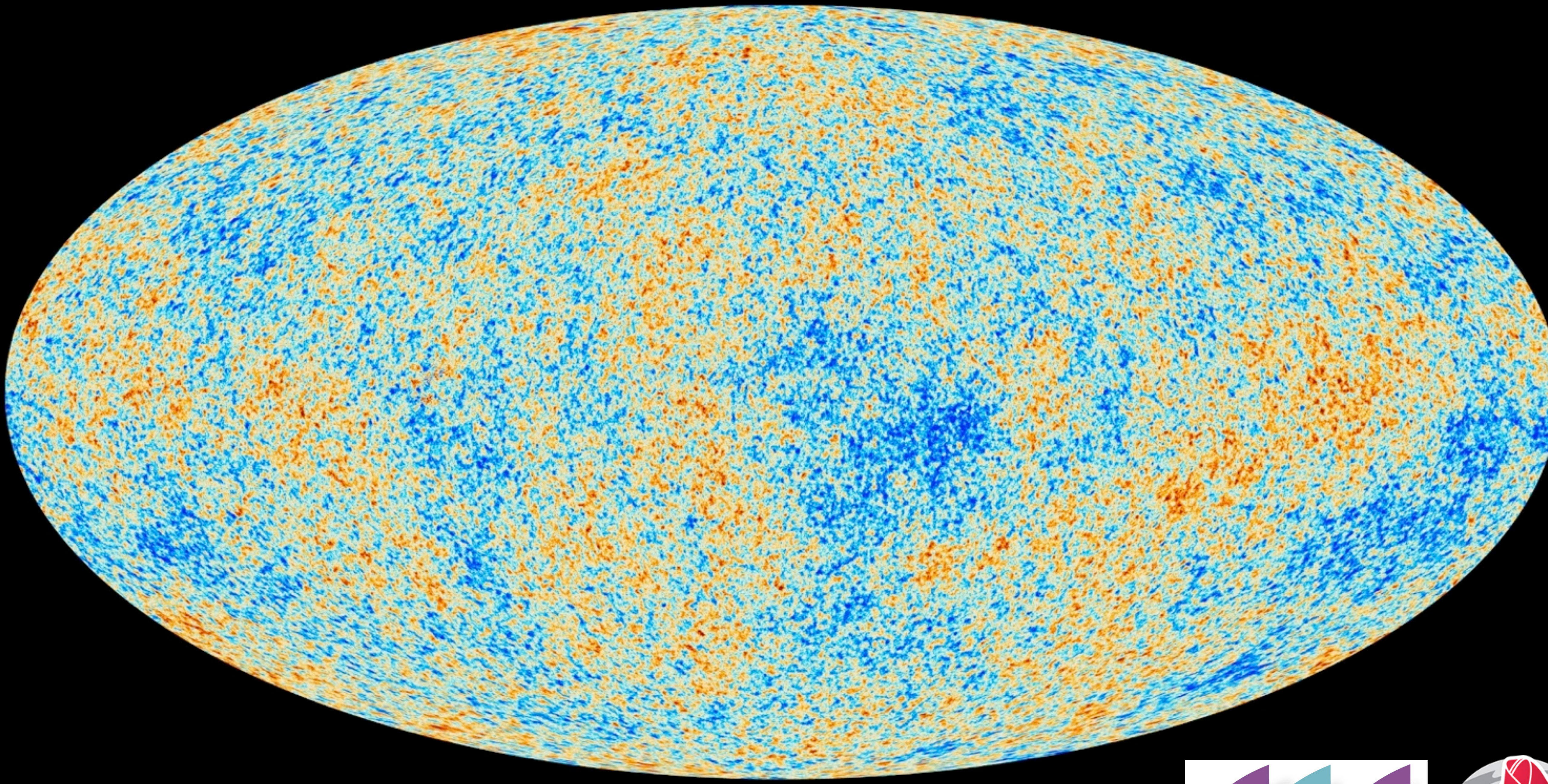
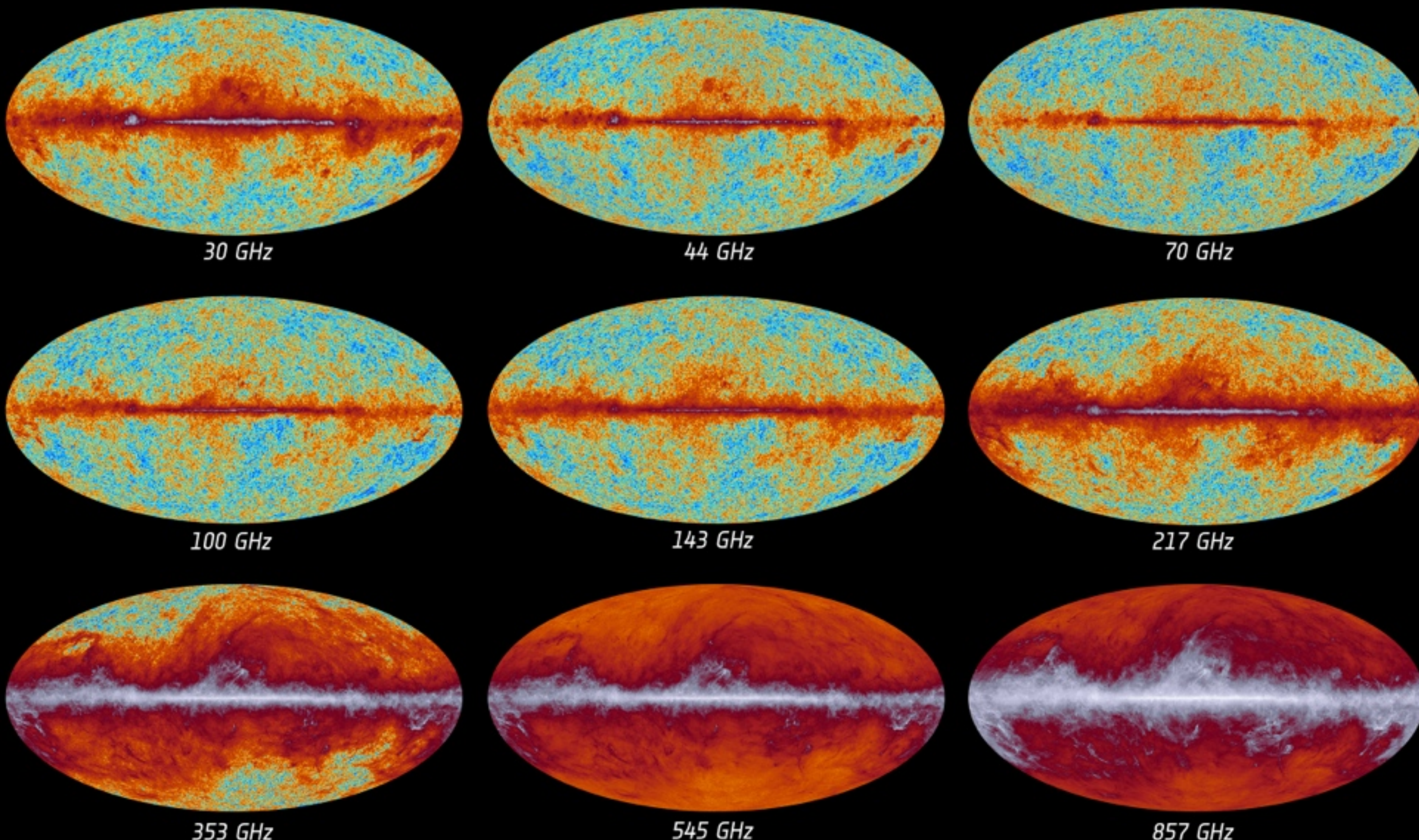
# Constraints on cosmology from the cosmic microwave background power spectrum measured by the Planck mission

