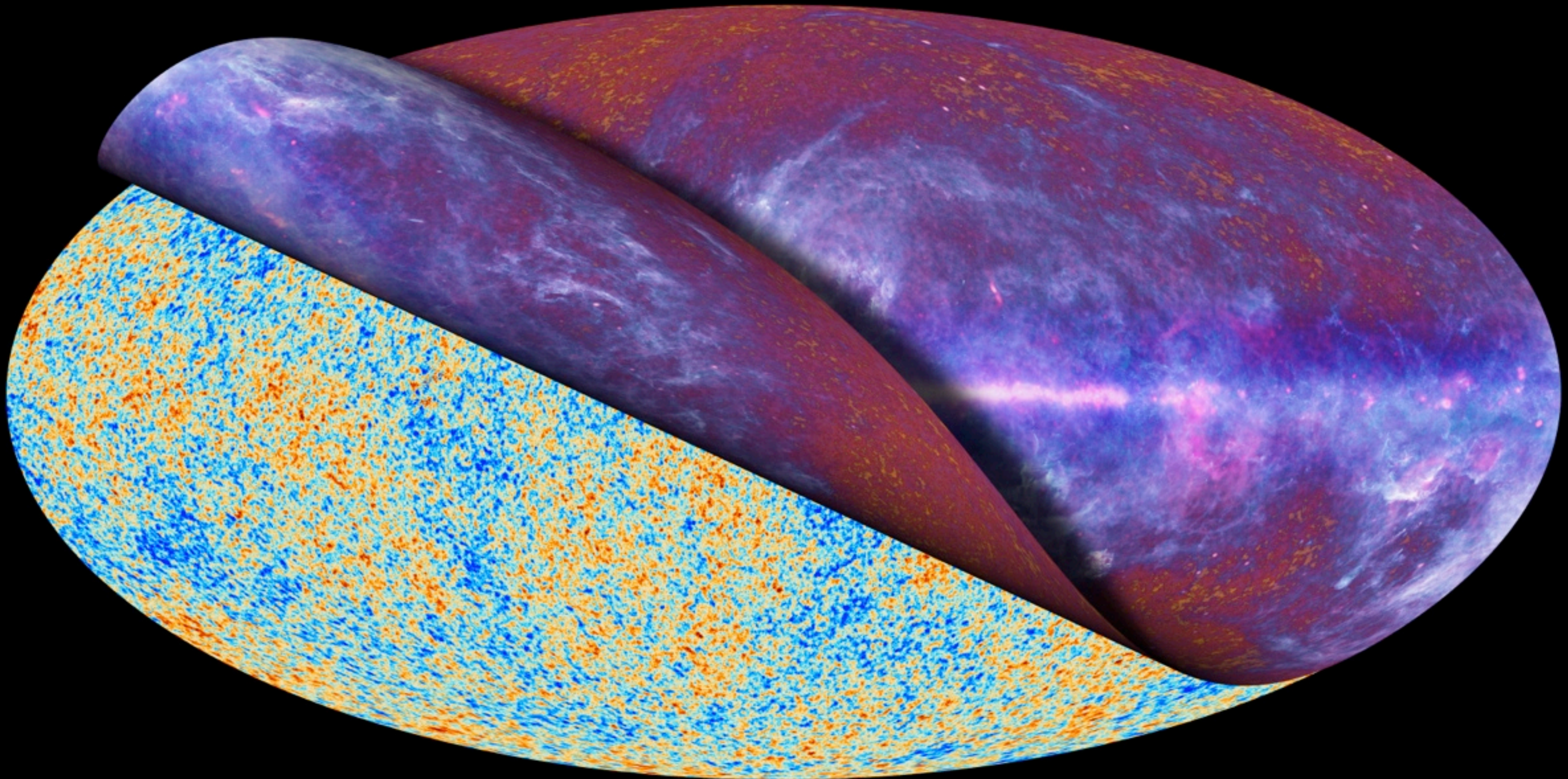
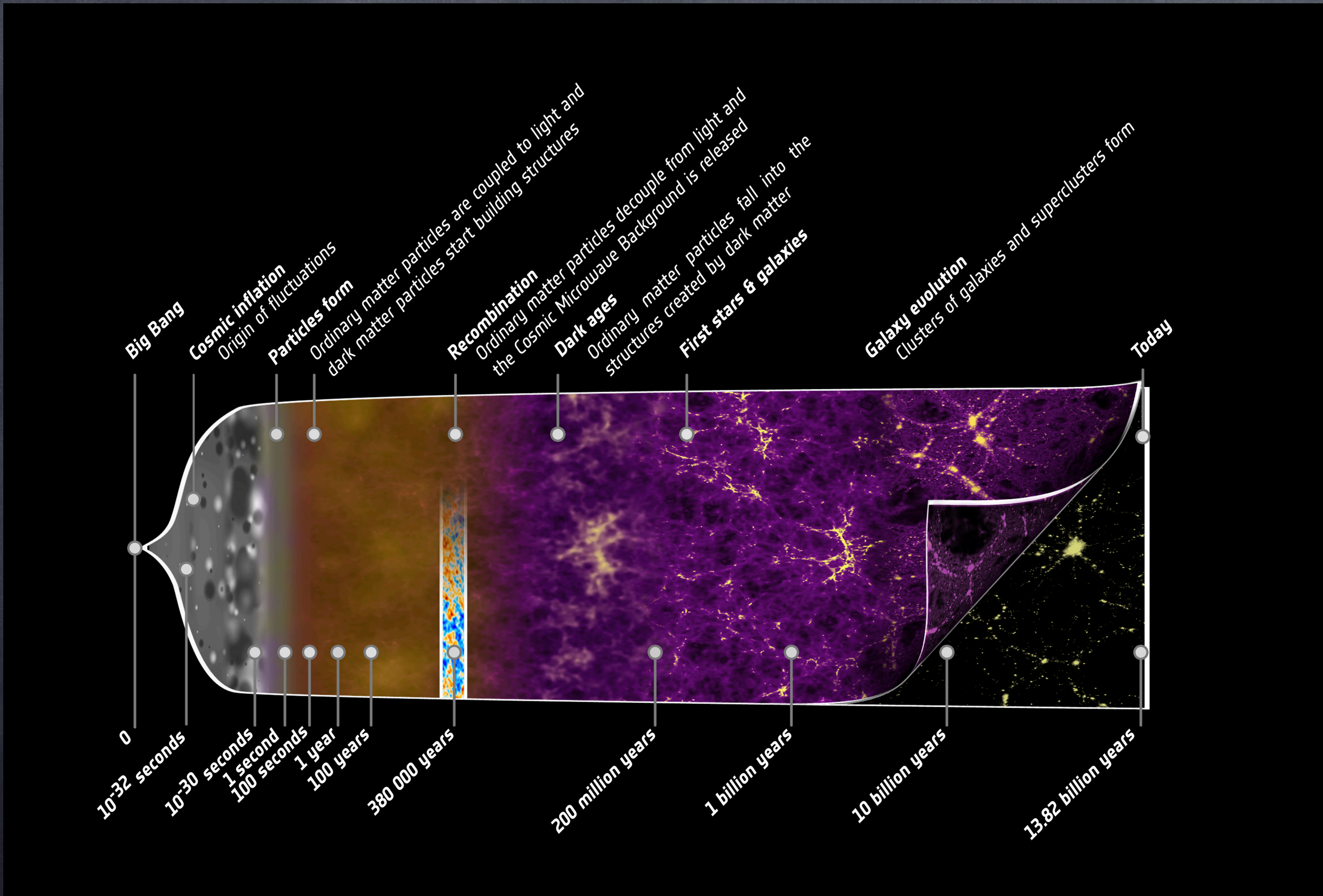


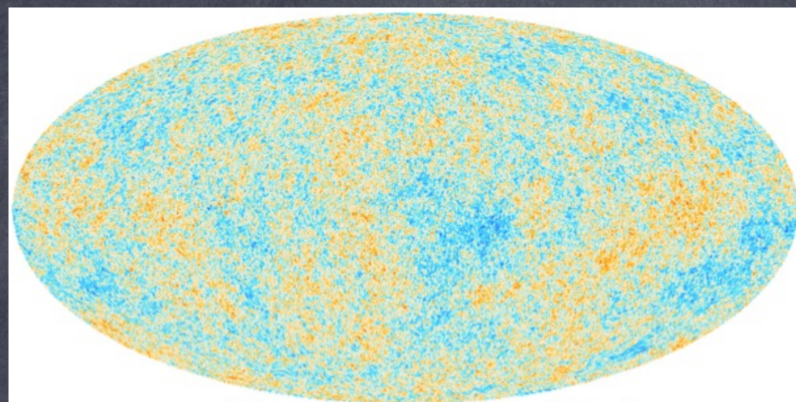
Planck unveils the Cosmic Microwave Background

J.F. Macías-Pérez on behalf of the Planck collaboration

Brief history of the universe

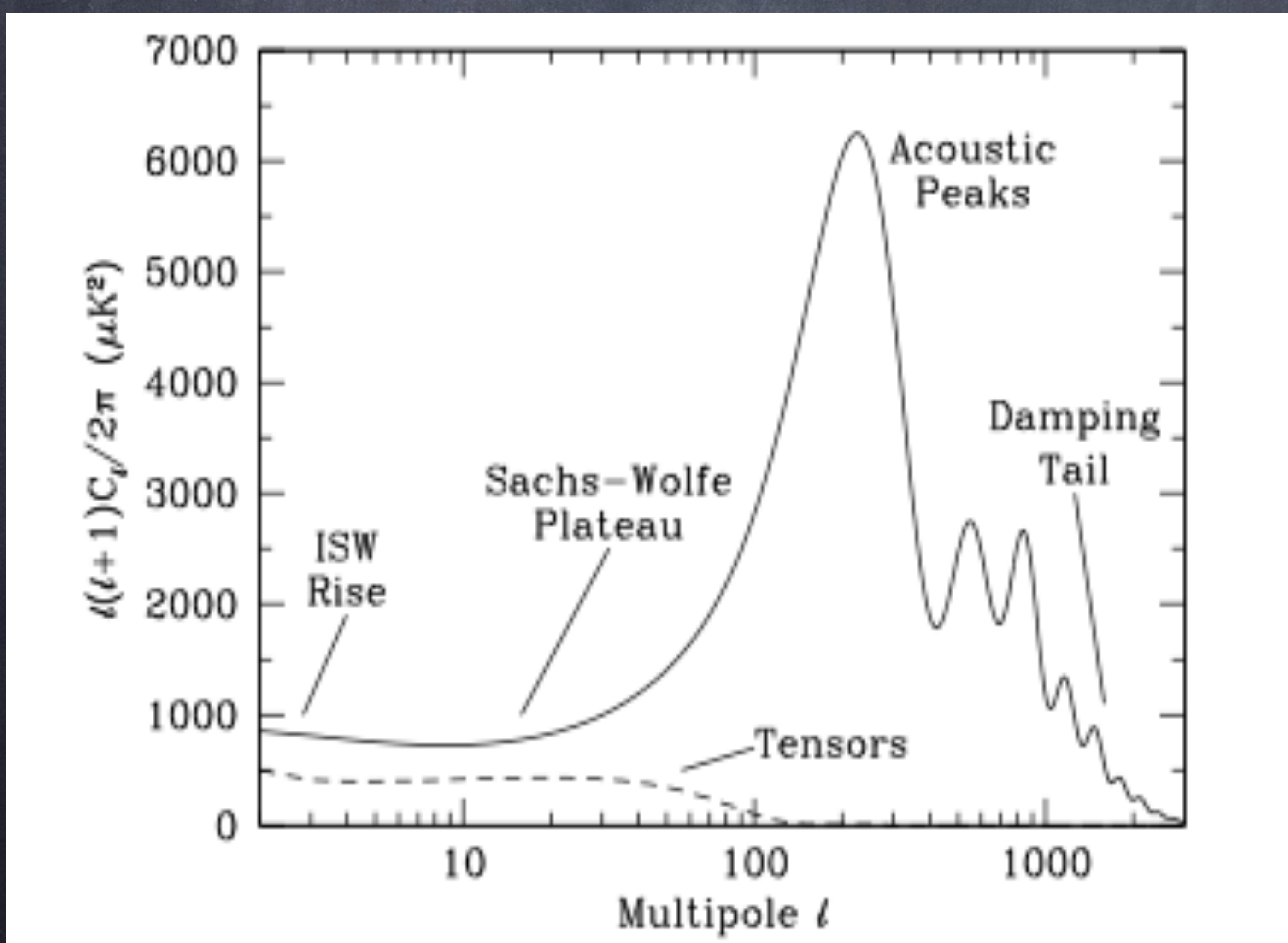


Primary CMB anisotropies



Spherical harmonic decomposition

$$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a^T_{\ell m} Y_{\ell m}(\mathbf{n})$$



