The Planck legacy: low ell polarization, reionization, Planck/B2P/Keck results on B modes and the future

Nazzareno Mandolesi

University of Ferrara

on behalf of the Planck Collaboration

Results presented mainly based on Planck 2015 papers I, VI, VIII, XIII, XV, XX

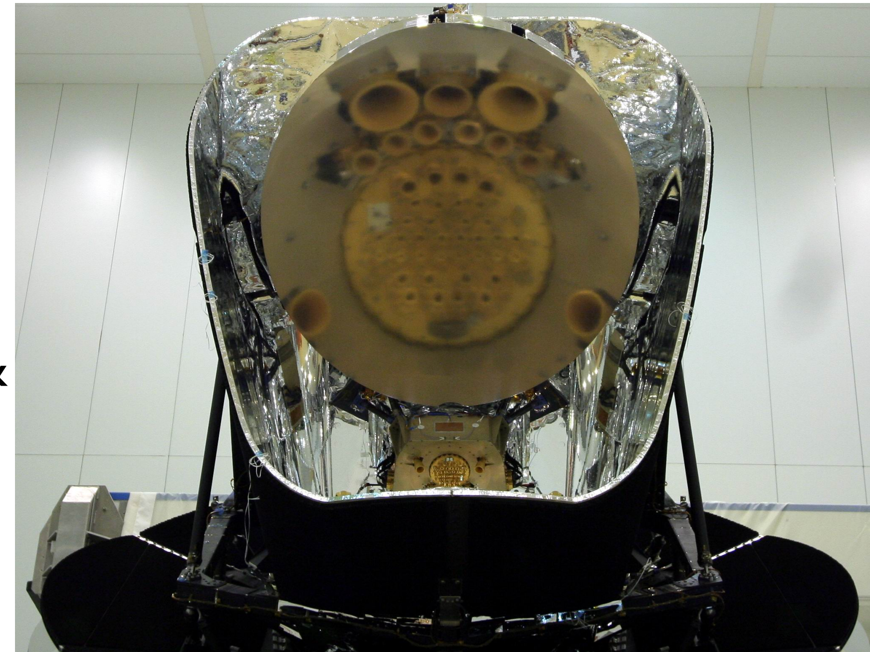
EWASS 2015 - The quest for detecting the primordial gravitational wave background

The Planck Satellite

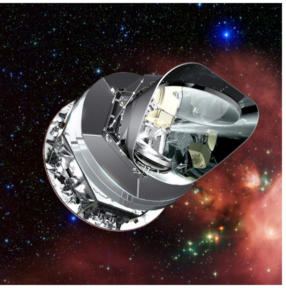
- Third-generation satellite, launched and operated by ESA, dedicated to the CMB
- Observed the sky continuously from 12 August 2009 to 23 October 2013
- Focal plane hosts 74 detectors between 30 GHz and 1 THz (9 bands) with angular resolution between 30′ and 5′, $\Delta T/T_{CMB} \sim 2 \times 10^{-6}$
- 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 (preview of the results presented at the Ferrara conference, Dec 2014)
- Update to the second cosmological release (summer 2015)
- Third and final (legacy) release in 2016

Planck history in short

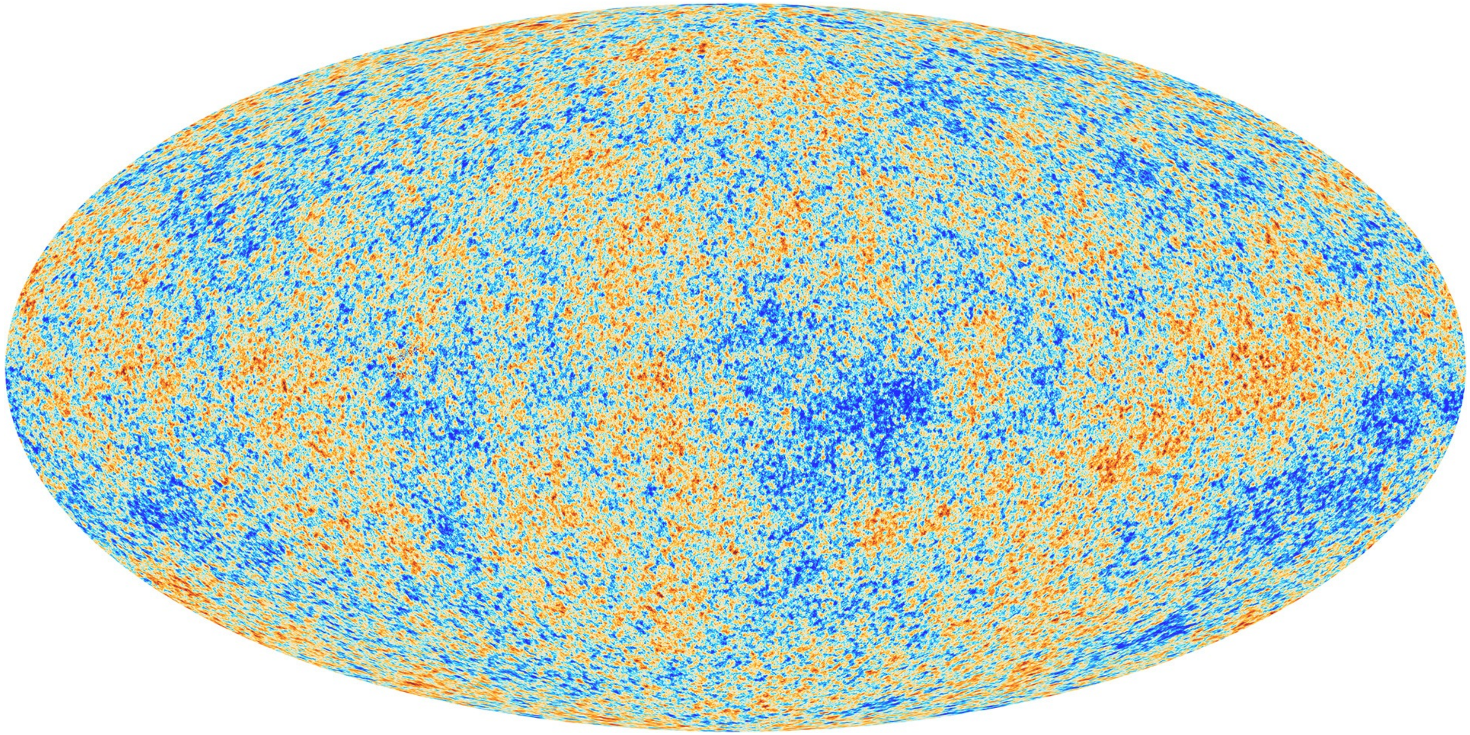
- 1993 – COBRAS & SAMBA proposals
- 1996 – Selection of COBRAS/SAMBA, then named Planck (LFI and HFI consortia are formed)
- […] Lots of Instrument development & tests
- 2009 – Planck is launched
- Jan 2012 – HFI End of life
- Mar 2013 – First cosmological data release
- Oct 2013 – LFI End of life
- Feb 2015 – Second cosmological data release (updates in summer 2015).
- 2016 – Final cosmological data release



esa



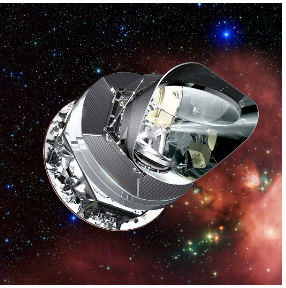
Full sky temperature map from Planck (2013)

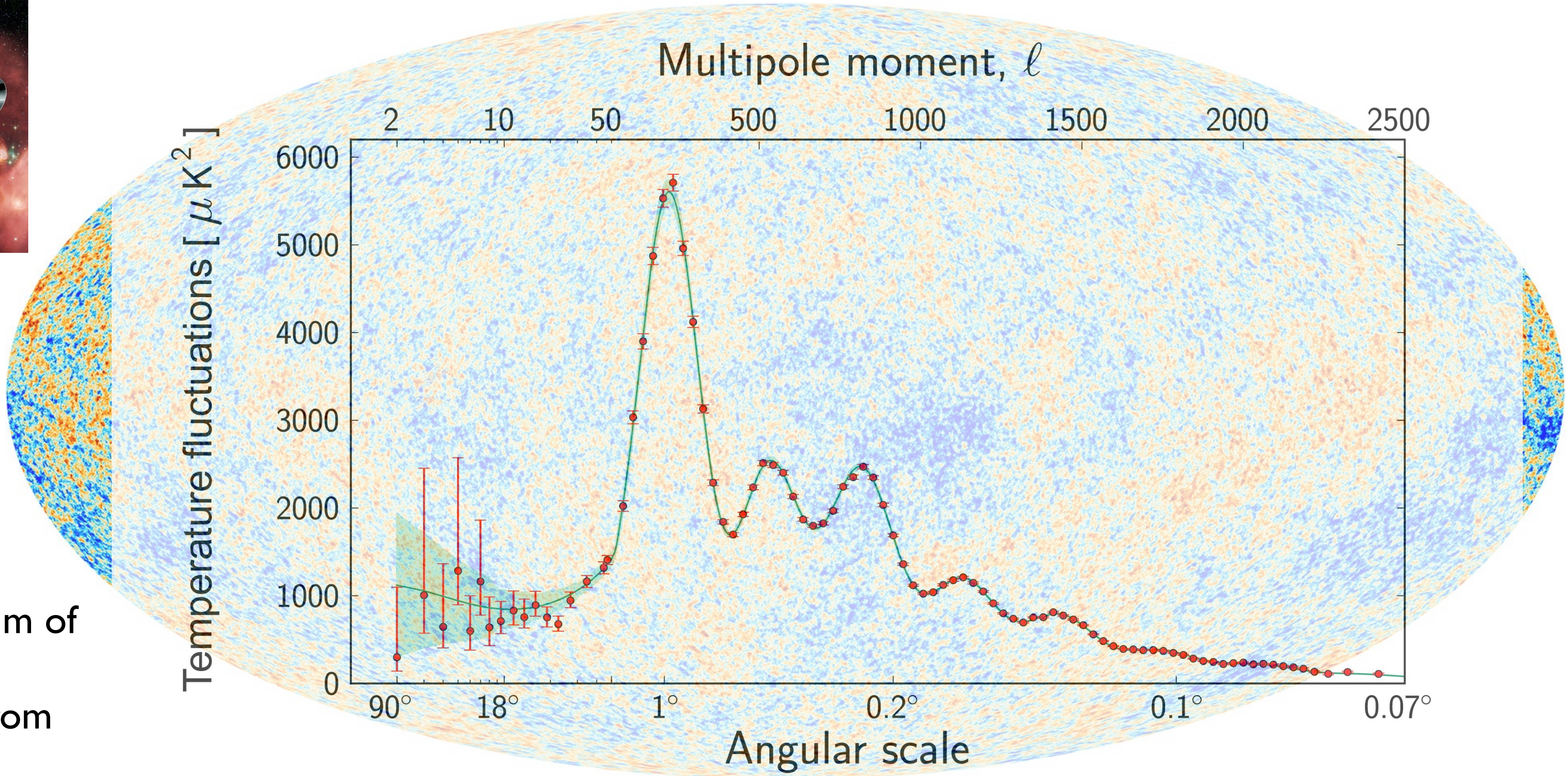


The main objective of Planck is to measure the spatial temperature and polarization anisotropies of the cosmic microwave background (CMB) radiation

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)

If the fluctuations are gaussian, all the statistical information in the map is encoded in the two point correlation function or in its harmonic transform, the angular power spectrum:

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

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

esa

planck

PLANCK LFI

HFI PLANCK

Feb 2015 data release

- Timelines for each detector at 30, 44, 70, 353, 545 and 858 GHz and for the unpolarized bolometers at 100, 143, 217 GHz
- Maps of the sky at 9 freqs in temp, and at 30, 44, 70, 353 GHz in pol
- Four high-res maps of the CMB sky in T (Commander, NILC, SEVEM, SMICA)
- Four high-pass filtered maps of the CMB sky in pol
- A low-res CMB T map (Commander)
- Maps of thermal dust, CIB, CO, synchrotron, free-free, spinning dust temperature emission
- Maps of synchrotron and dust polarized emission
- Map of the estimated lensing potential
- Map of the SZ Compton parameter
- MC chains used for cosmological parameter estimation
- Second Planck catalogue of SZ sources
- Planck catalogue of galactic cold clumps

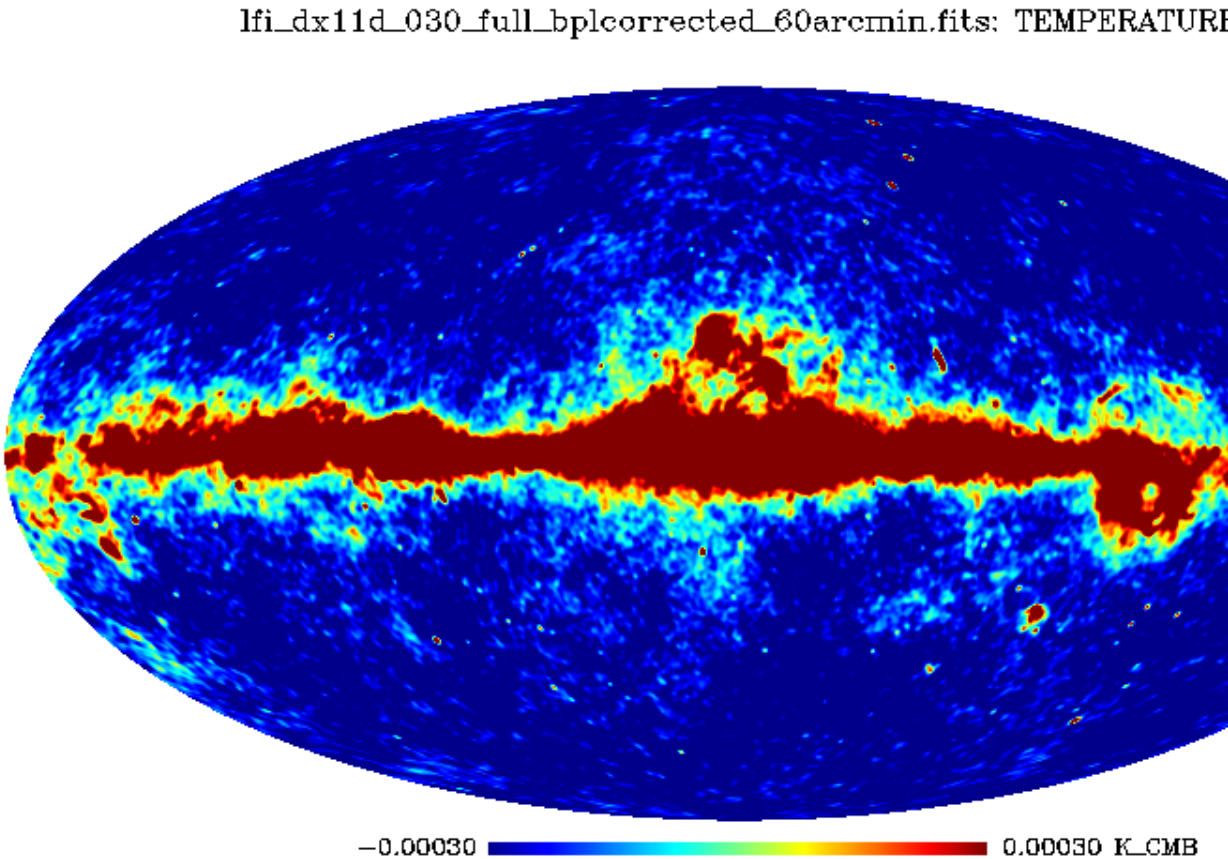
expected summer 2015 update

- Timelines for polarized bolometers at 100, 143, 217 GHz
- Maps of the sky at 100, 143, 217 GHz in pol
- Second Planck catalogue compact source (PCCS)

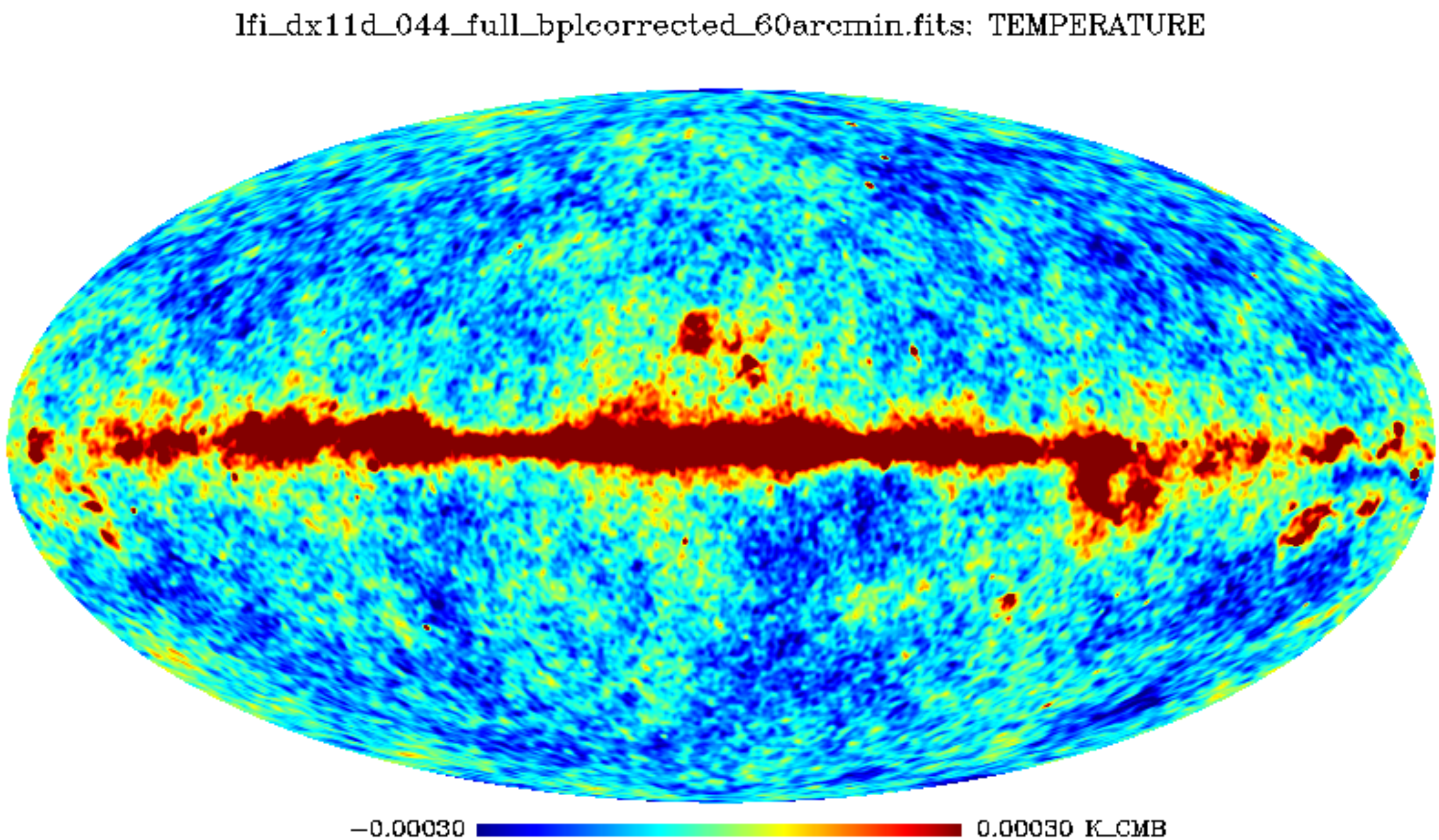
release 2016

- LFI: new release with better accuracy in systematics and more statistics
- HFI: better characterization of 2015 data release
- new papers

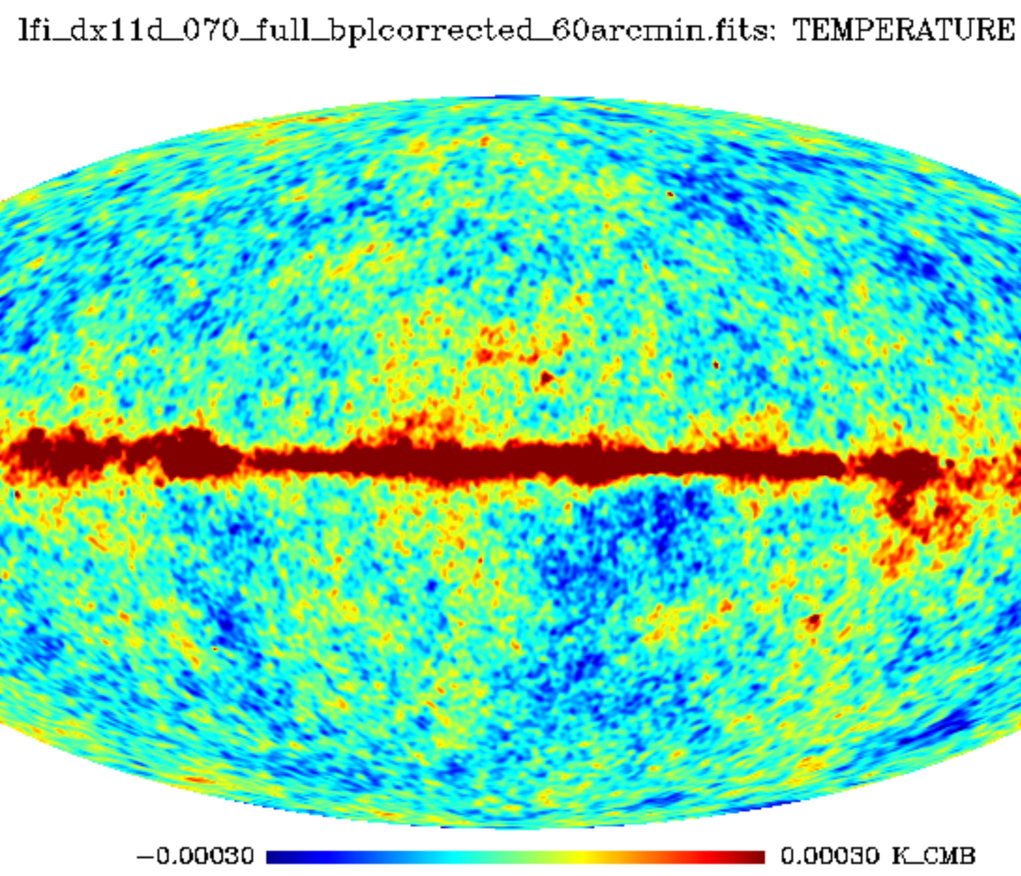
Frequency maps in temperature


lfi_dx11d_030_full_bplcorrected_60arcmin.fits: TEMPERATURE
−0.00030
0.00030 K_CMB

