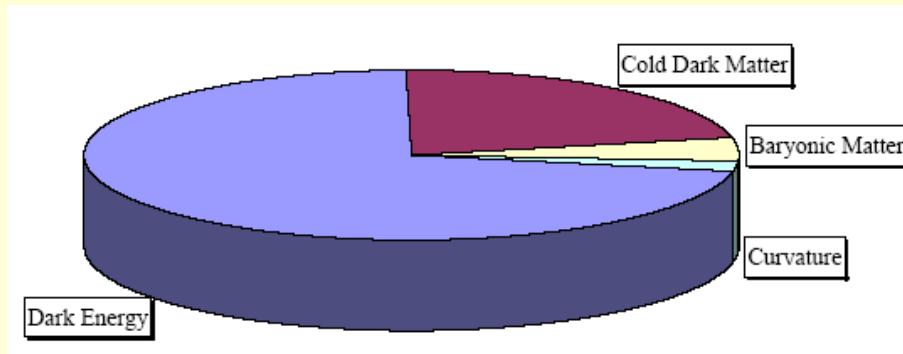


Cosmology overview

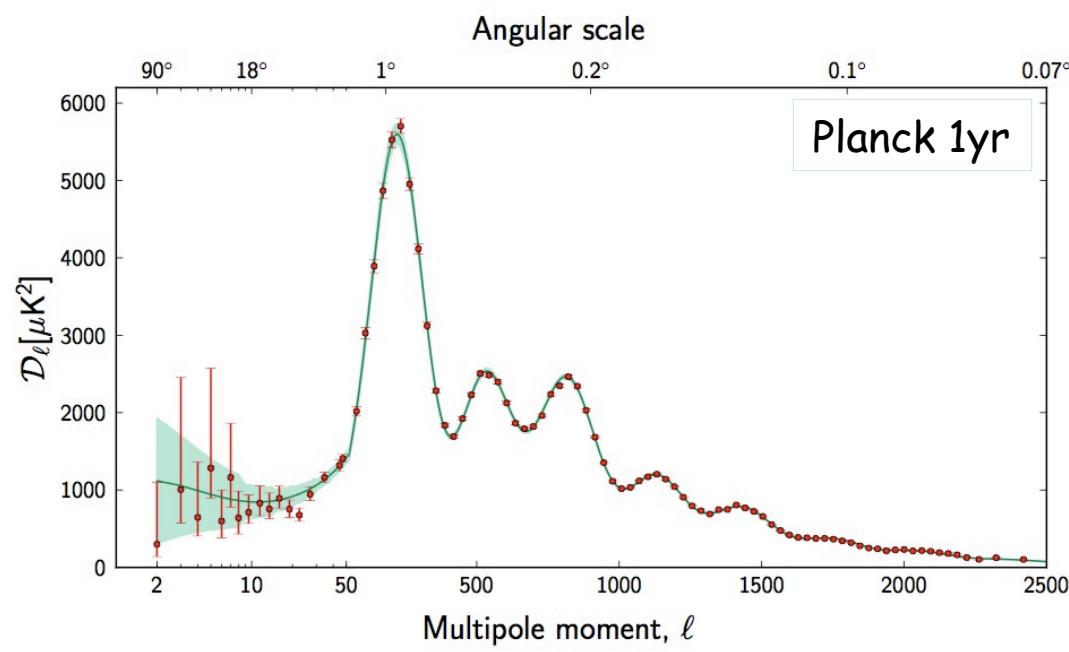
V.Ruhlmann-Kleider
CEA/Irfu/SPP - Saclay



$$\Omega_M + \Omega_\Lambda + \Omega_k = 1$$



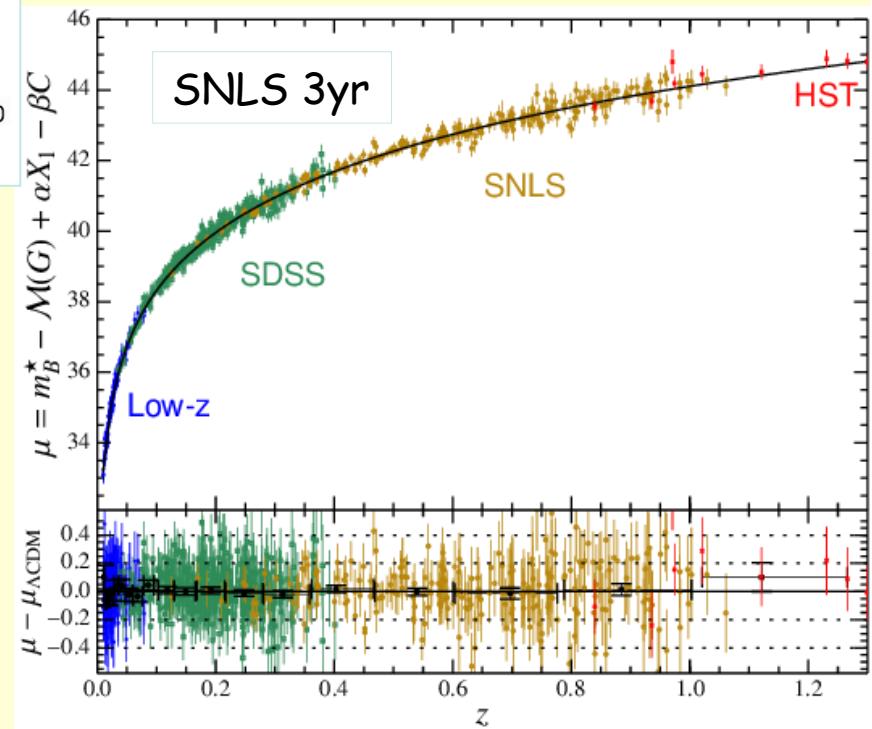
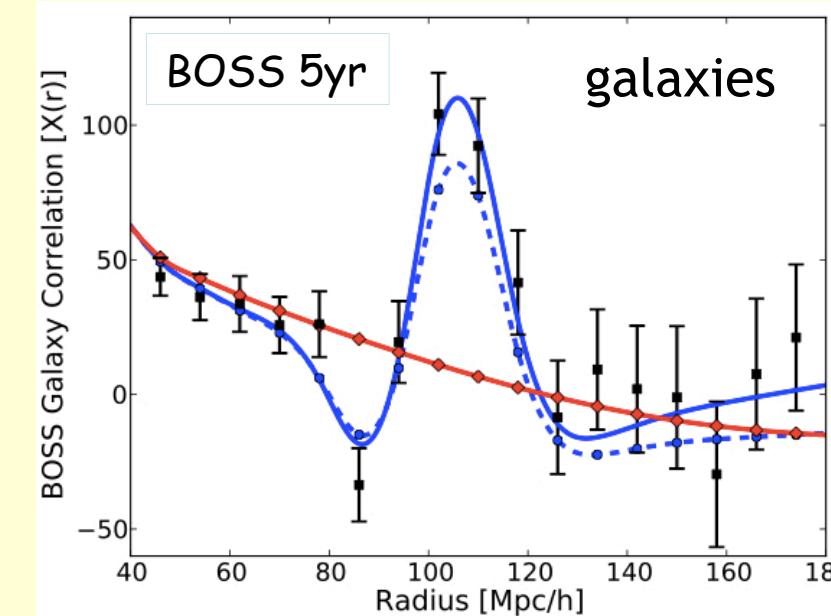
1. Cosmological probes
2. Cosmological constraints
3. Constraints on ν masses



