Planck and fundamental physics

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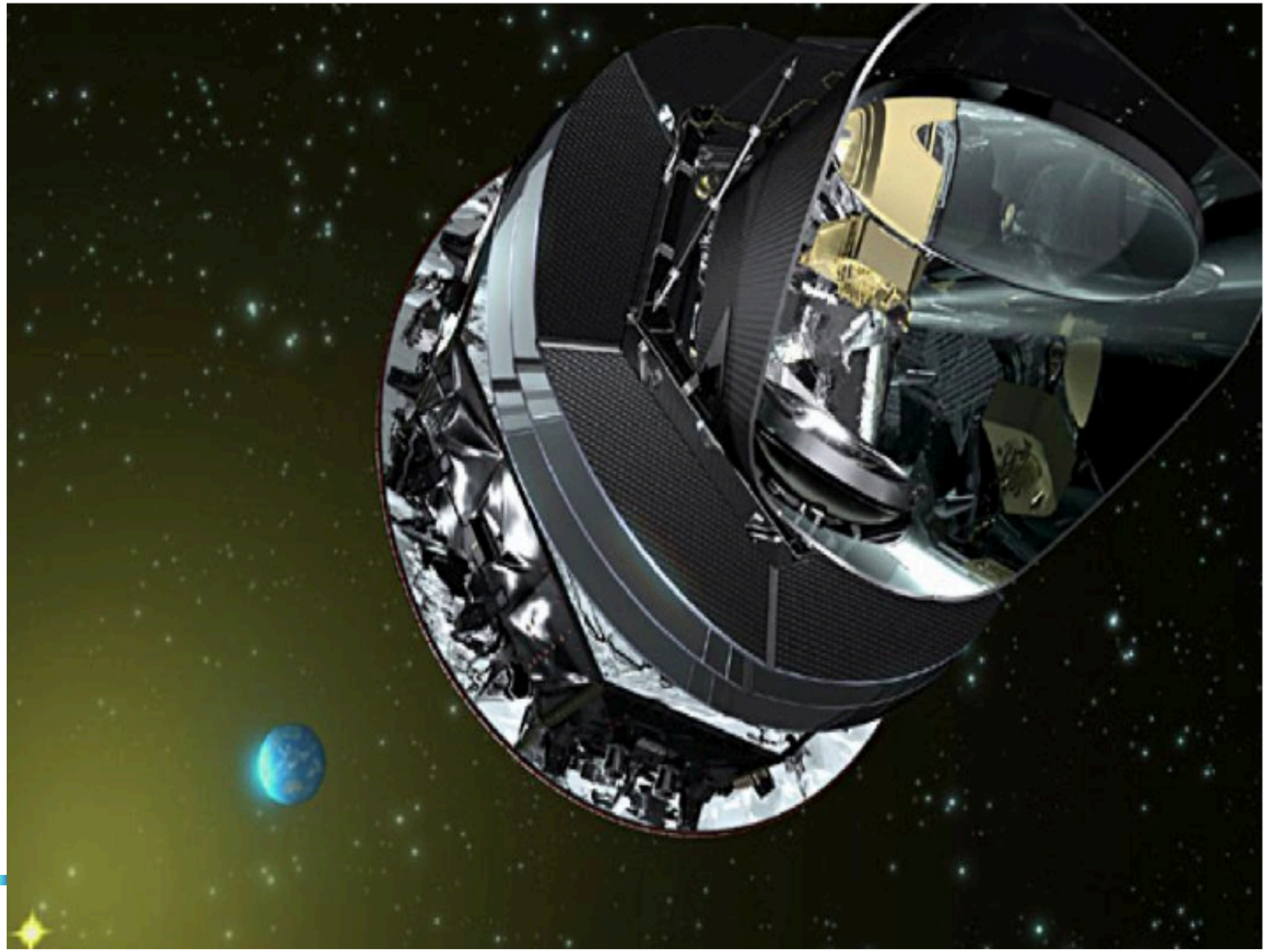


Outline

- Cosmology, established/new physics
- Microwave Background observations
- Planck goals and results
- Cosmological parameters for Λ-CDM
- Search for new physics
- Early universe physics

Cosmology, established and new physics

- Cosmological models are built out of
  - the established fundamental physics at a the present time: General relativity + standard model of particle physics
  - a set of "cosmological parameters" not provided by the model
- cosmological observations at "low" redshifts
  - dynamics of expansion (H_0, q_0, BAO)
  - lensing associated with LSS
  - mass and energy content (galaxies and clusters)
- cosmological observations relevant for high redshift and early universe
  - He and D abundance (primordial nucleosynthesis $z \approx 10^9$)
  - CMB z > 1100 + LSS through CMB lensing
  - primordial gravity waves indirectly through CMB Bmodes
- confrontation of models and observations give values of cosmological parameters and possible evidence of new physics
  - for dark matter,
  - dark energy
  - number of neutrinos species
  - time variation of physics "constants"
  - physics at extreme energies acting in the early universe

the $\Lambda-$CDM model

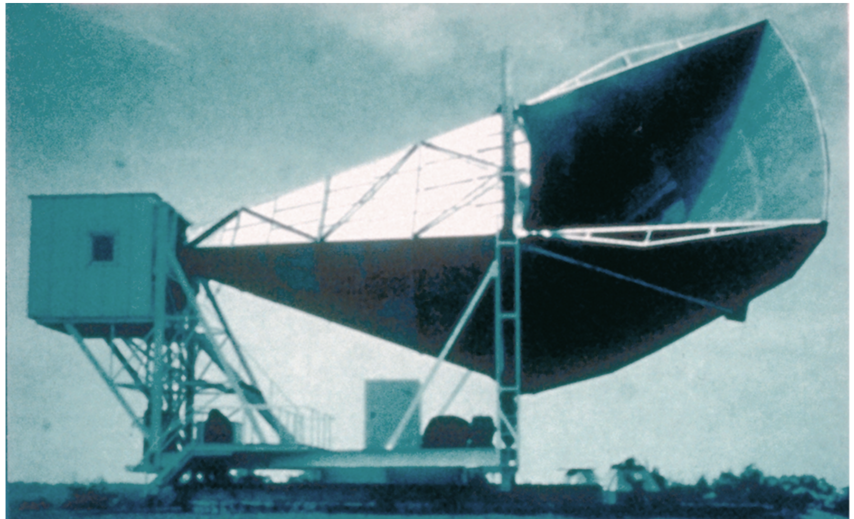
- in 1998 Type Ia Supernovae observations as tracers of the expansion lead to the evidence of the re-acceleration of the universe (Riess, Schmidt, Perlmutter)
- soon after (2000) the detection of the acoustic peaks of the CMB showed that the universe has a Euclidean geometry on large scale
- these resolved the contradictions between the cosmological observations through the concordance model
  – baryonic matter and radiation
  – cold dark matter
  – $\Lambda=$dark energy/cosmological constant
  – flat geometry of space on cosmological distances
  – gaussian nearly scale invariant spectrum of initial adiabatic fluctuations
  – GR and standard model of particle physics

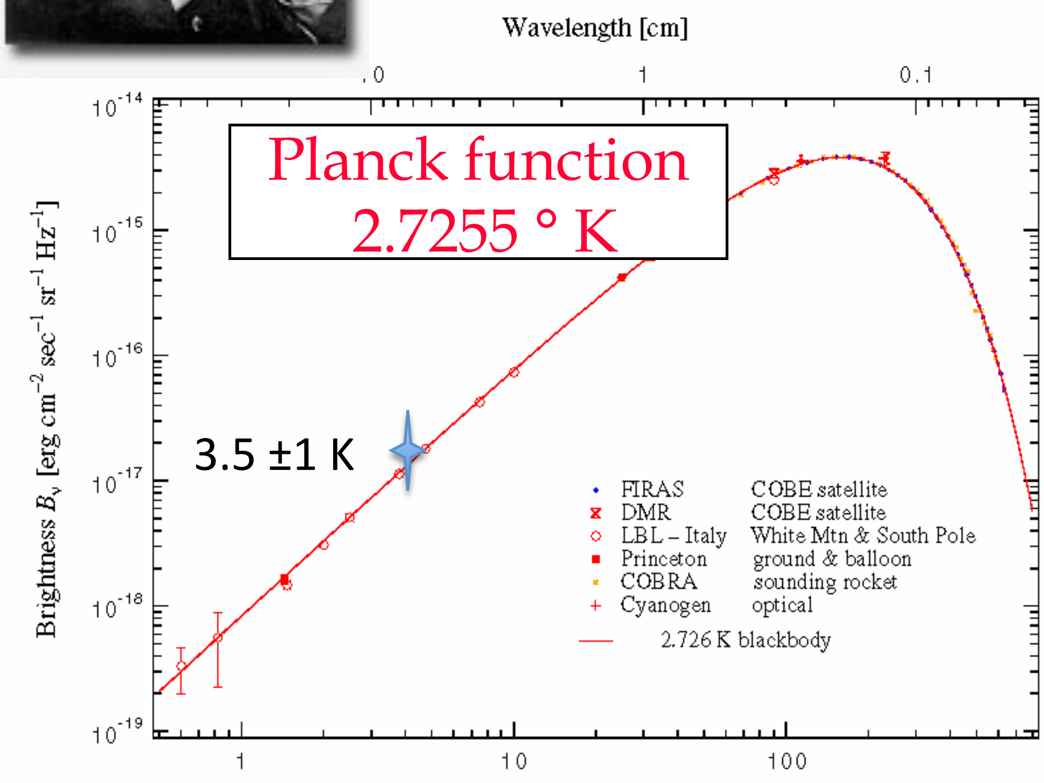
the cosmic microwave background

Penzias & Wilson 1965, Dicke, Peebles, Roll & Wilkinson 1965

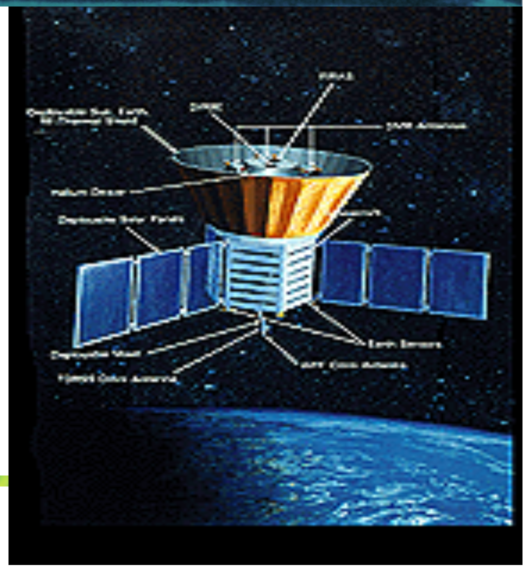
Cosmic Background predicted by Gamow in 1948, and by Ralph Alpher & Robert Herman in 1950. Serendipitously observed in **1965** par Arno Penzias and Robert Wilson at the Murray Hill Centre (NJ) of the Bell Telephone Laboratories as « A source of excess noise in a radio Receiver ». Joint interpretation article in Physical Review by Dicke, Peebles, Roll, Wilkinson… (Princeton).

