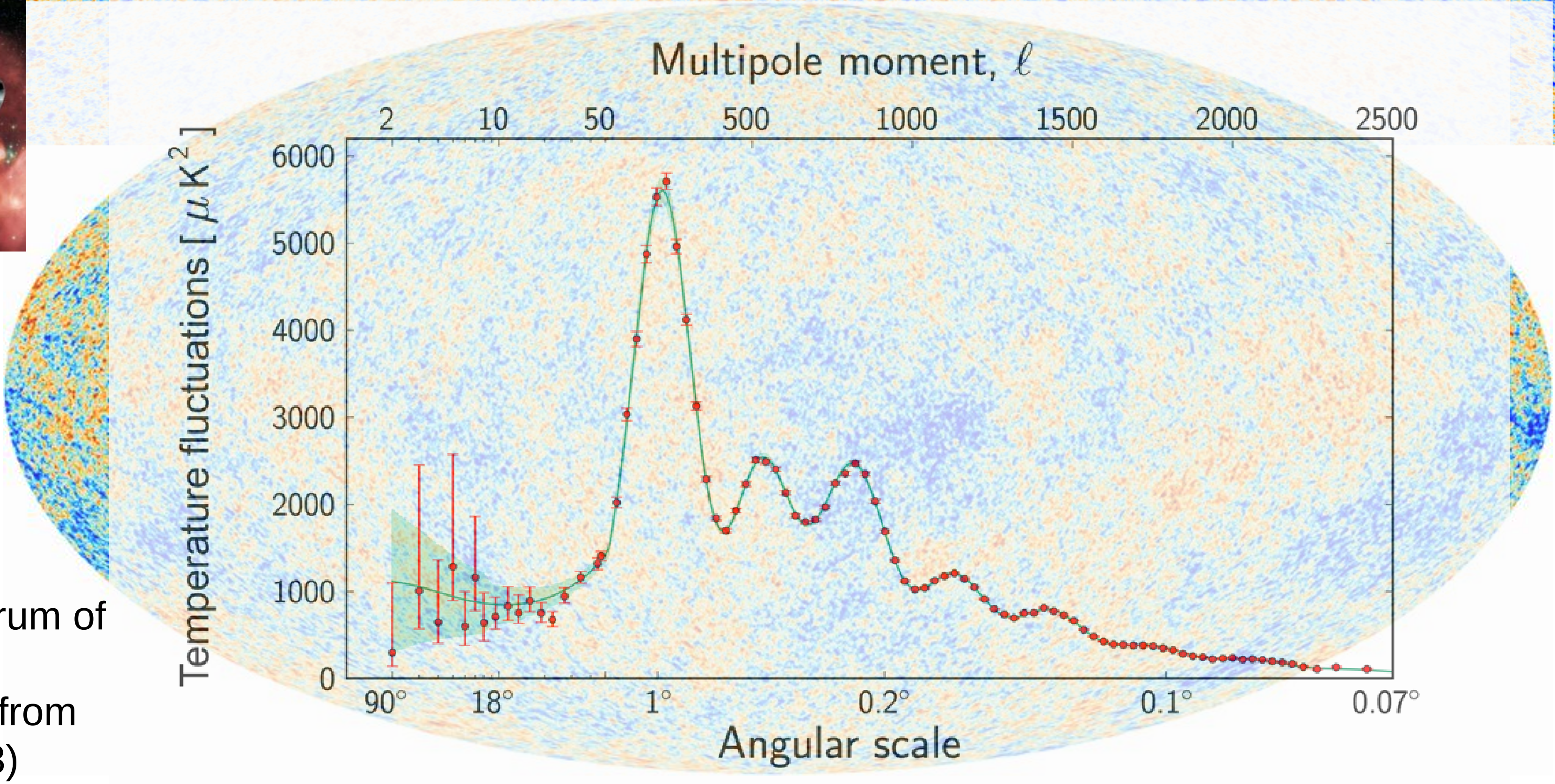
Full sky temperature map from Planck (2013)

The main objective of Planck is to measure the spatial temperature and polarization anisotropies of the cosmic microwave background (CMB) radiation

The CMB is a blackbody radiation with T=2.7 K extremely uniform across the whole sky; it is the relic radiation emitted at the time the nuclei and electrons recombined to form neutral hydrogen, when the Universe was ~ 400,000 years old.

Its tiny (~ 10^{-5}) temperature and polarization anisotropies encode a wealth of cosmological information.





Power spectrum of temperature fluctuations from Planck (2013)

The fluctuations are observed to be Gaussian distributed: all the statistical information in the map is encoded in the two point correlation function or in its harmonic transform, the angular power spectrum:

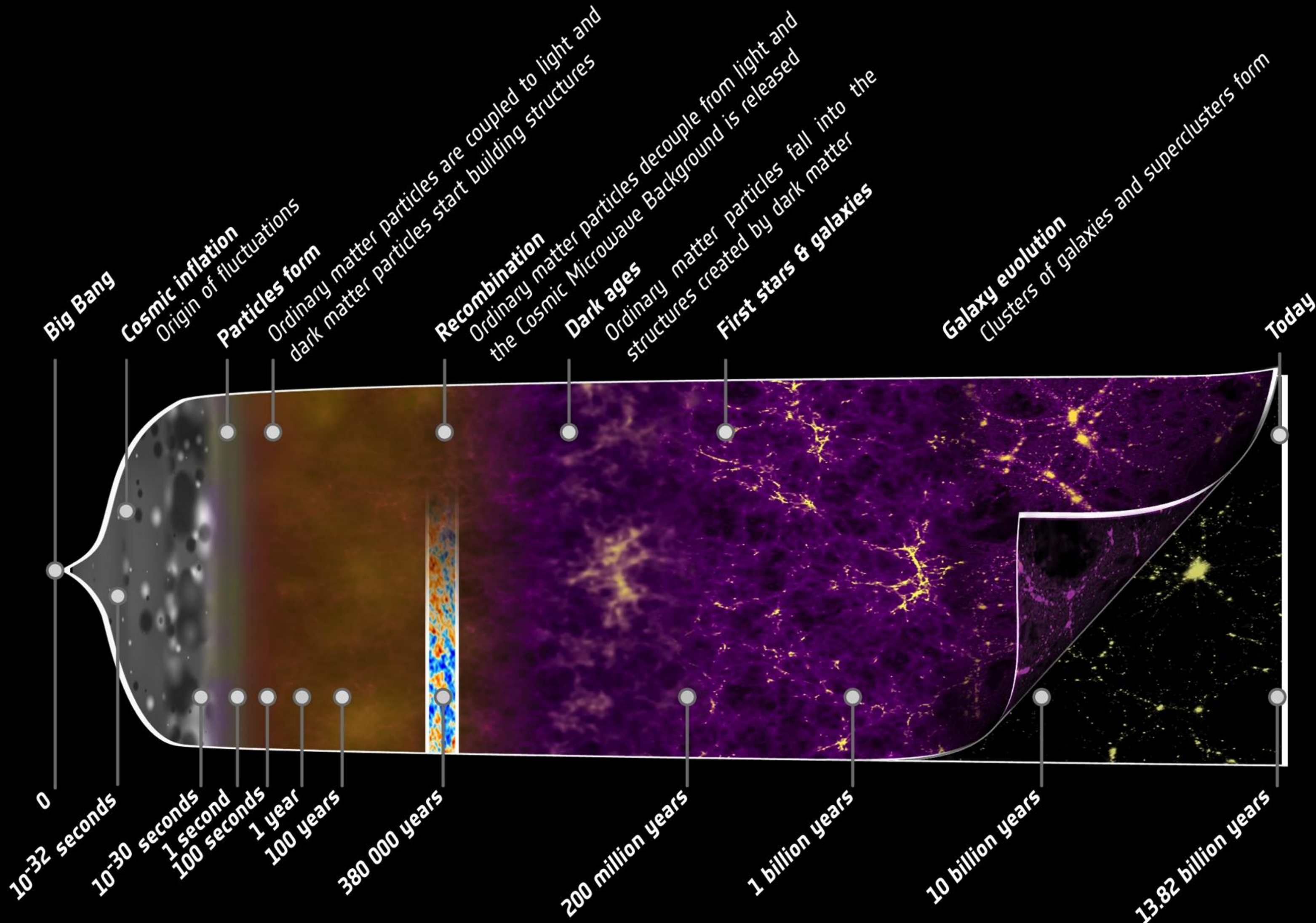
$$\Theta(\hat{n}) = \sum_{\ell=0}^{\ell=\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\hat{n})$$

$$\langle a_{\ell m} a^{*}_{\ell' m'} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_{\ell}$$

agenzia spaziale italiana

Istituto Nazionale di Astrofisica INAF

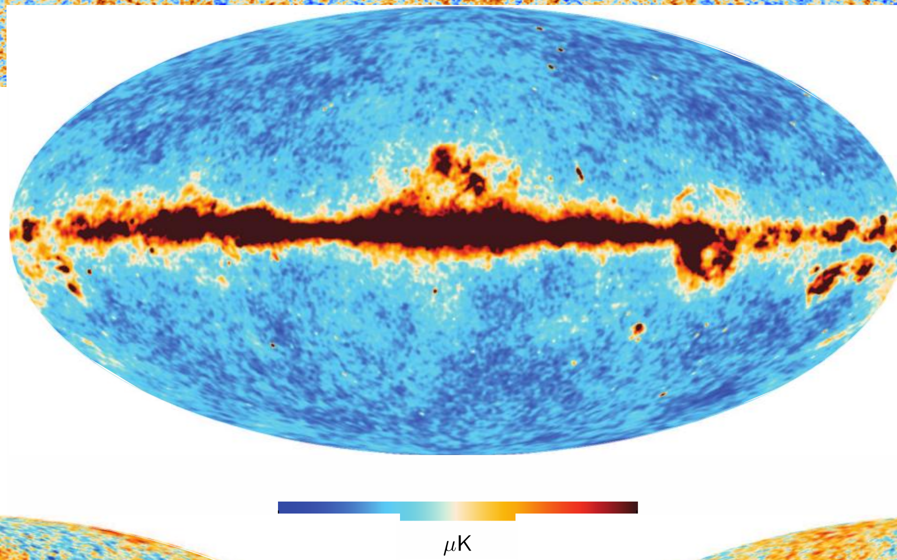
Università degli Studi di Ferrara - Ex labore fructus -

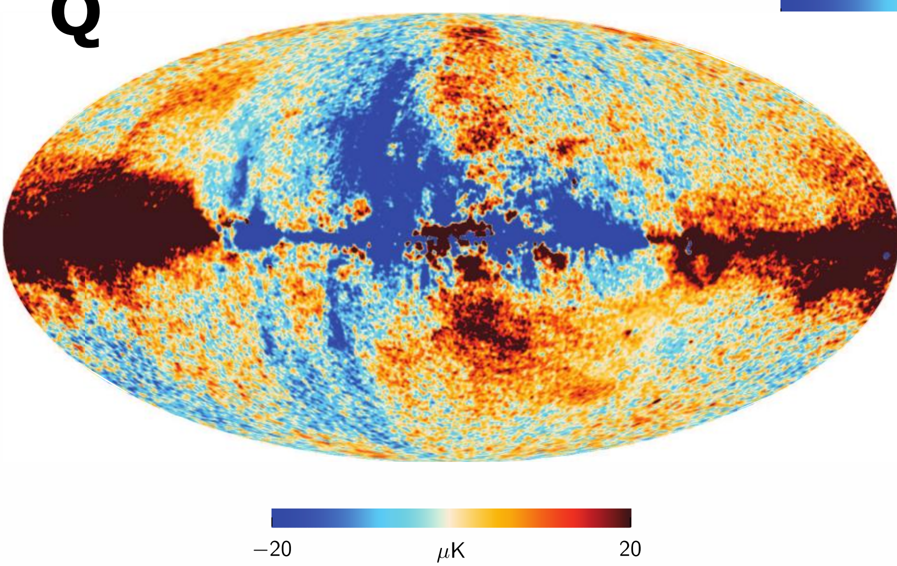


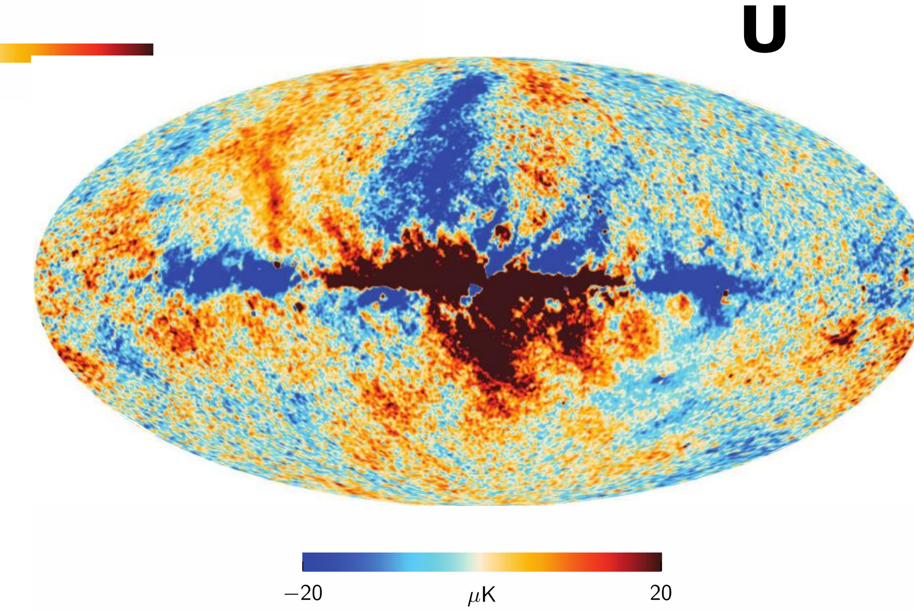
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles 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