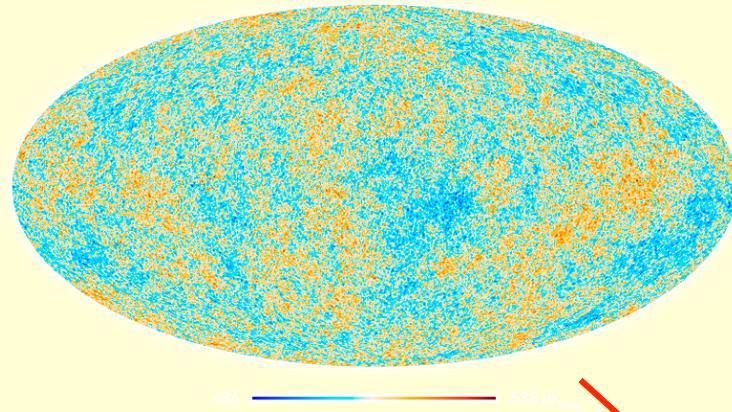
1. Cosmological probes

CMB spectrum: imprint of acoustic oscillations at the last scattering surface ($z=1089$)

SN Ia distances for $z \leq 1.5$

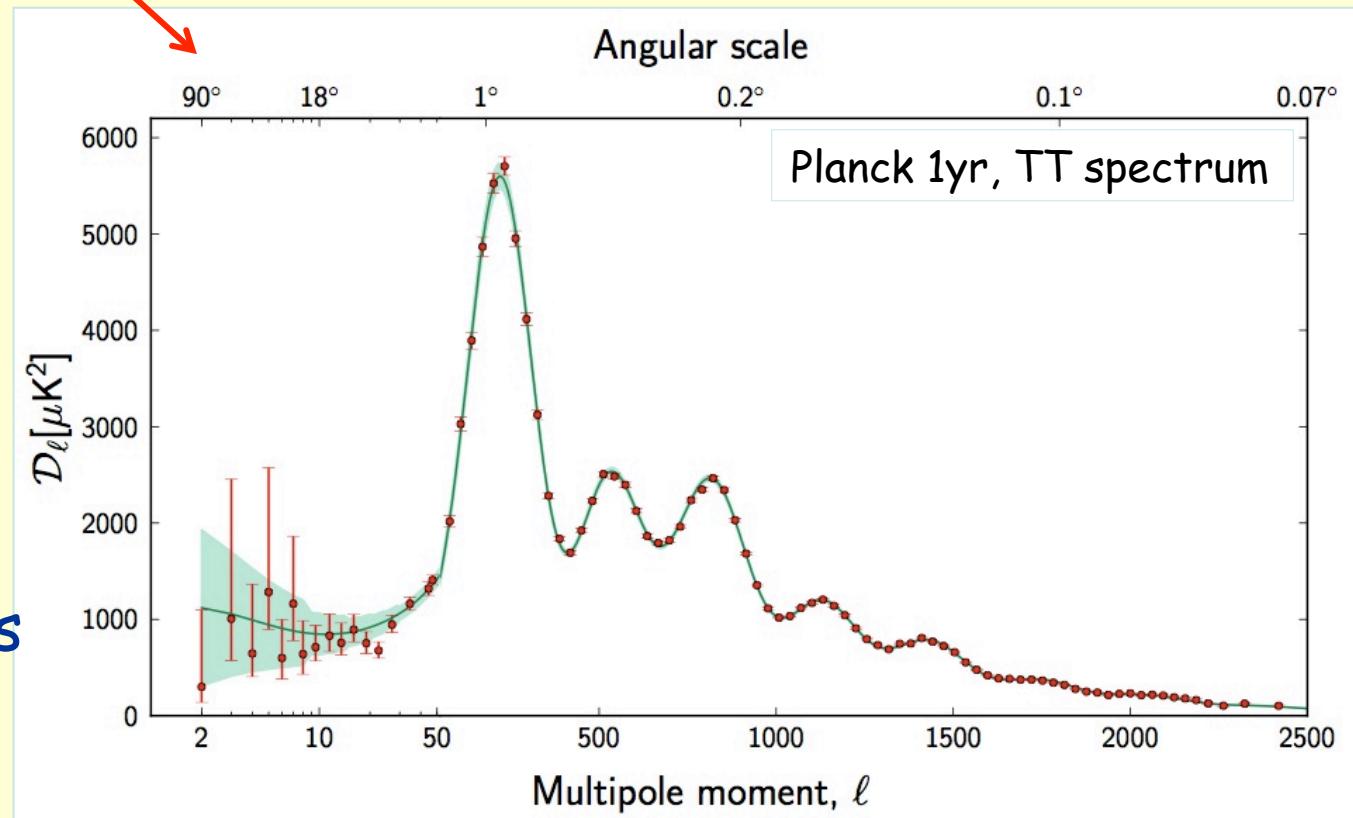


BAO: separation of pairs of e.g. galaxies related to primordial oscillations at different z