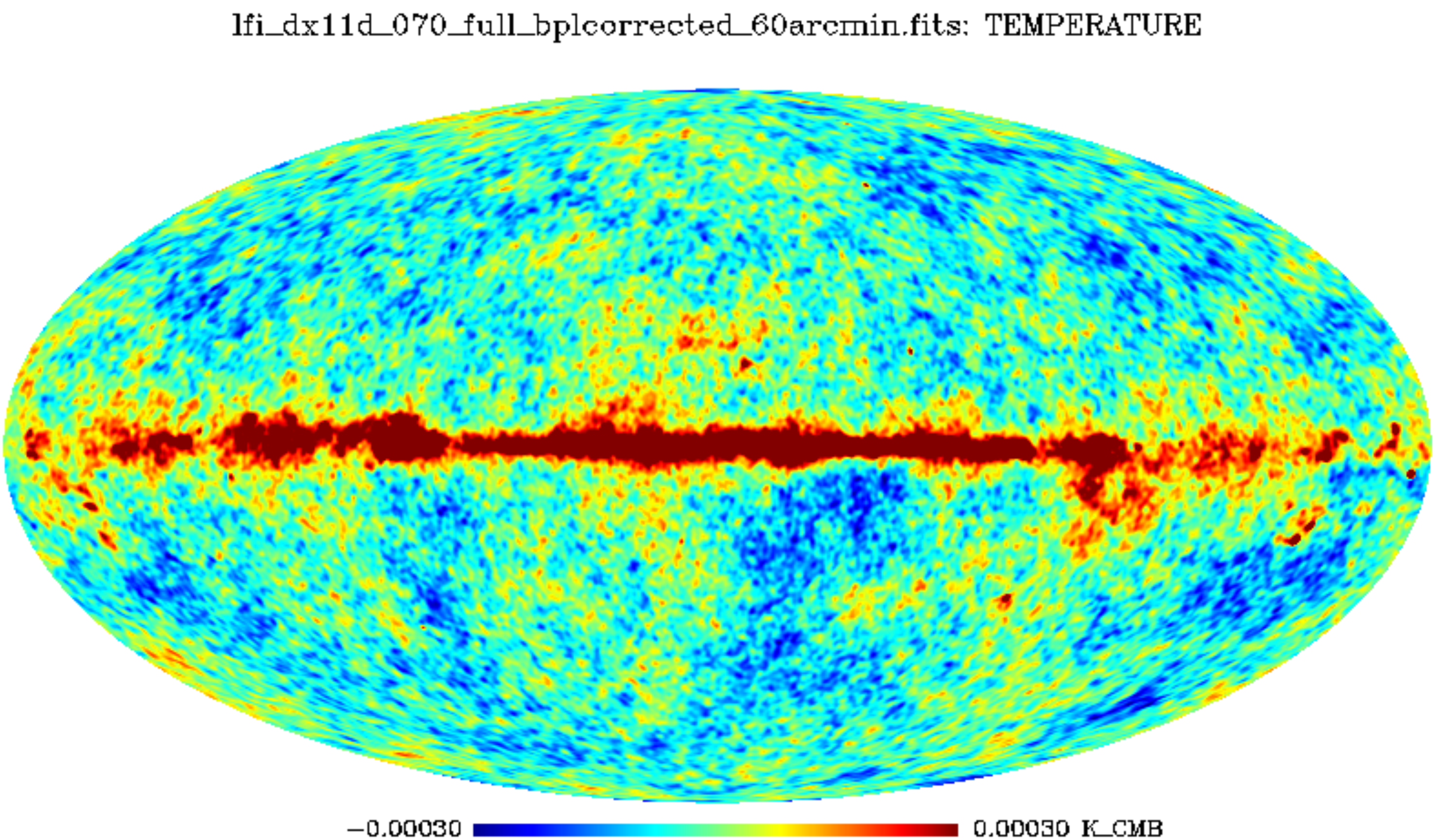
30GHz


lfi_dx11d_044_full_bplcorrected_60arcmin.fits: TEMPERATURE
−0.00030
0.00030 K_CMB

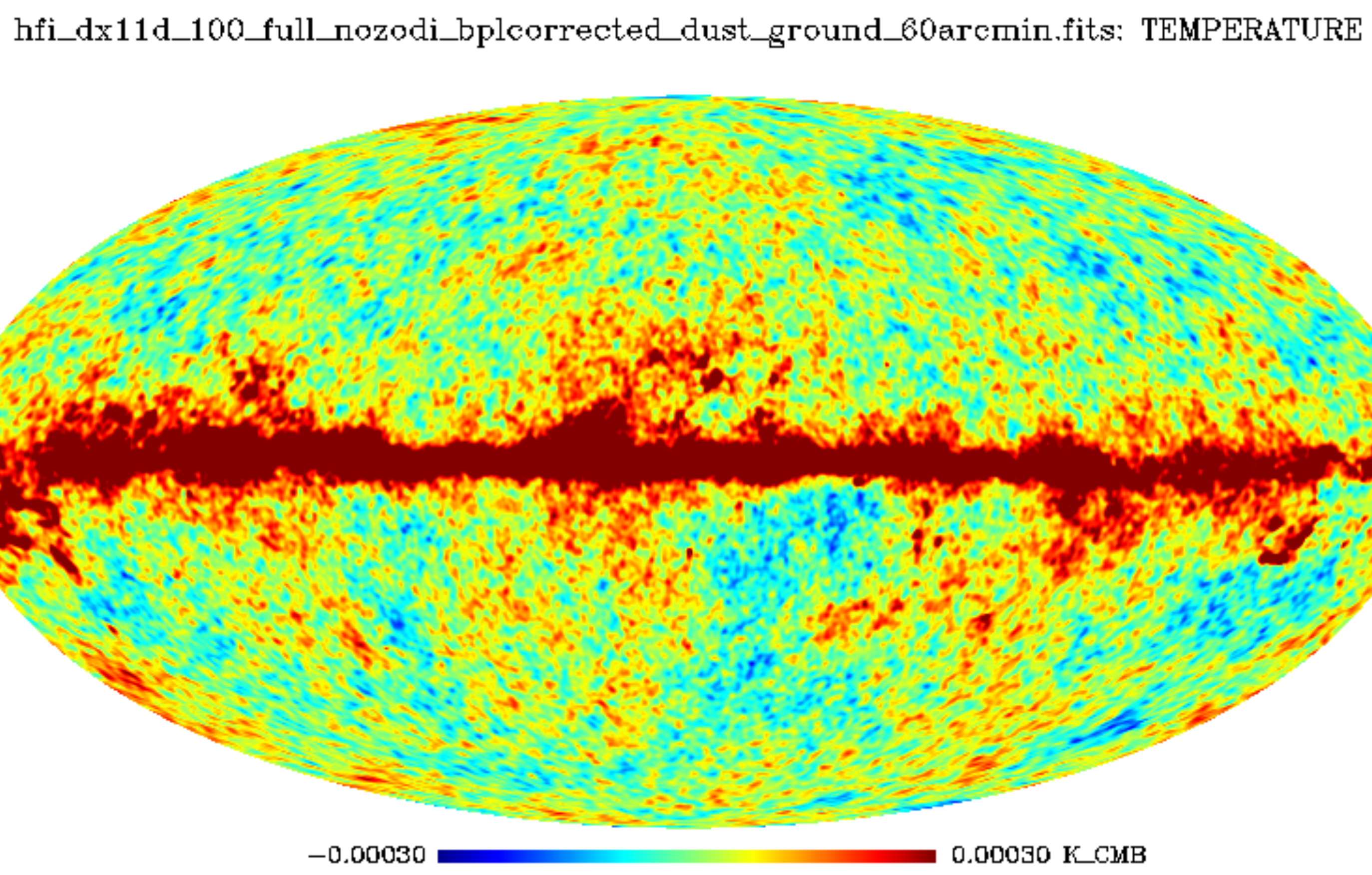
44GHz


lfi_dx11d_070_full_bplcorrected_60arcmin.fits: TEMPERATURE
−0.00030
0.00030 K_CMB

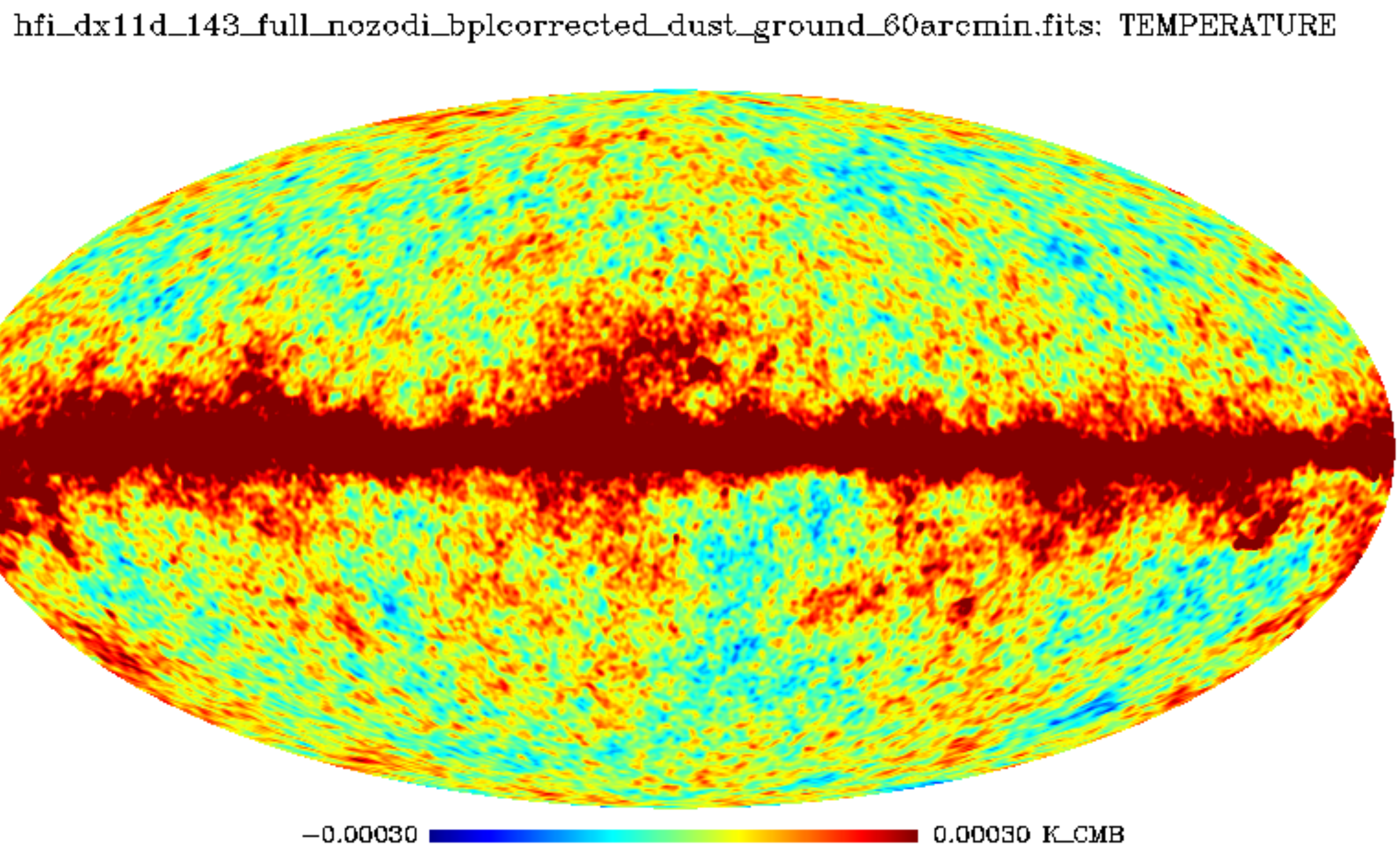
70GHz


lfi_dx11d_070_full_bplcorrected_60arcmin.fits: TEMPERATURE
−0.00030
0.00030 K_CMB

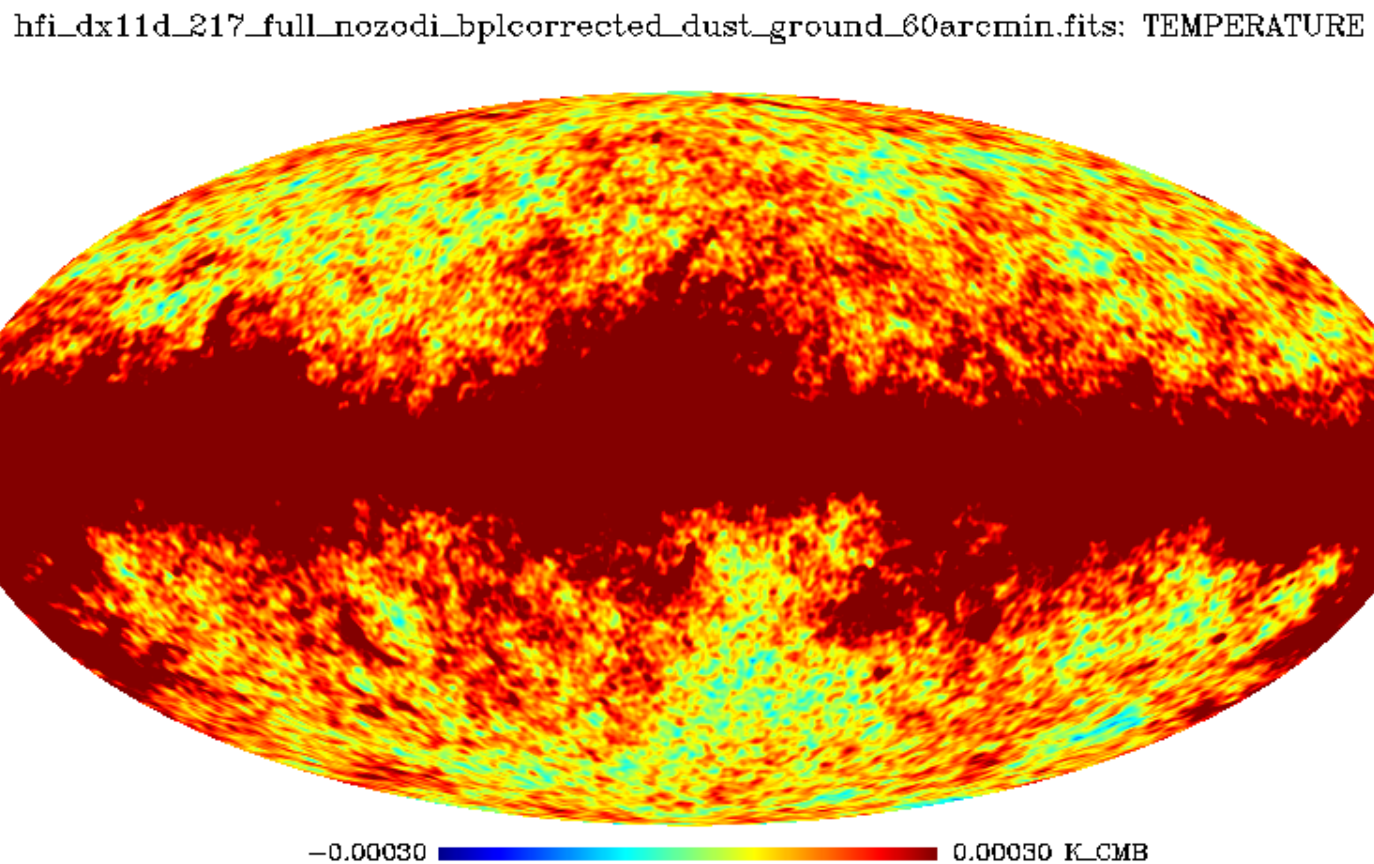
70GHz


hfi_dx11d_100_full_nozodi_bplcorrected_dust_ground_60arcmin.fits: TEMPERATURE
−0.00030
0.00030 K_CMB

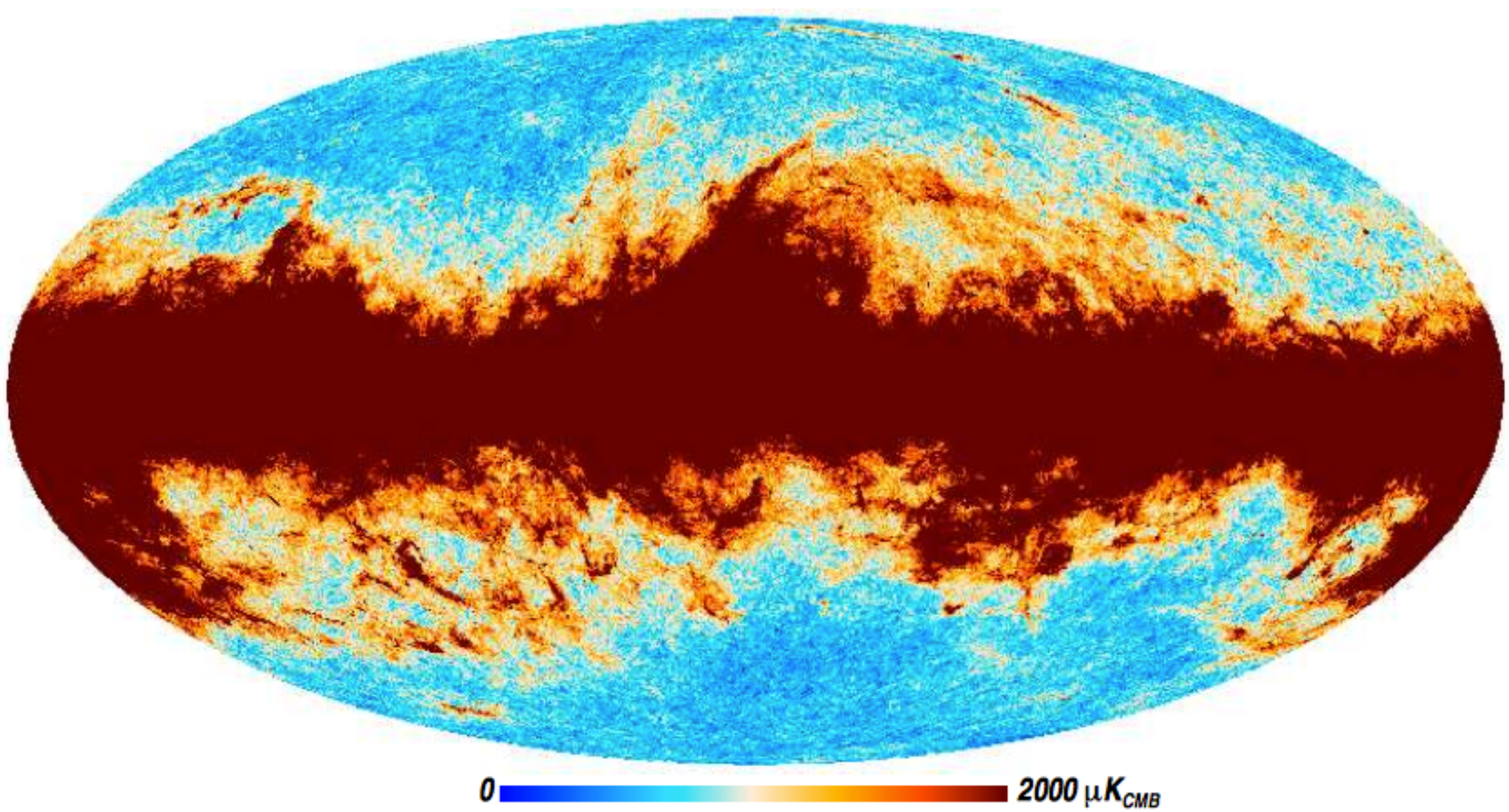
100GHz


hfi_dx11d_143_full_nozodi_bplcorrected_dust_ground_60arcmin.fits: TEMPERATURE
−0.00030
0.00030 K_CMB

143GHz


hfi_dx11d_217_full_nozodi_bplcorrected_dust_ground_60arcmin.fits: TEMPERATURE
−0.00030
0.00030 K_CMB