PLANCK FREQUENCY MAPS

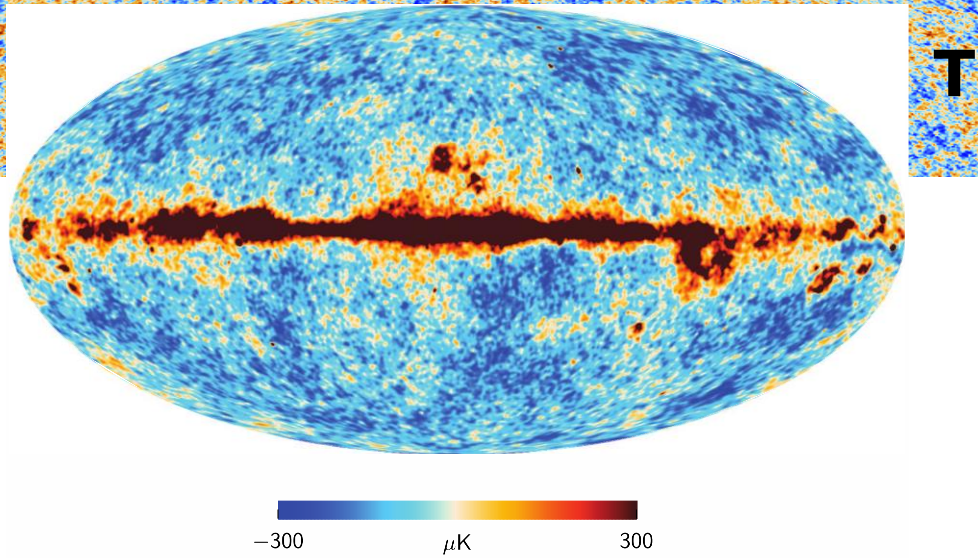
30 GHz

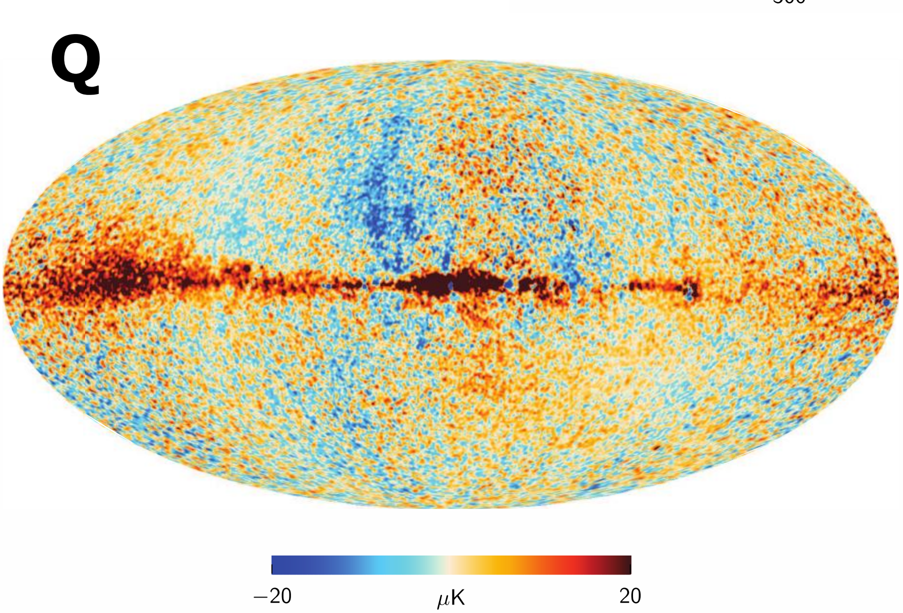


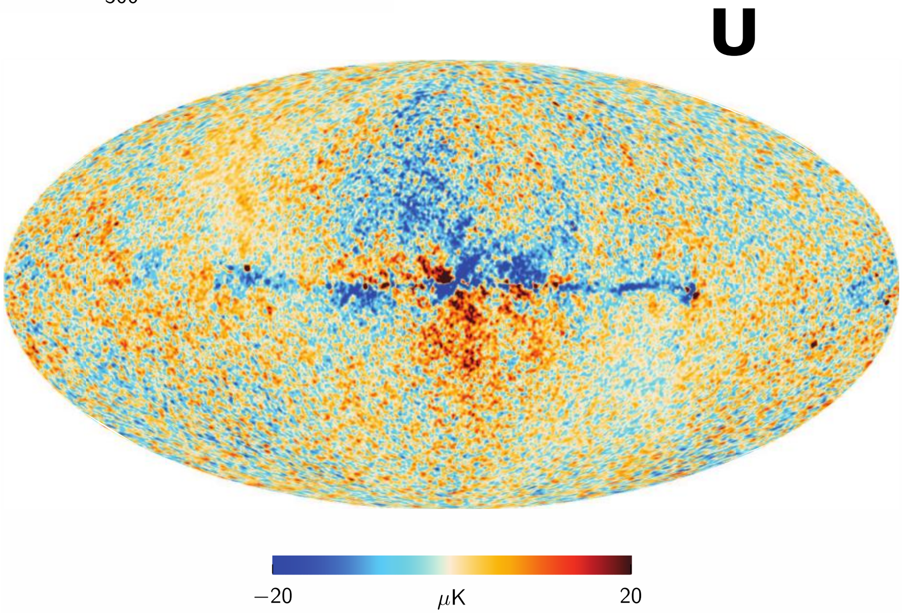




44 GHz

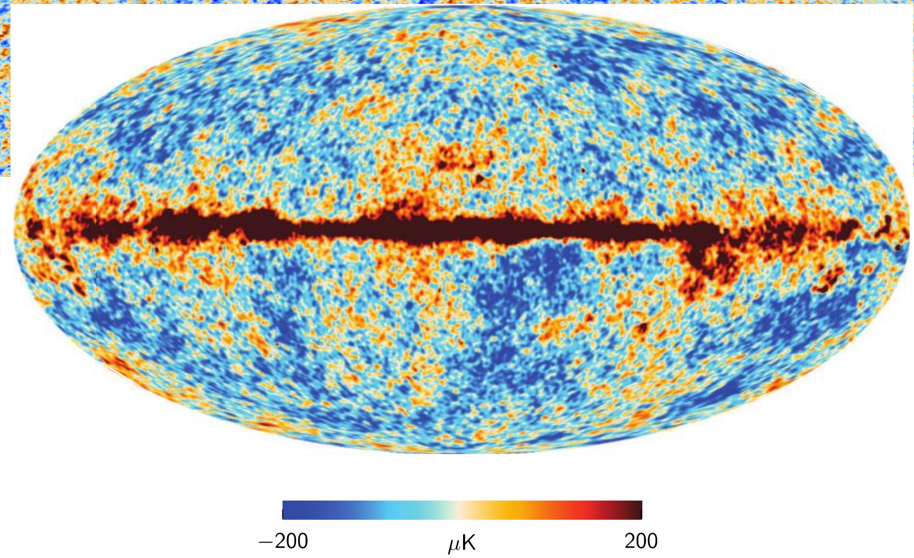




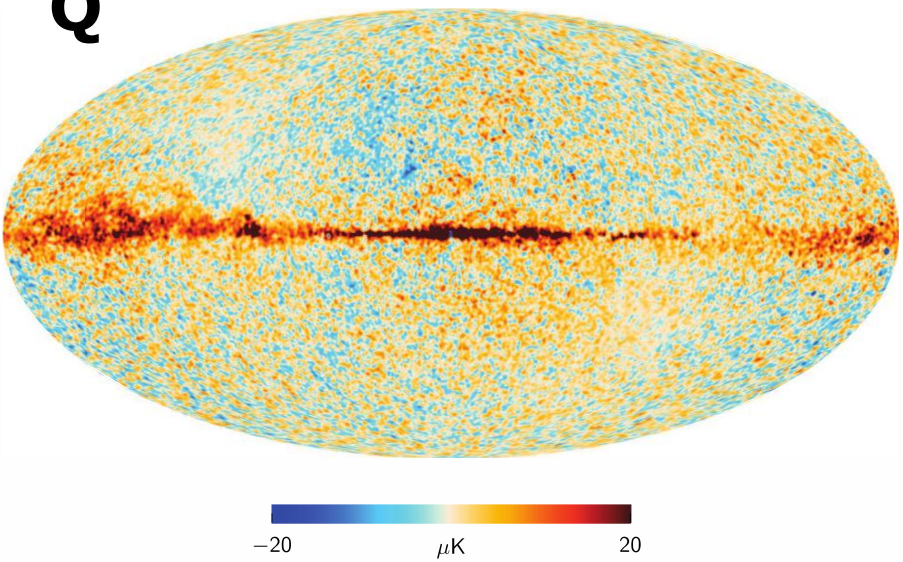


70 GHz

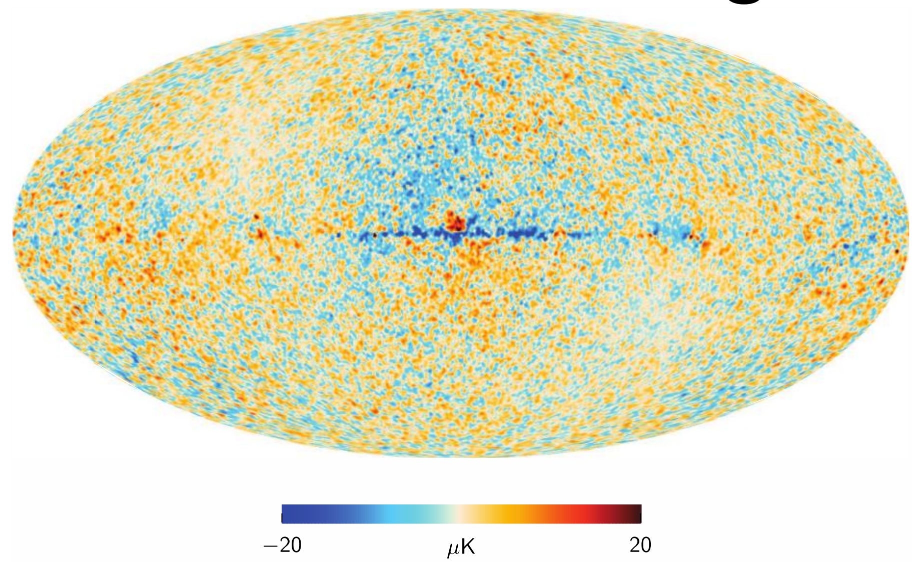
T

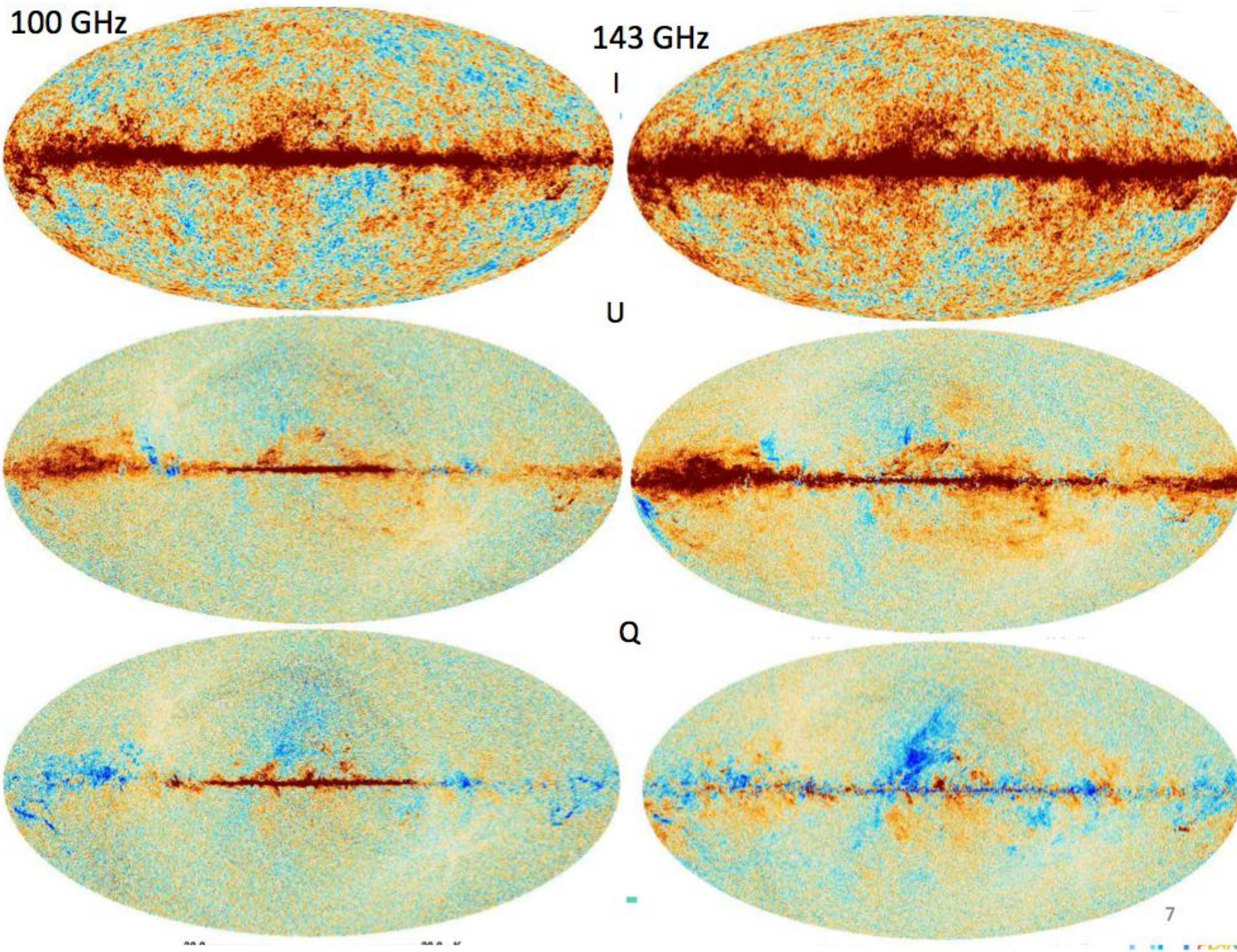


Q

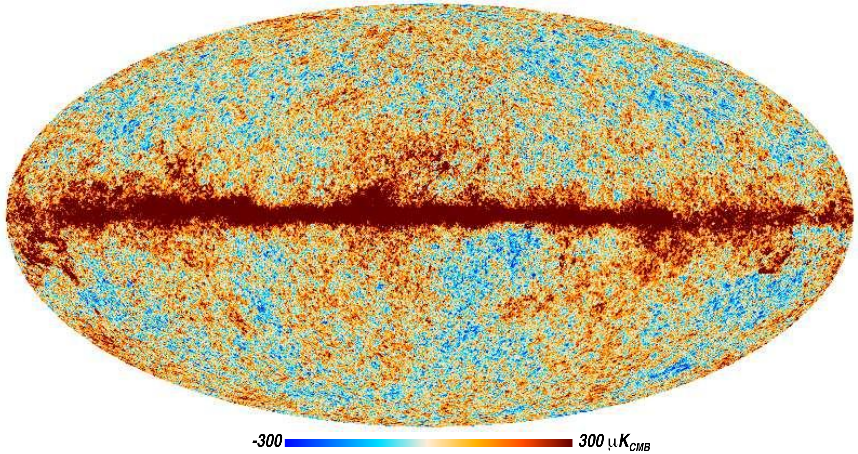


U

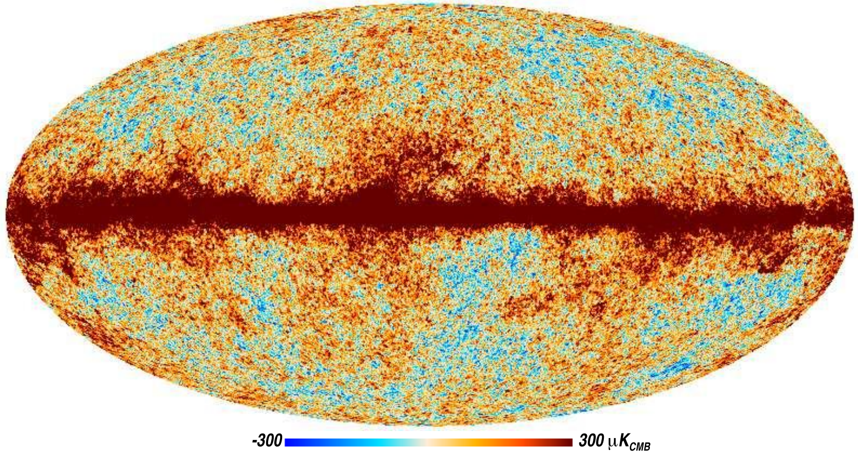



100 GHz
143 GHz
I
U
Q

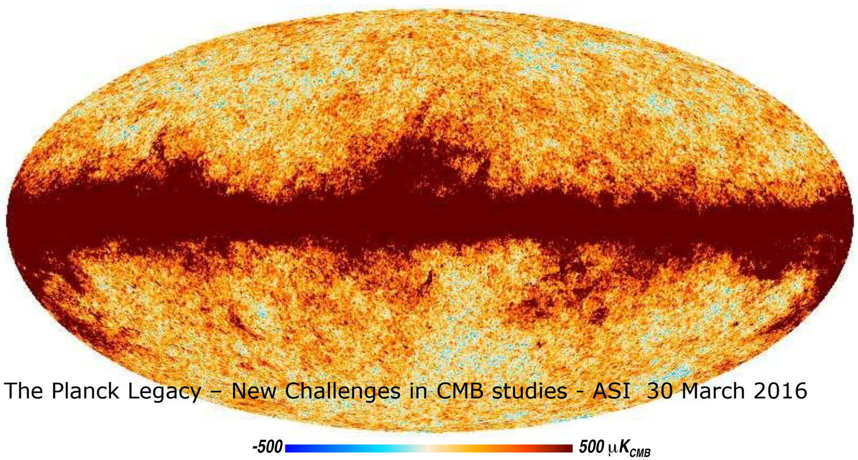
