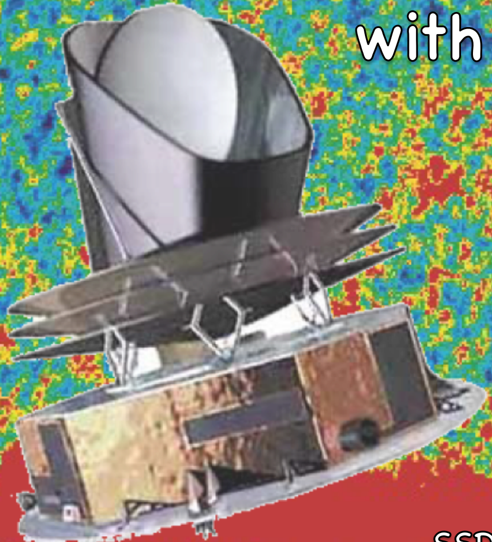
Cosmic Microwave Background Cosmology with Planck



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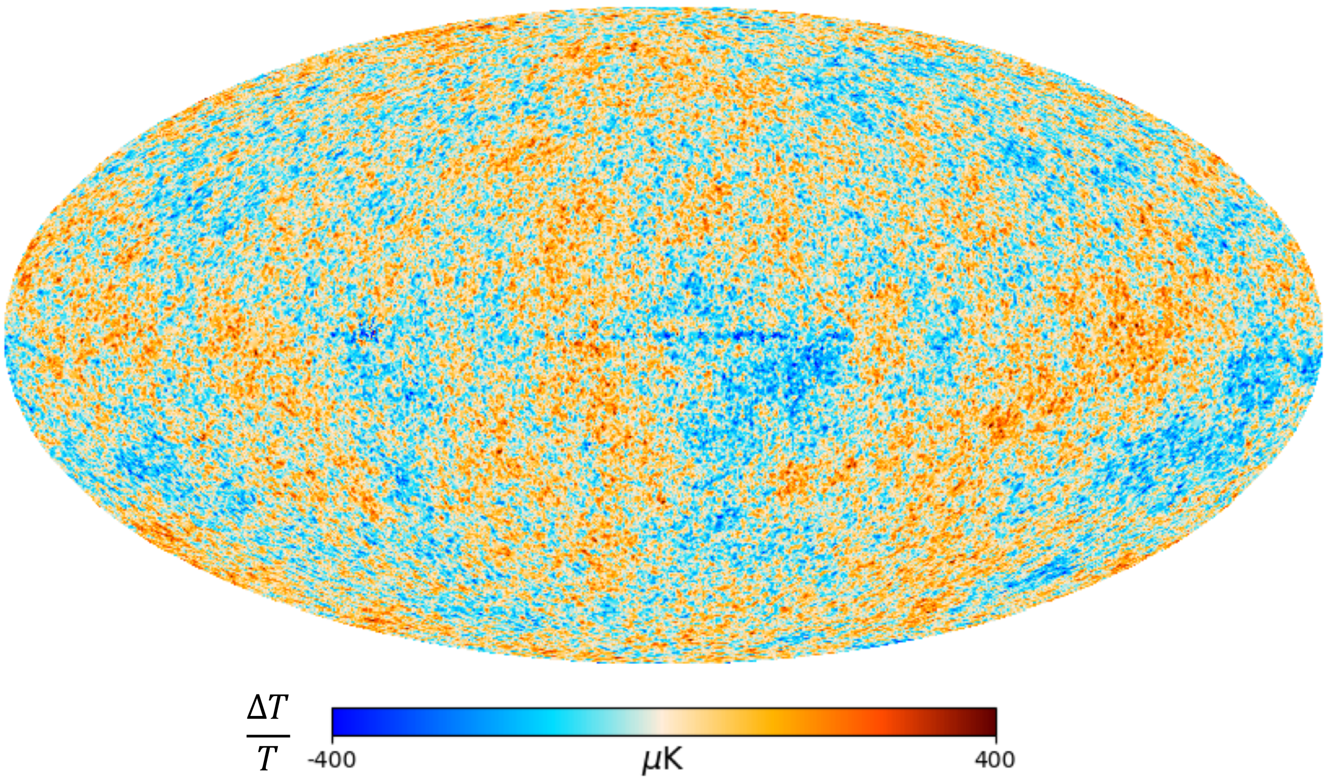
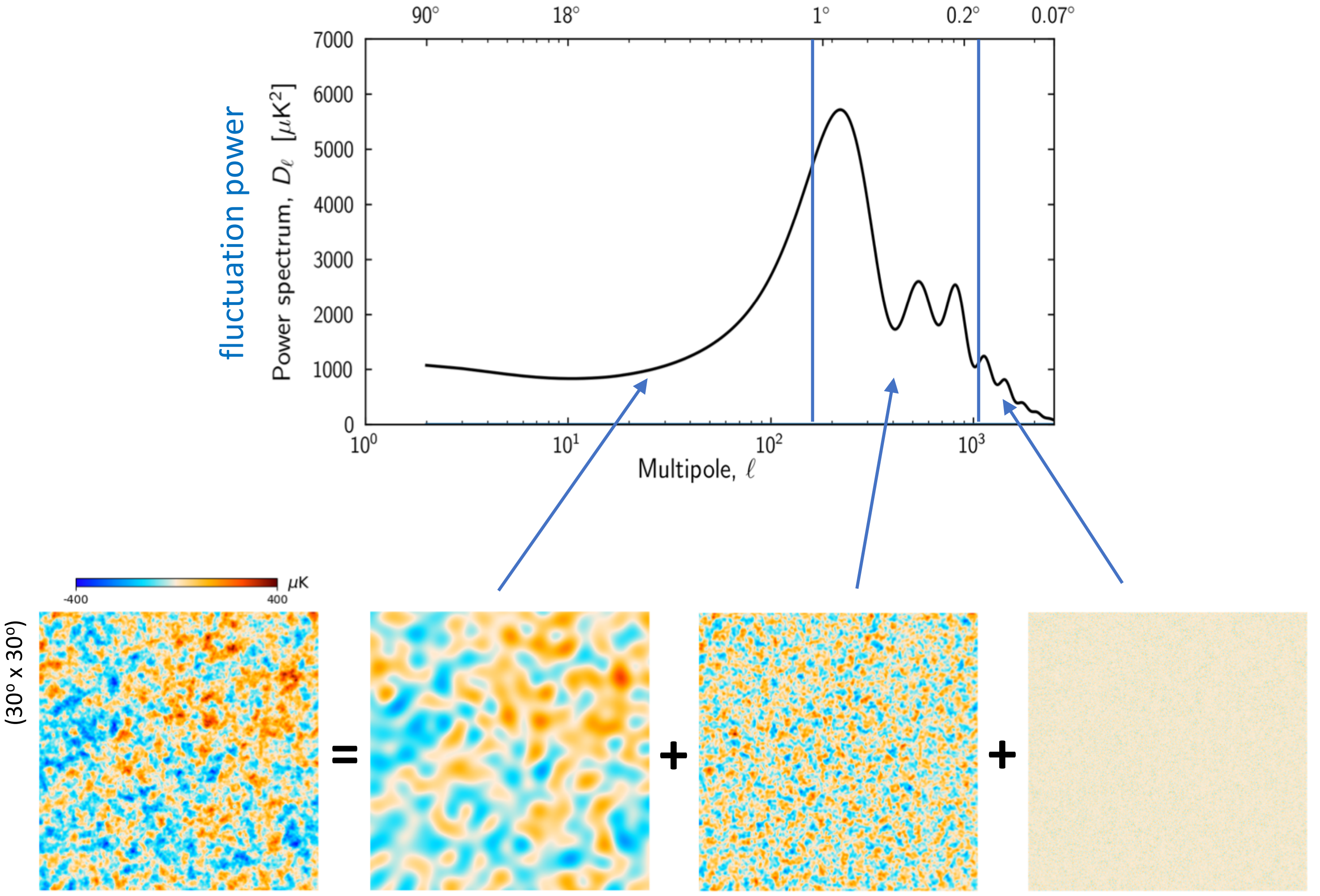
La Thuile 2018 - 26th February 2018

