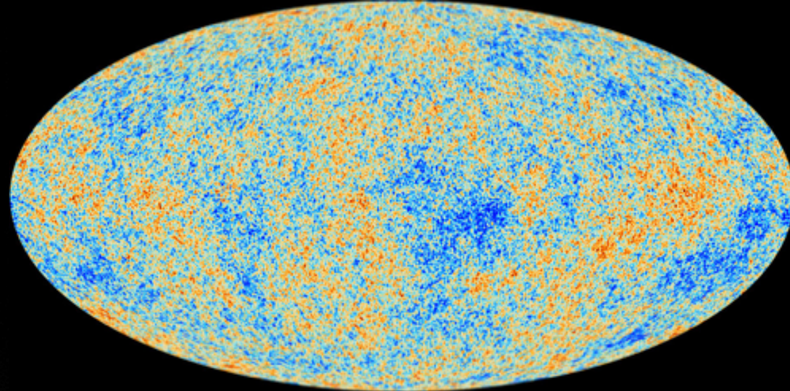
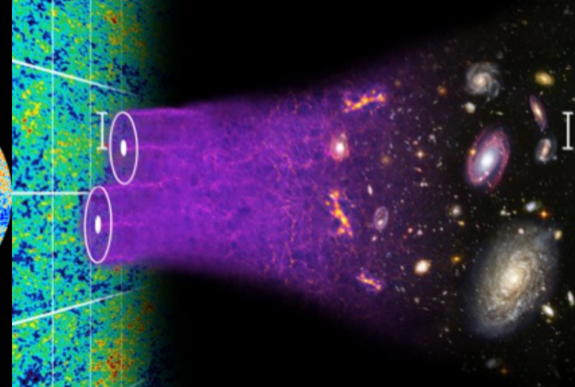




Implications of cosmological observations on hot dark matter properties

Elena Giusarma

Cosmology on Safari 2015

SAPIENZA
UNIVERSITÀ DI ROMA

Based on works in collaboration with:
E. Di Valentino, S. Gariazzo, M. Lattanzi,
A. Melchiorri, O. Mena

INFN

✓Introduction

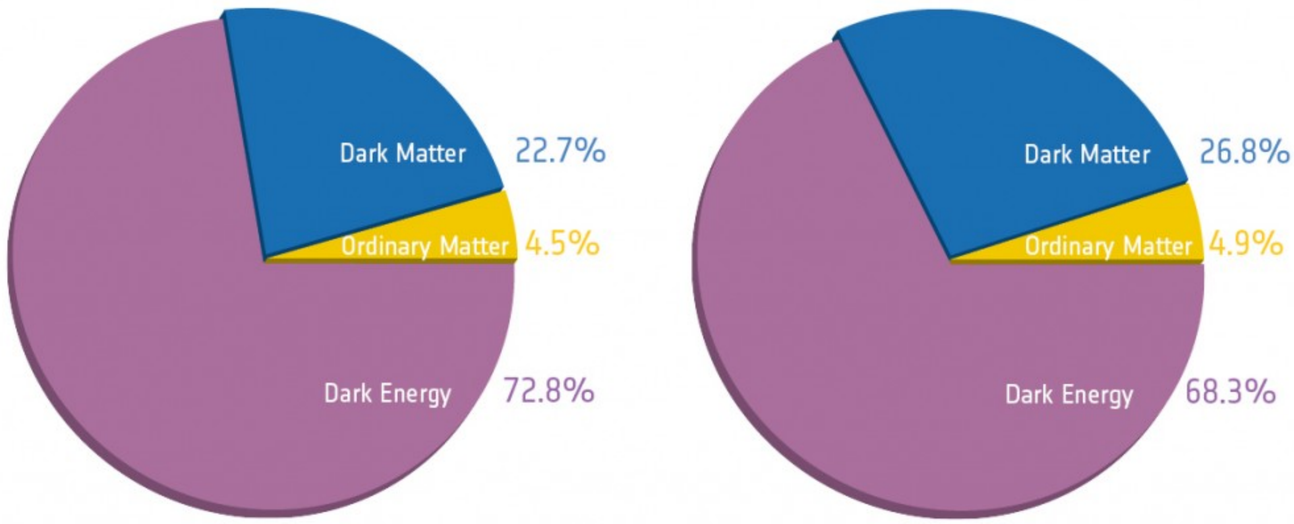
✓ Impact of HDM properties on cosmological observables:

- Neutrino masses
- Thermal axions
- Relativistic degrees of freedom N_{eff}

✓Existence of extra hot relic components as dark radiation relics, sterile neutrino species or thermal axions and constraints on the masses of the thermal relics in different scenarios using the available cosmological data

✓ Bounds on thermal axions using a non power-law Primordial Power Spectrum (Preliminary results)

Cosmic Pies



Before Planck

After Planck 2013

DARK MATTER → HDM + CDM

HDM → NEUTRINO, THERMAL AXION

CDM → AXION

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Cosmic Neutrinos

- In the standard cosmological model, cosmic neutrinos are produced at high temperature in the early Universe by frequent weak interactions and they are maintained in thermal equilibrium with the e.m. plasma.

- Neutrinos decouple at T ~ 1MeV ($n_\nu \sigma_\nu v \approx H$), keeping a spectrum as that of a relativistic species:

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

- $T_g \sim m_e$, $e^+ e^-$ annihilation heats the photons but not the decoupled neutrinos:

Temperature: $$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \rightarrow T_{\nu,0} = 1.945\text{K} \sim 1.676 \times 10^{-4}\text{eV}$$

Number density: $$n_\nu = \left(\frac{3}{11}\right) n_\gamma \rightarrow n_{\nu,0} \approx 56\text{cm}^{-3}$$

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

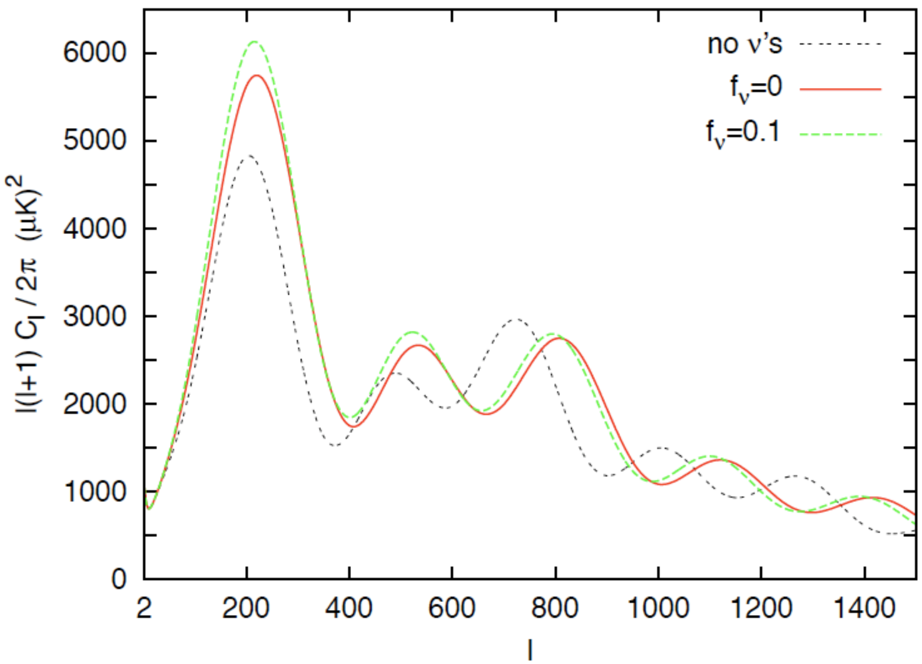
Energy density: $$\rho_\nu = \begin{cases} \frac{7\pi^2}{120}\left(\frac{4}{11}\right)^{1/3} T_\gamma^4 & \textit{Massless} \\ m_\nu n_\nu & \textit{Massive}\ m_\nu >> T_\nu \end{cases}$$

Neutrino energy density parameter

Sub-eV massive neutrinos cosmological signatures

In the standard cosmology hot, thermal relics are identified with the three light, active neutrino flavours of the Standard Model of elementary particles.

- CMB: a) *Early Integrated Sachs Wolfe effect.* The transition from the relativistic to the non relativistic neutrino regime affect the decay of the gravitational potentials at decoupling period (especially near the first acoustic peak).
  b) Suppression of lensing potential (with Planck). An increase of the neutrino mass suppresses clustering on scales smaller than the size of the horizon at the time of the non-relativistic transition, suppressing the lensing potential.



$$1 + z_{nr,\nu} \simeq 1890 \left(\frac{m_\nu}{1eV}\right)$$

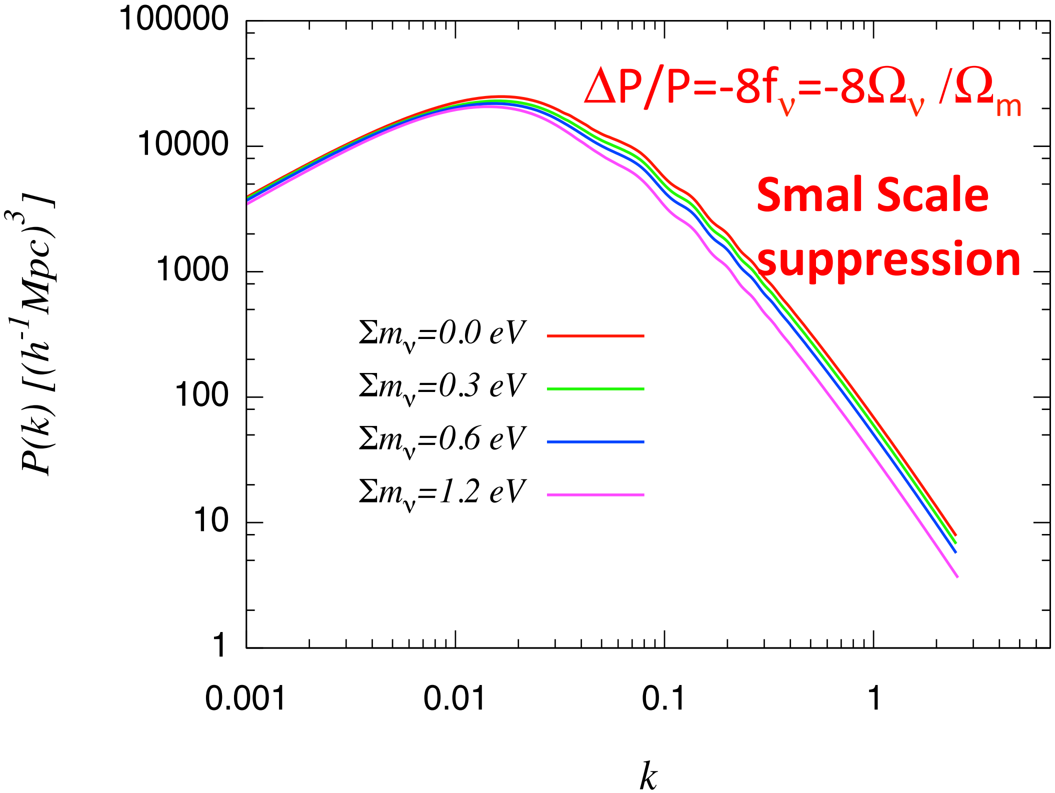
$$f_\nu = \Omega_\nu / \Omega_m$$

Lesgourgues, Pastor, Phys.Rept.'06

Sub-eV massive neutrinos cosmological signatures

- LSS: Suppression of structure formation on scales smaller than the free streaming scale when neutrinos turn non relativistic, affecting also the Baryon acoustic oscillation (BAO) scale which are the imprint on the matter distribution of the pressure-gravity competition in the baryon-photon fluid.

$$k_{fs,\nu}(z) \simeq 0.7 \left(\frac{m_\nu}{1eV}\right) \sqrt{\frac{\Omega_M}{1+z}}\ \mathbf{h\ Mpc^{-1}}$$

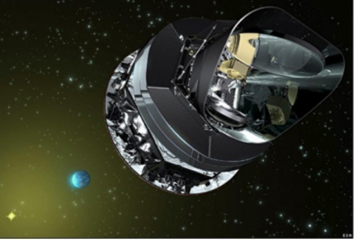


- Large scales ($k<k_{fs}$)

Neutrinos cluster and behave as cold dark matter: $\delta_\nu=\delta\rho/\delta\rho_c=\delta_{cdm} \sim a$.

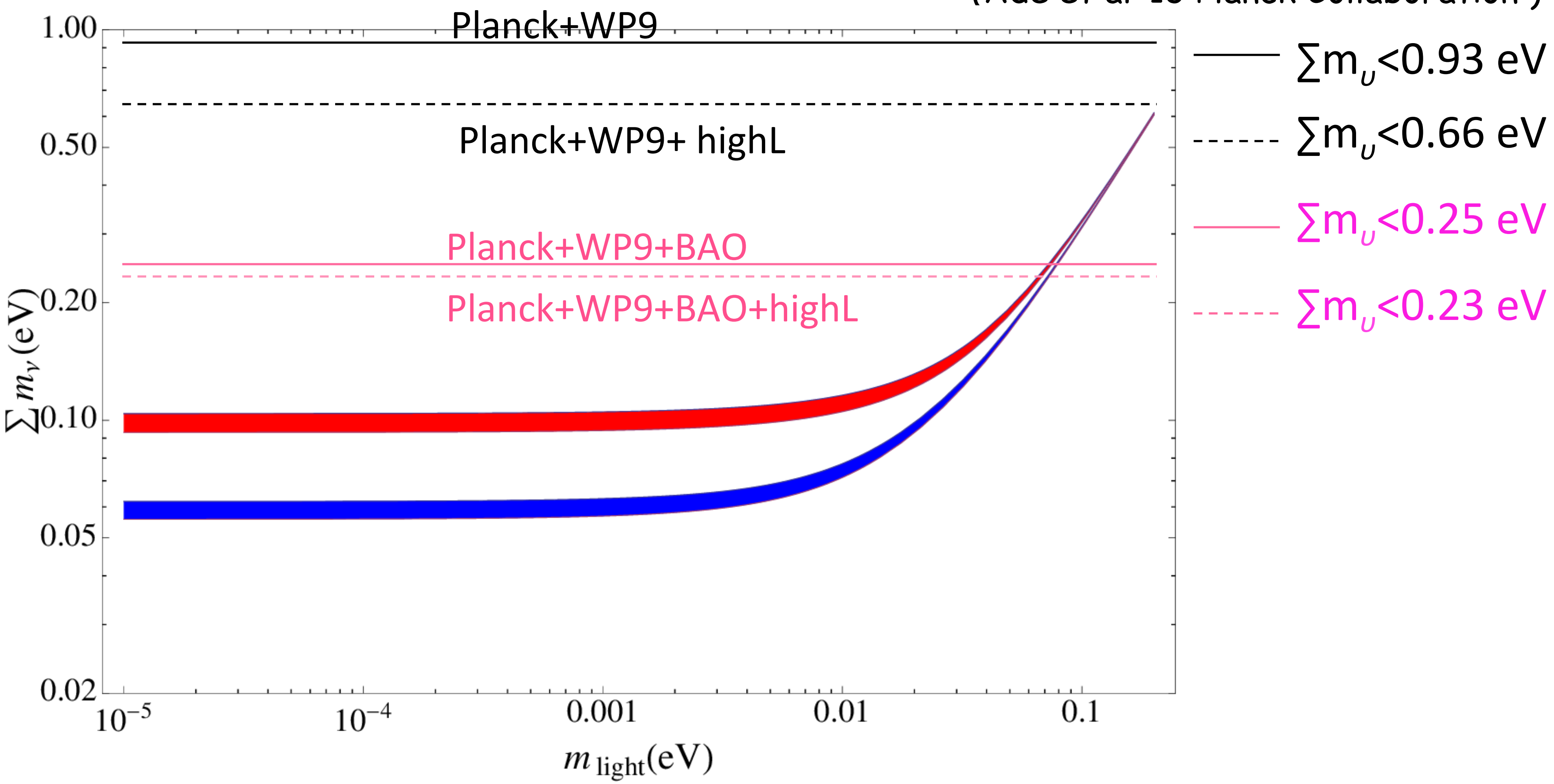
- Small scales ($k>k_{fs}$)

Perturbations can not grow due to the large neutrino velocity dispersion Matter power spectrum is suppressed.



2013 Planck state on neutrino mass 95% CL bounds

(Ade et al '13 Planck Collaboration)



Axions

- Axion was introduced to solve the CP problem of strong interactions.

- Axions are the Pseudo- Nambu-Goldstone bosons associated to a new global $U(1)_{PQ}$ symmetry, which is spontaneously broken at an energy scale f_a.

- The axion mass is inversely proportional to the axion coupling constant f_a:

$$m_a = \frac{f_\pi m_\pi}{f_a}\frac{\sqrt{R}}{1+R} = 0.6\ \mathrm{eV}\ \frac{10^7\ \mathrm{GeV}}{f_a} \qquad R = 0.553 \pm 0.043 \qquad f_\pi = 93\ \mathrm{MeV}$$

- Axions may be produced in the early Universe via thermal and non-thermal process

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Hot Dark Matter
Axions with sub-eV masses produced thermally

Cold Dark Matter
Axions with masses in the 10 μeV region produced non-thermally by the re-alignment mechanism

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Thermal Axions

- ✓ For $f_a \leq 10^8$ GeV axions attain thermal equilibrium at the QCD phase transition or later, and contribute to the cosmic radiation density and subsequently to the cosmic hot dark matter along with massive neutrinos.

- ✓ Axions will remain in thermal equilibrium until the expansion rate of the universe, $H(T)$, becomes larger than their thermally averaged interaction rate.

