Cosmological constraints on thermal axions and neutrinos from Planck 2015 temperature and polarization data

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Dark Side of the Universe 2016 in Bergen

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Hot dark matter

Standard active neutrinos behave in the universe as hot dark matter. With the CMB data, in combination with other cosmological probes, we can constrain the sum of active neutrino masses and the neutrino effective number.

The inclusion of additional low redshift priors is mandatory in order to sharpen the CMB neutrino bounds. We are close to test the neutrino mass hierarchy with existing cosmological probes.

Moreover, we can consider extended cosmological scenarios with additional hot dark matter particles, that account for the extra dark radiation, as thermal axions or sterile neutrinos.

Sum of active neutrino masses

If the total neutrino mass is of the order of 1 eV, then the three active neutrinos are still relativistic at the time of recombination.

We expect the transition to the non-relativistic regime after the time of the photon decoupling.

Because the shape of the CMB spectrum is related mainly to the physical evolution before recombination, the effect of the neutrino mass, can appear through a modified background evolution and some secondary anisotropy corrections.

Sum of active neutrino masses

These neutrinos are radiation at the time of equality, and non-relativistic matter today.

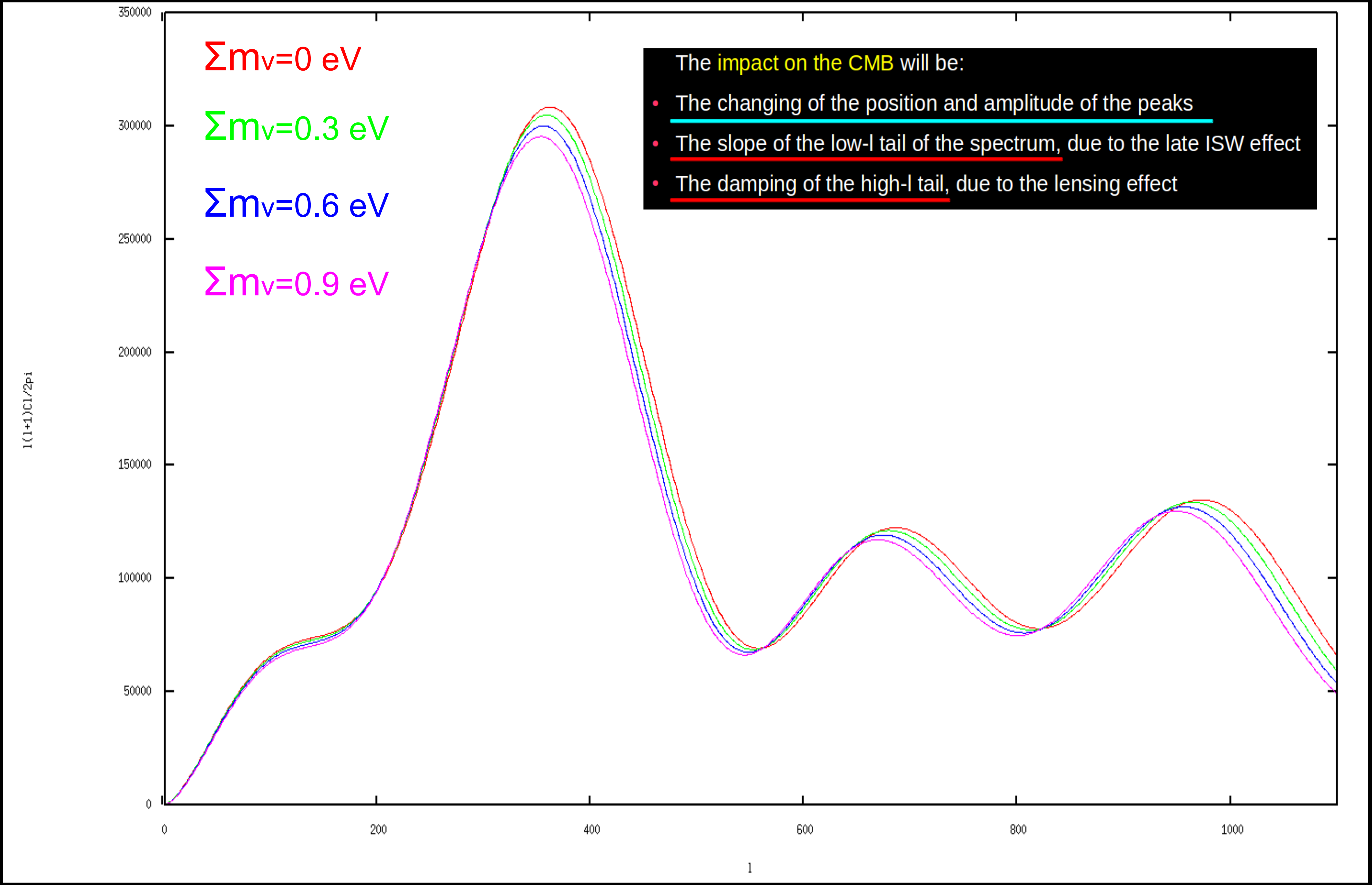
Varying their total mass we vary:

- The redshift of the matter-to-radiation equality z_{eq};
- The amount of matter density today.

The impact on the CMB will be:

- The changing of the position and amplitude of the peaks;
- The slope of the low-l tail of the spectrum, due to the late ISW effect;
- The damping of the high-l tail, due to the lensing effect.

Sum of active neutrino masses



CMB constraints on the total neutrino mass

Constraints at 95% cl.

	Planck	Planck pol	Planck +BAO	Planck pol +BAO	Planck +H070p6	Planck pol +H070p6	Planck +H073p0	Planck pol +H073p0
$\Omega_c h^2$	$0.1202^{+0.0047}_{-0.0044}$	$0.1200^{+0.0031}_{-0.0030}$	$0.1188^{+0.0028}_{-0.0029}$	$0.1192^{+0.0023}_{-0.0023}$	$0.1193^{+0.0042}_{-0.0041}$	$0.1196^{+0.0028}_{-0.0028}$	$0.1179^{+0.0040}_{-0.0041}$	$0.1189^{+0.0029}_{-0.0028}$
Σm_ν [eV]	< 0.754	< 0.497	< 0.220	< 0.175	< 0.337	< 0.291	< 0.195	< 0.180
H_0	$65.5^{+4.4}_{-5.9}$	$66.3^{+2.9}_{-3.8}$	$67.6^{+1.3}_{-1.3}$	$67.5^{+1.1}_{-1.2}$	$67.1^{+2.8}_{-3.1}$	$67.0^{+2.1}_{-2.4}$	$68.2^{+2.0}_{-2.3}$	$67.7^{+1.7}_{-1.7}$
σ_8	$0.79^{+0.08}_{-0.11}$	$0.811^{+0.058}_{-0.076}$	$0.825^{+0.039}_{-0.042}$	$0.832^{+0.033}_{-0.034}$	$0.819^{+0.049}_{-0.057}$	$0.824^{+0.043}_{-0.049}$	$0.829^{+0.038}_{-0.040}$	$0.831^{+0.035}_{-0.036}$
Ω_m	$0.340^{+0.088}_{-0.063}$	$0.329^{+0.052}_{-0.039}$	$0.311^{+0.017}_{-0.016}$	$0.312^{+0.015}_{-0.014}$	$0.318^{+0.041}_{-0.037}$	$0.319^{+0.031}_{-0.027}$	$0.304^{+0.029}_{-0.028}$	$0.310^{+0.023}_{-0.022}$
τ	$0.080^{+0.038}_{-0.038}$	$0.081^{+0.033}_{-0.034}$	$0.082^{+0.038}_{-0.037}$	$0.083^{+0.033}_{-0.032}$	$0.082^{+0.038}_{-0.037}$	$0.082^{+0.034}_{-0.034}$	$0.085^{+0.039}_{-0.038}$	$0.083^{+0.032}_{-0.033}$

The most stringent bound on the sum of neutrino masses is obtained when considering Planck TTTEEE+lowTEB+BAO.

The Baryon Acoustic Oscillations are regular, periodic fluctuations in the density of the visible baryonic matter of the universe. BAO matter clustering provides a "standard ruler" for length scale, and it can be measured by looking at the large scale structure of the universe in their geometrical form. They essentially measure the H(z) and D_A at a specific redshift.

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CMB constraints on the total neutrino mass

Constraints at 95% cl.

	Planck pol +BAO+SZ+tau6	Planck pol +BAO+SZ+tau5	Planck pol H073p0+SZ+tau6	Planck pol H073p0+SZ+tau5	Planck pol+BAO +H073p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.0021}_{-0.0021}$	$0.1195^{+0.0021}_{-0.0021}$	$0.1190^{+0.0026}_{-0.0025}$	$0.1192^{+0.0026}_{-0.0025}$	$0.1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.116	< 0.112	< 0.107	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$67.6^{+1.0}_{-1.0}$	$67.9^{+1.3}_{-1.4}$	$67.8^{+1.2}_{-1.4}$	$67.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
σ_8	$0.823^{+0.022}_{-0.024}$	$0.818^{+0.022}_{-0.023}$	$0.824^{+0.022}_{-0.023}$	$0.819^{+0.021}_{-0.022}$	$0.824^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.311^{+0.013}_{-0.013}$	$0.311^{+0.014}_{-0.013}$	$0.307^{+0.018}_{-0.017}$	$0.309^{+0.018}_{-0.017}$	$0.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.060^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$

Depending on the choice of the low redshift priors, we start to exclude the inverted hierarchy with cosmology…

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CMB constraints on the total neutrino mass

Constraints at 95% cl.

