



planck

Cosmological results from Planck

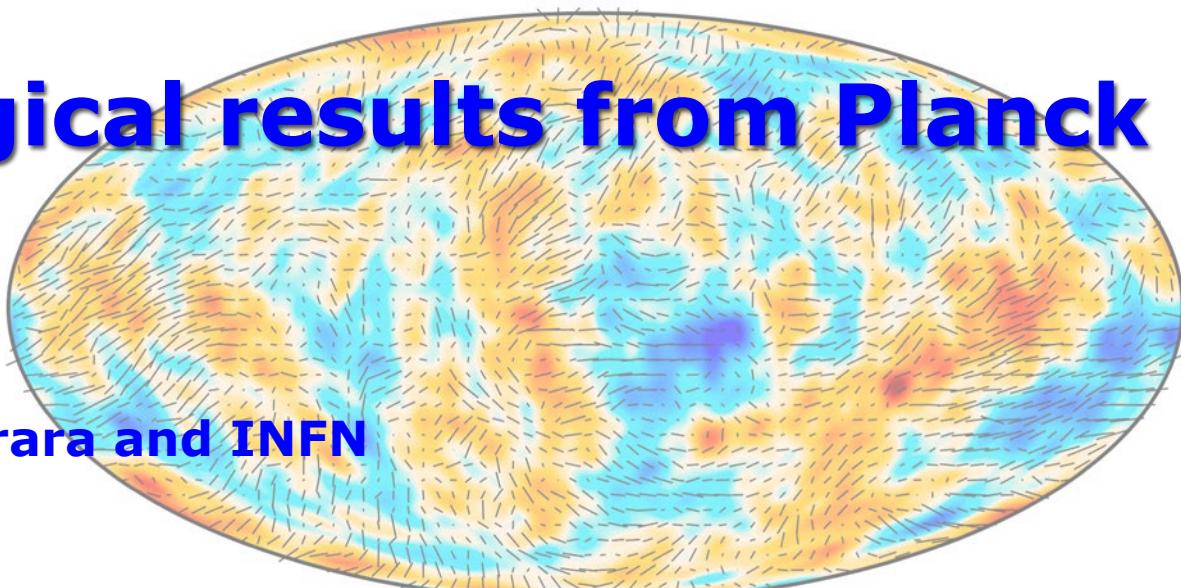
Paolo Natoli

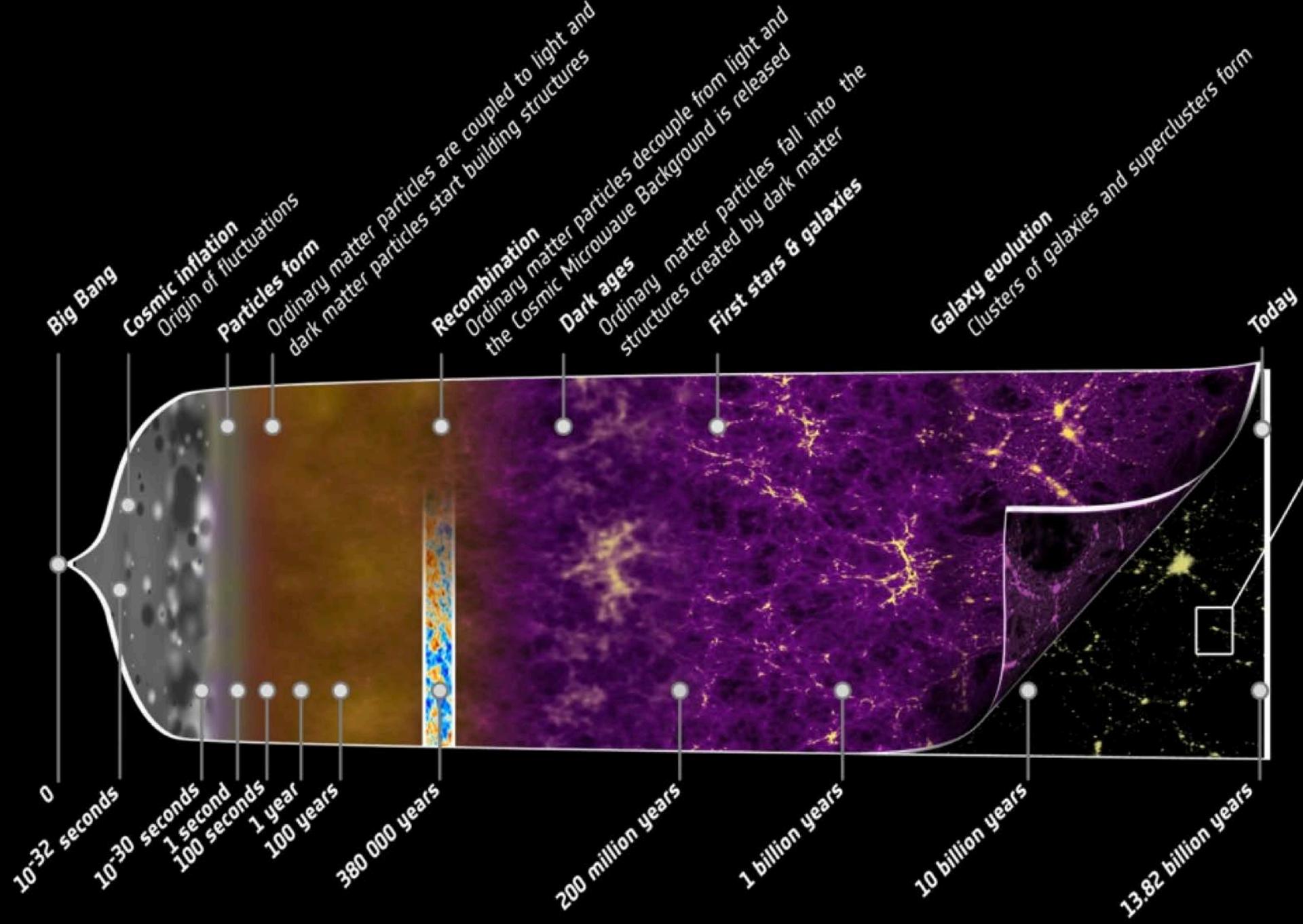
Università di Ferrara and INFN

SUSY 2018

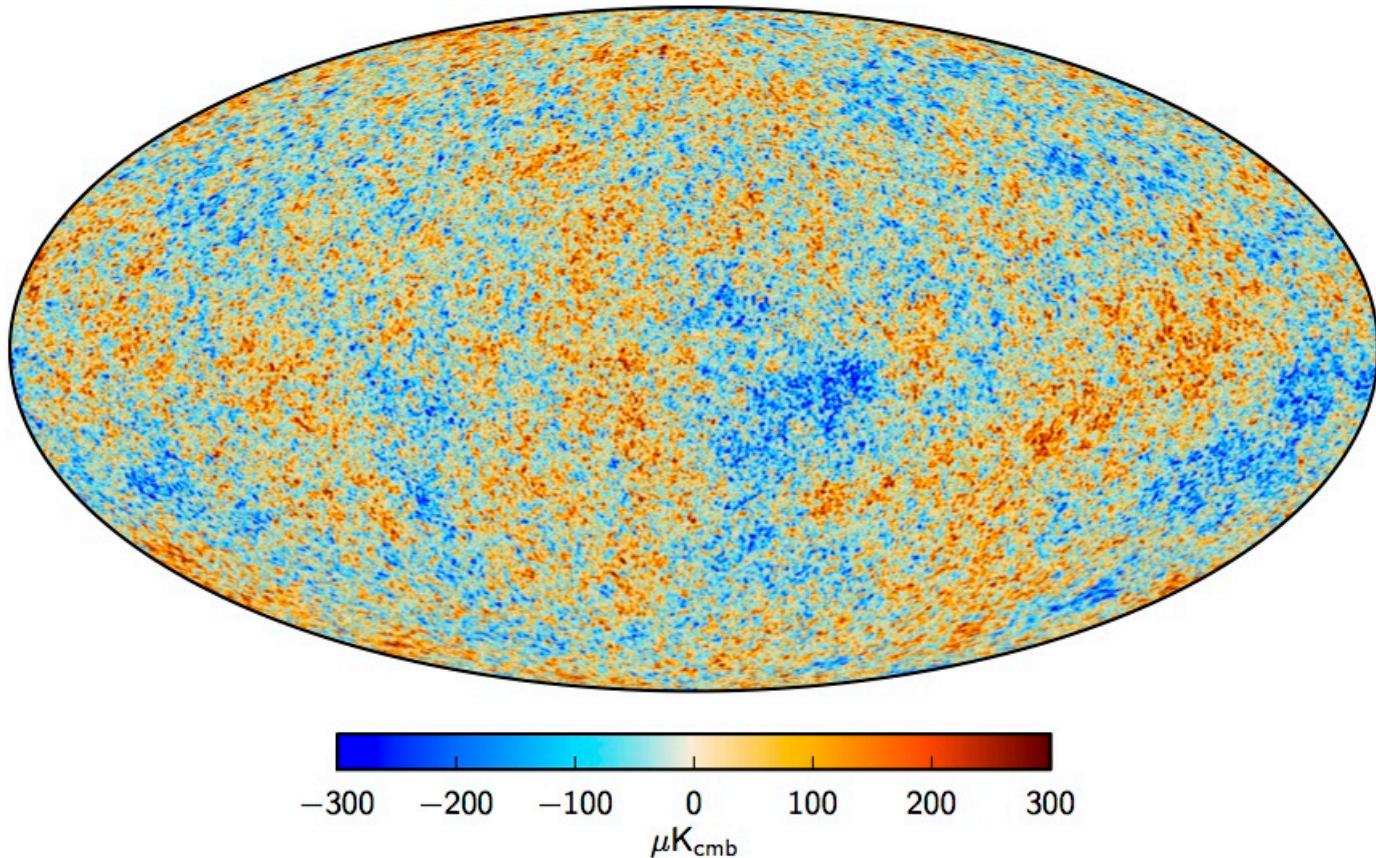
26th International Conference on Supersymmetry and Unification of Fundamental Interactions

Barcelona, 26 July 2018





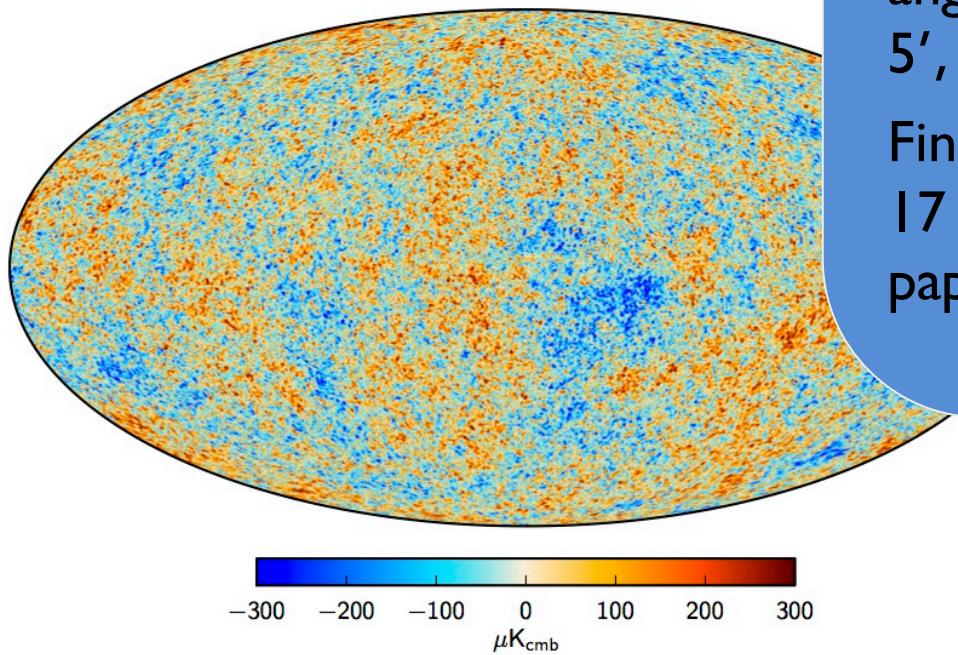
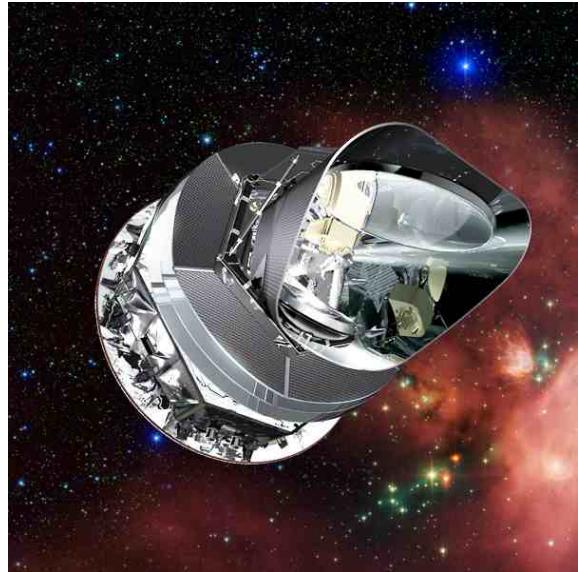
THE COSMIC MICROWAVE BACKGROUND



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 (the so-called last scattering surface, LSS).

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

THE PLANCK SATELLITE



Planck is a 3rd generation ESA satellite devoted to CMB

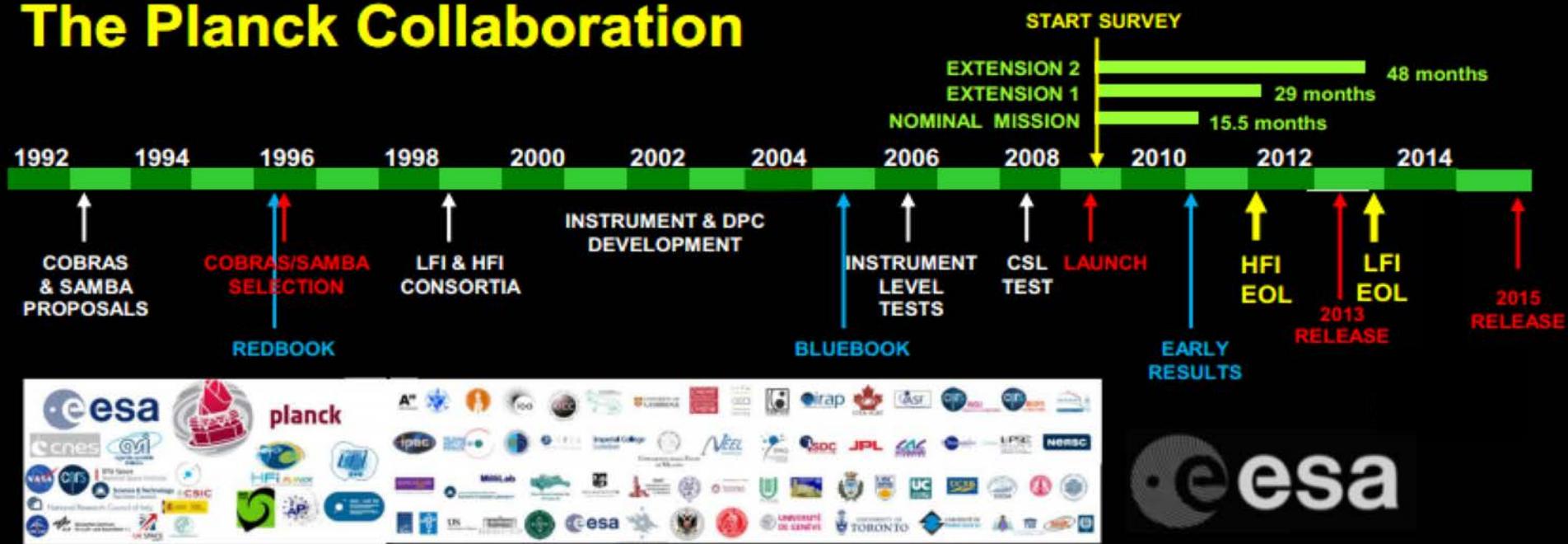
Ultimate characterization of the temperature anisotropies

74 detectors (radiometers and bolometers) in 9 frequency bands from 30 to 857 GHz

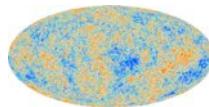
angular resolution between 30' and 5', $\Delta T/T \sim 2 \times 10^{-6}$

Final (legacy) release took place on 17 July 2018, for data and (most) papers.

The Planck Collaboration



May 2009: Launched from Kourou



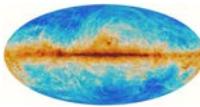
Mar 2013: Data Release and Cosmology Results
Nominal Mission Temperature data

32 papers



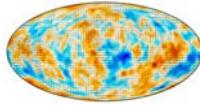
Oct 2013: Planck 'Shut Down'

52 papers / intermediate results



Feb 2015: Data Release and Cosmology Results
Full Mission Temperature and (preliminary) Polarization data