predictions of the temperature oscillated between 5K and tens of K



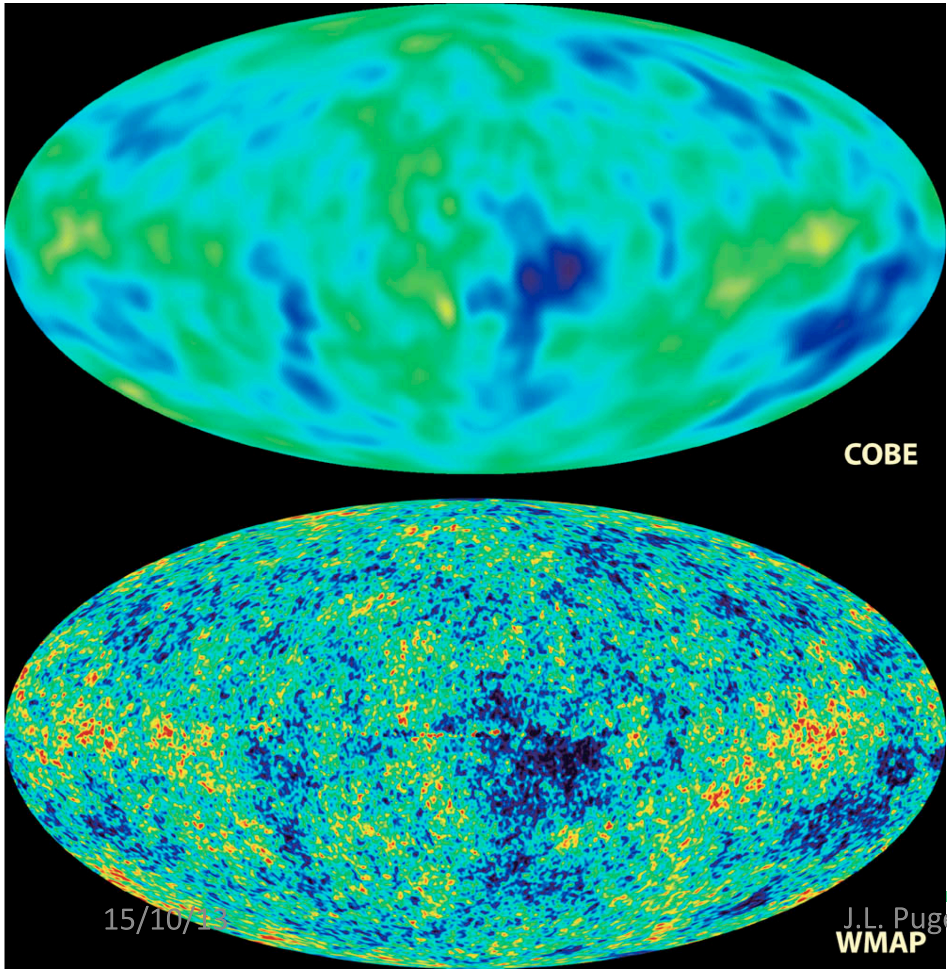


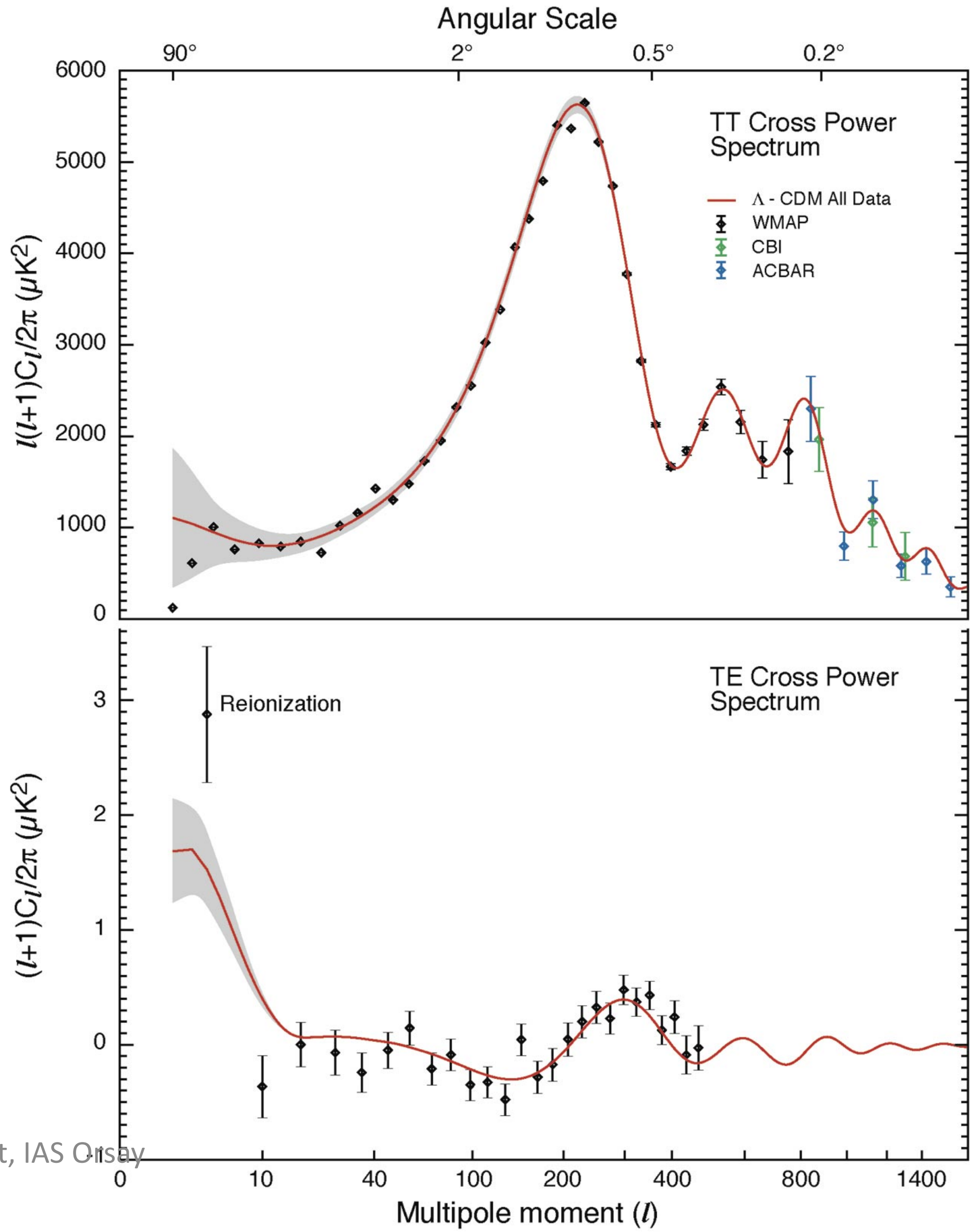
J. Mather et al 1990

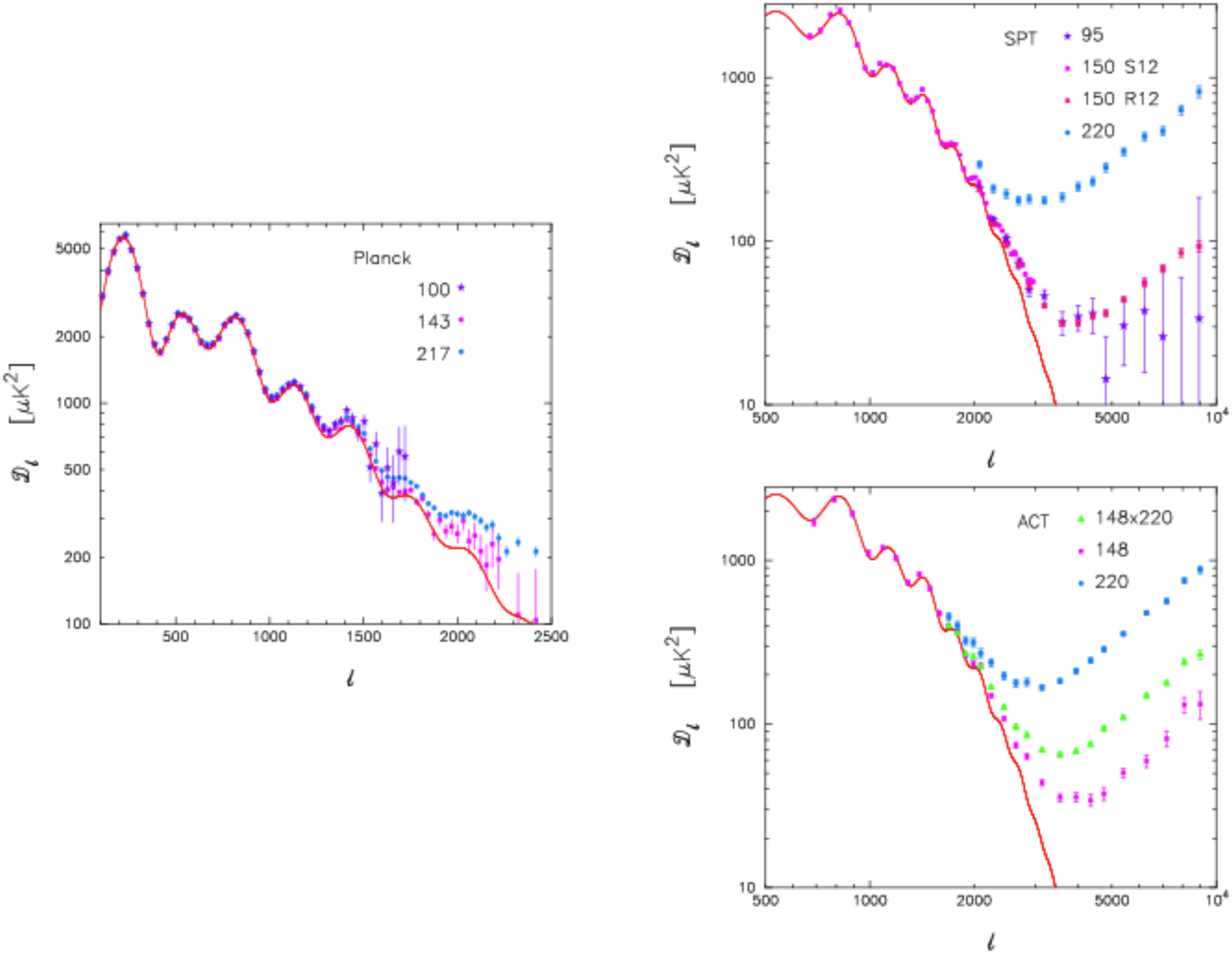


Measures of the CMB anisotropies

- DMR-COBE first detection of the large scale anisotropies (Smoot et al 1992)
- first clear detection of the first acoustic peak: Boomerang MAXIMA (De Bernardis et al 2000 , A. Lange et al 2001, Hanany et al 2000, Benoit et al)
- WMAP map and power spectrum







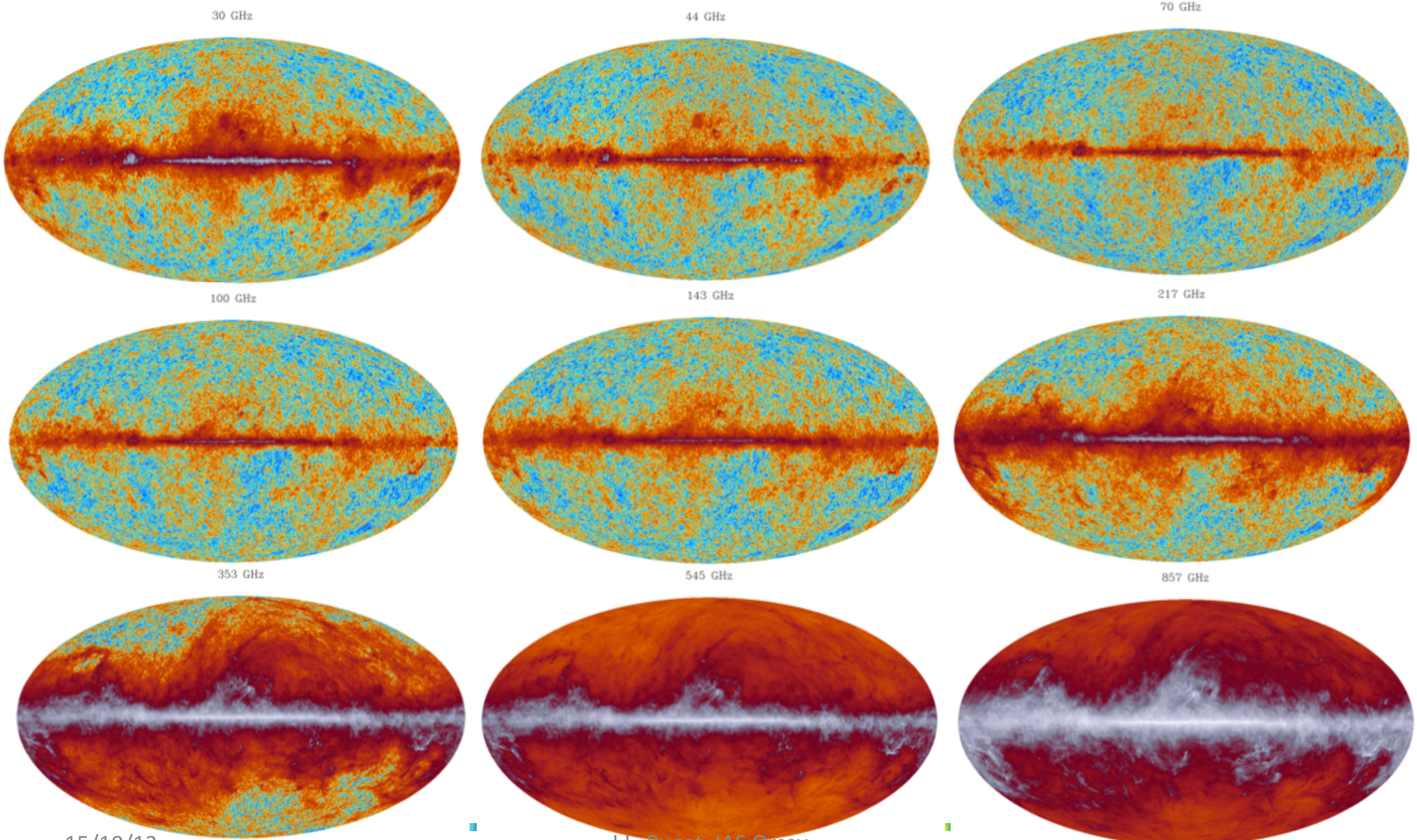
Planck
100
143
217
SPT
95
150 S12
150 R12
220
ACT
148x220
148
220
$\mathcal{D}_\ell$ [μK^2]
ℓ

Planck goals

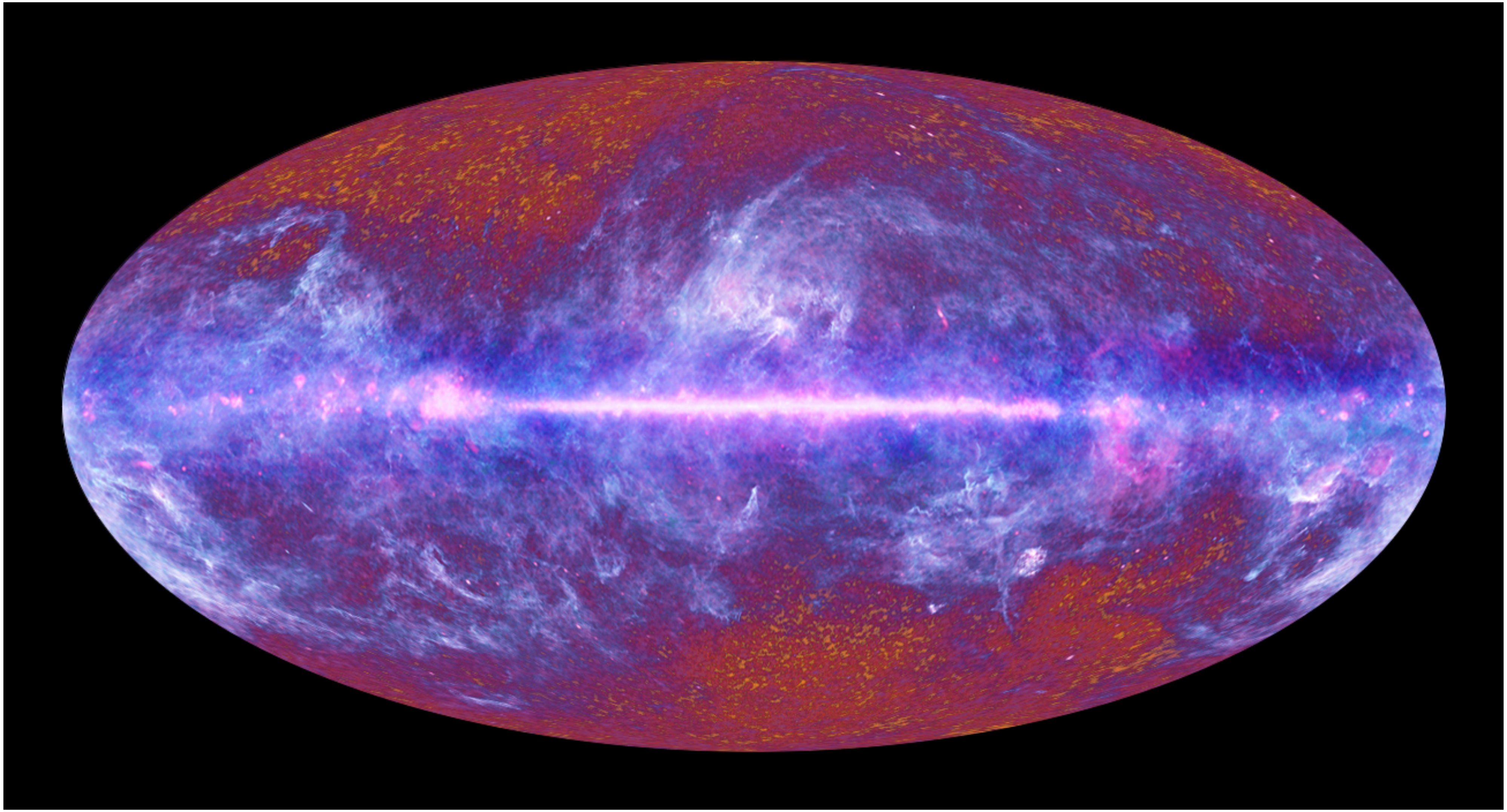
- Planck (like WMAP) aims at a much better determination of the $\Lambda-$CDM model parameters through measurements of the power spectrum up to 7 acoustic peaks (which remove some degeneracies)
- look for evidence of new physics
- it also aimed at measuring the lensing of the CMB by LSS with high accuracy
- detecting or putting lower limits on non gaussianity and limits on neutrino physics
- constraining early universe physics (especially inflation predictions)
- measuring the polarization with high signal to noise (5 acoustic peaks in TE and EE, detection or low upper limit on tensor to scalar ratio down to 3%)