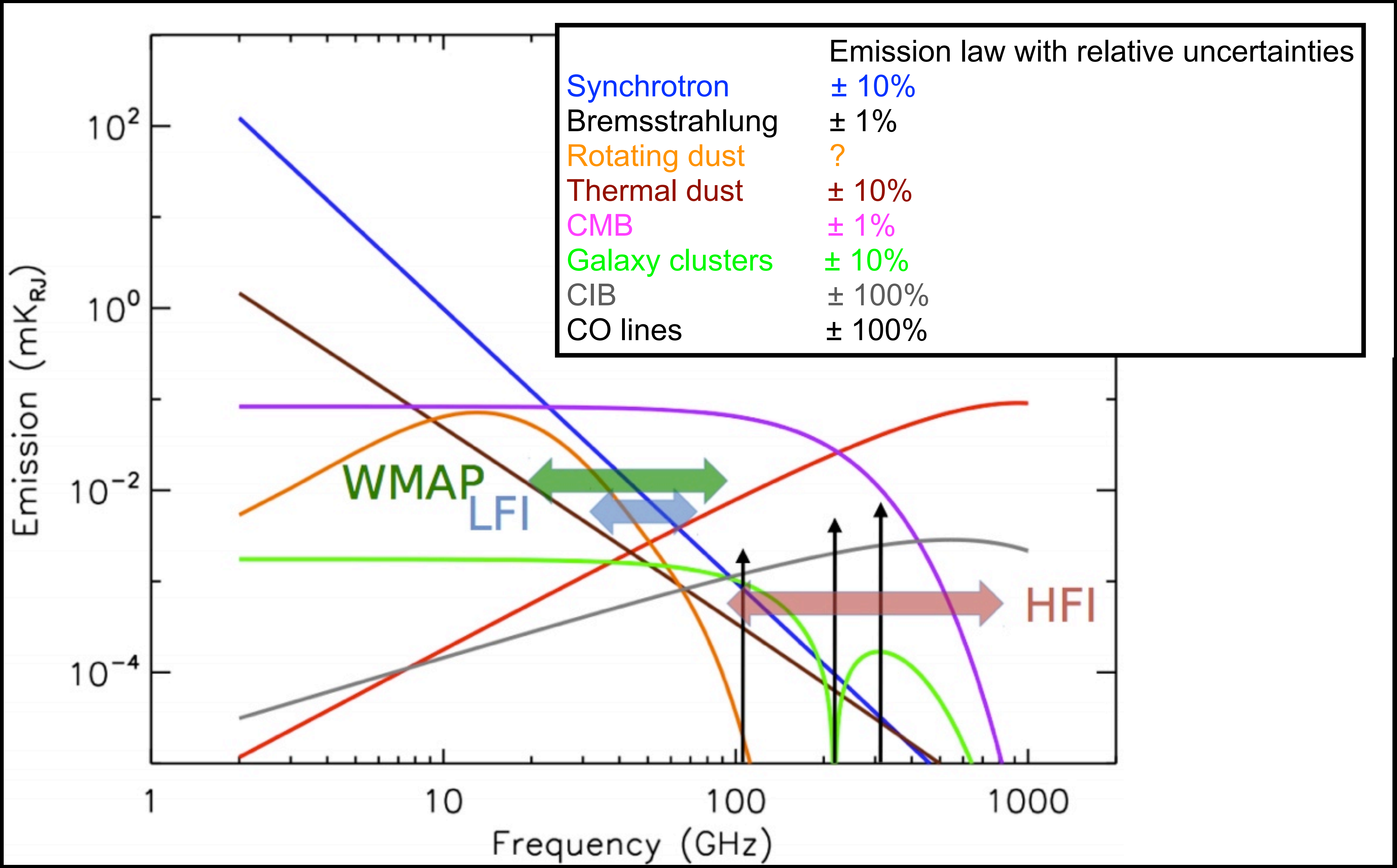


B. Rouillé d'Orfeuil for the Planck Collaboration
22ème Congrès Général de la SFP

# Actually what we really see is...



# CMB and foregrounds




CMB channels: 70 (LFI), 100, 143 and 217 (HFI) GHz

# How to analyze? *Planck* likelihood

Low-$l$ : $l$ < 50, pixel-based approach

- component separation on low resolution map
- uses ~90% of the sky

High-$l$ : 50 ≤ $l$ ≤ 2500, pseudo cross-power spectra

- we use the cleanest channels and apply big masks
- we have to deal with unresolved foregrounds (PS,SZ,CIB) and instrumental systematics (relative calibration factors, beams errors)

$$-2ln\mathcal{L} = \sum_{\ell=\ell_{min}}^{\ell_{max}} (C_\ell^{model} - C_\ell^{data})^t \Sigma^{-1} (C_\ell^{model} - C_\ell^{data})$$

what we are interested in

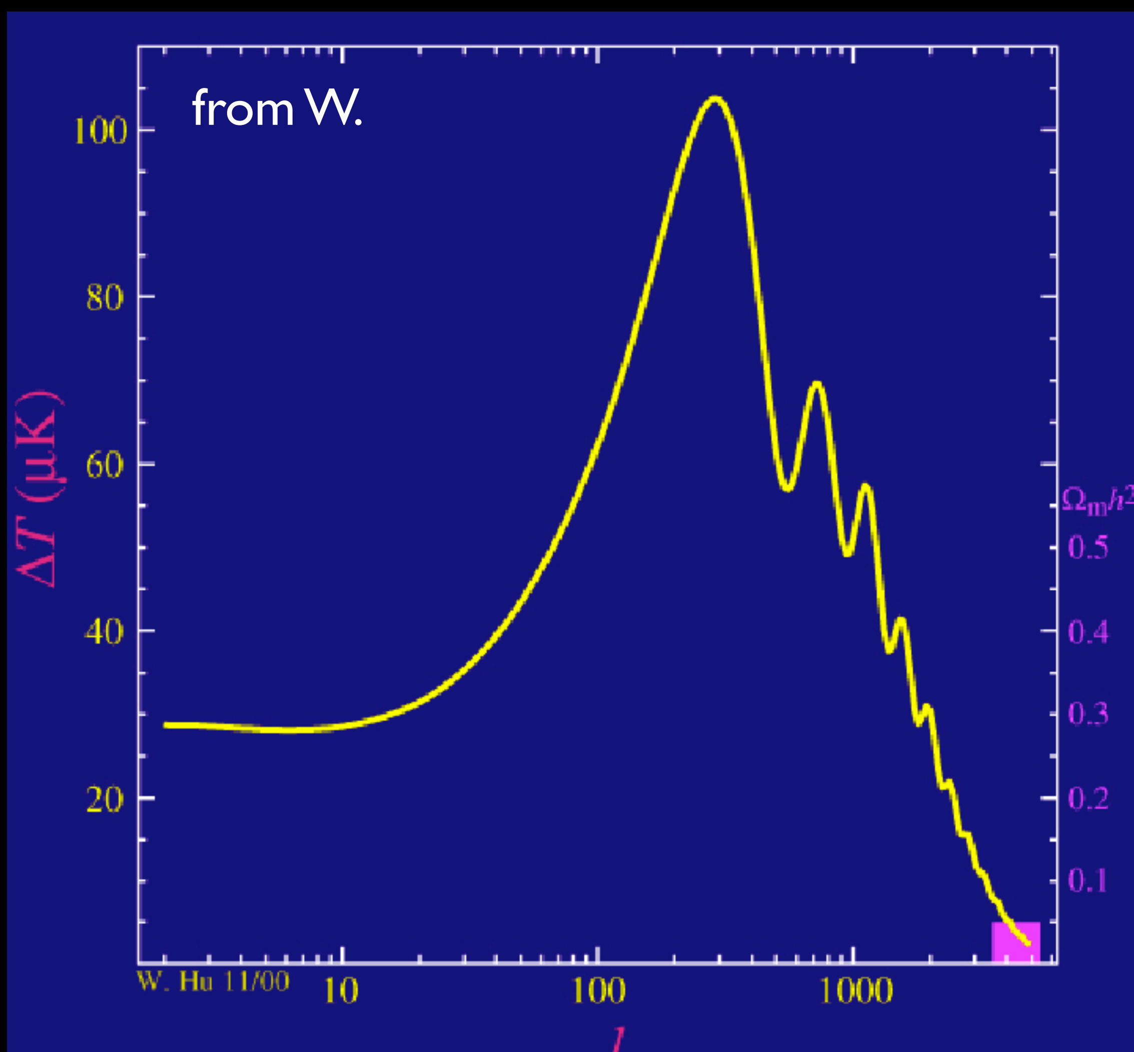
with: $C_\ell^{model} = (c^i c^j)(1 + \beta^{ij}\mu_\ell^{ij})(C_\ell^{CMB} + C_\ell^{PS} + C_\ell^{SZ} + C_\ell^{CIB})$