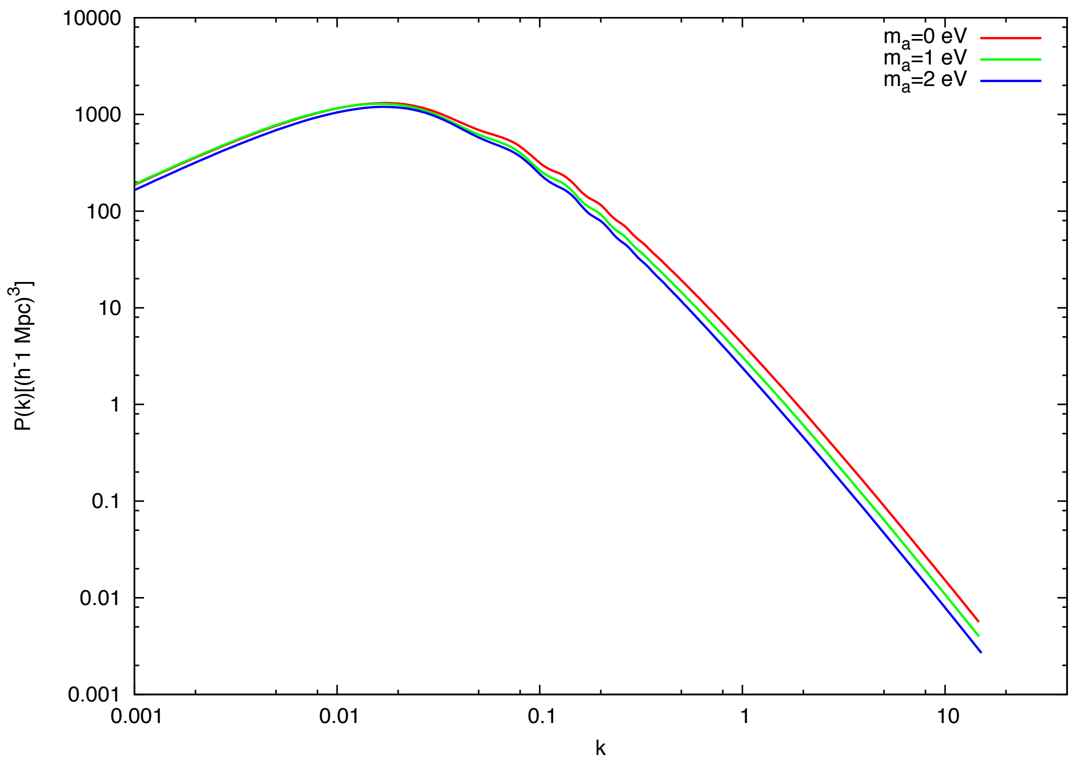
- ✓ Axions decoupled in the early universe at a temperature T_D given by the usual freeze out condition for a thermal relic:

$$\Gamma\,(T_D) = H(T_D)$$

- ✓ From T_D we can compute the current axion number density, related to the present photon density:

$$n_a = \frac{g_{\star S}(T_0)}{g_{\star S}(T_D)} \times \frac{n_\gamma}{2} \qquad g_{\star S}(T_0) = 3.91$$

Sub-eV massive axions cosmological signatures



Free-streaming of axion HDM suppresses small scale power similar to neutrinos.

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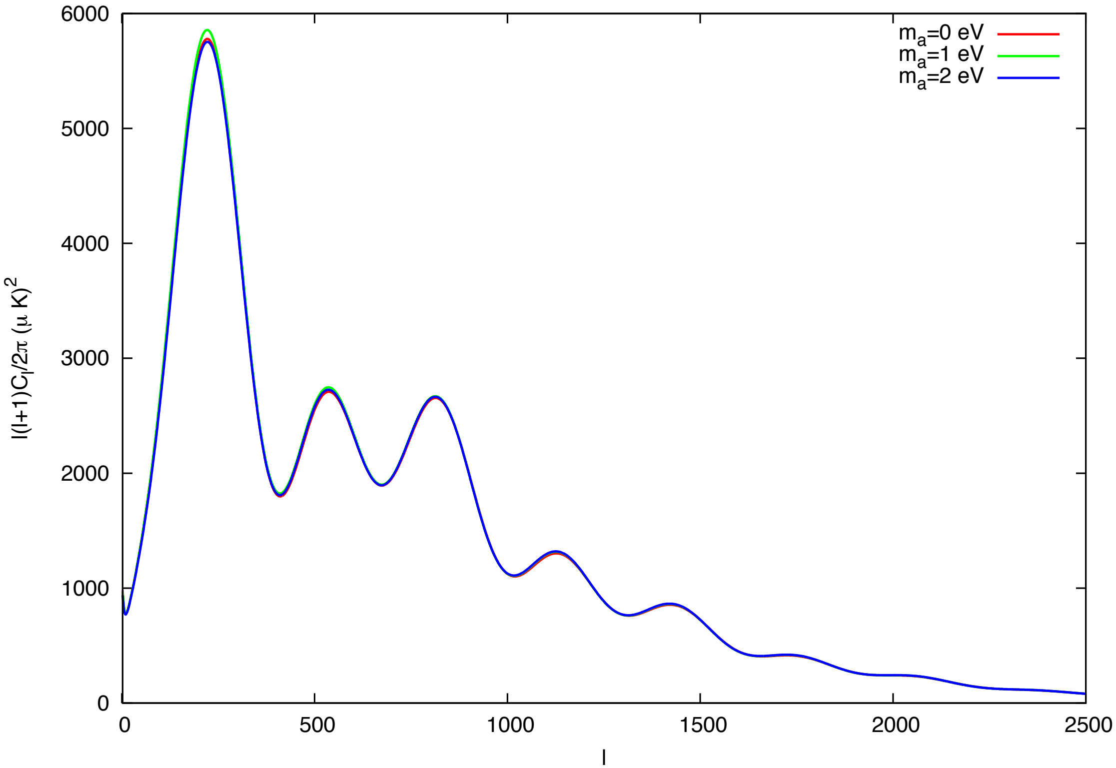


Free-streaming of axion HDM suppresses small scale power similar to neutrinos.

However, unlike neutrinos, axion HDM has no substantial effect on the CMB anisotropies.

Effective Number of Relativistic degrees of freedom N_{eff}

Radiation content of the Universe:

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

Standard Scenario: N_{eff}= 3.046 after considering non instantaneous neutrino decoupling, neutrino oscillations and QED corrections.

(Mangano et al, PLB'01 & NPB'05)

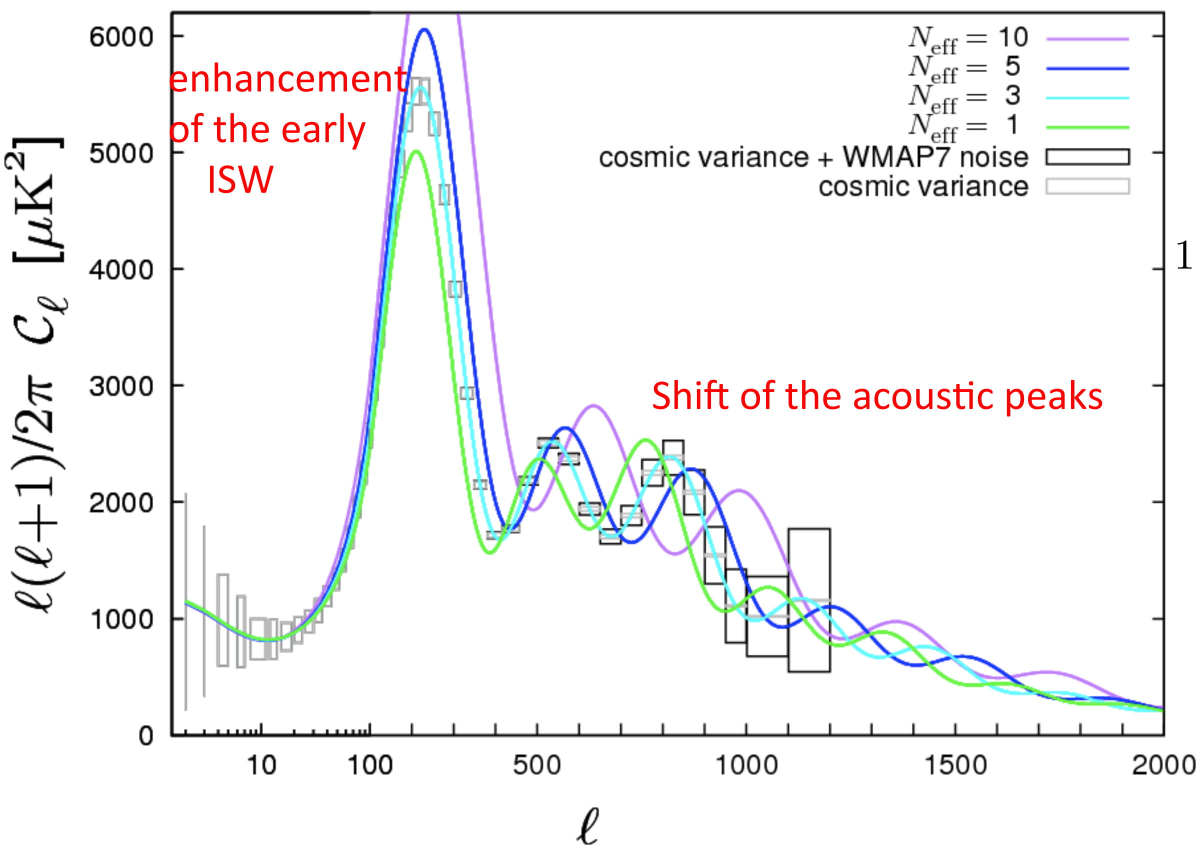
N_{eff}=3.046+ΔN_{eff} ⇒ Extra relativistic component (Dark Radiation)

⇓

Sterile neutrinos, thermal axions, extended dark sectors with light species (as in asymmetric dark matter models).

(Melchiorri et al PRD '07, Smith et al PRD '06, Calabrese et al PRD '11)

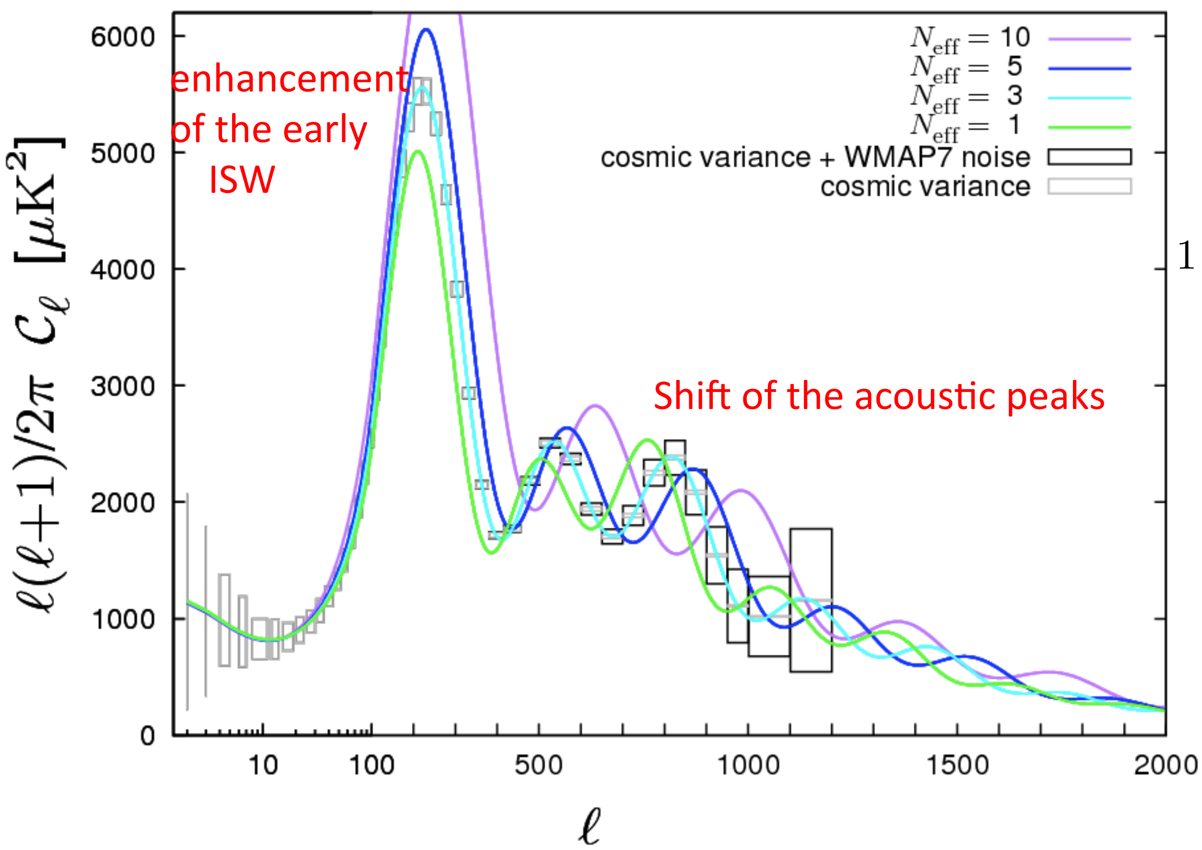
N_{eff} Cosmological signatures: CMB



$$(\omega_b, \omega_m, h, A_s, n_s, \tau, N_{eff})$$

$$1 + z_{eq} = \frac{\omega_m}{\omega_r} = \frac{\omega_m}{(1 + \frac{7}{8}(\frac{4}{11})^{4/3} N_{eff})\omega_\gamma}$$

N_{eff} Cosmological signatures: CMB



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Friedmann equation:

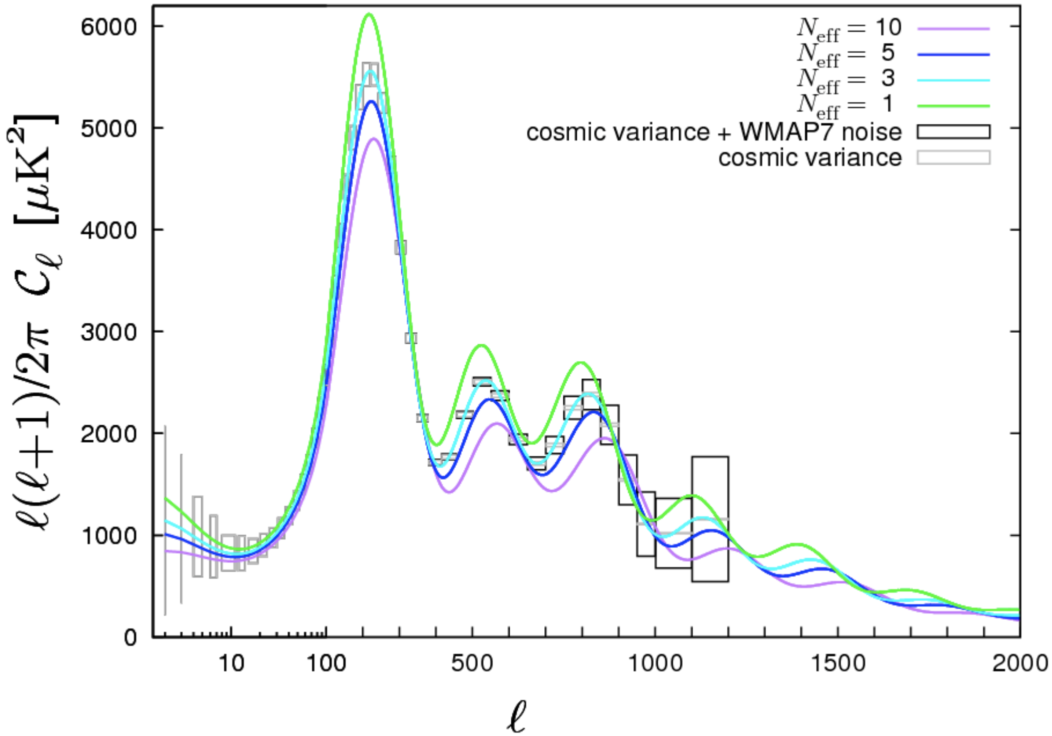
$$\left(\frac{H}{H_0}\right)^2 = \frac{\Omega_M}{a^3} + \frac{\Omega_\gamma}{a^4} + \frac{\Omega_\nu}{a^4} + \Omega_\Lambda + \frac{\Omega_{DR}}{a^4}$$

increase of the expansion rate *H* at recombination

$$r_s = \int_0^{t_*} c_s \frac{dt}{a} = \int_0^{a_*} \frac{c_s}{a^2} \frac{da}{H} \quad \downarrow$$

$$\theta_s = \frac{r_s}{D_A} \quad \downarrow \qquad l = \frac{\pi}{\theta_s} \quad \uparrow$$