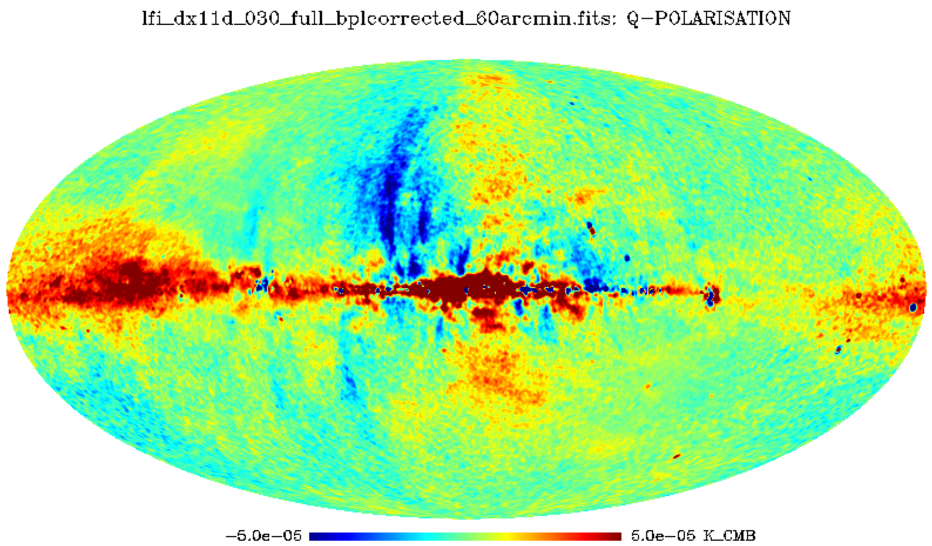
217GHz

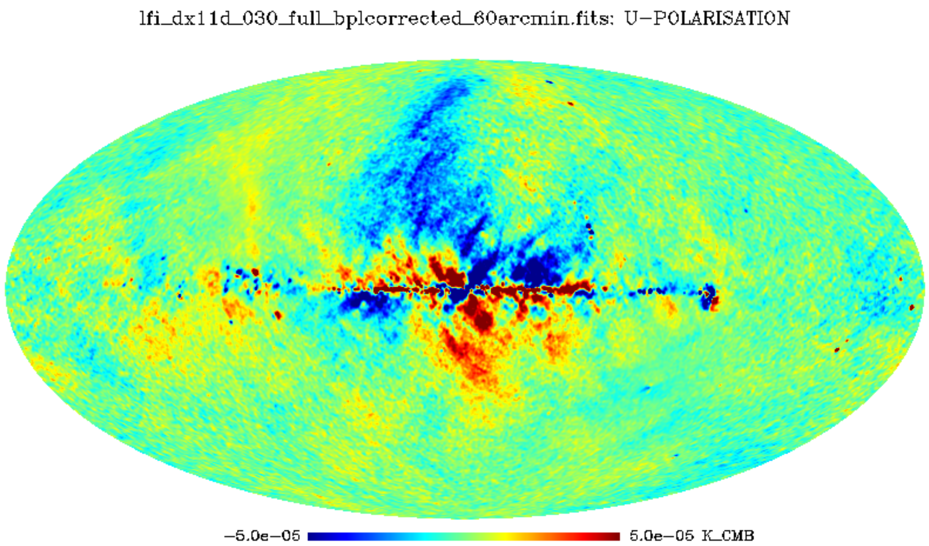


353GHz

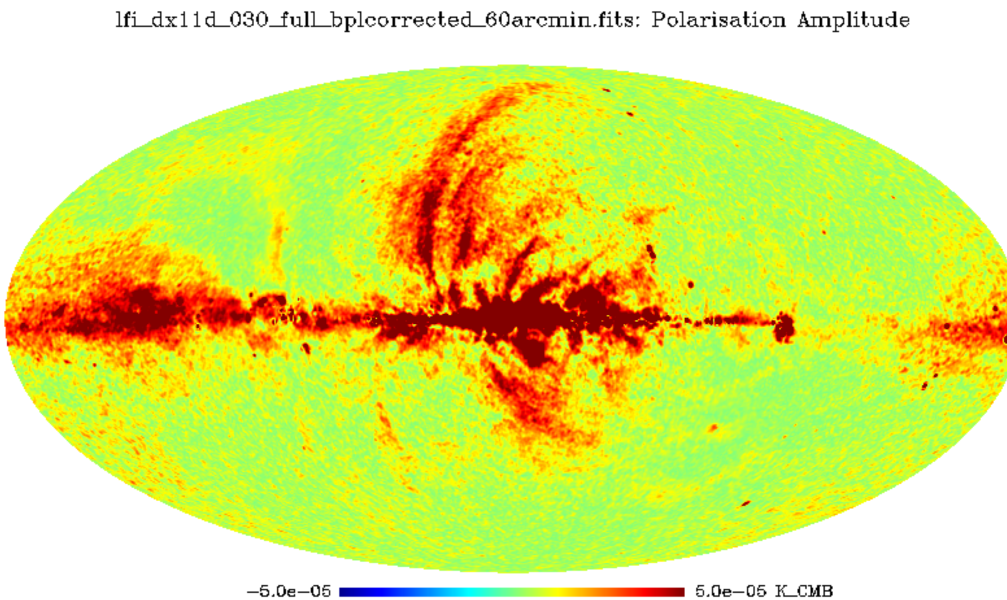
different color scale

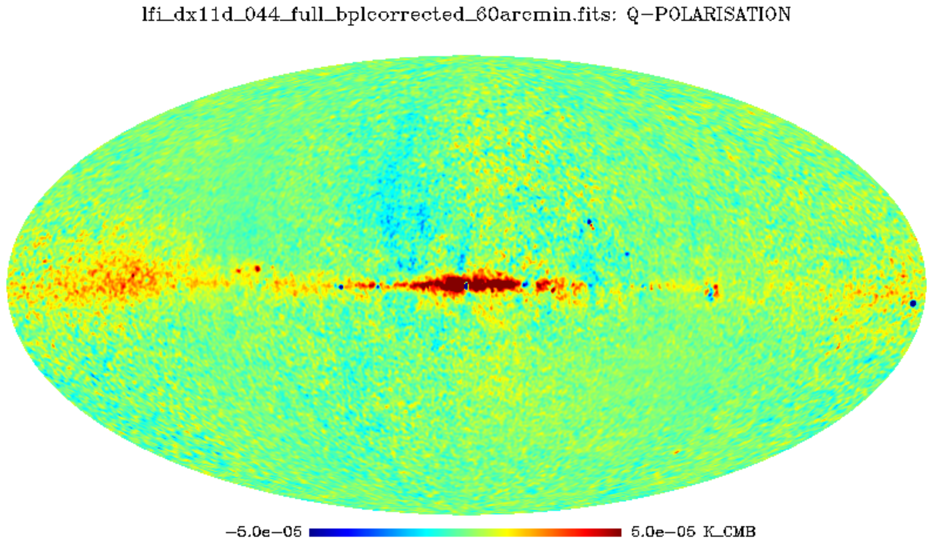
Frequency maps in polarization

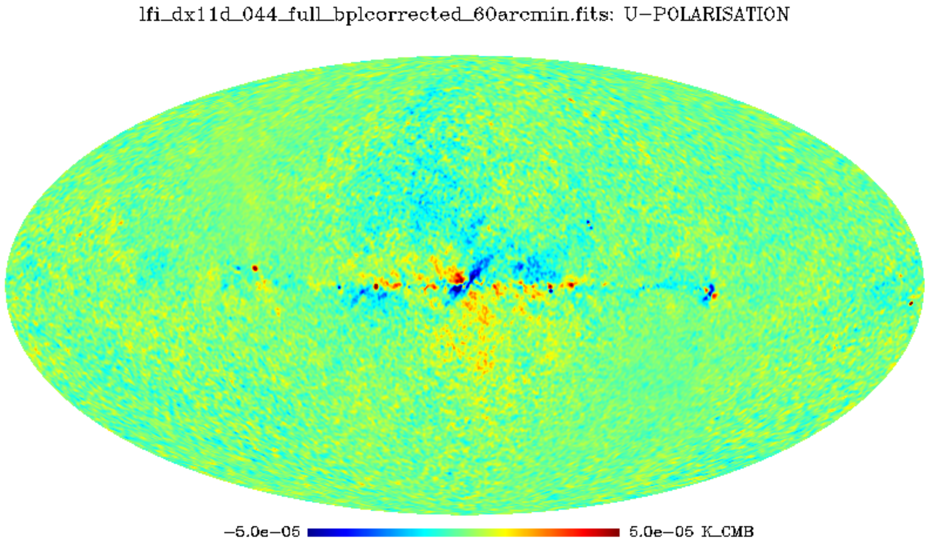

lfi_dx11d_030_full_bplcorrected_60arcmin.fits: Q-POLARISATION
-5.0e-05
5.0e-05 K_CMB


lfi_dx11d_030_full_bplcorrected_60arcmin.fits: U-POLARISATION
-5.0e-05
5.0e-05 K_CMB

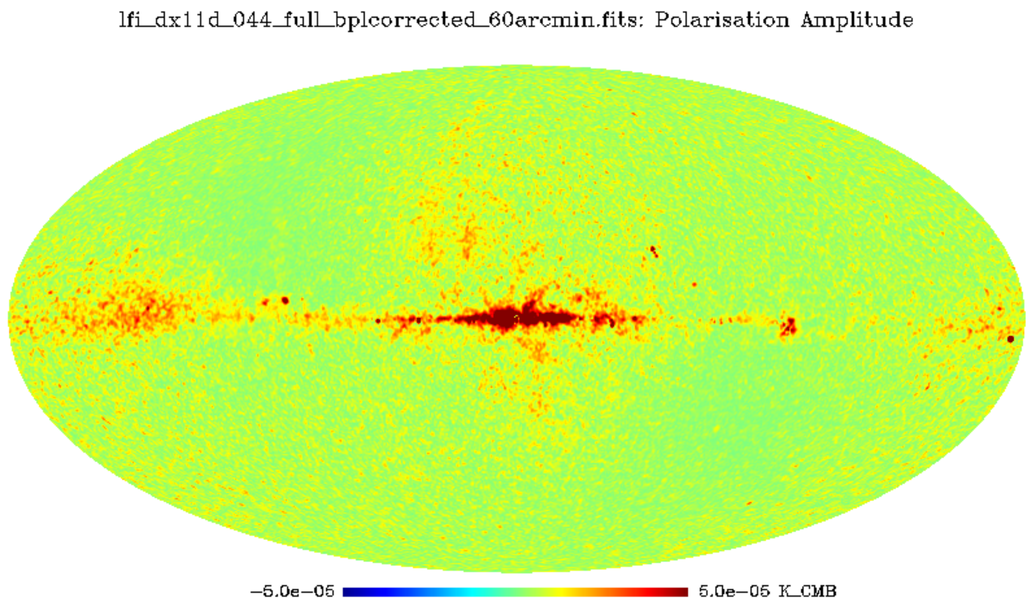
30GHz

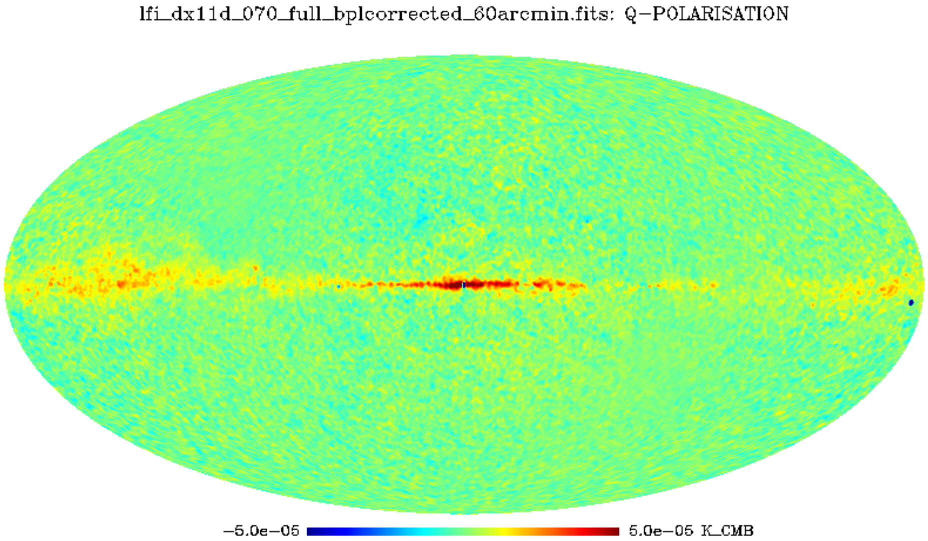

lfi_dx11d_030_full_bplcorrected_60arcmin.fits: Polarisation Amplitude
-5.0e-05
5.0e-05 K_CMB

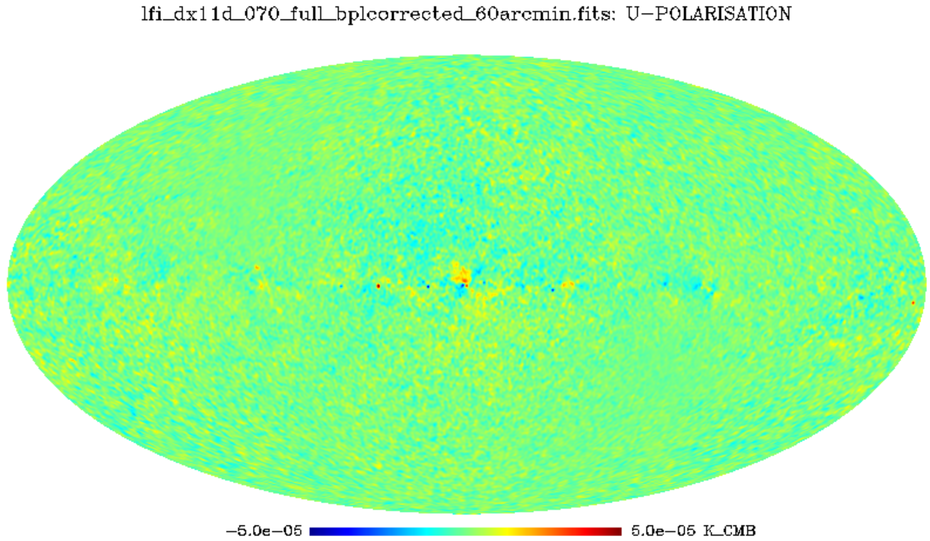

lfi_dx11d_044_full_bplcorrected_60arcmin.fits: Q-POLARISATION
-5.0e-05
5.0e-05 K_CMB


lfi_dx11d_044_full_bplcorrected_60arcmin.fits: U-POLARISATION
-5.0e-05
5.0e-05 K_CMB

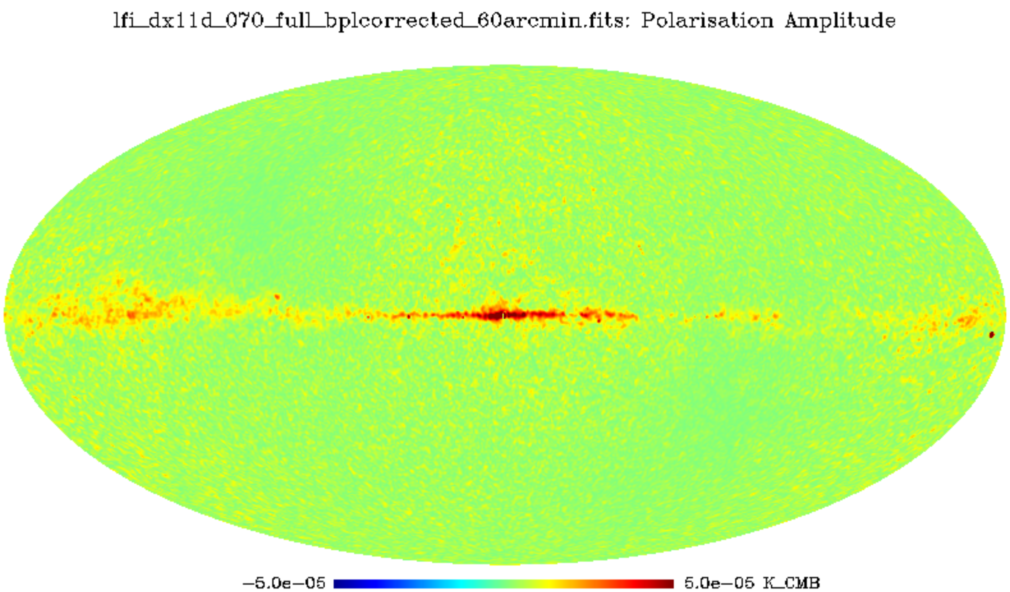
44GHz

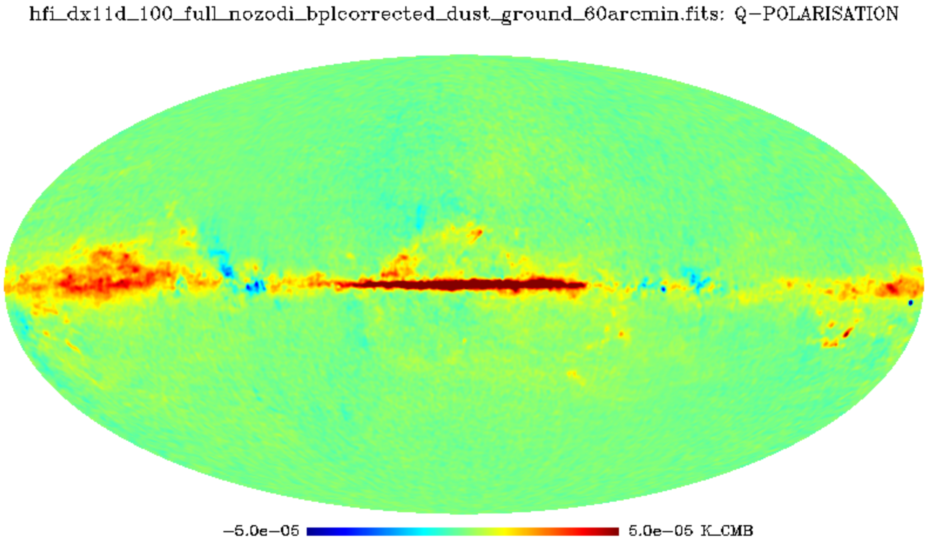

lfi_dx11d_044_full_bplcorrected_60arcmin.fits: Polarisation Amplitude
-5.0e-05
5.0e-05 K_CMB

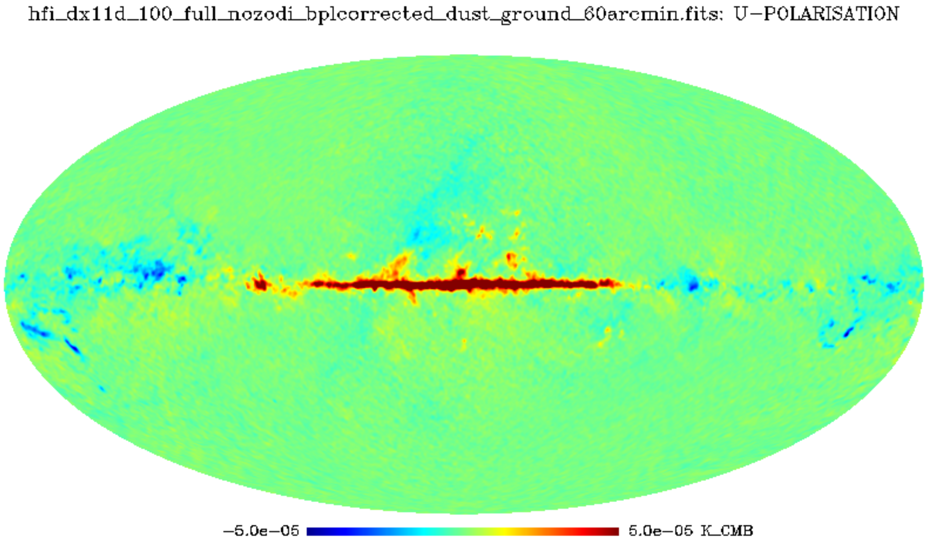

lfi_dx11d_070_full_bplcorrected_60arcmin.fits: Q-POLARISATION
-5.0e-05
5.0e-05 K_CMB


lfi_dx11d_070_full_bplcorrected_60arcmin.fits: U-POLARISATION
-5.0e-05
5.0e-05 K_CMB

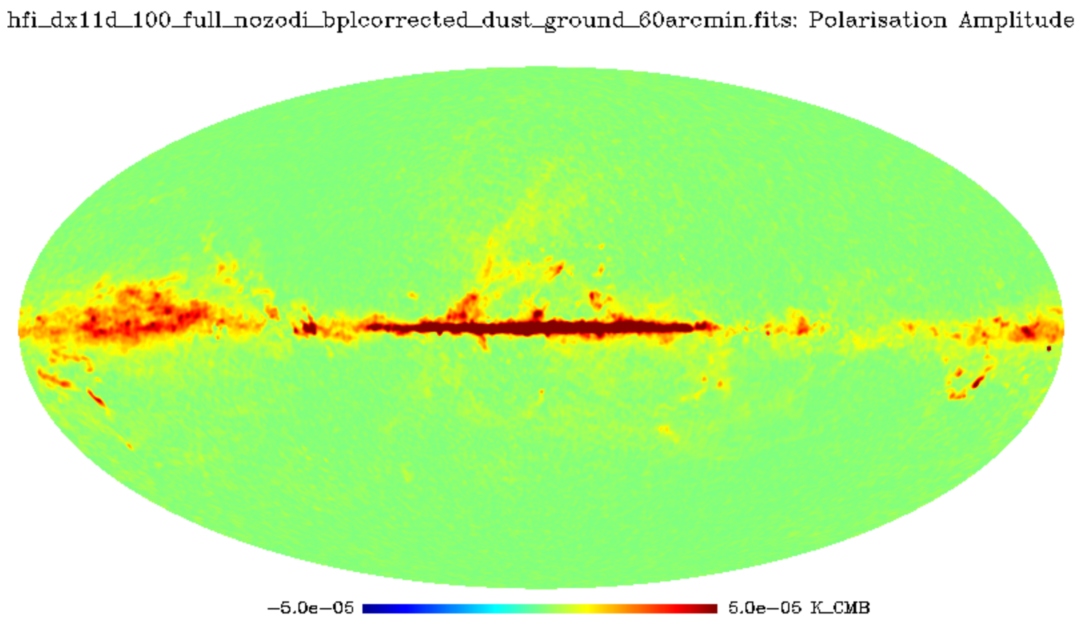
70GHz

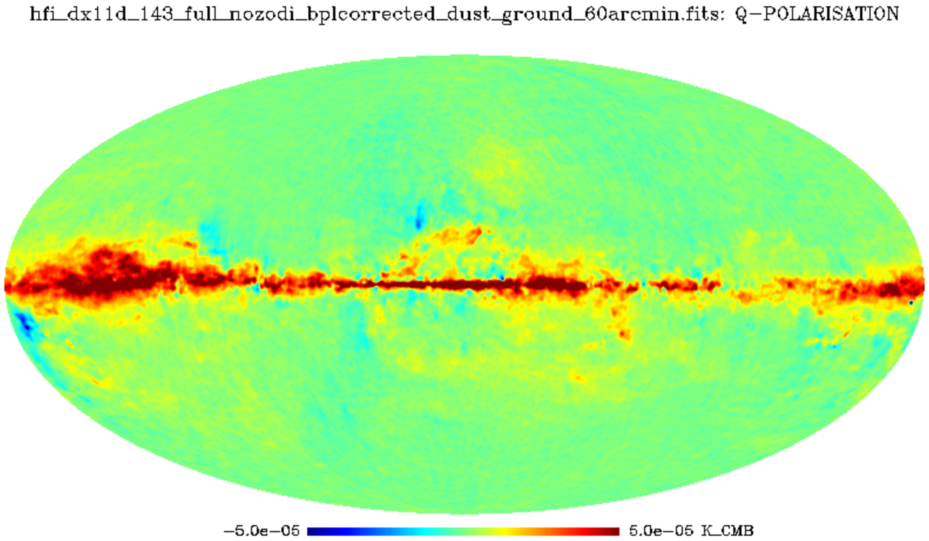

lfi_dx11d_070_full_bplcorrected_60arcmin.fits: Polarisation Amplitude
-5.0e-05
5.0e-05 K_CMB

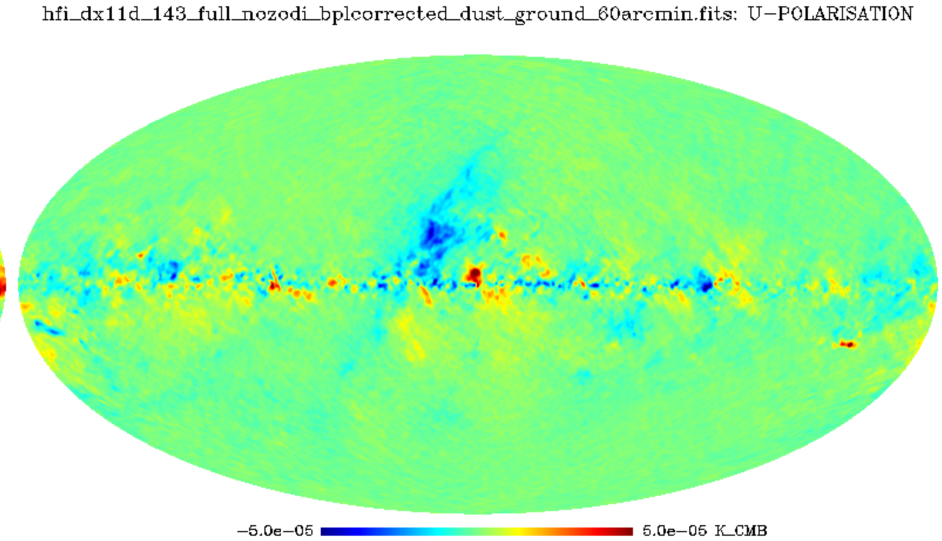




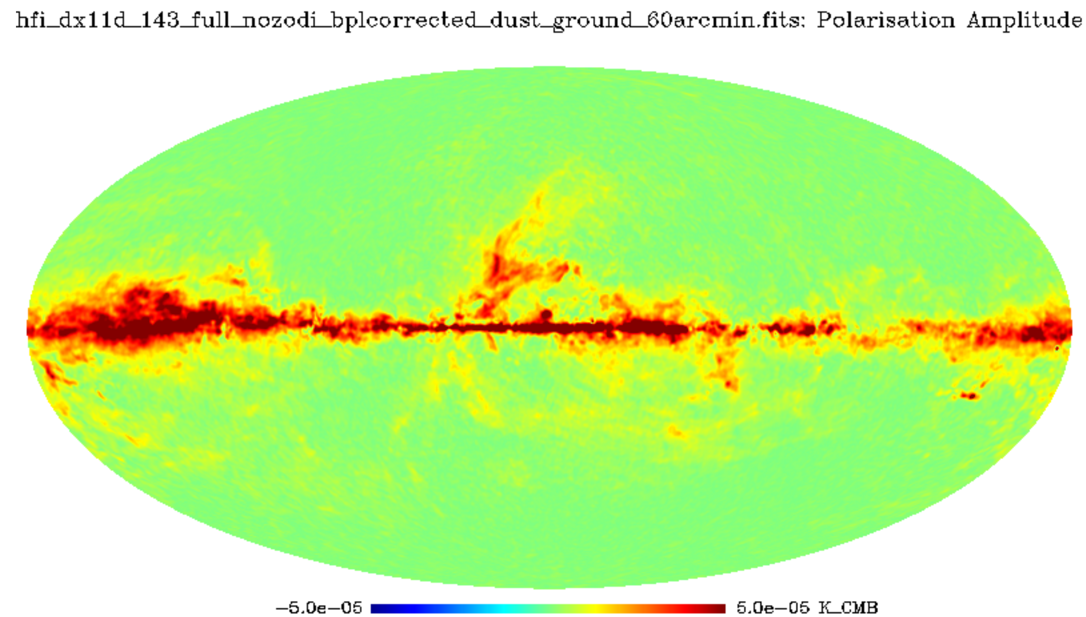
100GHz
(no CMB)

