Cosmological Axion and Neutrino mass constraints from Planck 2015 temperature and polarization data

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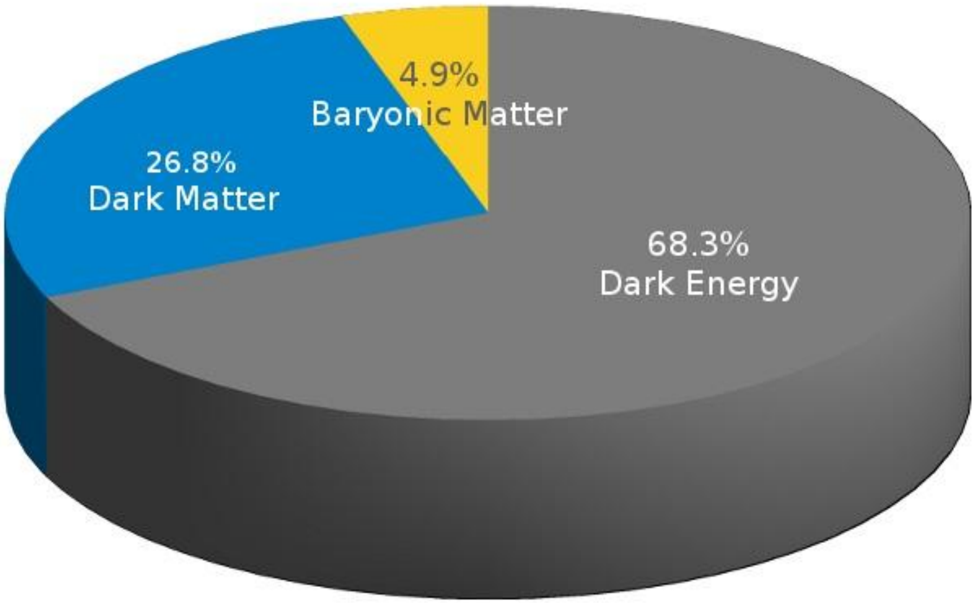
arXiv: 1507.08665

INFN

Outline

- Introduction
- Impact of massive neutrinos and thermal axions on cosmological observables
- Cosmological data used in the analysis
- Results
- Conclusions

Cosmic Pies



Planck 2015

"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T SEE THEM."

DARK MATTER → HDM + CDM

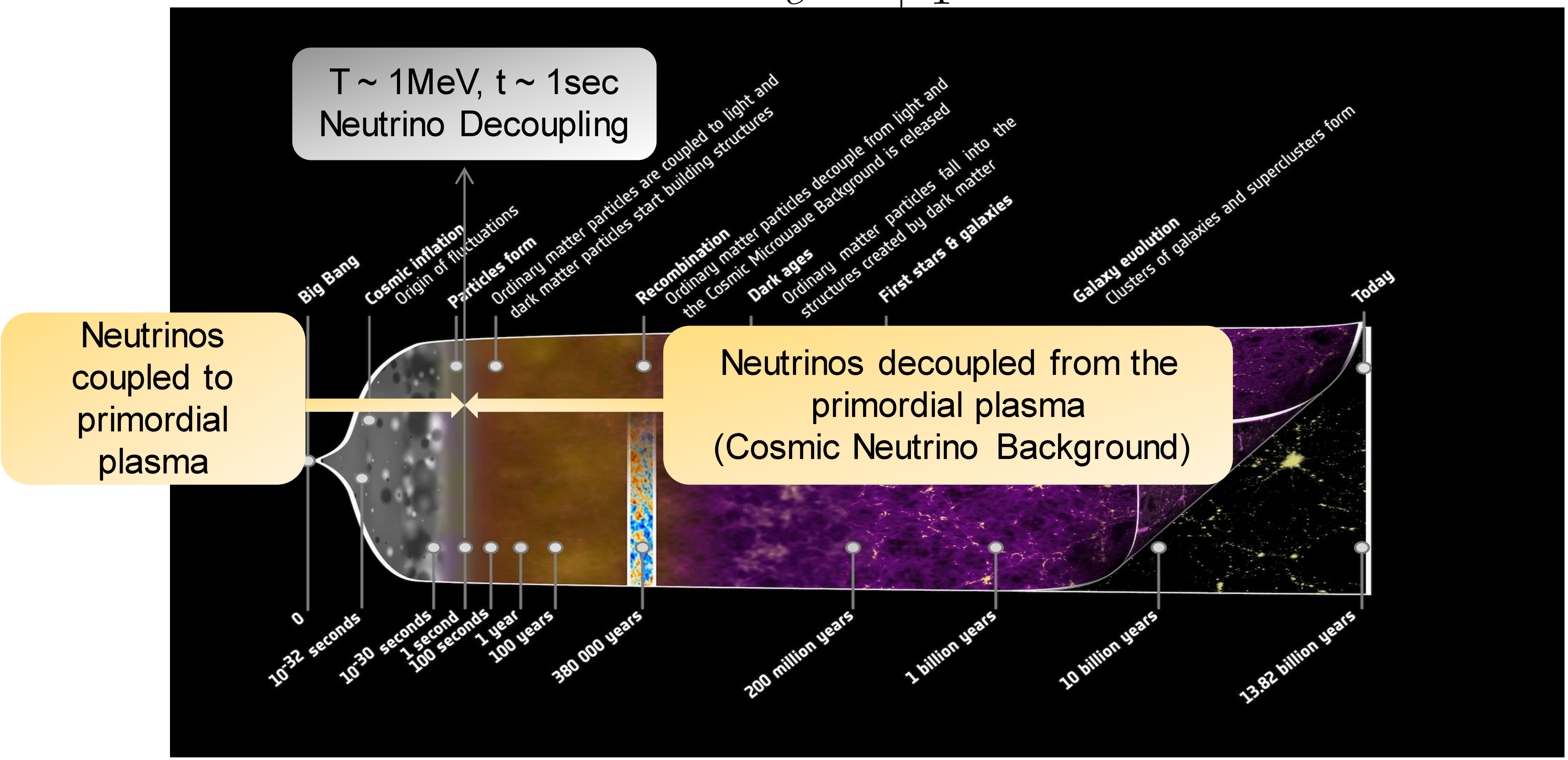
Neutrino,
Thermal Axion

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 Fermi-Dirac Distribution:

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



Cosmic Neutrinos

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

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

Number density: $$n_\nu = \left(\frac{3}{11}\right) n_\gamma \rightarrow\ n_{\nu,0} \approx 113\mathrm{cm}^{-3}$$

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

Massless $m_\nu << T_\nu$

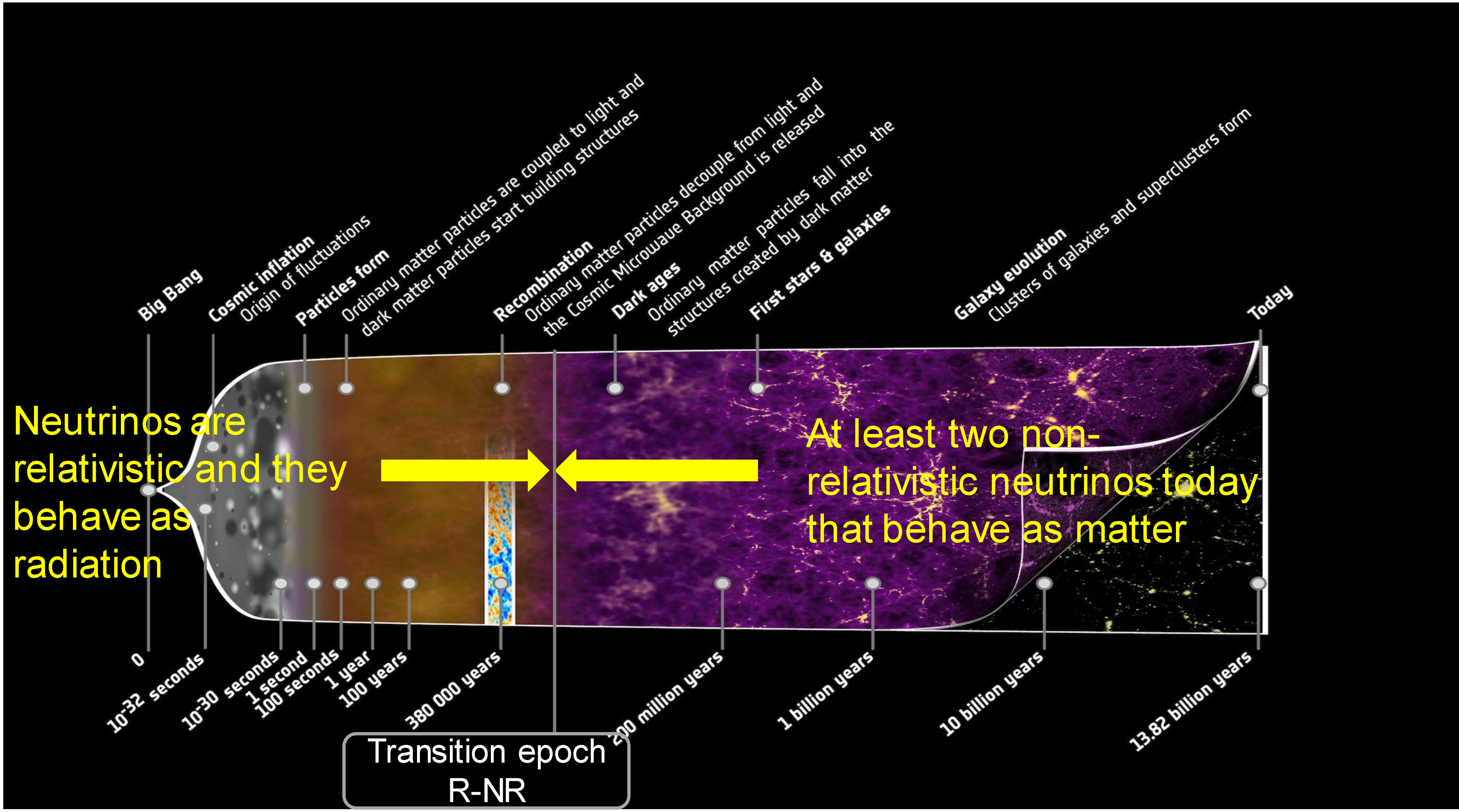
Massive $m_\nu >> T_\nu$

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

Neutrino energy density parameter

Cosmic Neutrinos

- Neutrinos behave as radiation at early time and as matter at late time.