Temperature maps for 100, 143, 217 GHz



100 GHz

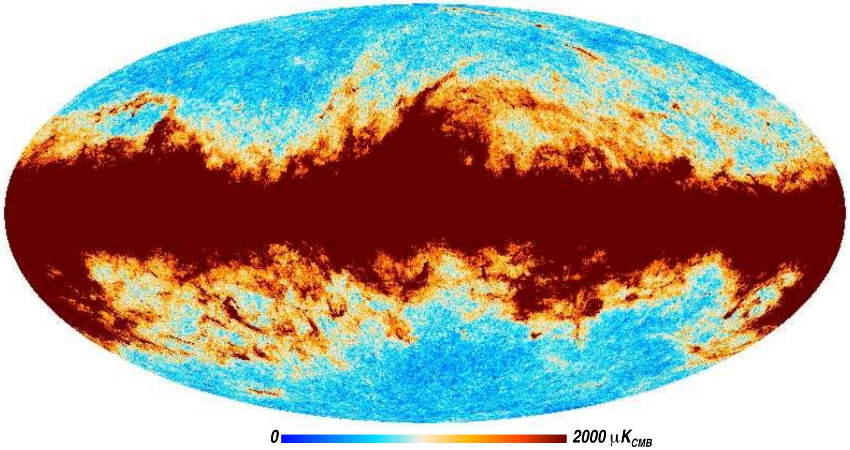


143 GHz

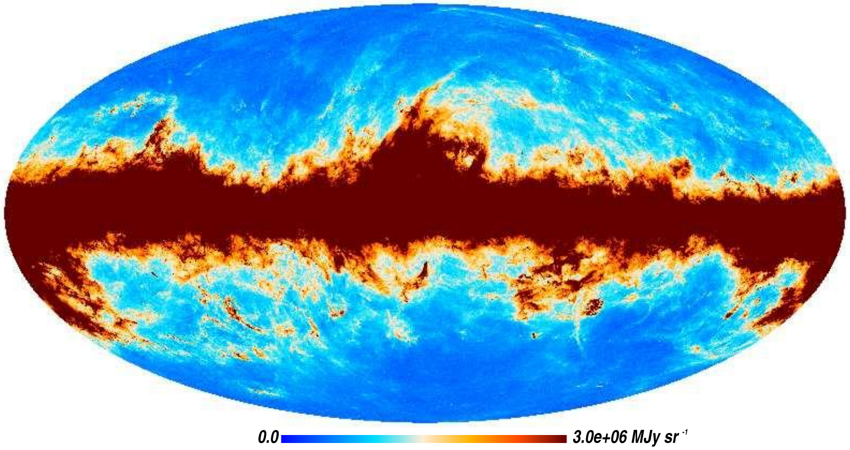


217 GHz

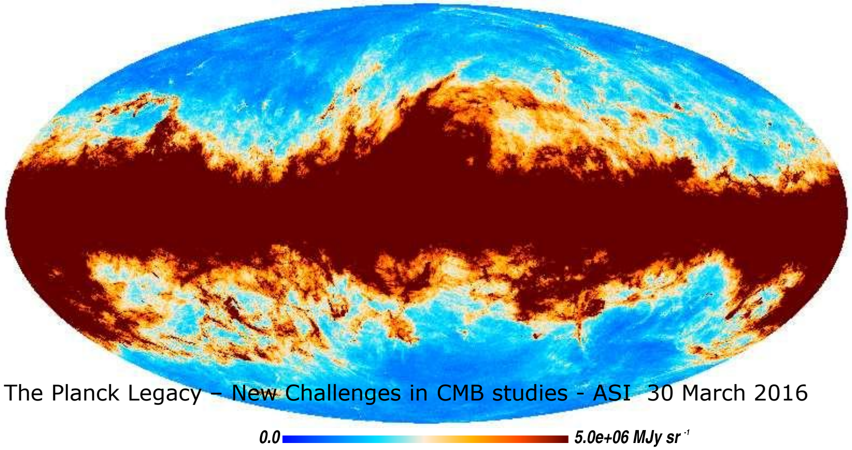
Temperature maps for 353, 545, 857 GHz



353 GHz

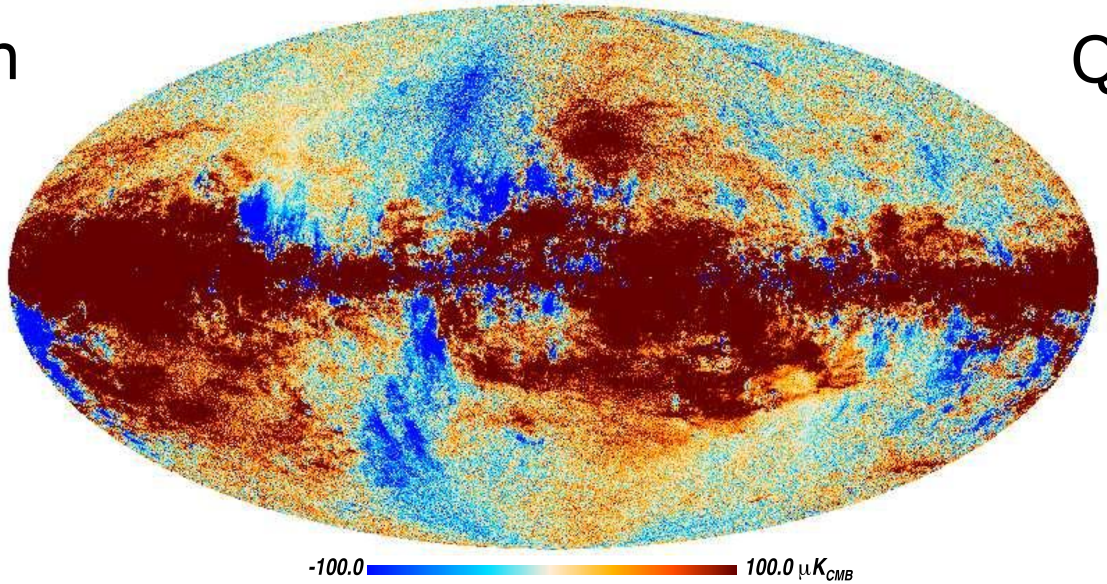


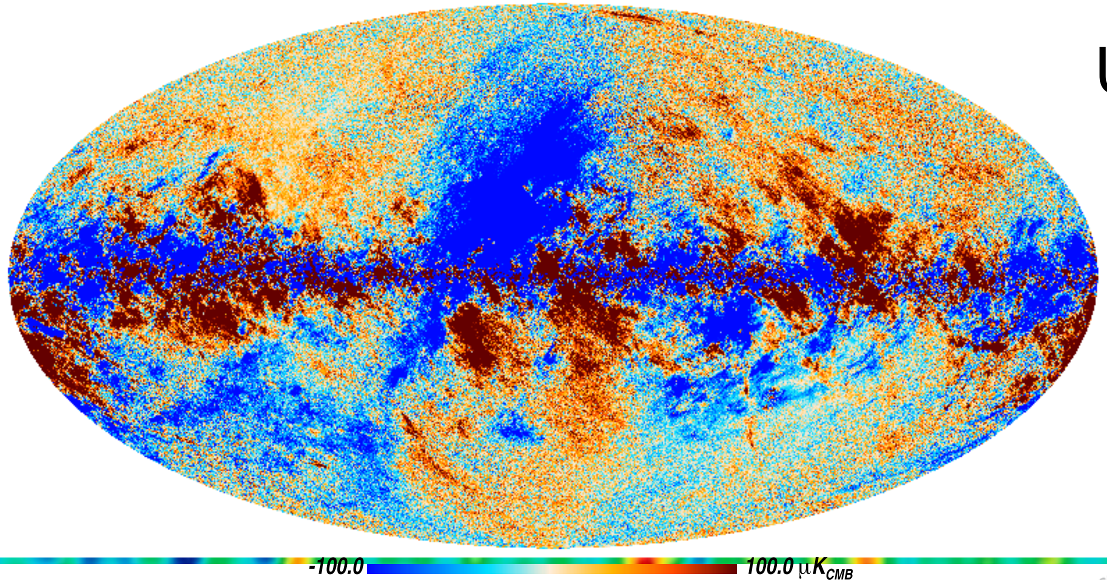
545 GHz



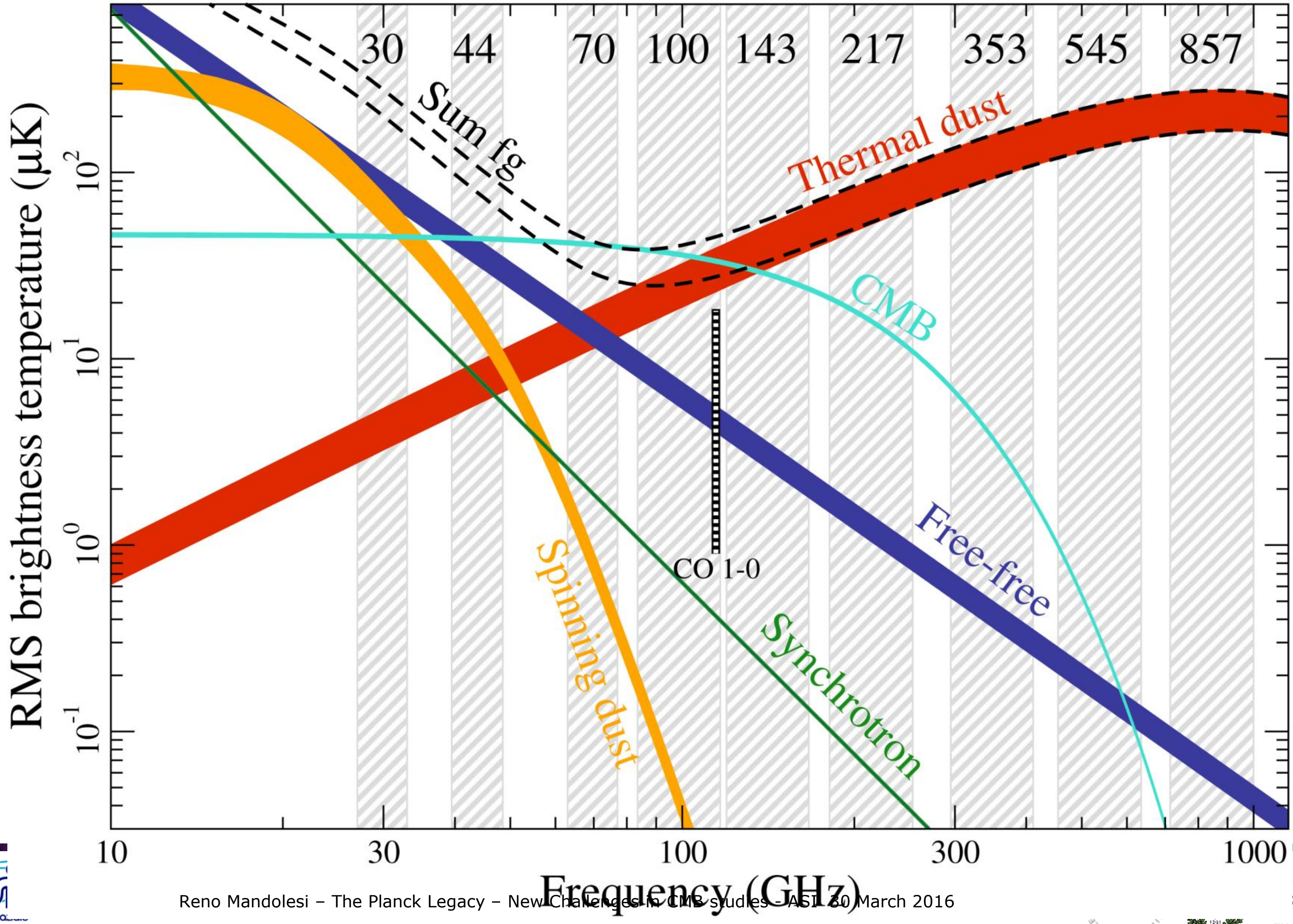
857 GHz

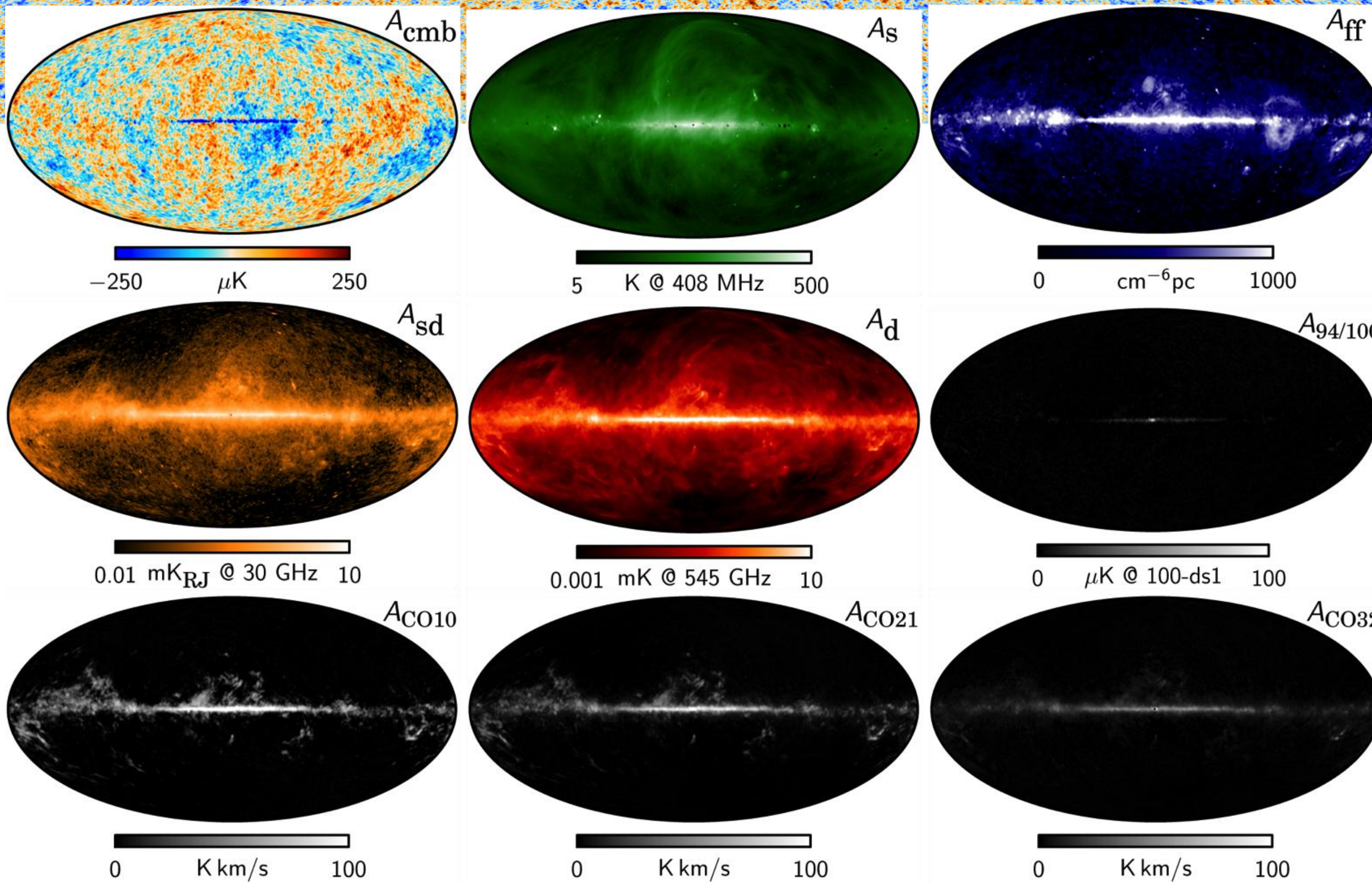
353 GHz Polarization maps





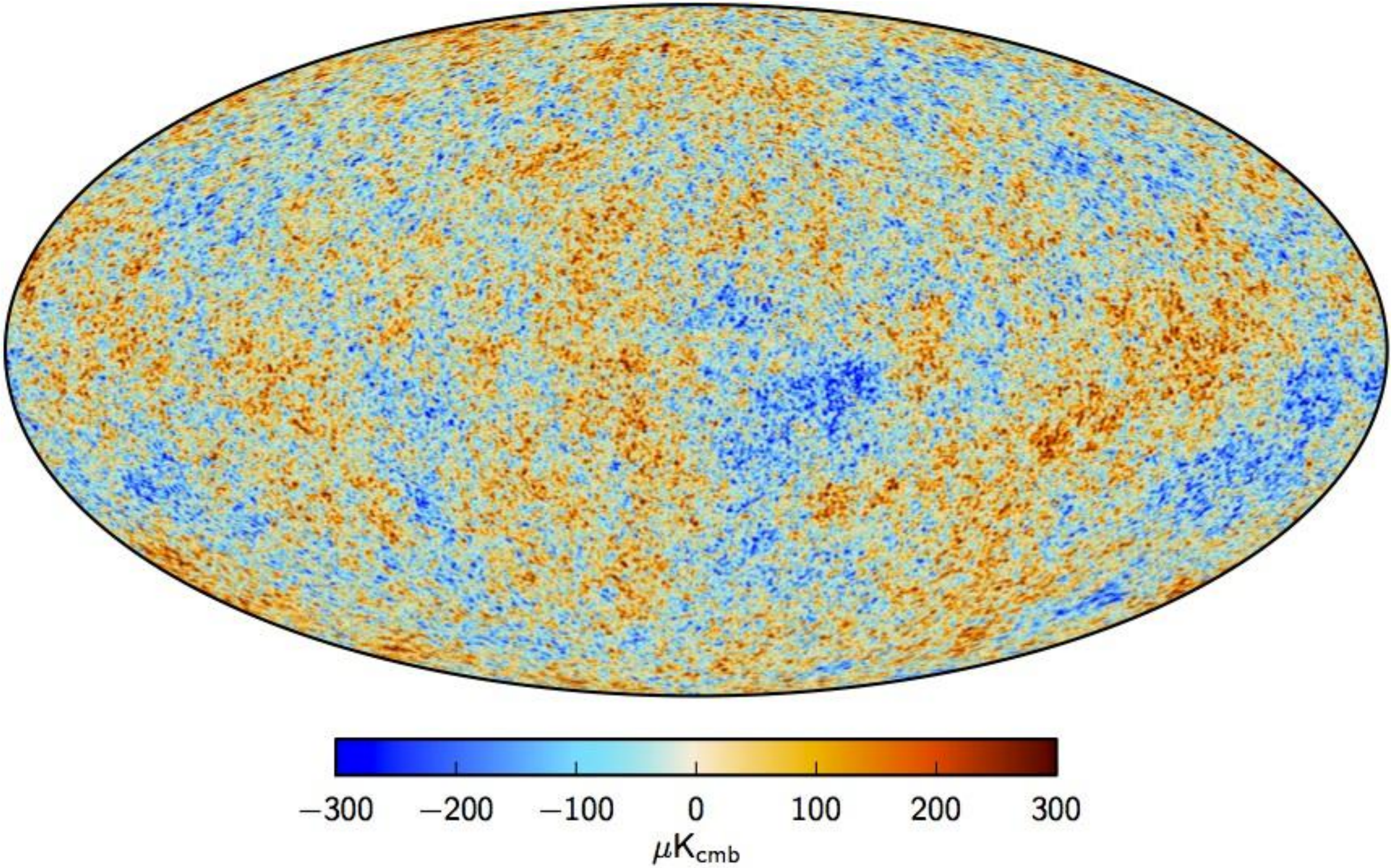
