Planck 2015 cosmology: a check up on the health of the ΛCDM model

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on behalf of the Planck Collaboration

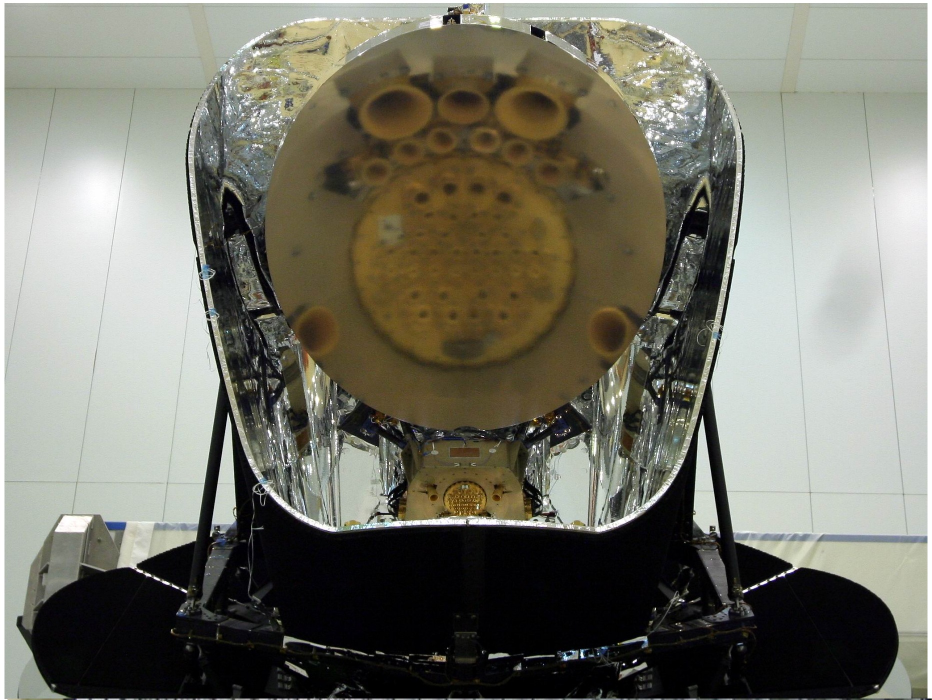
Results presented mainly based on Planck 2015 papers I, VI, VIII, XIII, XV, XX

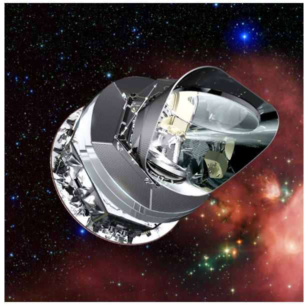
Les Rencontres de Physique de la Vallée d'Aoste

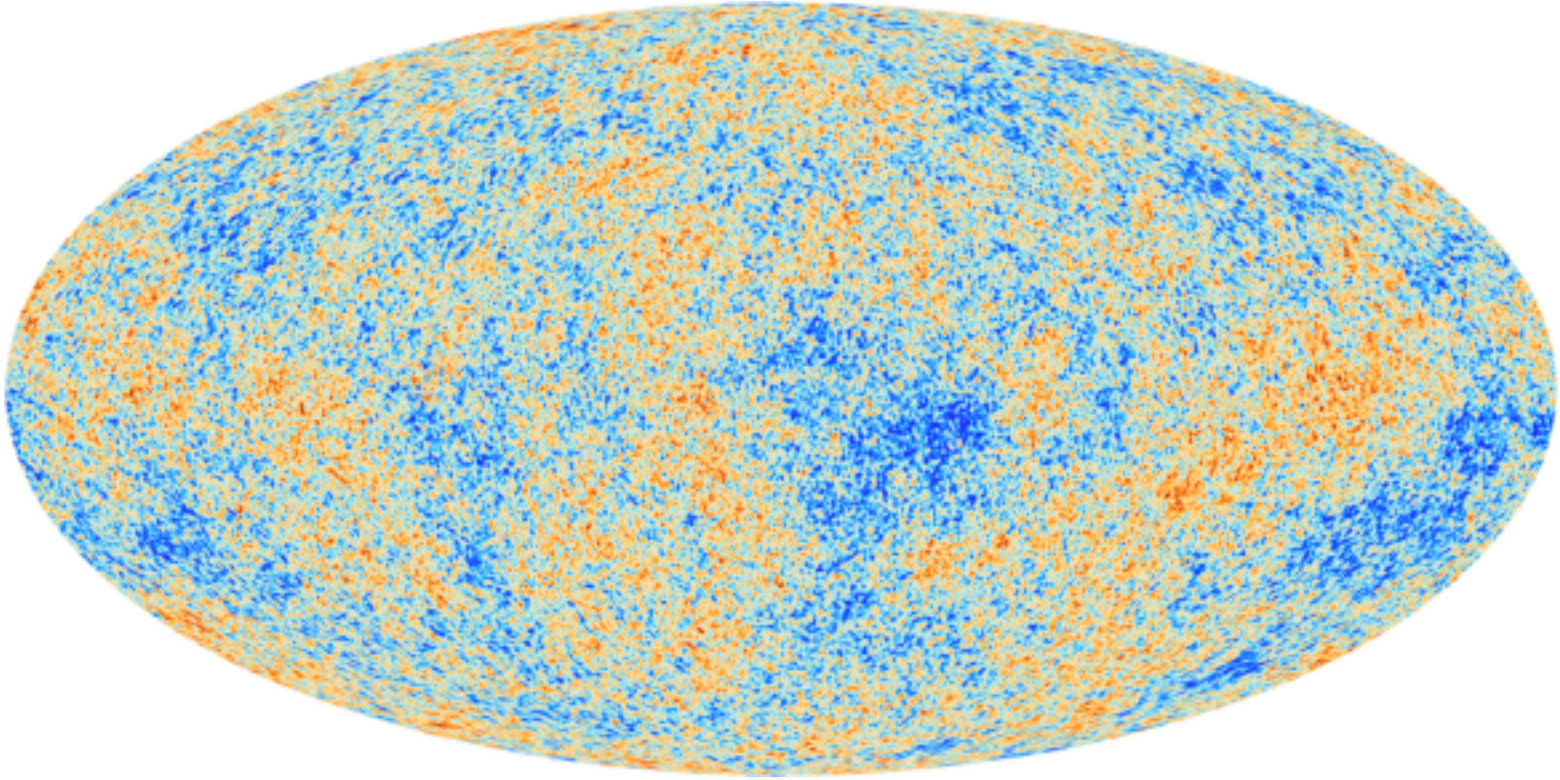
La Thuile– 7 March 2016

The Planck Satellite

- Third-generation satellite, launched and operated by ESA, dedicated to the CMB
- Observed the sky continously 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
- Third and final (legacy) release in 2016





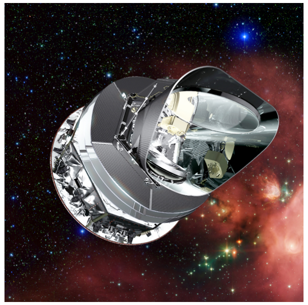


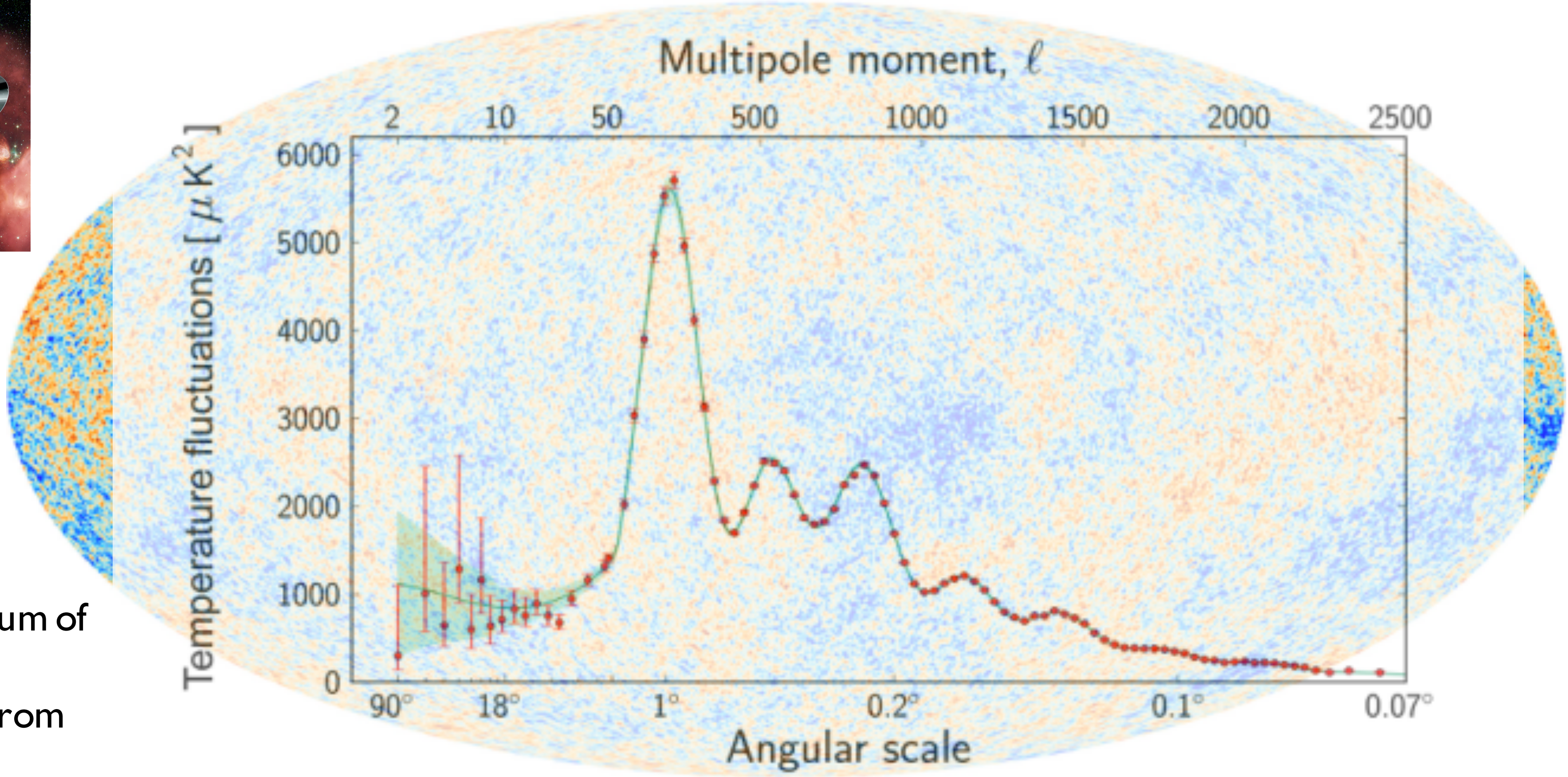
Full sky temperature map from Planck (2013)

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:

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

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

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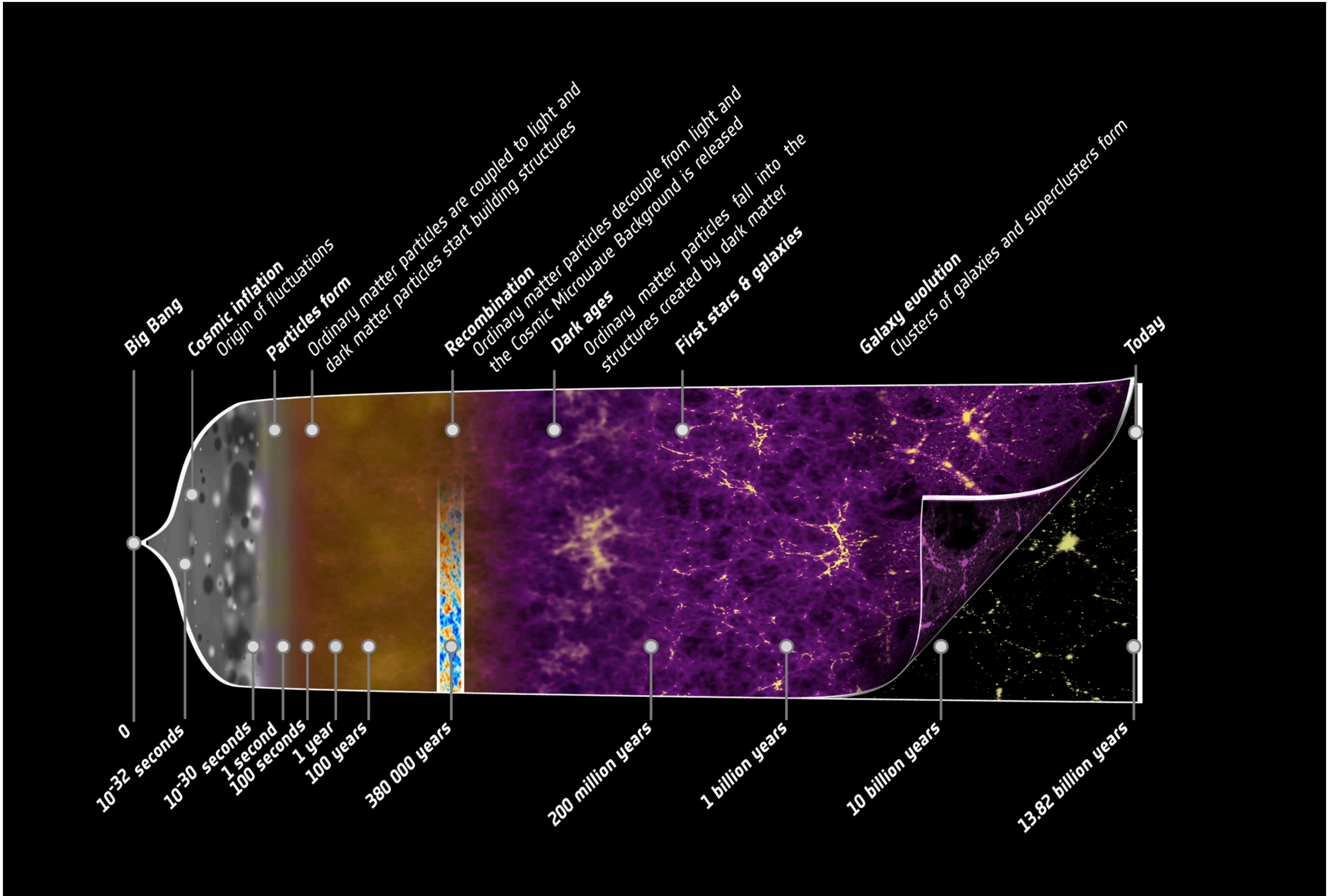
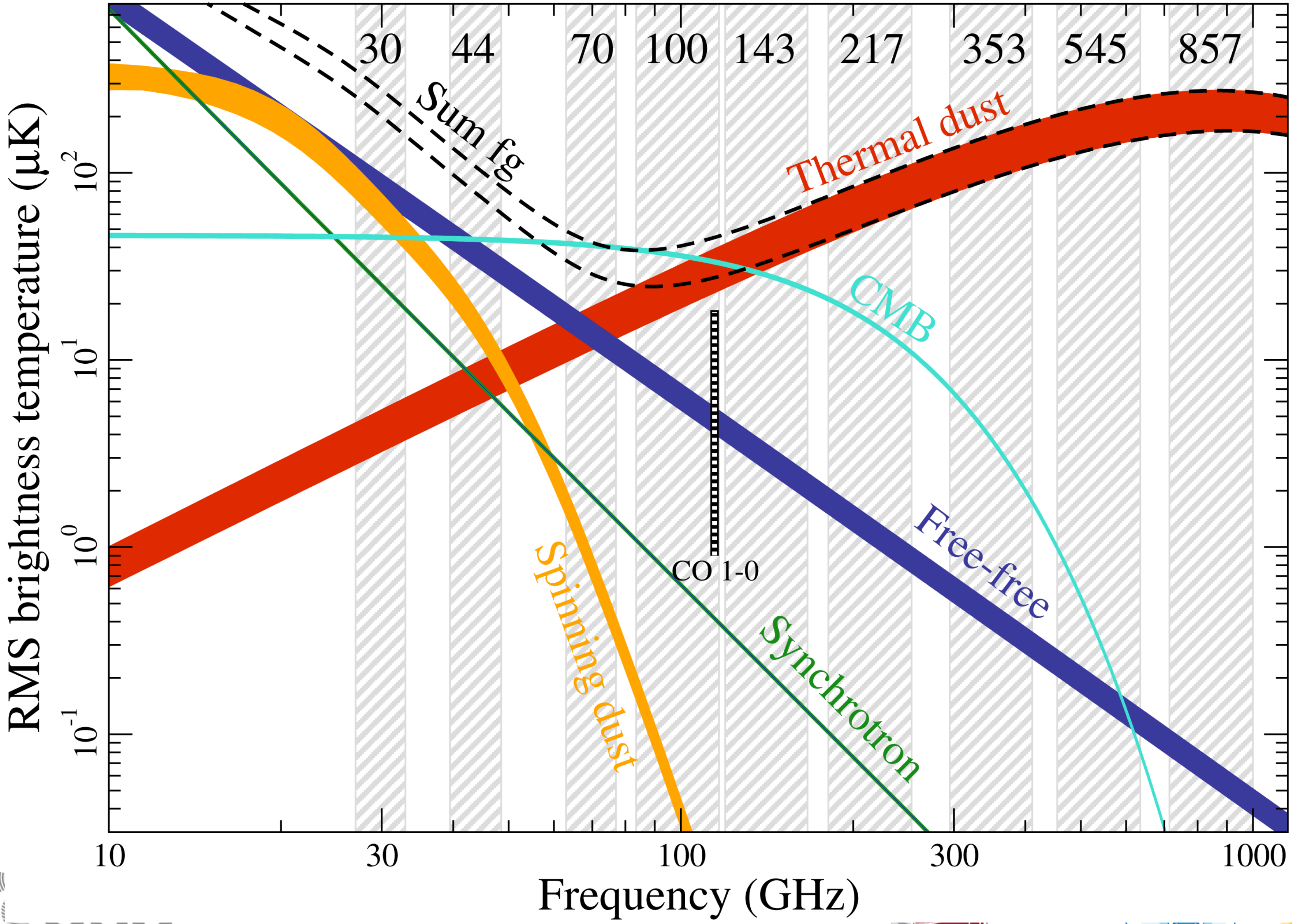
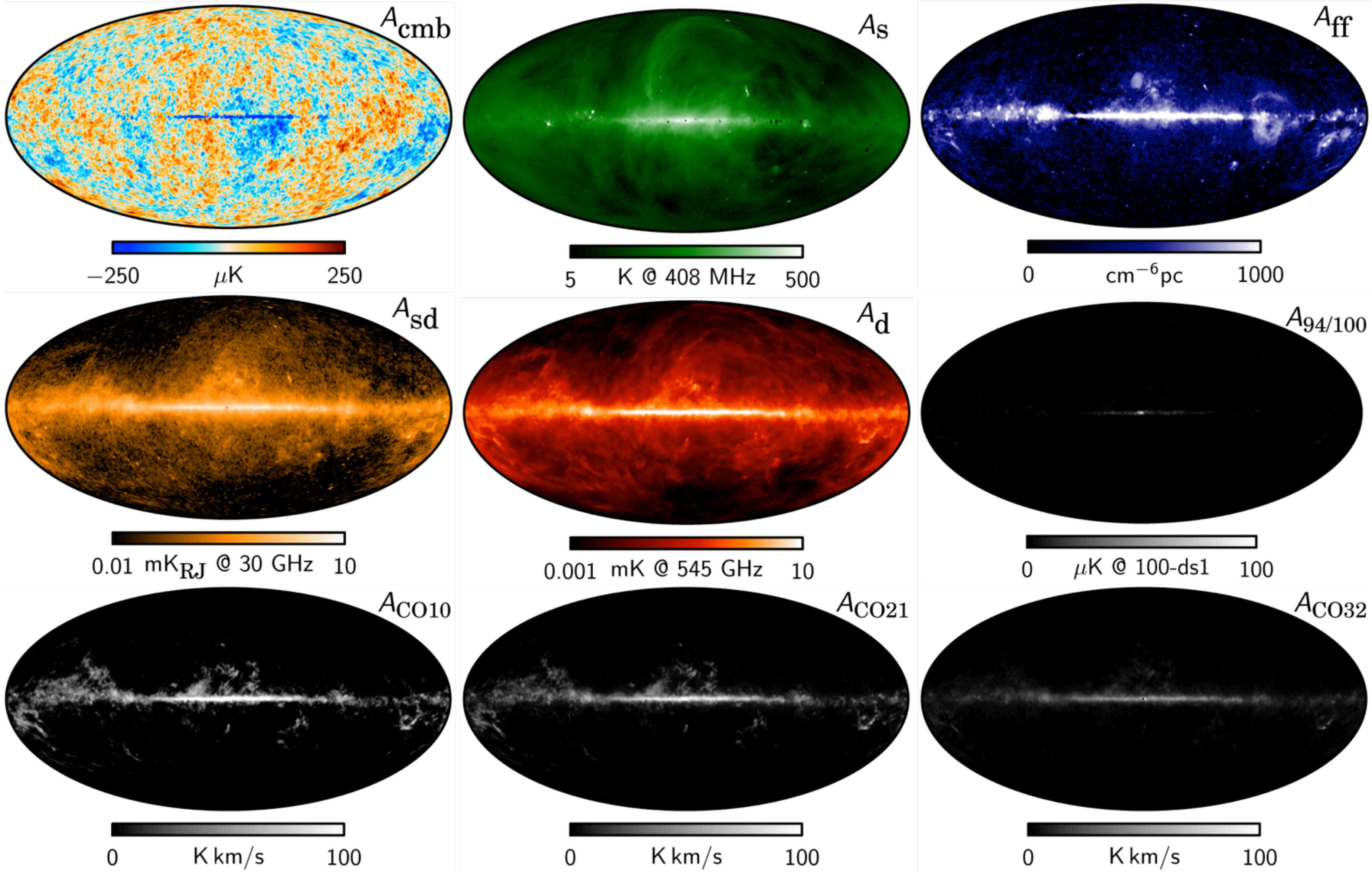