Power spectrum

$$\hat{C}_\ell^{TT} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

Large angular scales

Small angular scales

Contraints on primordial physics

r, n_S, n_T

Mesure cosmological parameters

$H_0, \Omega_0, \Omega_\Lambda, \Omega_b, \Omega_\nu$

And also,

SZ effet, Reionisation

Sachs-Wolfe 1967

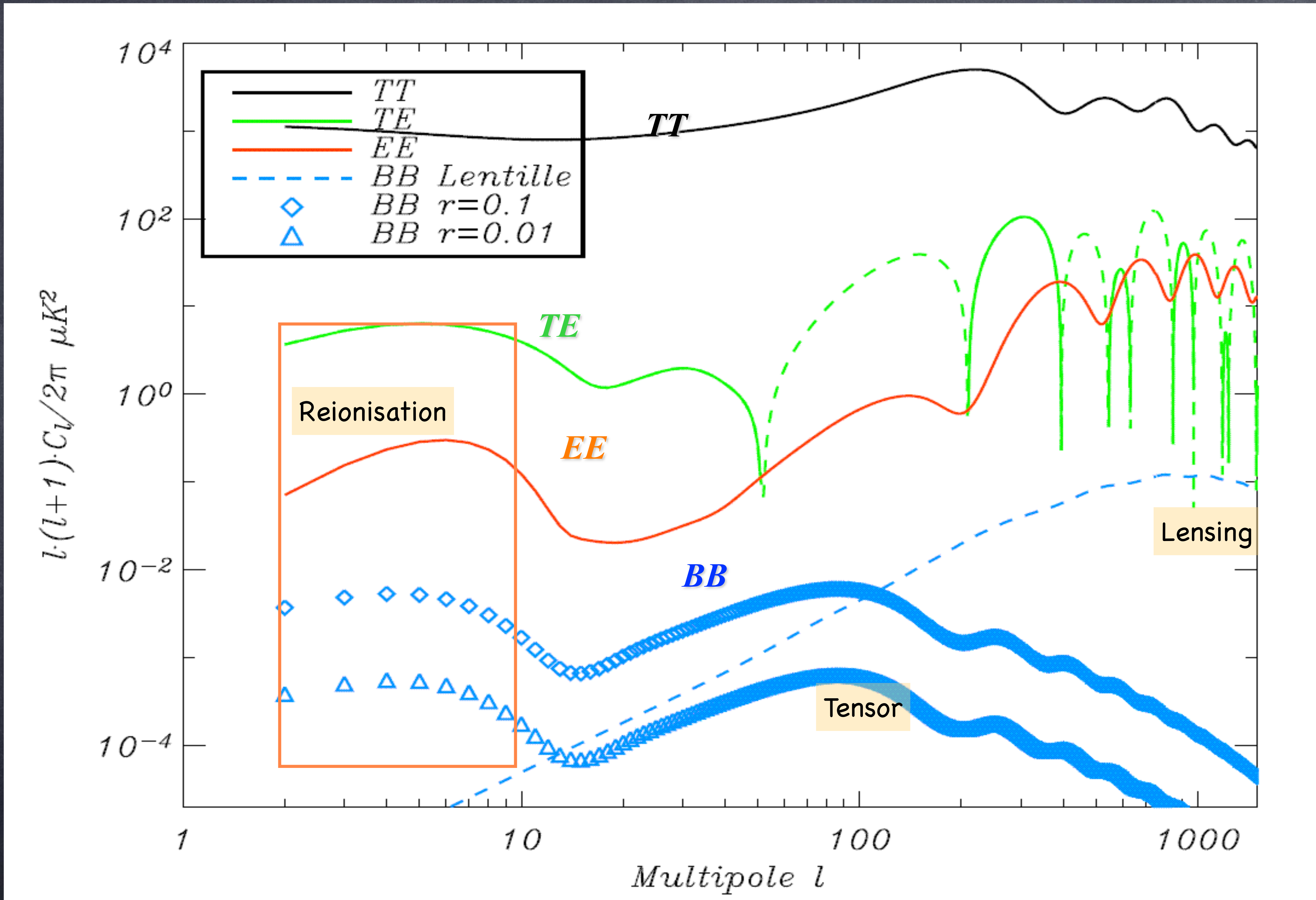
Hu & White 1997

Hu & Dodelson 200

Silk et al. 1968

Temperature and polarisation power spectra

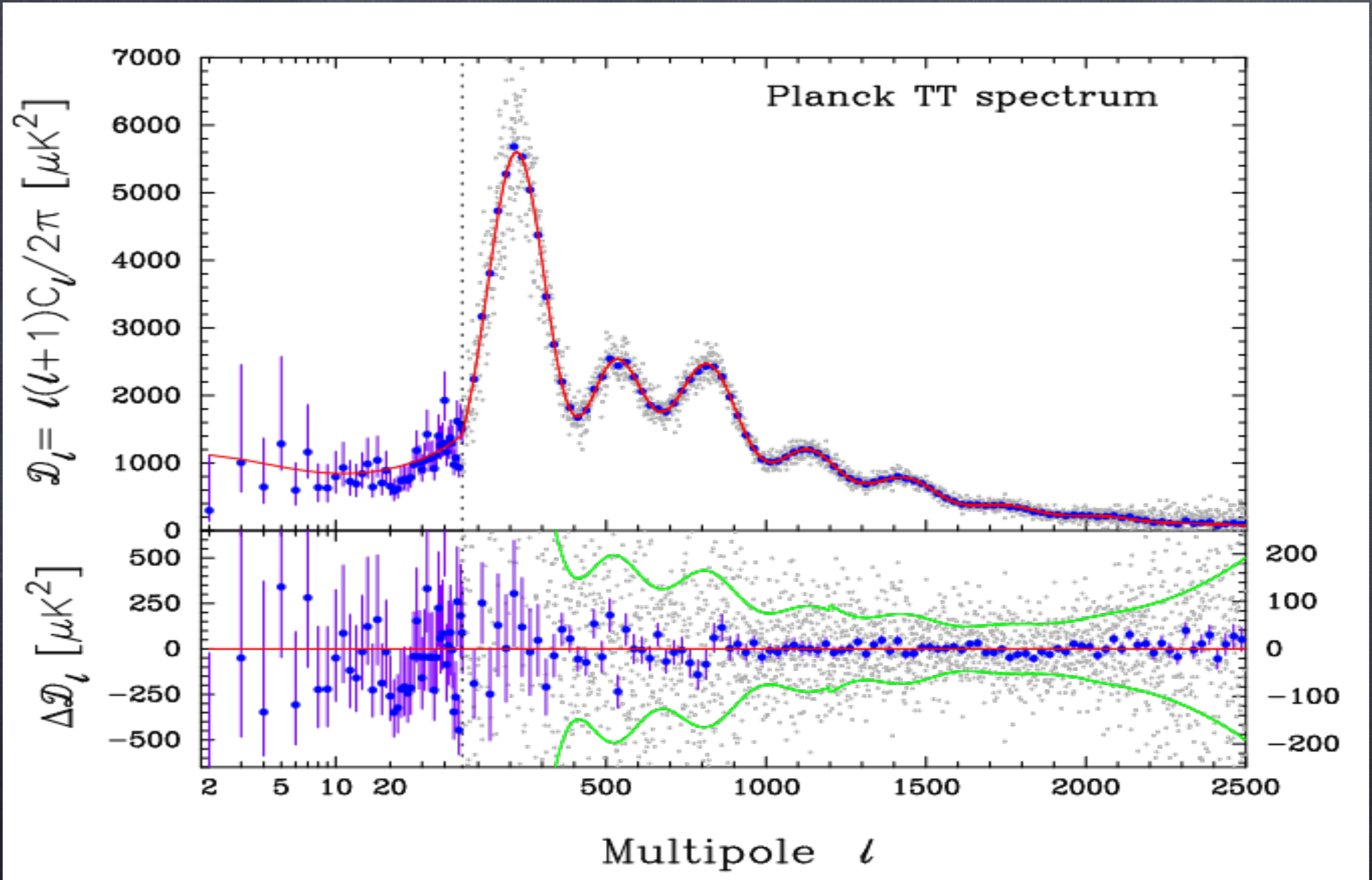
★ 6 possible combinations *TT*, *EE*, *BB*, *TE*, *TB* et *EB*



