

Cosmology and fundamental physics from Planck and other CMB probes

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Astrophysical Probes of Fundamental Physics

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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', $\Delta T/T_{\text{CMB}} \sim 2 \times 10^{-6}$
- 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
- Third and final (legacy) release in 2016



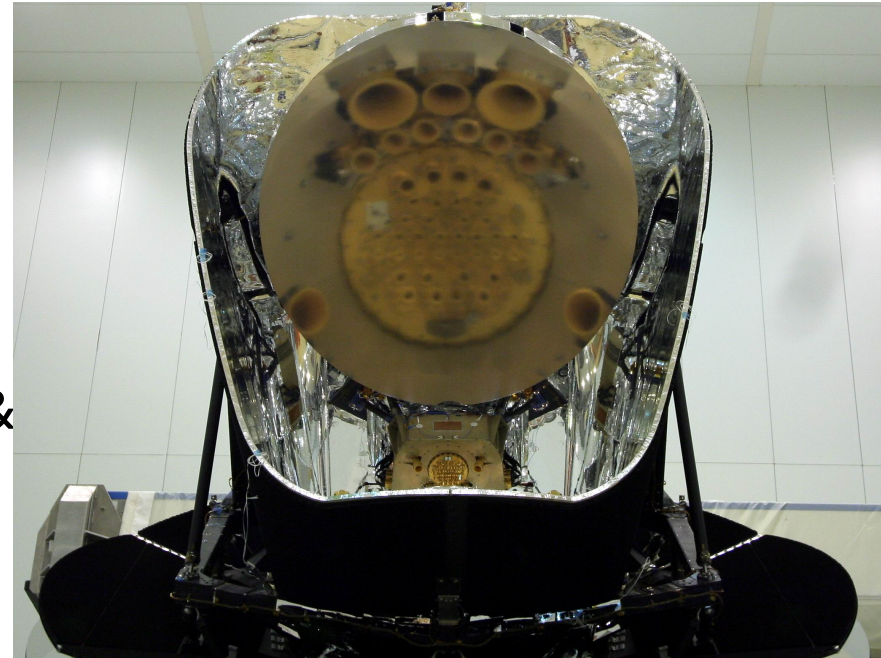
planck



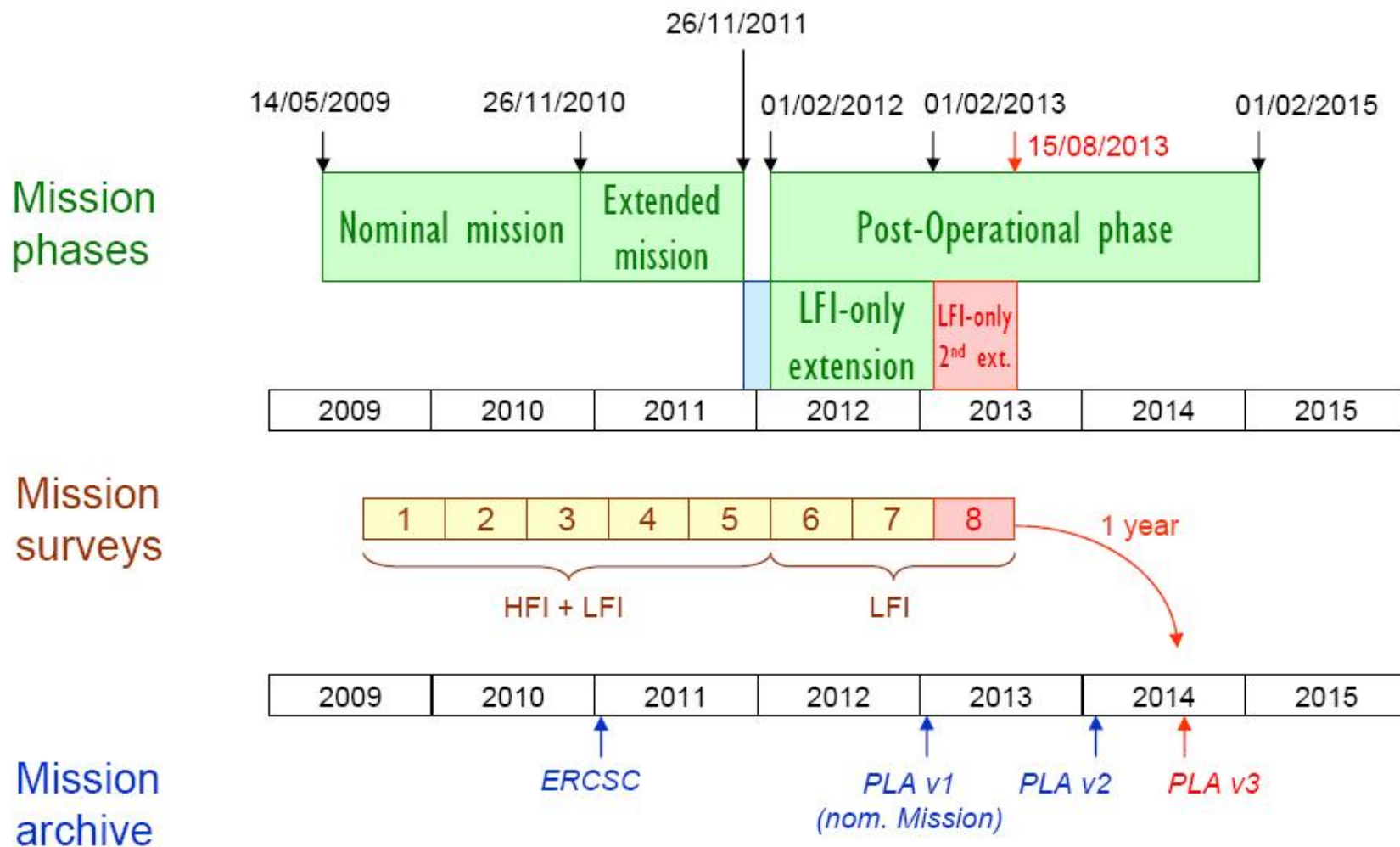
HFI PLANCK

Planck history in short

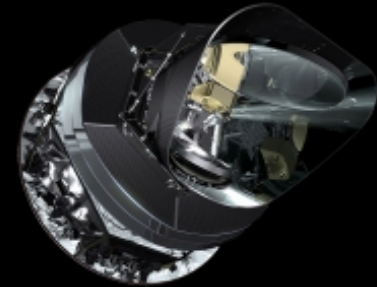
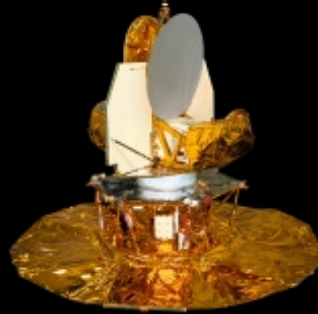
- 1993 – COBRAS & SAMBA proposals
- 1996 – Selection of COBRAS/SAMBA, then named Planck
- 1999 – LFI and HFI consortia are formed
- [...] Lots of Instrument development & tests
- 2009 – Planck is launched
- Jan. 2012 – HFI End of life
- Mar. 2013 – First cosmological data release
- Oct. 2013 – LFI End of life
- Feb 2015 – Second cosmological data release
- 2016 – Third cosmological data release



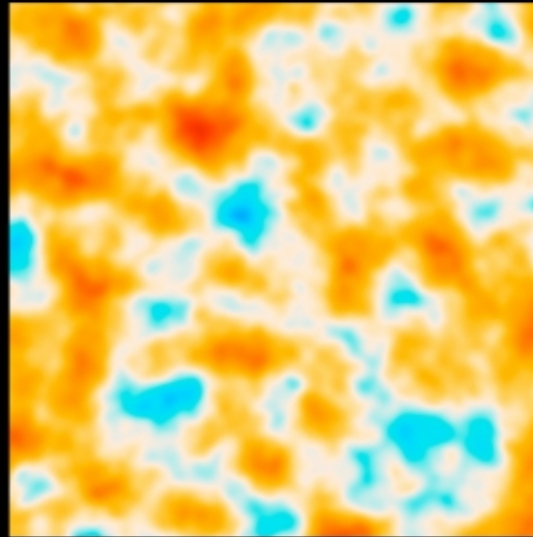
Planck's operational timeline



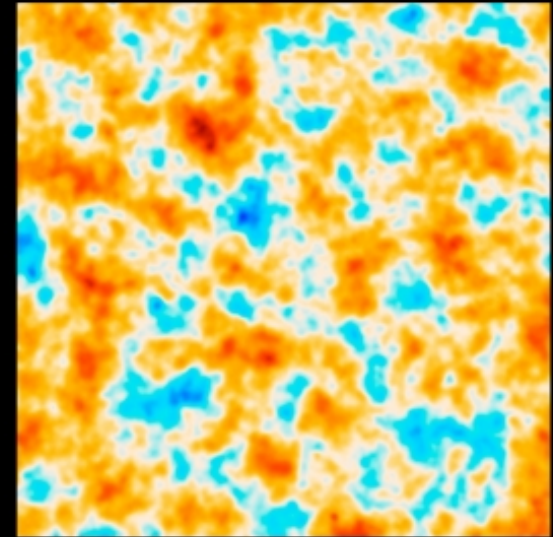
Comparison with forerunners



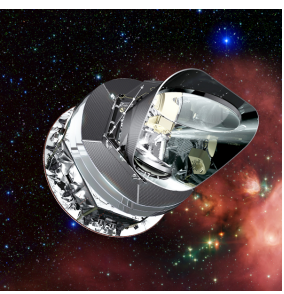
COBE



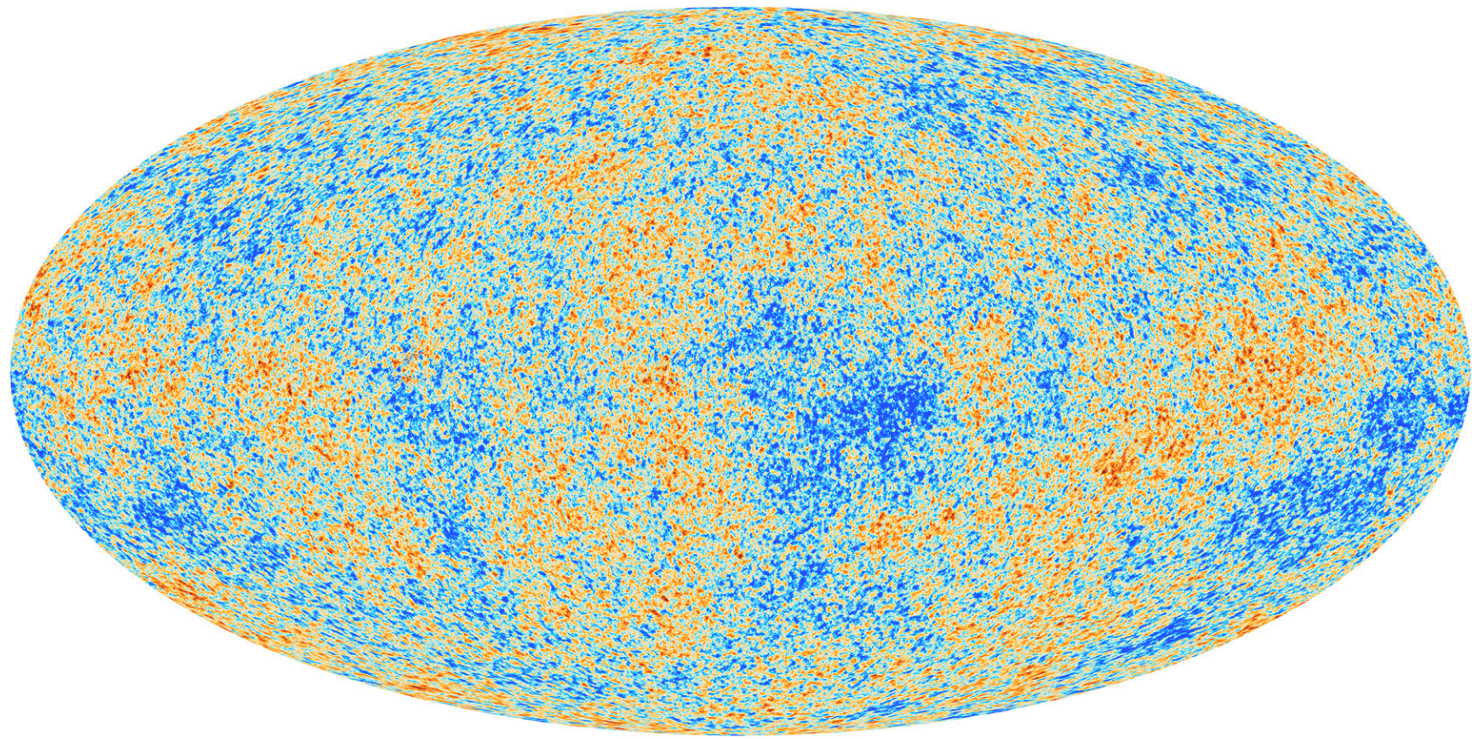
WMAP



Planck

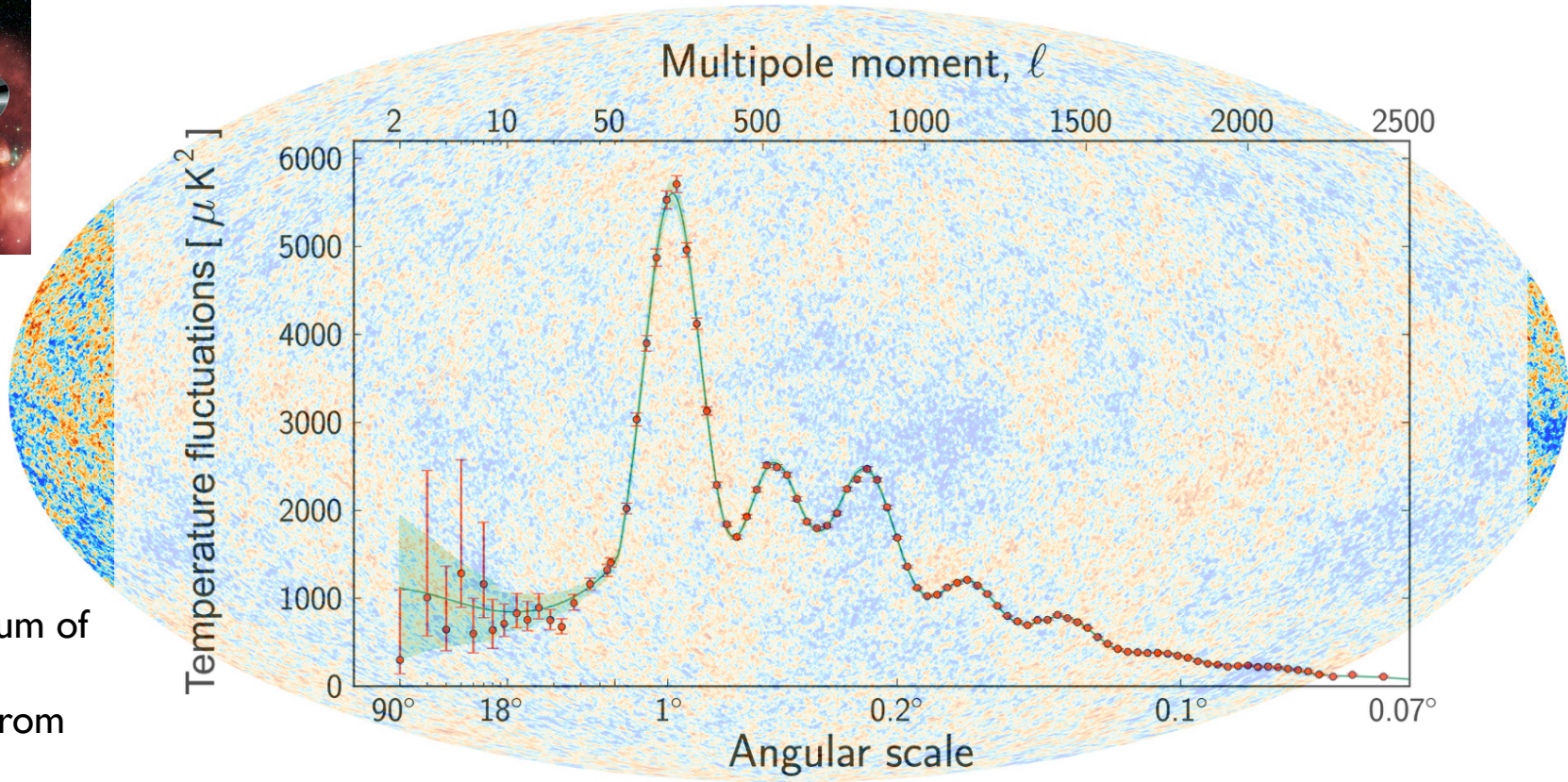
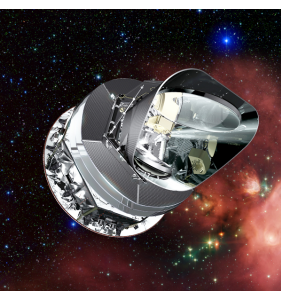


Full sky temperature map from Planck (2013)



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 $\sim 400,000$ years old.

Its tiny ($\sim 10^{-5}$) 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:

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

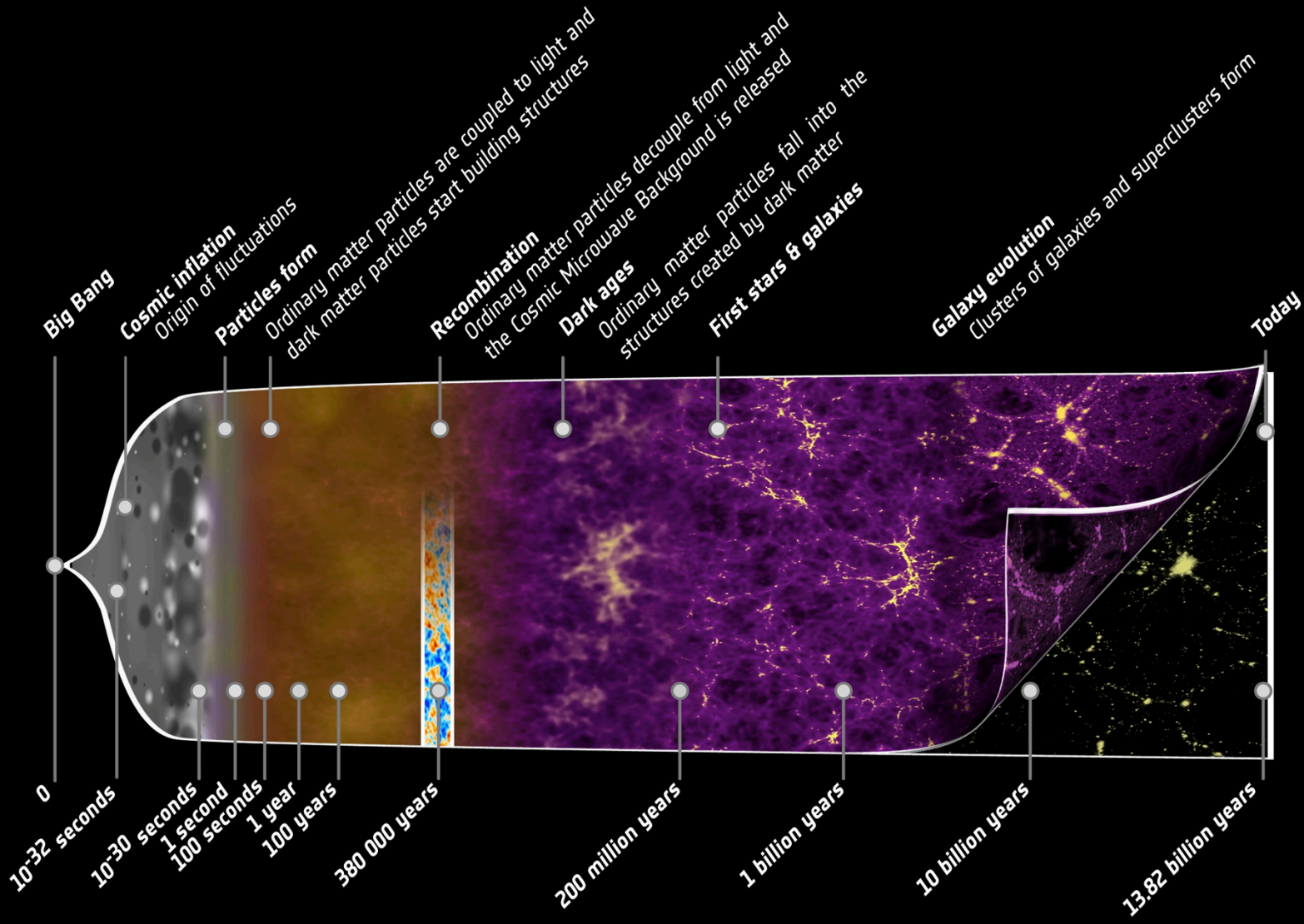
$$\langle a_{lm} a_{l'm'}^* \rangle = \delta_{ll'} \delta_{mm'} C_l$$



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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 hi-res maps of the CMB sky in T and pol
- Four high-pass filtered maps of the CMB sky in pol
- A low-res CMB T map
- 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



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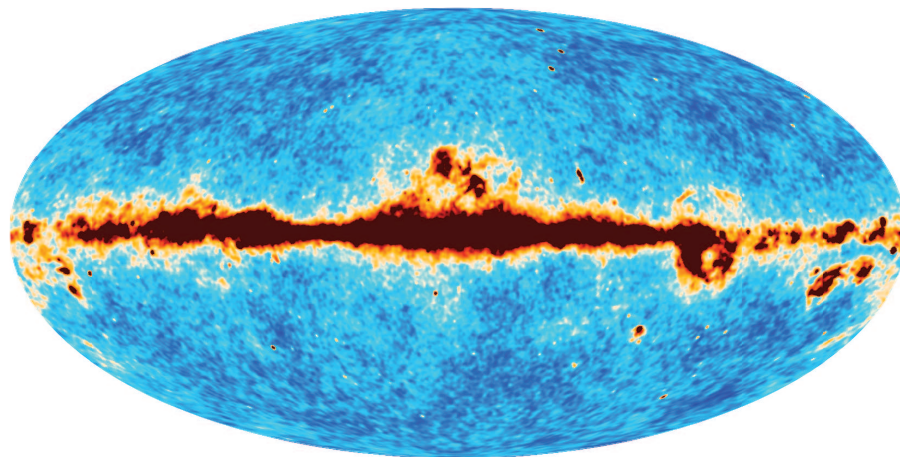
SINGLE FREQUENCY MAPS



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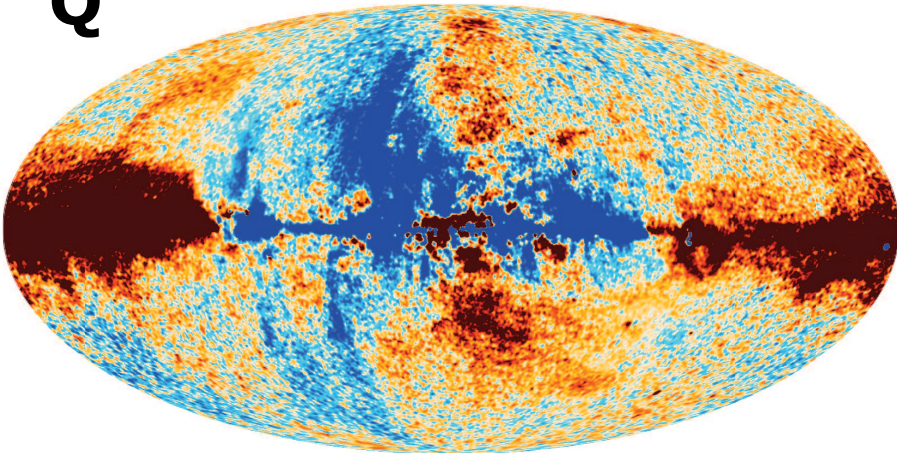
30 GHz