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles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

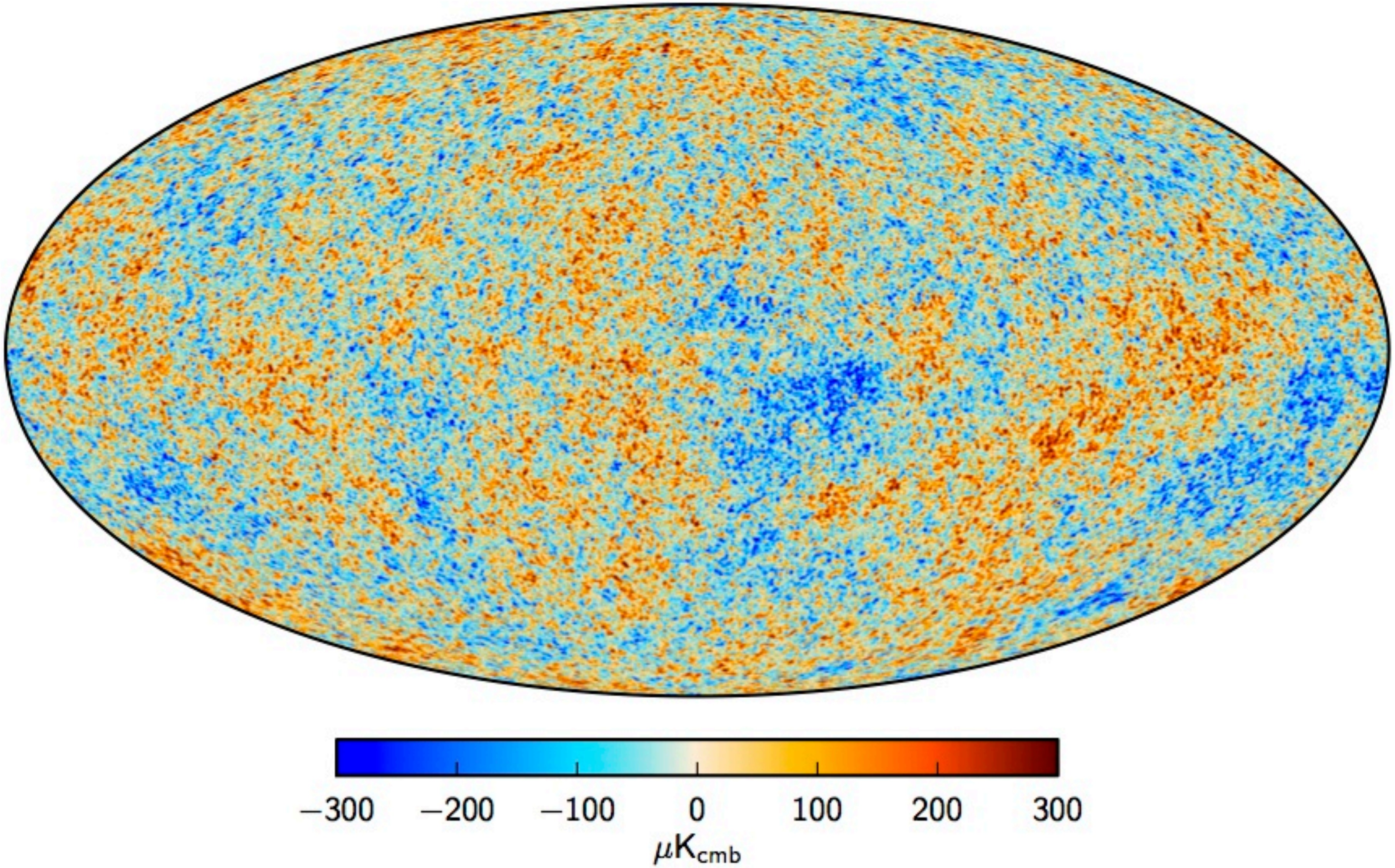
Frequency spectrum of RMS brightness temperature: CMB vs. astrophysical foregrounds



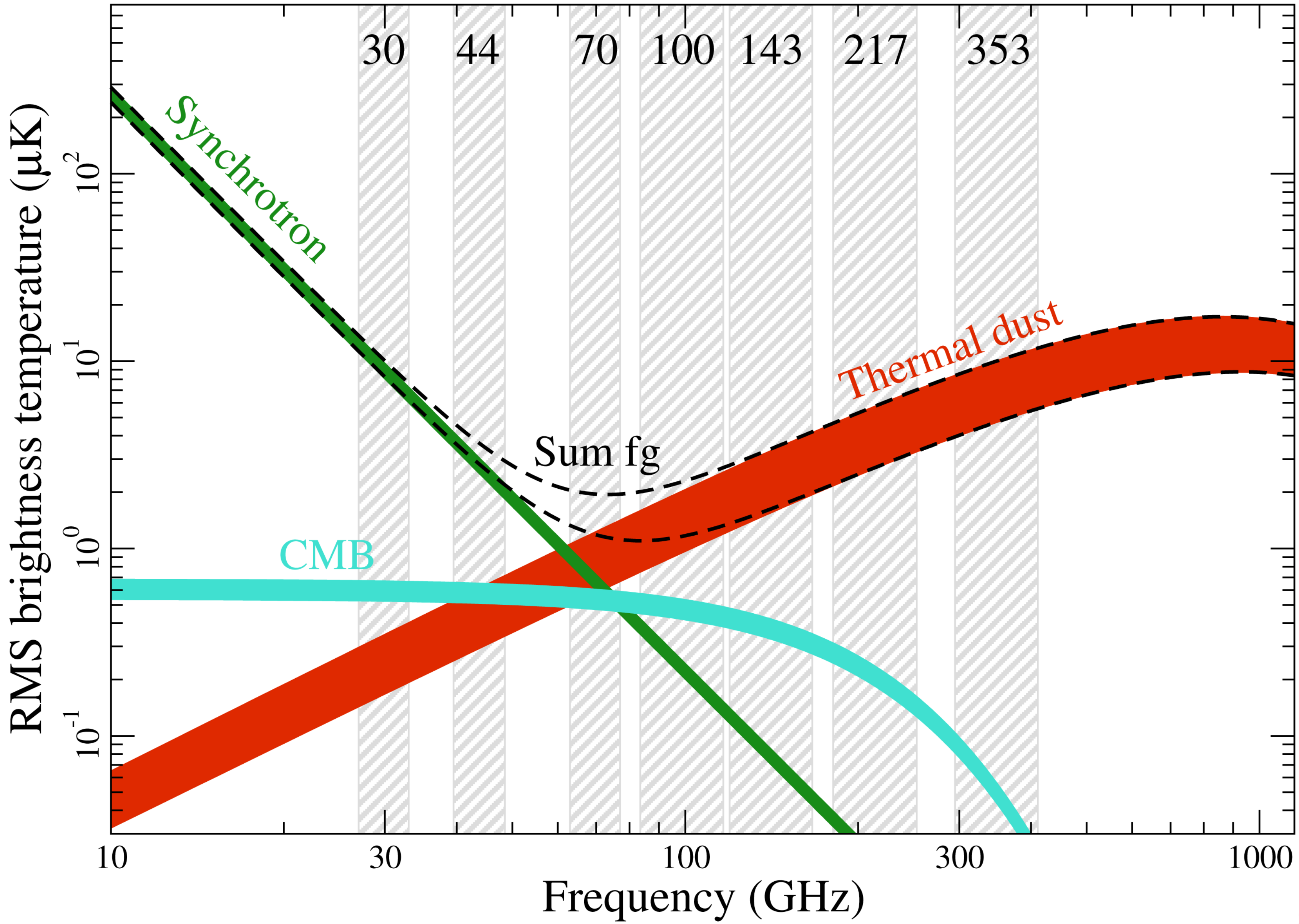


Maximum posterior intensity maps derived throughg the Commander algorithm from the joint analysis of Planck, WMAP and 408 MHz observations from Haslam

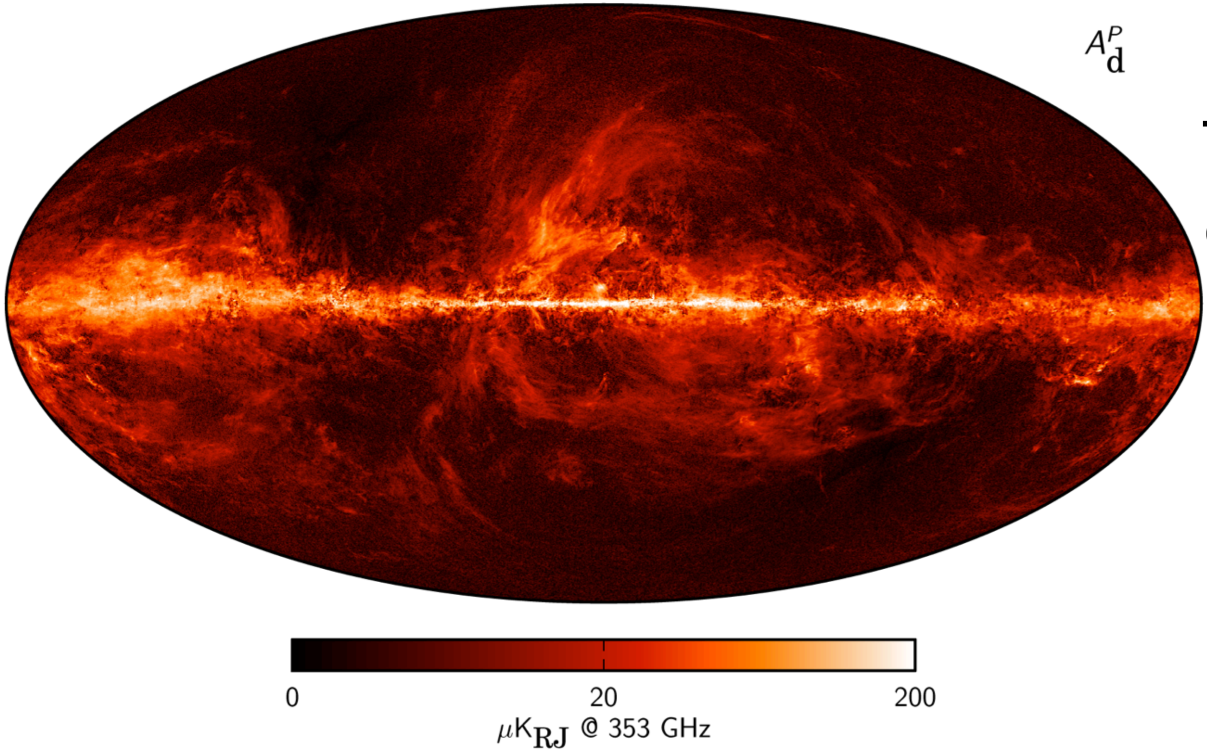
Planck 2015 Temperature map



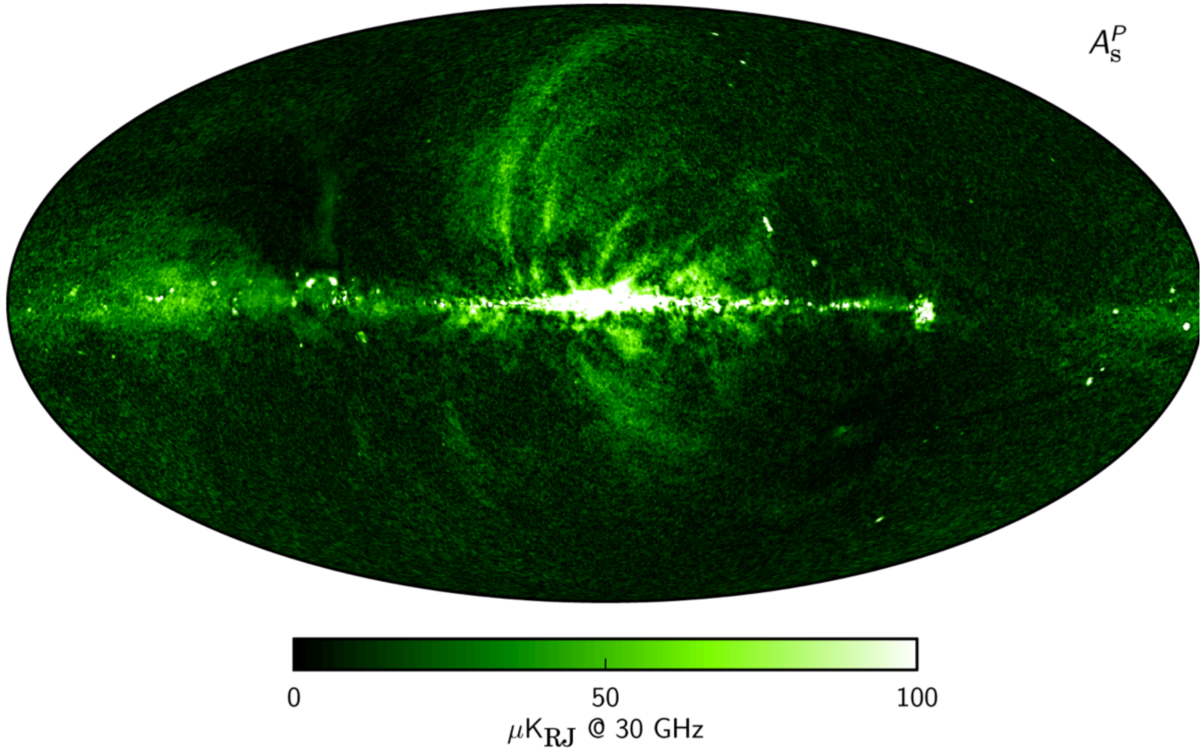
Frequency spectrum of RMS brightness polarization intensity: CMB vs. astrophysical foregrounds