Neutrino relativistic regime

•Massless neutrinos contribute to the dark radiation content of the universe, increasing the effective number of relativistic degrees of freedom, N_{eff}.

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

•Standard Scenario: N_{eff}= 3.046 corrispondng to 3 active neutrino contribution. 0.046 thakes to account corrections for the non-instantaneous neutrino decoupling from the primordial plasma.

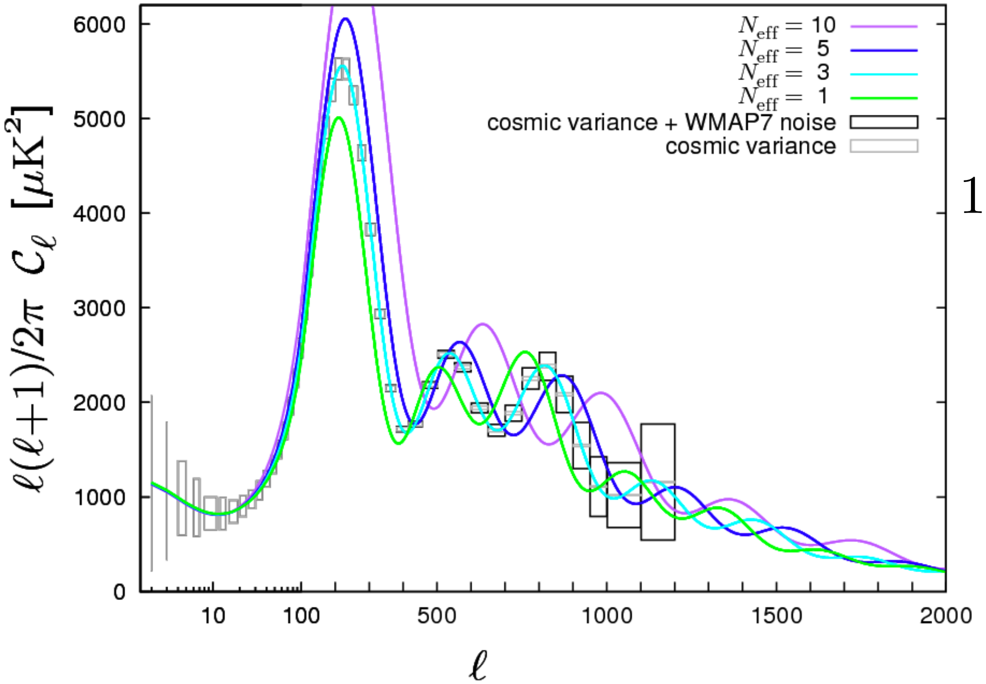
• $N_{eff}=3.046+\Delta N_{eff}$: Extra relativistic component, Dark Radiation.
Sterile neutrinos, thermal axions, extended dark sectors with light species (as in asymmetric dark matter models).

• $N_{eff}<3.046$: Non-standard neutrino couplings, neutrino decays, low reheating temperature models.

Neutrino relativistic regime

An extra ΔN_{eff} modifies :

1) the damping tail of the Cosmic Microwave Background (CMB) temperature angular power spectrum changing two important scales at recombination: the sound horizon and the Silk damping .



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

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

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

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

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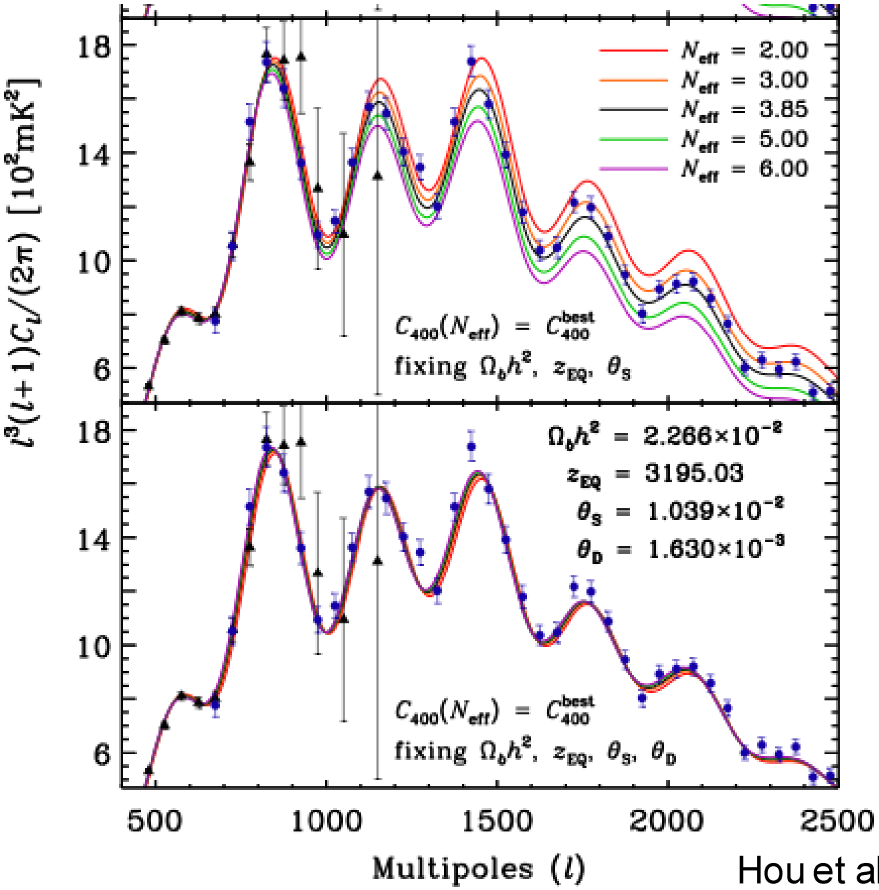


Hou et al, Phys. Rev. D '13

Increase of the Silk damping:

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

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

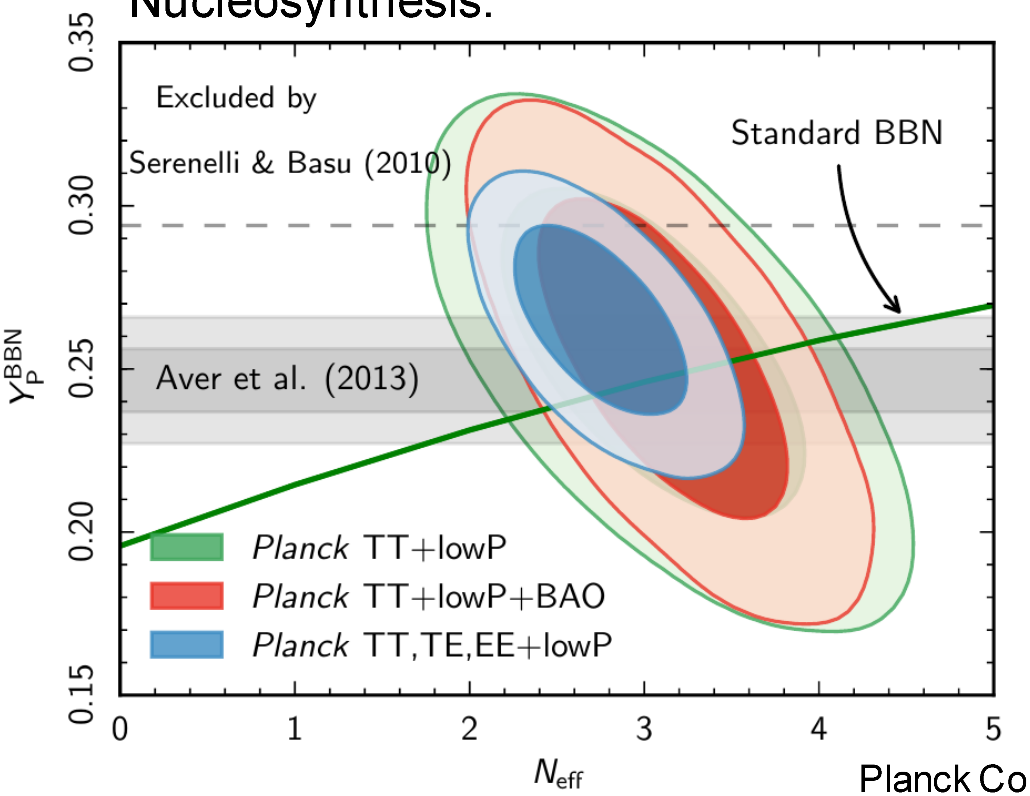
Increasing the damping at high multipoles.

