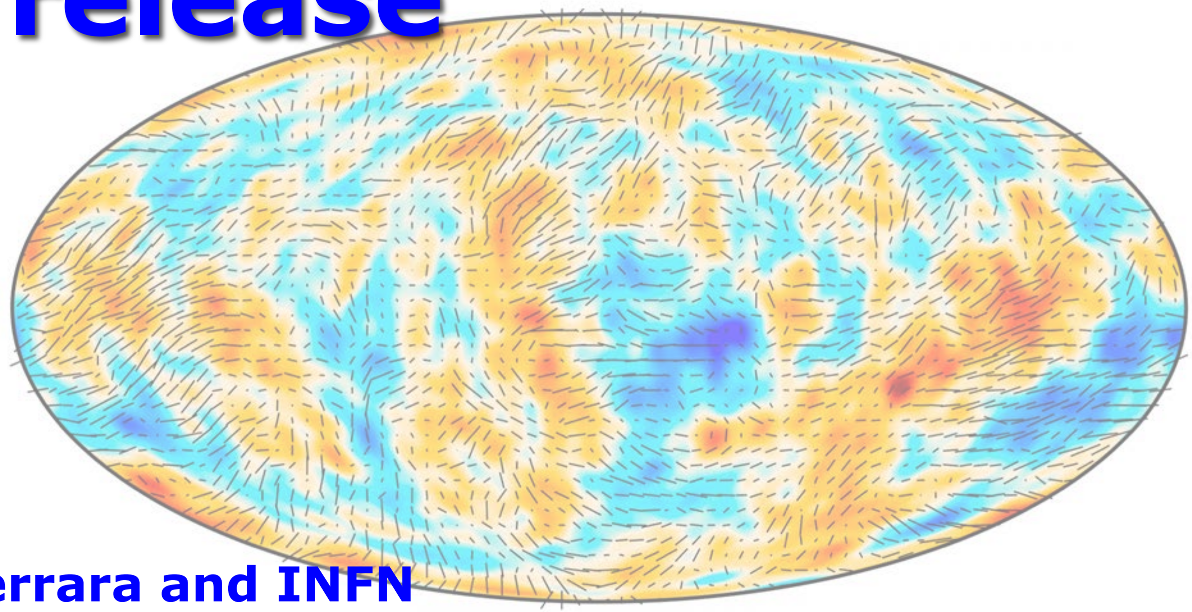
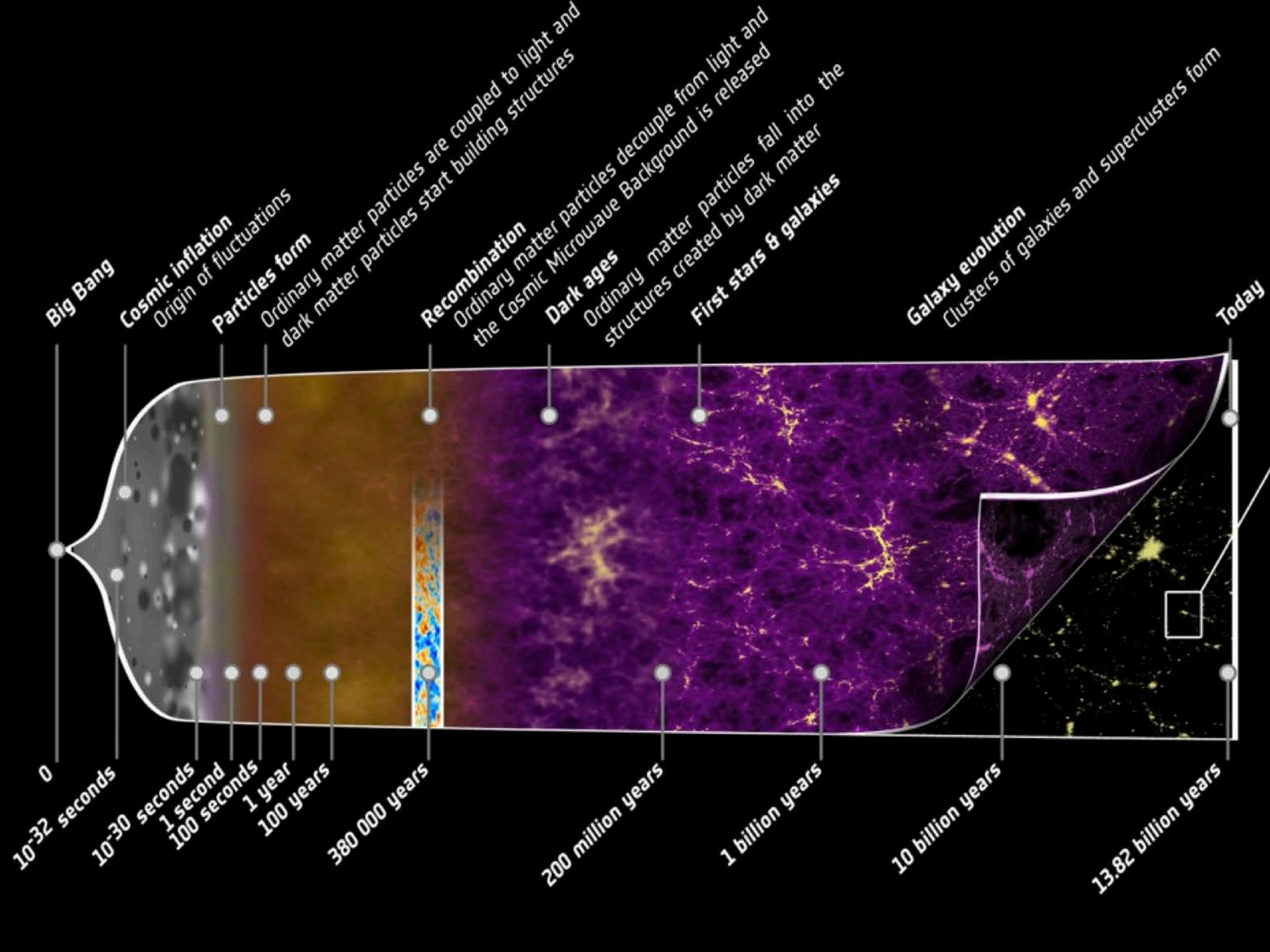
Cosmology after the Planck legacy release



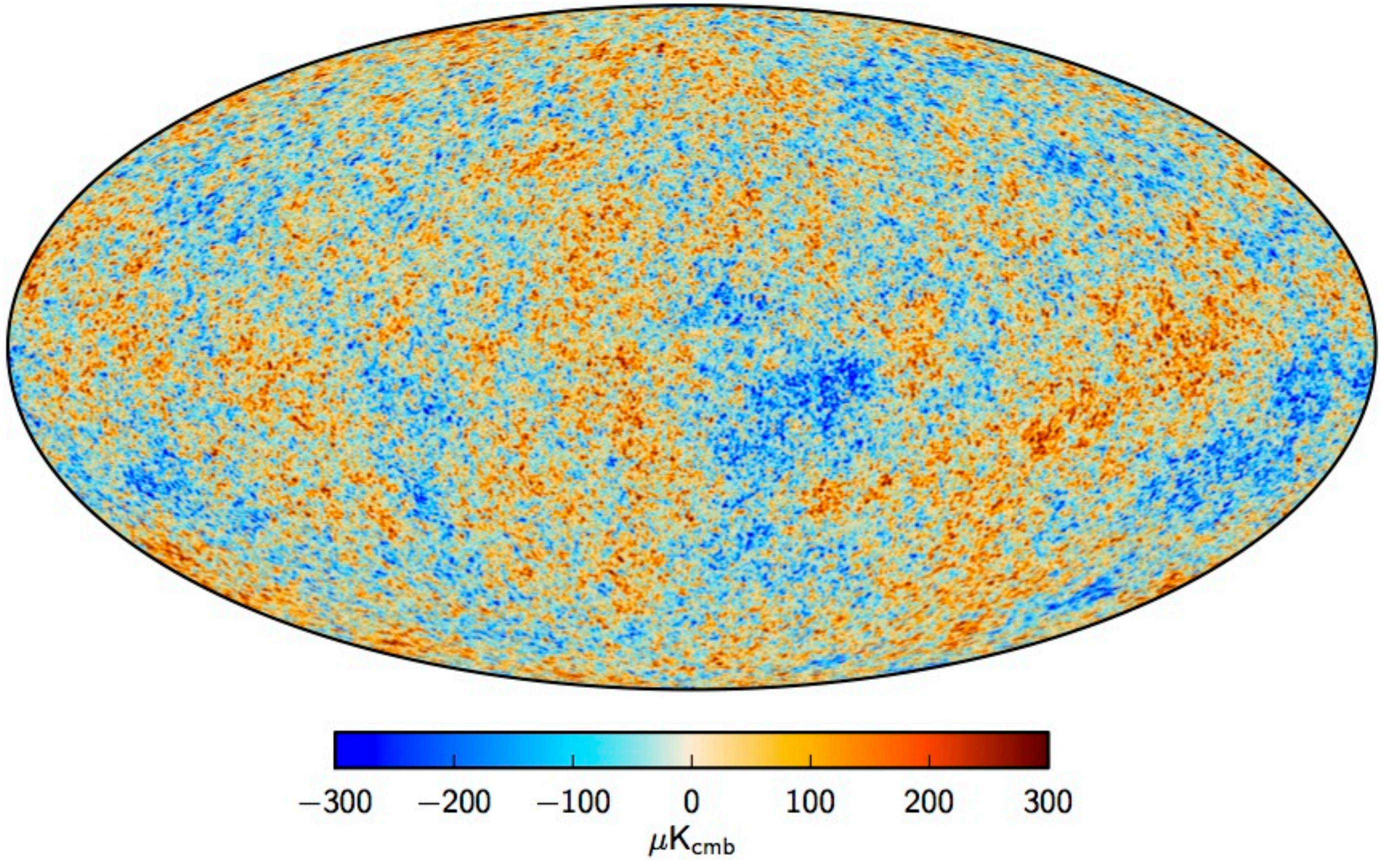
Paolo Natoli

Università di Ferrara and INFN

XVIII International Workshop on Neutrino Telescopes
Venezia, 21 March 2019


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

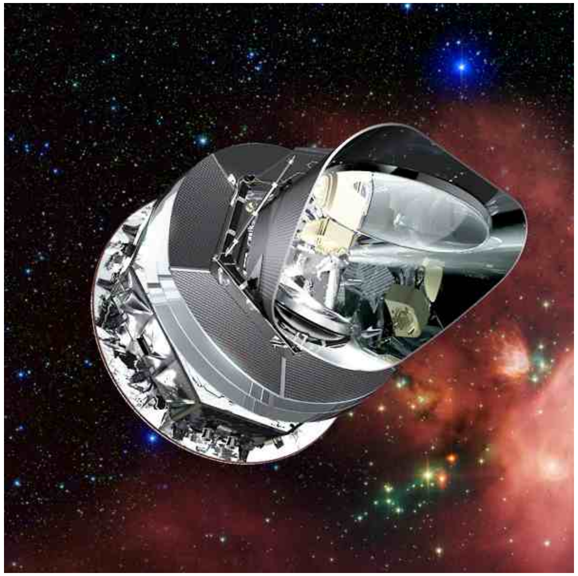
The Cosmic Microwave Background

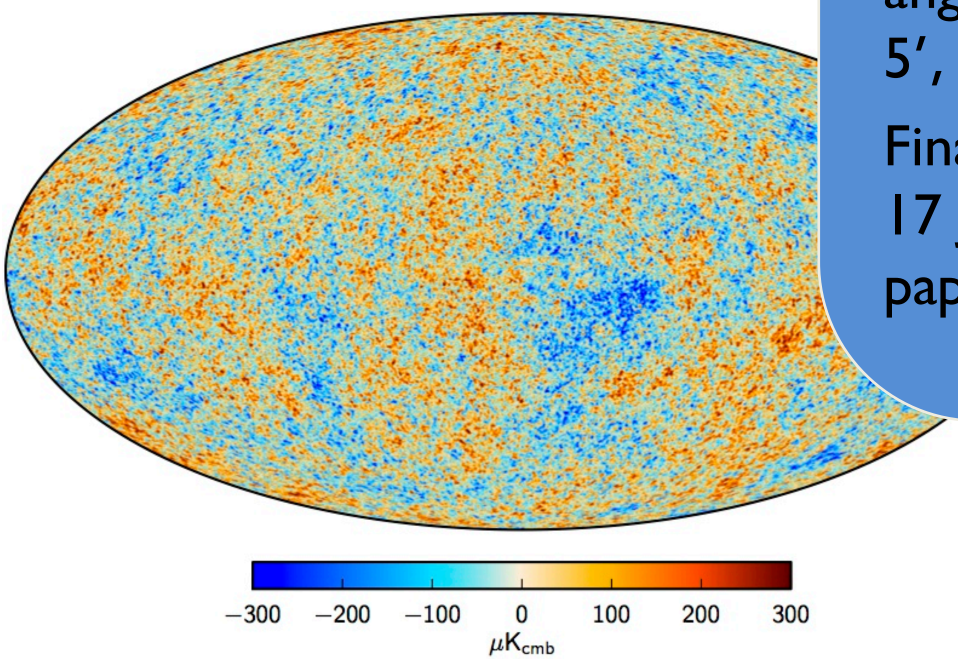


The CMB is a blackbody radiation with T=2.7 K extremely uniform across the whole sky; it is the relic radiation emitted at the time the nuclei and electrons recombined to form neutral hydrogen, when the Universe was ~ 400,000 years old (the so-called last scattering surface, LSS).

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

The Planck Satellite





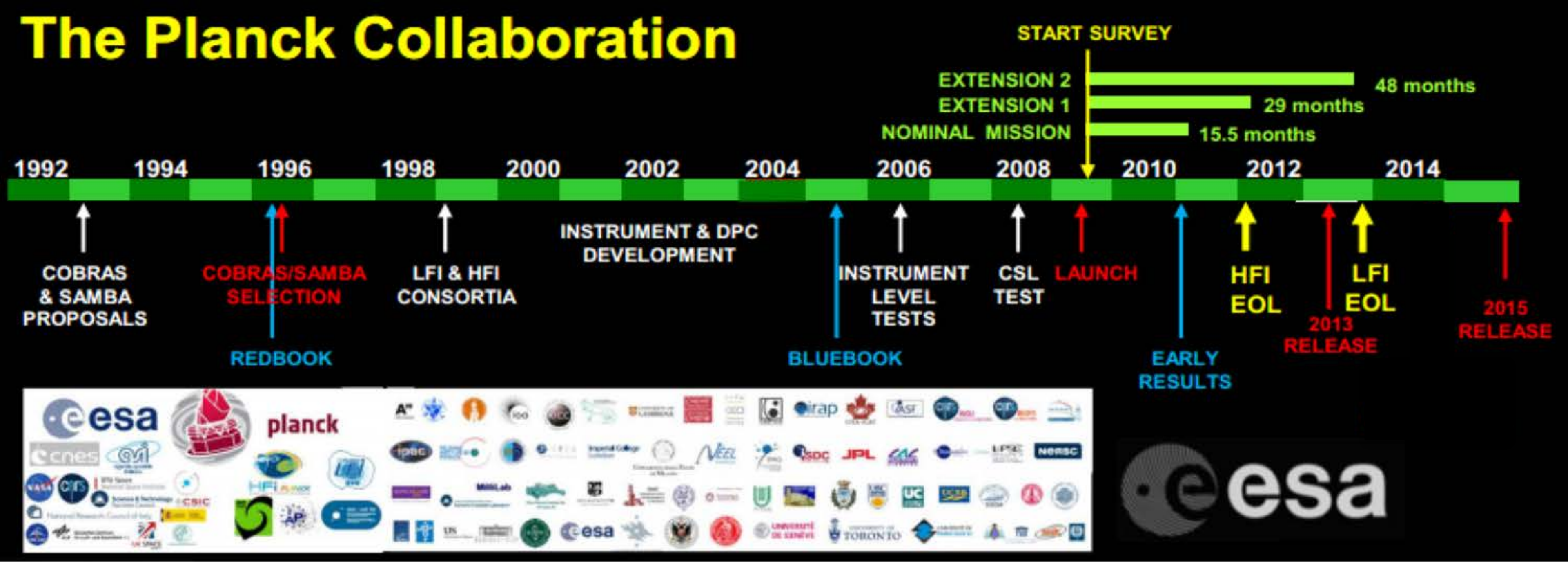
Planck is the 3rd generation ESA satellite devoted to CMB

Ultimate characterization of the temperature anisotropies

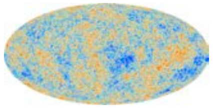
74 detectors (radiometers and bolometers) in 9 frequency bands from 30 to 857 GHz

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.



