
PLANCK 2014
THE MICROWAVE SKY IN
TEMPERATURE AND POLARIZATION

Planck constraints on neutrinos

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on behalf of the Planck Collaboration

The Cosmic Neutrino Background ($C\nu B$)

- The presence of a background of relic neutrinos is a basic prediction of the standard cosmological model

- Neutrinos are kept in thermal equilibrium with the cosmological plasma by weak interactions until T ~ 1 MeV (z ~ 10^{10});

- Neutrinos keep the energy spectrum of a relativistic fermion in equilibrium:

$$f_\nu(p) = \frac{1}{e^{p/T} + 1}$$

- The present Universe is filled by a relic neutrino background with T = 1.9 K and n = 113 part/cm^3 per species ($C\nu B$)

The Cosmic Neutrino Background ($C\nu B$)

- Neutrinos are nonrelativistic today…

$$\rho_\nu = m_\nu n_\nu = m_\nu g_\nu \int f(p) d^3p \propto m_\nu g_\nu T_\nu^3$$

$$\Longrightarrow \quad \Omega_\nu = \sum_\nu \frac{\rho_\nu}{\rho_c} = \frac{\sum_\nu m_\nu}{93.14 h^2\ \mathrm{eV}}$$

- … but they were ultrarelativistic in the early Universe

$$\rho_\nu = g_\nu \int p\, f(p) d^3p \propto g_\nu T_\nu^4$$

$$\rho_{\rm rad} = \rho_\nu + \rho_\gamma = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\nu\right] \rho_\gamma$$

The Cosmic Neutrino Background ($C\nu B$)

- The latter is recast as a ***definition*** the N_{eff} parameter:

$$\rho_{\rm rad} \equiv \rho_\nu + \rho_\gamma = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

i.e.,

$$N_{\rm eff} \equiv \frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\nu^{\rm (std)}}$$

indeed, also assuming a the standard thermal history, N_{eff} =3.046 (Mangano et al., 2005)

In general, N_{eff} parameterizes the presence of extra radiation components ("dark" radiation, not necessarily associated to neutrinos) in the early Universe.

Neutrino masses

- We know from oscillation experiments that neutrinos do have a mass
- Oscillation experiments measure the mass differences:

$$\delta m^2_{21} = 7.6 \pm 0.6 \times 10^{-5}\ eV^2, \delta m^2_{31} = 2.5 \times 10^{-3}\ eV^2$$

- Mixing angles are also quite well known….
- …however the absolute mass scale remains unknown
- this can be measured through tritium beta decay (m_β)…
- …. neutrinoless double β decay ($m_{\beta\beta}$) ….
- … and of course comsmology (Σm_ν)

Probing neutrino masses with CMB data

The effect of neutrinos with a mass between 10^{-3} and 1 eV on the primary CMB spectrum comes from the fact that they contribute to the radiation density at the time of equality, and to the nonrelativistic matter density today.

This induces an integrated Sachs-Wolfe effect (both at early and late times) and/or a change in the angular diameter distance to the last scattering surface.

Before Planck, these were the dominant effects in constraining the neutrino mass from CMB data.

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Planck has moved us to a new regime where instead the dominant effect is gravitational lensing.

Increasing the neutrino mass suppresses clustering on scales smaller than the size of the horizon at the time of the NR transition., suppressing the lensing potential.

Probing neutrino masses with CMB data

We quote constraints on the parameters obtained using different combinations of the following datasets:

-the Planck temperature power spectrum (2 < ell < 2500). This includes the effect of lensing of the CMB by large scale structures (***PlanckTT***);

-the large angular scale (low-ell, 2 < ell < 30) Planck polarization data (***lowP***);

-Planck TE and EE high-ell (30 < ell <2500) polarization spectra (**Planck TE, EE**). Be aware however that high-ell polarization could still be affected by low-level residual systematics.

-the Planck lensing potential power spectrum (40 < ell <400), as estimated from the Planck trispectrum (i.e., < TTTT>) data (***lensing***)

-astrophysical probes: Baryon acoustic oscillations (6dFGS, SDSS-MGS, BOSS-LOWZ, CMASS DR11) (***BAO***), Type Ia Supernovae (***JLA*** sample, including SNLS, SDSS and samples of low z SNe), Hubble constant (from Efstathiou 2014 reanalysis ot Riess et al. 2011) (***H0***), collectively denoted as "***ext***"

Planck constraints on neutrino masses

Planck constraints on Σm_ν

	2013	2014	2014 + PlanckTE,EE
PlanckTT+lowP	<0.93 eV		
PlanckTT+lowP+lensing	<1.1 eV		
PlanckTT+lowP+BAO	<0.25 eV		

(all limits are @95% CL)
(for 2013, 'lowP' refers to WMAP polarization)

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PlanckTT+lowP+BAO	<0.25 eV	<0.21 eV (16%)	
PlanckTT+lowP+ext		<0.20 eV	
PlanckTT+lowP+lensing+ext		<0.23 eV	

(all limits are @95% CL)
(for 2013, 'lowP' refers to WMAP polarization)

Planck constraints on neutrino masses

- the PlanckTT + large scale polarization (+lensing) constraints improve by nearly 25% (40%).