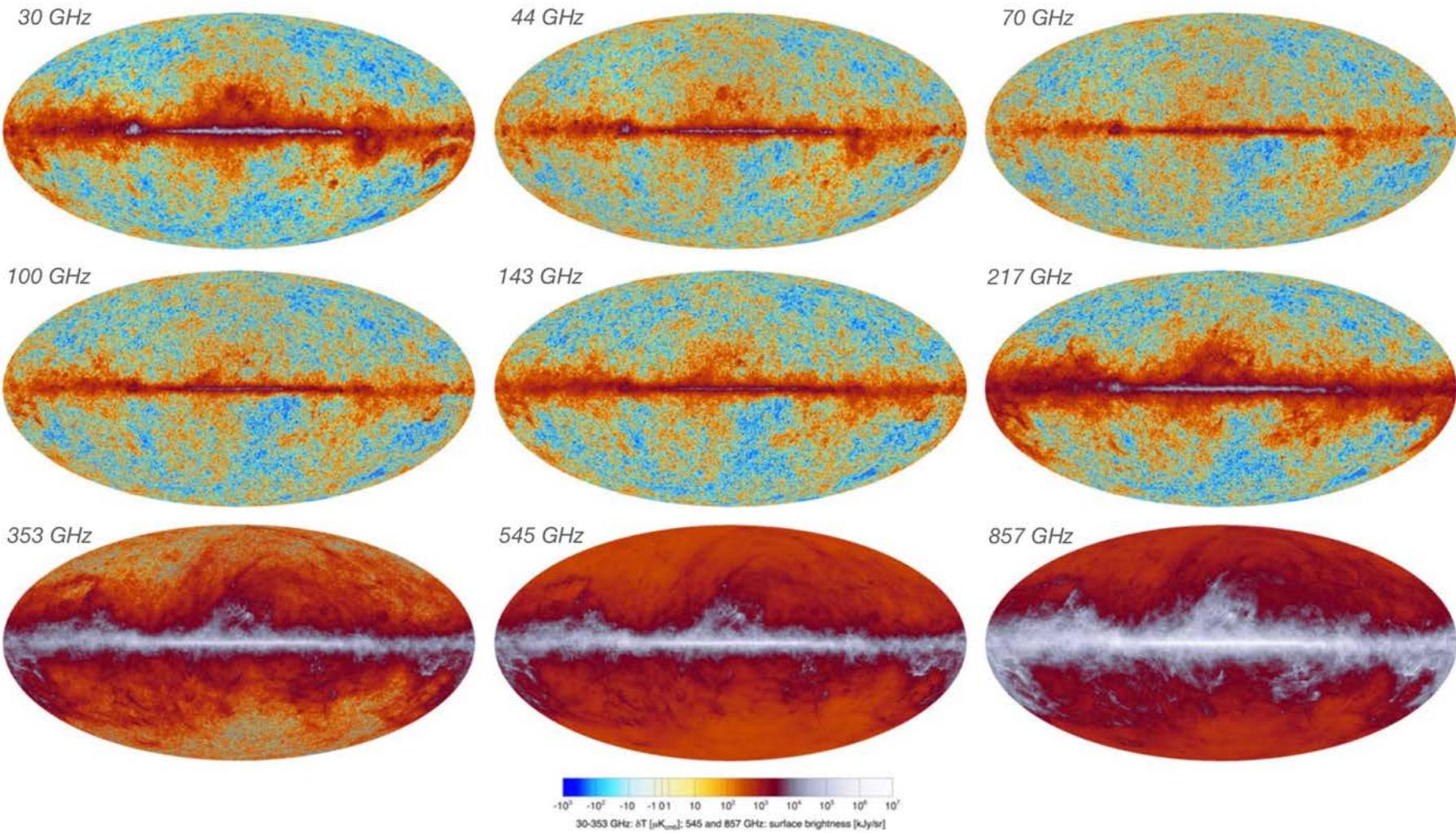
28 papers



Jul 2018: Legacy Data & Paper Release

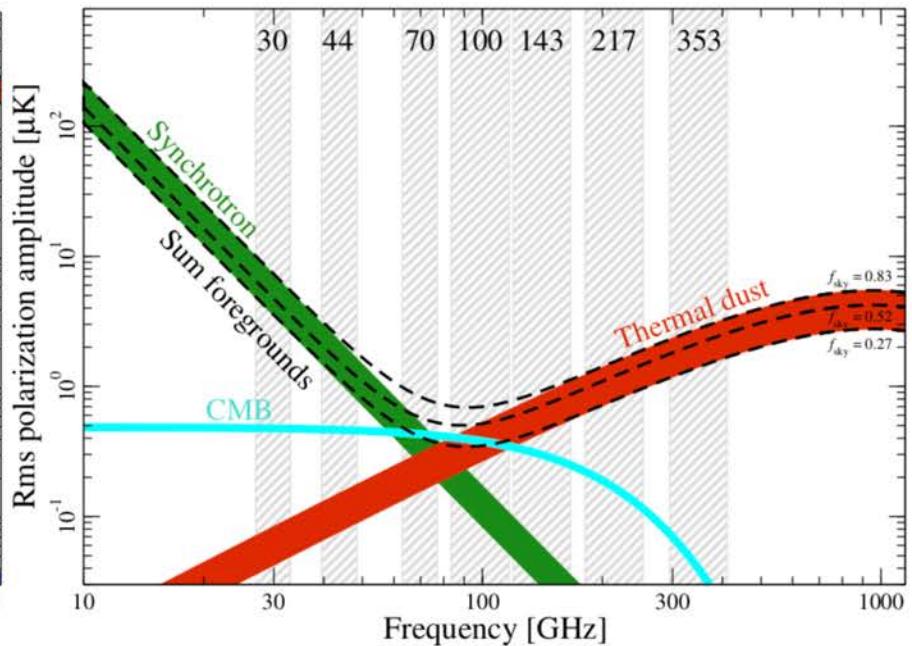
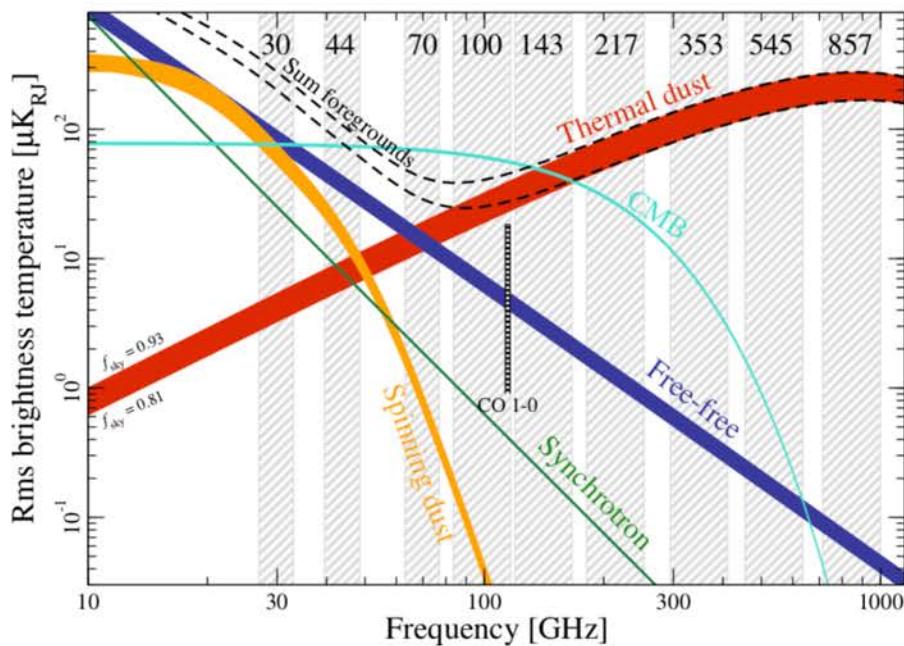
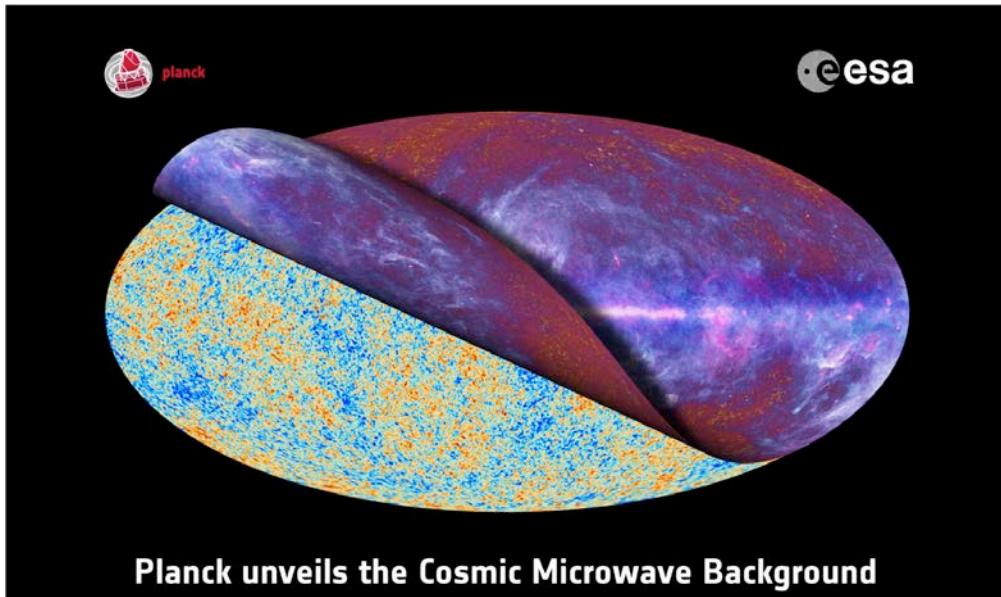
9 papers (+3 to appear soon)

THE TEMPERATURE SKY AS SEEN BY PLANCK 2018

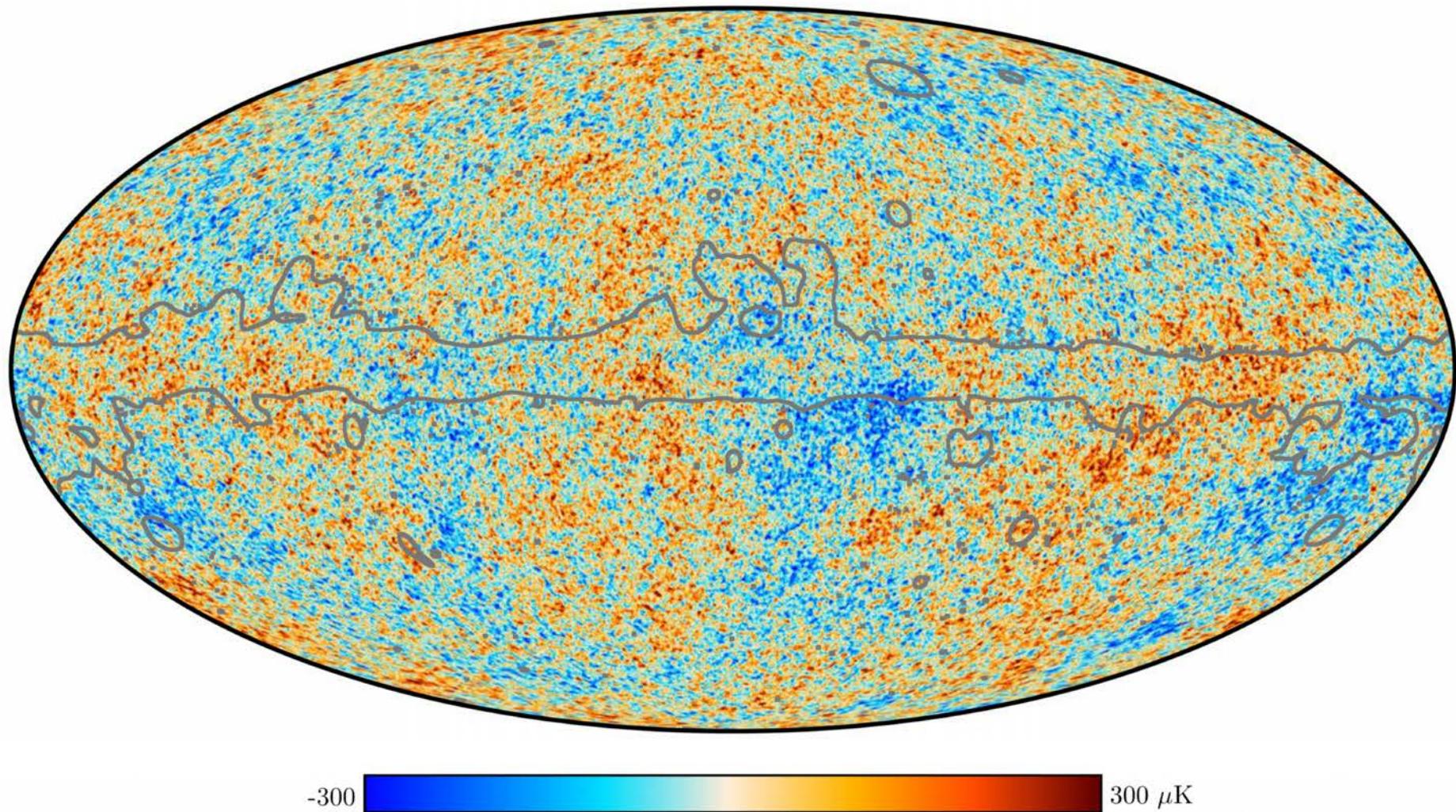


UNVEILING THE CMB SKY

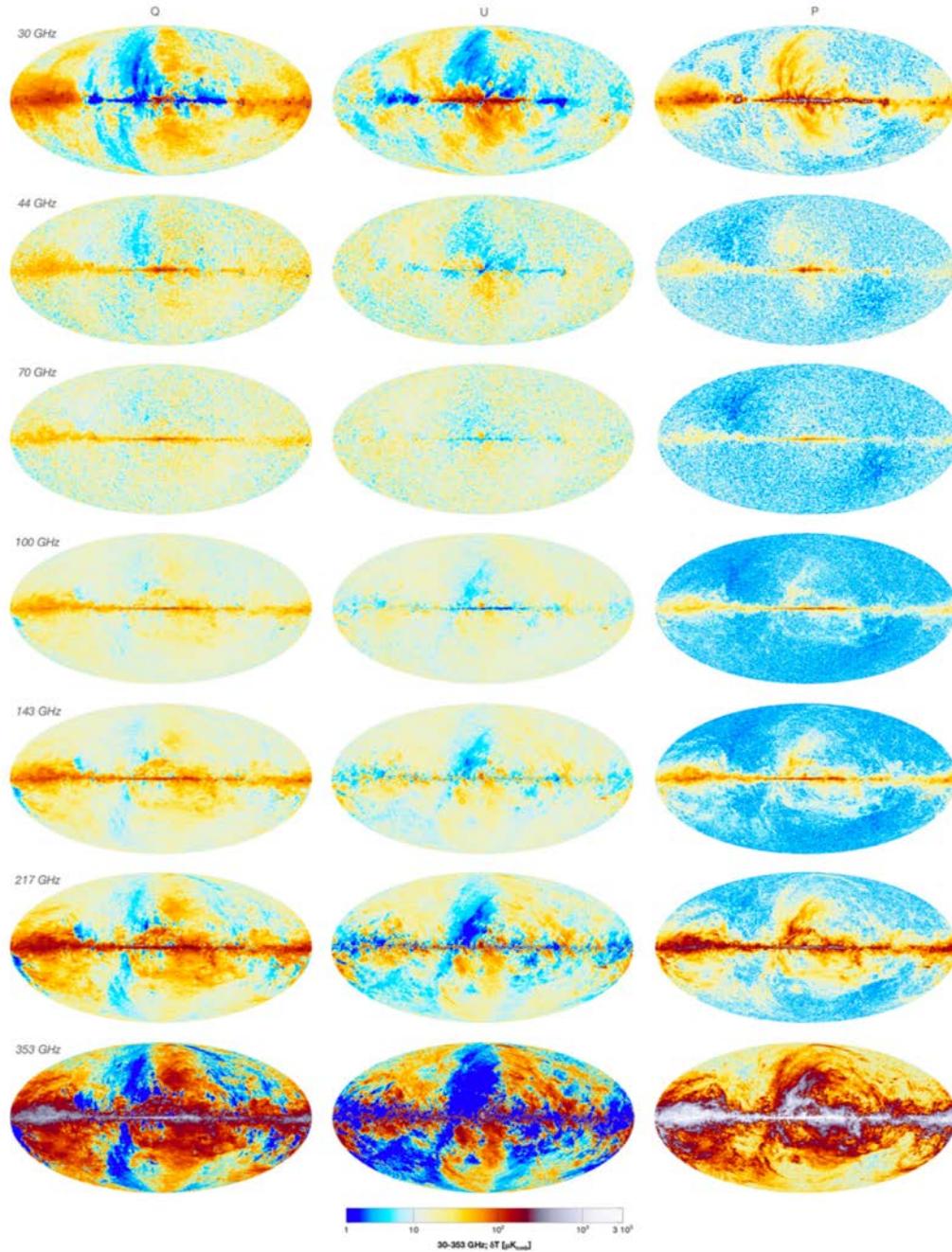
The *ultimate*
measurement of
the CMB
temperature
anisotropy field



