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for Research & Innovation

Dark radiation candidates: light sterile neutrinos and thermal axions

COSMOS meeting, Ferrara (IT), 26–27/06/2018

1 ***Light sterile neutrinos***
- Why a sterile neutrino
- Cosmological constraints

2 ***Thermal axions***
- Motivation and theory
- Cosmological constraints

3 ***Conclusions***

Neutrino Oscillations

Analogous to CKM mixing for quarks:

[Pontecorvo, 1958]
[Maki, Nakagawa, Sakata, 1962]

$$\boxed{\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau)}$$

ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates.

Current knowledge of the 3 active ν mixing: [de Salas et al. (2018)]

$\Delta m^2_{ji} = m^2_j - m^2_i$, θ_{ij} mixing angles
NO: Normal Ordering, $m_1 < m_2 < m_3$
IO: Inverted Ordering, $m_3 < m_1 < m_2$

$$\begin{aligned}
\Delta m^2_{21} &= (7.55^{+0.20}_{-0.16}) \cdot 10^{-5}\ \mathrm{eV}^2 \\
|\Delta m^2_{31}| &= (2.50 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO}) \\
&= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})
\end{aligned}$$

$$\begin{aligned}
\sin^2(\theta_{12}) &= 0.320^{+0.020}_{-0.016} \\
\sin^2(\theta_{13}) &= 0.0216^{+0.008}_{-0.007}\ (\mathrm{NO}) \\
&= 0.0222^{+0.007}_{-0.008}\ (\mathrm{IO}) \\
\sin^2(\theta_{23}) &= 0.547^{+0.020}_{-0.030}\ (\mathrm{NO}) \\
&= 0.551^{+0.018}_{-0.030}\ (\mathrm{IO})
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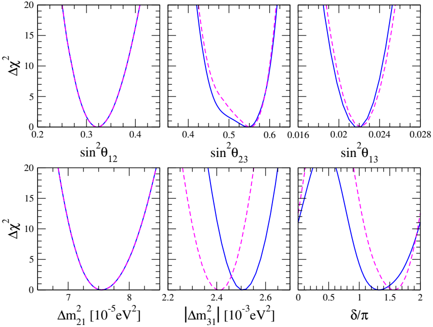

First hints for $\delta_{\rm CP} \simeq 3/2\pi$

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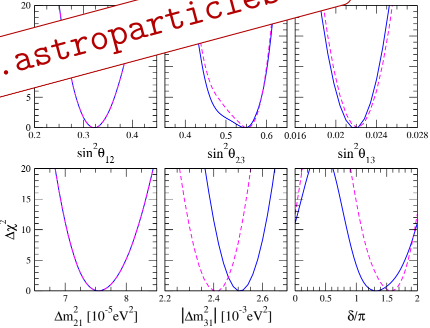
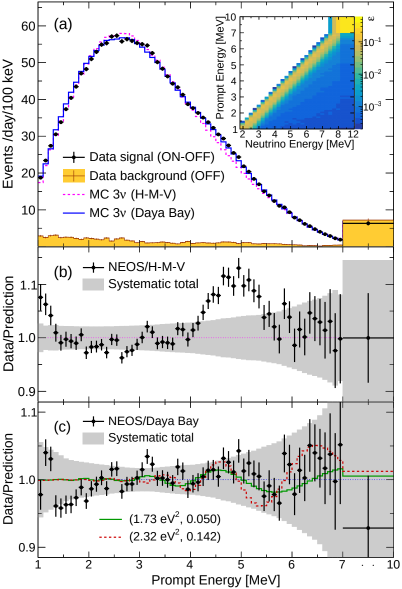
see also: http://globalfit.astroparticles.es

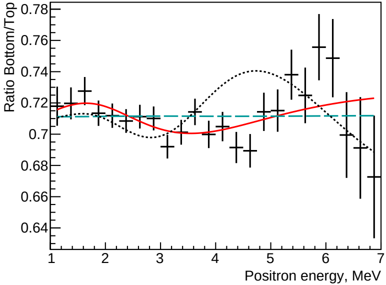


Recent results. . .