May 2009: Launched from Kourou

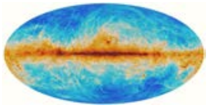


Mar 2013: Data Release and Cosmology Results
Nominal Mission Temperature data

32 papers

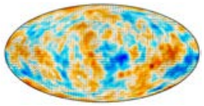
Oct 2013: Planck 'Shut Down'

52 papers / intermediate results



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

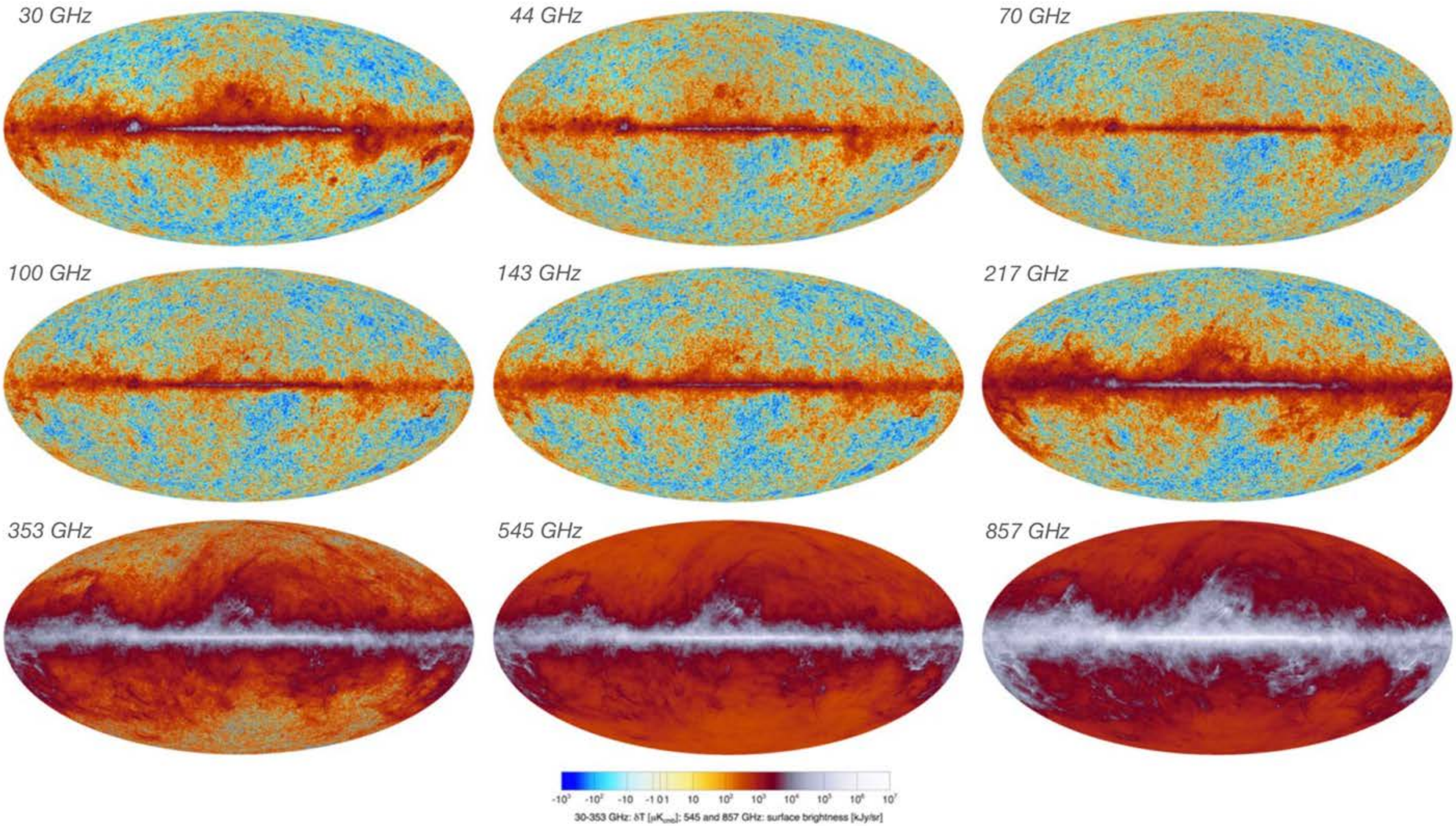
28 papers



Jul 2018: **Legacy Data & Paper Release**

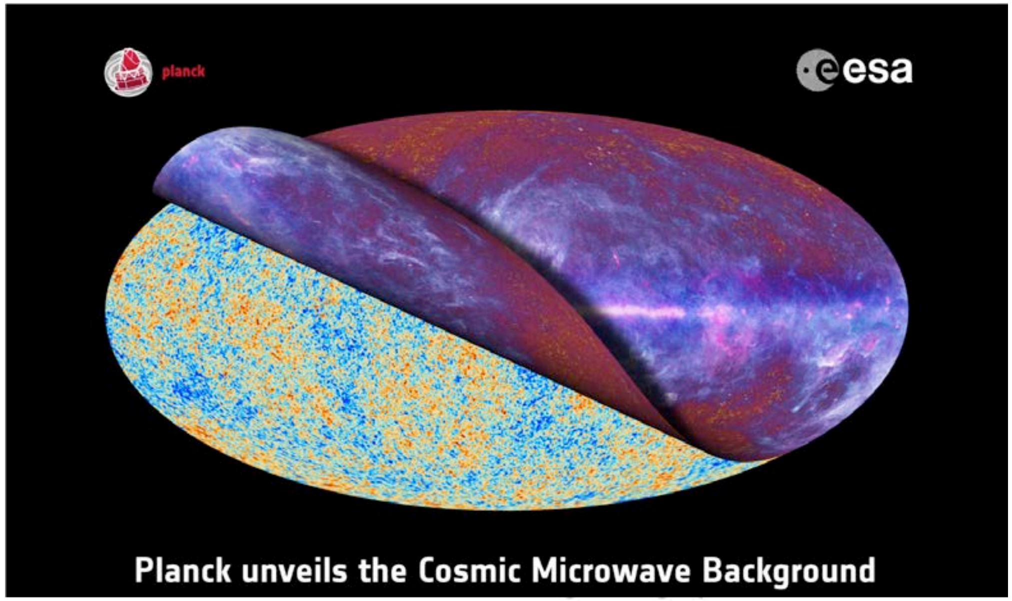
9 papers (+3 to appear soon)

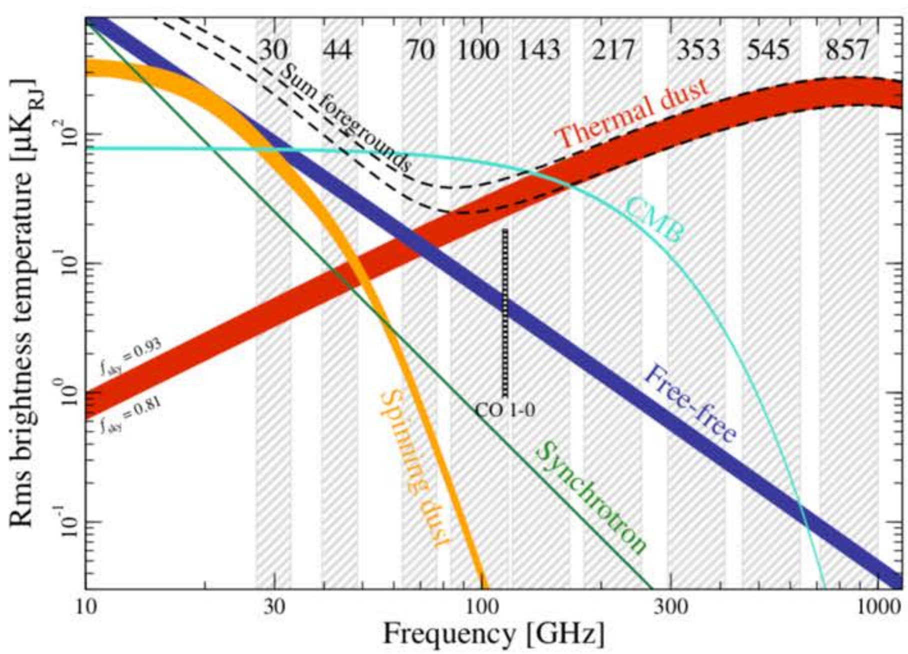
THE TEMPERATURE SKY AS SEEN BY PLANCK 2018

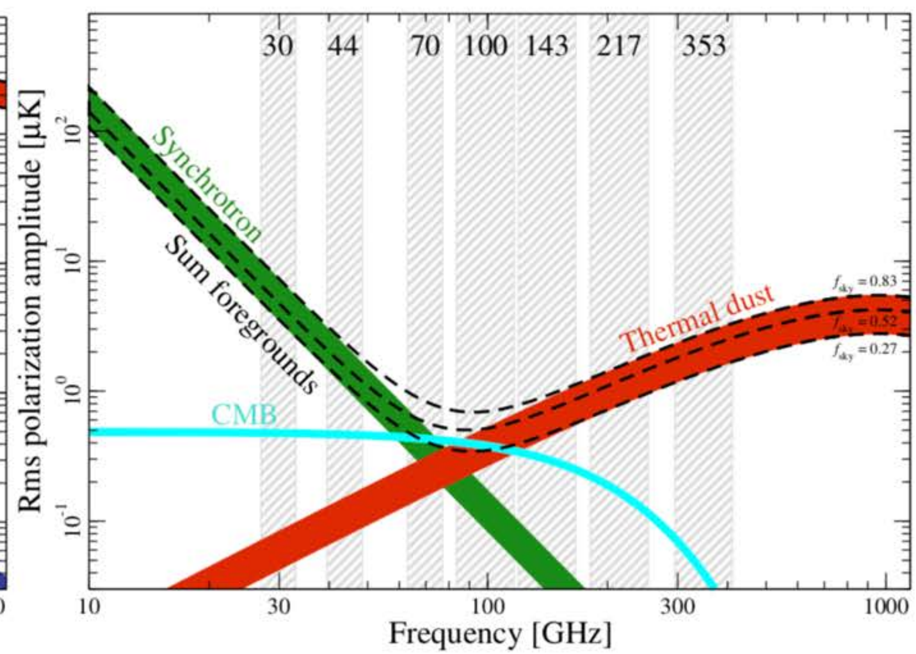


UNVEILING THE CMB SKY

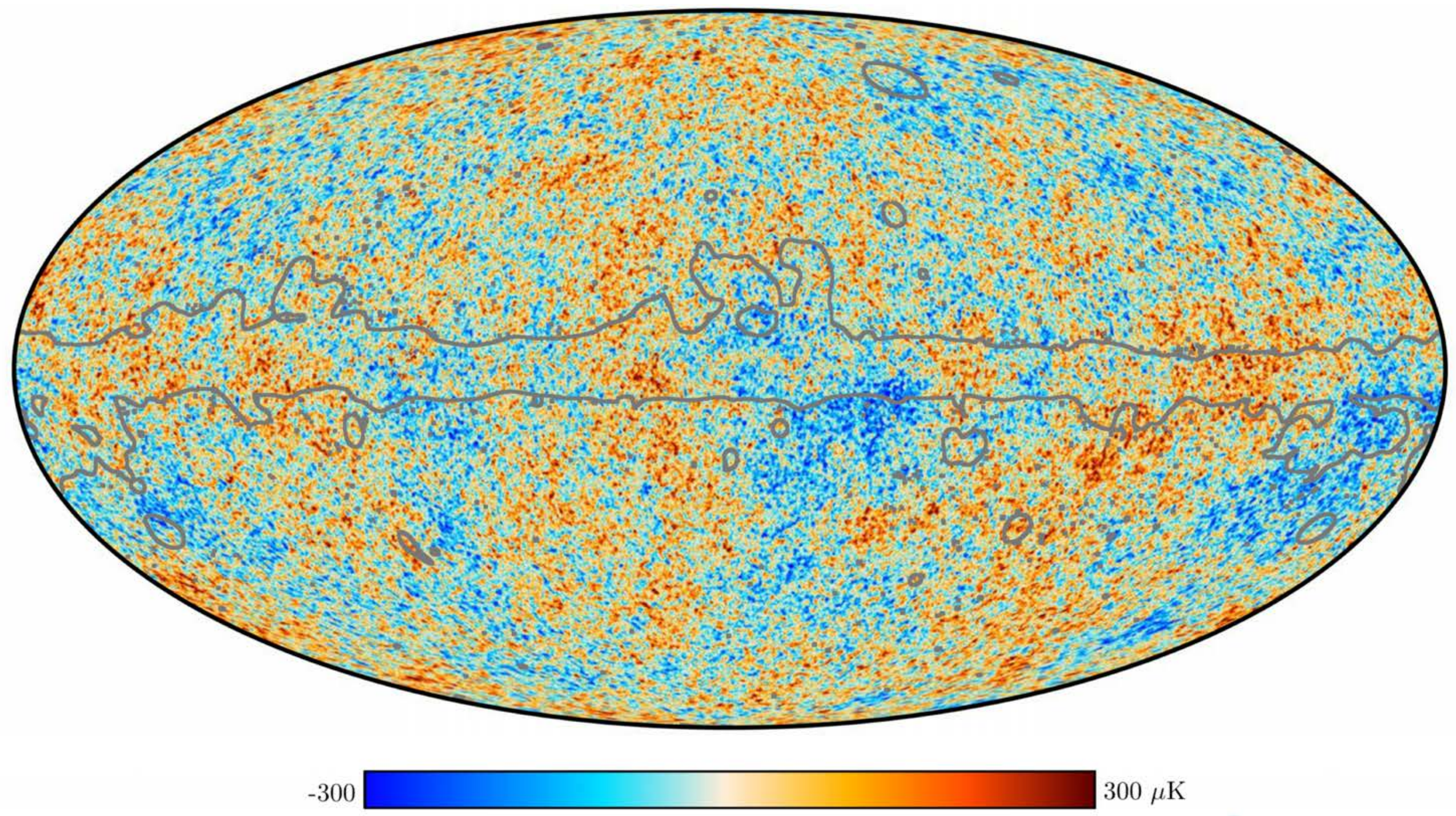
The *ultimate* measurement of the CMB temperature anisotropy field