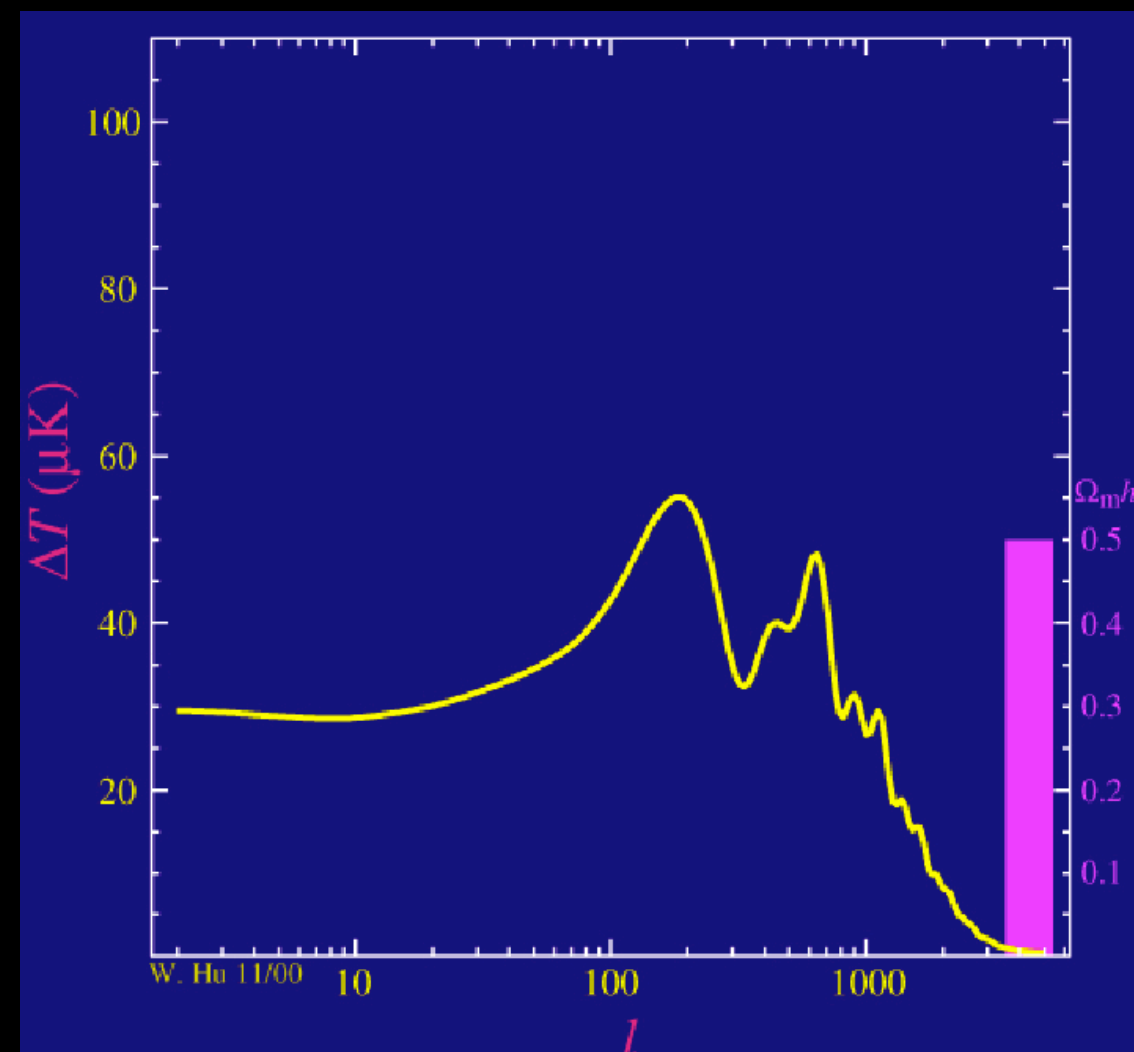
from instrument

from foregrounds

# CMB power spectrum

- Different theories lead to different predictions about what the CMB map should statistically look like
- Gives us a way to figure out what the Universe is like




To illustrate: increasing $\Omega_{cdm}$ at fixed $\Omega_b$

# The ΛCDM model

Simplest model (6 parameters)
Consistent with all cosmological observations so far

2 parameters control the primordial density spectrum: $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$

3 parameters control background dynamics: $\Omega_b h^2$ (baryons), $\Omega_c h^2$ (cold dark matter), $H_0$ (Hubble)

optical depth $\tau$ due to reionization (how much CMB gets lost on its way to us)

And a bunch of assumptions (which can be tested: '*extensions to ΛCDM*')

$\Omega_k = 0$ (flatness)

