Limit on the absolute mass scale of neutrinos with Planck

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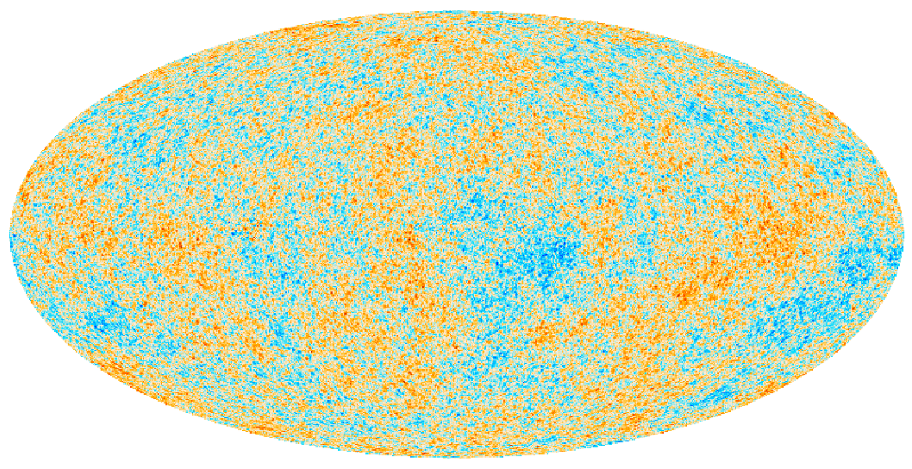
The Cosmic Microwave Background

$\frac{\Delta T}{T} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}$

$\Rightarrow \mathcal{C}_\ell = \langle a_{\ell m} a^*_{\ell m} \rangle$

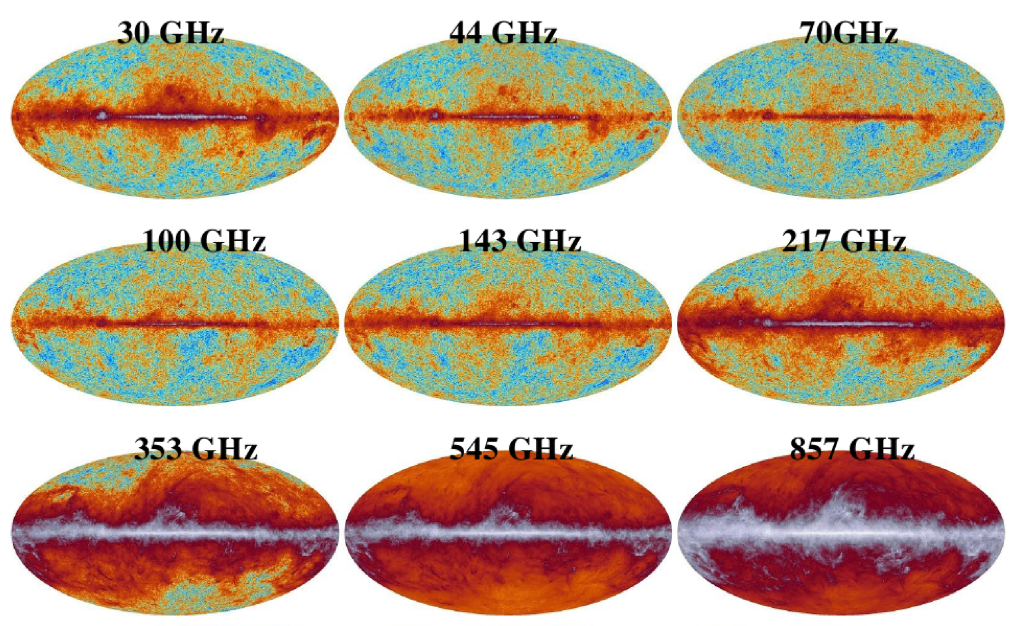
Anisotropies are gaussian distributed on the sky: *angular power spectrum* $\mathcal{C}_\ell$ contains all the information!

