Cosmological constraints on neutrinos with Planck data

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(on behalf of the Planck Collaboration)

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Motivations

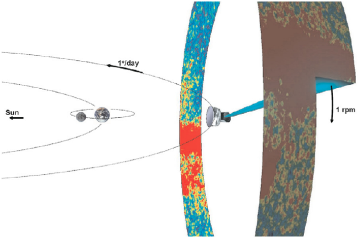
Cette obscure clarté qui tombe des étoiles

(Anselm Kiefer, 1945)

- Neutrinos: weak interaction and *gravity* $\Rightarrow$ influence on a variety of phenomena from early Universe to late time epochs
- Cosmic Microwave Background contains information about the whole story of the Universe
  $\Rightarrow$ we can constrain neutrino physics: masses ($\sum m_\nu$), density of light relics ($N_{\rm eff}$)
- Planck: full sky, high quality data on the CMB temperature anisotropies

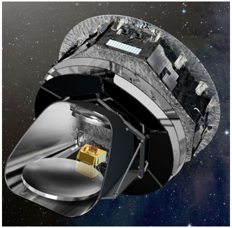
The Planck satellite

Mission at Lagrange point L2
(2009-2013)
Full scan of the sky every 6 months



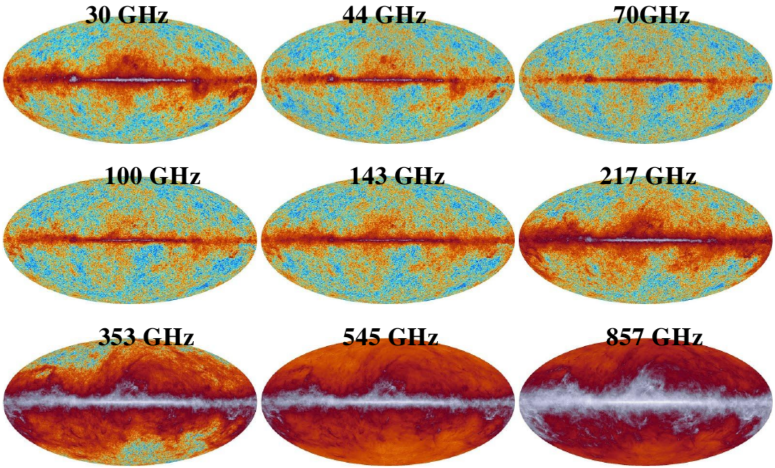
(!) large and redundant sky coverage

(!) low detector noise and high angular resolution

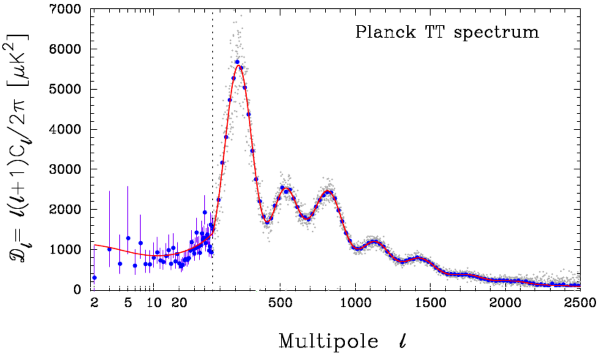


- 2 instruments: LFI/HFI
- 75 detectors:
  22 radiometers,
  52 bolometers
- 9 frequency channels

Planck frequency coverage



From data to parameters estimation



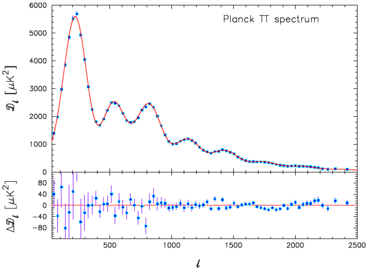
$$\text{maps} \Rightarrow \mathcal{C}_\ell(\vec{\Omega}) \Rightarrow \boxed{\mathcal{L}_{Planck}(\mathcal{C}_\ell, \psi)}$$

($\vec{\Omega}$: *cosmological parameters*, ψ: *nuisances*)[$\sim$ 40 params]

The great success of ΛCDM

The minimal standard model

- flat Universe
- expansion rate H_0, energy density $\Omega_b h^2$, $\Omega_c h^2$
- matter primordial perturbation (scalar, adiabatic) $P_s(k) = A_s(\frac{k}{k_0})^{n_s - 1}$
- reionization: τ (or z_{re})
- 3 active massive neutrinos $\sum m_\nu = 0.06$ eV (from oscillation experiments with $m_{light} \sim 0$ and NH)



ΛCDM is enough to perfectly fit the data

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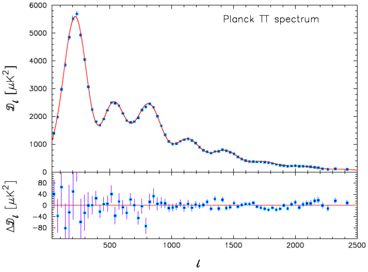

ΛCDM is enough to perfectly fit the data

Anyway..

test of well motivated extensions: $+N_{\rm eff}, + \sum m_\nu$, + ..