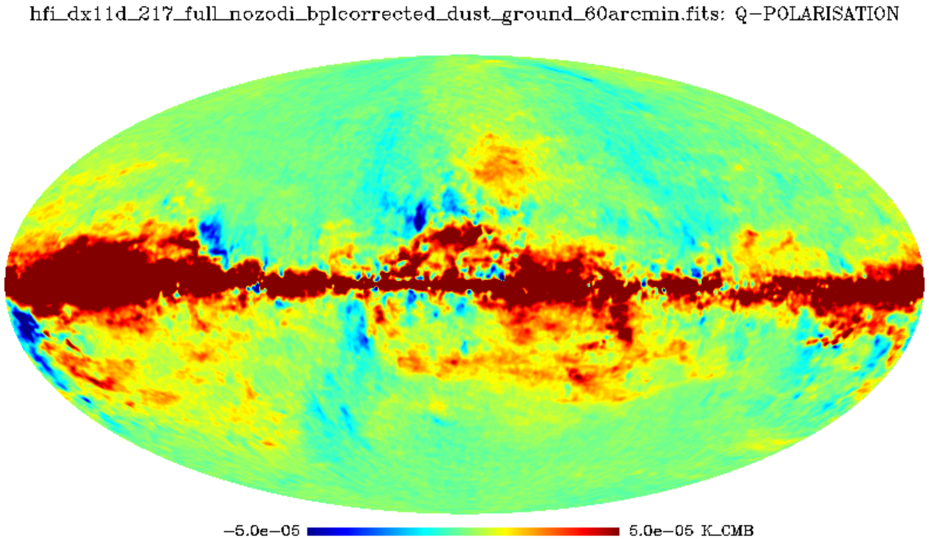


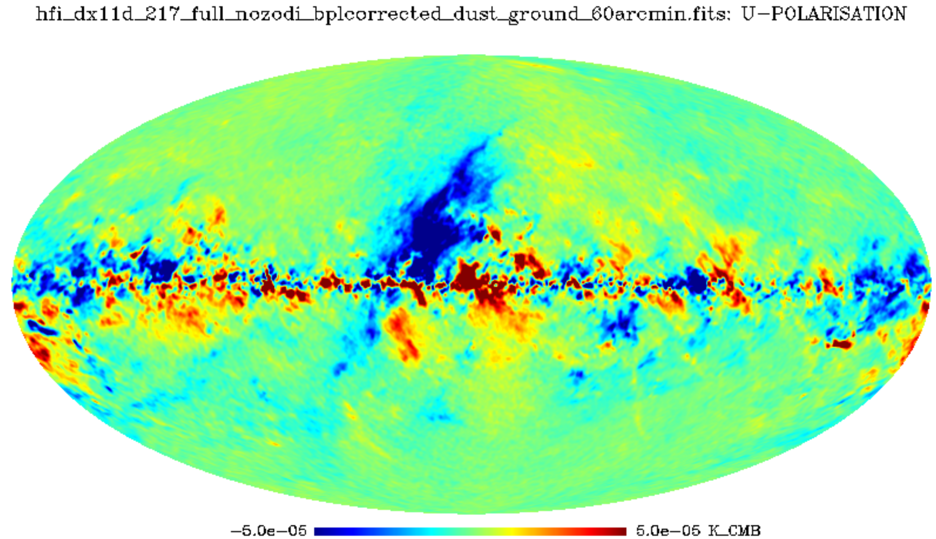




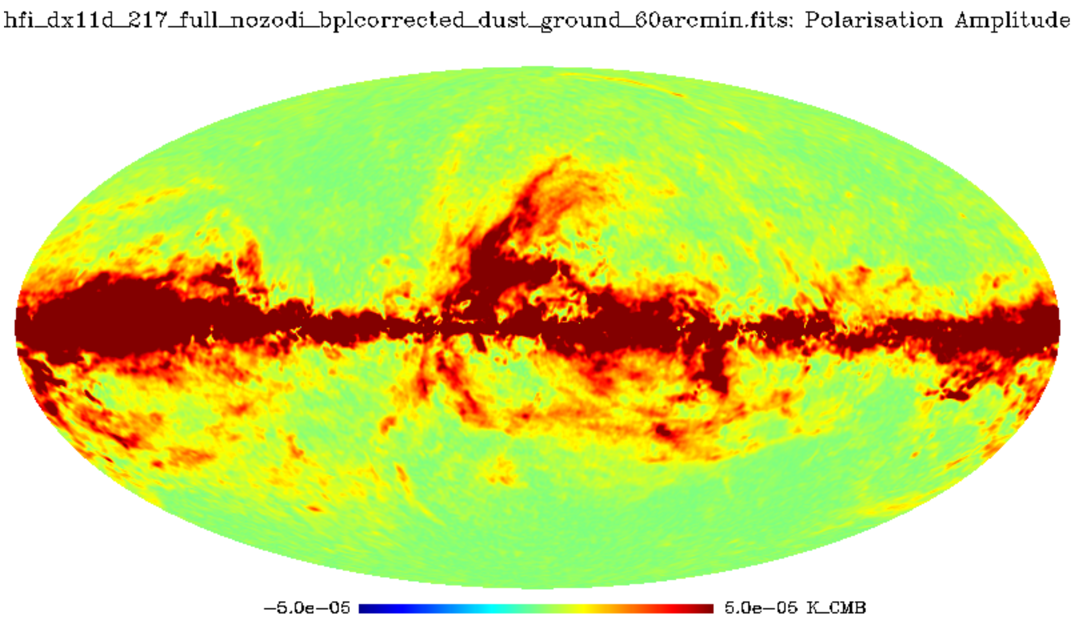
143GHz
(no CMB)

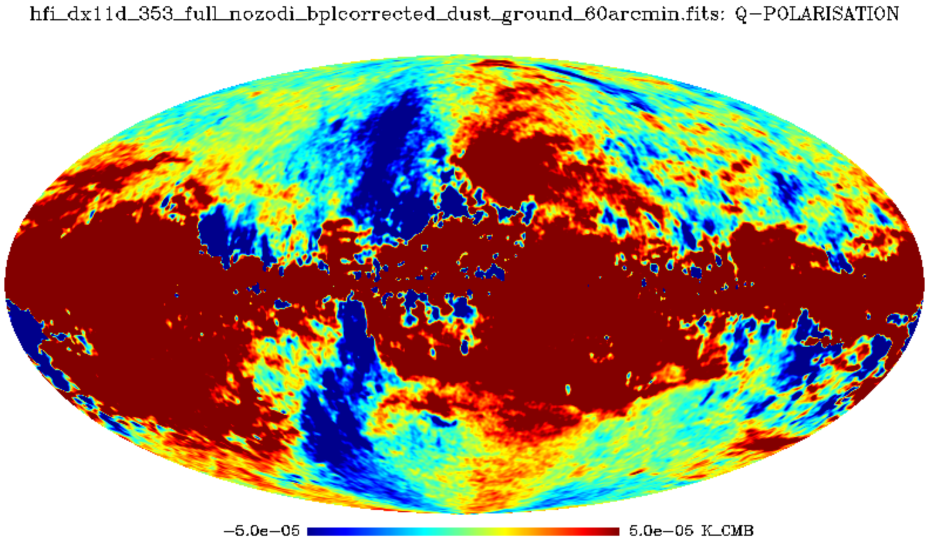


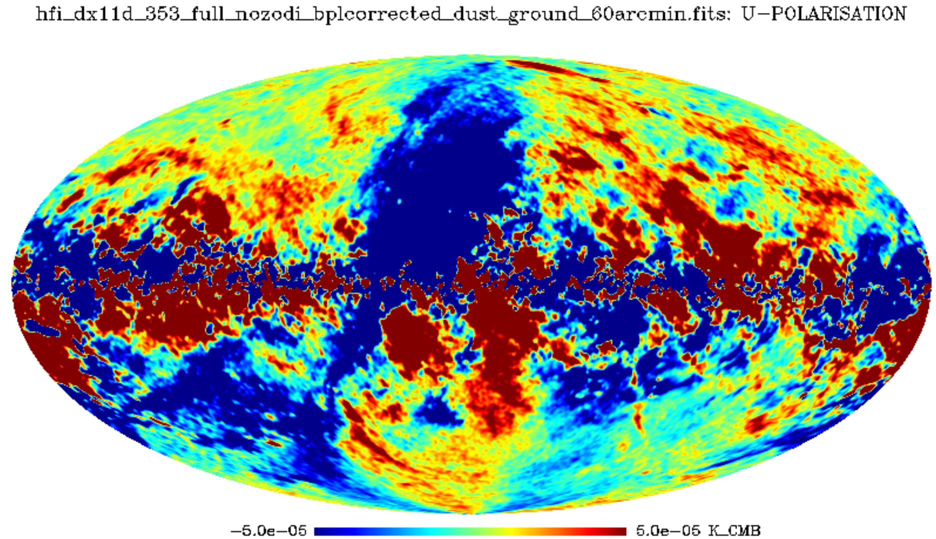




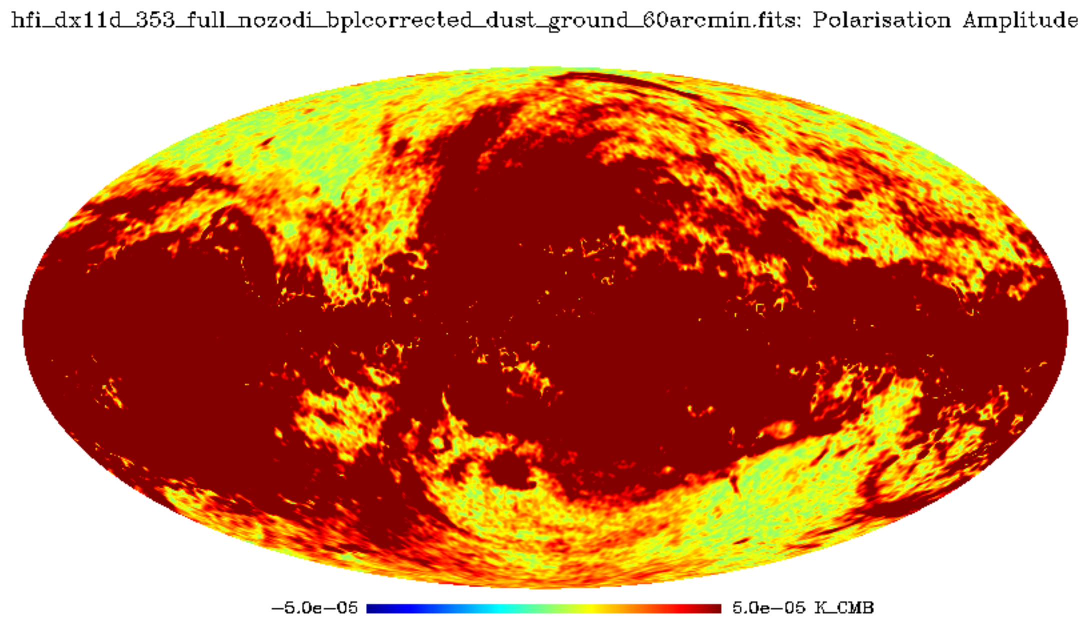
217GHz
(no CMB)





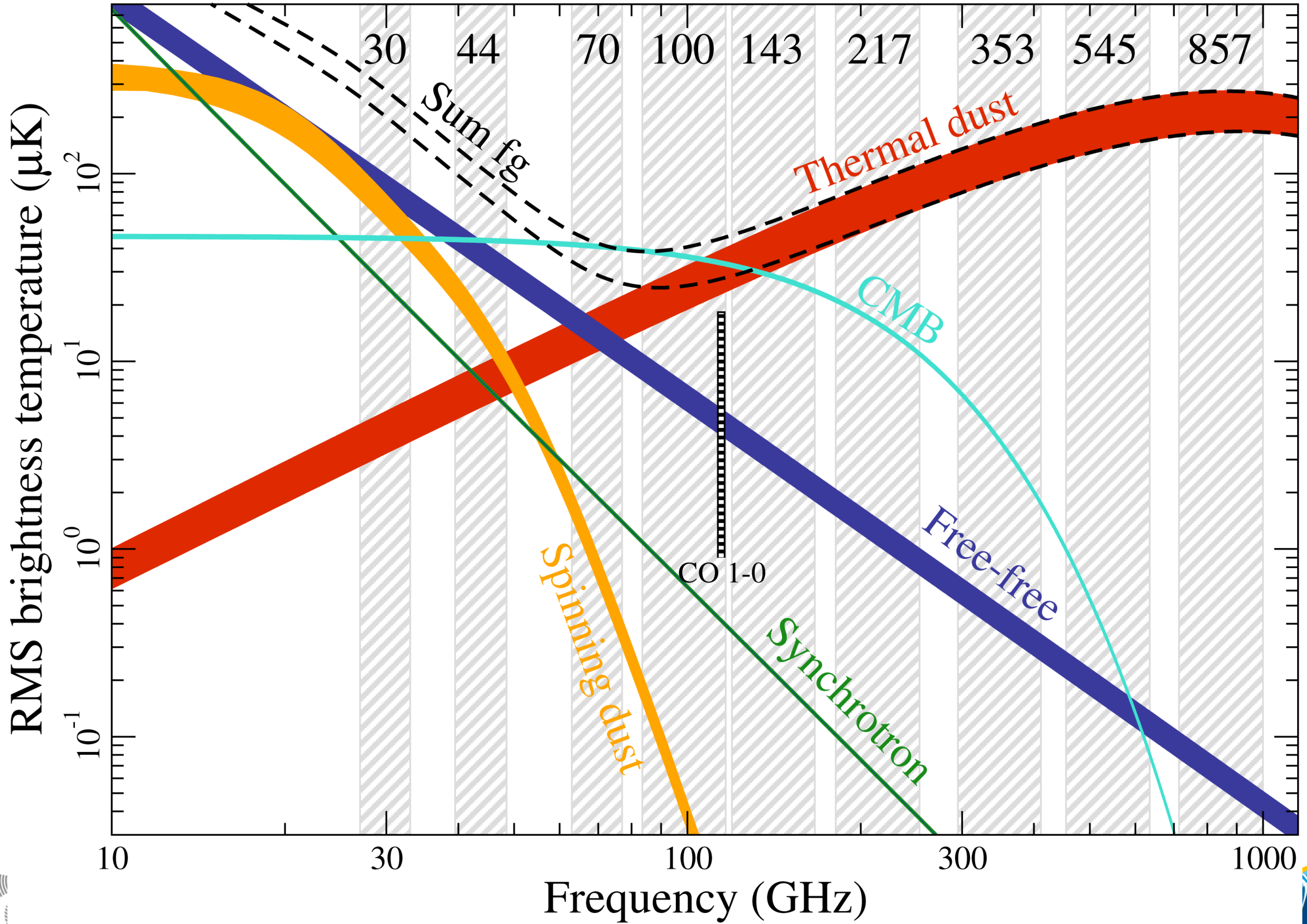


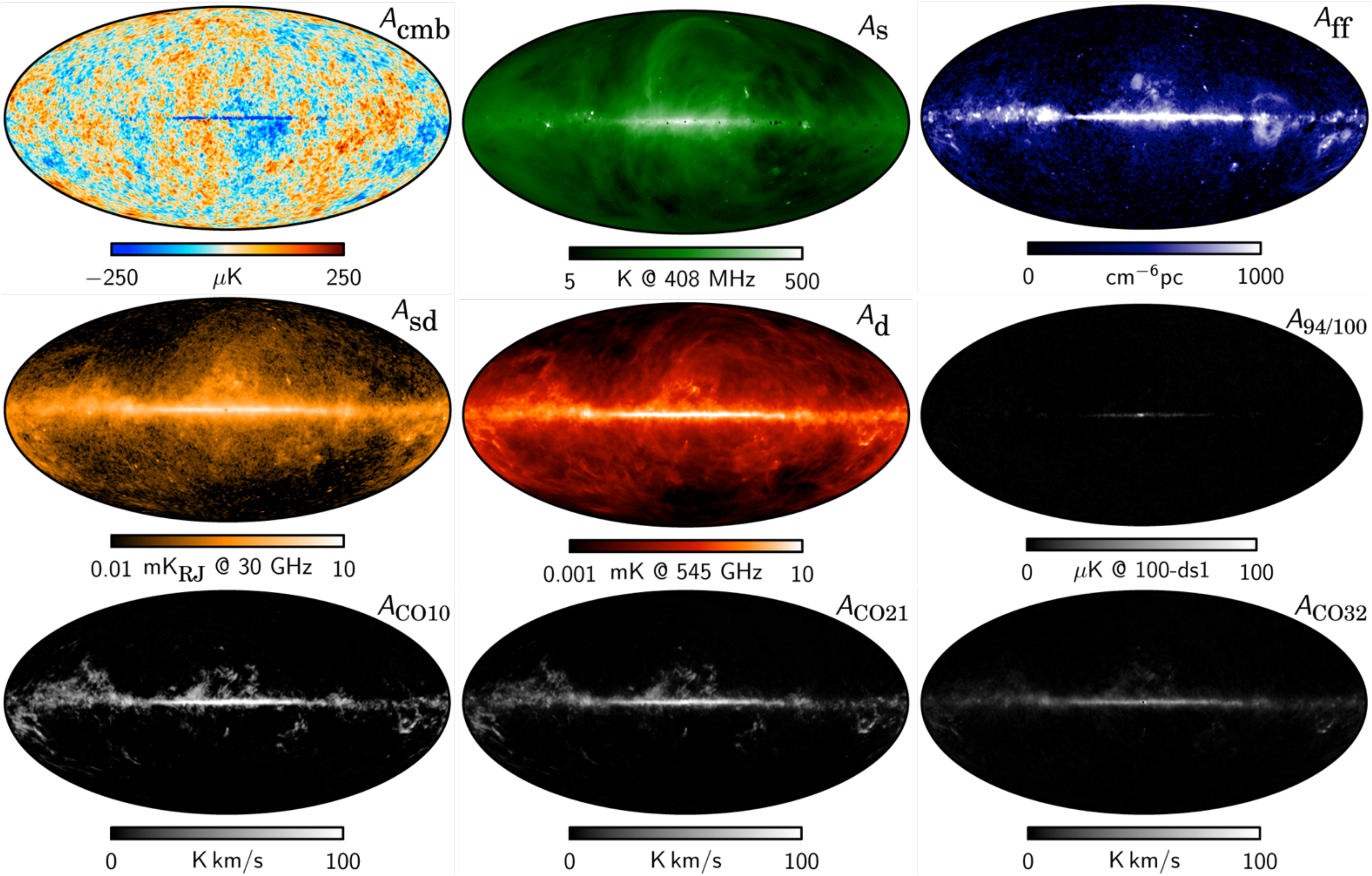
353GHz
(no CMB)



COMPONENT SEPARATION

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

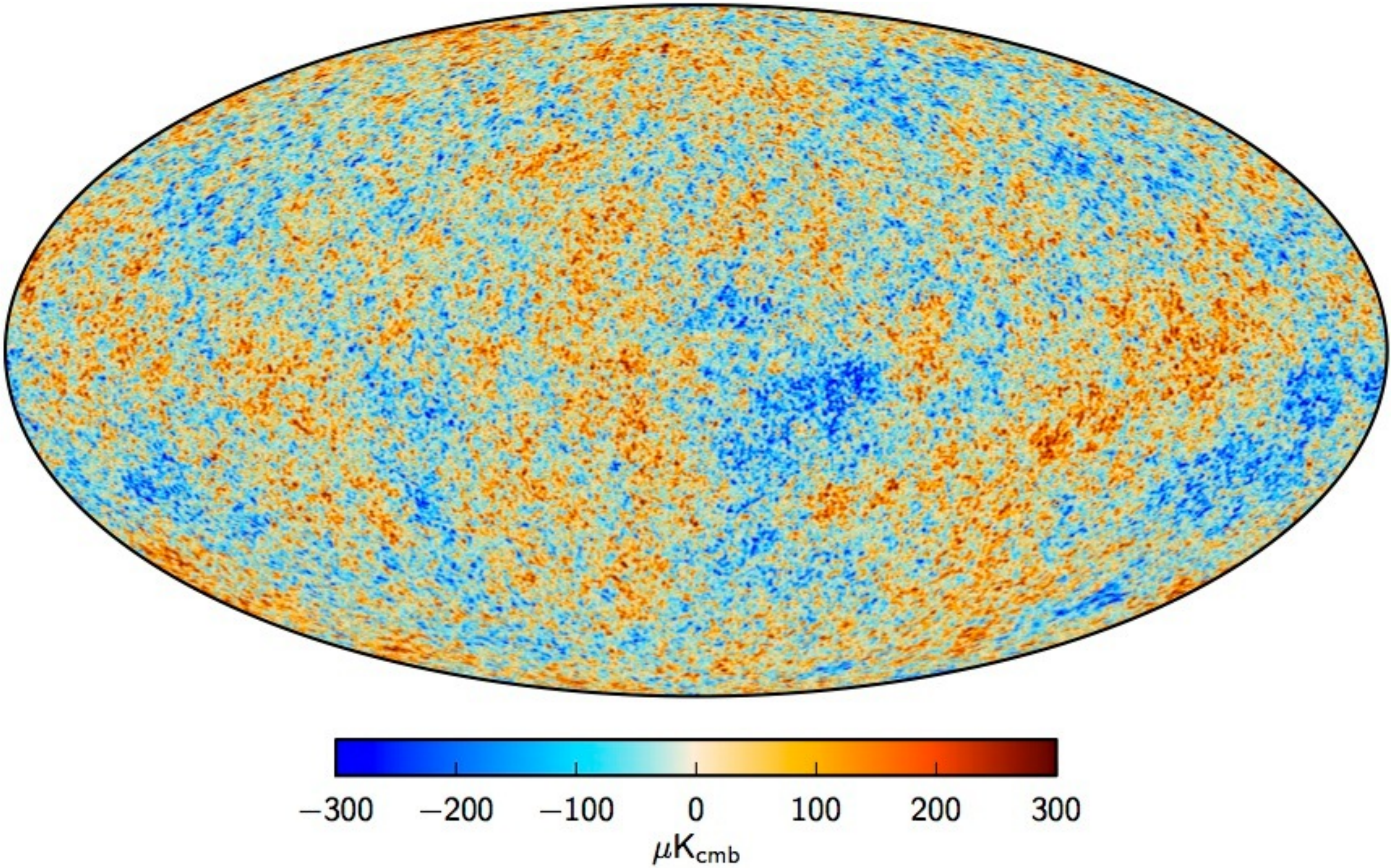




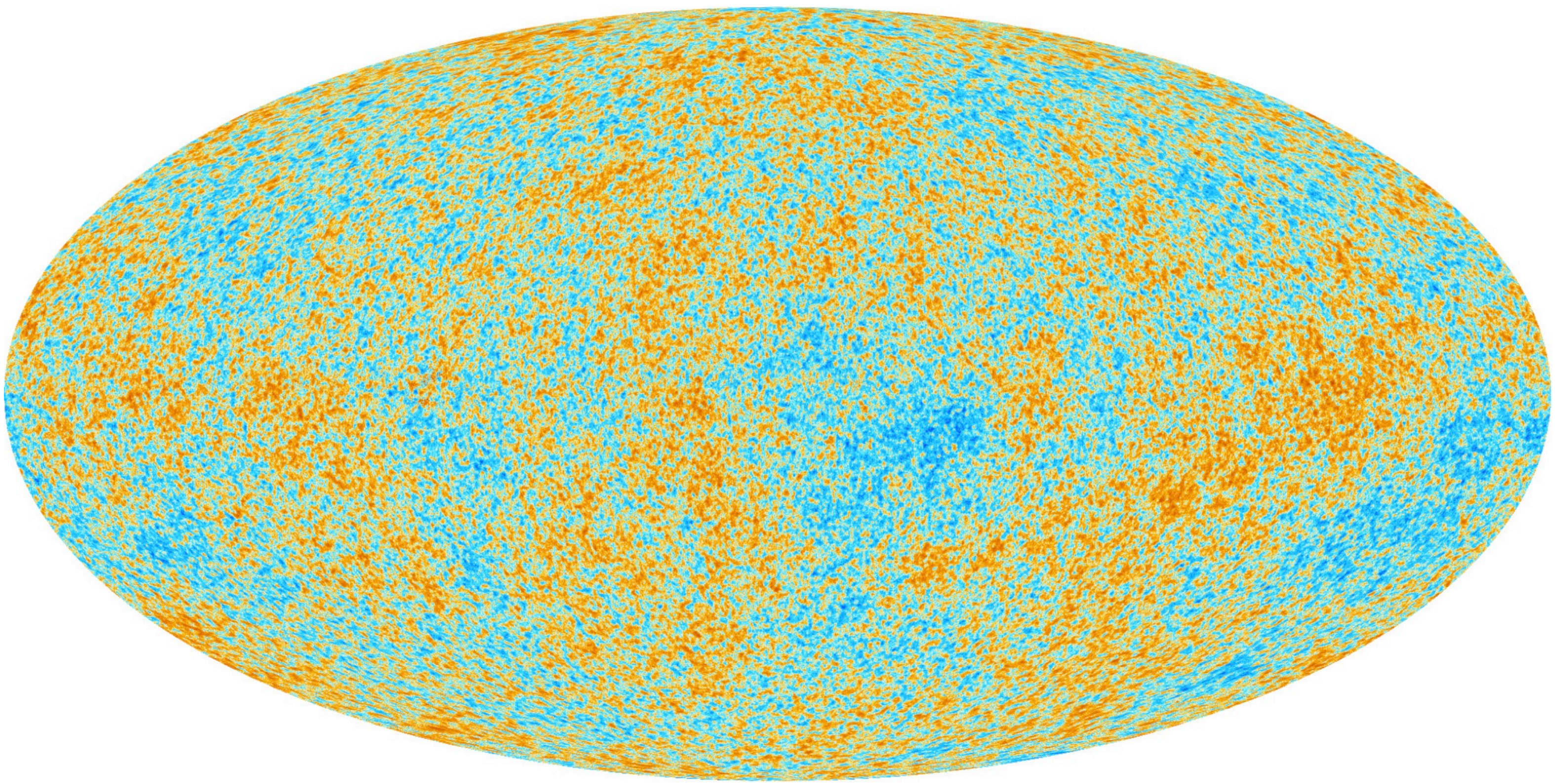
Maximum posterior intensity maps derived throughg the Commander algorithm from the joint analysis of Planck, WMAP and 408 MHz observations from Haslam

