Cosmological constraints on $\sum m_\nu$ with CMB

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Introduction

- Cosmological parameter estimation after Planck are limited by systematics
- We focus in neutrino mass(es) (3 ν generations) and systematics e.g. :
  - CMB foreground(s) description(s)
  - A_L
- Outlook of the talk :
  - $\sum m_\nu$ in cosmology
  - tools and methods
  - CMB (Planck) data
  - some results

Couchot et al. 2017 (arXiv:1703.10829 , A&A)

Λ CDM model fitted parameters

- we start from the minimal Λ CDM model (flat geometry, 3 νs with $\sum \mathrm{m}_\nu$=0.06eV, no tensor modes) - 6 parameters :
  - primordial scalar modes spectrum (n_s, A_s)
  - densities : ω_b, ω_cdm ($\omega = \Omega.h^2$)
  - sound horizon angular scale at decoupling θ_S
  - reionisation : optical depth τ
- we study the addition of the neutrino mass parameter(s) in the global fit(s) using primarily CMB (Planck) data and likelihoods

Neutrino masses

- Usefull constraints : m_ν^2 differences from (solar, atmospheric, accelerator, reactor) neutrino oscillations

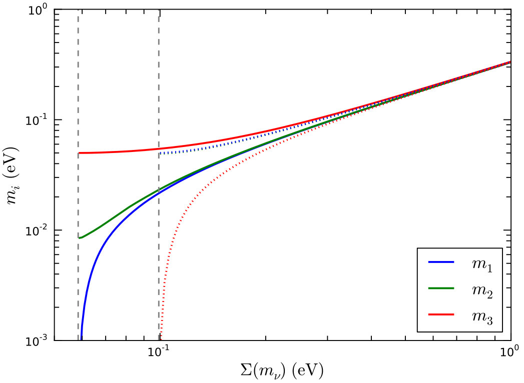
⇒ two hierarchies (Capozzi et al 2016) :

$$m_2^2 - m_1^2 = 7.37\ \mathrm{eV}^2 \quad (1)$$

$$m_3^2 - (m_1^2 + m_2^2) = +2.50\ \mathrm{eV}^2 \quad \textit{NH} \quad (2)$$

$$= -2.46\mathrm{eV}^2 \quad \textit{IH} \quad (3)$$

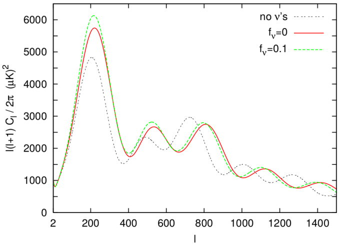
⇒ lower bounds on $\sum m_\nu$: 0.059 (NH) / 0.099 (IH) eV

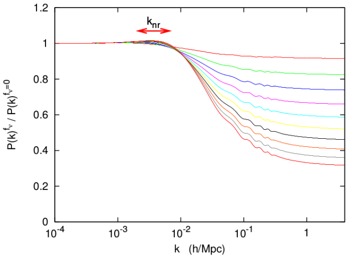


⇒ usual approximation : 3 degenerate massive neutrinos (but some authors use one massive + 2 massless)

Neutrino mass(es) and Λ CDM

- ν's produced in early universe → CNB
- ultra-relativistic in early universe, non-relativistic today
- ⇒ m_ν impacts early thermal history and energy density
- ν free streaming (while u.r.) "erases" small scales in LSS formation
- Effects on CMB observable(s) (C_ℓ) :
  - small change in peak positions and heights (effect on background geometry)
  - change in late matter anisotropy power spectrum ⇒ different lensing distorsion
  - extraction requires broad ℓ coverage
  - several degeneracies between $\sum m_\nu$ and other params (depending of the dataset)





(J. Lesgourgues & S. Pastor arXiv:astro-ph/0603494)

Methods

We used our public CAMEL (camel.in2p3.fr) suite including :