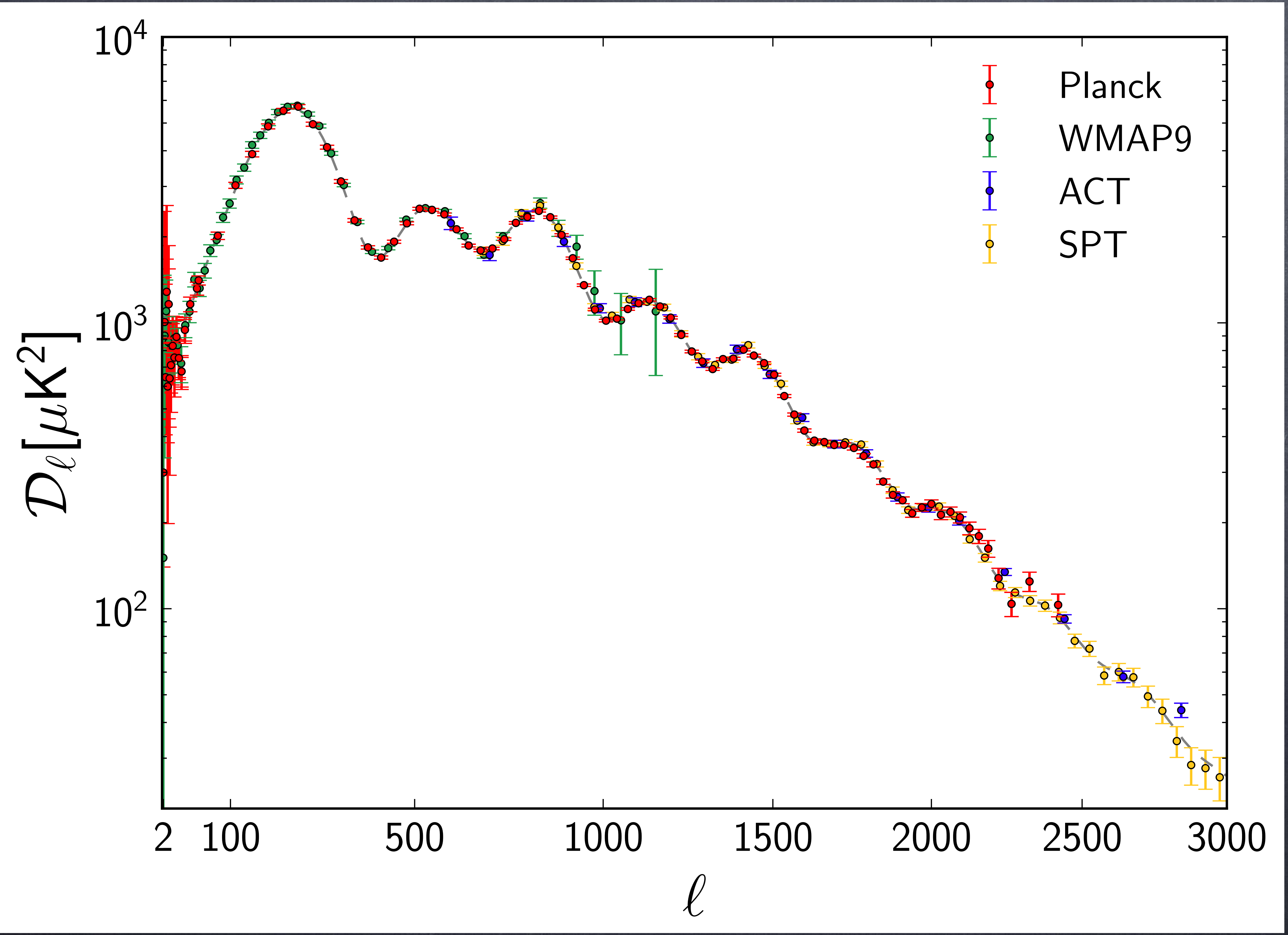
✓ break degeneracies between parameters

✓ + reionisation, ondes gravitationnelles primordiales, distribution de matière

Temperature power spectrum

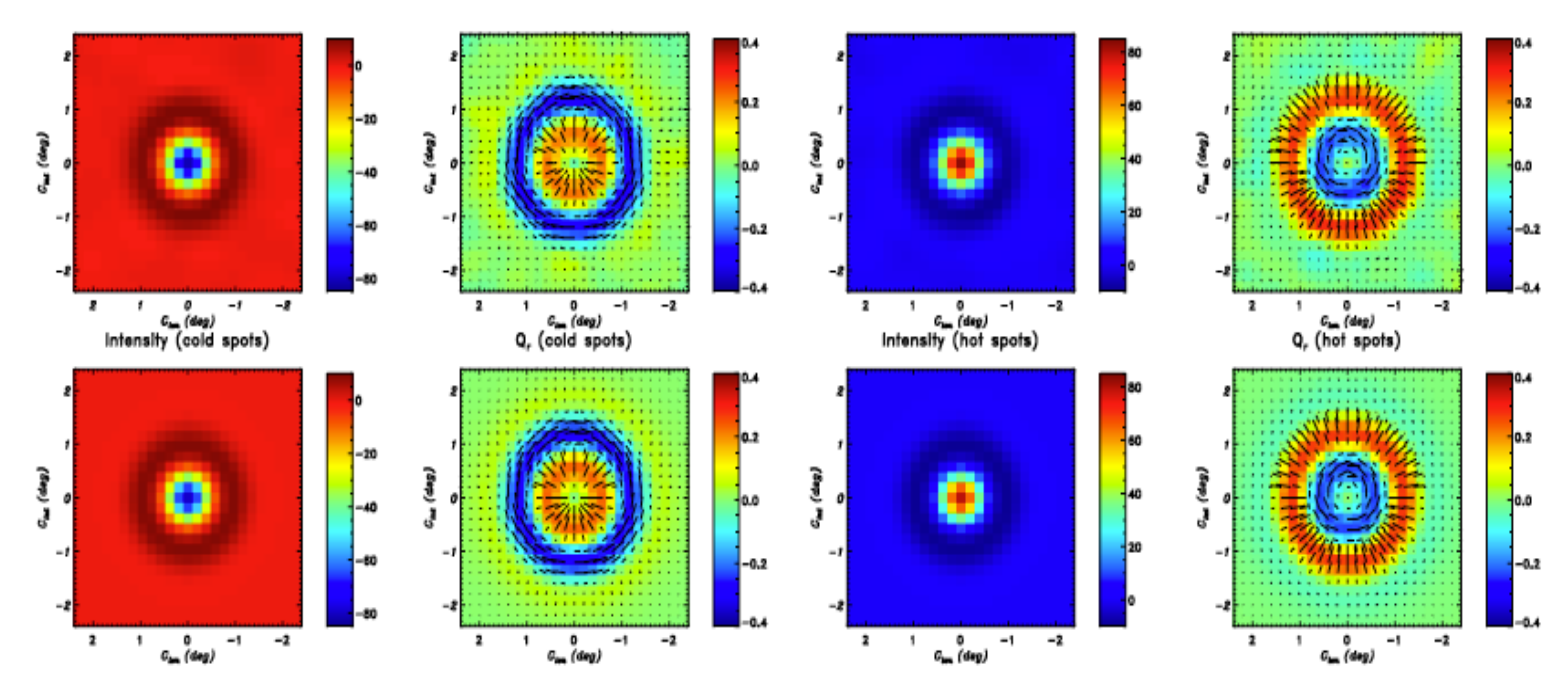


Temperature power spectrum consistency

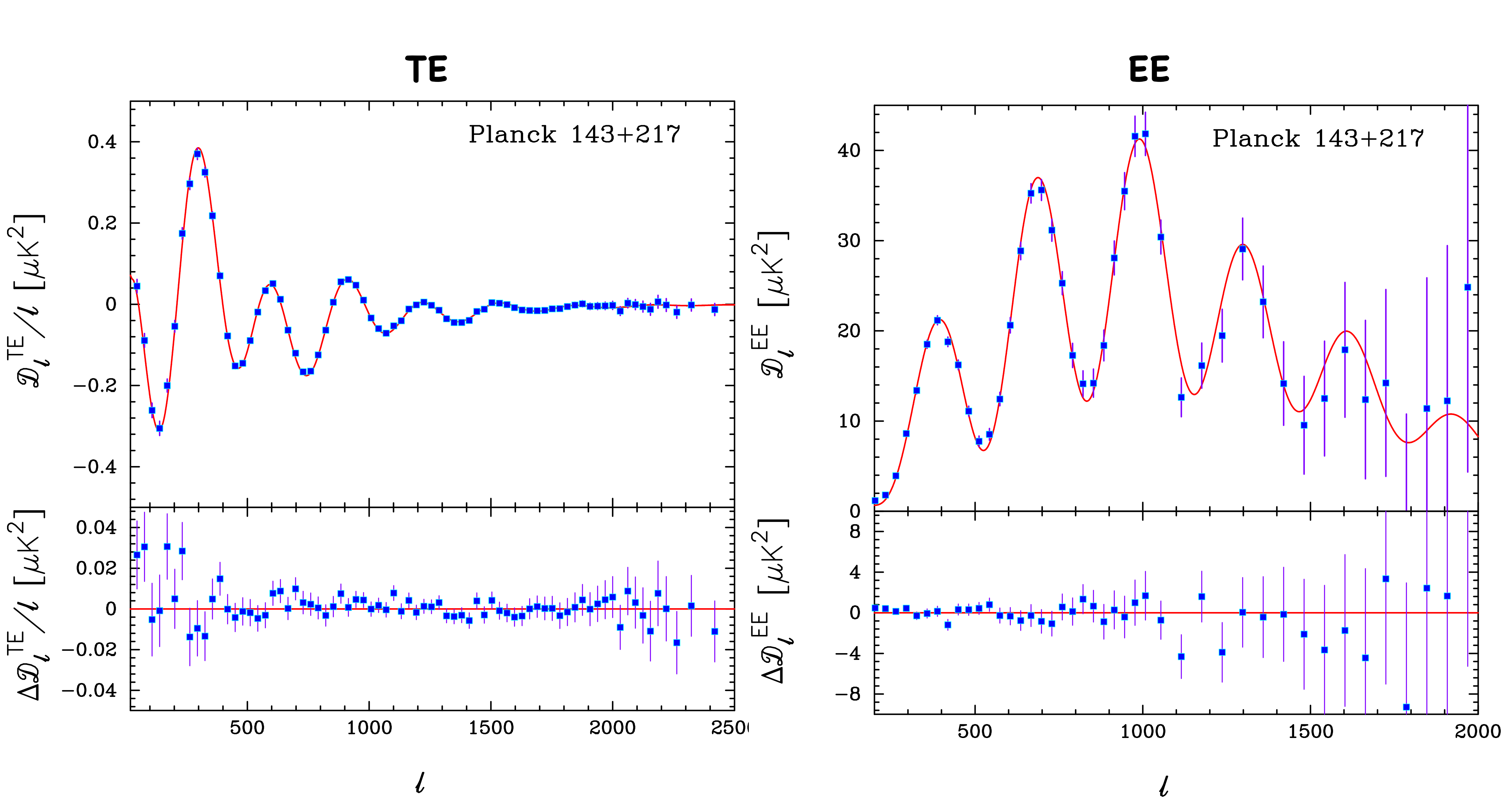


CMB polarisation anisotropies

Polarisation stacking of cold and hot spots, 30 arcmin



Polarisation power spectra

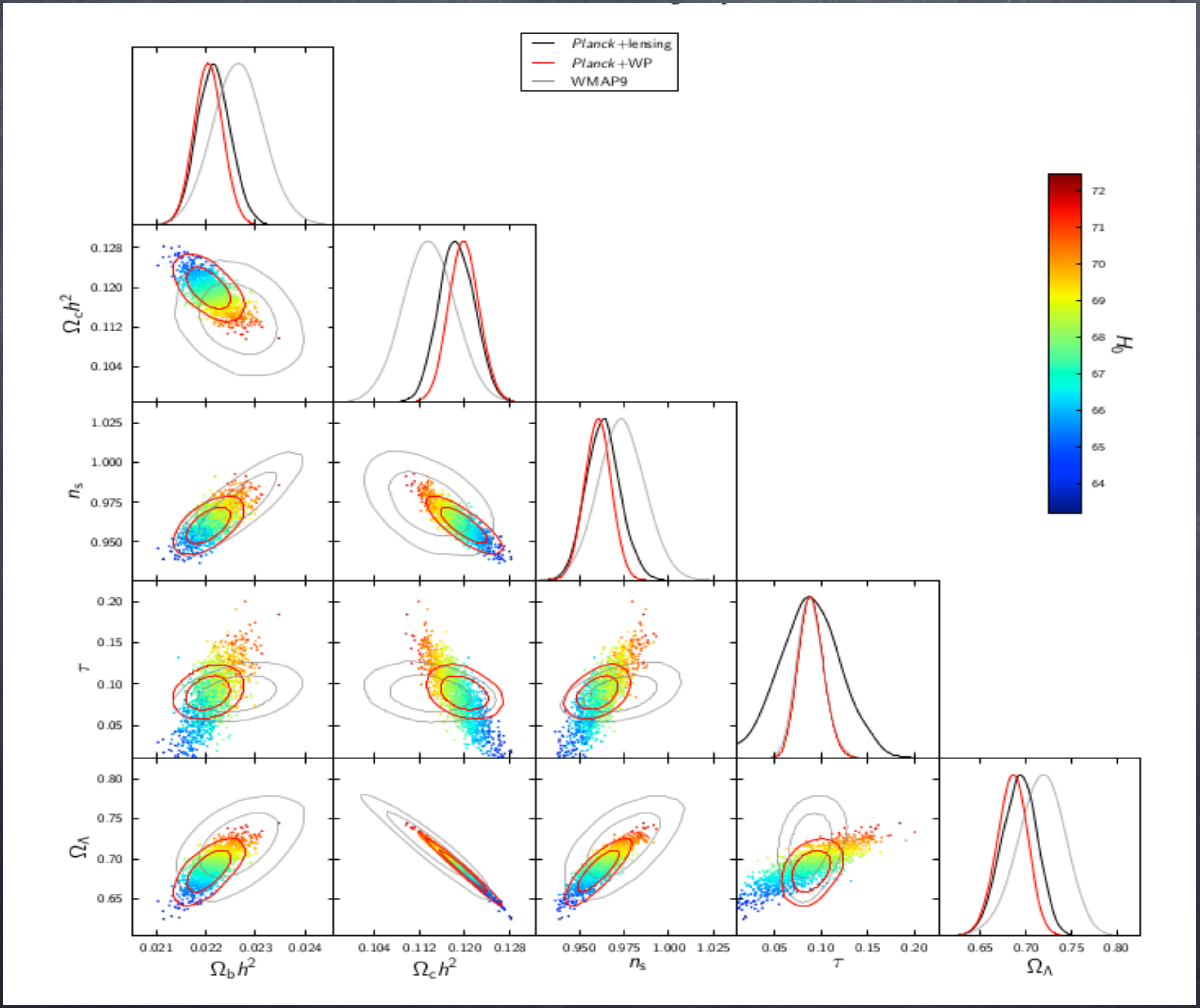


➡Sensitivity to polarisation is excellent, at large angular scales systematics need to be dealt with