PLANCK FREQUENCY MAPS

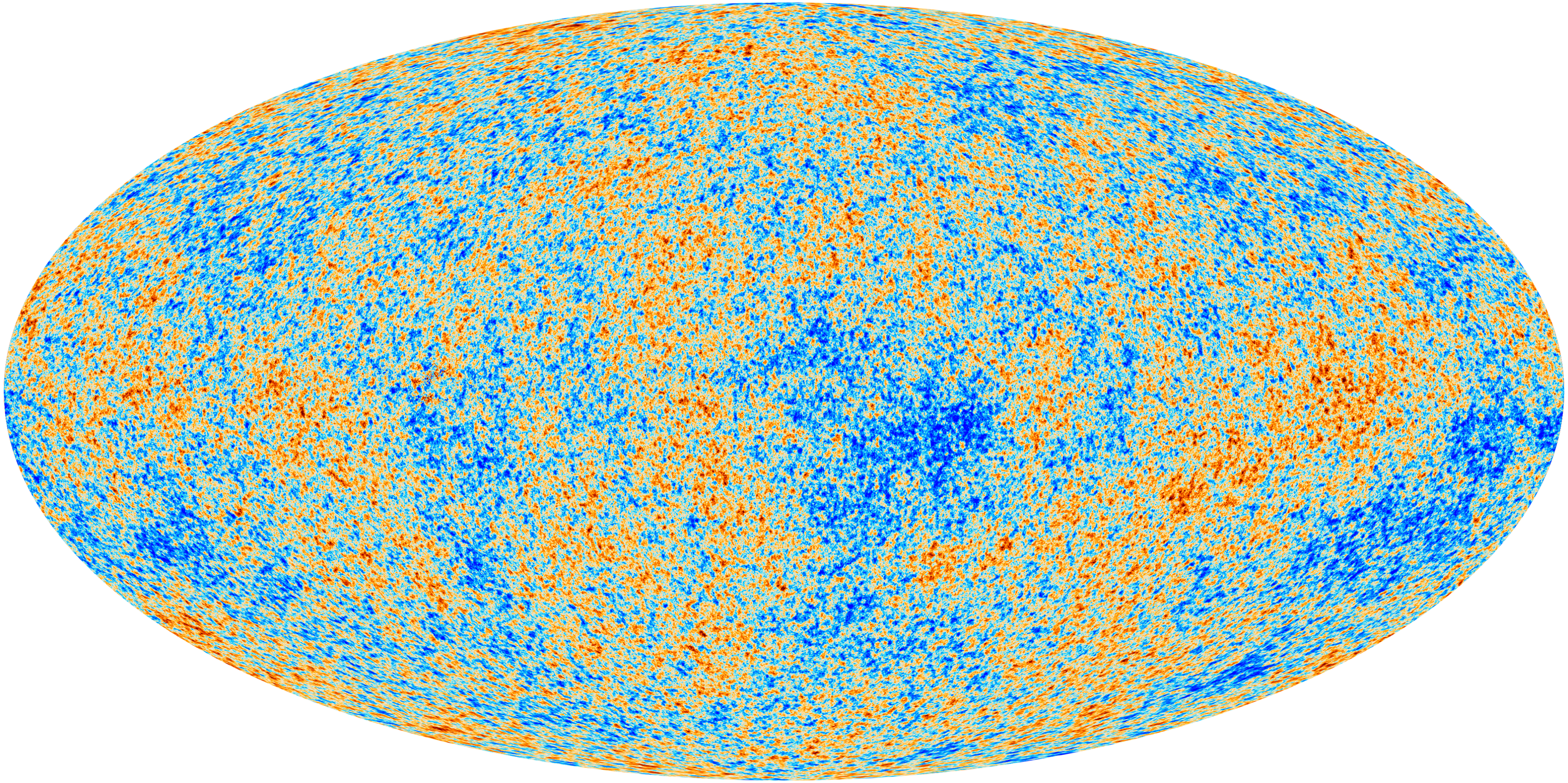
0.7 μK.deg at 143 GHz



THE PLANCK ALL SKY MAP SHOWING THE CMB AND THE FORGROUNDS



THE PLANCK CMB MAP OF CMB ANISOTROPIES



Step 2 in analysis: the parameters of the ΛCDM model from the power spectra

- the Planck consortia built and delivers to the community a hybrid likelihood code which compares the observed power spectrum for ($\ell > 50$) and with the map ($\ell < 50$) with any combination of cosmological parameters
- it also contains a Planck weak lensing likelihood
- the input data are cross spectra between 100-143 and 217 GHz and a low resolution CMB map from the "commander" component separation using LHI and HFI data
- the high ℓ component separation is done at spectral level
- a best model is built using Planck alone or a combination Planck WMAP EE polar power spectra for τ_{reion} but using the 353 GHz Planck data for dust correction (little change induced)

Step 1:test gaussianity of CMB signal

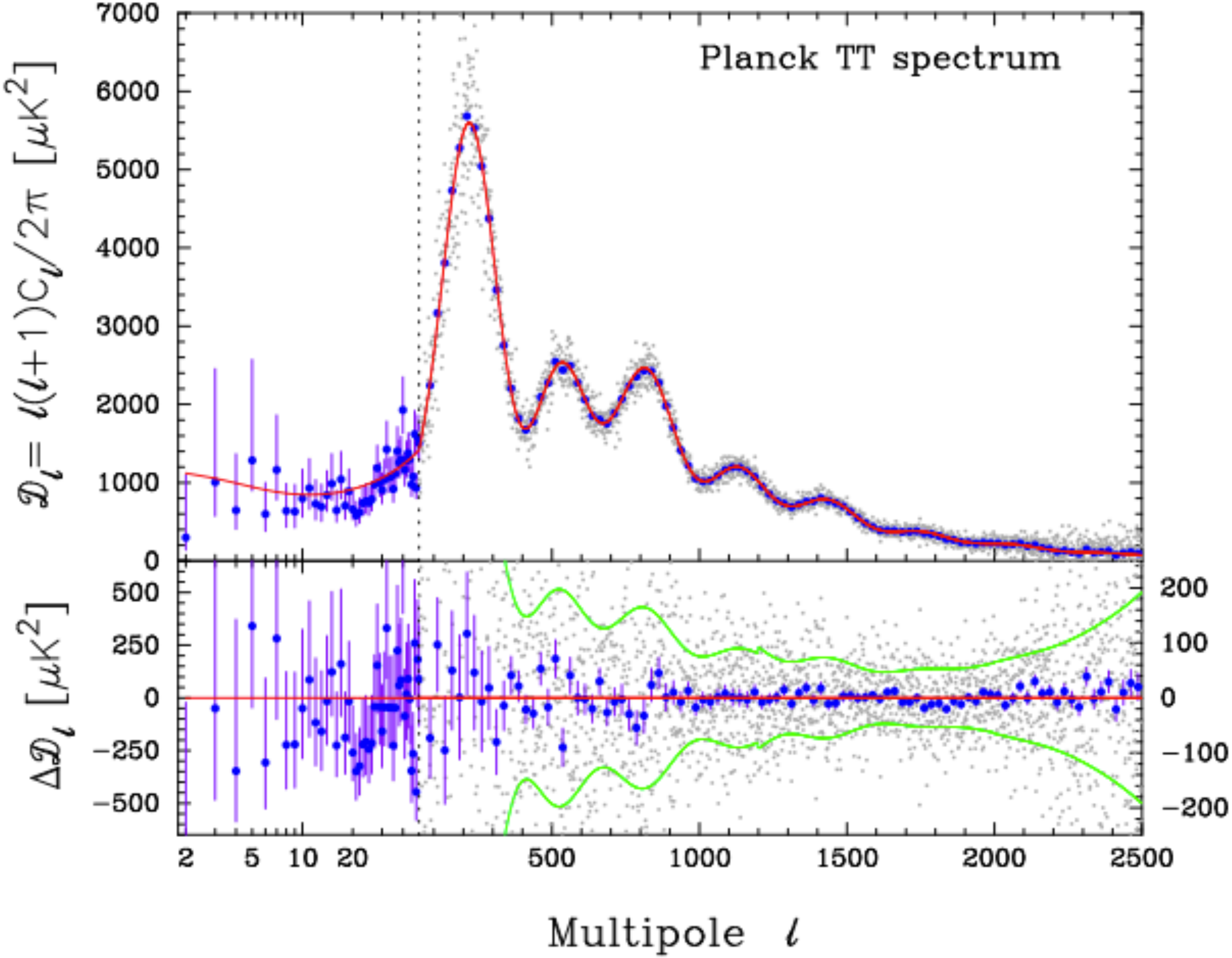
- the simplest inflation model predicts undetectable non gaussianity contrary to many more complicated inflation models
- the input for this analysis is an HFI only map from the SMICA component separation (2 others are also delivered and give nearly equivalent results)
- the bispectrum from 3 point correlations can be characterized by 3 factors f_{NL}

	Planck	**WMAP**
– local	2.7±5.8	37±20
– equilateral	-42±75	-51±136
– orthogonal	-25 ±39	-245±100

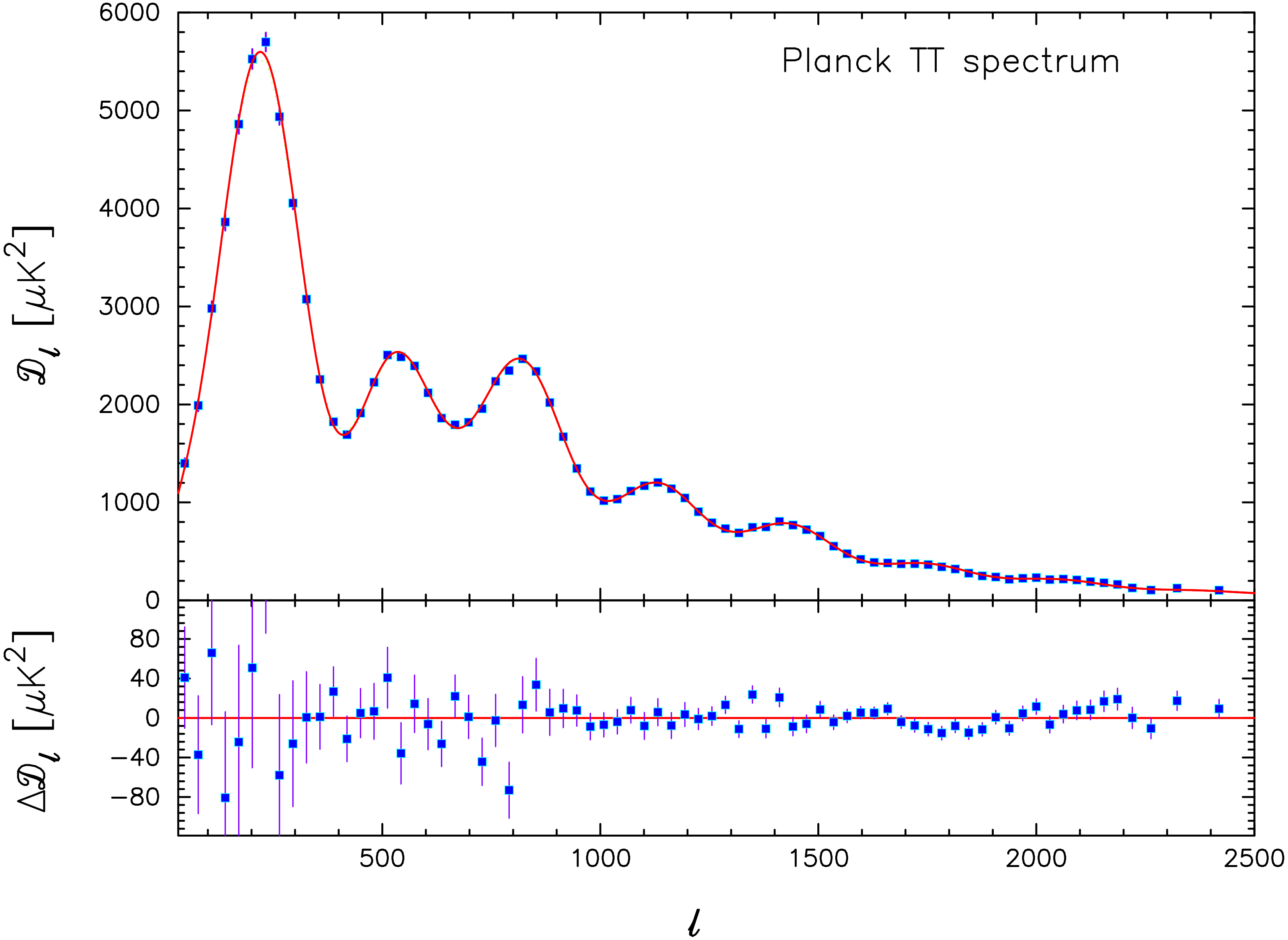
- Planck primordial non Gaussinity upper limits also constrain inflation models beyond the single field slow roll

ΛCDM model parameters

- the 6 basic measured parameters are
  - θ_* (angular size of sound horizon at recombination)
  - $\Omega_b.h^2$ (baryons)
  - $\Omega_c.h^2$ (cold dark matter)
  - τ (reionization optical depth)
  - A (amplitude of the power spectrum)
  - ns (the slope of the initial fluctuations)
- derived
  - H_0 (Hubble constant)
  - $\Omega_\Lambda = 1 - \Omega_b - \Omega_c$ (dark energy)
  - z_{re} (redshift of reionization)