N_{eff} Cosmological signatures: CMB



Fixed: z_{eq}

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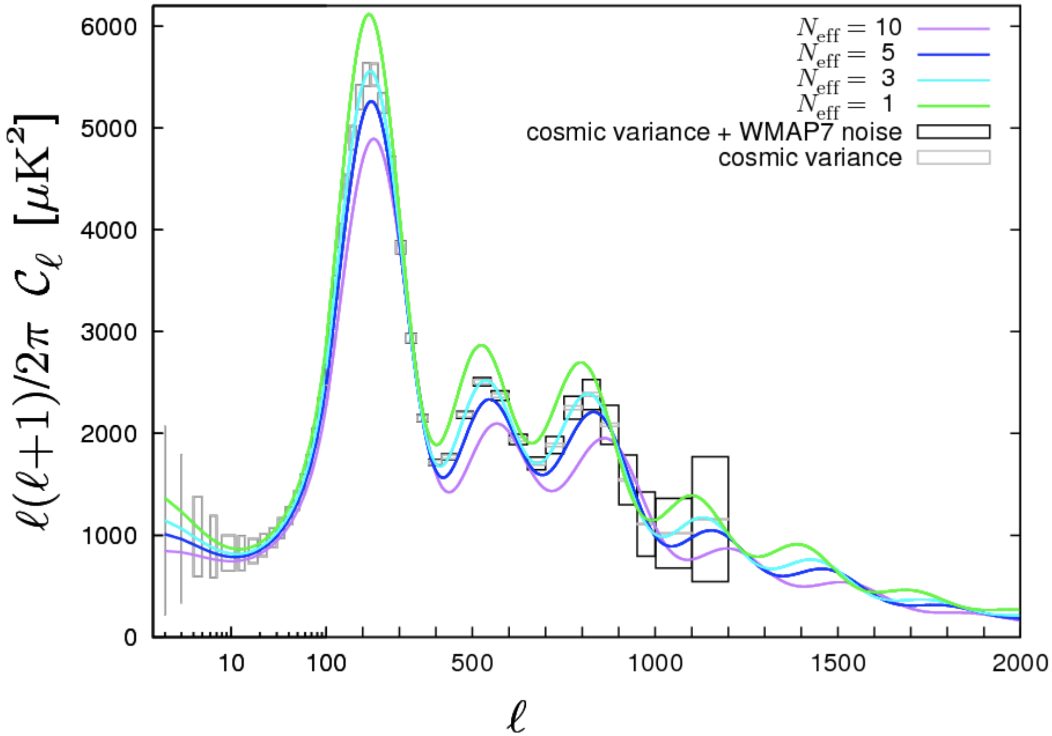

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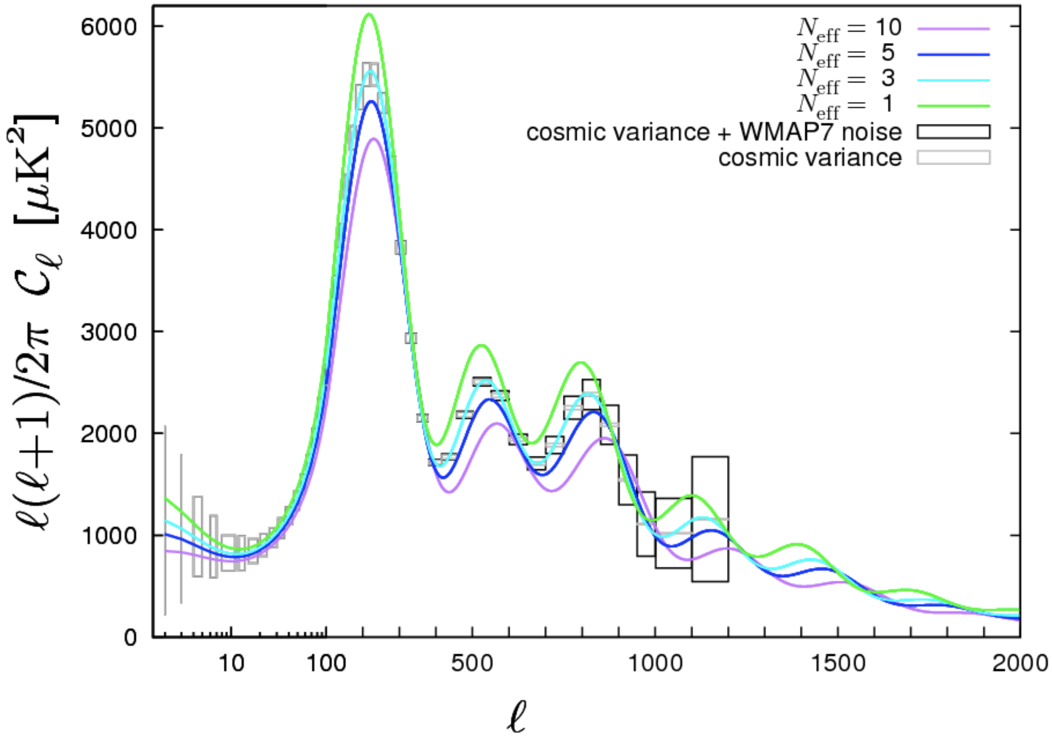

Fixed: z_{eq}, ω_b, θ_s, A_s (l=200)

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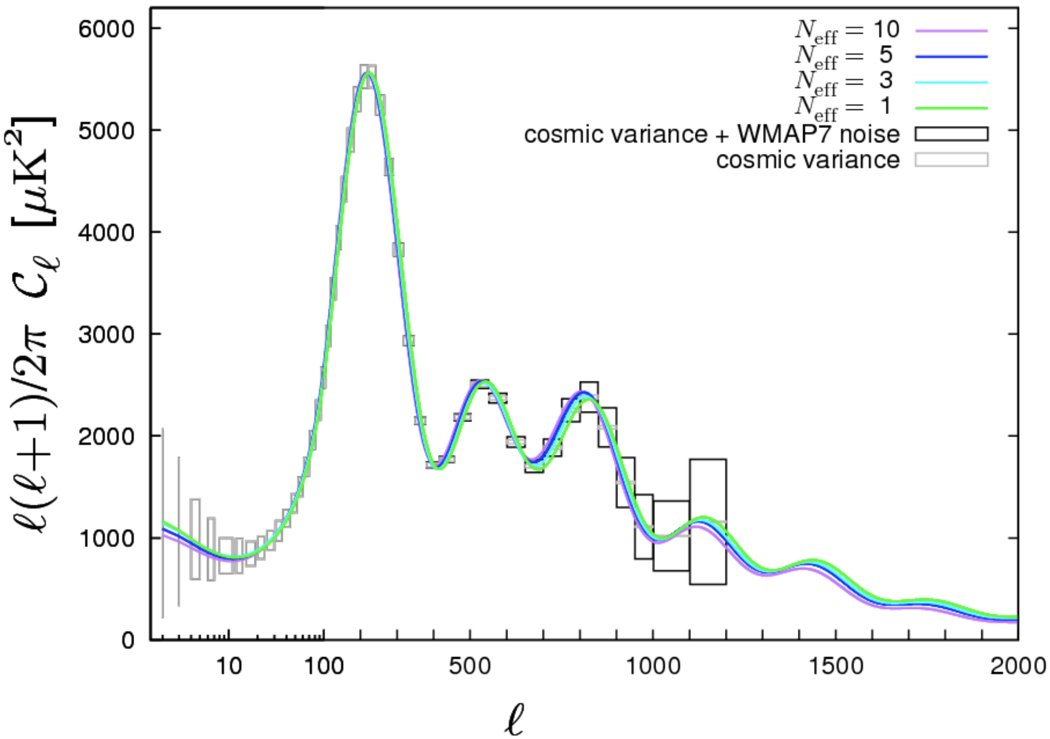

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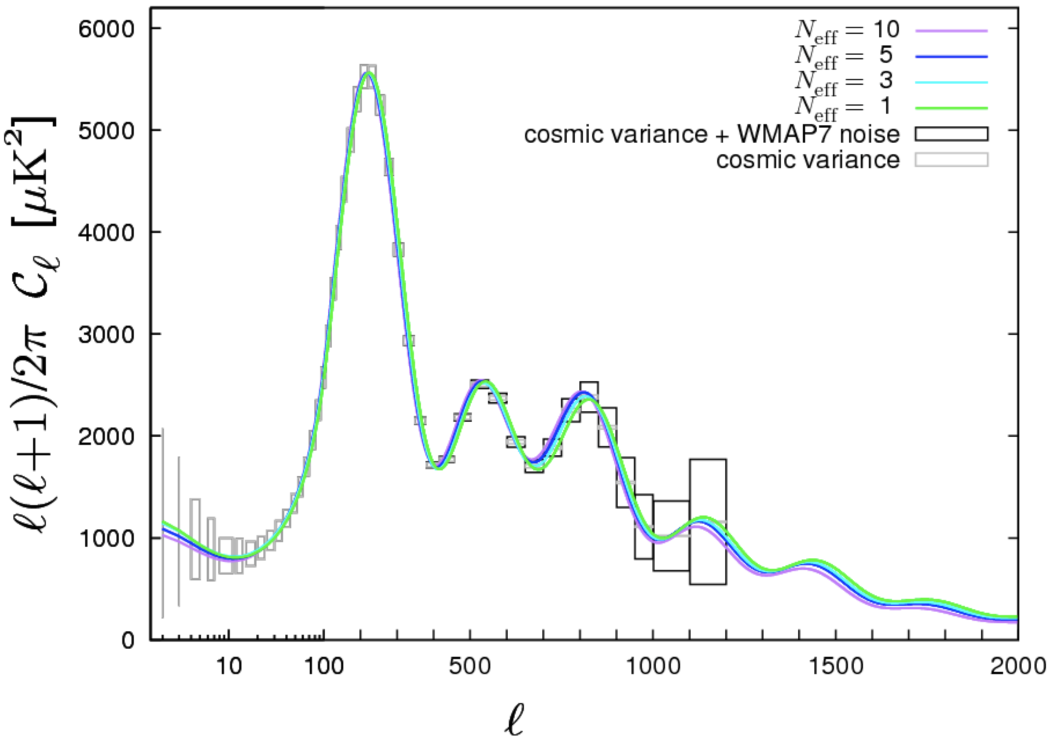

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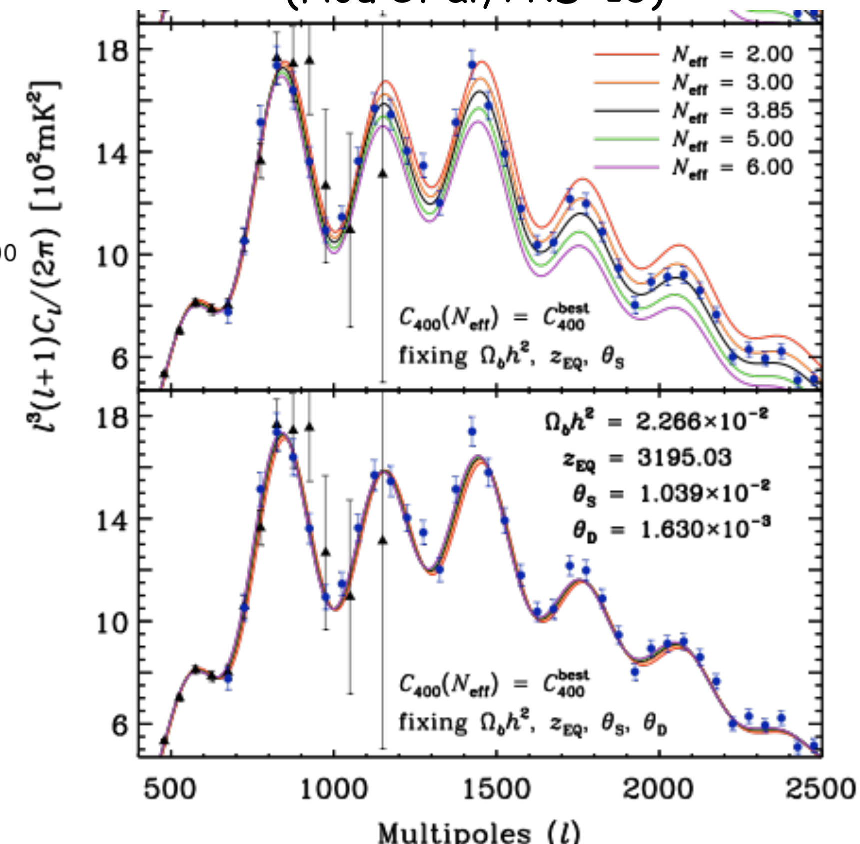
(Hou et al, PRD '13)



Increase of the Silk damping:

Higher N_{eff}, higher H(z), modifying the photon diffusion scale at recombination

$$r_d^2 \propto \int_0^{a_\star} \frac{da}{a^3 \sigma_T n_e H}$$

Increasing the damping at high multipoles.

N_{eff} Cosmological signatures: BBN

N_{eff} affects the expansion rate during BBN:

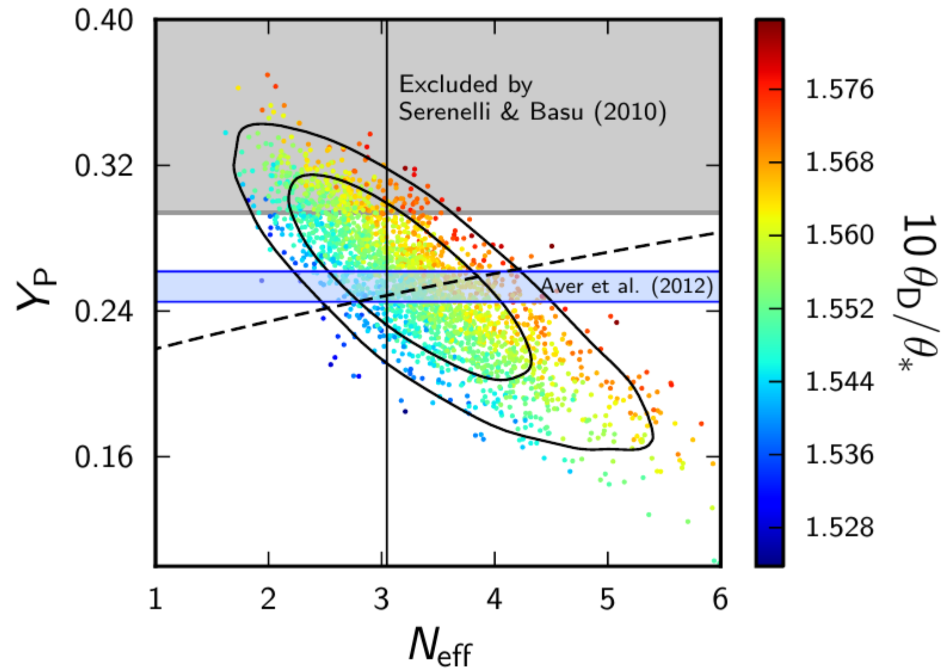
$$H = \sqrt{\frac{8\pi\rho_r}{3M_{Pl}^2}} \qquad \rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

- 1-0.1 MeV: Particles in thermal equilibrium → lost of equilibrium → n/p freezes out at T<0.7MeV ($\Gamma_{np} \sim H$) → residual free neutrons β-decay
- 0.1-0.01 MeV Formation of the light elements starting from D

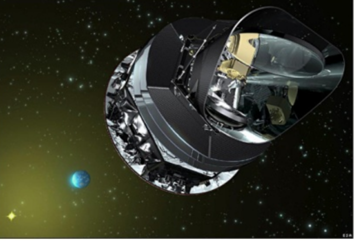
Larger N_{eff}, higher expansion rate, higher freeze out temperature, higher ^{4}He fraction:

$$n/p \simeq e^{-\frac{m_n - m_p}{T_{freeze}}}$$

$$Y_P = \frac{2(n/p)}{1 + n/p}$$



(Ade et al '13 Planck Collaboration)



2013 Planck state on N_{eff}

$$N_{eff} = 3.36^{+0.68}_{-0.64}$$

$$(95\%; Planck + WP + highL)$$

$$N_{eff} = 3.30^{+0.54}_{-0.51}$$

$$(95\%, Planck + WP + highL + BAO)$$

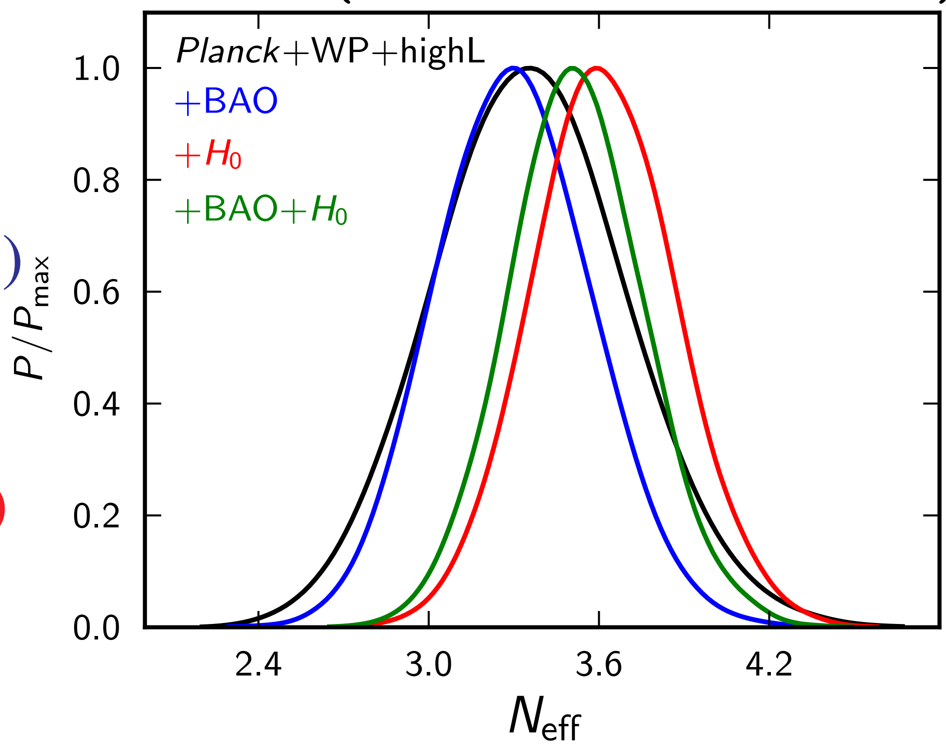
$$N_{eff} = 3.62^{+0.50}_{-0.48}$$

$$(95\%, Planck + WP + highL + H_0)$$

$$N_{eff} = 3.52^{+0.48}_{-0.45}$$

$$(95\%, Planck + WP + highL + BAO + H_0)$$

(Ade et al '13 Planck Collaboration)