1. N_{eff}

N_{eff} ($\sim$massless) degrees of freedom beyond photons relativistic during radiation domination (account for any light relics, GW, etc.)

- $\rho_\nu \propto N_{\mathrm{eff}} T^4_{CMB}$
- standard neutrinos
  $N_{\mathrm{eff}} = 3.046$
- previous hints for $N_{\mathrm{eff}} > 3$
  from SPT, ACT...

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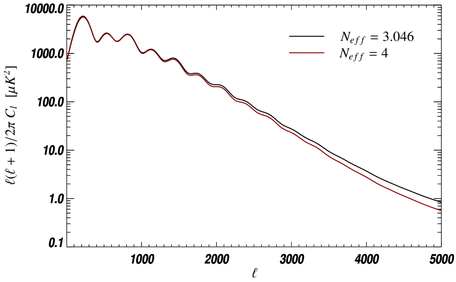
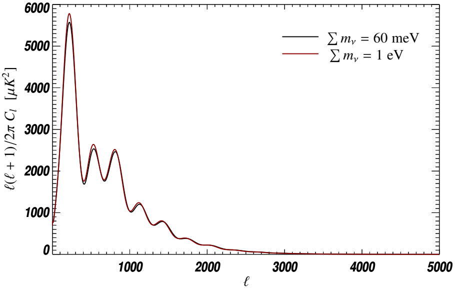
if N_{eff} ⇑, the age of the Universe at recombination ⇓
⇒ **effect on the damping tail**



2. $\sum m_\nu$

CMB only (sligthly) sensitive to $M_\nu = \sum m_\nu$ (degenerate)



a. effect around first acoustic peak

WMAP: $\sum m_\nu < 1.3$ eV $(95\% CL)$

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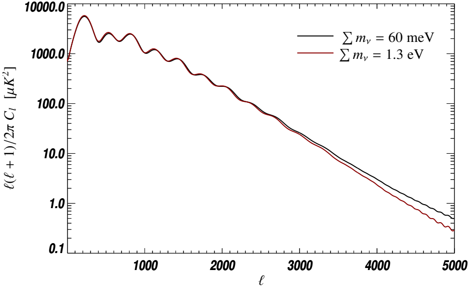


a. effect around first acoustic peak
WMAP: $\sum m_\nu < 1.3$ eV $(95\% CL)$

b. Neutrinos free-streaming suppress small scale clustering

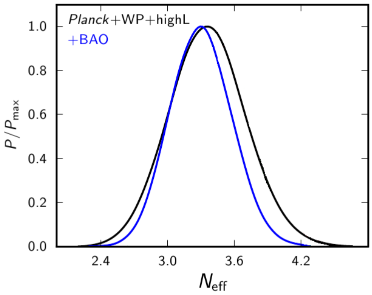
$\rightarrow$ effect on CMB lensing potential reconstructed from non gaussian tri-spectrum
Planck 2013 results. XVII.

1. The CMB sky with Planck
2. Effect of N_{eff} and $\sum m_\nu$ on the CMB
3. **Planck results**
   - Results on N_{eff}
   - Limits on $\sum m_\nu$
   - Some other extensions
4. Conclusions

Results on N_{eff}

- $N_{\mathrm{eff}} = 3.36 \pm 0.34$ (Planck+WP+Highℓ)
- tighter constraint adding BAO data $N_{\mathrm{eff}} = 3.30 \pm 0.27$
- ACT/SPT used a high H_0 value in tension with Planck data

[Planck 2013 results.XVI.]

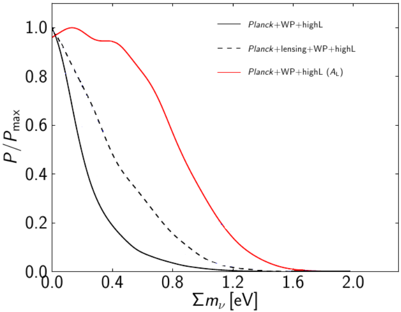


$\boxed{\text{Compatible with 3 species}}$

Results on $\sum m_\nu$

- $\sum m_\nu < 0.66$ eV (95%CL; Planck+WP+High-ℓ)
- $+lensing$ $\sum m_\nu < 0.85\ eV$
- removing lensing information we go back to ~WMAP

[Planck 2013 results.XVI.]