[NEOS, PRL 118 (2017) 121802]



[DANSS, arxiv:1804.04046]

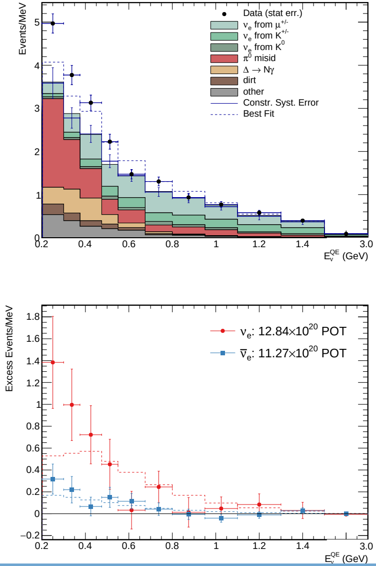


first *model independent* indications in favor of SBL oscillations

DANSS alone gives a $\Delta\chi^2 \simeq 13$ in favor of a light sterile neutrino!

Recent results. . .

[MiniBooNE, arxiv:1805.12028]



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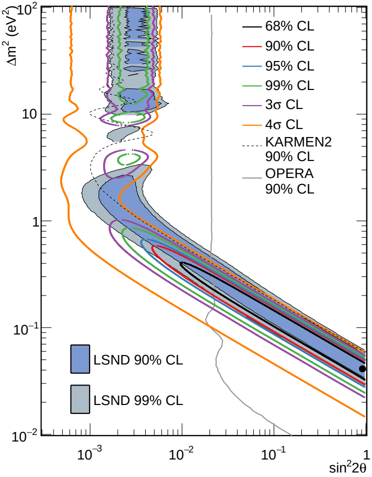

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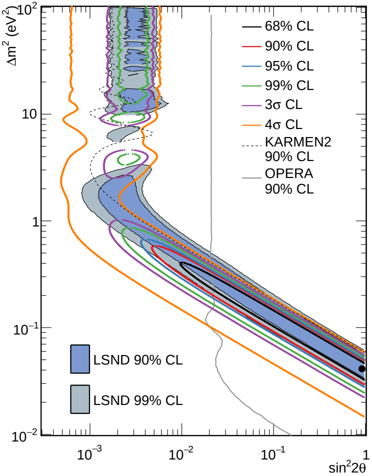
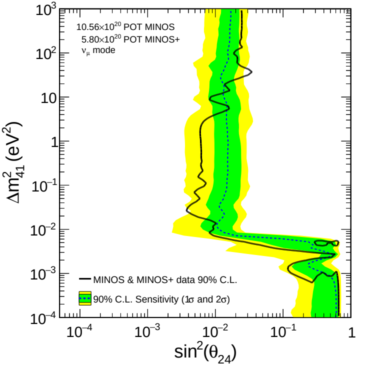
[MiniBooNE, arxiv:1805.12028]

[MINOS+, arxiv:1710.06488]





3+1 Neutrino Model

new $\Delta m^2_{\text{SBL}} \Rightarrow$ 4 neutrinos!

↓

ν_4 with $m_4 \simeq 1$ eV,
no weak interactions

↓

light sterile neutrino (LSν)

3 (active) + 1 (sterile) mixing:

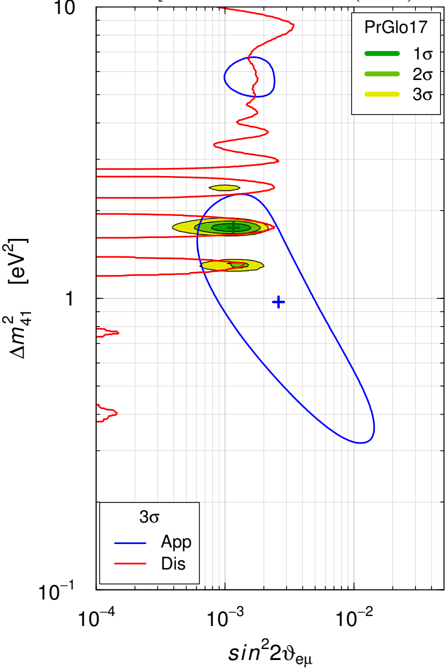
$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau, s)$$