- Boltzman solver (from parameters to anisotropies) : CLASS (J. Lesgourgues)
- Multi-parameter minimizer : Minuit (F. James, CERN, 1994)
- Adaptative MCMC sampler

Most results derived from profile likelihoods :

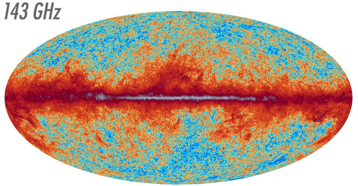
- choose a parameter p
- for each fixed value of p minimize the likelihood w.r.t. all other parameters

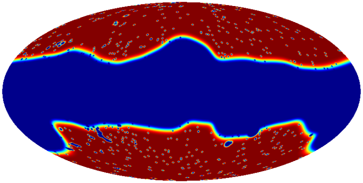
$\Rightarrow$ robust central value & error estimation (e.g. Planck intermediate results. XVI)

$\sum m_\nu$ limits extracted following Feldman & Cousins method : well suited for bound parameter space ($m \geq 0$)

CMB high ℓ likelihoods (Planck data)

- auto- and cross power spectra of masked frequency maps (100, 143, 217 GHz)
- residual foregrounds (dust, kSZ, tSZ, CIB, point sources) handled at power-spectrum level (nuisance parameters)
- several likelihoods : `plik (Planck public module,` Planck 2015 - XI`) and hlp(home made - see` Couchot et al. 2016`) relying on Planck data for fg models, 2 PS flavors), w/o and with polarisation`
- `differences between them` $\longleftrightarrow$ `foreground systematics`



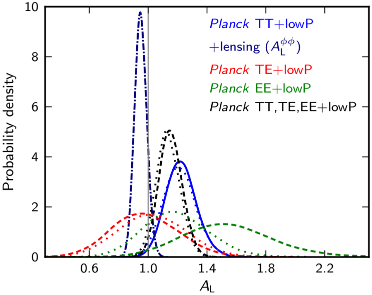


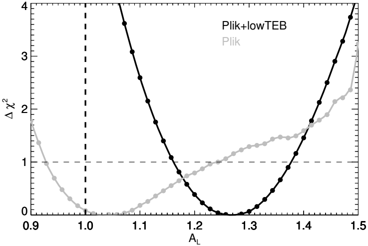
Other likelihoods & datasets

- CMB at low ℓ (<50)
  - Planck public likelihoods : temperature only (Commander), T+P (lowTEB)
  - in 2016, Planck improved large scale polarisation reconstruction and likelihood (e.g. Mangilli et al. 2015) $\Rightarrow$ lower τ value (and smaller error !)
  - usefull for ν constraint due to (τ , $\sum m_\nu$) correlation but likelihood ot (yet) public
  - we used an external constraint $\tau = 0.058 \pm 0.12$ (Planck intermediate results. XLVII, 2016)
- CMB lensing likelihood (Planck direct lensing (tri)spectrum : Planck 2015 results. XV)
- BAO : results from BOSS DR12 (arXiv:1607.03155)
- SNIa peak luminosities : JLA likelihood (Bétoule et al.)

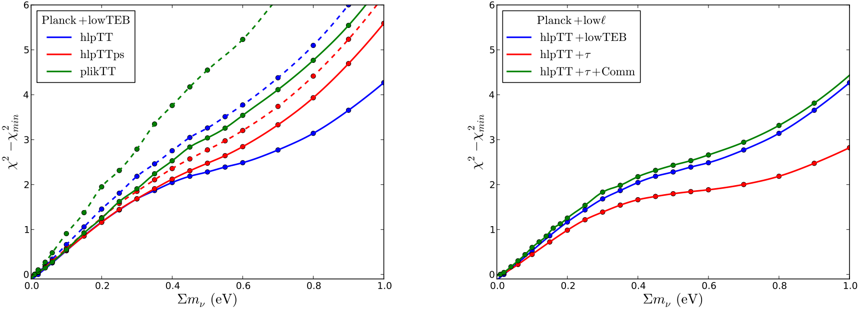
The A_L parameter

- Phenomenological parameter scaling the amplitude of lensing distorsions on the CMB map
- Fitting for A_L : consistency check (should find 1 !)
- Planck TT data seem to favor $A_L \sim 1.2$ ($\gtrsim 2\sigma$ deviation) [Planck 2015 - XI]
- seems to be related to mild tension between high and low ℓ and foregrounds
- also analysed in Couchot et al. 2015
- we used Planck CMB lensing likelihood to mitigate this effect + checked the fitted A_L value