➡ Polarisation power spectra in very good agreement with temperature

6-parameters Λ-CDM model

Flat universe (no curvature) including photons, ordinary matter, cold dark matter and a cosmological constant

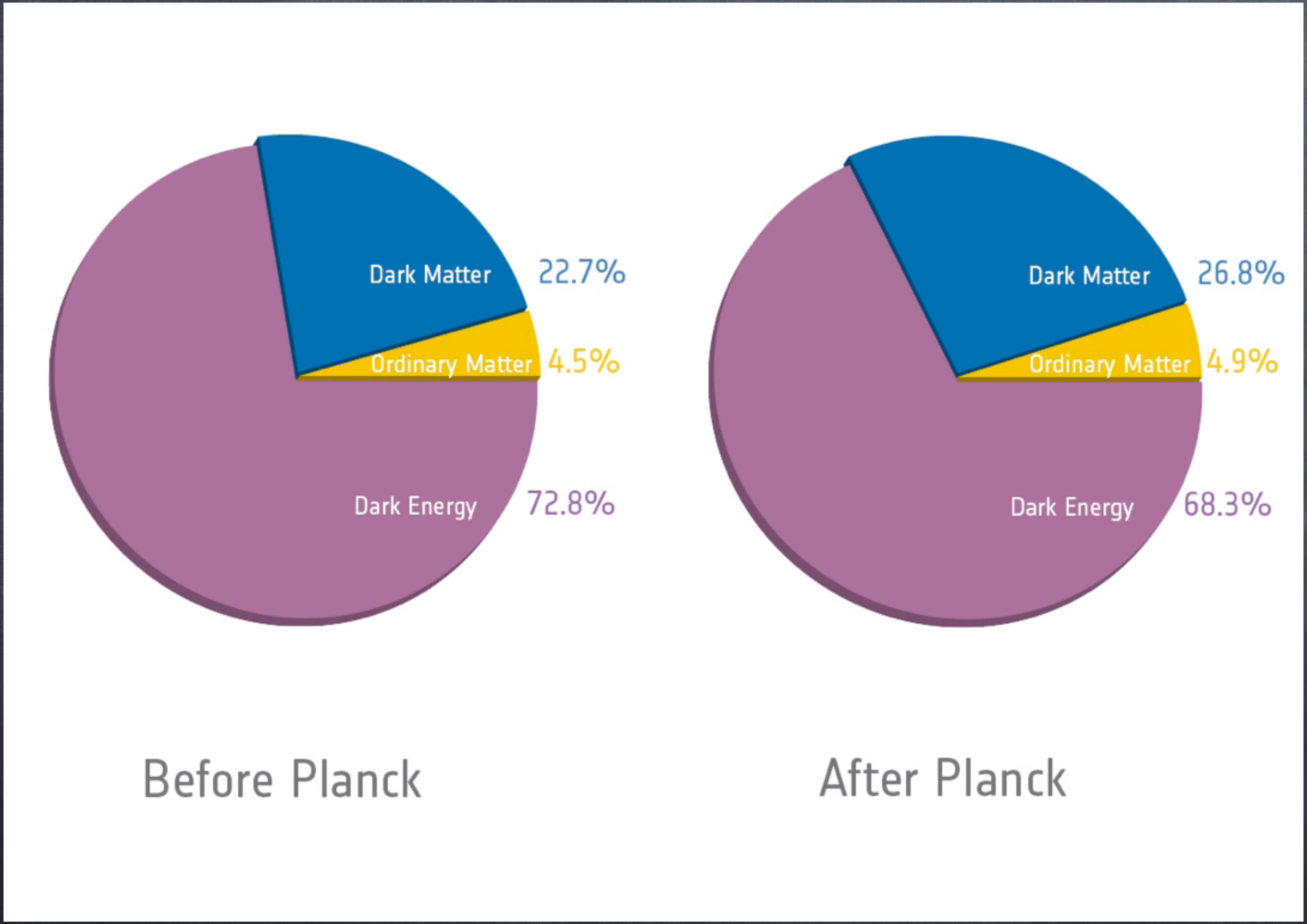


6-parameters Λ-CDM model

Flat universe (no curvature) including photons, ordinary matter, cold dark matter and a cosmological constant

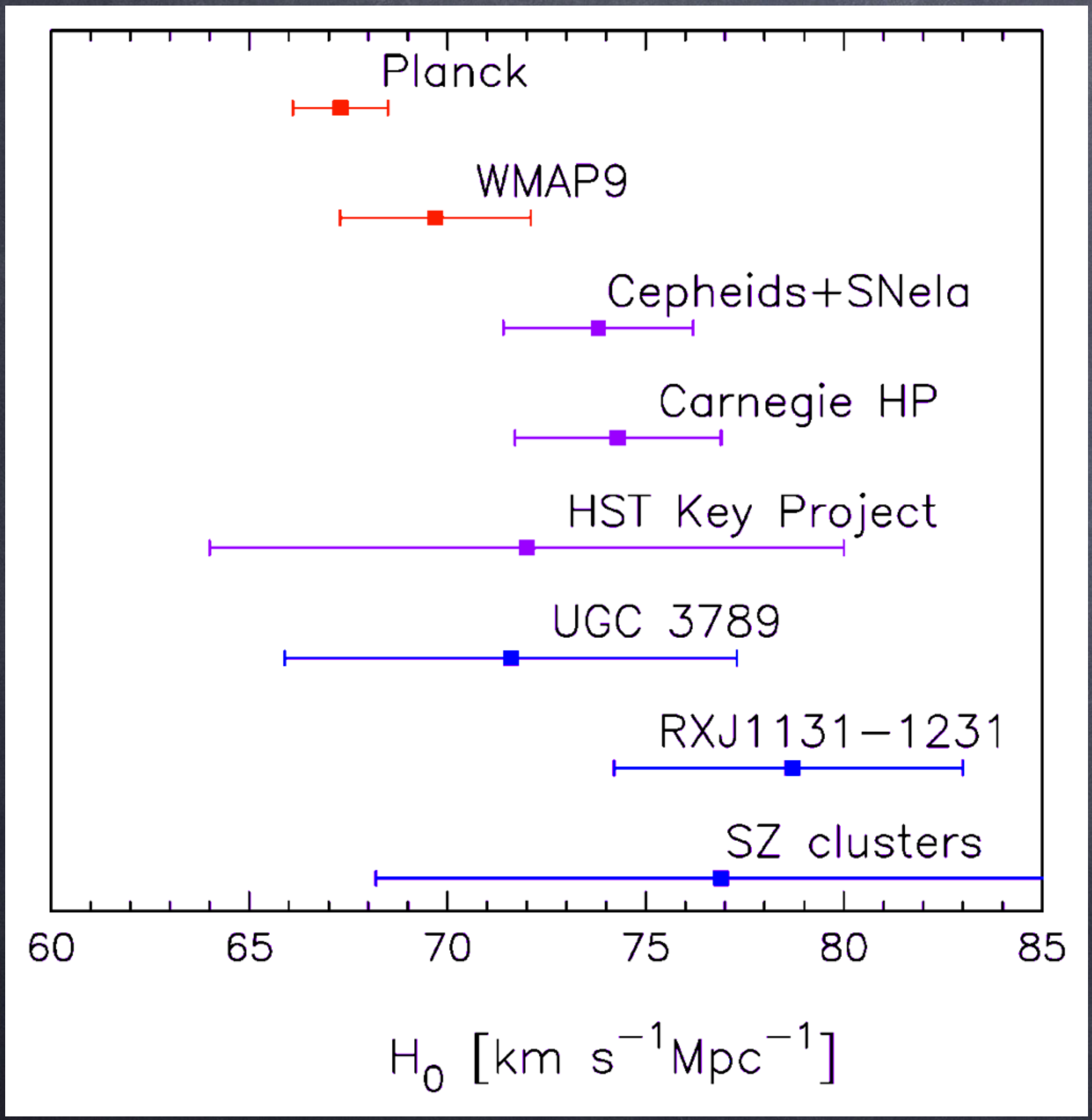
	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