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Candidates for extra hot relic components

- Massless sterile neutrino species: e.g. extra degrees of freedom produced by the annihilation of asymmetric Dark Matter
- Extra steriles massive neutrino species: motivated by the so-called neutrino oscillation anomalies
- Thermal axion: motivated by the strong CP problem

$$m_a = \frac{f_\pi m_\pi}{f_a} \frac{\sqrt{R}}{1+R} = 0.6 \text{ eV} \ \frac{10^7 \text{ GeV}}{f_a} \qquad R = 0.553 \pm 0.043 \qquad f_\pi = 93 \text{ MeV}$$

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These extra species

Have an associated free streaming scales, reducing the growth of matter fluctuations at small scales

Contribute to the effective number of relativistic degrees of freedom N_{eff}

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

$N_{\mathrm{eff}} = 3.046 + \Delta N_{\mathrm{eff}}$

Data1

✓ CMB:

- Planck temperature anisotropies, including lensing potential
- WMAP 9-year polarization
- ACT and SPT measurements at small scales
- B-mode polarization measurements from BICEP2

✓ Large scale structure:

- SDSS Data Release 7
- 6-degree Field Galaxy Survey
- BOSS Data Release 11

} Baryon Acoustic Oscillation (BAO) data

- WiggleZ survey (the full shape of the matter power spectrum and the geometrical BAO information)

Data2

- ✓ Hubble constant measurements:
  - Hubble Space Telescope

- ✓ σ_8 measurements:
  - CFHTLens survey
  - Planck Sunyaev-Zeldovich cluster catalog

- ✓ Big Bang Nucleosynthesis light elements abundance:

$$(D/H)_P = (2.87 \pm 0.22) \times 10^{-5} \text{ [Iocco et al. PRD '09]}$$

$$(D/H)_P = (2.53 \pm 0.04) \times 10^{-5} \text{ [Cooke et al. arXiv:1308.3240]}$$

$$Y_P = 0.254 \pm 0.003 \text{ [Izotov et al. arXiv: 1308.2100]}$$

Cosmological parameters

1. ΛCDM model with 3 massive neutrino species:

$$\{\omega_b, \omega_c, \Theta_s, \tau, n_s, \log[10^{10} A_s], \sum m_\nu\}$$

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2. ΛCDM model with 3 massive neutrino species and thermal axion:

$$\{\omega_b, \omega_c, \Theta_s, \tau, n_s, \log[10^{10} A_s], \sum m_\nu, m_a\}$$

$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{3}{2}\frac{n_a}{n_\nu}\right)^{4/3}$$

→ Extra Radiation Component at the BBN period

$$n_\nu = 112\ \mathrm{cm}^{-3}$$

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$$n_\nu = 112 \text{ cm}^{-3}$$

→ Extra Radiation Component at the BBN period

3. ΛCDM model with 3 massive neutrino and ΔN_{eff} massless dark radiation species:

$$\{\omega_b, \omega_c, \Theta_s, \tau, n_s, \log[10^{10} A_s], \sum m_\nu, N_{\text{eff}}\}$$

Cosmological parameters

4. ΛCDM model with 3 active massive neutrinos plus ΔN_{eff} massive steriles neutrino species:

$$\{\omega_b, \omega_c, \Theta_s, \tau, n_s, \log[10^{10}A_s], \sum m_\nu, N_{\rm eff}, m_s^{\rm eff}\}$$

$$m_s^{\rm eff} = (T_s/T_\nu)^3 m_s = (\Delta N_{\rm eff})^{3/4} m_s$$

$\Delta N_{eff} = N_{eff} - 3.46 = (T_s / T_\nu)^4$

T_s, T_ν current temperature of the sterile and active neutrino species.
m_s real mass of sterile neutrino species.

UNIFORM PRIORS for the cosmological parameters:

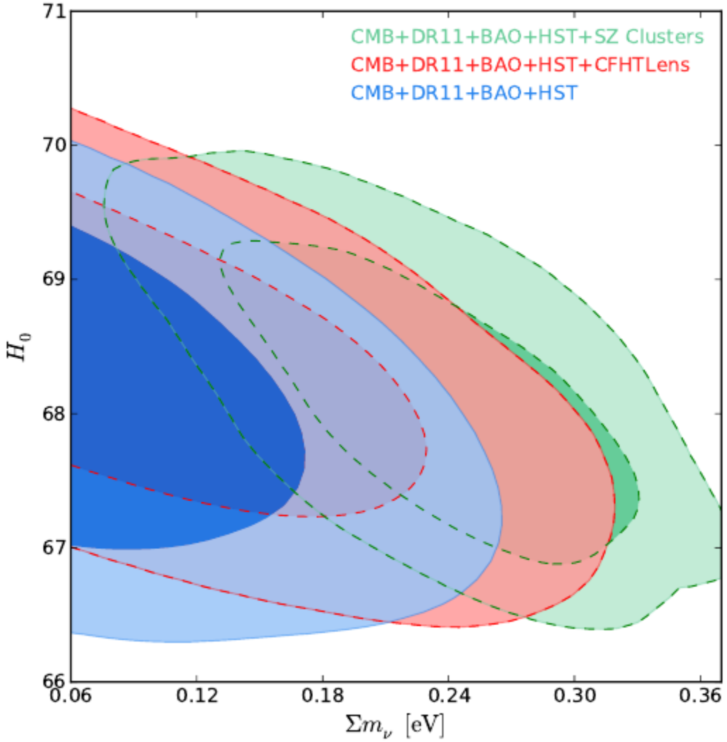
Parameter	Prior
$\Omega_b h^2$	$0.005 \to 0.1$
$\Omega_c h^2$	$0.01 \to 0.99$
Θ_s	$0.5 \to 10$
τ	$0.01 \to 0.8$
n_s	$0.9 \to 1.1$
$\ln(10^{10} A_s)$	$2.7 \to 4$
$\sum m_\nu$ [eV]	$0.06 \to 3$
m_a [eV]	$0.1 \to 3$
$N_{\rm eff}$	$0(3.046) \to 10$
$m_s^{\rm eff}$ [eV]	$0 \to 3$

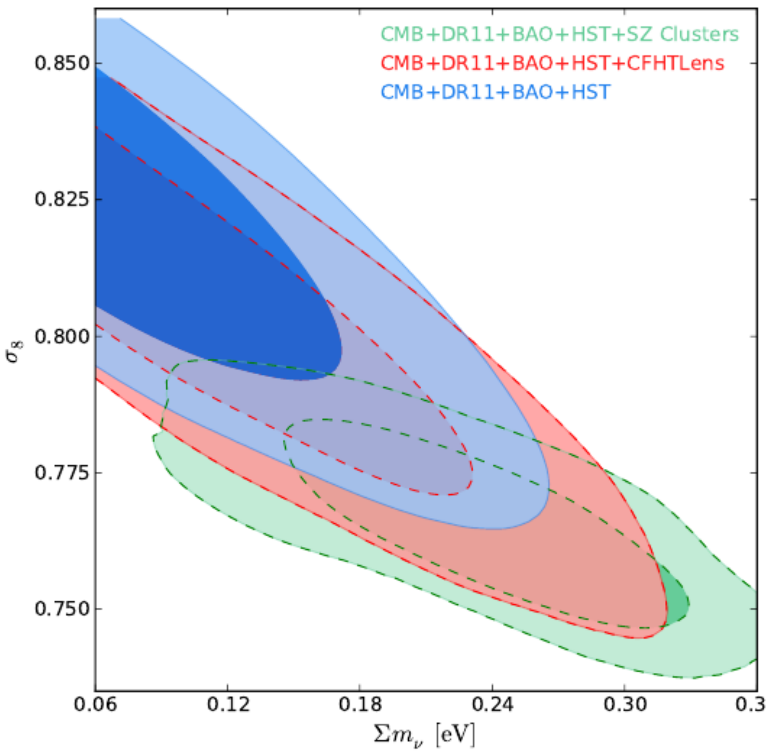
N_{eff} priors refer to the massless (massive) case

Main Results(1)

1. ΛCDM model with 3 massive neutrino species:

68% and 95% CL allowed regions in the $(\sum m_\nu, H_0)$ and in the $(\sum m_\nu, \sigma_8)$ plane





Giusarma et al Phys. Rev. D '14

CMB+DR11+BAO+HST: $\sum m_\nu < 0.22$ eV at 95% CL

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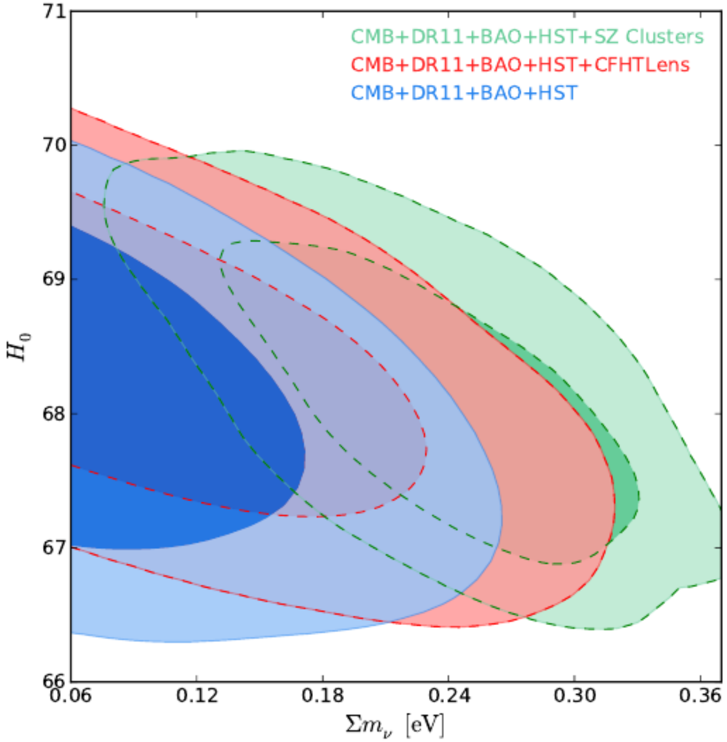
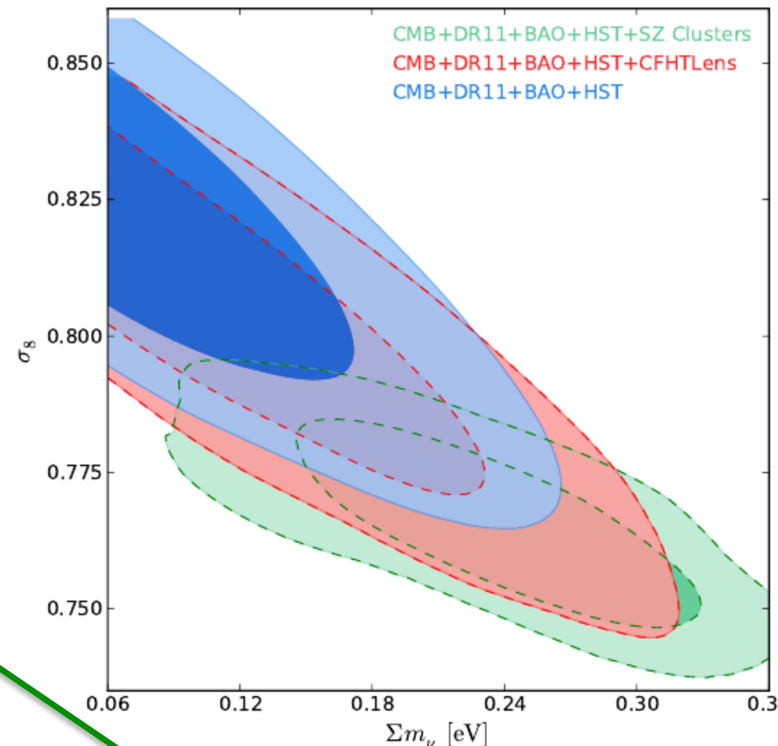


The allowed neutrino mass regions are displaced after considering Planck cluster data and a non zero value on $\sum m_\nu$ is favoured.



Giusarma et al Phys. Rev. D '14

CMB+DR11+BAO+HST: $\sum m_\nu < 0.22$ eV at 95% CL

CMB+DR11+BAO+HST+SZ Cluster: $\sum m_\nu = 0.23^{+0.10}_{-0.12}$ eV at 95% CL

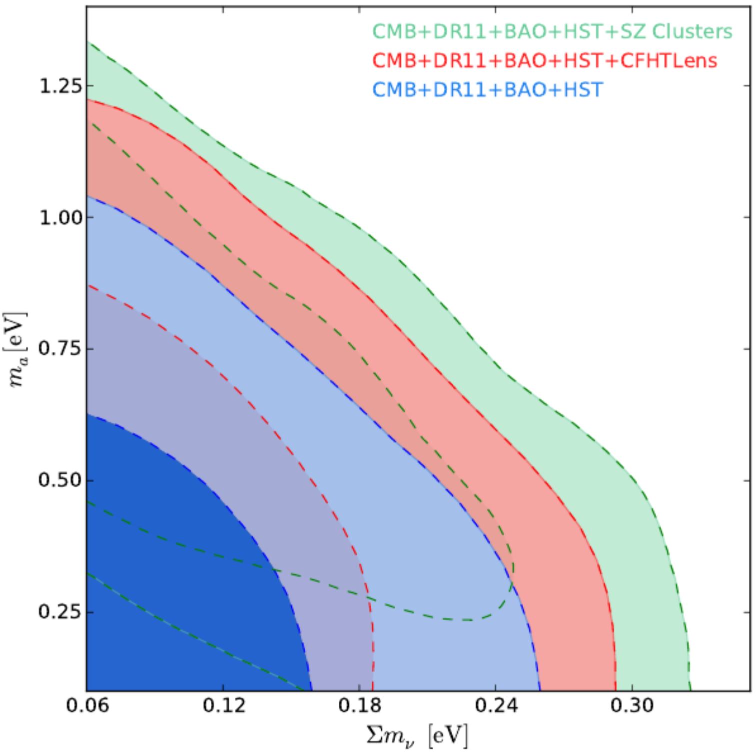
CMB+DR11+BAO+HST+CFHTLens: $\sum m_\nu < 0.27$ eV at 95% CL

The addition of the constraints on σ_8 and Ω_m from the CFHTLens survey displaces the bounds on the neutrino mass to higher values.

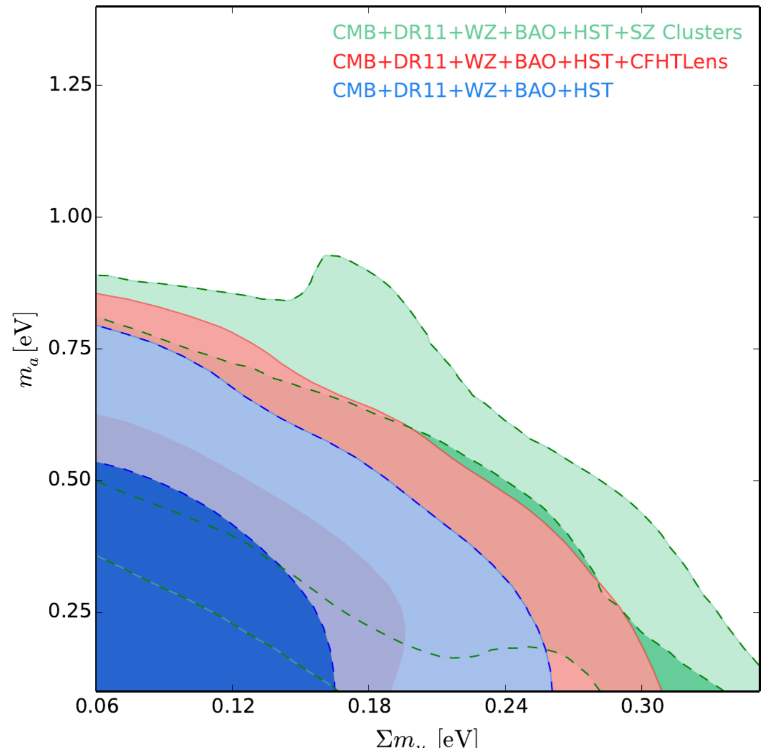
Main Results(2)

2. ΛCDM model with 3 massive neutrino species and thermal axion:

68% and 95% CL allowed regions in the ($\sum m_\nu$, m_a) plane for different combinations of data



Only with Planck SZ cluster data a non zero value of axion mass is favoured at the 2.2σ



Giusarma et al Phys. Rev. D '14

CMB+DR11+BAO+HST+SZ Cluster: $m_a = 0.62^{+0.46}_{-0.48}$ eV at 95% CL

Main Results(2)

2. ΛCDM model with 3 massive neutrino species and thermal axion:

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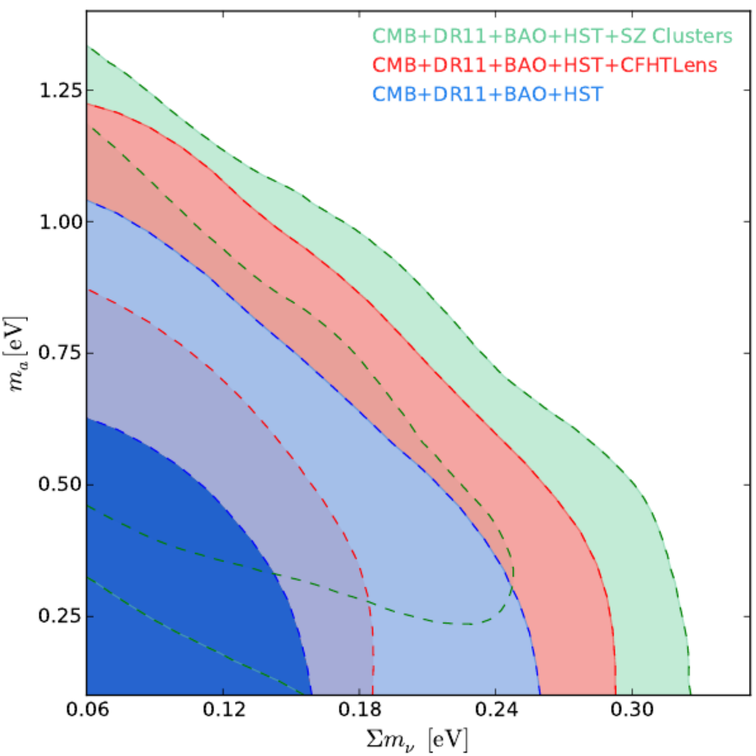

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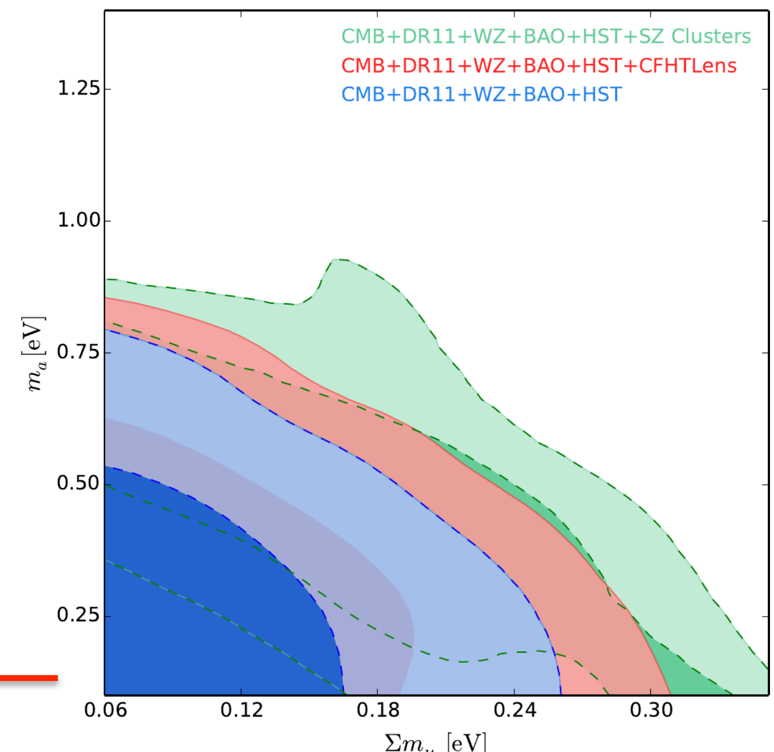
No evidence for non-zero neutrino masses nor for non-zero axion mass.