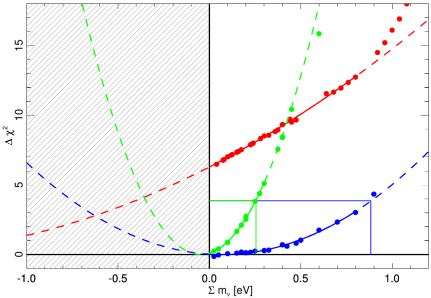


$+BAO$: $\boxed{\sum m_\nu < 0.23 \text{ eV}}$

Results on $\sum m_\nu$ $(profile - \mathcal{L})$

- **frequentist analysis**: Planck alone gives an *artificially low* results
- $+lensing$ $\sum m_\nu < 0.85$ eV
- we use Feldman-Cousins prescription
- $+BAO$: $\boxed{\sum m_\nu < 0.26 \text{ eV}}$

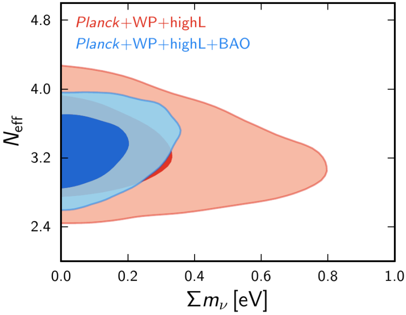
[Planck intermediate results.XVI.]



Planck+WP+Highℓ + lensing + BAO

Simultaneous constraints on $\sum m_\nu$ and N_{eff}

[Planck 2013 results.XVI.]

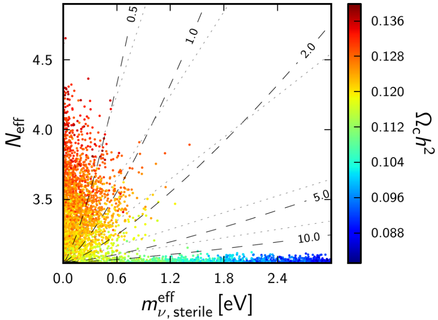


- assumption: 3 active neutrinos coexisting with extra massless species
- $\sum m_\nu$ and N_{eff} different impact on CMB: **no significant correlation**
- results adding BAO:

$$\begin{cases} N_{\text{eff}} = 3.32 \pm 0.27 \ (68\% CL) \\ \sum m_\nu < 0.28 \text{ eV} \ (95\% CL) \end{cases}$$

Any evidence of sterile neutrinos?

Model: extra massive neutrino thermally distributed with arbitrary temperature T_s ($\Delta N_{\rm eff} = (T_s/T_\nu)^4$)



$$m_{\nu,\rm sterile}^{\rm eff} = (\Delta N_{\rm eff})^{3/4} m_{\rm sterile}^{\rm thermal}$$

- for low $N_{\rm eff}$ unconstrained within $\Omega_c h^2$
- for $m_{\rm sterile}^{\rm thermal} < 10$ eV
  $N_{\rm eff} < 3.91$
  $m_{\nu,\rm sterile}^{\rm eff} < 0.59$ eV
  only marginally compatible with oscillation anomalies

(same results valid for Dodelson-Widrow scenario)

Conclusions

- Cosmology is a rich laboratory to test neutrinos properties
- Using high quality CMB data from Planck we obtained (model dependent) constraints on the sum of the masses ($\sum m_\nu$) or on the presence of extra relativistic degree of freedom (N_{eff})
- N_{eff} is compatible with 3 families
- our best limit on the sum of the masses, in combination with BAO measurements is $\sum m_\nu < 0.23$ eV
- no clear indications for sterile neutrinos
- Full Mission and Polarization data: October 2014

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Backup

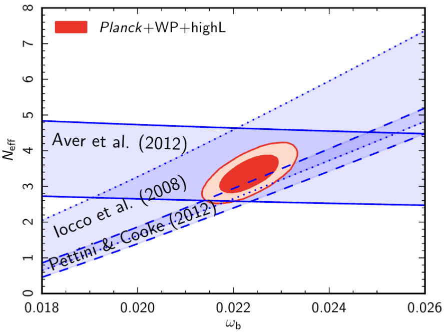
Constraints on $N_{\rm eff}$ from BBN

- $Y_p(\omega_b, N_{\rm eff})$ from PArthENoPE (Pisanti et al 2008)
- with $N_{\rm eff}$ free:

$$\begin{cases} N_{\rm eff} = 3.41 \pm 0.30 \; Y_P \,(\text{Aver et al.}) \\ N_{\rm eff} = 3.43 \pm 0.34 \; Y_{DP} \,(\text{Iocco et al.}) \\ N_{\rm eff} = 3.41 \pm 0.30 \; Y_{DP} \,(\text{Pettini\&Cooke}) \end{cases}$$

- if both $N_{\rm eff}$ and Y_P free still compatible with 3 species but larger errors (degenerate effects on CMB)

Planck 2013 results. XVI.