CMB results : Planck

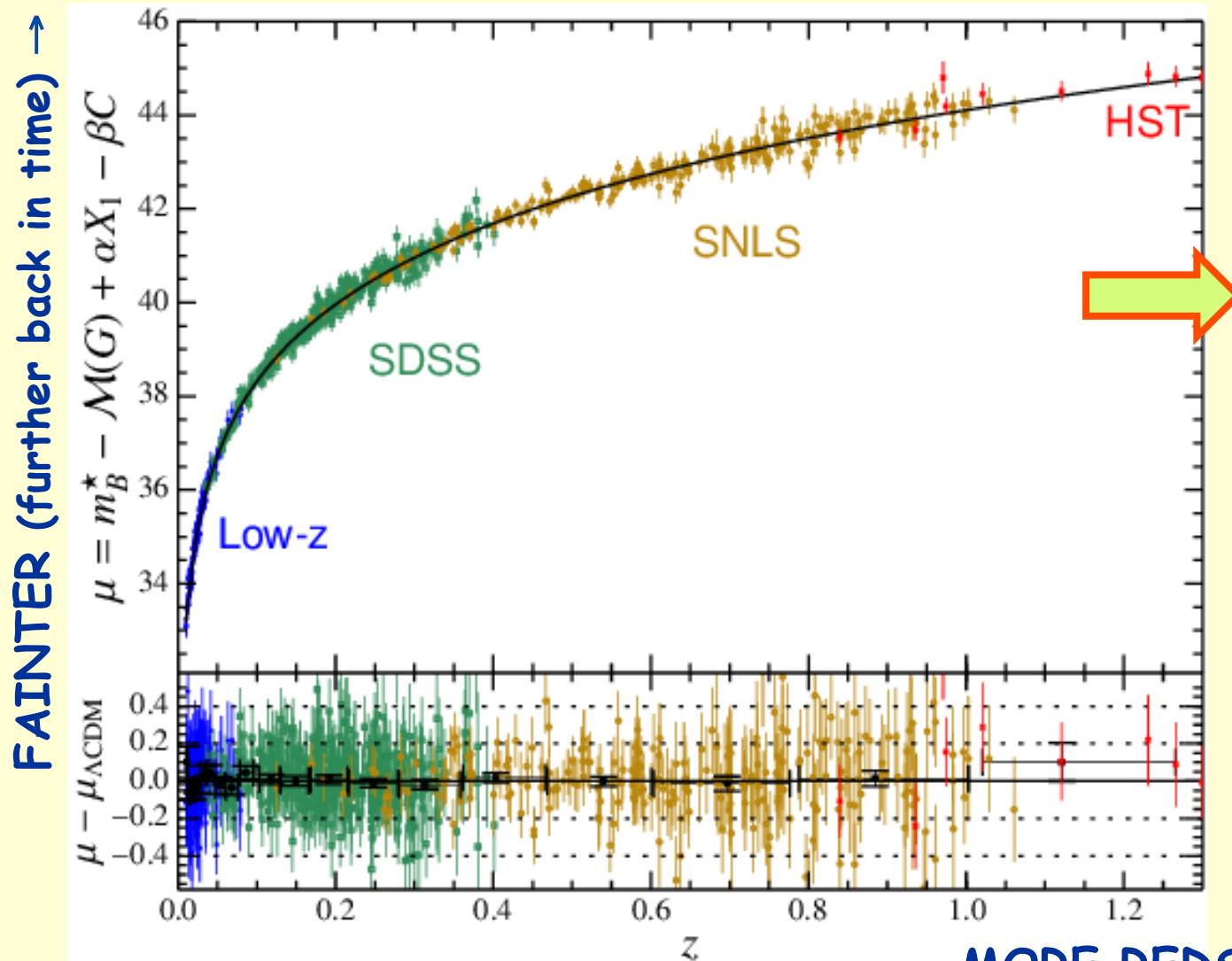
- CMB power spectrum: measured with unprecedented accuracy up to 7th peak
- Constraints on curvature and matter content of the Universe (Ω_k , Ω_m , Ω_b , N_v , $\Sigma m_v \dots$)
- New: constraints on dark energy, through lensing



Planck Collaboration., arXiv:1303.5075, to appear in A&A

Most precise SNIa results : SNLS

High quality data for 740 SNeIa, SDSS-SNLS cross-calibration

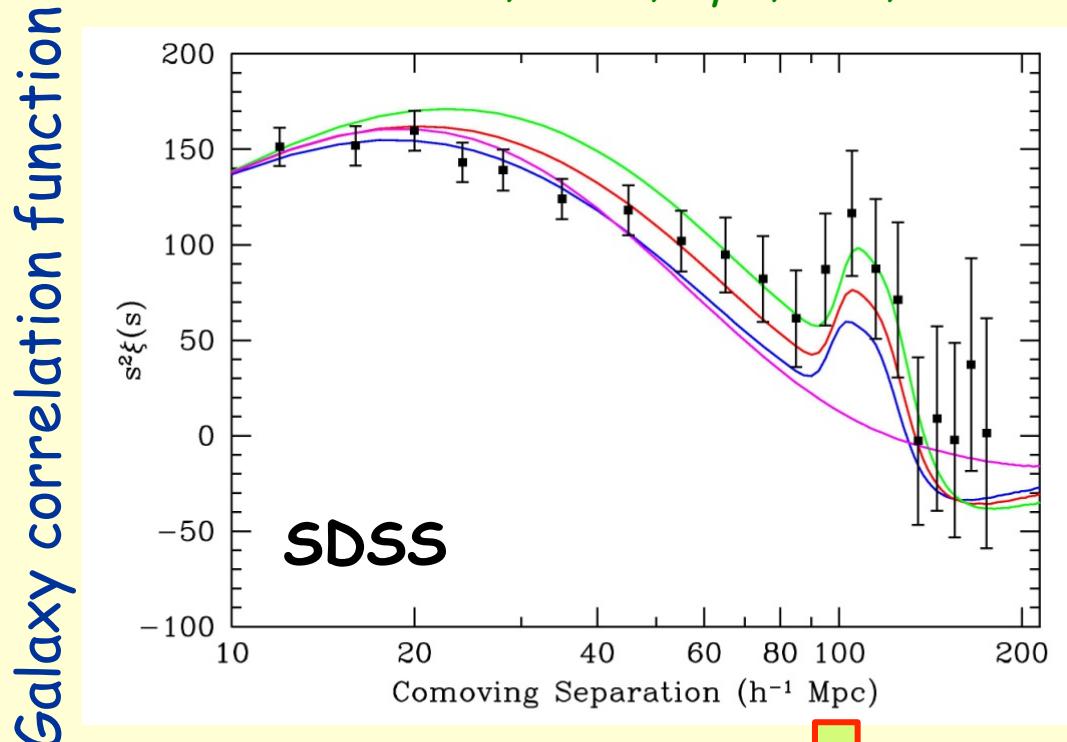


Λ CDM flat
Universe best-fit:
 $\Omega_m \sim 0.295$
Accelerated expansion
confirmed from
SNe Ia alone
($>99.9\%$ CL)