- the lensing reconstruction data prefers lower lensing amplitudes with respect to the CMB power spectrum (best-fit for lensing only is around 0.6eV) → the lensing information improves only slightly or even worsens the constraints.

Planck constraints on neutrino masses

Planck constraints on Σm_ν

	2013	2014	2014 + PlanckTE,EE
PlanckTT+lowP	<0.93 eV	<0.72 eV (23%)	<0.48 eV (48%)
PlanckTT+lowP+lensing	<1.1 eV	<0.70 eV (36%)	<0.58 eV (47%)
PlanckTT+lowP+BAO	<0.25 eV	<0.21 eV (16%)	<0.16 eV (36%)
PlanckTT+lowP+ext		<0.20 eV	<0.15 eV
PlanckTT+lowP+lensing+ext		<0.23 eV	<0.19 eV

(all limits are @95% CL)
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Planck constraints on neutrino masses

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(all limits are @95% CL)
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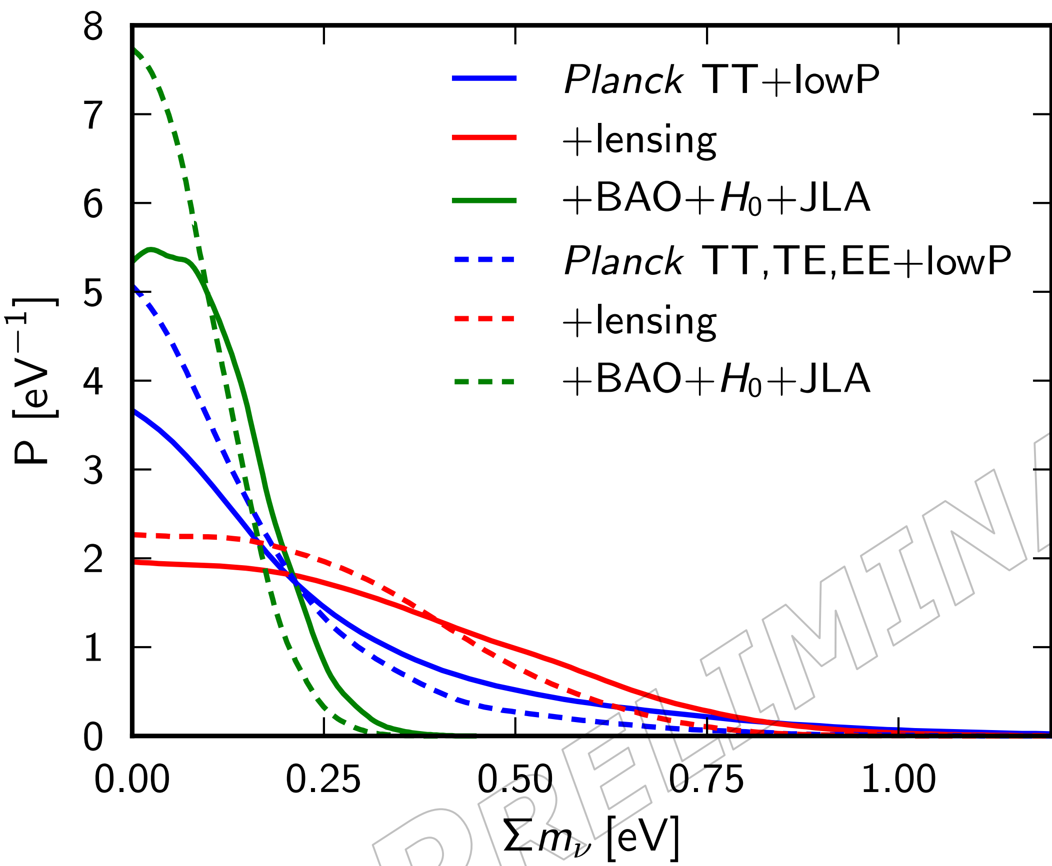
Small-scale polarization improves CMB only limits by nearly a factor 2

Planck constraints on neutrino masses



Σm_ν < 0.72 eV (PlanckTT+lowP)

Σm_ν < 0.70 eV (…. + lensing)

Σm_ν < 0.23 eV (… + ext)