PLANCK: TEMPERATURE ANISOTROPIES

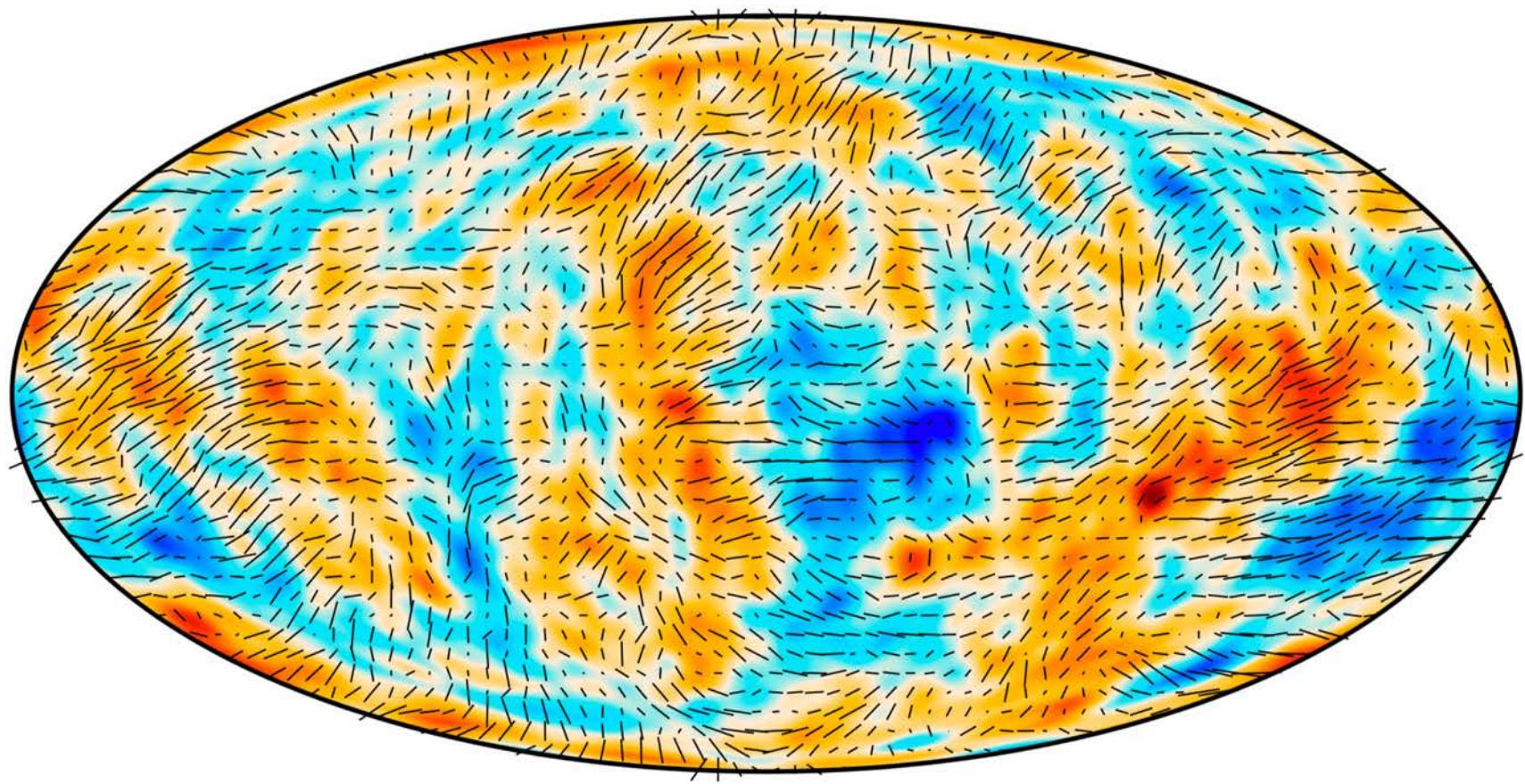


THE POLARIZATION SKY AS SEEN BY PLANCK 2018



Significant reduction of
large scale polarization
systematics in 2018

PLANCK: POLARIZATION ANISOTROPIES



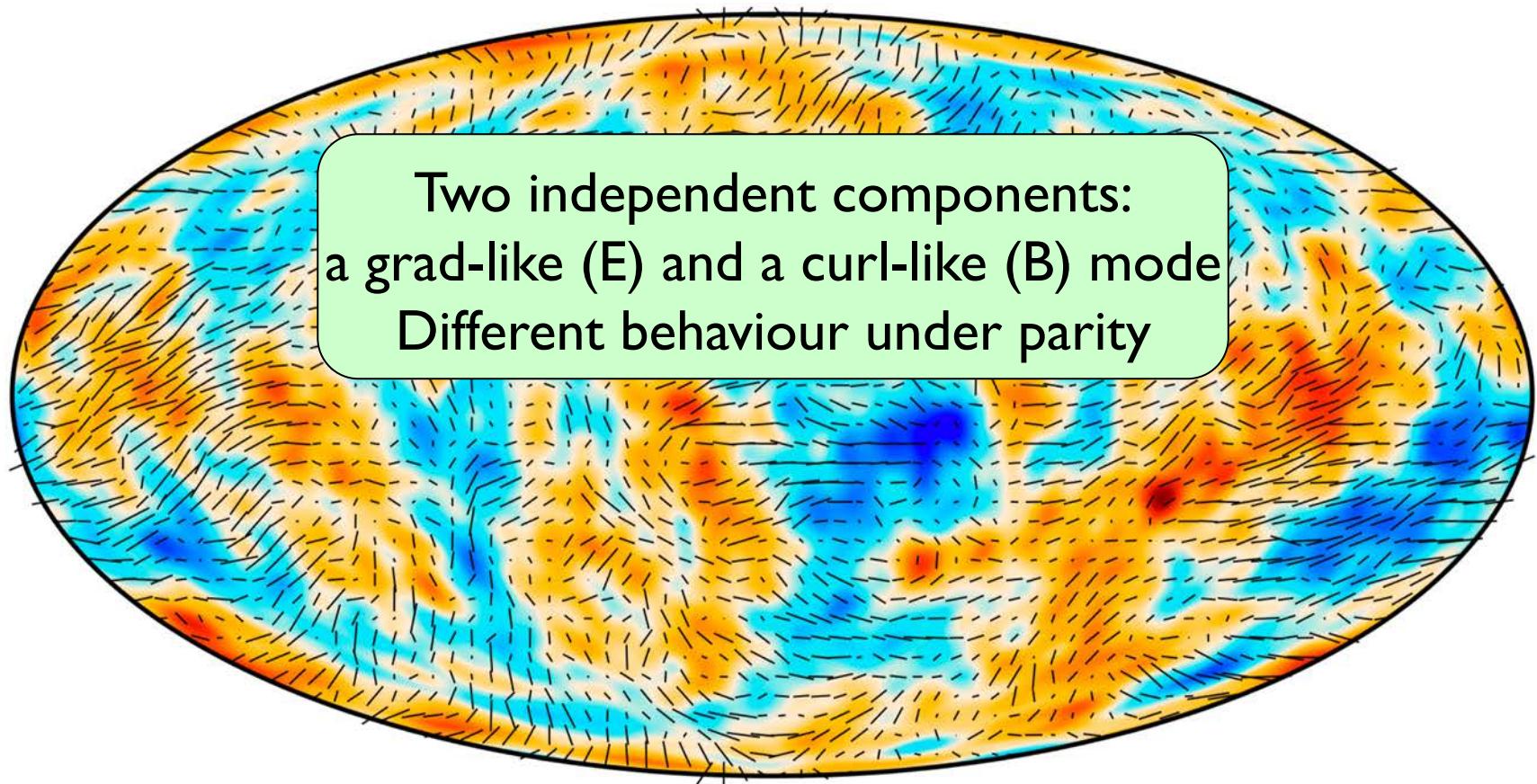
| 0.41 μK

-160

160 μK

Temperature smoothed to 5 degrees

PLANCK: POLARIZATION ANISOTROPIES



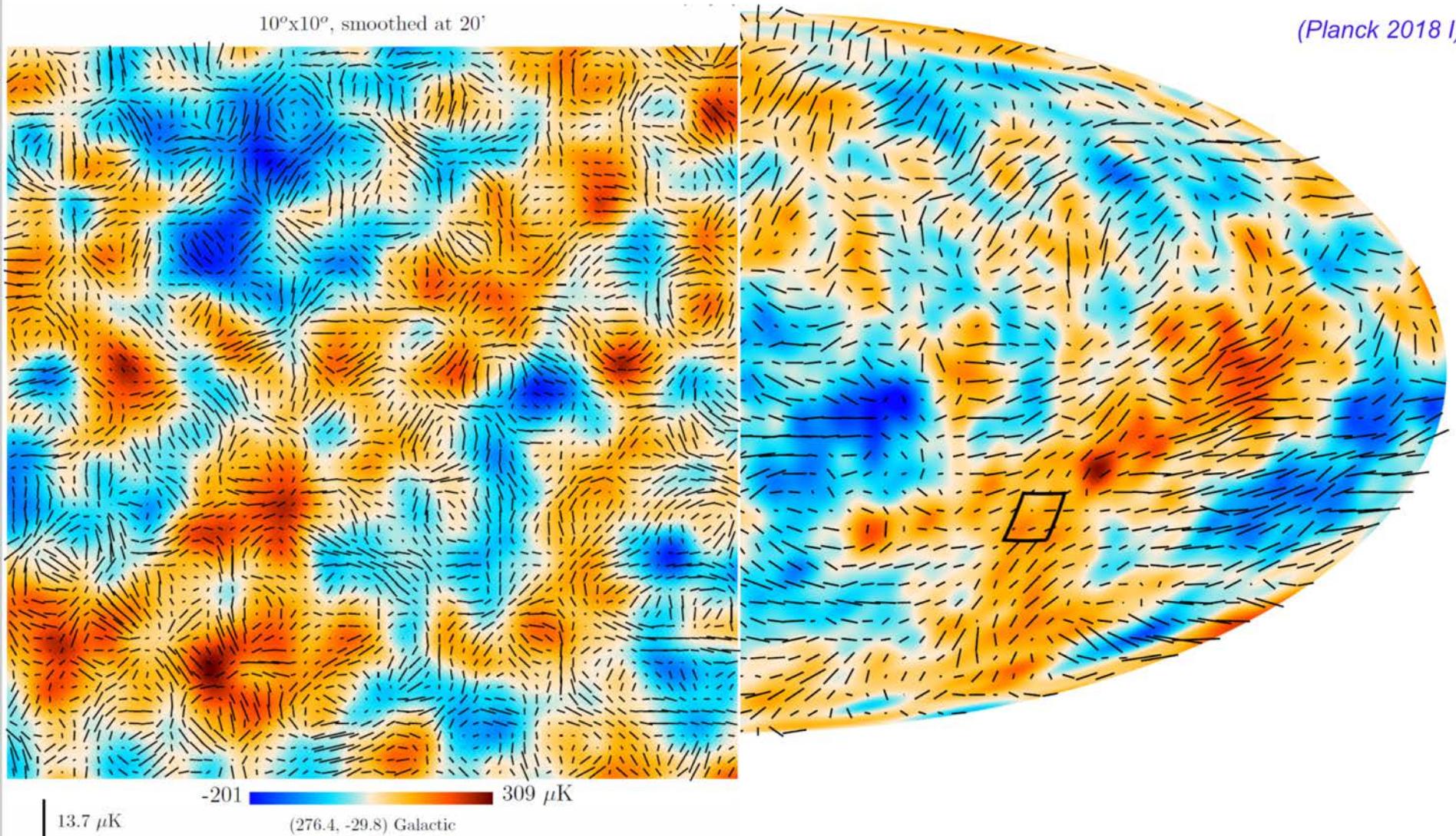
| $0.41 \mu\text{K}$

-160

160 μK

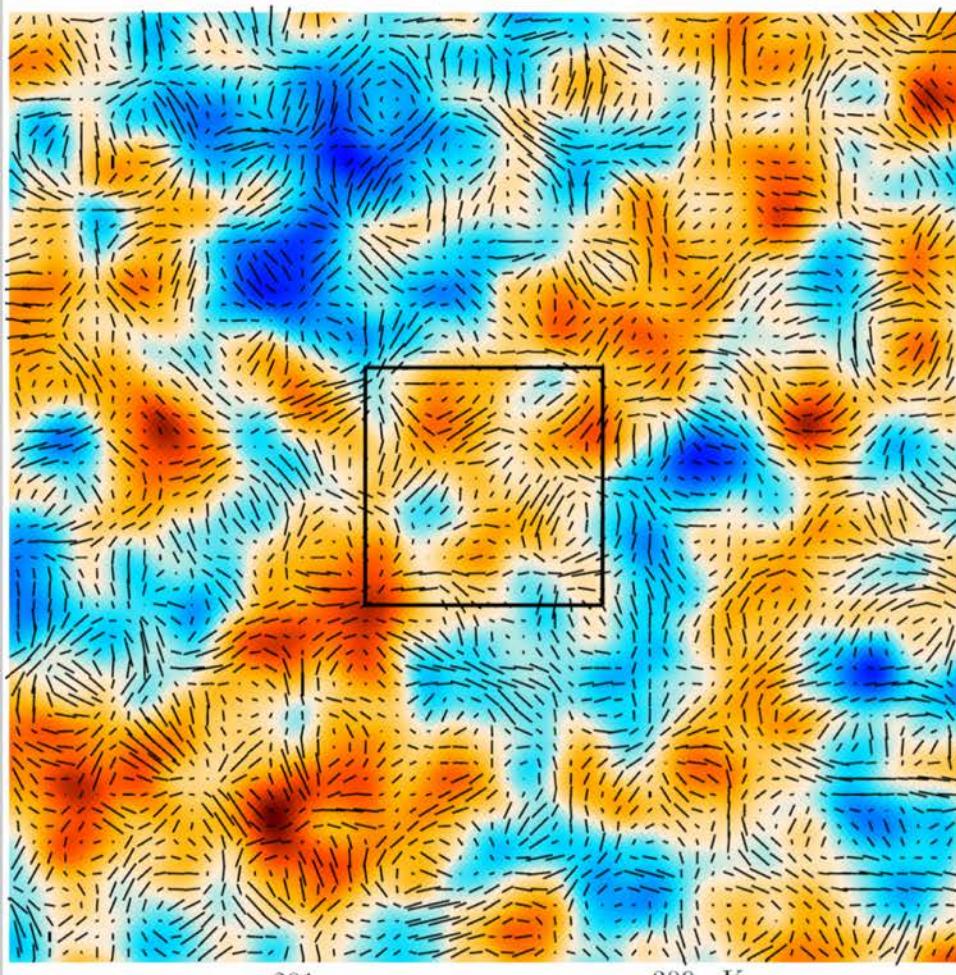
Temperature smoothed to 5 degrees

PLANCK: POLARIZATION ANISOTROPIES



PLANCK: POLARIZATION ANISOTROPIES

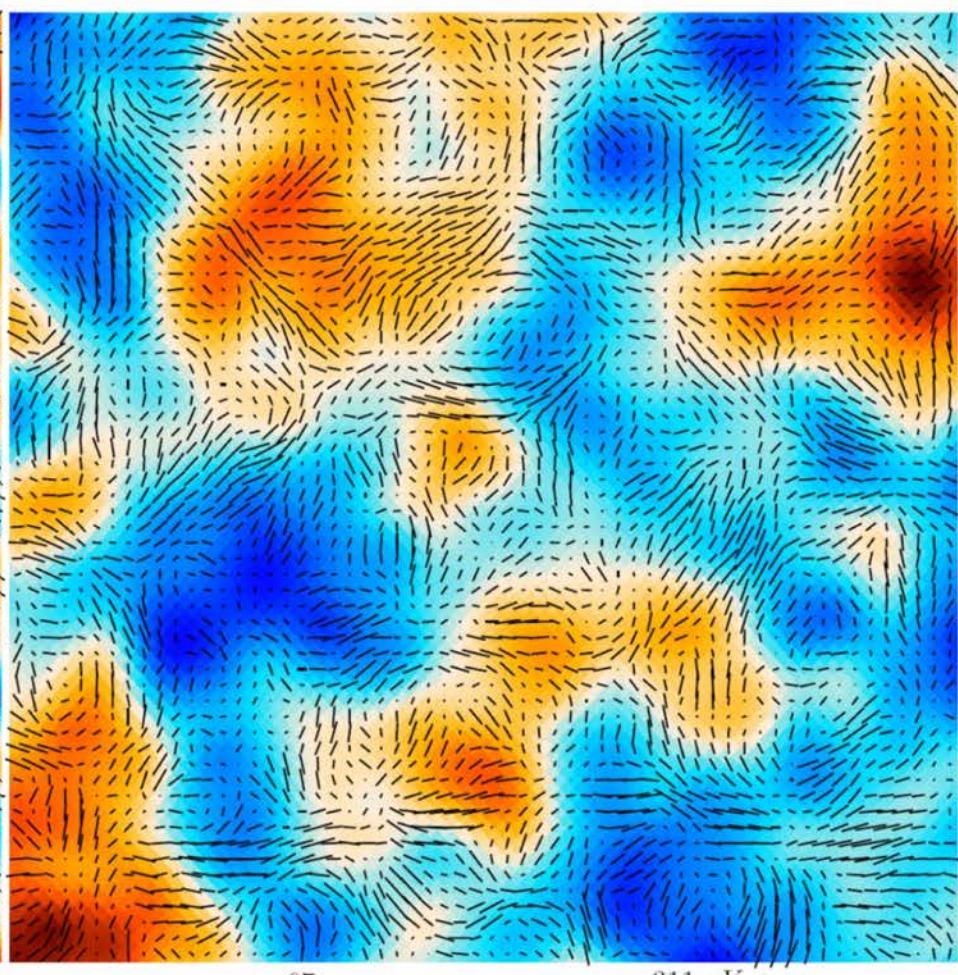
$10^\circ \times 10^\circ$, smoothed at $20'$



$13.7 \mu\text{K}$

-201 309 μK
(276.4, -29.8) Galactic

$2.5^\circ \times 2.5^\circ$, smoothed at $7'$

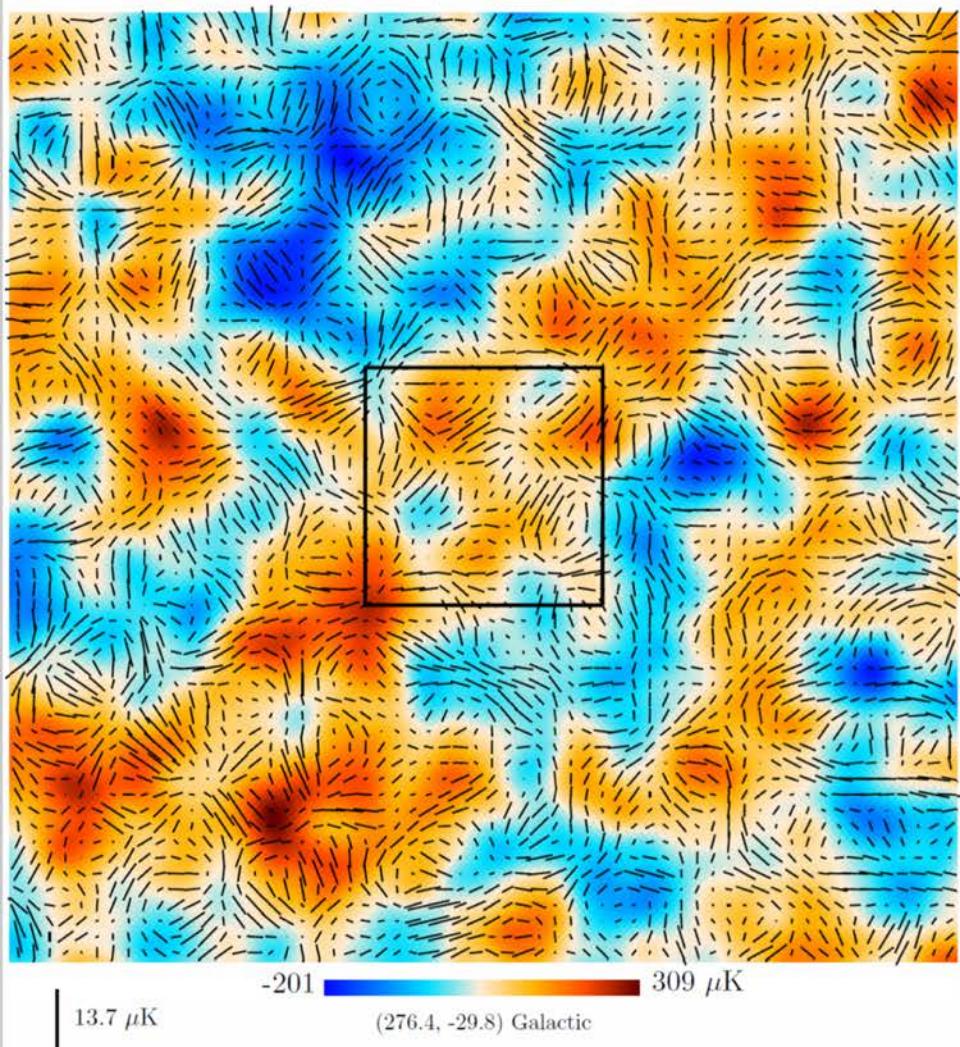


$36.1 \mu\text{K}$

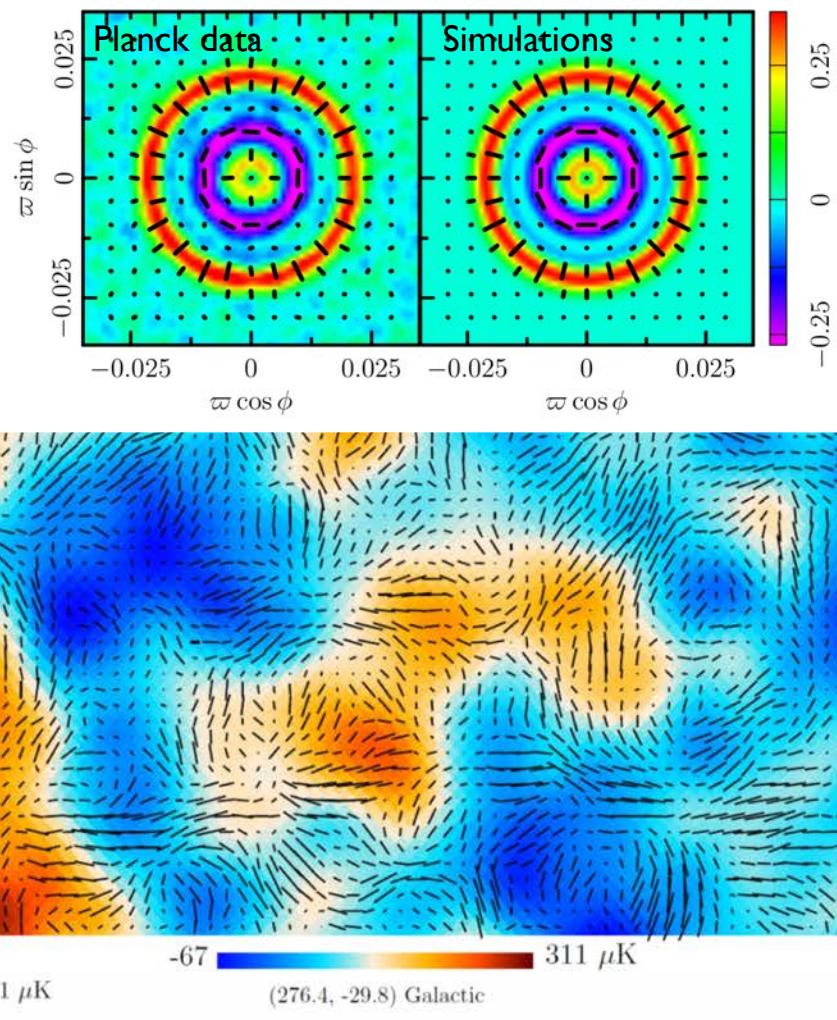
-67 311 μK
(276.4, -29.8) Galactic

PLANCK: POLARIZATION ANISOTROPIES

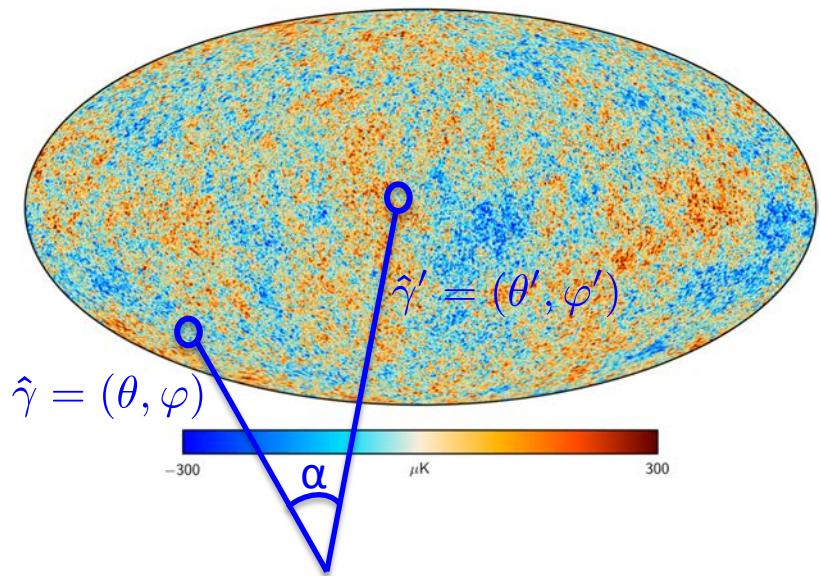
$10^\circ \times 10^\circ$, smoothed at $20'$



$2.5^\circ \times 2.5^\circ$, smoothed at $7'$



STATISTICAL DESCRIPTION



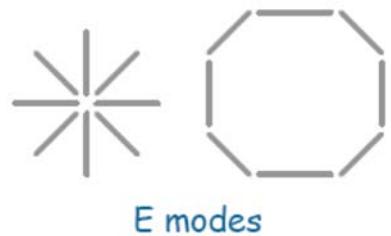
CORRELATION FUNCTIONS

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}) \frac{\Delta T}{T}(\vec{\gamma}') \right\rangle \quad \text{← from Inflation}$$

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}) \frac{\Delta T}{T}(\vec{\gamma}') \frac{\Delta T}{T}(\vec{\gamma}'') \right\rangle$$

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}) \frac{\Delta T}{T}(\vec{\gamma}') \frac{\Delta T}{T}(\vec{\gamma}'') \frac{\Delta T}{T}(\vec{\gamma}''') \right\rangle$$

...