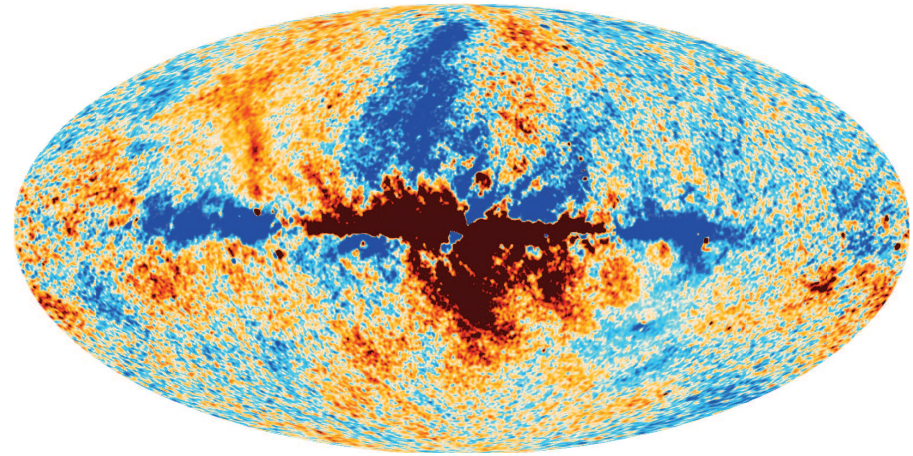
T



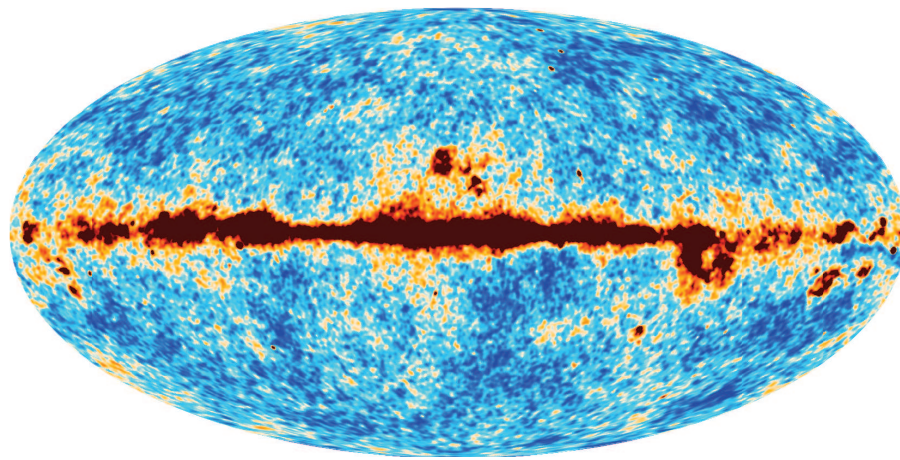
Q



U



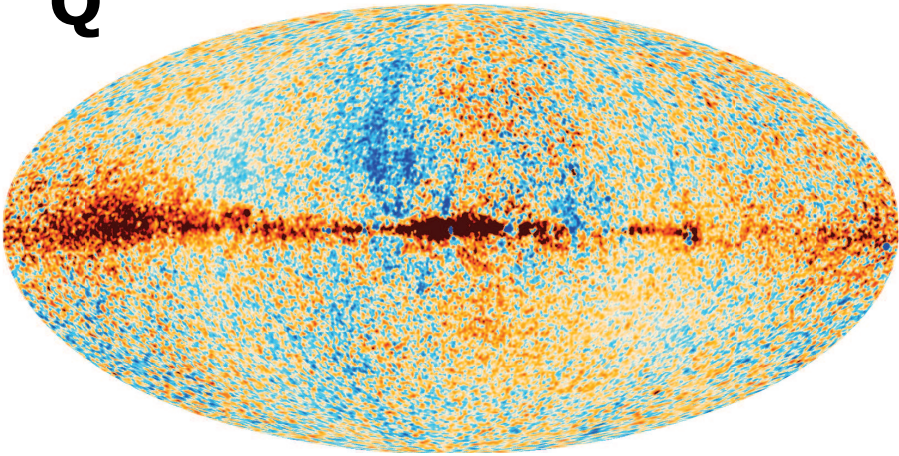
44 GHz



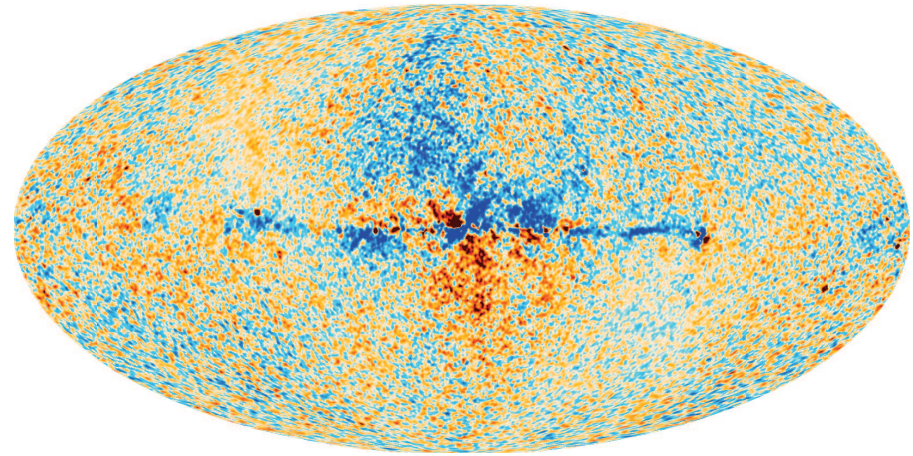
T



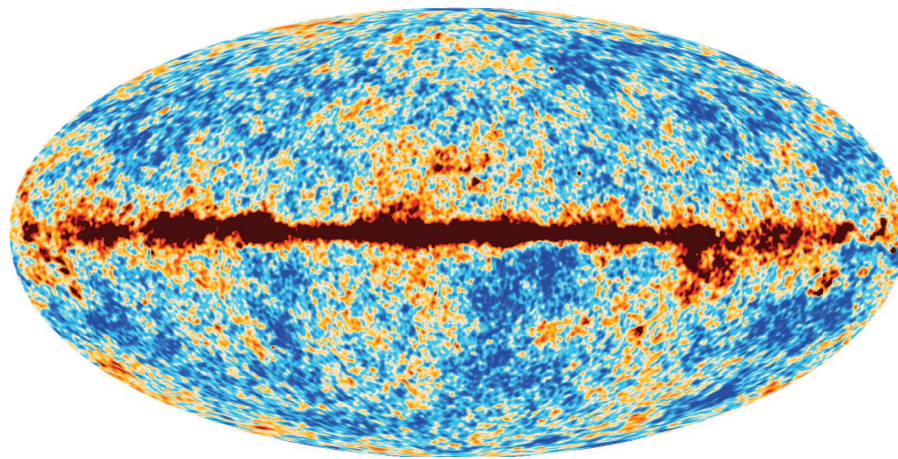
Q



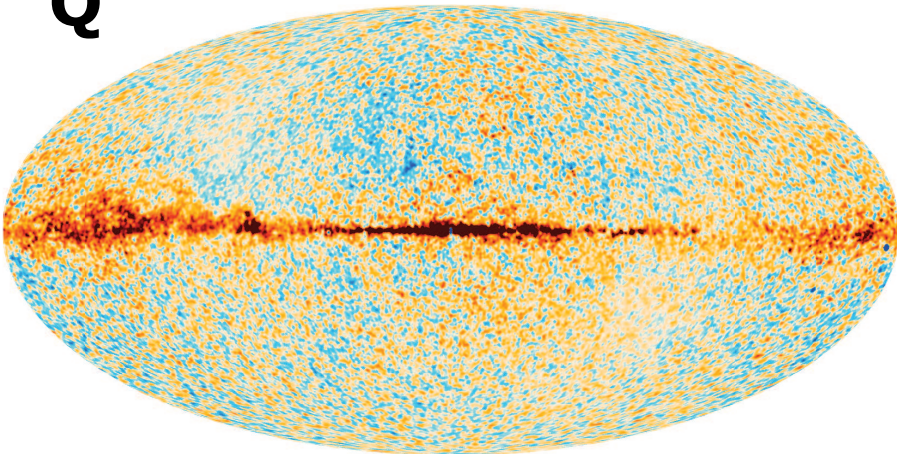
U



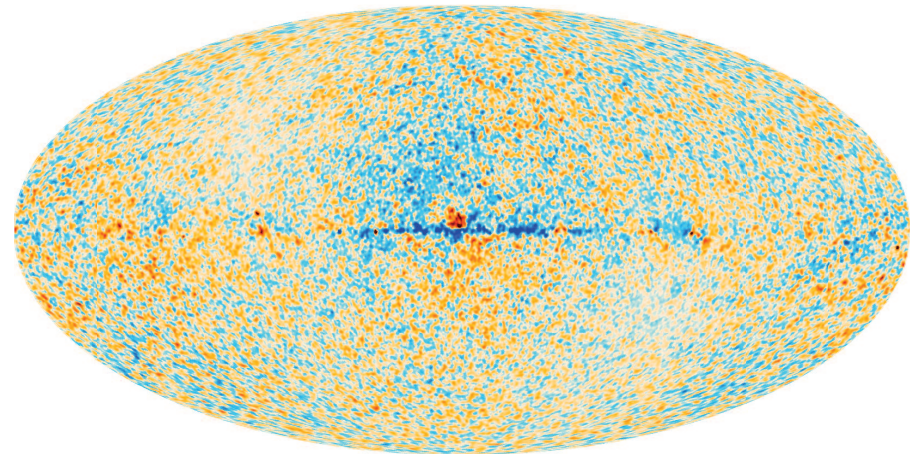
70 GHz



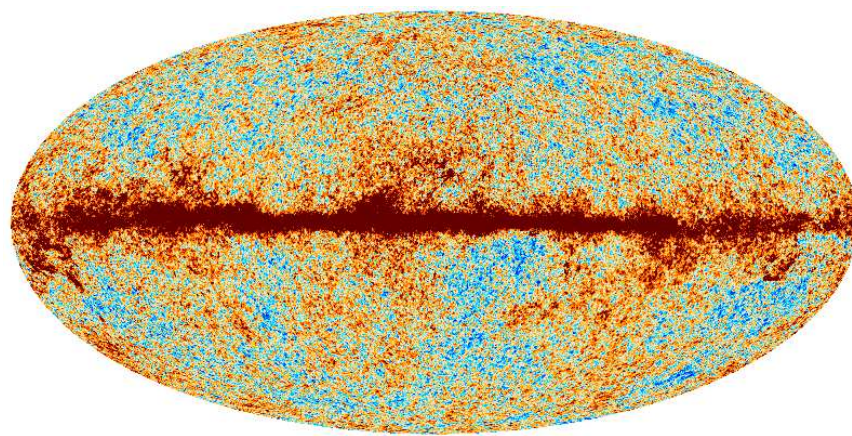
Q



U

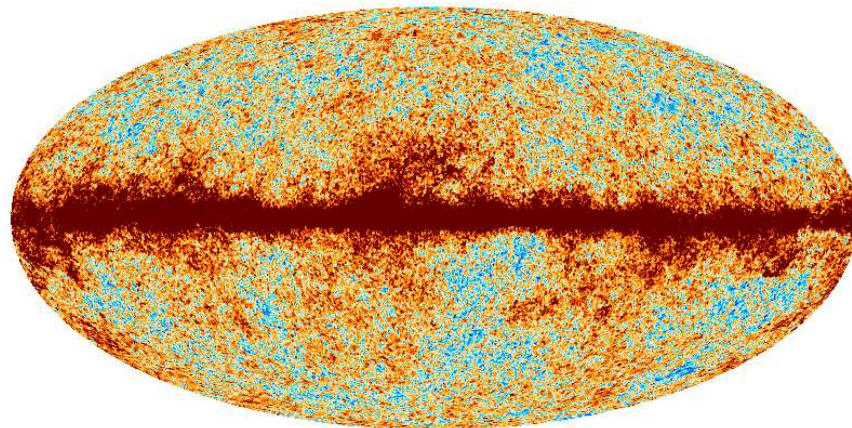


Temperature maps for 100, 143, 217 GHz



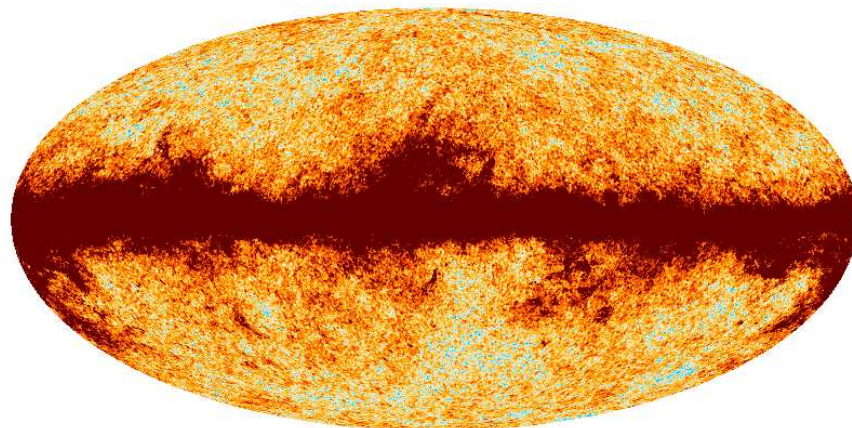
100 GHz

-300 300 μK_{CMB}



143 GHz

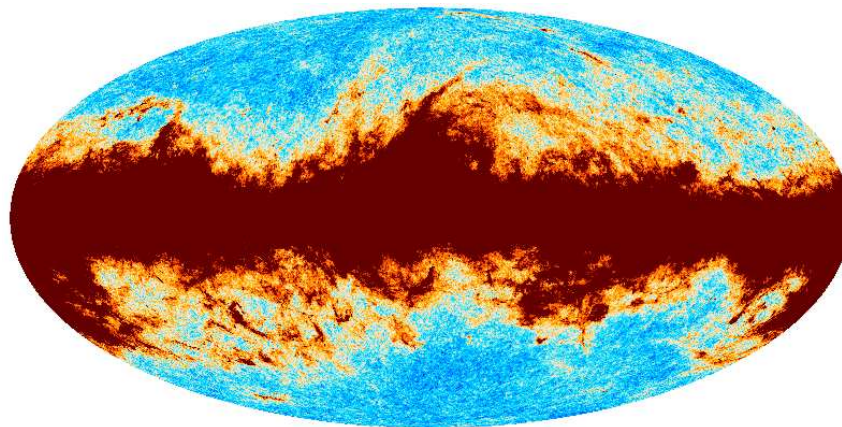
-300 300 μK_{CMB}



217 GHz

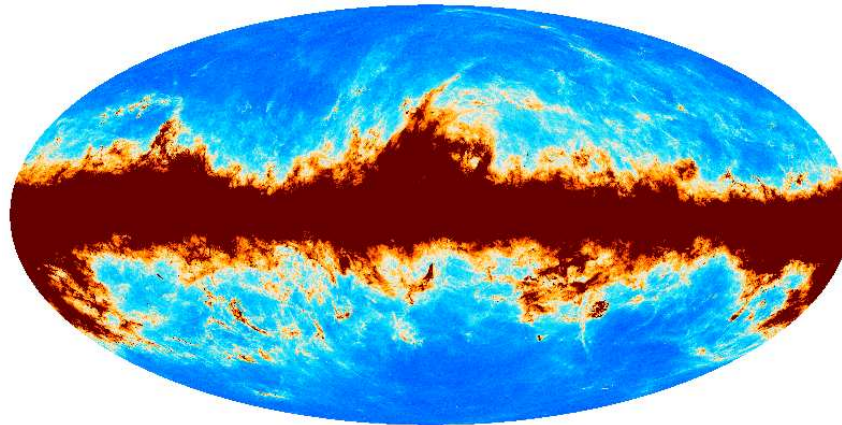
-500 500 μK_{CMB}

Temperature
maps for 353,
545, 857 GHz



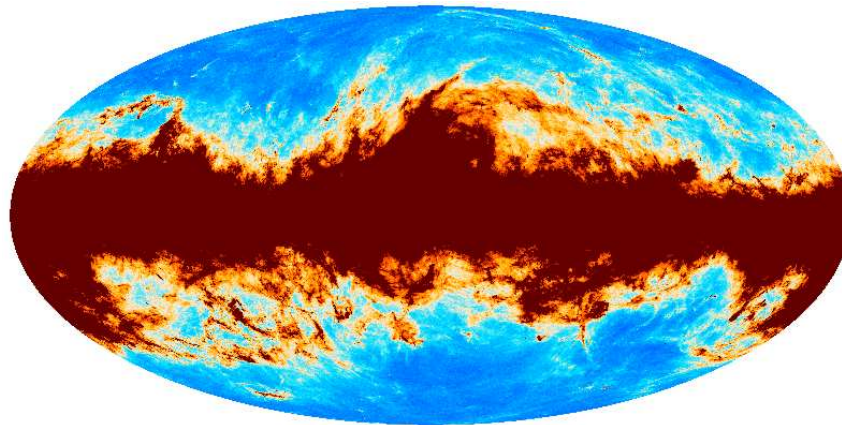
353 GHz

0 2000 μK_{CMB}



545 GHz

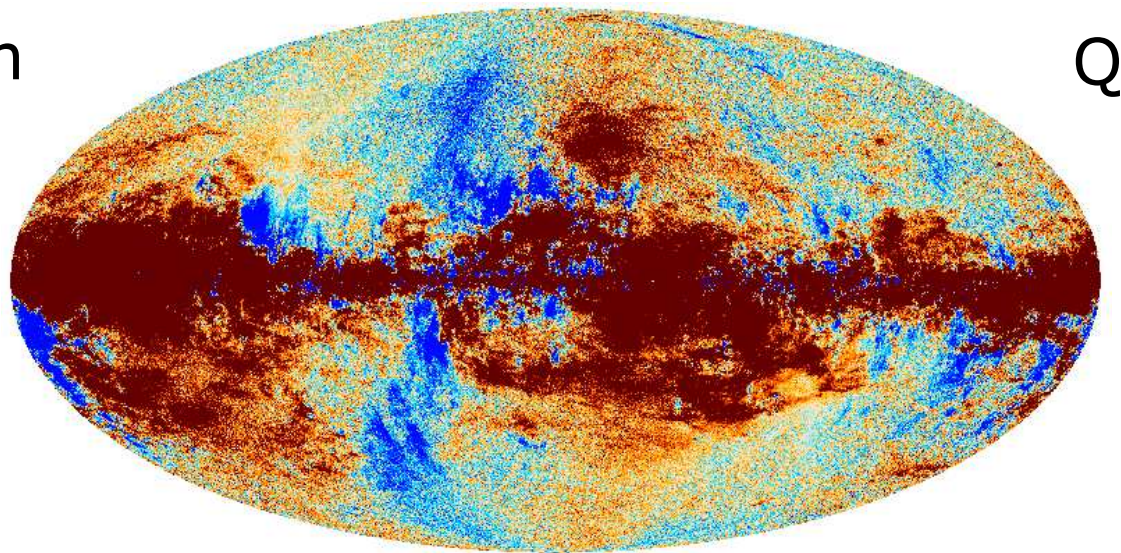
0.0 3.0e+06 MJy sr^{-1}



857 GHz

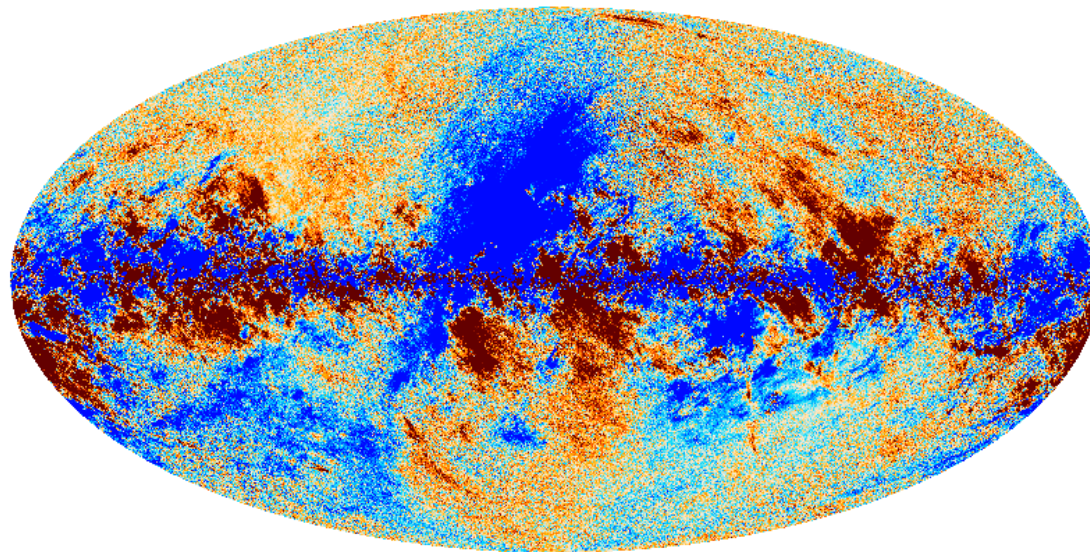
0.0 5.0e+06 MJy sr^{-1}

353 GHz Polarization maps



Q

-100.0 100.0 μK_{CMB}



U

-100.0 100.0 μK_{CMB}

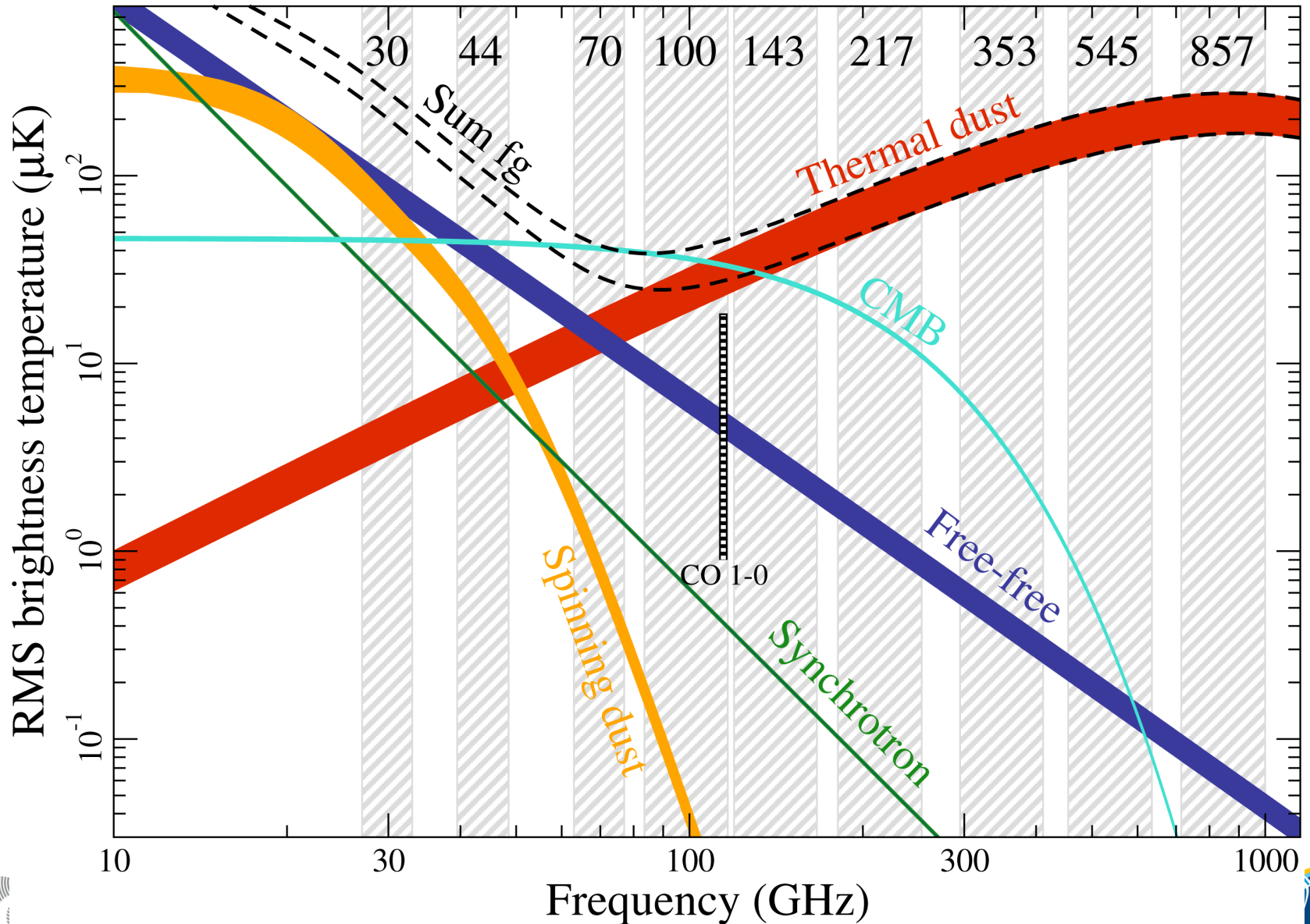
COMPONENT SEPARATION

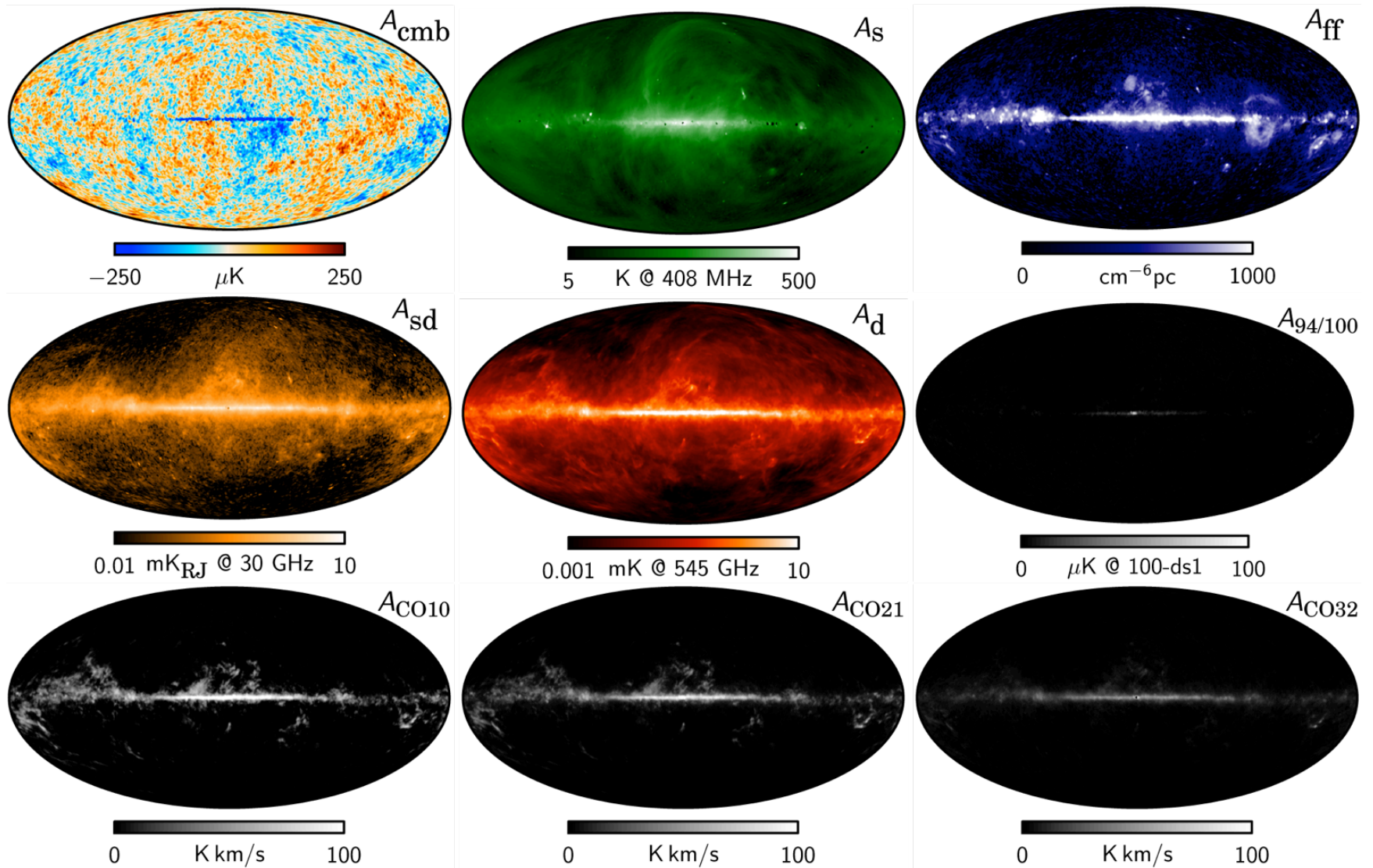