Baryonic acoustic oscillations

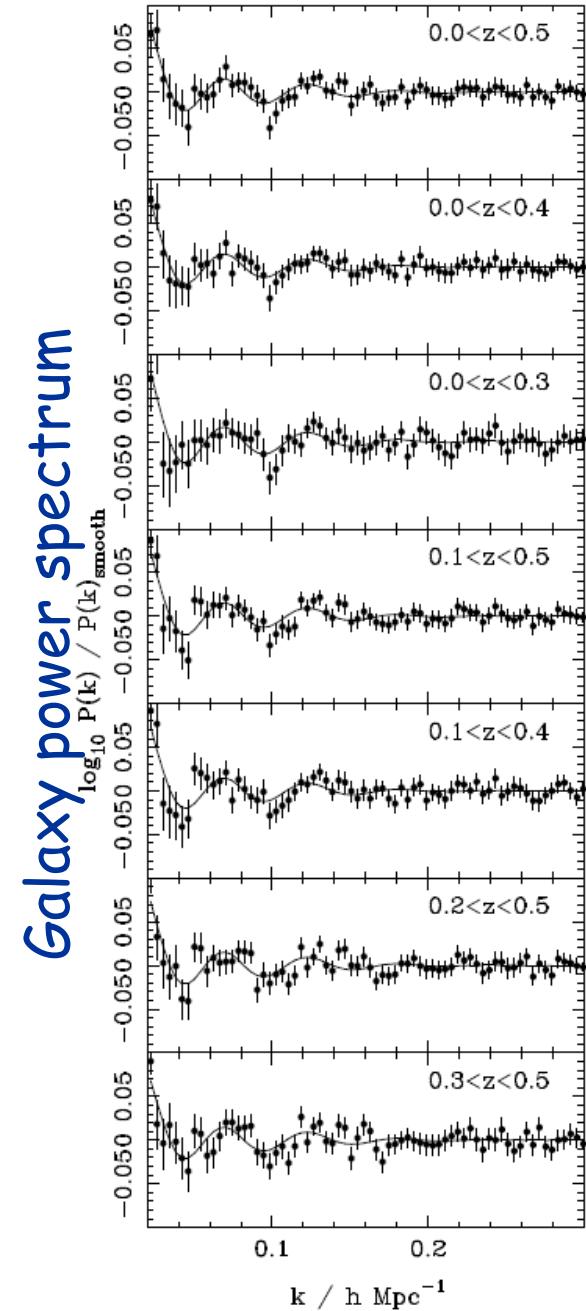
First evidence for BAO signal: 2005

D.Eisenstein et al., 2005, ApJ, 633, 560



preferred comoving
separation $\sim 150 \text{ Mpc}$

0.7 Gpc^3 50,000 LRG's $0.2 < z < 0.5$

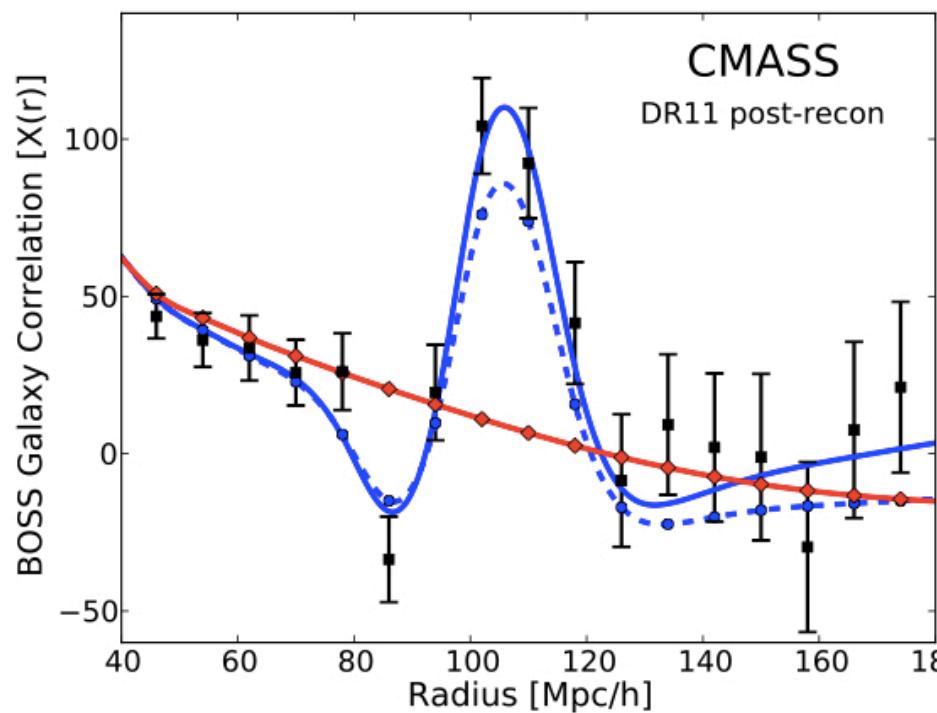


W.Percival et al., 2010, MNRAS, 401, 2148

Latest SDSS results : BOSS survey

- Galaxy correlation function

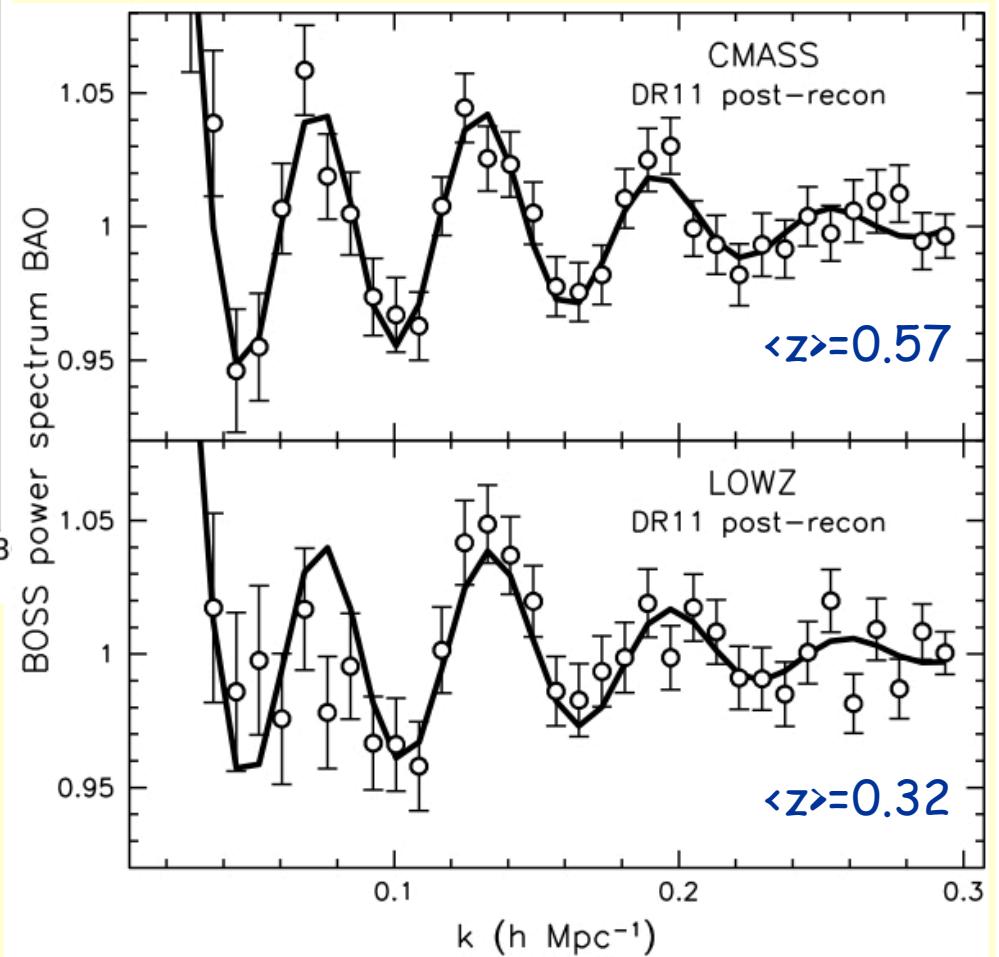
L. Anderson et al., 2014, MNRAS, 441, 24A