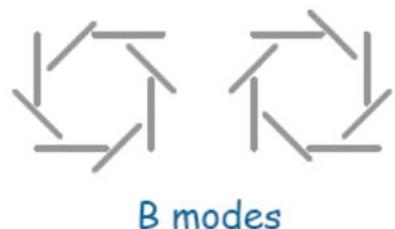


POLARIZATION

$$\mathbf{P}(\hat{\gamma}) = \nabla \mathbf{E} + \nabla \times \mathbf{B}$$

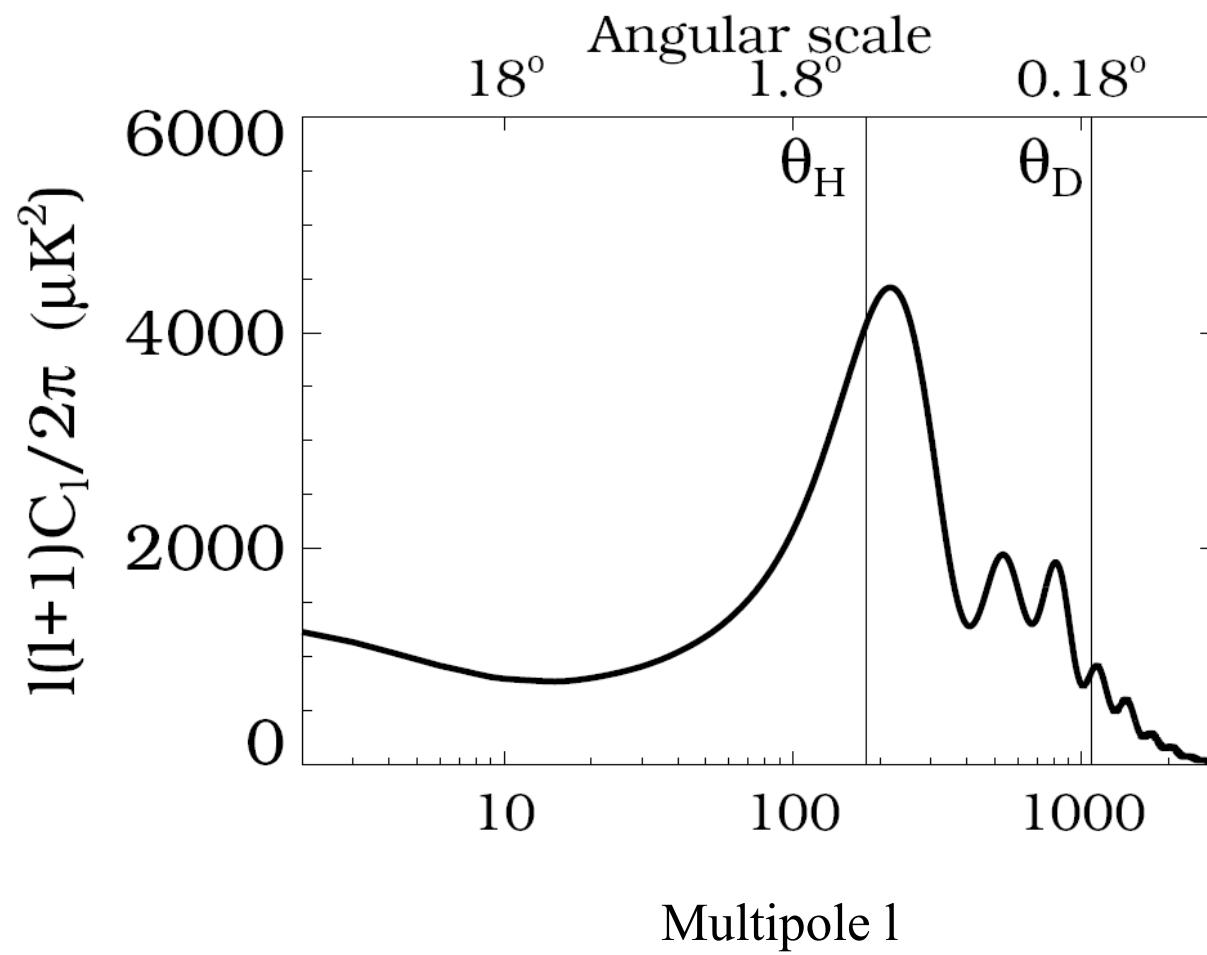
E-modes: even under parity

B-modes: odd under parity



Density perturbations → E-modes

Gravitational Waves → E- and B-modes



spatial curvature

relative abundance of matter and radiation

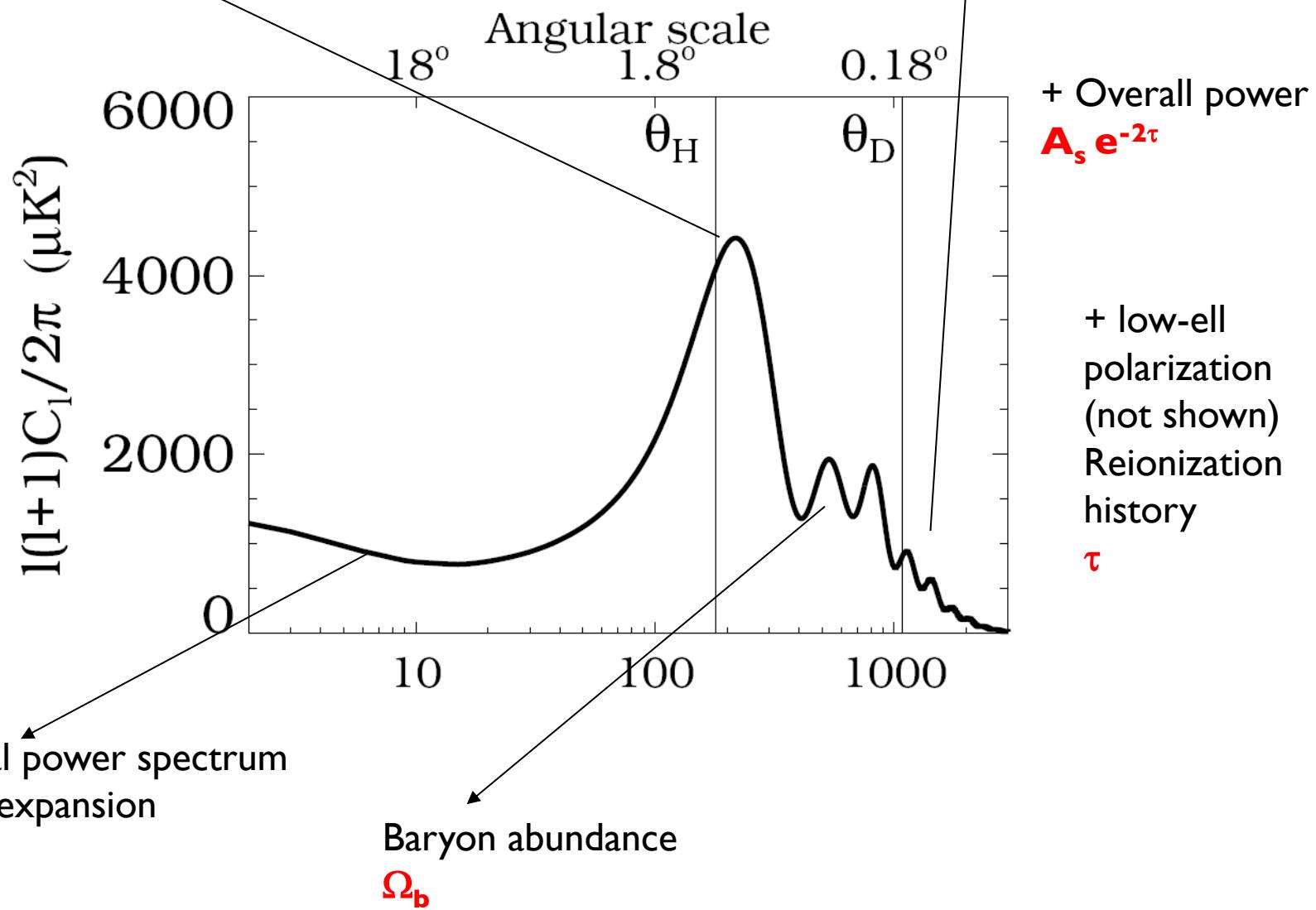
distance to the last scattering surface

H_0, Ω_m, Ω_k

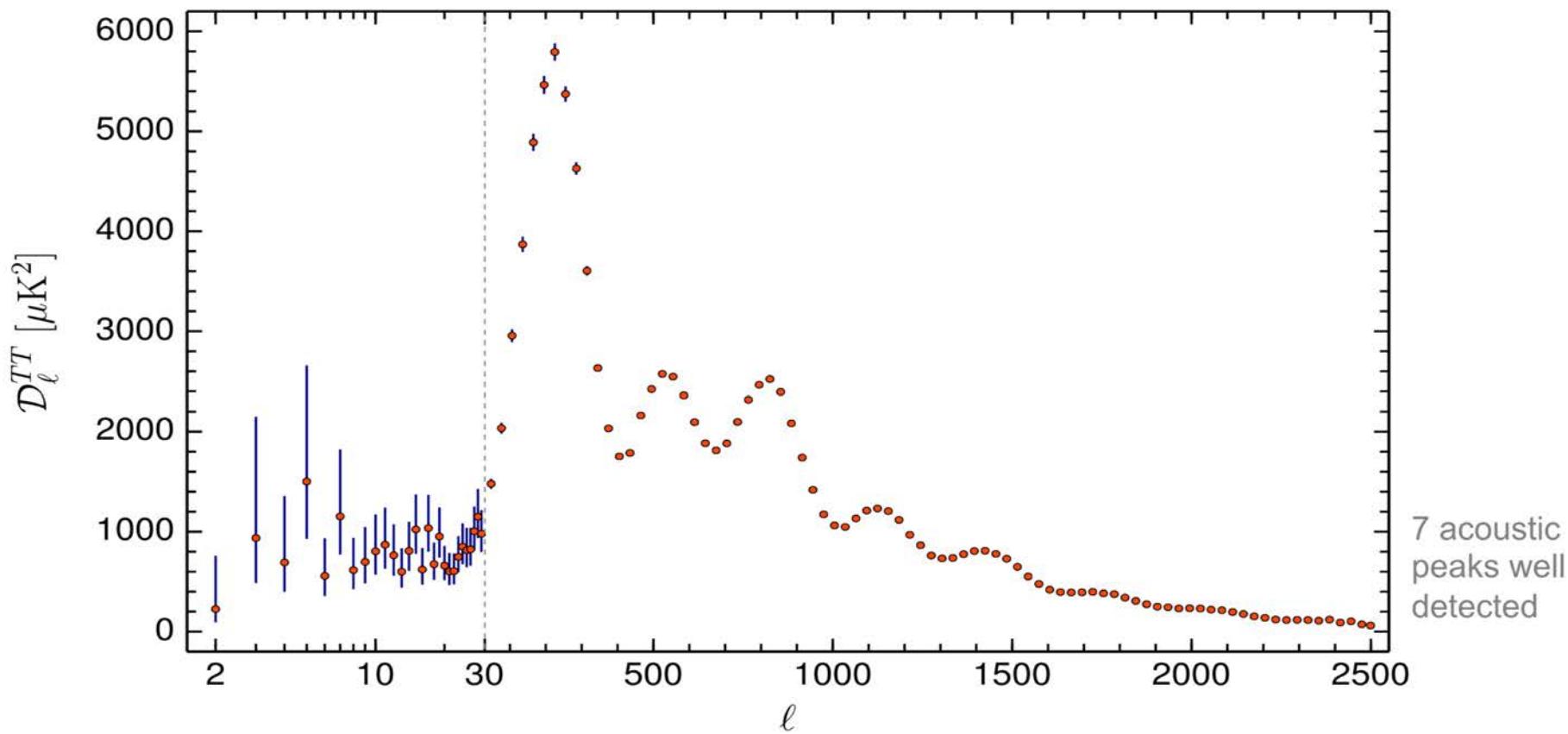
Photon diffusion length at recombination

Slope of the primordial spectrum

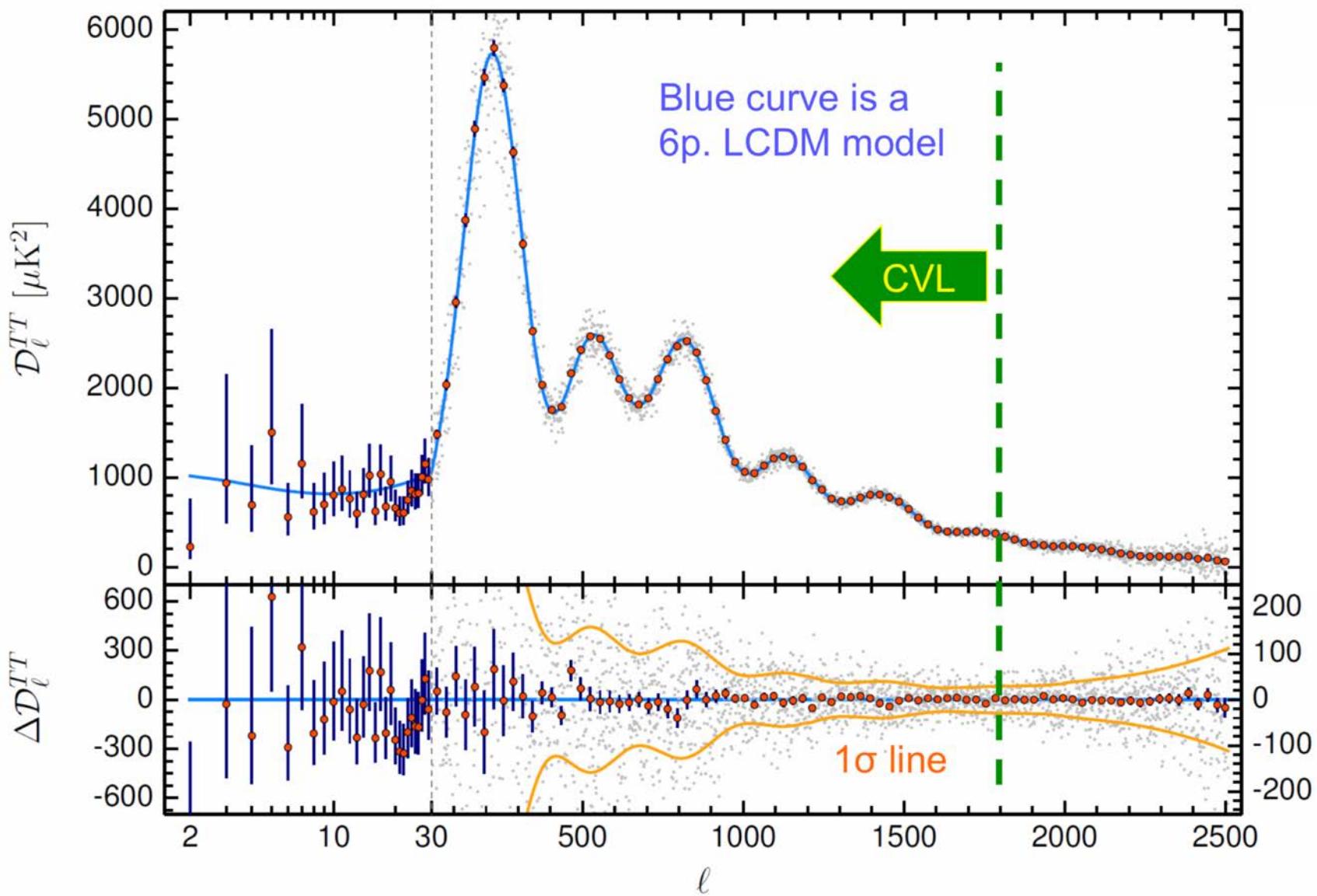
$N_{\text{eff}}, \Omega_b, Y_p, n_s$



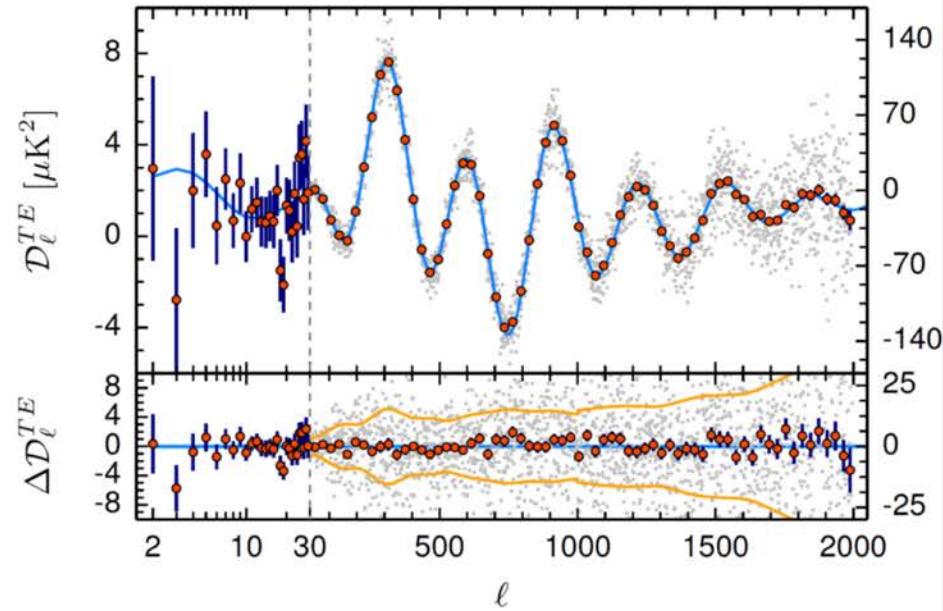
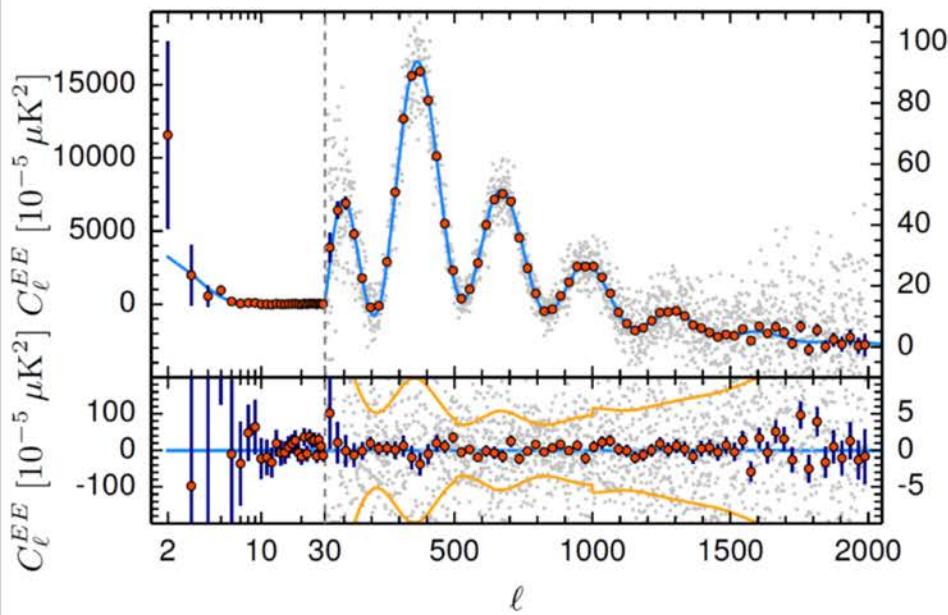
Planck 2018 TT power spectrum



Planck 2018 TT power spectrum

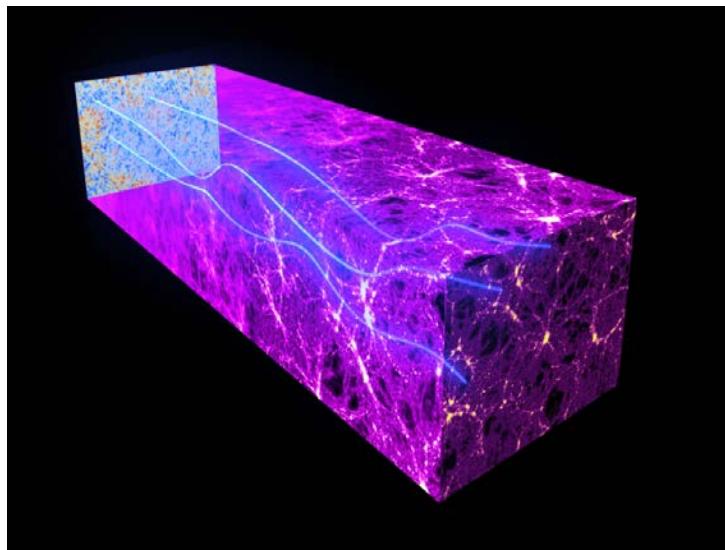


Planck 2018 TE, EE power spectra



Blue line is not a fit, but a prediction given the TT spectrum!