Total polarized dust emission



Total polarized synchrotron emission



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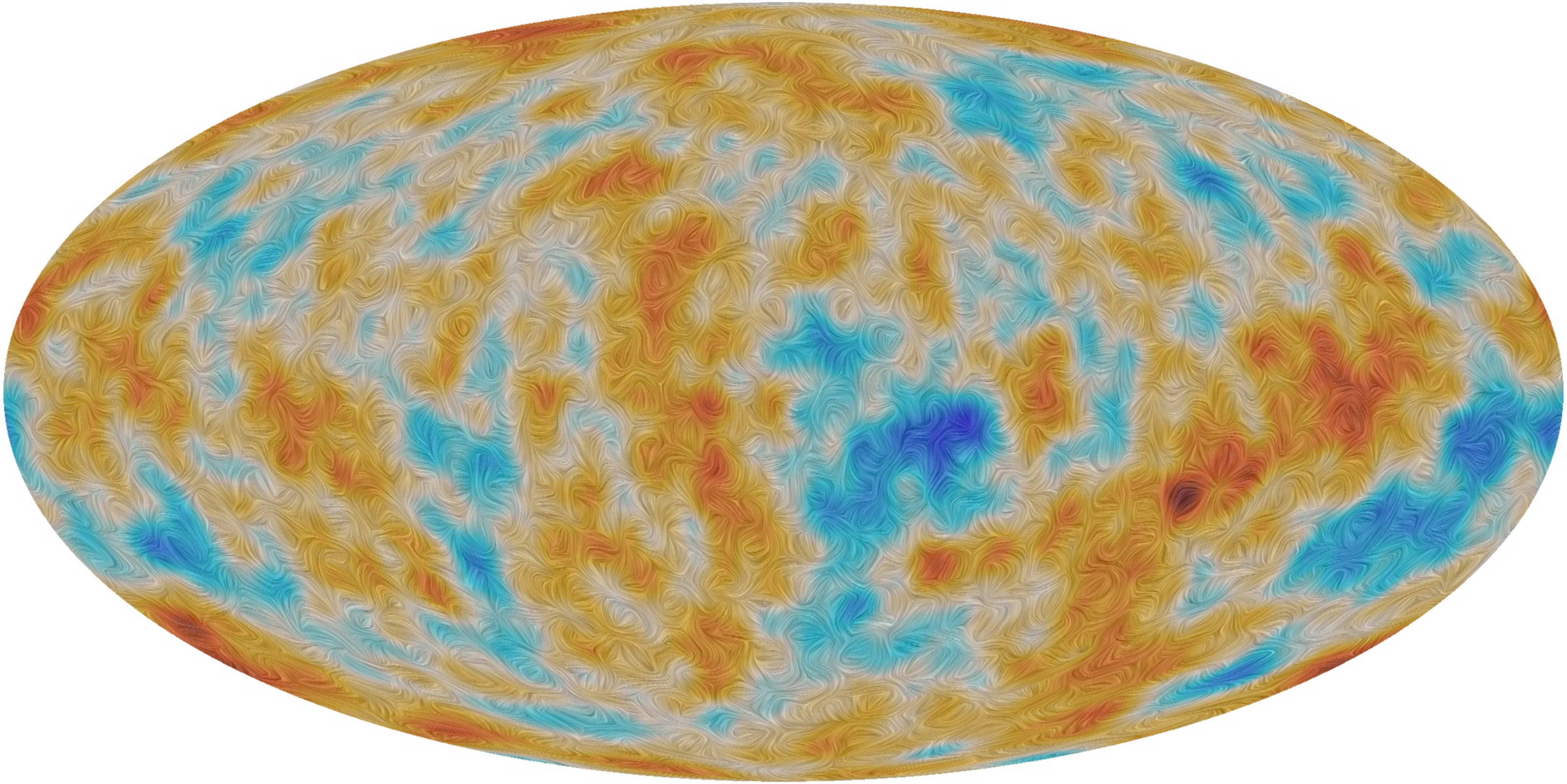
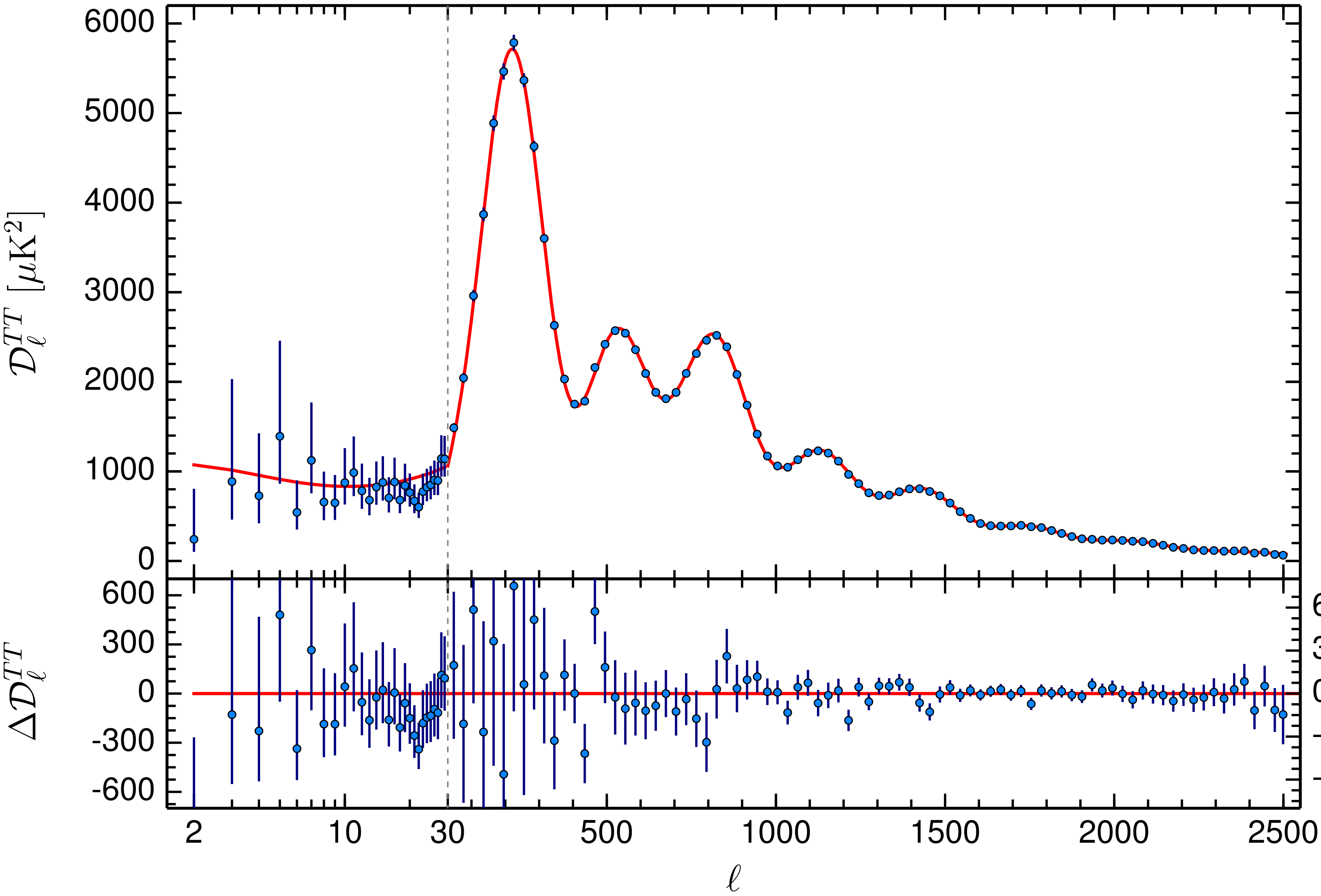
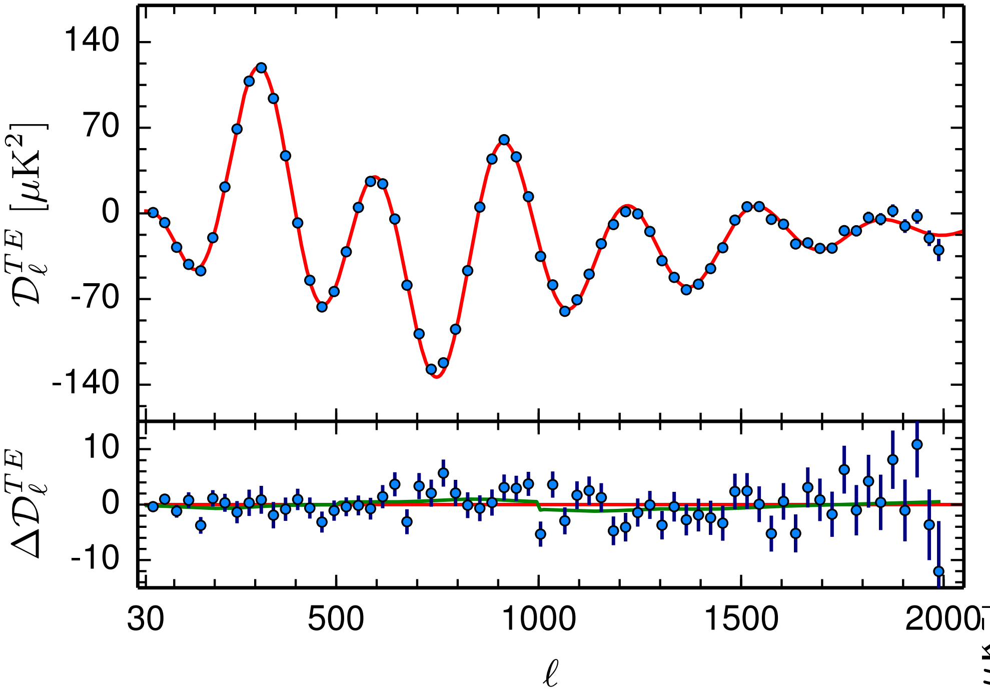
Planck 2015 Polarization map



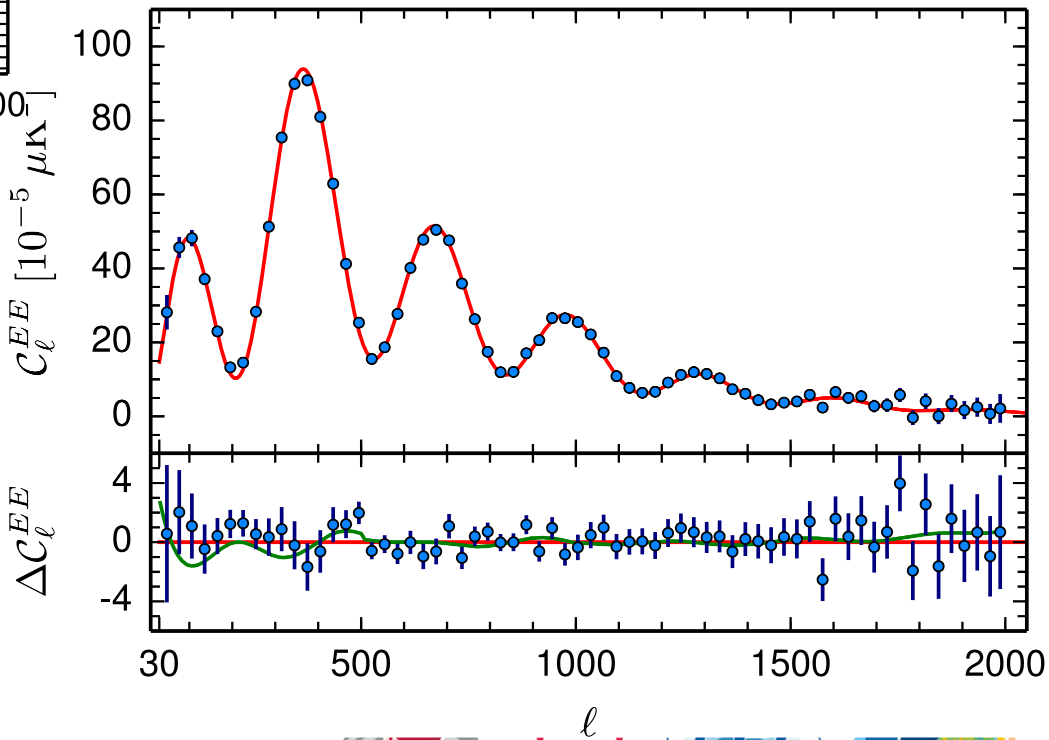
TT Angular power spectrum



TE and EE angular power spectra

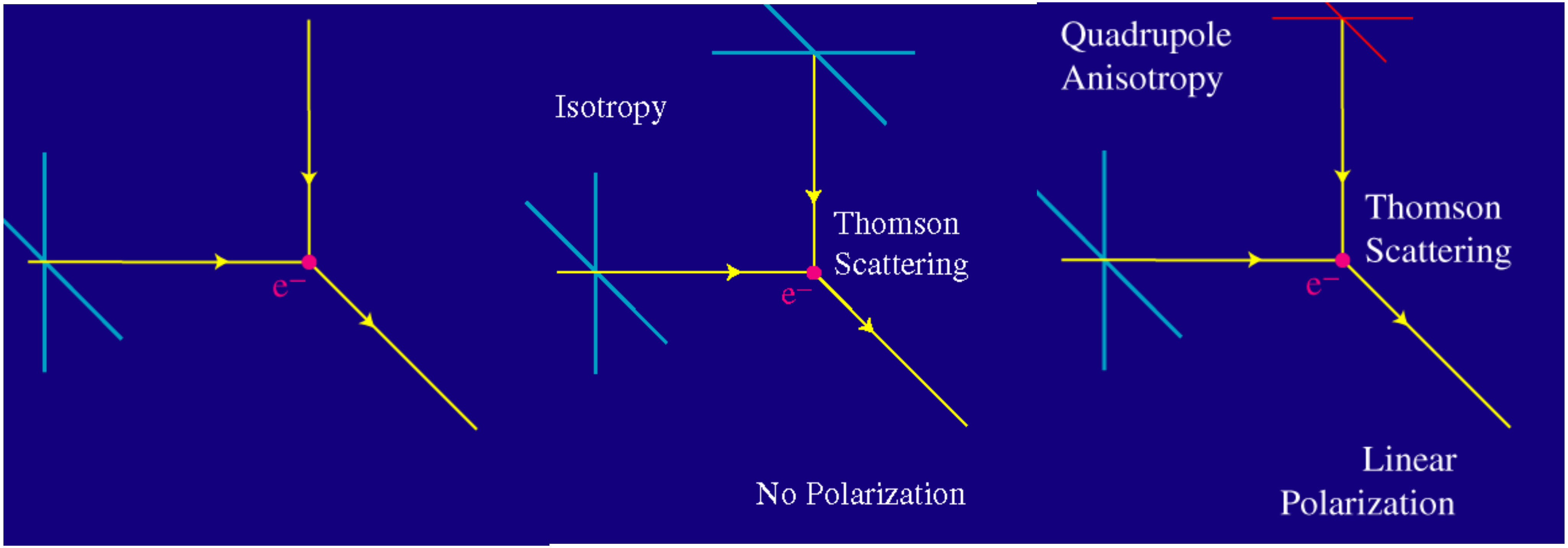


Red curves are fitted to the TT spectrum only!! (without accounting for T to P leakage)



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

CMB polarization



Wayne Hu

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

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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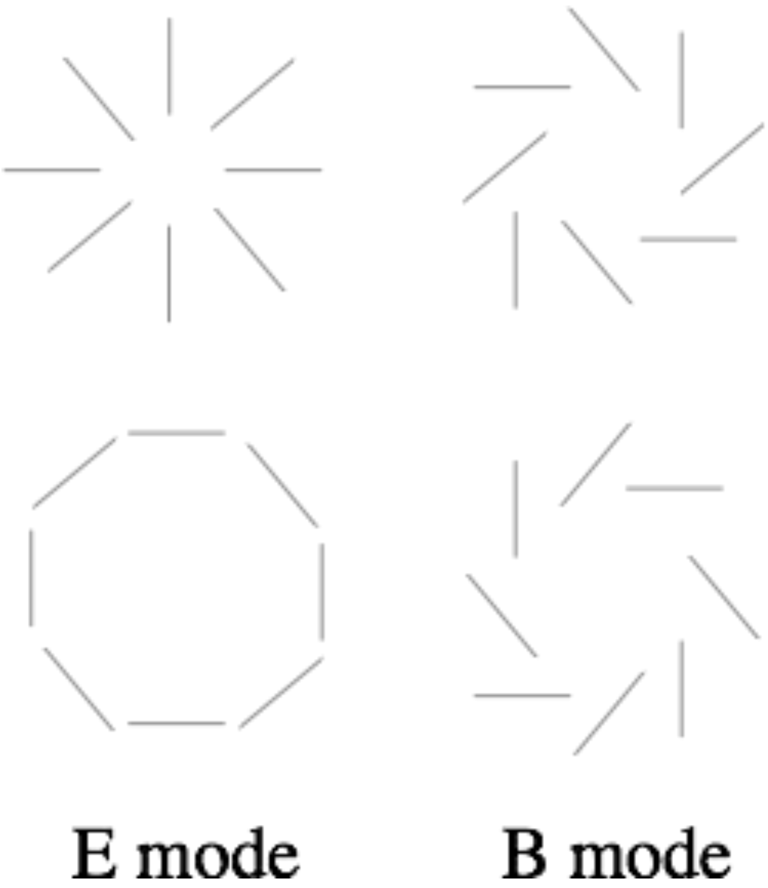
E-mode and B-mode



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!