BAO signal detected at 7σ

$13 Gpc^3$ 10^6 galaxies $0.2 < z < 0.7$

- Galaxy power spectrum

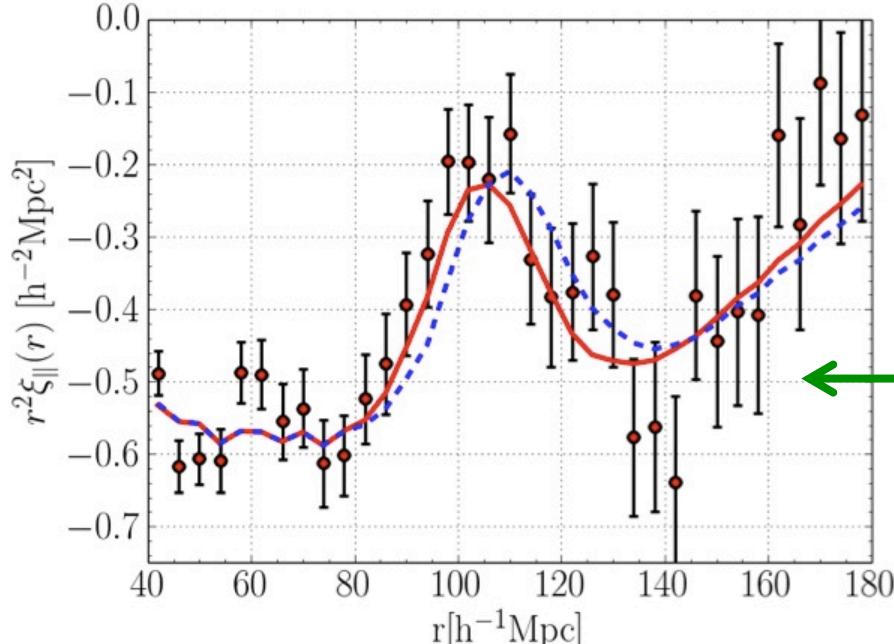


BAO from quasars : BOSS results

2013: BAO signal detected in intergalactic H distribution (via absorption lines in quasar spectra)