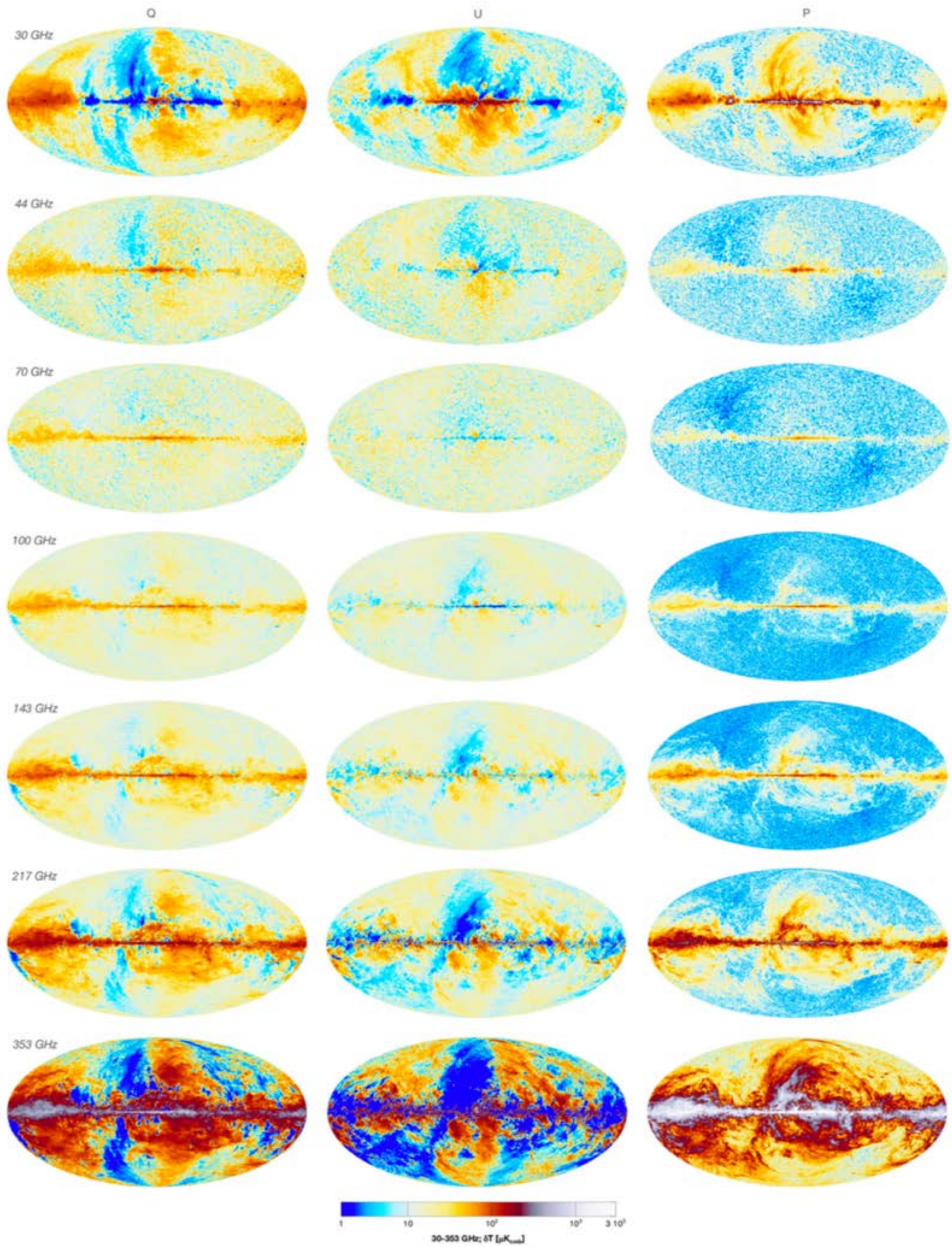




PLANCK: TEMPERATURE ANISOTROPIES

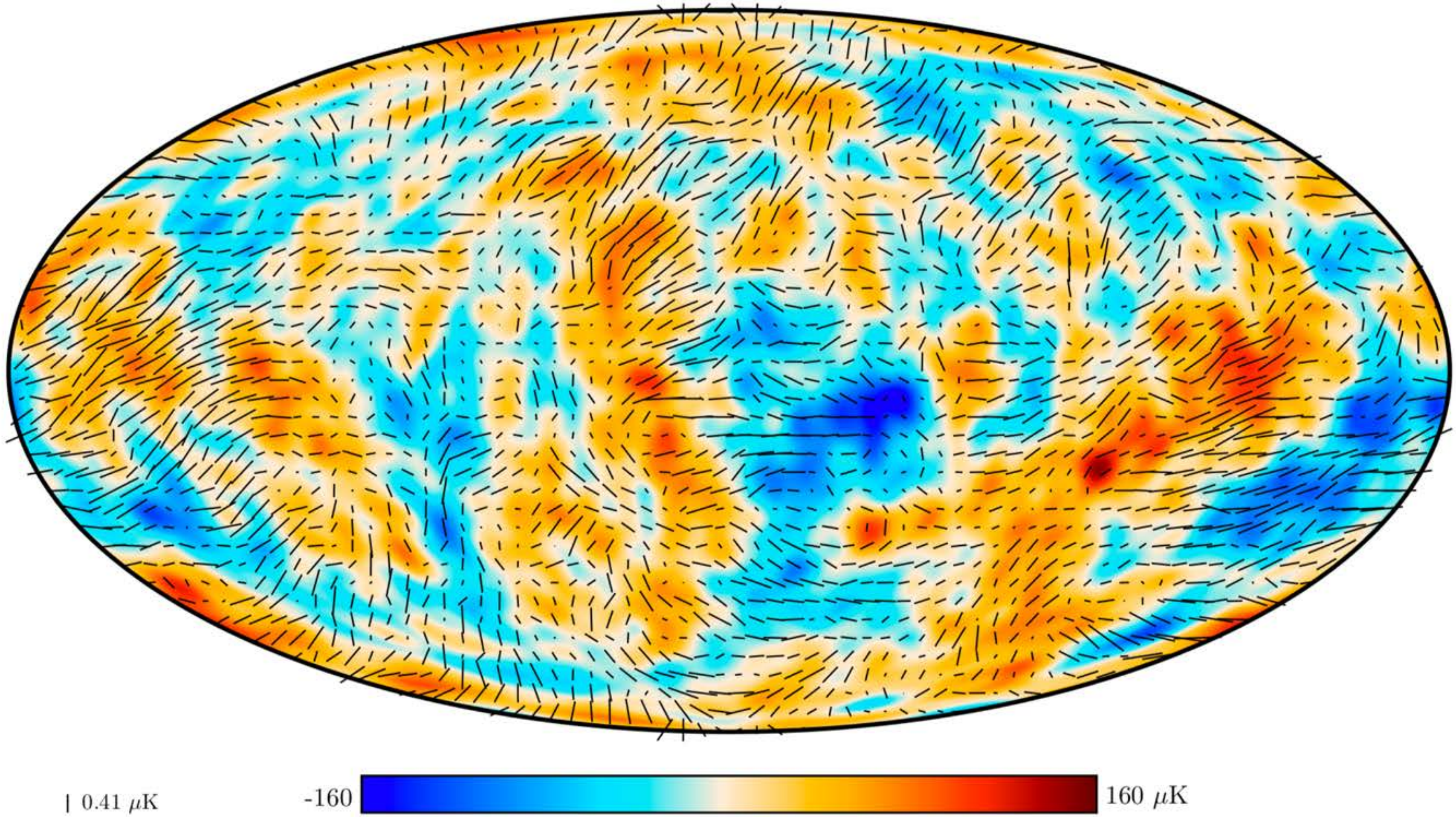


THE POLARIZATION SKY AS SEEN BY PLANCK 2018



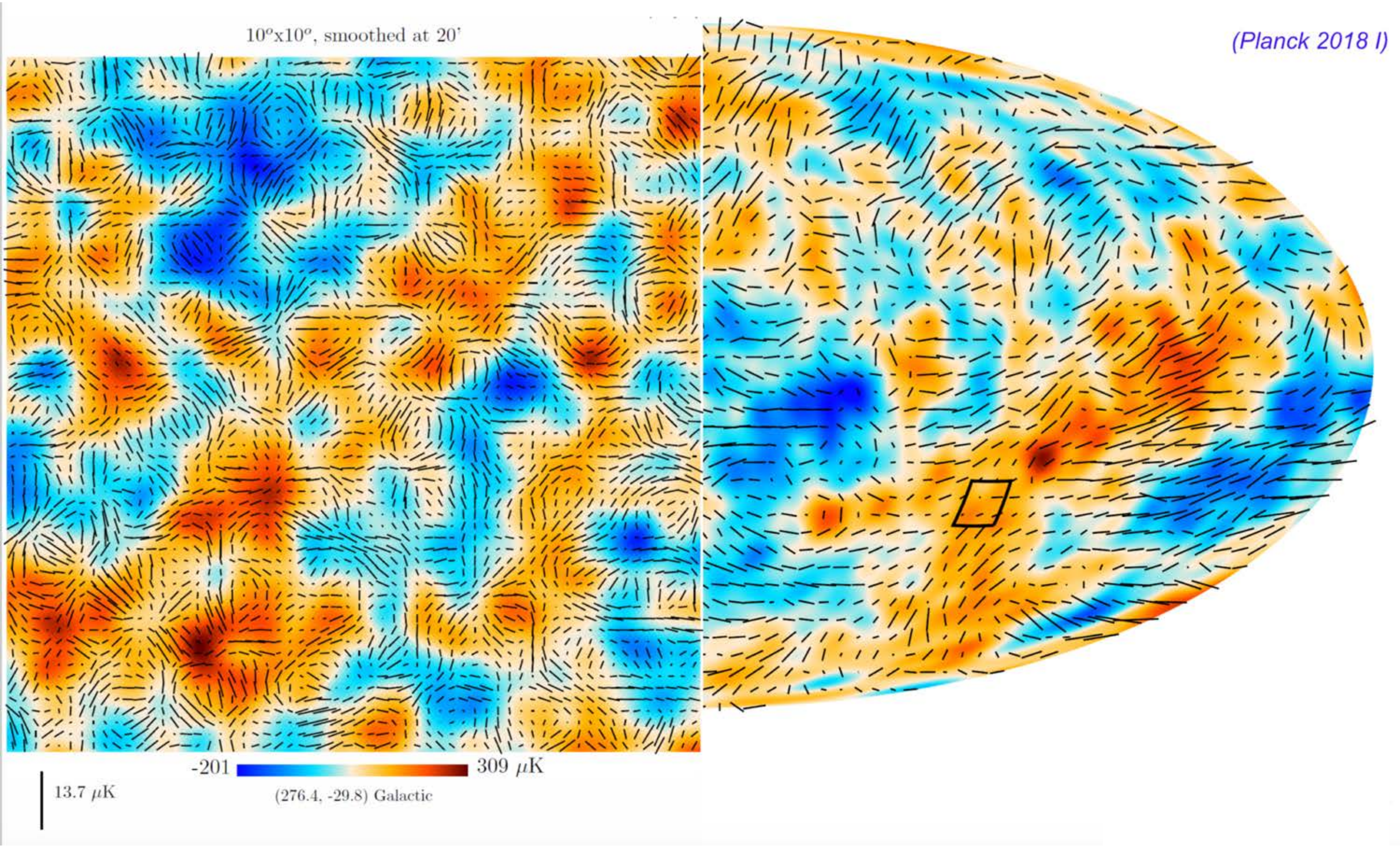
Significant reduction of large scale polarization systematics in 2018