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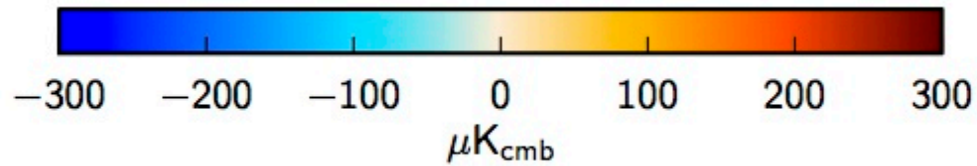
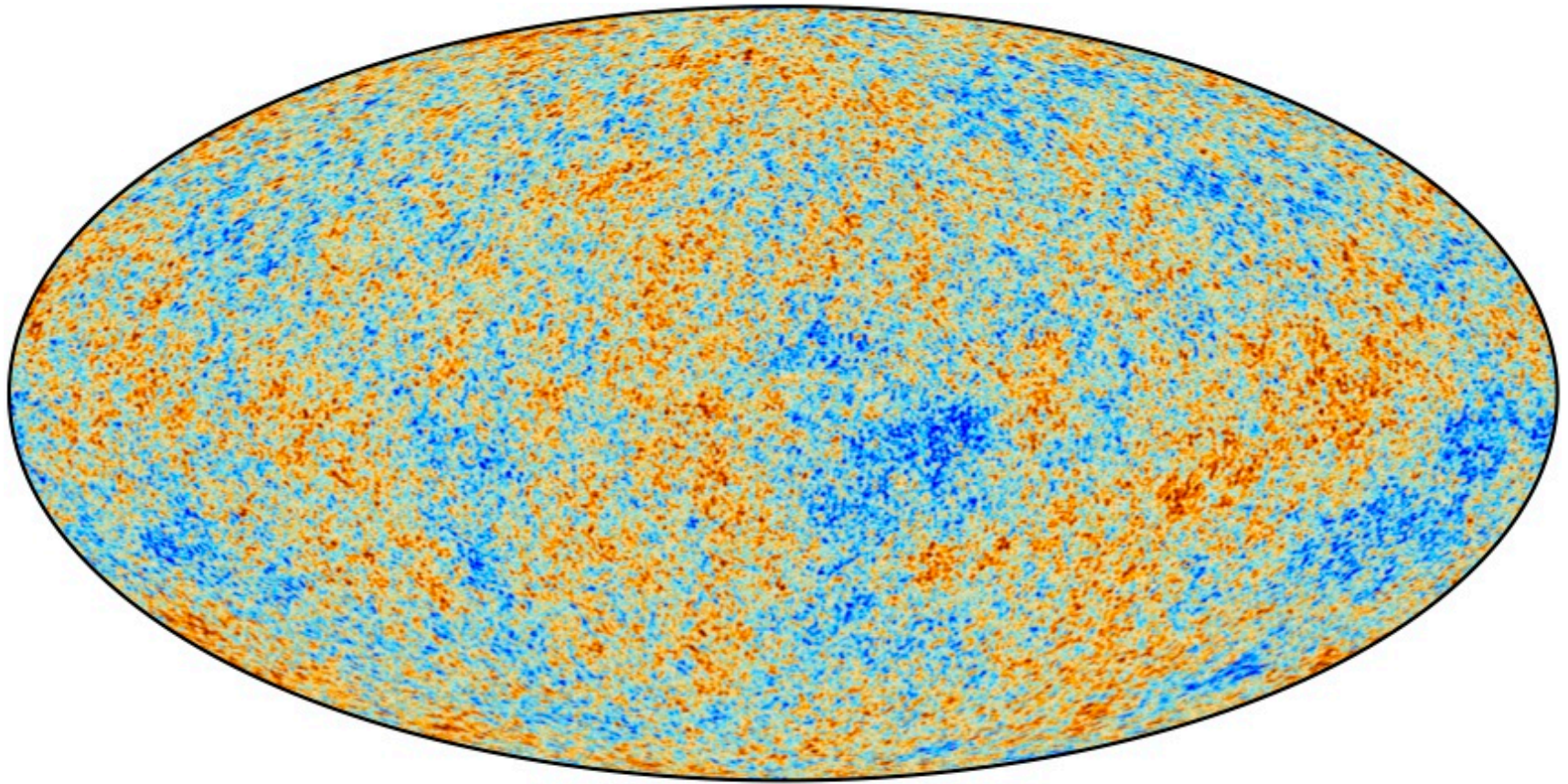
Frequency spectrum of RMS brightness temperature: CMB vs. astrophysical foregrounds



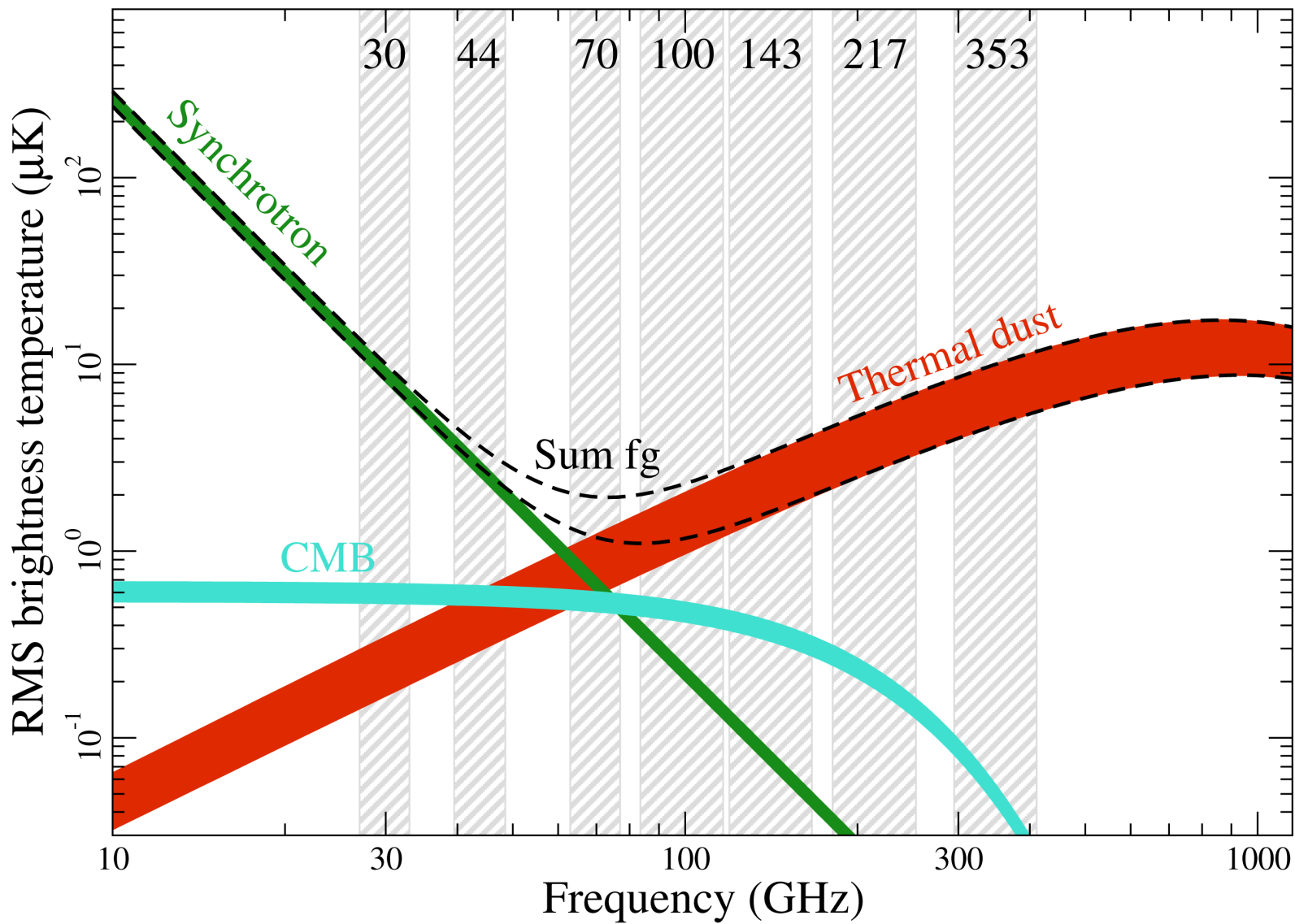


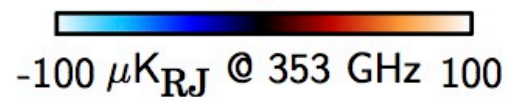
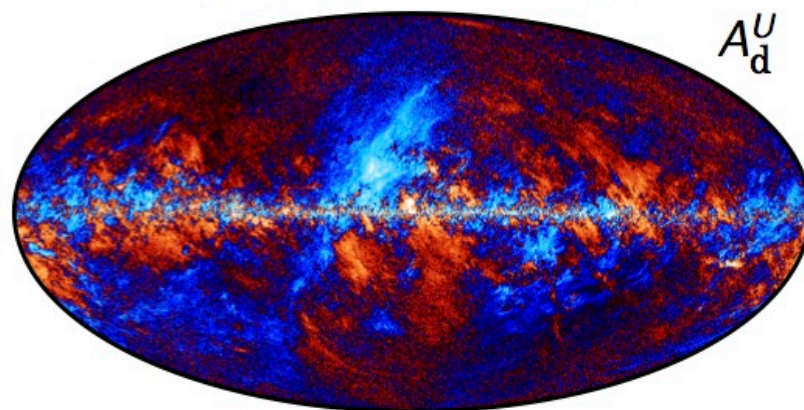
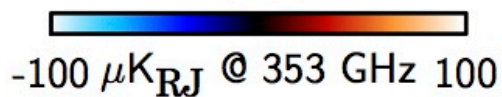
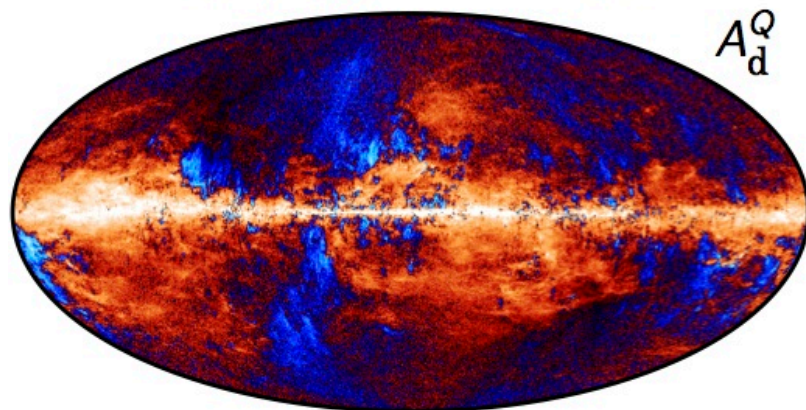
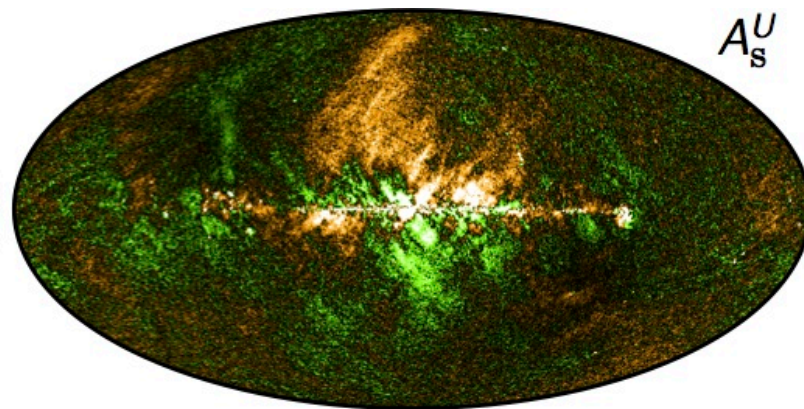
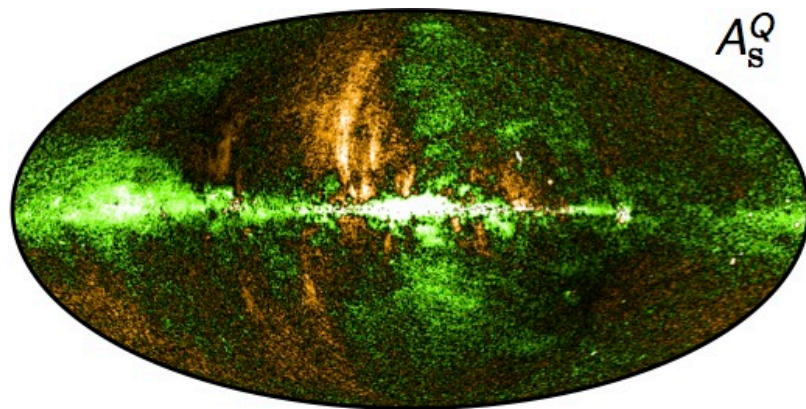
Maximum posterior intensity maps derived through the Commander algorithm from the joint analysis of Planck, WMAP and 408 MHz observations from Haslam

Planck 2015 Temperature map

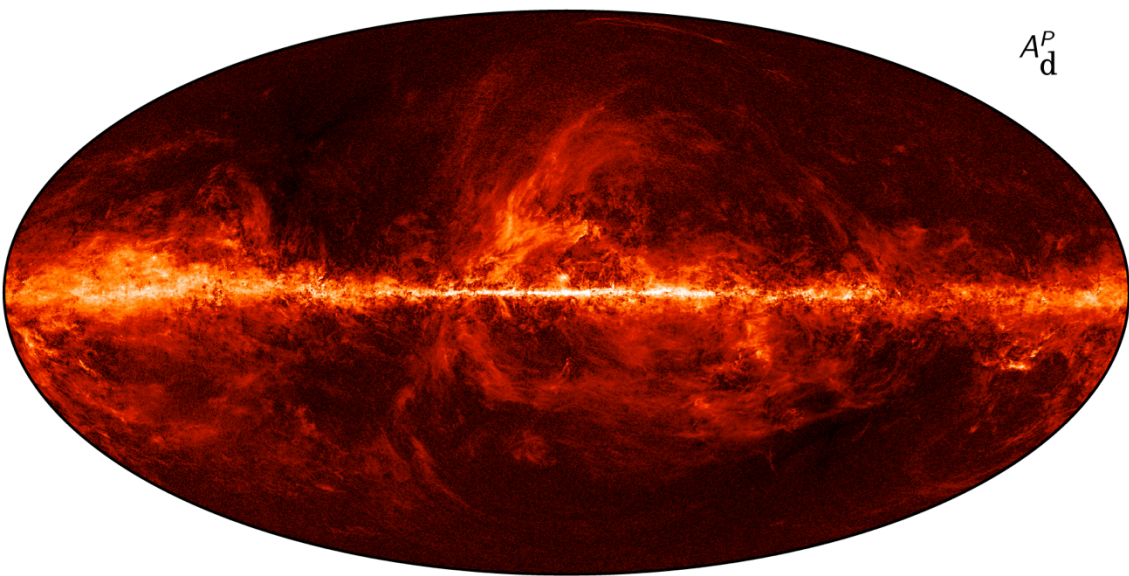


Frequency spectrum of RMS brightness polarization intensity: CMB vs. astrophysical foregrounds

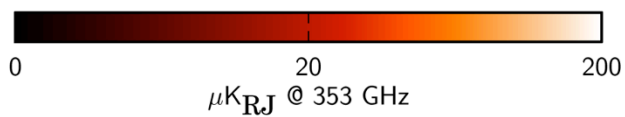




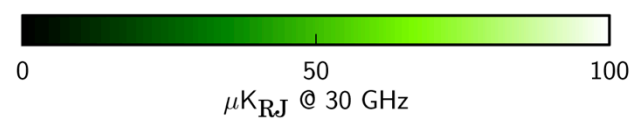
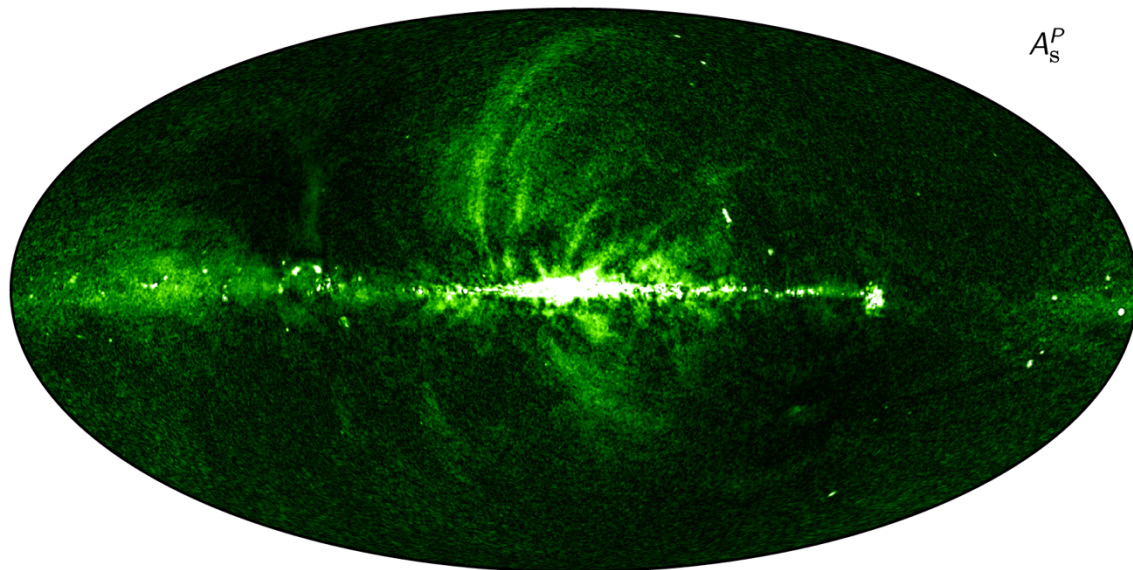
Maximum posterior polarization Q and U amplitude maps for synchrotron and dust derived through the Commander algorithm from Planck observations between 30 and 353 GHz

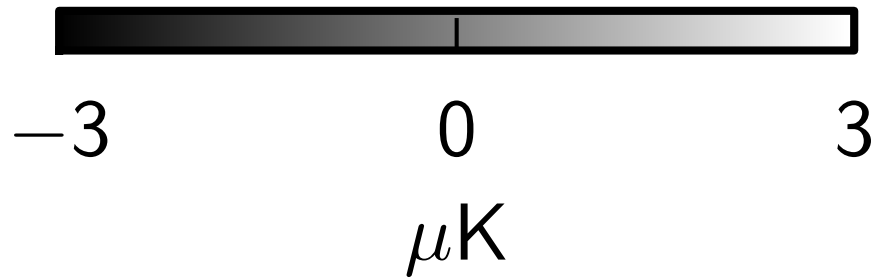
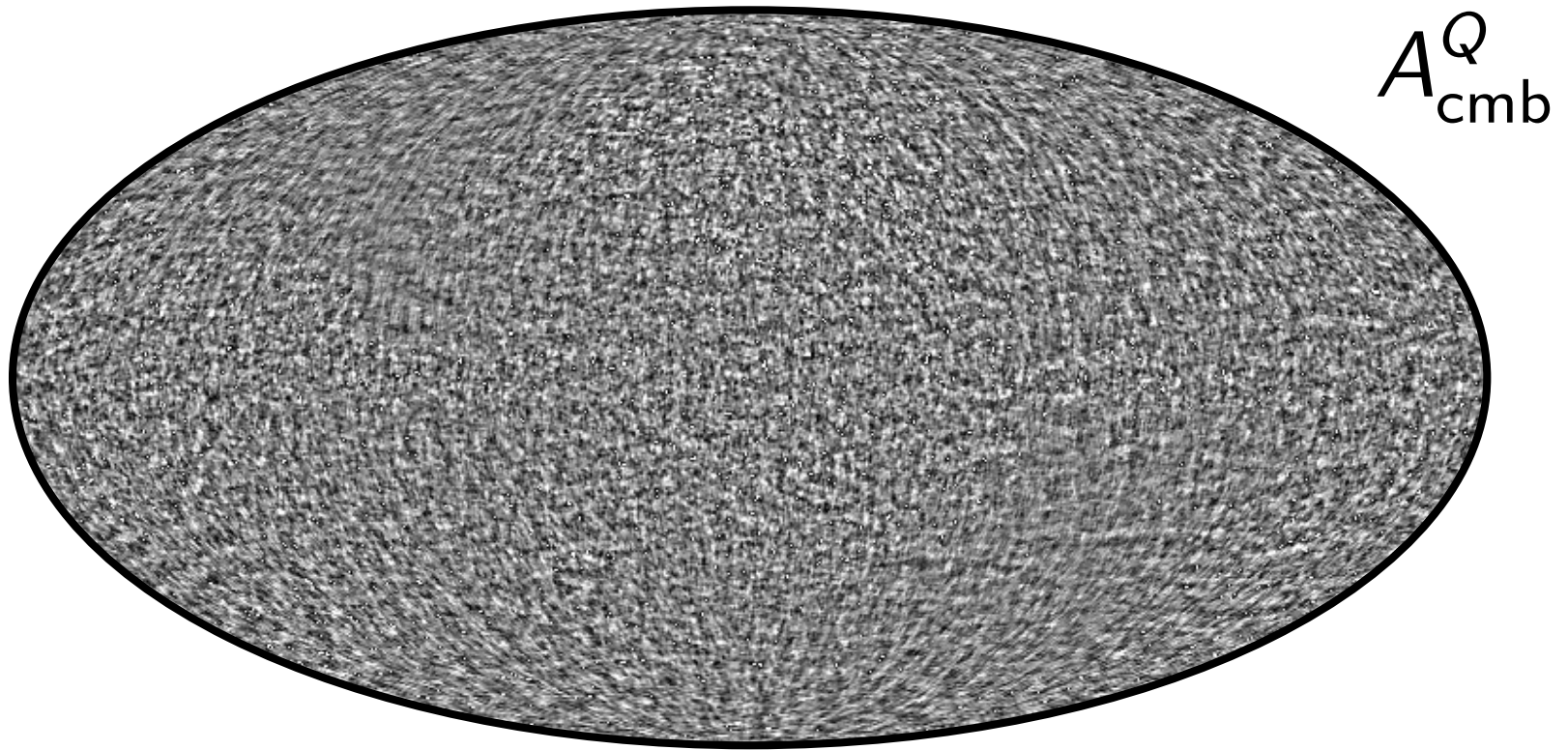