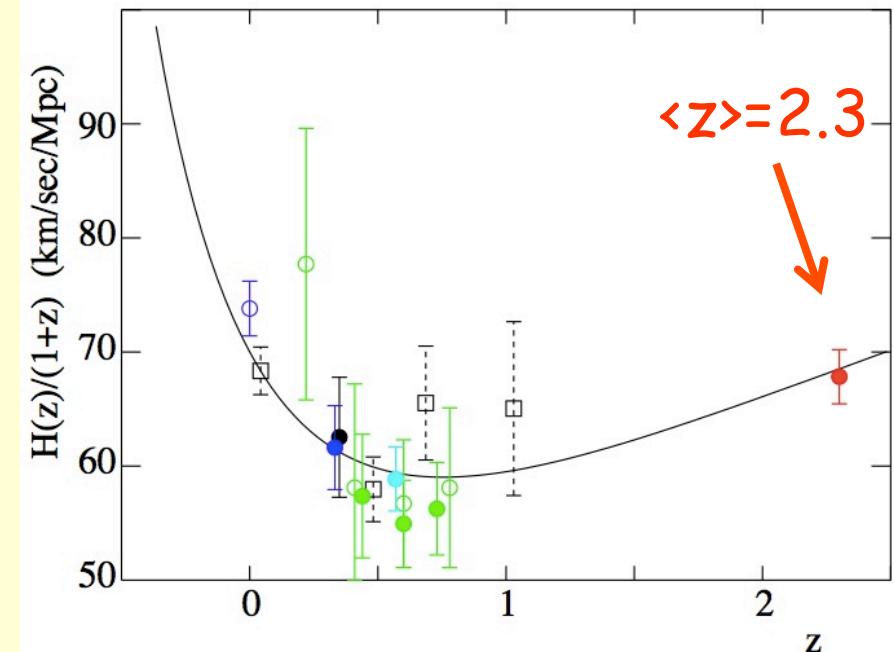
48,000 QSO spectra, $2.1 < z < 3.5$

- Ly α forest correlation function



T. Delubac et al., arXiv:1404.1801

N. Busca et al., 2013, A&A, 552A, 96B



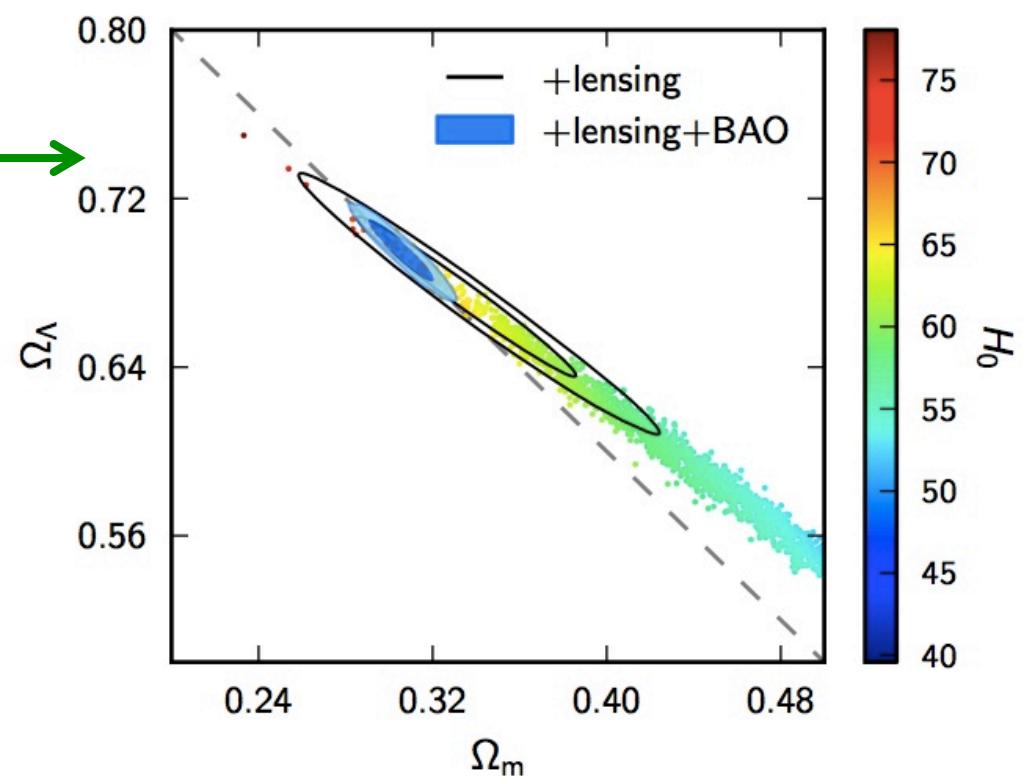
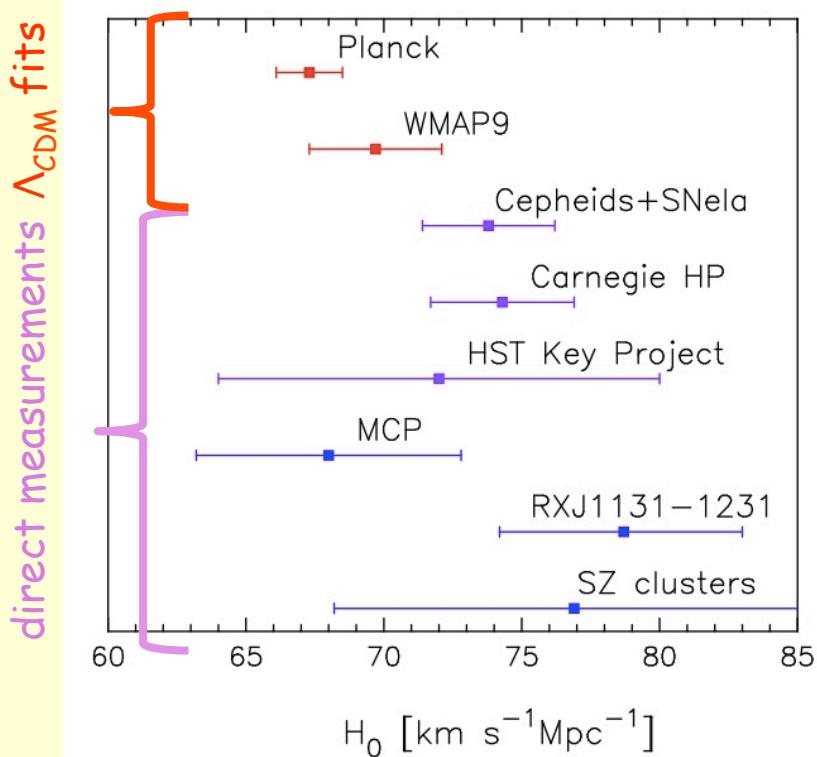
2014: BAO peak in Ly α forest correlation function now at 5σ
137,000 QSO spectra, $2.1 < z < 3.5$

Signal also seen in quasar - Ly α forest cross-correlation function

2. Cosmological constraints

Λ CDM constraints :

flat geometry preferred
(CMB alone, CMB+BAO)



Spatially-flat Λ CDM constraints :

$$\Omega_m^0 = 0.313 \pm 0.013$$

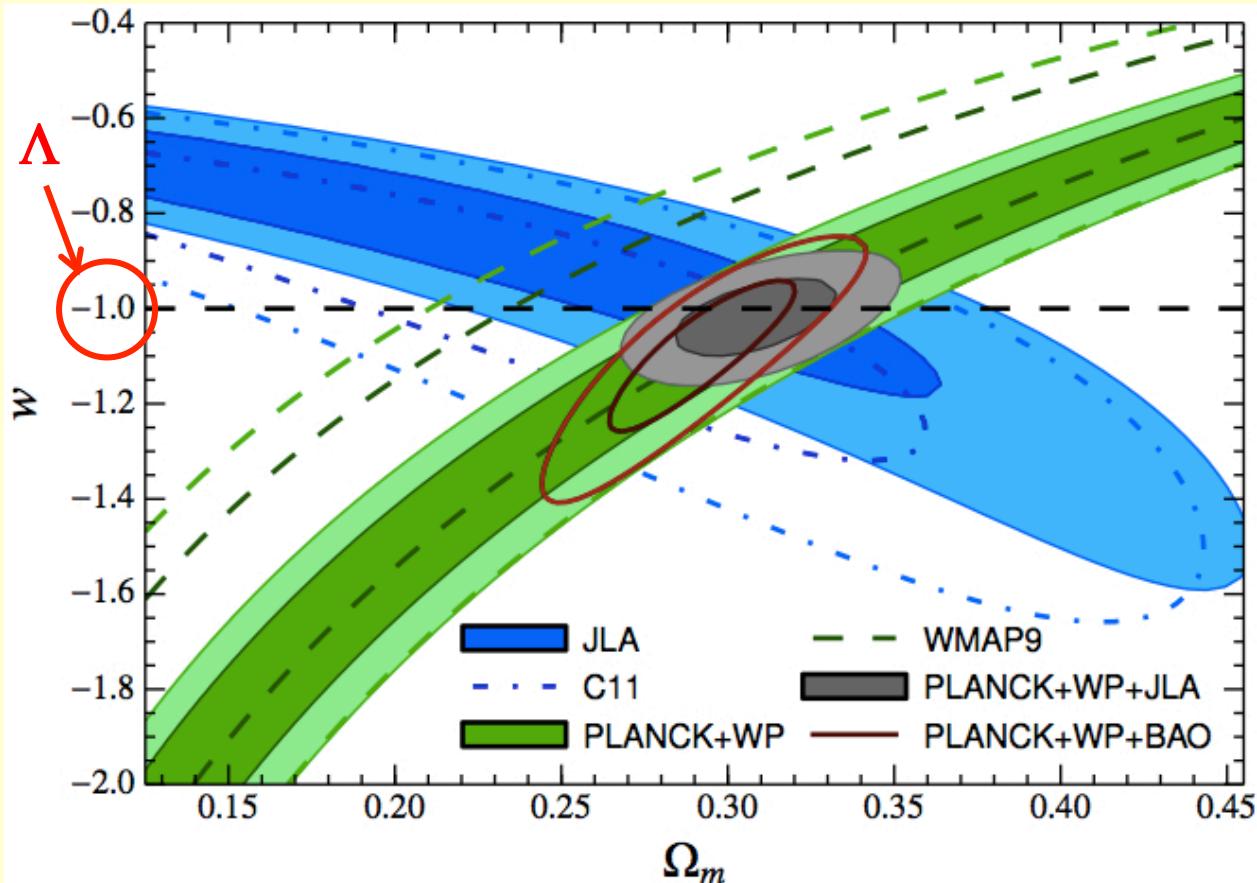
$$H_0 = (67.3 \pm 1.2) \text{ km s}^{-1} \text{ Mpc}^{-1}$$

(CMB alone, similar with CMB+BAO)