esa planck PLANCK LFI HFI PLANCK

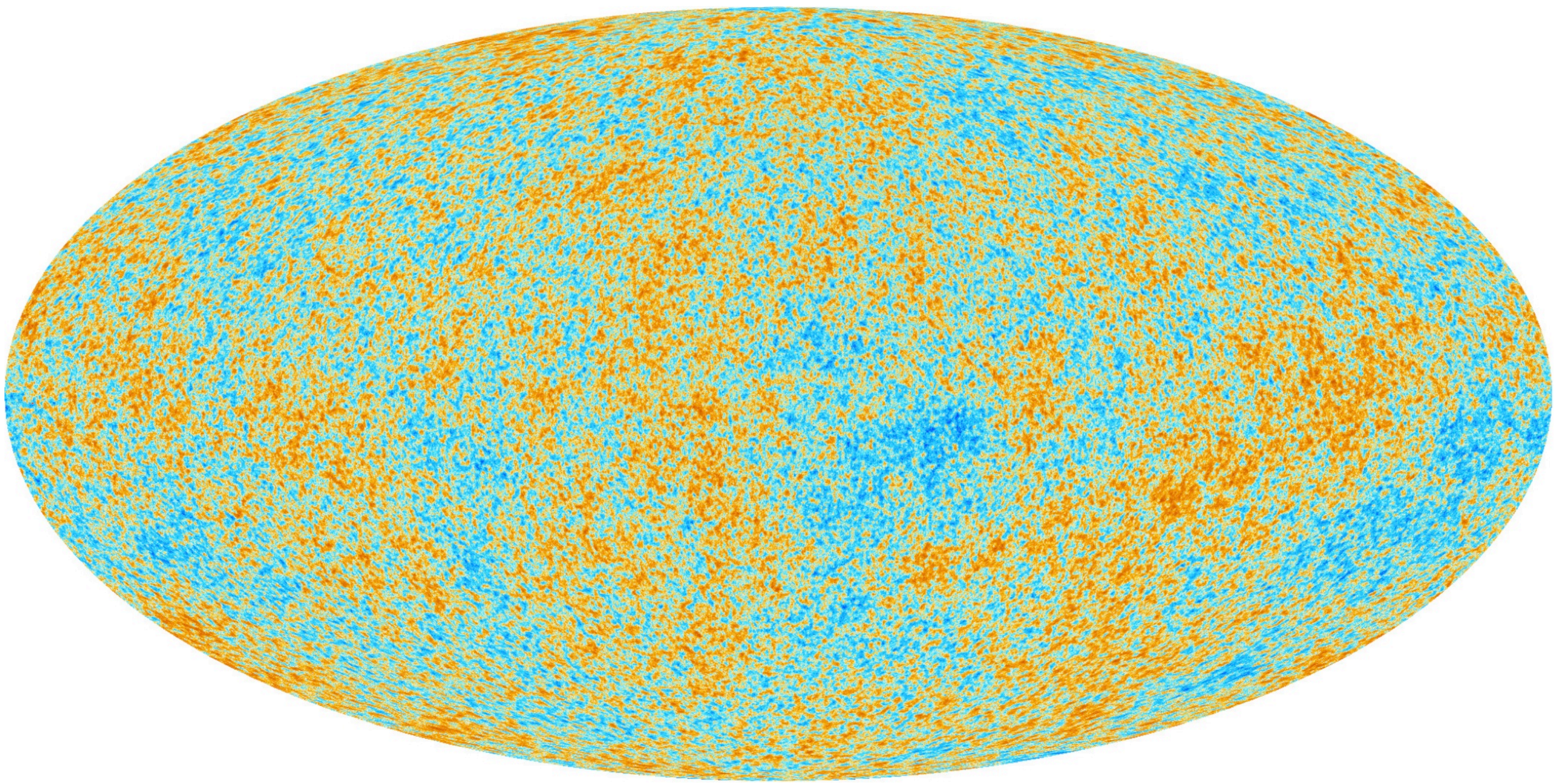
Planck 2015 Temperature map



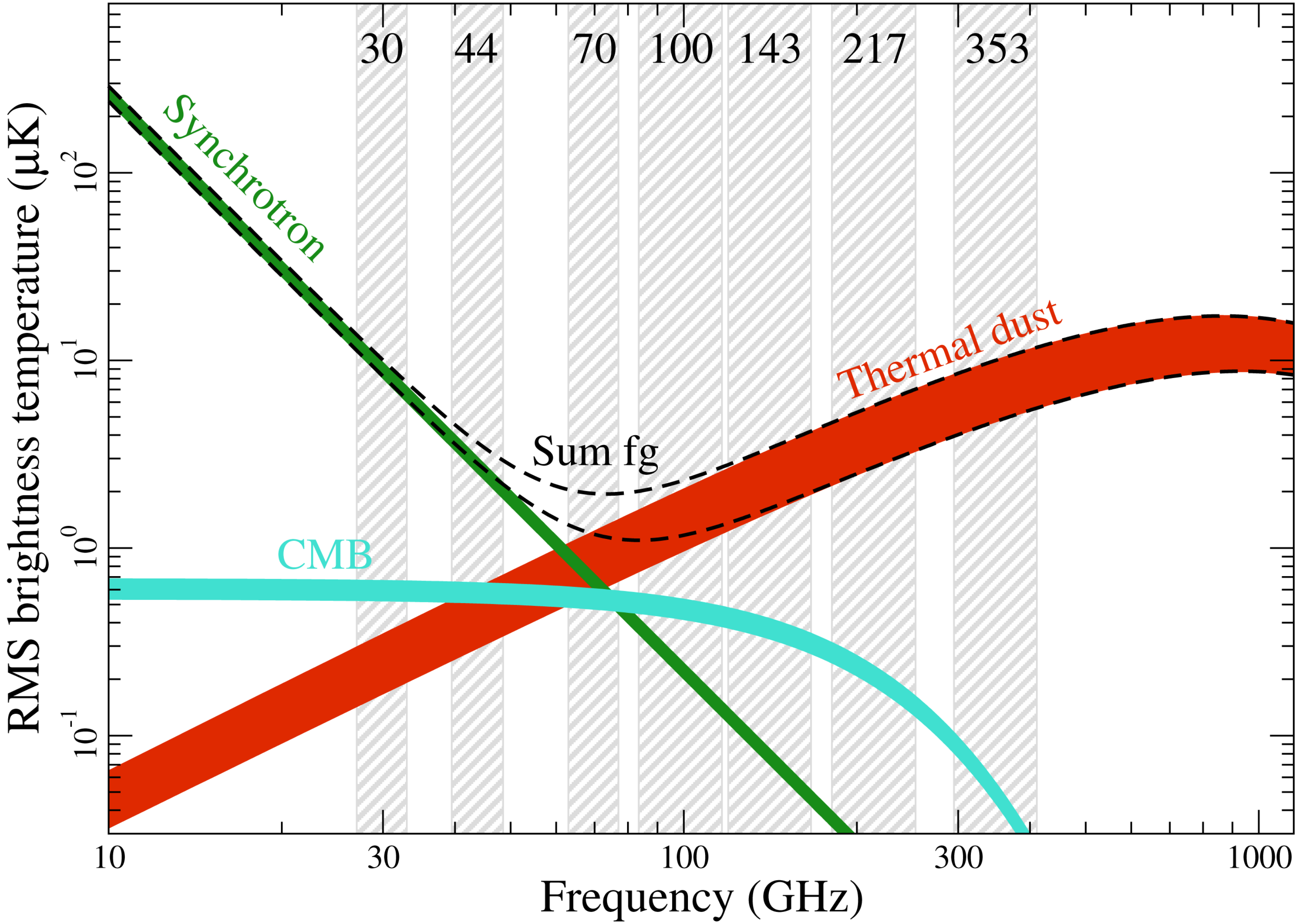
Planck 2013 CMB

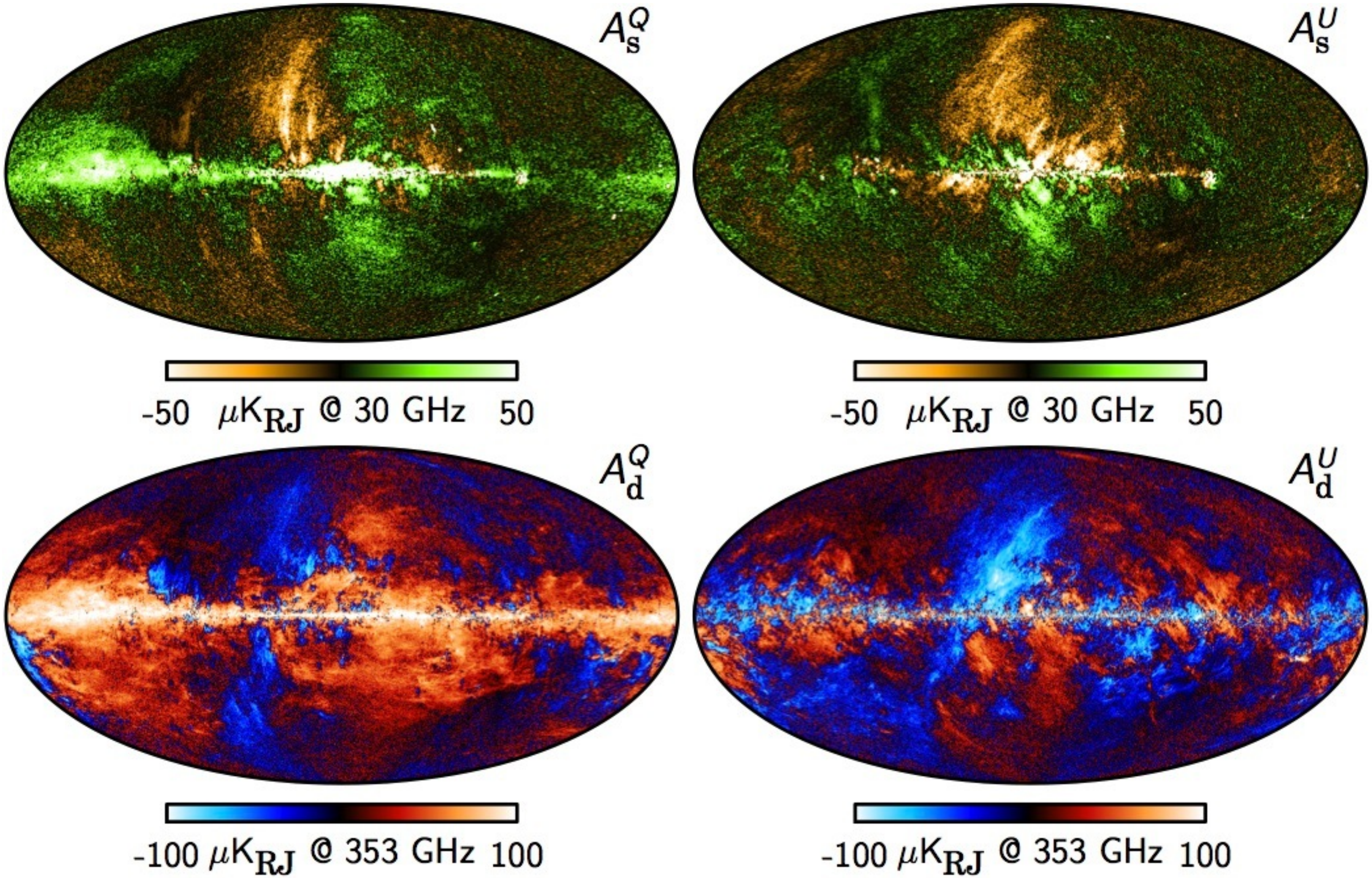


Planck 2015 CMB

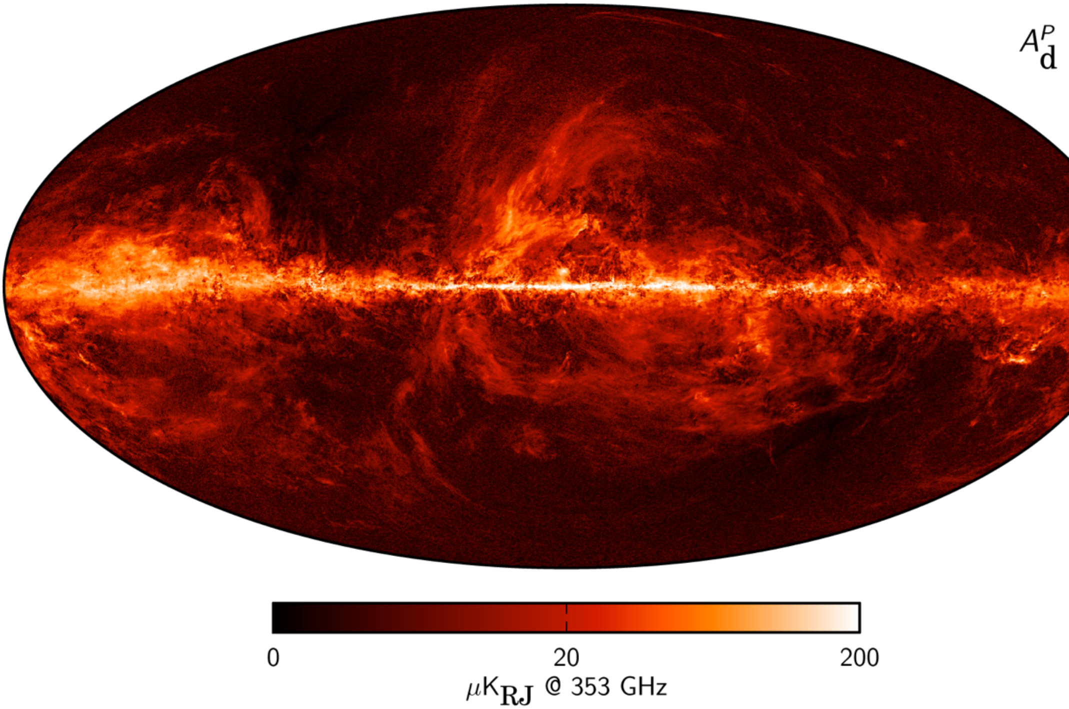


Frequency spectrum of RMS brightness polarization intensity: CMB vs. astrophysical foregrounds



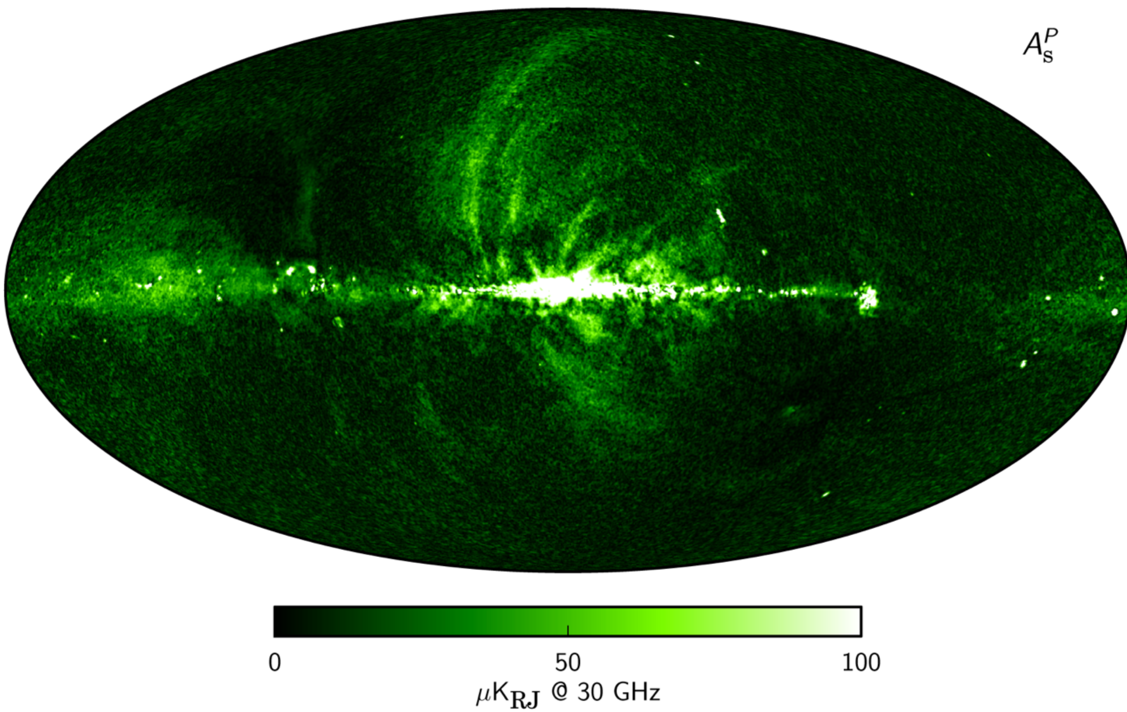


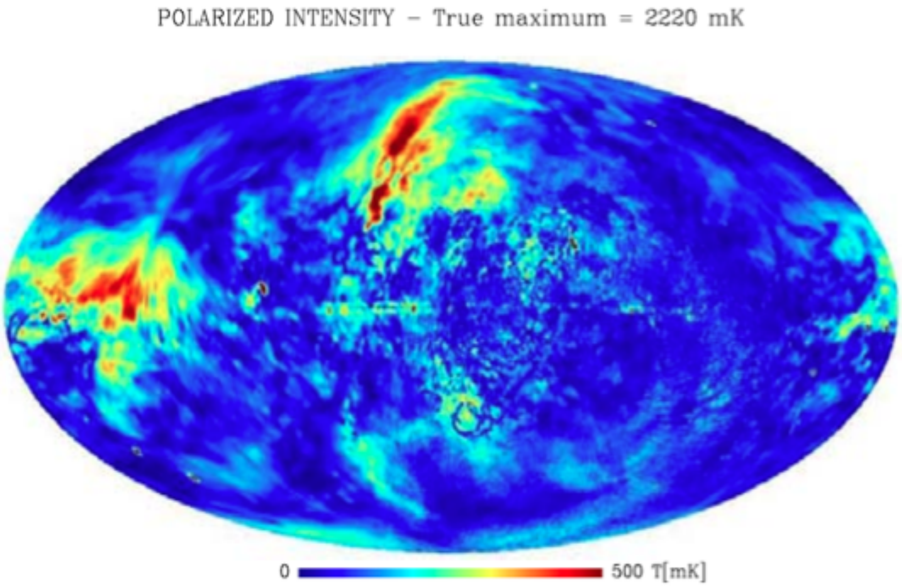
Maximum posterior polarization Q and U amplitude maps for synchrotron and dust derived through the Commander algorithm from Planck observations between 30 and 353 GHz