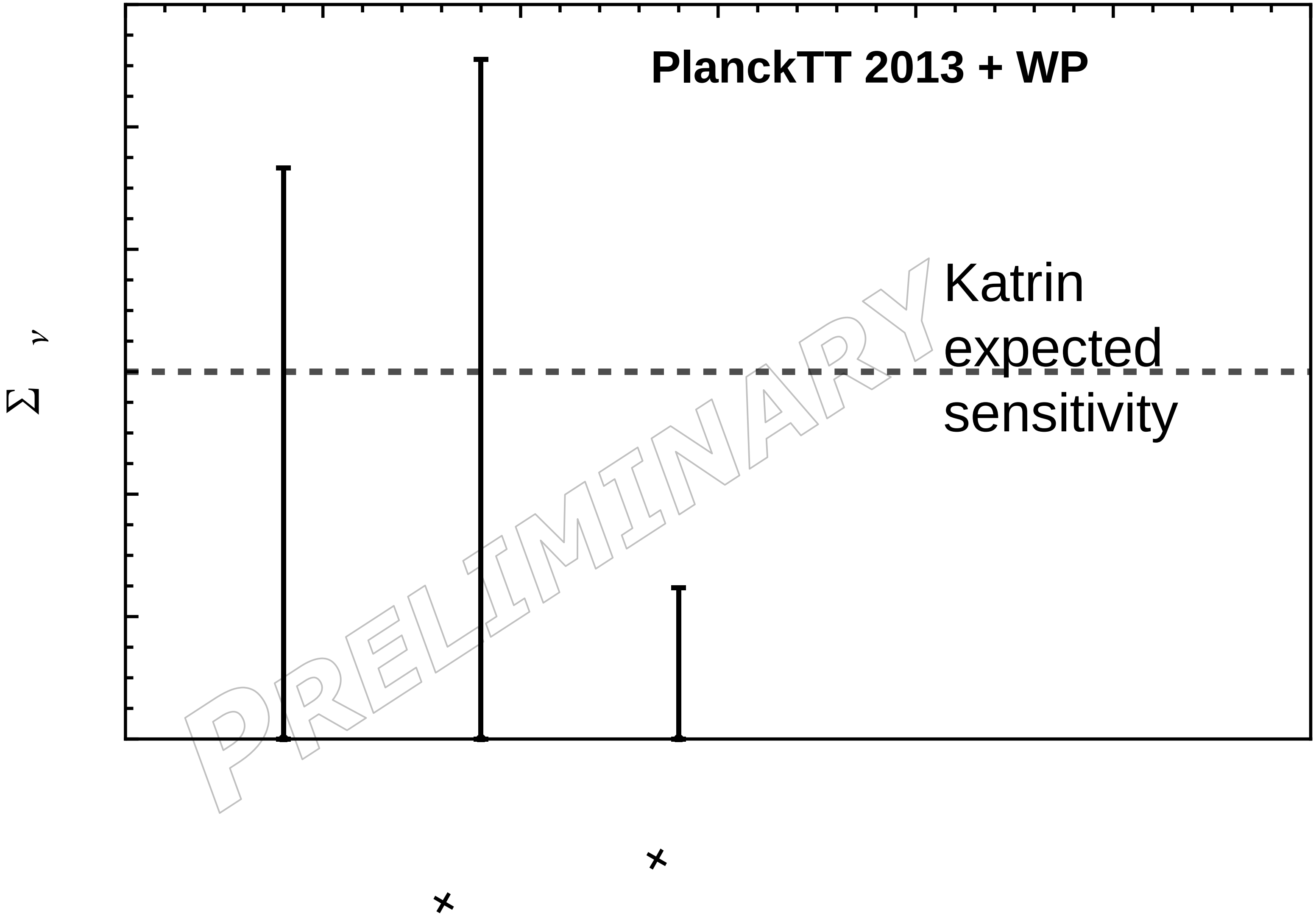
Σm_ν < 0.48 eV (PlanckTT,TE,EE +lowP)

Σm_ν < 0.58 eV (…. + lensing)

Σm_ν < 0.19 eV (… + ext)

(all limits are 95% CL)