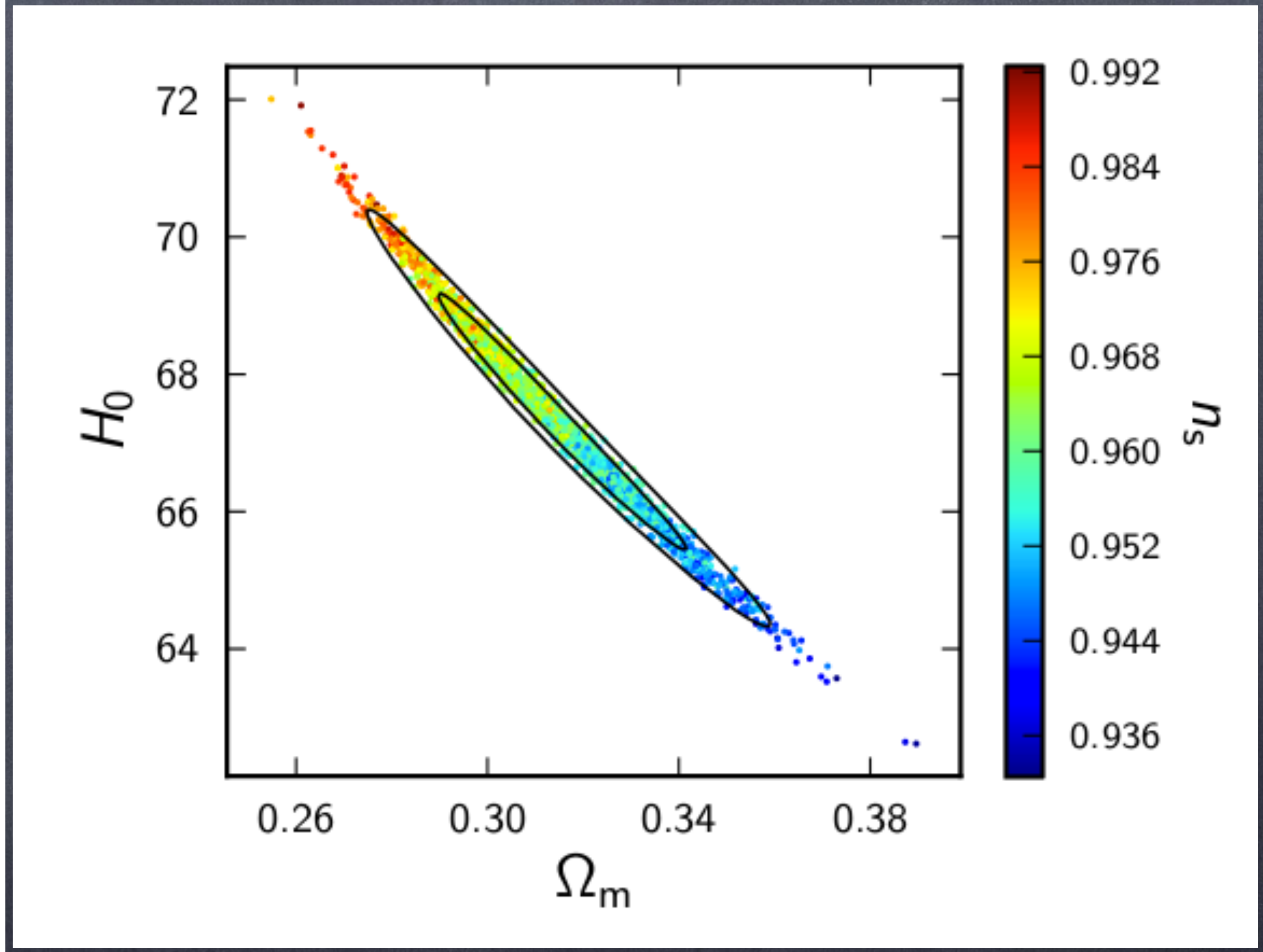
Energy content of the universe



Hubble constant

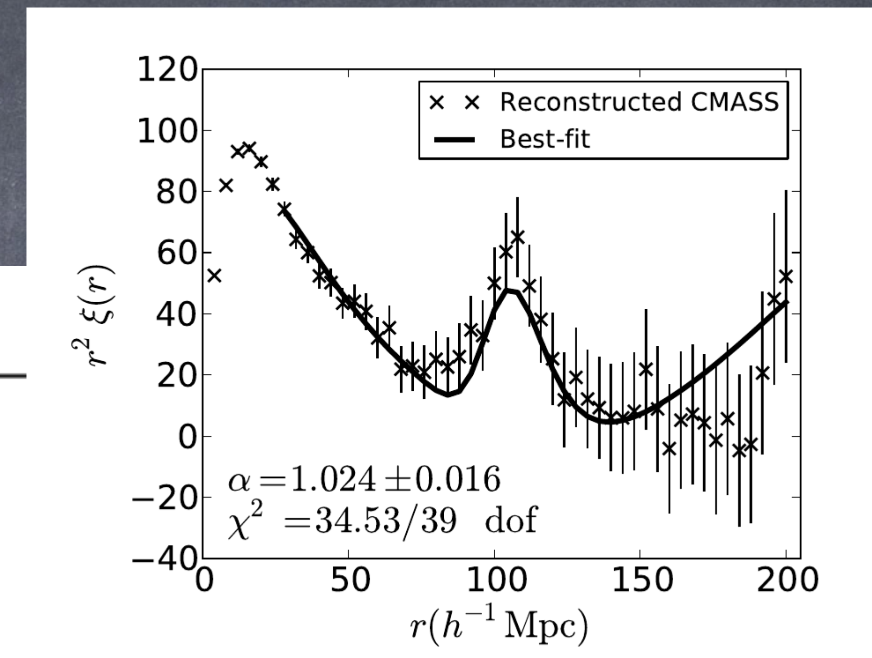
Expansion rate of the universe

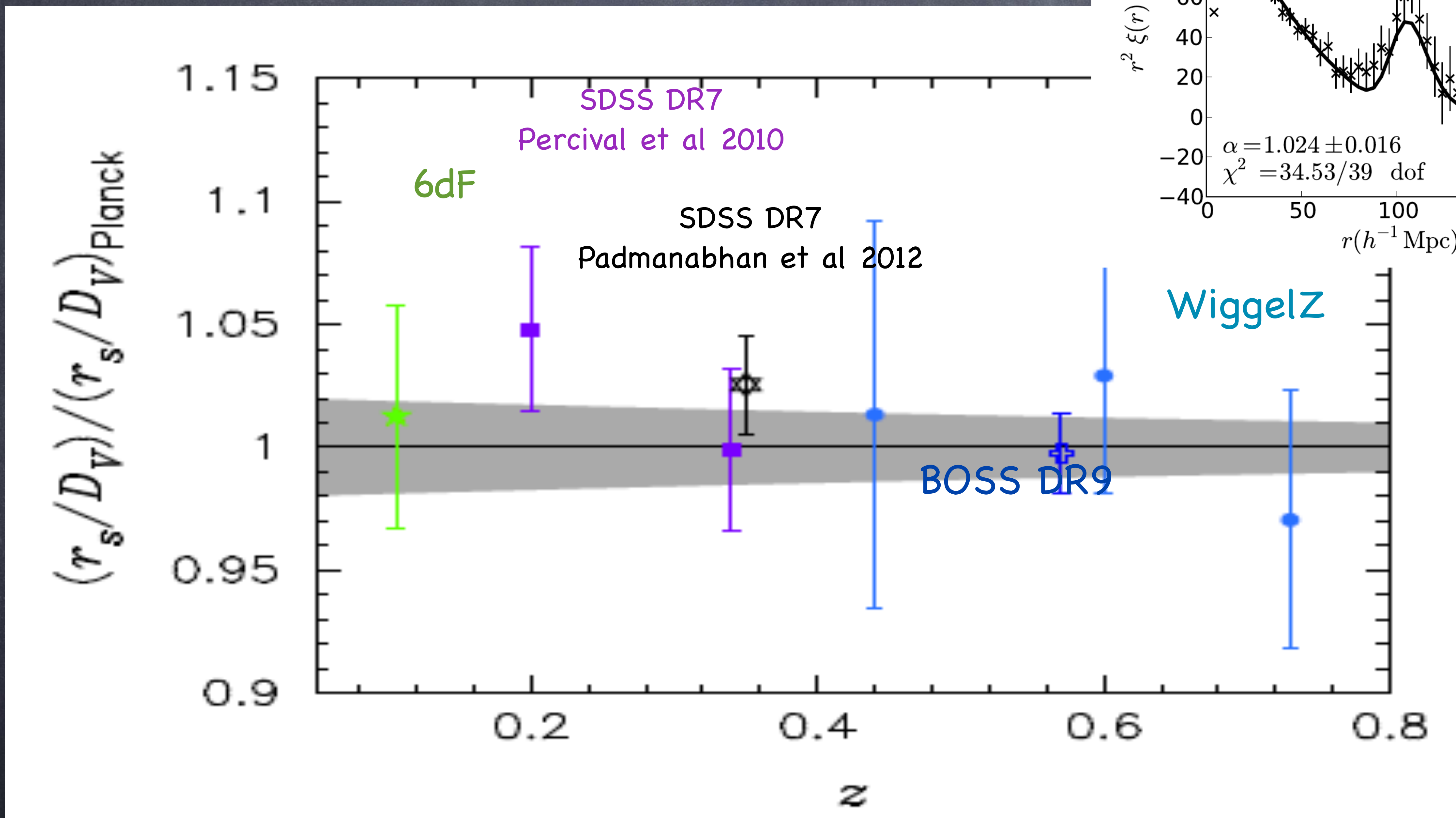




Planck best-fit model and BAO

Standard ruler

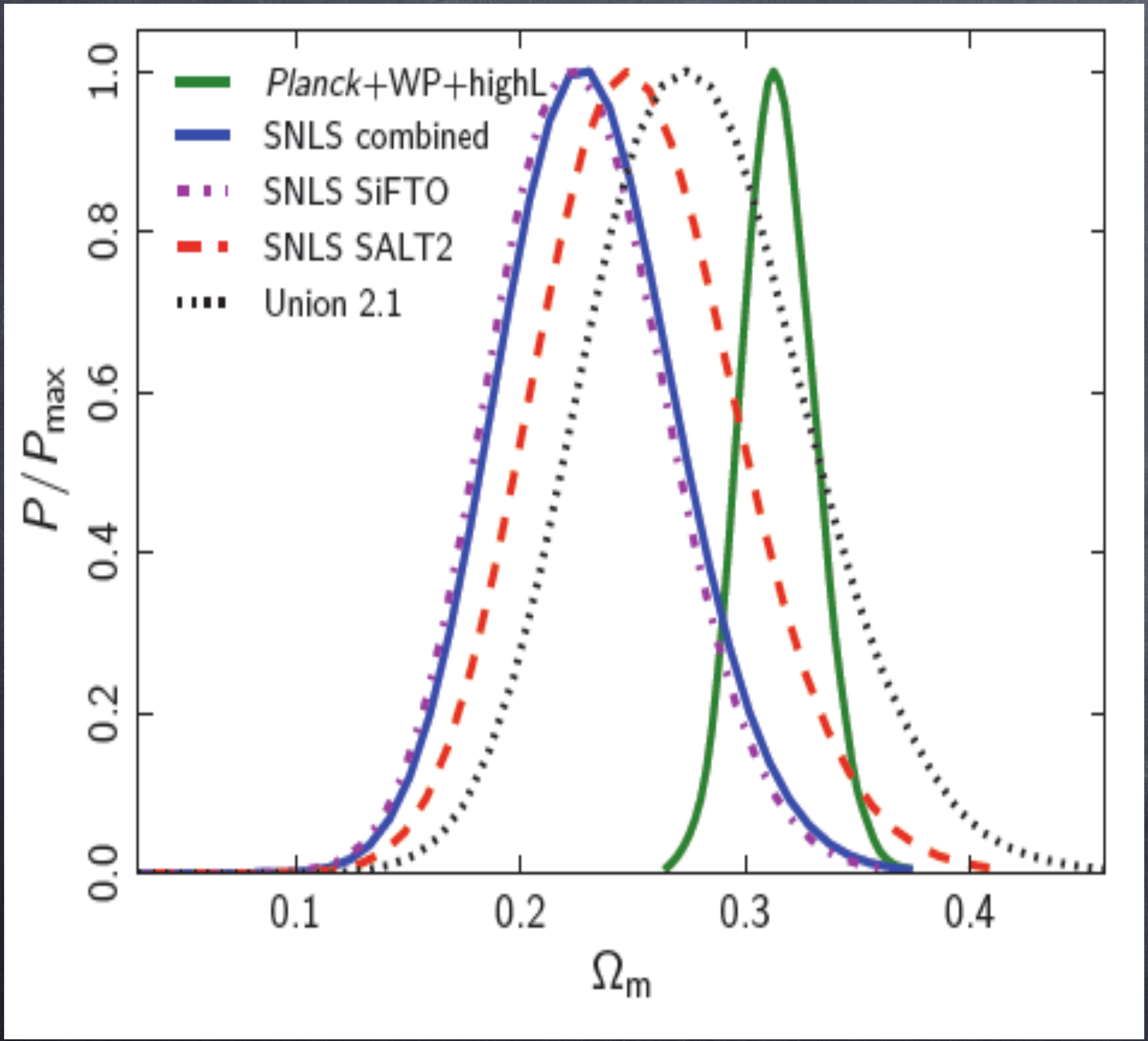




Current BAO data are in good agreement with Planck best-fit 6-parameter model

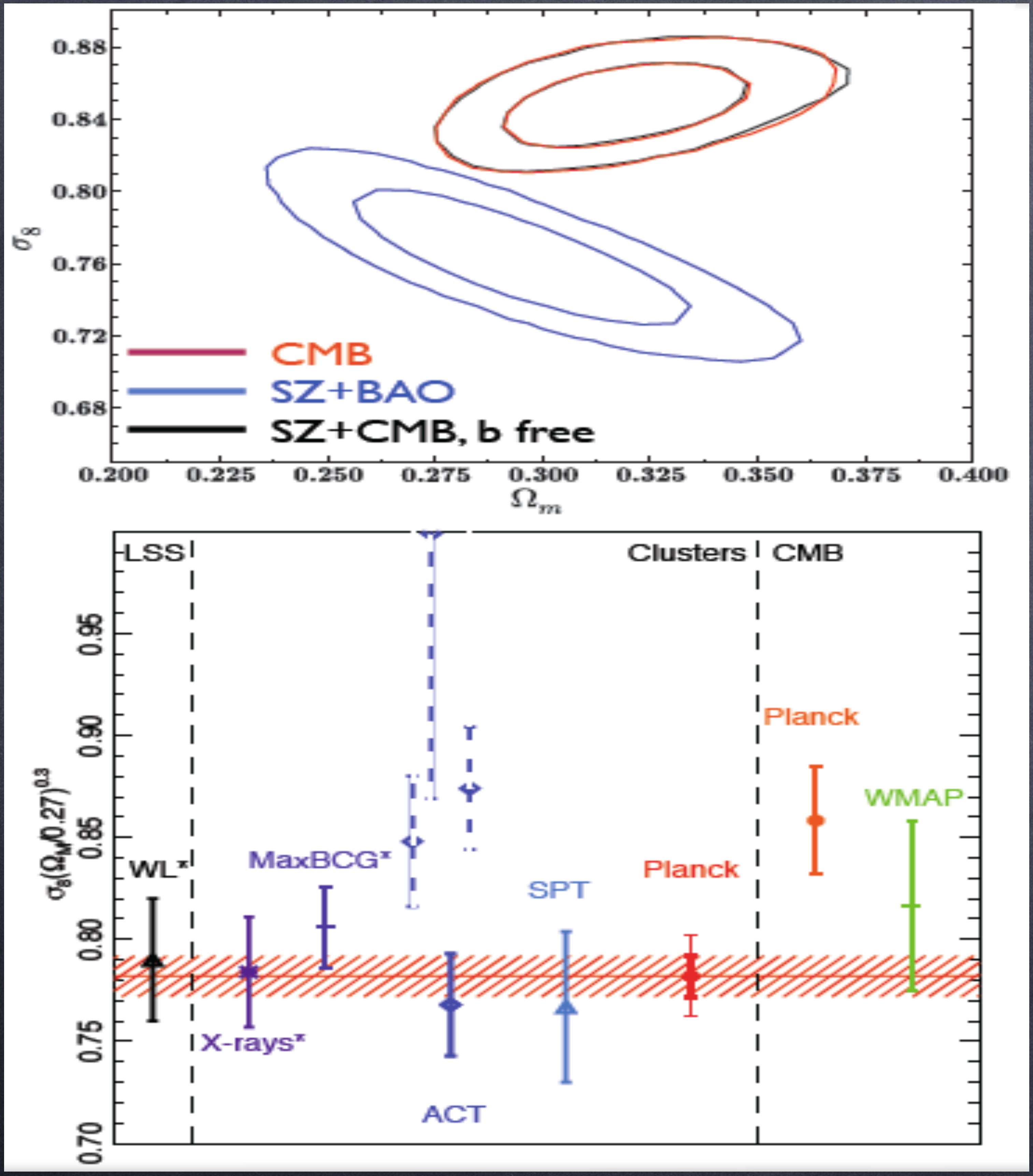
Supernovae

Standard candle allow to measure universe acceleration



Planck and supernovae come into agreement when we consider new calibration techniques for SN distances [Betoule et al 2012]

SZ effect on cluster of galaxies