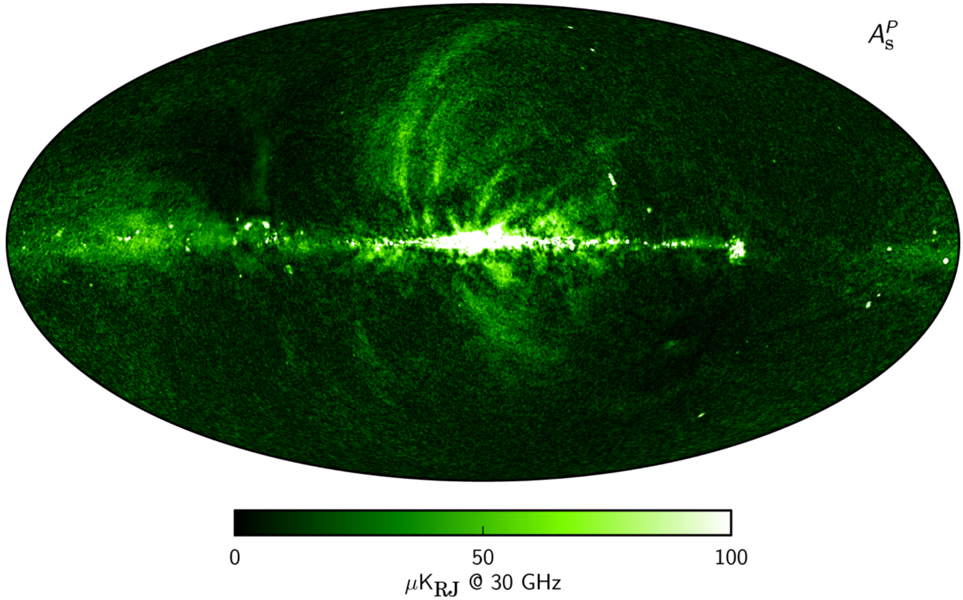


Total polarized dust emission

Total polarized synchrotron emission



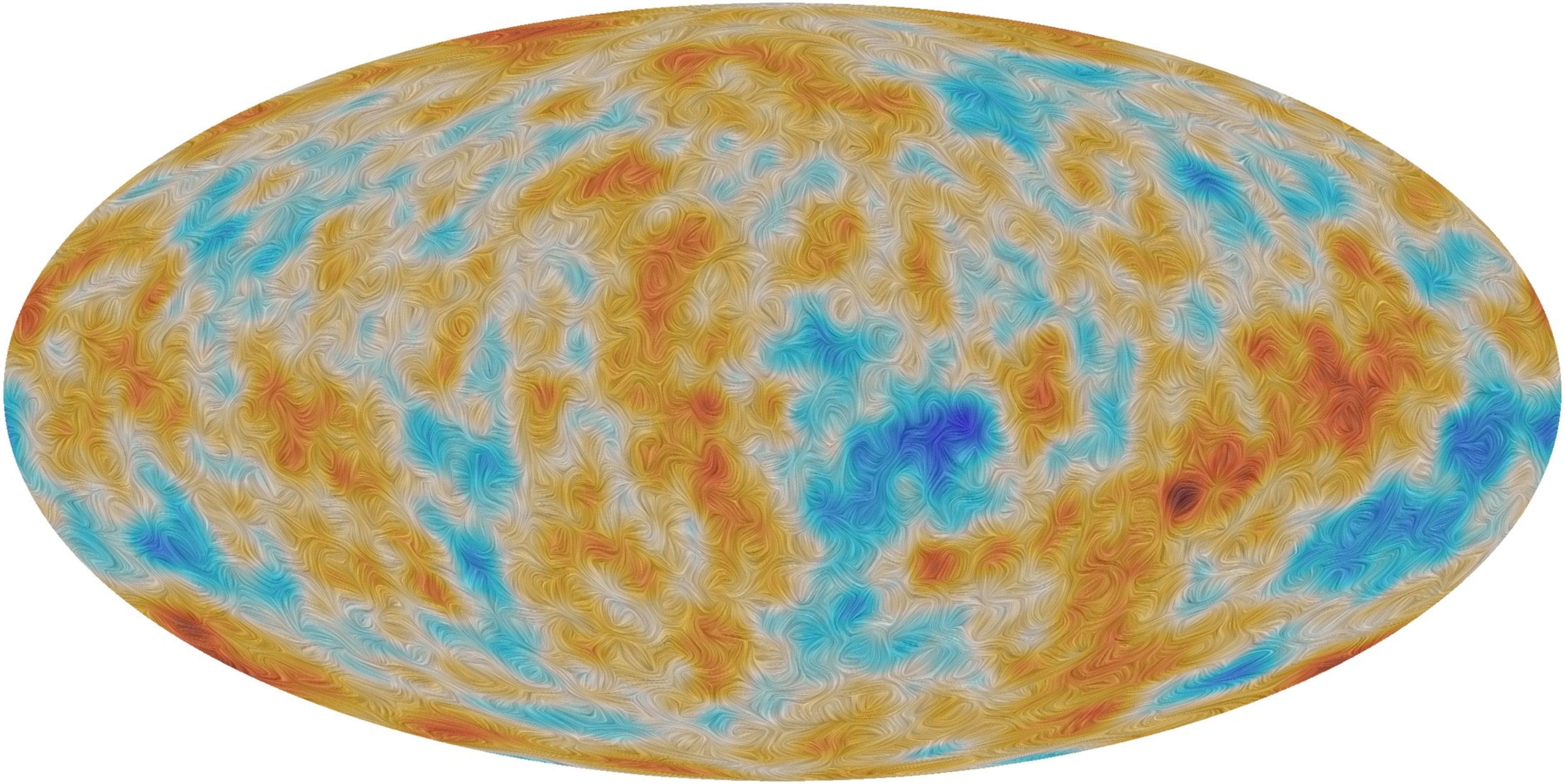




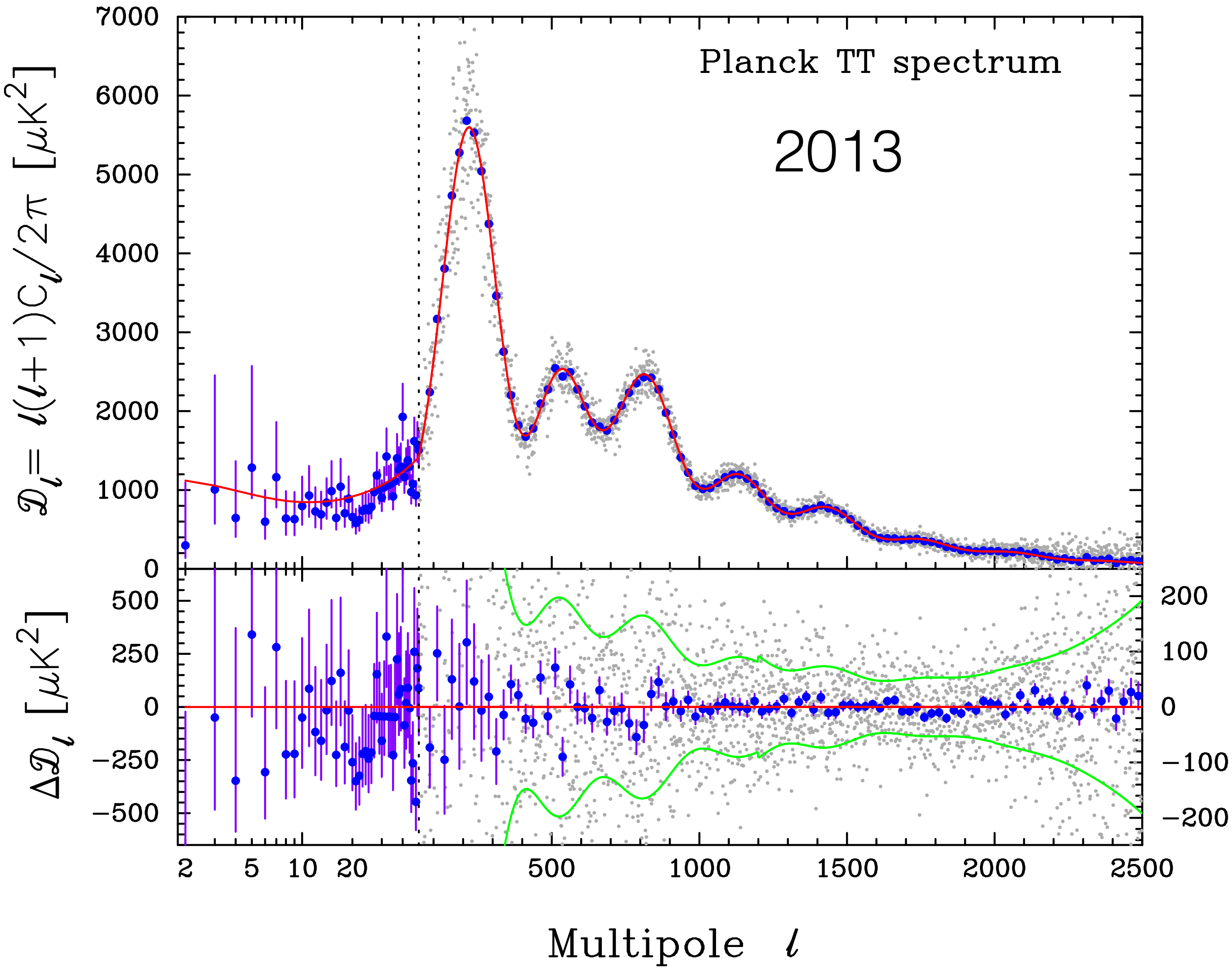
All-sky maps of Galactic polarized emission at radio (1.4 GHz, left image; from Burigana et al. '06) and synchrotron polarized emission from Planck.

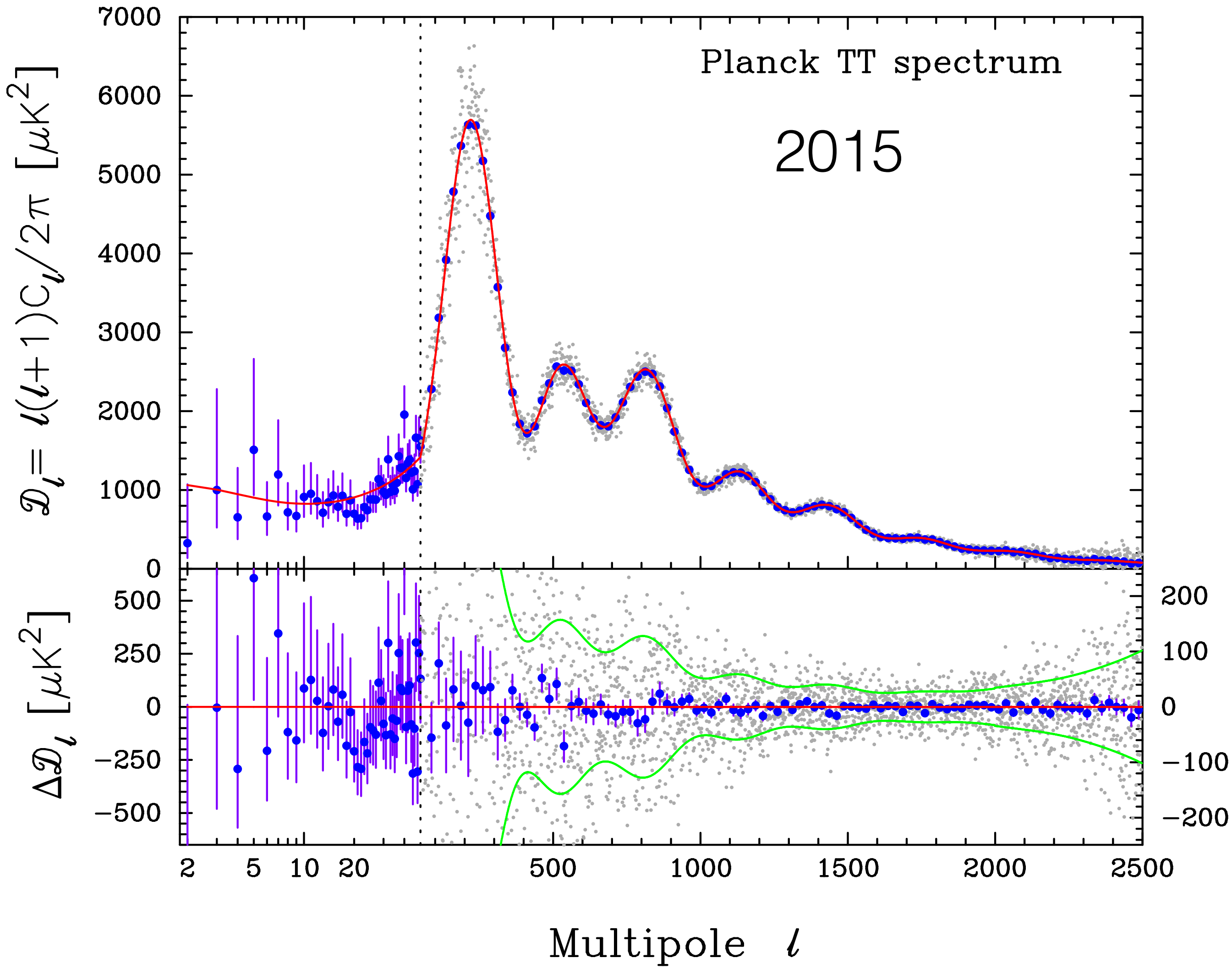
Regarding the synchrotron emission, produced by relativistic cosmic ray electrons spiralling in the Galactic magnetic field, a remarkable feature of the Galactic radio sky is the significant depolarization appearing in a wide region around the Galactic center. This effect is certainly much less relevant in the microwaves, as evident by the comparison of available radio surveys with millimeter surveys.

Planck 2015 Polarization map

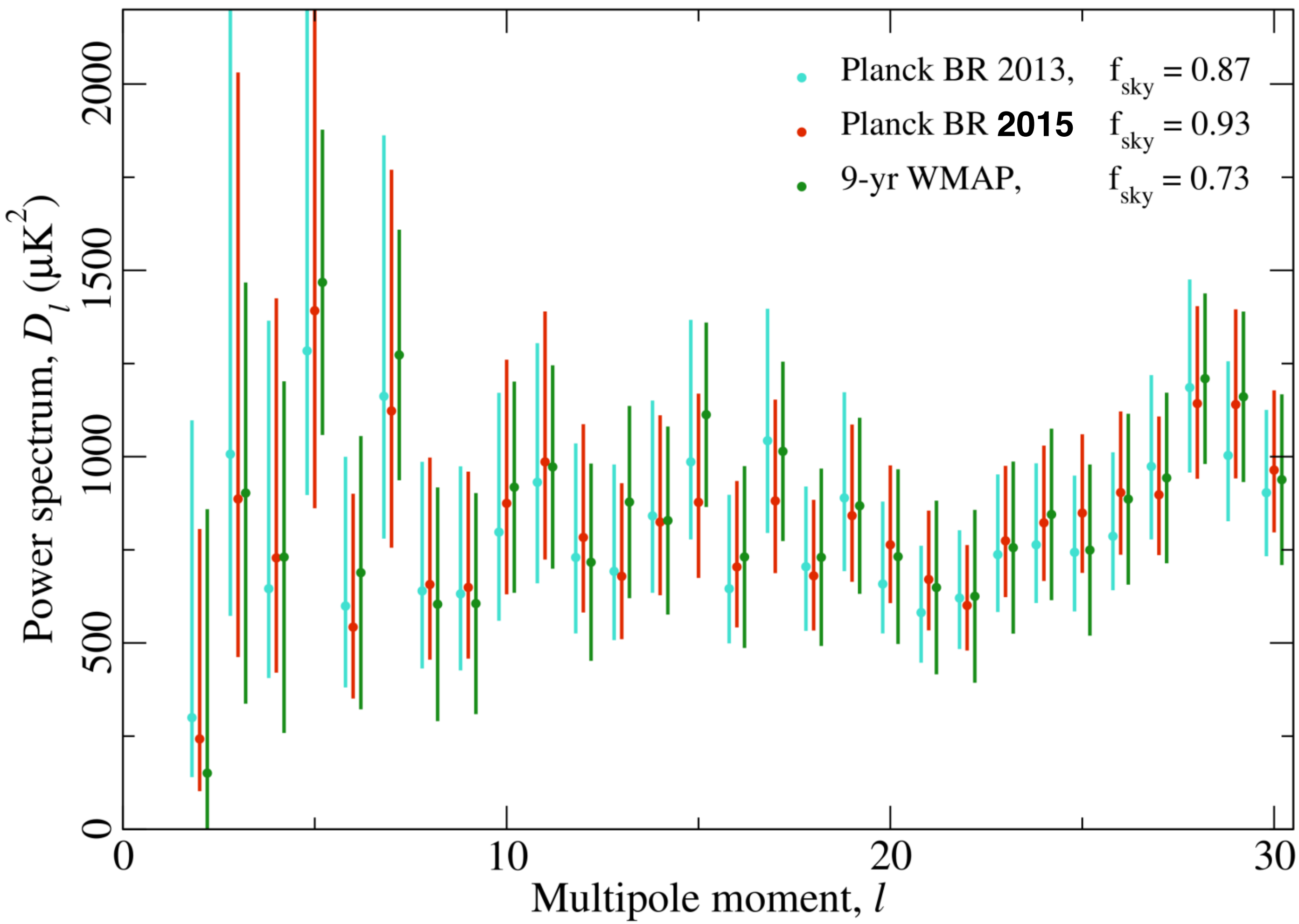


ANGULAR POWER SPECTRA

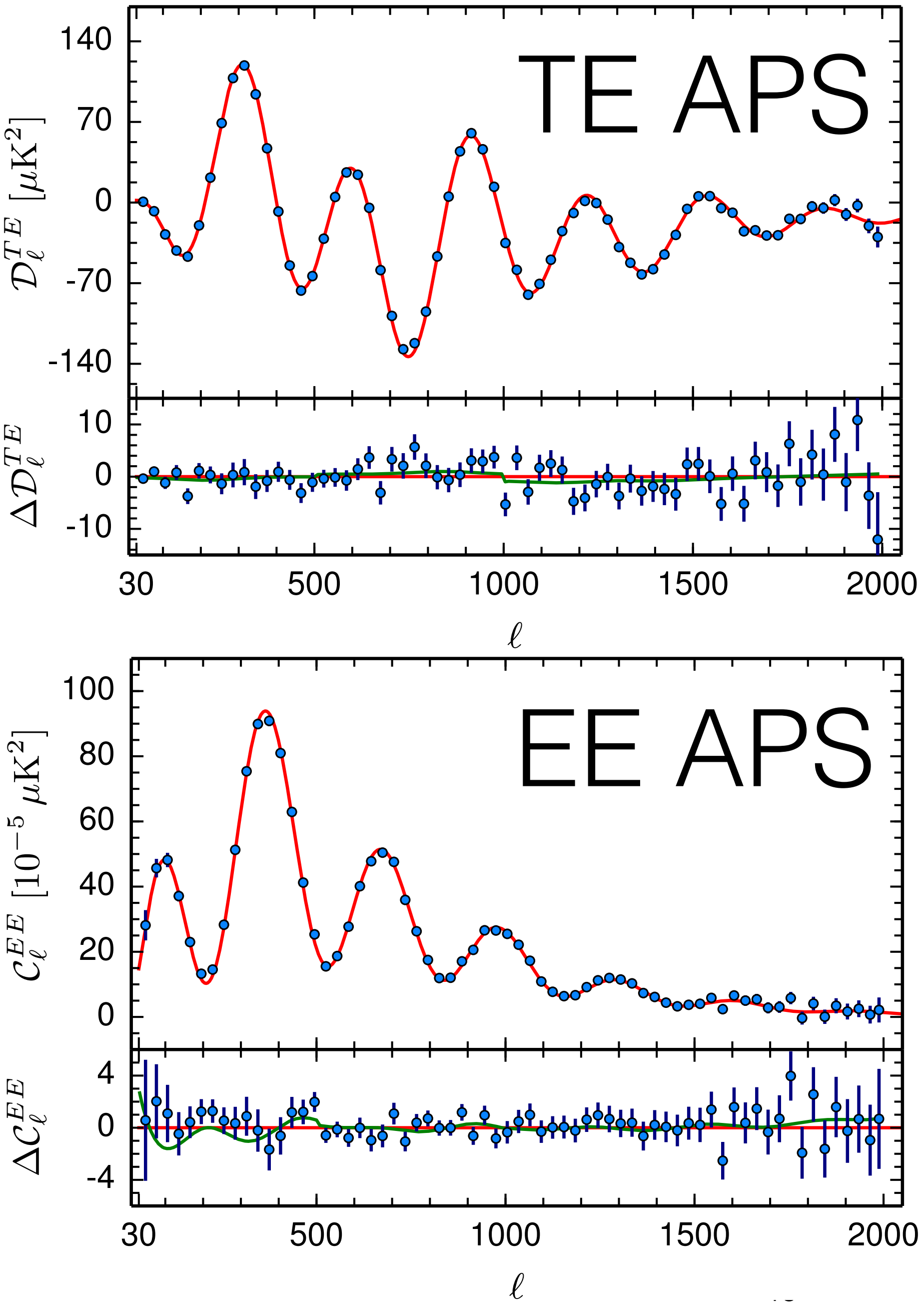

Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500


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

Low-l Commander temperature spectrum



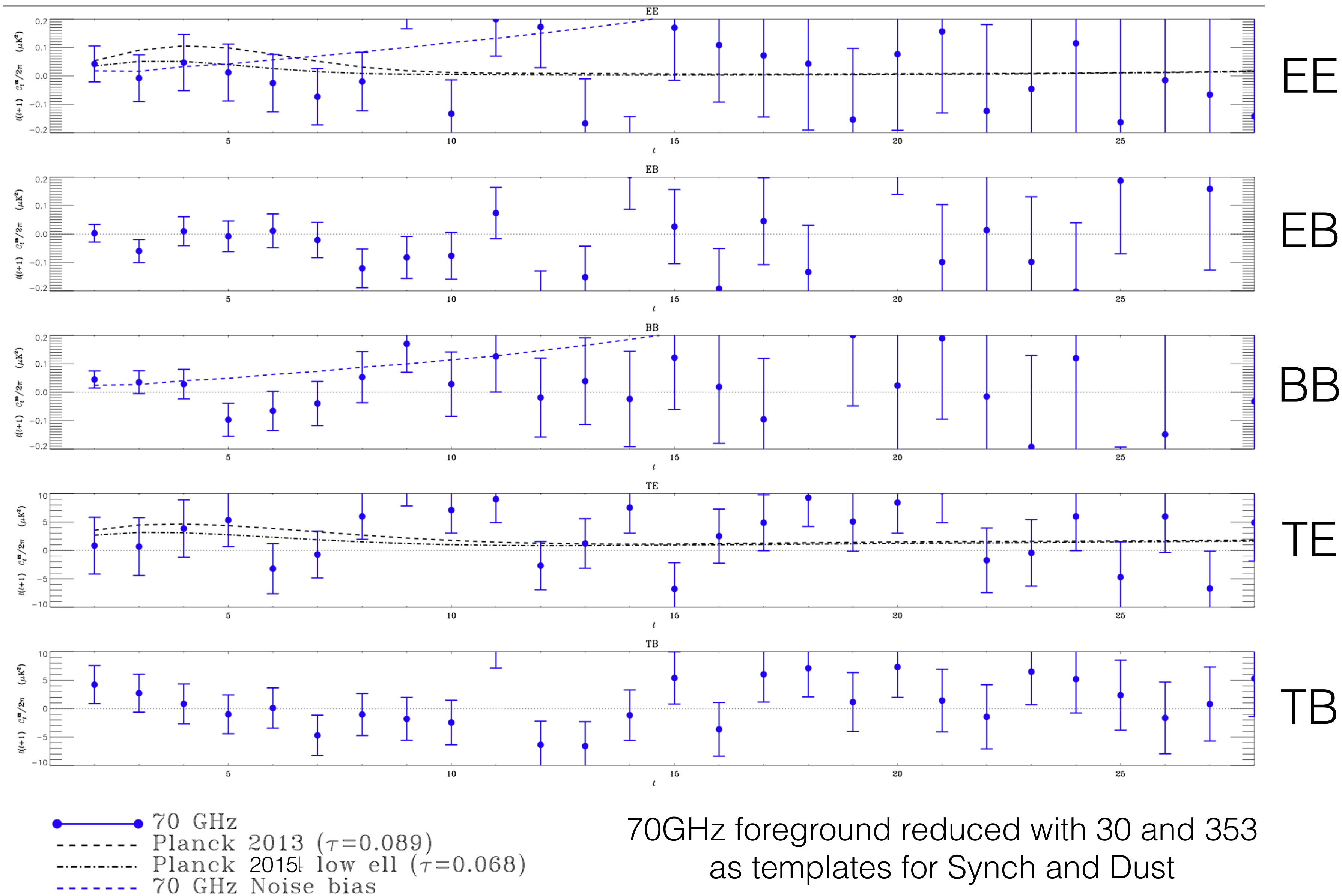
All TT spectra shown here are computed with the Blackwell-Rao estimator from temperature data alone. The low-l Planck 2015 TT spectrum is on average ~1.5% higher than the 2013 spectrum, primarily because of revised dipole calibration. Excellent agreement with WMAP



POL APS

Frequency-averaged TE (upper panel) and EE (lower panel) spectra (without fitting for T–P leakage). The theoretical TE and EE spectra plotted in the upper panel of each plot are computed from the best-fit model of Fig. 9. Residuals with respect to this theoretical model are shown in the lower panel in each plot. The error bars show ±1σ errors. The green lines in the lower panels show the best-fit temperature-to-polarization leakage model, fitted separately to the TE and EE spectra