Frequency spectrum of RMS brightness temperature: CMB vs. astrophysical foregrounds



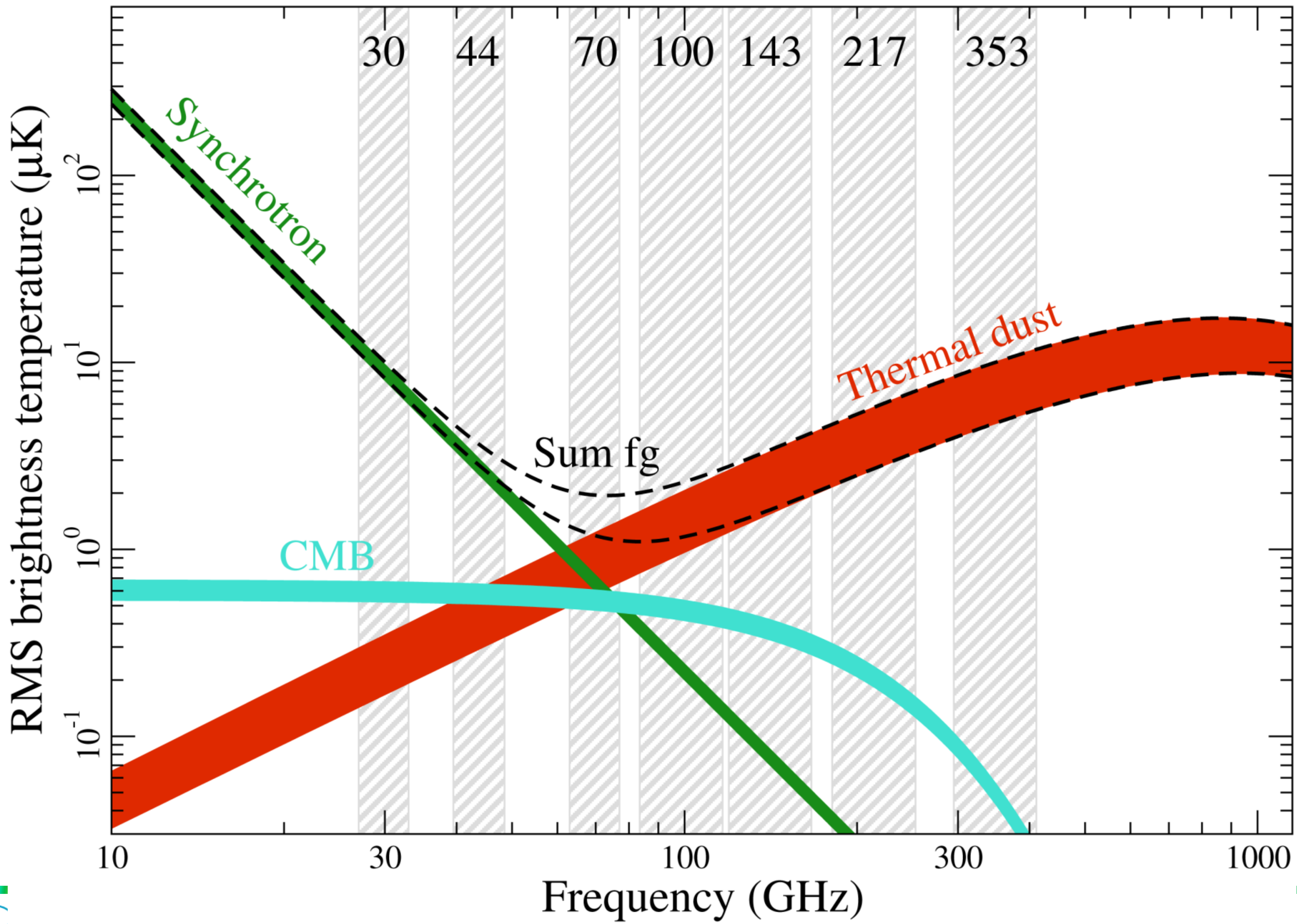


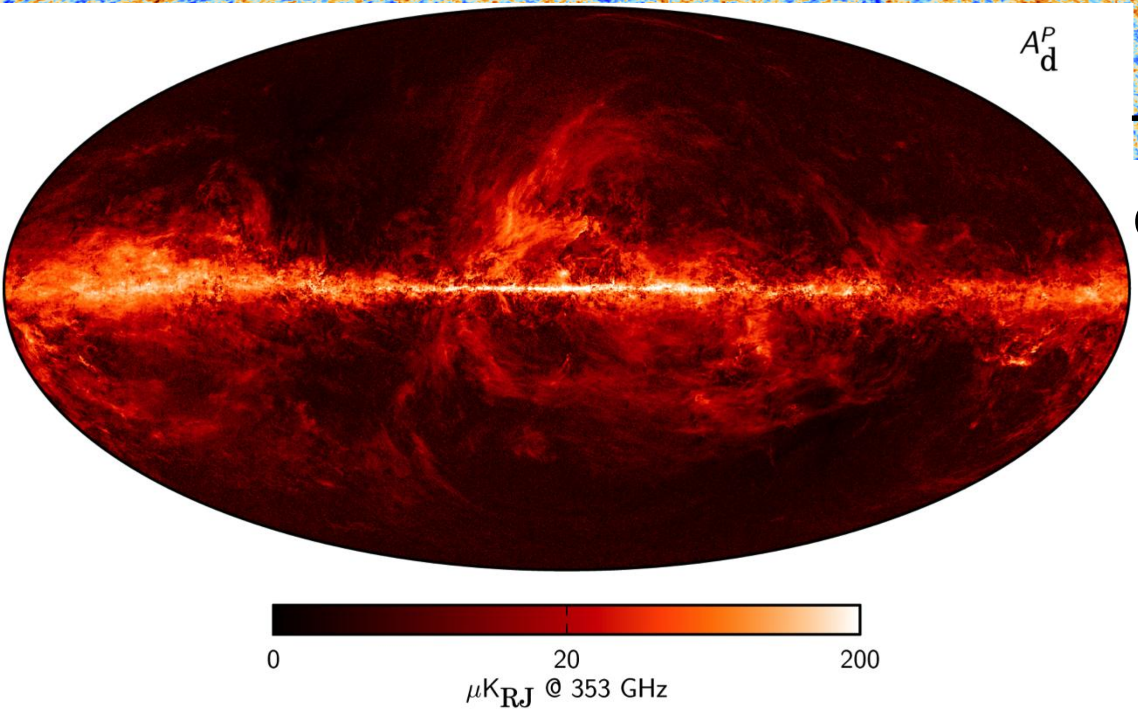
Maximum posterior intensity maps derived throughg the Commander algorithm from the joint analysis of Planck, WMAP and 408 MHz observations from Haslam

Planck 2015 Temperature map



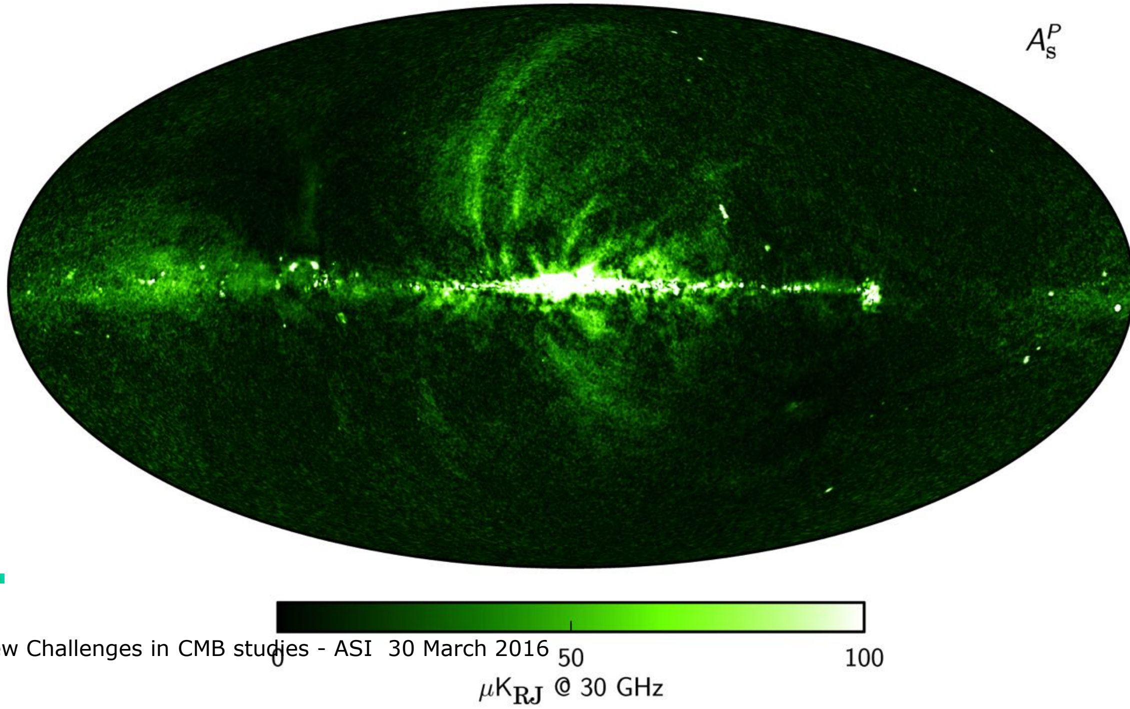
Frequency spectrum of RMS brightness polarization intensity: CMB vs. astrophysical foregrounds