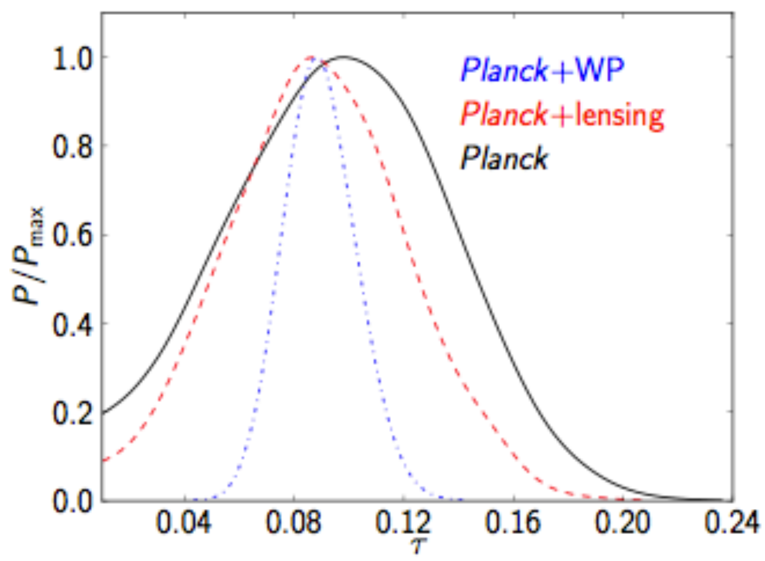

Planck TT spectrum
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

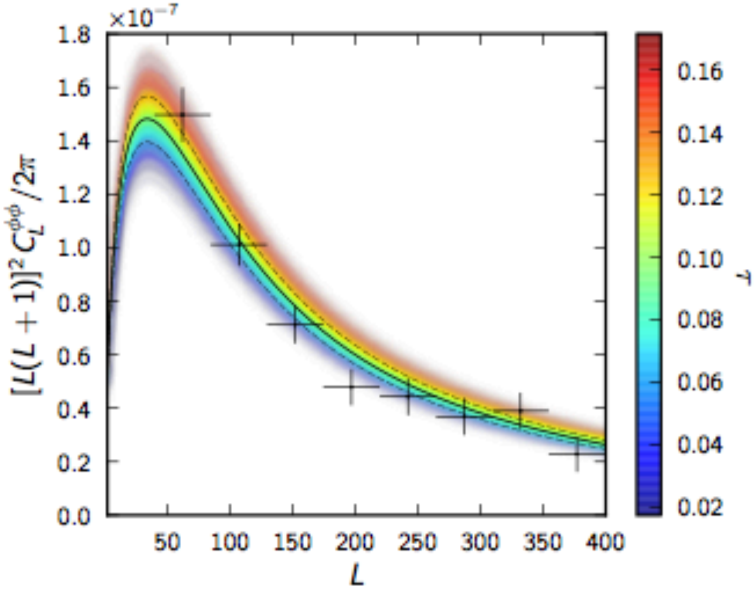
Planck data vs model and residuals



Cosmology - I

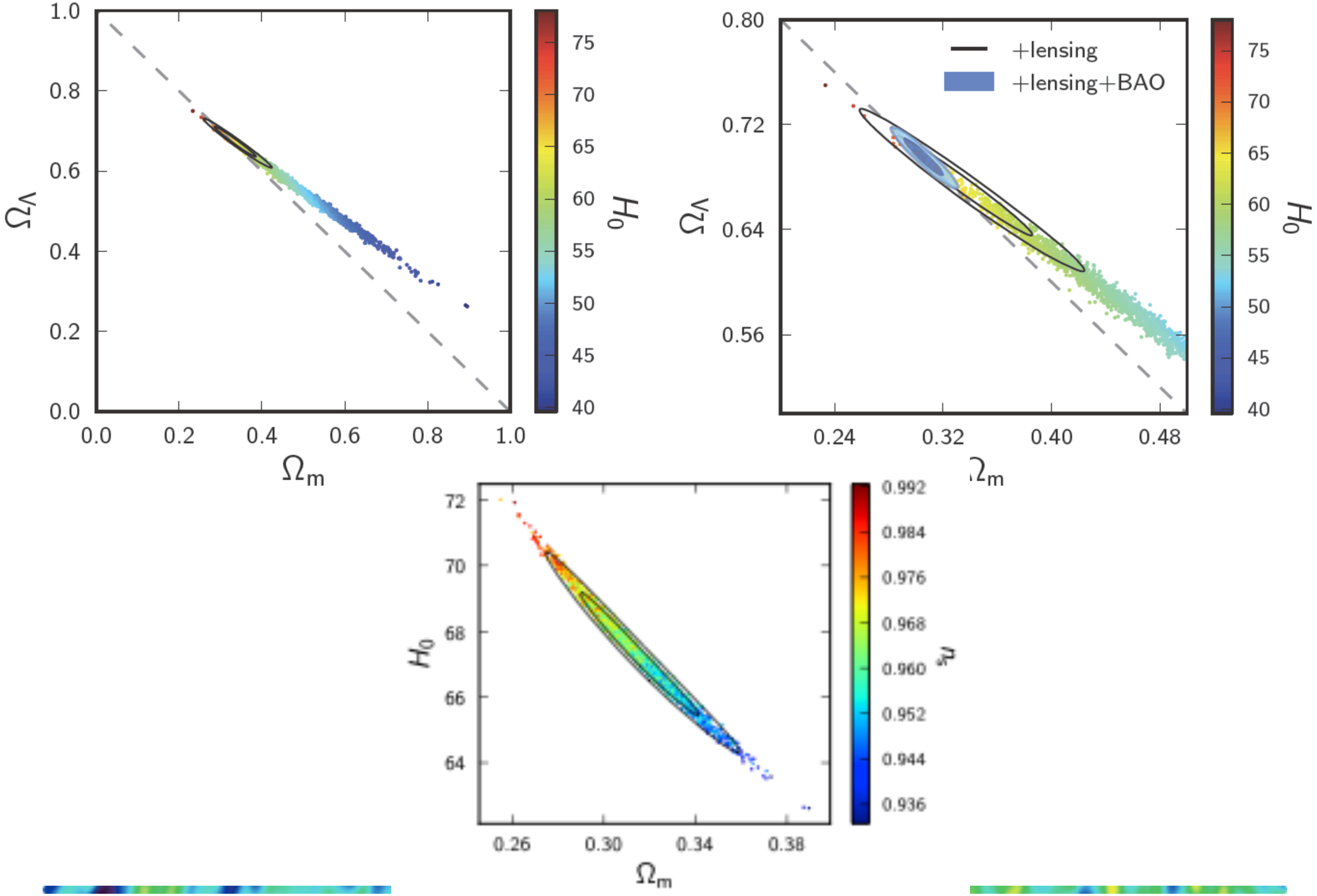
Constraining the reionization from Planck alone strengthen the Polarization result





$$\tau = 0.097 \pm 0.038 \quad (68\%; \textit{Planck})$$
$$\tau = 0.089 \pm 0.032 \quad (68\%; \textit{Planck}+\text{lensing}).$$

CMB degeneracies: Ω_Λ, Ω_m, n_s, H_0



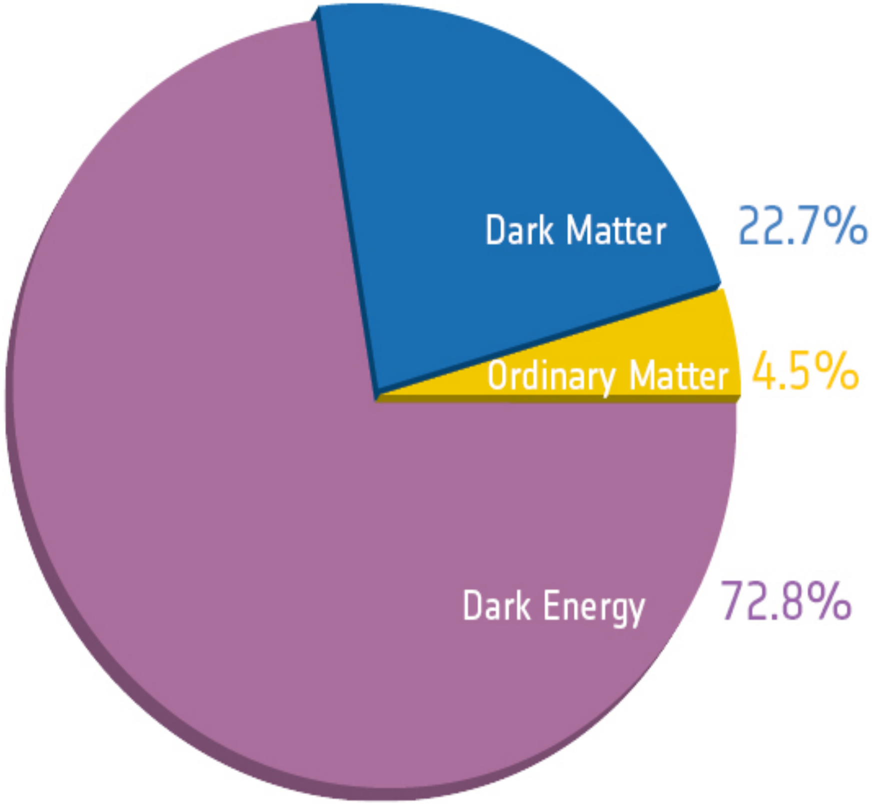
Planck with temperature only + WMAP pol for τ

- note 6 10^{-4} error bar
- Planck +WMAP pol
- 7 σ /scale invariance
- note accuracy1.8%

BASE ΛCDM MODEL

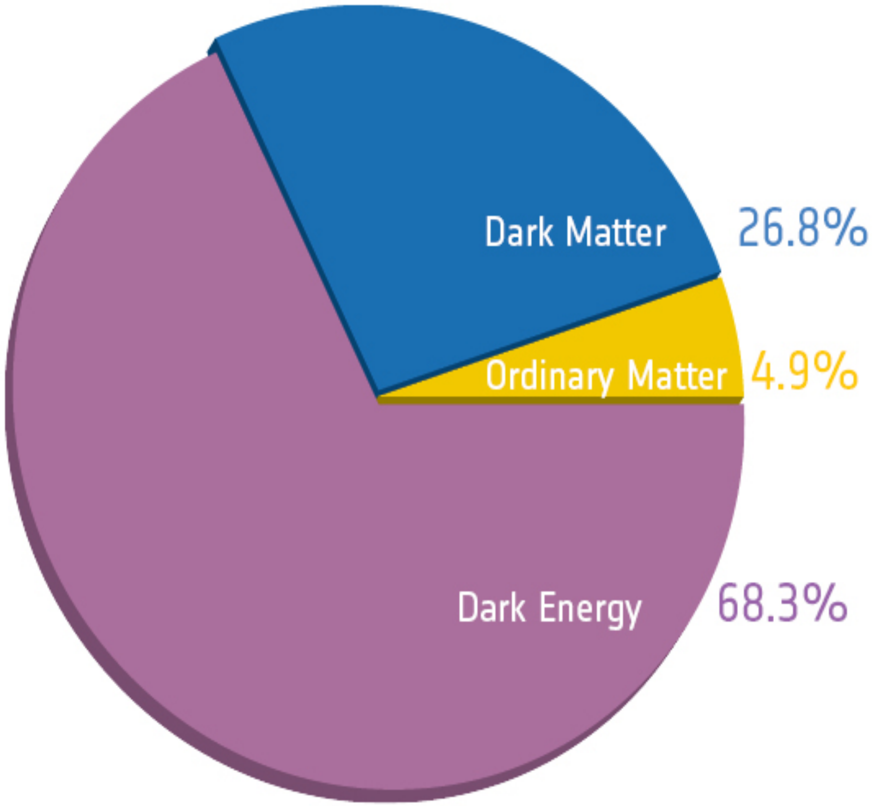
Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026
$100\theta_*$	1.04148±0.00062
τ	0.091±0.014
n_s	0.9585±0.0070
H_0	67.3±1.2
Ω_Λ	0.685±0.017
σ_8	0.828±0.012
z_{re}	11.1±1.1