Neutrino relativistic regime

An extra ΔN_{eff} modifies :

1) the damping tail of the Cosmic Microwave Background (CMB) temperature angular power spectrum changing two important scales at recombination: the sound horizon and the Silk damping .

2) the primordial abundances of the light elements predicted by Big Bang Nucleosynthesis.



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

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

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

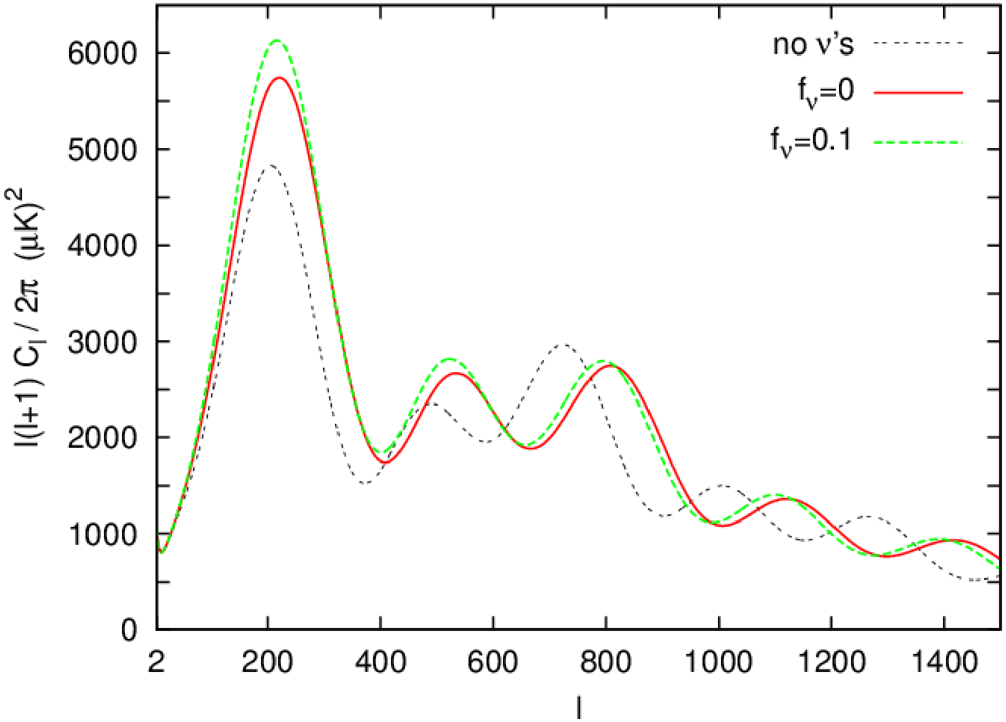
Planck Collaboration 2015, arXiv:1502.01582

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.



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

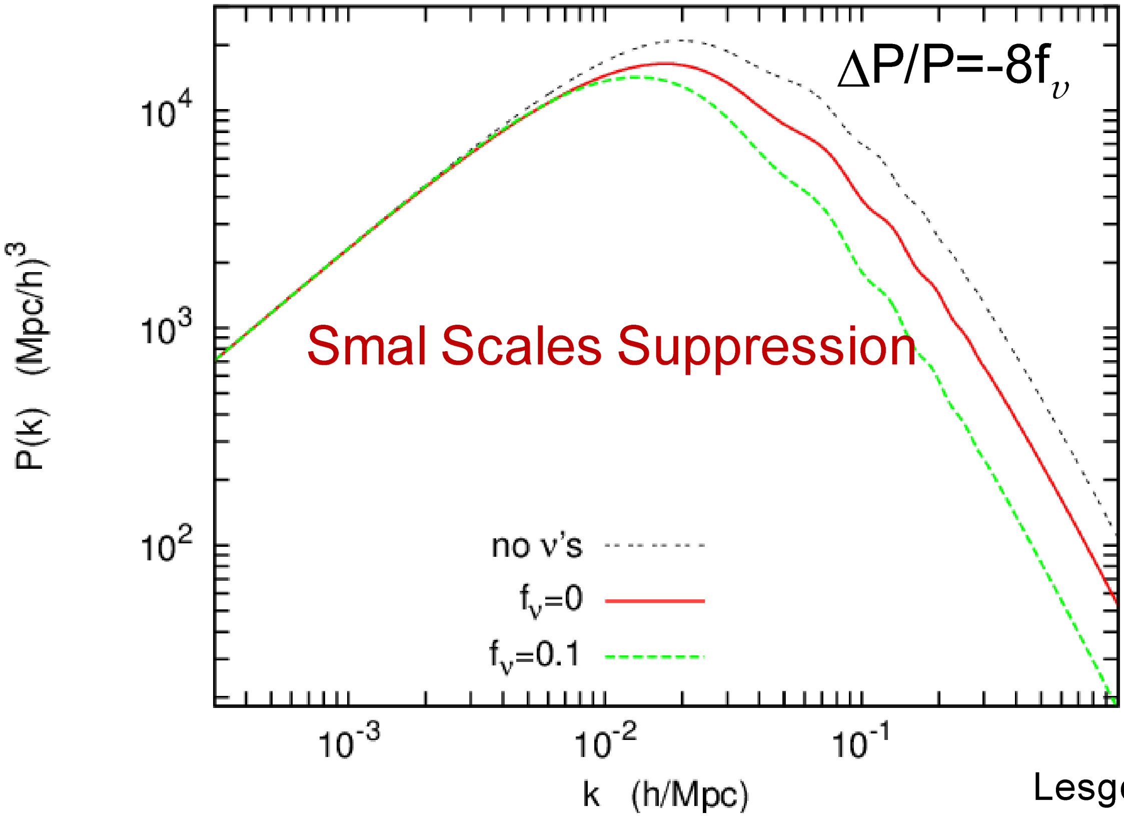
$$f_\nu = \Omega_\nu / \Omega_m$$

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:

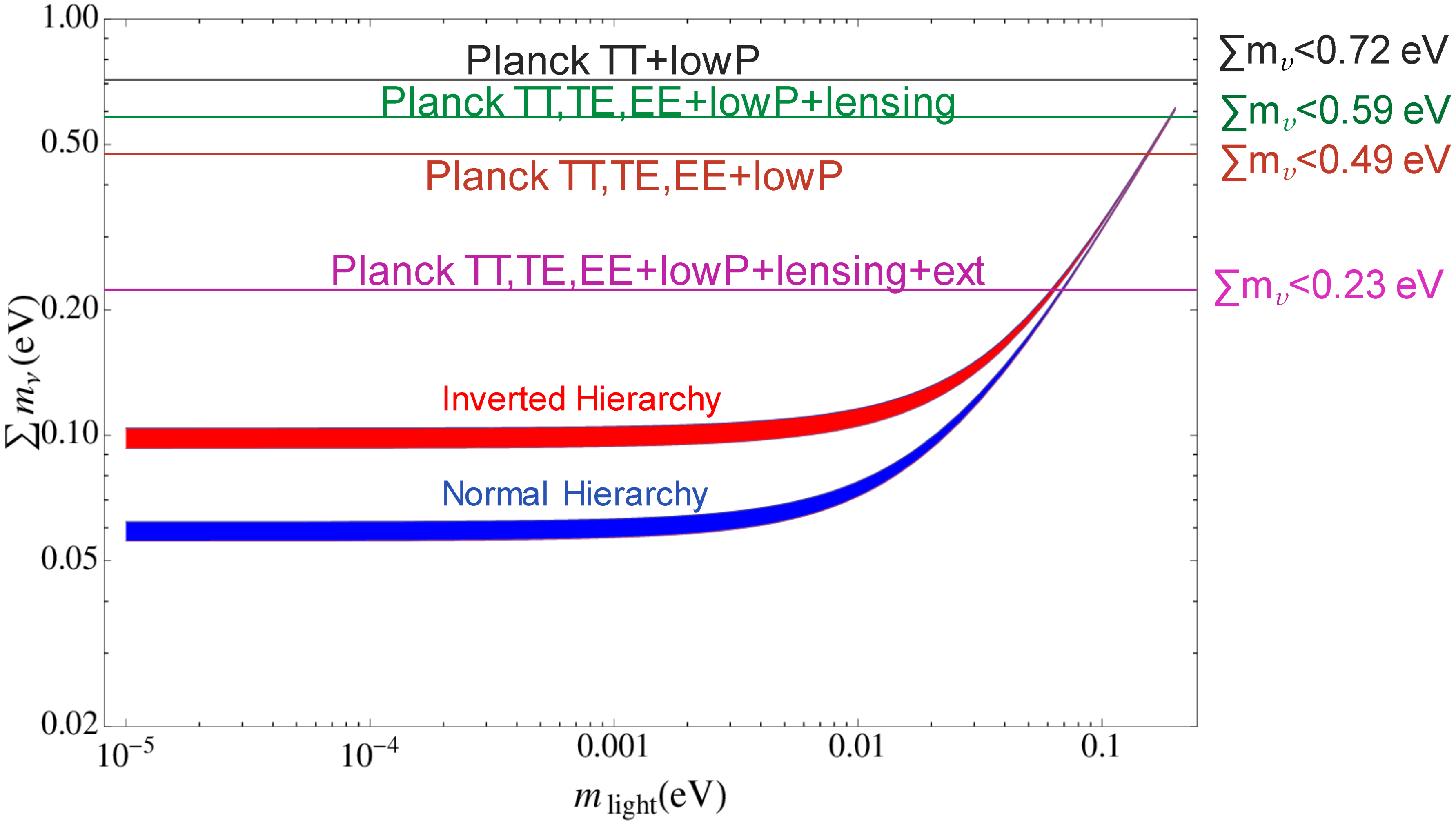
$$\delta_\nu = \delta\rho/\rho = \delta_{cdm} \approx a$$

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

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

Lesgourgues, Pastor, Phys.Rept.'06

2015 Planck state on neutrino mass 95% CL bounds



ext=BAO+JLA+H_0

Planck Collaboration 2015, arXiv:1502.01582

Axions

- Axions were introduced to solve the CP problem of strong interactions in Quantum-Chromodynamics.