CMB is sensitive to the late-time density field, too....

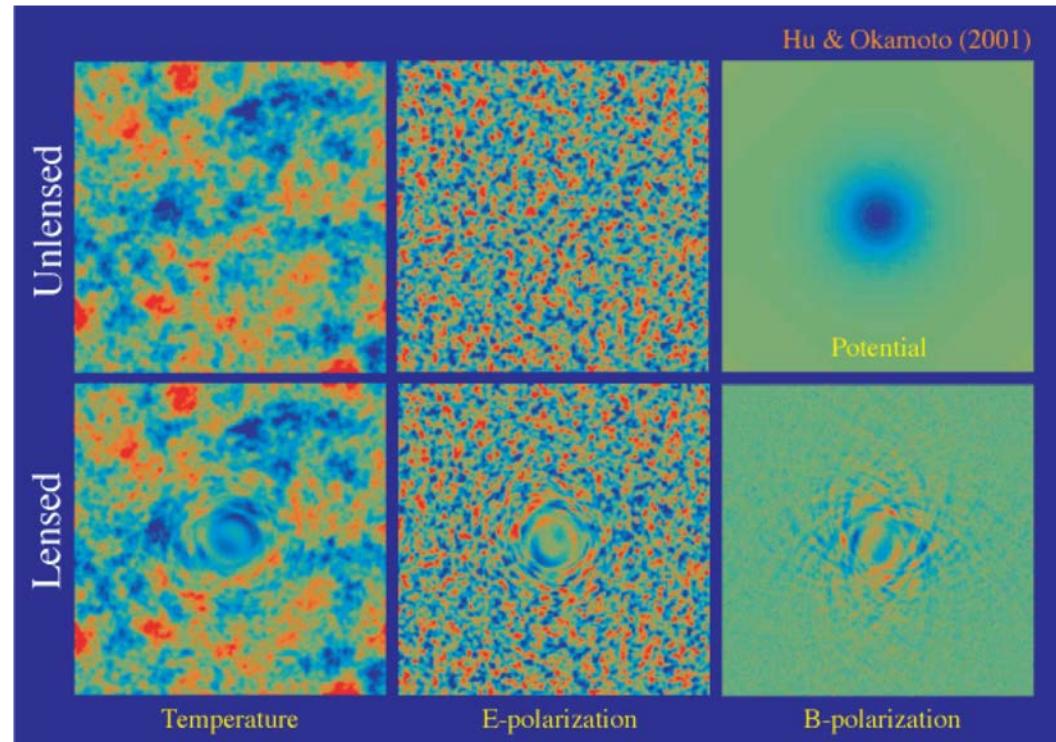


Deflection field

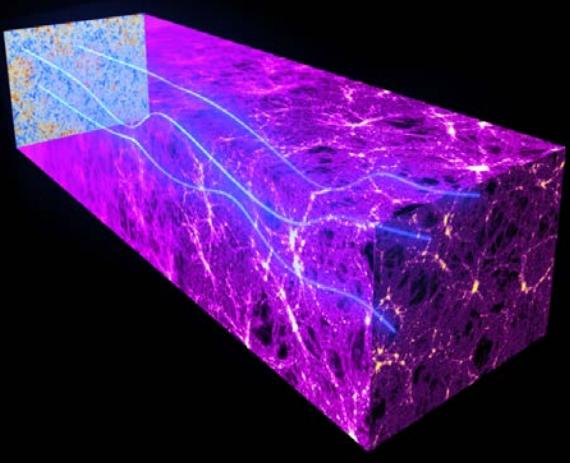
$$\vec{d} = \vec{\nabla} \phi$$

Line-of-sight integral of the gravitational potentials

$$\phi(\hat{n}) = - \int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)$$



CMB is sensitive to the late-time density field, too....



Deflection field

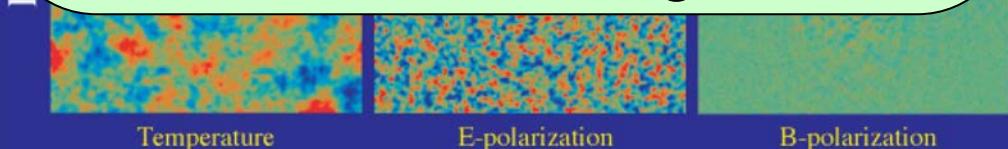
$$\vec{d} = \vec{\nabla} \phi$$

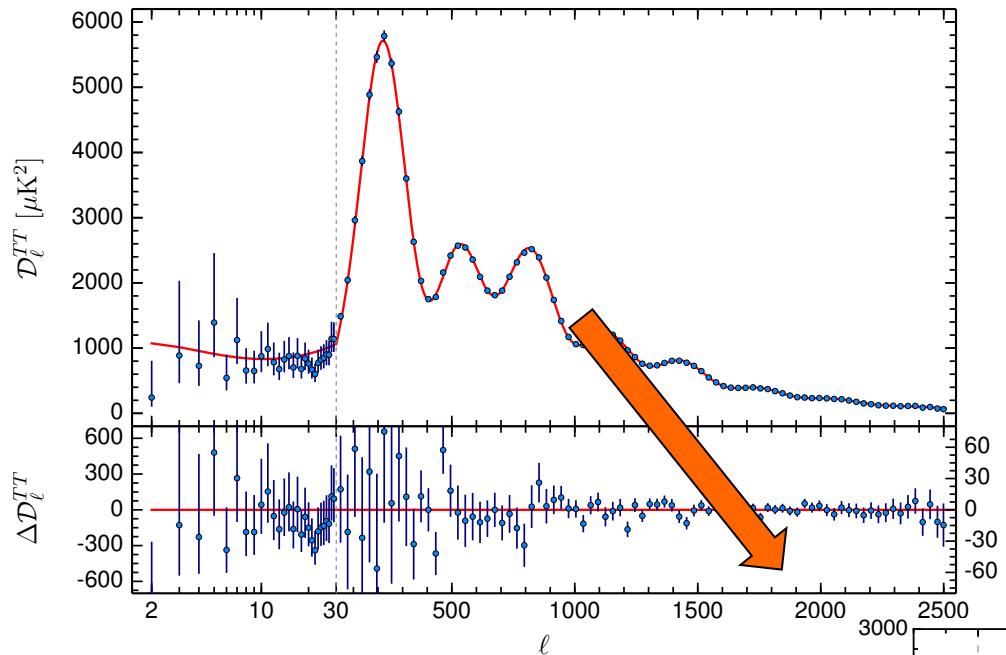
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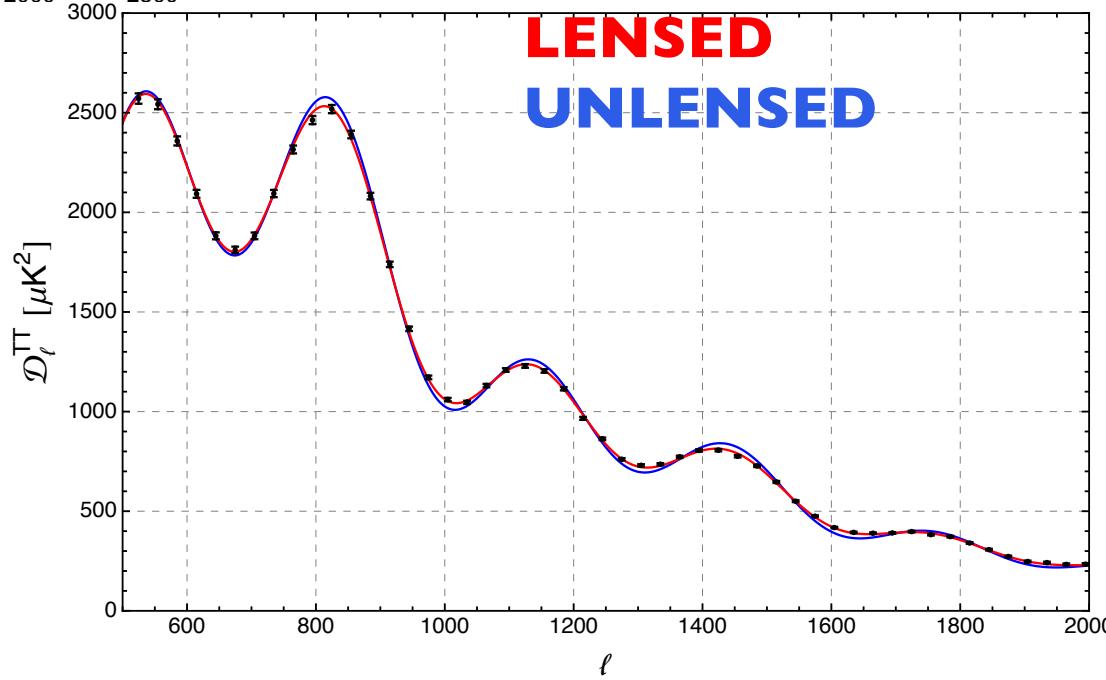
Measures deflection of light due to intervening structures
(average deflection angle is ~ 2.5 arcmin)

Gives integrated information about the matter distribution between us and the last scattering surface

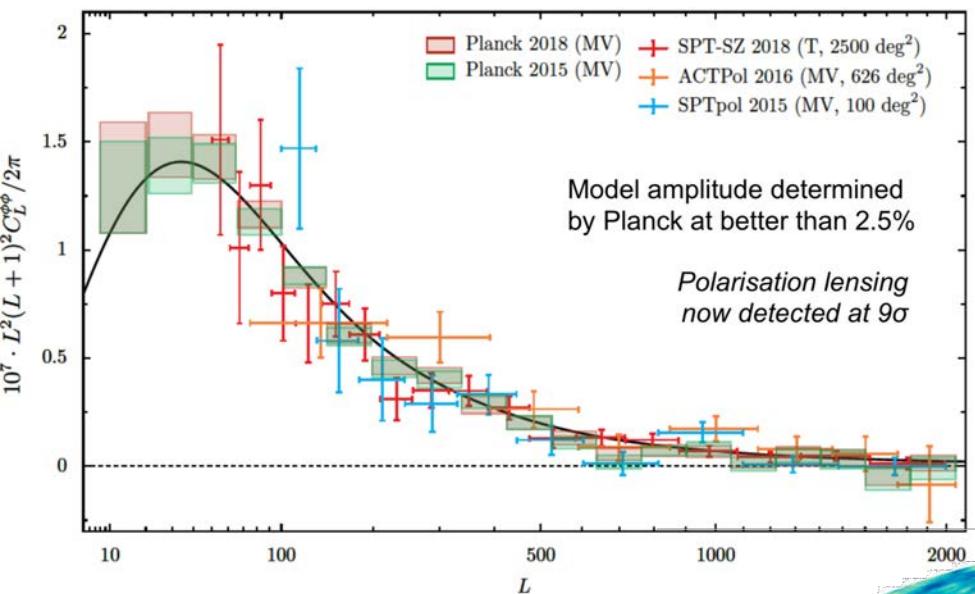




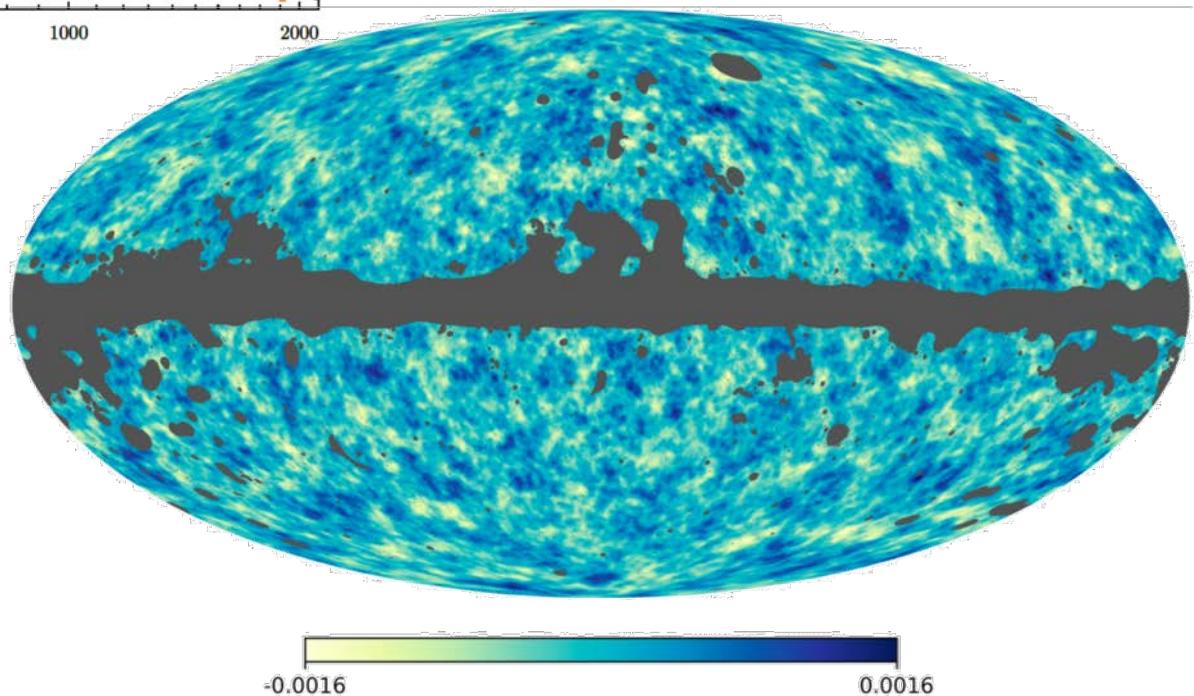
Lensing smooths the peaks
of the CMB power
spectrum...
... and introduces non-
gaussianities in the map
(nonzero 4-point c.f.)



LENSING



Lensing potential estimated from the four-point correlation function



Λ CDM 6 parameter fit

(Planck temperature, polarization and lensing)

		Mean	Stdev	Rel. err.
primary	$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.007
	$\Omega_c h^2$ Dark matter density	0.1200	0.0012	0.01
	100θ CMB acoustic scale	1.04092	0.00031	0.0003
	τ Optical depth to last scattering surface	0.0544	0.0073	0.13
	$\ln(A_s 10^{10})$ Primordial amplitude of perturbation	3.044	0.014	0.007
derived	n_s Primordial Scalar spectral index	0.9649	0.0042	0.004
	H_0 Hubble parameter today	67.36	0.54	0.008
	Ω_m Total matter density	0.3153	0.0073	0.023
	σ_8 Matter perturbation amplitude	0.8111	0.0060	0.007

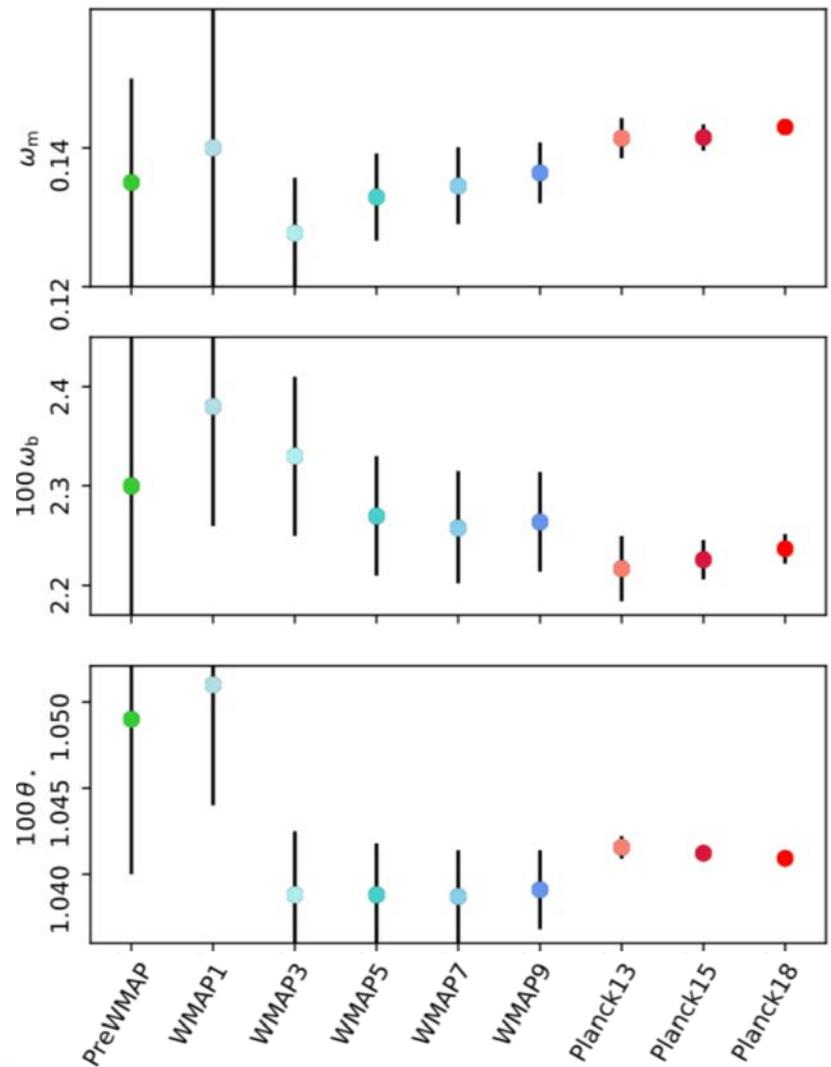
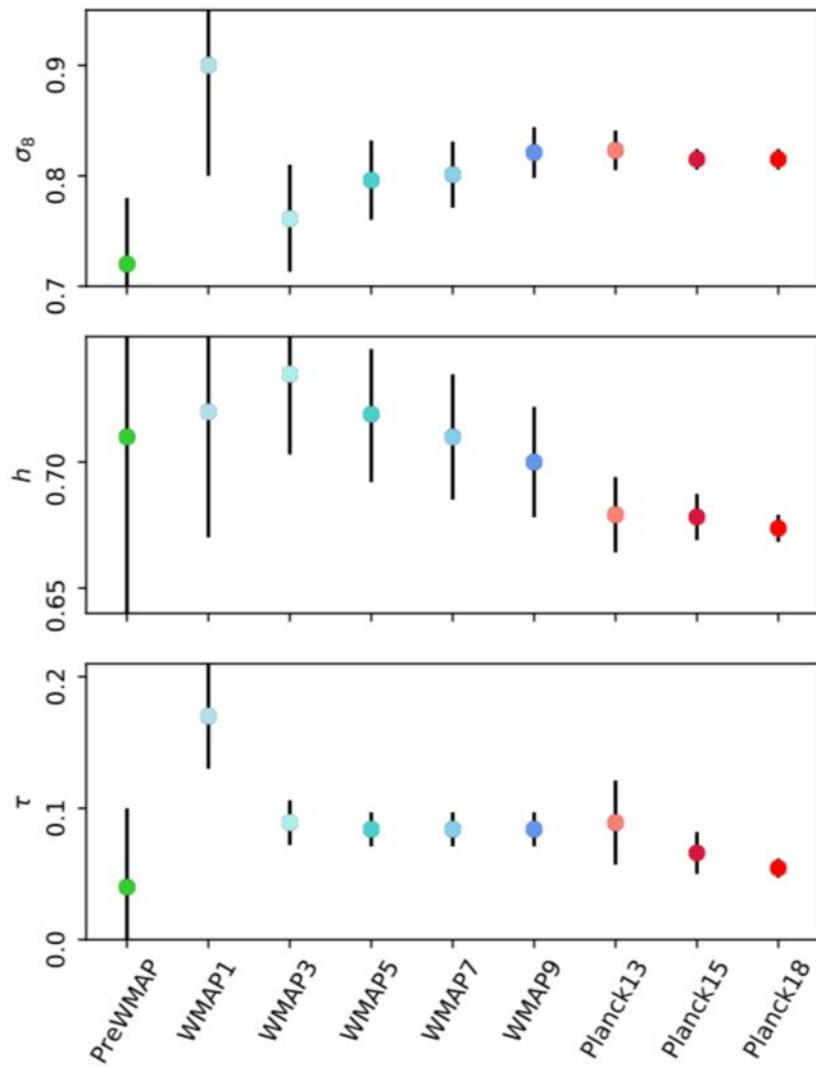
Λ CDM 6 parameter fit (Planck temperature, polarization and lensing)