Total polarized dust emission



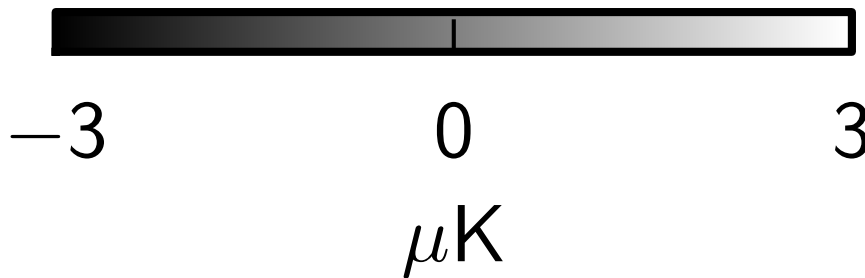
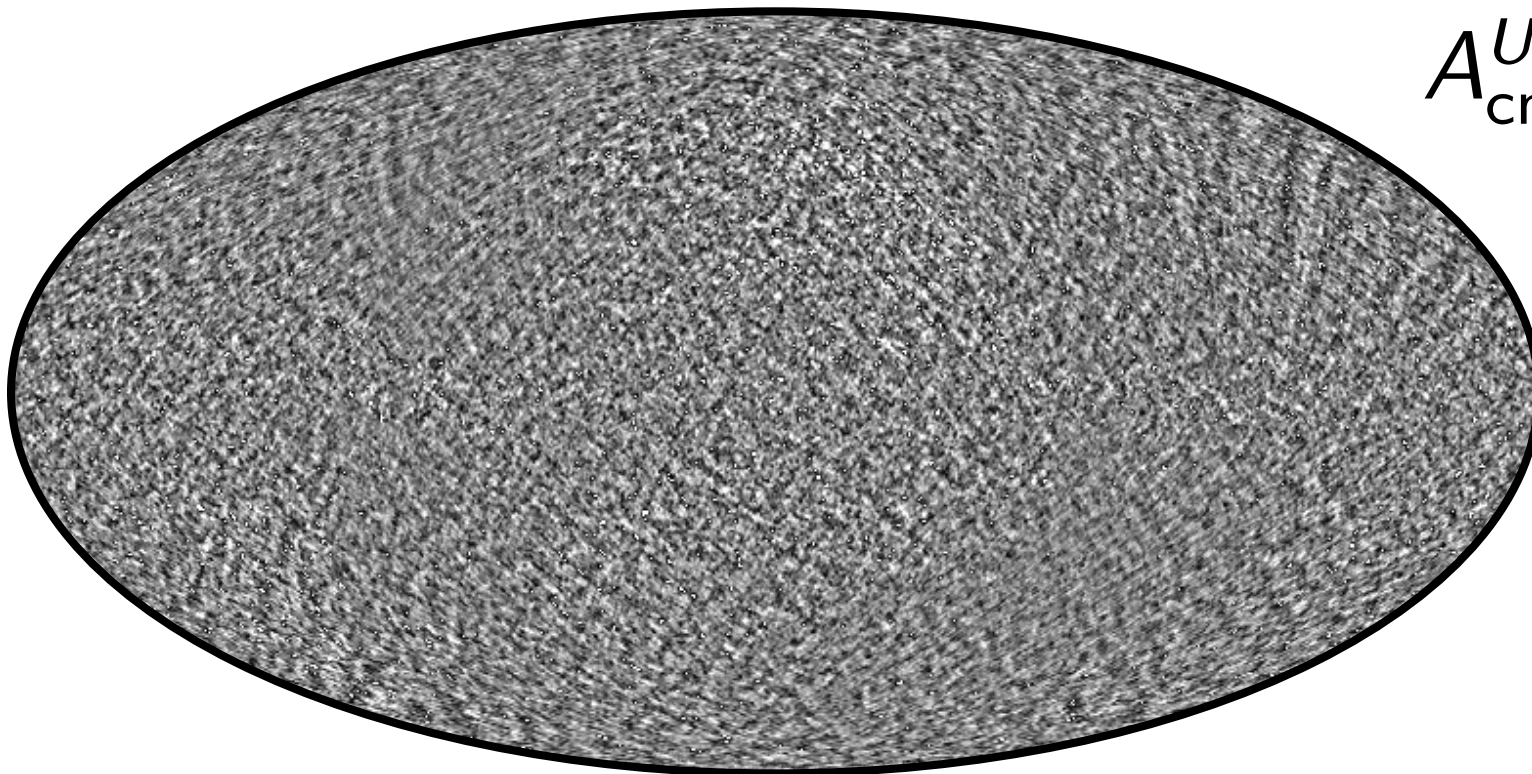
Total polarized synchrotron emission





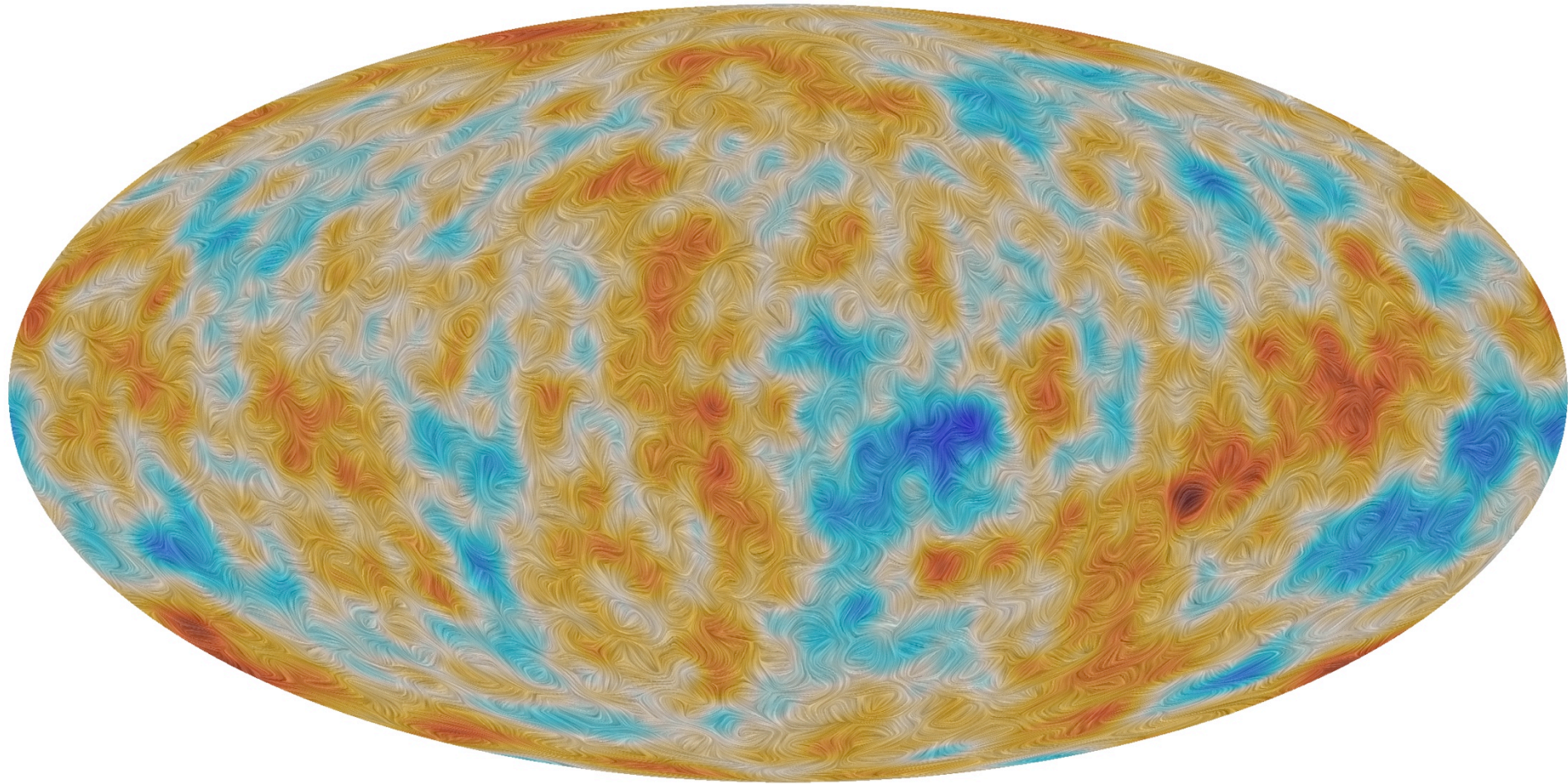
Maximum posterior amplitude Q CMB map from Planck observations between 30 and 353 GHz

A_{cmb}^U



Maximum posterior amplitude U CMB map from Planck observations between 30 and 353 GHz

Planck 2015 Polarization map



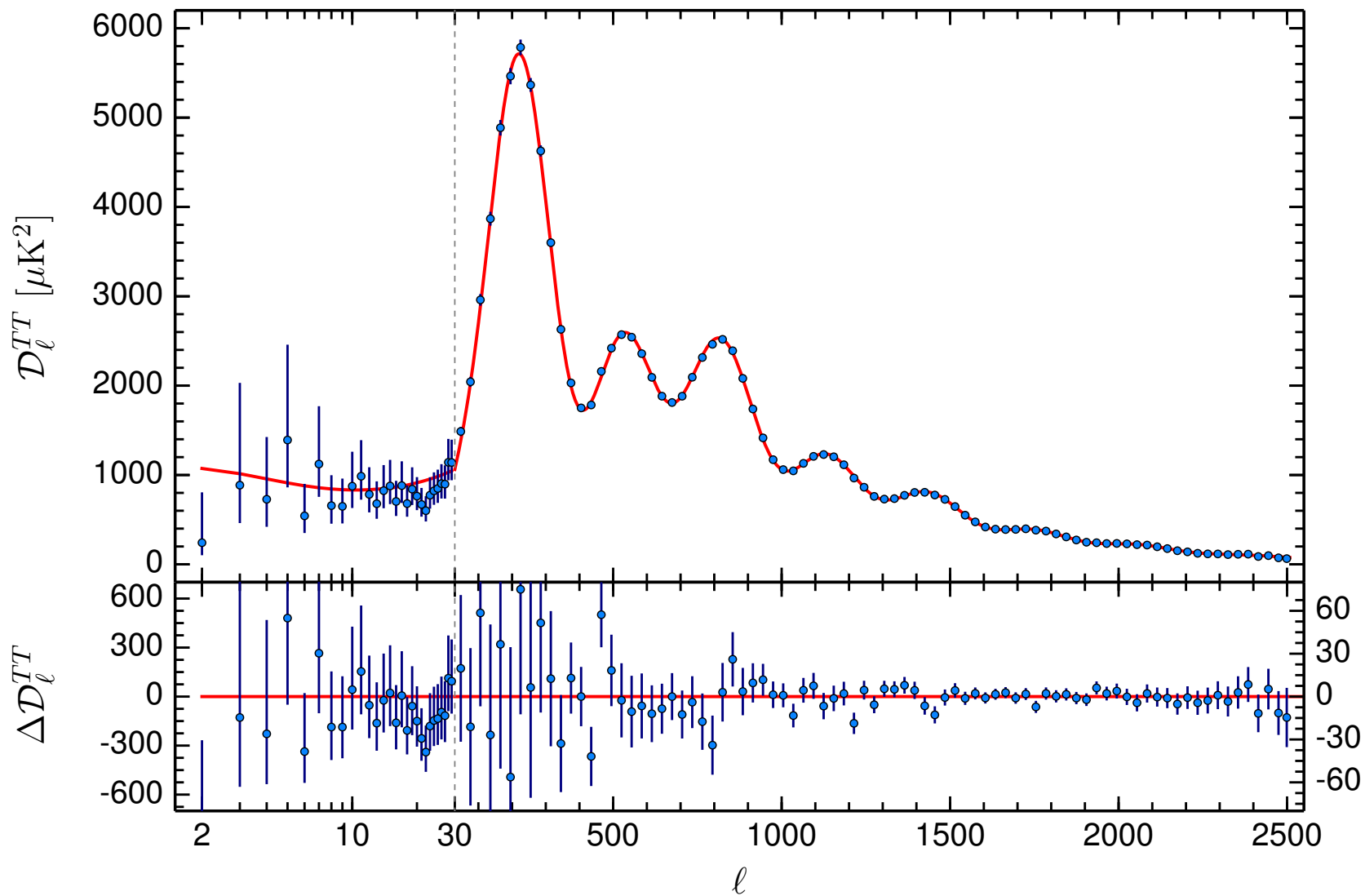
ANGULAR POWER SPECTRA



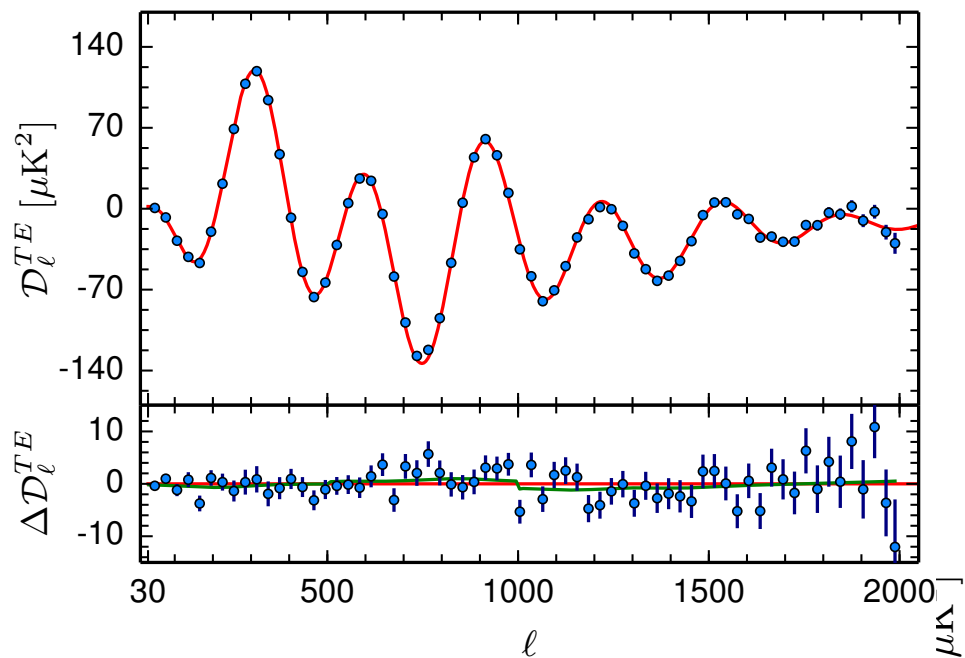
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TT Angular power spectrum

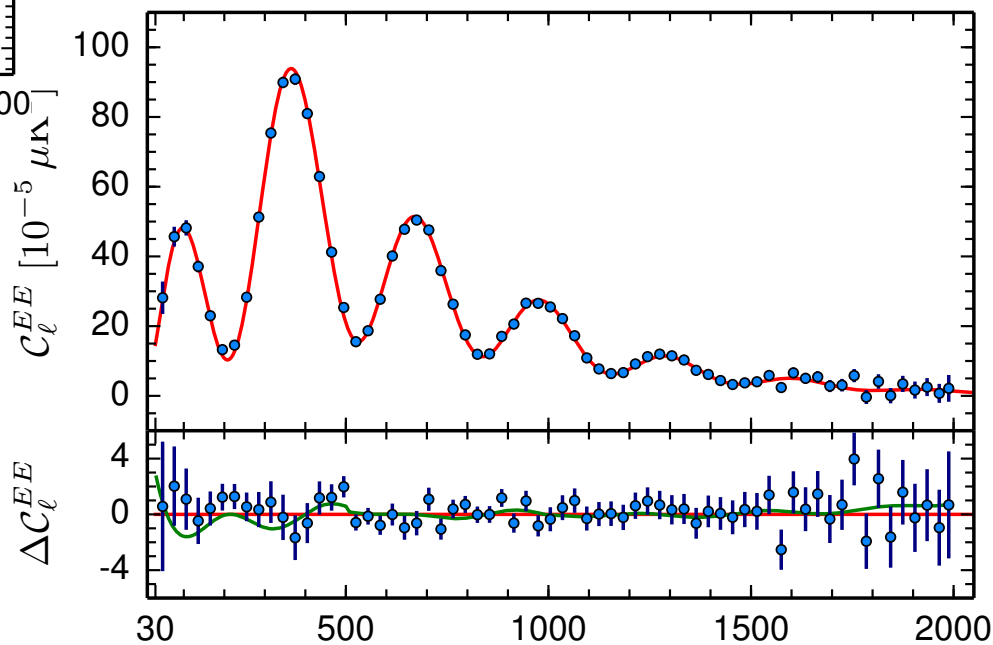


TE and EE angular power spectra

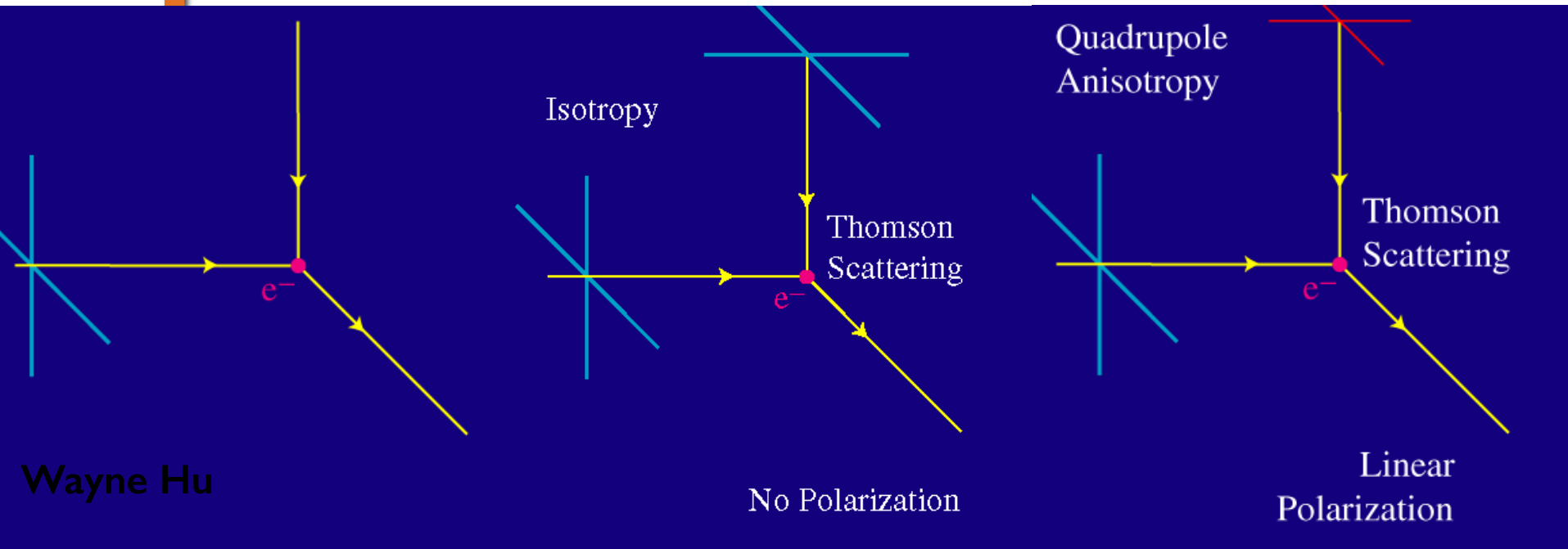


Red curves are fitted to the TT spectrum only!!
(without accountin for T to P leakage)

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



Why is the CMB polarized?