Planck constraints on neutrino masses



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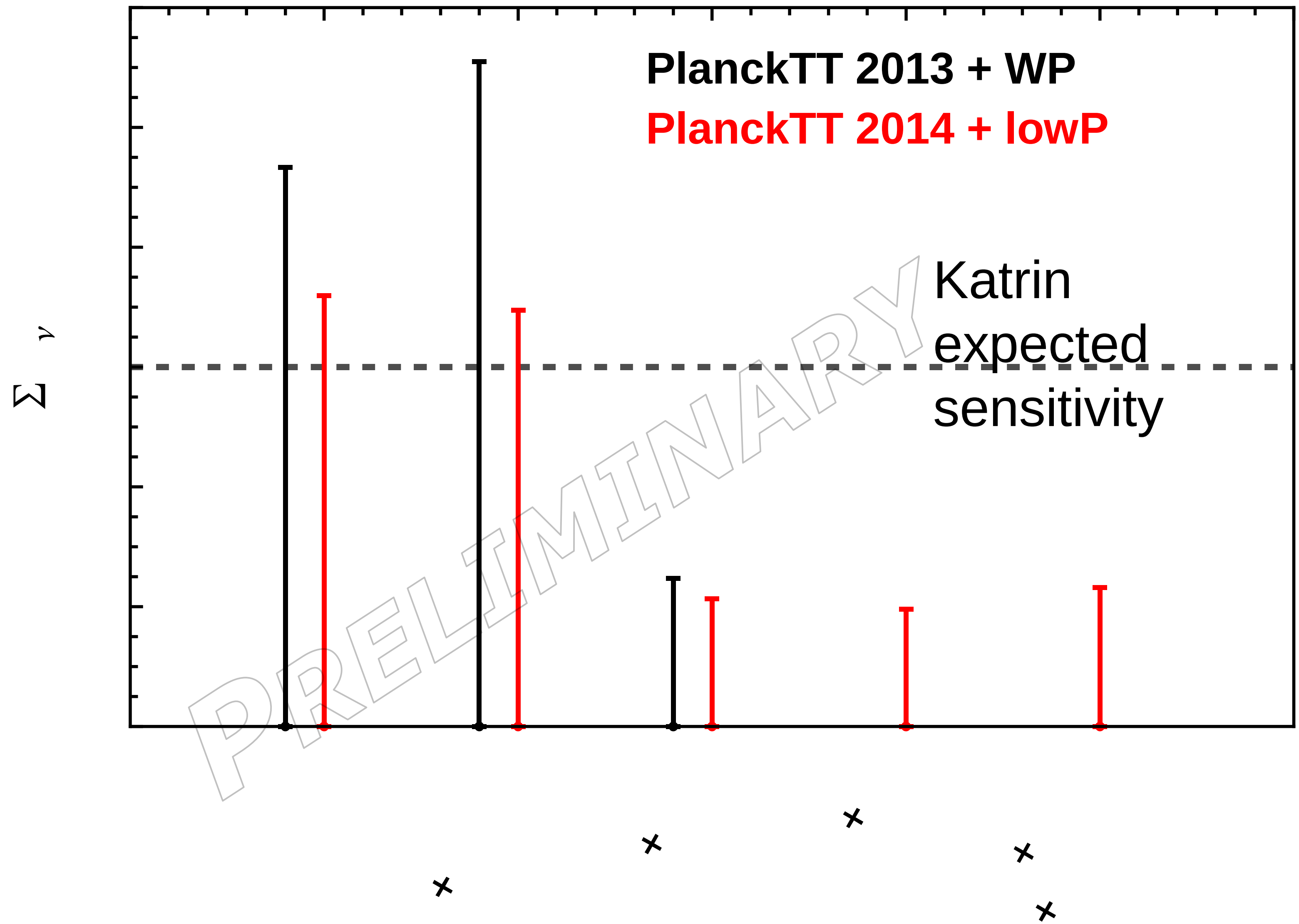