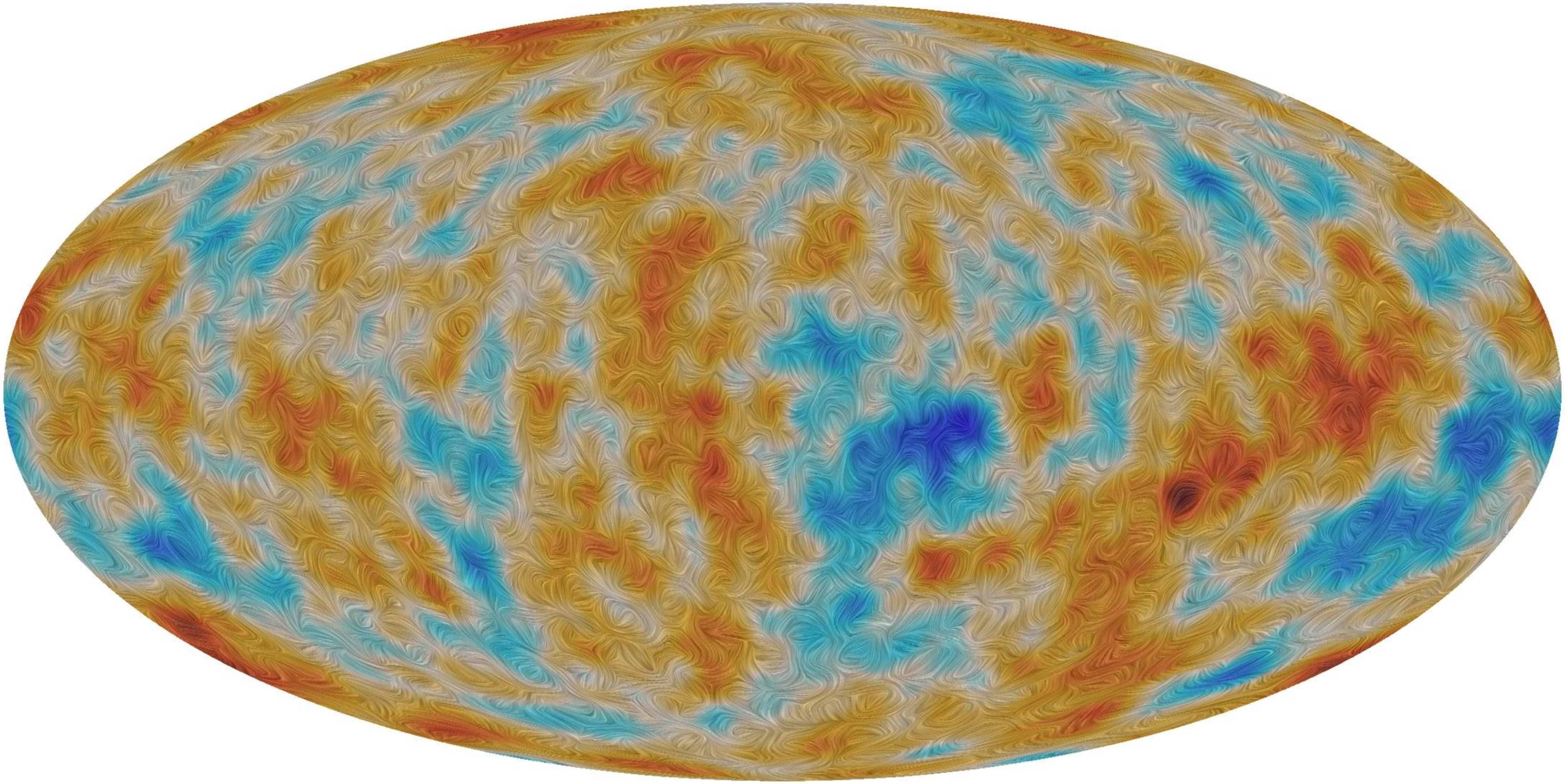


Total polarized dust emission

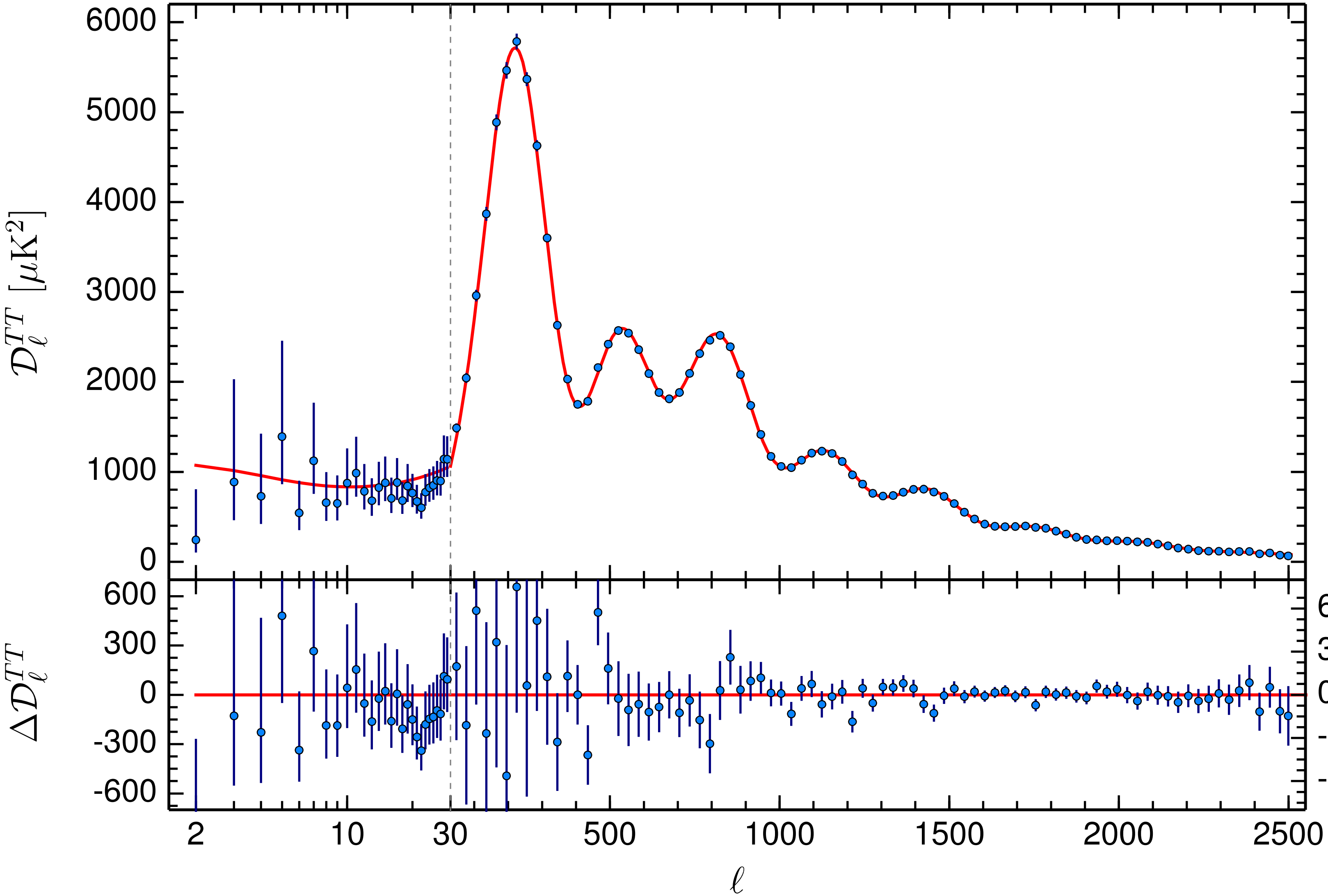
Total polarized synchrotron emission



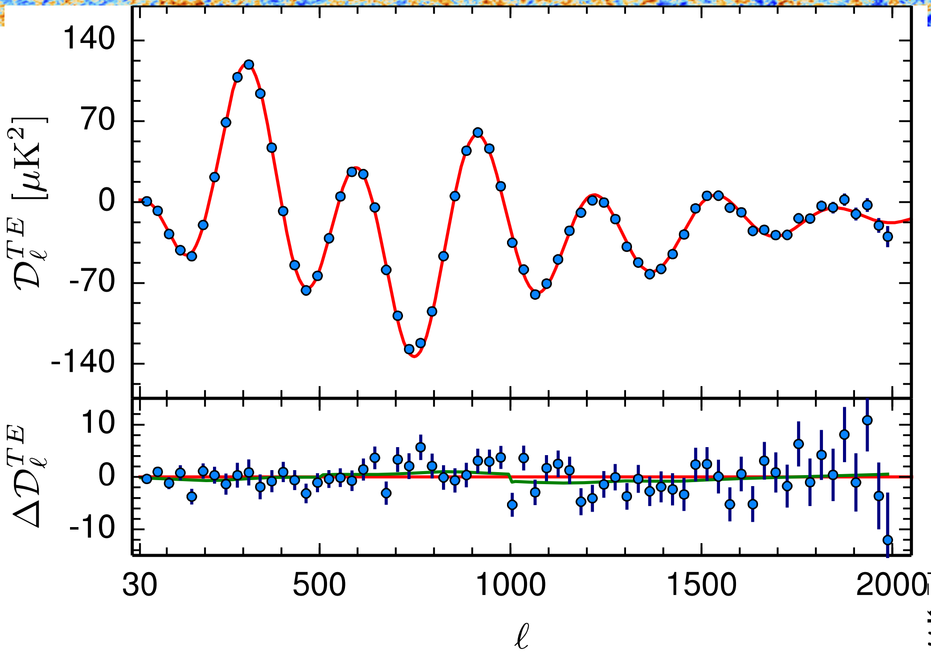
Planck 2015 Polarization map



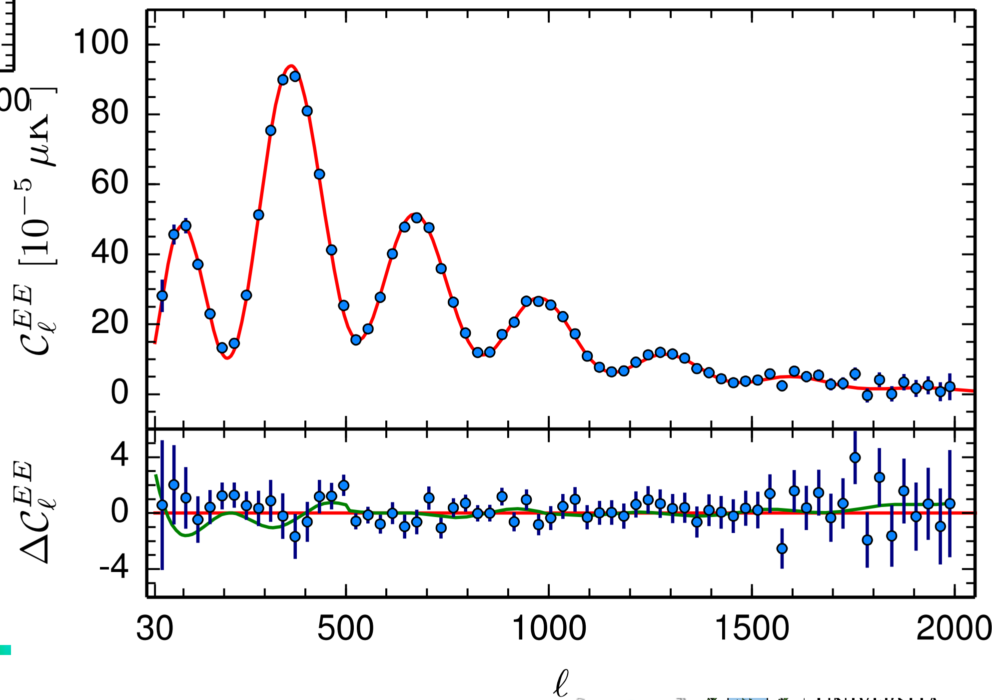
TT Angular power spectrum



TE and EE angular power spectra

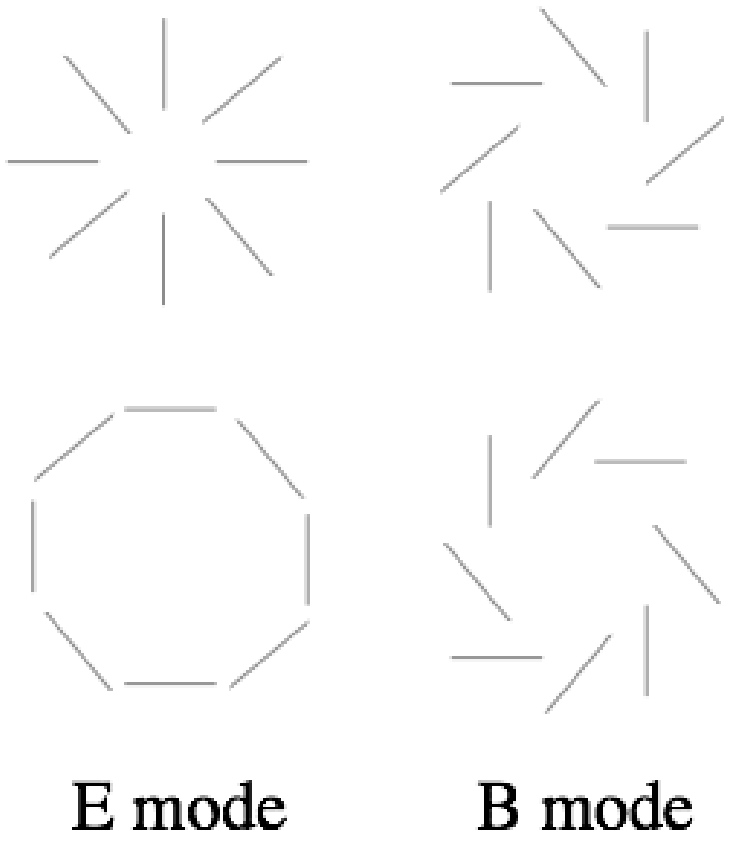


Red curves are fitted to the TT spectrum only!! (without accounting for T to P leakage)



Green lines in the residuals are fits to the T-P leakage model

E-mode and B-mode



1. Polarization is a spin 2 tensor, can be decomposed in parity even and parity odd component (“E” and “B”)

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

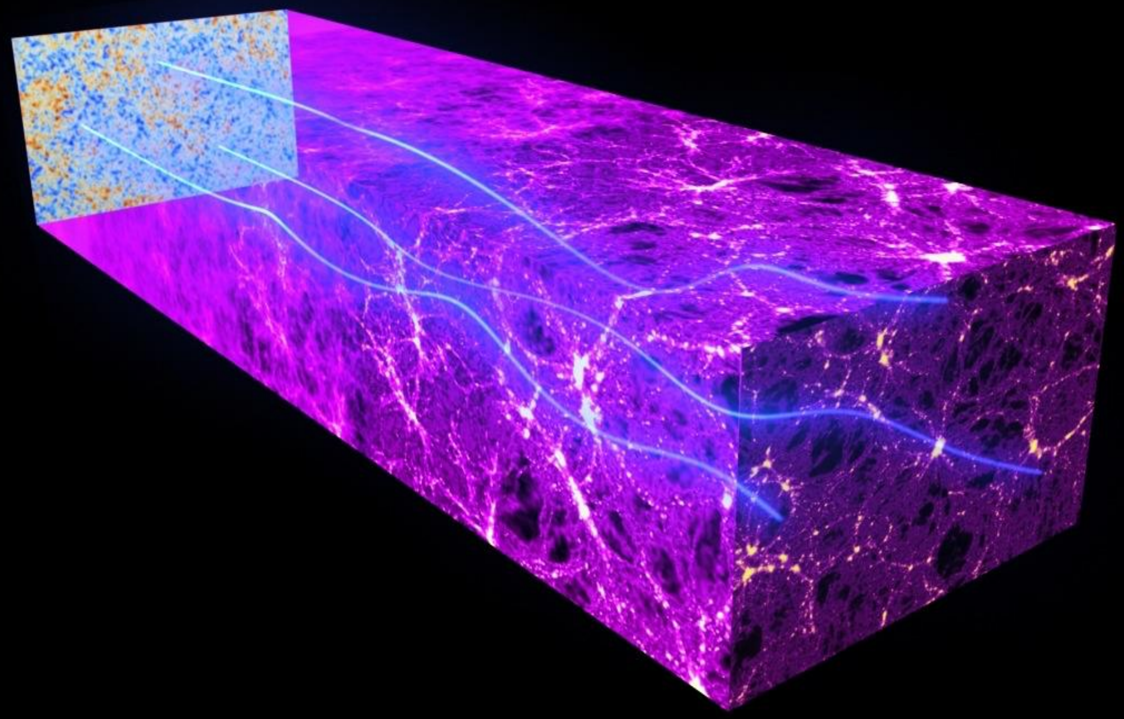
3. Gravitational waves can generate both E- and B-modes!