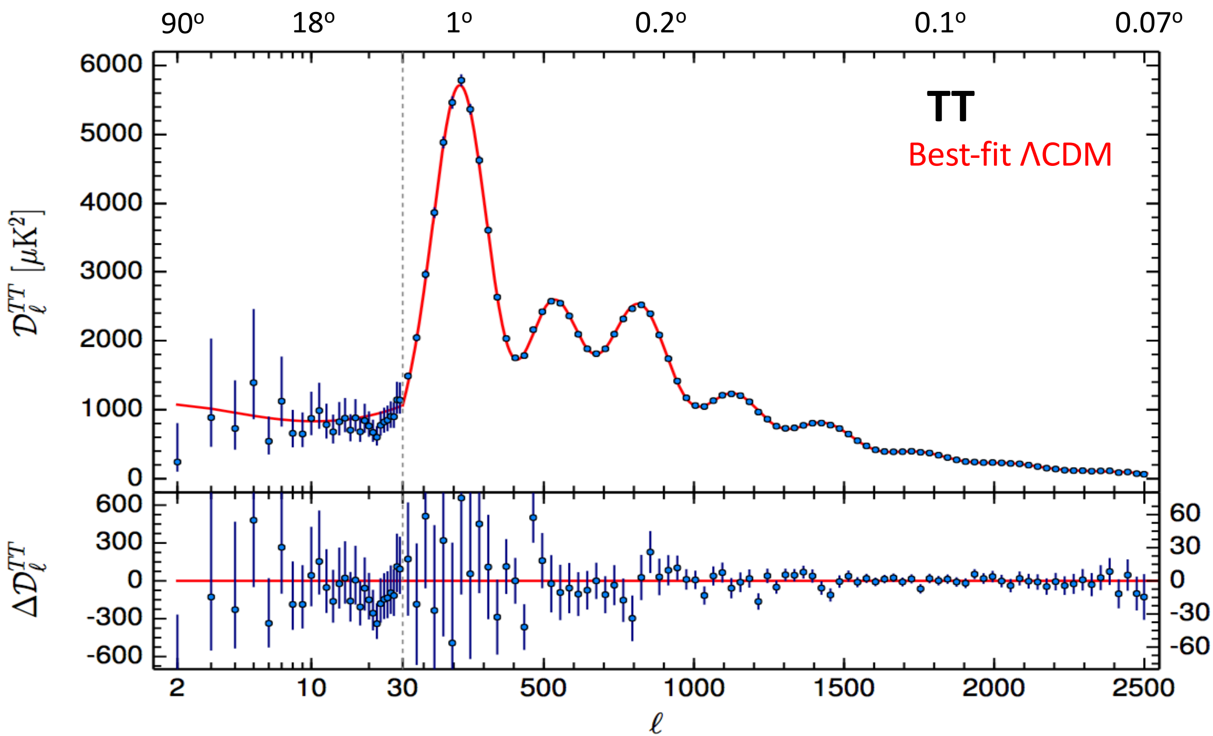
The *ultimate* measurement of the CMB temperature anisotropy field



For the first time Planck mapped all the relevant angular scales with a single mission