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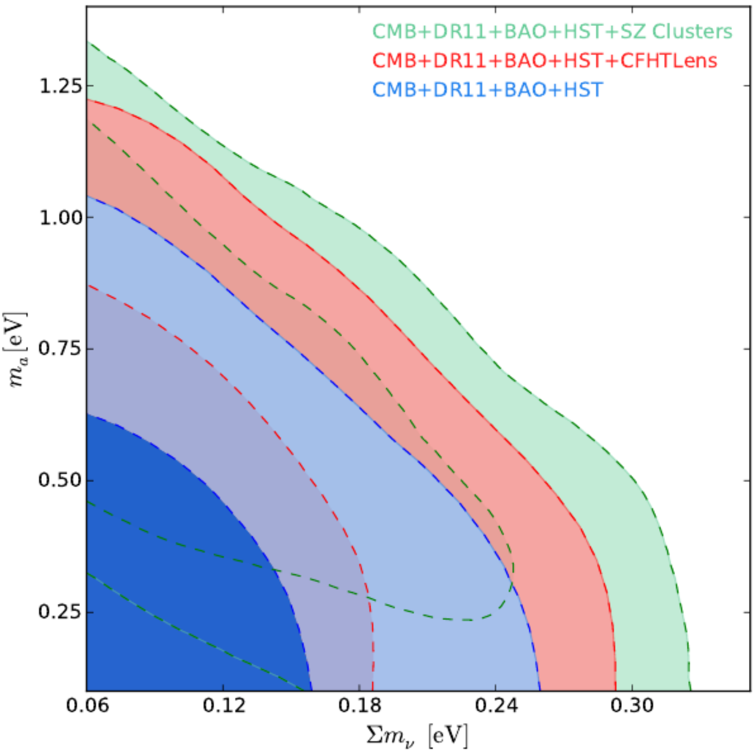

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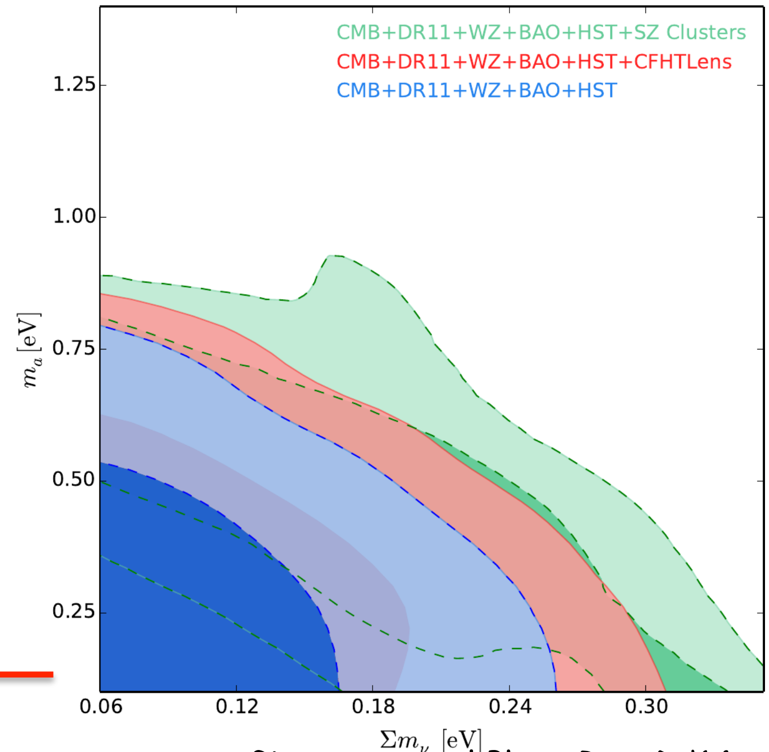


Giusarma et al Phys. Rev. D '14

CMB+DR11+BAO+HST+SZ Cluster: $m_a = 0.62^{+0.46}_{-0.48}$ eV at 95% CL

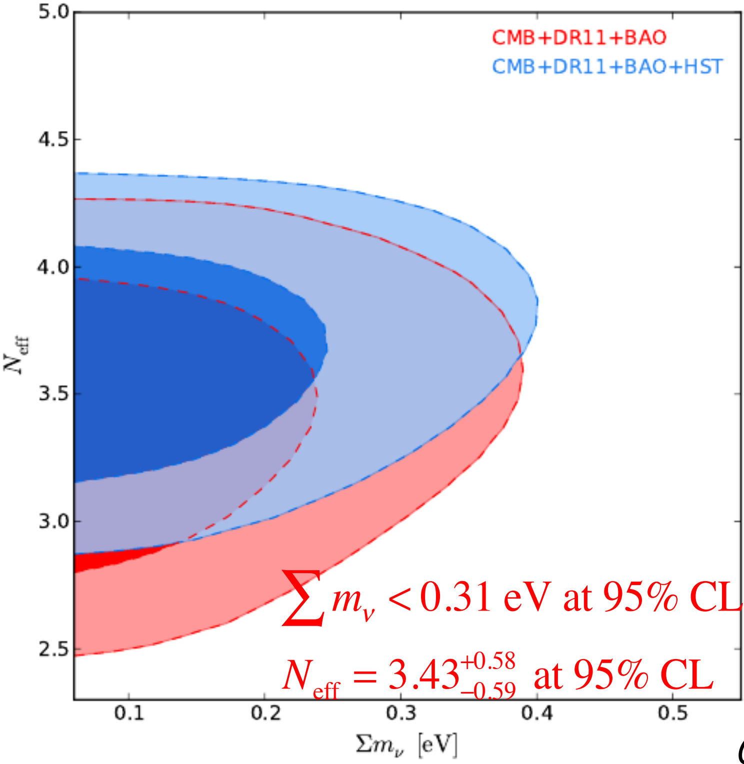
CMB+DR11+WZ+HST+SZ Cluster: $\sum m_\nu = 0.20^{+0.13}_{-0.14}$ eV at 95% CL

Evidence for neutrino mass of 0.2 eV at 3σ on only for one case

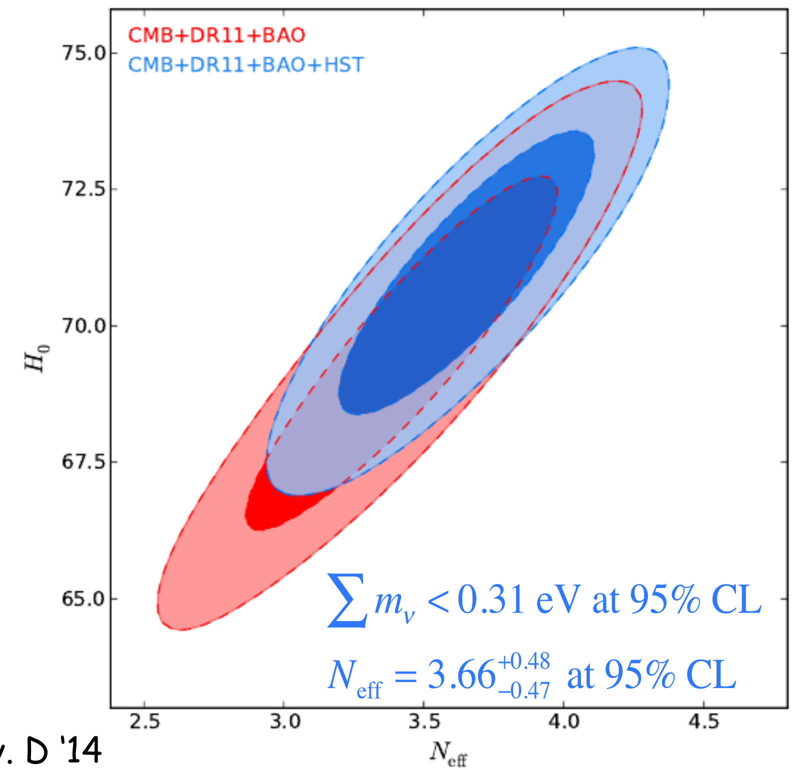
Main Results(3)

3. ΛCDM model with 3 massive neutrino and $\Delta N_{eff}=N_{eff}-3.46$ massless dark radiation species:

68% and 95% CL allowed regions in the $(\sum m_\nu, N_{eff})$ and in the (N_{eff}, H_0) plane



The prior on the value of the Hubble constant from HST increases the mean value on N_{eff}



Giusarma et al Phys. Rev. D '14

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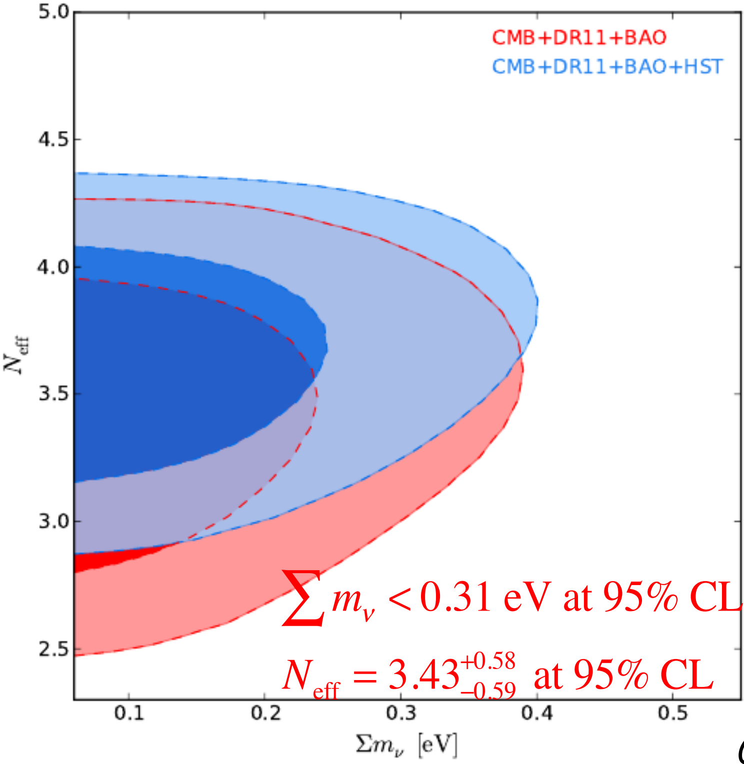

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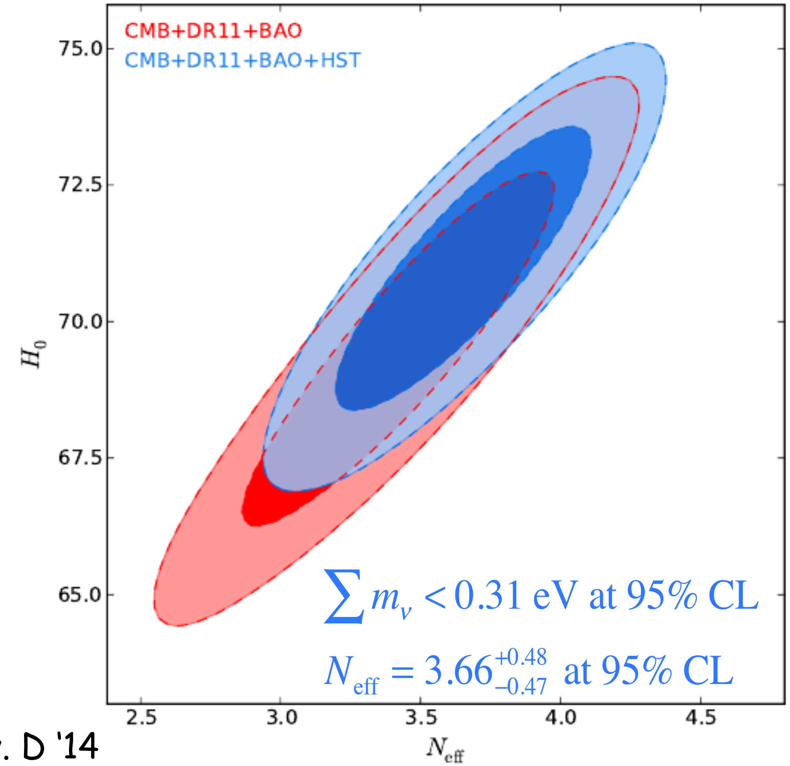


Giusarma et al Phys. Rev. D '14

CMB+DR11+WZ+HST+BBN (Cooke et al.): NO EVIDENCE FOR N_{eff} >3

$$\sum m_\nu < 0.24 \text{ eV at 95\% CL} \quad N_{eff} = 3.25^{+0.25}_{-0.24} \text{ at 95\% CL}$$

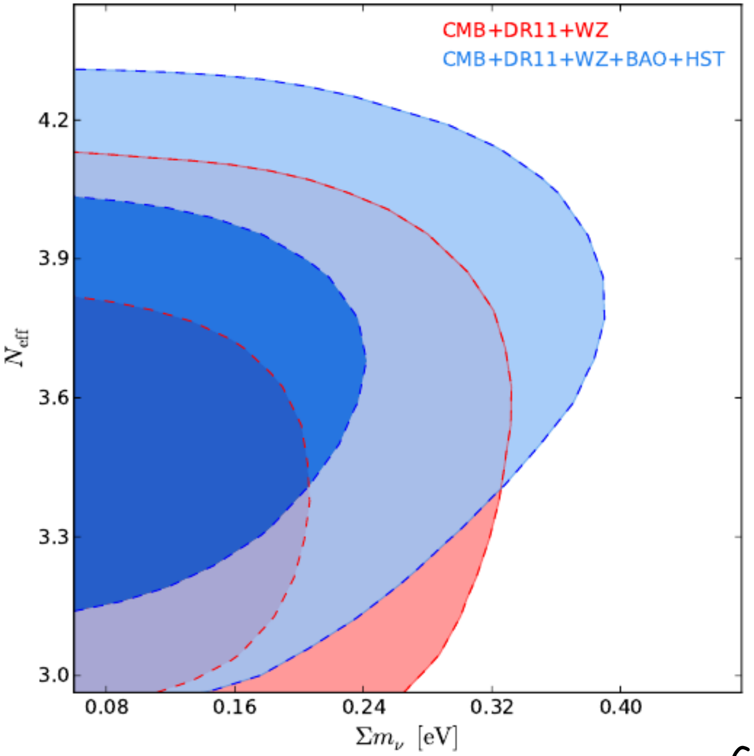
CMB+DR11+WZ+HST+BBN (Iocco et al.): EVIDENCE FOR N_{eff} >3

$$\sum m_\nu < 0.31 \text{ eV at 95\% CL} \quad N_{eff} = 3.52^{+0.27}_{-0.26} \text{ at 95\% CL}$$