Spatially-flat wCDM constraints :

wCDM = CDM + dark energy component of **constant** $w=P/\rho$

From **CMB + BAO + SNeIa** (= JLA below) :



$$\begin{aligned} \Omega_m^0 &= 0.303 \pm 0.012 \\ H_0 &= (68.50 \pm 1.27) \text{ km s}^{-1} \text{ Mpc}^{-1} \\ w &= -1.027 \pm 0.055 \end{aligned}$$

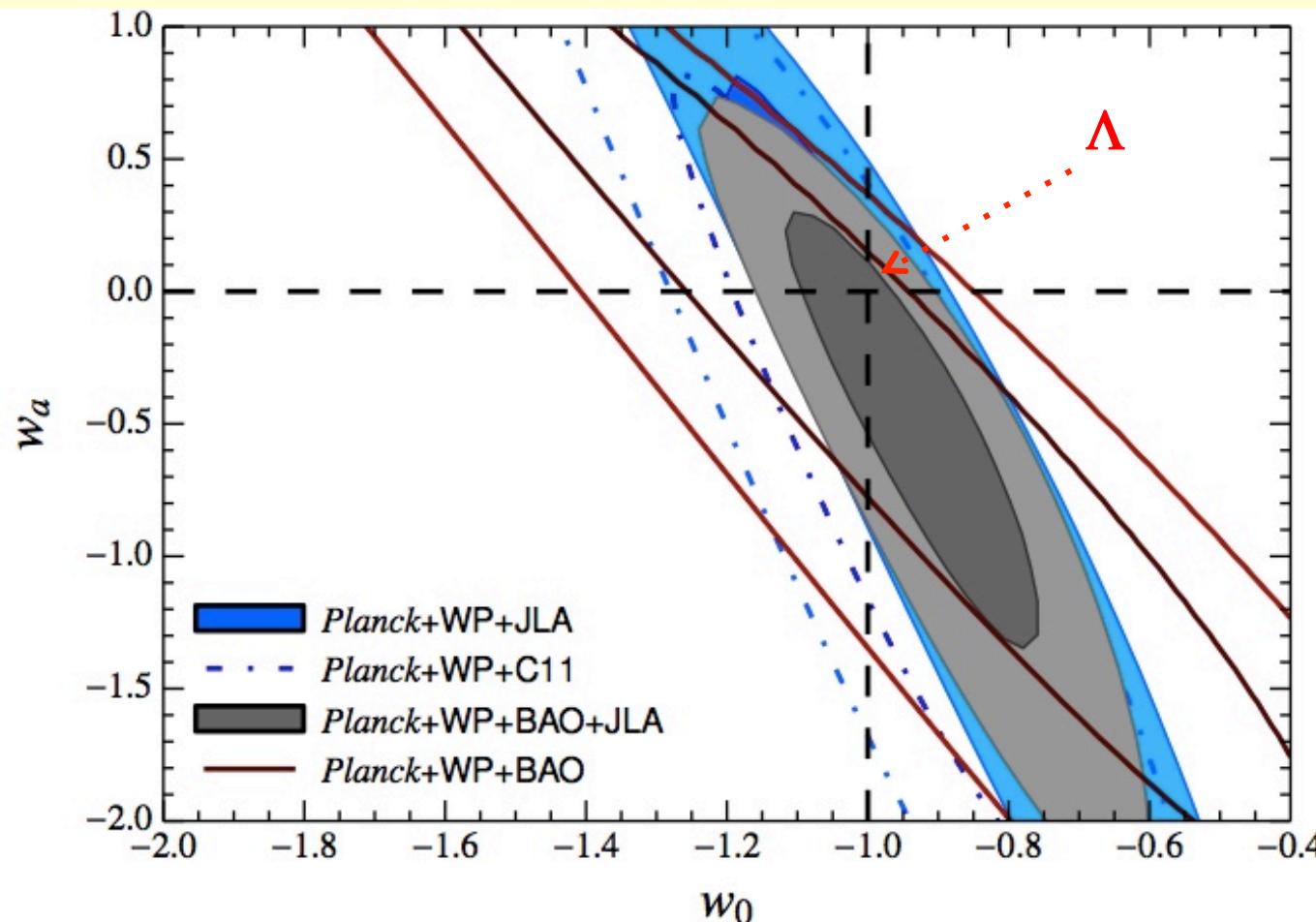
without SNeIa:
 $\delta w \approx 0.11$

M.Betoule et al., 2014, 2014, A&A, 568, A22

Spatially-flat w_z CDM constraints :

w_z CDM = CDM + dark energy component with $w(a) = w_0 + w_a(1-a)$, $a = (1+z)^{-1}$

From CMB + BAO + SNeIa (= JLA below) :



$$(\delta_{\text{stat}} \oplus \delta_{\text{syst}})$$

$$\Omega_m^0 = 0.304 \pm 0.012$$

$$w_0 = -0.957 \pm 0.124$$

$$w_a = -0.336 \pm 0.552$$

without SNeIa:
 $\delta w_0 \approx 0.5$ $\delta w_a \approx 1.3$

Massive neutrinos in cosmology

- Neutrinos decoupled at $T \approx 1$ MeV \rightarrow no oscillation, free propagation BUT ν 's have some effects, e.g.

- ν 's contribute to the cosmic expansion \rightarrow impact on b- γ oscillations and matter perturbation growth
- massive ν 's do not cluster at low-scales (small-scale ν fluctuations suppressed by *free streaming*)

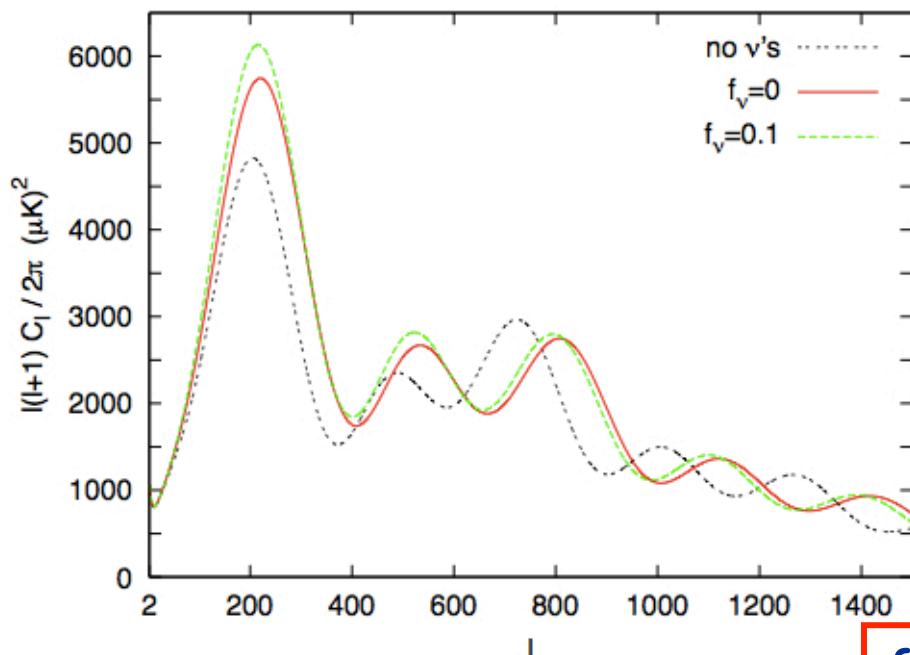
$$\lambda_{fs}(t) = 2\pi \frac{v_{th}(t)}{H(t)} \Rightarrow \lambda_{fs}(t_0) \approx 10 \text{ Mpc} \frac{1 \text{ eV}}{m_\nu} \quad \begin{matrix} \text{today free-streaming} \\ \text{scale of NR } \nu \text{'s} \end{matrix}$$