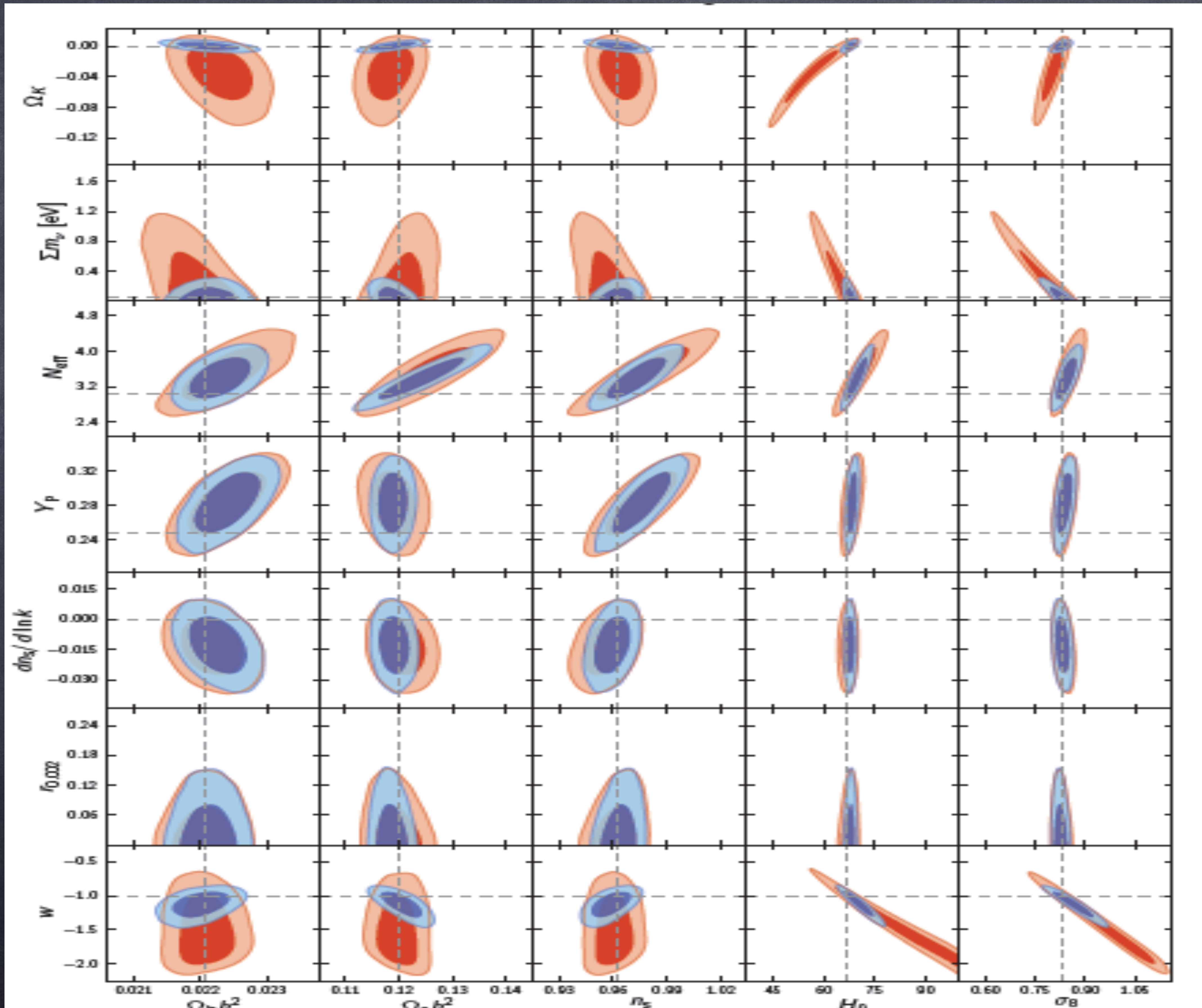
Planck reveals the importance of understanding cluster physics for cosmology

Extension of the base model

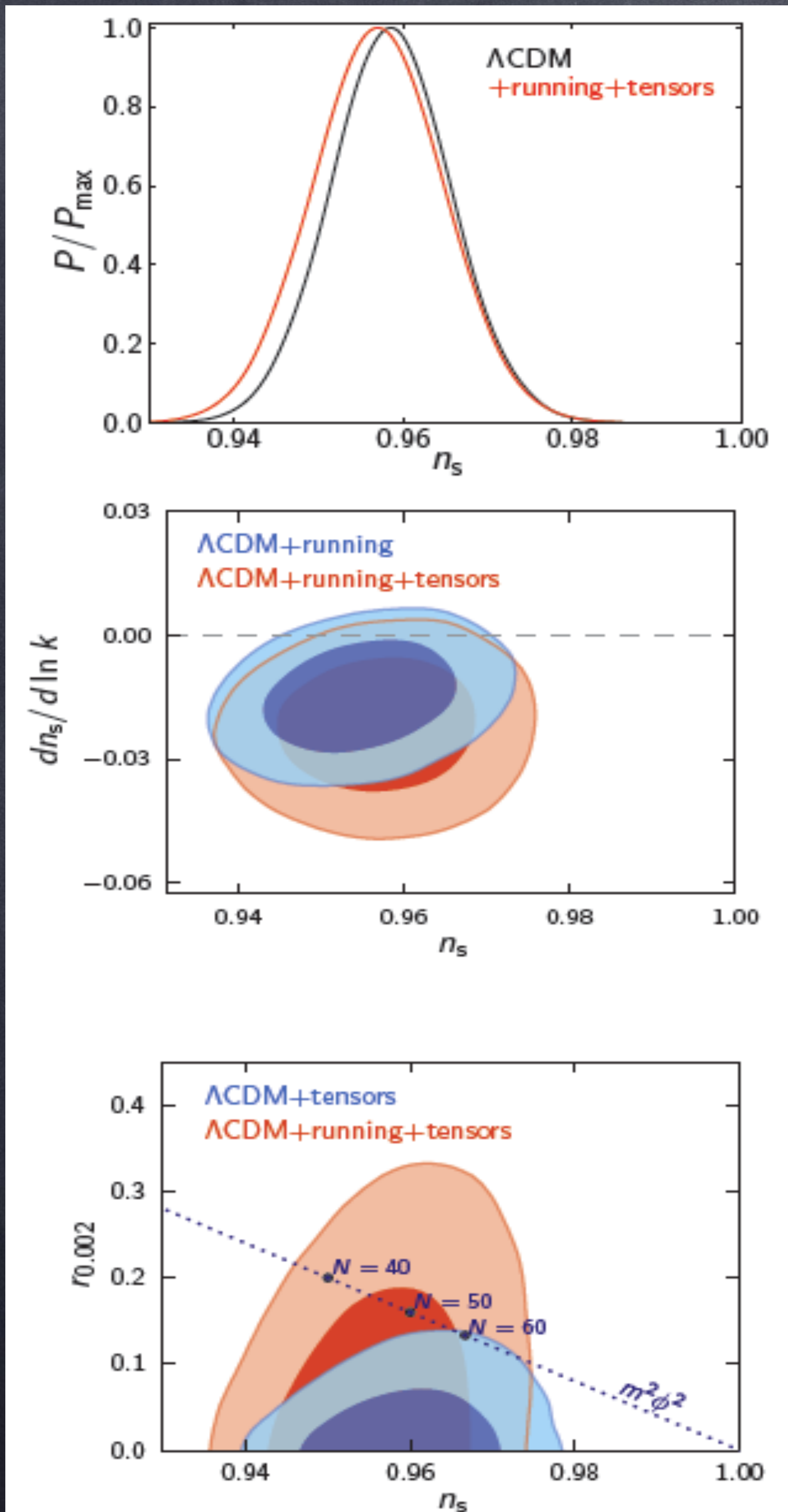
	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
N_{eff}	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
Y_{P}	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_s/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

➡The universe seems to be really flat
➡Dark energy equation of state compatible cosmological constant
➡Tight constraints on neutrino physics, total mass and number of neutrino species
➡Compatible with Big Bang nucleosynthesis