	Planck pol +BAO+SZ+tau6	Planck pol +BAO+SZ+tau5	Planck pol H073p0+SZ+tau6	Planck pol H073p0+SZ+tau5	Planck pol+BAO +H073p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.0021}_{-0.0021}$	$0.1195^{+0.0021}_{-0.0021}$	$0.1190^{+0.0026}_{-0.0025}$	$0.1192^{+0.0026}_{-0.0025}$	$0.1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.116	< 0.112	< 0.107	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$67.6^{+1.0}_{-1.0}$	$67.9^{+1.3}_{-1.4}$	$67.8^{+1.2}_{-1.4}$	$67.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
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Ω_m	$0.311^{+0.013}_{-0.013}$	$0.311^{+0.014}_{-0.013}$	$0.307^{+0.018}_{-0.017}$	$0.309^{+0.018}_{-0.017}$	$0.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.060^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$

The low redshift probes that we are considering in this case are:

- The Hubble constant, H0=73.0+/-2.4,
- The Planck SZ clusters count,
- The reionization optical depth, tau=0.05+/-0.01.

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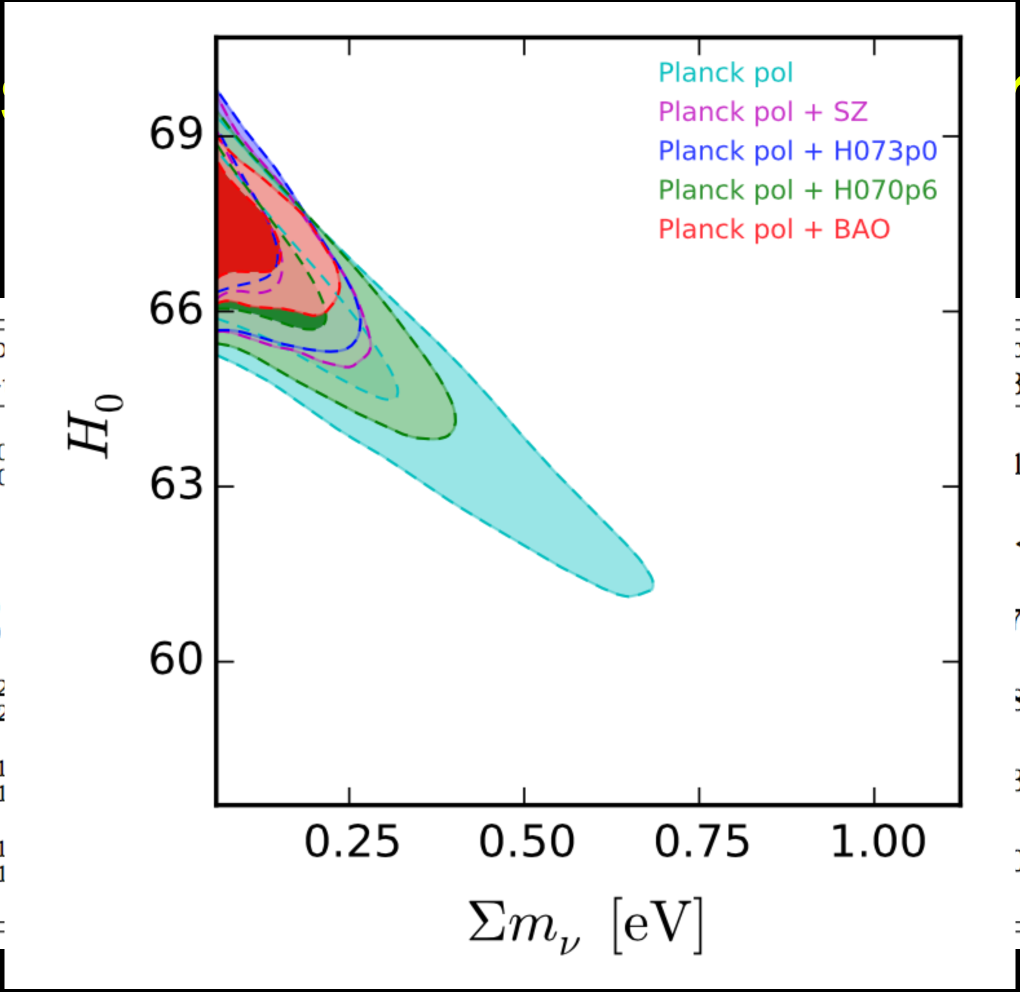
CMB cons… …rino mass

Constraints at 95% cl.

	Planck po… +BAO+SZ+…	…k pol+BAO …3p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194\,^{+0.00\ldots}_{-0.00\ldots}$	$\ldots190\,^{+0.0020}_{-0.0020}$	$0.1192\,^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7\,^{+1.0}_{-1.0}$	$\ldots.88\,^{+0.96}_{-0.98}$	$67.83\,^{+0.99}_{-0.98}$
σ_8	$0.823\,^{+0.02\ldots}_{-0.02\ldots}$	$\ldots324\,^{+0.021}_{-0.022}$	$0.819\,^{+0.021}_{-0.022}$
Ω_m	$0.311\,^{+0.01\ldots}_{-0.01\ldots}$	$\ldots308\,^{+0.013}_{-0.012}$	$0.308\,^{+0.013}_{-0.013}$
τ	$0.066\,^{+0.01\ldots}_{-0.01\ldots}$	$\ldots067\,^{+0.017}_{-0.017}$	$0.059\,^{+0.017}_{-0.017}$



The low redshift probes that we are considering in this case are:

- The Hubble constant, H_0=73.0+/-2.4:

  \- There exists a strong, well-known degeneracy between the neutrino mass and the Hubble constant. In the absence of an independent measurement of H_0, the change in the CMB temperature anisotropies induced by the presence of massive neutrinos can be easily compensated by a smaller value of the Hubble constant. Recently Riess et al. in arXiv:1604.01424v3 confirm the value of H_0=73.24 +/- 1.74 Km/s/Mpc.

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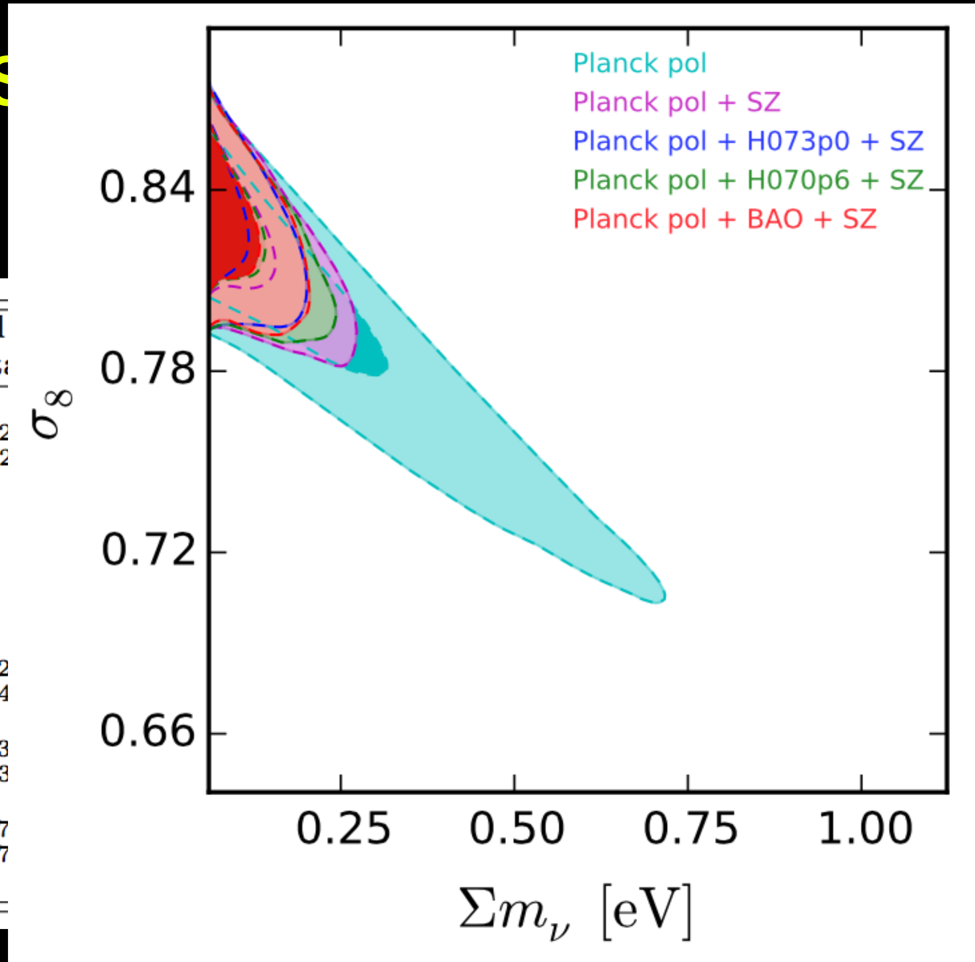
CMB cons rino mass

Constraints at 95% cl.

	Planck pol +BAO+SZ+ta	ck pol+BAO 73p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.002}_{-0.002}$	$1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$7.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
σ_8	$0.823^{+0.022}_{-0.024}$	$.824^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.311^{+0.013}_{-0.013}$	$.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$



The low redshift probes that we are considering in this case are:

- The Planck SZ clusters count:

  - Cluster surveys usually focus on the cluster number count function dN/dz, which measures the number of clusters of a certain mass M over a range of redshift, and it depends on the underlying cosmological model. The main uncertainties arise from the cluster mass bias. In our work the cluster mass bias is a free parameter, determined with a bayesian statistics.