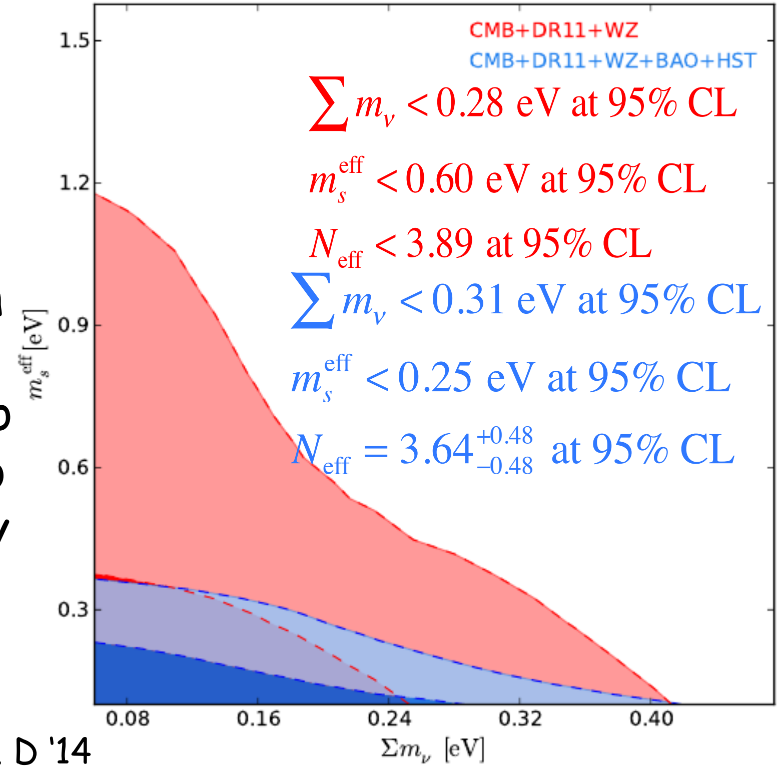
Main Results(4)

4. ΛCDM model with 3 active massive neutrinos plus ΔN_{eff} massive steriles neutrino species:

68% and 95% CL allowed regions in the $(\sum m_\nu, N_{eff})$ and in the $(\sum m_\nu, m_s^{eff})$ plane



The bound on N_{eff} $(\sum m_\nu)$ is slightly larger (more stringent) than in massless sterile neutrino scenario due to the degeneracy with m_s^{eff}



Giusarma et al Phys. Rev. D '14

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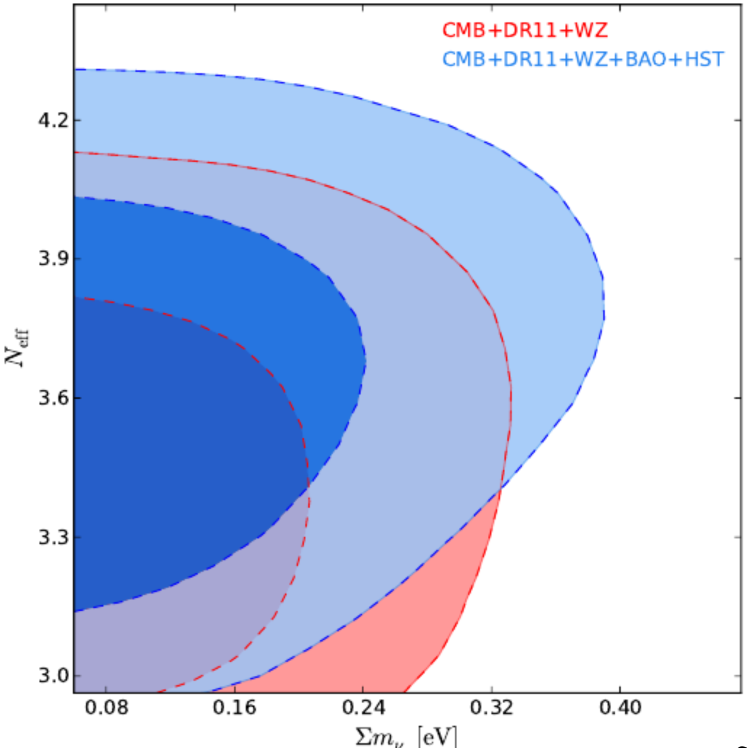

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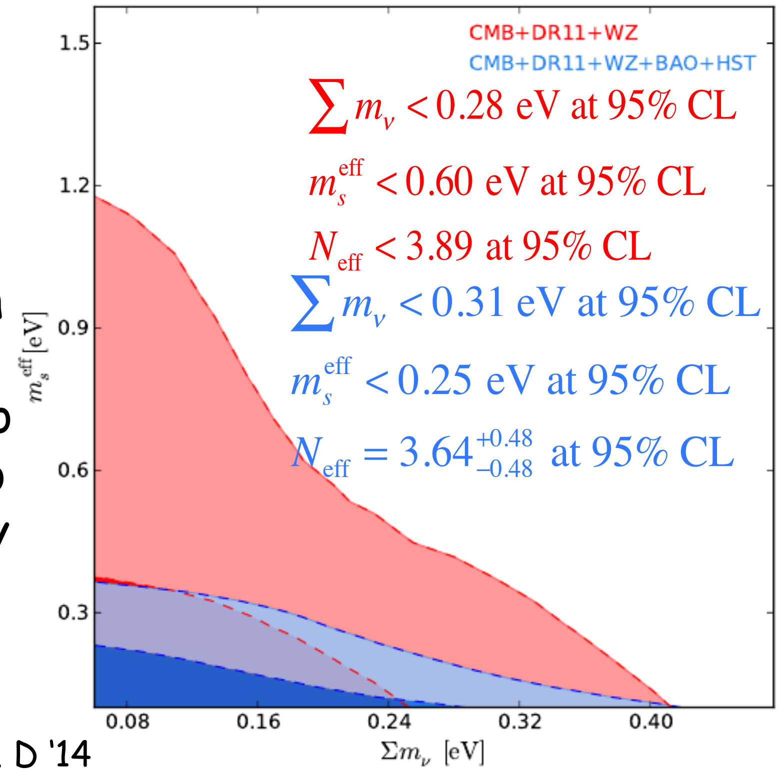

$\sum m_\nu < 0.28$ eV at 95% CL

$m_s^{eff} < 0.60$ eV at 95% CL

$N_{eff} < 3.89$ at 95% CL

$\sum m_\nu < 0.31$ eV at 95% CL

$m_s^{eff} < 0.25$ eV at 95% CL

$N_{eff} = 3.64^{+0.48}_{-0.48}$ at 95% CL

Giusarma et al Phys. Rev. D '14

CMB+DR11+WZ+HST+BBN(Cooke et al.): NO SIGNIFICANT PREFERENCE FOR $N_{eff}>3$

$$\sum m_\nu < 0.27 \text{ eV at 95\% CL} \quad m_s^{eff} < 0.14 \text{ eV at 95\% CL} \quad N_{eff} = 3.28^{+0.22}_{-0.21} \text{ at 95\% CL}$$

CMB+DR11+WZ+HST+BBN(Iocco et al.): SIGNIFICANT PREFERENCE FOR $N_{eff}>3$

$$\sum m_\nu < 0.28 \text{ eV at 95\% CL} \quad m_s^{eff} < 0.23 \text{ eV at 95\% CL} \quad N_{eff} = 3.56^{+0.33}_{-0.32} \text{ at 95\% CL}$$

✓Introduction

✓ Impact of HDM properties on cosmological observables:

- Neutrino masses
- Thermal axions
- Relativistic degrees of freedom N_{eff}

✓Existence of extra hot relic components as dark radiation relics, sterile neutrino species or thermal axions and constraints on the masses of the thermal relics in different scenarios using the available cosmological data

✓ Bounds thermal axions using a non power-law Primordial Power Spectrum (Preliminary results)

Primordial Power Spectrum (PPS)

The simplest model of inflation predicts a power law (PL) form for the PPS of scalar and tensor perturbations:

$$P_R(k) \; = \; A_s \left(\frac{k}{k_0}\right)^{1-n_s+\frac{1}{2}\frac{dn_s}{d\ln k}\ln\left(\frac{k}{k_0}\right)}$$

$$P_T(k) \; = \; A_t \left(\frac{k}{k_0}\right)^{n_t}$$

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BUT

In principle inflation can be generated by more complicated mechanisms, thus given a differnt shape for the PPS.

PPS Parametrization

- ✓ PPS parametrization: piecewise cubic Hermite interpolating polinomial (PCHIP)
- ✓ Give the value of the PPS in a discrete number of nodes and interpolate among them.
- ✓ We use 12 nodes which cover a wide range of values of the wavenumbers *k*:

$$\begin{aligned} k_1 &= 5 \times 10^{-6}\,\mathrm{Mpc}^{-1}, \\ k_2 &= 10^{-3}\,\mathrm{Mpc}^{-1}, \\ k_j &= k_2 (k_{11}/k_2)^{(j-2)/9} \quad \text{for} \quad j \in [3, 10], \\ k_{11} &= 0.35\,\mathrm{Mpc}^{-1}, \\ k_{12} &= 10\,\mathrm{Mpc}^{-1}. \end{aligned}$$

- ✓ The PCHIP PPS is described by:

$$P_s(k) = P_0 \times \mathrm{PCHIP}(k; P_{s,1}, \ldots, P_{s,12})$$

$P_0 = 2.36 \times 10^{-9}$ Larson et al Astr. J. Suppl. '11

Data1

- ✓ CMB:
  - Planck temperature anisotropies, including lensing potential
  - WMAP 9-year polarization
  - ACT and SPT measurements at small scales

- ✓ Large scale structure:
  - SDSS Data Release 7
  - 6-degree Field Galaxy Survey
  - BOSS Data Release 11
  - WiggleZ

  } Baryon Acoustic Oscillation (BAO) data

Data2

- ✓ Hubble constant measurements:
  - Hubble Space Telescope: $H_0 = 70.6 \pm 3.3\ \mathrm{km/s/Mpc}$

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- ✓ σ_8 measurements:
  - CFHTLens survey:

$$\sigma_8(\Omega_m/0.27)^{0.46} = 0.774 \pm 0.040$$

  - Planck Sunyaev-Zeldovich cluster catalog:

$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.782 \pm 0.01$$

Cosmological models

1. ACDM model with linear PPS:

$$\{\omega_b, \omega_c, \Theta_s, \tau, n_s, \log[10^{10} A_s], m_a\} \qquad \sum m_\nu = 0.06 \text{ eV}$$

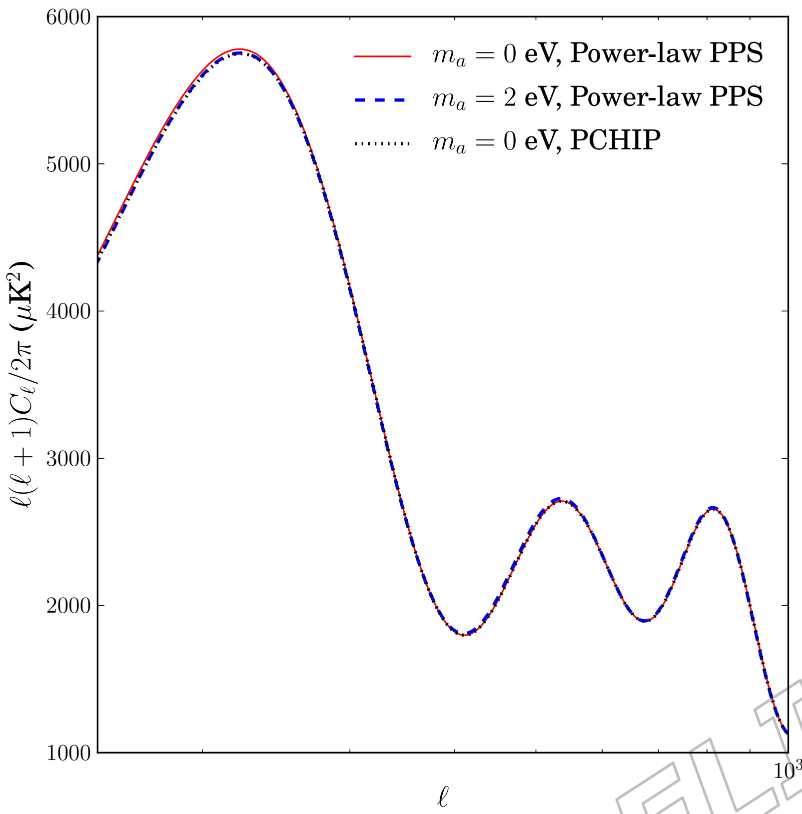
2. ACDM model with PCHIP PPS:

$$\{\omega_b, \omega_c, \Theta_s, \tau, n_s, \log[10^{10} A_s], m_a, P_{s,1}, \ldots, P_{s,12}\} \qquad \sum m_\nu = 0.06 \text{ eV}$$

UNIFORM PRIORS for the cosmological parameters:

Parameter	Prior
$\Omega_{\rm b} h^2$	$[0.005, 0.1]$
$\Omega_{\rm cdm} h^2$	$[0.001, 0.99]$
$\theta_{\rm s}$	$[0.5, 10]$
τ	$[0.01, 0.8]$
n_s	$[0.9, 1.1]$
$\log[10^{10} A_s]$	$[2.7, 4]$
m_a	$[0.1, 3]$
$P_{s,1}, \ldots, P_{s,12}$	$[0.01, 10]$

Results(1)



A 2eV thermal axion can be easily mimicked by a massless axion but relaxing the assumptions concerning the PPS shape.

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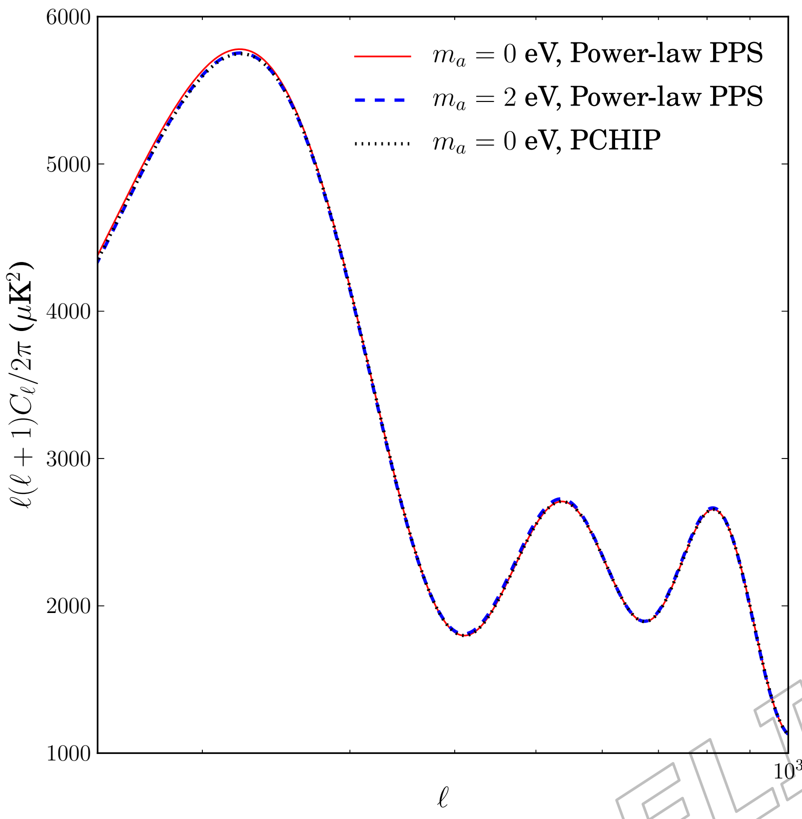
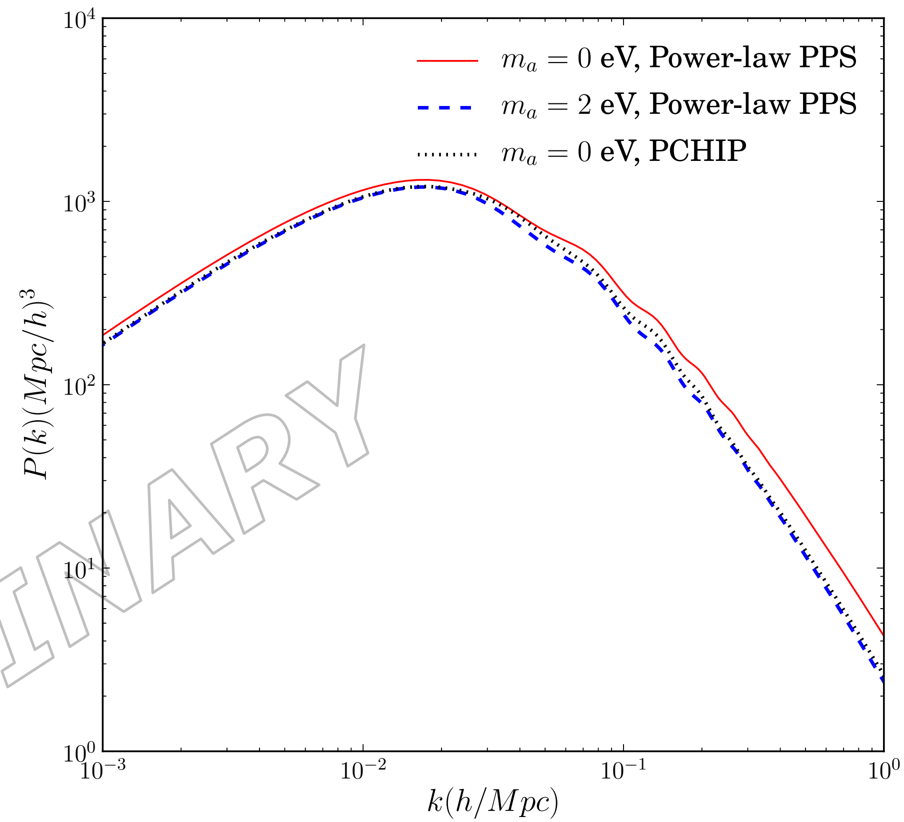




PRELIMINARY

A 2eV thermal axion can be easily mimicked by a massless axion but relaxing the assumptions concerning the PPS shape.

There exists a set of values for the $P_{s,j}$ parameters which can reproduce the small scale suppression of the matter power spectrum induced by thermal axions.