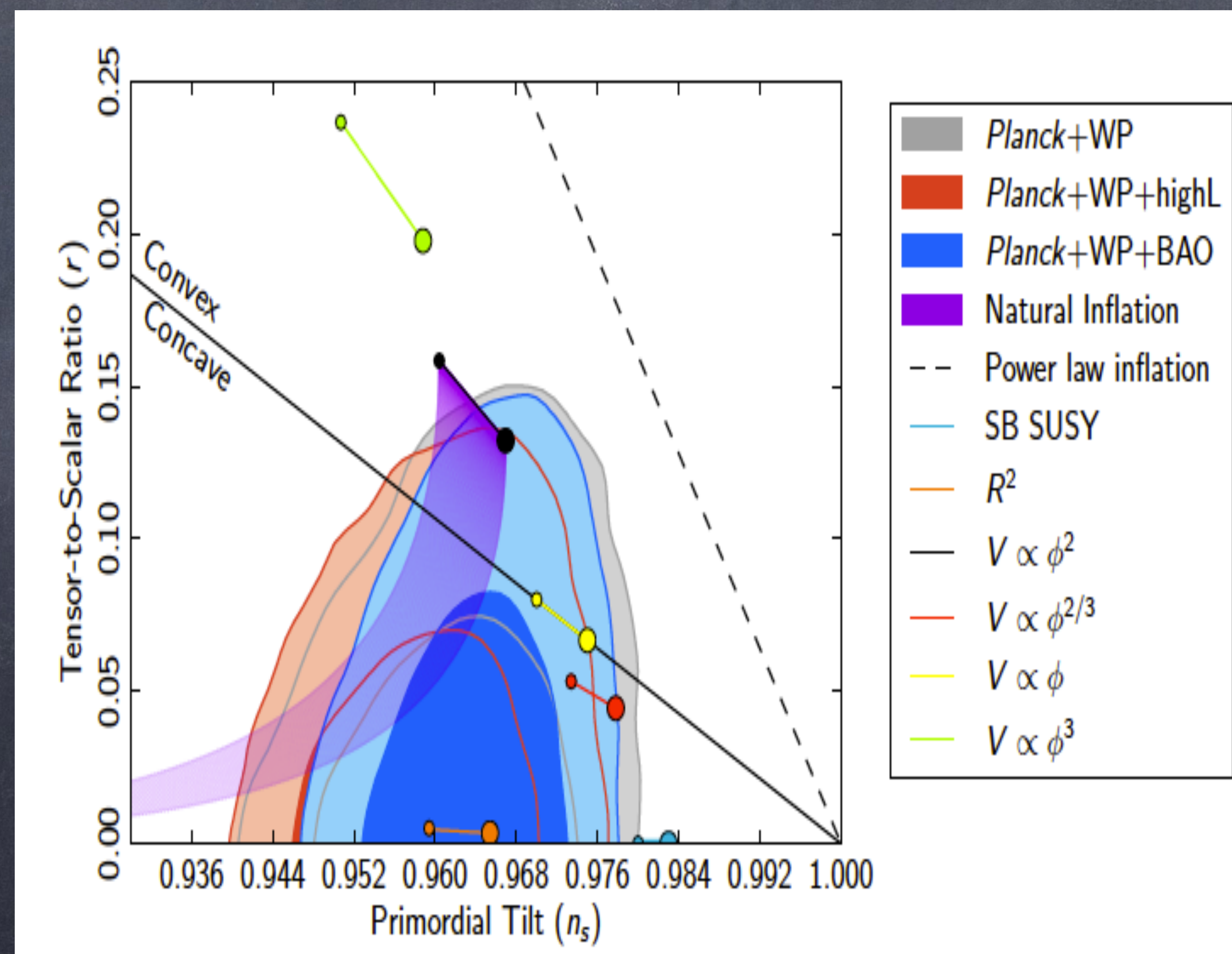
Joint BAO and CMB constraints



Constraints on inflationary physics

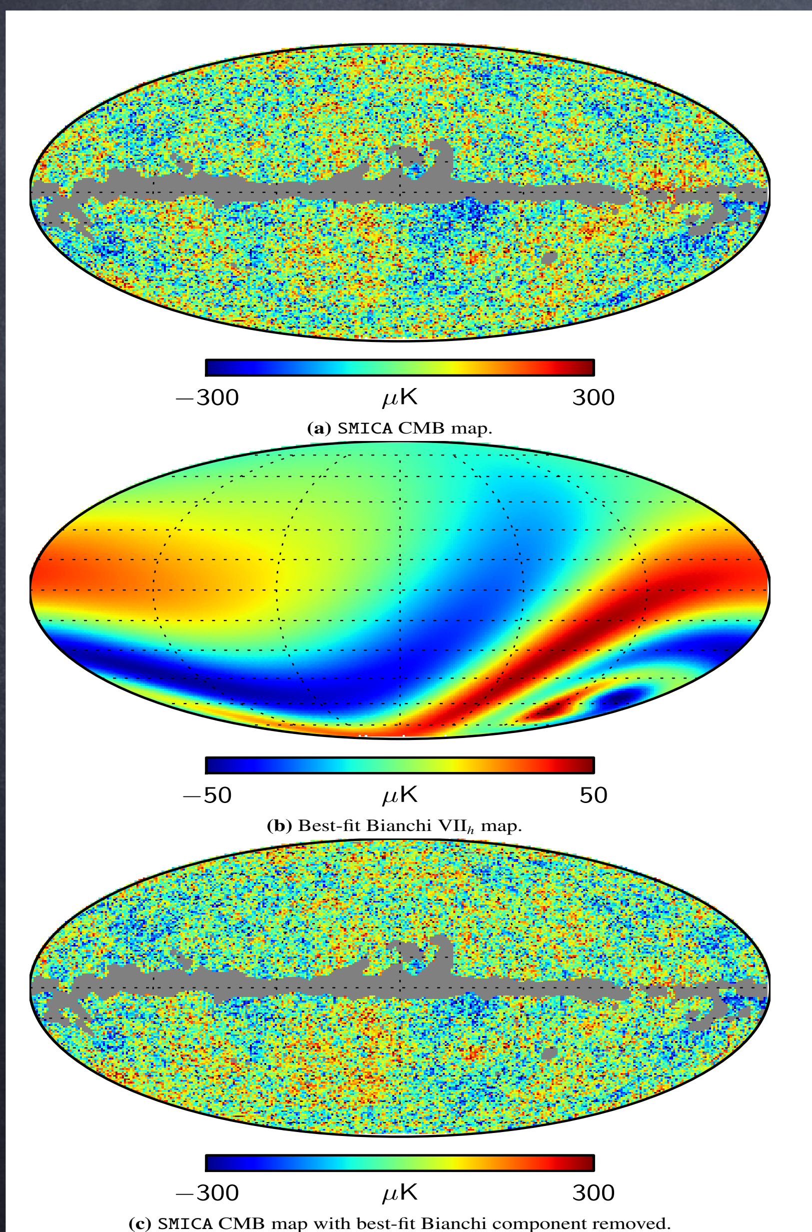


- Parameters of the model
  - n_S : spectral index of scalar perturbations
  - $dn_S/d\ln k$
  - n_T : tensor spectral index
  - r : tensor to scalar ratio
  - f_{NL} : non-linear paramter = non-gaussianity

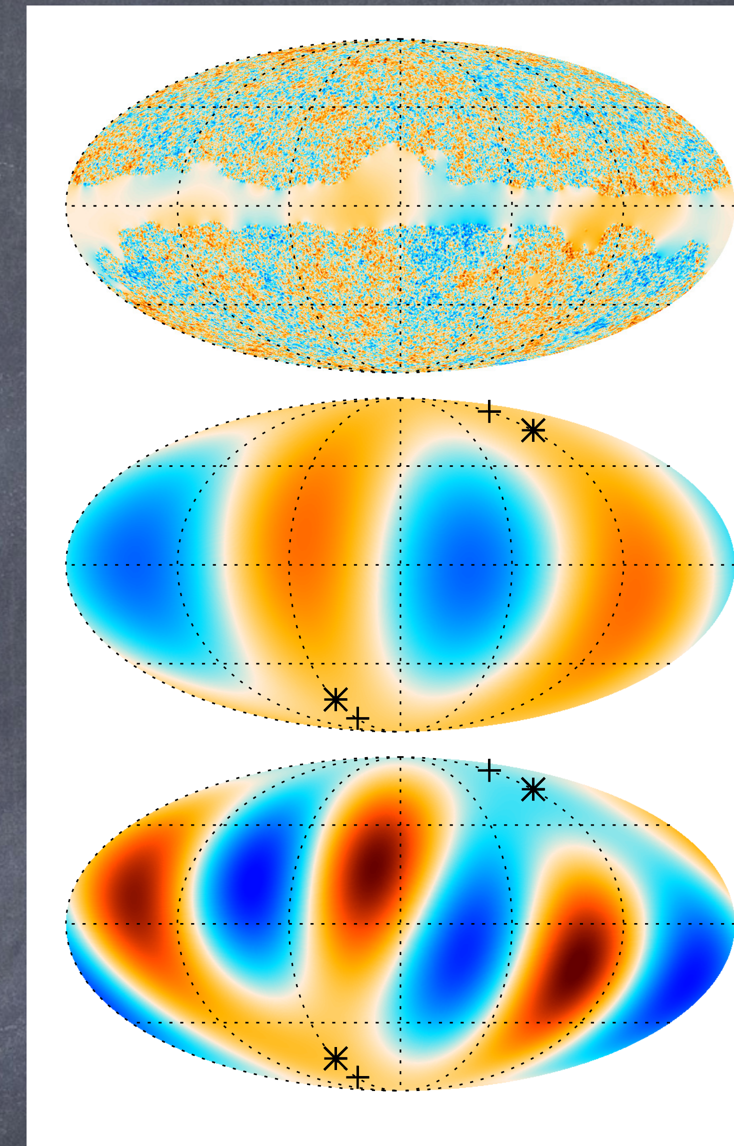


Non-Gaussianity and topology

- Primordial CMB as measured by Planck compatible with Gaussianity: $f_{NL}^{local} = 2.7 \pm 5.8,\ f_{NL}^{equil} = -42 \pm 75$, and $f_{NL}^{ortho} = -25 \pm 39$
- Detect non-Gaussian features from non-linear physics via ISW-lensing bispectrum



(a) SMICA CMB map.
(b) Best-fit Bianchi VII_h map.
(c) SMICA CMB map with best-fit Bianchi component removed.



- Evidence for north-south asymmetries, cold spot and octopole and quadripole alignment as in WMAP
- Topology might be complex

BACKUP

L'inflation

Guth 1981
Starobinsky 1982

Principe

Expansion accélérée de l'Univers qui permet de répondre aux problèmes du modèle de Big-Bang

$$\ddot{a}(t) > 0 \quad \Leftrightarrow \quad p < -\frac{\rho}{3}$$

CHAMPS SCALAIRE

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{(\nabla\phi)^2}{2a^2} + V(\phi)$$

$$p_\phi = \frac{1}{2}\dot{\phi}^2 - \frac{(\nabla\phi)^2}{6a^2} - V(\phi)$$

conditions de roulement-lent

$$\epsilon = \frac{m_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$\eta = m_{Pl}^2\left(\frac{V''}{V}\right) \ll 1$$

- Fluctuations quantiques produisent des perturbations gaussiennes
  - scalaires : fluctuations de densité
  - tensorielles: ondes gravitationnelles
  - vectorielles: vortex

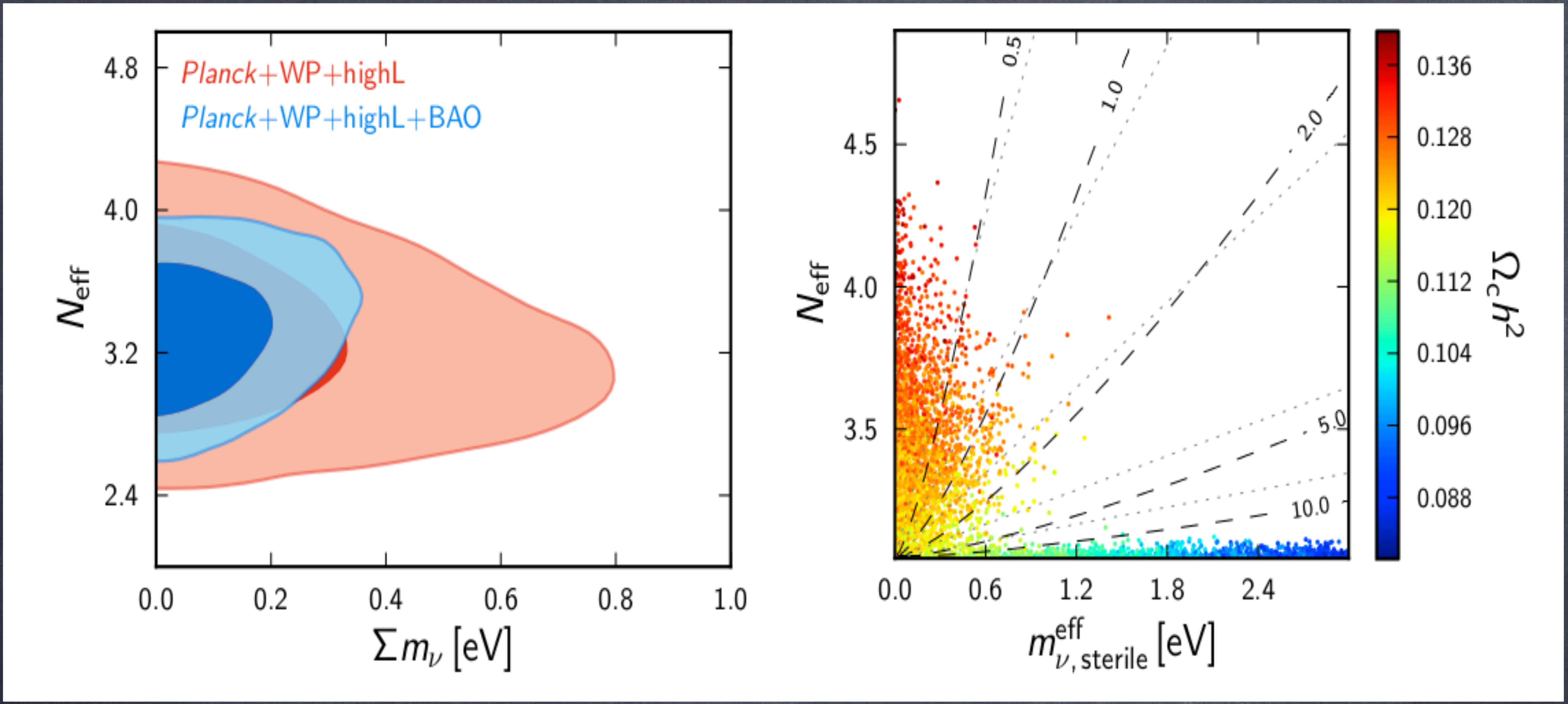
$$P_S(k) = \left(\frac{H^2}{2\pi\dot{\phi}^2}\right)^2 \left(\frac{k}{aH}\right)^{n_S-1}$$