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CMB constraints on the total neutrino mass

Constraints at 95% cl.

	Planck pol +BAO+SZ+tau6	Planck pol +BAO+SZ+tau5	Planck pol H073p0+SZ+tau6	Planck pol H073p0+SZ+tau5	Planck pol+BAO +H073p0+SZ+tau6	Planck pol +BAO +H073p0+SZ+tau5
$\Omega_c h^2$	$0.1194^{+0.0021}_{-0.0021}$	$0.1195^{+0.0021}_{-0.0021}$	$0.1190^{+0.0026}_{-0.0025}$	$0.1192^{+0.0026}_{-0.0025}$	$0.1190^{+0.0020}_{-0.0020}$	$0.1192^{+0.0020}_{-0.0021}$
Σm_ν [eV]	< 0.122	< 0.116	< 0.112	< 0.107	< 0.104	< 0.0993
H_0 [km s^{-1} Mpc^{-1}]	$67.7^{+1.0}_{-1.0}$	$67.6^{+1.0}_{-1.0}$	$67.9^{+1.3}_{-1.4}$	$67.8^{+1.2}_{-1.4}$	$67.88^{+0.96}_{-0.98}$	$67.83^{+0.99}_{-0.98}$
σ_8	$0.823^{+0.022}_{-0.024}$	$0.818^{+0.022}_{-0.023}$	$0.824^{+0.022}_{-0.023}$	$0.819^{+0.021}_{-0.022}$	$0.824^{+0.021}_{-0.022}$	$0.819^{+0.021}_{-0.022}$
Ω_m	$0.311^{+0.013}_{-0.013}$	$0.311^{+0.014}_{-0.013}$	$0.307^{+0.018}_{-0.017}$	$0.309^{+0.018}_{-0.017}$	$0.308^{+0.013}_{-0.012}$	$0.308^{+0.013}_{-0.013}$
τ	$0.066^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.060^{+0.017}_{-0.017}$	$0.067^{+0.017}_{-0.017}$	$0.059^{+0.017}_{-0.017}$

The low redshift priors that we are considering in this case are:

- The reionization optical depth, τ=0.05+/-0.01:

  - This prior is motivated by hints from high-redshift quasar absorption and Lyman α emitters. CMB measurements provide constraints via the integrated optical depth τ on when and how cosmic reionization takes place. Very recently the Planck collaboration provided the value of τ=0.055 +/- 0.009 from HFI data in arXiv:1605.02985.

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The effective number of relativistic degrees of freedom

The relativistic neutrinos contribute to the present energy density of the Universe:

$$\rho_{rad} = \rho_\gamma + \rho_\nu = g_\gamma \left(\frac{\pi^2}{30}\right) T_\gamma^4 + g_\nu \left(\frac{\pi^2}{30}\right)\left(\frac{7}{8}\right) T_\nu^4$$

$$\rho_{rad} = \left(1 + \left(\frac{7}{8}\right)\left(\frac{4}{11}\right)^{\frac{4}{3}}\left(\frac{g_\nu}{g_\gamma}\right)\right)\rho_\gamma$$

We can introduce the effective number of relativistic degrees of freedom:

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

The expected value is $N_{\mathrm{eff}} = 3.046$, if we assume standard electroweak interactions and three active massless neutrinos. The 0.046 takes into account effects for the non-instantaneous neutrino decoupling and neutrino flavour oscillations. (Mangano et al. 2005)

The effective number of relativistic degrees of freedom

If we measure a Neff>3.046, we are in presence of extra, dark radiation. This extra radiation, essentially, increases the expansion rate H:

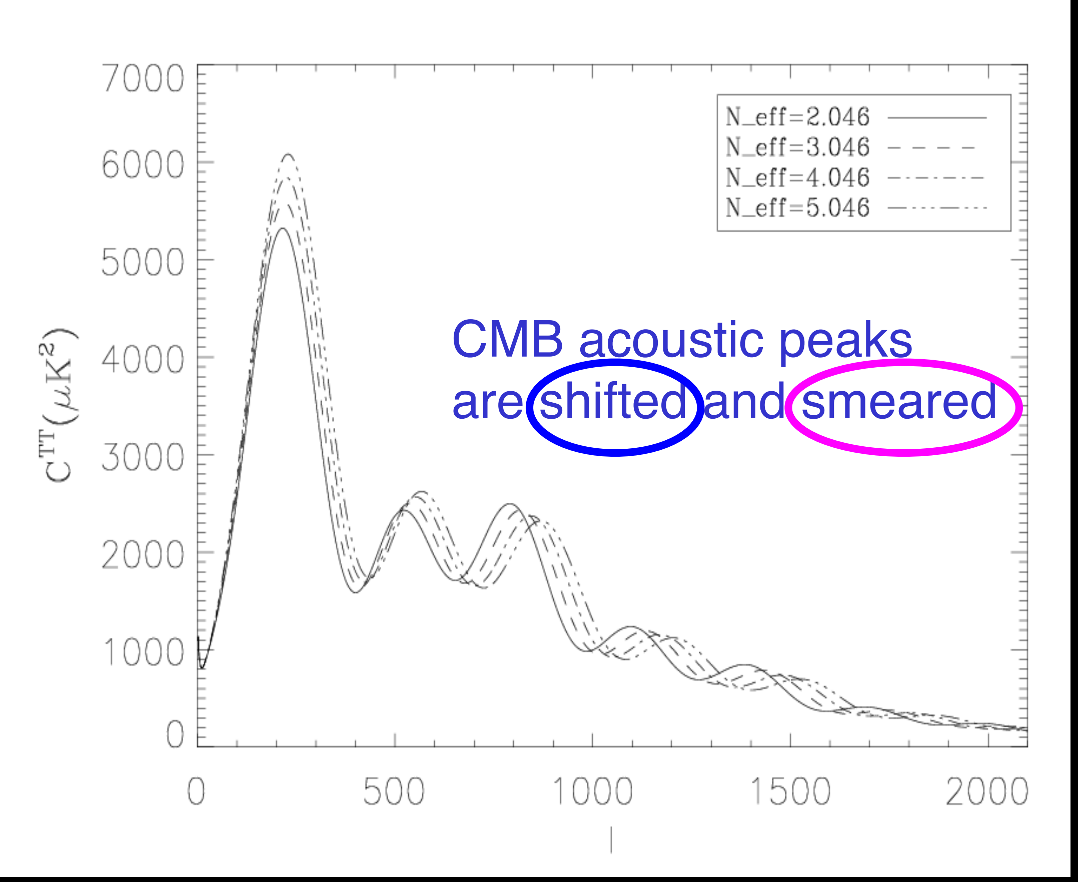
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left(\frac{\Omega_r}{a^4} + \frac{\Omega_m}{a^3} + \frac{\Omega_k}{a^2} + \Omega_\Lambda\right)$$

and it decreases the sound horizon at recombination,

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

and the diffusion distance (damping scale):

$$r_d^2 = (2\pi)^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H}\left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)}\right]$$



CMB acoustic peaks are shifted and smeared

CMB constraints on the neutrino effective number

Constraints at 95% cl.

	Planck	Planck pol	Planck +BAO	Planck pol +BAO	Planck +H070p6	Planck Pol +H070p6	Planck +H073p0	Planck Pol +H073p0
$\Omega_c h^2$	$0.1205^{+0.0080}_{-0.0077}$	$0.1192^{+0.0060}_{-0.0057}$	$0.1212^{+0.0077}_{-0.0071}$	$0.1193^{+0.0062}_{-0.0058}$	$0.1222^{+0.0074}_{-0.0073}$	$0.1190^{+0.0062}_{-0.0060}$	$0.1235^{+0.0071}_{-0.0070}$	$0.1215^{+0.0053}_{-0.0054}$
Σm_ν [eV]	< 0.796	< 0.582	< 0.289	< 0.224	< 0.417	< 0.365	< 0.337	< 0.249
$N_{\rm eff}$	< 3.592	< 3.359	< 3.636	< 3.384	< 3.707	< 3.374	< 3.961	< 3.539
H_0 [km s^{-1} Mpc^{-1}]	$64.9^{+7.2}_{-8,4}$	$65.0^{+4.4}_{-5.0}$	$68.4^{+3.0}_{-2.8}$	$67.4^{+2.4}_{-2.3}$	$68.2^{+4.6}_{-4.7}$	$66.6^{+3.2}_{-3.5}$	$70.5^{+4.2}_{-4.1}$	$68.2^{+2.7}_{-2.8}$
σ_8	$0.781^{+0.091}_{-0.119}$	$0.794^{+0.067}_{-0.085}$	$0.823^{+0.042}_{-0.044}$	$0.823^{+0.037}_{-0.039}$	$0.819^{+0.057}_{-0.062}$	$0.813^{+0.047}_{-0.055}$	$0.835^{+0.047}_{-0.053}$	$0.831^{+0.038}_{-0.043}$
Ω_m	$0.351^{+0.104}_{-0.080}$	$0.342^{+0.061}_{-0.046}$	$0.310^{+0.019}_{-0.017}$	$0.315^{+0.017}_{-0.016}$	$0.316^{+0.044}_{-0.043}$	$0.326^{+0.035}_{-0.031}$	$0.298^{+0.034}_{-0.032}$	$0.313^{+0.024}_{-0.024}$
τ	$0.081^{+0.035}_{-0.035}$	$0.086^{+0.031}_{-0.034}$	$0.088^{+0.039}_{-0.038}$	$0.079^{+0.035}_{-0.046}$	$0.088^{+0.044}_{-0.041}$	$0.083^{+0.035}_{-0.035}$	$0.098^{+0.044}_{-0.041}$	$0.091^{+0.034}_{-0.035}$

When varying also $N_{\rm eff}$, the bounds on the total neutrino mass are less stringent, due to the large degeneracy between Σm_ν and $N_{\rm eff}$, in order to leave unchanged both the matter-to-radiation equality era and the location of the CMB acoustic peaks. The neutrino effective number is totally consistent with its standard value 3.046. Anyway, there is still the possibility to have some relic components.