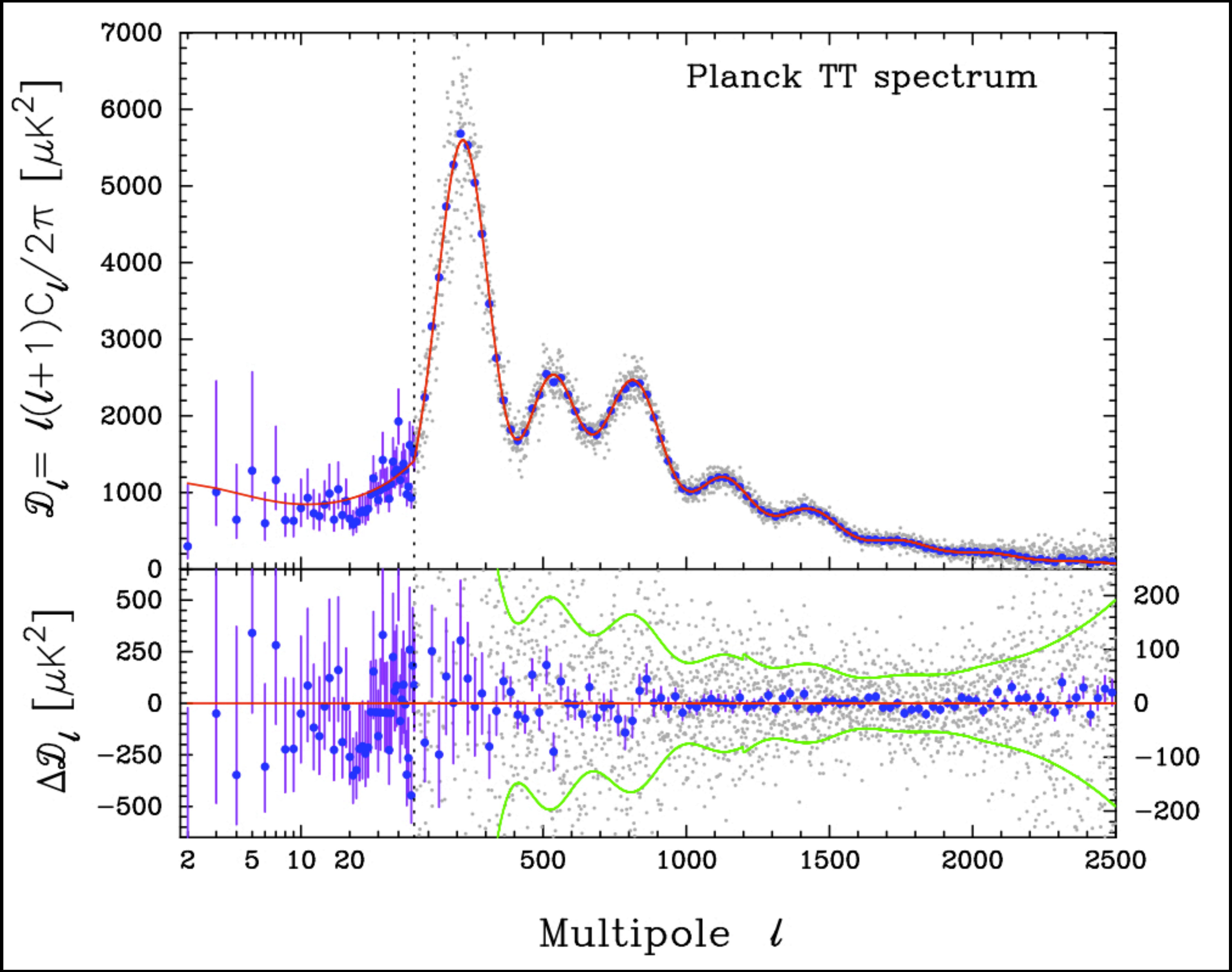
$\mathcal{P}_t(k) = A_t \left(\frac{k}{k_0}\right)^{n_t} = 0$ (no tensor power)

$\mathrm{d}n_s/\mathrm{d}\ln k = 0$ (no running)

$\sum m_\nu = 0.06\ \mathrm{eV}$ (negligible mass)

$N_{\mathrm{eff}} = 3.046$ (no extra relativistic species)

# *Planck* 2013 with the vanilla ΛCDM



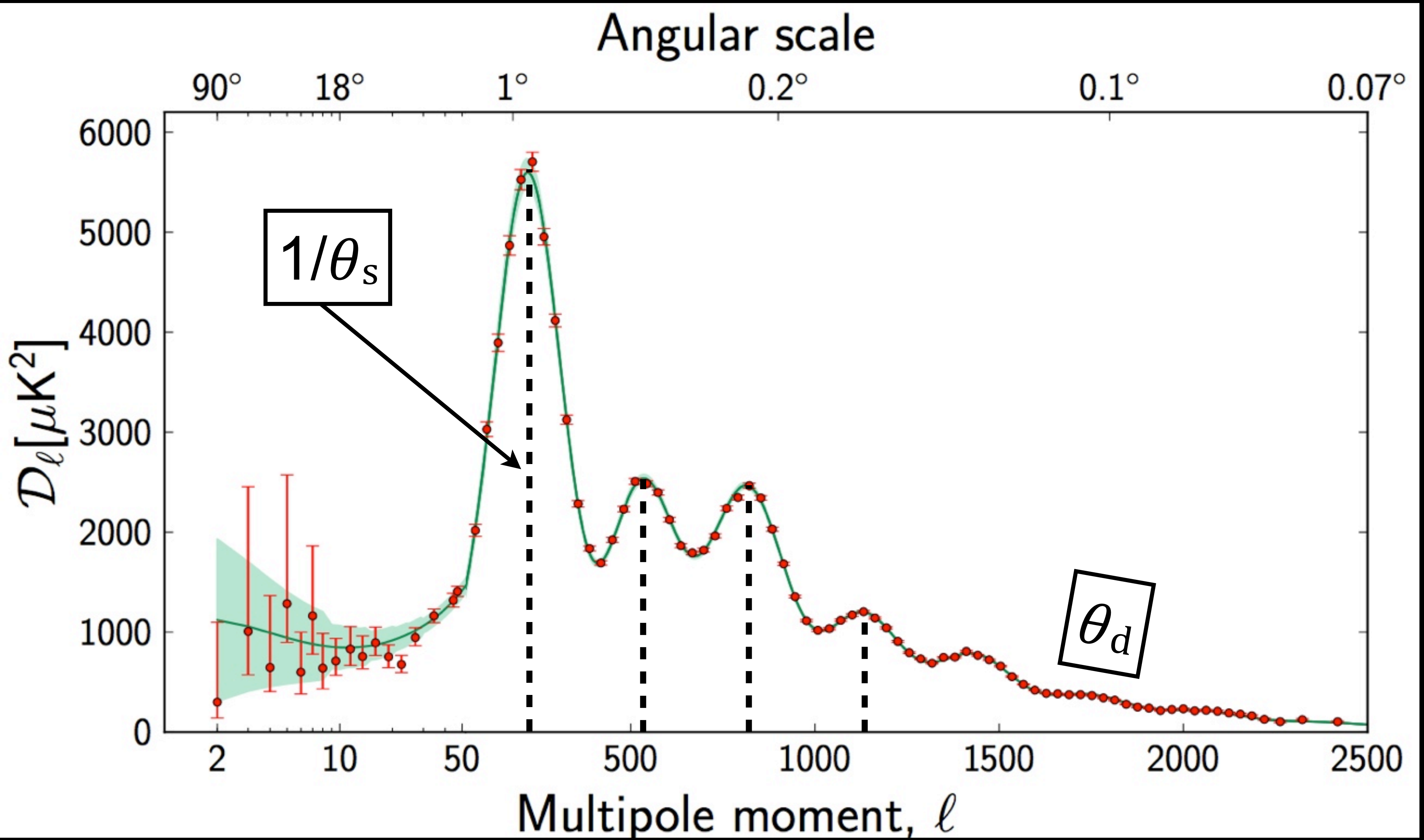
# Number of relativistic species $N_{eff}$

Standard value = 3.046:

3 neutrino species + energy injected by $e^+e^-$ annihilation

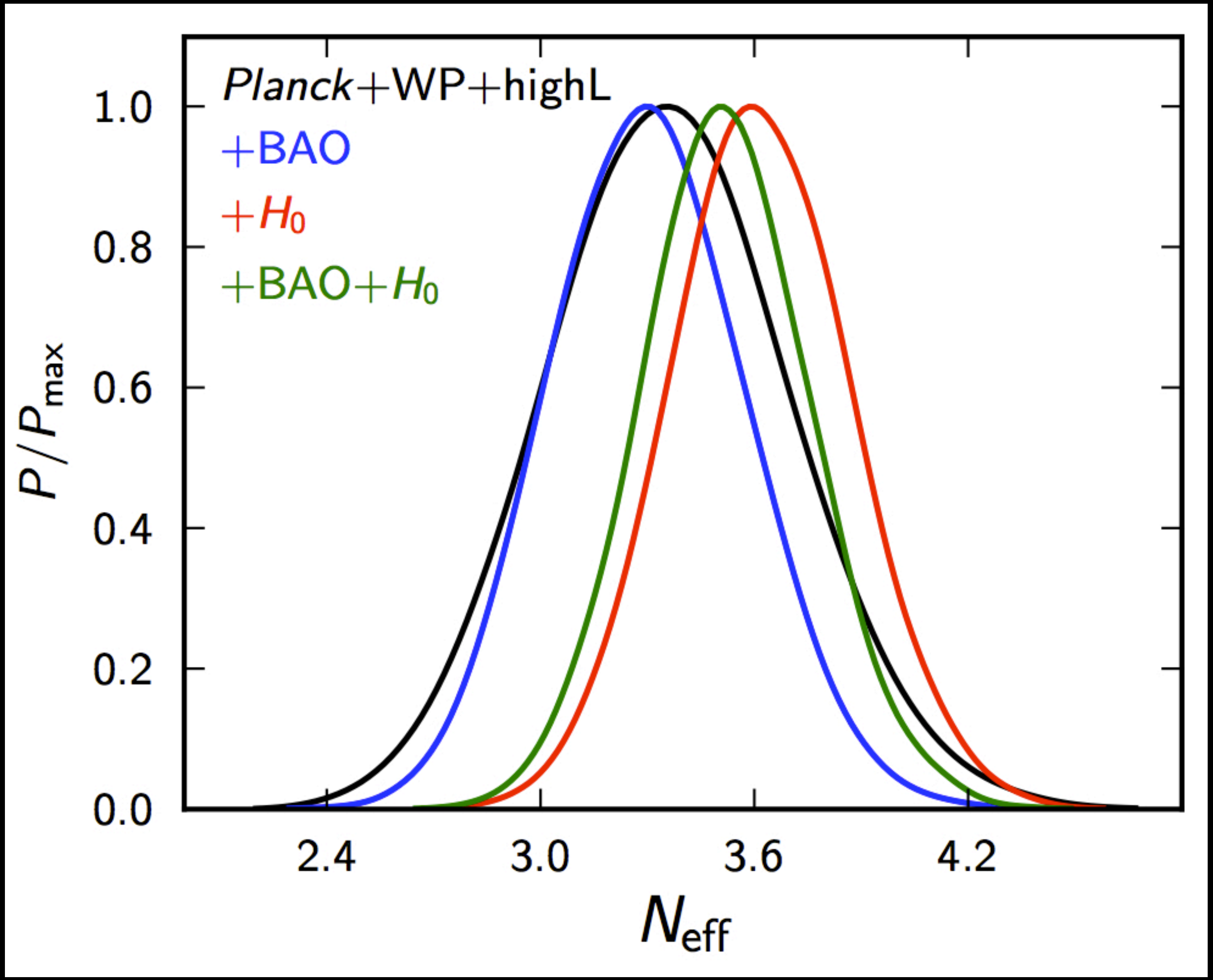
Affects the expansion rate in primordial Universe:

$N_{eff} \leftrightarrow \theta_d/\theta_s \propto H^{0.5}$



# $N_{eff}$ from CMB

- Mild preference for $N_{eff} > 3.046$ suggested from recent CMB anisotropy measurements (WMAP/ACT/SPT)
- *Planck* results:



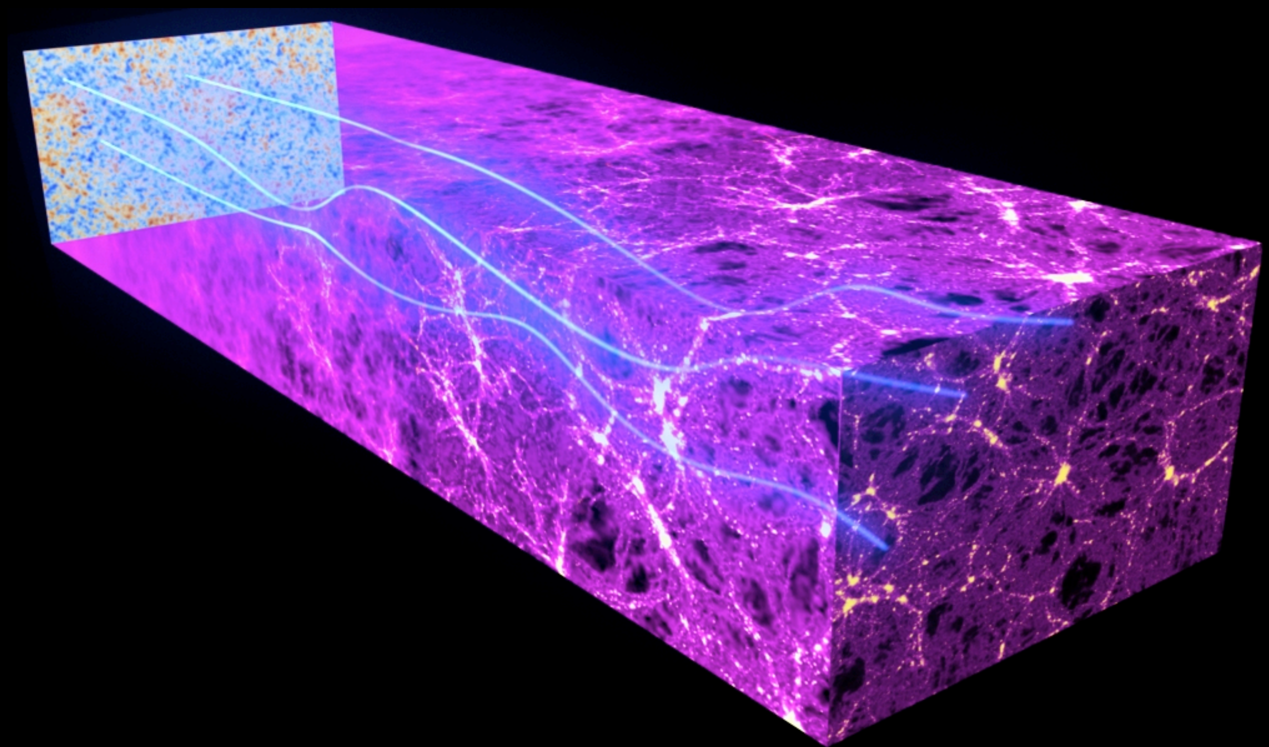

$$N_{\rm eff} = 3.30 \pm 0.27 \quad +{\rm BAO}$$

# Total mass of active neutrinos: $M_\nu$

- $\nu$ oscillations → $\nu$ are massive
- Universe cooled → $\nu$ transitioned to non-relativistic