Highlights:

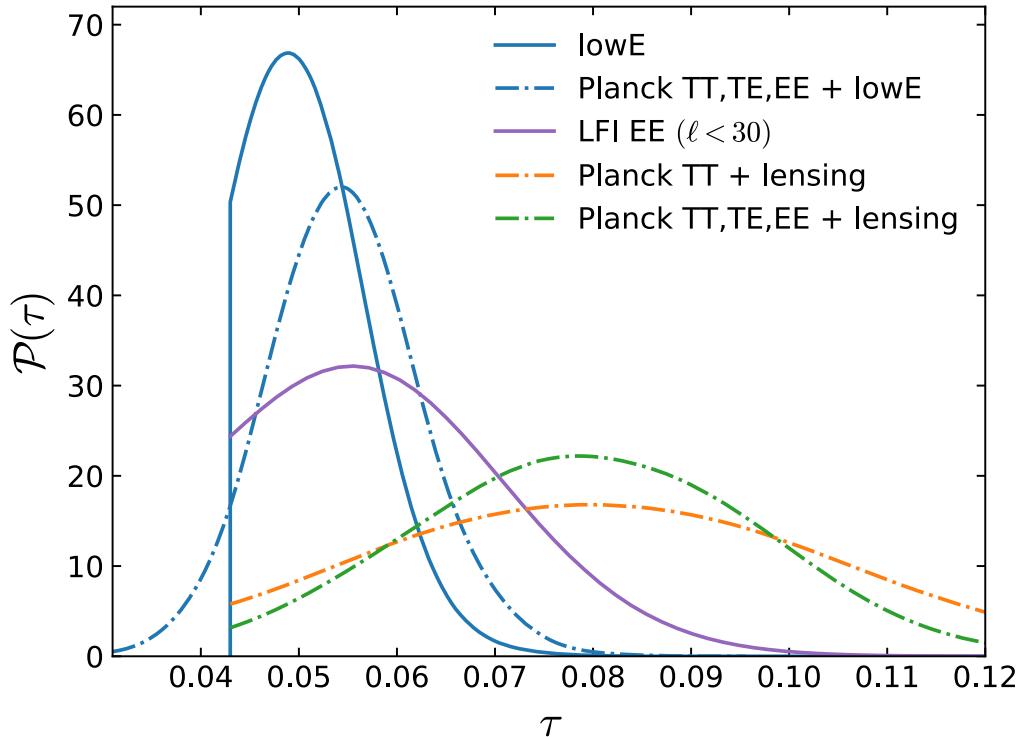
1. Best determination of H_0 to date (indirect, in strong tension with direct measurements)
2. Scalar spectral index is now 8σ away from 1 (a signature of inflation). Even in extended
3. Optical depth τ greatly improved after taming of large-angle polarization systematics. Still, at 13% relative error, by far the worst parameter determined from CMB

	Mean	Stdev	Rel. err.
$\Omega_b h^2$ Baryon density	0.02237	0.00015	0.007
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Improvement in parameter accuracy



Optical depth to reionization

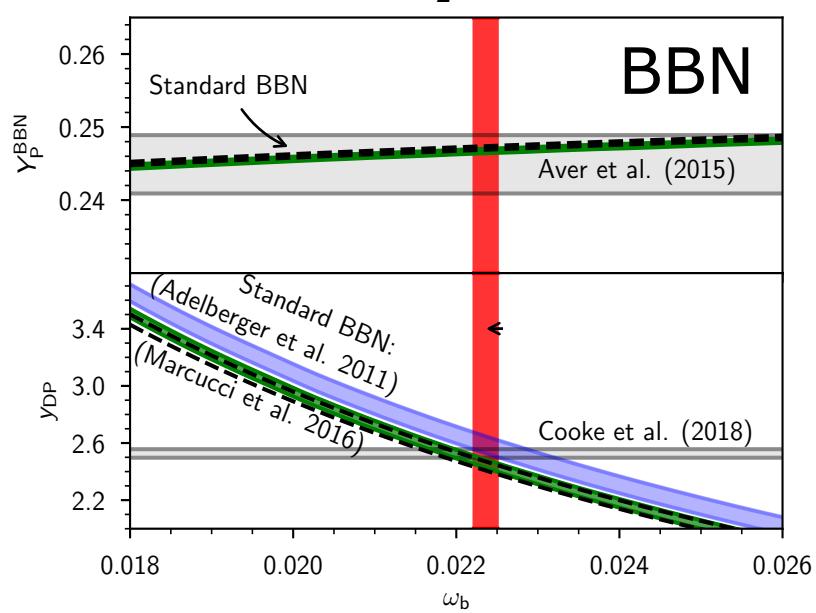
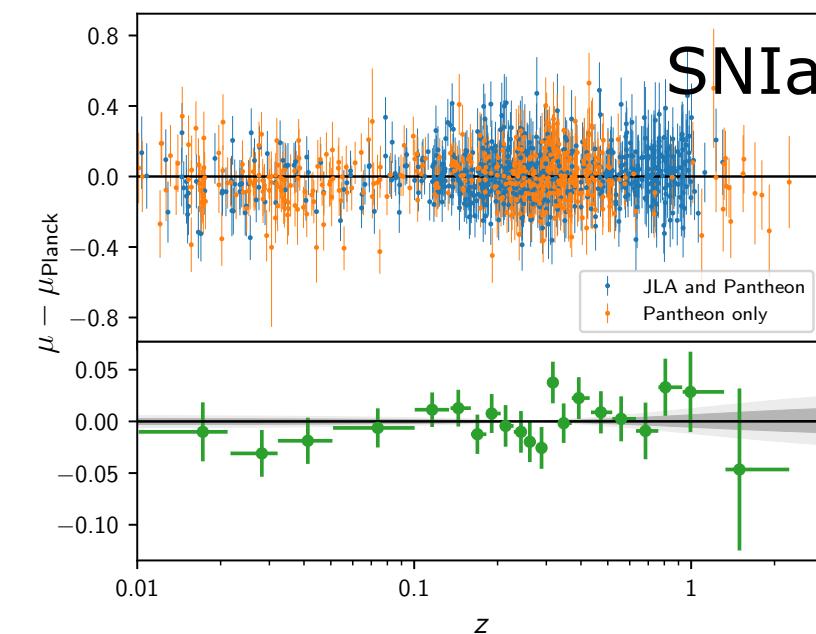
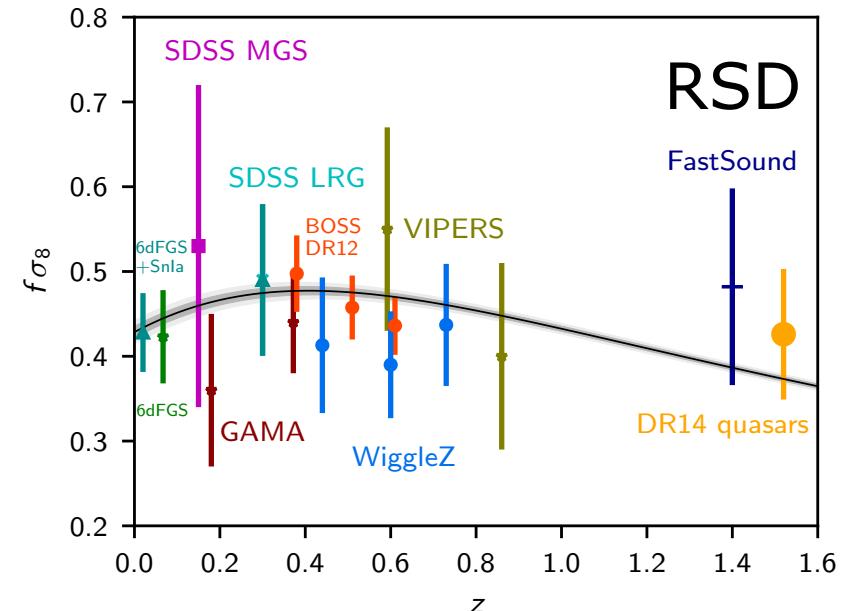
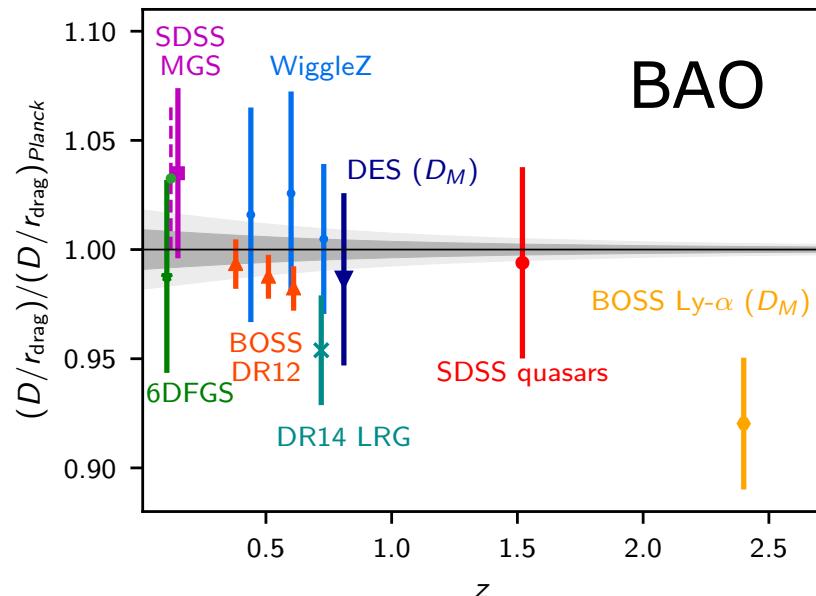


$$\tau = 0.0506 \pm 0.0086 \quad (68\%, \text{lowE})$$

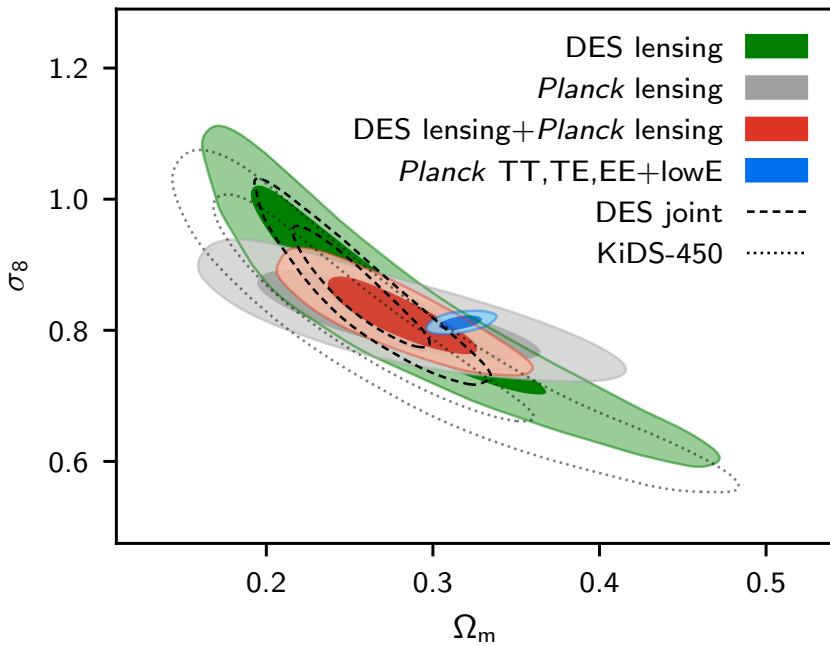
Planck 2015

$$\tau = 0.051^{+0.022}_{-0.020} \quad (68\%, \text{LFI EE})$$

Consistency with other datasets



And tensions with other datasets...



Strong tension with H_0 distance ladder measurements.

$H_0 = 67.36 \pm 0.54$ km/s/Mpc Planck Λ CDM
 $H_0 = 73.5 \pm 1.6$ km/s/Mpc SH0ES (Riess+ 18)
Inverse distance ladder:
 $H_0 = 67.9 \pm 1.3$ km/s/Mpc BAO+D/H+CMB lensing