CMB temperature power spectrum



Cosmic Variance Limited up to ℓ =1600, sky fraction =75-40%

As good as it gets for cosmological parameters

ΛCDM is an excellent fit to Planck data: χ^2 = 2545 with 2479 d.o.f. → PTE = 17%

Base ΛCDM model

Spatially-flat expanding Universe. Dynamics governed by GR. Constituents are cold dark matter, a cosmological constant Λ, baryons and radiation (photons + 3 neutrino species). The primordial seeds of cosmic structures are Gaussian-distributed fluctuations with an almost scale-invariant spectrum generated by inflation $P(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$

Parameter	[1] *Planck* TT+lowP (68% CL)
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

Fully described by 6 parameters. With Planck:

- **Determined with high precision (< 1% level)**
- **Improving on previous constraints by a factor 1.5 – 2**
- **Very powerful in constraining extensions to the base model**

No preference for extensions

Curvature

No evidence for deviations from flatness

$$\Omega_k = -0.052^{+0.049}_{-0.055}$$

Helium Abundance

In agreement with measurements of primordial abundances and BBN predictions

$$Y_P = 0.252^{+0.041}_{-0.042}$$

Running of the spectral index

Consistent with no running

$$dn_s/d\ln k = -0.008 \pm 0.016$$

Dark Energy equation of state

Compatible with a cosmological constant

$$w = -1.54^{+0.62}_{-0.50}$$

Sum of neutrino masses

Complementary bounds to those from laboratories

$$\sum m_\nu < 0.715 \text{ eV}$$

Number of relativistic species

Compatible with 3 active neutrinos N_{eff} =3.046

Neutrino background detected at 10σ

$$N_{\rm eff} = 3.13^{+0.64}_{-0.63}$$

Planck TT + LowP (95% CL)

Base ΛCDM model

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No preference for extensions

Curvature

No evidence for deviations from flatness

$$\Omega_k = -0.0001^{+0.0055}_{-0.0050}$$

Helium Abundance

In agreement with measurements of primordial abundances and BBN predictions

$$Y_P = 0.251^{+0.035}_{-0.036}$$

Running of the spectral index

Consistent with no running

$$dn_s/d\ln k = -0.003^{+0.015}_{-0.014}$$

Dark Energy equation of state

Compatible with a cosmological constant

$$w = -1.006^{+0.085}_{-0.091}$$

Sum of neutrino masses

Complementary bounds to those from laboratories

$$\sum m_\nu < 0.234\ \mathrm{eV}$$

Number of relativistic species

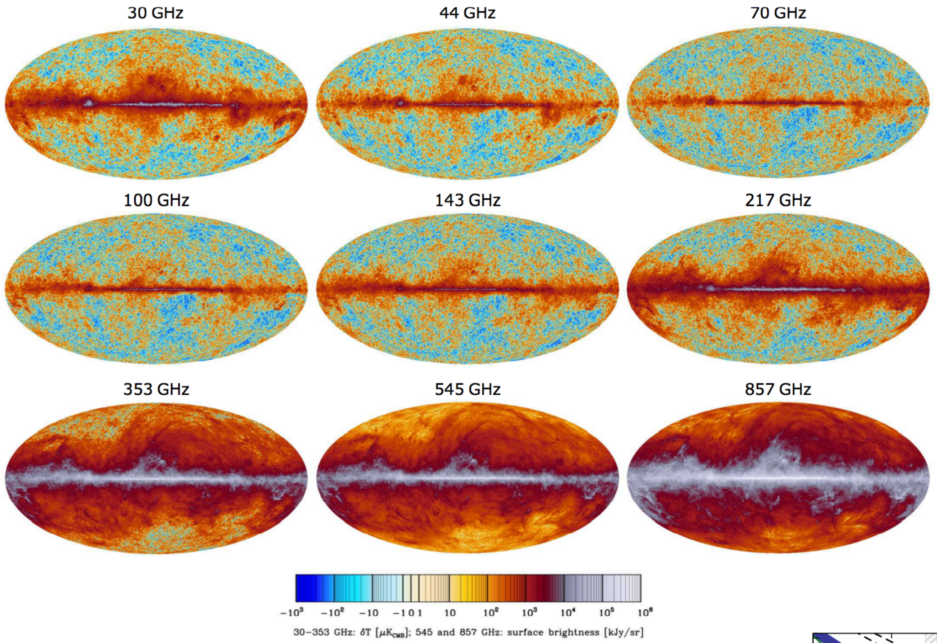
Compatible with 3 active neutrinos N_{eff} =3.046

Neutrino background detected at 15σ

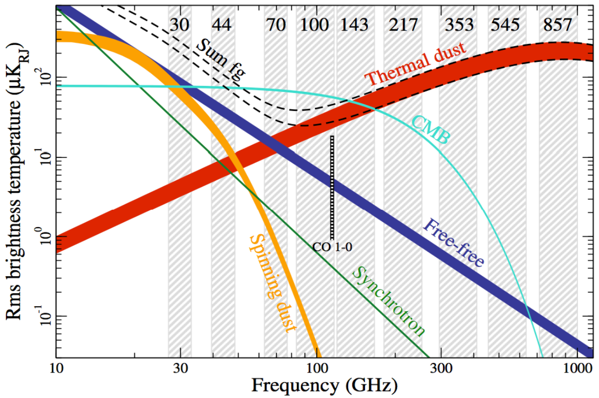
$$N_{\mathrm{eff}} = 3.15^{+0.41}_{-0.40}$$