PLANCK: POLARIZATION ANISOTROPIES

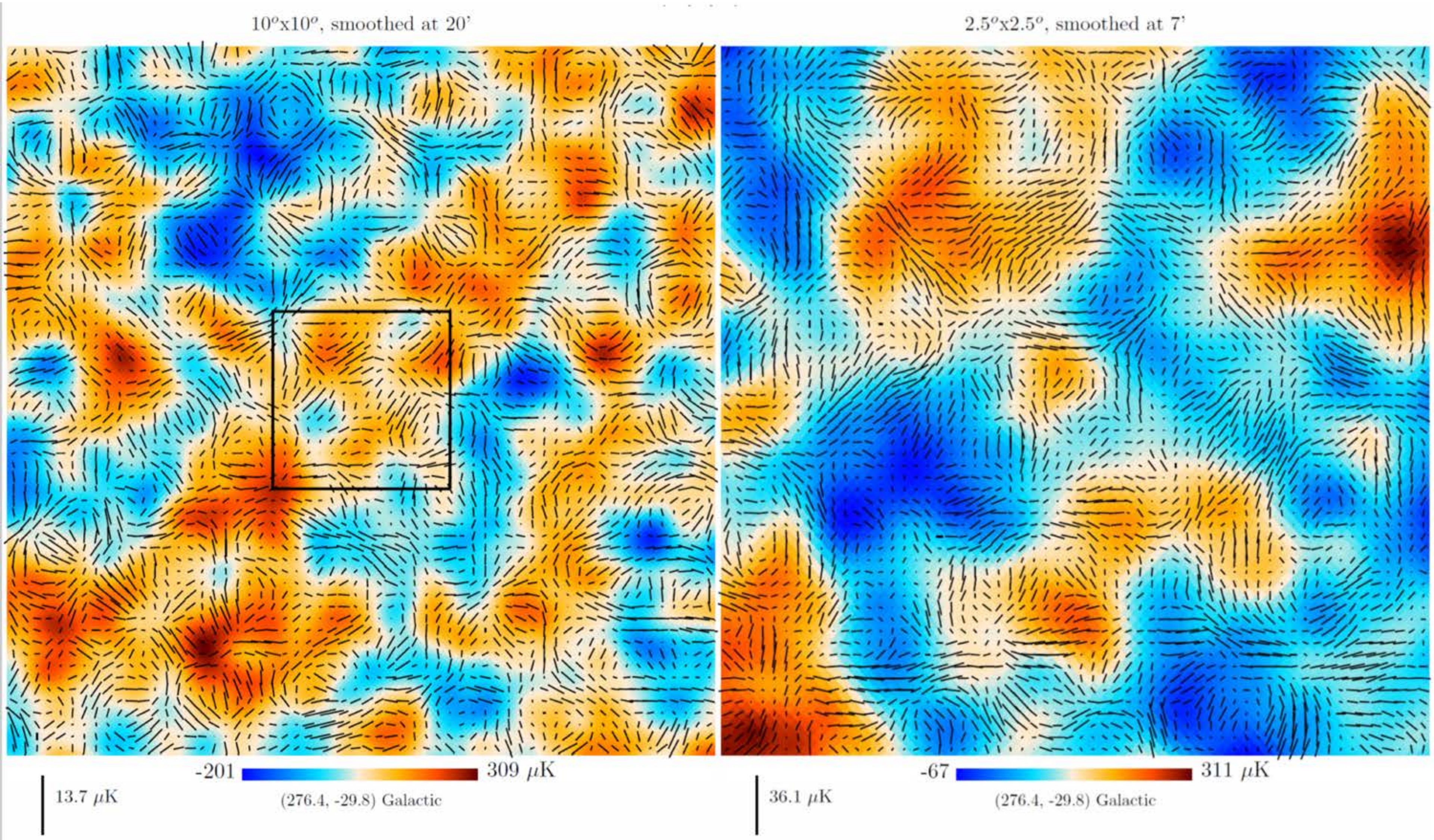


Temperature smoothed to 5 degrees

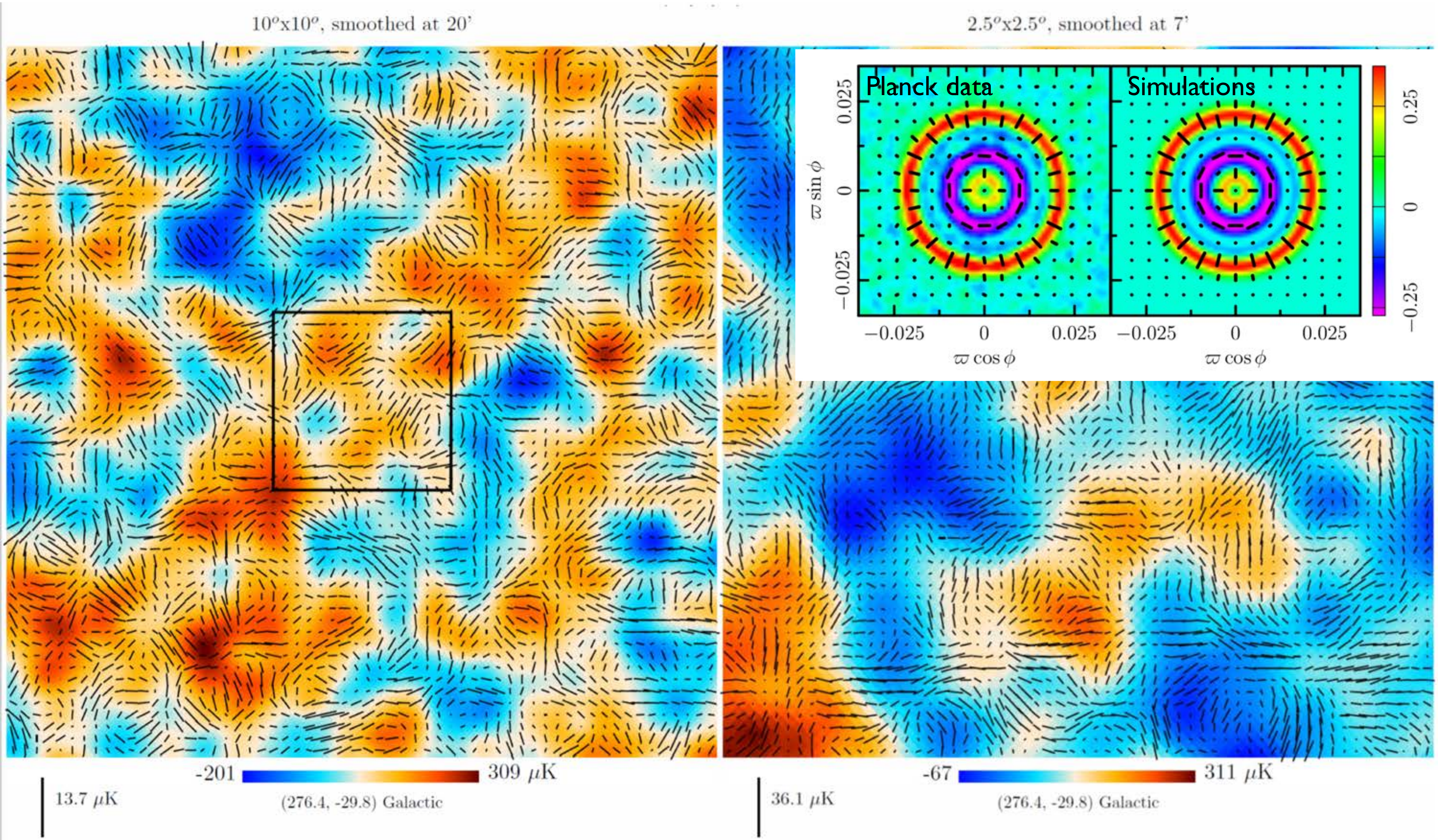
PLANCK: POLARIZATION ANISOTROPIES



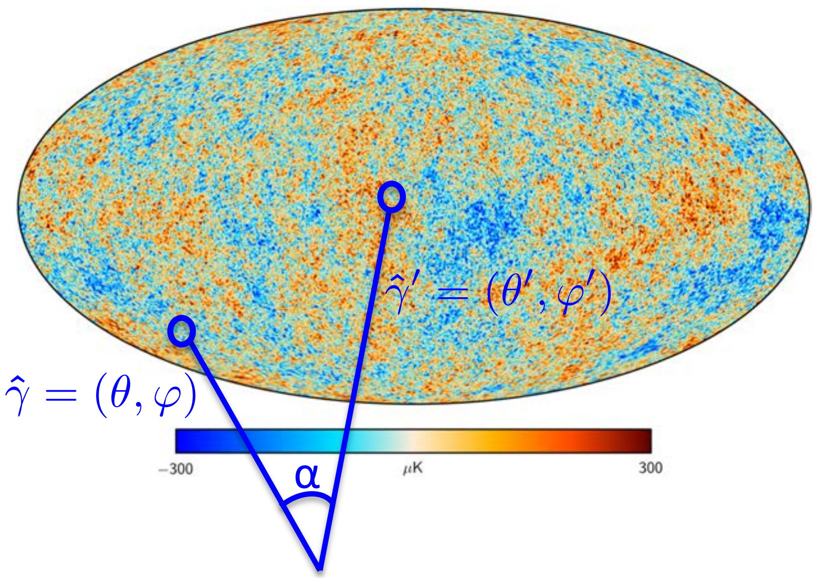
PLANCK: POLARIZATION ANISOTROPIES



PLANCK: POLARIZATION ANISOTROPIES



STATISTICAL DESCRIPTION



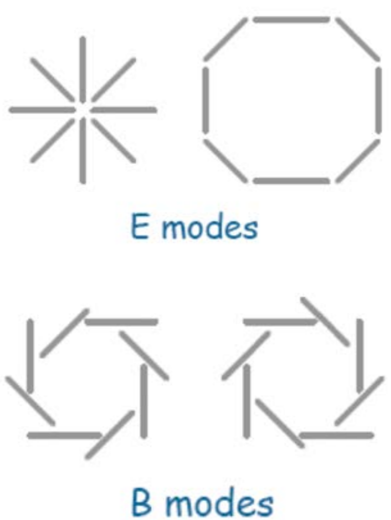
CORRELATION FUNCTIONS

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

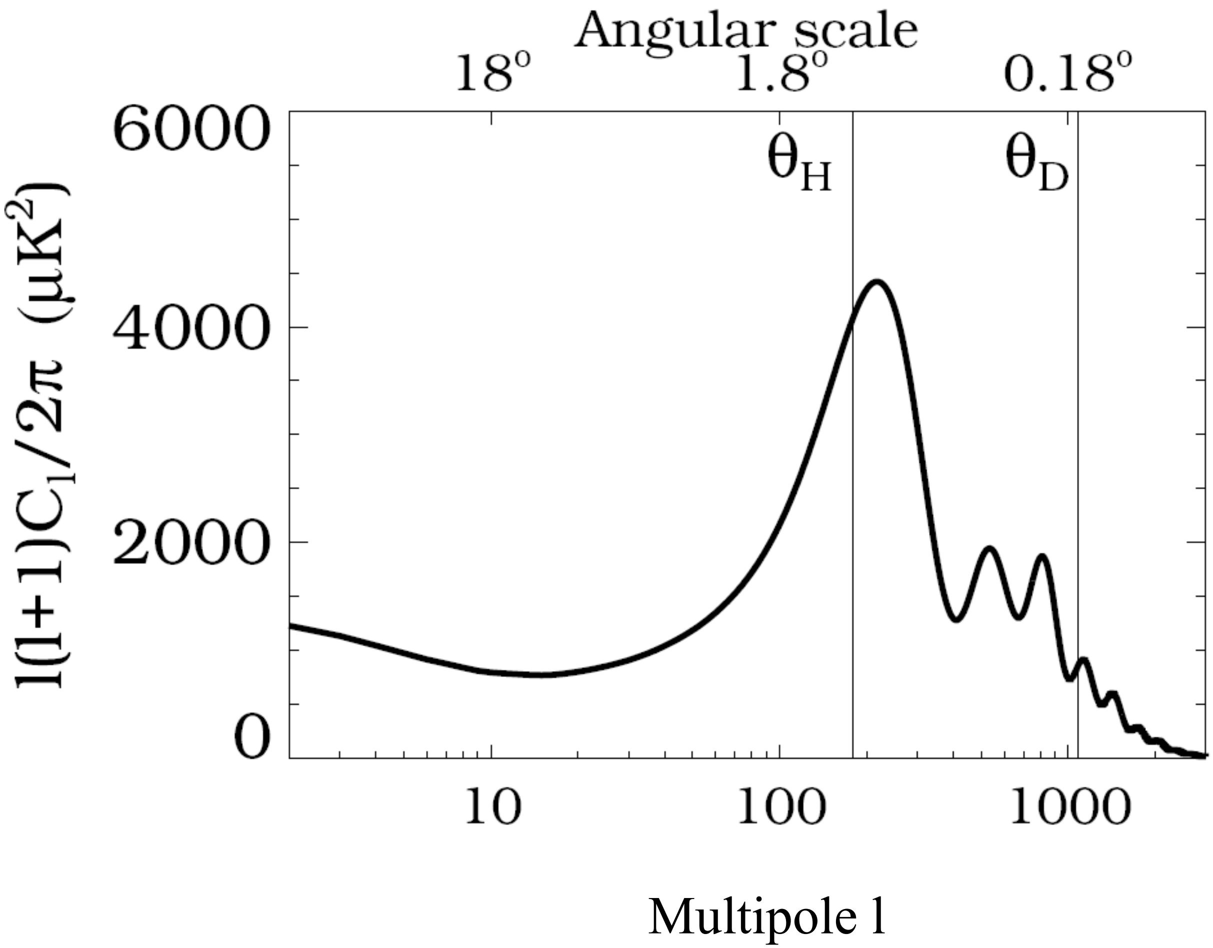
$$\mathbf{P}(\hat{\gamma}) = \nabla\mathbf{E} + \nabla \times \mathbf{B}$$

E-modes: even under parity

B-modes: odd under parity

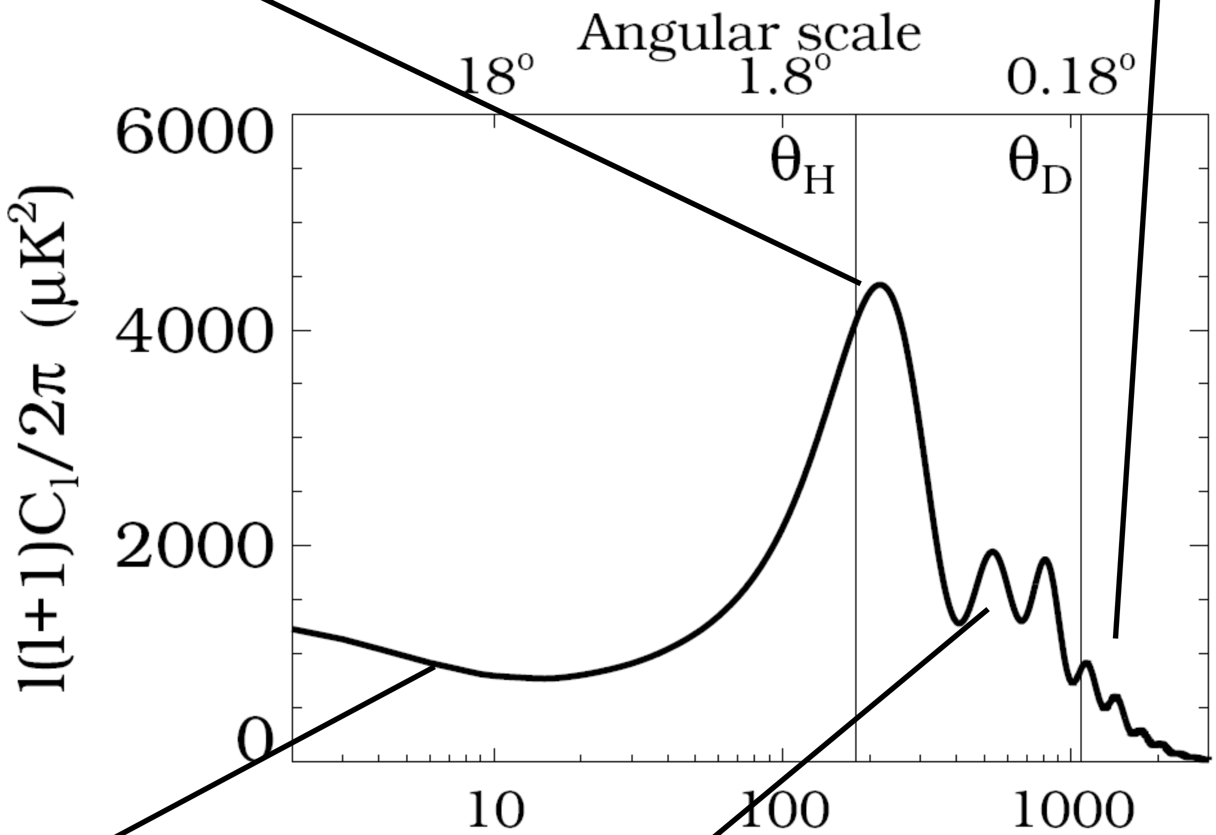
Density perturbations -> E-modes

Gravitational Waves -> E- and B-modes


Angular scale
18°
1.8°
0.18°
6000
4000
2000
0
θ_H
θ_D
$l(l+1)C_l/2\pi$ (μK^2)
10
100
1000
Multipole l