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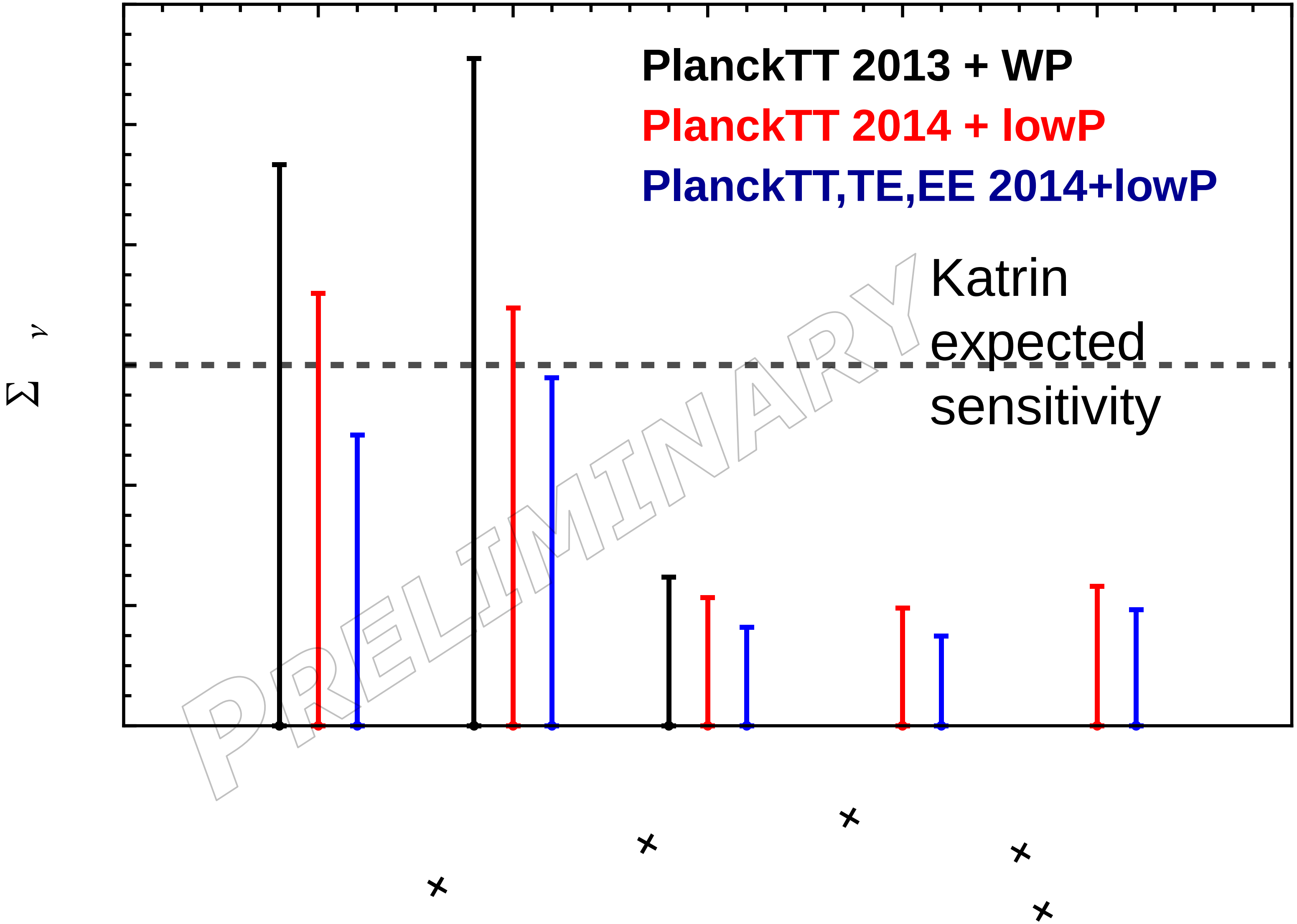
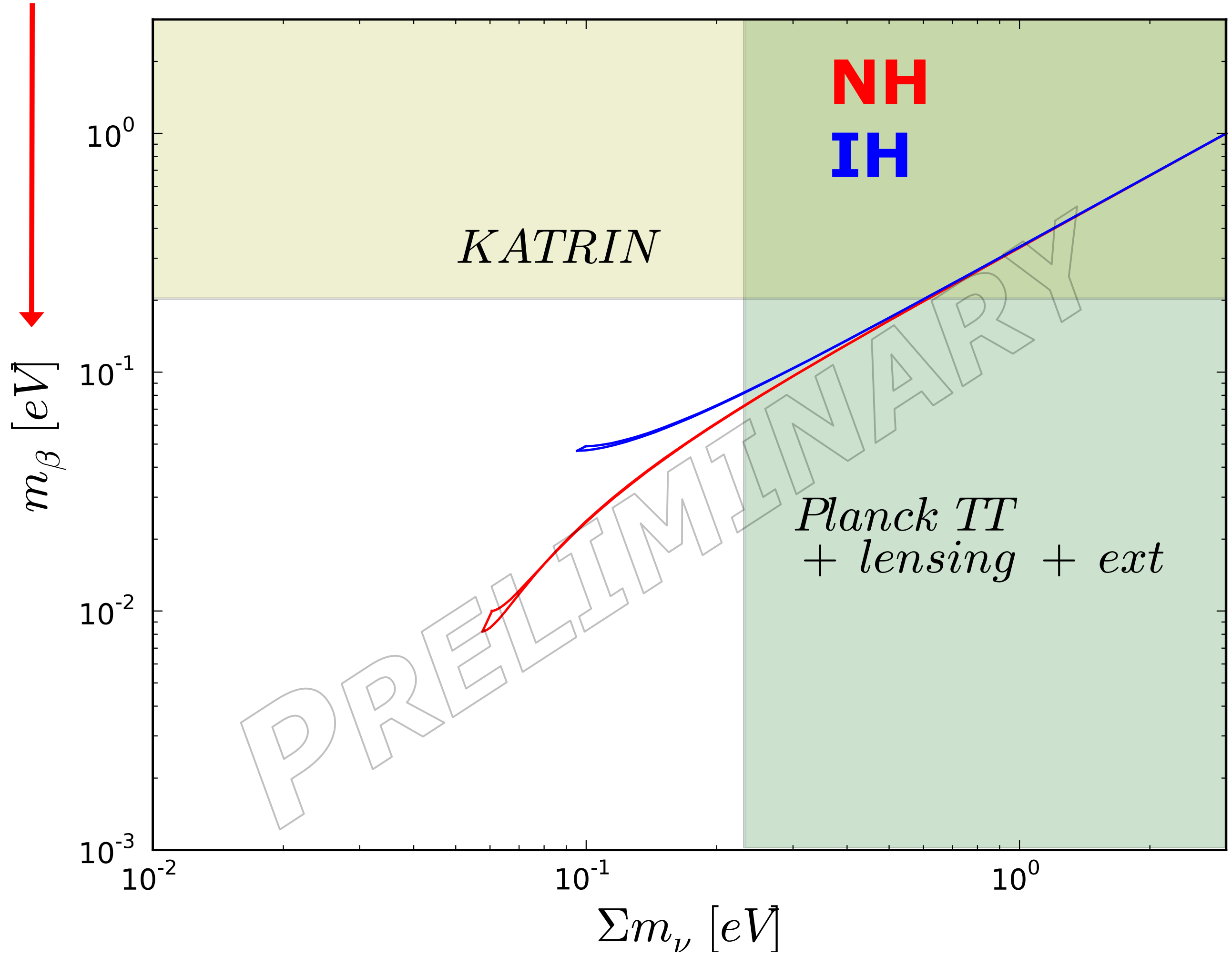