CMB polarization in a nutshell

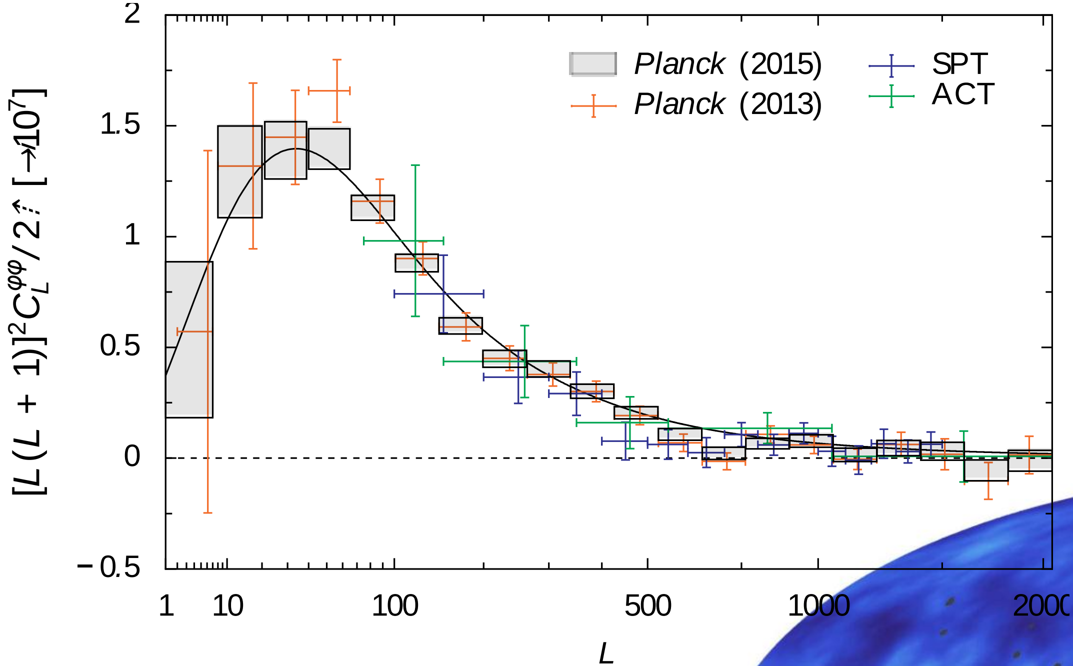
- The CMB is polarized with an amplitude of a few μK
- Most of this polarization pattern is generated by density perturbations at the time of last scattering….
- …. but a small part of it (peaking at ~ degree scales) could have been be generated by primordial gravitational waves – so called polarization B-modes

PLANCK PROBES AND EXPLOITS CMB LENSING

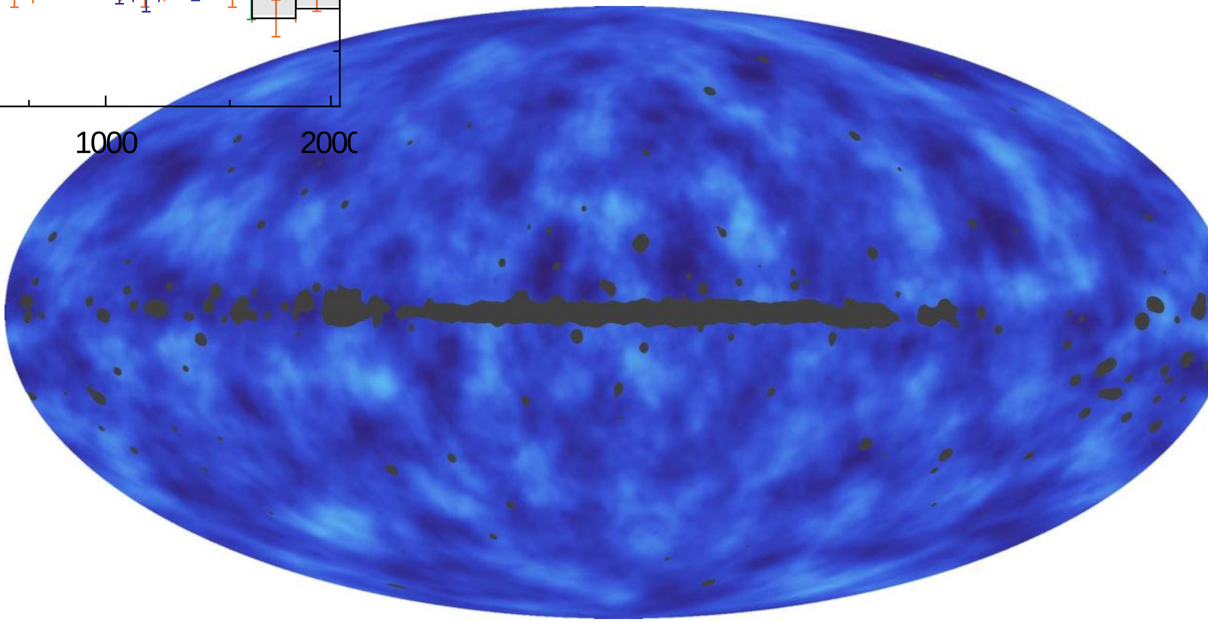
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB



LENSING



Lensing potential estimated from the four-point correlation function



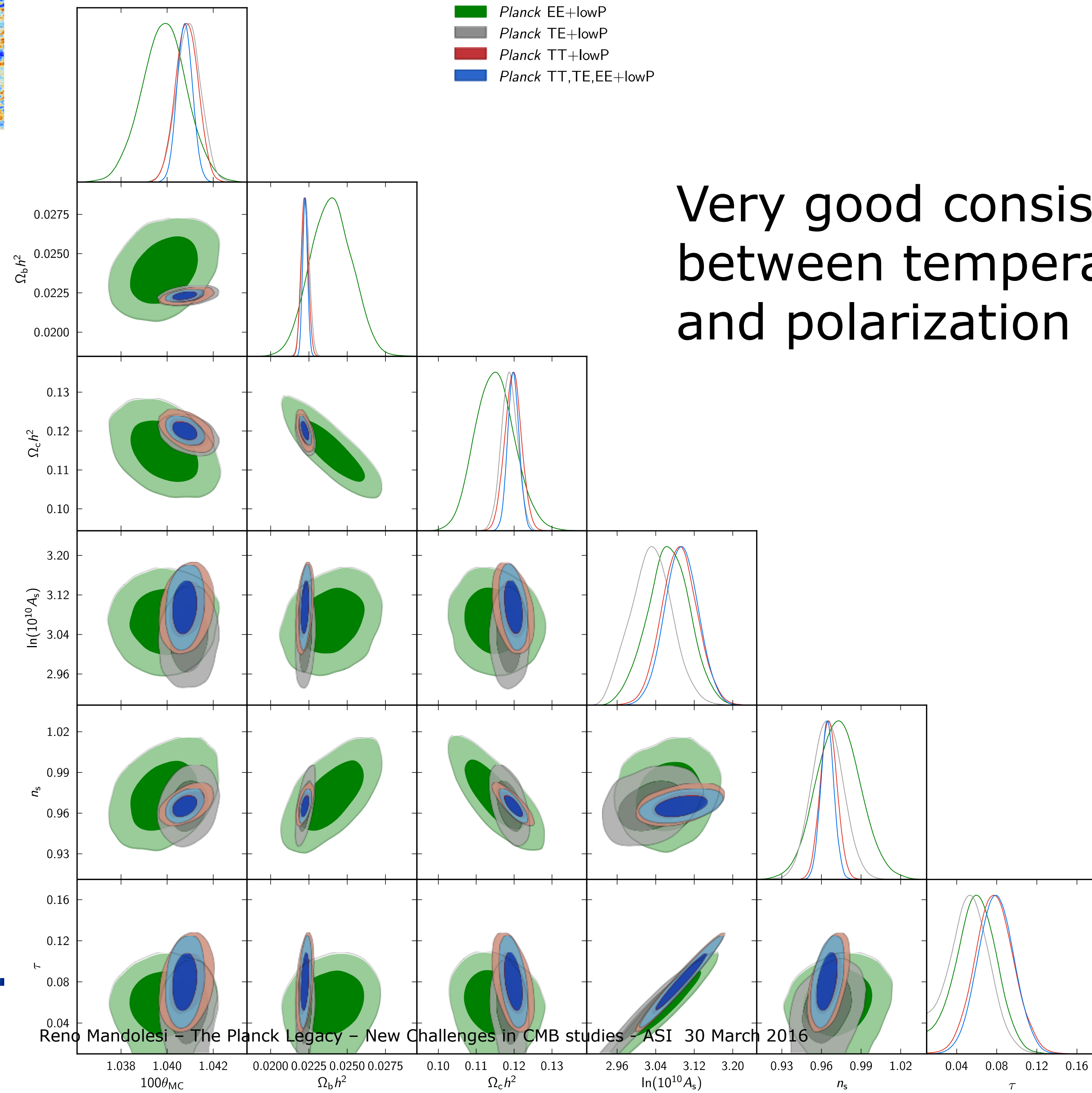
COSMOLOGICAL PARAMETERS: STANDARD ΛCDM

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

Very good consistency between temperature and polarization

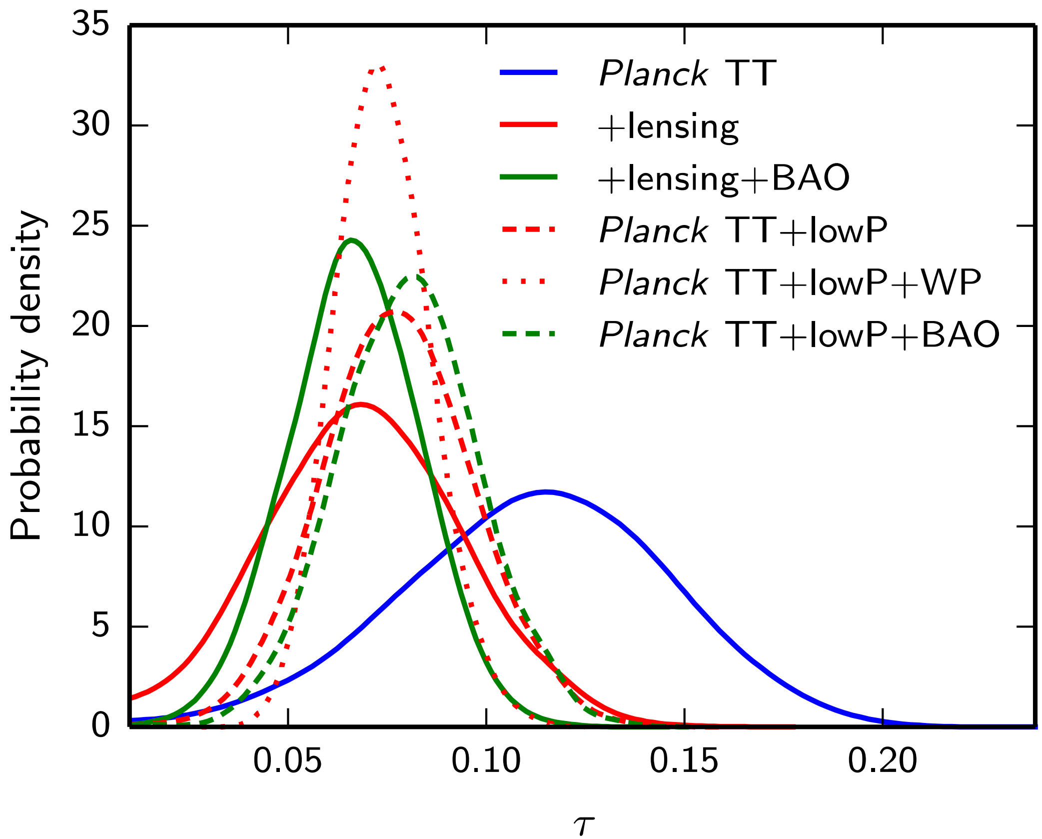


Constraints on the reionization optical depth

Planck TT+lowP
τ = 0.078 +/- 0.019
(z_{re} = 9.9 +/- 1.7)

Planck TT+lensing
τ = 0.070 +/- 0.024
(z_{re} = 9.0 +/- 2.3)

Compare with 2013 result (driven by WMAP low-ell polarization):
τ = 0.089 +/- 0.013
(z_{re} = 11.1 +/- 1.0)