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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

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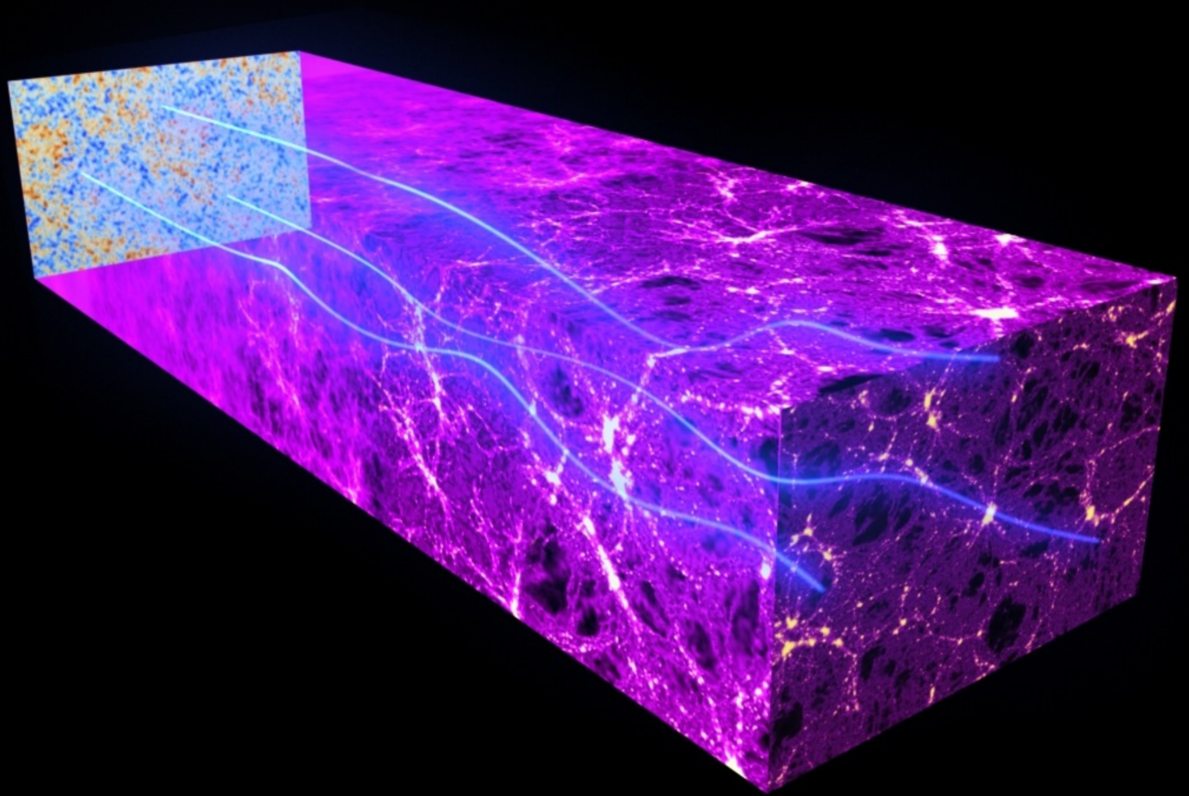
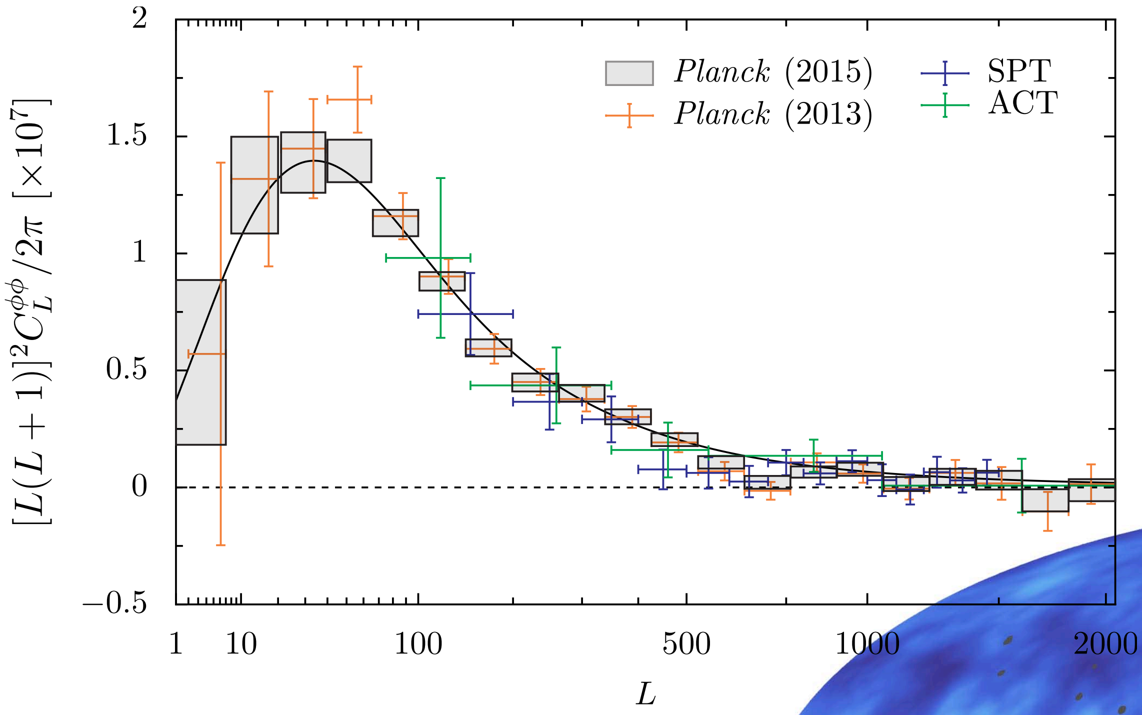
PLANCK PROBES AND EXPLOITS CMB LENSING

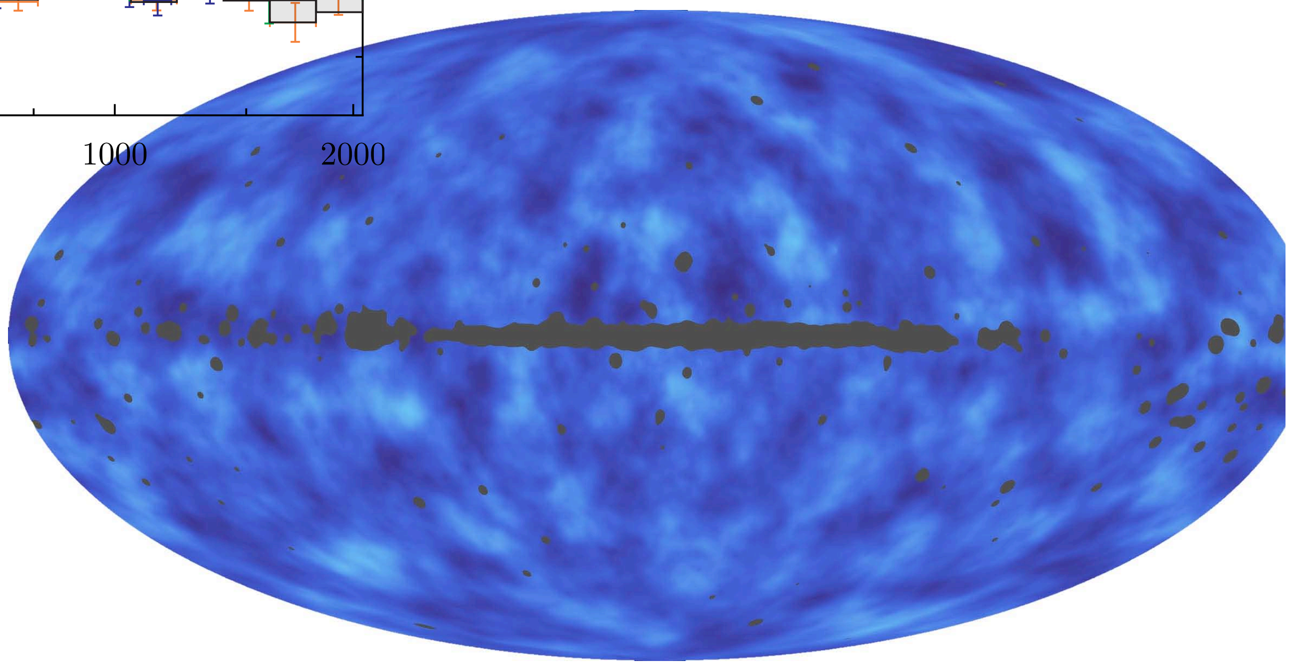
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB



LENSING



Lensing potential estimated from the four-point correlation function

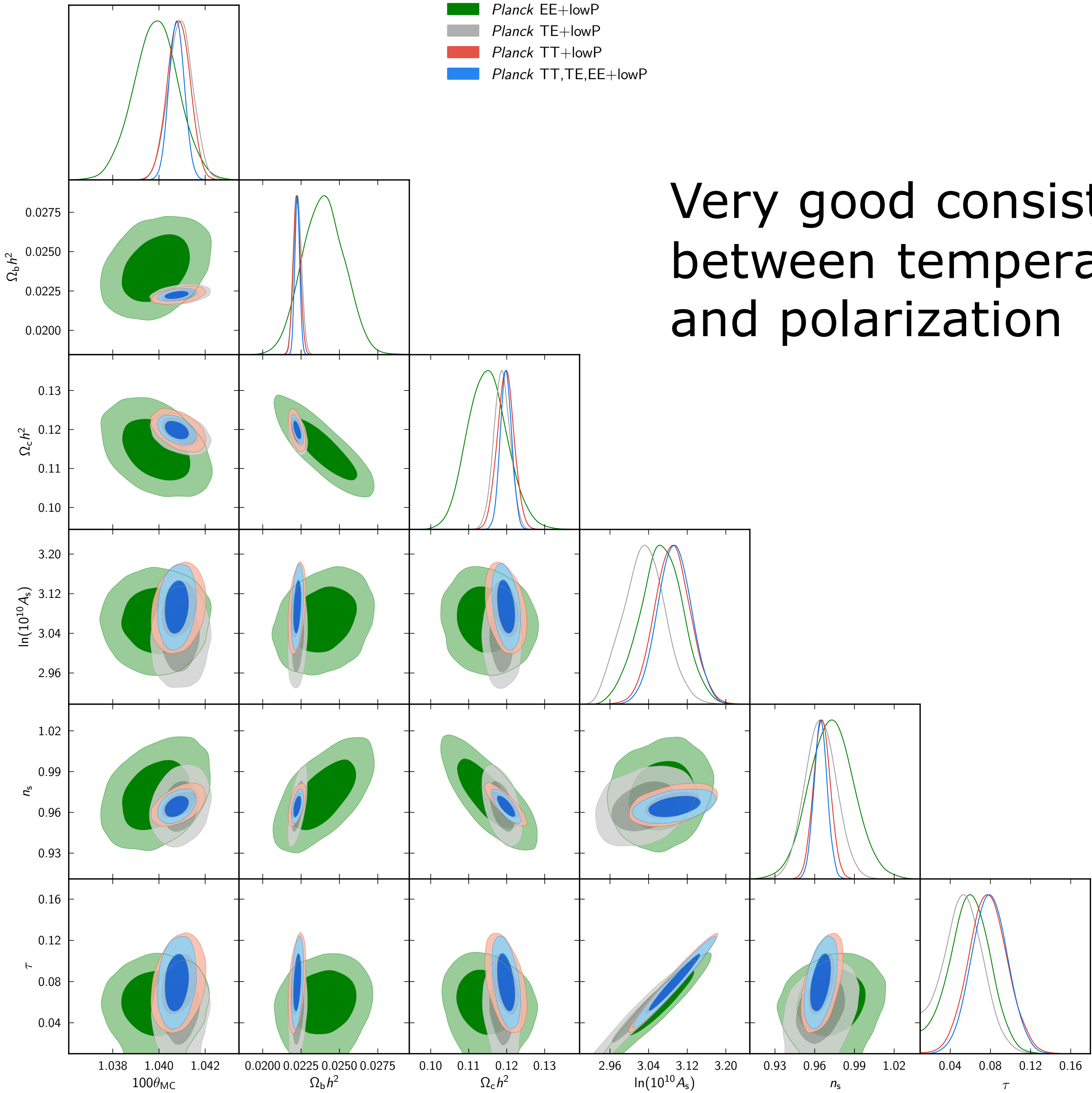


COSMOLOGICAL PARAMETERS: STANDARD ΛCDM

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



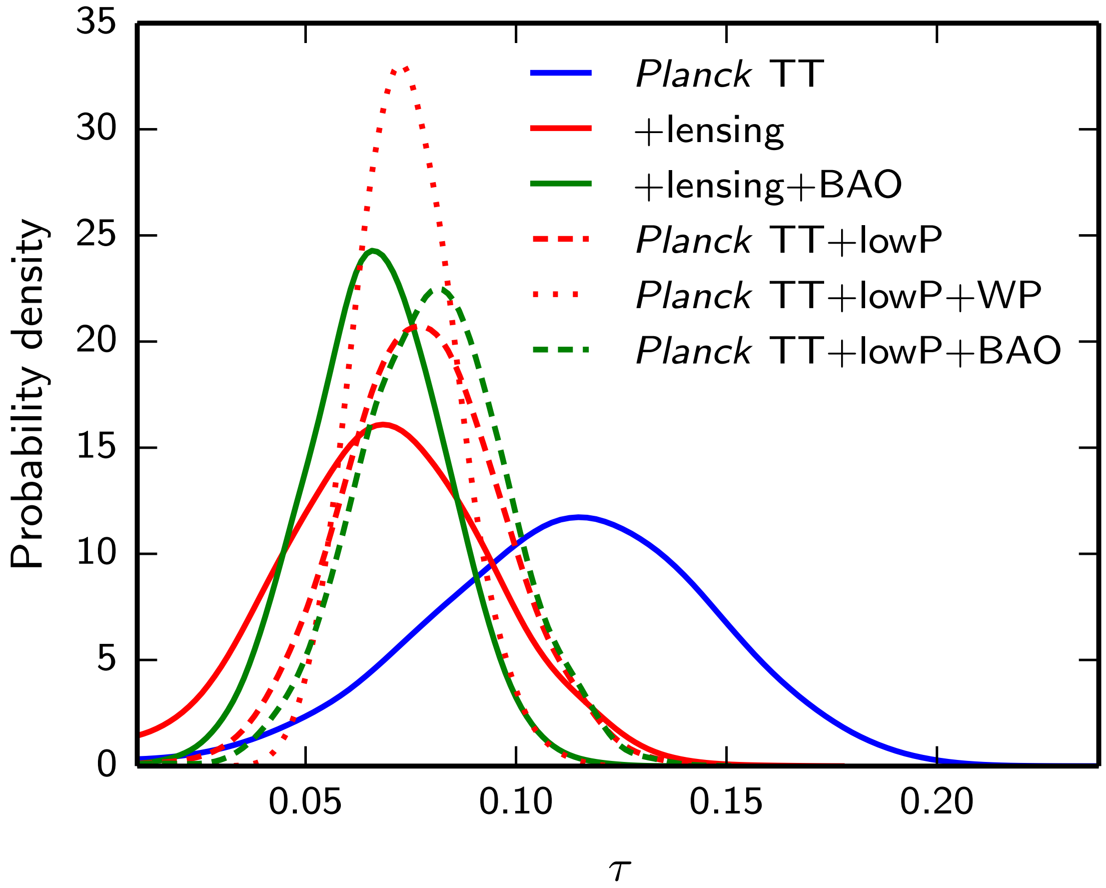
Very good consistency between temperature and polarization