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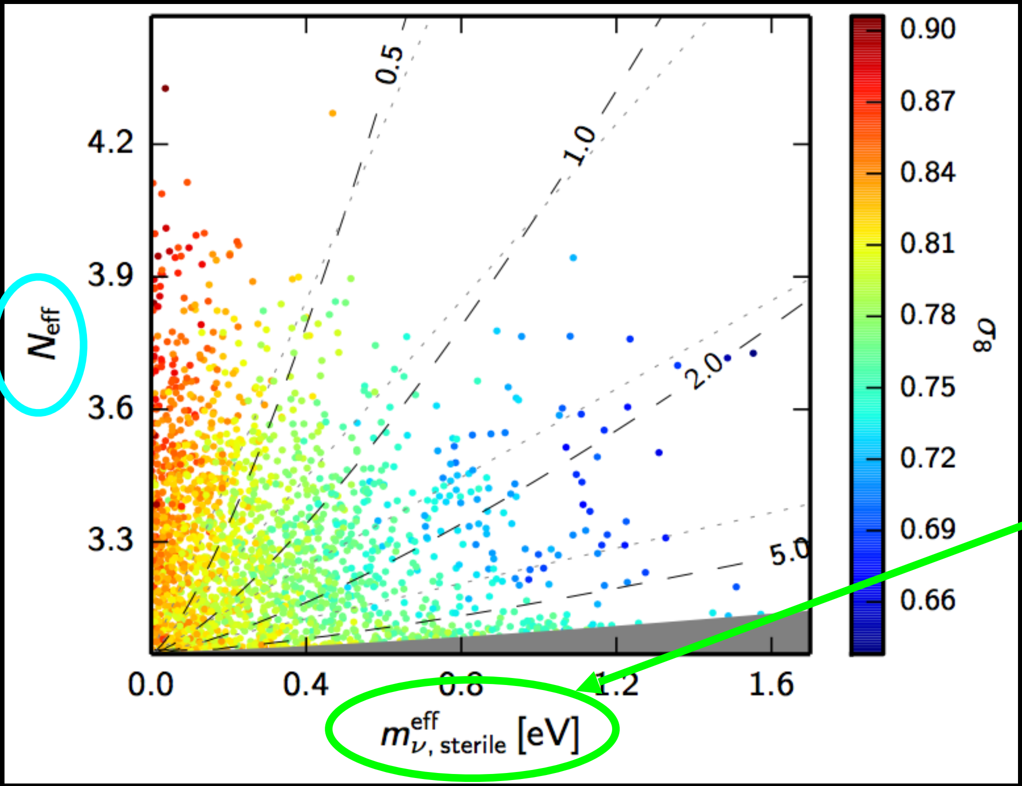
The sterile neutrino

The main candidate to explain this extra dark radiation is a sterile neutrino. With the CMB we can only constrain the effective sterile neutrino mass, but fixing the model, we can infer also the physical mass of the particle. The relationship between Neff and meff is model dependent.

Contribution of the sterile neutrino when it is massless.



Contribution of the sterile neutrino when it is massive.

(Planck collaboration 2015)

Thermally distributed

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

CMB constraints on the sterile neutrino mass

Constraints at 95% cl.

	Planck	Planck pol	Planck +BAO	Planck pol + BAO	Planck +H070p6	Planck Pol +H070p6	Planck +H073p0	Planck Pol +H073p0
$\Omega_c h^2$	$0.1215^{+0.0090}_{-0.0105}$	$0.1207^{+0.0061}_{-0.0071}$	$0.1214^{+0.0081}_{-0.0081}$	$0.1189^{+0.0068}_{-0.0081}$	$0.1217^{+0.0088}_{-0.0107}$	$0.1205^{+0.0068}_{-0.0077}$	$0.1235^{+0.0090}_{-0.0082}$	$0.1205^{+0.0064}_{-0.0071}$
Σm_ν [eV]	< 0.676	< 0.528	< 0.263	< 0.199	< 0.422	< 0.337	< 0.291	< 0.321
$m_s^{\rm eff}$ [eV]	< 0.972	< 0.820	< 0.449	< 0.694	< 0.822	< 0.773	< 0.462	< 0.630
$N_{\rm eff}$	< 3.648	< 3.401	< 3.762	< 3.405	< 3.705	< 3.445	< 3.961	< 3.434
H_0[km s^{-1} Mpc^{-1}]	$65.7^{+5.7}_{-6.1}$	$65.5^{+3.2}_{-3.7}$	$67.7^{+1.8}_{-1.6}$	$68.7^{+2.8}_{-2.4}$	$67.4^{+4.4}_{-4.2}$	$66.5^{+2.7}_{-2.8}$	$70.0^{+4.6}_{-4.2}$	$67.4^{+2.3}_{-2.1}$
σ_8	$0.762^{+0.095}_{-0.107}$	$0.768^{+0.077}_{-0.087}$	$0.801^{+0.051}_{-0.058}$	$0.806^{+0.048}_{-0.054}$	$0.786^{+0.076}_{-0.083}$	$0.785^{+0.066}_{-0.075}$	$0.818^{+0.064}_{-0.068}$	$0.803^{+0.056}_{-0.062}$
$\Omega_{\rm m}$	$0.350^{+0.083}_{-0.069}$	$0.347^{+0.054}_{-0.045}$	$0.311^{+0.017}_{-0.017}$	$0.316^{+0.015}_{-0.015}$	$0.328^{+0.051}_{-0.045}$	$0.334^{+0.037}_{-0.034}$	$0.305^{+0.038}_{-0.037}$	$0.323^{+0.023}_{-0.027}$
τ	$0.088^{+0.043}_{-0.041}$	$0.087^{+0.035}_{-0.036}$	$0.095^{+0.041}_{-0.040}$	$0.089^{+0.034}_{-0.034}$	$0.090^{+0.042}_{-0.040}$	$0.087^{+0.035}_{-0.035}$	$0.103^{+0.043}_{-0.044}$	$0.091^{+0.036}_{-0.035}$

When varying also the sterile neutrino mass, the bounds on the total neutrino mass and on the neutrino effective number are less stringent.

The strongest bound we have on the sterile neutrino mass is when considering PlanckTT+lowTEB+BAO.

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Axions

The most elegant and promising solution of the so-called *strong CP problem* in Quantum Chromodynamics (QCD) was provided by Peccei and Quinn, adding a new global $U(1)_{PQ}$ symmetry. This is spontaneously broken at an energy scale f_a, generating a new spinless particle, the axion.

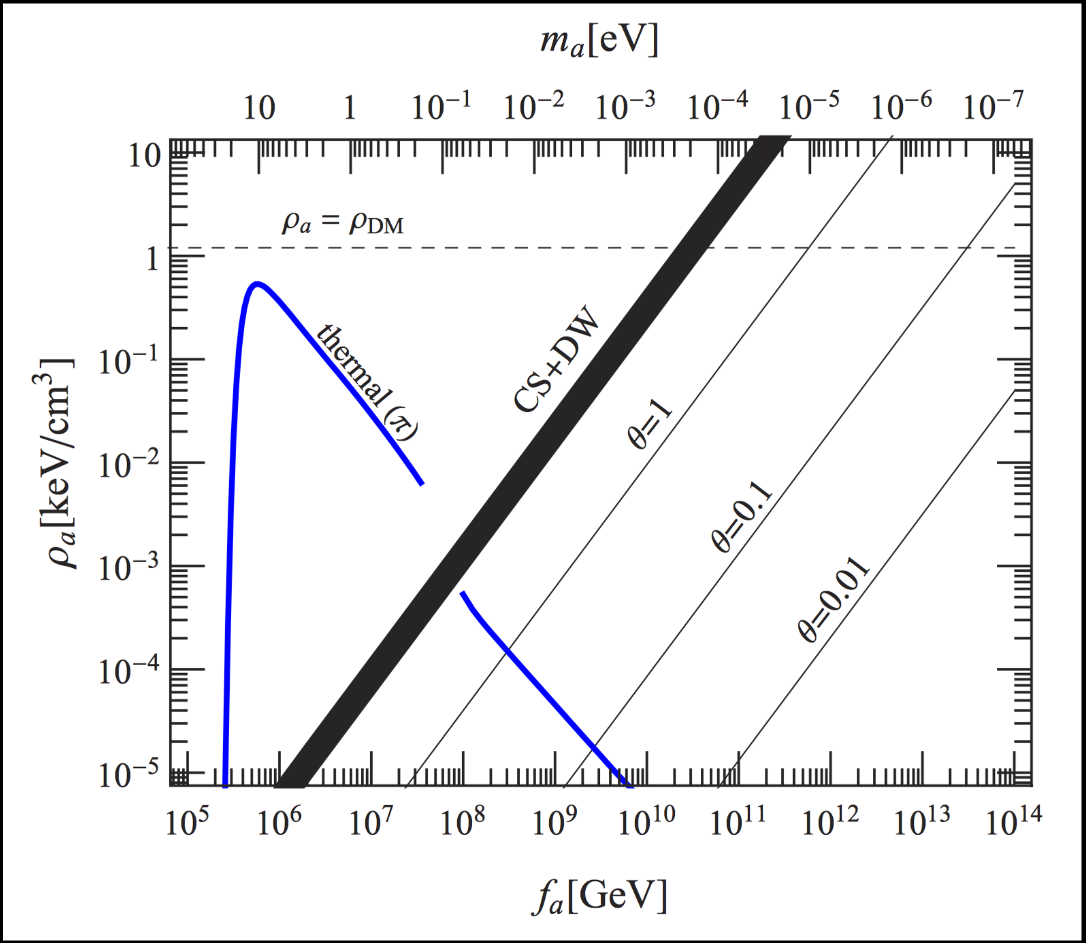
The axion can be copiously produced in the universe's early stages, both via thermal and non-thermal processes.