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

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

  - Axions with sub-eV masses produced thermally contribute to the hot dark matter component of the universe, as neutrinos.
    (EG, E. Di Valentino, M. Lattanzi, A. Melchiorri and O. Mena, Phys. Rev. D '14, 043507.)

  - Axions with masses in the 10 μeV region produced non-thermally, as for example by the re-alignment mechanism, are postulated as candidates for the cold dark matter component.
    (E. Di Valentino, EG, M. Lattanzi, A. Melchiorri and O. Mena, Phys. Rev. D '14, 043534.)

Thermal Axions

In order to compute the present thermal axion relic density, the most relevant process is the axion-pion interaction:

$$\pi + \pi \rightarrow \pi + a$$

The characteristic parameter for the thermal axion is the axion coupling constant, f_a, that is related to the axion mass by:

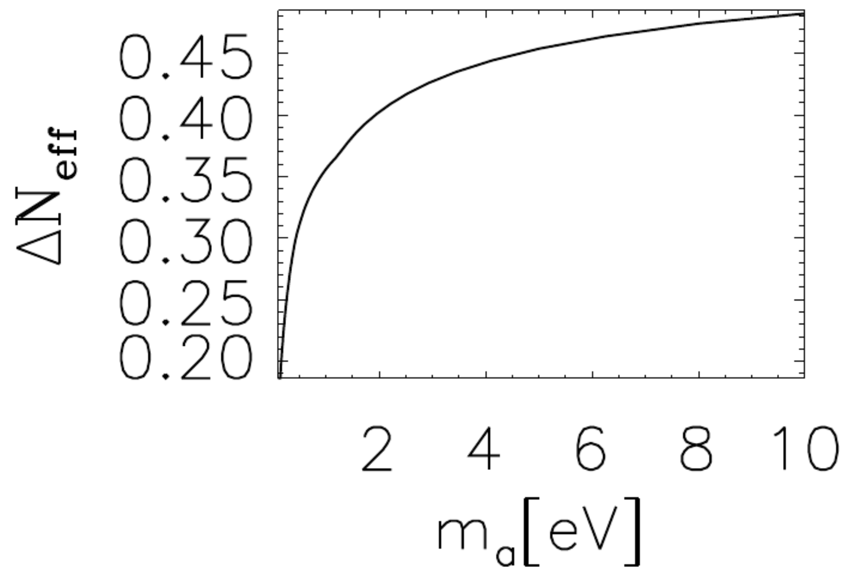
$$m_a = \frac{f_\pi m_\pi}{f_a} \frac{\sqrt{R}}{1+R} = 0.6 \text{ eV } \frac{10^7 \text{ GeV}}{f_a} \qquad R = 0.553 \pm 0.043 \qquad f_\pi = 93 \text{ MeV}$$

Thermal axions affect the cosmological observables in a very similar way to that induced by the presence of massive neutrinos.

Axions in the relativistic regime

Thermal axions increase the amount of radiation in the universe, contributing to the effective number of relativistic degrees of freedom, N_{eff}:

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

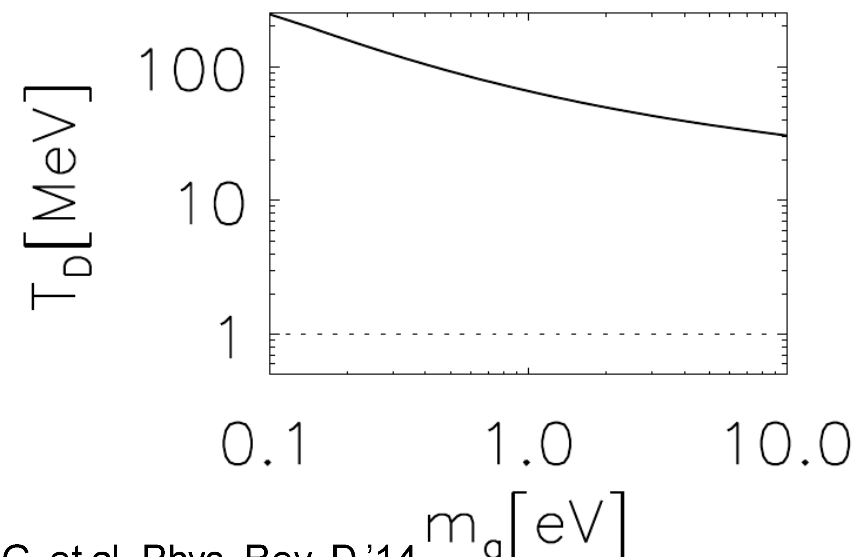


where n_a is the axion number density related to the present photon density:

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

T_D is the axion temperature decoupling given by solving the usual freeze out equation for a thermal relic:

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

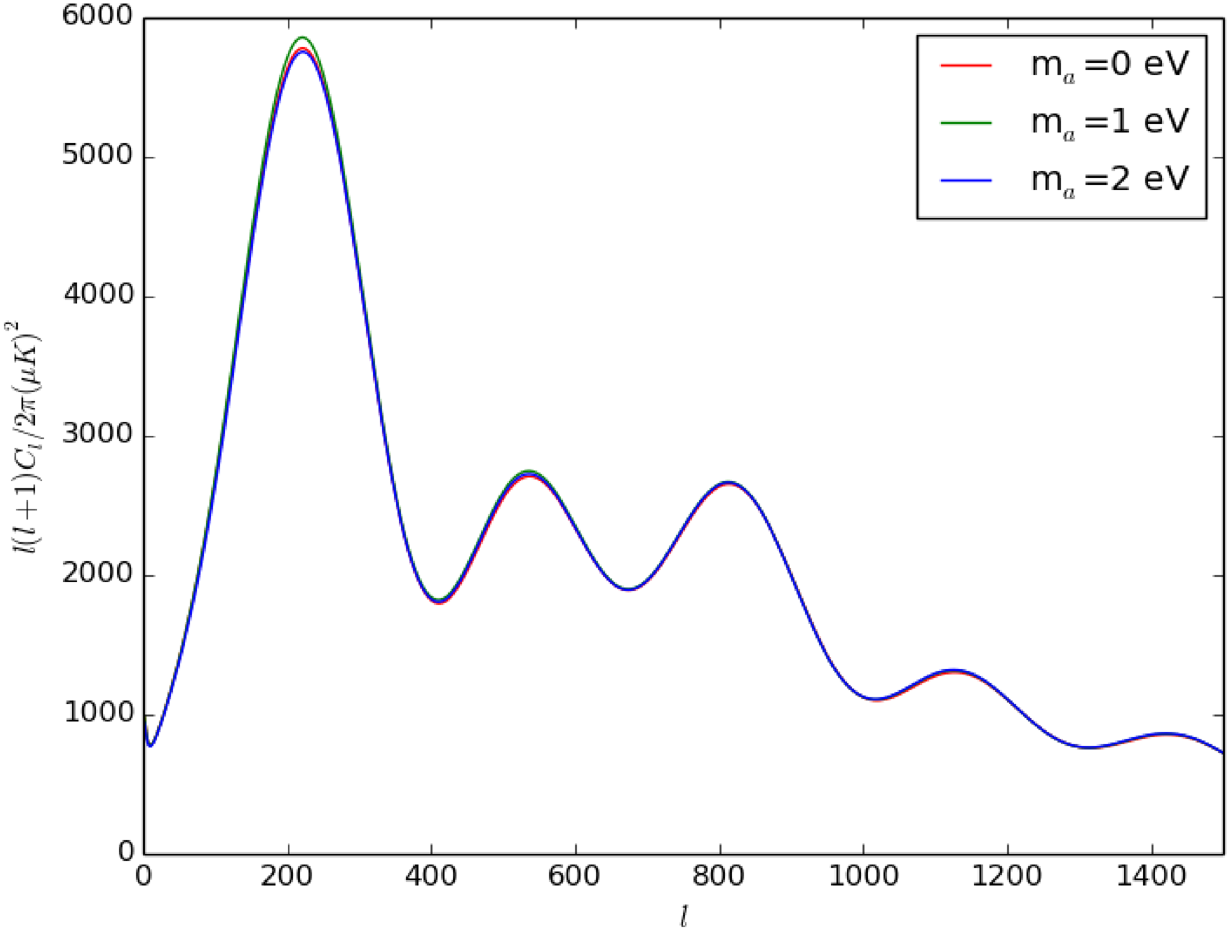


Di Valentino, EG, et al. Phys. Rev. D '14,

Axions in the non-relativistic regime

Thermal axions contribute to the matter density of the universe, i.e by increasing the amount of the hot dark matter density:

$$\Omega_a h^2 = \frac{m_a n_a}{1.054 \cdot 10^4 \text{ eVcm}^{-3}} = \frac{m_a}{131\text{eV}} \left(\frac{10}{g_{*S}(T_D)} \right)$$



Unlike massive neutrinos, axions HDM have no substantial effect on the CMB temperature anisotropies.