Constraints on the reionization optical depth

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

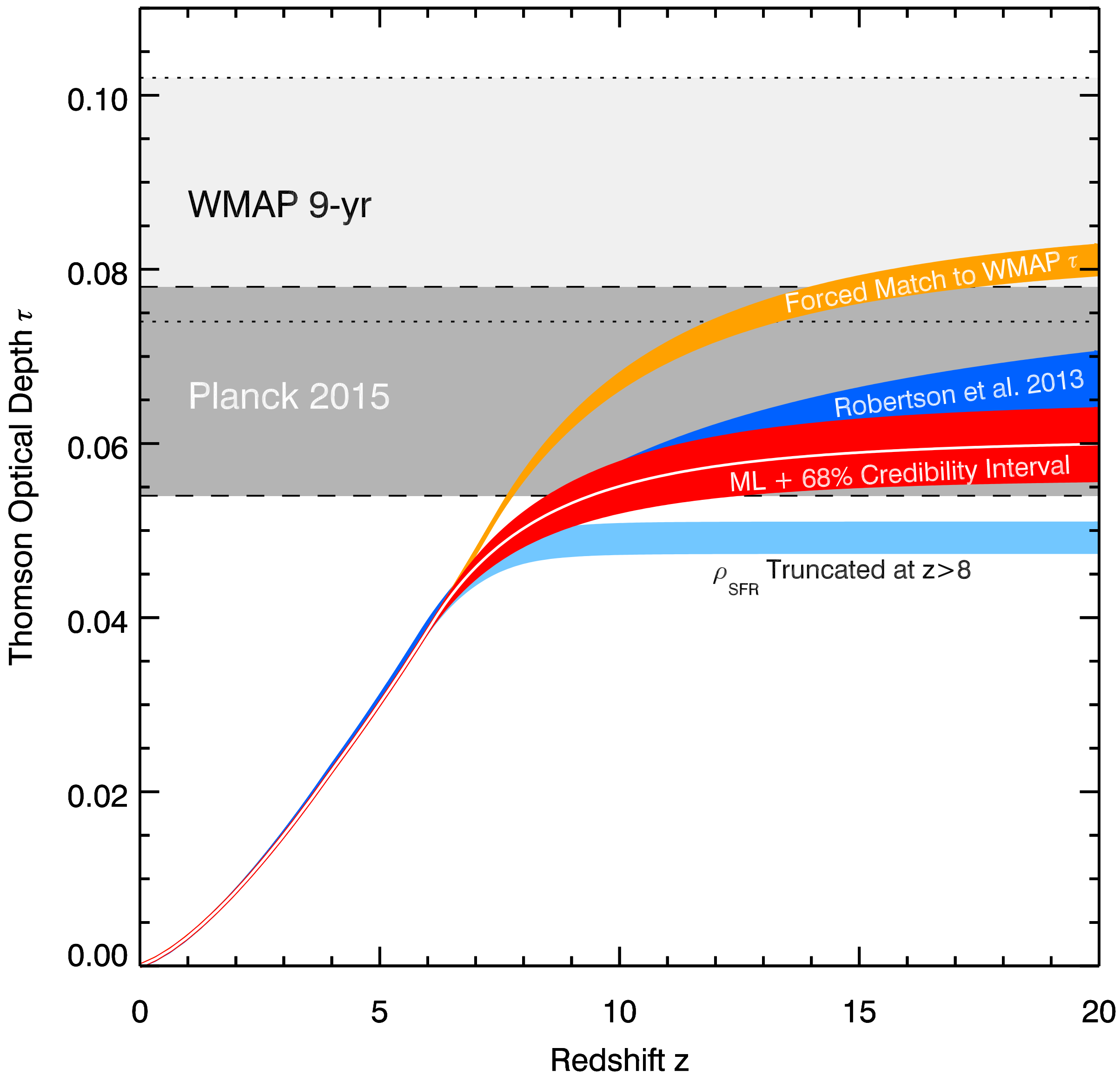
Planck TT+lensing
τ = 0.070 +/- 0.024
(z_{re} = 9.0 +/- 2.3)

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



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 >> 10) galaxies

Robertson et al., arXiv 1502.02024

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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.

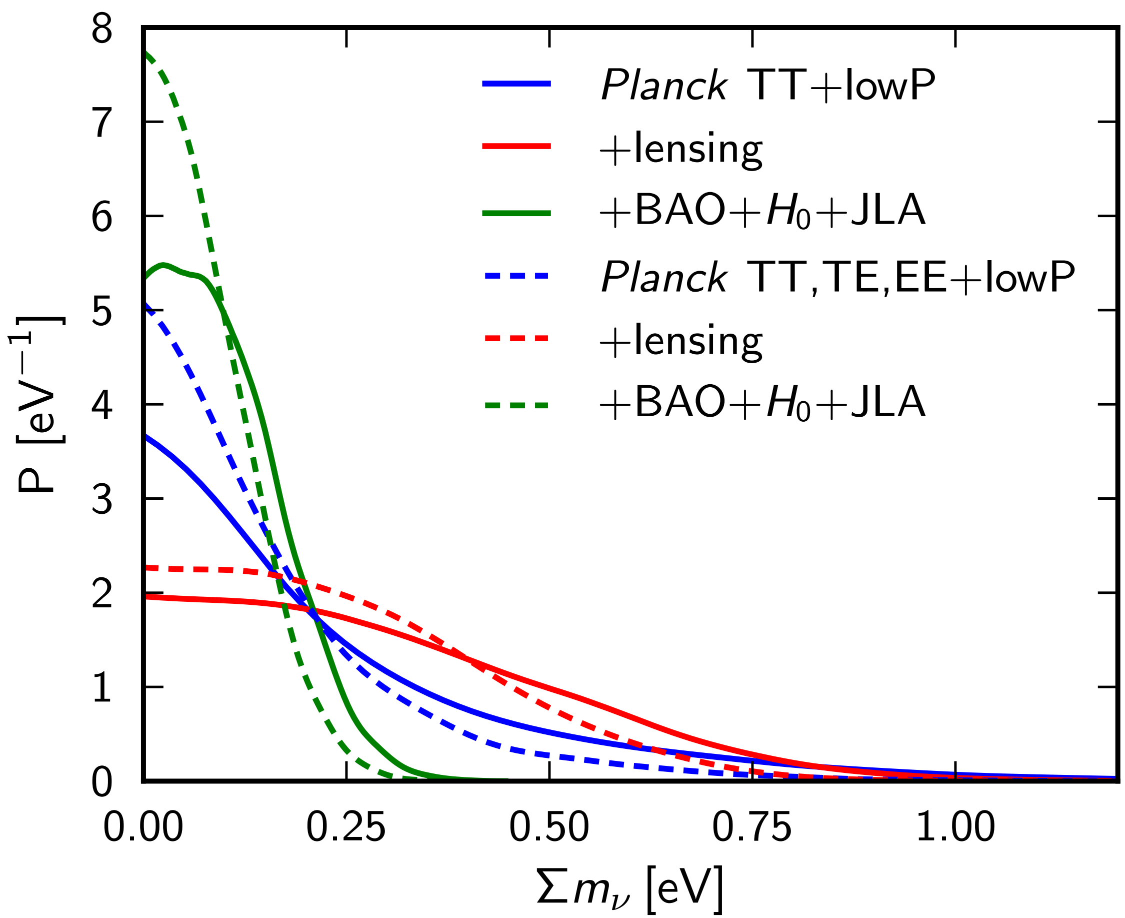
This induces an integrated Sachs-Wolfe effect (both at early and late times) and/or a change in the angular diameter distance to the last scattering surface.

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

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.

Planck constraints on neutrino masses



Σm_ν < 0.72 eV (PlanckTT+lowP)

Σm_ν < 0.68 eV (…. + lensing)

Σm_ν < 0.23 eV (… + ext)

Σm_ν < 0.49 eV (PlanckTT,TE,EE +lowP)

Σm_ν < 0.59 eV (…. + lensing)

Σm_ν < 0.19 eV (… + ext)

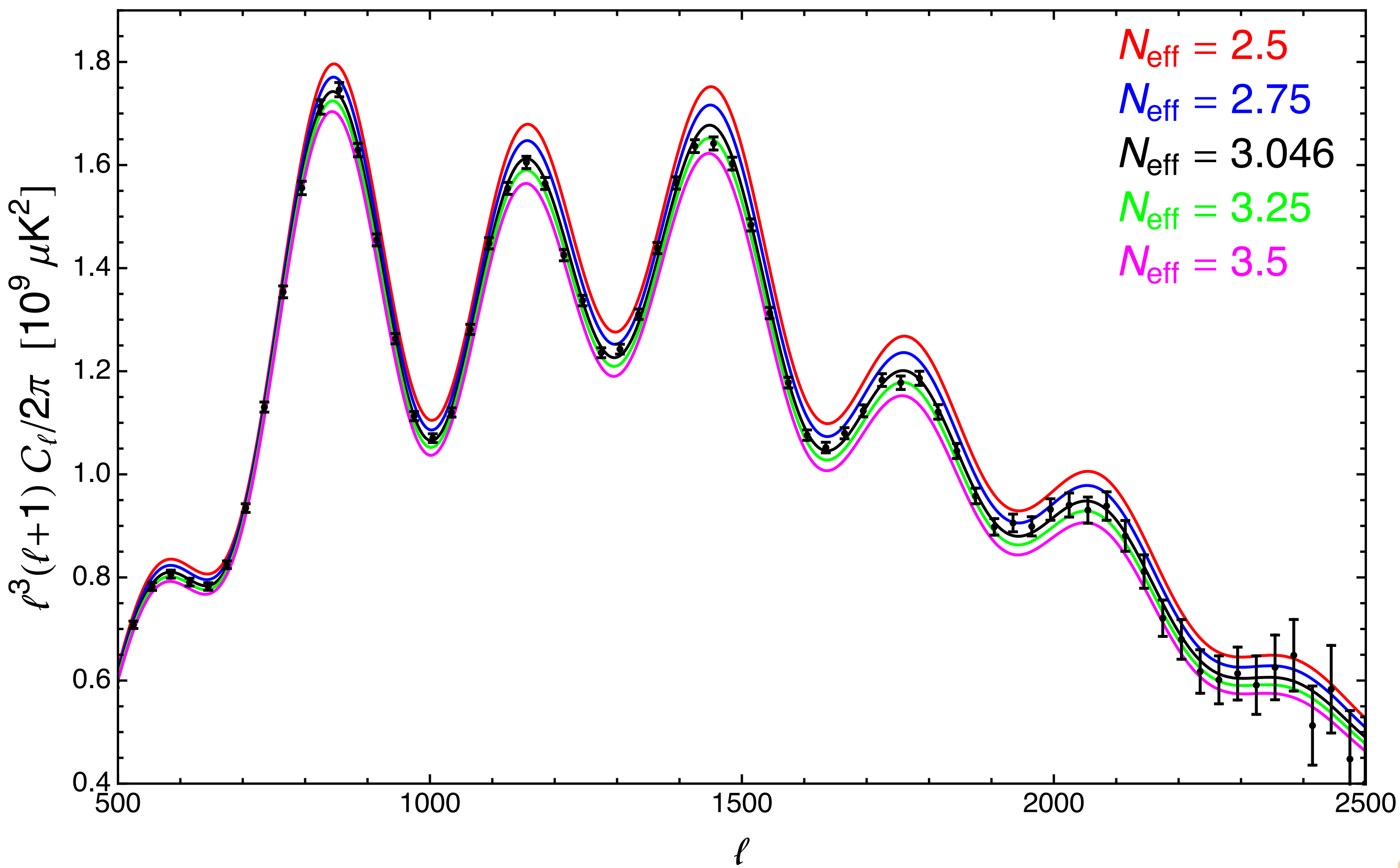
Planck alone is already at the level of the expected sensitivity of KATRIN, an experiment for the direct measurement of neutrino mass from tritium beta decay (will allow to constrain Σm_ν < 0.6 eV)

(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:



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_{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 $N_{eff} < 3.046$ 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.

N_{eff} constraints from Planck

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

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

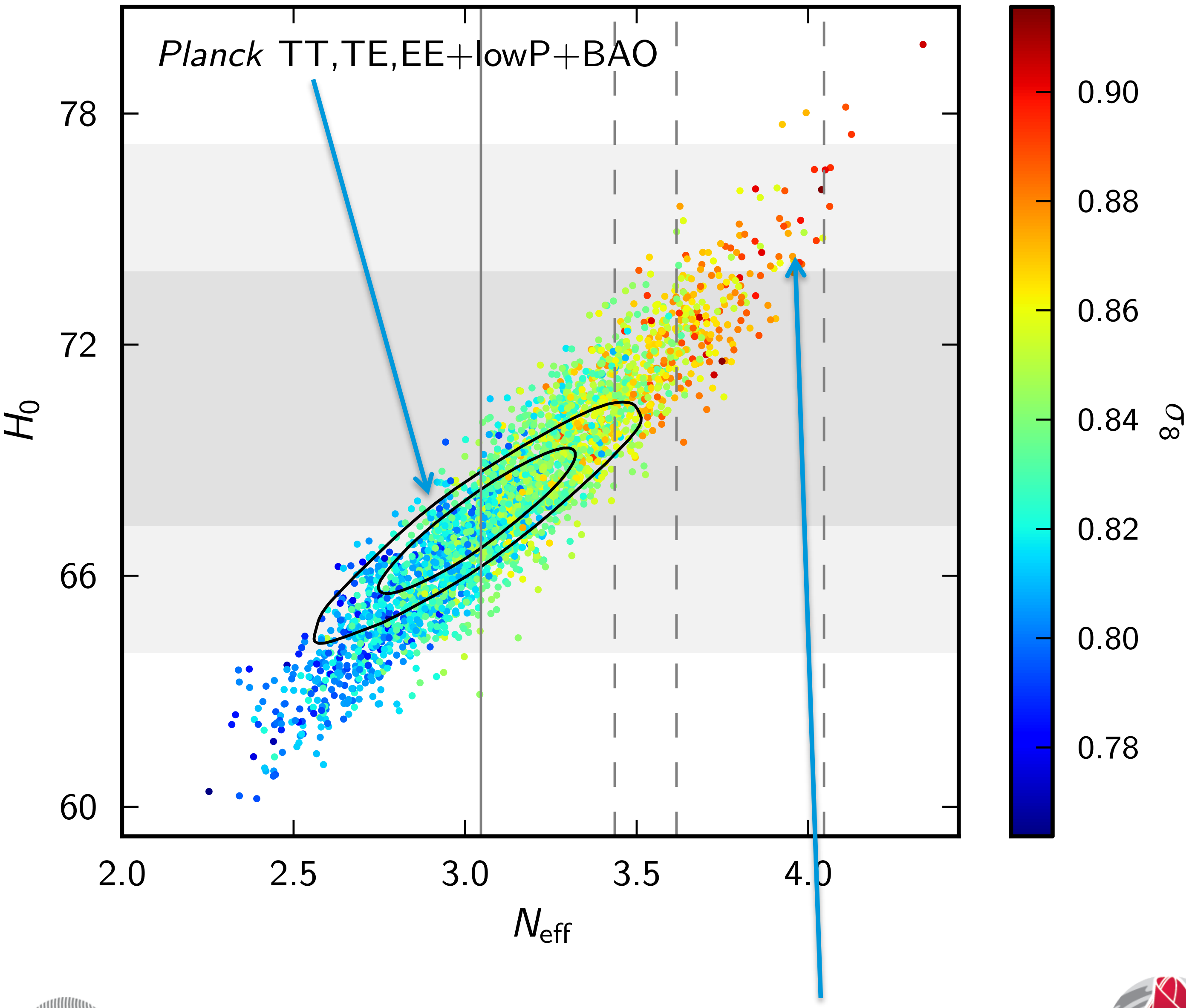
$N_{\mathrm{eff}} = 2.98 \pm 0.20$ (PlanckTT,TE,EE+lowP)

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

(uncertainties are 68% CL)