- Thermal axions with sub-eV masses contribute to the hot dark matter component of the universe, as neutrinos.

Di Valentino et al. Phys.Lett. B752 (2016) 182-185.

- Axion-like particles produced non-thermally, as for example by the misalignment mechanism, instead were postulated as natural candidates for the cold dark matter component.

Di Valentino et al., Phys. Rev. D90 (2014), 043534.
Visinelli and Gondolo, Phys.Rev.Lett. 113 (2014) 011802



Archidiacono et al. JCAP 1505 (2015) no.05, 050

Thermal QCD Axions

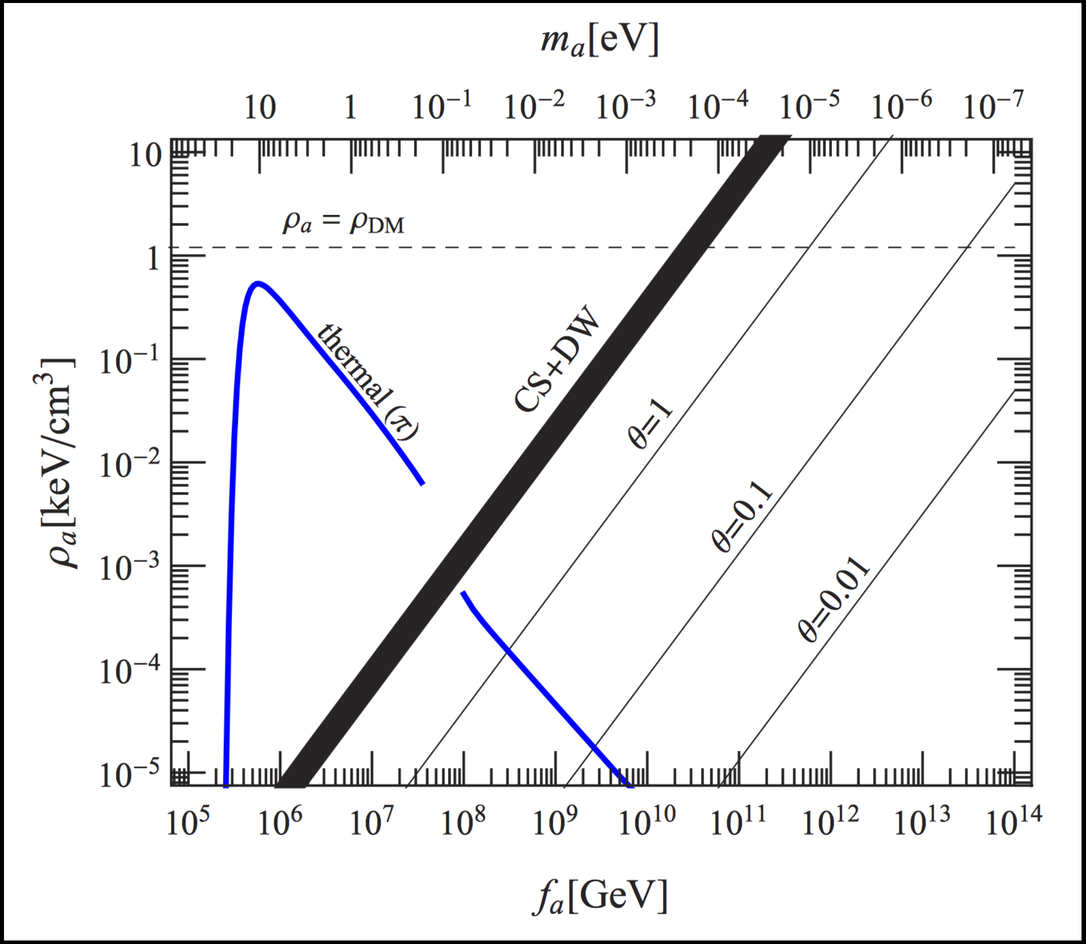
For axion thermalization purposes, only the axion-pion interaction will be relevant.

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

The axion particles are very similar to neutral pions, but their masses and interactions strengths are suppressed by a factor of order f_π/f_a, respect to the pion case:

$$m_a = \frac{f_\pi m_\pi}{f_a}\frac{\sqrt{R}}{1+R} = 0.6\ \text{eV}\ \frac{10^7\ \text{GeV}}{f_a}$$

where R=0.553±0.043 is the up-to-down quark masses ratio and f_π=93MeV is the pion decay constant.



Archidiacono et al. JCAP 1505 (2015) no.05, 050

Thermal QCD Axions

Massive thermal axions will affect the cosmological observables in a very similar way to that induced by the presence of neutrino masses.

When axions are relativistic, will contribute to the dark radiation content of the universe, increasing the effective number of relativistic degrees of freedom N_{eff}.

When they become non-relativistic, will only cluster at scales larger than their free streaming scale, suppressing therefore structure formation at small scales, and affecting the large scale structures.
Axion mass will also lead to a signature in the CMB photon temperature anisotropies via the early integrated Sachs-Wolfe effect.

Thermal axions, when are relativistic, will contribute to the hot dark matter component of the universe, so to the extra radiation component, by an amount given by:

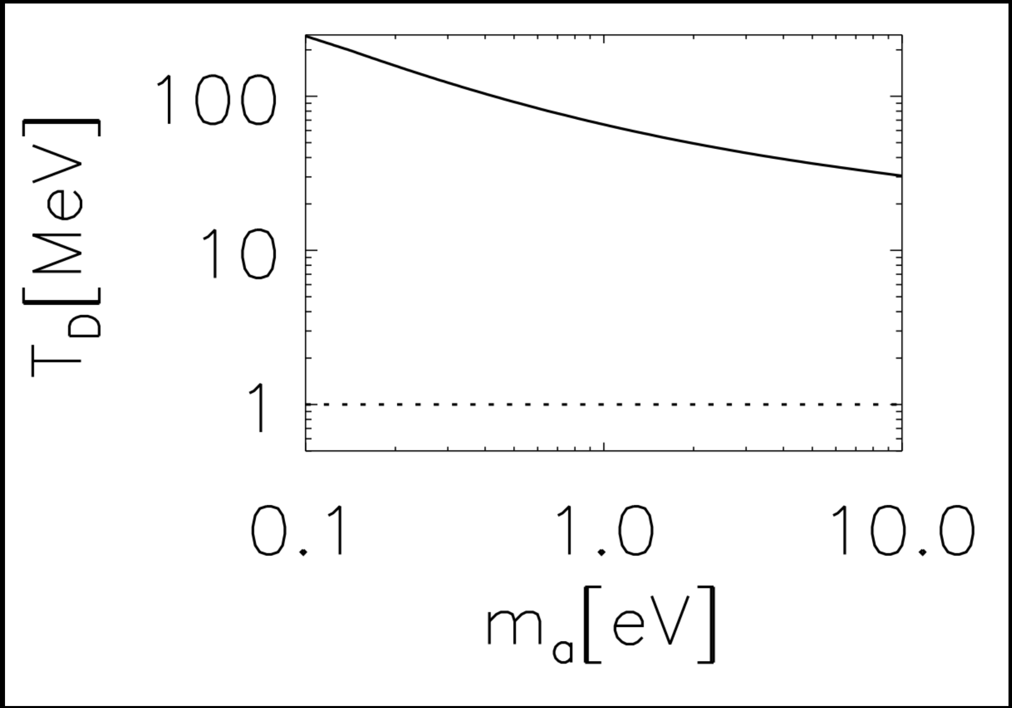
$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{3}{2}\frac{n_a}{n_\nu}\right)^{4/3}$$

We computed the current axion number density n_a, related to the present photon density by:

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

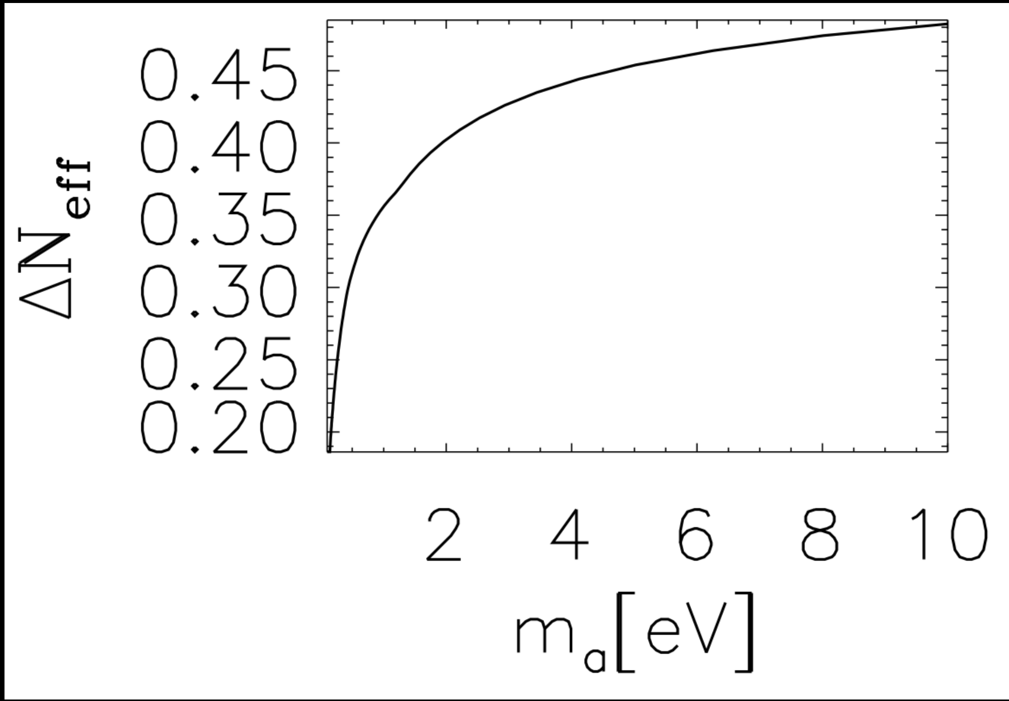
and the axion decoupling temperature T_D, that will be a function of the axion mass m_a, numerically solving the freeze out equation of the axion-pion interaction:

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



The temperature of decoupling is a function of the axion mass (solid curve). The higher the axion mass, the lower the temperature of decoupling is.