Even tighter bounds for

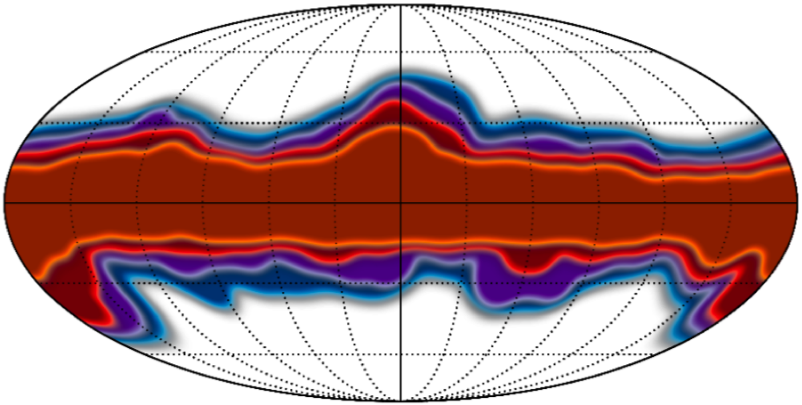
Planck TT + LowP **+ lensing + BAO + SNIa** (95% CL)



TEMPERATURE



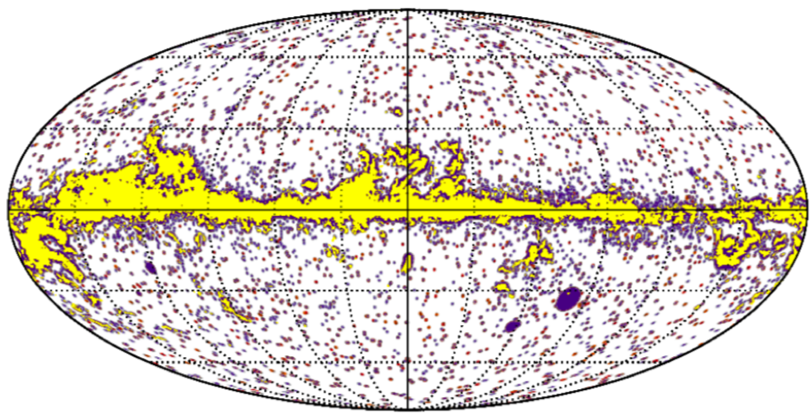
Galactic Masks



Masks used for the high-ℓ analysis.

Frequency [GHz]	Mask	
	Temperature	Polarization
100	T66	P70
143	T57	P50
217	T47	P41

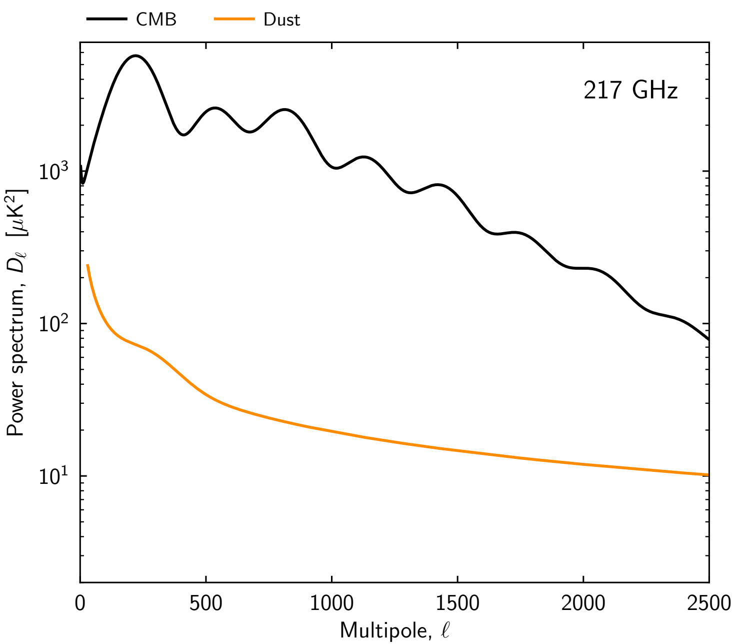
CO and Compact Source Mask



PARAMETRIC FOREGROUND MODEL

$$-\ln \mathcal{L}(\hat{\boldsymbol{C}}|\boldsymbol{C}(\theta)) = \frac{1}{2}\left[\hat{\boldsymbol{C}} - \boldsymbol{C}(\theta)\right]^{\mathsf{T}} \mathsf{C}^{-1}\left[\hat{\boldsymbol{C}} - \boldsymbol{C}(\theta)\right] + \text{const.}$$

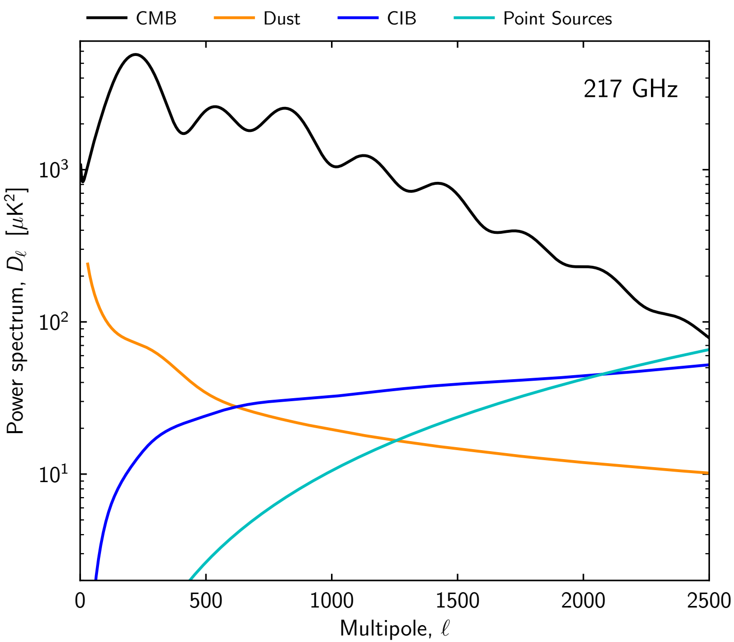
C(θ) = CMB theoretical spectra plus physically motivated templates for the foregrounds
θ = {cosmological and nuisance (foreground and instrumental) parameters}