LowP → 70 GHz

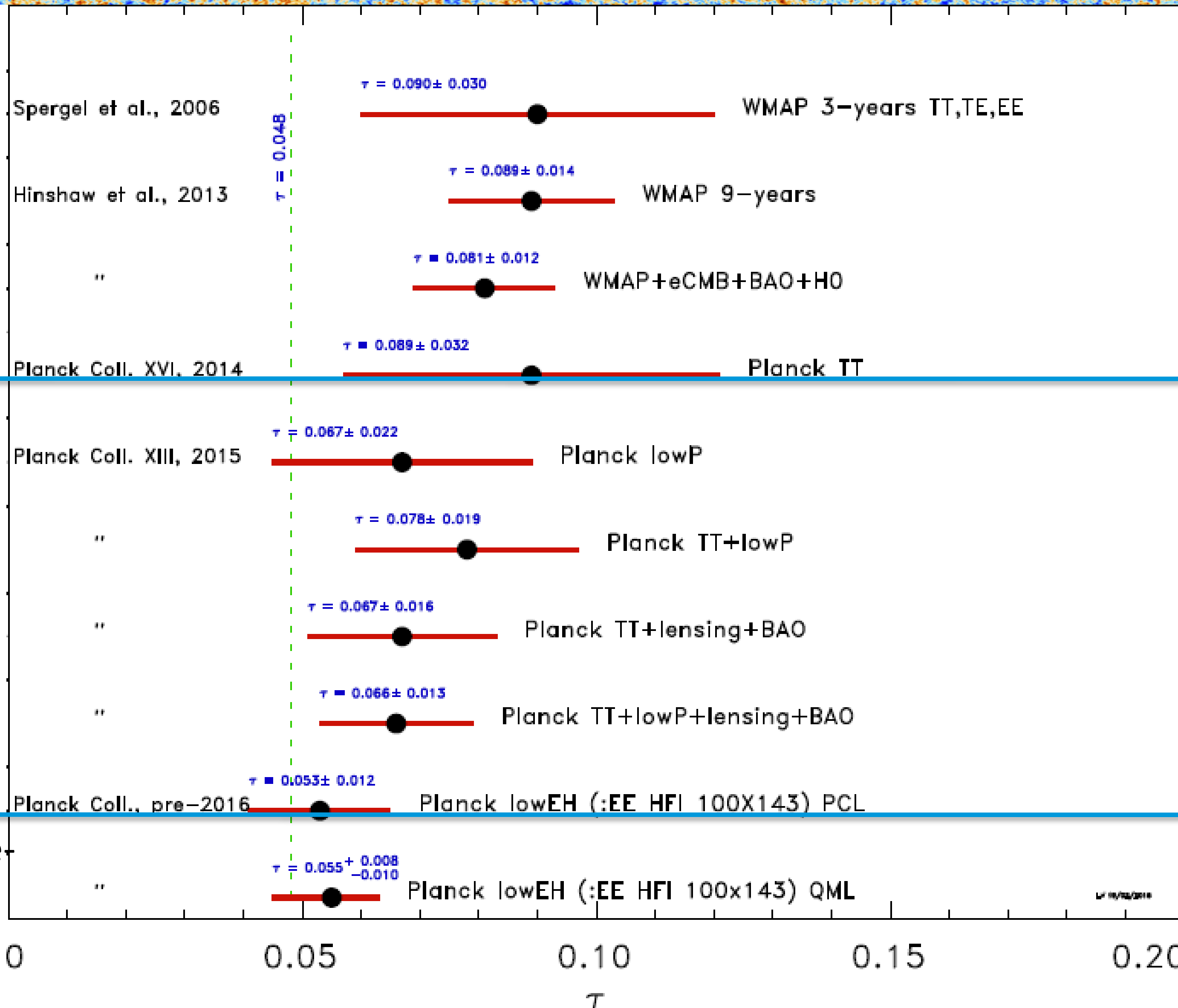
BUT WMAP polarization *cleaned with Planck 30 and 353 GHz* gives results consistent with Planck lowP

τ from CMB (history slide)

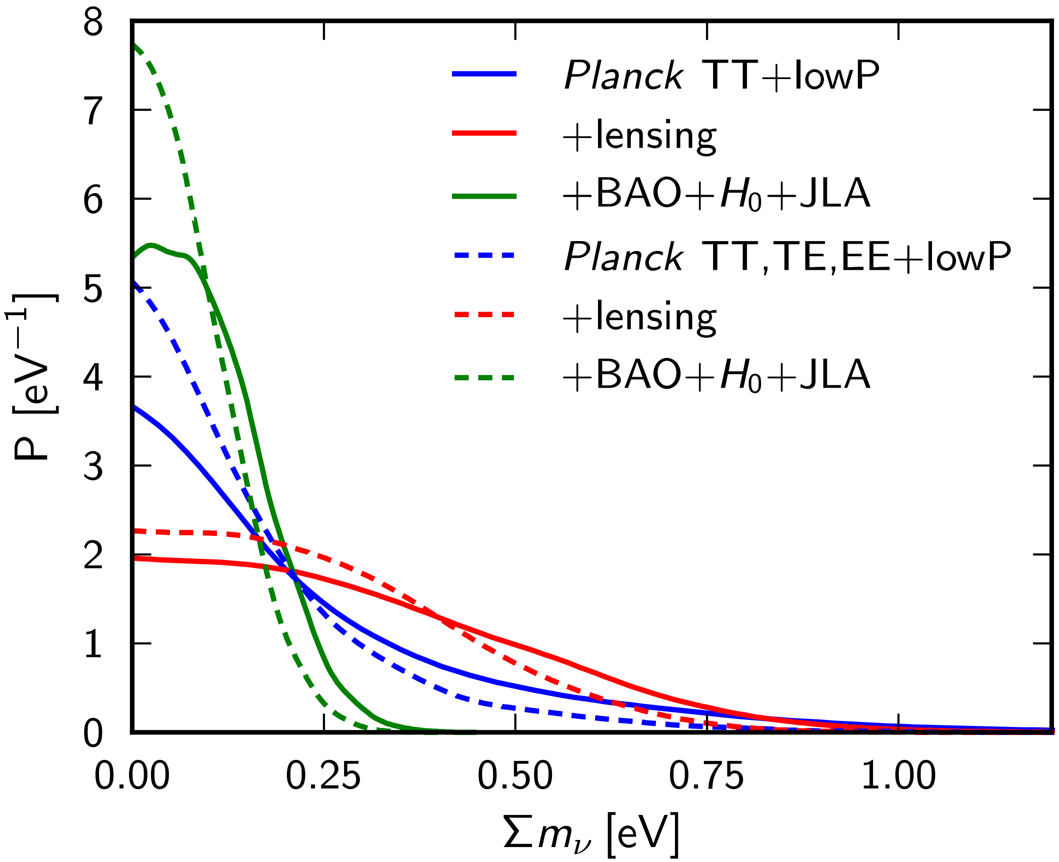
WMAP

Planck 2015

Planck pre-2016



Planck constraints on neutrino masses



$\Sigma m_\nu < 0.72$ eV (PlanckTT+lowP)

$\Sigma m_\nu < 0.68$ eV (…. + lensing)

$\Sigma m_\nu < 0.23$ eV (… + ext)

$\Sigma m_\nu < 0.49$ eV (PlanckTT,TE,EE +lowP)

$\Sigma m_\nu < 0.59$ eV (…. + lensing)

$\Sigma m_\nu < 0.19$ eV (… + ext)

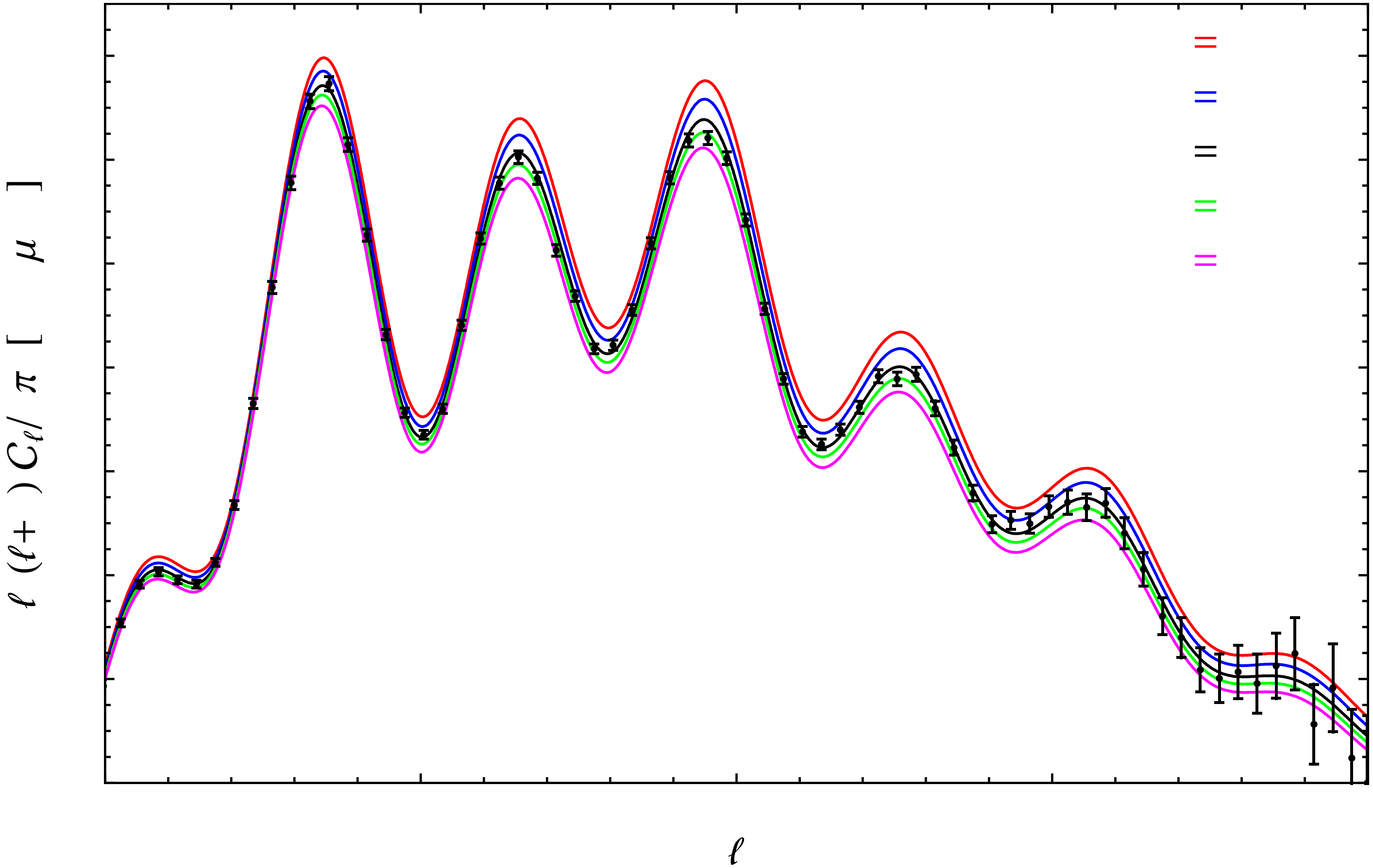
Planck alone is already at the level of the expected sensitivity of KATRIN, an experiment for the direct measurement of neutrino mass from tritium beta decay (will allow to constrain $\Sigma m_\nu < 0.6$) eV)

(all limits are 95% CL)

Probing the neutrino number with Planck

N_{eff} parameterizes the density of relativistic particles in the Universe. The standard value, for the three active neutrinos, is $N_{eff} = 3.046$.

Increasing N_{eff} reduces the small scale anisotropies:



N_{eff} constraints from Planck

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

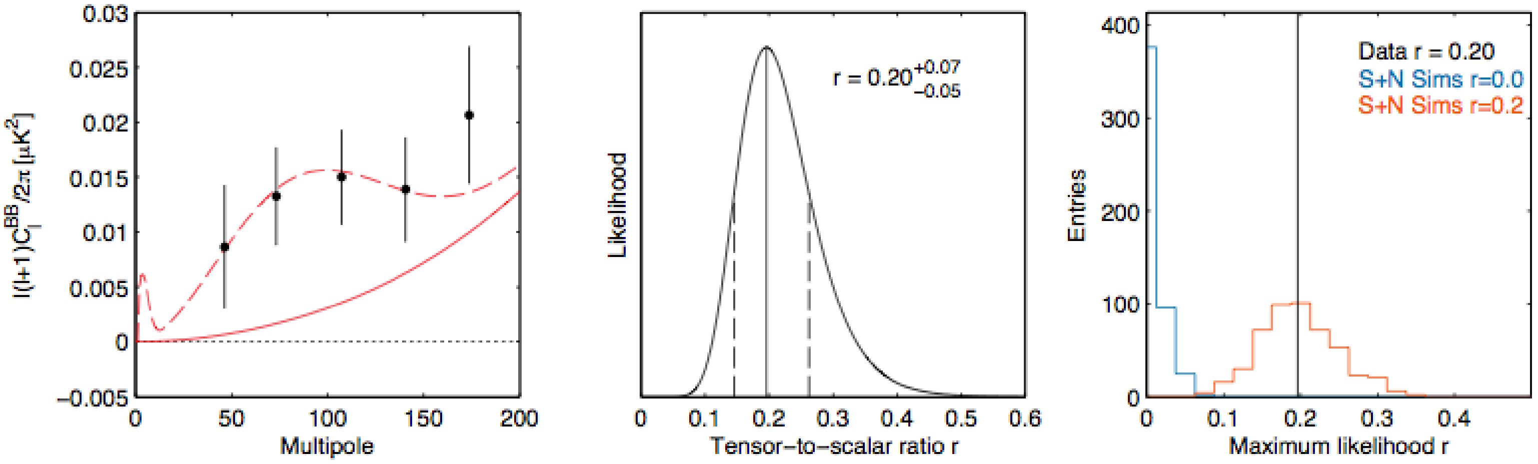
$N_{\rm eff} = 3.15 \pm 0.23$ (PlanckTT+lowP+BAO)

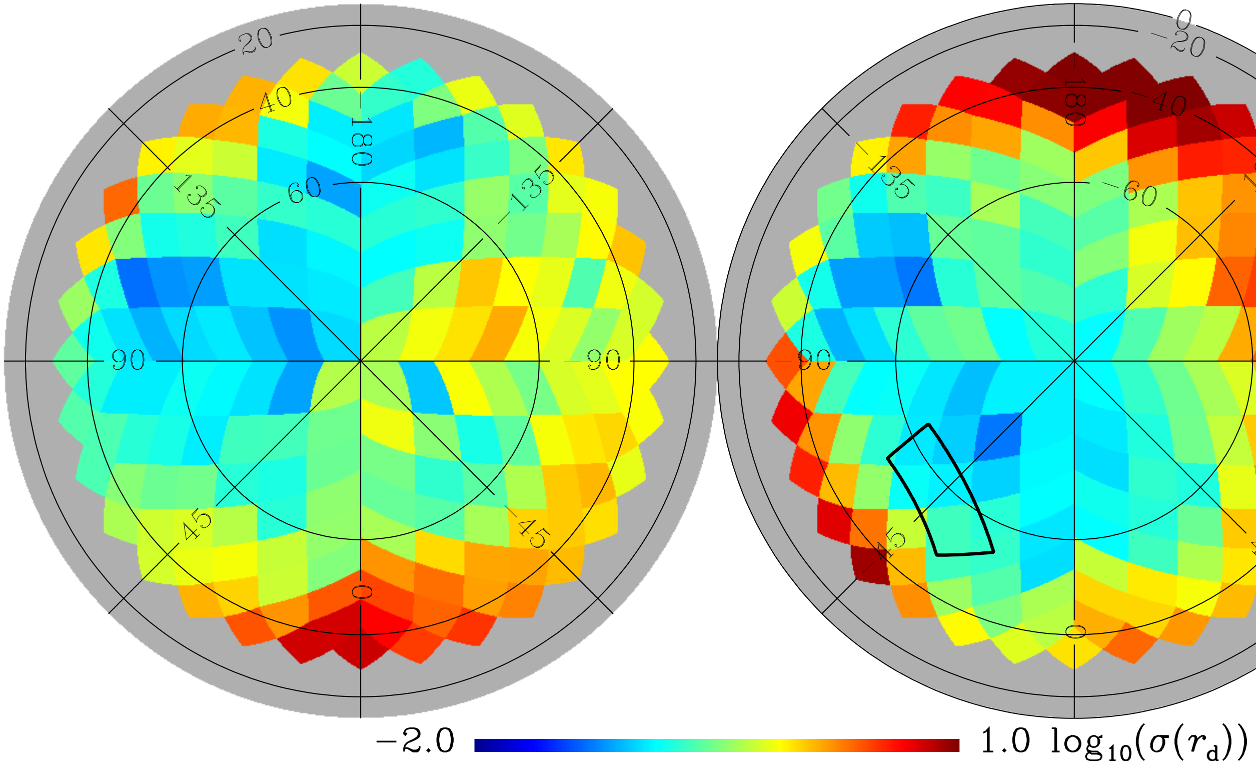
$N_{\rm eff} = 2.98 \pm 0.20$ (PlanckTT,TE,EE+lowP)

$N_{\rm eff} = 3.04 \pm 0.18$
(PlanckTT,TE,EE+lowP+BAO) (uncertainties are 68% CL)

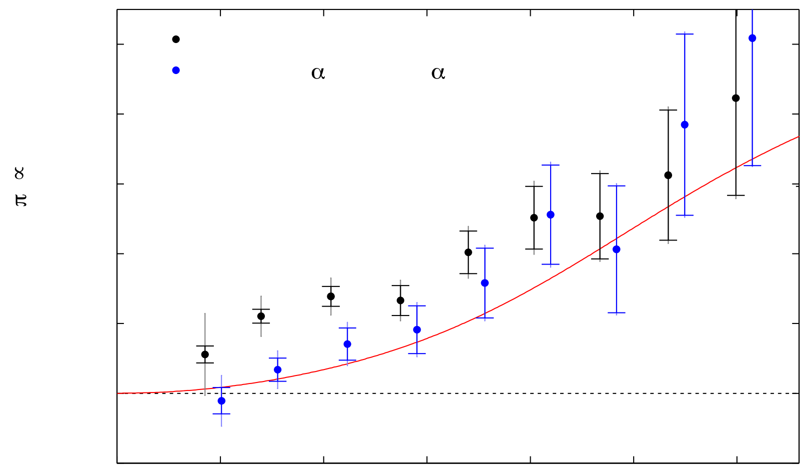
$N_{\rm eff} = 4$ (i.e., one extra thermalized neutrino)
is excluded at between ~ 3 and 5 sigma.