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_{eff}, Ω_b, Y_p, n_s



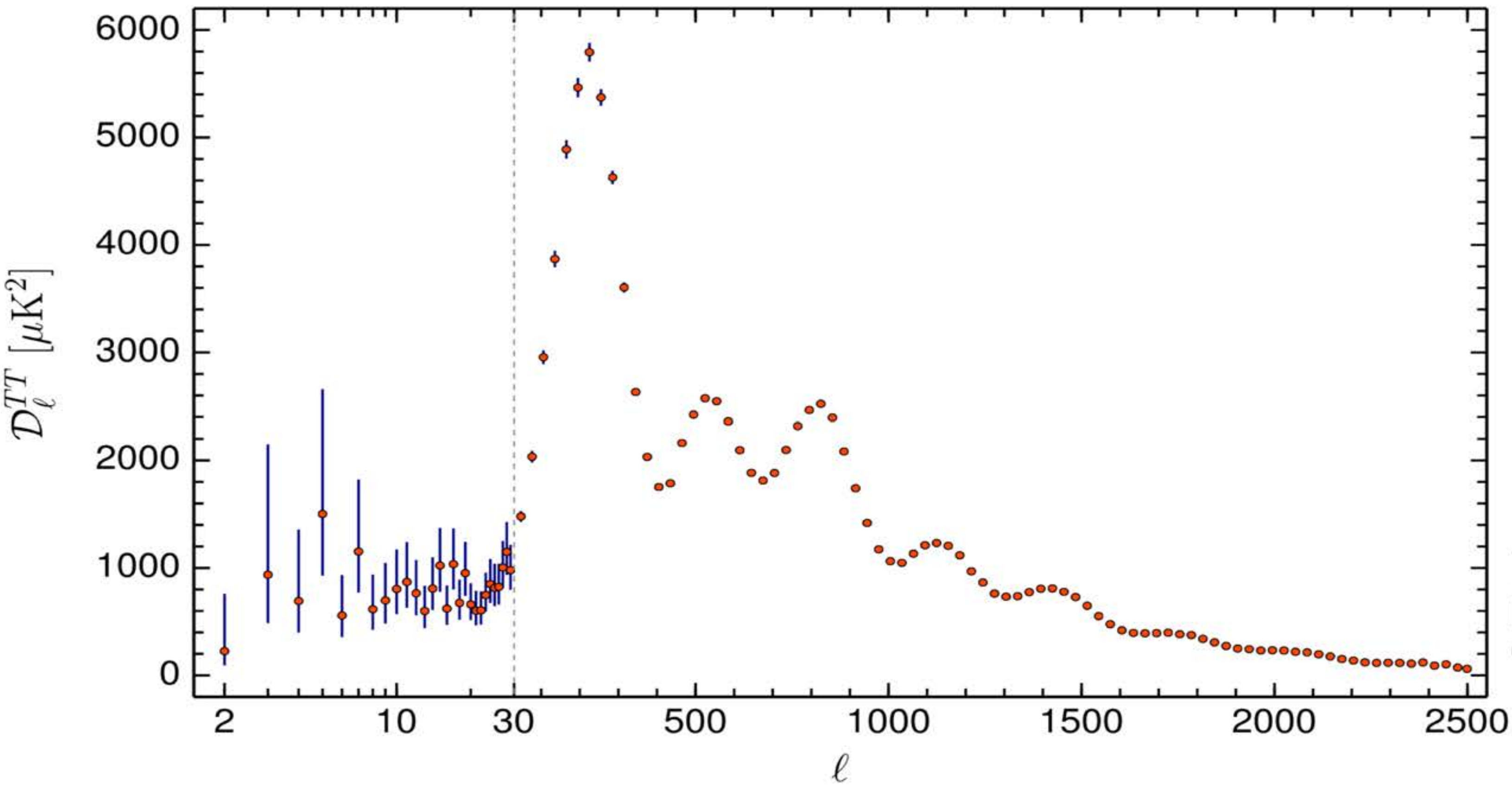
+ Overall power
$A_s\, e^{-2\tau}$

+ low-ell polarization (not shown)
Reionization history
τ

Primordial power spectrum
late time expansion
A_s, Ω_Λ

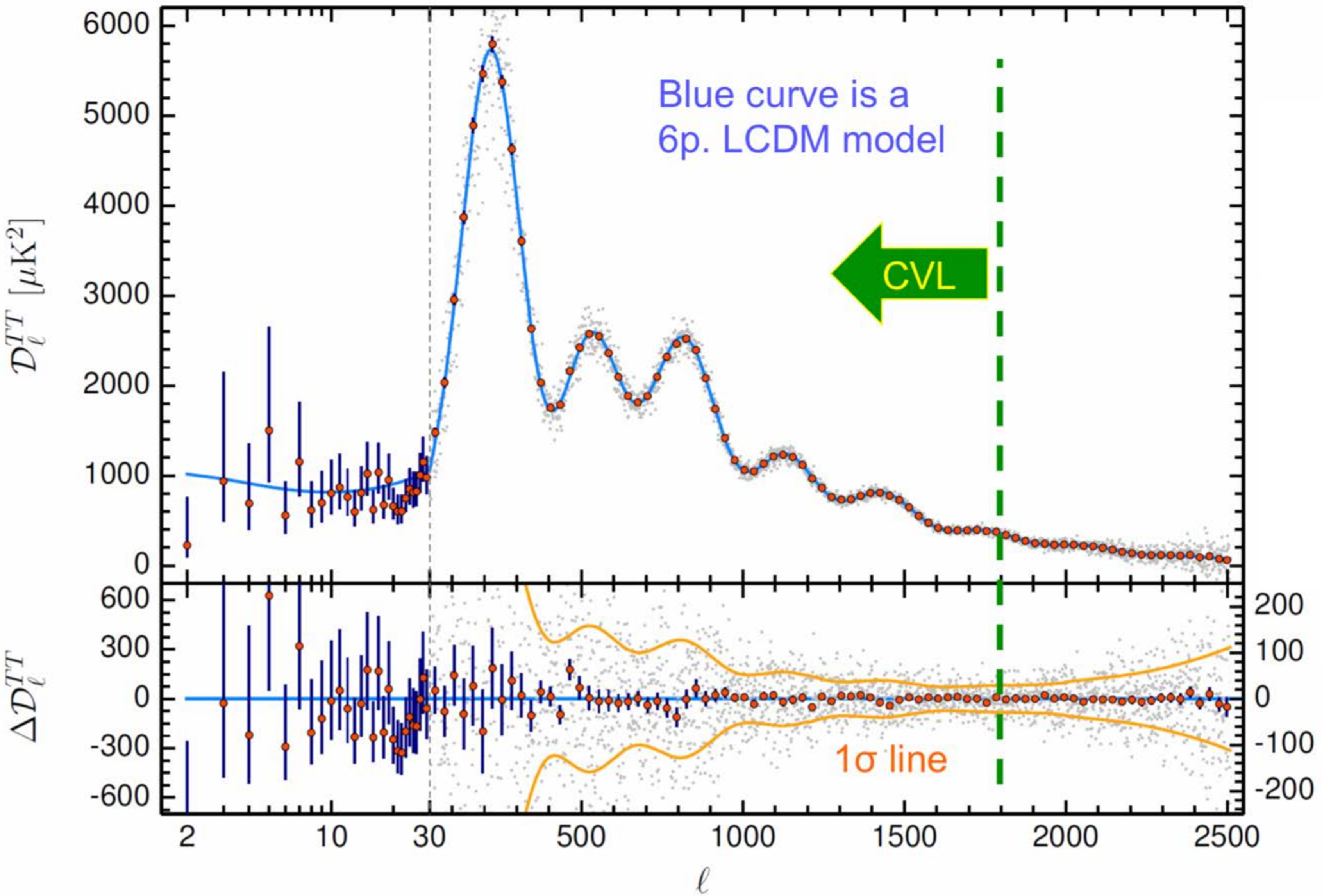
Baryon abundance
Ω_b

Planck 2018 TT power spectrum

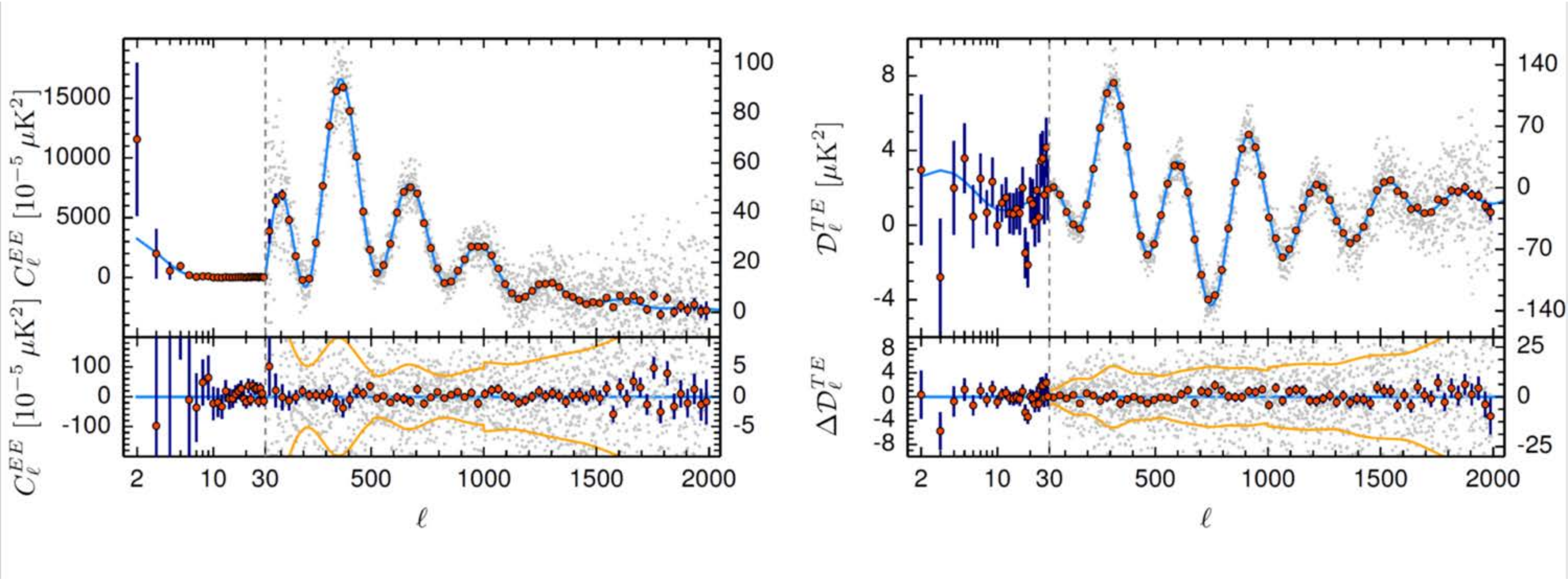


7 acoustic peaks well detected

Planck 2018 TT power spectrum

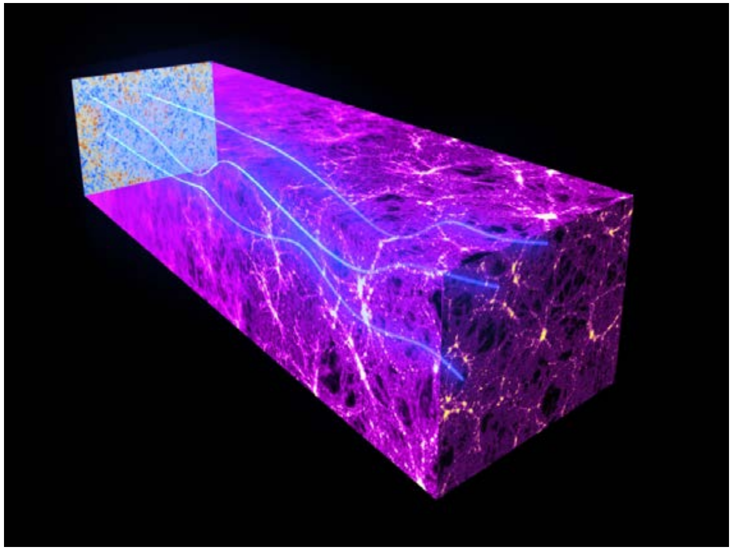


Planck 2018 TE, EE power spectra



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

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

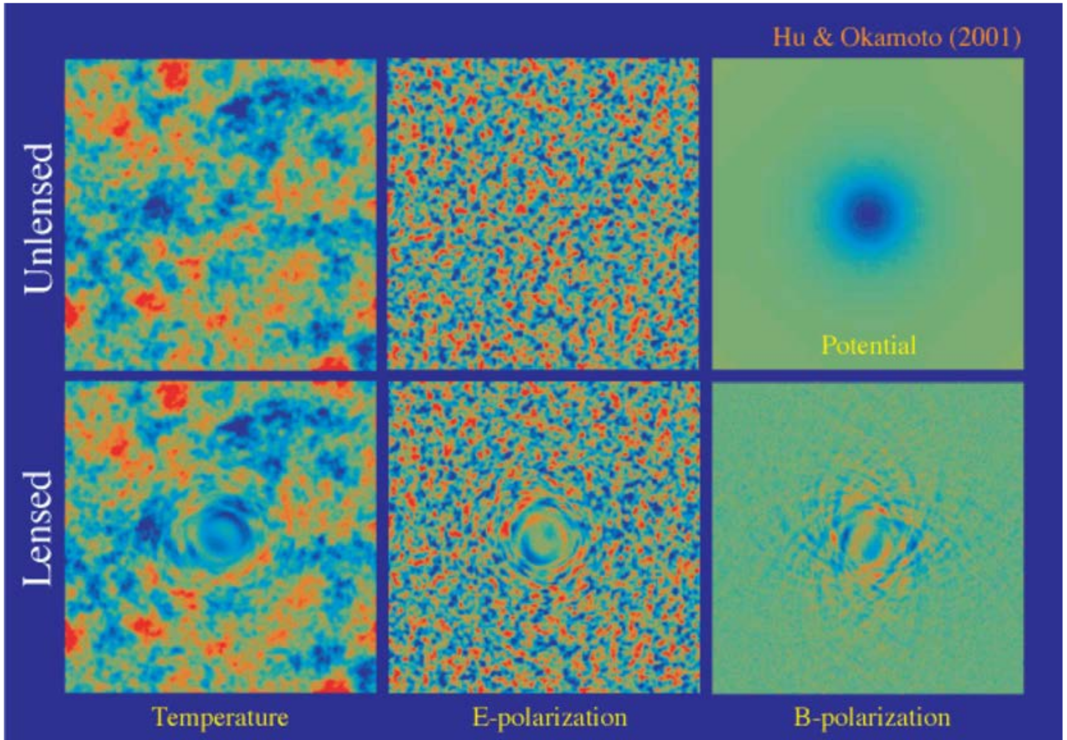


Line-of-sight integral of the gravitational potentials

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

Deflection field

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



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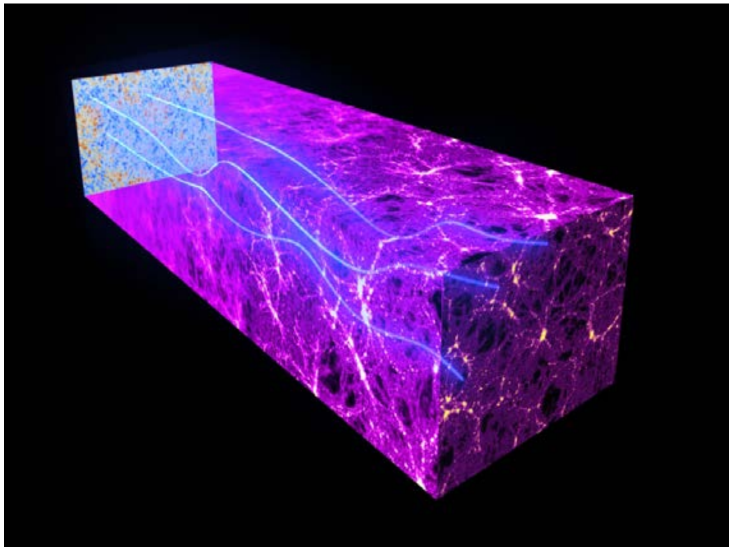

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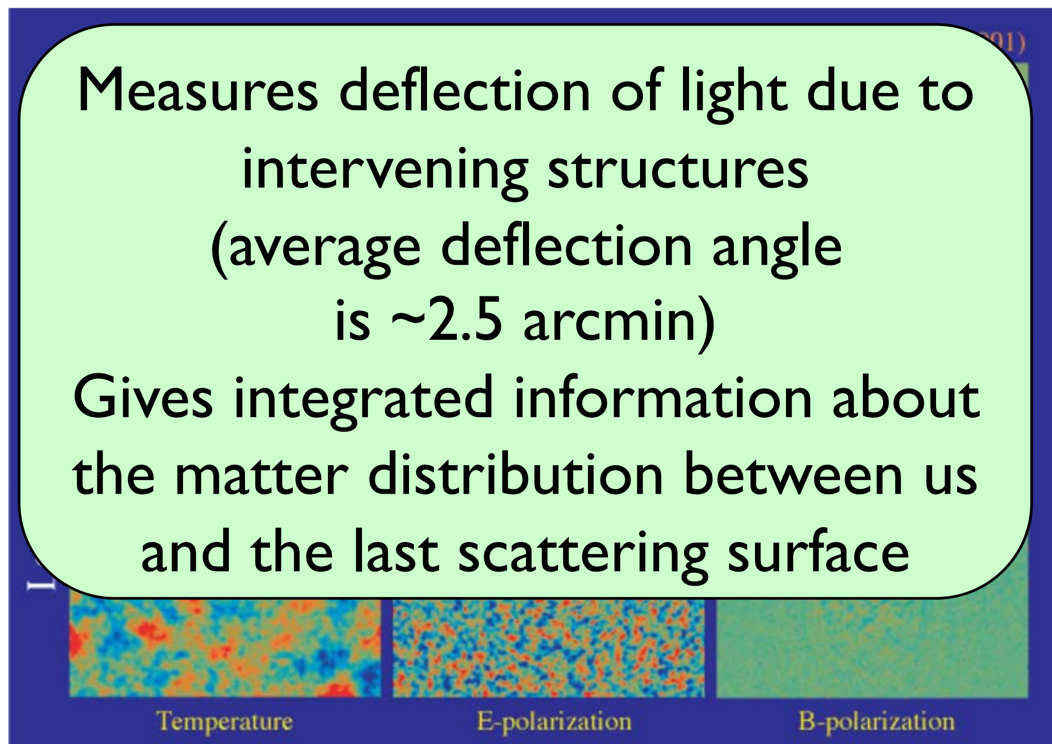
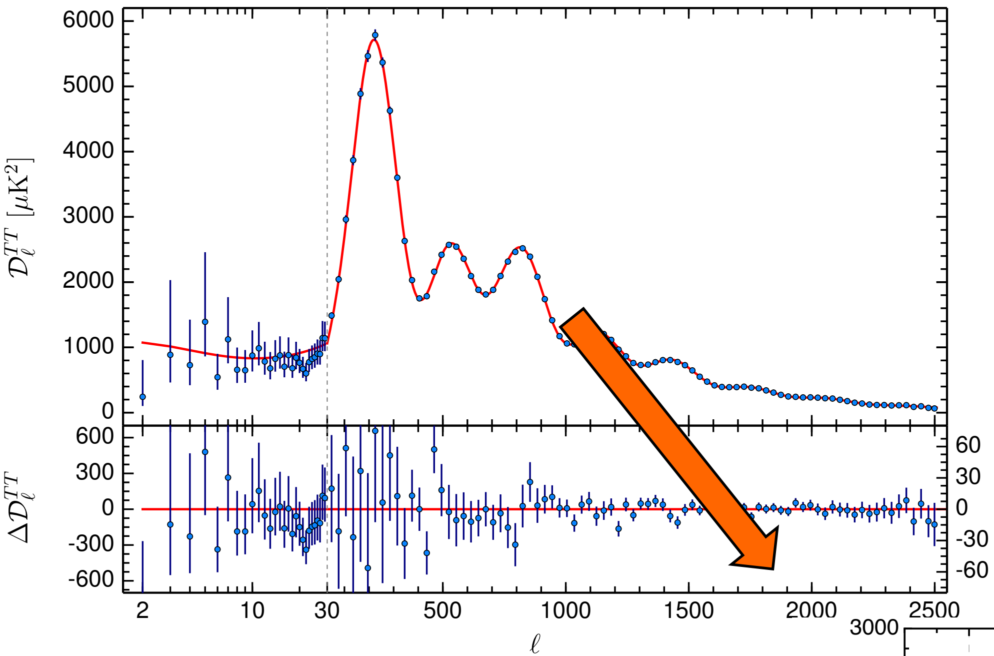
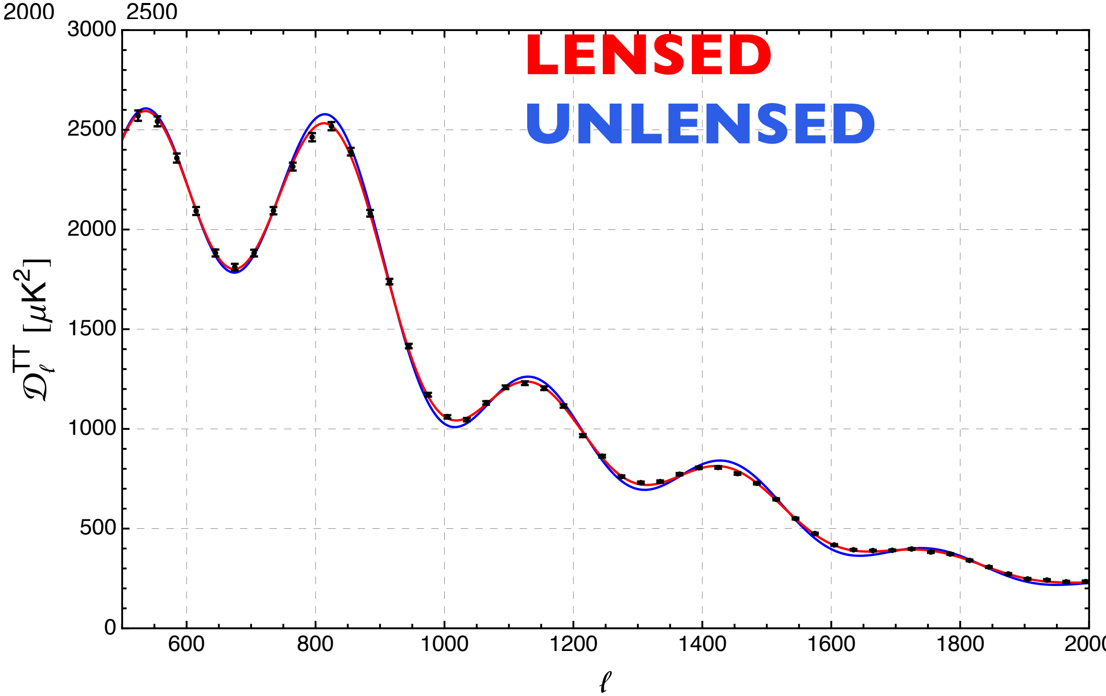


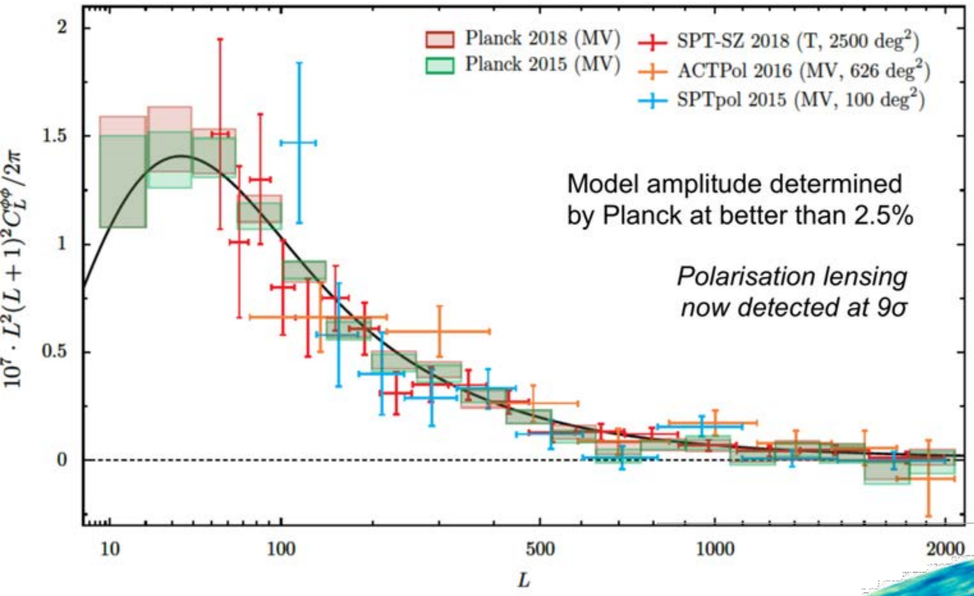
Measures deflection of light due to intervening structures
(average deflection angle is ~2.5 arcmin)
Gives integrated information about the matter distribution between us and the last scattering surface



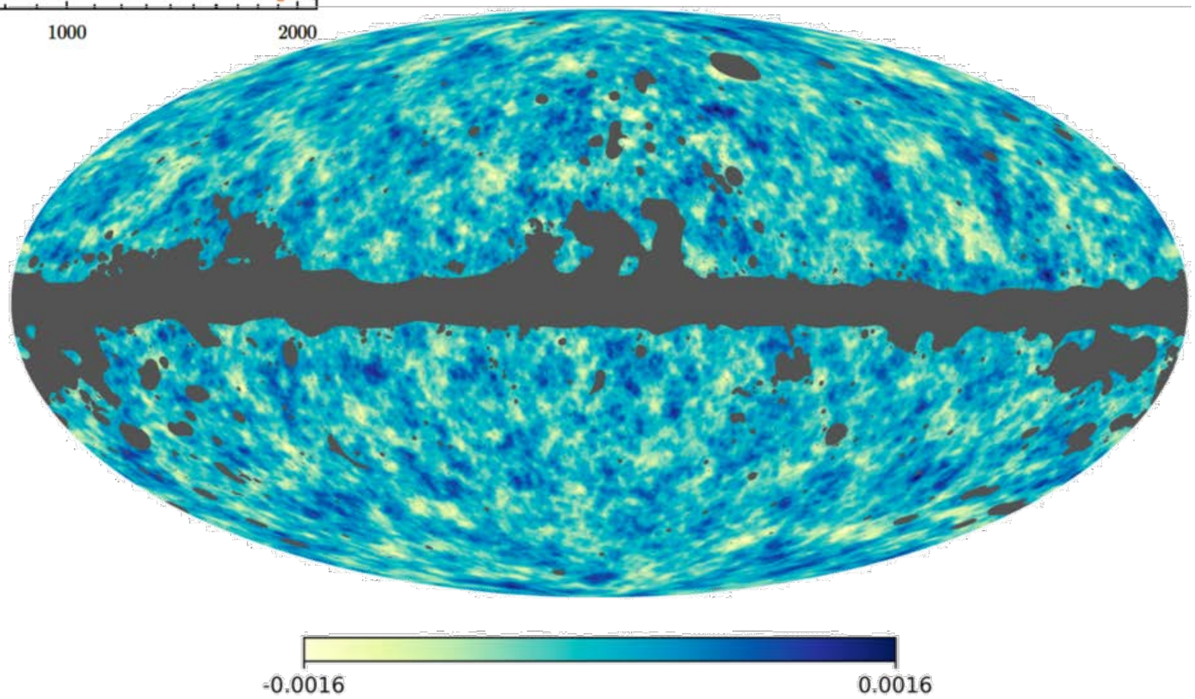
Lensing smooths the peaks of the CMB power spectrum…
… and introduces non-gaussianities in the map (nonzero 4-point c.f.)