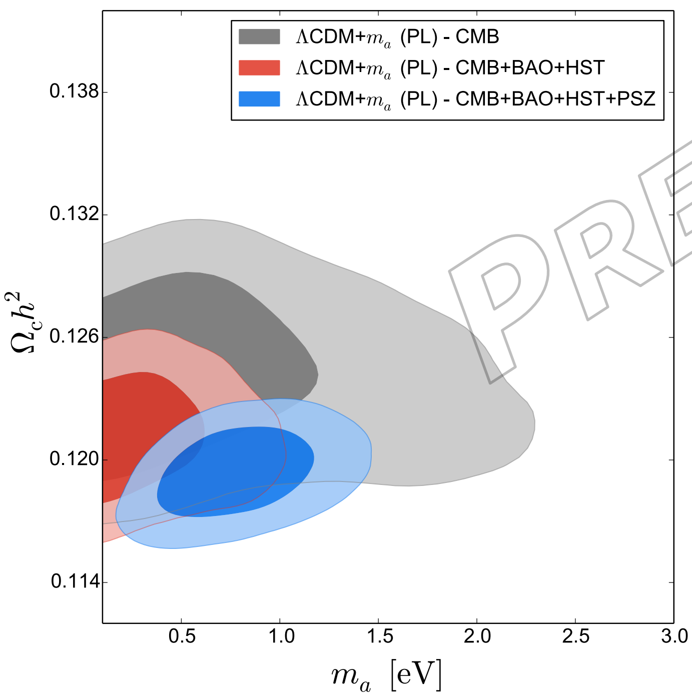
Results(2)

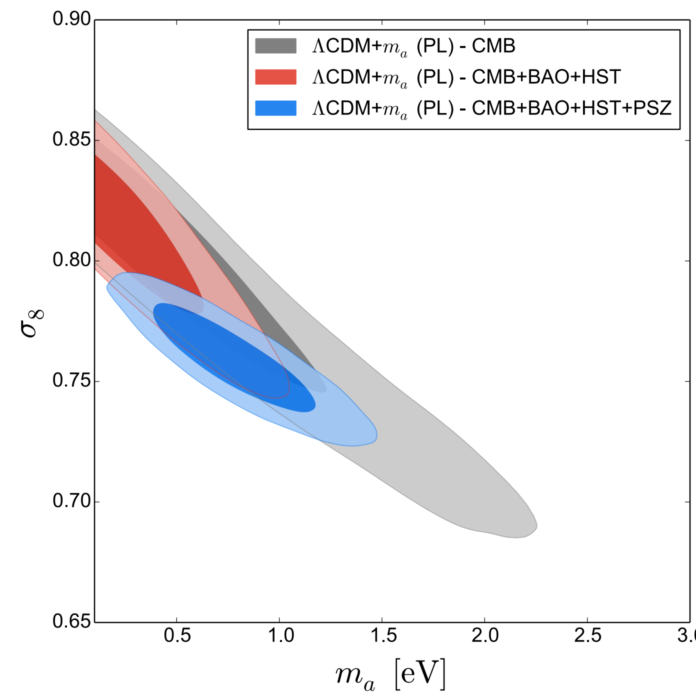
1. ΛCDM model with linear PPS:

	CMB	CMB+HST	CMB+BAO	CMB+BAO +HST	CMB+BAO HST+CFHT	CMB+BAO +HST+PSZ
$\Omega_c h^2$	$0.124^{+0.006}_{-0.005}$	$0.124^{+0.005}_{-0.005}$	$0.122^{+0.004}_{-0.004}$	$0.121^{+0.004}_{-0.004}$	$0.120^{+0.003}_{-0.004}$	$0.119^{+0.003}_{-0.003}$
m_a [eV]	< 1.82	< 1.58	< 0.85	< 0.83	< 1.15	$0.79^{+0.52}_{-0.50}$
σ_8	$0.785^{+0.064}_{-0.083}$	$0.791^{+0.058}_{-0.077}$	$0.803^{+0.042}_{-0.048}$	$0.803^{+0.041}_{-0.048}$	$0.783^{+0.047}_{-0.054}$	$0.759^{+0.028}_{-0.028}$
Ω_m	$0.336^{+0.047}_{-0.044}$	$0.329^{+0.042}_{-0.039}$	$0.310^{+0.026}_{-0.023}$	$0.308^{+0.024}_{-0.022}$	$0.304^{+0.025}_{-0.024}$	$0.307^{+0.027}_{-0.026}$
$\ln(10^{10} A_s)$	$3.10^{+0.05}_{-0.05}$	$3.10^{+0.05}_{-0.05}$	$3.10^{+0.05}_{-0.05}$	$3.10^{+0.05}_{-0.05}$	$3.10^{+0.05}_{-0.05}$	$3.09^{+0.05}_{-0.05}$
n_s	$0.96^{+0.01}_{-0.02}$	$0.96^{+0.01}_{-0.01}$	$0.97^{+0.01}_{-0.01}$	$0.97^{+0.01}_{-0.01}$	$0.97^{+0.01}_{-0.01}$	$0.97^{+0.01}_{-0.01}$

95% CL

68% and 95% CL allowed regions in the $(m_a, \Omega_c h^2)$ and in the (m_a, σ_8) plane





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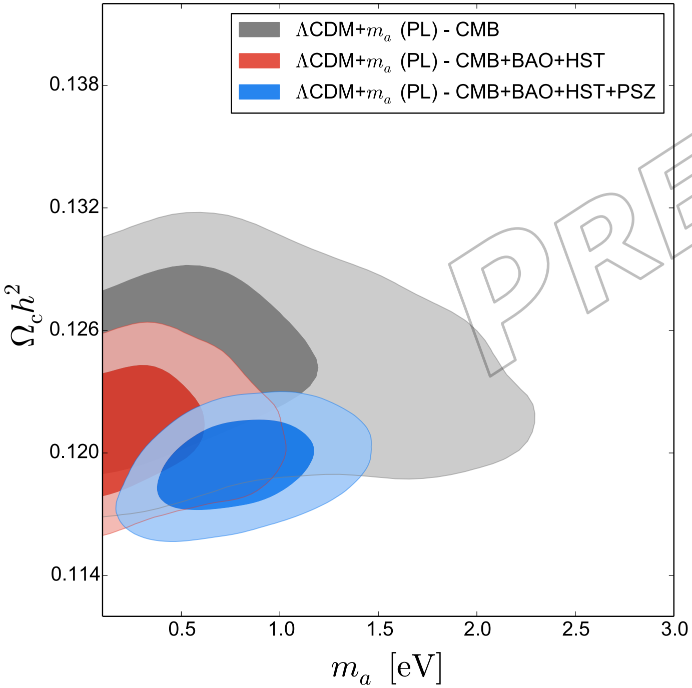
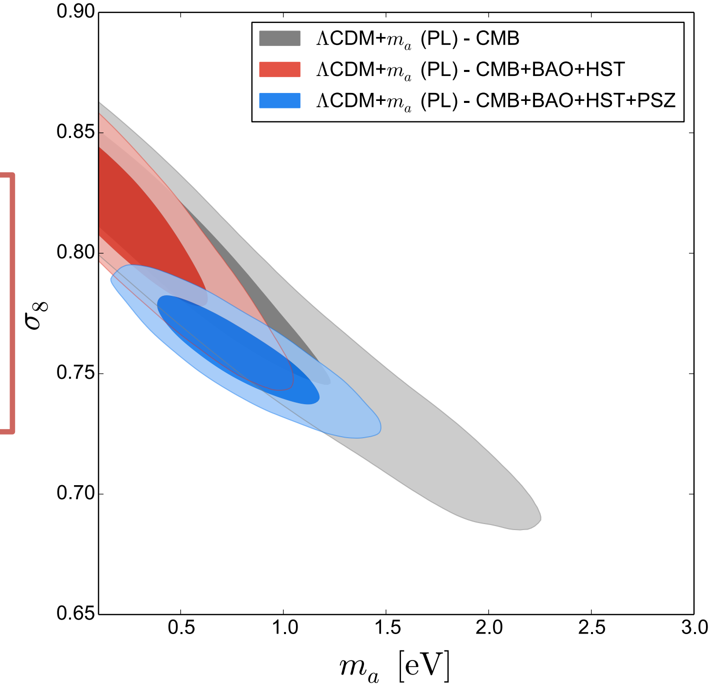


Evidence for thermal axion using Planck SZ clustering data



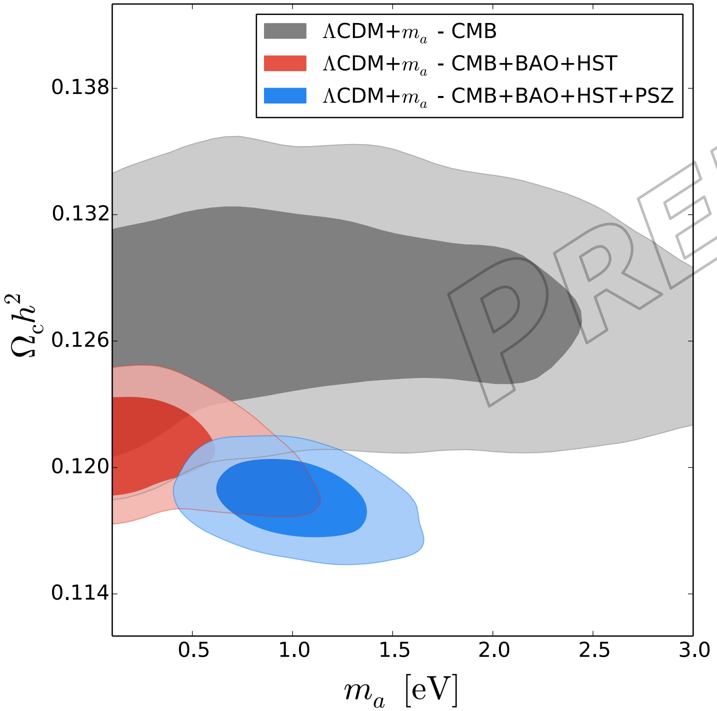
Results(3)

2. ΛCDM model with PCHIP PPS:

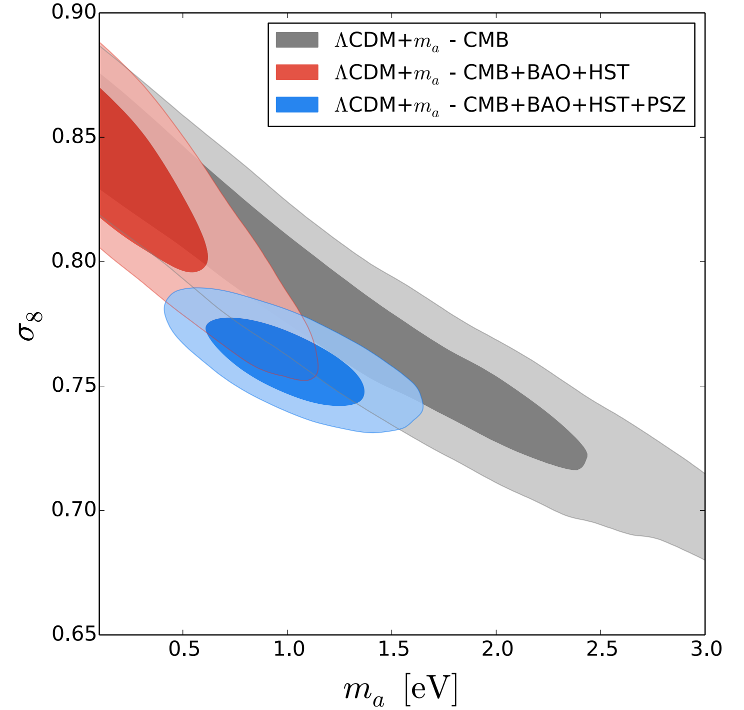
95% CL

	CMB	CMB+HST	CMB+BAO	CMB+BAO +HST	CMB+BAO HST+CFHT	CMB+BAO +HST+PSZ
$\Omega_c h^2$	$0.127^{+0.007}_{-0.007}$	$0.122^{+0.006}_{-0.006}$	$0.122^{+0.003}_{-0.003}$	$0.121^{+0.003}_{-0.003}$	$0.120^{+0.003}_{-0.003}$	$0.118^{+0.002}_{-0.002}$
m_a [eV]	Unconstrained	< 1.31	< 0.89	< 0.91	< 1.29	$1.00^{+0.50}_{-0.48}$
σ_8	$0.788^{+0.079}_{-0.086}$	$0.821^{+0.052}_{-0.074}$	$0.827^{+0.044}_{-0.057}$	$0.825^{+0.045}_{-0.059}$	$0.793^{+0.049}_{-0.058}$	$0.760^{+0.023}_{-0.022}$
Ω_m	$0.369^{+0.070}_{-0.065}$	$0.314^{+0.045}_{-0.039}$	$0.308^{+0.016}_{-0.015}$	$0.304^{+0.016}_{-0.014}$	$0.302^{+0.016}_{-0.015}$	$0.304^{+0.016}_{-0.015}$

68% and 95% CL allowed regions in the $(m_a, \Omega_c h^2)$ and in the (m_a, σ_8) plane



Adding BAO measurements, lower values of the physical matter density are preferred.



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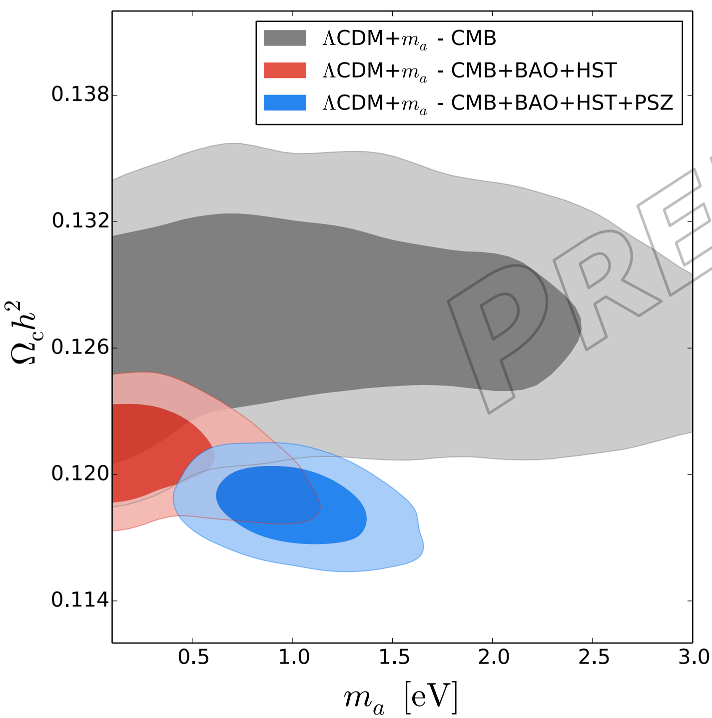
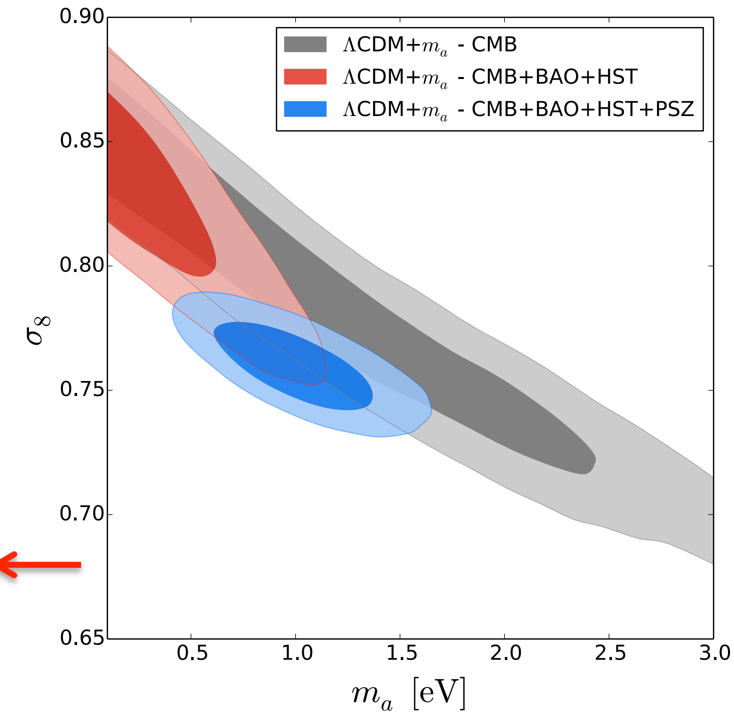


Adding BAO measurements, lower values of the physical matter density are preferred.