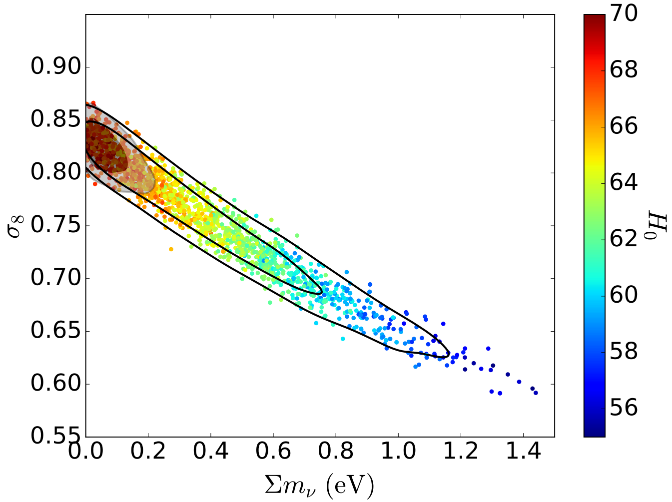


Profile likelihood for $\sum m_\nu$: Planck alone



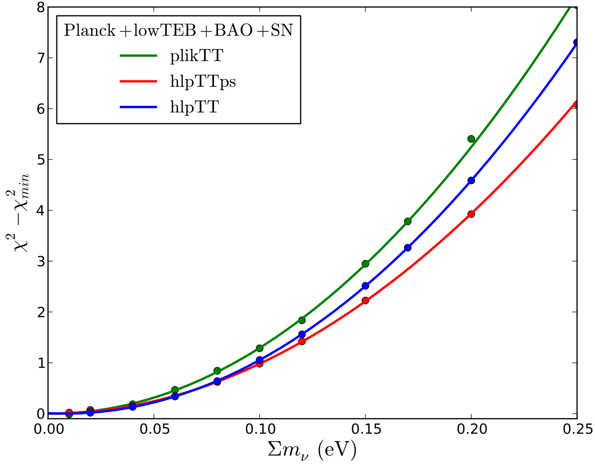
- non standard shape (expect a parabola)
- sensitive to foregrounds (dashed = w/o SZ external constraint)
- mild impact of low-ℓ part

Adding BAO & SNIa helps

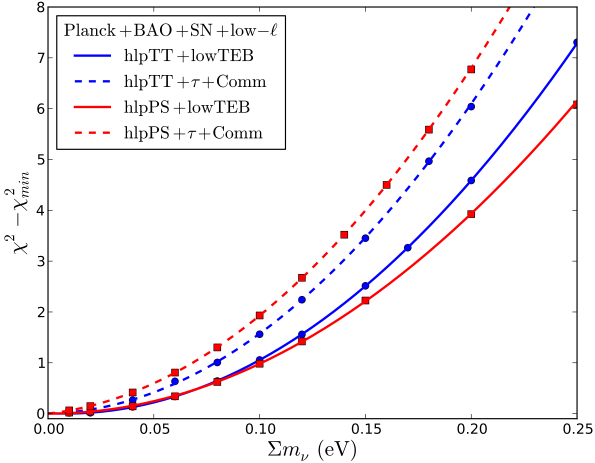


BAO and SNIa ⇒ less degeneracies (filled contours)