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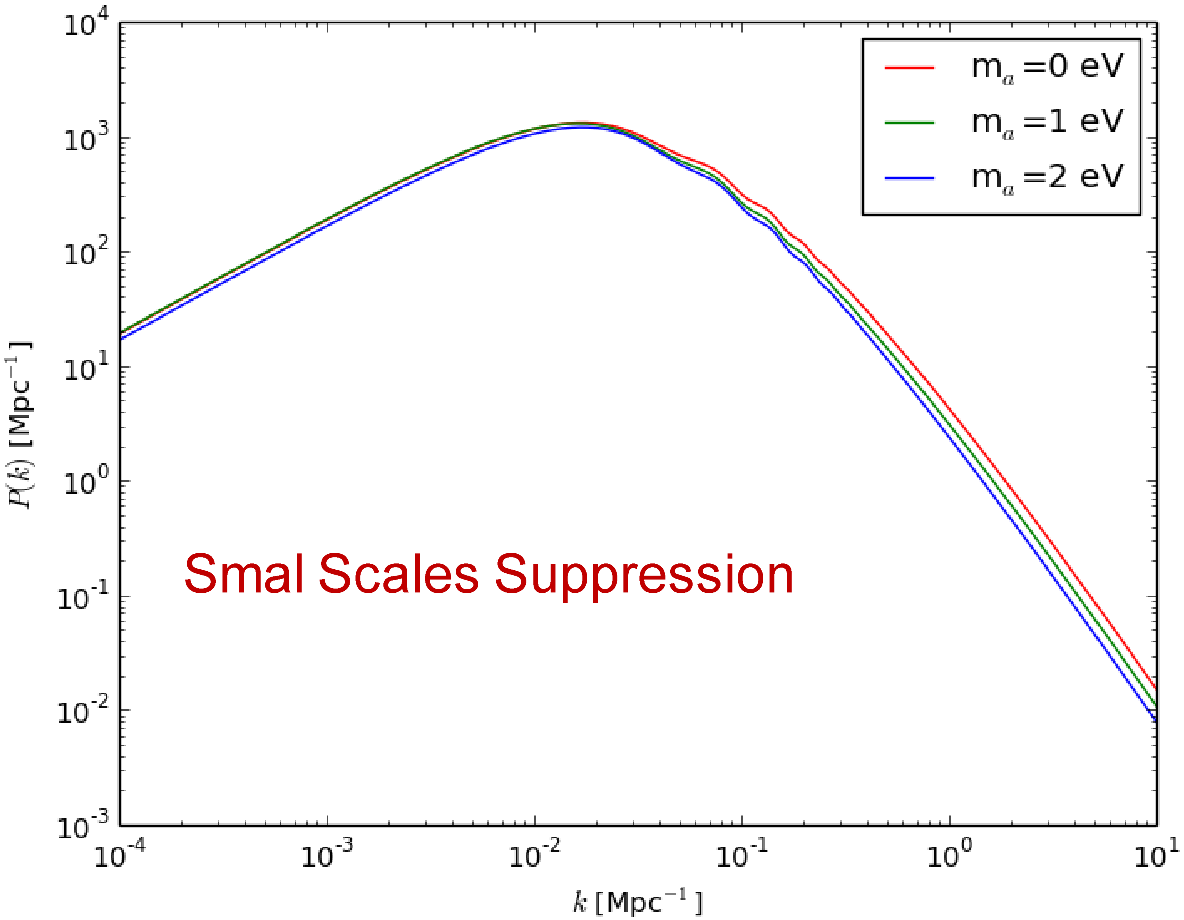

Axions HDM suppress matter power spectrum on scale smaller than free-streaming scale similar to massive neutrinos.

Thermal axion cosmological model

We consider a ΛCDM model with both axion and neutrinos as extra hot thermal relics.

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

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	$[0.01, 0.8]$
m_a (eV)	$[0.1, 3]$
$\sum m_\nu$ (eV)	$[0.06, 3]$
n_s	$[0.9, 1.1]$
$\log[10^{10} A_s]$	$[2.7, 4]$

Uniform priors for the cosmological parameters

Cosmological datasets

- ✓ CMB:
  - Planck 2015 temperature and polarization measurements. We combine the likelihood at $30 \leq l \leq 2500$ using TT, TE and EE power spectra and the Planck low-l multipole likelihood in the range $2 \leq l \leq 29$.
  - Planck 2015 lensing likelihood.

- ✓ Hubble constant measurements:
  - Gaussian prior on the Hubble constant, $H_0=73.8 \pm 2.4$ km/s/Mpc, from the Hubble Space Telescope.

Cosmological datasets

✓ σ_8 measurements:

- The constraint on the relationship $\sigma_8(\Omega_m/0.27)^{0.46}=0.774 \pm 0.040$ from the CFHTLens survey.
- Planck Sunyaev-Zeldovich cluster catalog.

✓ Large scale structure:

- SDSS-MGS.
- 6-degree Field Galaxy Survey.
- BOSS Data Release 11.
- The full shape of the matter power spectrum from WiggleZ survey.

} Baryon Acoustic Oscillation (BAO) data

Results

95% CL constraints on the parameters for a ΛCDM+m_a +Σm_ν model and for different combinations of data sets.

	TT,TE,EE+lowP	TT,TE,EE+lowP +lensing	TT,TE,EE+lowP +WL
$\Omega_c h^2$	$0.1235^{+0.0034}_{-0.0036}$	$0.1235^{+0.0034}_{-0.0034}$	$0.1225^{+0.0032}_{-0.0032}$
m_a [eV]	< 2.09	< 1.67	< 1.87
$\sum m_\nu$ [eV]	< 0.441	< 0.538	< 0.360
σ_8	$0.779^{+0.083}_{-0.094}$	$0.767^{+0.065}_{-0.072}$	$0.789^{+0.074}_{-0.096}$
Ω_m	$0.342^{+0.054}_{-0.048}$	$0.344^{+0.055}_{-0.048}$	$0.328^{+0.048}_{-0.041}$
$\log[10^{10} A_s]$	$3.131^{+0.067}_{-0.070}$	$3.109^{+0.064}_{-0.062}$	$3.117^{+0.071}_{-0.068}$
n_s	$0.972^{+0.011}_{-0.012}$	$0.972^{+0.010}_{-0.011}$	$0.974^{+0.011}_{-0.012}$

CMB lensing measurement from the Planck satellite pulls the constraints slightly away from zero towards higher neutrino masses.

Di Valentino, EG, et al. arXiv:1507.08665

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$\Omega_{\rm m}$	$0.342^{+0.054}_{-0.048}$	$0.344^{+0.055}_{-0.048}$	$0.328^{+0.048}_{-0.041}$
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Weak lensing constraints on the σ_8-Ω_m relationship only mildly tightens the thermal neutrino and axion masses.

Di Valentino, EG, et al. arXiv:1507.08665

Results

95% CL constraints on the parameters for a ΛCDM+m_a +Σm_ν model and for different combinations of data sets.