Low-l polarized spectra



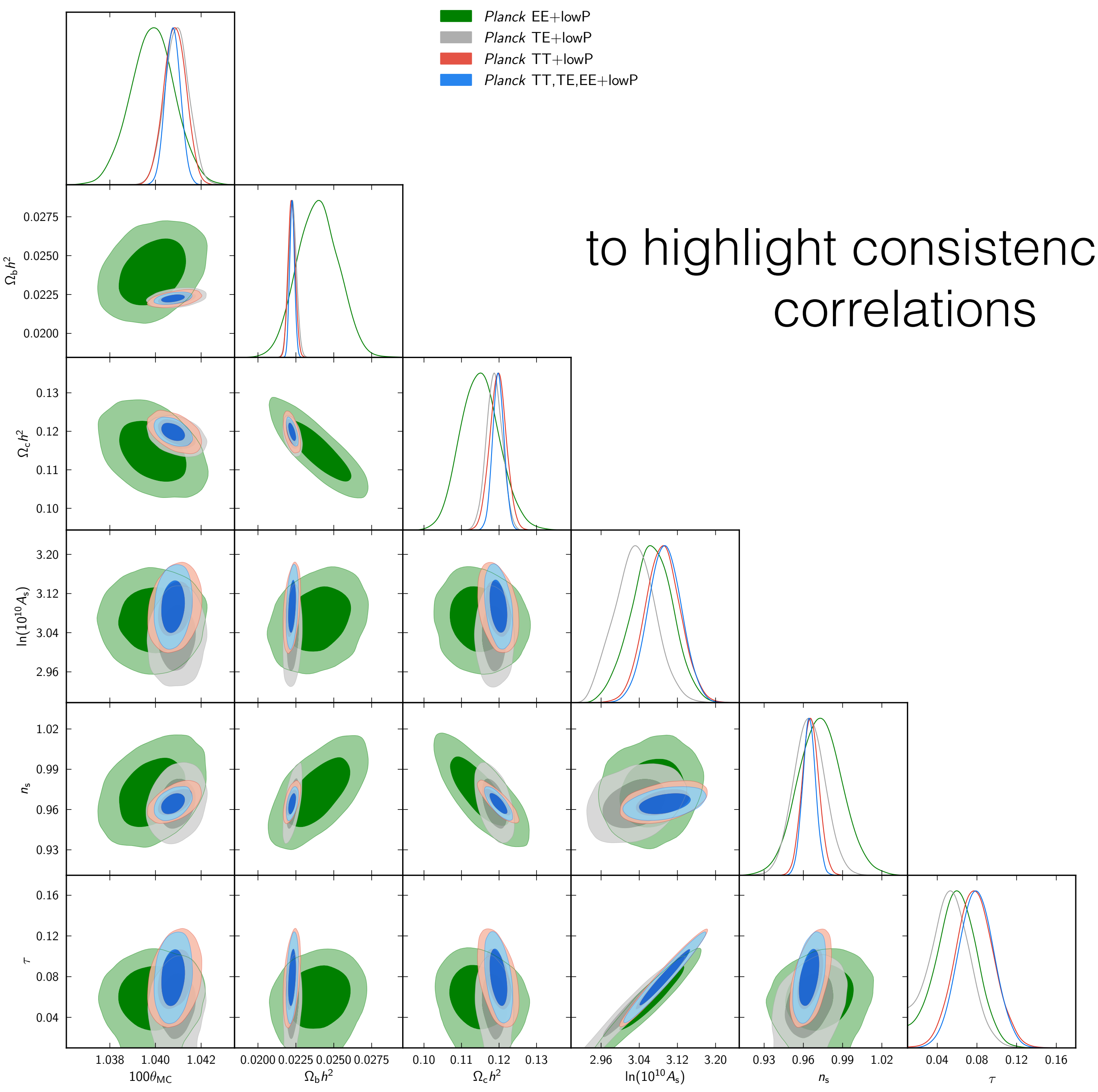
70GHz foreground reduced with 30 and 353 as templates for Synch and Dust

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



to highlight consistency and correlations

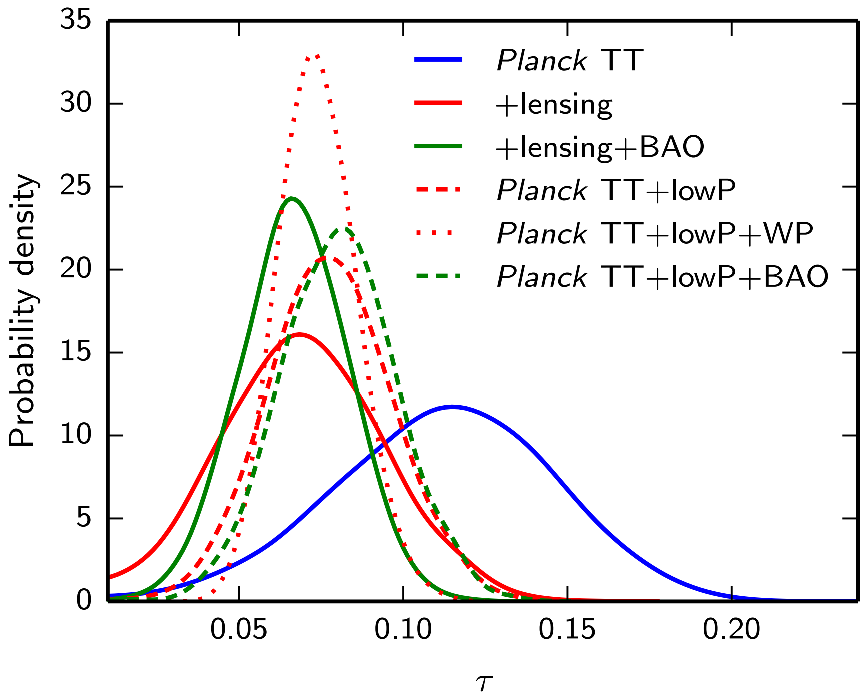
extended models

Table 5. Constraints on 1-parameter extensions to the base ΛCDM model for combinations of *Planck* power spectra, *Planck* lensing, and external data (BAO+JLA+H_0, denoted "ext"). Note that we quote 95 % limits here.

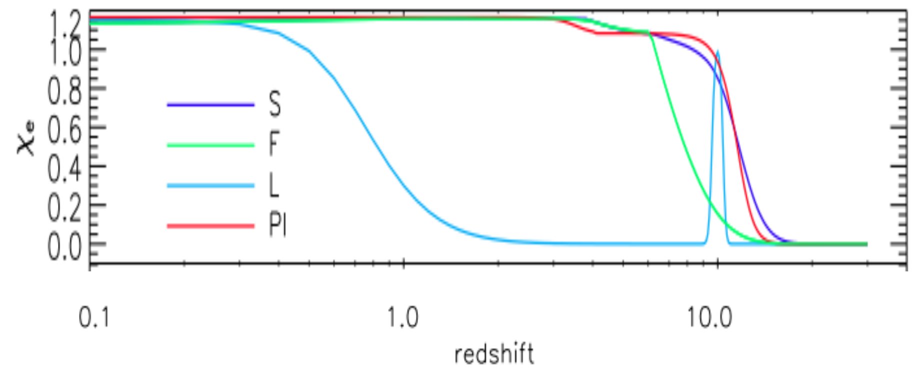
Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	$-0.040^{+0.038}_{-0.041}$	$-0.004^{+0.015}_{-0.015}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	< 0.492	< 0.589	< 0.194
$N_{\rm eff}$	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$
$Y_{\rm P}$	$0.252^{+0.041}_{-0.042}$	$0.251^{+0.040}_{-0.039}$	$0.251^{+0.035}_{-0.036}$	$0.250^{+0.026}_{-0.027}$	$0.247^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.003^{+0.015}_{-0.015}$	$-0.003^{+0.015}_{-0.014}$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.103	< 0.114	< 0.114	< 0.0987	< 0.112	< 0.113
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	$-1.55^{+0.58}_{-0.48}$	$-1.42^{+0.62}_{-0.56}$	$-1.019^{+0.075}_{-0.080}$

one additional cosmological parameter for each case

Re-ionization



First luminous sources in the Universe: cosmological reionization



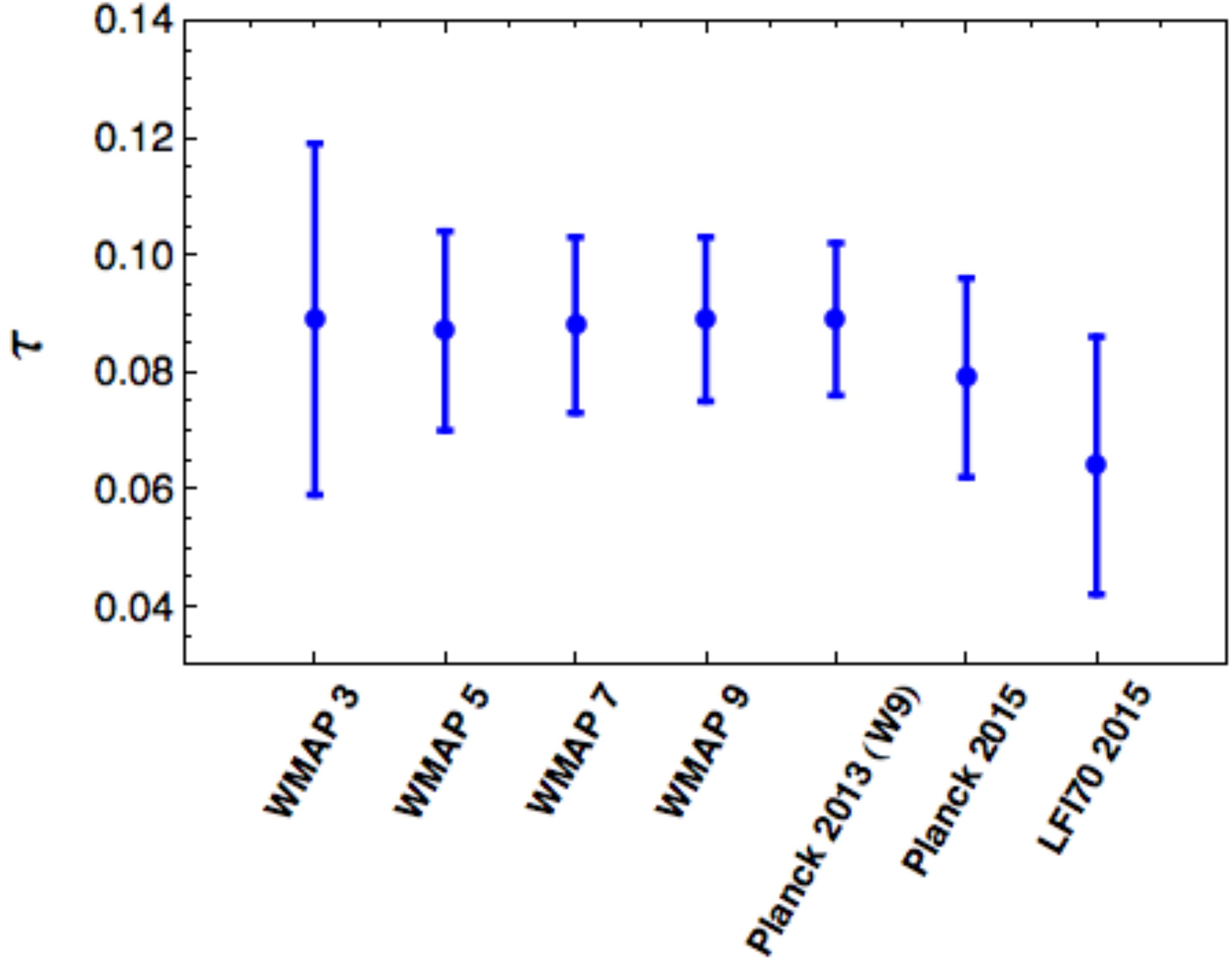
WP (WMAP 9) reanalysed with *Planck* dust emission maps

$$\tau = 0.066 \pm 0.0016 \quad z_{\rm re} = 8.8^{+1.7}_{-1.4} \quad (68\,\%{\rm CL}\,, \textit{Planck}\,{\rm TT} + {\rm lensing} + {\rm lowP})$$

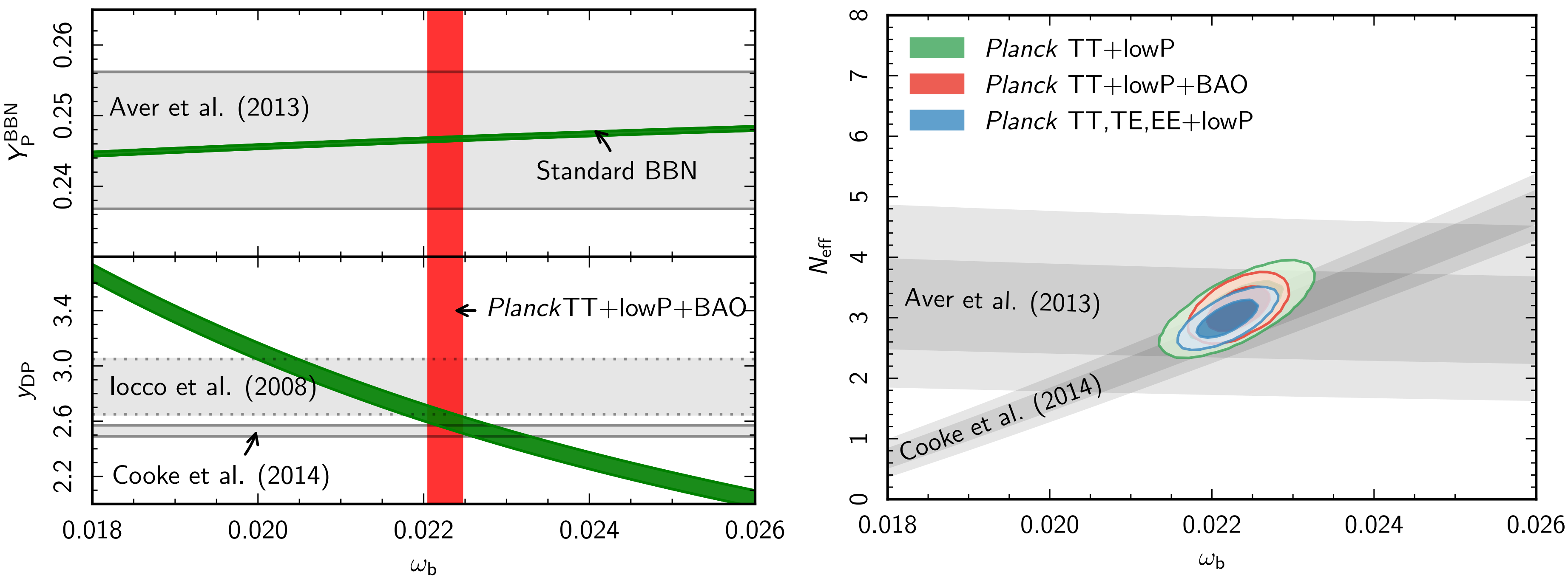
$$\tau = 0.074^{+0.011}_{-0.013} \quad z_{\rm re} = 9.6 \pm 1.1 \quad (68\,\%{\rm CL}\,, \textit{Planck}\,{\rm TT} + {\rm lowP} + {\rm WP})$$

More accurate CMB polarization measurements will allow reionization history reconstruction **"beyond the τ approximation"** with both "blind" methods" (e.g. principal component method, reconstruction of χ_e in z bins) and estimation (e.g. with MCMC methods) of physical / phenomenological reionization model parameters.

re-ionization vs time



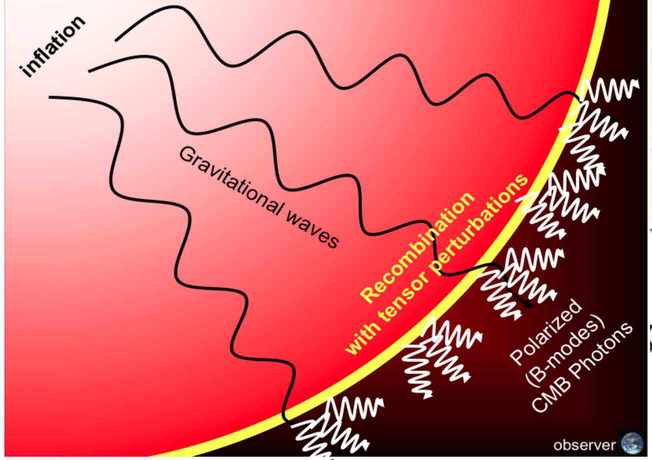
Primordial nucleosynthesis

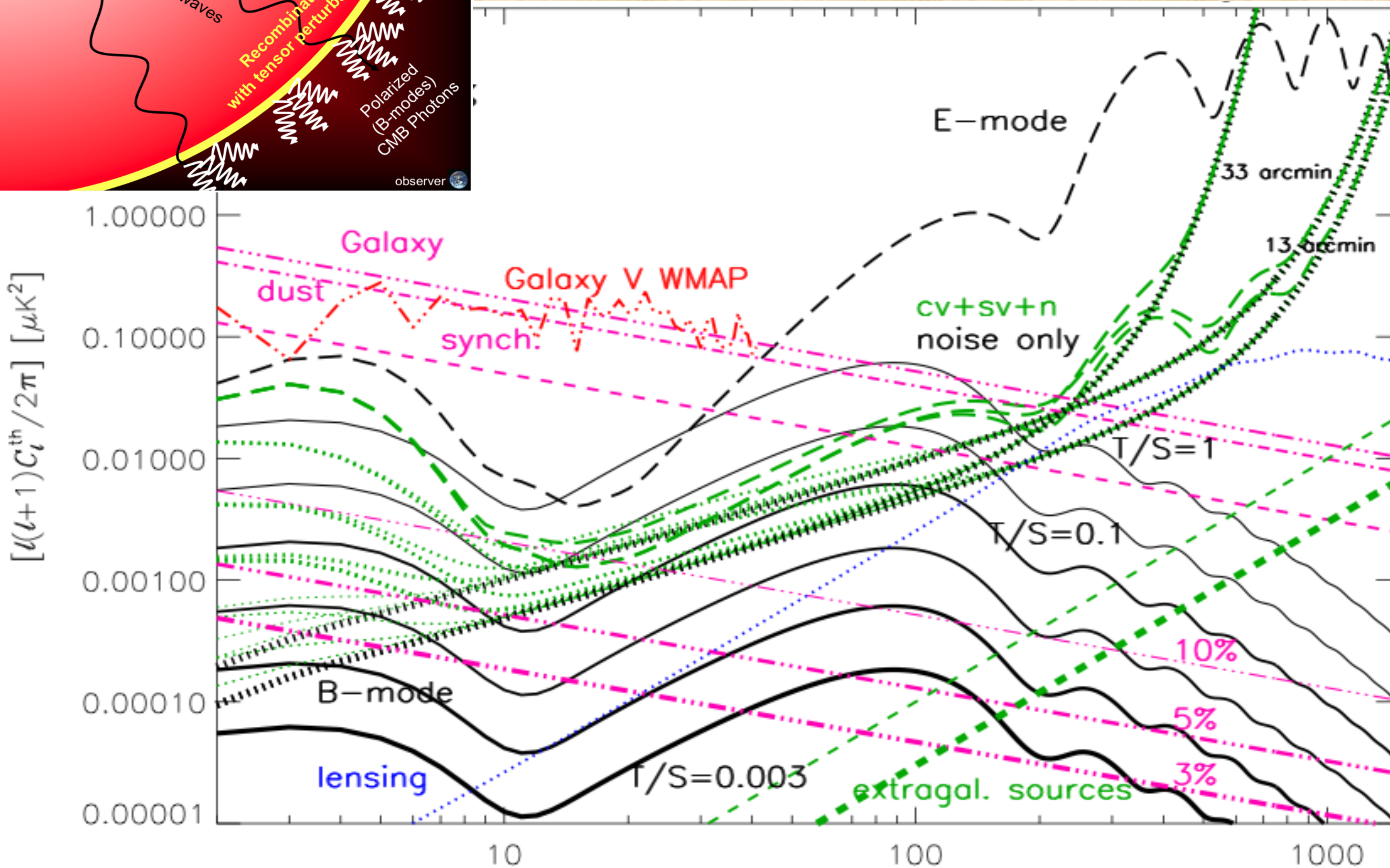


Consistent with measurements of the primordial abundances

COSMOLOGICAL PARAMETERS: INFLATION AND B MODES

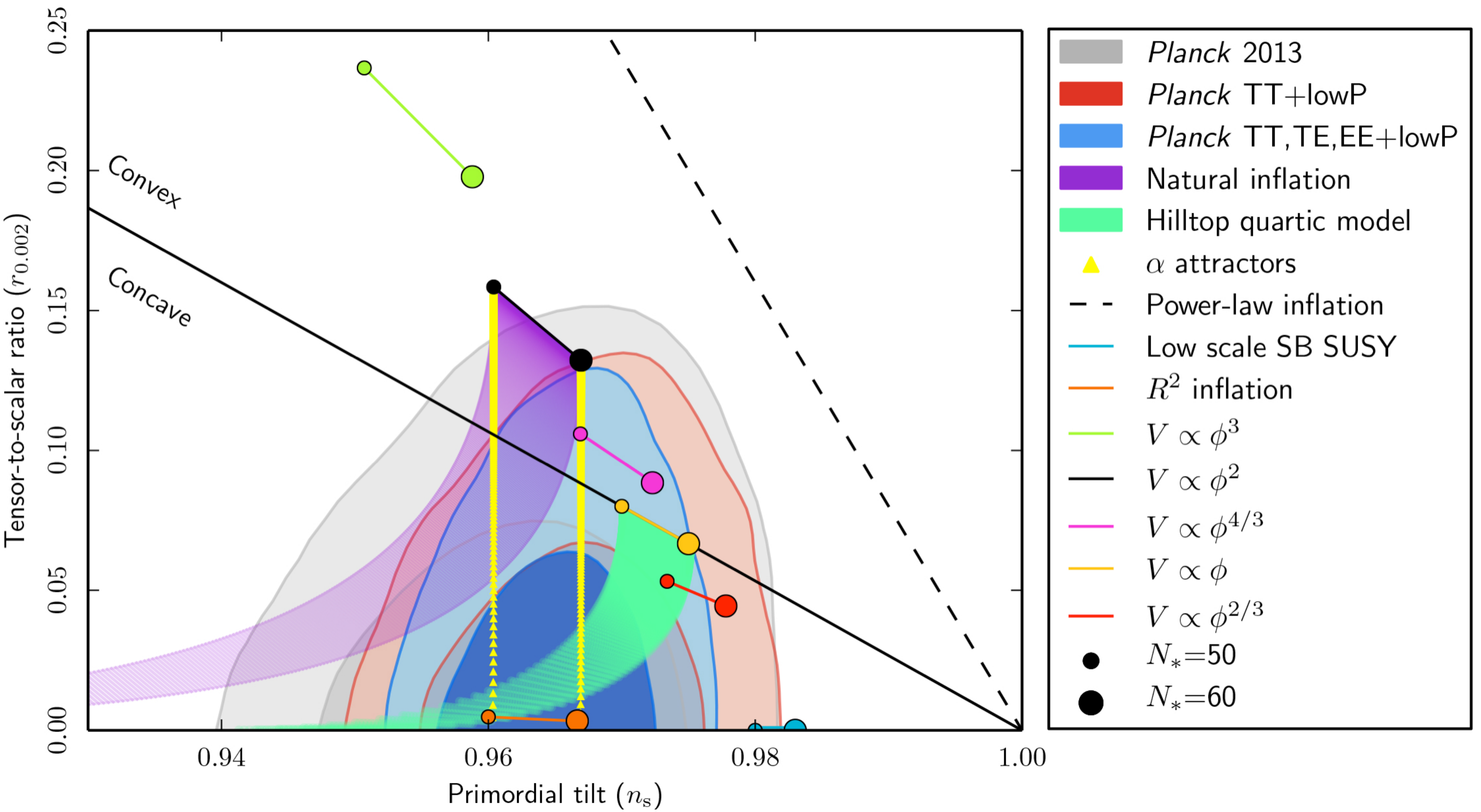
CMB polarization with *Planck*
E & B – 30% binning, f_{sky}=74%