Temperature Galactic Dust Model

C_ℓ^{dust} from 545 GHz

PARAMETRIC FOREGROUND MODEL



Unresolved Extragalactic Sources

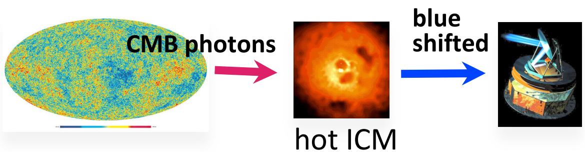
- Shot noise from **Poisson fluctuations** in the number density of point sources, C_ℓ^{PS}

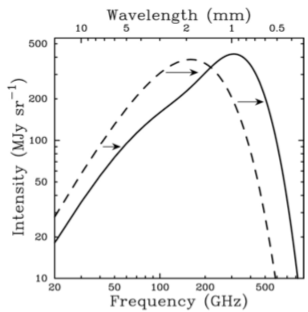
- Power due to clustering of high-redshift dusty star forming galaxies that trace large-scale structures: **Cosmic Infrared Background**, C_ℓ^{CIB} (Planck Collaboration XXX. 2014,A&A, 571, A30).

PARAMETRIC FOREGROUND MODEL

GALAXY CLUSTERS: Sunyaev-Zel'dovich effect

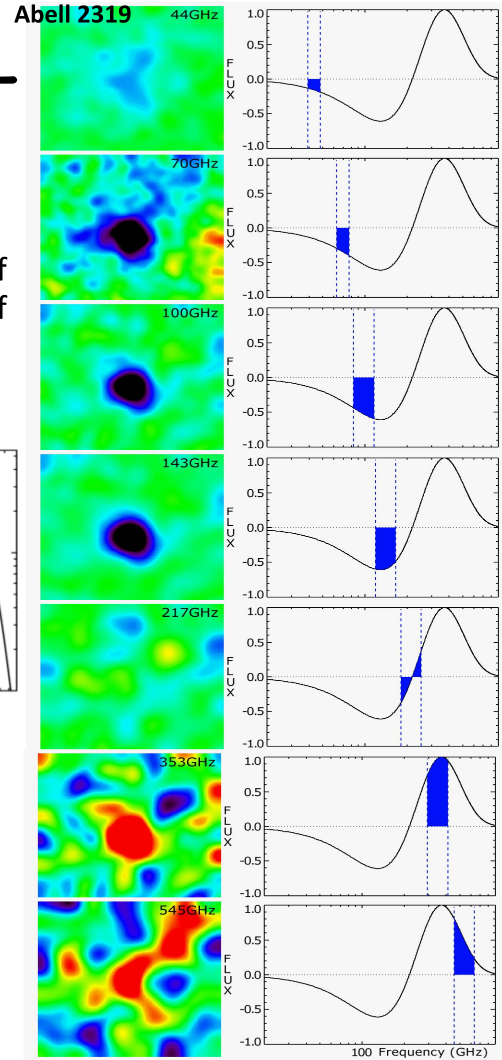
Thermal SZ: Signal caused by inverse-Compton scattering of CMB photons (~ 3 meV) by the hot plasma in clusters of galaxies (~ a few keV). C_ℓ^{tSZ} from Efstathiou & Migliaccio 2012



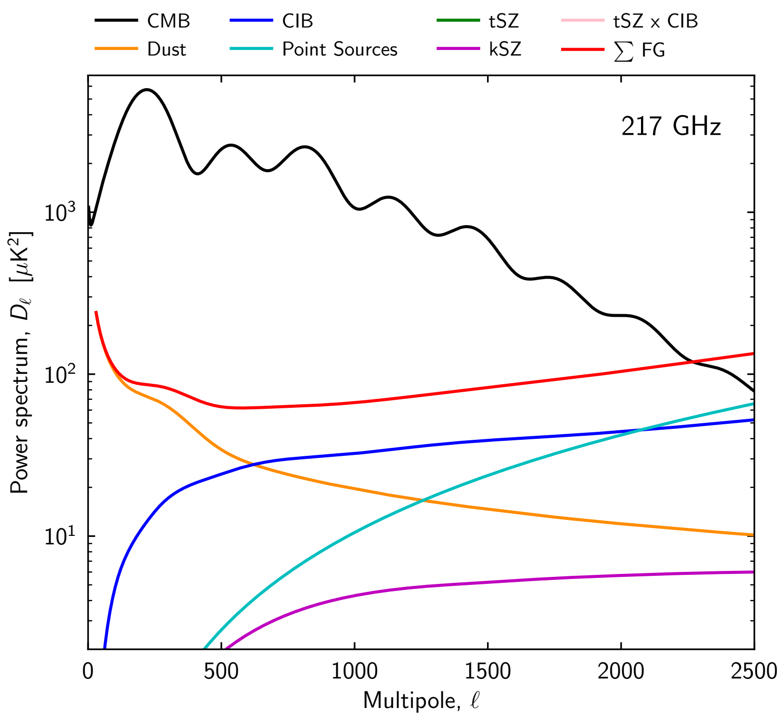


Kinetic SZ: CMB photons are scattered by electrons in bulk motion. C_ℓ^{kSZ} from Trac, Bode & Ostriker 2011