	TT,TE,EE+lowP +MPK	TT,TE,EE+lowP +BAO	TT,TE,EE+lowP +HST	TT,TE,EE+lowP +BAO +HST	TT,TE,EE+lowP +BAO +HST +SZ
$\Omega_c h^2$	$0.1237^{+0.0034}_{-0.0031}$	$0.1223^{+0.0023}_{-0.0023}$	$0.1223^{+0.0032}_{-0.0032}$	$0.1220^{+0.0024}_{-0.0023}$	$0.1216^{+0.0023}_{-0.0023}$
m_a [eV]	< 0.835	< 0.763	< 1.21	< 0.709	< 0.529
$\sum m_\nu$ [eV]	< 0.291	< 0.159	< 0.182	< 0.136	< 0.126
σ_8	$0.814^{+0.049}_{-0.056}$	$0.827^{+0.039}_{-0.042}$	$0.820^{+0.051}_{-0.062}$	$0.829^{+0.036}_{-0.039}$	$0.835^{+0.033}_{-0.035}$
Ω_m	$0.326^{+0.033}_{-0.029}$	$0.312^{+0.016}_{-0.014}$	$0.315^{+0.031}_{-0.027}$	$0.309^{+0.015}_{-0.014}$	$0.306^{+0.014}_{-0.013}$
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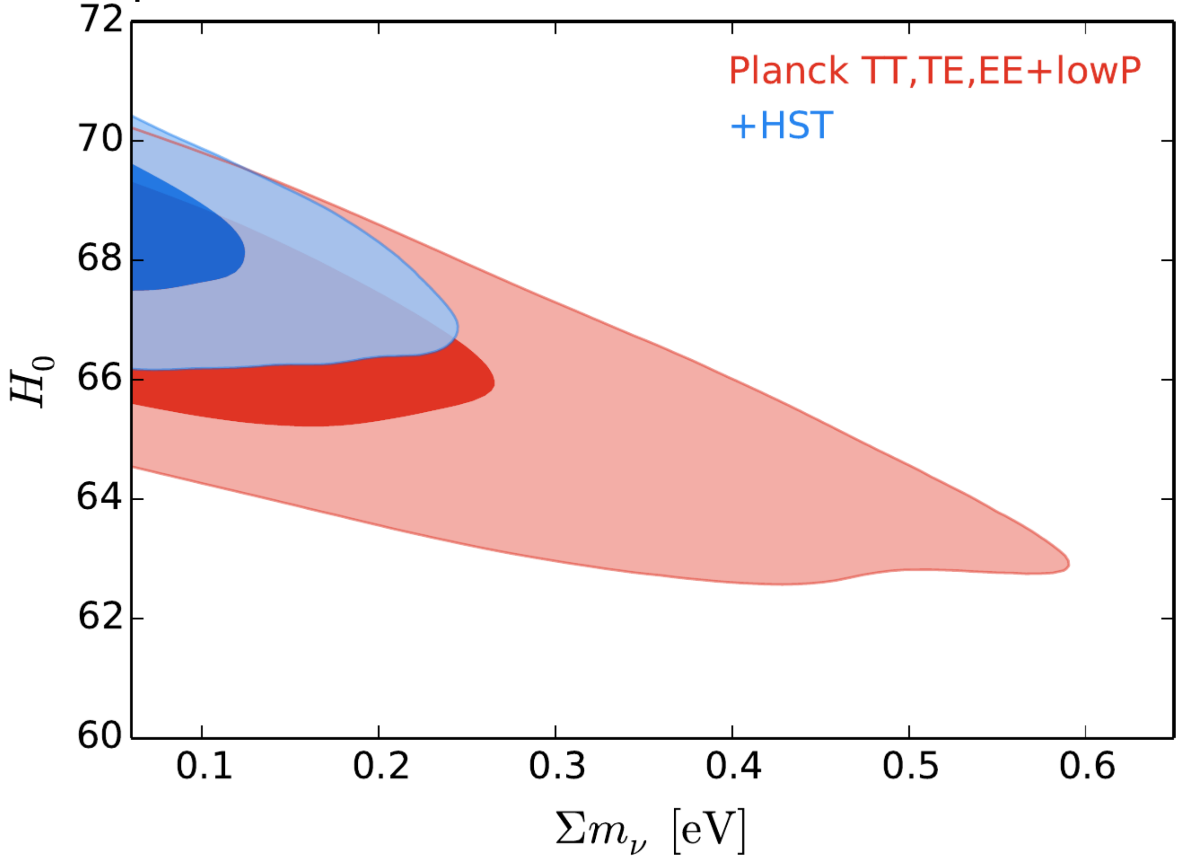
n_s	$0.97278^{+0.009}_{-0.009}$	$0.9754^{+0.0093}_{-0.0089}$	$0.976^{+0.010}_{-0.010}$	$0.9763^{+0.0095}_{-0.0091}$	$0.9768^{+0.0089}_{-0.0089}$

Large improvement on neutrino mass bound due to the strong degeneracy between Σm_ν and H_0.

Di Valentino, EG, et al. arXiv:1507.08665

Results

68% and 95% CL allowed regions in the (Σm_ν , H_0) plane.



When Σm_ν increases there is a shift in the distance to last scattering surface. This shift can be easily compensated by lowering H_0 , resulting in a strong degeneracy between these two parameters.

Di Valentino, EG, et al. arXiv:1507.08665

Results

95% CL constraints on the parameters for a ΛCDM+m_a +Σm_ν model and for different combinations of data sets.

Di Valentino, EG, et al. arXiv:1507.08665

	TT,TE,EE+lowP +MPK	TT,TE,EE+lowP +BAO	TT,TE,EE+lowP +HST	TT,TE,EE+lowP +BAO +HST	TT,TE,EE+lowP +BAO +HST +SZ
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The tightest axion and neutrino mass constraints arise when LSS data are exploited, in particular via BAO signature. The upper bound on Σm_ν for Planck TT,TE,EE+lowP and BAO combination is very similar to the one quoted by the Planck collaboration for the same data sets, Σm_ν <0.17 eV.

Results

95% CL constraints on the parameters for a ΛCDM+m_a +Σm_ν model and for different combinations of data sets.

Di Valentino, EG, et al. arXiv:1507.08665

	TT,TE,EE+lowP +MPK	TT,TE,EE+lowP +BAO	TT,TE,EE+lowP +HST	TT,TE,EE+lowP +BAO +HST	TT,TE,EE+lowP +BAO +HST +SZ
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- The addition of the BAO and the HST data sets leads to the strongest constraint on the neutrino mass to date in the linear perturbation regime.
- Furthermore, the addition of the Planck SZ cluster number counts data provide a competitive 95% CL upper limit on m_a and Σm_ν.

Results

95% CL constraints on the parameters for a ΛCDM+m_a +Σm_ν model and for different combinations of data sets.

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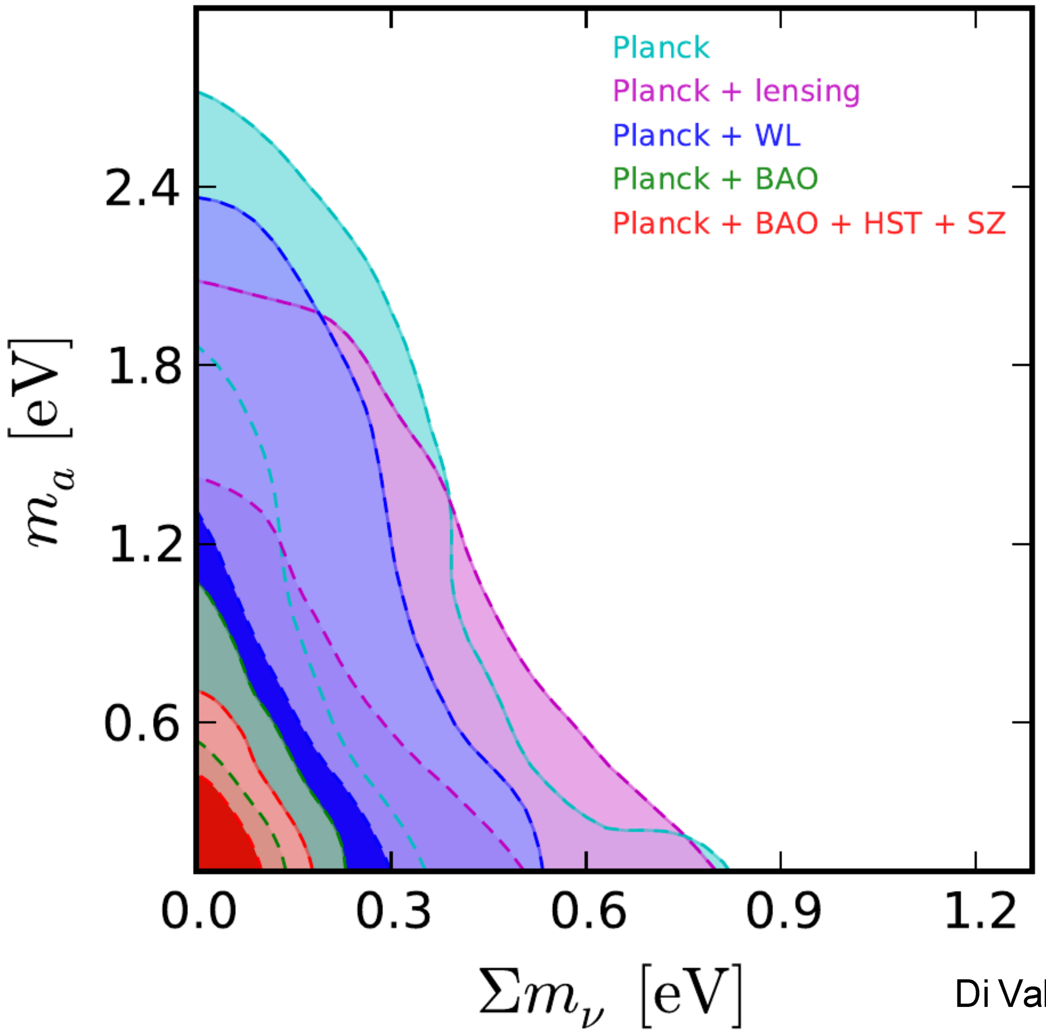
$\Omega_{\rm m}$	$0.326^{+0.033}_{-0.029}$	$0.312^{+0.016}_{-0.014}$	$0.315^{+0.031}_{-0.027}$	$0.309^{+0.015}_{-0.014}$	$0.306^{+0.014}_{-0.013}$
$\log[10^{10} A_s]$	$3.121^{+0.066}_{-0.071}$	$3.126^{+0.066}_{-0.070}$	$3.129^{+0.066}_{-0.068}$	$3.128^{+0.065}_{-0.069}$	$3.132^{+0.063}_{-0.064}$
n_s	$0.97278^{+0.009}_{-0.009}$	$0.9754^{+0.0093}_{-0.0089}$	$0.976^{+0.010}_{-0.010}$	$0.9763^{+0.0095}_{-0.0091}$	$0.9768^{+0.0089}_{-0.0089}$

This bound is competitive with that one obtained using the one-dimensional Lyman-α forest power spectrum of the BOSS experiment, at 95% CL $\Sigma m_\nu < 0.12$ eV (Palanque-Delabrouille et al. arXiv:1506.05976). This limit is very close to the expectations for Σm_ν in the inverted hierarchical neutrino mass scenario.

Results



68% and 95% CL allowed regions in the (Σm_ν , m_a) plane.