The axion contribution to the extra dark radiation content of the universe, as a function of the axion mass. Notice that the extra dark radiation arising from a 1 eV axion is still compatible (at 95% CL) with the most recent measurements of N_{eff} from the Planck 2015 data release.

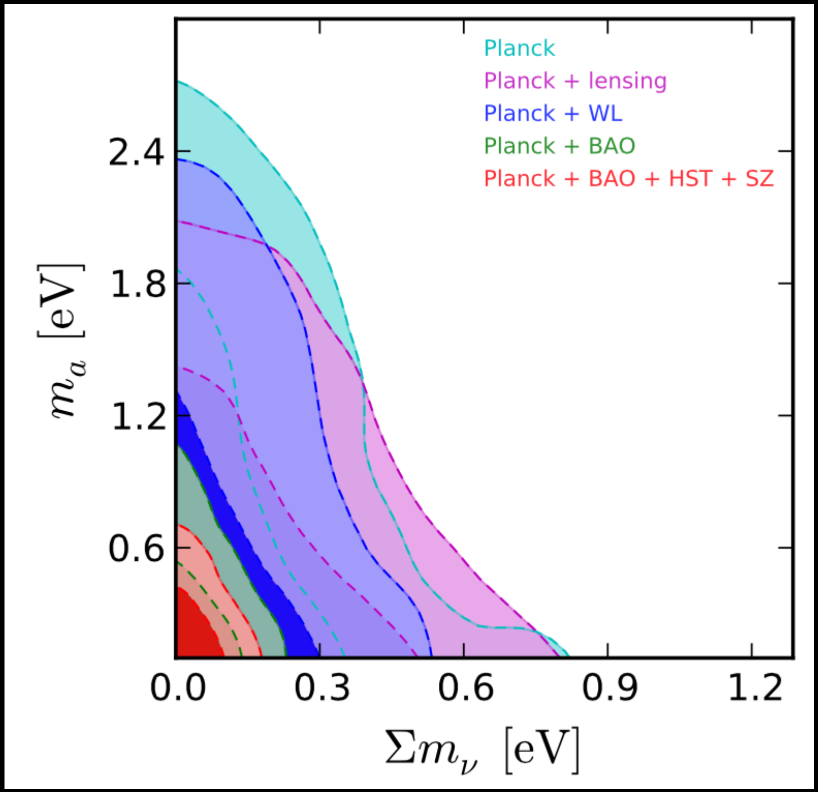


E. Di Valentino et al., Phys. Rev. D. 91, 123505 (2015), arXiv:1503.00911

When massive axion particles become non-relativistic, will contribute to the matter density of the universe:

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

However their effect is degenerate with massive neutrinos, in particular they are negatively correlated. In fact, an increase in the axion mass will increase the hot dark matter component, and in order to keep the total amount consistent with the data, the contribution to the hot dark matter from the neutrinos should be reduced.



Di Valentino et al. Phys.Lett. B752 (2016) 182-185.

CMB constraints on the thermal axion mass

Constraints at 95% cl.

	TT,TE,EE+lowP	TT,TE,EE+lowP +lensing	TT,TE,EE+lowP +WL	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
$\Omega_c h^2$	$0.1235^{+0.0034}_{-0.0036}$	$0.1235^{+0.0034}_{-0.0034}$	$0.1225^{+0.0032}_{-0.0032}$	$0.1237^{+0.0034}_{-0.0031}$	$0.1223^{+0.0023}_{-0.0023}$	$0.1223^{+0.0032}_{-0.0032}$	$0.1220^{+0.0024}_{-0.0023}$	$0.1216^{+0.0023}_{-0.0023}$
m_a [eV]	< 2.09	< 1.67	< 1.87	< 0.835	< 0.763	< 1.21	< 0.709	< 0.529
$\sum m_\nu$ [eV]	< 0.441	< 0.538	< 0.360	< 0.291	< 0.159	< 0.182	< 0.136	< 0.126
σ_8	$0.779^{+0.083}_{-0.094}$	$0.767^{+0.065}_{-0.072}$	$0.789^{+0.074}_{-0.096}$	$0.814^{+0.049}_{-0.056}$	$0.827^{+0.039}_{-0.042}$	$0.820^{+0.051}_{-0.062}$	$0.829^{+0.036}_{-0.039}$	$0.835^{+0.033}_{-0.035}$
Ω_m	$0.342^{+0.054}_{-0.048}$	$0.344^{+0.055}_{-0.048}$	$0.328^{+0.048}_{-0.041}$	$0.326^{+0.033}_{-0.029}$	$0.312^{+0.016}_{-0.014}$	$0.315^{+0.031}_{-0.027}$	$0.309^{+0.015}_{-0.014}$	$0.306^{+0.014}_{-0.013}$
$\log[10^{10} A_s]$	$3.131^{+0.067}_{-0.070}$	$3.109^{+0.064}_{-0.062}$	$3.117^{+0.071}_{-0.068}$	$3.121^{+0.066}_{-0.071}$	$3.126^{+0.066}_{-0.070}$	$3.129^{+0.066}_{-0.068}$	$3.128^{+0.065}_{-0.069}$	$3.132^{+0.063}_{-0.064}$
n_s	$0.972^{+0.011}_{-0.012}$	$0.972^{+0.010}_{-0.011}$	$0.974^{+0.011}_{-0.012}$	$0.97278^{+0.009}_{-0.009}$	$0.9754^{+0.0093}_{-0.0089}$	$0.976^{+0.010}_{-0.010}$	$0.9763^{+0.0095}_{-0.0091}$	$0.9768^{+0.0089}_{-0.0089}$

When considering a thermal axion mass, the bounds on the total neutrino mass are more stringent, due to the large degeneracy between Σm_ν and m_a.

The strongest bound we have on the thermal axion mass is obtained when considering Planck TTTEEE+lowTEB+BAO+HST+SZ.

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Summary:

- With the CMB we can constrain two important neutrino parameters:
  - the total neutrino mass
  - the neutrino effective number

- The most stringent bound on the sum of neutrino masses is obtained when considering Planck TTTEEE+lowTEB+BAO: $\Sigma m_\nu < 0.175$eV. By adding some low redshift priors, in agreement with recent measurements, we can start to exclude the inverted hierarchy. We obtain that $\Sigma m_\nu < 0.0993$eV by adding $H_0 = 73.0 \pm 2.4$, $\tau = 0.05 \pm 0.01$ and Planck SZ cluster counts. We are close to test the neutrino mass hierarchy with existing cosmological probes.

- The neutrino effective number is consistent with its standard value 3.046. Anyway, there is still the possibility to have some relic components:
  - a sterile neutrino
  - a thermal axion

- The most stringent bound we have on the sterile neutrino mass is when considering PlanckTT+lowTEB+BAO, and it is $m_{eff} < 0.449$eV.

- The most stringent bound we have on the thermal axion mass is $m_a < 0.529$eV, when considering Planck TTTEEE+lowTEB+BAO+HST+SZ.