Mild tension with DES year I results

$$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$$

DES Joint

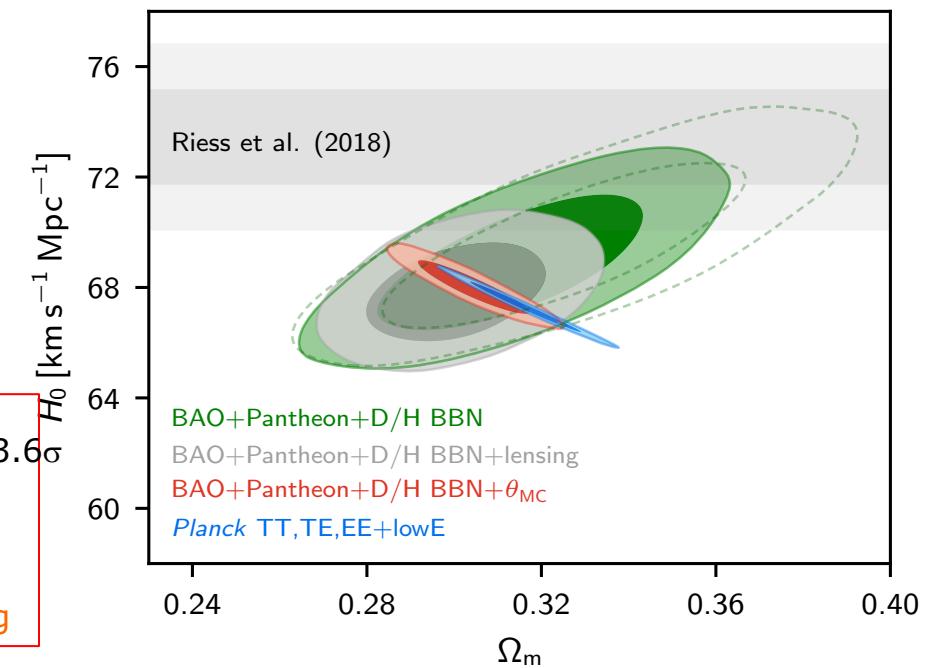
$$S_8 \equiv 0.792 \pm 0.024$$

$$\Omega_m = 0.257^{+0.023}_{-0.031}$$

Planck TTTEEE+lowE+lensing

$$S_8 = 0.832 \pm 0.013$$

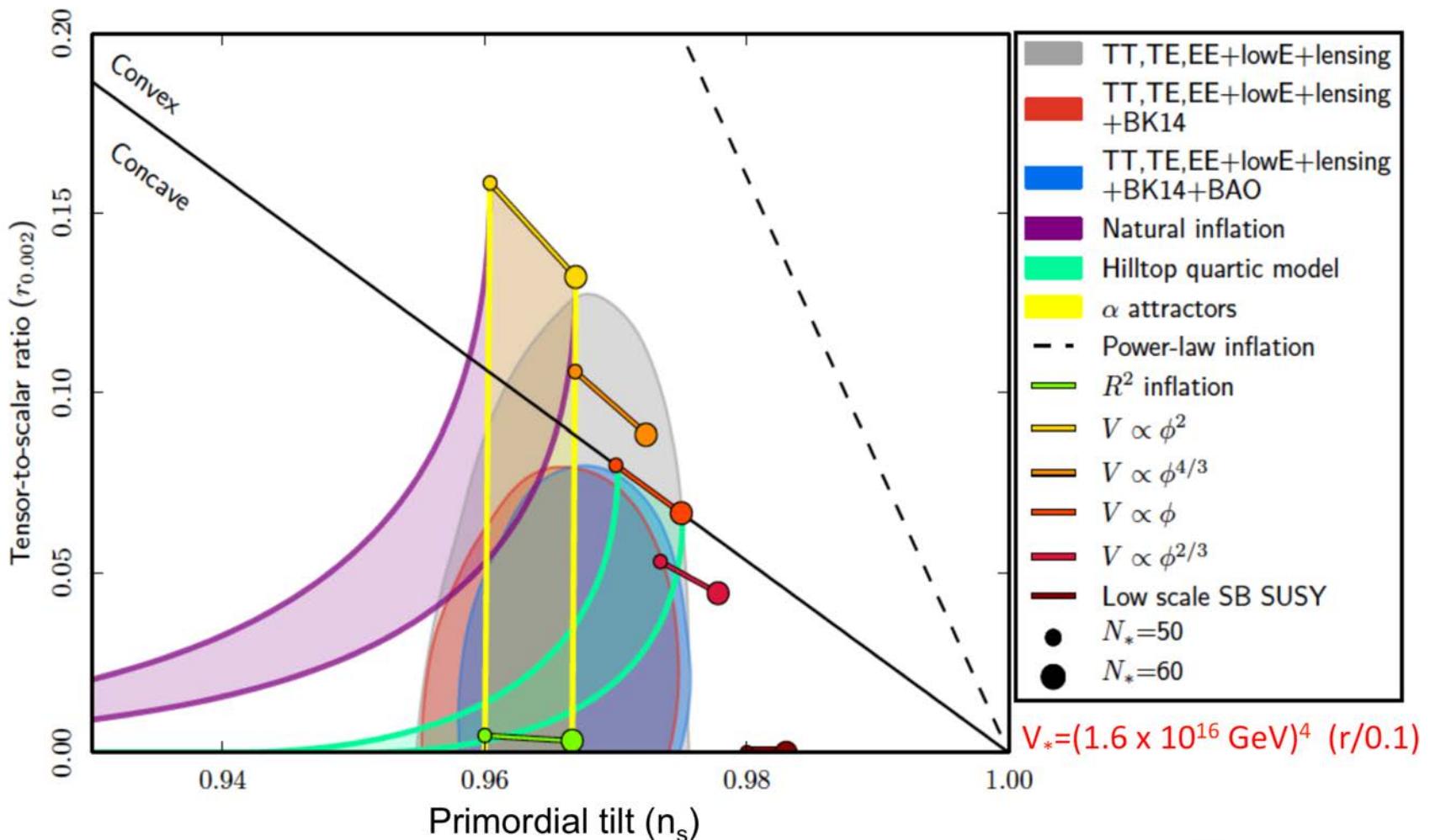
$$\Omega_m = 0.315 \pm 0.007.$$



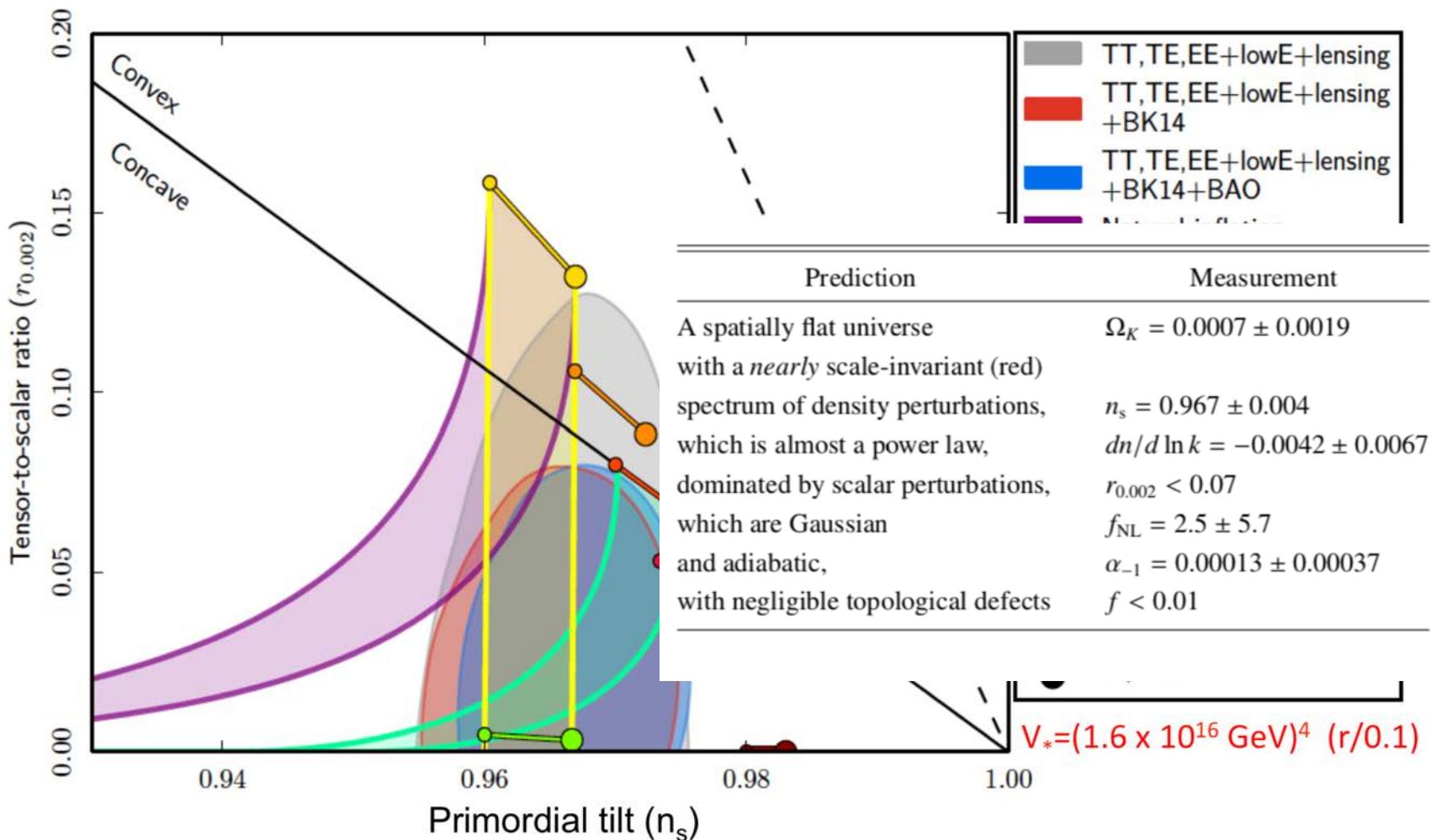
Λ CDM 6 parameter fit + extensions (where surprises might hide)

- Tensor modes, i.e. primordial gravitational waves, $r = A_T/A_s$
- Running spectral index $d n_s / d \ln k$
- Primordial non Gaussianity f_{NL}
- Non adiabatic (isocurvature) primordial perturbations
- Dark energy equation of state, w
- Spatial curvature $\Omega_k = 1 - \Omega_m - \Omega_\Lambda$
- Neutrino masses $\sum m_\nu$
- Number of relativistic species N_{eff}
- ...

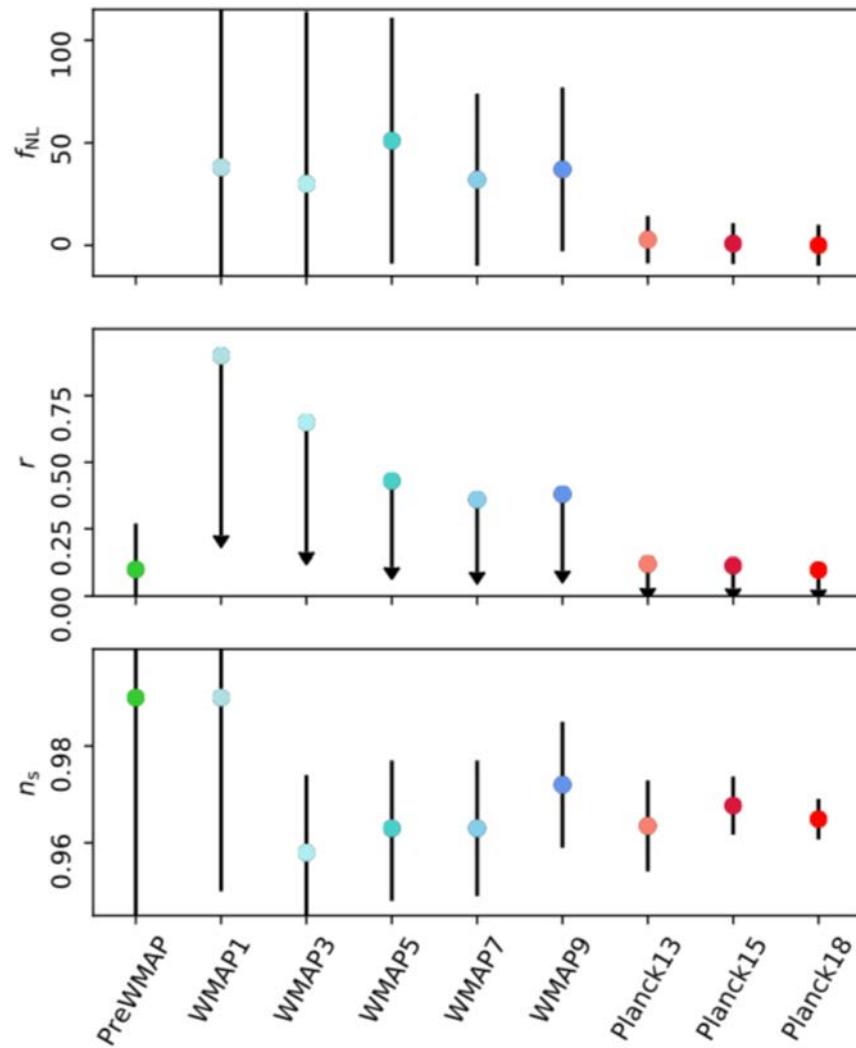
Constraints for tensor perturbations



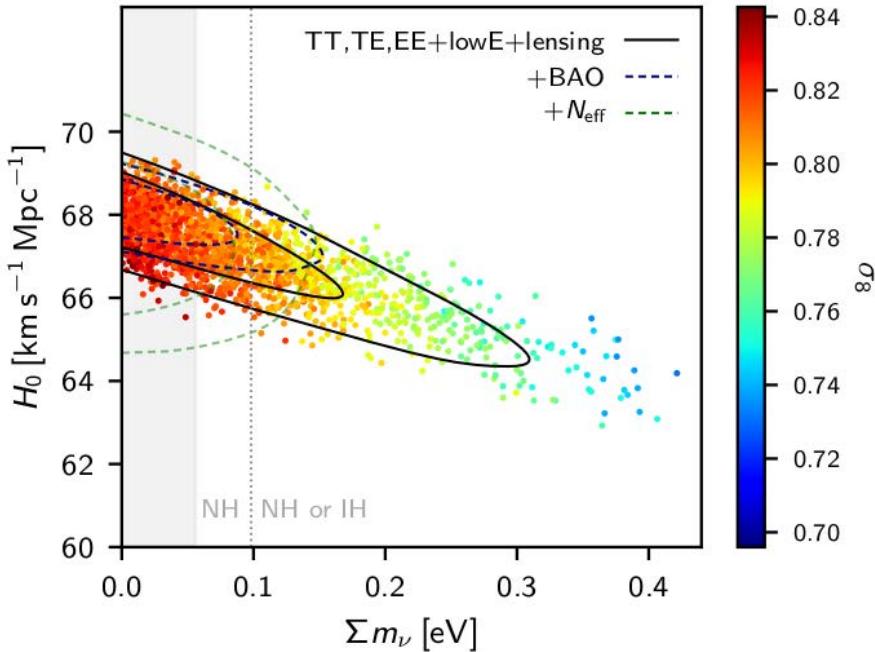
Constraints for tensor perturbations



Improvement in inflationary parameters



Neutrino legacy of Planck: Σm_ν

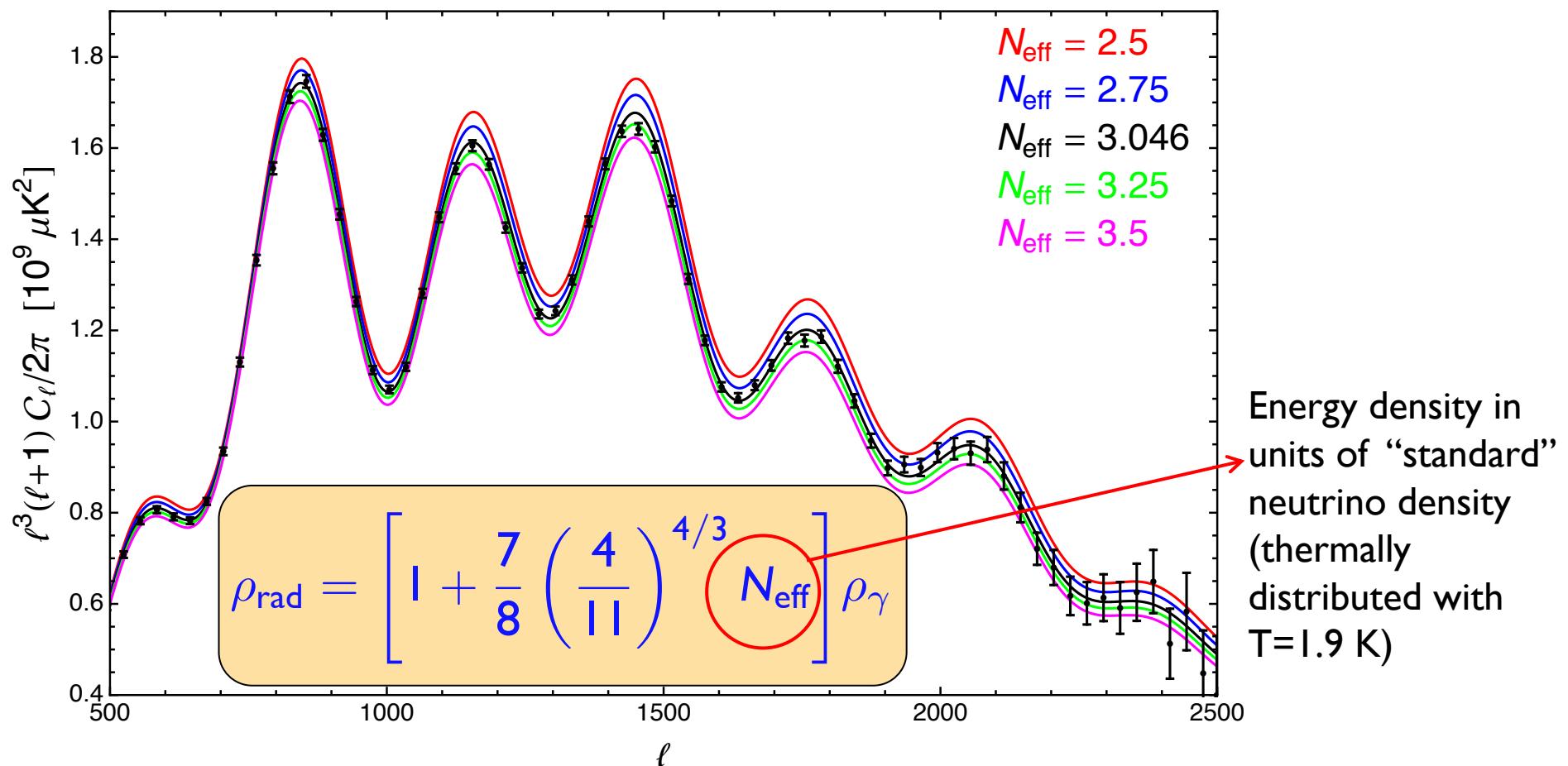


- Tightest constraint from a single experiment
- First constraint exploiting the information encoded in the CMB weak lensing
- One order of magnitude better than present kinematic constraints, already at the same level than future expectations for KATRIN
- The combined limits from Planck and large scale structure probes are starting to corner the inverted hierarchy scenario

$m_\nu < 0.44 \text{ eV}$ (95%CL, TT + lowE + lensing)

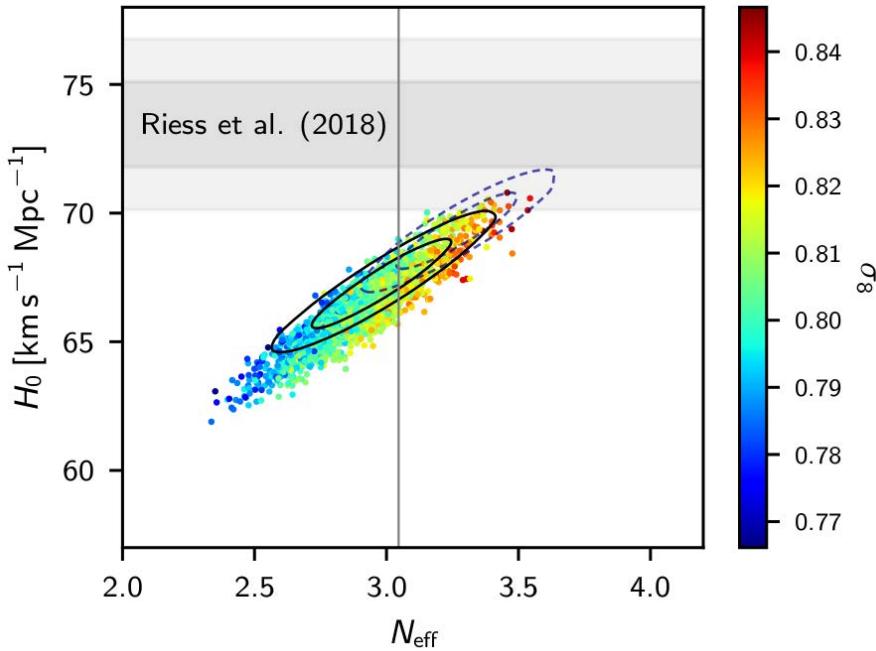
$m_\nu < 0.13 \text{ eV}$ (95% CL, TT+lowE+lensing+BAO)

Effective number of relativistic species



Due to non-instantaneous decoupling, the standard expectation is **$N_{eff} = 3.046$**

Neutrino legacy of Planck: Neff



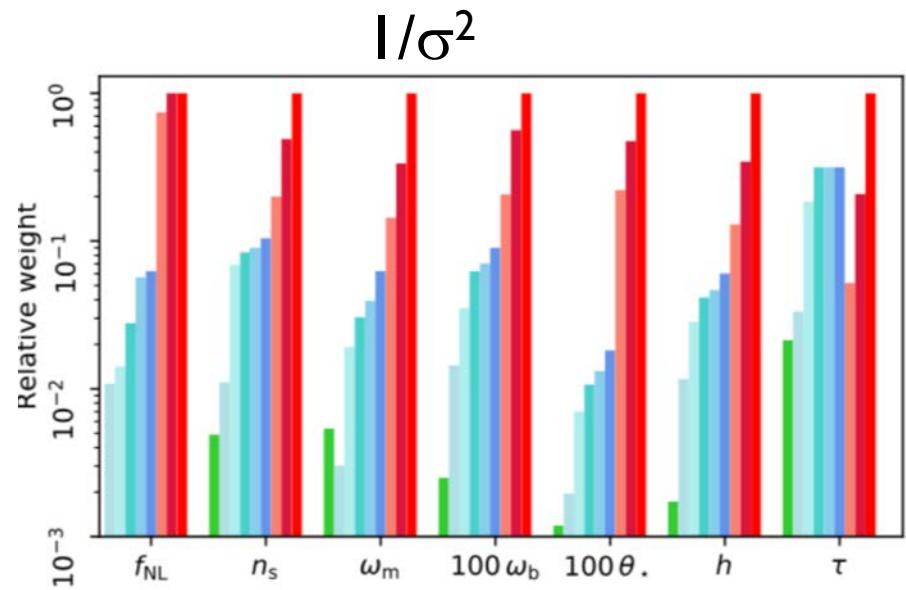
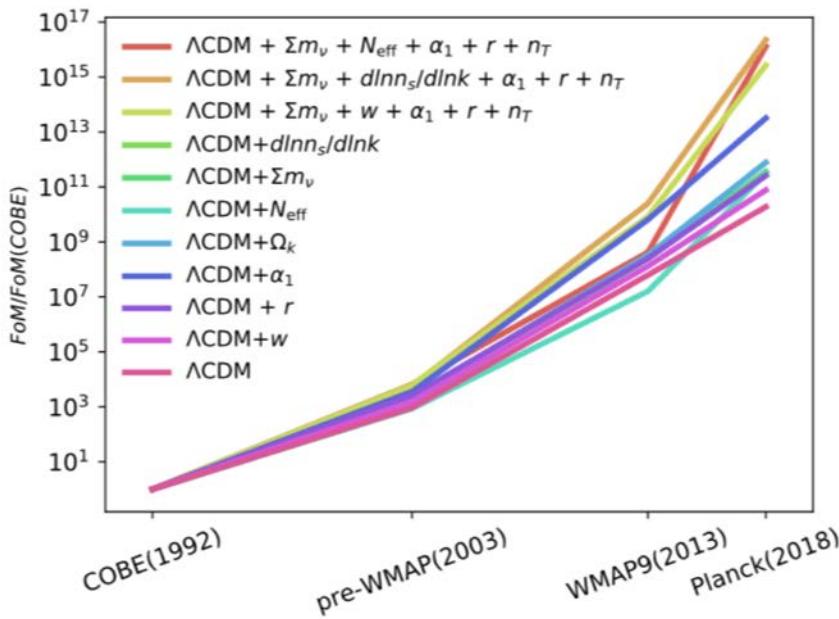
$$N_{\text{eff}} = 3.00^{+0.57}_{-0.53} \quad (\text{95\% CL, TT+lowE})$$

$$N_{\text{eff}} = 3.11^{+0.44}_{-0.43} \quad (\text{95\% CL, TT+lowE+lensing+BAO})$$