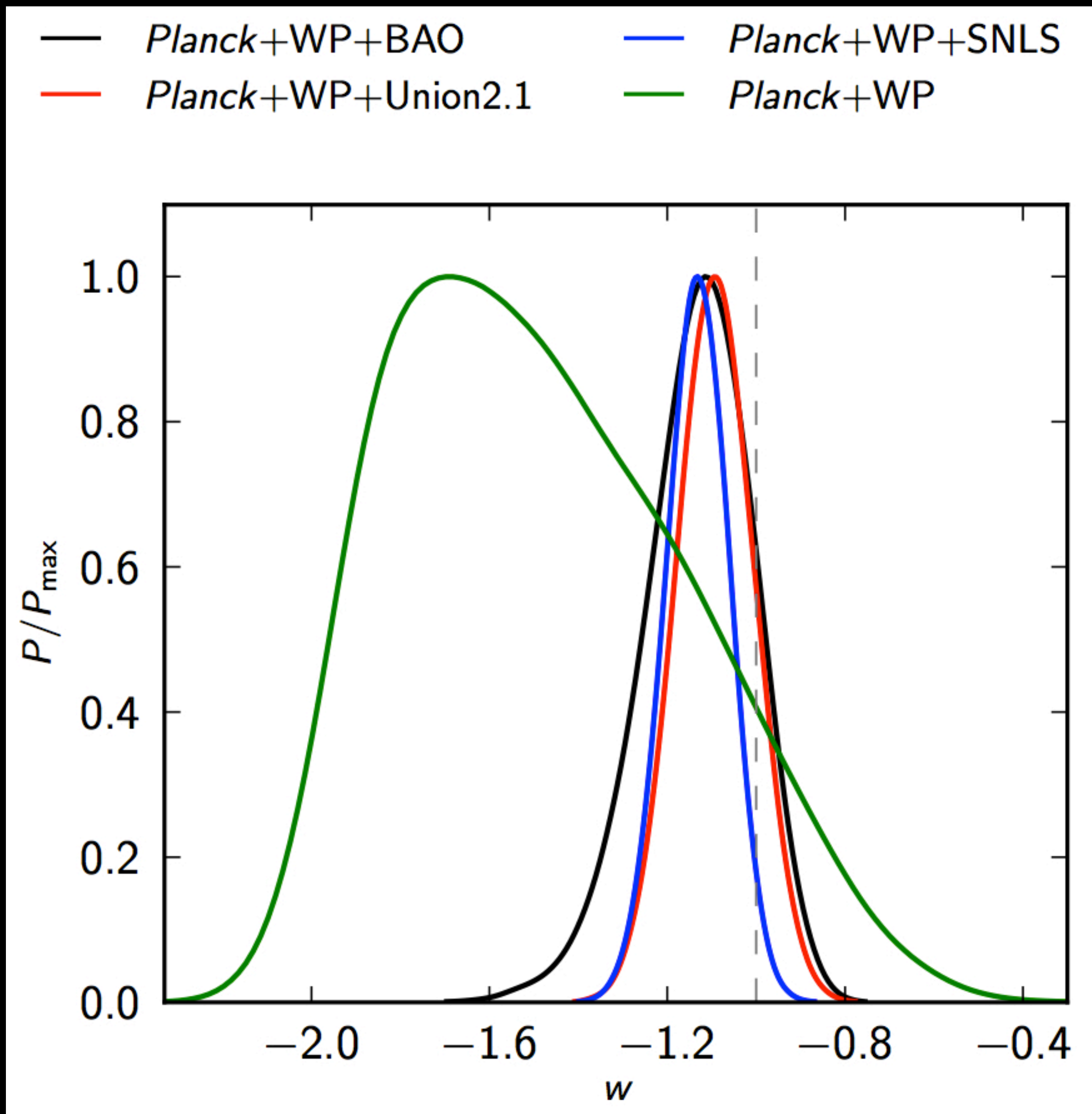
➡ $\nu$ contribute to $\Omega_m$ but not to structure formation below their free streaming scale

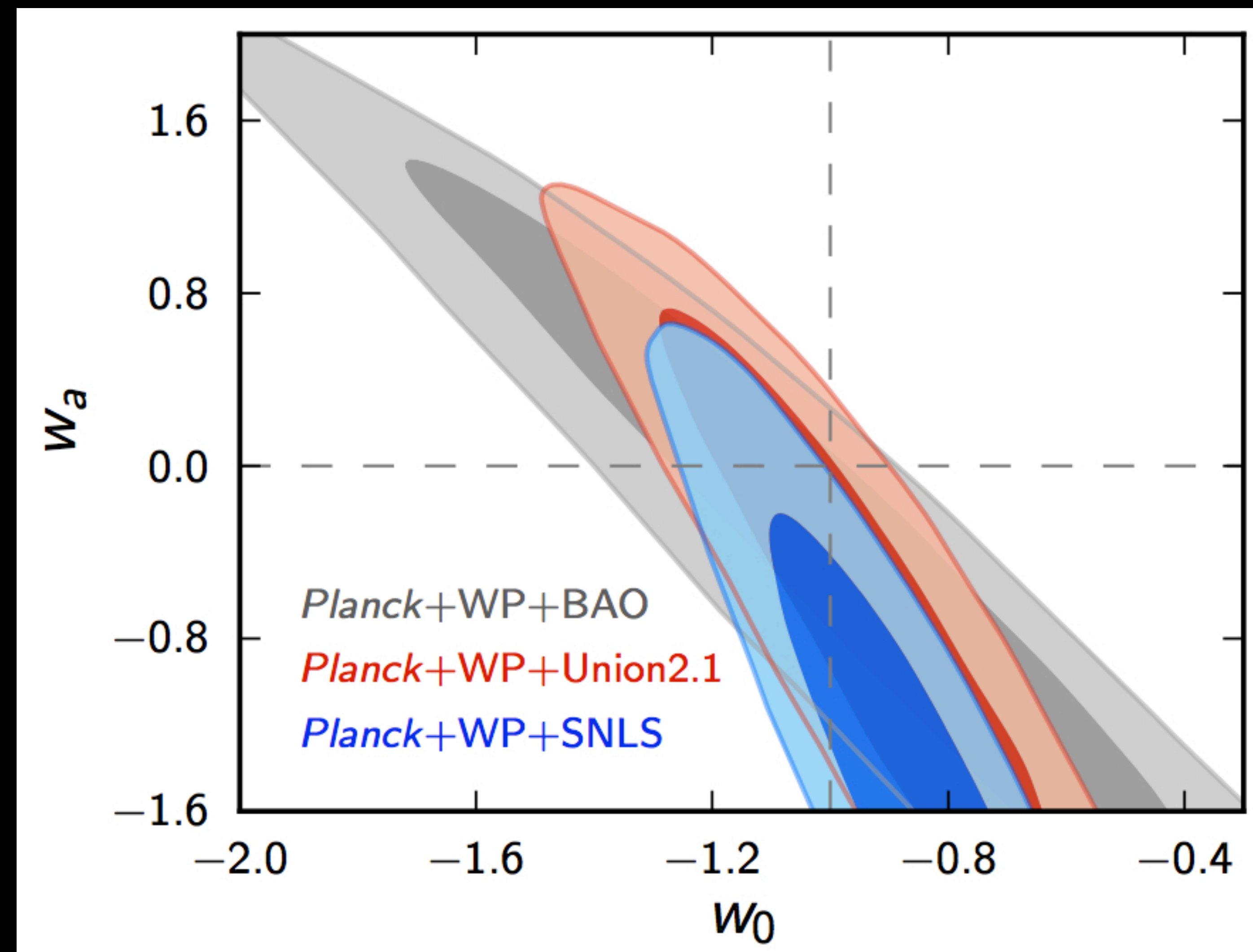
Suppression of the CMB gravitational lensing potential 10% in power for $M_\nu$ = 0.66 eV



$$\begin{aligned} &95\%\ \text{C.L.} \\ &M_\nu < 0.85\ \text{eV} \quad +\text{lensing} \\ &M_\nu < 0.25\ \text{eV} \quad +\text{lensing} + \text{BAO} \end{aligned}$$