- $a_{\ell m} \sim \mathcal{N}(0, \mathcal{C}_\ell)$ (same variance at given ℓ)
- the shape of the $\mathcal{C}_\ell$ is sensible to cosmology (the concordance model ΛCDM : $\{\theta, \omega_b, \omega_{cdm}, \tau, A_s, n_s\}$)



Planck 2013 results, Planck Collaboration

Planck sky coverage



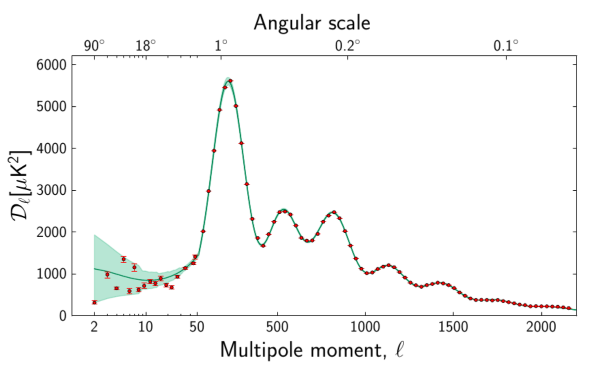
LFI: 22 radiometers (30-70 GHz),

HFI: 52 bolometers (100-857 GHz)

Data and model(s)

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

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



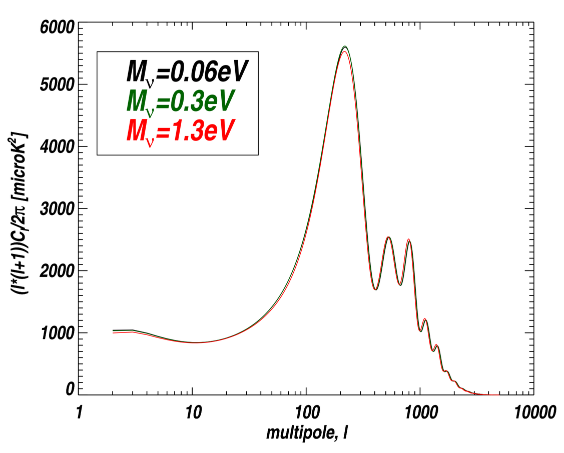
Planck 2013 results. XVI.

- Planck data +WP (WMAP polar at low ℓ) + High-ℓ (ACT, SPT) + *BAO*, *Lensing*
- ΛCDM-model $+N_{\rm eff}, +\sum m_\nu$, + ..

Massive neutrinos and the CMB

- history: decoupling at $T \sim 1MeV$ and then cooling as the CMB
- when they become **non-relativistic** $\langle E_c \rangle \propto T_\nu(z) < m$ $\rightarrow$ they contribute to matter content
- today $T^0_\nu = (\frac{4}{11})^{\frac{1}{3}} T^0_\gamma = 1.1 * 10^{-4} eV \rightarrow 3$ (or 2) are already NR (according to oscillation experiments)

CMB is **slightly** sensitive to the total neutrinos mass $M_\nu = \sum_i m_\nu$ (with Planck precision mass splitting is negligible $\rightarrow$ degenerate)



1. Effect at low-ℓ and first acoustic peak via the *Integrated Sachs-Wolfe effect*

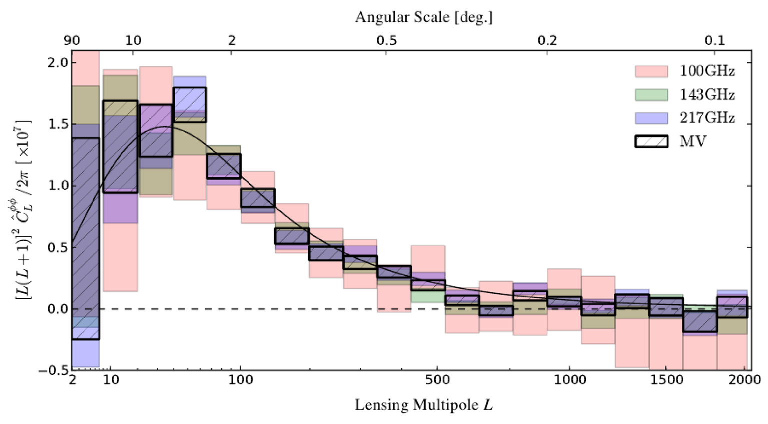
WMAP limit:
$\sum m_\nu < 1.3 eV$ $(95\% CL)$

2. also a modification of $\mathcal{C}_\ell$ at high ℓ (suppression of clustering on small scales)

$\rightarrow$ add small scales matter power spectrum measurement

CMB-Lensing:

$T_{obs}(\vec{n}) = T_{CMB}(\vec{n} + \vec{\nabla}\phi(\vec{n}))$ (deflection field ϕ)