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Thermal QCD Axions

$$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a} \left(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0\right)\partial_\mu a$$

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

freeze-out equation

$$\Gamma = \frac{3}{1024\pi^5}\frac{1}{f_a^2 f_\pi^2} C_{a\pi}^2 I$$

thermally averaged interaction rate

axion-pion coupling constant

$$C_{a\pi} = \frac{1-R}{3(1+R)}$$

kinematical variables

$x_i = |\vec{p}_i|/T,\ y_i = E_i/T$

$$I = n_a^{-1} T^8 \int dx_1 dx_2 \frac{x_1^2 x_2^2}{y_1 y_2} f(y_1) f(y_2) \times \int_{-1}^{1} d\omega \frac{(s-m_\pi^2)^3(5s-2m_\pi^2)}{s^2 T^4},$$

$s = 2(m_\pi^2 + T^2(y_1 y_2 - x_1 x_2 \omega))$

A. Melchiorri et al, arXiv:0705.2695v1

Thermal QCD Axions

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

$$n_\gamma = 410.5 \pm 0.5 \text{ cm}^{-3}$$

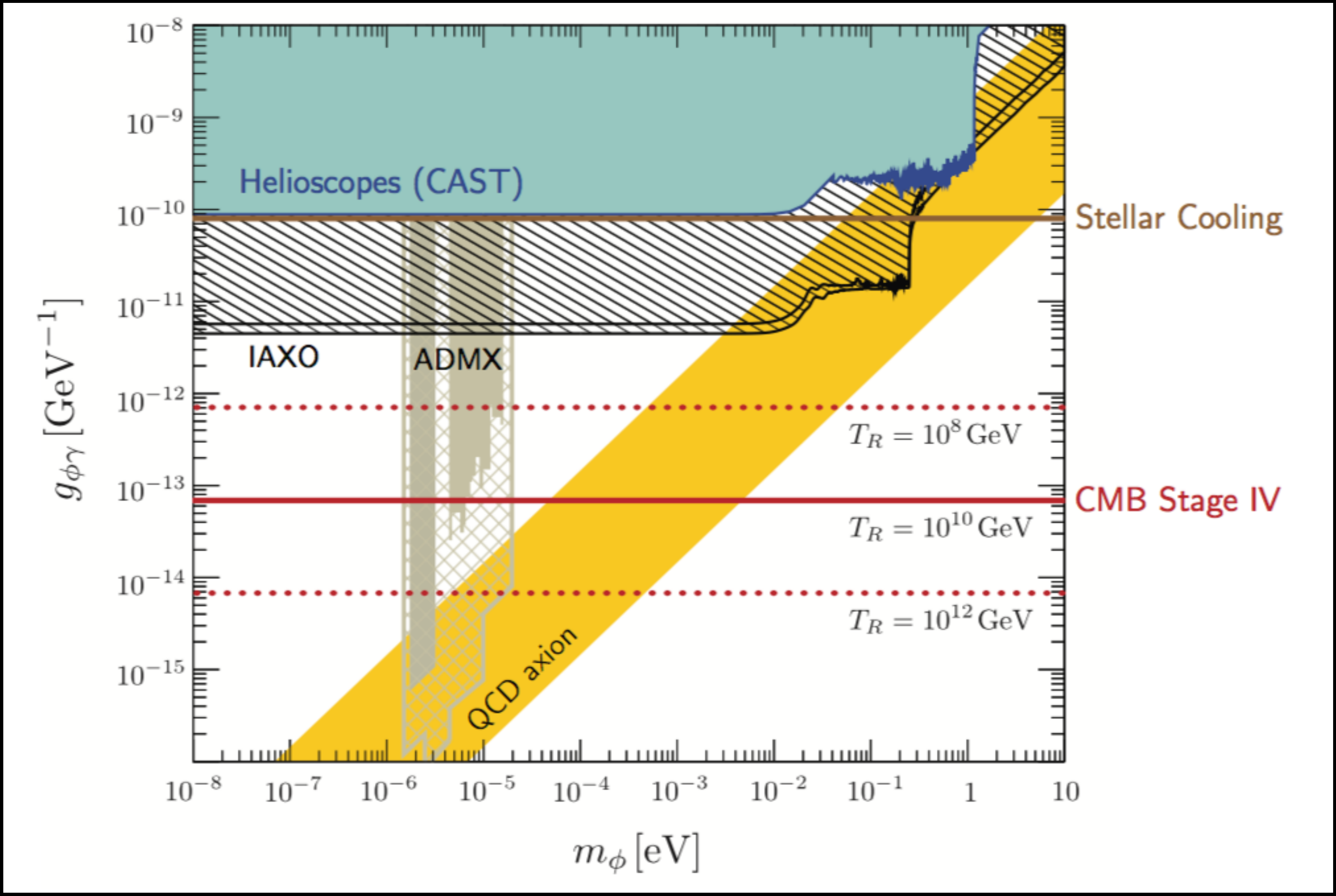
$$g_{\star S}(T_0) = 3.91$$

number of entropic degrees of freedom

Axion parameter		
m_a (eV)	0.1	3
T_D (MeV)	245.6	43.2
$\Omega_a h^2$	0.0003	0.016
ΔN_{eff}	0.18	0.43
k_{fs} (h/Mpc)	0.06	1.46

E. Di Valentino et al., Phys. Rev. D. 91, 123505 (2015), arXiv:1503.00911

Thermal QCD Axions



D. Baumann et al., arXiv:1604.08614v1

Axion Cold Dark Matter

For temperatures between the energy scale f_a and the QCD phase transition Λ_{QCD}, the axion is a massless particle, then the axion acquires a mass via instanton effects. The effective potential V for the axion field a(x) is generated through non-pertubative QCD effects, and may be written as

$$V(a) = f_{\mathrm{a}}^2 m_{\mathrm{a}}^2(T)\left[1 - \cos\left(\frac{a}{f_{\mathrm{a}}}\right)\right]$$

Introducing the misalignment angle $\theta = a/f_a$, the field evolves according to the Klein-Gordon equation on a flat Friedmann-Robertson-Walker background:

$$\ddot{\theta} + 3H\dot{\theta} + m_{\mathrm{a}}^2(T)\theta = 0$$

with

$$m_{\mathrm{a}} \simeq 6.2\,\mu\mathrm{eV}\left(\frac{f_{\mathrm{a}}}{10^{12}\,\mathrm{GeV}}\right)^{-1}$$

Axion Cold Dark Matter

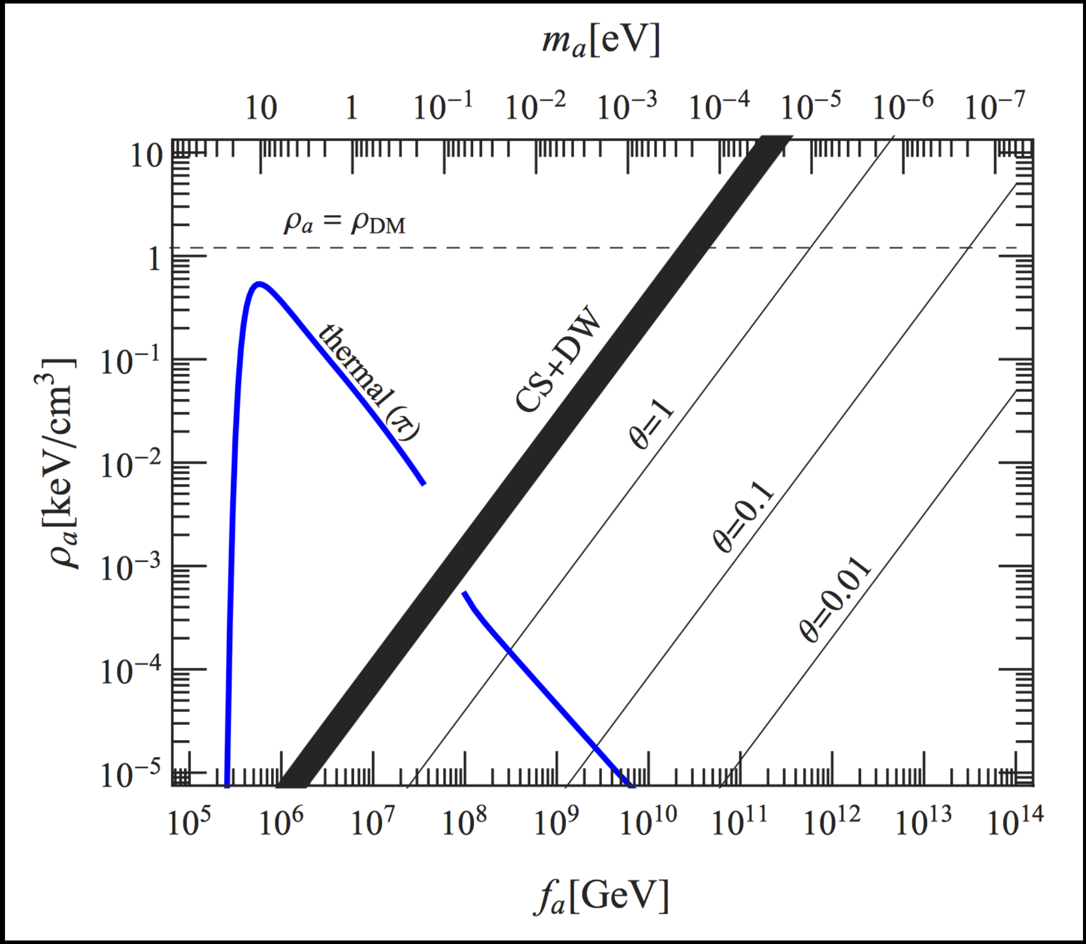
The PQ symmetry breaking can occur before or after inflation:

- If the PQ symmetry is broken after inflation, there are no axion isocurvature perturbations since there are not axion quantum fluctuations;

$$f_{\mathrm{a}} < \left(\frac{H_I}{2\pi}\right)$$

- If the PQ symmetry is broken before or during inflation, there will exist, together with the standard adiabatic perturbations generated by the inflaton field, axion isocurvature perturbations, associated to quantum fluctuations in the axion field.

$$f_{\mathrm{a}} > \left(\frac{H_I}{2\pi}\right)$$



Archidiacono et al. JCAP 1505 (2015) no.05, 050

$f_a < \left(\frac{H_I}{2\pi}\right)$

Axion Cold Dark Matter

If the axion created non-thermally in the early Universe through the misalignment mechanism and the decay of axionic strings, we can constrain the "axion dark matter" scenario in which the PQ symmetry is broken after inflation, using the most precise CMB data available to date.

$$\Omega_a h^2 = 2.41 \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{7/6}$$

We consider the hypothesis that the axion accounts for all the CDM present in the Universe, i.e $\Omega_{CDM} = \Omega_{a,mis}$.