THE COSMIC RECIPE



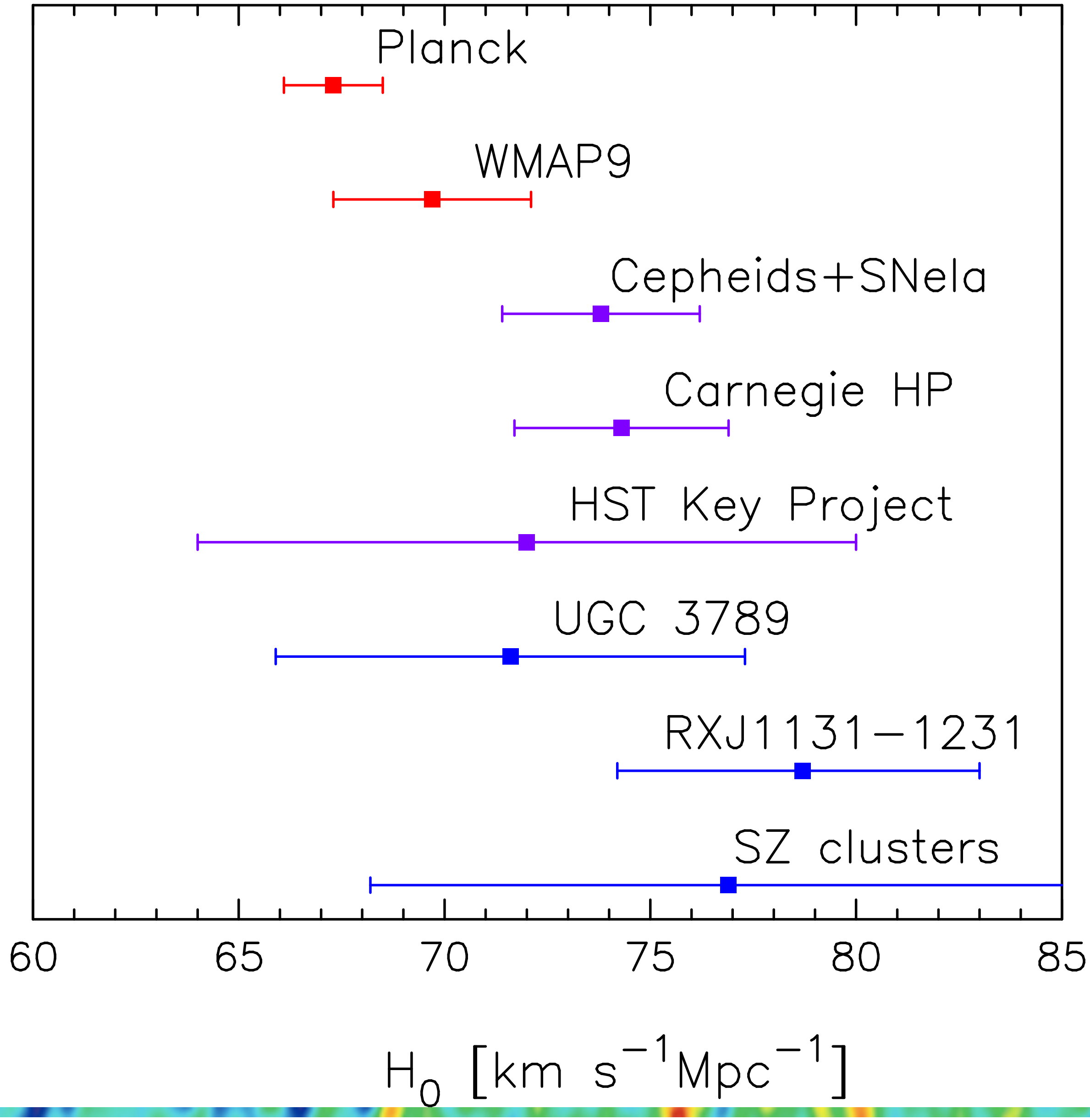
> BEFORE PLANCK

THE COSMIC RECIPE

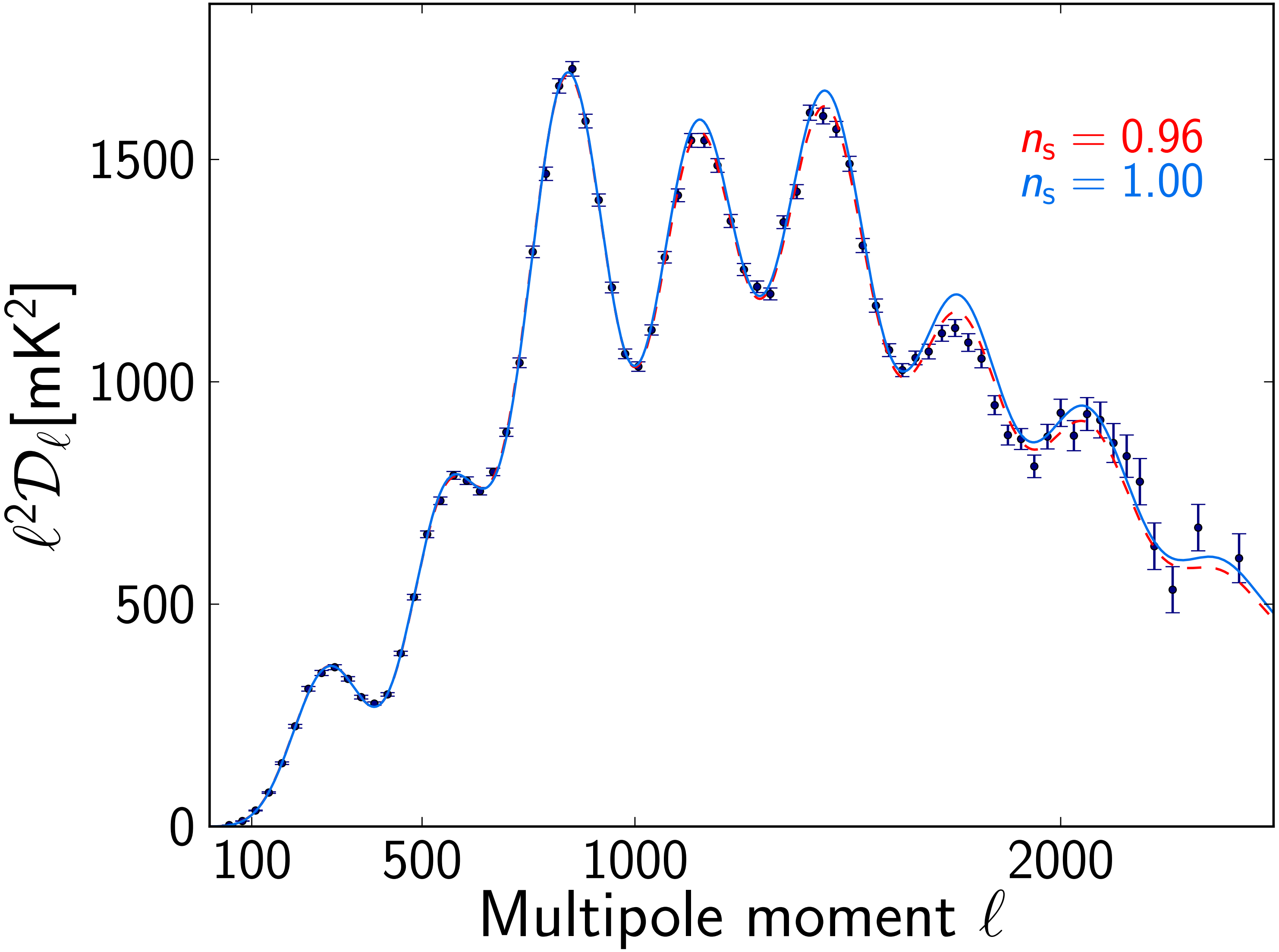


> AFTER PLANCK

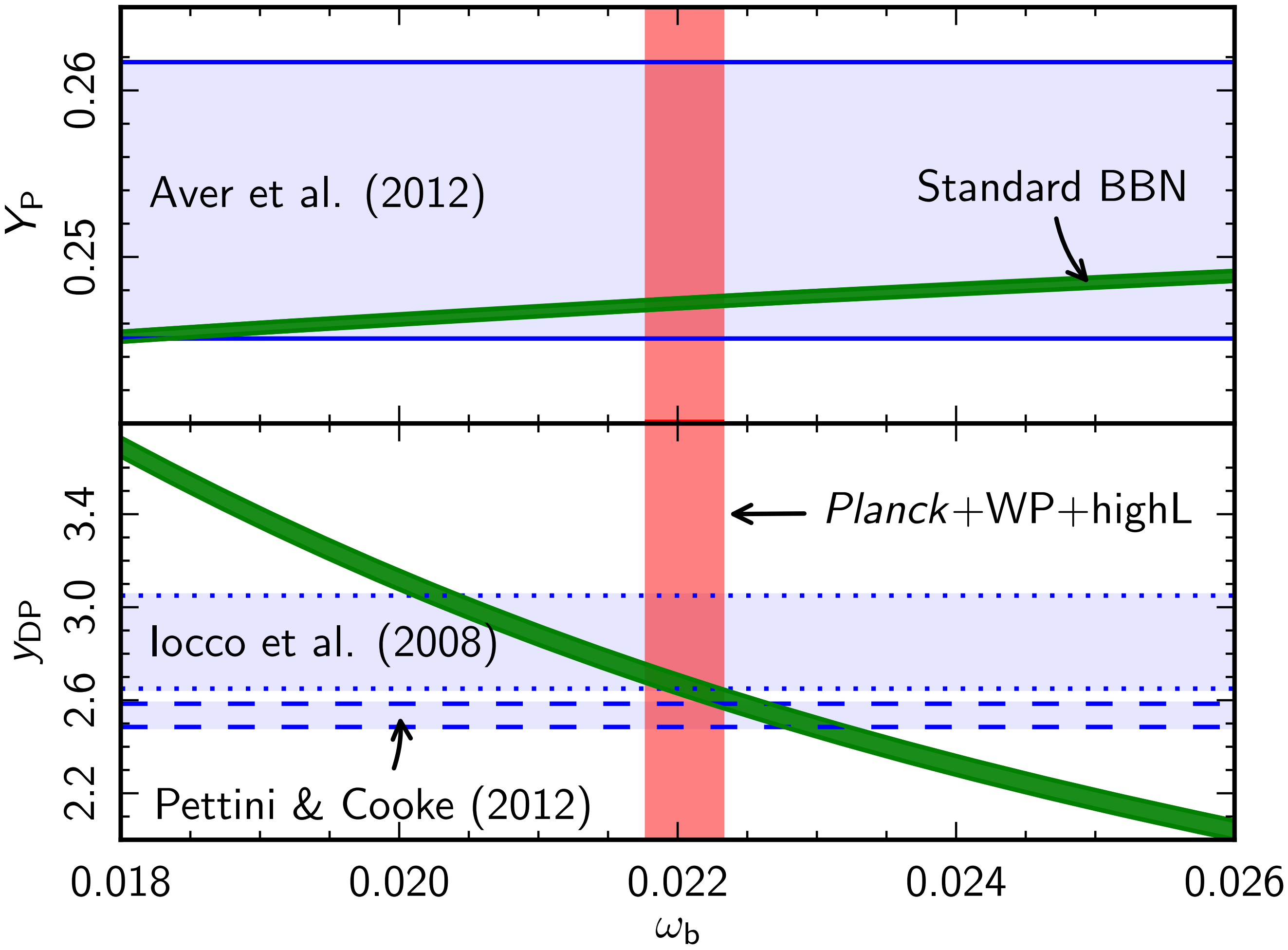
Hubble Constant: deviation from astrophysical measurements



deviation from scale invariance
showing the power of the broad multipoles coverage



BBN of Helium and deuterium checked with high accuracy

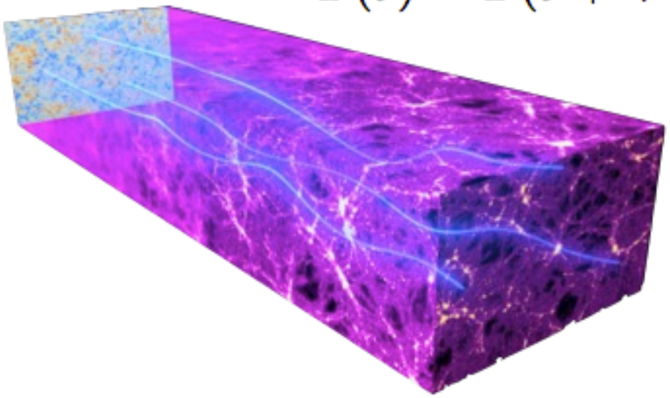


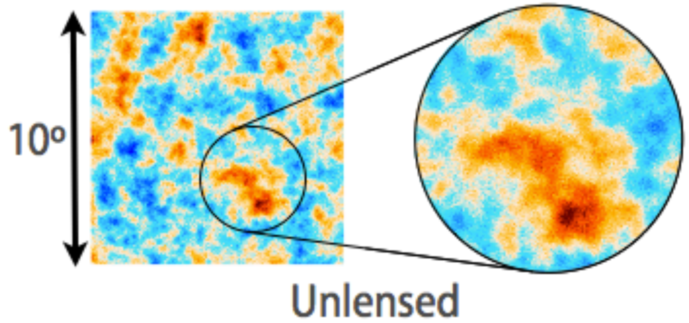
CMB data can now be used to constrain the astrophysics side of determinations of the primordial He and D abundances

Planck also detects lensing of CMB by LSS

CMB lensing reconstruction

$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$





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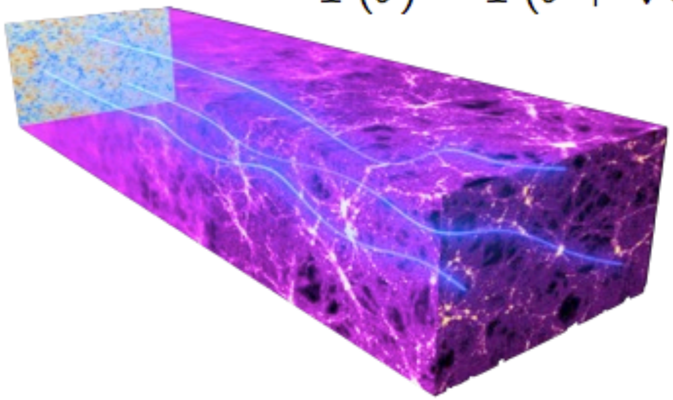
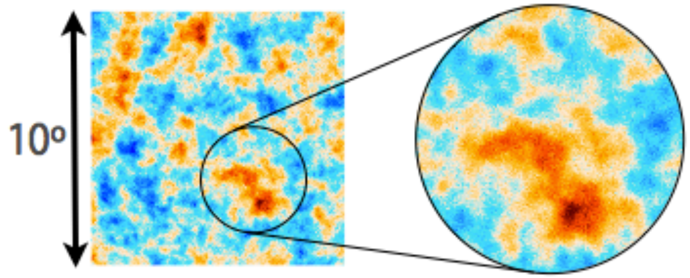
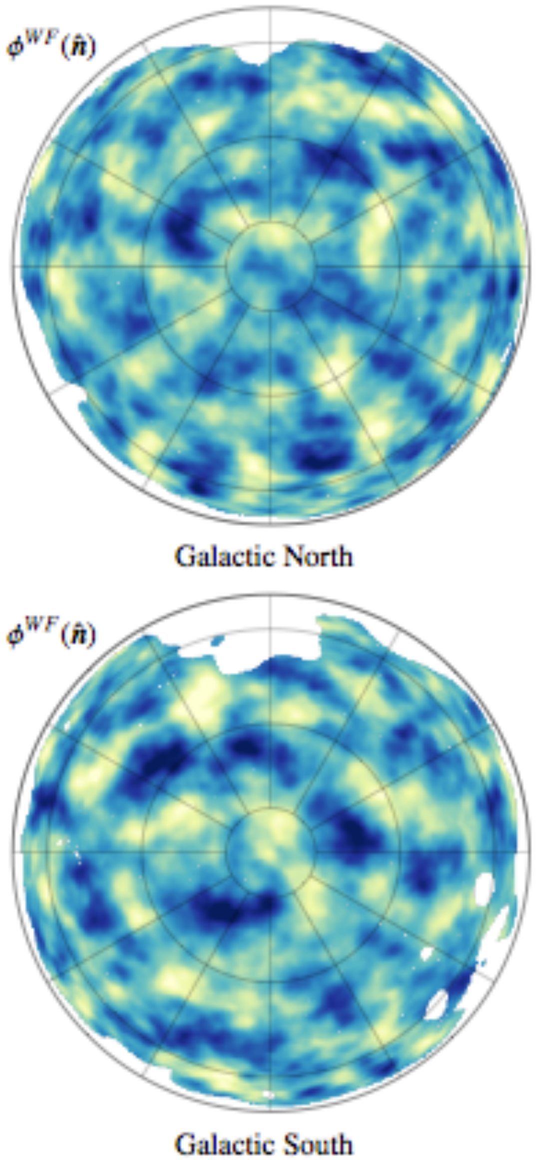
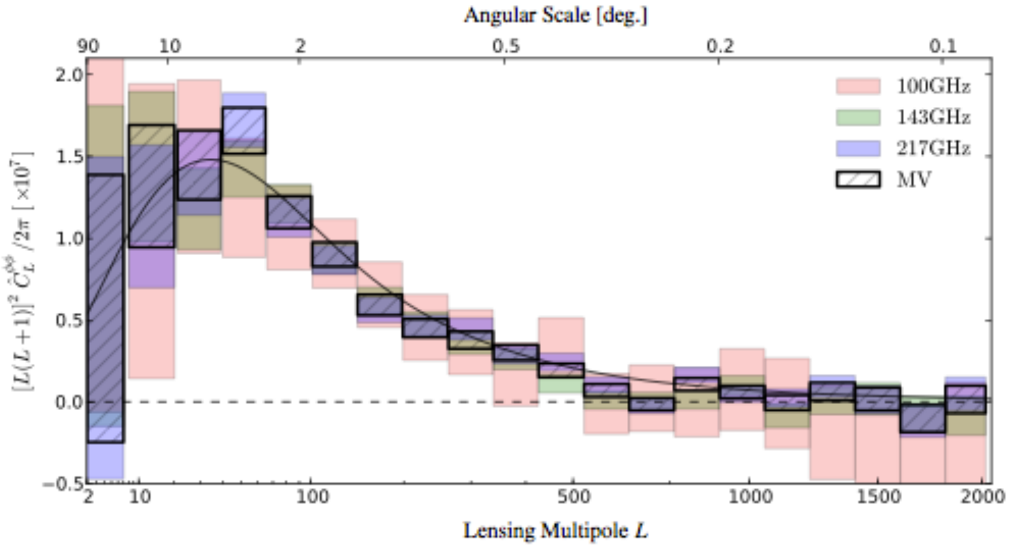