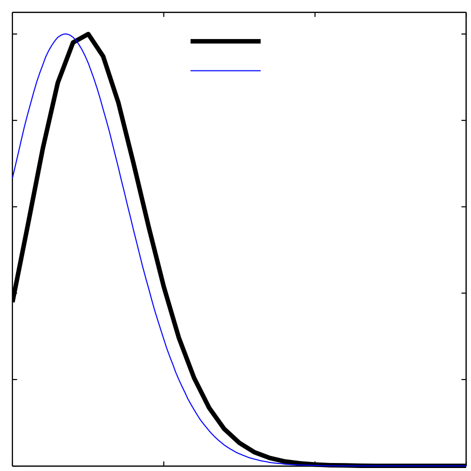
MARCH 2014: BICEP2 CLAIMS THEY HAVE OBSERVED GRAVITIONAL WAVES



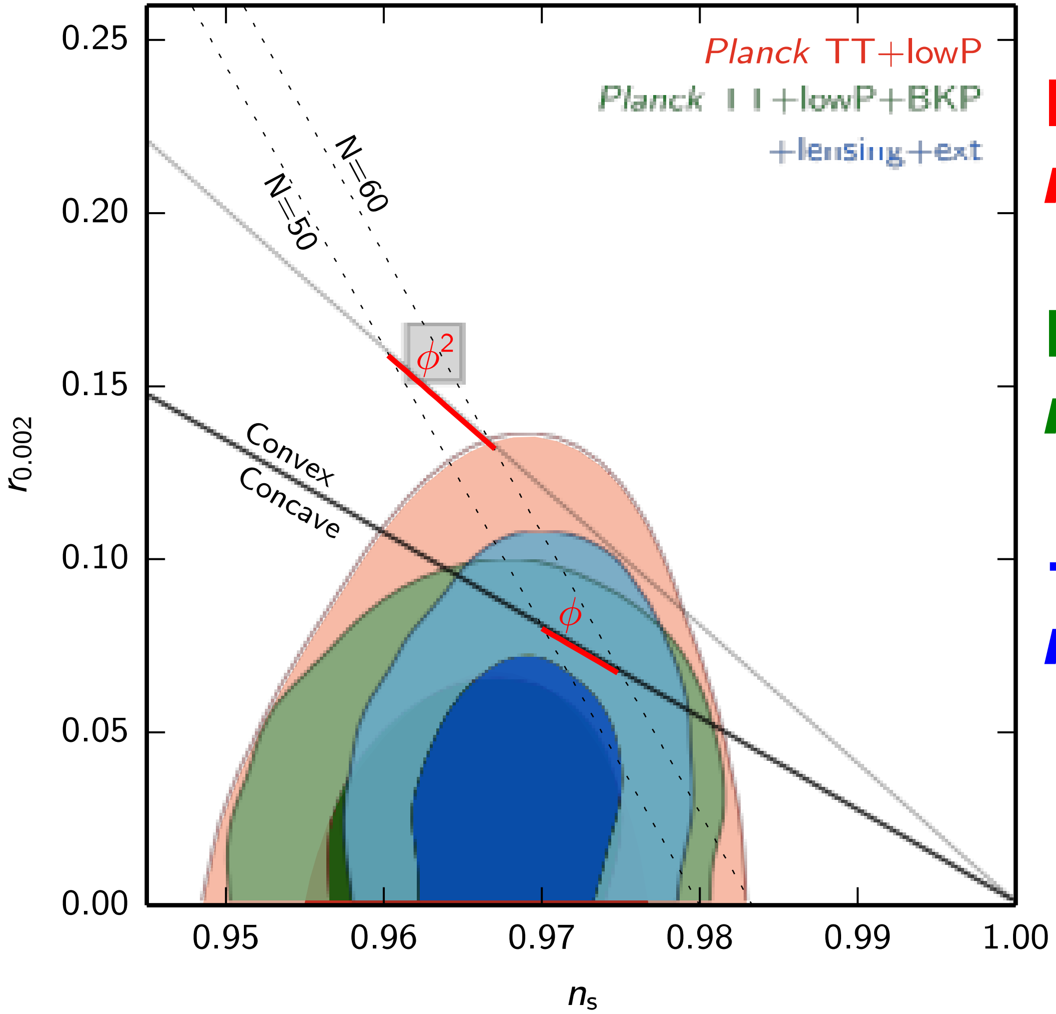


Planck BB amplitude from the 353 GHz data, extrapolated to 150 GHz, normalized to the CMB expectation for r=1
The thick black contour outlines the BICEP2 deep-field region


α
α
π ∝



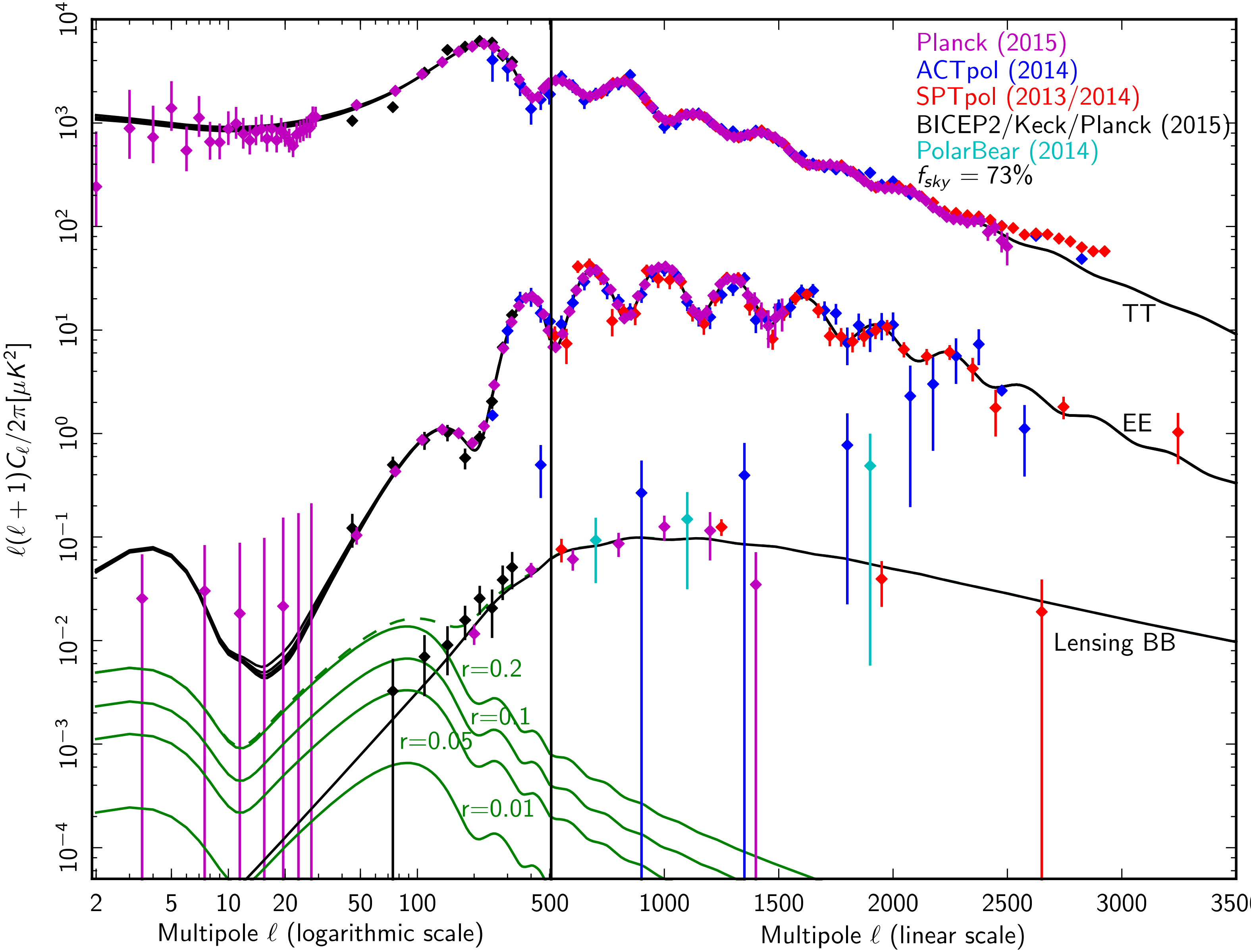
Scalar spectral index and tensors fluctuations

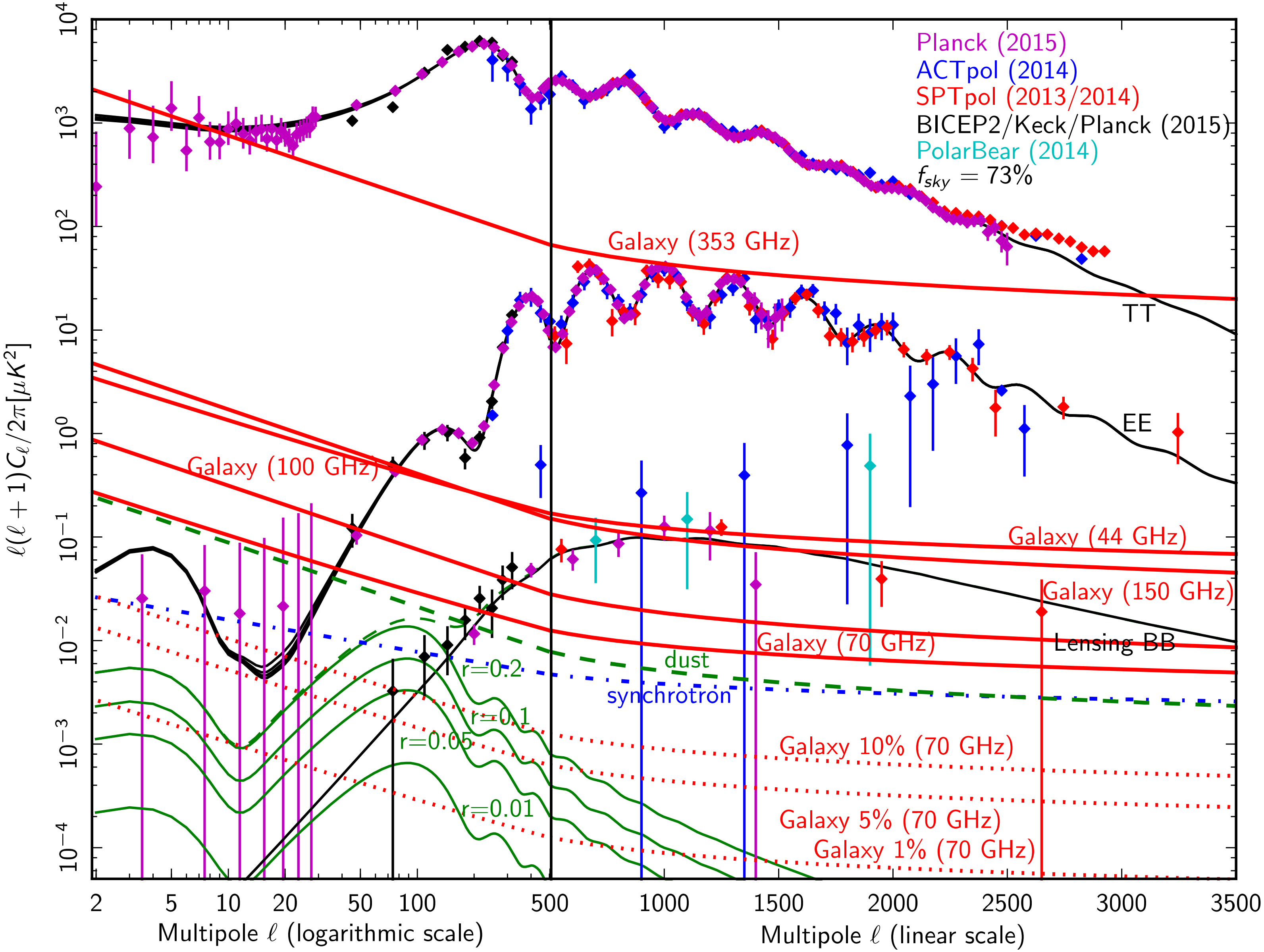


Planck TT + lowP
$r_{0.002} < 0.10$

Planck TT + lowP+BKP
$r_{0.002} < 0.08$

+ lensing + ext
$r_{0.002} < 0.09$


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
$\ell(\ell+1)C_\ell/2\pi[\mu K^2]$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
2 5 10 20 50 100 500 1000 1500 2000 2500 3000 3500
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)

Conclusions

- Planck has definitely set a milestone in the history of the CMB: the ultimate temperature anisotropy dataset and opened a new era for polarization
- The frontiers of Cosmology and Fundamental Physics are still far to be reached
- Planck has certainly been the driving force for growth of the Italian CMB community and to its international leading role in the field
- To maintain and increase this leading role synergies with other communities are crucial
- Technological Planck's legacy (optics, microwaves, mm-waves, cryogenics) and future developments need to be transferred to the Italian Industry
- The legacy of Planck cannot be dispersed

What's next?


Thank you