Lower values on σ_8 clustering parameter and thermal axion mass evidence, using PSZ data



Results(3)

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95% CL

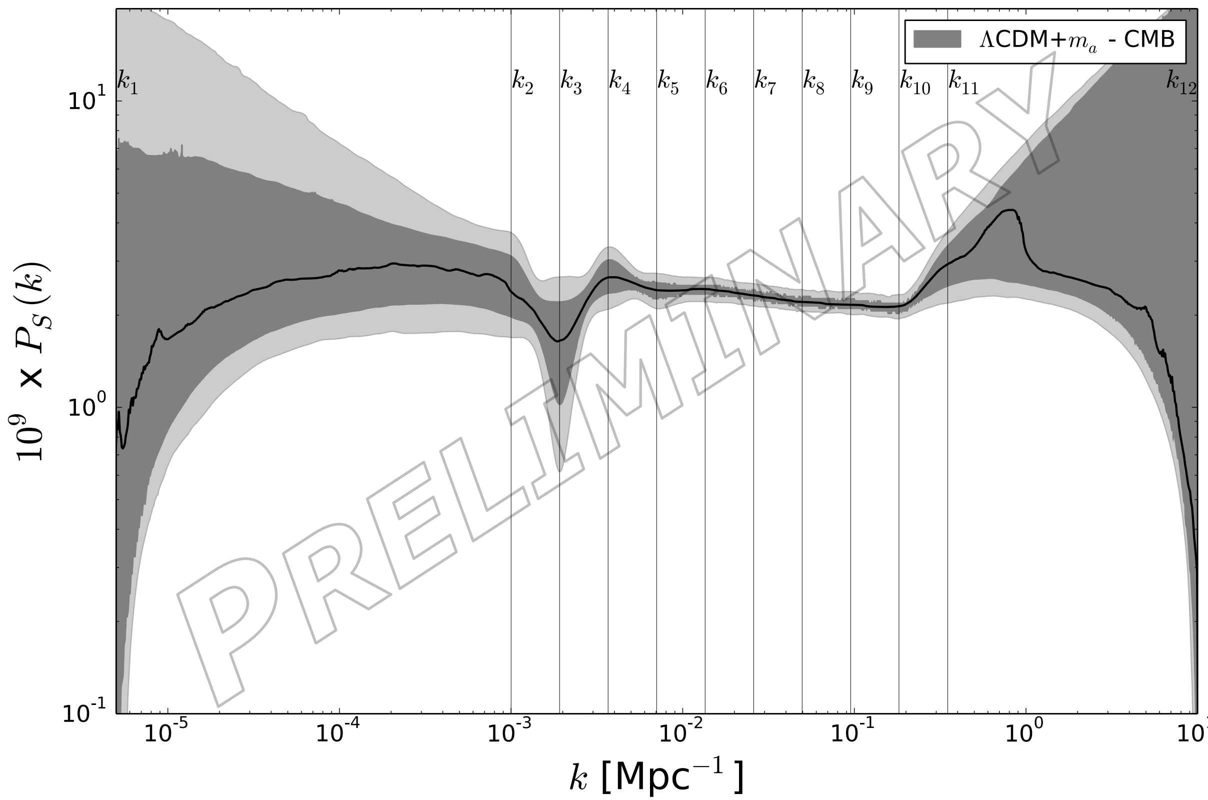
	CMB	CMB+HST	CMB+BAO	CMB+BAO +HST	CMB+BAO HST+CFHT	CMB+BAO +HST+PSZ
$P_{s,1}$	< 8.13	< 8.17	< 7.91	< 8.06	< 7.85	< 8.09
$P_{s,2}$	$1.09^{+0.42}_{-0.35}$	$1.01^{+0.43}_{-0.35}$	$1.01^{+0.40}_{-0.32}$	$0.99^{+0.42}_{-0.33}$	$1.02^{+0.43}_{-0.34}$	$1.01^{+0.42}_{-0.33}$
$P_{s,3}$	$0.68^{+0.39}_{-0.36}$	$0.71^{+0.39}_{-0.39}$	$0.71^{+0.39}_{-0.37}$	$0.72^{+0.39}_{-0.38}$	$0.69^{+0.39}_{-0.37}$	$0.70^{+0.40}_{-0.38}$
$P_{s,4}$	$1.14^{+0.24}_{-0.22}$	$1.15^{+0.24}_{-0.22}$	$1.15^{+0.23}_{-0.21}$	$1.15^{+0.23}_{-0.20}$	$1.15^{+0.23}_{-0.21}$	$1.15^{+0.23}_{-0.21}$
$P_{s,5}$	$1.02^{+0.11}_{-0.10}$	$1.01^{+0.11}_{-0.11}$	$1.00^{+0.11}_{-0.10}$	$1.00^{+0.11}_{-0.10}$	$0.99^{+0.11}_{-0.10}$	$0.99^{+0.11}_{-0.10}$
$P_{s,6}$	$1.03^{+0.08}_{-0.07}$	$1.00^{+0.08}_{-0.07}$	$1.00^{+0.08}_{-0.07}$	$1.00^{+0.08}_{-0.07}$	$0.98^{+0.07}_{-0.06}$	$0.98^{+0.07}_{-0.07}$
$P_{s,7}$	$0.99^{+0.07}_{-0.06}$	$0.98^{+0.08}_{-0.07}$	$0.98^{+0.07}_{-0.07}$	$0.98^{+0.08}_{-0.07}$	$0.96^{+0.07}_{-0.06}$	$0.95^{+0.07}_{-0.06}$
$P_{s,8}$	$0.94^{+0.06}_{-0.06}$	$0.95^{+0.08}_{-0.07}$	$0.95^{+0.07}_{-0.06}$	$0.95^{+0.08}_{-0.07}$	$0.94^{+0.07}_{-0.06}$	$0.94^{+0.07}_{-0.06}$
$P_{s,9}$	$0.92^{+0.06}_{-0.05}$	$0.94^{+0.08}_{-0.06}$	$0.94^{+0.07}_{-0.06}$	$0.94^{+0.08}_{-0.06}$	$0.93^{+0.07}_{-0.06}$	$0.93^{+0.07}_{-0.06}$
$P_{s,10}$	$0.90^{+0.06}_{-0.06}$	$0.91^{+0.08}_{-0.07}$	$0.91^{+0.07}_{-0.06}$	$0.91^{+0.08}_{-0.06}$	$0.90^{+0.07}_{-0.06}$	$0.90^{+0.07}_{-0.06}$
$P_{s,11}$	$1.25^{+0.30}_{-0.28}$	$1.24^{+0.32}_{-0.31}$	$1.23^{+0.31}_{-0.31}$	$1.24^{+0.31}_{-0.31}$	$1.22^{+0.30}_{-0.31}$	$1.22^{+0.32}_{-0.28}$
$P_{s,12}$	Unconstrained	Unconstrained	Unconstrained	Unconstrained	Unconstrained	Unconstrained

PPS can be described by the power-law parametrization

Results(3)

2. ΛCDM model with PCHIP PPS:

68% and 95% CL allowed regions the PCHIP PPS in the ΛCDM model using CMB data only



Increase of the PPS at k_{10}≈0.2 Mpc^{-1}, necessary to compensate the effects of the thermal axion during the evolution of the Universe

Summery and Conclusions

- ✓ The bounds on hot dark matter properties ($\sum m_\nu$, m_a and N_{eff}) depend on the combination of data sets and on the cosmological model.

- ✓ Constraints on the masses of the different thermal relics in different scenarios using recent comological data

- ✓ In the minimal three active massive neutrino scenario we found that CFHTLens survey displaces the bound on neutrino masses to higher value. Planck cluster data favours a non zero value on $\sum m_\nu$ and axion mass

- ✓ In the scenario with thermal axions and active massive neutrino species we found that only considering the Planck SZ cluster data plus CMB+DR11+ BAO+HST there exists a prefernce for axion mass of 0.6 eV at the obout 2.2σ and only combining Planck SZ cluster data with CMB+DR11+ WZ+HST there is an evidence for neutrino mass of 0.2 eV at about 3σ

- ✓ In a scenario with thermal axions and with a non-standard PPS we found a non zero value for the axion mass at obout 4σ only considering the Planck SZ cluster data combined with CMB+ BAO+HST measurements.

Conclusions

- Constraints on the masses of the different thermal relics in different scenarios using the most recent comological data
- In the minimal three active massive neutrino scenario we found that CFHTLens survey displaces the bound on neutrino masses to higher value. Planck cluster data favours a non zero value on $\sum m_\nu$ of about 0.3 eV at 4σ.
- In the scenario with thermal axions and active massive neutrino species we found that only considering the Planck SZ cluster data plus CMB+DR11+ BAO+HST there exists a prefernce for axion mass of 0.6 eV at the obout 2.2σ and only combining Planck SZ cluster data with CMB+DR11+ WZ+HST there is an evidence for neutrino mass of 0.2 eV at about 3σ.
- In the scenario with massive neutrinos and ΔN_{eff} dark radiation species the bounds on $\sum m_\nu$ are less stringent. BBN constraints reduce both mean value and the errors ok N_{eff} significantly.
- Considering B-mode polarization measurements by BICEP2 experiment +Planck+WP data, we found that an extra realivistic component could solve the tension between the two experiments on the amplitude of tensor mode.

Implications of cosmological observations on hot dark matter properties

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Cosmology on Safari 2015

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Based on works in collaboration with:
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INFN

Planck constraints on H_0

- No evidence for extra dark radiation from CMB measurements

- When others data sets are including there is a better agreement with N_{eff}=3.046

- In particular only with HST data we have an evidence for extra dark radiation at about 2.7 σ. $N_{eff} = 3.73^{+0.54}_{-0.51}$ Planck+WP+HST

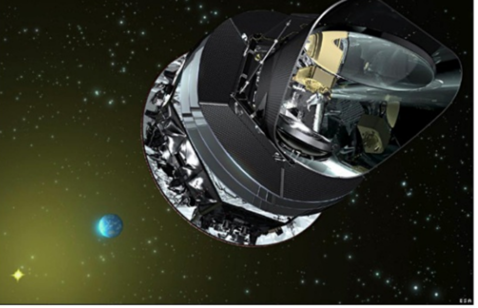
- This is due to the tension between Planck and HST on the value of the Hubble constant

$H_0 = 67.3^{+1.2}_{-1.1}$ [km/s/Mpc] Planck+WP Under the assumption of N_{eff}=3.046

$H_0 = 73.8^{+2.4}_{-2.4}$ [km/s/Mpc] HST (Riess et al)

$H_0 = 70.7^{+3.0}_{-3.2}$ [km/s/Mpc] Planck+WP If N_{eff} free parameter

Only when N_{eff}>3.046, Planck and HST are compatible



Planck Results: $N_{eff} + \sum m_\nu$

- 3 Degenerate massive neutrinos
- Extra massless neutrinos

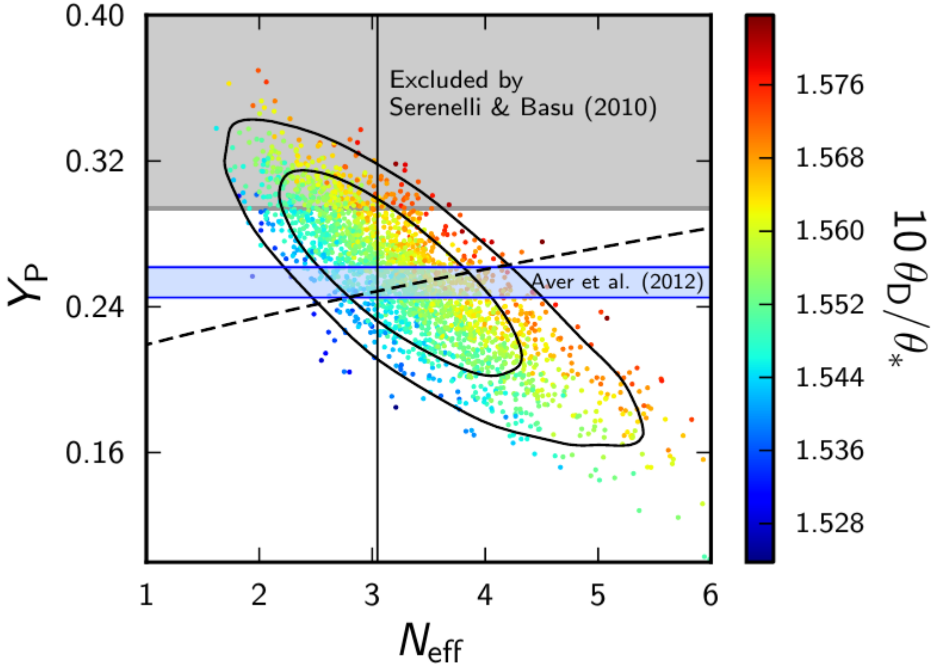
$$N_{eff} = 3.29^{+0.67}_{-0.64}, \quad \sum m_\nu < 0.60 \text{ eV}$$ (95% Planck+WP +highL)

$$N_{eff} = 3.29^{+0.54}_{-0.60}, \quad \sum m_\nu < 0.28 \text{ eV}$$ (95% Planck+WP +highL+BAO)

- 3 active massive neutrinos($\sum m_\nu$=0.06 eV)
- ΔN_{eff} massive sterile neutrinos with total mass $m_{\nu,s}$

$$N_{eff} < 3.91, \quad m_{\nu,s} < 0.59 \text{ eV}$$ (95% Planck+WP +highL)

$$N_{eff} < 3.80, \quad m_{\nu,s} < 0.42 \text{ eV}$$ (95% Planck+WP +highL+BAO)



$$r_s \propto \frac{1}{H} = (1 - f_\nu)^{-0.25}$$

$$r_d \propto \frac{1}{n_e H} = (1 - Y_P)^{-0.5}$$

$$n_e \propto (1 - Y_P)$$

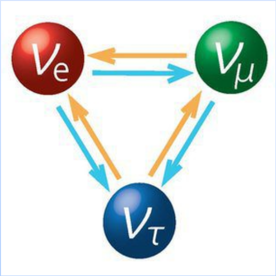
$$H^2 \propto \rho_r \approx (1 - f_\nu)$$

N_{eff} increase, f_ν increase, we have to reduce Y_P

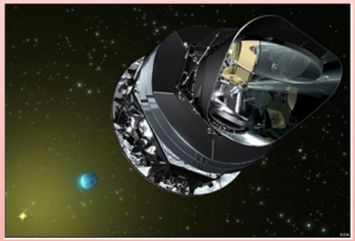
$$\frac{\theta_d}{\theta_s} = \frac{(1 - f_\nu)^{0.25}}{(1 - Y_P)^{0.5}}$$

Neutrino Mass Measurements

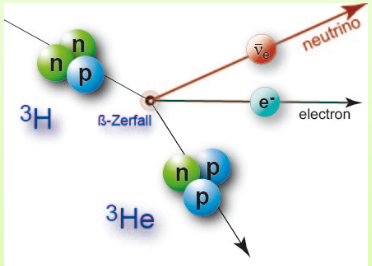
Neutrino Oscillations
- Sensitive to the mass differences
- Uses quantum mechanical effects
- Sources: Solar, atmospheric reactor



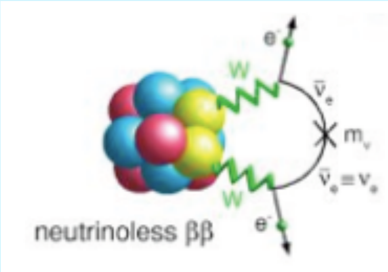
Cosmology
- Sensitive to the total neutrino mass
- Uses General Relativity
- Measured by satellites and ground-based observatories



Single Beta Decay
- Sensitive to the absolute neutrino mass scale
- Uses conservation of energy
- Model independent



0ν Double Beta Decay
- Sensitive to the Majorana masses
- Uses decay
- Probes the nature of neutrinos

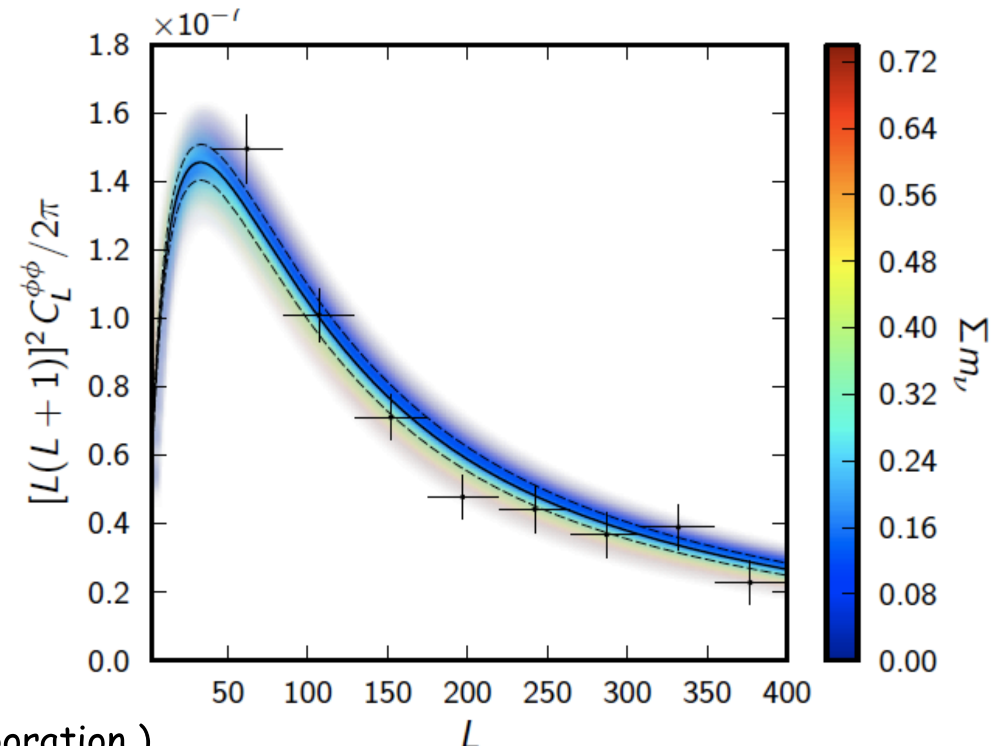


Lensing Potential

The trajectories of CMB photons are slightly deflected by matter fluctuations localized at z≤3 . The deflection field is the difference between the direction $\hat{n}$ in which photons have been emetted from LSS and the direction in which they are actually observed ($\hat{n}+\hat{d}(\hat{n})$).

$$\varphi(\hat{n}) = -\int_{\eta_{LS}}^{\eta_0} d\eta \frac{\chi(\eta_{LS})-\chi(\eta)}{\chi(\eta)\chi(\eta_{LS})}(\varphi+\psi)$$ Deflection

The free streaming nature of the neutrino suppresses the power spectrum and the lensing potential that depends on the gravitational potential.



(Ade et al '13 Planck Collaboration)