E. Di Valentino, E. Giusarma, M. Lattanzi, A. Melchiorri, O. Mena, Phys. Rev. D90 (2014), 043534

Axion Cold Dark Matter

Planck+WP

Parameter	ADM+r	ADM+r $+N_{\rm eff}$	ADM+r $+\sum m_\nu$	ADM+r $+\sum m_\nu + N_{\rm eff}$	ADM+r $+ m_s^{\rm eff} + N_{\rm eff}$	ADM+r $+w$	ADM+r $+ n_t$	ADM+r $+ dn_s/d\ln k$
$\Omega_{\rm b}h^2$	0.02204 ± 0.00028	0.02261 ± 0.00043	0.02189 ± 0.00033	0.02245 ± 0.00047	0.02246 ± 0.00039	0.02208 ± 0.00028	0.02211 ± 0.00029	0.02229 ± 0.00031
$\Omega_{\rm a}h^2$	0.1194 ± 0.0027	0.1280 ± 0.0054	0.1203 ± 0.0029	0.1277 ± 0.0054	0.1275 ± 0.0055	0.1192 ± 0.0026	0.1206 ± 0.0030	0.1198 ± 0.0027
θ	1.04127 ± 0.00064	1.04053 ± 0.00072	1.04097 ± 0.00070	1.04039 ± 0.00073	1.04040 ± 0.00074	1.04132 ± 0.00063	1.04117 ± 0.00063	1.04133 ± 0.00064
τ	0.089 ± 0.013	0.097 ± 0.015	0.089 ± 0.013	0.096 ± 0.015	0.096 ± 0.014	0.089 ± 0.013	0.089 ± 0.013	0.100 ± 0.016
n_s	0.9614 ± 0.0075	0.991 ± 0.018	0.9576 ± 0.0088	0.985 ± 0.019	0.982 ± 0.018	0.9617 ± 0.0073	0.9615 ± 0.0074	0.9572 ± 0.0080
$log[10^{10}A_s]$	3.086 ± 0.025	3.122 ± 0.033	3.086 ± 0.025	3.119 ± 0.033	3.119 ± 0.032	3.087 ± 0.024	3.149 ± 0.026	3.114 ± 0.031
H_0[km/s/Mpc]	67.4 ± 1.2	73.2 ± 3.5	64.5 ± 3.3	70.4 ± 4.7	70.2 ± 3.4	84 ± 10	67.0 ± 1.2	67.5 ± 1.2
r	< 0.12	< 0.19	< 0.13	< 0.19	< 0.18	< 0.13	< 0.93	< 0.23
$m_{\rm a}(\mu eV)$	81.5 ± 1.6	76.8 ± 2.8	81.0 ± 1.6	77.0 ± 2.7	77.1 ± 2.9	81.6 ± 1.5	80.8 ± 1.7	81.3 ± 1.6
$N_{\rm eff}$	(3.046)	3.79 ± 0.41	(3.046)	3.71 ± 0.41	3.72 ± 0.37	(3.046)	(3.046)	(3.046)
$\sum m_\nu(eV)$	(0.06)	(0.06)	< 0.97	< 0.83	(0.06)	(0.06)	(0.06)	(0.06)
w	(-1)	(-1)	(-1)	(-1)	(-1)	-1.50 ± 0.31	(-1)	(-1)
$m_s^{\rm eff}(eV)$	(0)	(0)	(0)	(0)	< 0.87	$< (0)$	(0)	(0)
n_t	(0)	(0)	(0)	(0)	(0)	(0)	2.19 ± 0.87	(0)
$dn_s/d\ln k$	(0)	(0)	(0)	(0)	(0)	(0)	(0)	-0.022 ± 0.011

Considering also extended scenario we obtain an axion with mass in the range 70-80 μeV.

E. Di Valentino, E. Giusarma, M. Lattanzi, A. Melchiorri, O. Mena, Phys. Rev. D90 (2014), 043534

Axion Cold Dark Matter

We find that, in the minimal ADM scenario, the largest dataset including the precise distance BAO constraints from the BOSS Data Release 11 (DR11), implies

$$m_{\rm a} = 82.2 \pm 1.1\, \mu{\rm eV}$$

$$f_{\rm a} = (7.54 \pm 0.10) \times 10^{10}\, {\rm GeV}$$

- while with an additional number of relativistic degrees of freedom N_{eff}

$$m_{\rm a} = 76.6 \pm 2.6\, \mu{\rm eV}$$

$$f_{\rm a} = (8.08 \pm 0.27) \times 10^{10}\, {\rm GeV}$$

$$N_{\rm eff} = 3.69 \pm 0.30$$

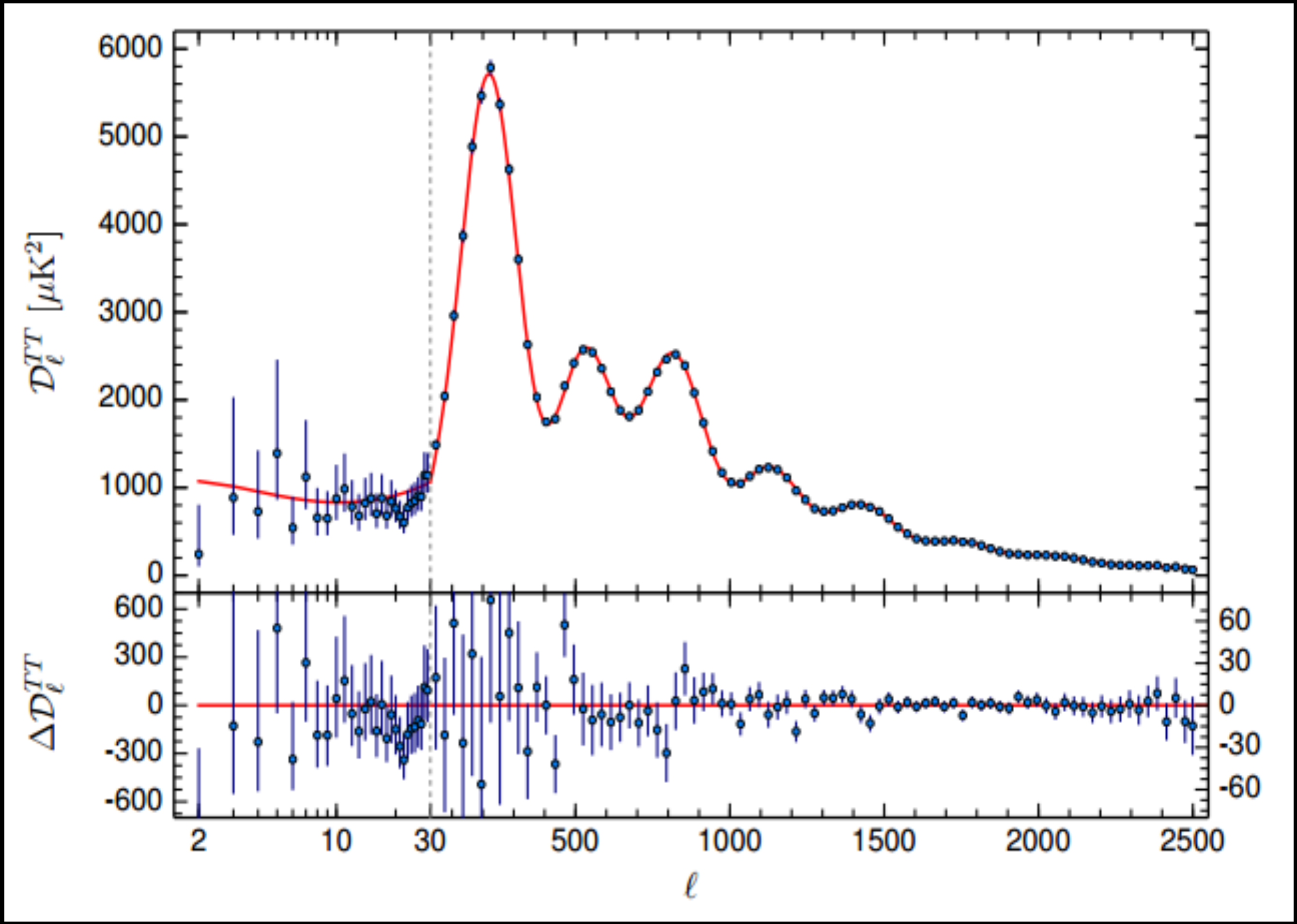
E. Di Valentino, E. Giusarma, M. Lattanzi, A. Melchiorri, O. Mena, Phys. Rev. D90 (2014), 043534

Axion Cold Dark Matter

- The search for axion dark matter is also the target of laboratory experiments like the Axion Dark Matter eXperiment (ADMX), that uses a tunable microwave cavity positioned in a high magnetic field to detect the conversion of axions into photons. ADMX has been operating in the range 0.3 - 1 GHz, thus being able to exclude DM axions in the mass range between 1.9 and 3.53 μeV.

- To reach the typical masses found in our study, this should be enhanced at a resonant frequency of 20 GHz, if the PQ symmetry is broken after inflation.

- A smaller experiment called ADMX-HF is currently being built, that will allow to probe the 4 - 40 Ghz range, thus being in principle sensitive to axion masses in the 100 μeV range, allowing to directly test the ADM scenario.



Planck collaboration, 2015

The main tool of research in cosmology is the angular power spectrum of CMB temperature anisotropies.

$$\left\langle \frac{\Delta T}{T}(\vec{\gamma}_1)\frac{\Delta T}{T}(\vec{\gamma}_2)\right\rangle = \frac{1}{2\pi}\sum_\ell (2\ell+1)C_\ell P_\ell(\vec{\gamma}_1\cdot\vec{\gamma}_2)$$