LENSING



Lensing potential estimated from the four-point correlation function



ΛCDM 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 amolitude of perturbation	3.044	0.014	0.007
	n_s Primordial Scalar spectral index	0.9649	0.0042	0.004
derived	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

ΛCDM 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 8 σ away from 1 (a signature of inflation). Even in extended
3. Optical depth t greatly improved after taming of large-angle polarization systematics. Still, at 13% relative error, by far the worst parameter determined from CMB

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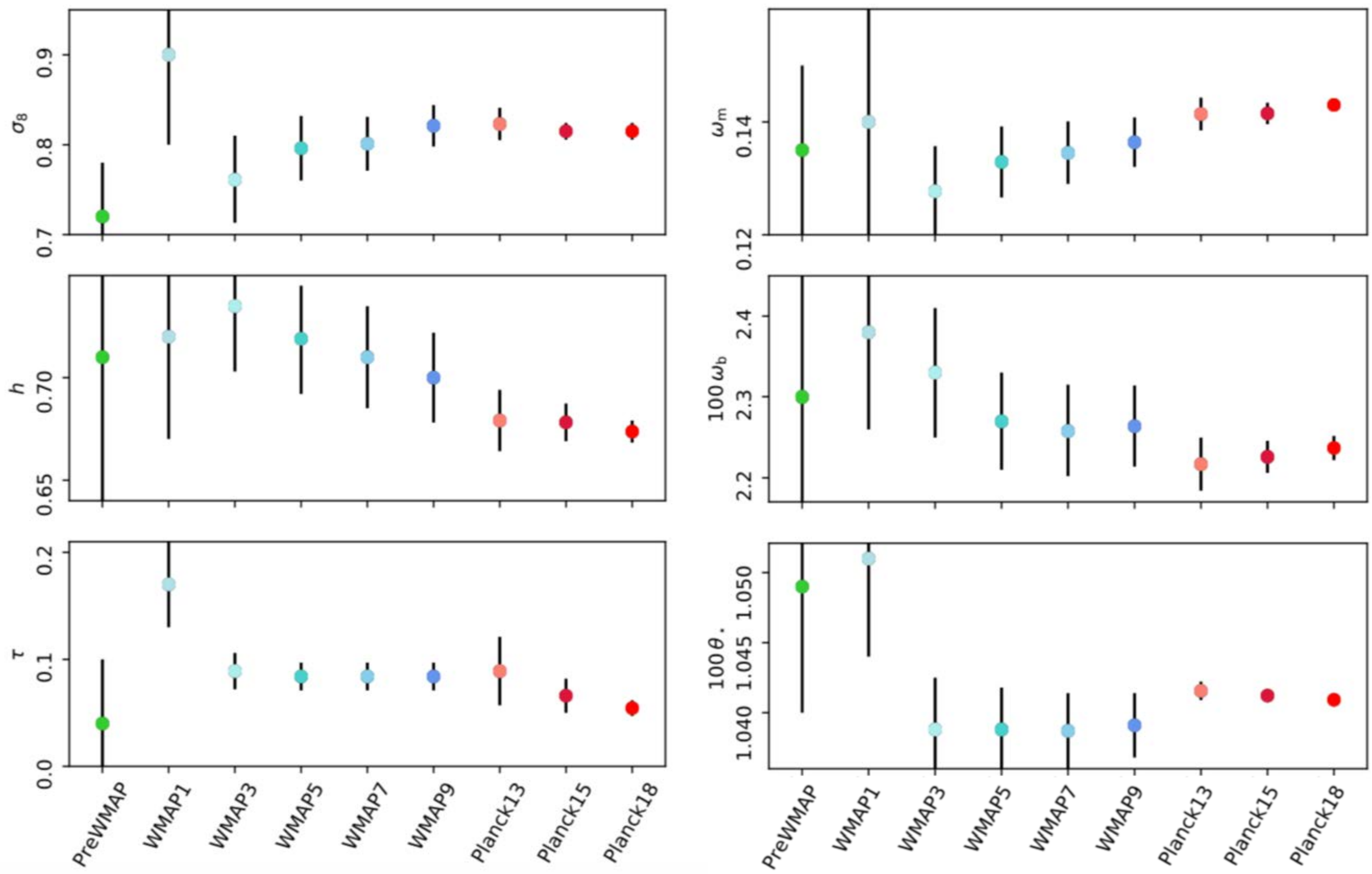
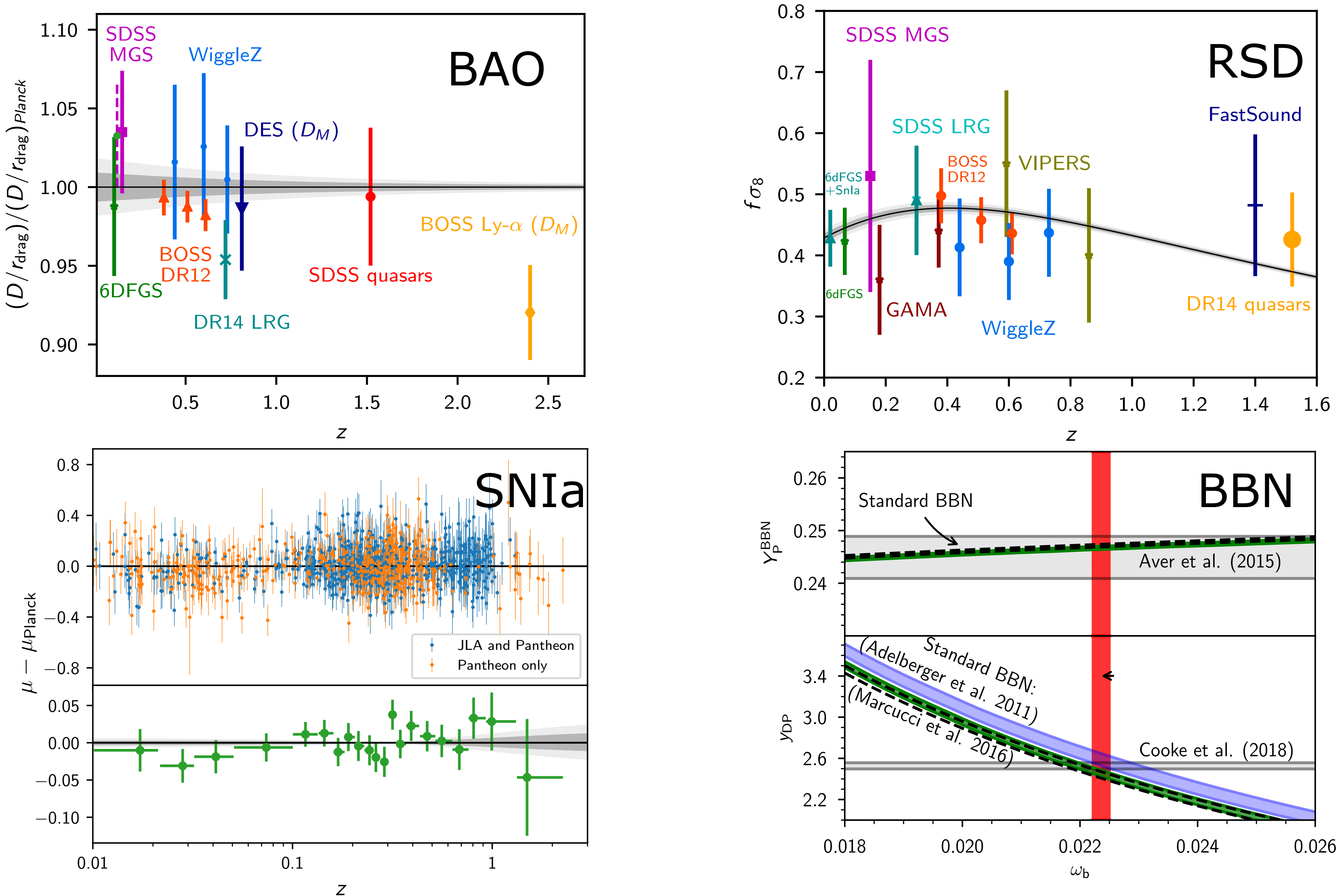
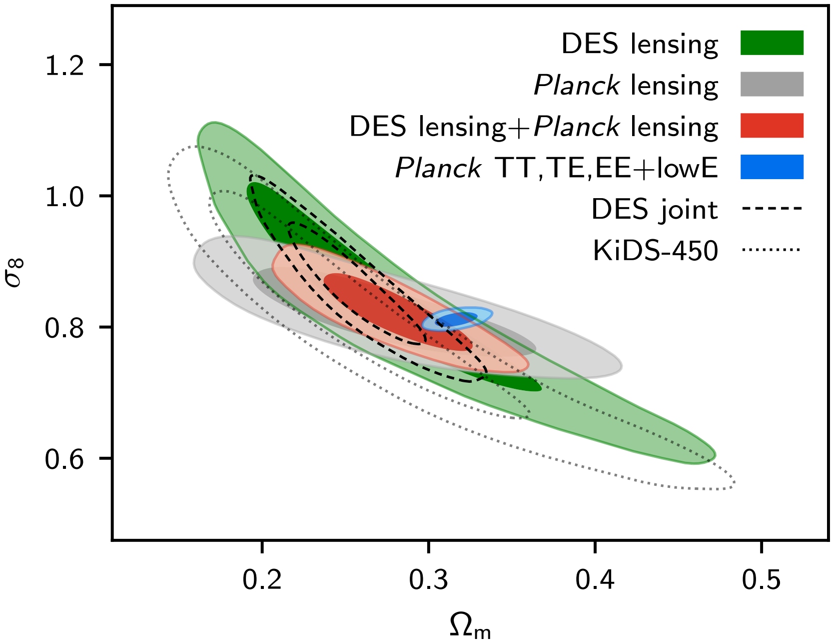
Improvement in parameter accuracy



Consistency with other datasets



Tensions with other datasets...



Mild tension with DES year 1 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 TTTEE+lowE+lensing

$S_8 = 0.832 \pm 0.013$

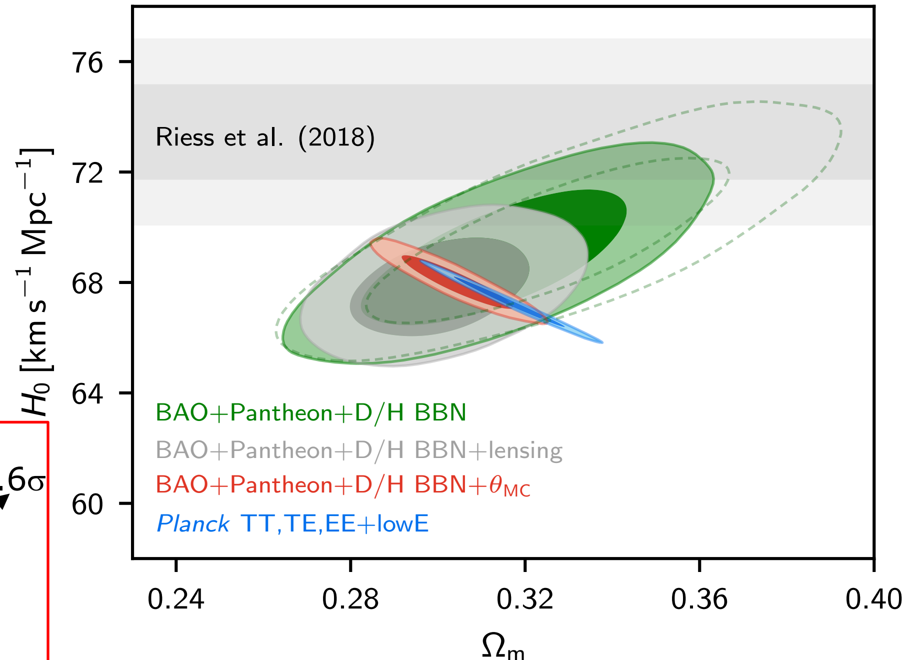
$\Omega_m = 0.315 \pm 0.007.$

Strong tension with H_0 distance ladder measurements.

H_0= 67.36±0.54 km/s/Mpc Planck ΛCDM
H_0= 73.5 ±1.6 km/s/Mpc SH0ES (Riess+ 18)

3.6σ

Inverse distance ladder:
H_0= 67.9 ± 1.3 km/s/Mpc BAO+D/H+CMB lensing

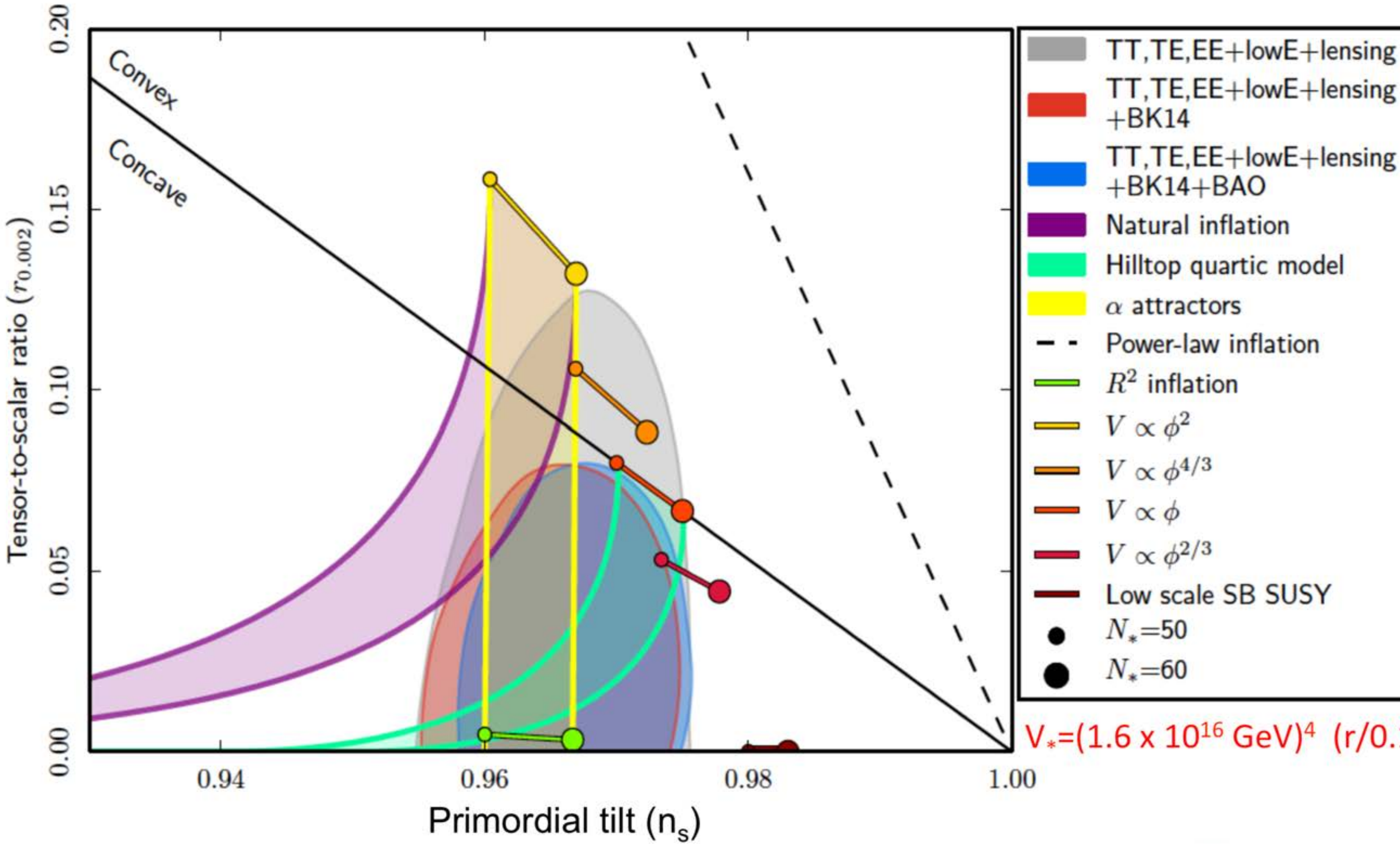


Now > 4σ, next talk by Martina Gerbino

ΛCDM 6 parameter fit + extensions (where surprises might hide)