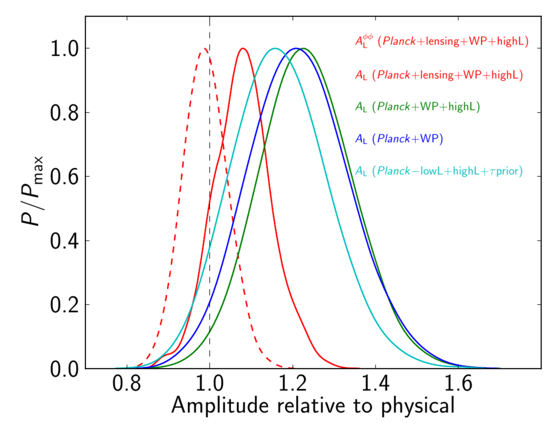


Planck 2013 results. XVII.: estimate of $\mathcal{C}^{\phi\phi}_\ell$ from the non-Gaussian trispectrum

$\vec{\Omega} \rightarrow \mathcal{C}_\ell \rightarrow \tilde{\mathcal{C}}_\ell$

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

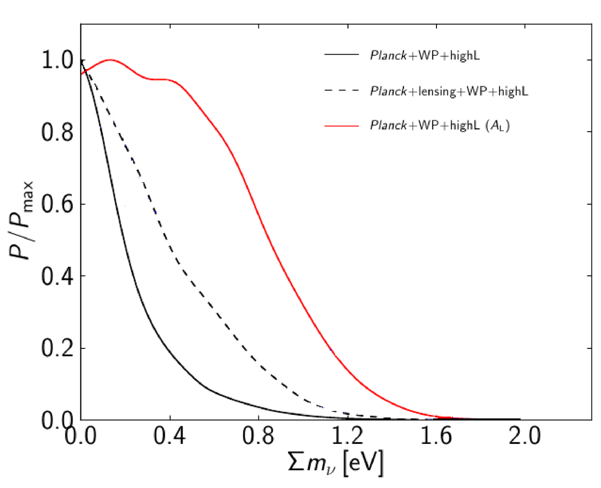
A_L scales the explicit $\mathcal{C}^{\phi\phi}_\ell$ expect $A_L = 1 \rightarrow > 1 (2\sigma)$



Preference for $A_L > 1$ in *Planck* temperature power spectrum

$\rightarrow$ **slightly more lensing in the $\mathcal{C}_\ell$ than expected!**

Limit on neutrino mass

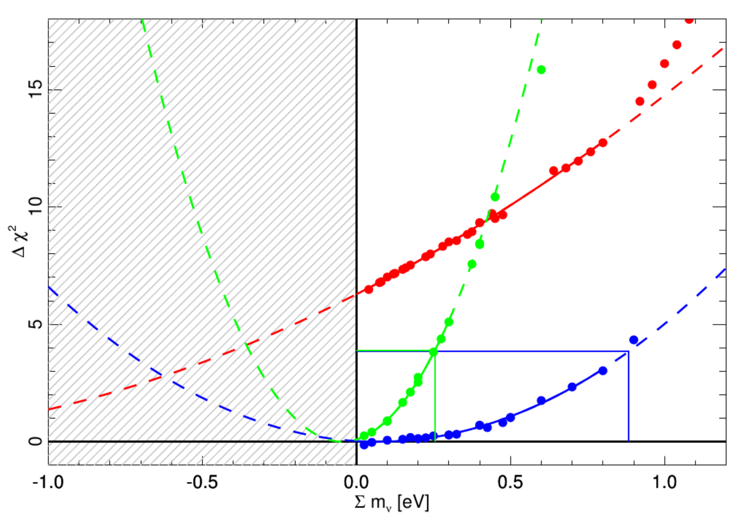


- $M_\nu < 0.66 eV$
- *+lensing* $M_\nu < 0.85 eV$
- without lensing information (marginalizing on A_L) we go back to $\sim$WMAP

presence of a physical boundary $\rightarrow$ differences may appear between Bayesian and frequentist methodologies

Profile-Likelihood analysis

- Planck alone gives an *artificially low* results (what drives A_L high may drive M_ν low)
- *+lensing* $M_\nu < 0.85 eV$
- we use Feldman-Cousins prescription
- *+BAO*: $M_\nu < 0.26 eV$ (*vs.* $< 0.25 eV$ (MCMC))



Planck+WP+Highℓ + lensing + BAO

Planck intermediate results. XVI. Profile likelihoods for cosmological parameters

Statistical methodologies

Bayesian approach: the main-stream method

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

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

Monte Carlo Markov Chain:

- method to sample from this high dimensional probability distribution
- marginalization: 1-D histograms from the chain $\Rightarrow$ posterior on each parameter (mean and CL)