1. The Compton scattering cross section depends on photon polarization: $\frac{d\sigma_T}{d\Omega} \propto |\hat{\epsilon} \cdot \hat{\epsilon}'|^2$

2. CMB polarization is created **only** by a local temperature **quadrupole** anisotropy.

This is generated only when the photon diffusion length grows enough to reveal higher order moments in the brightness distribution (e.g. at recombination)



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Origin of quadrupole anisotropy

1. We see anisotropy in the CMB density perturbation in the matter distribution (large scale structure)
2. These two things barely talk each other today, but were tightly connected in the early universe.
3. Perturbations to smooth background metric $g_{\mu\nu}$ must have existed in the early universe.
4. Standard paradigm says that they origin in quantum fluctuation amplified by the cosmic inflation. Two kinds of perturbations:

a. Scalar perturbations: these can grow under self gravity



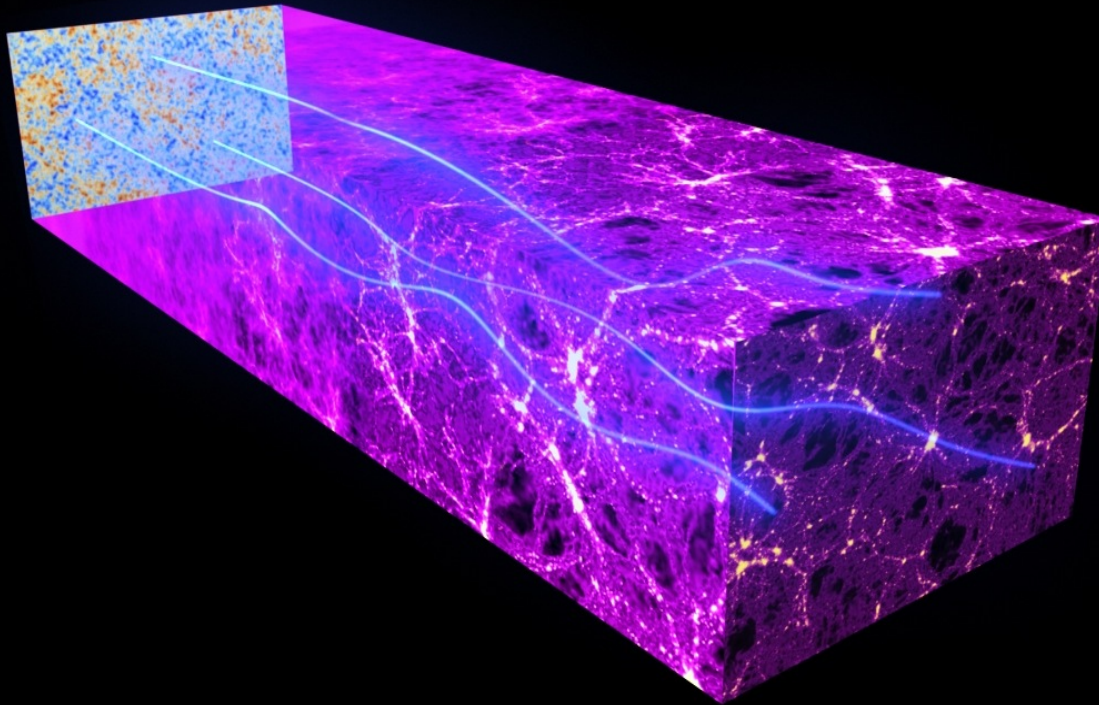
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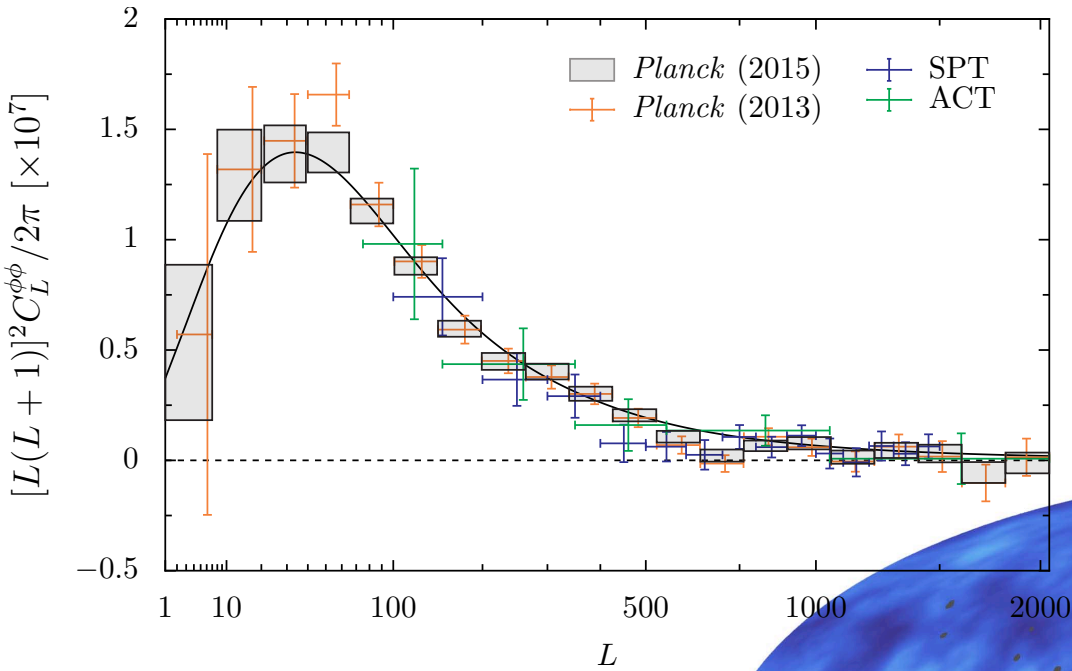
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PLANCK PROBES AND EXPLOITS CMB LENSING

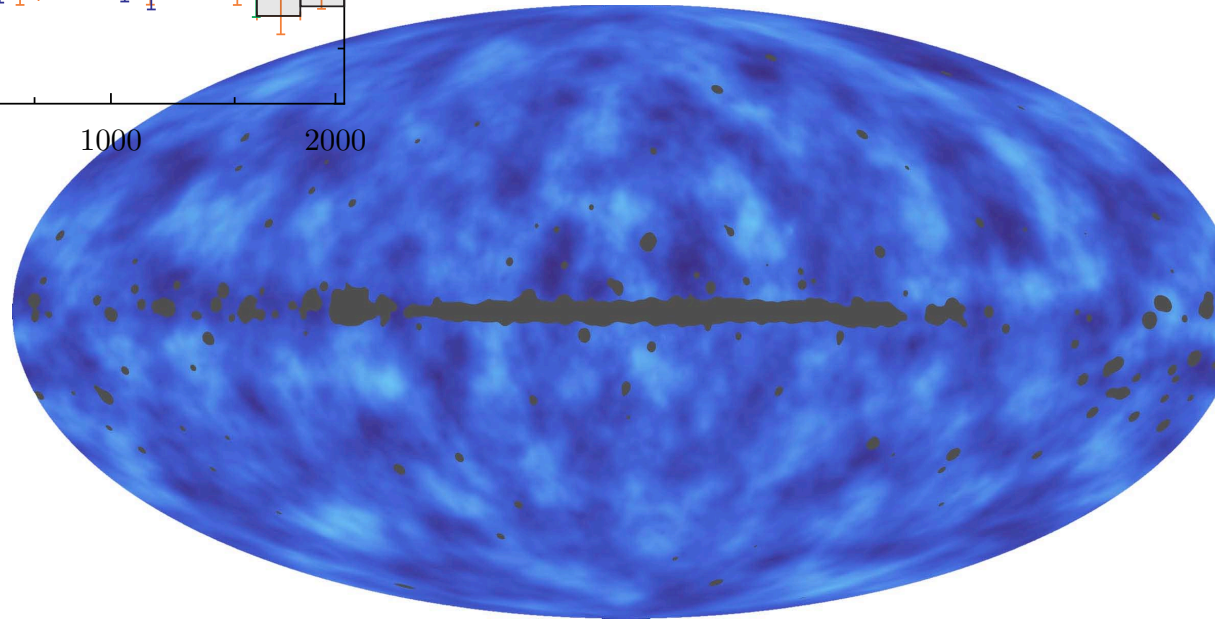
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB



LENSING



Lensing potential estimated from the four-point correlation function



COSMOLOGICAL PARAMETERS



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Main changes in the 2015 analysis

- Full mission temperature and polarization data
- Changes in the low-level data processing (better removal of "4K" cooler lines); resolved the small calibration difference between Planck and WMAP
- Foreground cleaned LFI 70 GHz polarization at low l s (instead than WMAP9) to probe large scale CMB polarization
- Half mission cross-spectra at high l s (instead than DetSets)
- More aggressive use of the sky
- Minor changes to FG modeling

2015 Planck Likelihood Code

- Same methodology as 2013, extended to include Planck polarization data;
- Hybrid combination of a low-resolution (“low-ell”) pixel-based likelihood and of a high-ell likelihood based on cross spectra;
- Low-ell (2-29) likelihood uses 70 GHz LFI polarization maps on 46% of the sky, cleaned with LFI 30 GHz and HFI 353 GHz to reduce foreground contamination, and the Commander temperature map over 94% of the sky.
- High-ell (>29) likelihood uses “half-mission” cross-spectra from HFI 100, 143 and 217 GHz maps. Unresolved FGs are modeled parametrically using power spectrum templates
- Lensing likelihood based on lensing power spectrum measurements ($40 < L < 400$)



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Datasets

I will report constraints on the parameters obtained using different combinations of the following datasets:

- the Planck temperature power spectrum ($2 < \ell < 2500$). This includes the effect of lensing of the CMB by large scale structures (**PlanckTT**);
- the large angular scale (low- ℓ , $2 < \ell < 30$) Planck polarization data (**lowP**);
- Planck TE and EE high- ℓ ($30 < \ell < 2500$) polarization spectra (**Planck TE, EE**). Be aware however that high- ℓ polarization could still be affected by low-level residual systematics.
- the Planck lensing potential power spectrum ($40 < \ell < 400$), as estimated from the Planck trispectrum (i.e., $\langle TTTT \rangle$) data (**lensing**)
- astrophysical probes: Baryon acoustic oscillations (6dFGS, SDSS-MGS, BOSS-LOWZ, CMASS DR11) (**BAO**), Type Ia Supernovae (**JLA** sample, including SNLS, SDSS and samples of low z SNe), Hubble constant (from Efstathiou 2014 reanalysis or Riess et al. 2011) (**H0**), collectively denoted as “**ext**”



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COSMOLOGICAL PARAMETERS: STANDARD Λ CDM



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High Frequency Instrument

Parameters of the base Λ CDM cosmology

Parameter	[1] <i>Planck</i> TT+lowP	[2] <i>Planck</i> TE+lowP	[3] <i>Planck</i> EE+lowP	[4] <i>Planck</i> 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



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Very good consistency
between temperature
and polarization

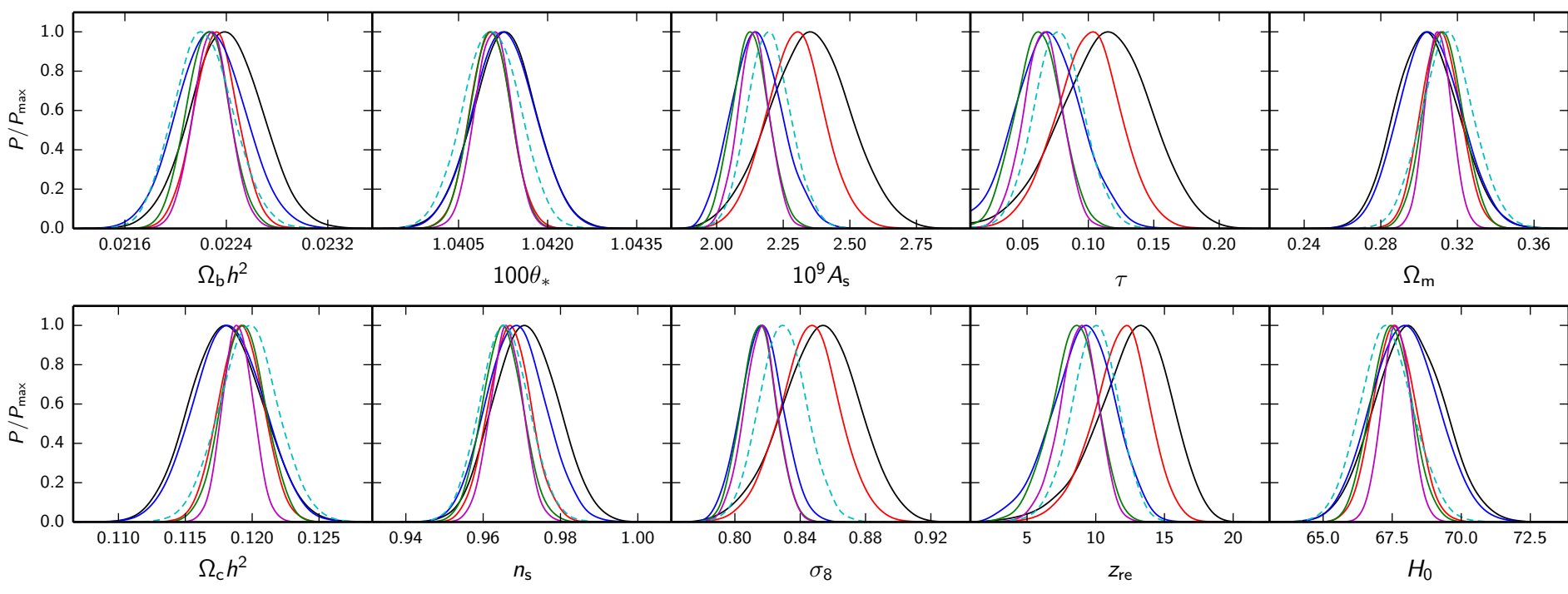


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PLANCK

— Planck TT — Planck TT,TE,EE — Planck TT+lensing — Planck TT,TE,EE+lensing — Planck TT,TE,EE+lensing+BAO - - - Planck TT+lowP



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Constraints on the reionization optical depth

Planck TT+lowP

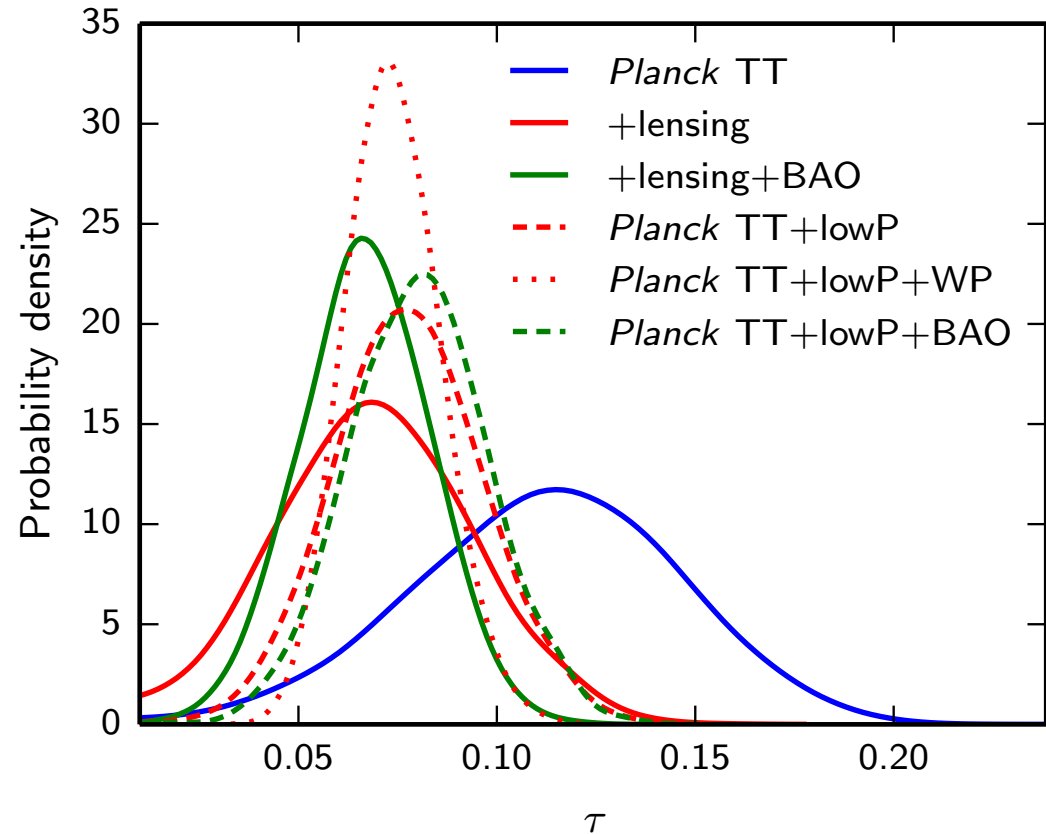
$$\tau = 0.078 \pm 0.019$$
$$(z_{\text{re}} = 9.9 \pm 1.7)$$

Planck TT+lensing

$$\tau = 0.070 \pm 0.024$$
$$(z_{\text{re}} = 9.0 \pm 2.3)$$

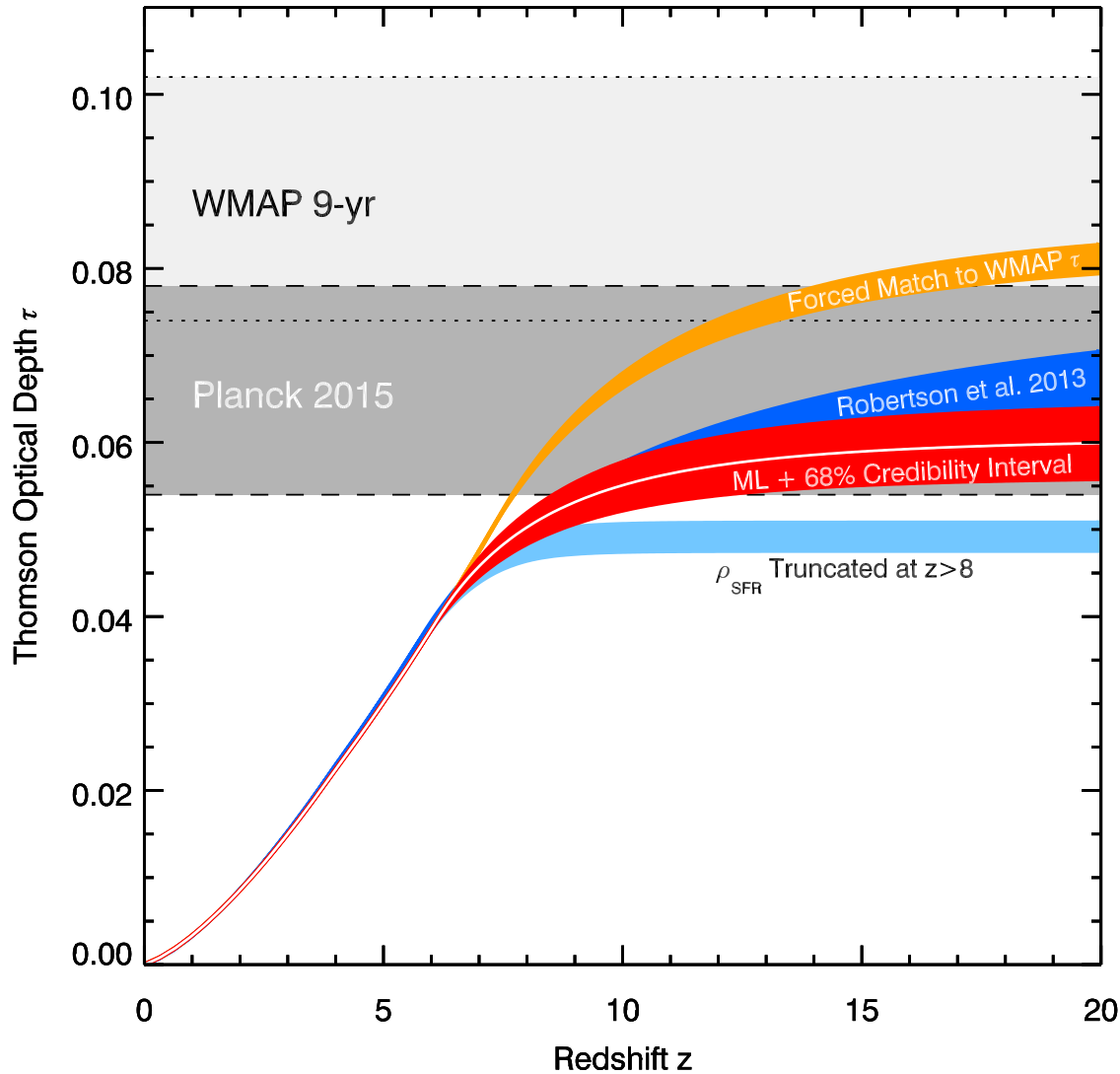
Compare with 2013 result
(driven by WMAP low-ell
polarization):

$$\tau = 0.089 \pm 0.013$$
$$(z_{\text{re}} = 11.1 \pm 1.0)$$



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

Constraints on the reionization optical depth



Much better agreement with HST data on the abundance and luminosity distribution of distant galaxies.

Reduces the requirement for a significant population of very high redshift ($z \gg 10$) galaxies

Robertson et al., arXiv 1502.02024

COSMOLOGICAL PARAMETERS: NEUTRINOS



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Probing neutrino masses with CMB data

The effect of neutrinos with a mass between 10^{-3} and 1 eV on the primary CMB spectrum comes from the fact that they contribute to the radiation density at the time of equality, and to the nonrelativistic matter density today.

This induces an integrated Sachs-Wolfe effect (both at early and late times) and/or a change in the angular diameter distance to the last scattering surface.

Before Planck, these were the dominant effects in constraining the neutrino mass from CMB data.

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This induces an integrated Sachs-Wolfe effect (both at early and late times) and/or a change in the angular diameter distance to the last scattering surface.

Before Planck, these were the dominant effects in constraining the neutrino mass from CMB data.

Planck has moved us to a new regime where instead the dominant effect is gravitational lensing.

Increasing the neutrino mass suppresses clustering on scales smaller than the size of the horizon at the time of the NR transition, suppressing the lensing potential.



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Planck constraints on neutrino masses

Planck constraints on Σm_ν

	2013	2014	2014 + PlanckTE,EE
PlanckTT+lowP	<0.93 eV		
PlanckTT+lowP+lensing	<1.1 eV		
PlanckTT+lowP+BAO	<0.25 eV		

(all limits are @95% CL)
(for 2013, 'lowP' refers to
WMAP polarization)



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	2013	2014	2014 + PlanckTE,EE
PlanckTT+lowP	<0.93 eV	<0.72 eV (23%)	
PlanckTT+lowP+lensing	<1.1 eV	<0.68 eV (38%)	
PlanckTT+lowP+BAO	<0.25 eV	<0.21 eV (16%)	
PlanckTT+lowP+ext		<0.20 eV	
PlanckTT+lowP+lensing +ext		<0.23 eV	

(all limits are @95% CL)
(for 2013, 'lowP' refers to
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Planck constraints on neutrino masses

- the PlanckTT + large scale polarization (+lensing) constraints improve by nearly 25% (40%).
- the lensing reconstruction data prefer lower lensing amplitudes with respect to the CMB power spectrum (best-fit for lensing only is around 0.6 eV) → the lensing information improves only slightly or even worsens the constraints.

Planck constraints on neutrino masses

Planck constraints on Σm_ν

	2013	2014	2014 + PlanckTE,EE
PlanckTT+lowP	<0.93 eV	<0.72 eV (23%)	<0.49 eV (48%)
PlanckTT+lowP+lensing	<1.1 eV	<0.68 eV (38%)	<0.59 eV (47%)
PlanckTT+lowP+BAO	<0.25 eV	<0.21 eV (16%)	<0.17 eV (36%)
PlanckTT+lowP+ext		<0.20 eV	<0.15 eV
PlanckTT+lowP+lensing +ext		<0.23 eV	<0.19 eV

(all limits are @95% CL)
(for 2013, 'lowP' refers to
WMAP polarization)



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Planck constraints on neutrino masses

Planck constraints on Σm_ν

	2013	2014	2014 + PlanckTE,EE
PlanckTT+lowP	<0.93 eV	<0.72 eV (23%)	<0.48 eV (48%)
PlanckTT+lowP+lensing	<1.1 eV	<0.70 eV (36%)	<0.58 eV (47%)
PlanckTT+lowP+BAO	<0.25 eV	<0.21 eV (16%)	<0.16 eV (36%)
PlanckTT+lowP+ext		<0.20 eV	<0.15 eV
PlanckTT+lowP+lensing +ext		<0.23 eV	<0.19 eV

(all limits are @95% CL)
(for 2013, 'lowP' refers to
WMAP polarization)

Small-scale polarization
improves CMB only limits by
nearly a factor 2

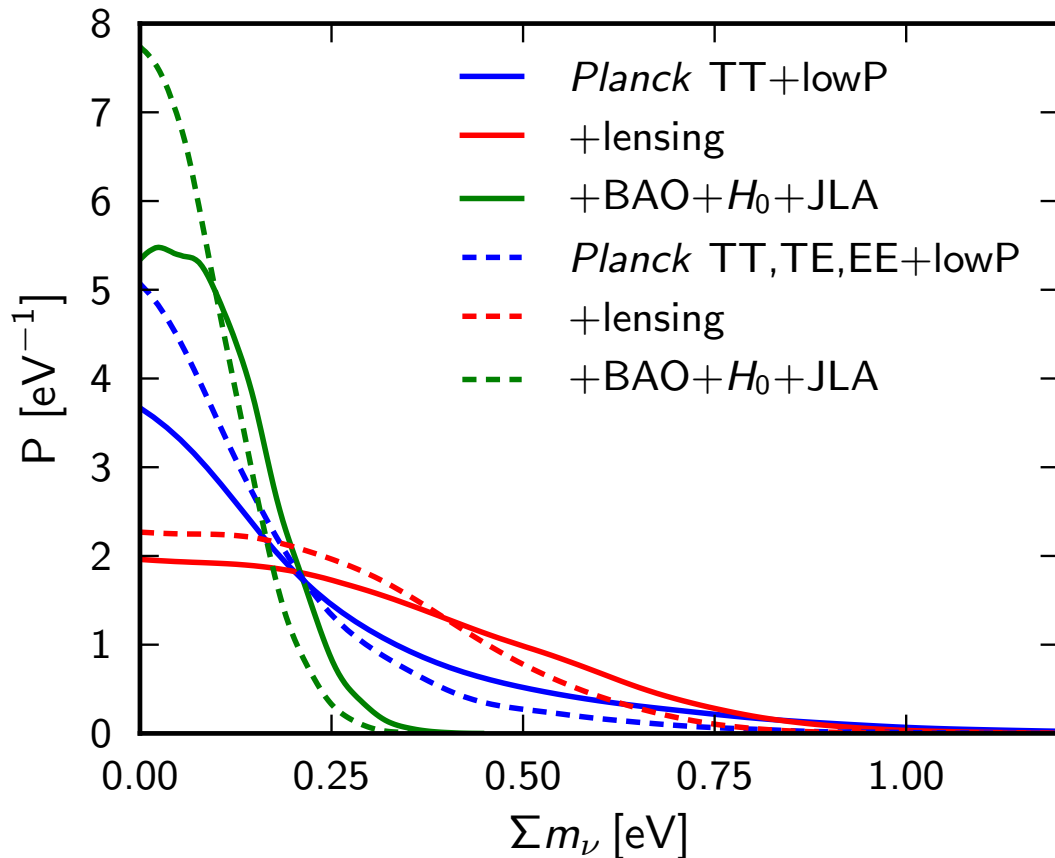


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Planck constraints on neutrino masses