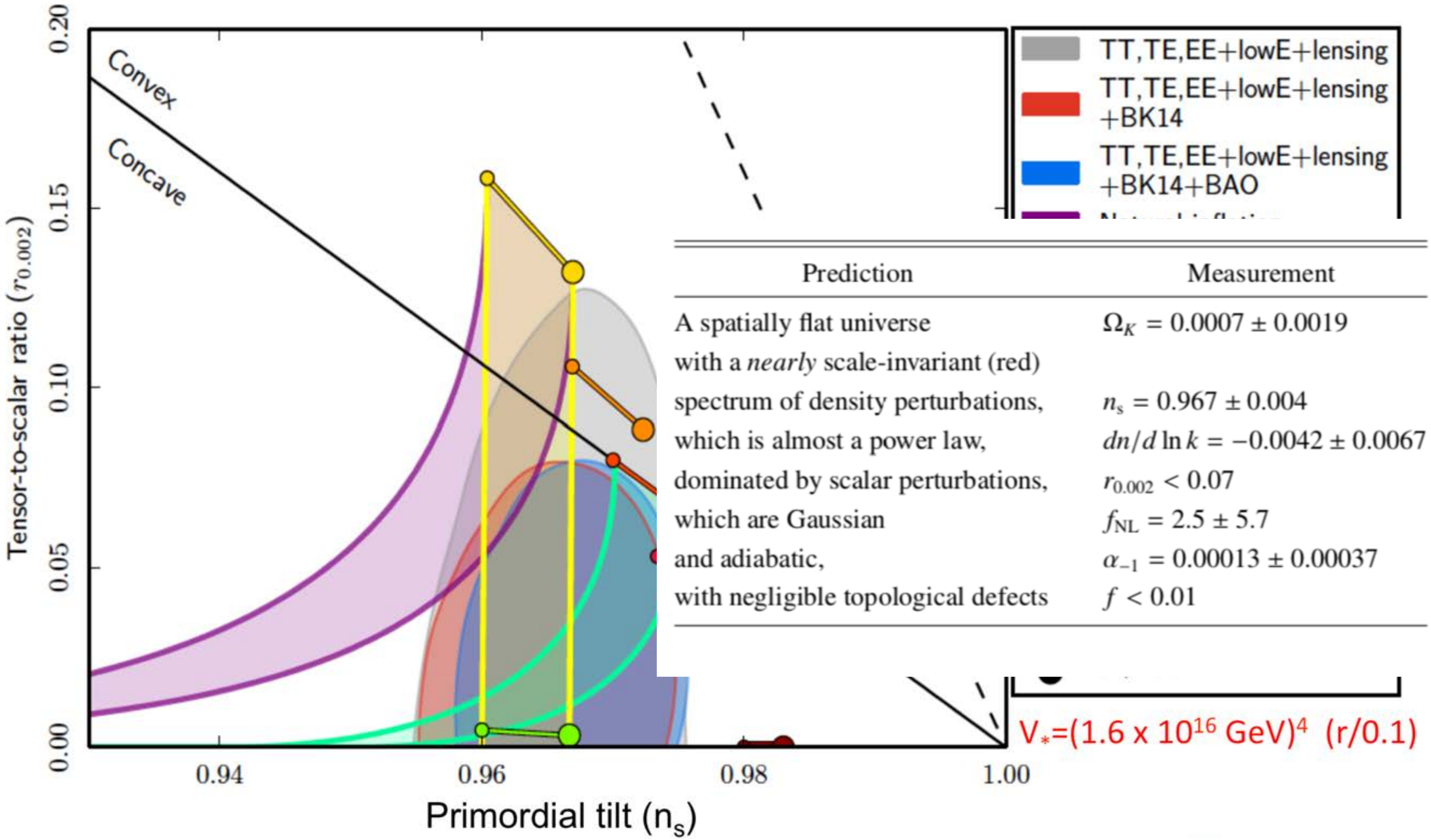
- Tensor modes, i.e. primordial gravitational waves, $r = A_T/A_s$
- Running spectral index $dn_s/d\ln k$
- Primordial non Gaussianity f_{NL}
- Non adiabatic (isocurvature) primordial perturbations
- Dark energy equation of state, w
- Spatial curvature $\Omega_k = 1 - \Omega_m - \Omega_\Lambda$
- Neutrino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

Constraints for tensor perturbations



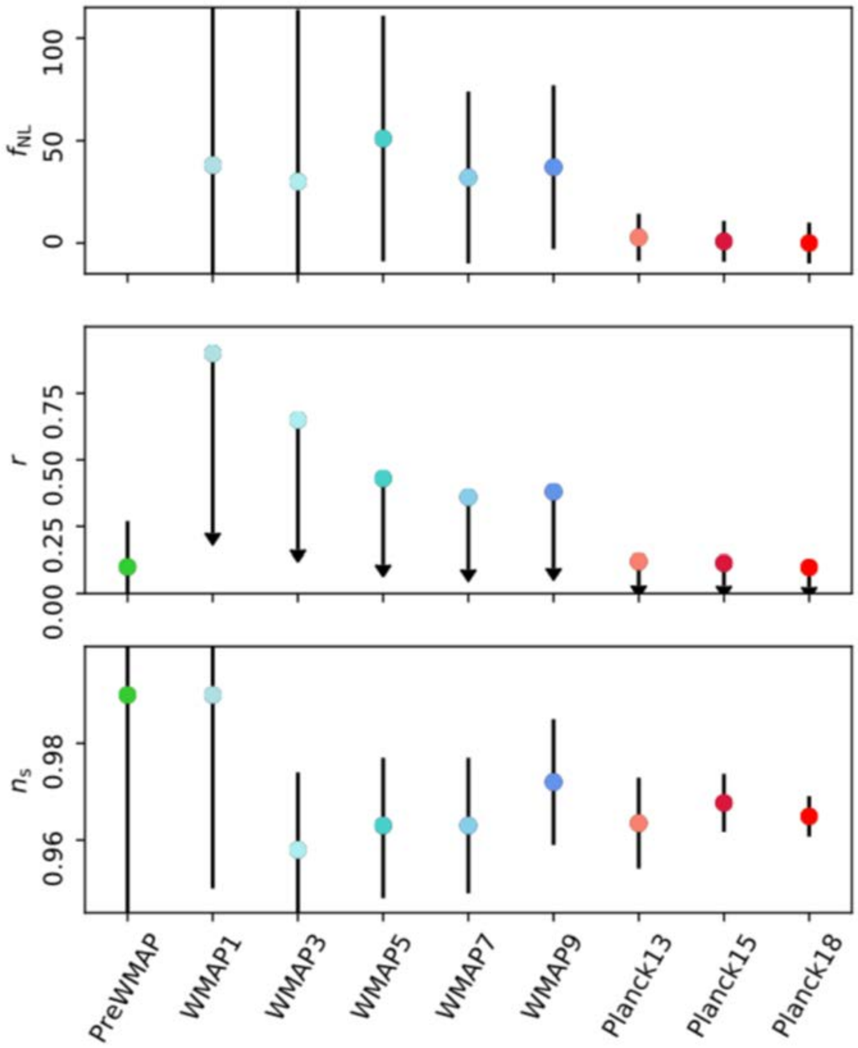
$V_* = (1.6 \times 10^{16}\ \text{GeV})^4\ (r/0.1)$

Constraints for tensor perturbations

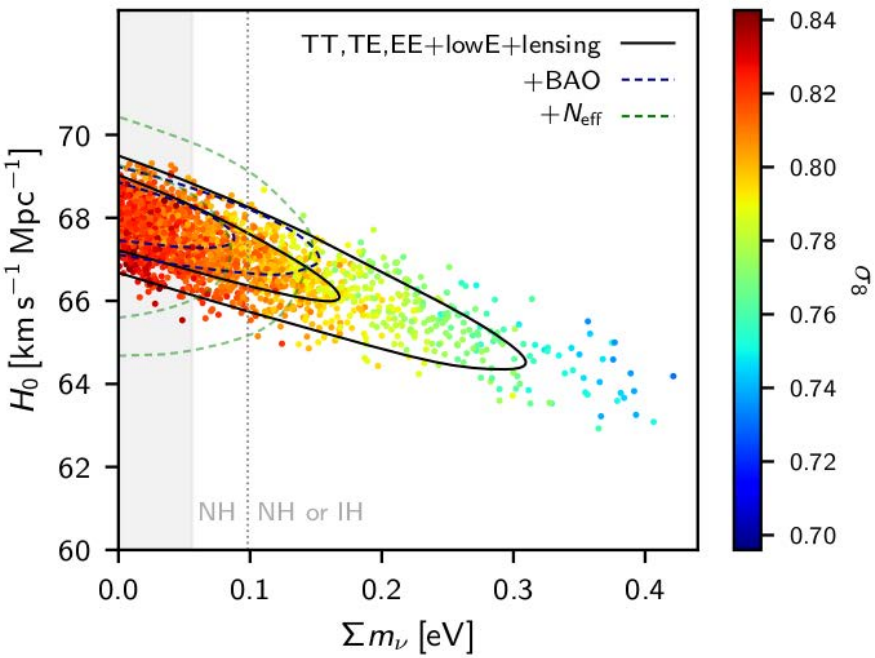


Prediction	Measurement
A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$
with a *nearly* scale-invariant (red)	
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$
dominated by scalar perturbations,	$r_{0.002} < 0.07$
which are Gaussian	$f_{NL} = 2.5 \pm 5.7$
and adiabatic,	$\alpha_{-1} = 0.00013 \pm 0.00037$
with negligible topological defects	$f < 0.01$

Improvement in inflationary parameters



Neutrino legacy of Planck: Σ m_ν

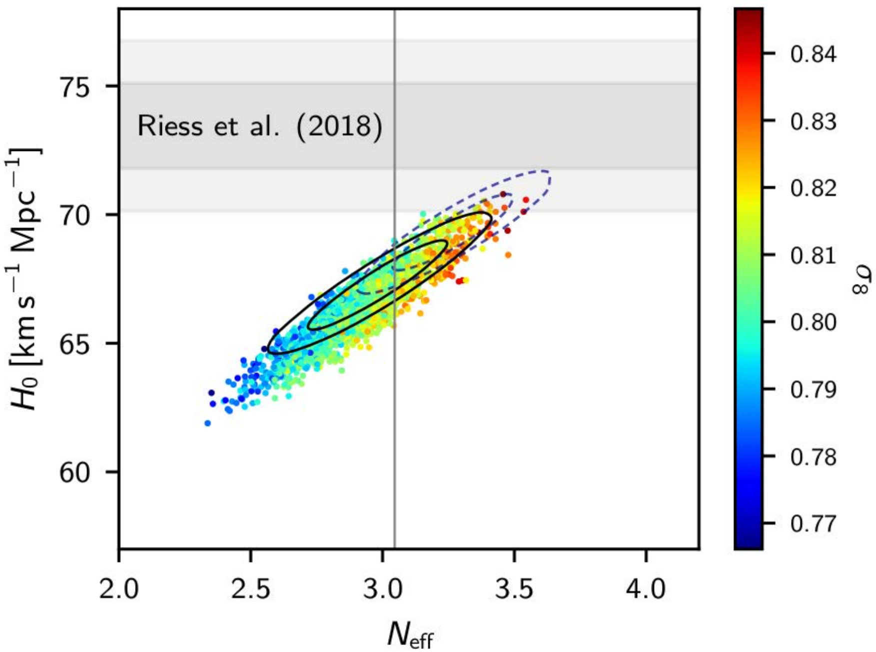


- Tightest constraint from a single experiment
- First constraint exploiting the information encoded in the CMB weak lensing
- One order of magnitude better than present kinematic constraints, already at the same level than future expectations for KATRIN
- The combined limits from Planck and large scale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

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

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

Neutrino legacy of Planck: Neff



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

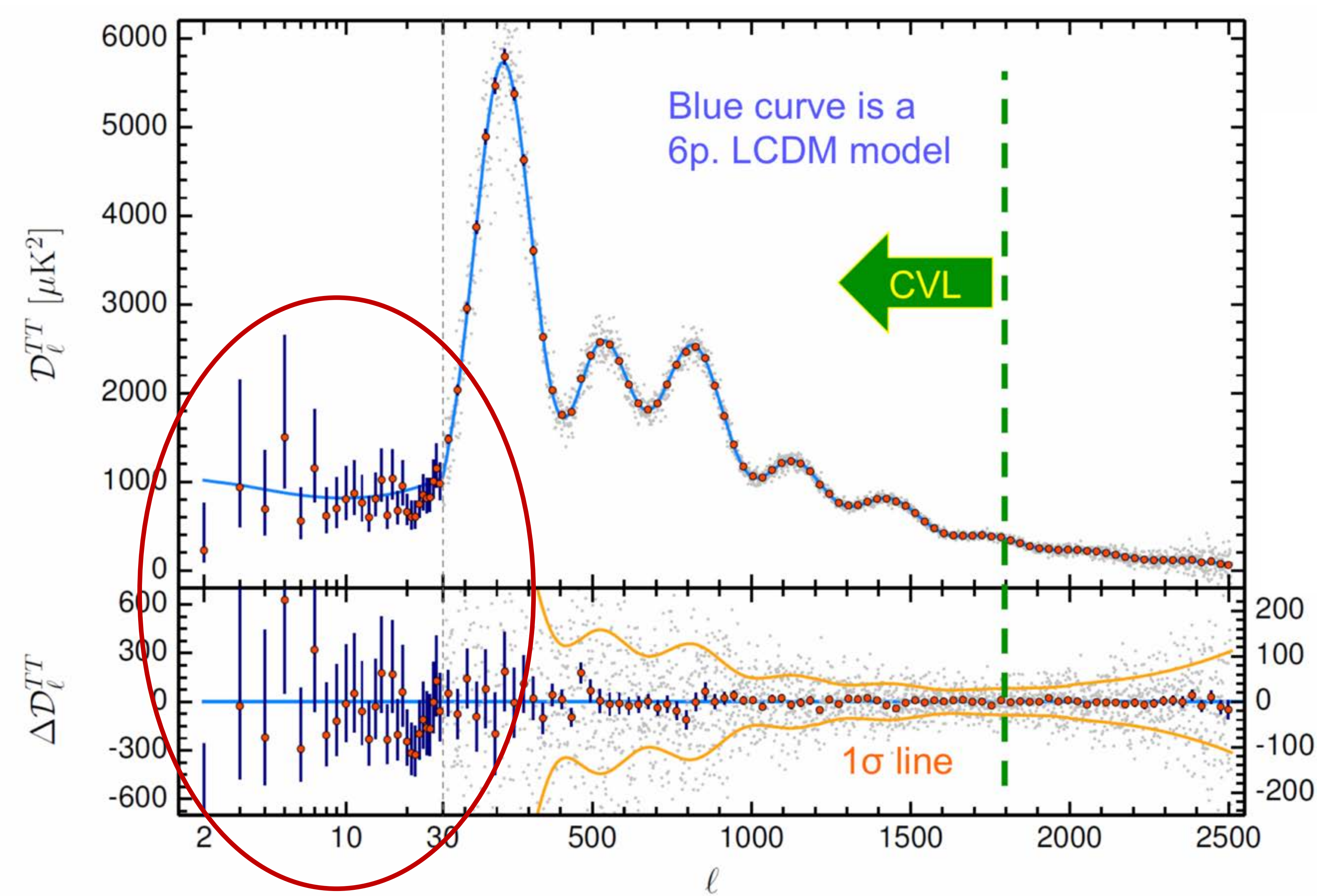
$$N_{eff} = 3.11^{+0.44}_{-0.43}$$ (95% CL, TT+lowE+lensing+BAO)

- Effective number of relativistic species is consistent with the standard expectation N_{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_{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

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.

Planck 2018 TT power spectrum



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

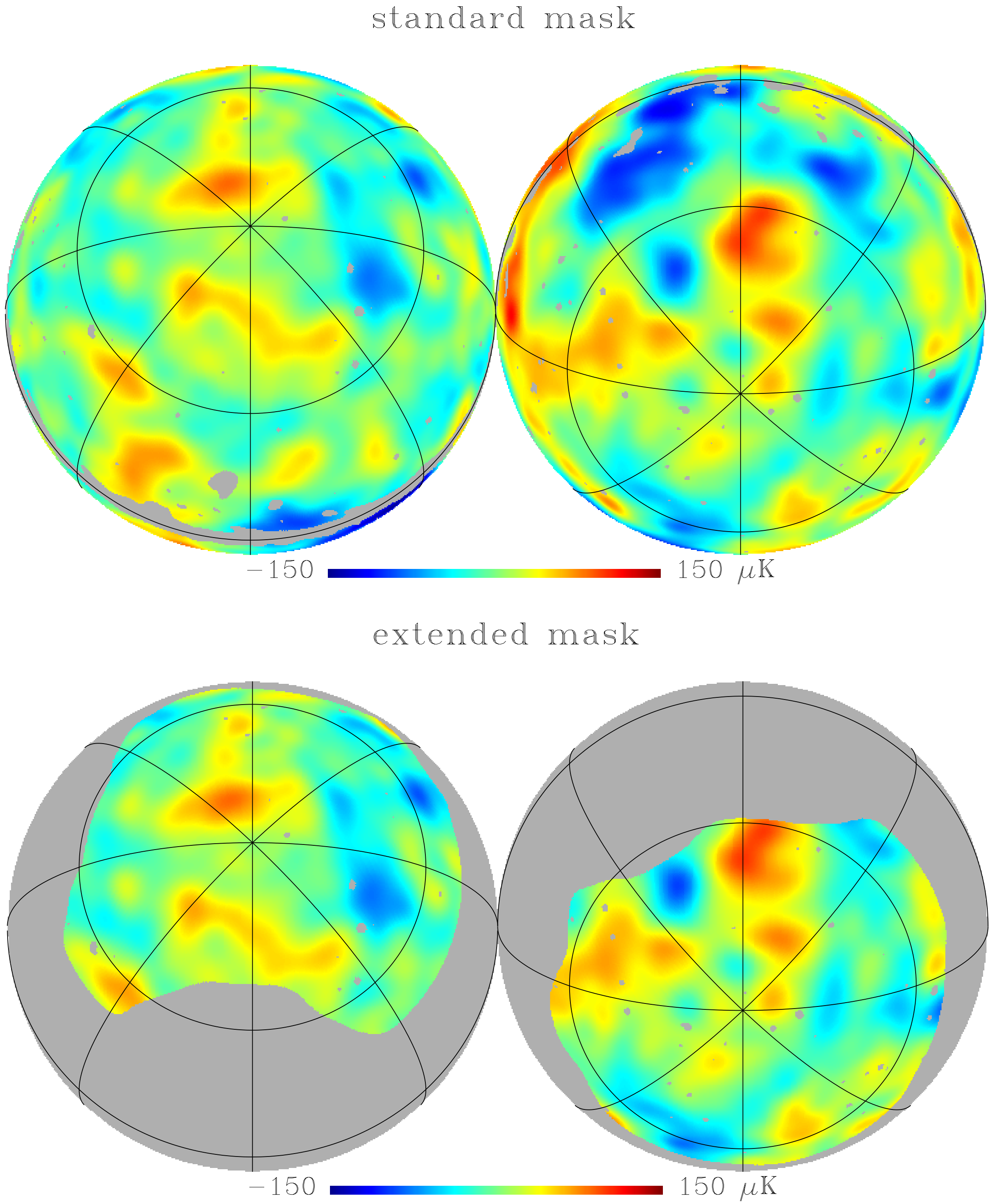
Transition from a pre-inflationary "fast-roll" phase to slow-roll would suppress power in the primordial spectrum.