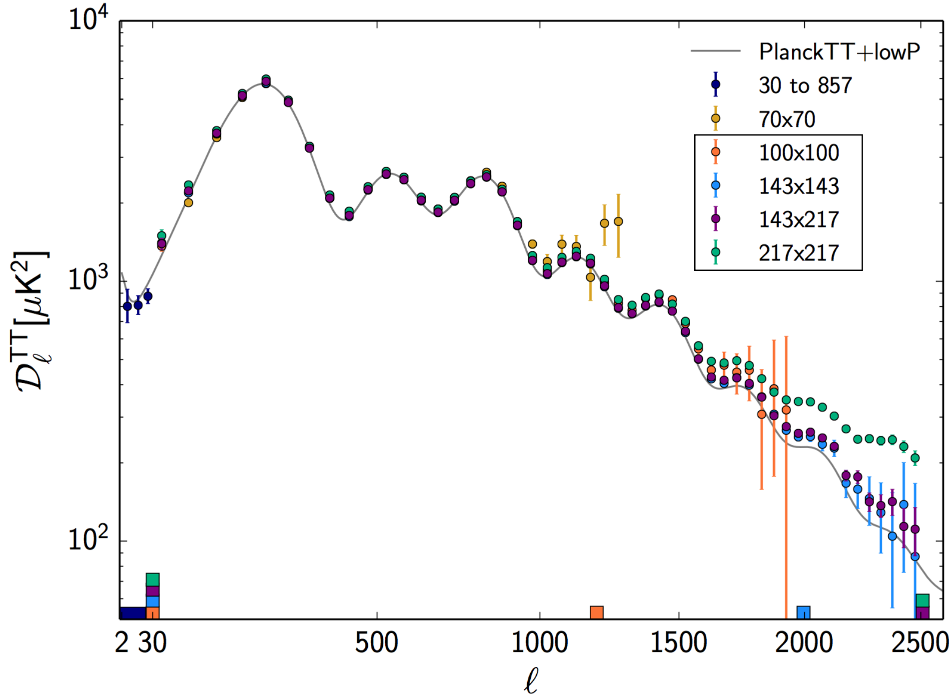
tSZ x CIB: correlation between the tSZ and CIB sources. $C_\ell^{tSZ\ x\ CIB}$ model from Addison et al. 2012



PARAMETRIC FOREGROUND MODEL

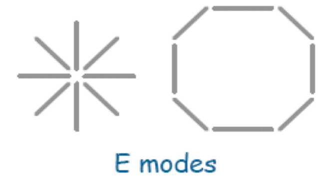


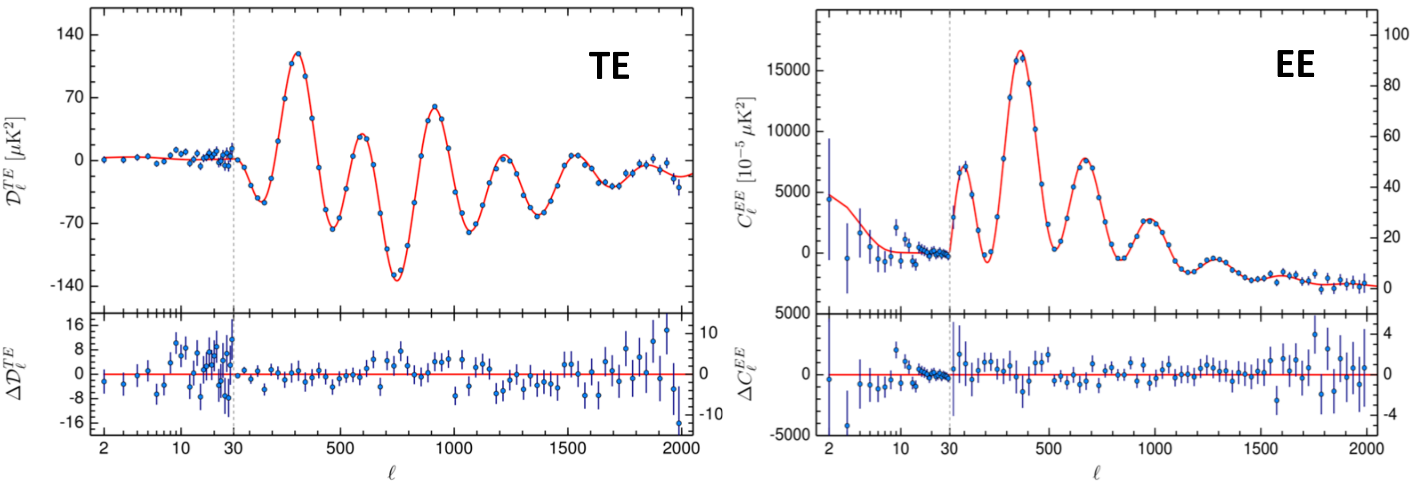
TEMPERATURE FREQUENCY POWER SPECTRA



After fitting and removing the foreground model to the data, the CMB angular power spectra estimated from different frequencies agree to high accuracy. Each of them is a good fit to the ΛCDM model.

POLARIZATION POWER SPECTRA



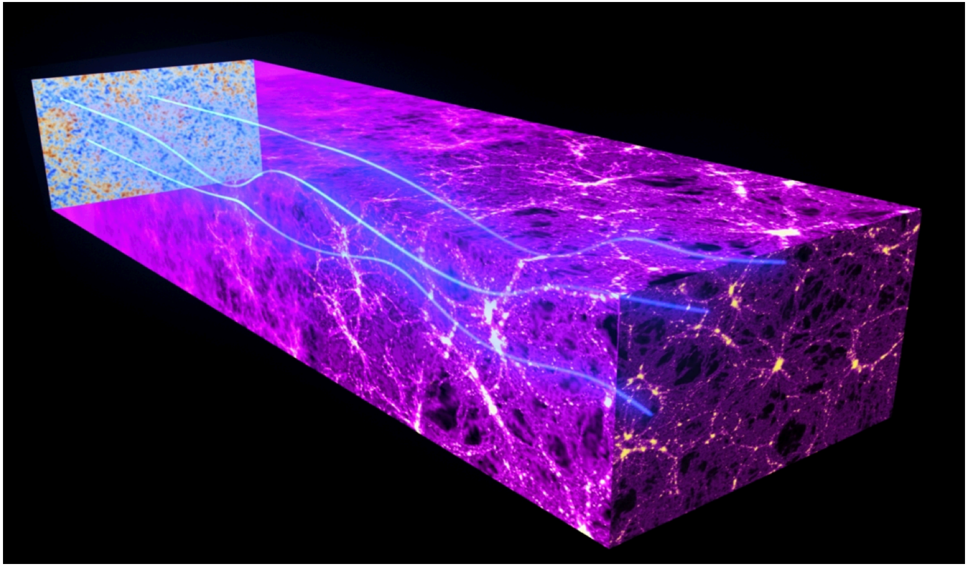


Red line is the best-fit cosmology from temperature data: success of the ΛCDM model