# Dark energy: Λ or dynamical?




$$p_\Lambda = w\rho_\Lambda$$

$$w(a) = w_0 + (1-a)w_a$$

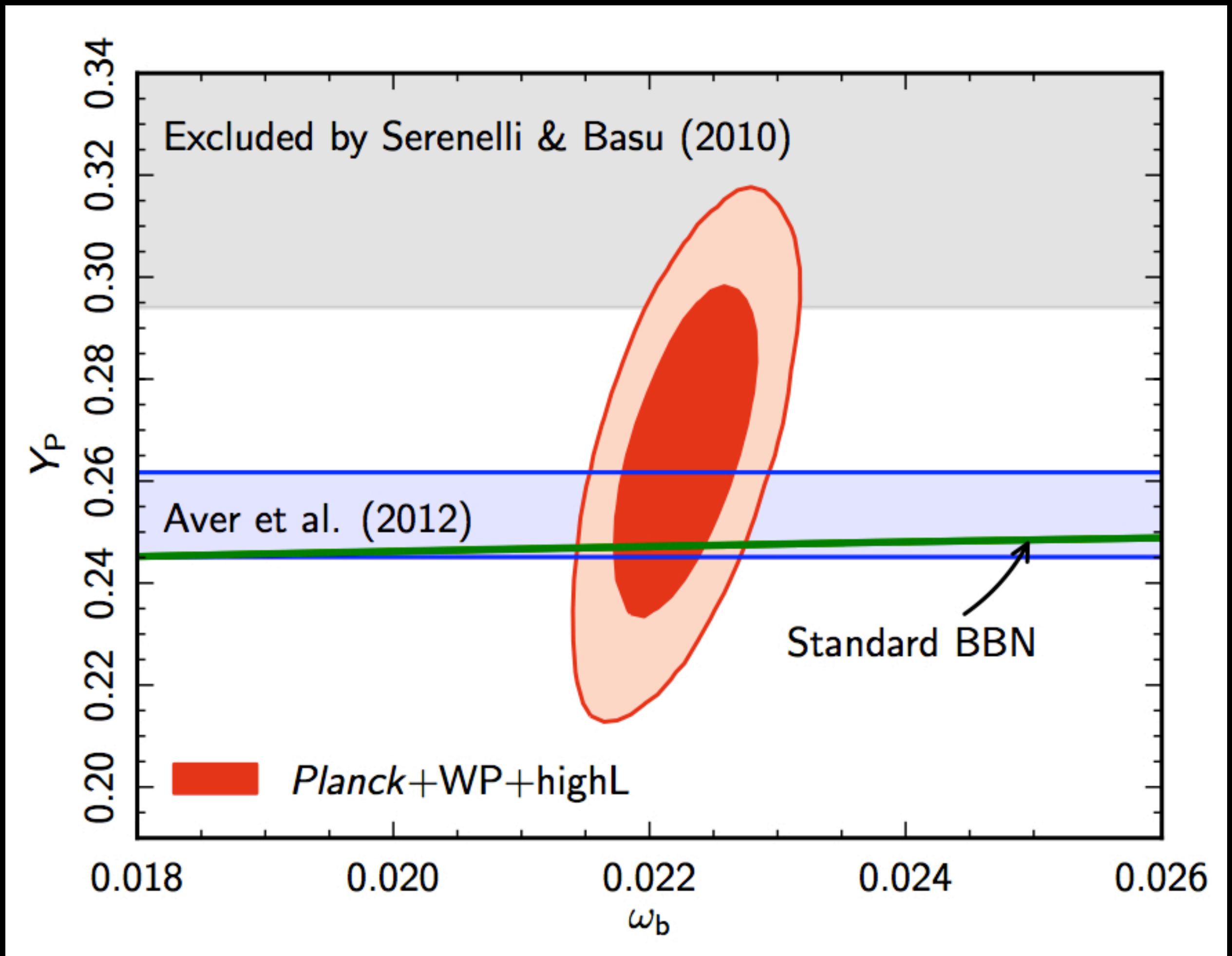
$$w = -1.13^{+0.10}_{-0.10}$$

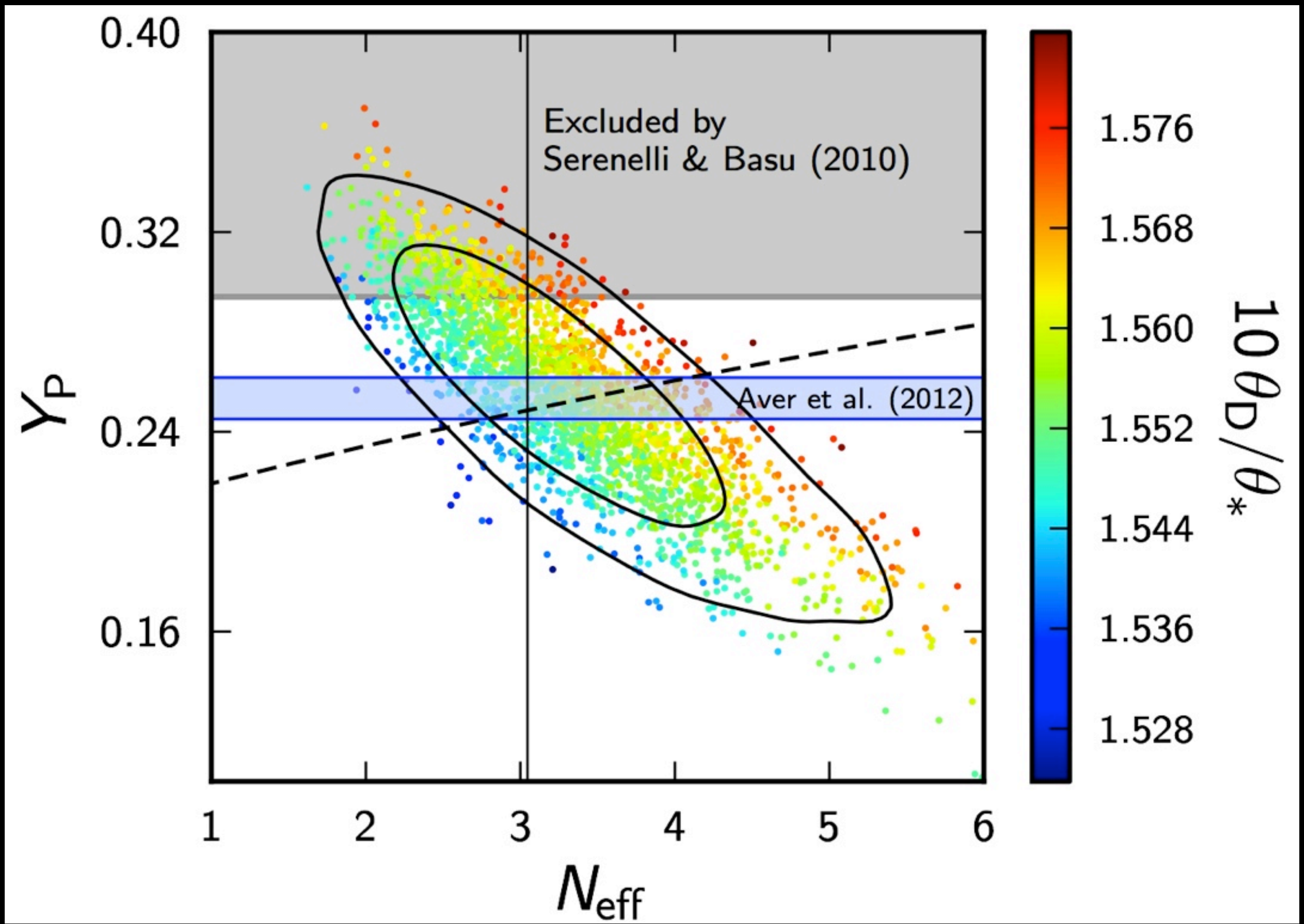
$$w_0 = -1.04^{+0.47}_{-0.33}$$

$$w_a = -0.30^{+0.88}_{-1.3}$$

# Helium abundance: $Y_P$

It can be predicted as a function of $\omega_b$ and $N_{eff}$
$Y_P$ will impact the damping tail