$\sum m_\nu$ profiles with Planck TT + BAO + SN

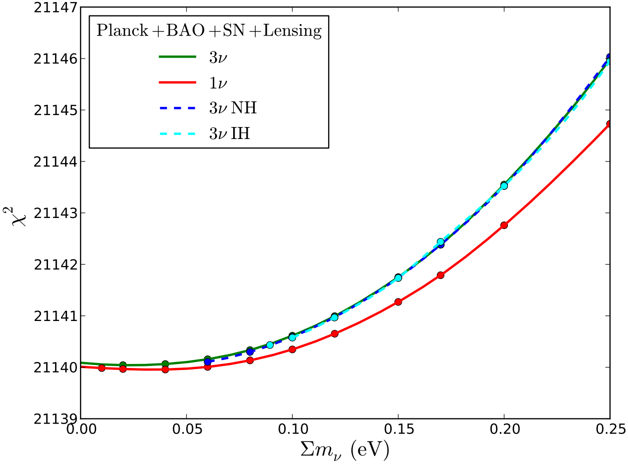


Better shape but still $A_L \sim 1.15$



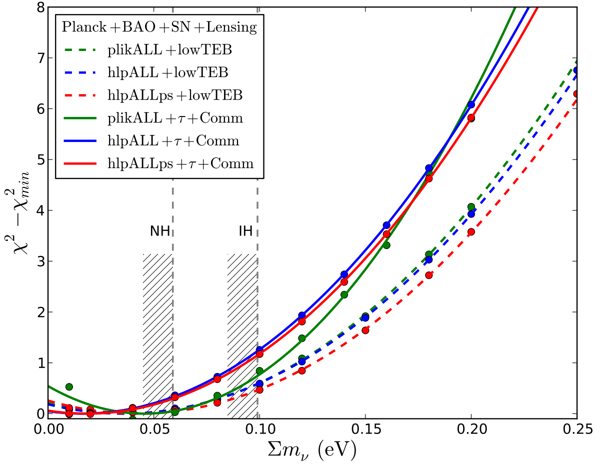
tighter τ constraint (- -) ⇒ lower bound (but $A_L \sim 1.15$ still)

Adding CMB lensing



A_L compliant ! (fitting for $A_L \rightarrow 1.06 \pm 0.05$)
no constraint on the ν hierarchy

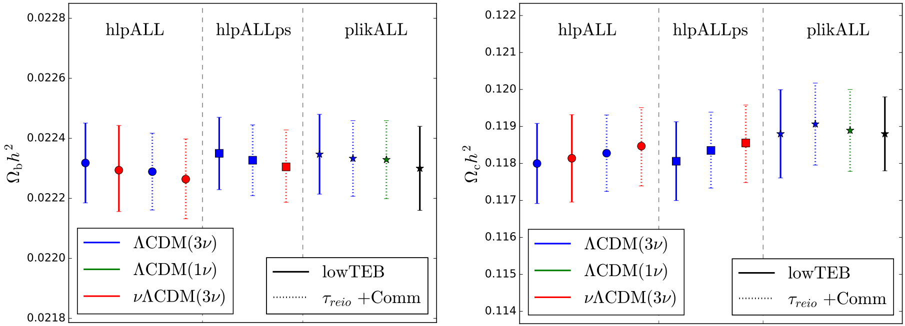
Final result with CMB polarisation



$\sum m_\nu < 0.17 eV (95\% CL)$

difference between likelihoods : 0.01 eV fg. syst.

Effet on (some) other parameters



Fitting for $\sum m_\nu$: larger error bars, (very) small shifts

Conclusions

- study of $\sum m_\nu$ constraints with CMB(Planck) data with emphasis on systematics uncertainties
- foreground systematics invertigated using different modelling (likelihoods)
- A_L mild deviation with Planck alone mitigated using Planck CMB lensing measurement
- final result :

$$\sum m_\nu < 0.17 \text{ [incl. 0.01 (foreground syst.)] eV at 95\% CL}$$

- more in Couchot et al. 2017 (arXiv:1703.10829 , A&A)
- THANK YOU