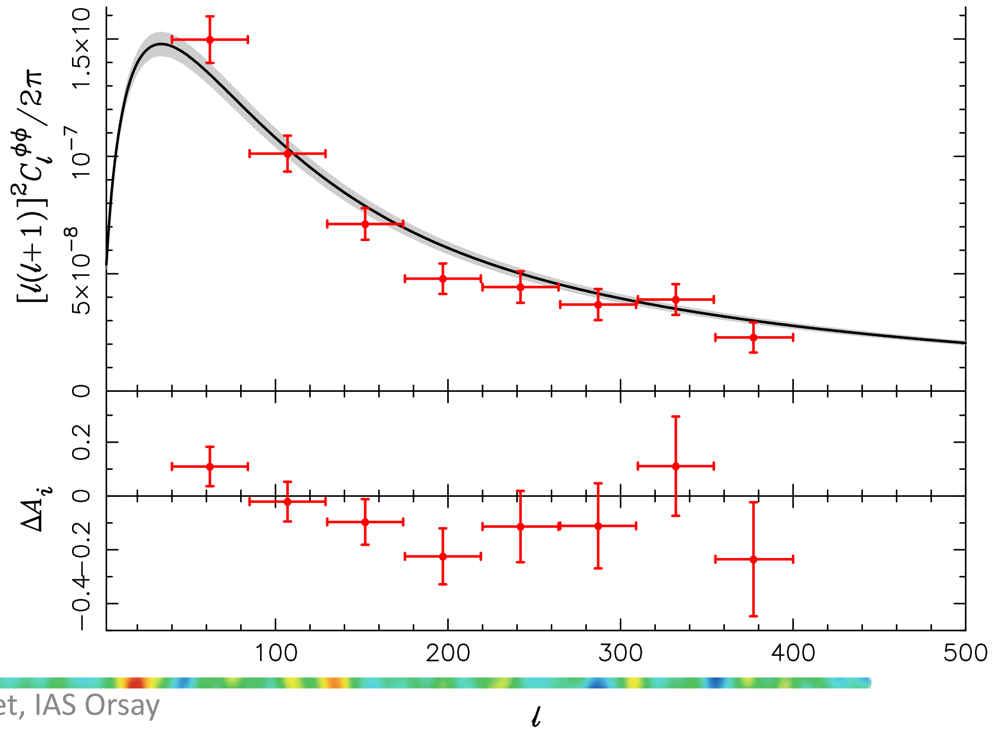
Lensed



$\phi^{WF}(\hat{n})$
Galactic North
$\phi^{WF}(\hat{n})$
Galactic South

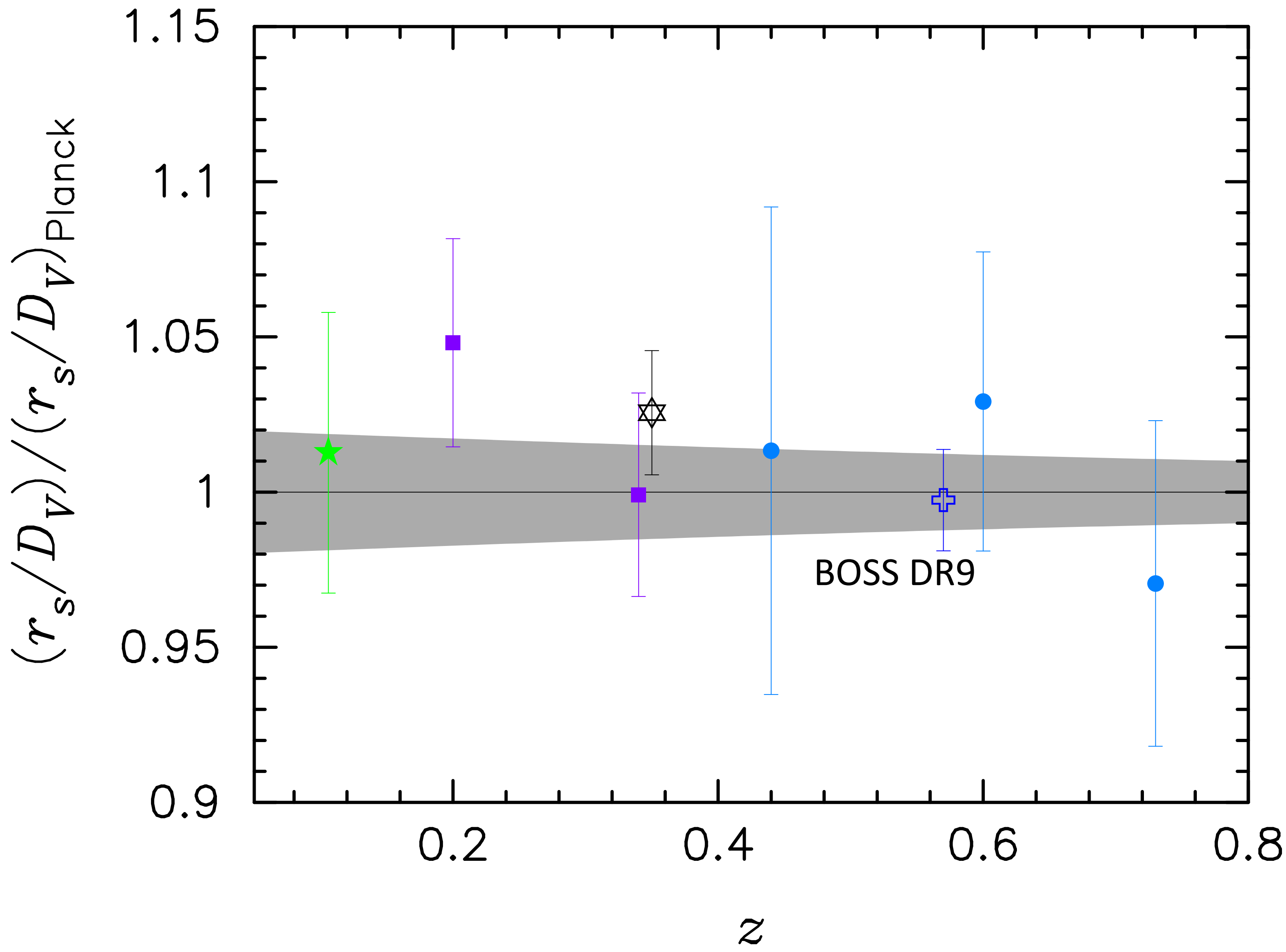


Angular Scale [deg.]
90
10
2
0.5
0.2
0.1
100GHz
143GHz
217GHz
MV
$[L(L+1)]^2 \hat{C}_L^{\phi\phi}/2\pi\ [\times 10^7]$
Lensing Multipole L



$[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/2\pi$
ΔA_i
ℓ

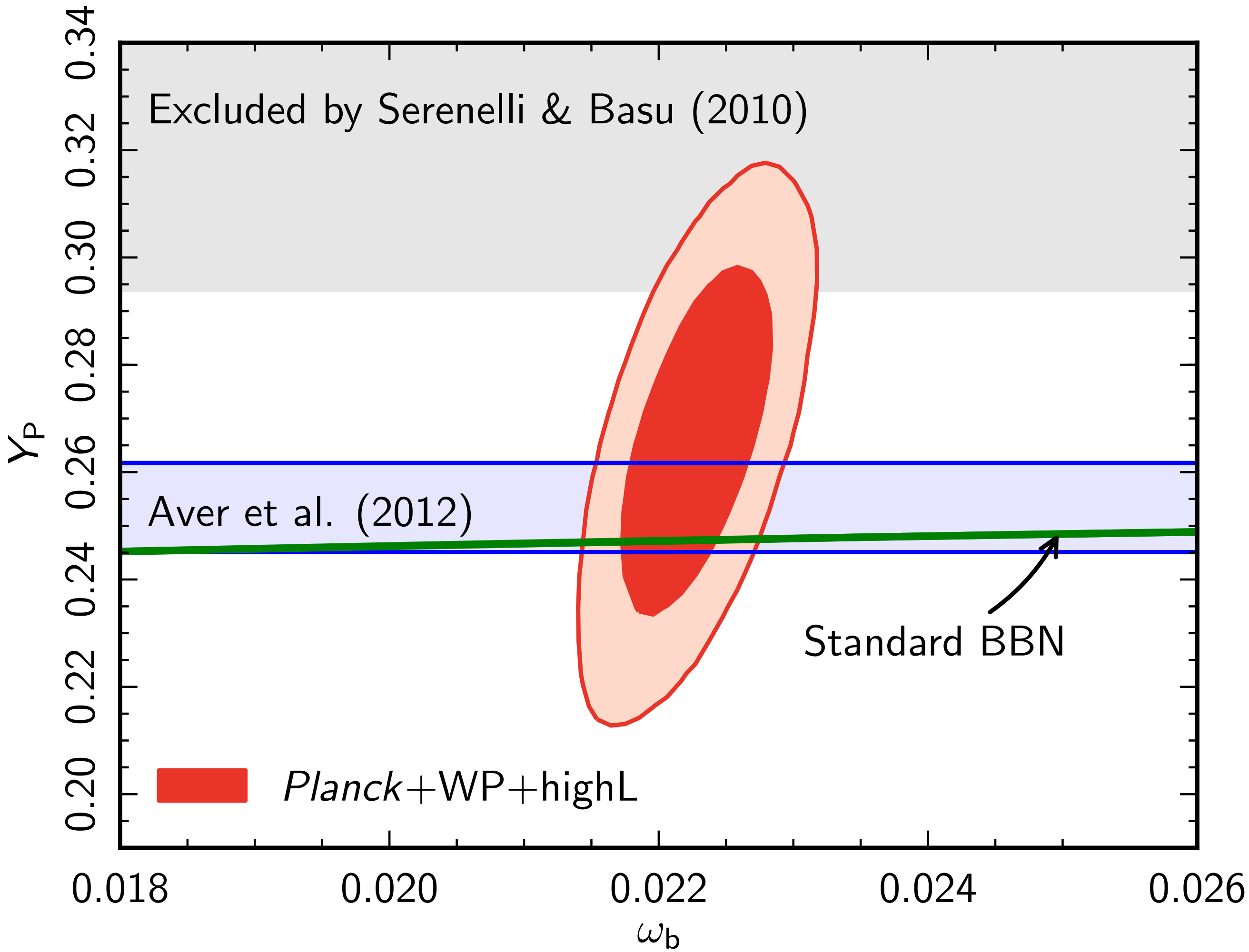
comparison with Baryon Acoustic Oscillations



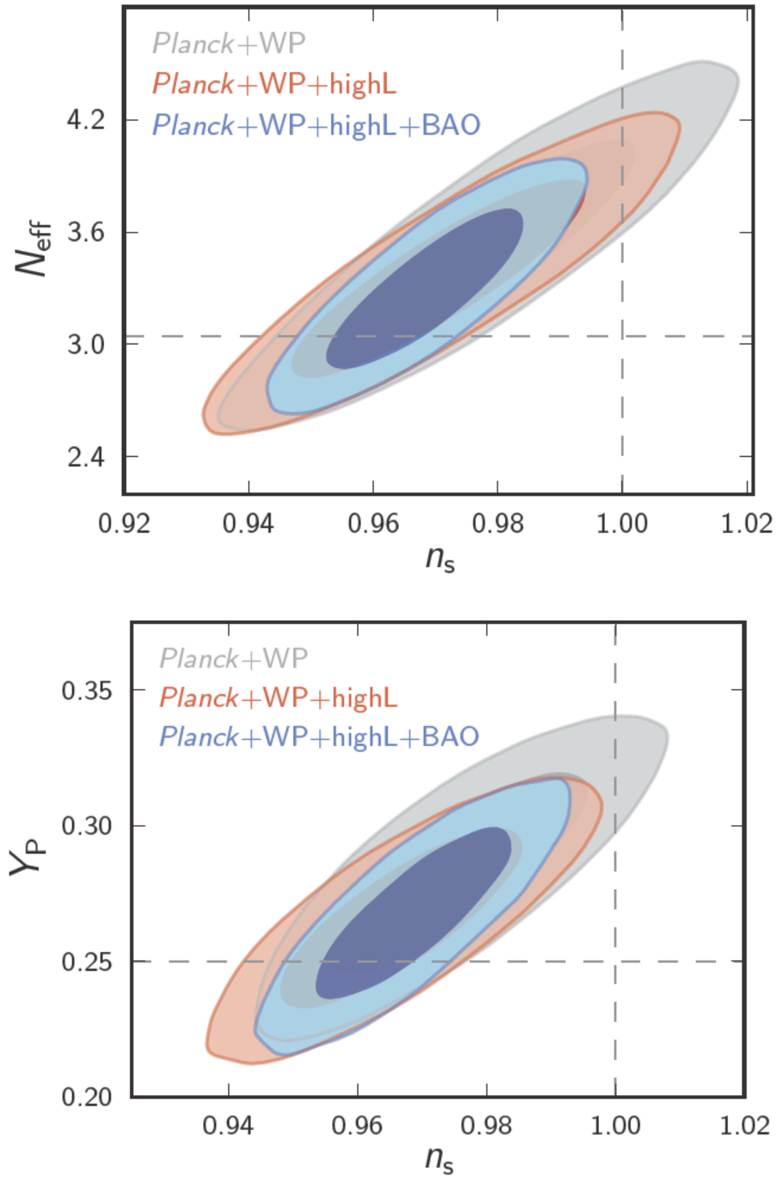
Planck constraining physics

EXTENDED ΛCDM MODELS (Planck+BAO)

	Parameter	Value (95%)
spatially flat universe	Ω_K	-0.0005±0.0066
neutrinos: mass	$\Sigma\, m_\nu$ (eV)	<0.23
extra relativistic species	N_{eff}	3.30±0.54
check nucleosynthesis	Y_P	0.267±0.040
inflation: running index	$dn_s/d\ln k$	-0.014±0.017
ratio tensor/scalar	$r_{0.002}$	<0.11
dark energy P/ρ	w	-1.13±0.24


Excluded by Serenelli & Basu (2010)
Aver et al. (2012)
Standard BBN
Planck+WP+highL
Y_P
ω_b
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.34
0.018
0.020
0.022
0.024
0.026

neutrinos: no evidence for more relativistic species
Helium : excellent agreement Planck model/primordial He abundance



Variations of fundamental physics constant

- variation of the fine structure constant has been searched
  - in the laboratory (z=0)
  - using Big Bang Nucleosynthesis ($z=10^8$)
  - CMB anisotropies is sensitive to changes of the fine-structure constant α (and also to m_e/m_p)
- Planck +BAO+WP
  - finds α/α_0 = 0.9989±0.0037 (error bar about 5 times smaller than WMAP)

Early universe physics, the inflation paradigm

- introduction of an exponential inflation phase in the early universe provides (1979-1982 Guth, Linde, Starobinsky, Mukhanov)
  - the acceleration which sets up the expansion
  - the origin of the structures as vacuum quantum fluctuations brought to macroscopic scales
  - the flat space geometry
- many inflation and other models have been produced over 30 years all of them with physics beyond the standard model
- CMB is the only tool we have at present to test these
- It requires a very accurate knowledge of the cosmological parameters to disentangle the traces of the early universe phase and the effects of the later phases on the CMB

single field power law inflation potential

- using a classical thermodynamical representation of the inflation field and its negative pressure (Mukhanov 2013 arXiv 1303.3925)
- $P/E = -1+\beta/(N+1)^{\alpha}$ with α of order 1 and and $\beta<1$
- N being the number of inflationary e-folds between time CMB scales crossed the horizon and end of inflation ($N > 50$ for $\Omega_K < 10^{-5}$)
- $n_s - 1 = -3\,\beta/(N+1)^{\alpha} - \alpha/(N+1)$ 4% for with $\alpha = 1$ and $\beta < 1/3$
- $r = T/S = 1+P/E) = 24\,\beta/(N+1)^{\alpha}$ $r \approx 0.16$
- energy scale of inflation $V = 3.3\ 10^{16}\ r^{1/4}$ GeV