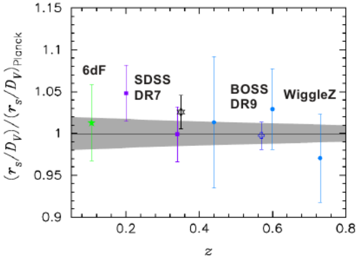


The BAO information improves constraints

Late distance measurements breaks degeneracies:

- M_ν neutrino mass affects D_A to the last scattering (constrained using first acoustic peak) $\rightarrow$ BAO breaks *geometrical* degeneracy
- $N_{\rm eff}$ At θ_s andz_{EQ} fixed, if N_{eff} $\Uparrow$, expansion rate $\Uparrow$ (at low z also) Effect similar on r_s and D_V $\rightarrow$ not as powerfull as for M_ν

BAO data:



- 6dF: $z_{\rm eff} = 0.1$ (*Beutler et al. 2011*)
- SDSS(R): $z_{\rm eff} = 0.32$ (*Padmanahhan et al. 2012*)
- BOSS: $z_{\rm eff} = 0.57$ (*Anderson et al. 2013*)

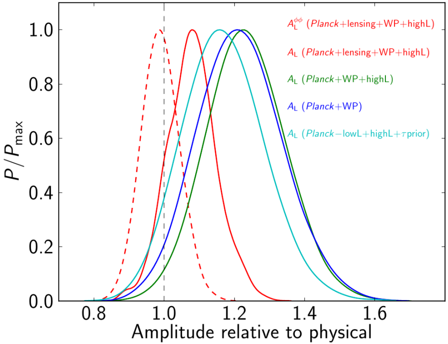
Subtlety of lensing: A_L

$$\vec{\Omega} \to \mathcal{C}_\ell^{TT} \to \tilde{\mathcal{C}}_\ell^{TT}$$

$$\mathcal{C}_\ell^{\phi\phi} \to (A_L)\mathcal{C}_\ell^{\phi\phi}$$

A_L scales the explicit $\mathcal{C}_\ell^{\phi\phi}$
expect $A_L = 1 \to > 1 (2\sigma)$

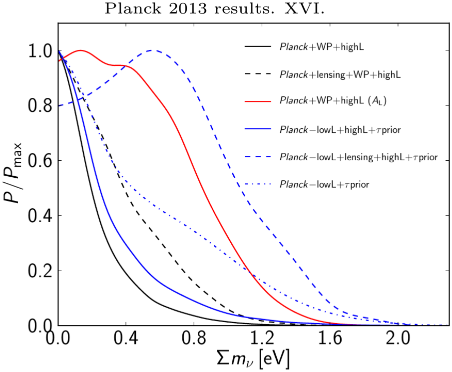
→ slightly more lensing in the *Planck* temperature power spectrum than expected!



More on $\sum m_\nu$

preference for $A_L > 1$ futher investigated

- removal of low-ℓ (τ prior replaces WP)
- removal of Highℓ (limit degrades)
- mild preference for higher masses from lensing 4points respect to 2points info

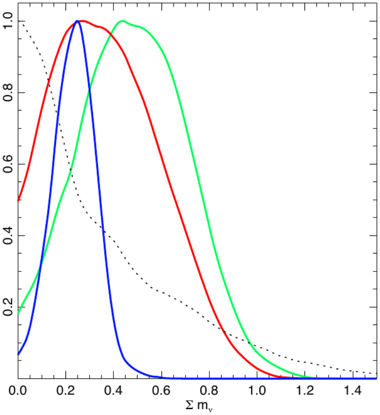


SZ clusters constraints on $\sum m_\nu$

tension CMB *vs* Planck SZ clusters
(residual systematics?, statistical fluctuation?,..)

- Planck+WP+Highℓ
- $\boxed{+\text{SZ } (1-b=0.8)}$
- +SZ ($1-b$ in $[0.7,1]$)
- +SZ+BAO ($1-b$ in $[0.7,1]$)

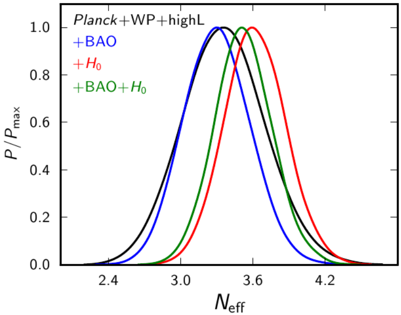
Planck 2013 results. XX.