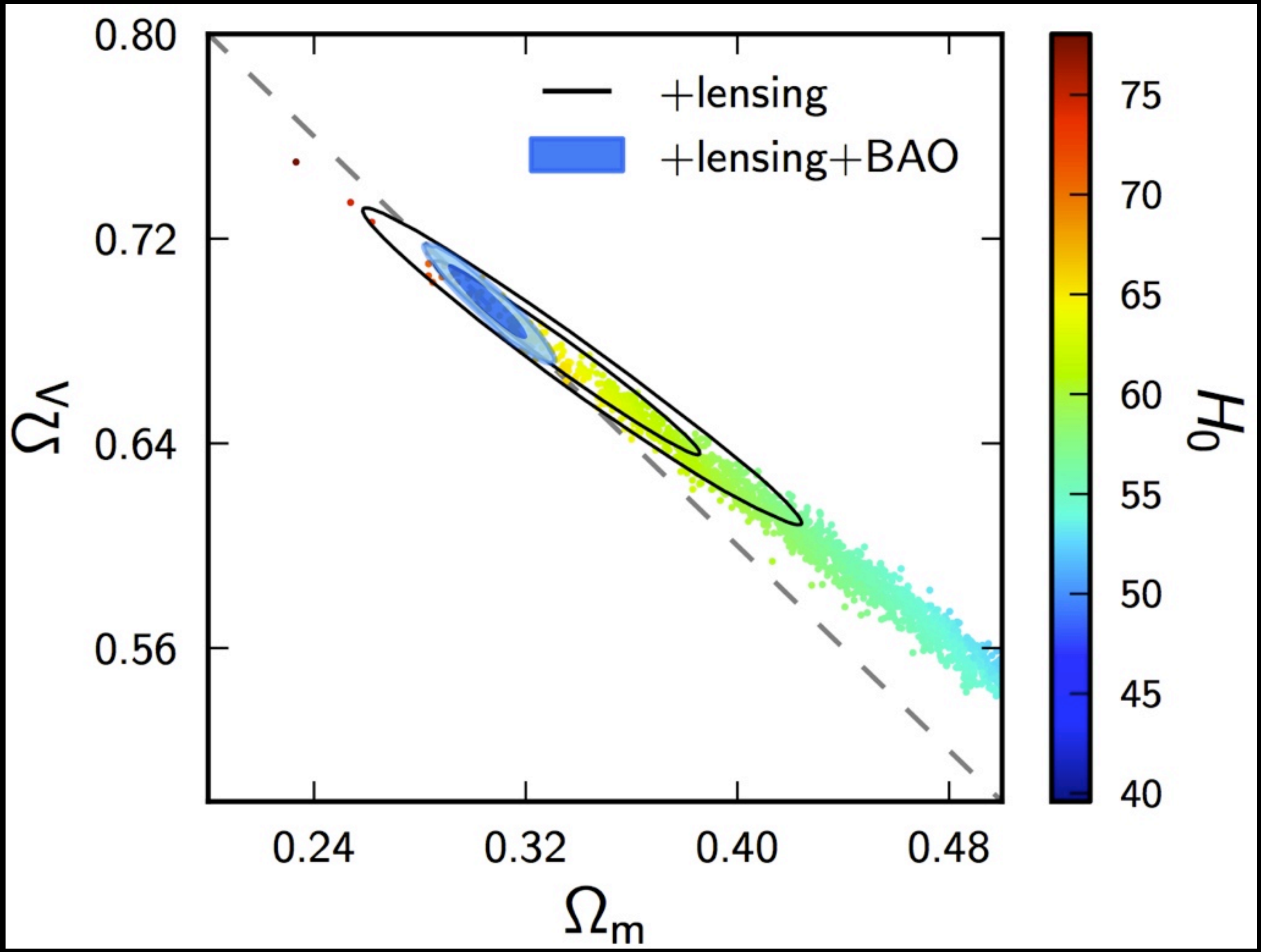

fixing $N_{eff}$ (= 3.046)

$$Y_P = 0.266 \pm 0.21$$

$$N_{eff} = 3.33^{+0.59}_{-0.83}$$
$$Y_P = 0.254^{+0.041}_{-0.033}$$

# Curvature: $\Omega_k$

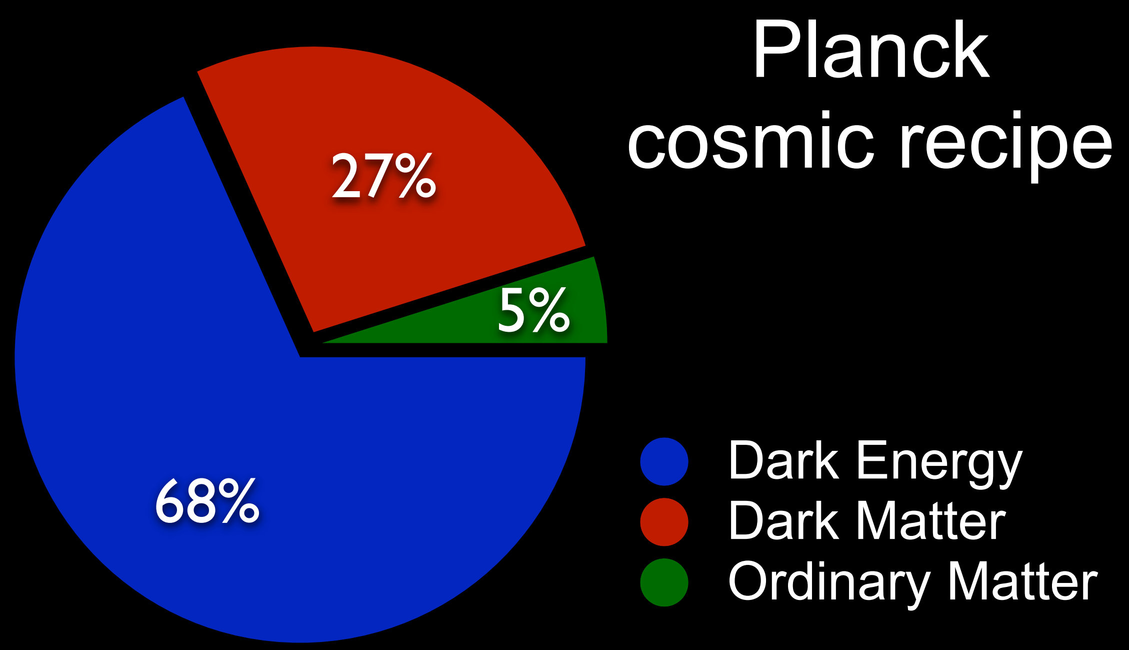
CMB suffers from the "geometrical degeneracy"
It can be broken with addition of probes of late time physics




$$100\Omega_k = -0.0096^{+1.0}_{-0.82} \quad \text{+lensing}$$

$$100\Omega_k = -0.0099 \pm 0.32 \quad \text{+lensing + BAO}$$

# Take Home Message




- The *Planck* mission has provided a stress test to the spatially-flat 6 parameters $\Lambda$CDM model.

- *Planck* sets some strong contraints on tensor-to-scalar ratio, neutrinos, $M_\nu$, curvature, dark energy, Helium and deuterium abundances, variation of the fine structure constant, ...

- Stay tuned. Mid 2014: full mission (29 months) + polarization