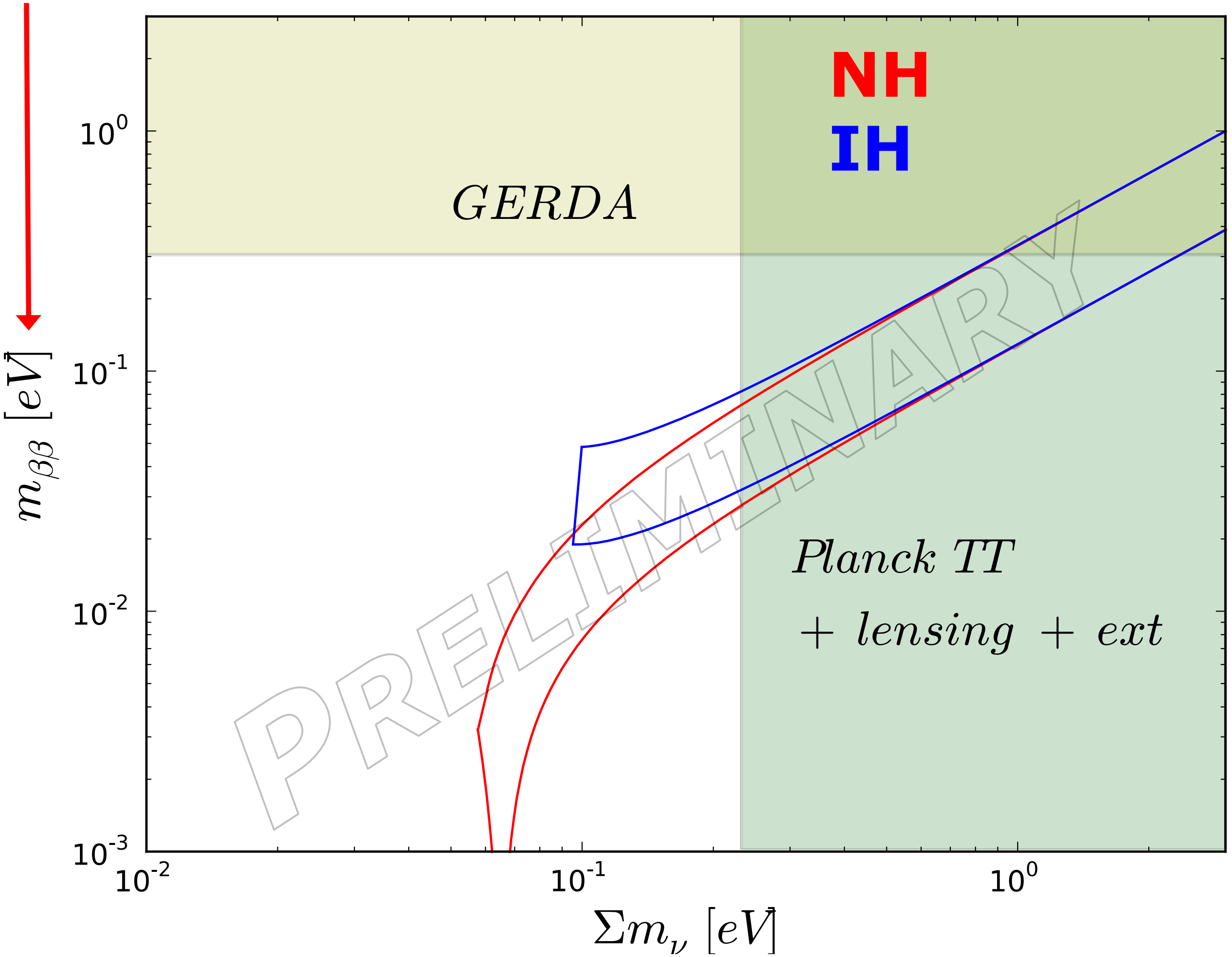
Tritium decay, 02 and Cosmology

$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

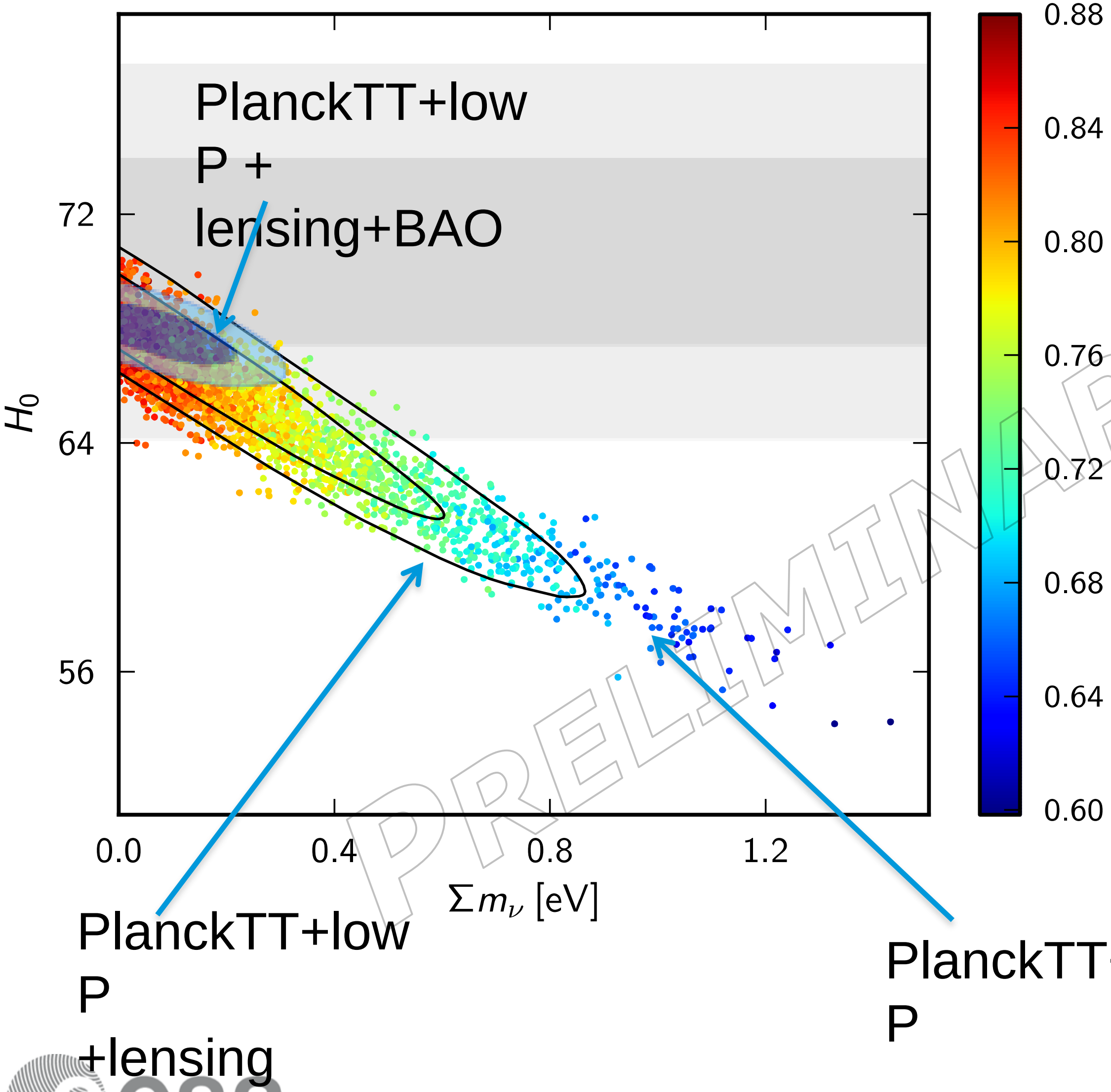


Tritium □ decay, 0□2□ and Cosmology

$$\left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



Neutrino masses and tension with external data



- m_ν alone does not solve the tension with LSS – σ_8 still too large!
- Larger masses also increase tension with direct measurements of the Hubble parameter

Probing N_{eff} with CMB data

N_{eff} parameterizes the density of radiation (other than photons) in the Universe, in units of the density of a single neutrino family in thermodynamic equilibrium at T=1.9 K. The standard value is N_{eff} = 3.046

An excess in N_{eff} could be caused by a neutrino/antineutrino asymmetry, sterile neutrinos, or other light relics in the Universe. The case N_{eff} < 3.046 is also possible (e.g. low reheating scenarios).

The main effect of increasing N_{eff} while keeping both θ_* and z_{eq} fixed is to increase the expansion rate before recombination and thus make the Universe younger at recombination. This increases the angular scale of the photon diffusion length and thus reduces the power in the damping tail.

N_{eff} is correlated mainly with H_0, Y_p and n_s.

N_{eff} constraints from Planck

$N_{\rm eff} = 3.13 \pm 0.32$ (PlanckTT+lowP)

$N_{\rm eff} = 3.15 \pm 0.23$ (PlanckTT+lowP+BAO)

$N_{\rm eff} = 2.98 \pm 0.20$ (PlanckTT,TE,EE+lowP)

$N_{\rm eff} = 3.04 \pm 0.18$
(PlanckTT,TE,EE+lowP+BAO)

(uncertainties are 68% CL)