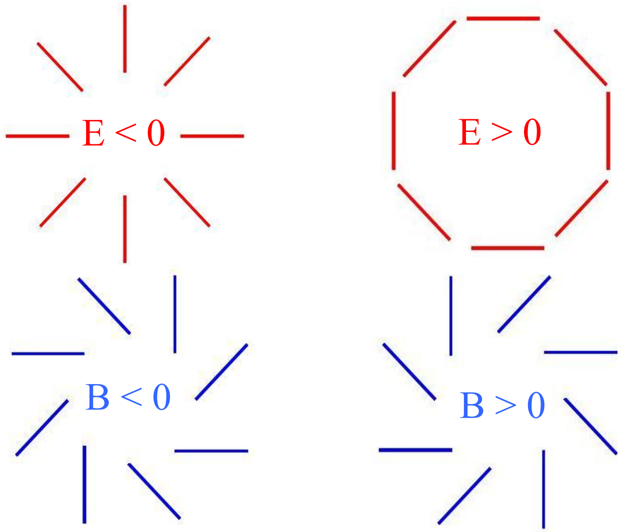
- this shows that n_s-1 is of order 4% and

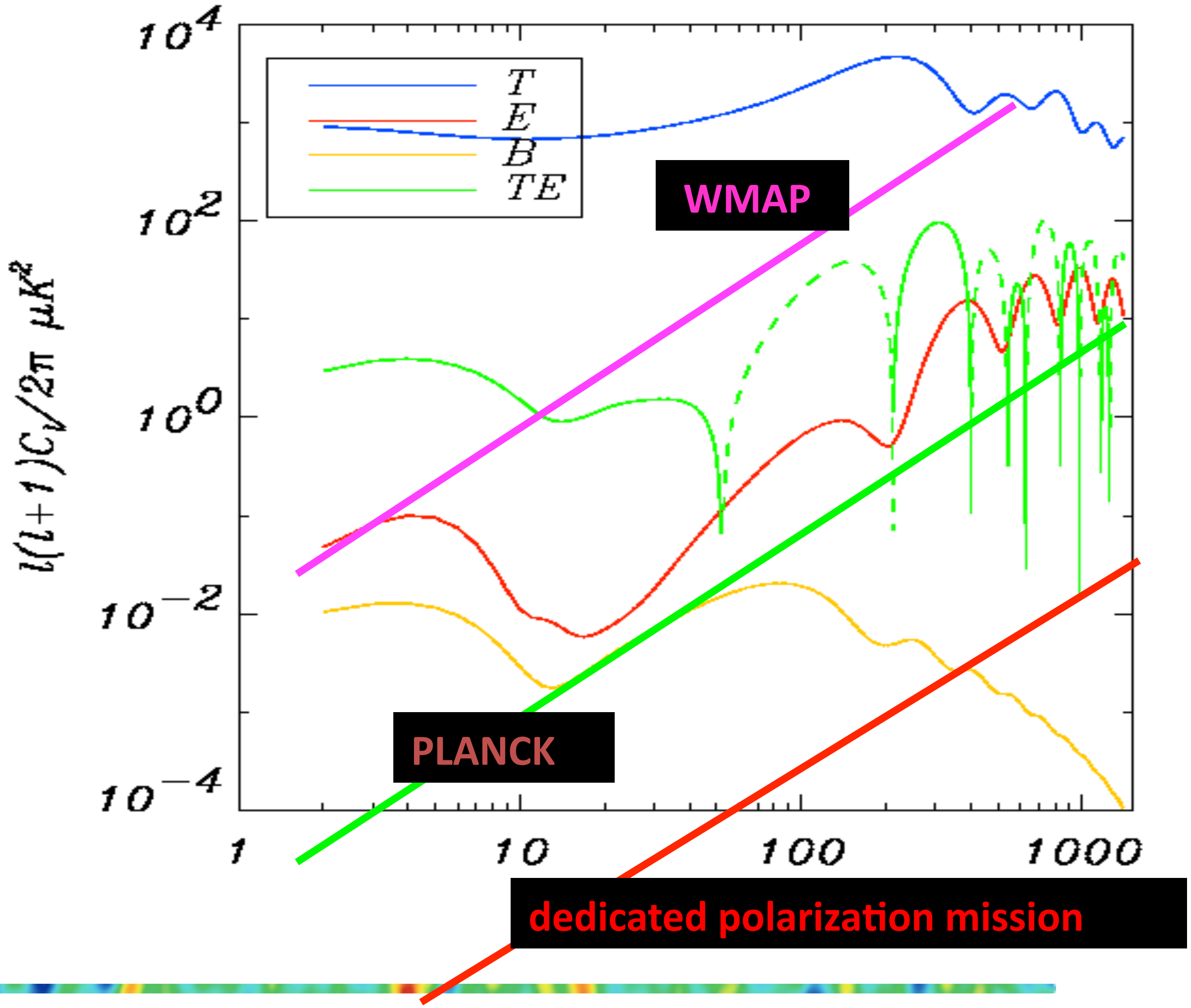
r of order 0.1 for $\alpha=1$ and a few 10^{-3} for for $\alpha=2$

- marginal indications for small tilt from WMAP and other CMB experiments : 0.97
- Planck demonstrated that $\Omega_K < 7\ 10^{-3}$ and the tilt with respect to scale invariance (0.958 +-0.007)
- the newt step is to test the tensor to scalar ratio r
-

CMB spectra: T, E and B polarization

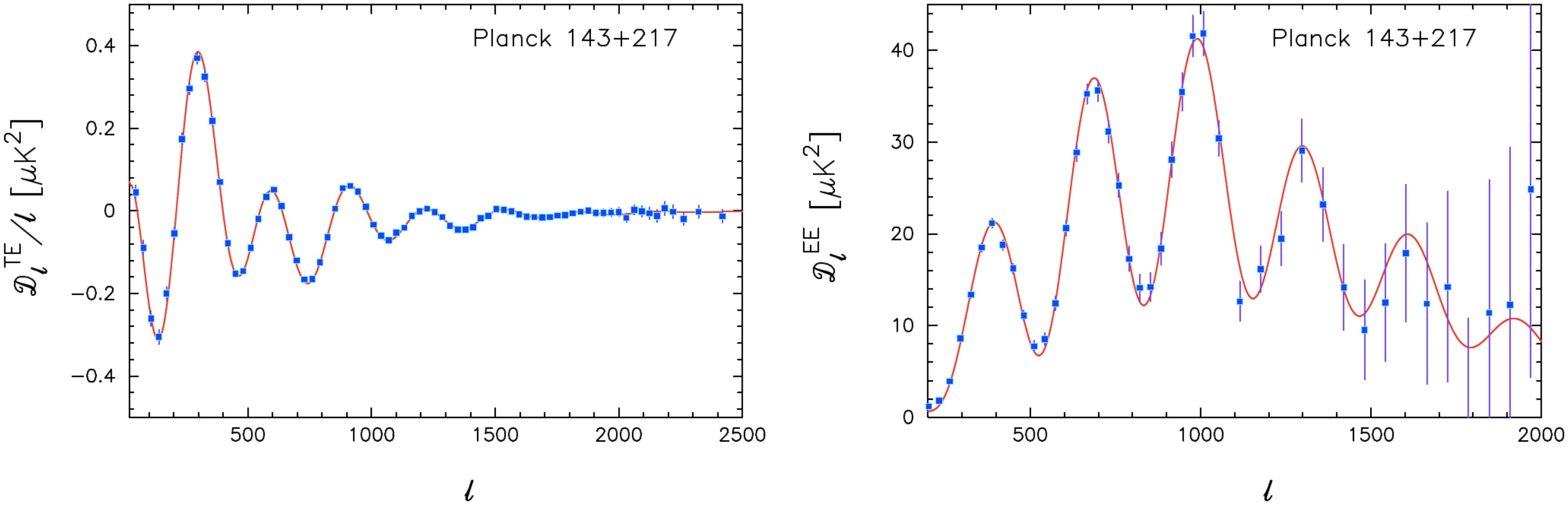
3 observables : T, E, B



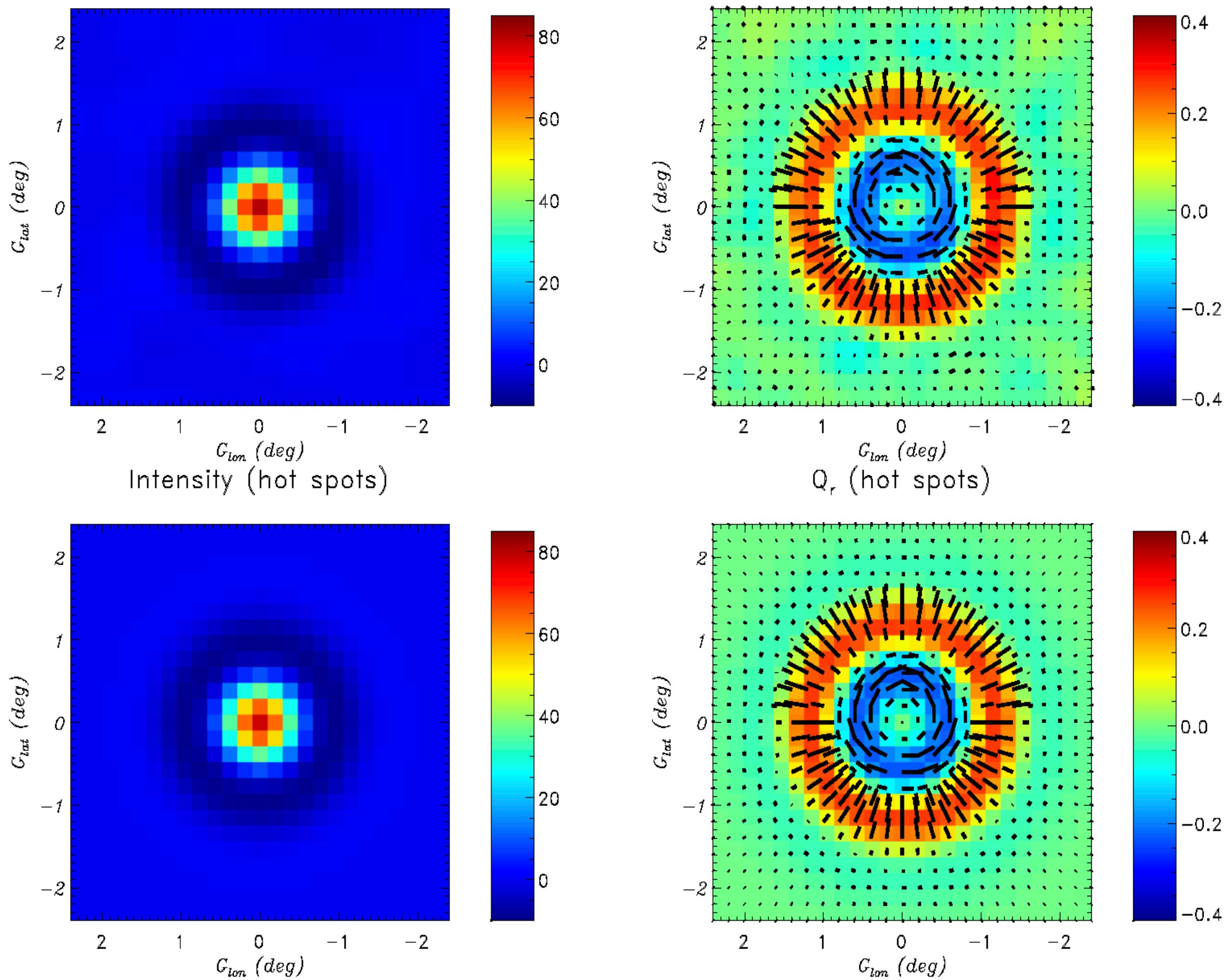


B polarization power spectrum is 5 orders of magnitude weaker than T for tensor/scalar =0.1 !