- Effective number of relativistic species is consistent with the standard expectation $N_{\text{eff}} = 3.046$
- Data are consistent with these relativistic species behaving as free-streaming neutrinos – a strong indication that they are indeed the SM neutrinos!
- A fourth thermalized species ($N_{\text{eff}}=4$) is excluded at 3.5 to 6 σ , depending on the dataset
- A light sterile neutrino species is allowed if not thermalized. Still, the sterile neutrino interpretation of the short-baseline anomalies is excluded by Planck

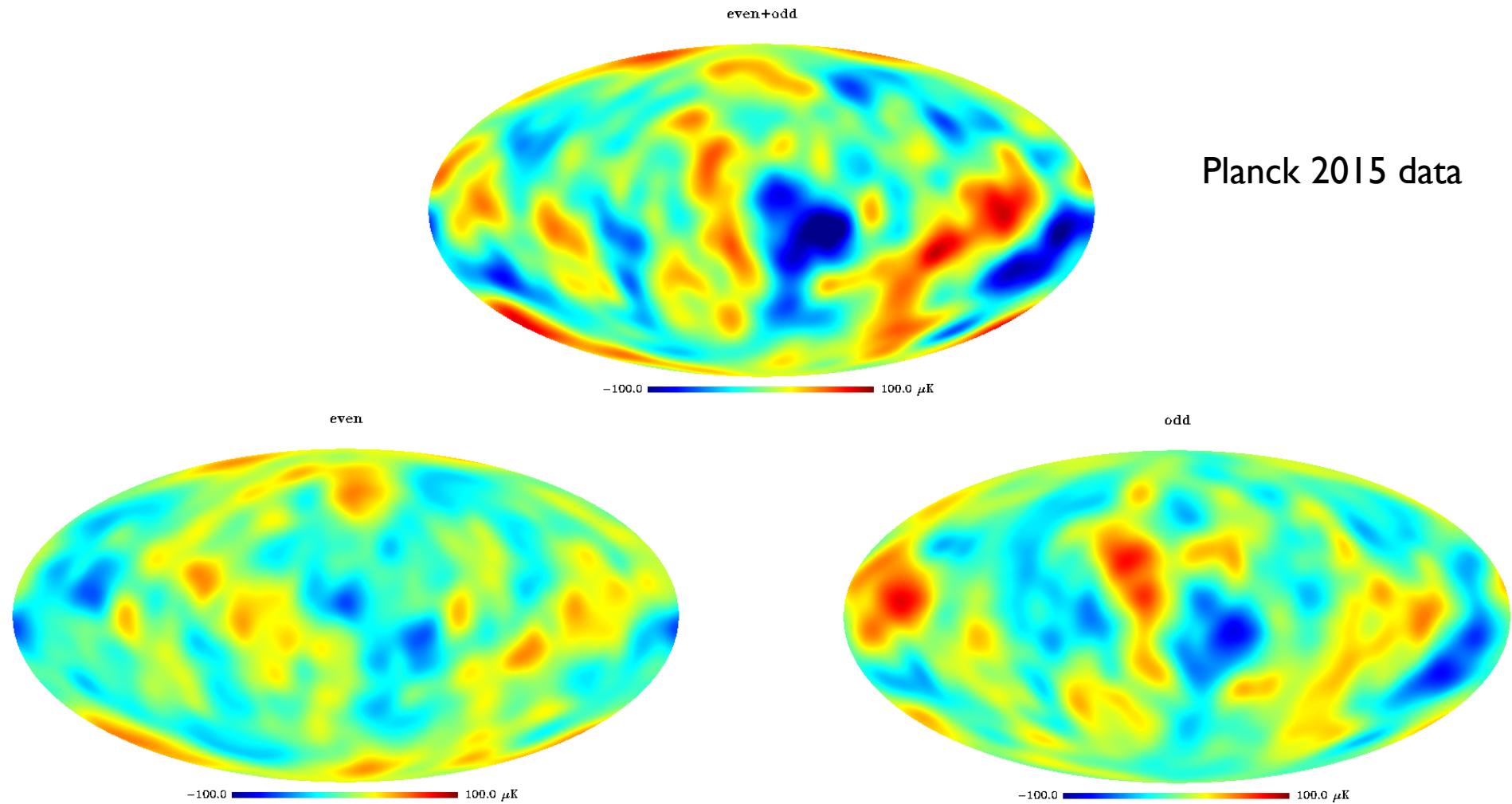
Improvement in extended parameter accuracy

$$\left\{ \det \left[\text{Cov}(\Omega_b h^2; \Omega_c h^2; \tau, A_s; n_s; \dots) \right] \right\}^{-1/2}$$



Anomalies in the CMB field

- At large angles, the CMB field is known to exhibit anomalies:
 - Lack of power
 - Hemispherical asymmetry
 - Even-odd asymmetry
 - And others
- For temperature, Planck has reached cosmic variance. For polarization, there is much room for improvement.



$$\left(\frac{\delta T}{T}(\hat{n}) \right)_{\pm} \equiv \frac{1}{2} \left[\frac{\delta T}{T}(\hat{n}) \pm \frac{\delta T}{T}(-\hat{n}) \right]$$

A. Gruppuso, N. Kitazawa, M. Lattanzi, N.
Mandolesi, PN, A. Sagnotti 2017

Scale-invariance of the large-scale perturbations is a prediction of single-field, slow-roll inflation.

Transition from a pre-inflationary “fast-roll” phase to slow-roll would suppress power in the primordial spectrum.

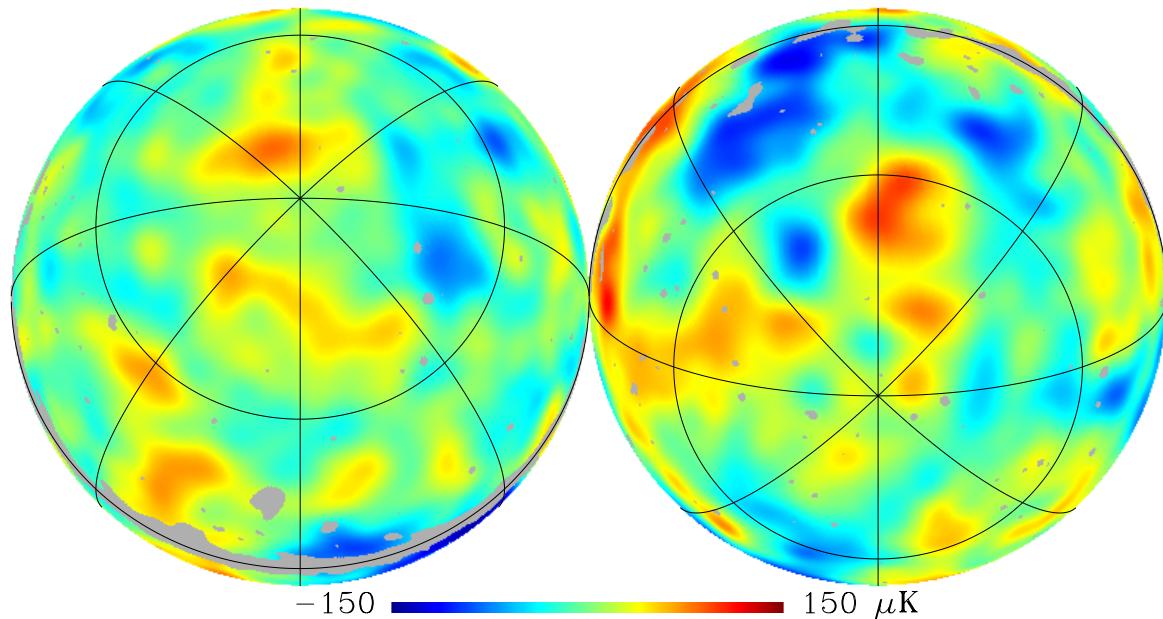
Are we seeing relics of a decelerating inflaton?

See e.g. Contaldi, Peloso, Kofman, Linde (2003); Destri, de Vega, Sanchez (2010); Dudas, Kitazawa, Patil, Sagnotti (2012); Kitazawa, Sagnotti (2014)

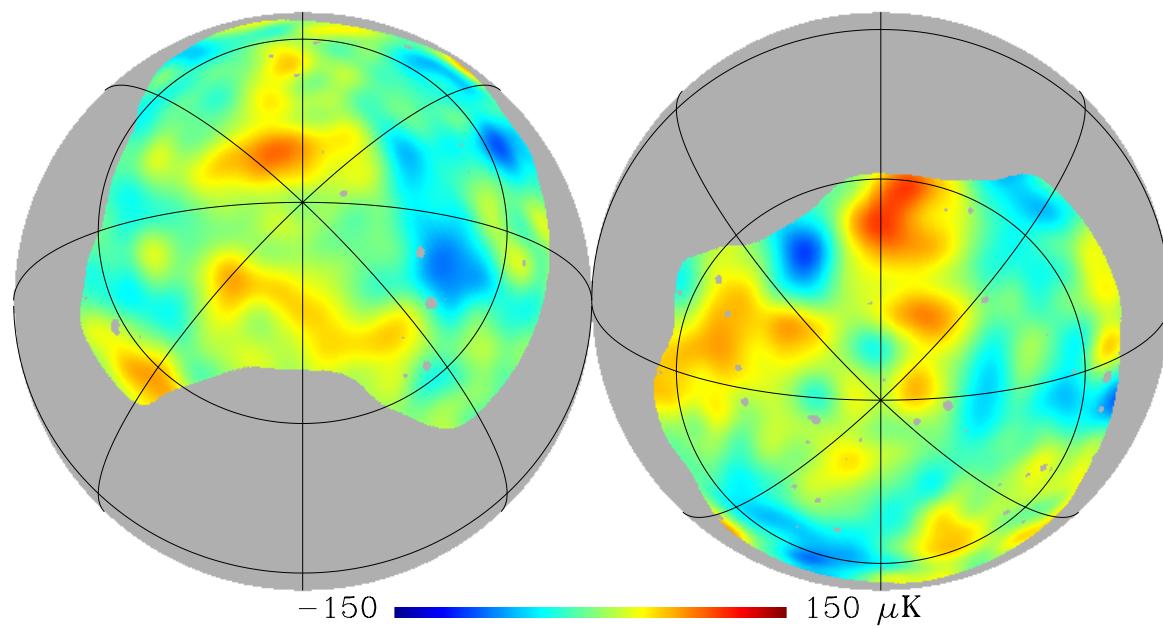
$$P(k) \sim \frac{k^3}{[k^2 + \Delta^2]^{2 - \frac{n_s}{2}}}$$

↓
~ scale that enters the horizon at the onset of slow roll

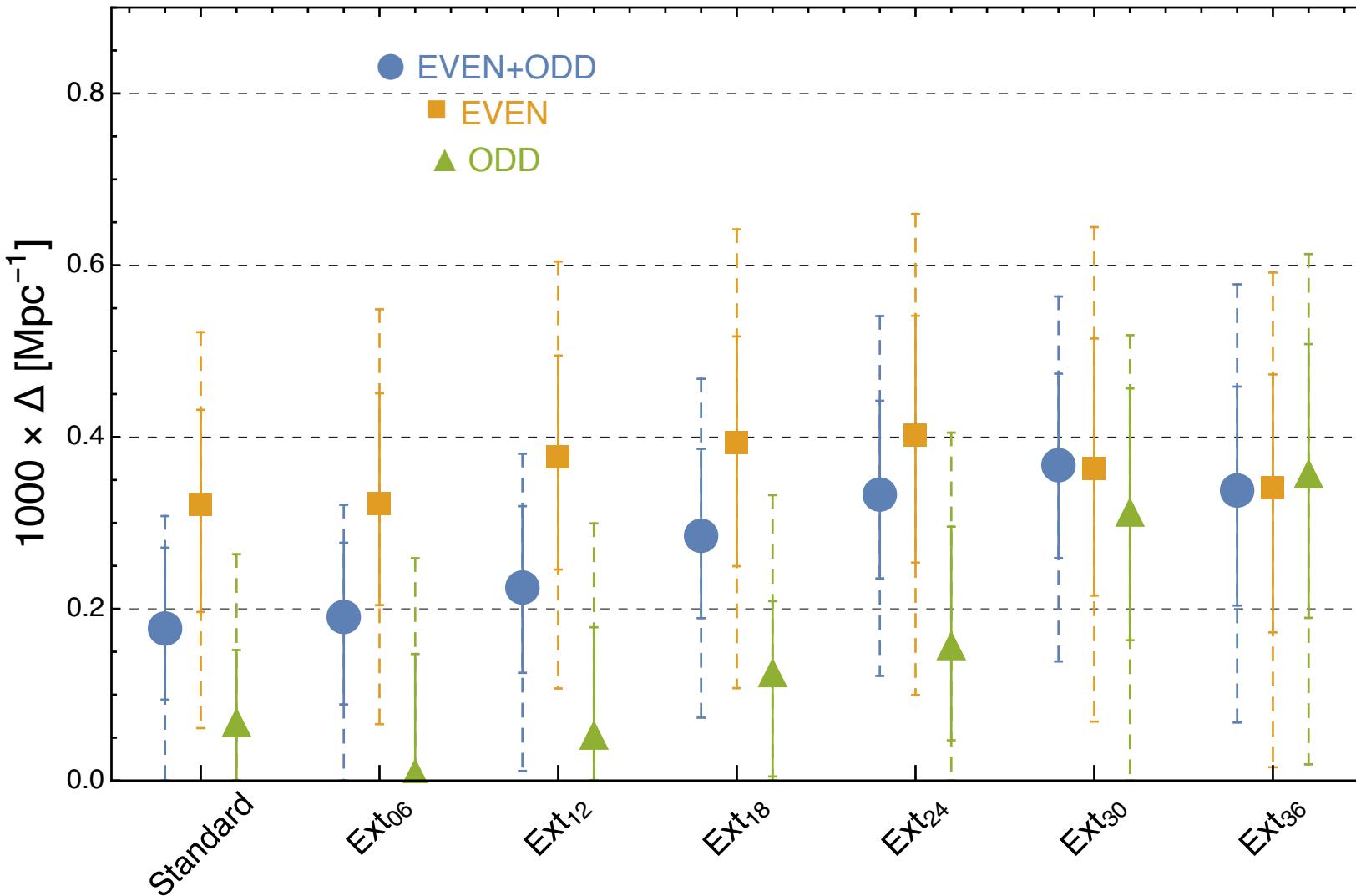
standard mask



extended mask



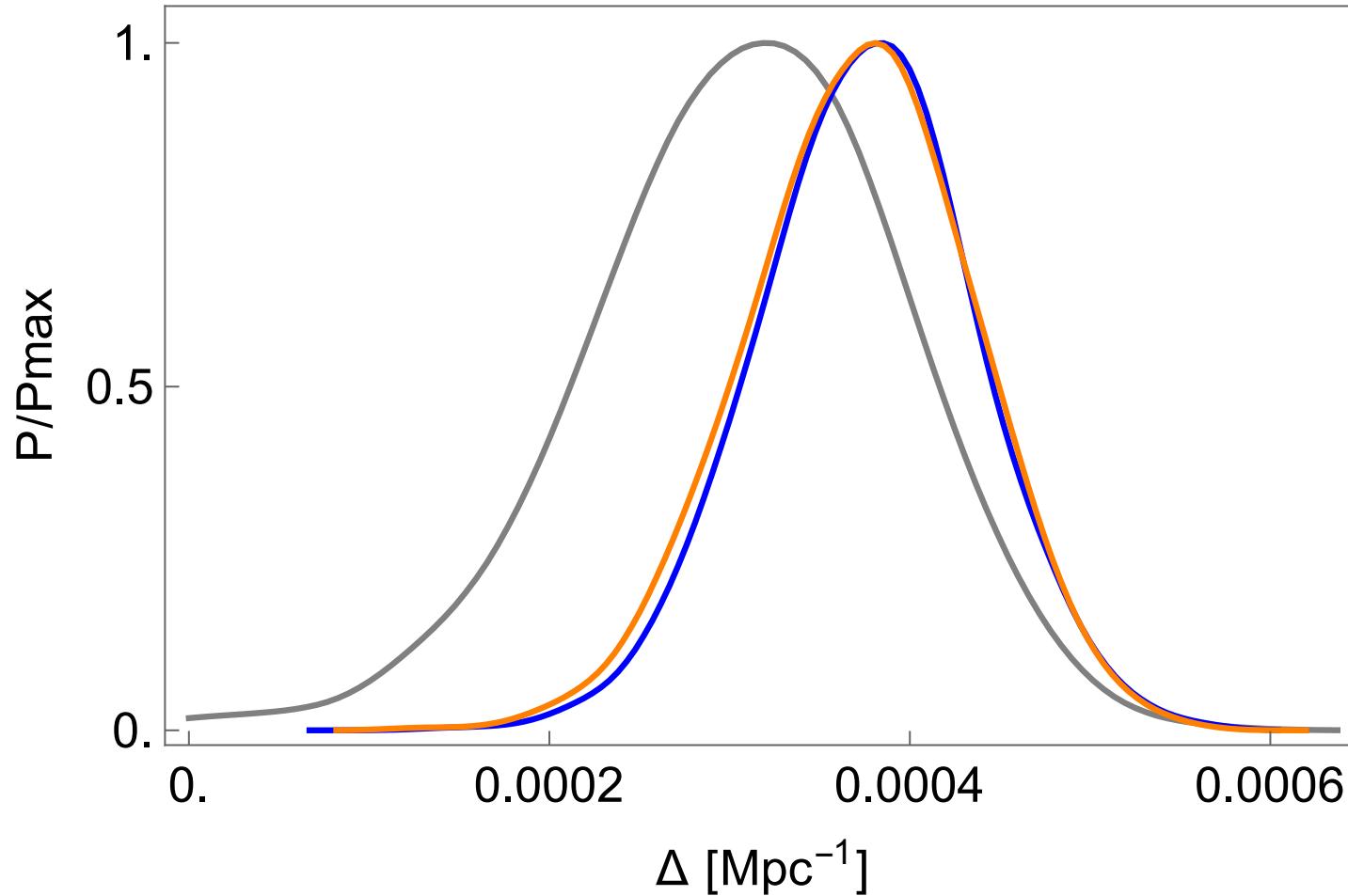
Constraints on Δ from Planck 2015



A. Gruppuso, N. Kitazawa, M. Lattanzi, N. Mandolesi,
PN, A. Sagnotti 2017

- The even multipoles are consistently lower than the LCDM expectation, independently on the galactic masking
- The odd multipoles are consistent with the LCDM expectation for the smaller masks (more sky). In larger masks (less sky), they are consistent with the even multipoles (and then have low power)
- The power at large scales is concentrated around the galactic plane, in the odd multipoles
- 3.16σ detection of Δ in the Ext30 mask

Forecasted constraints on Δ from future experiments



Grey: Planck-like noise, standard masking

Orange: CVL large-scale pol., ext30 mask

Blue: CVL large-scal pol, full sky

Conclusions

- Planck has delivered its final (legacy) release
- It has provided the ultimate (cosmic variance limited) measurement of CMB anisotropy
- ... But just opened the door of CMB polarization (which was never designed to measure, by the way)
- It has fulfilled its promise of measuring the fundamental cosmological parameters to percent accuracy
- And brought remarkable constraints on particle physics parameters as well, excluding a fourth fully thermalized neutrino and constraining the total neutrino masses in the 100 meV range.
- Has measured well one relevant inflationary parameter, the primordial spectral index, allowing constraints on the inflationary paradigm
- Yet has uncovered several tensions with astrophysical measurements, which may or may not hint at new physics.
- Intrinsic anomalies do exist in the large-angle CMB field, which may also be a tracer of something new.
- If these tension/anomalies are really hinting at new physics, its signature in the CMB is scant. Accurate measurements are needed to pin down the issue.
- Primordial gravitational waves remain unseen.
- To exploit the wealth of information that still is in the CMB, we need to cope with the extraordinary complexity of the sky. This can be credibly done only with a future space mission.

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.