Frequentist approach: an *unusual* method

why: we can test the results against statistical method

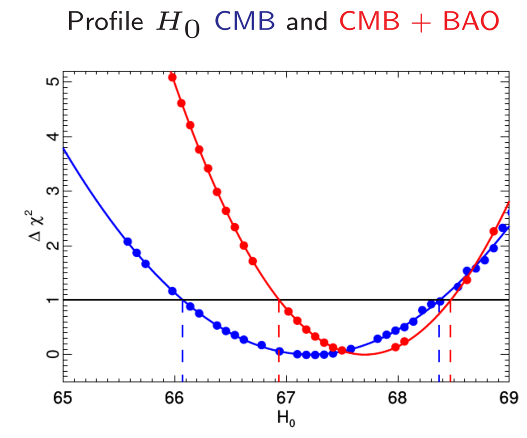
- no priors (true parameters have no distribution)
- MLE (χ^2_{min}) global Maximum Likelihood Estimate is invariant with respect to the choice of the set of parameters
- no *volume effects* from marginalization

how: MINUIT as high precision minimizer

$\rightarrow$ minimum $\chi^2 = -2 \ln \mathcal{L}$ and its *Hessian* matrix.

$\rightarrow$ **Profile-Likelihood** to estimate errors

- $\mathcal{L}_p(\theta) = \mathcal{L}(\theta, \hat{\hat{\psi}}(\theta))$ with $\hat{\hat{\psi}}(\theta)$ the ψ that maximizes $\mathcal{L}$ at fixed θ.
- minimum $\chi^2(\theta) = -2ln\mathcal{L}_p(\theta)$ coincides with χ^2_{min}



Perfect agreement on ΛCDM: Planck intermediate. XVI.

Effective neutrino number: $N_{\rm eff}$

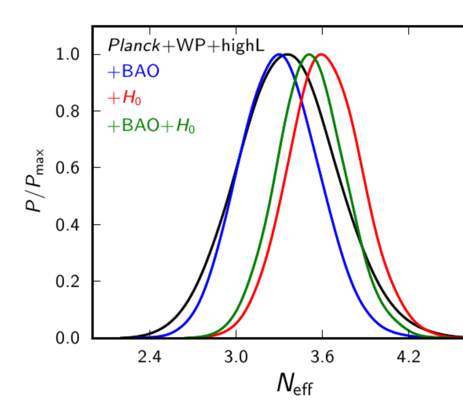
$N_{\rm eff}$ ($\sim$massless) degrees of freedom beyond photons that are relativistic during radiation domination (account for an light relics, GW, etc.)

- $\rho_\nu = N_{\rm eff} \frac{7}{8} (\frac{4}{11})^{\frac{4}{3}} \rho_\gamma$
- standard neutrinos $N_{\rm eff} = 3.046$
- hints for $N_{\rm eff} > 3$ from SPT, ACT...

Effects on $\mathcal{C}_\ell$:
At θ_s fixed (position of the peaks) and z_{EQ} fixed (height of the first peak), if $N_{\rm eff} \Uparrow$, the age of the Universe at recombination $\Downarrow$
$\Rightarrow$ effect in the damping tail

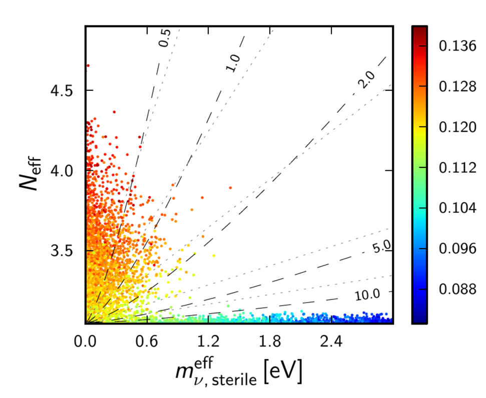
Results on $N_{\rm eff}$

- $N_{\rm eff} = 3.36 \pm 0.34$ (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**



Compatible with 3 species

Steriles Neutrinos



$m^{\rm eff}_{\nu,\rm sterile} = (\Delta N_{\rm eff})^{\frac{3}{4}} m^{\rm thermal}_{\rm sterile}$

- for low $N_{\rm eff}$ unconstrained with CDM
- for $m^{\rm thermal}_{\rm sterile} < 10 eV$ $N_{\rm eff} < 3.91$ $m^{\rm eff}_{\nu,\rm sterile} < 0.59 eV$