- growth rate of b, CDM perturbations reduced at low scales by the absence of gravitational clustering from free-streaming ν 's

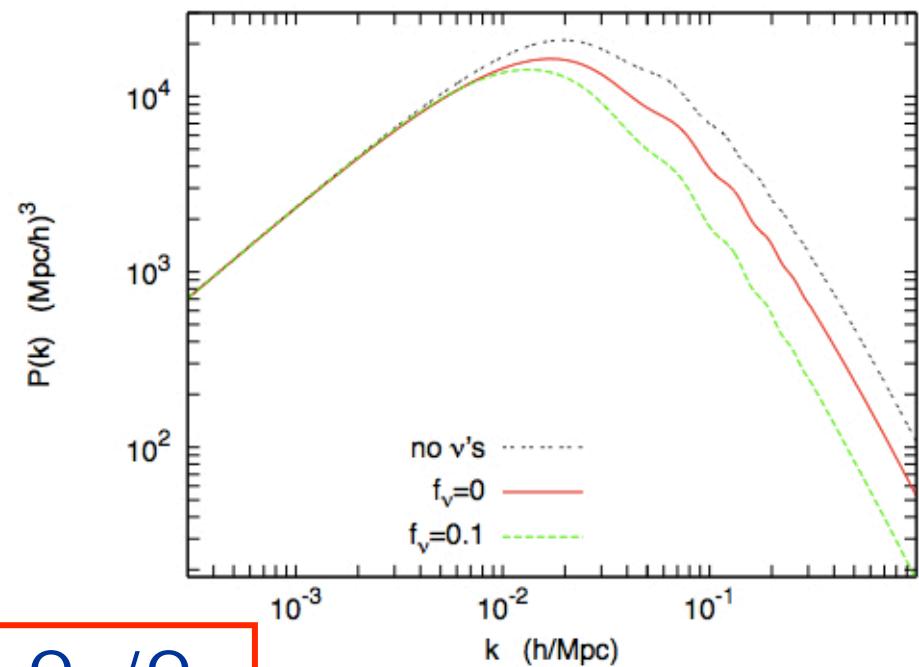
\rightarrow effect on CMB & matter power spectra

Effect of massive v's on CMB and matter spectra

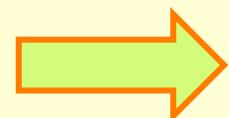
CMB spectrum in monopole space



Matter spectrum in Fourier space



$$f_v = \Omega_v / \Omega_m$$



Constraints on Σm_i from CMB / matter spectrum

J.Lesgourges & S.Pastor, Phys.Rept. 429 (2006) 307

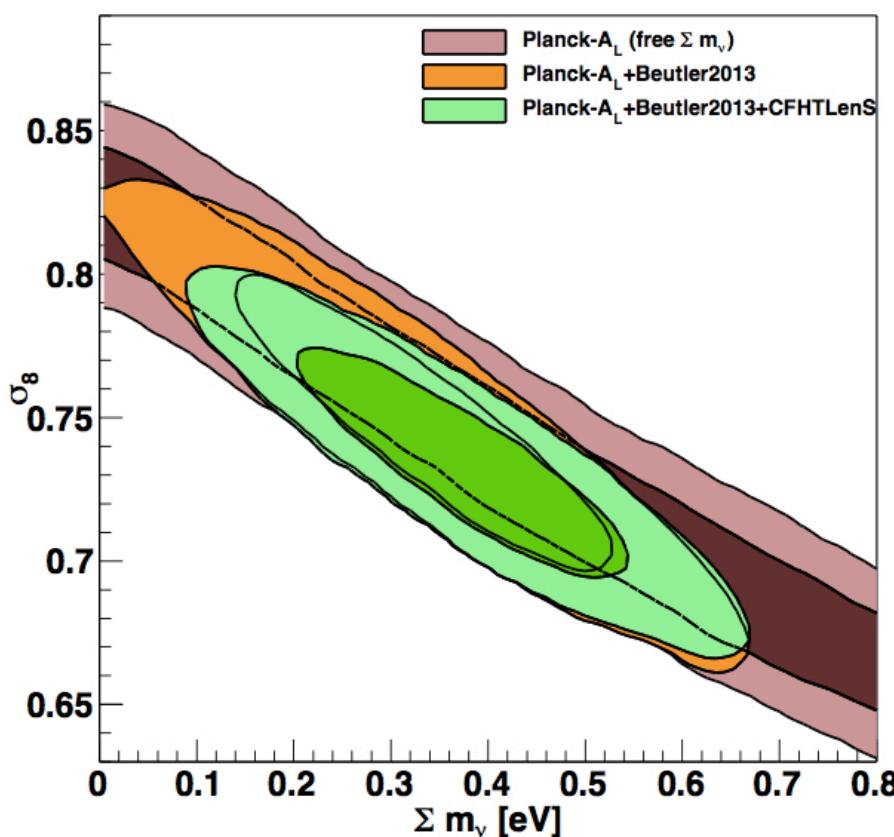
Most recent results

Assuming only 3 active neutrinos and a flat Universe

- Planck 2013 (Planck + WP + A_L + BAO) :

$$\Sigma m_i < 0.23 \text{ eV} \quad (95\% \text{ CL})$$

Planck coll., arXiv:1303.5076, to appear in A&A



- BOSS 2014 (BAO + growth data + Planck- A_L + lensing) :

$$\Sigma m_i = 0.36 \pm 0.10 \text{ eV}$$

First signs of Σm_i from cosmology (3.4σ) ?

F.Beutler et al., arXiv:1403.4599

Conclusions

- CMB, SNe Ia, BAO : measurements getting more and more precise → three powerful cosmological probes
- Current data are consistent with Λ CDM and with a wide diversity of dark energy models: static dark energy is not necessarily the true answer → need more observations / probes sensitive to $w(z)$
- Constraints on neutrino masses: first sign of Σm_i from cosmology ?