Planck polarization data: check the TT based model



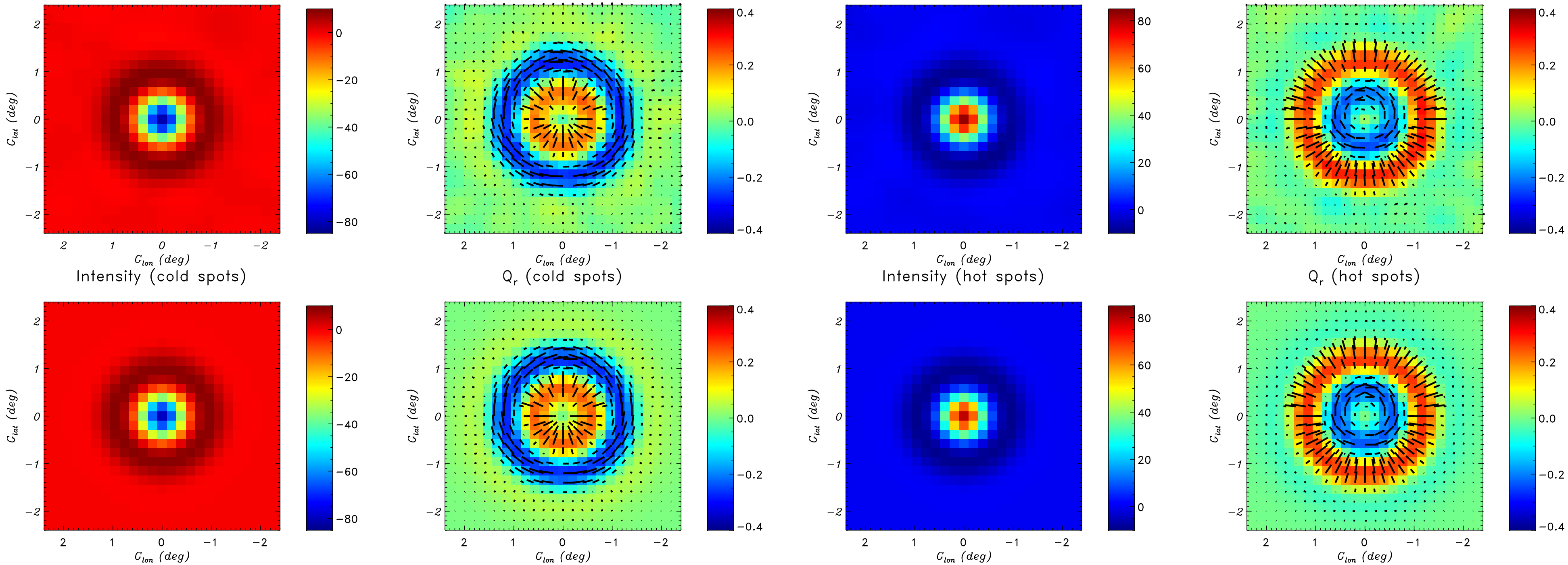
Polarisation around hot spots



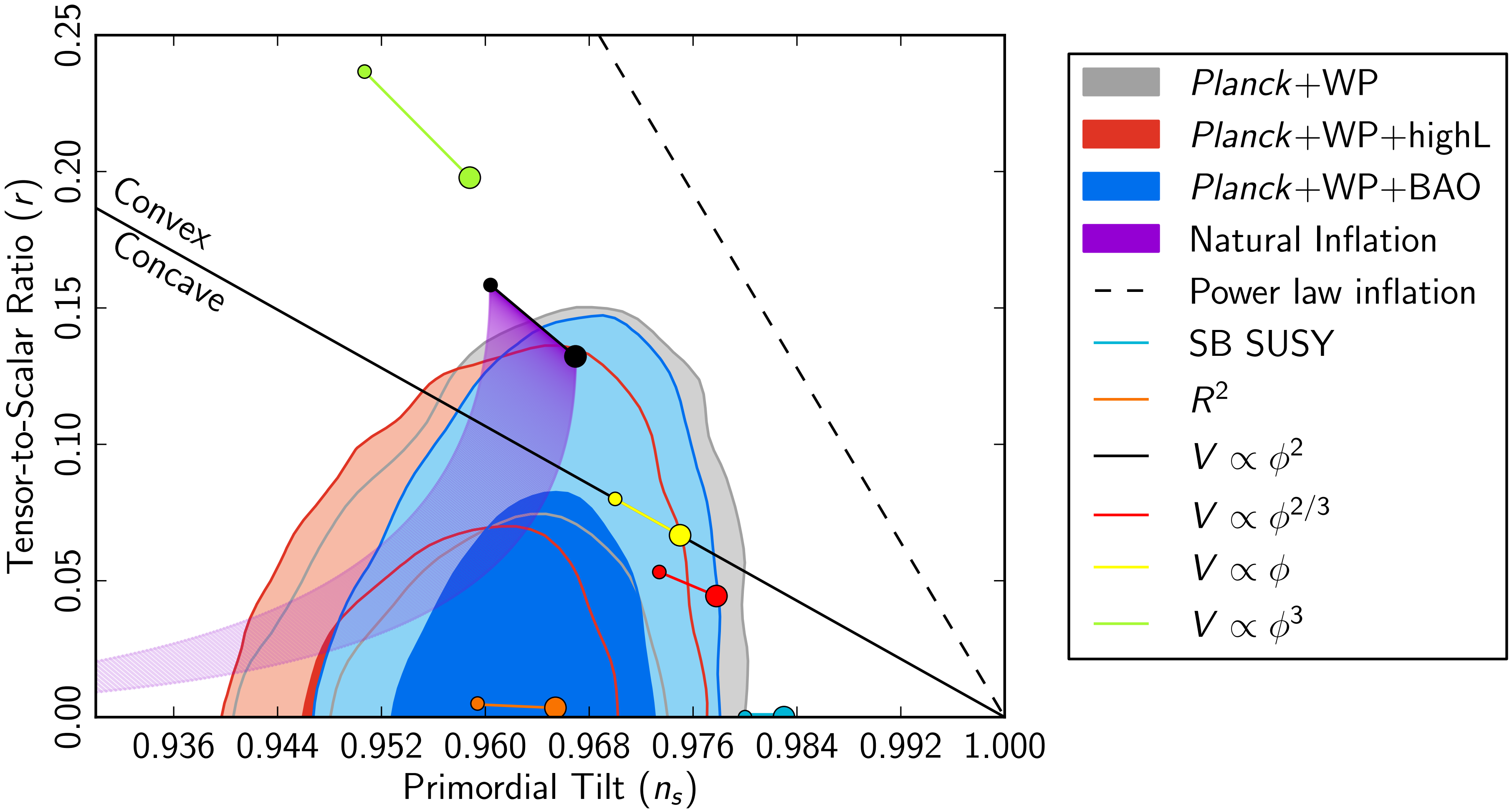
Data (top) versus expectation (bottom)

→ Planck "sees" precisely the dynamics of fluctuations, at ~380 000 years

stacking of Planck polarization on T peaks and troughs



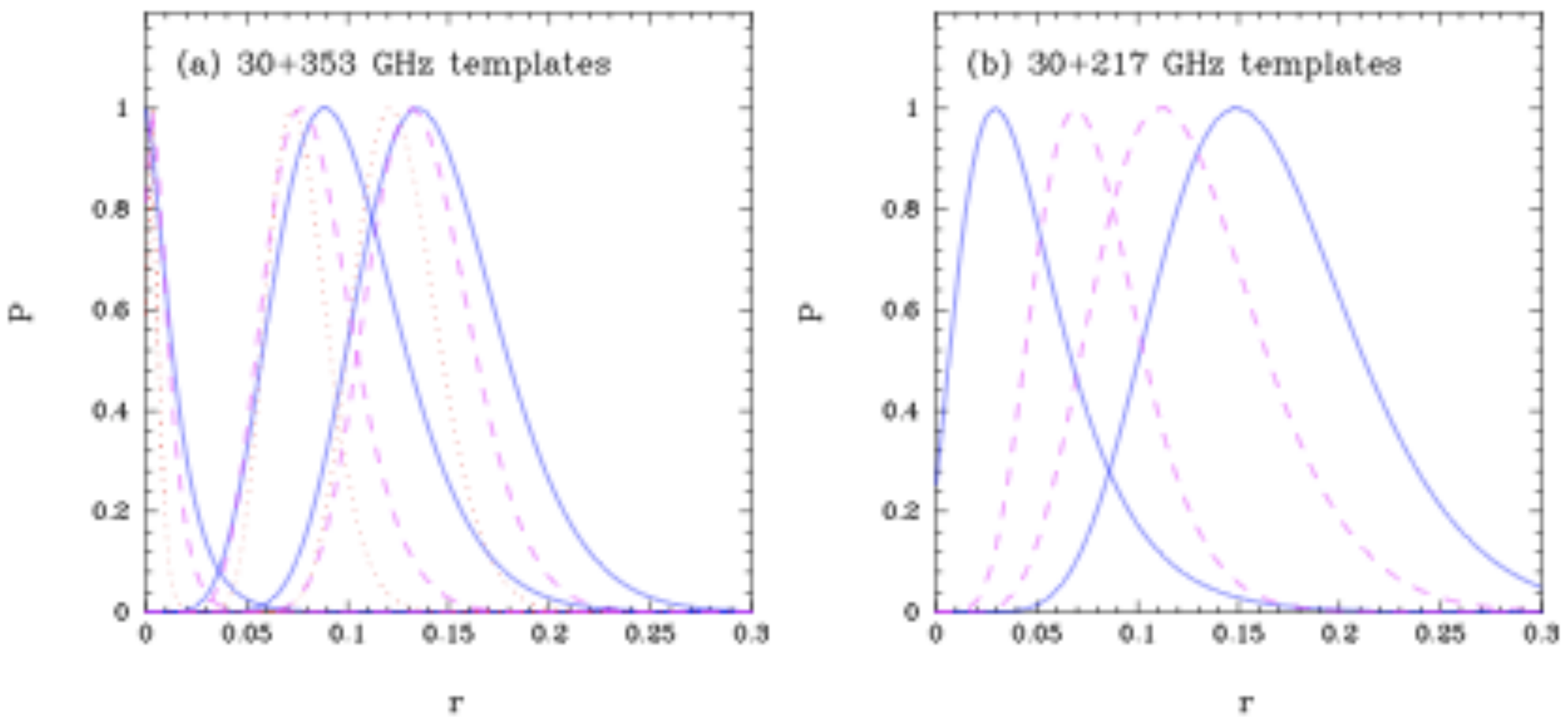
Planck power spectrum constrains inflation models



Planck B modes sensitivity can detect r down to 0.05 and put a 3 sigma upper limit at 0.03 if we get to the noise limit (Efstathiou Gratton)

Simulation of B modes detection (Efstathiou, Gratton 2009)

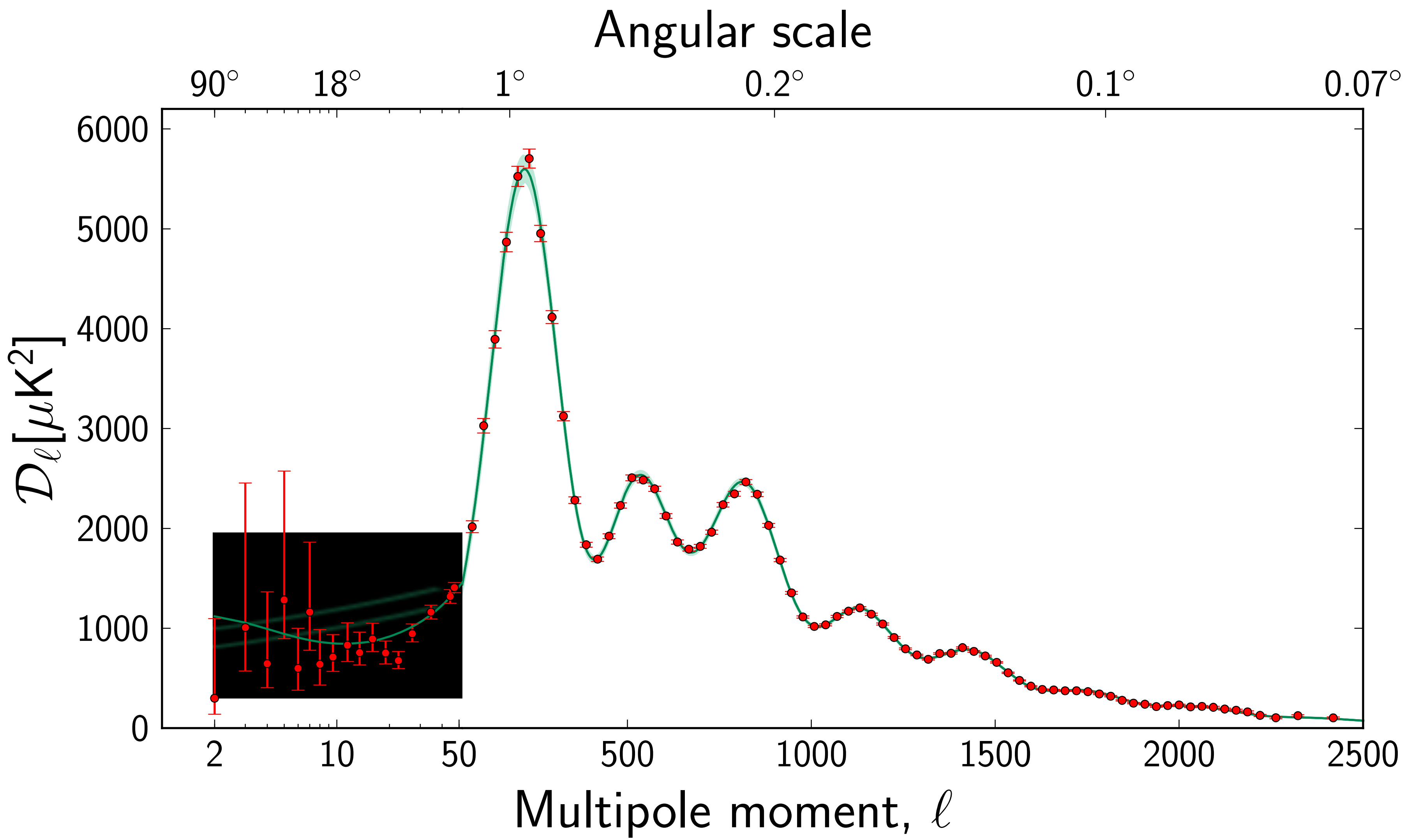
- Planck can detect tensor to scalor ratio down to 0.05 (present best direct upper limit is 0.3 one sigma, Bicep Chiang et al 2009)



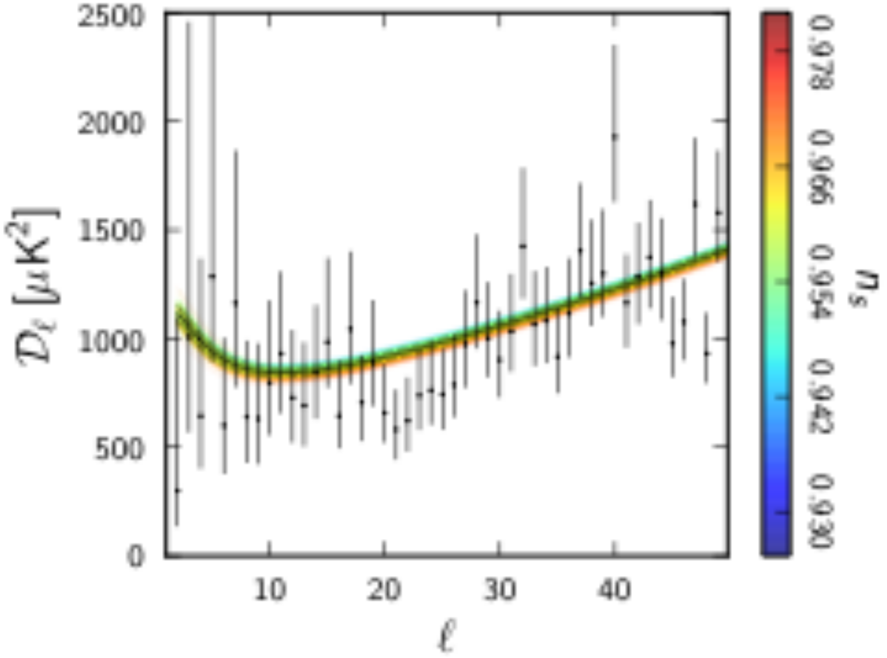
Anomalies

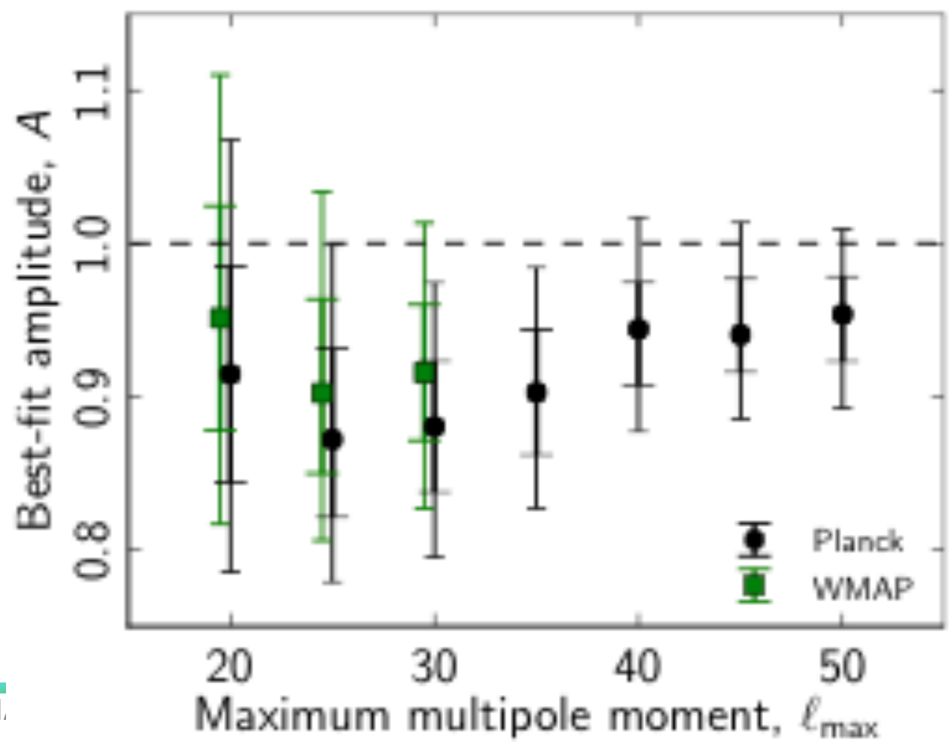
- WMAP data showed a number of “anomalies” in the statistics of large scale features in the CMB maps
  - the cold spot
  - the alignement of octupole and quadrupole
  - the hemispheric anisotropy of higher l anisotropies
- Planck confirmed them with slighly higher but still marginal significance

Planck CMB power spectrum



Low ell anomaly





Thank you.