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

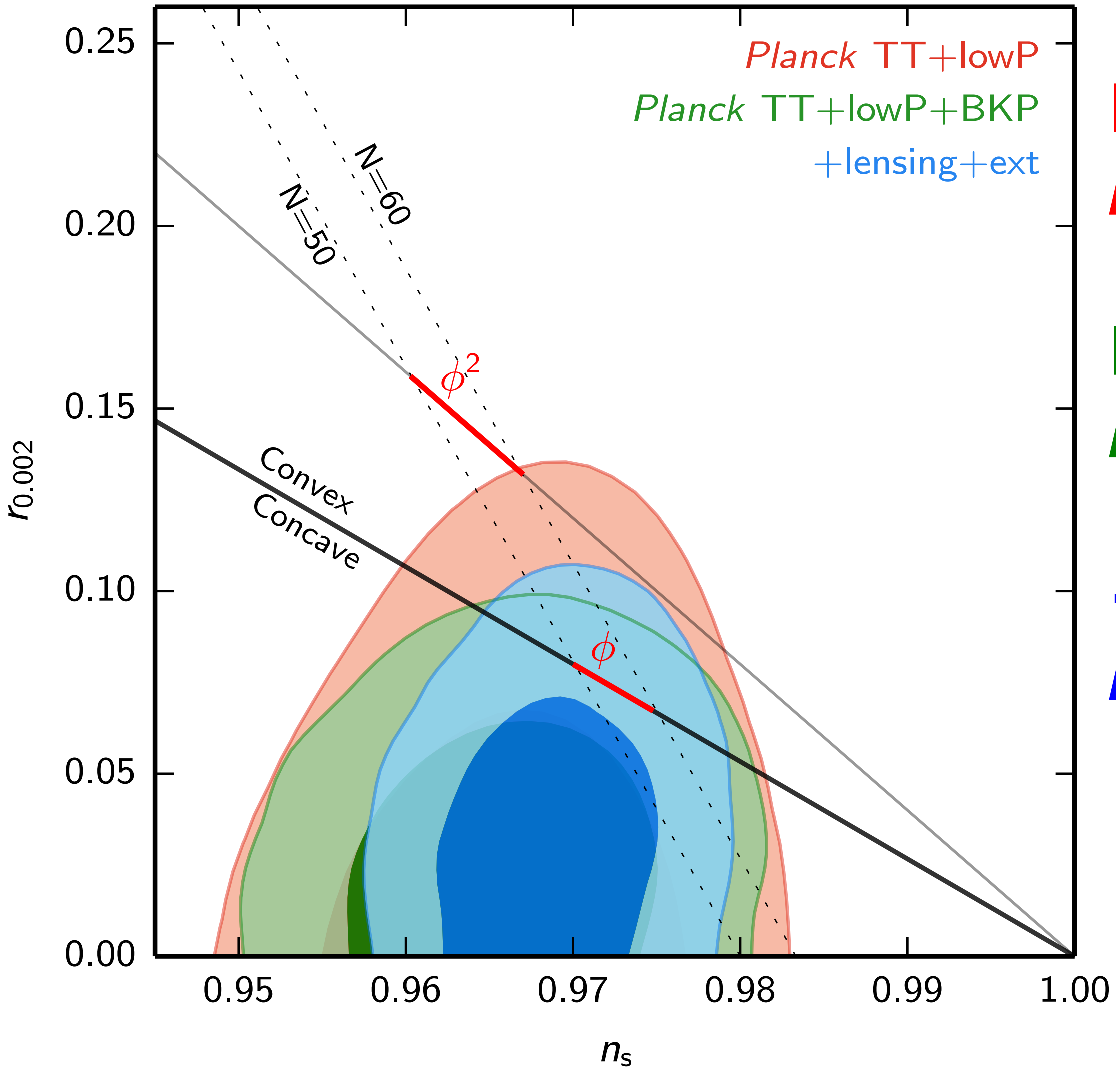
N_{eff} constraints from Planck



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.

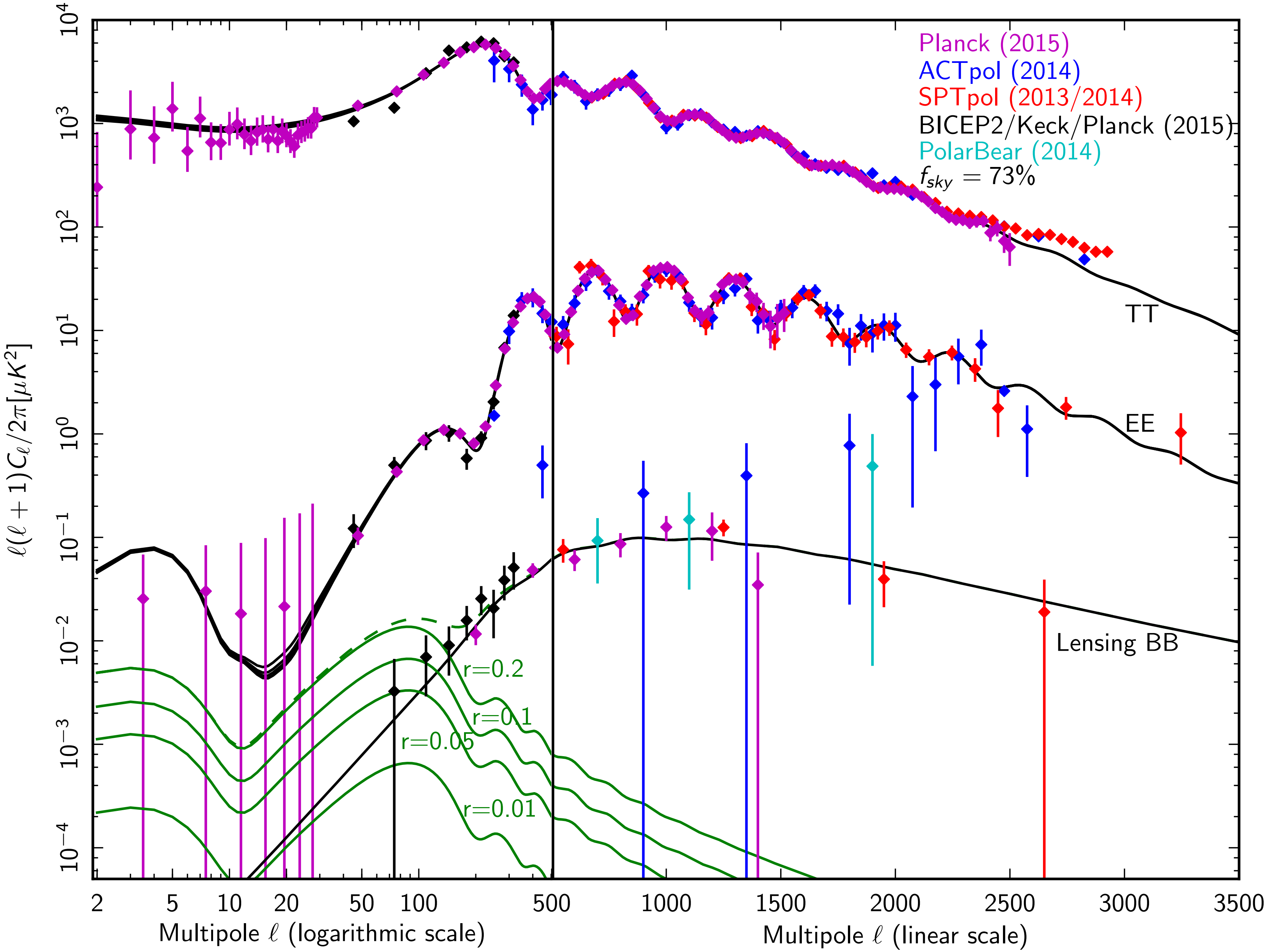
Scalar spectral index and tensors fluctuations



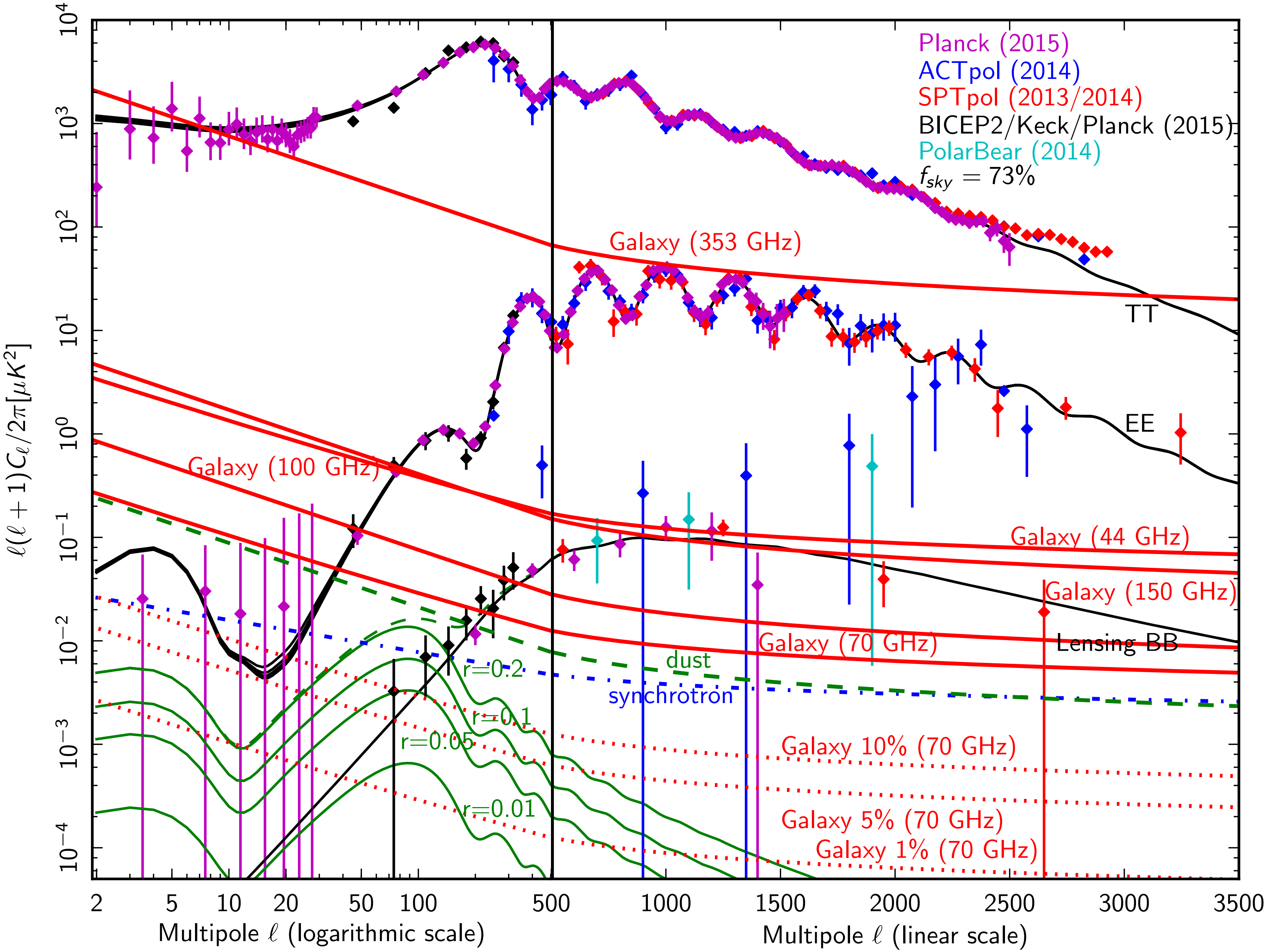
Planck TT + lowP
$r_{0.002} < 0.10$

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

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

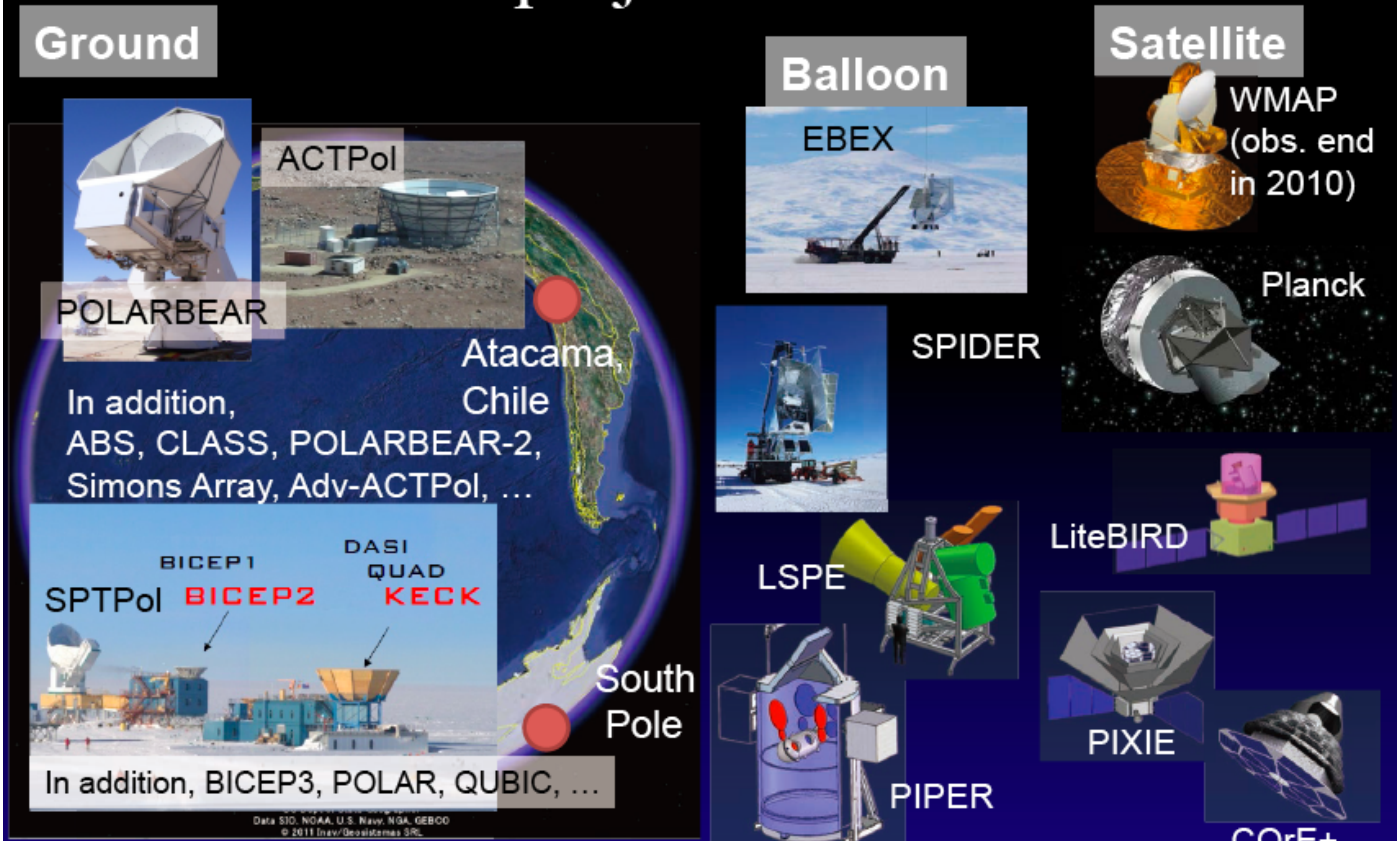


Planck (2015)
ACTpol (2014)
SPTpol (2013/2014)
BICEP2/Keck/Planck (2015)
PolarBear (2014)
$f_{sky} = 73\%$
TT
EE
Lensing BB
r=0.2
r=0.1
r=0.05
r=0.01
$\ell(\ell+1)C_\ell/2\pi[\mu K^2]$
Multipole ℓ (logarithmic scale)
Multipole ℓ (linear scale)



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)

B-mode projects in the world



In addition, QUIJOTE in Canary island, AMiBA in Hawaii

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
- 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