$\Sigma m_\nu < 0.72$ eV (*Planck*TT+lowP)

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

$\Sigma m_\nu < 0.23$ eV (... + ext)

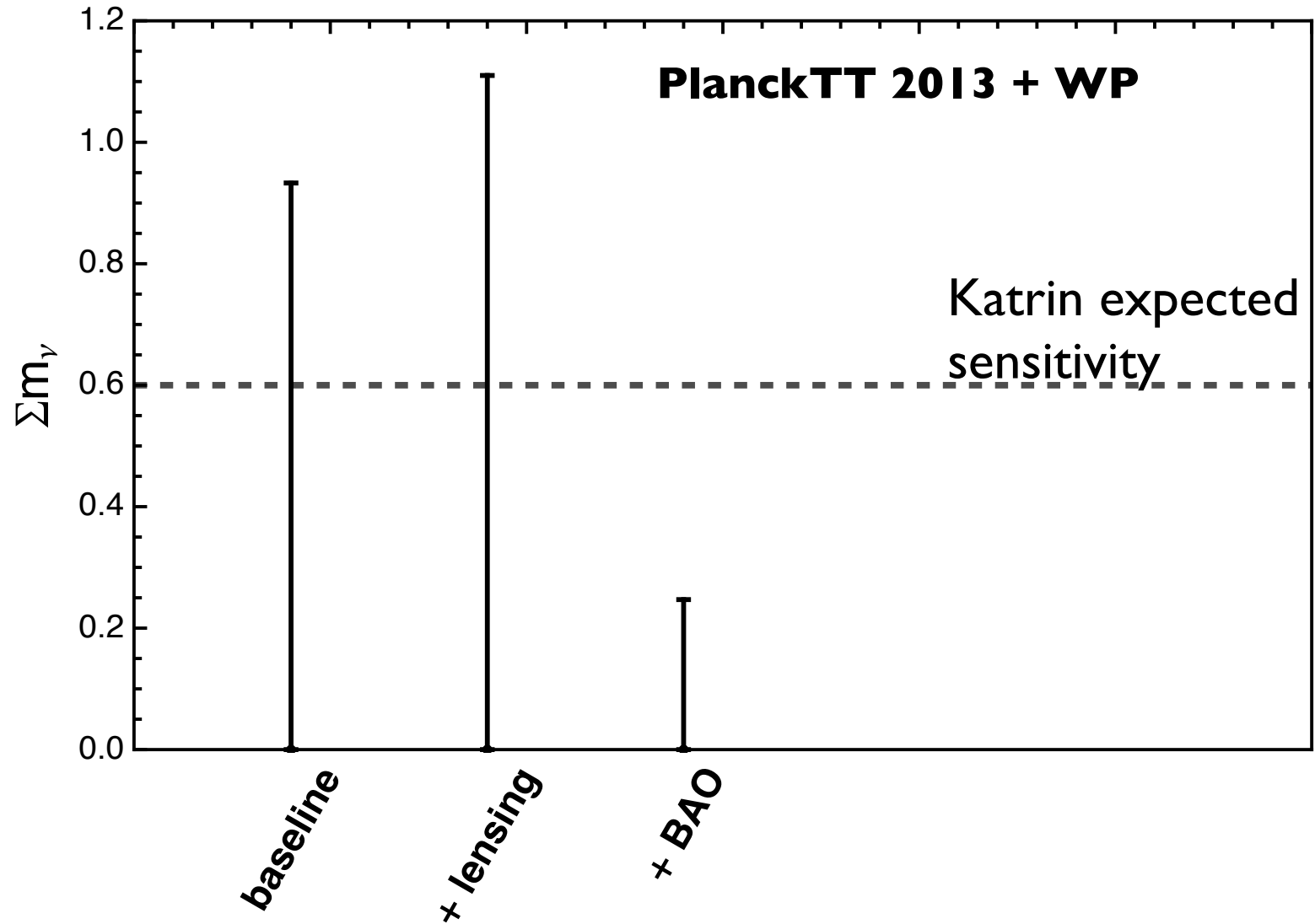
$\Sigma m_\nu < 0.49$ eV (*Planck*TT,TE,EE
+lowP)

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

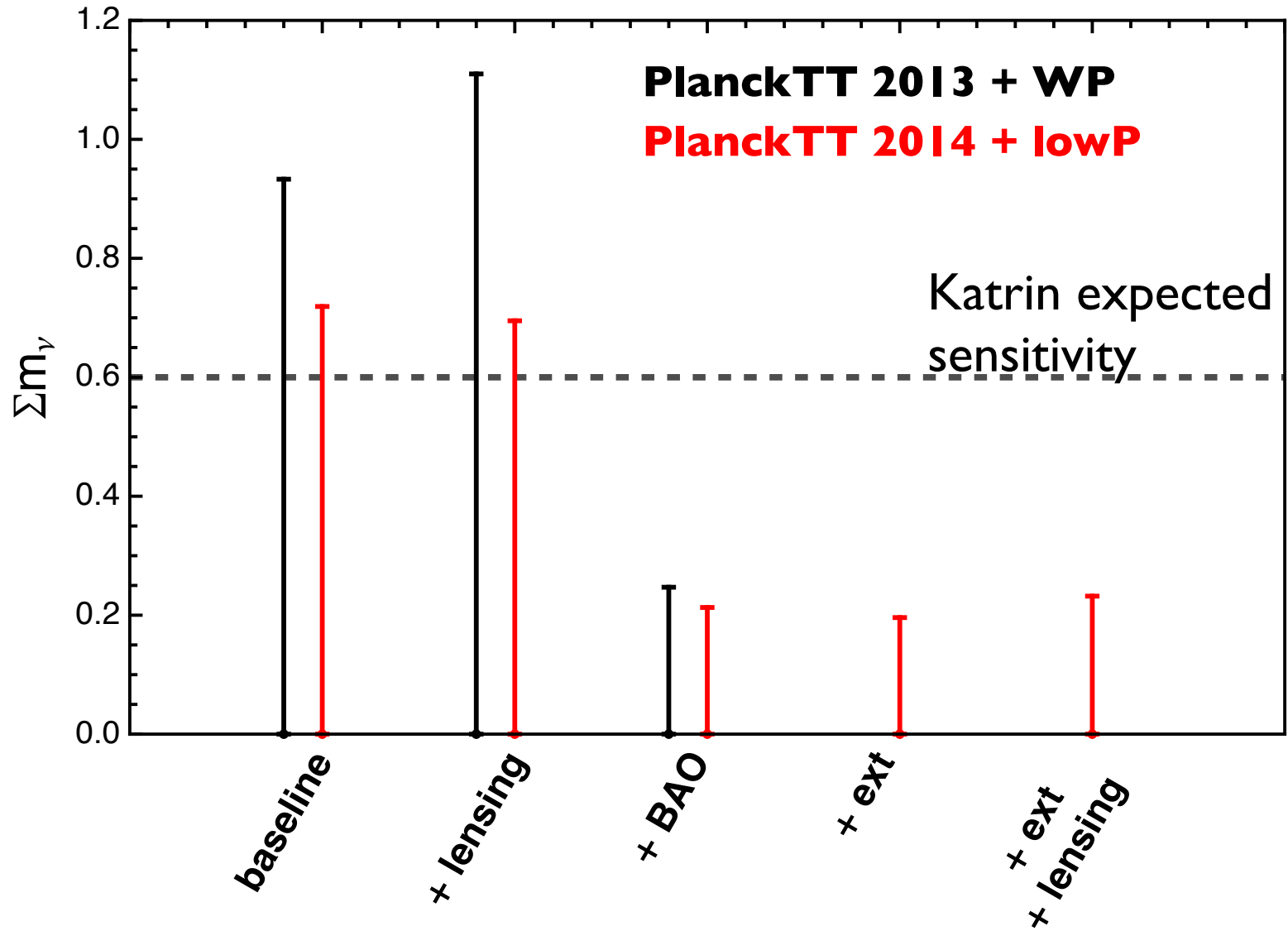
$\Sigma m_\nu < 0.19$ eV (... + ext)

(all limits are 95% CL)

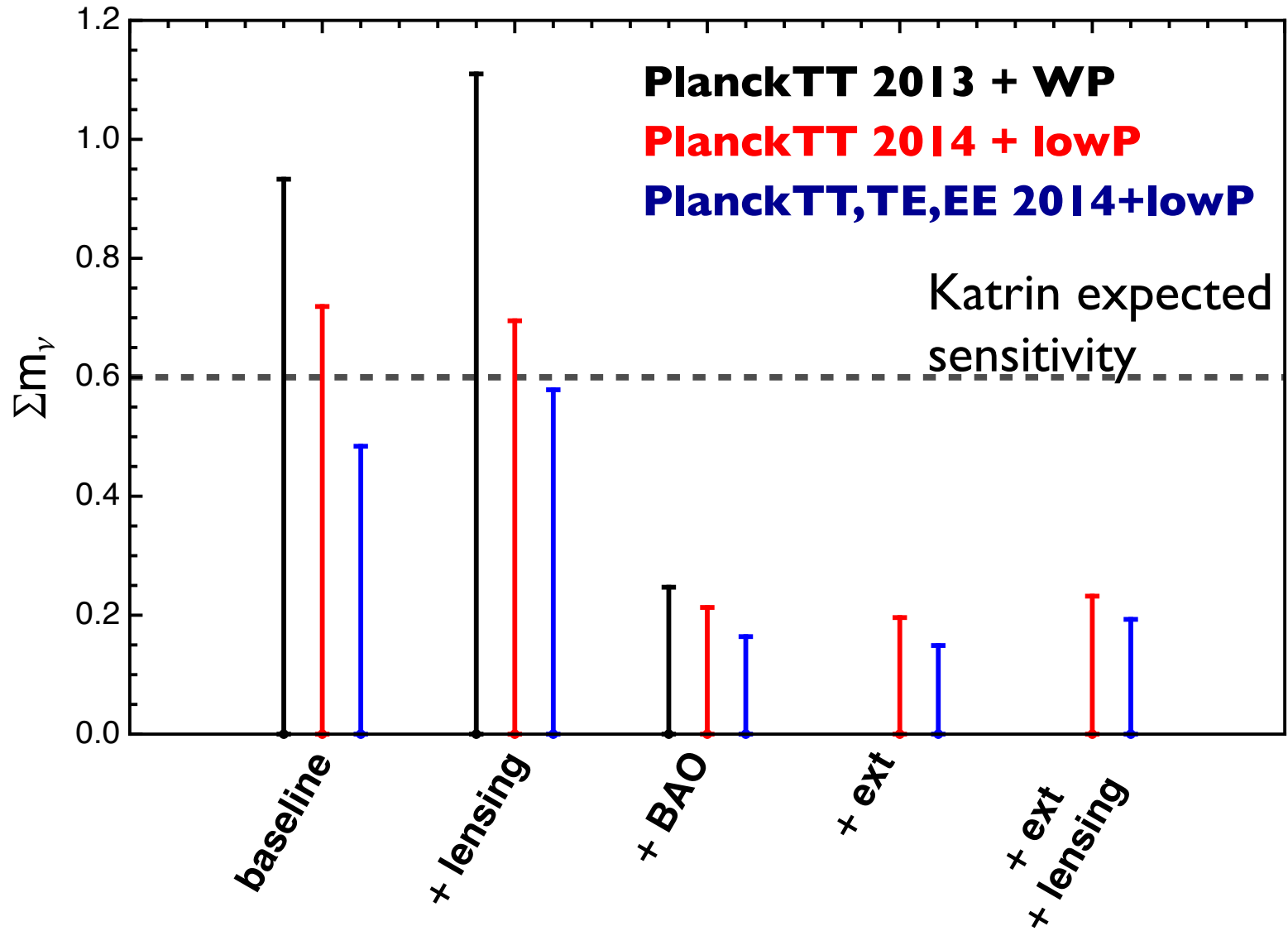
Planck constraints on neutrino masses



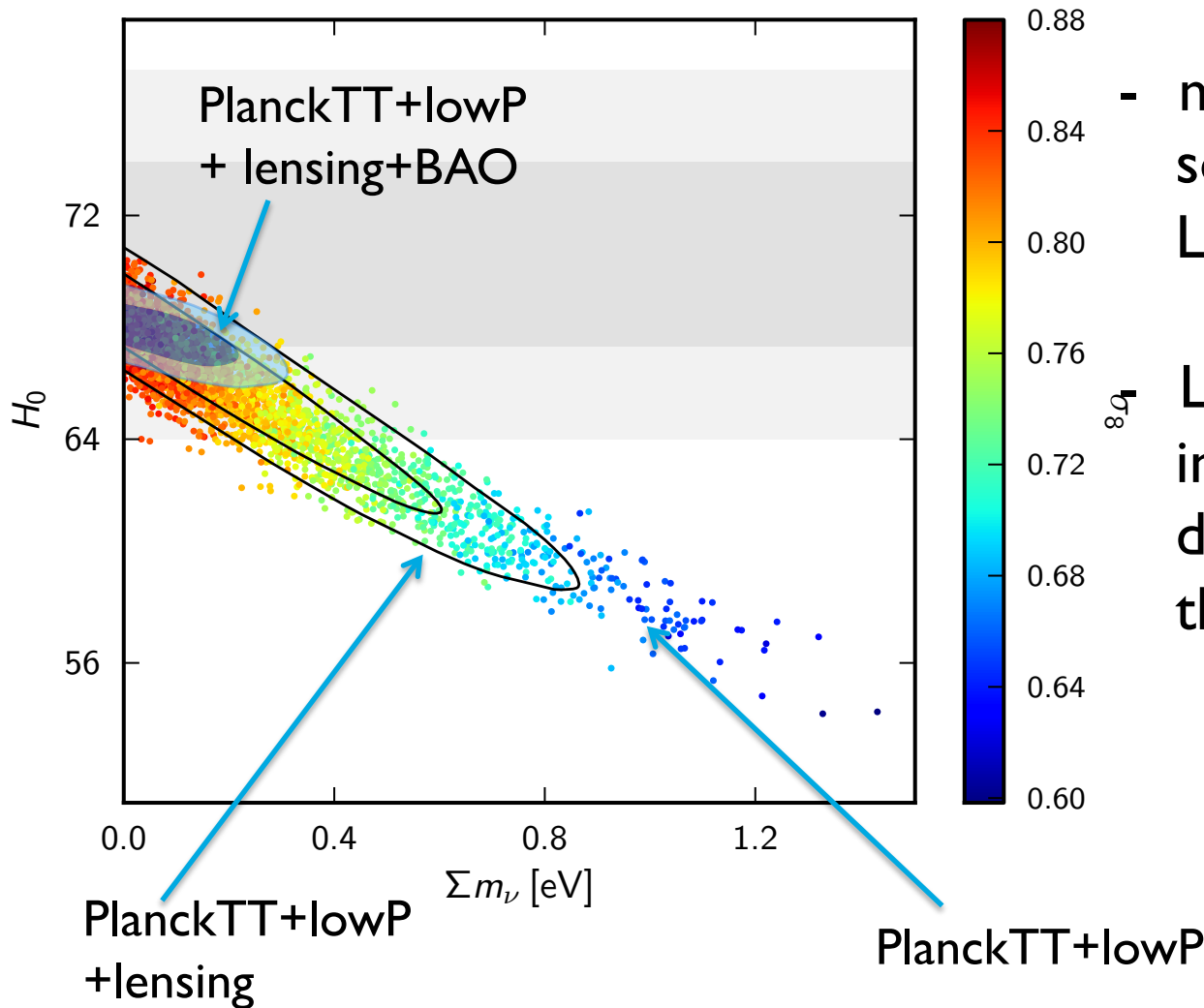
Planck constraints on neutrino masses



Planck constraints on neutrino masses



Neutrino masses and tension with external data



- m_ν alone does not solve the tension with LSS – σ_8 still too large!

Larger masses also increase tension with direct measurements of the Hubble parameter

Probing N_{eff} with CMB data

N_{eff} parameterizes the density of radiation (other than photons) in the Universe, in units of the density of a single neutrino family in thermodynamic equilibrium at $T=1.9$ K. The standard value is $N_{\text{eff}} = 3.046$

An excess in N_{eff} could be caused by a neutrino/antineutrino asymmetry, sterile neutrinos, or other light relics in the Universe. The case $N_{\text{eff}} < 3.046$ is also possible (e.g. low reheating scenarios).

The main effect of increasing N_{eff} while keeping both θ_* and z_{eq} fixed is to increase the expansion rate before recombination and thus make the Universe younger at recombination. This increases the angular scale of the photon diffusion length and thus reduces the power in the damping tail.

N_{eff} is correlated mainly with H_0 , Y_p and n_s .



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N_{eff} constraints from Planck

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

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

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

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

(uncertainties are 68% CL)

N_{eff} constraints from Planck

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

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

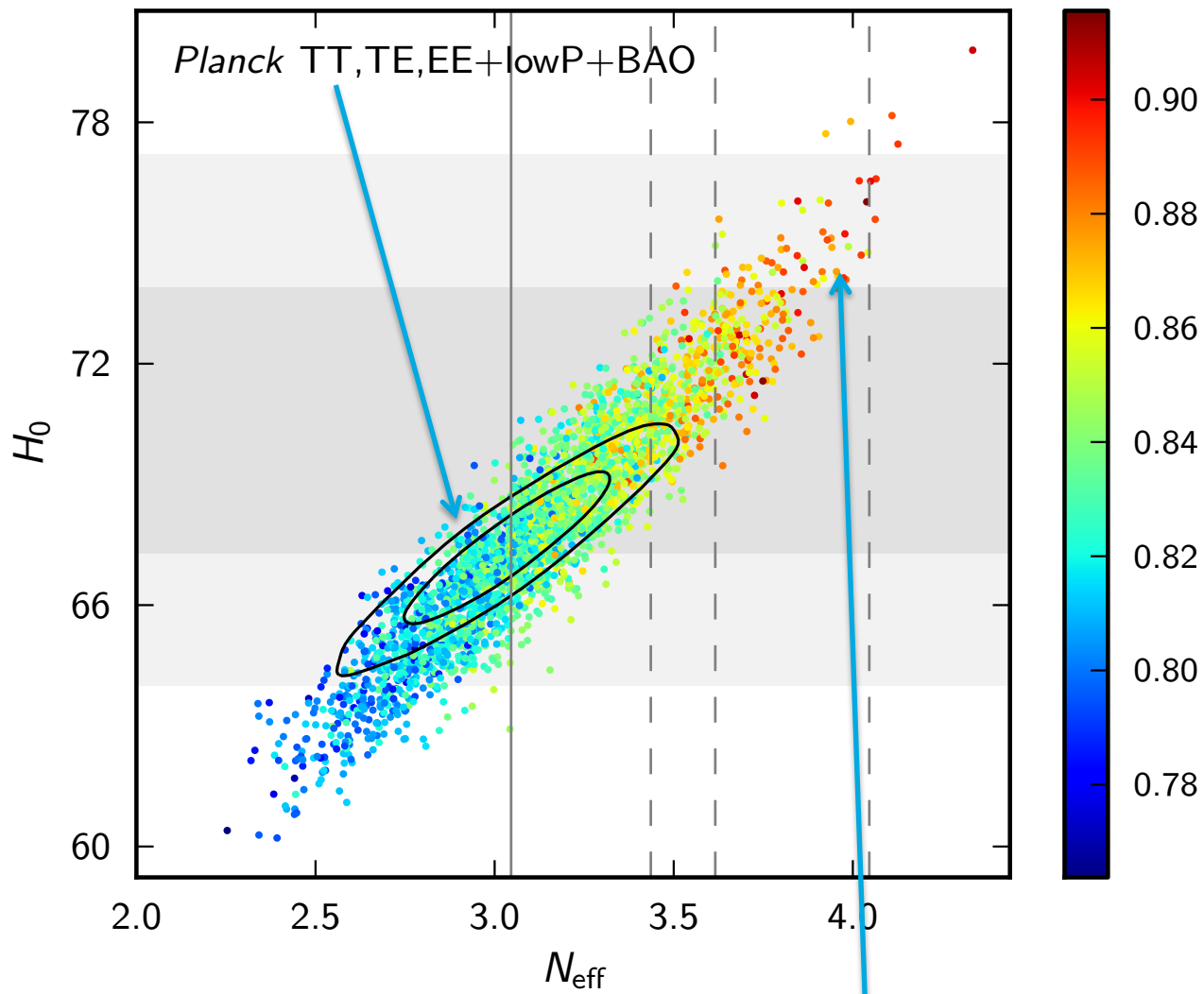
$$N_{\text{eff}} = 2.98 \pm 0.20 \quad (\text{PlanckTT,TE,EE+lowP})$$

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

(uncertainties are 68% CL)

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

N_{eff} constraints from Planck



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.