Residual low level systematics are still unaccounted for O(1 uK^2) (e.g., T → P leakage,…)

Gravitational Lensing

The gravitational tug of the intervening large scale structure distorts photon paths. Deflections ~ 2 arcmin, coherent over 2 degree scales. A subtle effect that may be measured statistically with high angular resolution, low-noise observations of the CMB, like those from Planck.



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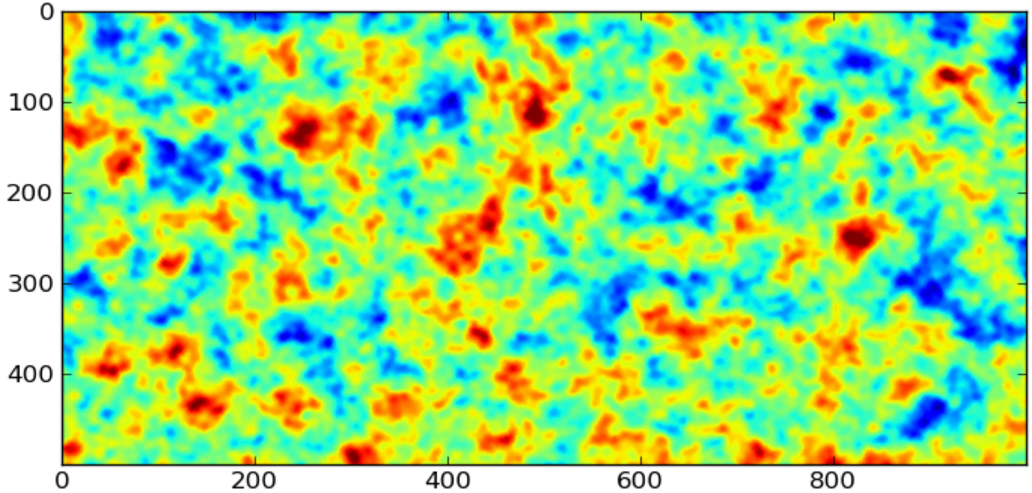
simulation

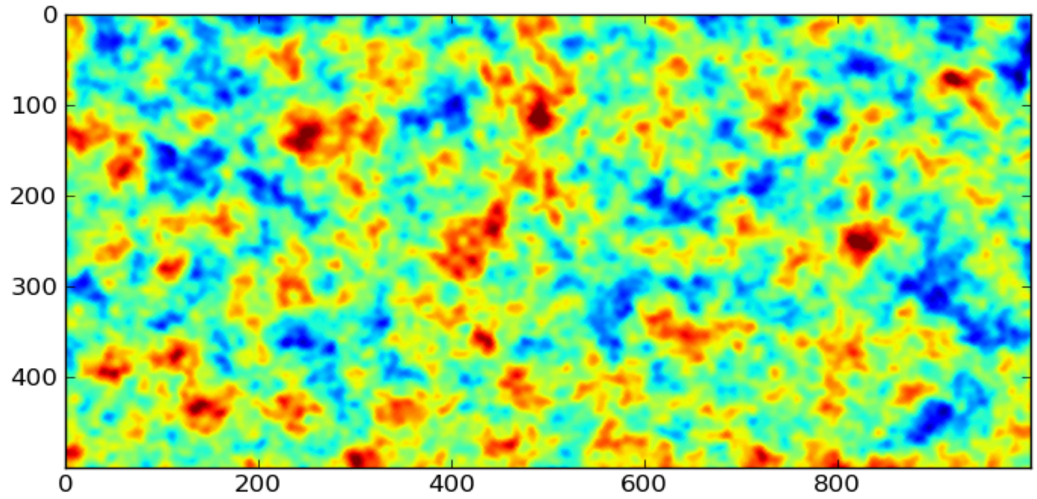


UNLENSED

Gravitational Lensing

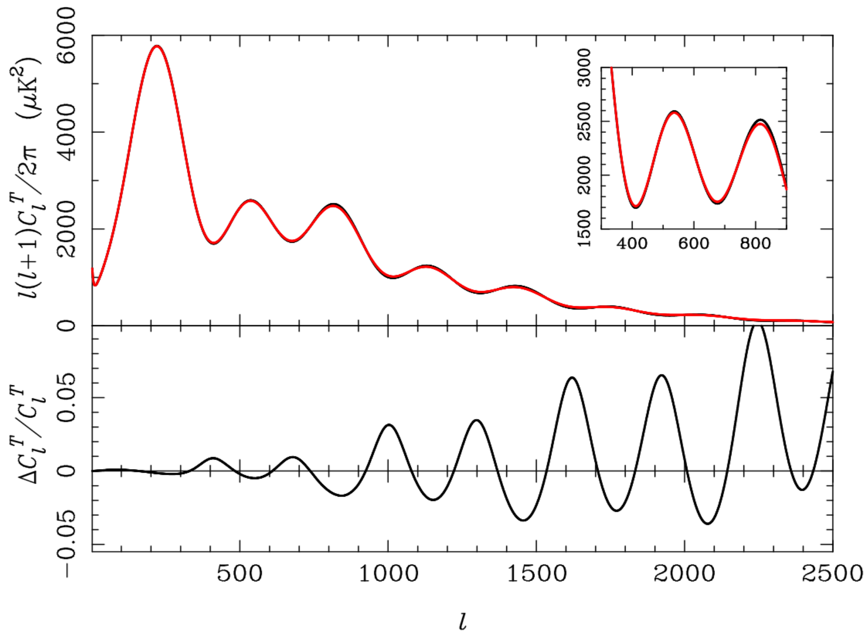
The gravitational tug of the intervening large scale structure distorts photon paths. Deflections ~ 2 arcmin, coherent over 2 degree scales. A subtle effect that may be measured statistically with high angular resolution, low-noise observations of the CMB, like those from Planck.