Results on $N_{\rm eff}$

- $N_{\rm eff} = 3.36 \pm 0.34$ (Planck+WP+Highℓ)
- tighter constraint adding BAO data $N_{\rm eff} = 3.30 \pm 0.27$
- tension H_0 *vs* CMB+BAO relieved at the cost of extra neutrino physics: $N_{\rm eff} = 3.62 \pm 0.25$ **no strong preference**

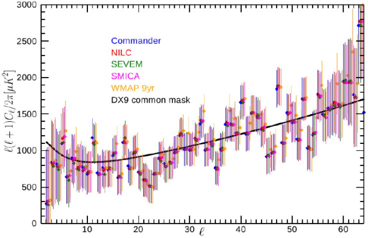
Planck 2013 results. XVI.



Compatible with 3 species

Planck TT Likelihood

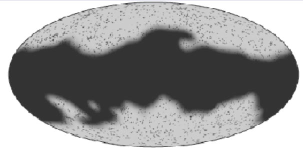
Low ℓ $(2 \le \ell \le 40)$



- from low resolution maps (30GHz-353GHz)
- 91% of the sky
- accounts for errors in foreground cleaning

Highℓ $(\ell \ge 50)$

- uses 100GHz, 143GHz and 217GHz maps
- masking strategy to limit contamination from foregrounds



- likelihood approximated as gaussian

Bayesian approach

Inference on the *true* parameters $\boldsymbol{\theta}$ using posterior probability: given the data, the degree of belief in an assumed model

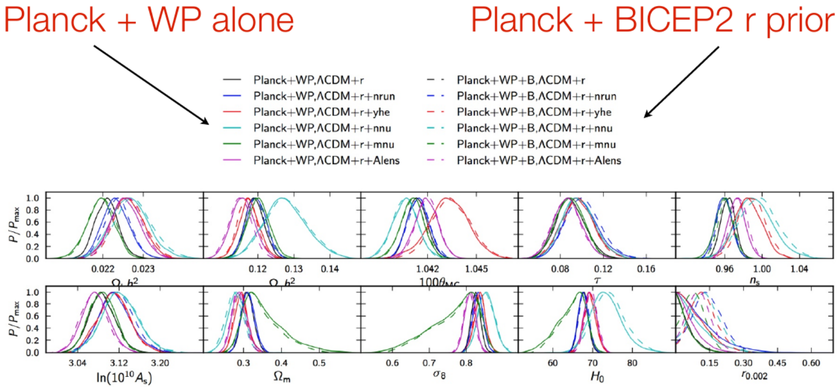
$$\boxed{P(\boldsymbol{\theta}|Planck) \propto \mathcal{L}_{Planck}(\mathcal{C}_l, \boldsymbol{\psi})\pi(\boldsymbol{\theta})}$$

priors $\pi(\boldsymbol{\theta})$: encode previous knowledge

Monte Carlo Markov Chain:

- method to sample from this high dimensional probability distribution
- ergodic Markov chain $\{X_t\}$ with desired stationary distribution
- marginalization: 1-D histograms from the chain
  $\Rightarrow$ posterior on each parameter (mean and CL)

Combining Planck and BICEP2



from Silvia Galli

Planck 2013 statistical methodology comparison on ΛCDM

	CMB		CMB+BAO	
Parameter	MCMC	Profile-likelihood	MCMC	Profile-likelihood
H_0	67.3 ± 1.2	67.2 ± 1.2	67.8 ± 0.8	67.7 ± 0.8
$100\omega_b$	2.207 ± 0.027	2.208 ± 0.027	2.214 ± 0.024	2.215 ± 0.024
ω_c	0.1198 ± 0.0026	0.1201 ± 0.0026	0.1187 ± 0.0017	0.1190 ± 0.0017
n_s	0.9585 ± 0.0070	0.9575 ± 0.0071	0.9608 ± 0.0054	0.9598 ± 0.0055
$\ln(10^{10}A_s)$	3.090 ± 0.025	3.087 ± 0.025	3.091 ± 0.025	3.088 ± 0.025
z_{re}	11.2 ± 1.1	11.0 ± 1.1	11.2 ± 1.1	11.2 ± 1.1

Perfect agreement

Planck intermediate results. XVI. Profile likelihoods for cosmological parameters

arXiv:1311.1657