$$P_T(k) = \frac{8}{m_{pl}^2}\left(\frac{H^2}{2\pi}\right)\left(\frac{k}{aH}\right)^{n_T}$$

- Paramètres du modèle
  - n_S : indice spectral du spectre perturbations scalaires
  - n_T : indice spectral du spectre perturbations tensorielles
  - r : rapport tenseurs-scalaires
  - f_{NL} : paramètre de couplage non-linéaire

Liddle & Lyth 2000

Neutrino physics

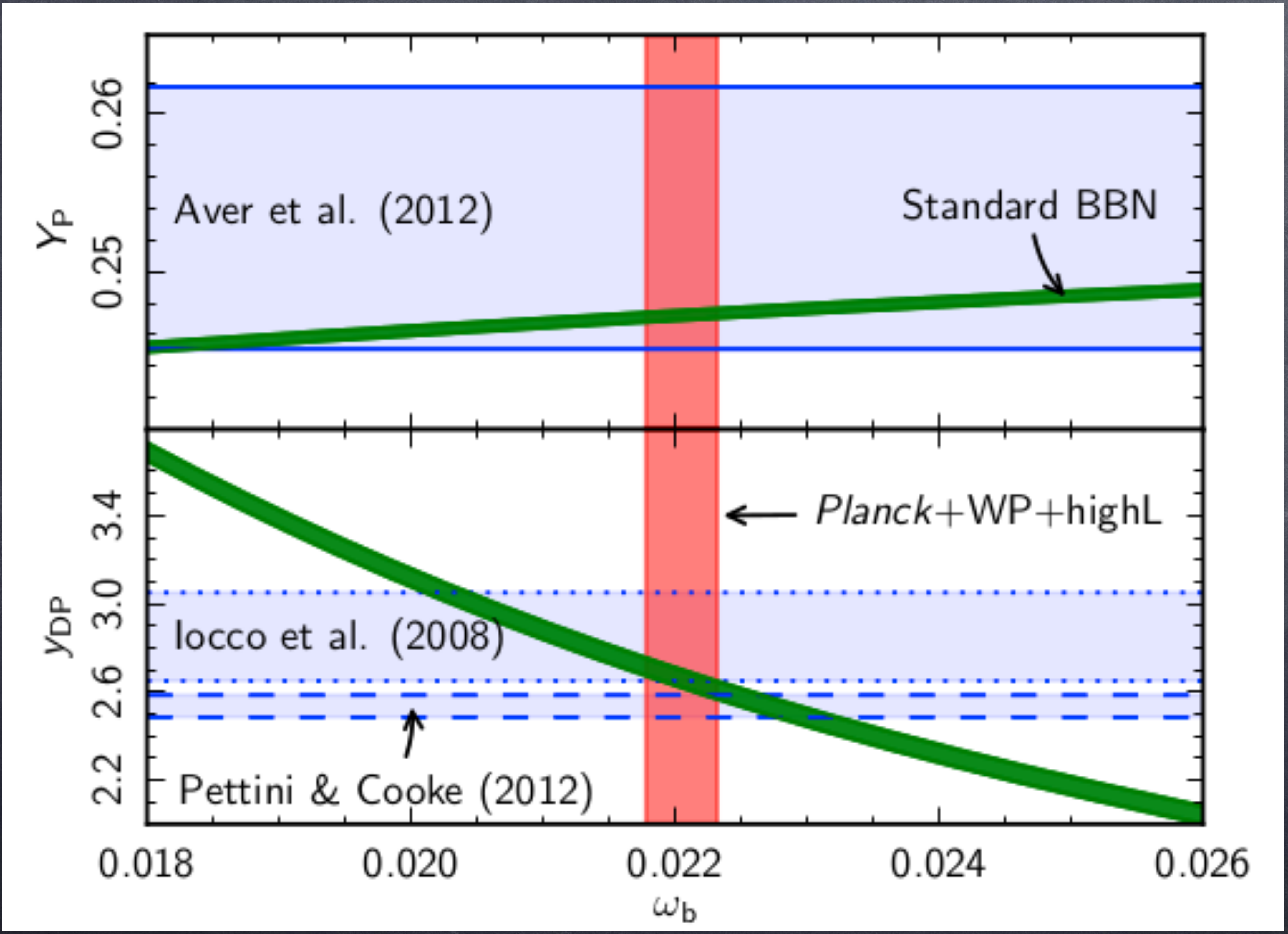


➡ Neff = 3.30 + 0.54 - 0.51 (95 % C.L.)

➡ Neff<3.8 & m(sterile nu)<0.42 eV (95%) put pressure on evidence of a light sterile neutrino (mini-BooNE (1 eV2) and neutrino reactor anomaly experiments)

➡Tight constraints on the sum of neutrino masses $\sum m_\nu$

Primordial nucleosynthesis



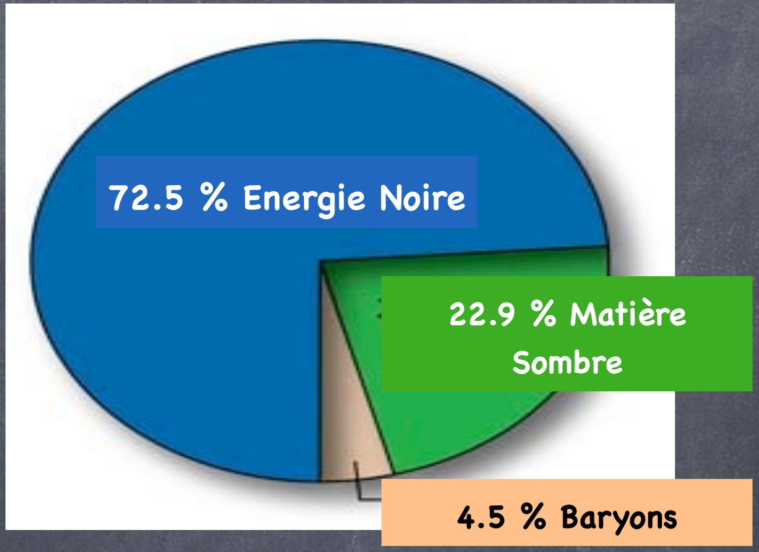
Contraintes sur les paramètres cosmologiques avant Planck

CMB + diagramme de Hubble de Supernova de type I + spectre de matière et BAO + constante de Hubble

CMB [Komatsu et al. 2011, Dunkley et al. 2010]; Supernova [Reiss et al. 1998, Perlmutter et al. 1999]; Pk et BAO [*Eisenstein et al. 2005, Padmanabhan et al. 2006, Sanchez et al. 2006, Blake et al. 2007*] ; *Hubble constant [Freedman et al. 2001, Riess et al. 2009].*

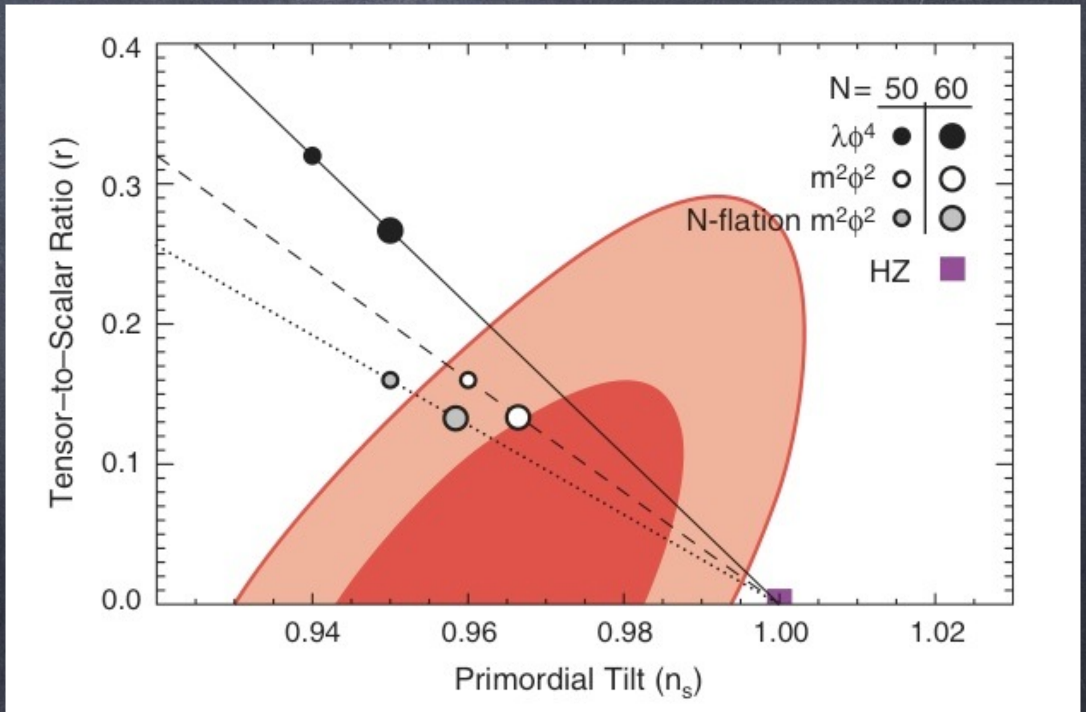
✓ **Le modèle Λ-CDM plat ajuste bien les données:**

Ω_Λ = 0.725 ± 0.016, Ω_{CDM} = 0.229 ± 0.015,
Ω_b =0.0458±0.0016, H_0 =70.2±1.4, n_s=0.968±0.012,
τ_{reio}=0.088±0.014 et σ_8 =0.816±0.024,
t_0 = 13.76 ± 0.11 Gyr, z_{reion} = 10.6 ± 1.2



✓ **Contraintes fortes sur les modèles d'inflation (ou autres alternatives):**

n_s=0.968±0.012, r < 0.19 (95 %CL),
$-0.061 < dn_s/d\ln k < 0.017$



✓ **Equation d'état de l'énergie noire**

w= -1.10 ± 0.14 (constant) ; w_0 = -0.93 ± 0.13 et w_a = -0.41 ± 0.71
$w = w_0 + w_a (1-a)$

✓ **Neutrinos et nucléosynthèse**

N_{eff}= 4.6 ± 0.8, Σm_ν < 0.44 eV (95%CL), Y_P= 0.313 ± 0.044