There is a degeneracy between the axion mass and the total neutrino mass. This is due to the fact that both of particles contribute to the hot dark matter energy density of the universe. Therefore, if the axion mass increases, in order to keep fixed the hot dark matter content of the universe, the contribution from massive neutrinos has to decrease.

Di Valentino, EG, et al. arXiv:1507.08665

Conclusions

❖ The polarization measurements from Planck 2015 data release offer a unique opportunity for testing the dark matter paradigm.

❖ We have explored a mixed hot dark matter model with two thermal relics, neutrinos and axions.

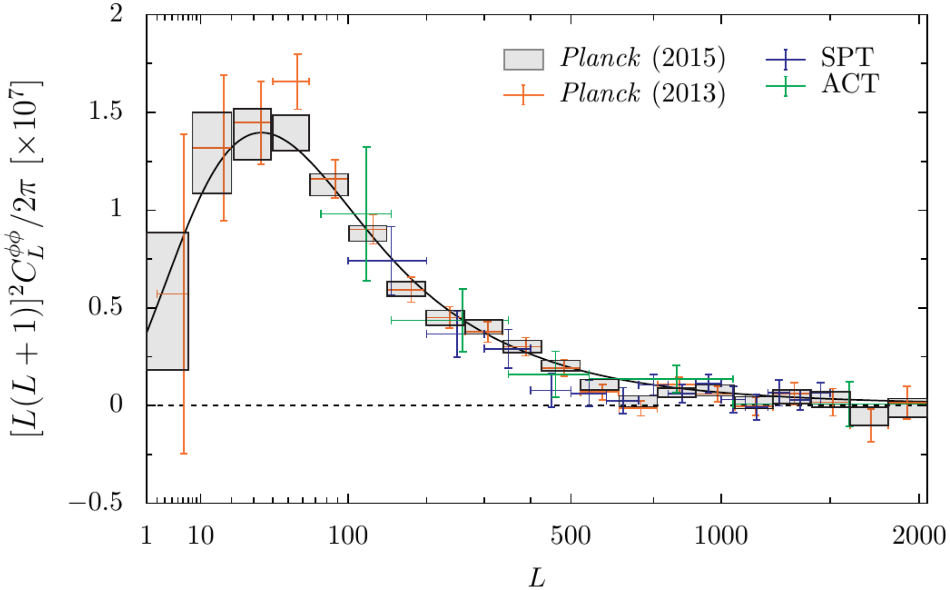
❖ We derived the tightest bounds on termal relic masses ($\Sigma m_\nu < 0.126$ eV and $m_a < 0.529$ eV at 95% CL) combining Planck temperature and polarization data with the Planck Sunyaev-Zeldovich cluster catalog as well as including measurements of the Barion Acoustic peak in galaxy clustering and of the Hubble constant.

❖ These results motivate the need for improved cluster mass calibrations.

❖ They also illustrate the power of combining low and high redshift probes to obtain information on the dark matter thermal properties.

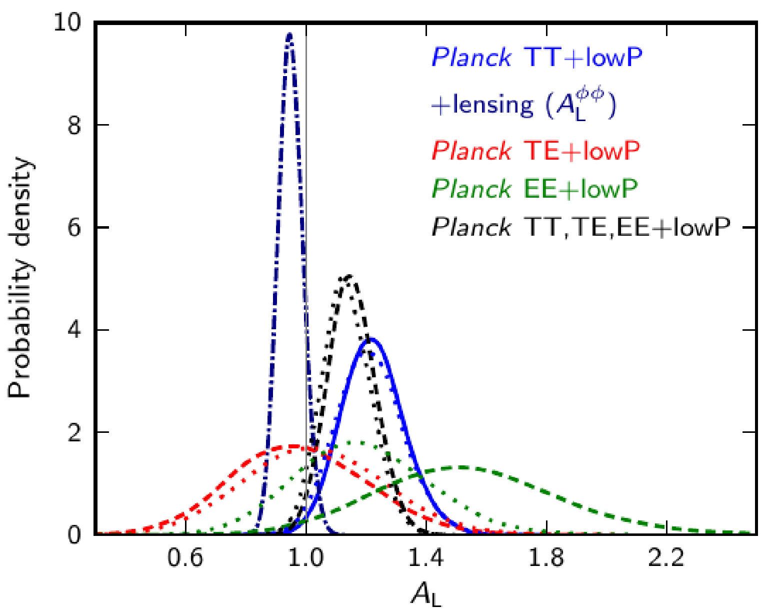
Backup Slides

Lensing Likelihood and neutrinos



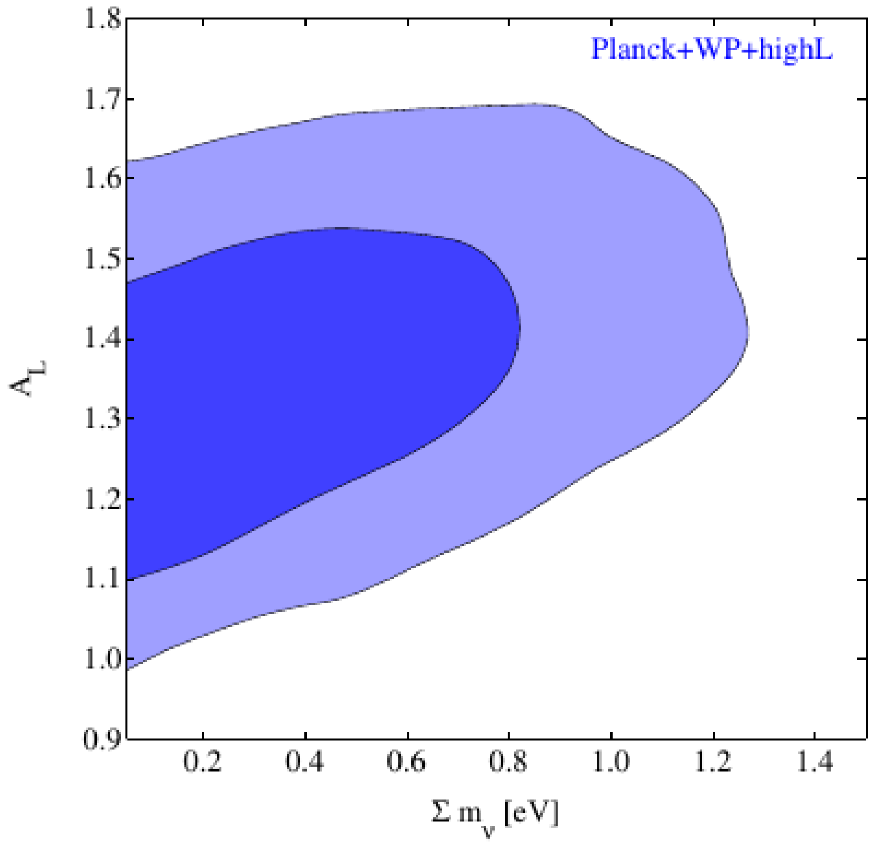
Lensing potential power spectrum obtained from the four-points correlation function.

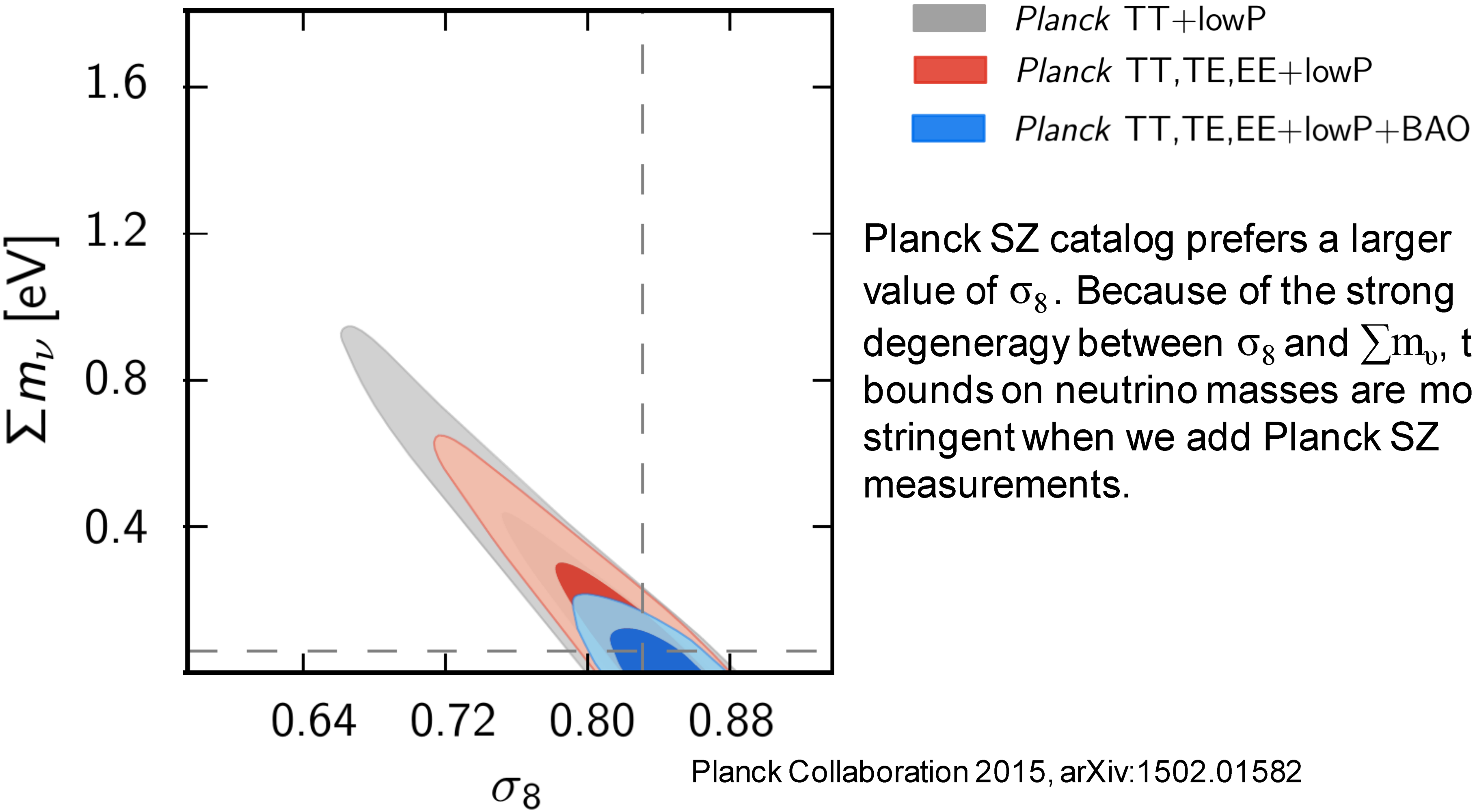
Planck collaboration '15 arXiv:1502.01591