Joint constraints on N_{eff} and Σm_ν

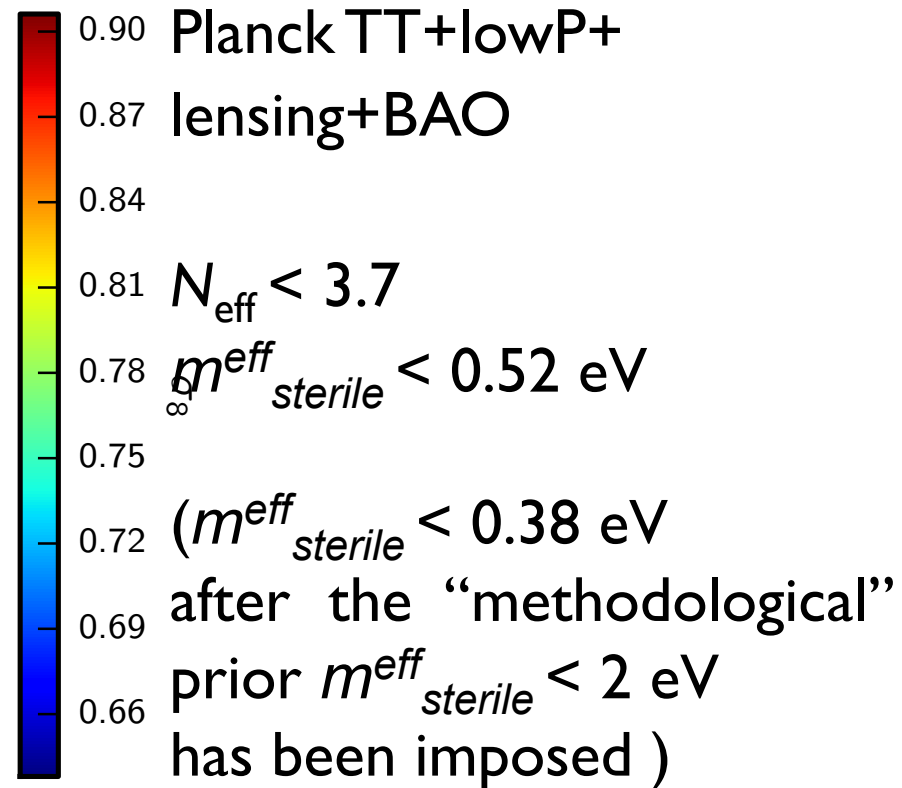
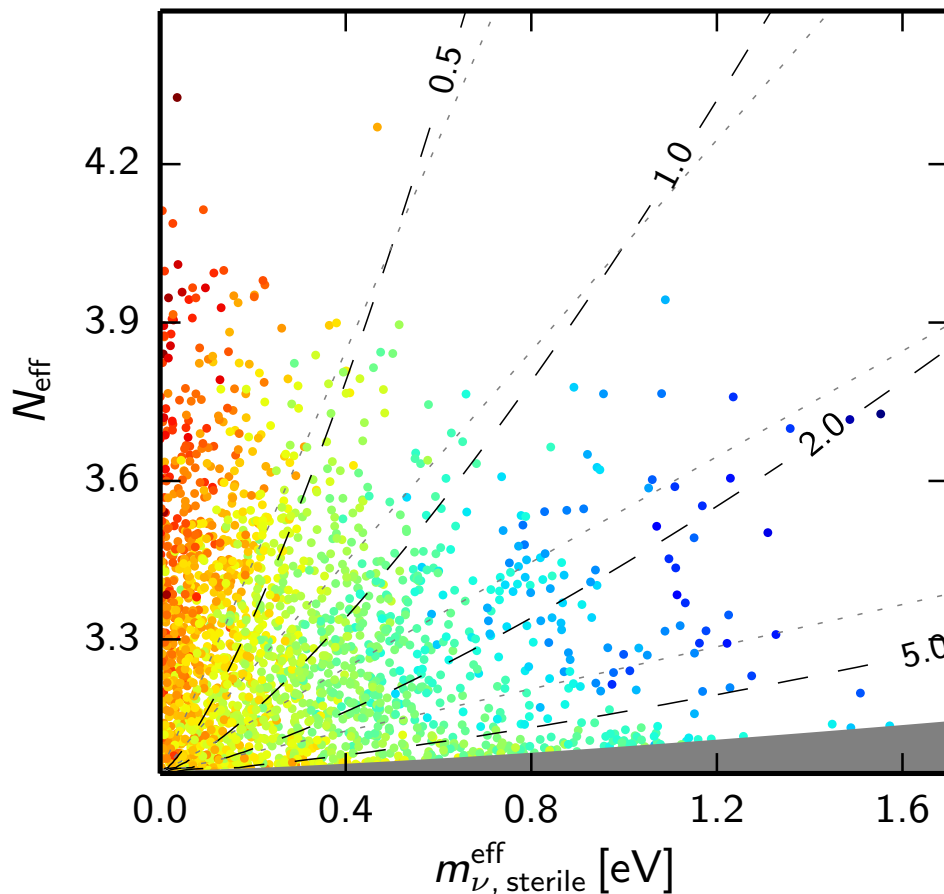
When both the mass and number of families are allowed to vary we get the following joint constraints:

$$N_{\text{eff}} = 3.2 \pm 0.5 \quad (95\% \text{ PlanckTT+lowP} \\ \Sigma m_\nu < 0.32 \text{ eV} \quad \text{+lensing+BAO})$$

$$N_{\text{eff}} = 3.0 \pm 0.4 \quad (95\% \text{ PlanckTT,TE,EE} \\ \Sigma m_\nu < 0.22 \text{ eV} \quad \text{+lowP+lensing+BAO})$$

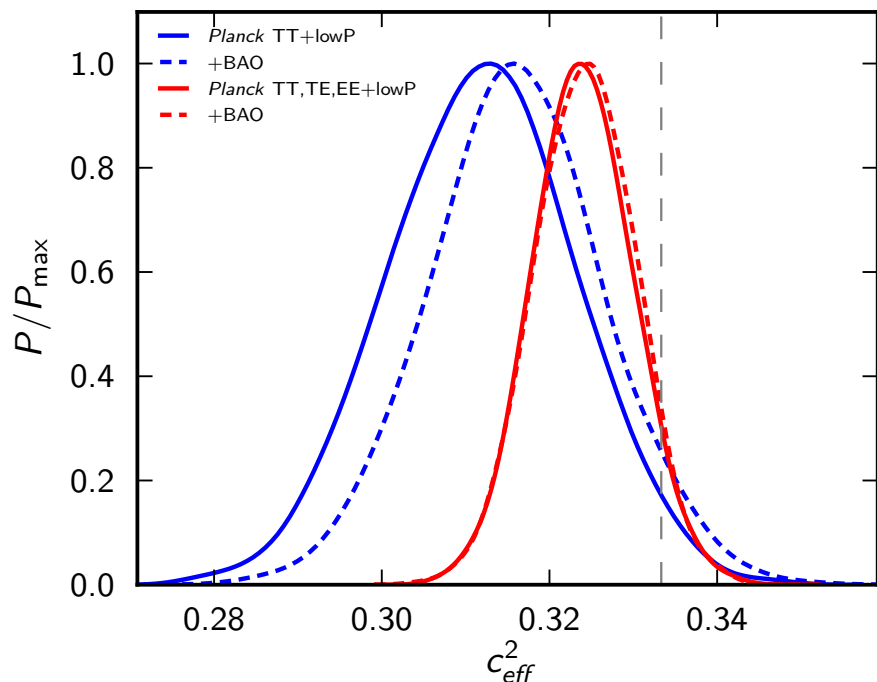
Significance of $N_{\text{eff}} < 4$ is reduced.

Planck constraints on sterile neutrinos



Probing $C_{\nu B}$ perturbations

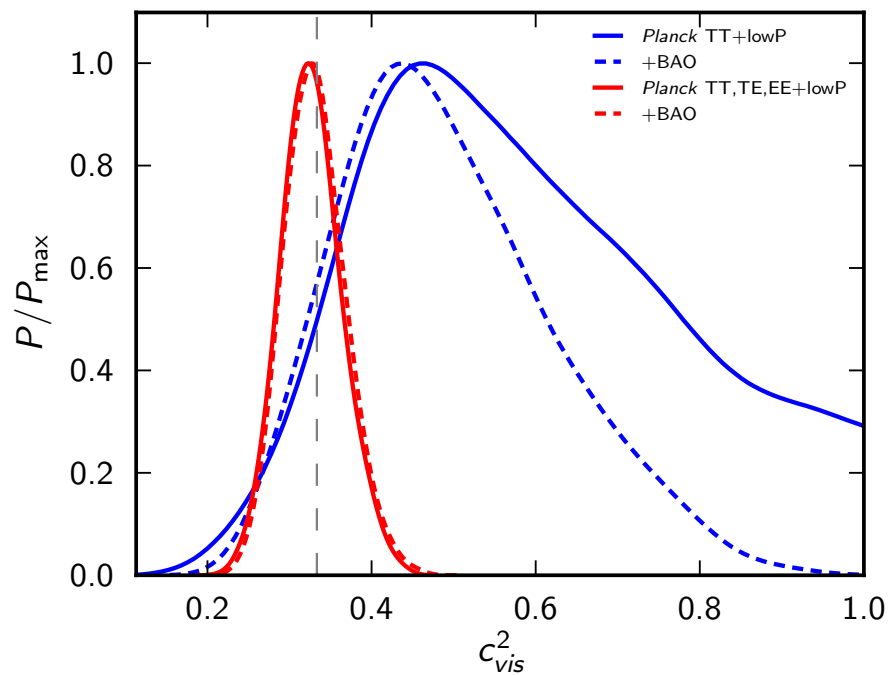
Parameterized by the effective ν sound speed and viscosity
 Consistent with free-streaming neutrinos ($c_{\text{vis}}^2 = c_{\text{eff}}^2 = 1/3$)



PlanckTT+lowP+BAO

$$c_{\text{eff}}^2 = 0.316 \pm 0.010$$

$$c_{\text{vis}}^2 = 0.44^{+0.15}_{-0.10}$$

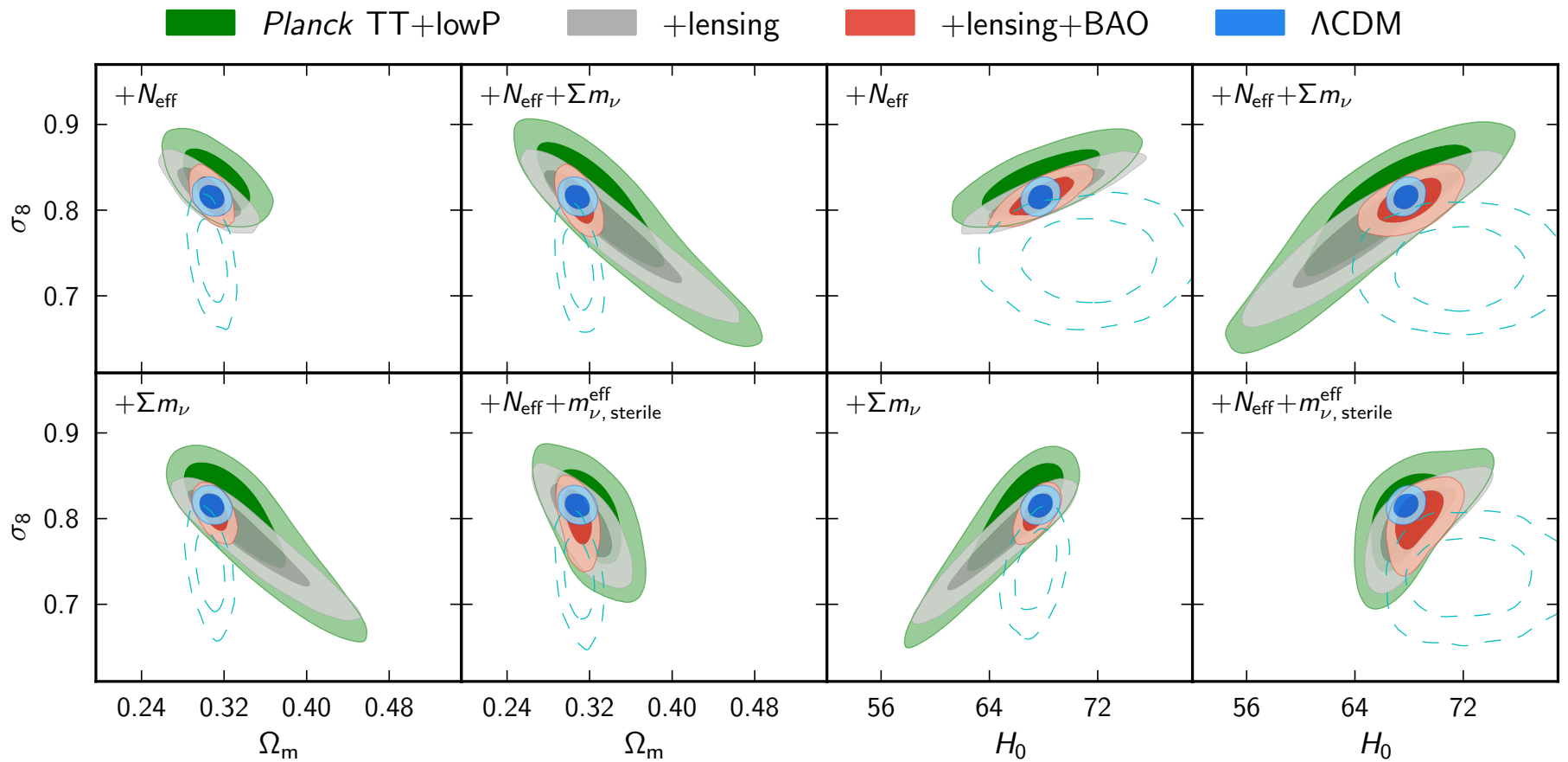


PlanckTT,TE,EE+lowP+BAO

$$c_{\text{eff}}^2 = 0.3242 \pm 0.0059$$

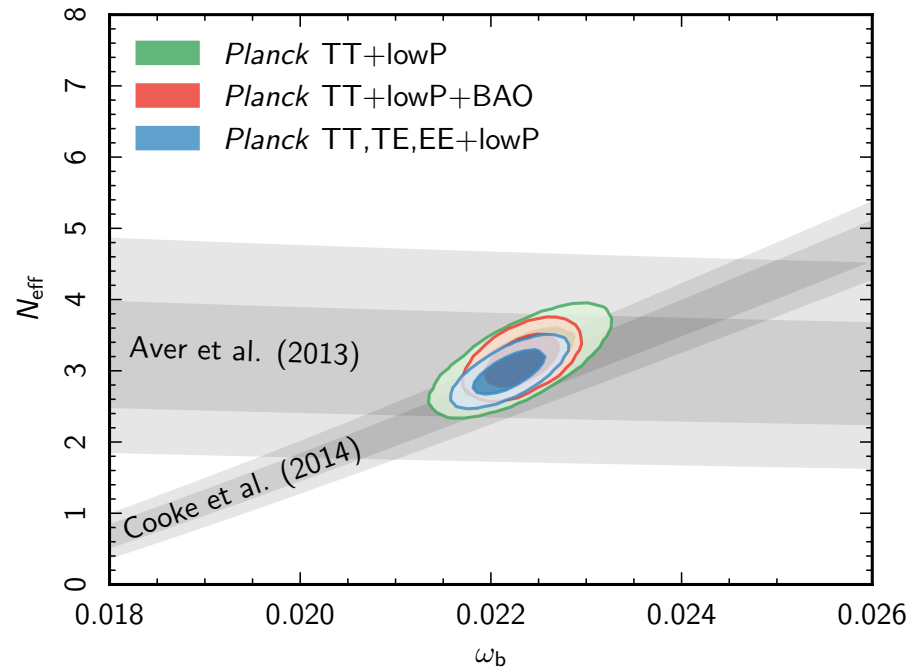
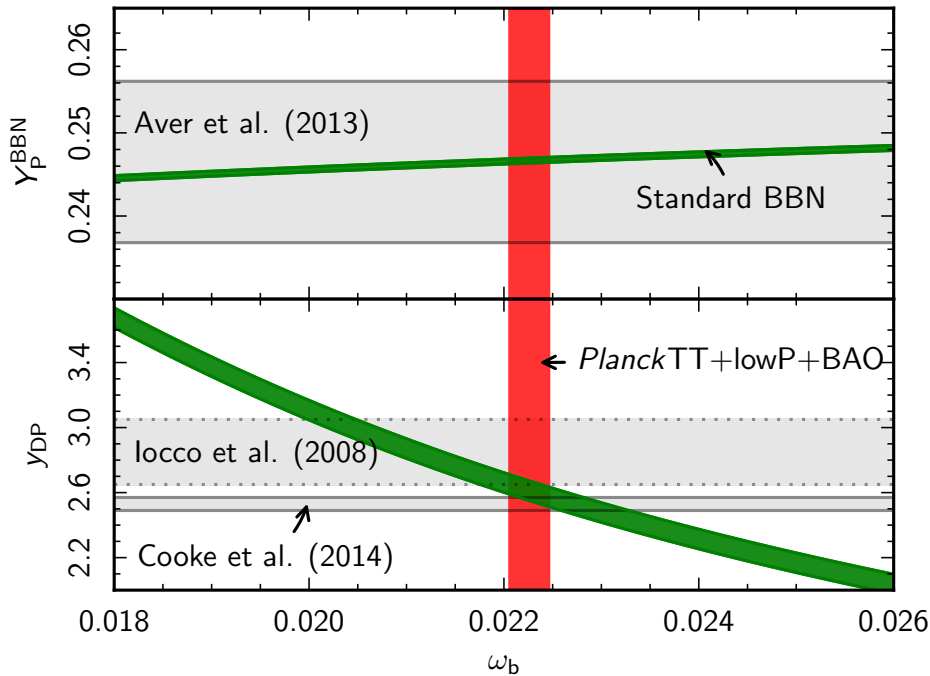
$$c_{\text{vis}}^2 = 0.331 \pm 0.037$$

Tension with external data



The tension still remains, also in 2-parameter extensions

Primordial nucleosynthesis



Consistent with measurements of the primordial abundances

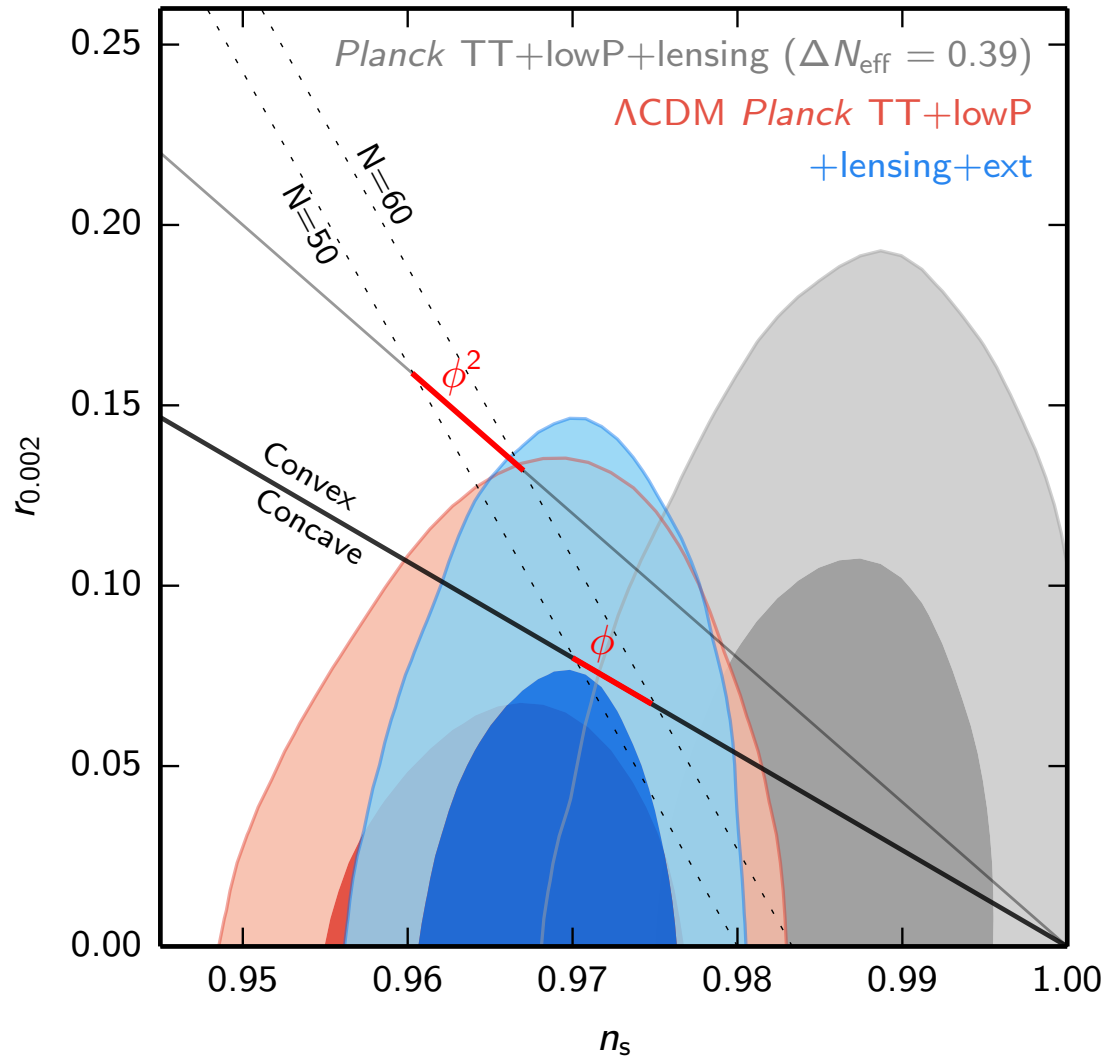
COSMOLOGICAL PARAMETERS: INFLATION



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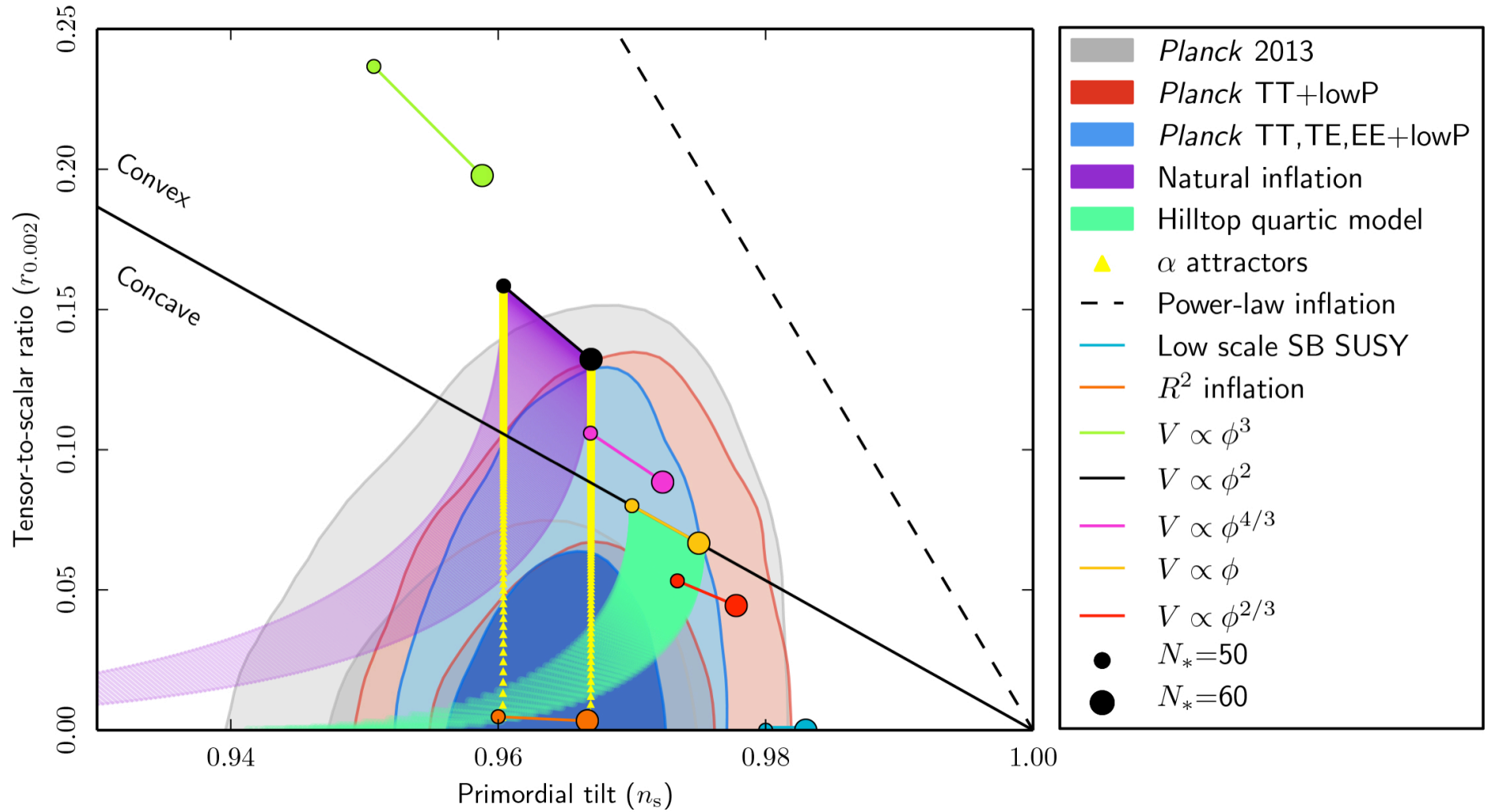
Scalar spectral index and tensors fluctuations