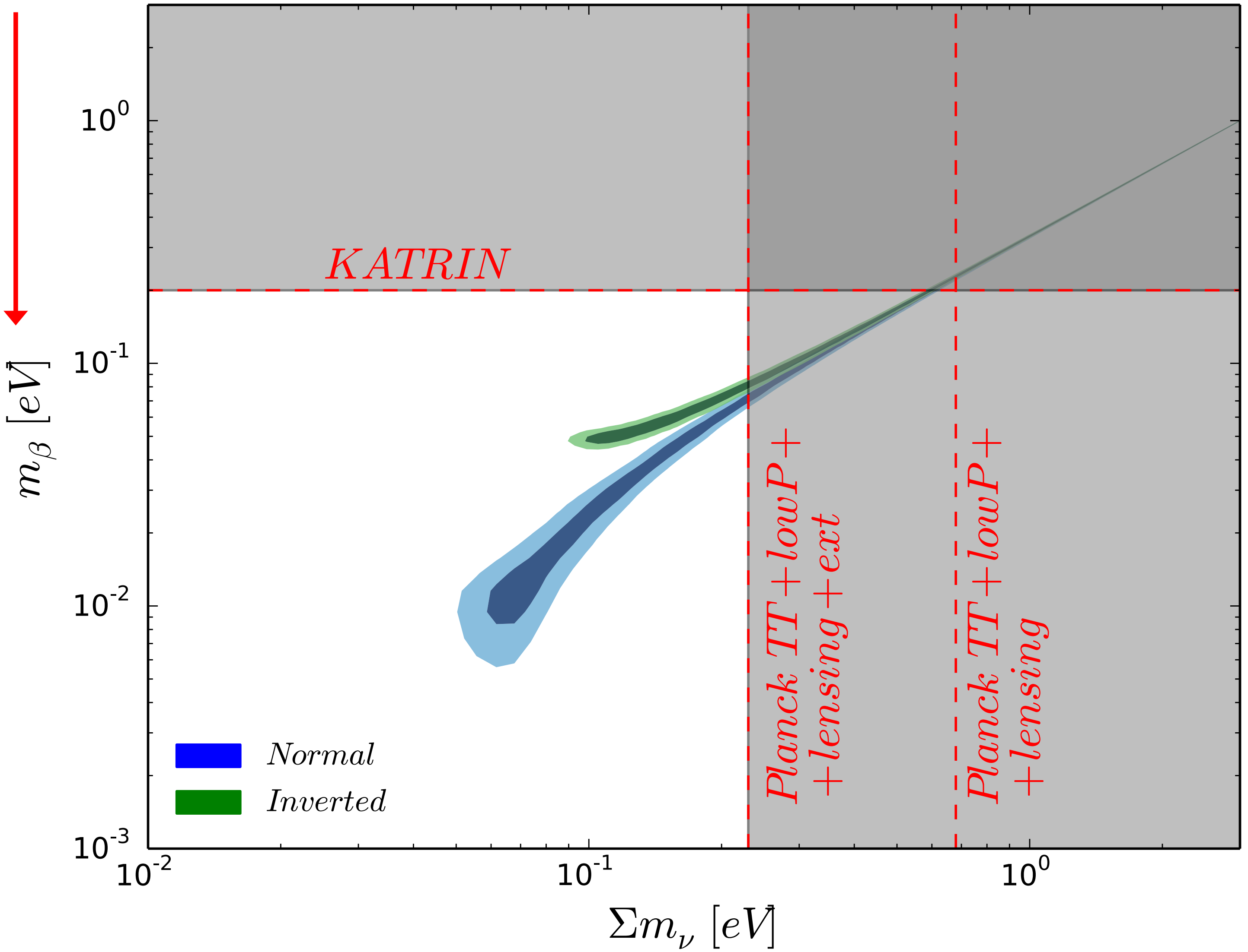
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

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

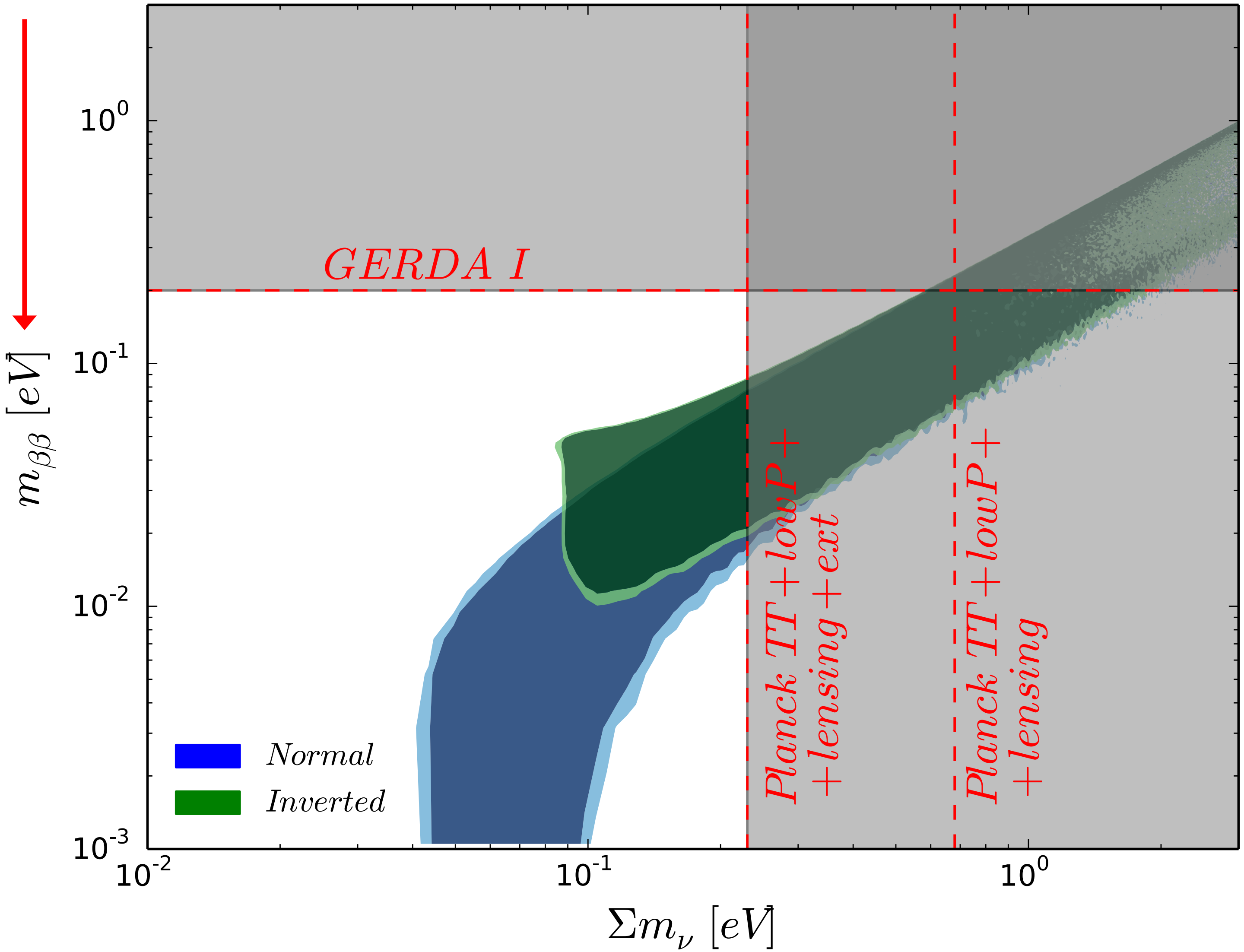
Tritium 🚲 decay, 0⬤2🚲 and Cosmology

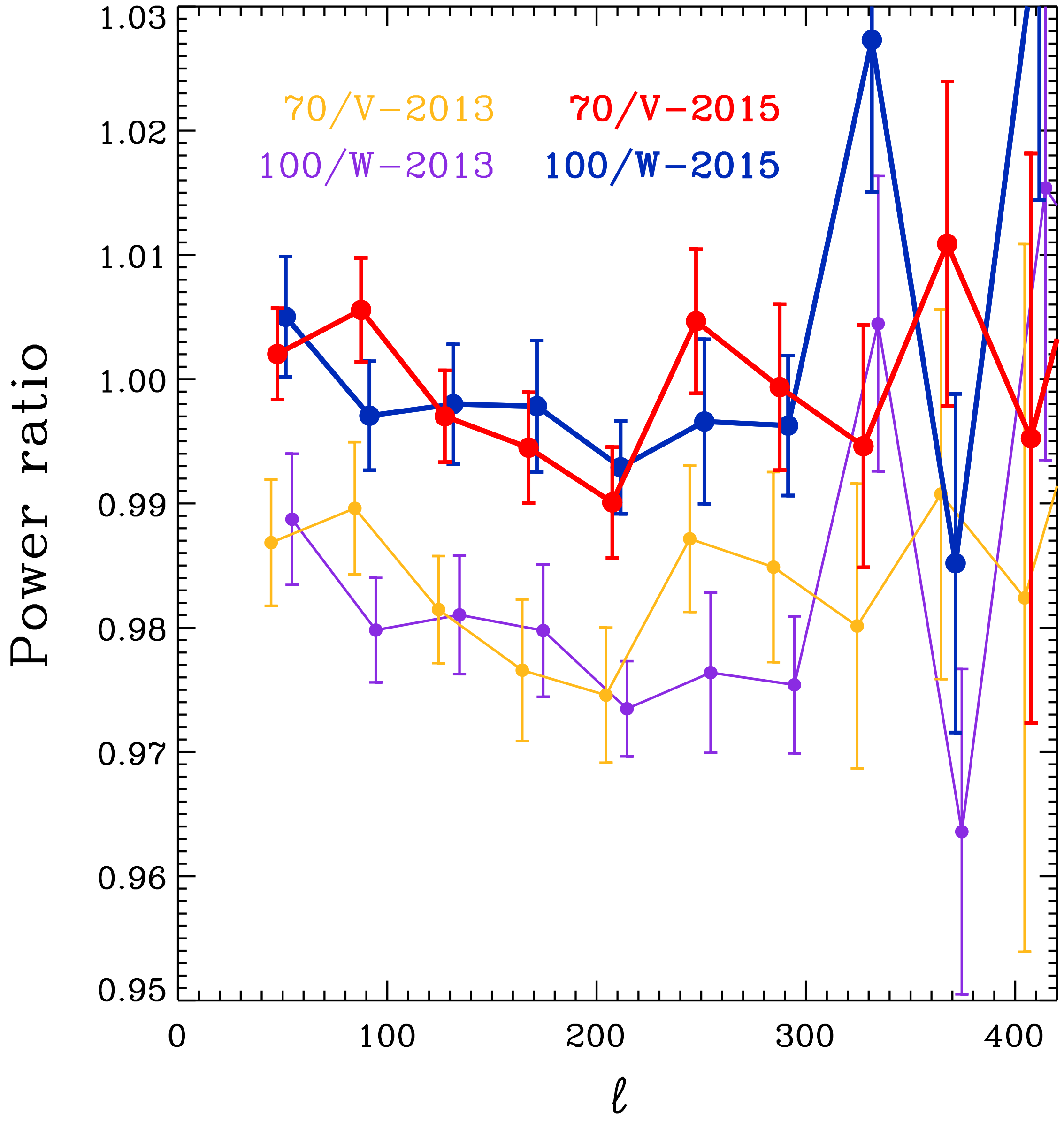
$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$



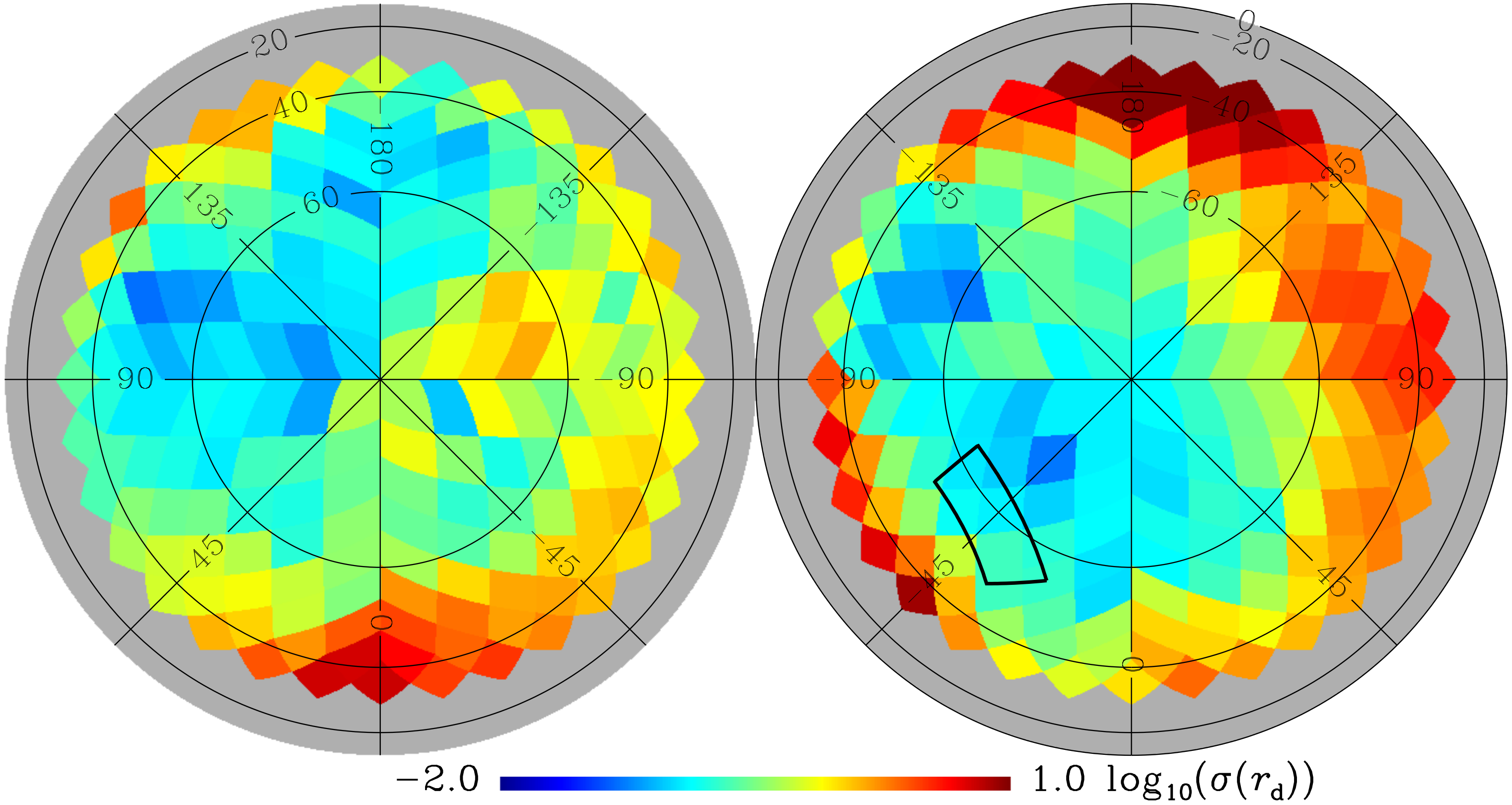
Tritium β decay, 0ν2β and Cosmology

$$\left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

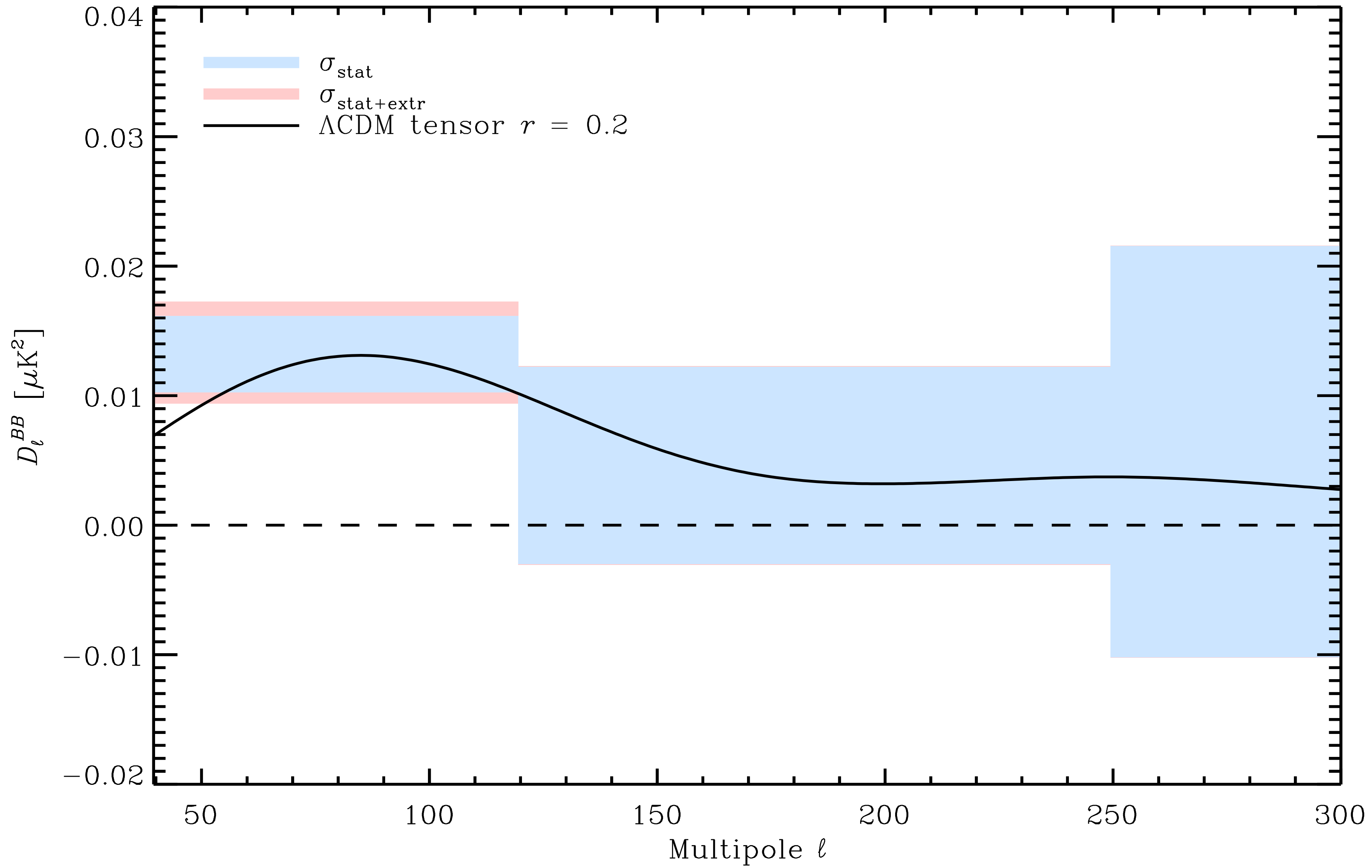




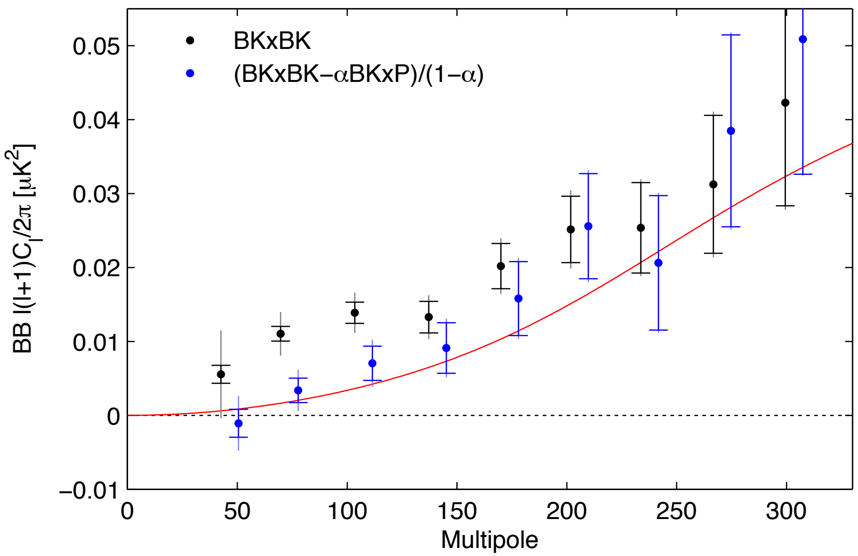
70/V–2013
70/V–2015
100/W–2013
100/W–2015
Power ratio
1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.95
0
100
200
300
400
ℓ