Planck CMB power spectra prefer somewhat more lensing smoothing than predicted in ΛCDM.The neutrino mass constraint from the power spectra is therefore quite tight, since increasing the neutrino mass lowers the predicted smoothing even further compared to base ΛCDM. On the other hand the lensing reconstruction data, which directly probes the lensing power, prefers lensing amplitudes slightly below the base ΛCDM prediction and this favours higher neutrino masses.

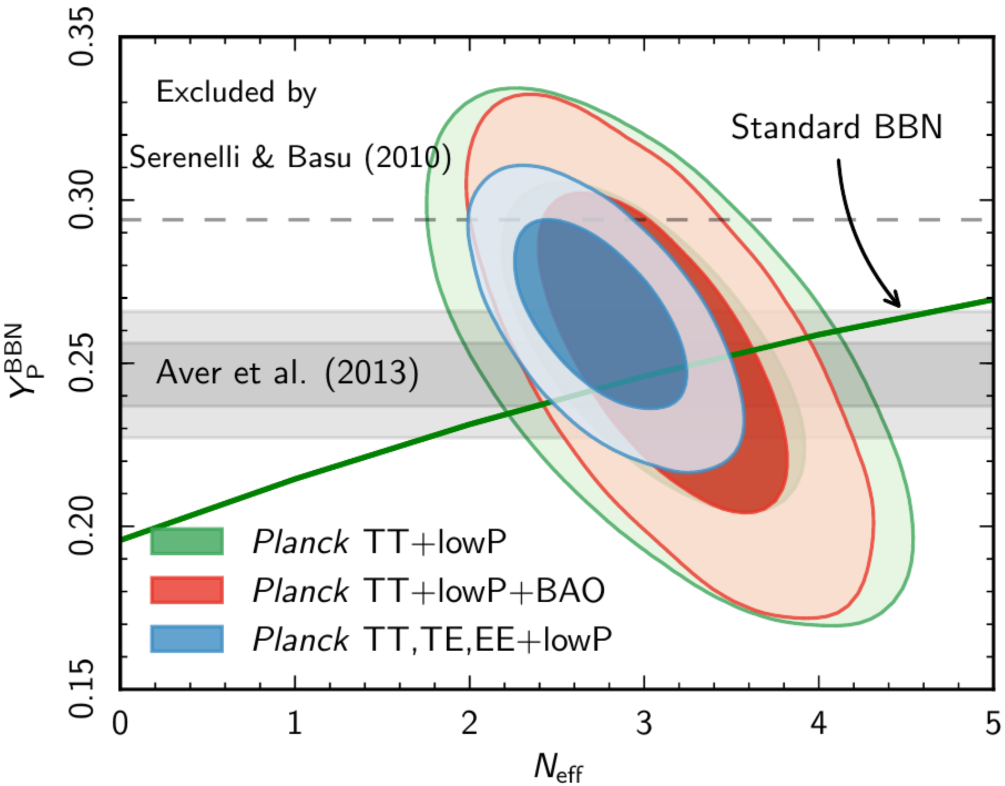
68% and 95% c.l. 2D marginalized posterior in the plane $\sum m_\nu - A_L$





Planck SZ catalog prefers a larger value of σ_8. Because of the strong degeneragy between σ_8 and $\sum m_\upsilon$, the bounds on neutrino masses are more stringent when we add Planck SZ measurements.

Planck Collaboration 2015, arXiv:1502.01582



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

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

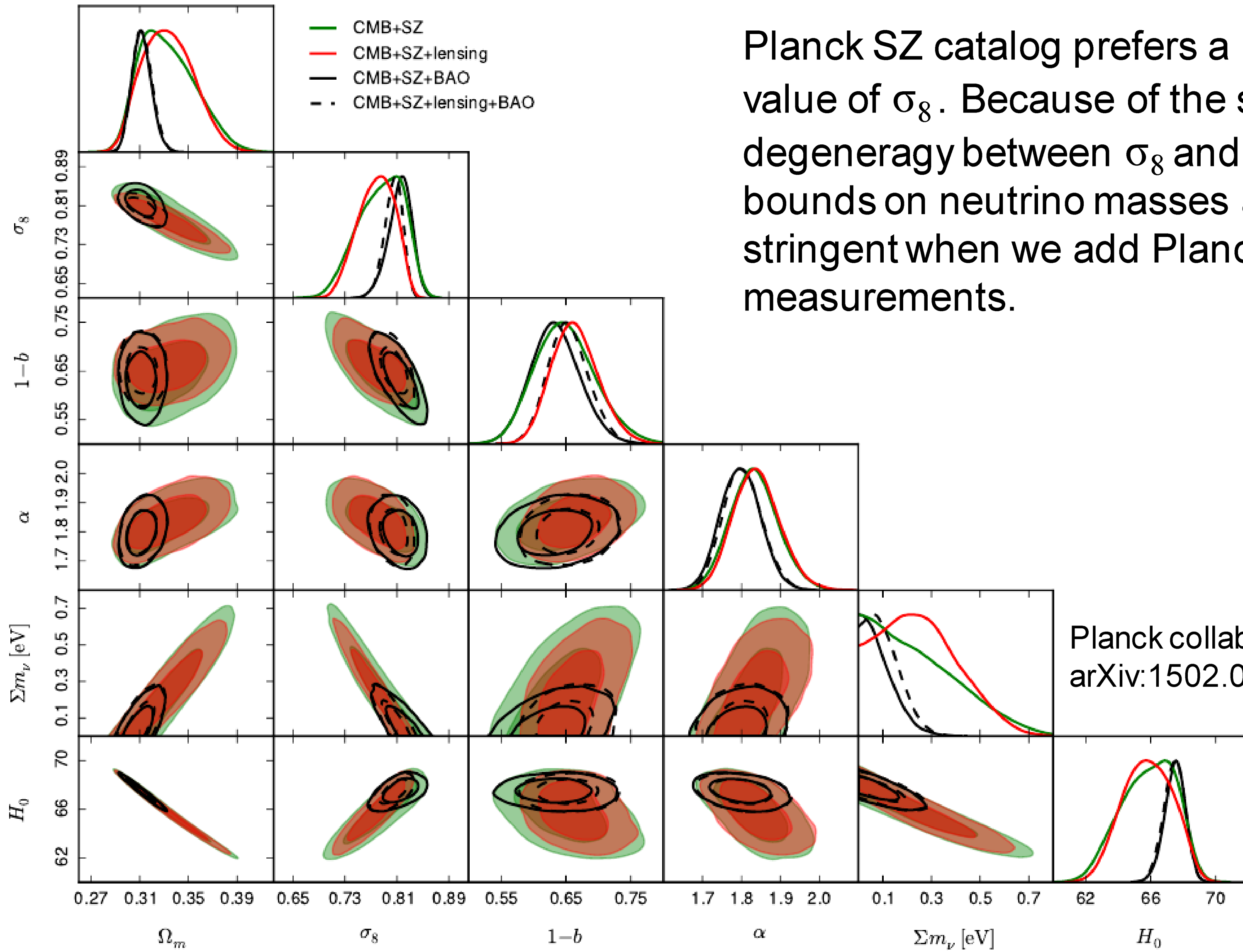
$$n_e \propto (1 - Y_P)$$

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

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

If N_{eff} increases, the angular scale of diffusion and of the sound horizon decrease. Moreover if N_{eff} increases also f_ν increase. Therefore to keep fixed the ratio we have to reduce Y_P.

Planck SZ catalog prefers a larger value of σ_8. Because of the strong degeneragy between σ_8 and $\sum m_\upsilon$, the bounds on neutrino masses are more stringent when we add Planck SZ measurements.



Planck collaboration '15
arXiv:1502.01597v2

Fig. 11: Parameter constraints on the ΛCDM+non-minimal neutrino mass model. For this study, we adopt the CCCP prior on the mass bias (see Tab. 2) and leave the scaling exponent, α, free. The green and red shaded regions show, respectively, the 1 and 2σ confidence regions for joint analyses of the cluster counts using the primary CMB, and the primary CMB plus the lensing power spectrum. The solid and dashed black contours add to these two cases constraints from BAO.