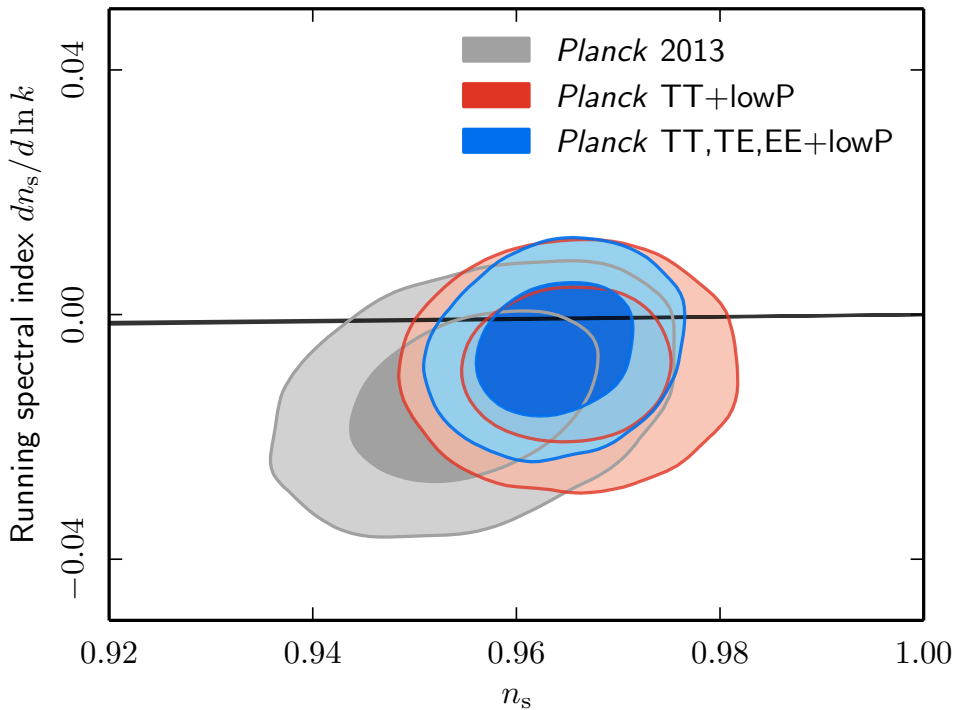
Planck TT + lowP
 $r_{0.002} < 0.10$

+ lensing + ext
 $r_{0.002} < 0.11$

Scalar spectral index and tensors fluctuations



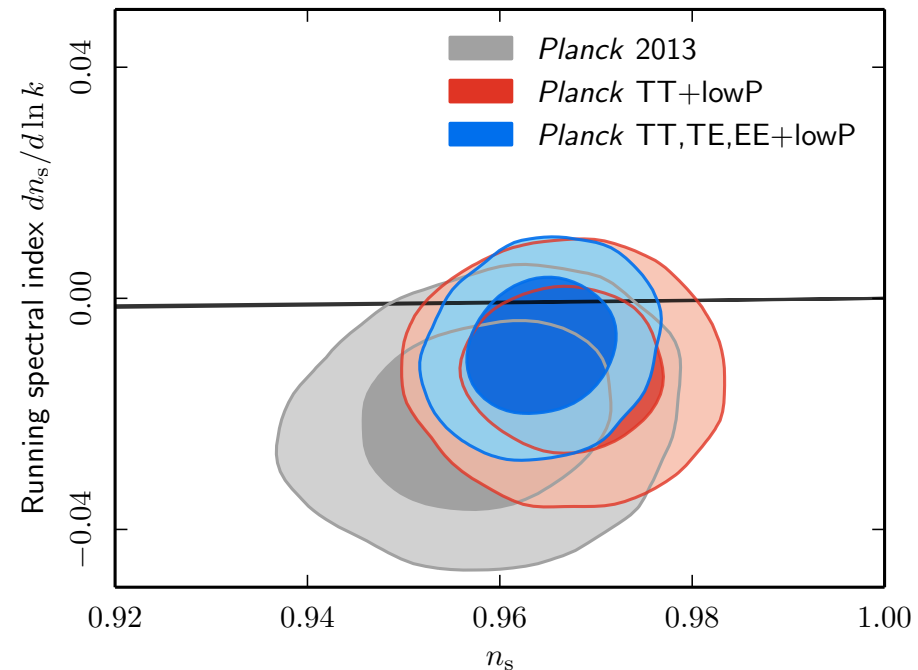
Running of the scalar spectral index



No tensors

$$n_{\text{run}} = -0.0084 \pm 0.0082$$

$$n_{\text{run}} = -0.0057 \pm 0.0071$$



with tensors

$$r_{0.002} < 0.18$$

$$n_{\text{run}} = -0.013 \pm 0.010$$

$$r_{0.002} < 0.15$$

$$n_{\text{run}} = -0.009 \pm 0.008$$

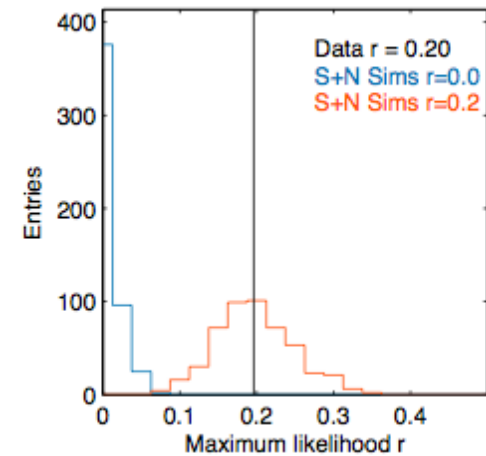
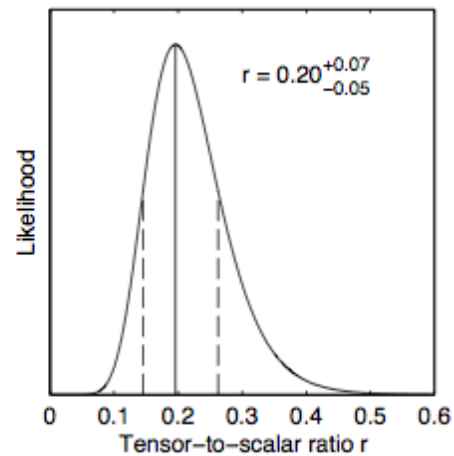
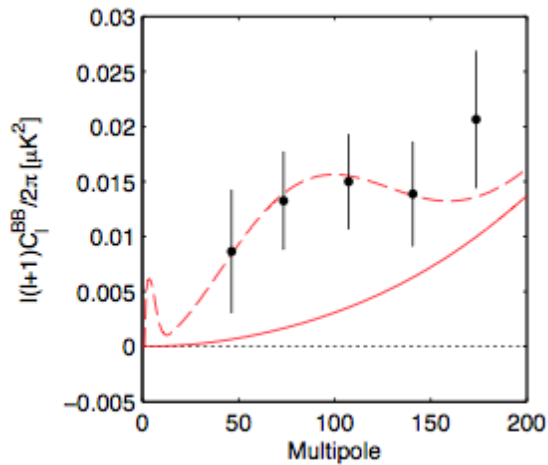
PLANCK AND BICEP2

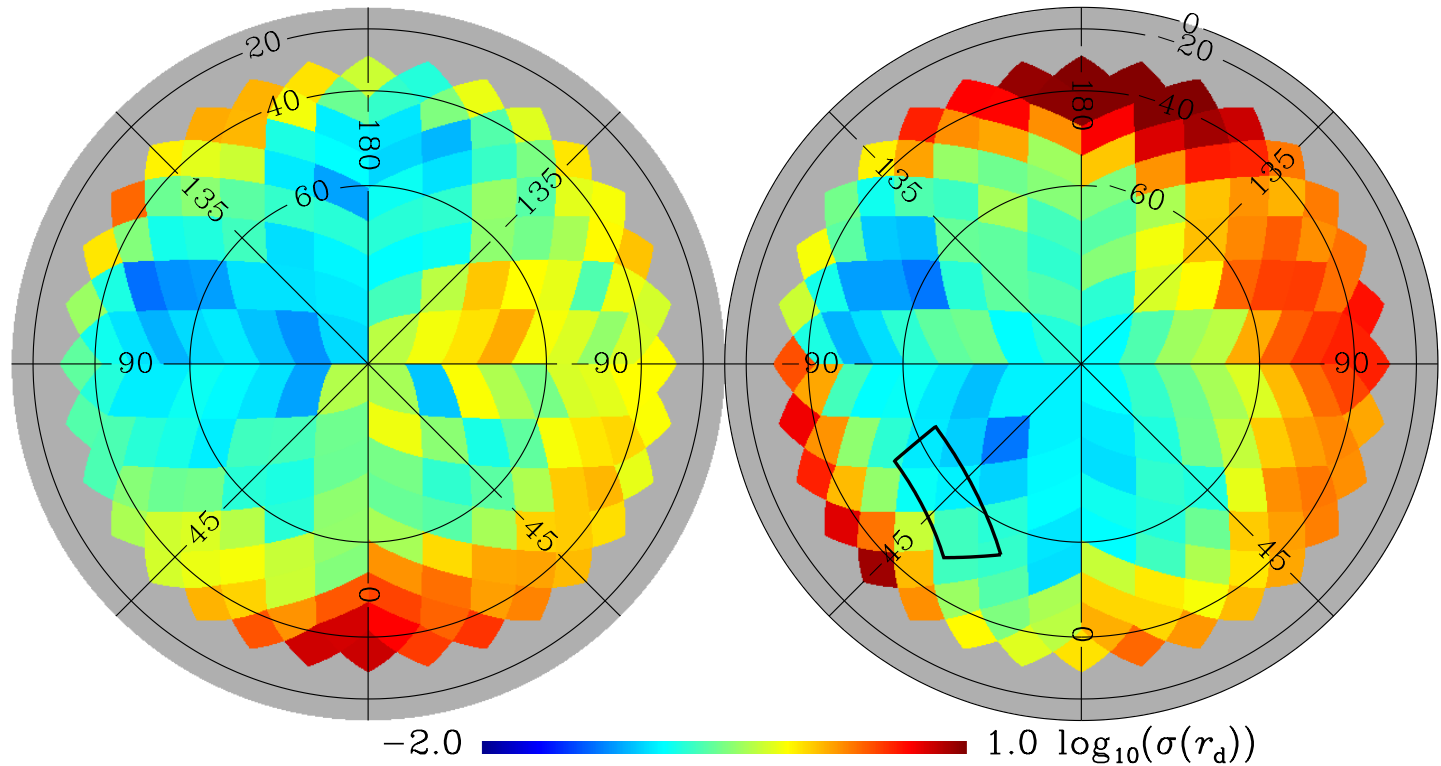


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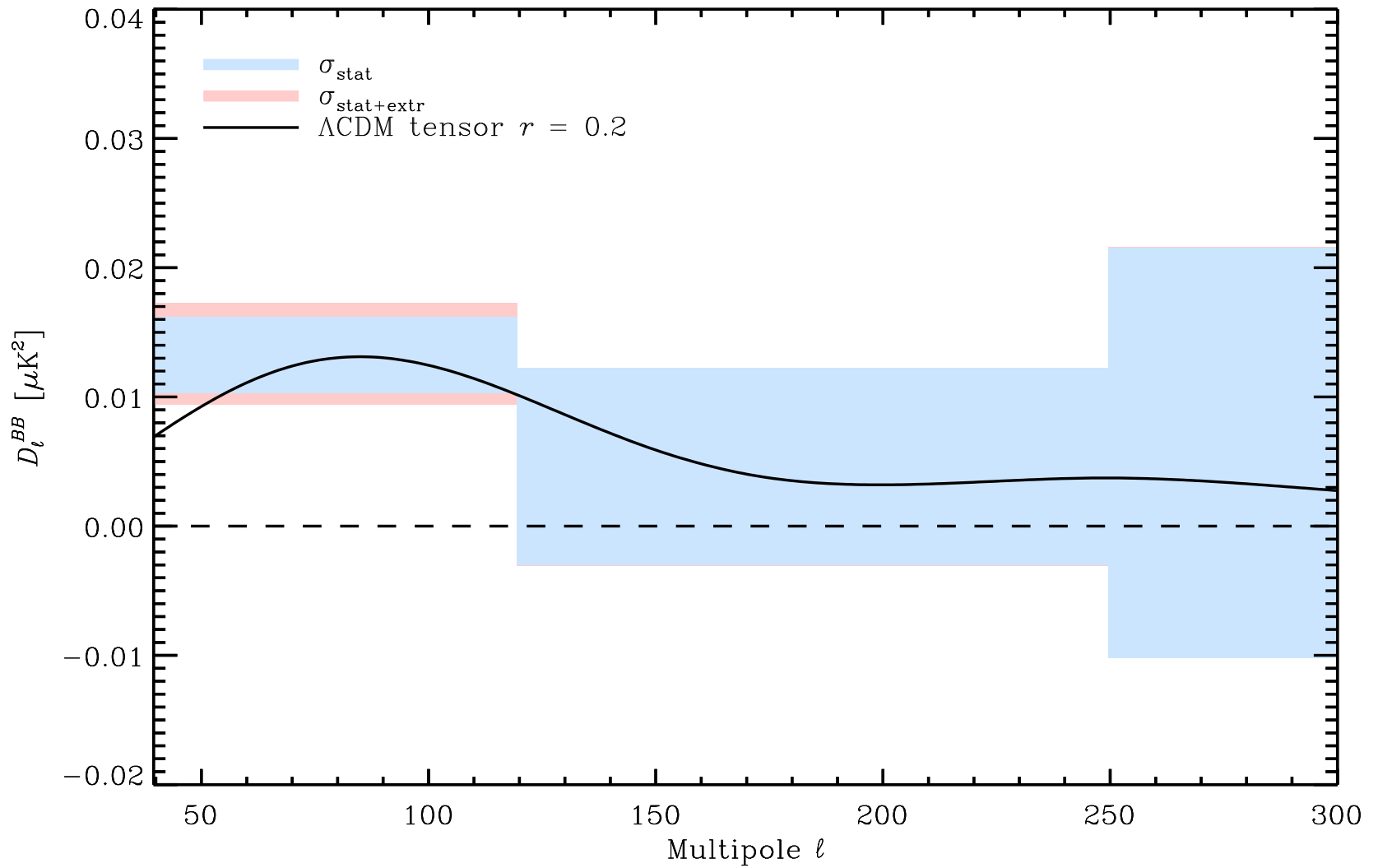


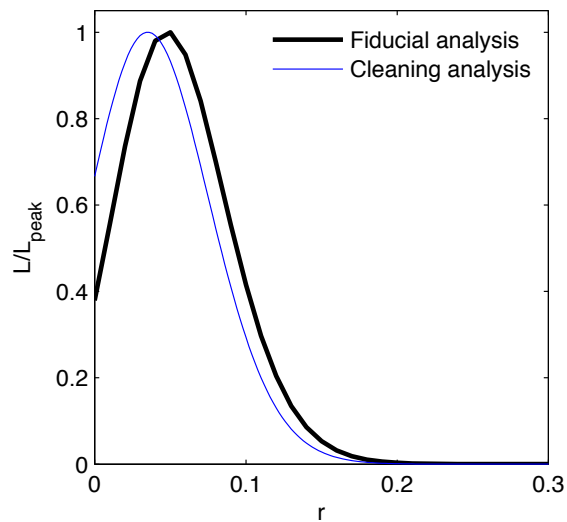
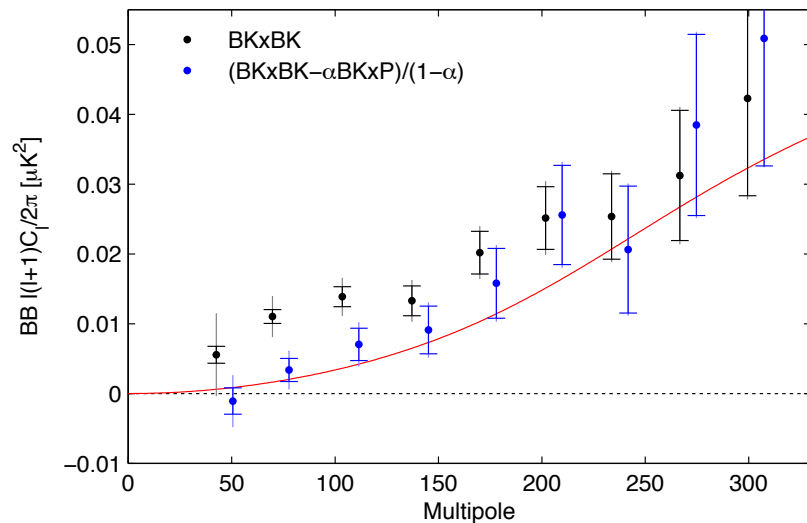
MARCH 2016: BICEP2 CLAIMS THEY HAVE OBSERVED GRAVITATIONAL WAVES



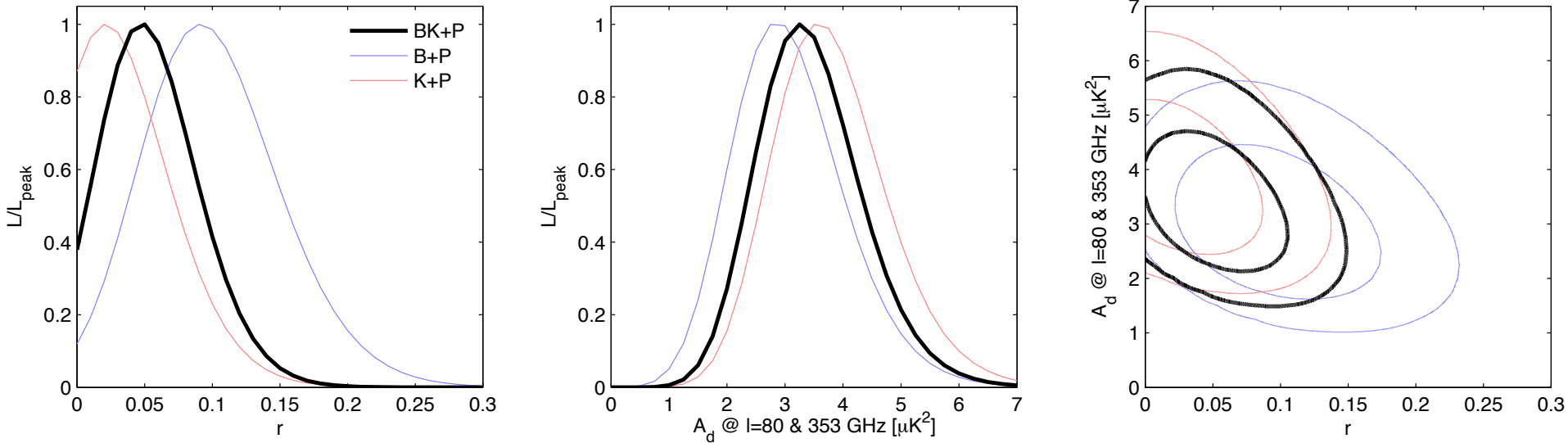


Planck BB amplitude from the 353 GHz data, extrapolated to 150 GHz, normalized to the CMB expectation for $r=1$
 The thick black contour outlines the BICEP2 deep-field region





Joint Planck/Bicep2/Keck analysis



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

$$r < 0.12$$

arXiv:1502.00612

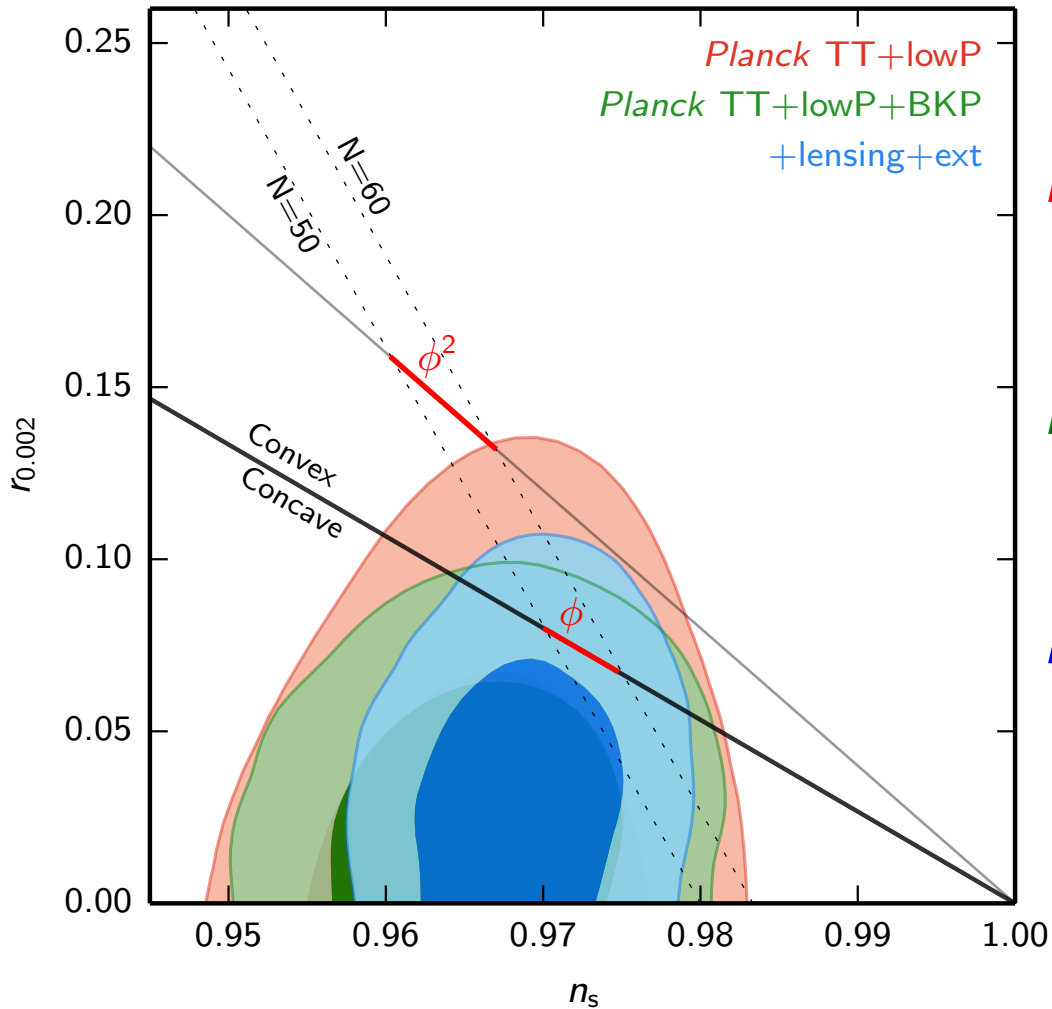


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Scalar spectral index and tensors fluctuations



Planck TT + lowP

$r_{0.002} < 0.10$

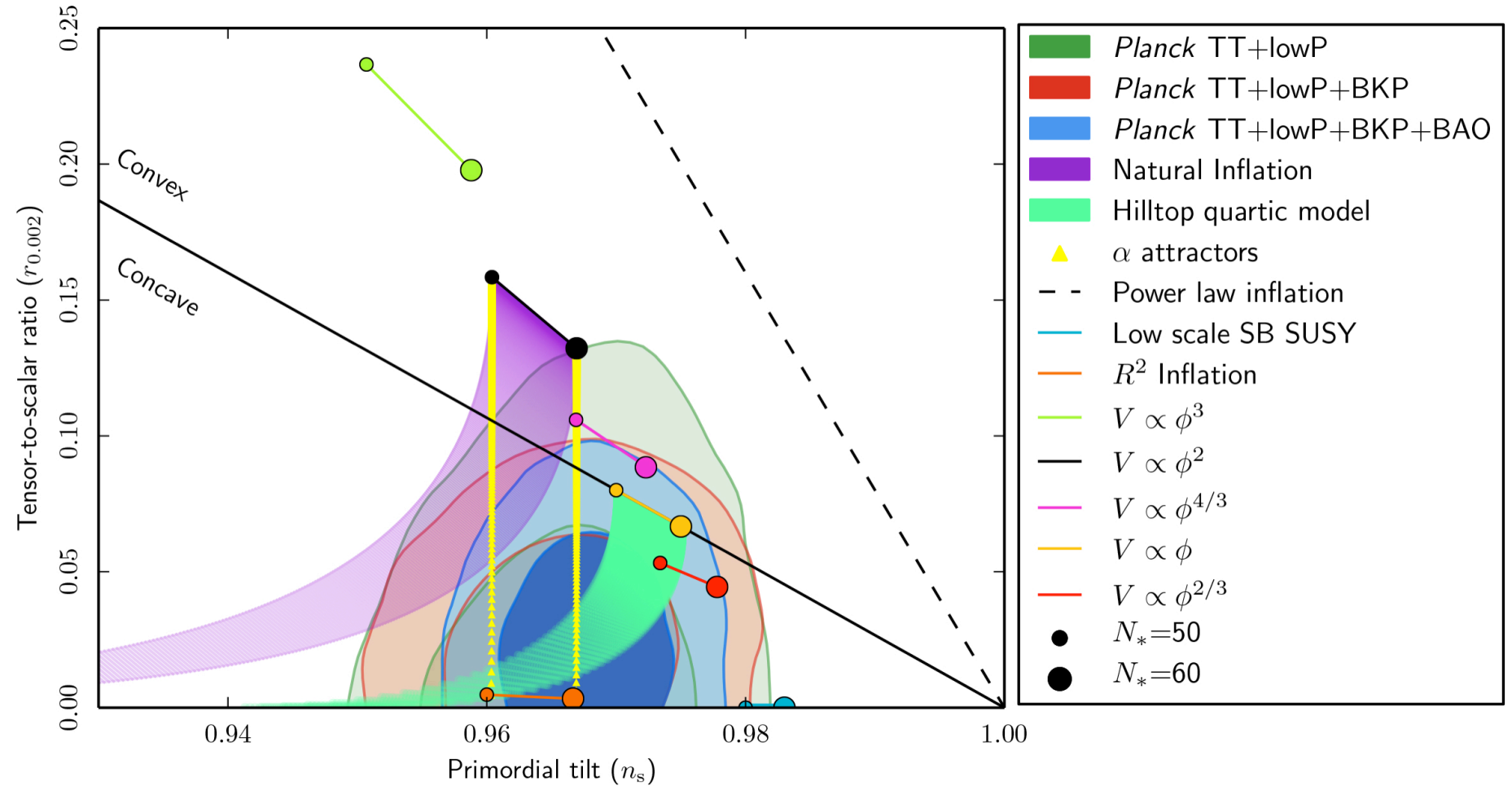
Planck TT + lowP+BKP

$r_{0.002} < 0.08$

+ 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)
- Λ CDM is in very good shape
- 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 ν 's
- No evidence of tensor modes, but still plenty of room for them!
- ϕ^2 and natural inflation are in trouble
- No trace of parity violation so far... Constraints are improving.



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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