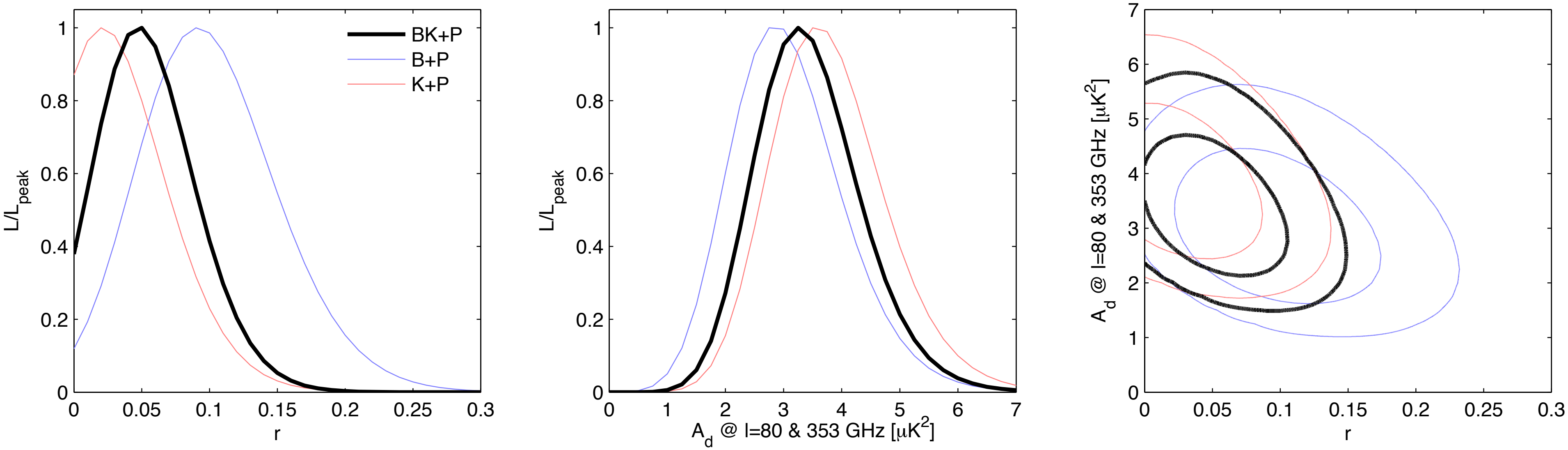


B-mode: "smoking gun of inflation" energy scale

Scalar spectral index and tensors fluctuations



Joint Planck/Bicep2/Keck analysis

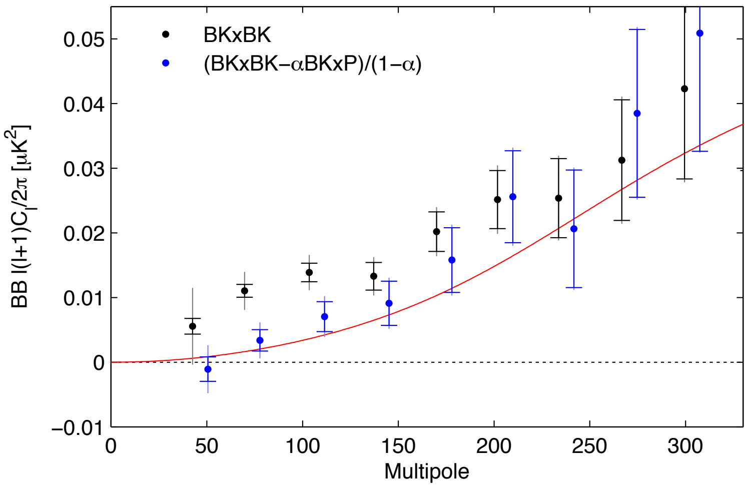


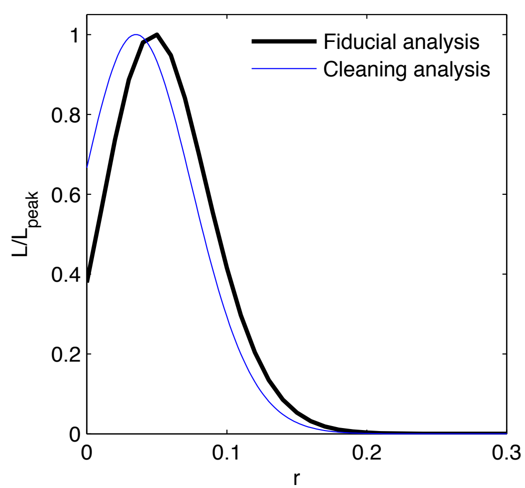
Joint fit of a lensend ΛCDM+r+dust model to the cross-spectra between the BICEP2/Keck maps and the polarized bands of Planck:

$$r < 0.12$$

arXiv:1502.00612

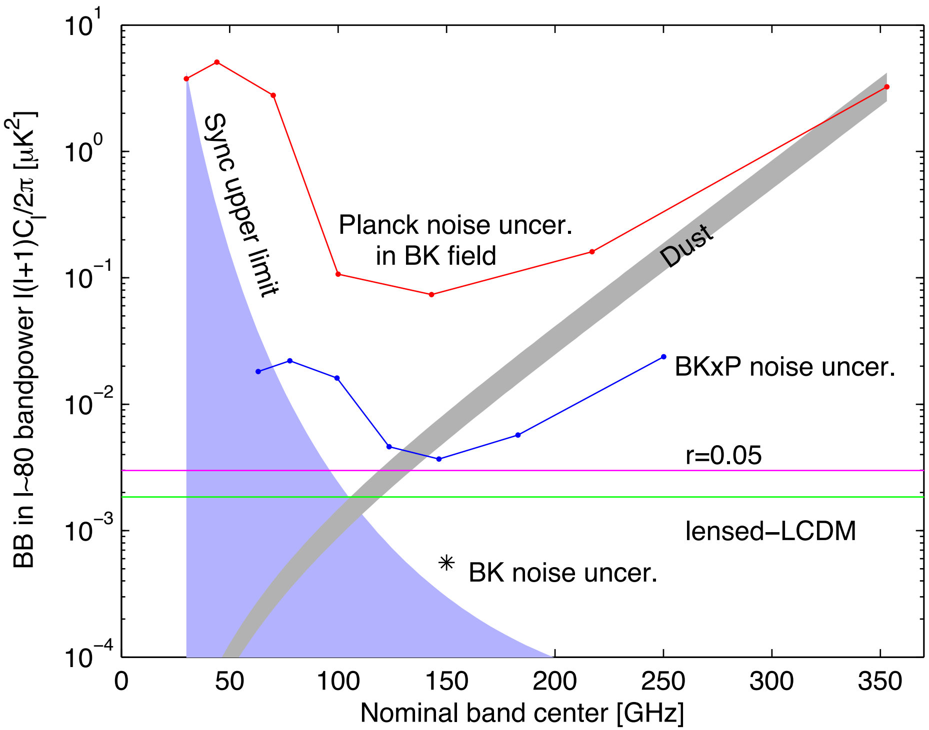
Bicep2 and Planck





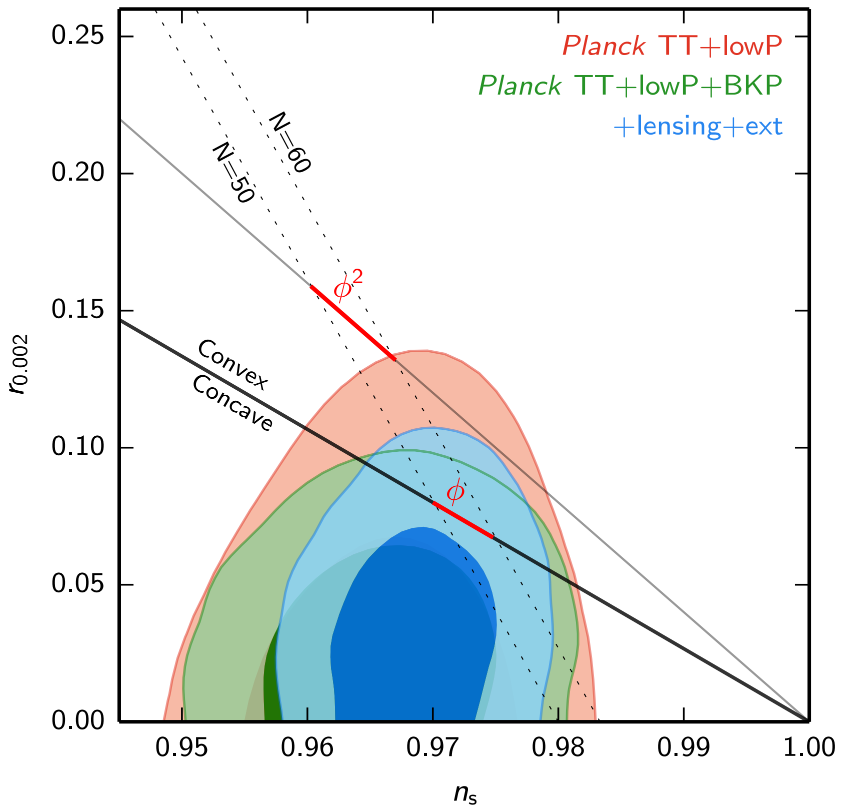
Upper: BB spectrum of the BICEP2/Keck maps before and after subtraction of the dust contribution, estimated from the cross-spectrum with Planck 353 GHz. The error bars are the standard deviations of simulations, which, in the latter case, have been scaled and combined in the same way. The inner error bars are from lensed-ΛCDM +noise simulations as in the previous plots, while the outer error bars are from the lensed-ΛCDM+noise+dust simulations. Lower: constraint on r derived from the cleaned spectrum compared to the fiducial analysis shown in previous Figure.

Bicep2 and Planck



Expectation values, and uncertainties thereon, for the ell ~ 80 BB bandpower in the BICEP2/Keck field. The green and magenta lines correspond to the expected signal power of lensed-ΛCDM and r = 0.05. Since CMB units are used, the levels corresponding to these are flat with frequency. The grey band shows the best fit dust model (see Section III B) and the blue shaded region shows the allowed region for synchrotron (see Sec. III C). The BICEP2/Keck noise uncertainty is shown as a single starred point, and the noise uncertainties of the Planck single-frequency spectra evaluated in the BICEP2/Keck field are shown in red. The blue points show the noise uncertainty of the cross-spectra taken between BICEP2/Keck and, from left to right, Planck 30, 44, 70, 100, 143, 217 & 353 GHz, and plotted at horizontal positions such that they can be compared vertically with the dust and sync curves

Scalar spectral index and tensors fluctuations

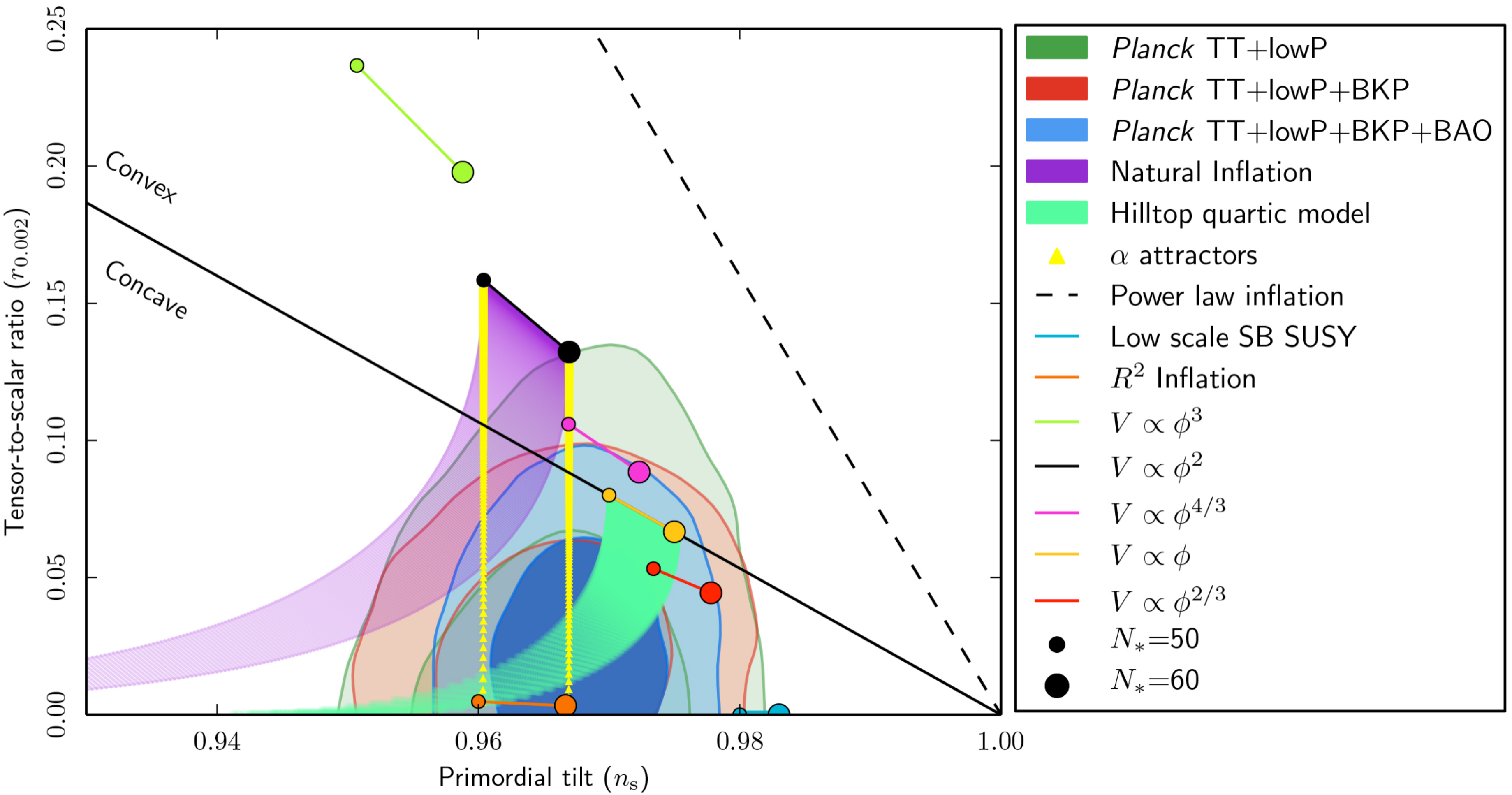


Planck TT + lowP
$r_{0.002} < 0.10$

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

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

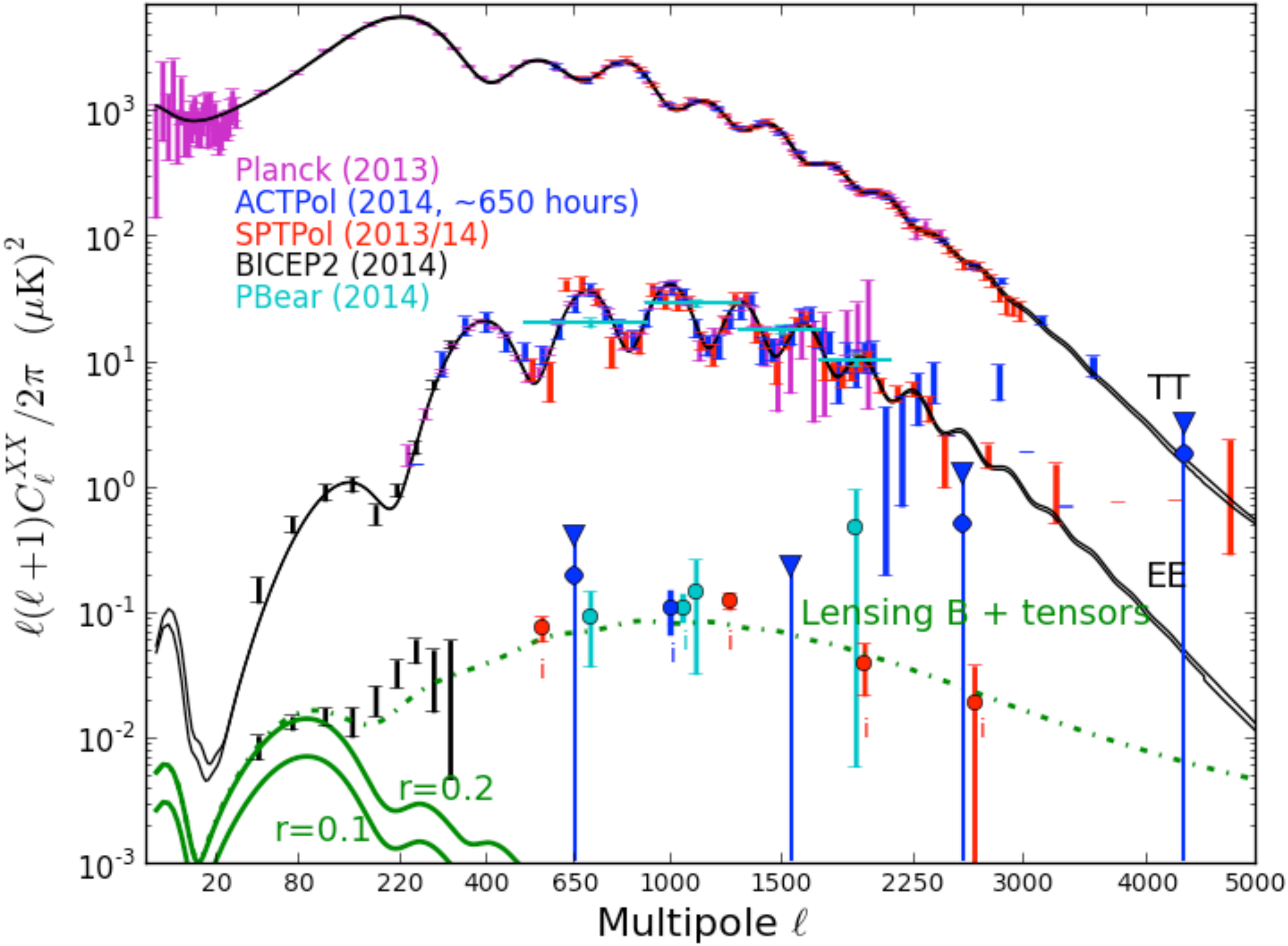
Scalar spectral index and tensors fluctuations



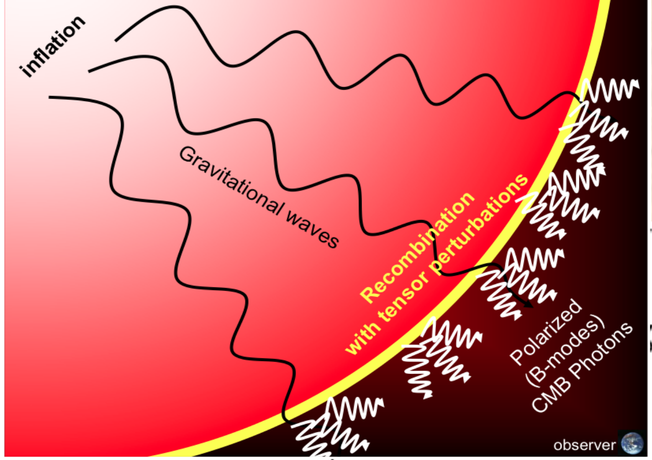
Conclusions

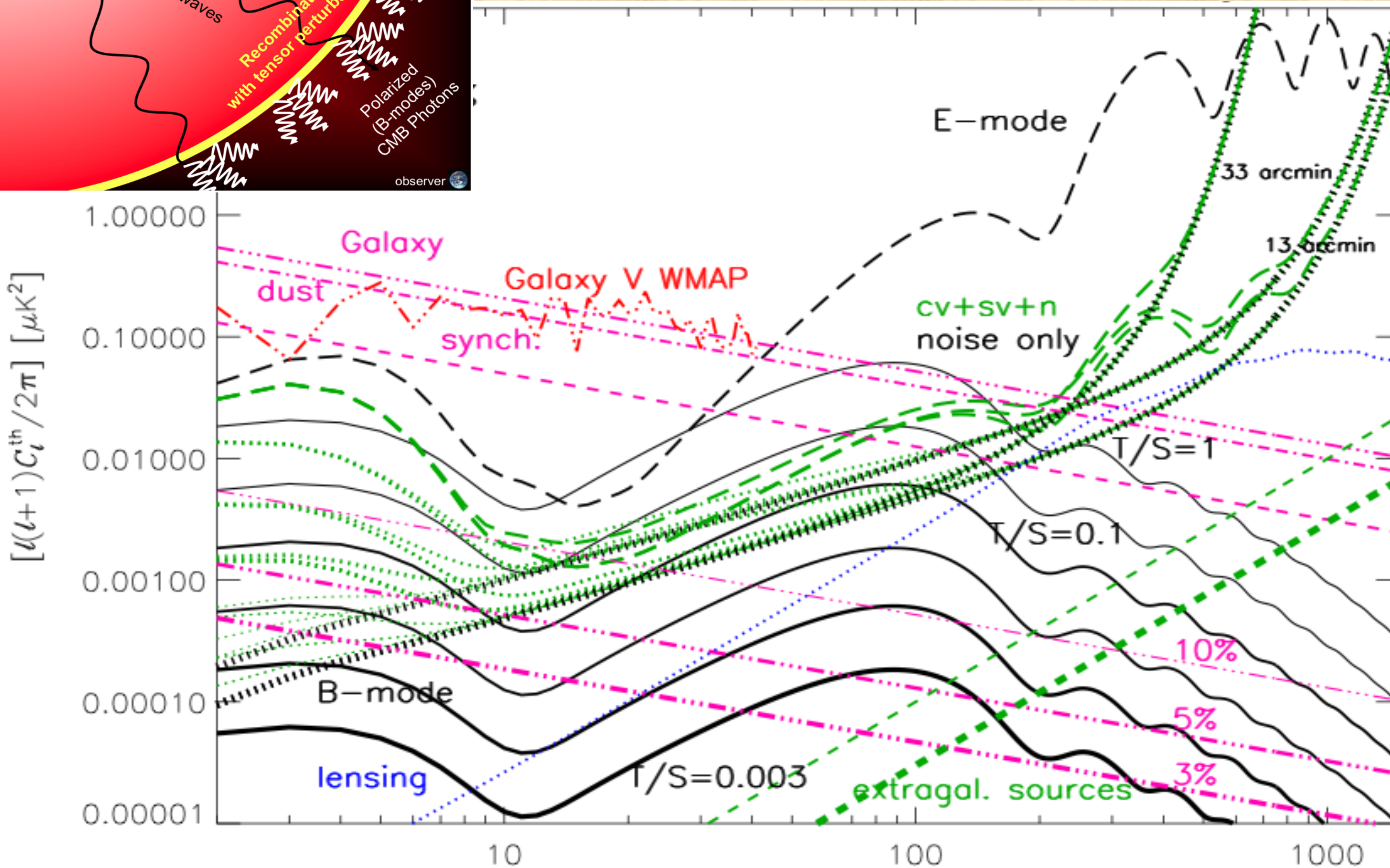
- Planck 2015 data products are built from the full mission temperature and polarization observations
- Many improvements wrt to 2013 (e.g. improved calibration)
- LCDM is in very good shape
- $\tau \sim 0.06$ driven by LFI low ell is in agreement with astrophysical measurements. The re-ionization history is compatible with non-extreme models of galaxies evolution and star formation.
- Planck can constrain neutrino masses mainly thanks to the lensing of the power spectrum. PlanckTT+lowP+BAO gives $\Sigma m_\nu < 0.23$ eV
- Planck alone is already better or at the same level as KATRIN!
- Planck is compatible with 3 neutrino families; $N_{eff} = 4$ is excluded at between 3 and 5 sigma, depending on the dataset
- Consistent with standard BBN
- Neutrino perturbations consistent with free-streaming nu's
- No evidence of tensor modes, but still plenty of room for them!
- ϕ^2 and natural inflation are in trouble

State of the art - end 2014



CMB polarization with *Planck*
E & B – 30% binning, f_{sky}=74%





B-mode: "smoking gun of inflation" energy scale

The Future

1. From now on foregrounds are the name of the game on top of systematics
2. We have to worry about dust but not to underestimate sync, on the contrary
3. Technology: near term 1,000s bolometers, then 10,000s
4. "Bets" on r<0.01 (or detection) from "ground" and "balloons"
5. Sum of neutrino <0.06 eV
6. New results from accelerators, tests on GR, LSS and "cross correlation"
7. CMB satellites: WELCOME, BUT HURRY UP
8. Need "smart" new theories

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