simulation



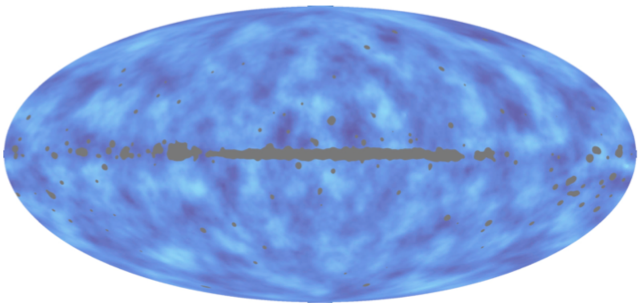
LENSED

Gravitational Lensing



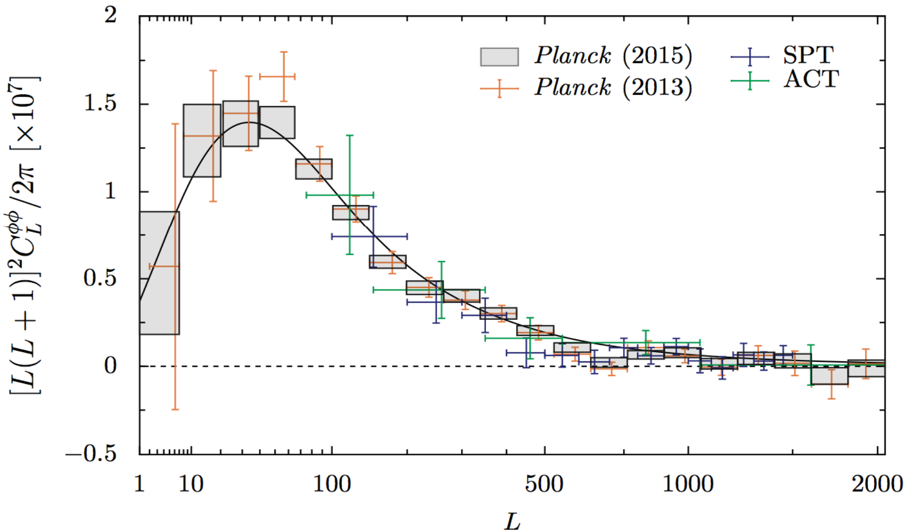
Lensing smooths the peaks and troughs of the angular power spectrum: detected at 10σ level

Gravitational Lensing



Deflections induce a distinctive non-Gaussianity -> 4pt correlation function -> gravitational potential

Planck 2015 results. XV



Amplitude constrained to ~ 2.5%
40 sigma detection
success of the ΛCDM model

Breaks degeneracies in constraining: Dark Matter, Large scale structure evolution, Curvature, Neutrino masses, …

Final Remarks

Planck provided the most precise yet measurement of the CMB anisotropy field and stringent tests of the cosmological model

Base inflationary ΛCDM model is very successful in explaining Planck Temperature, Polarization, and Lensing data

Planck is internally consistent (lots of robustness tests) and also consistent with other CMB experiments (e.g. WMAP, ACT and SPT), with Baryon Acoustic Oscillation, Type Ia SN, Big Bang Nucleosynthesis predictions.

There are however tensions with some low-redshift observables that cannot be reconciled by simple extensions to ΛCDM

PLANCK

H_0 = 67.31 ± 0.96 km $s^{-1}Mpc^{-1}$ (PlanckTT+LFI LowP)

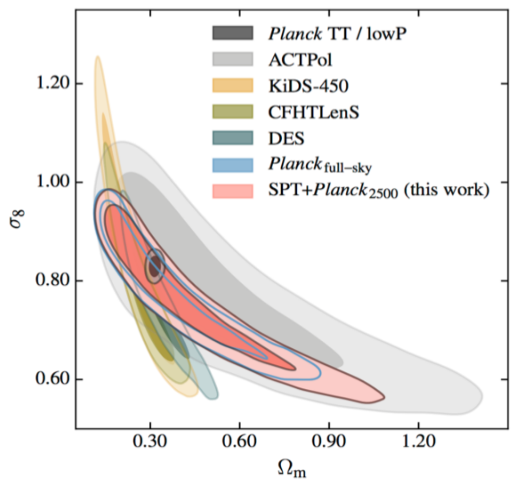
H_0 = 66.88 ± 0.91 km $s^{-1}Mpc^{-1}$ (PlanckTT+HFI LowP)

DIRECT (LOCAL) MEASUREMENTS (Riess et al. 2016)

H_0 = 73.24 ± 1.74 km $s^{-1}Mpc^{-1}$ (> 3σ tension)

RMS of linear matter fluctuations σ_8 from Planck > estimates from galaxy weak lensing in optical surveys and (possibly) large galaxy clusters number counts.

G. Simard et al. SPT Collaboration 2018



Acknowledgements: the scientific results presented here are a product of the Planck Collaboration, including individuals from more than 100 institutes in Europe, the USA and Canada.

THANK YOU