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$N_{\rm eff} = 3.04 \pm 0.18$
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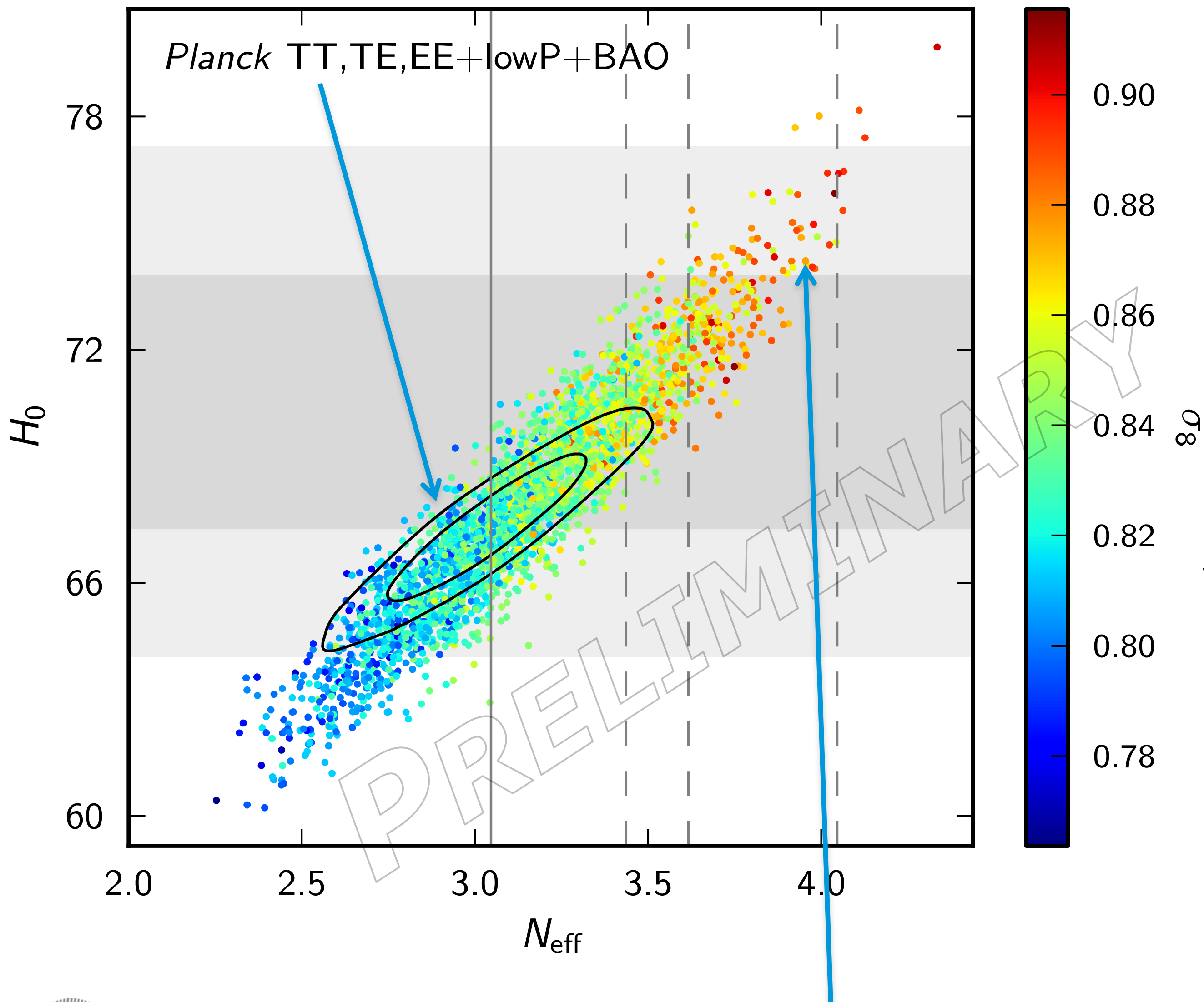
(uncertainties are 68% CL)

PRELIMINARY

- $N_{\rm eff} = 4$ (i.e., one extra thermalized neutrino) is excluded at between ~ 3 and 5 sigma.

N_{eff} constraints from Planck



PlanckTT + lowP

Higher values of N_{eff} can help relieve the tension with astrophysical measurements of H_0

However, they imply a larger σ_8 and thus worsen the tension with LSS probes.

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Joint constraints on N_{eff} and Σm_ν

When both the mass and number of families are allowed to vary we get the following joint constraints:

$$N_{\rm eff} = 3.2 \pm 0.5$$
$$\Sigma m_\nu < 0.32 \text{ eV}$$

(95% PlanckTT+lowP+lensing+BAO)

$$N_{\rm eff} = 3.0 \pm 0.4$$
$$\Sigma m_\nu < 0.22 \text{ eV}$$

(95% PlanckTT,TE,EE+lowP+lensing+BAO)

Significance of $N_{\rm eff} < 4$ is reduced.

Conclusions

- Planck can constrain neutrino masses mainly thanks to the lensing of the power spectrum
- Without using polarization at high-ells, Planck-only constraints improve by between 25 and 40% wrt 2013
- PlanckTT+lowP+BAO gives $\Sigma m_\nu < 0.23$ eV
- When high-ell polarization is used the Planck-only constraints improve by nearly a factor 2 wrt 2013. Planck alone is already better or at the same level as KATRIN!
- PlanckTT,TE,EE+lowP+BAO gives $\Sigma m_\nu < 0.16$ eV
- Planck is compatible with 3 neutrino families; $N_{eff} = 4$ is excluded at between 3 and 5 sigma, depending on the dataset
- The significance of $N_{eff} < 4$ is reduced when N_{eff} and Σm_ν are varied jointly

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.

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.


Thank you
X. Ferrara, Dec 2014