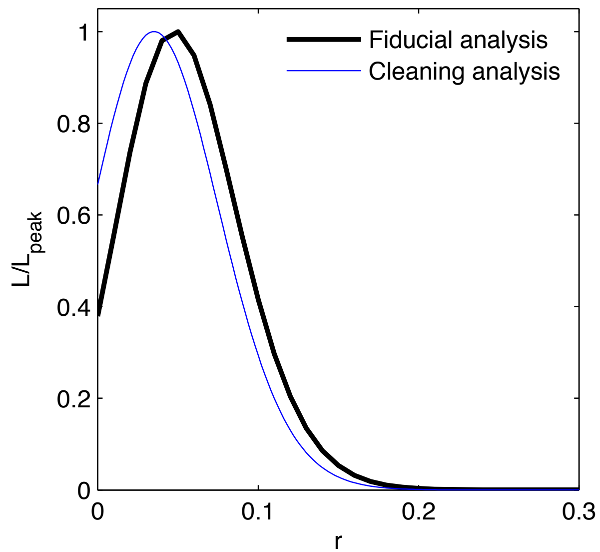


Planck BB amplitude from the 353 GHz data, extrapolated to 150 GHz, normalized to the CMB expectation for r=1
The thick black contour outlines the BICEP2 deep-field region



σ_{stat}
$\sigma_{stat+extr}$
ΛCDM tensor $r = 0.2$
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
D_ℓ^{BB} [μK^2]
50
100
150
200
250
300
Multipole ℓ


BKxBK
(BKxBK−αBKxP)/(1−α)
BB l(l+1)C_l/2π [μK^2]
Multipole
0.05
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200
250
300


Fiducial analysis
Cleaning analysis
L/L_peak
r
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3

The Cosmic Neutrino Background (CνB)

- The presence of a background of relic neutrinos is a basic prediction of the standard cosmological model

- Neutrinos are kept in thermal equilibrium with the cosmological plasma by weak interactions until T ~ 1 MeV (z ~ 10^{10});

- Neutrinos keep the energy spectrum of a relativistic fermion in equilibrium:

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

- The present Universe is filled by a relic neutrino background with T = 1.9 K and n = 113 part/cm^3 per species (CνB)

The Cosmic Neutrino Background (CνB)

- Neutrinos are nonrelativistic today…

$$\rho_\nu = m_\nu n_\nu = m_\nu g_\nu \int f(p) d^3p \propto m_\nu g_\nu T_\nu^3$$

$$\Omega_\nu = \sum_\nu \frac{\rho_\nu}{\rho_c} = \frac{\sum_\nu m_\nu}{93.14 h^2 \text{ eV}}$$

- … but they were ultrarelativistic in the early Universe

$$\rho_\nu = g_\nu \int p\, f(p) d^3p \propto g_\nu T_\nu^4$$

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

The Cosmic Neutrino Background (CνB)

- The latter is recast as a ***definition*** the N_{eff} parameter:

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

i.e.,

$$N_{\rm eff} \equiv \frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\nu^{\rm (std)}}$$

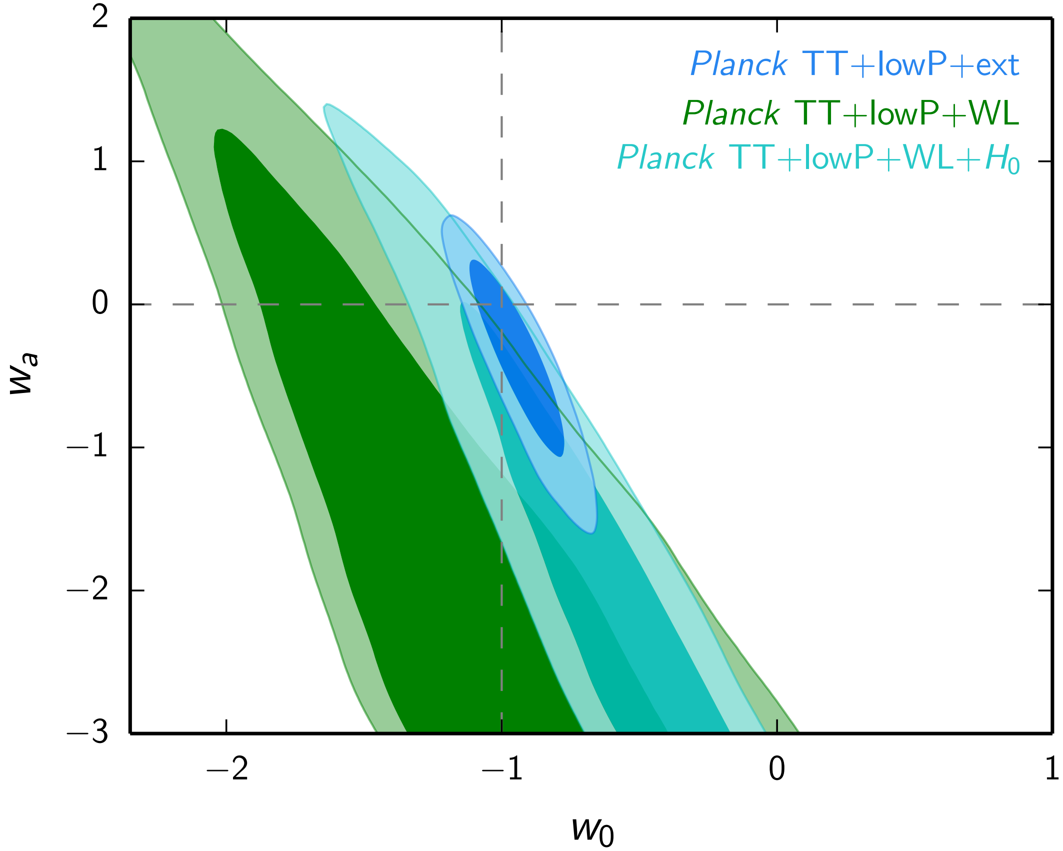
indeed, also assuming a the standard thermal history, N_{eff} =3.046 (Mangano et al., 2005)

In general, N_{eff} parameterizes the presence of extra radiation components ("dark" radiation, not necessarily associated to neutrinos) in the early Universe.

Neutrino masses

- We know from oscillation experiments that neutrinos do have a mass
- Oscillation experiments measure the mass differences: $\delta m^2_{21} = 7.6 \pm 0.6 \times 10^{-5}\ eV^2$, $\delta m^2_{31} = 2.5 \times 10^{-3}\ eV^2$
- Mixing angles are also quite well known….
- …however the absolute mass scale remains unknown
- this can be measured through tritium beta decay (m_β)…
- …. neutrinoless double β decay ($m_{\beta\beta}$) ….
- … and of course comsmology (Σm_ν)

DARK ENERGY

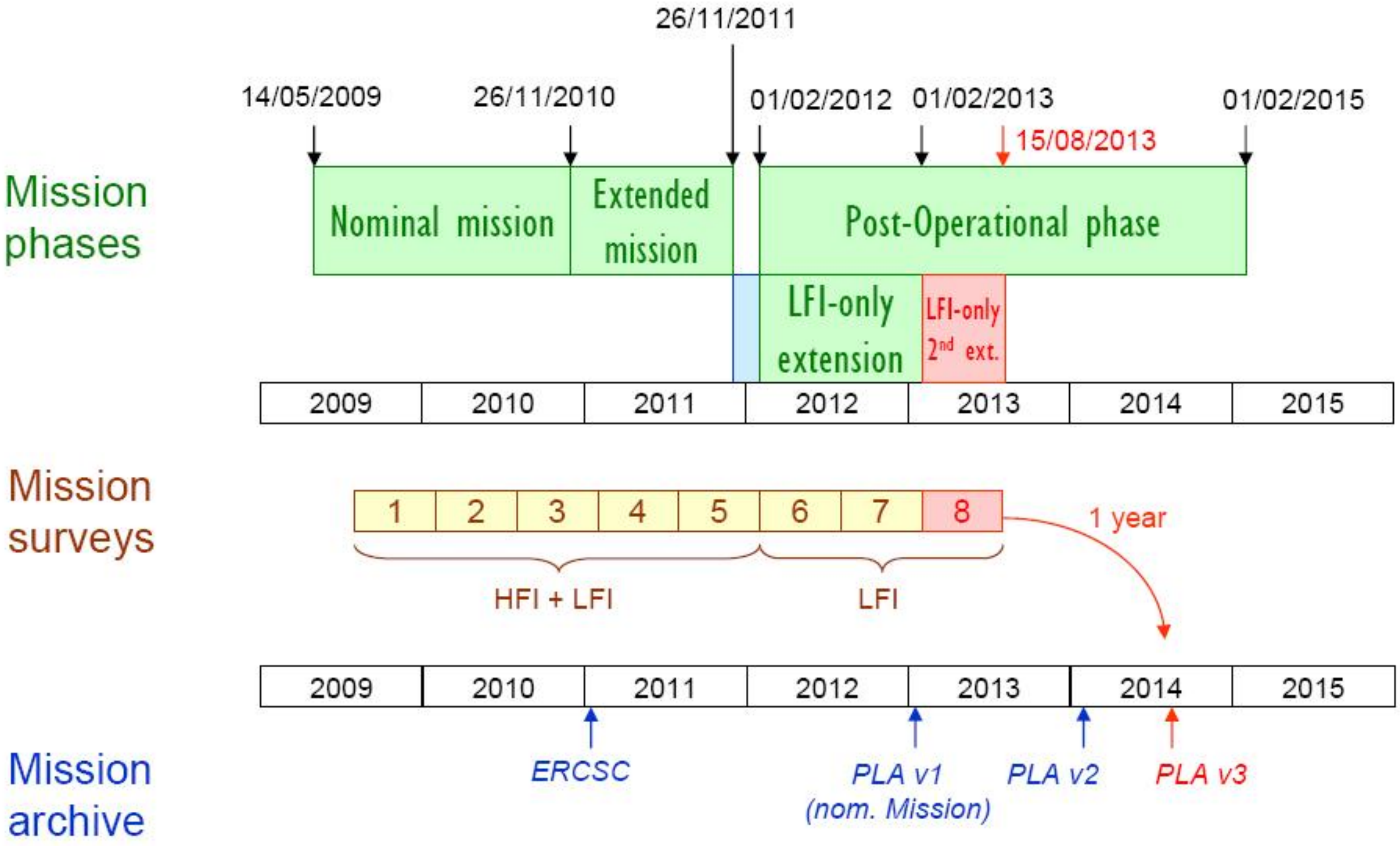


Planck TT+lowP+ext
Planck TT+lowP+WL
Planck TT+lowP+WL+H_0
2
1
0
−1
−2
−3
w_a
−2
−1
0
1
w_0

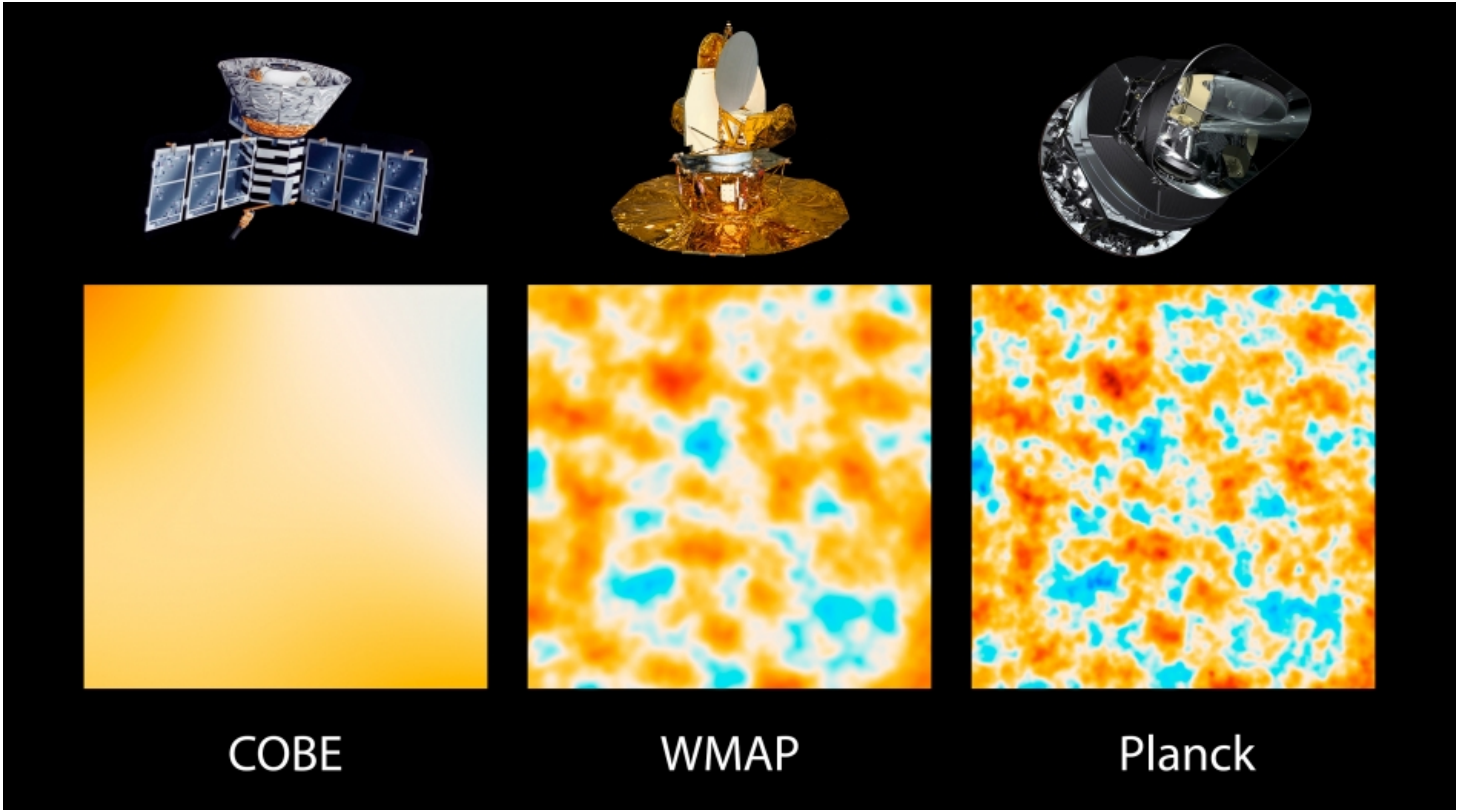
CMB polarization in a nutshell

- 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

Planck's operational timeline



Comparison with forerunners



esa planck PLANCK LFI HFI PLANCK