Are we seeing relics of a decelerating inflaton?

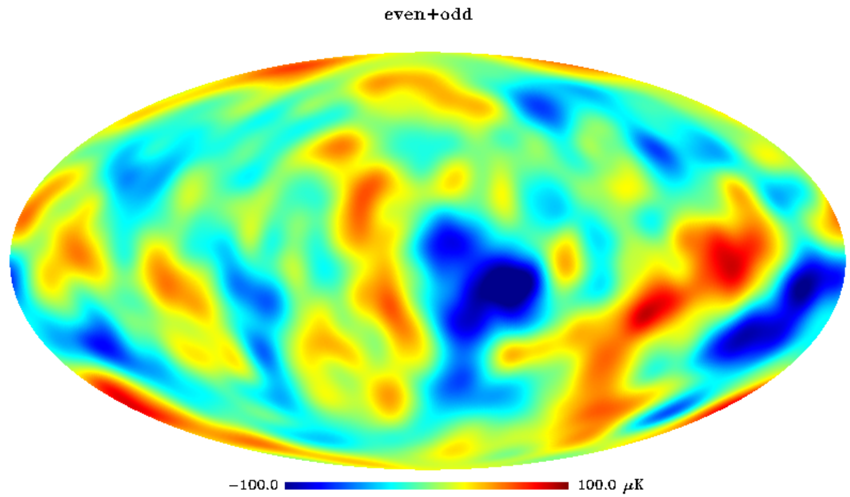
See e.g. Contaldi, Peloso, Kofman, Linde (2003); Destri, de Vega, Sanchez (2010); Dudas, Kitazawa, Patil, Sagnotti (2012); Kitazawa, Sagnotti (2014)

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

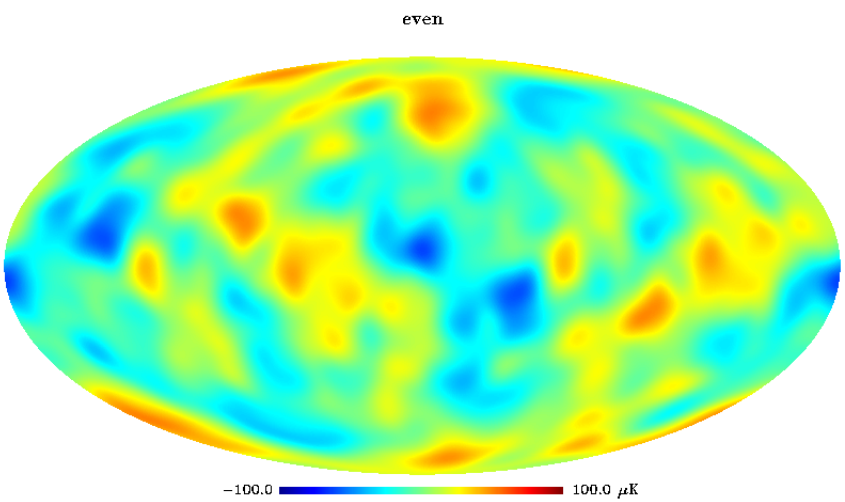
Δ ~ scale that enters the horizon at the onset of slow roll

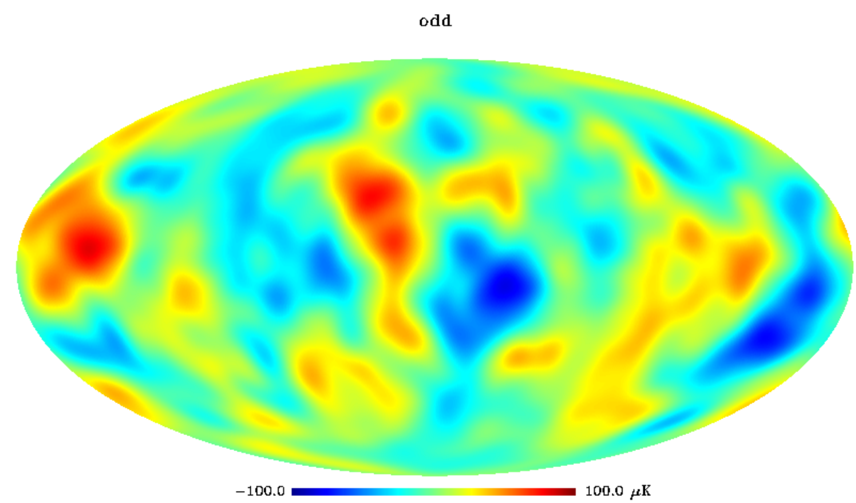


A. Gruppuso, N. Kitazawa, N. Mandolesi, PN, A. Sagnotti 2017



Planck 2015 data





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

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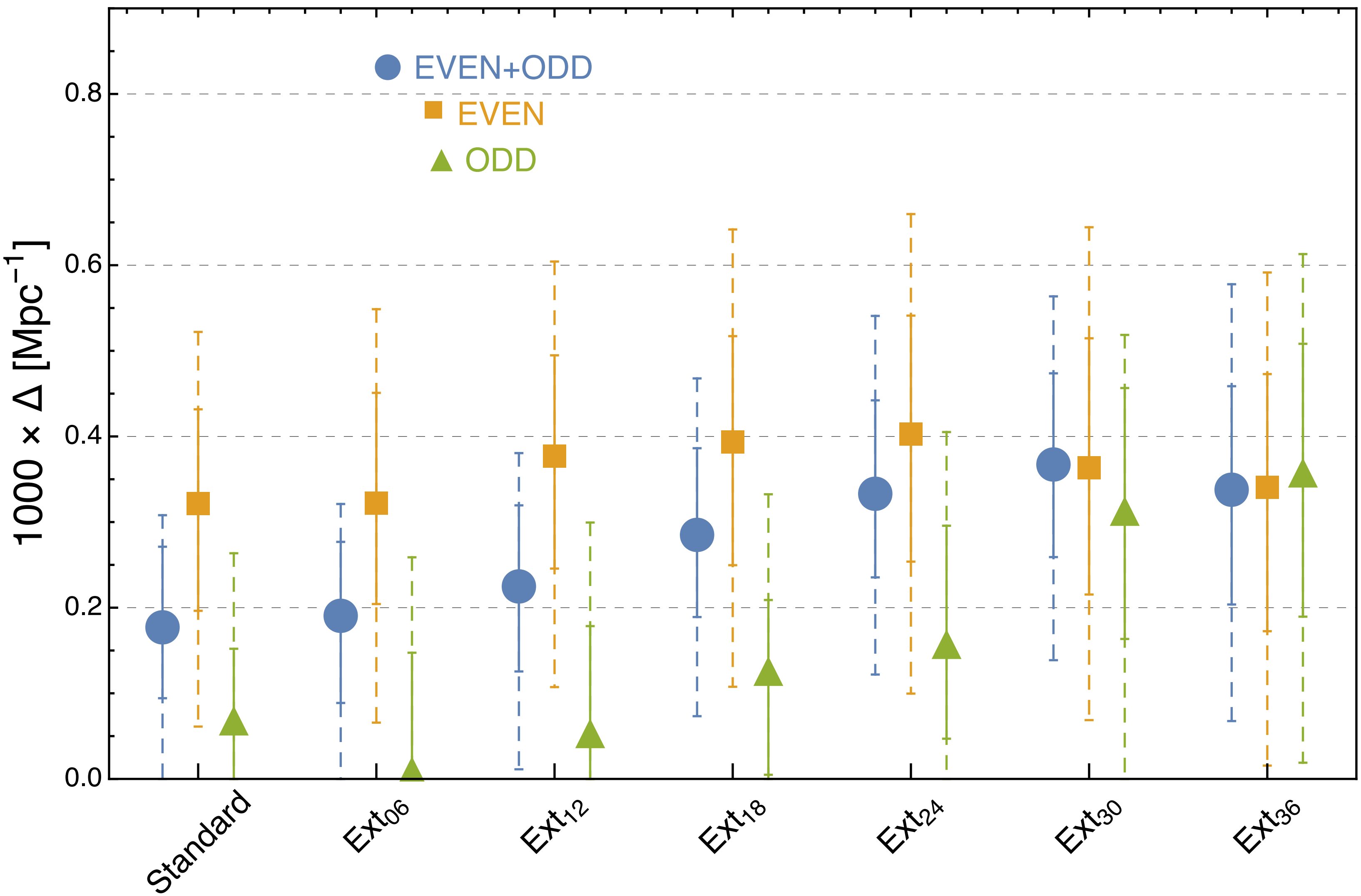
Constraints on Δ from Planck 2015



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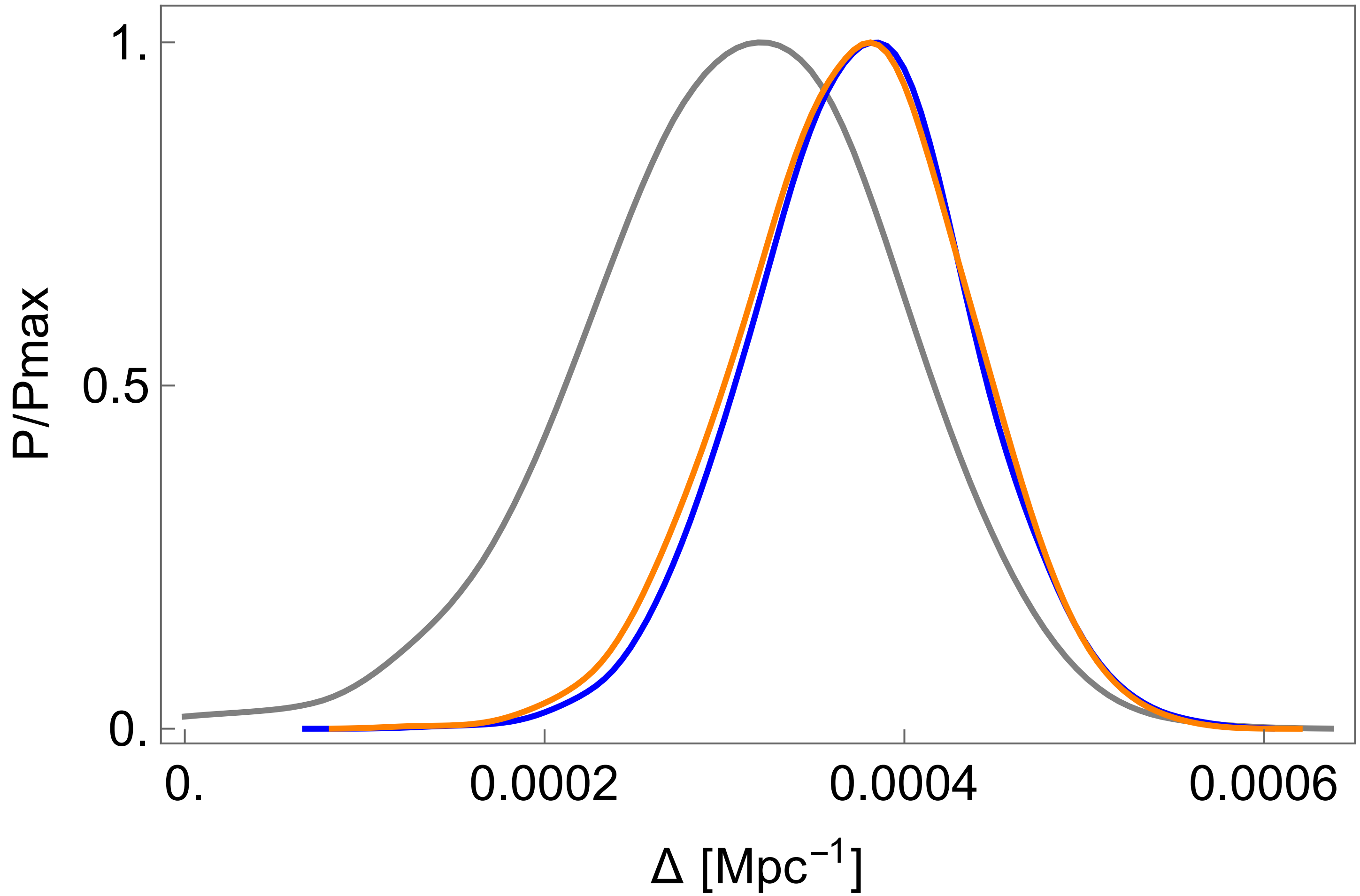
- The even multipoles are consistently lower than the LCDM expectation, independently on the galactic masking

- 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

Forecasted constraints on Δ from future experiments

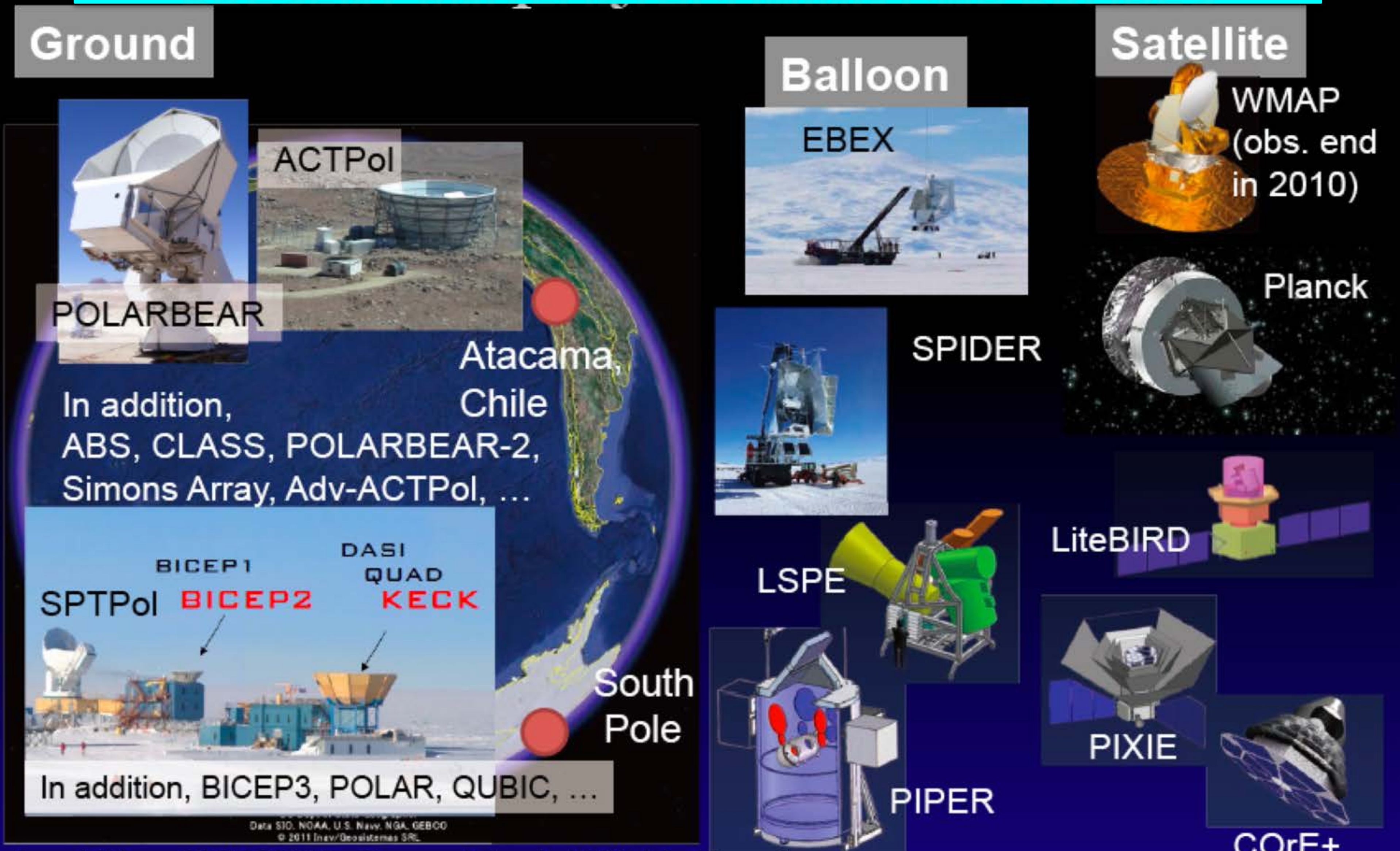


Grey: Planck-like noise, standard masking

Orange: CVL large-scale pol., ext30 mask

Blue: CVL large-scal pol, full sky

PRESENT AND FORTHCOMING CMB PROBES



In addition, QUIJOTE in Canary island, AMiBA in Hawaii

PRESENT AND FORTHCOMING CMB PROBES

In addition, QUIJOTE in Canary island, AMiBA in Hawaii

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 paridigm
- 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.