ν_s is mainly ν_4:

$$m_s \simeq m_4 \simeq \sqrt{\Delta m^2_{41}} \simeq \sqrt{\Delta m^2_{\text{SBL}}}$$

assuming $m_4 \gg m_i$ $(i = 1, 2, 3)$

[SG et al., JHEP 06 (2017) 135]



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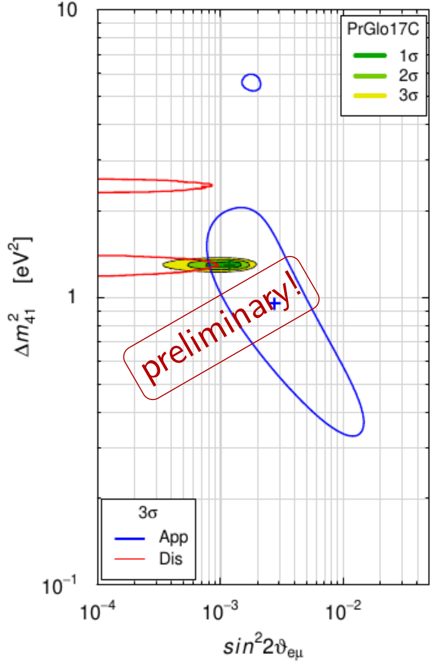

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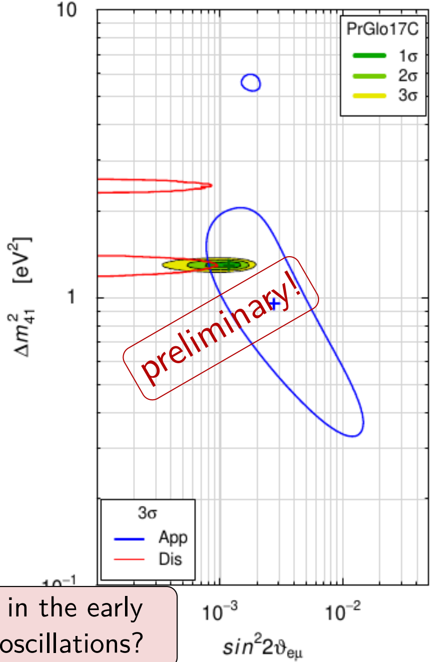
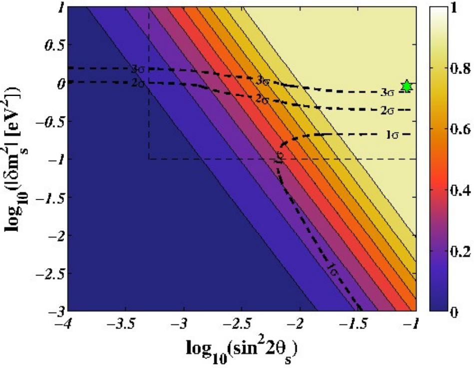


can ν_4 thermalize in the early Universe through oscillations?

LSν thermalization

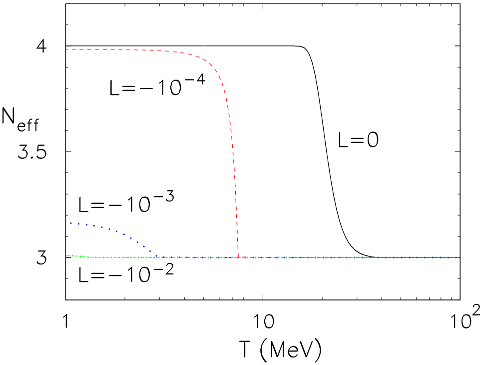
Using SBL best-fit parameters for the LSν (Δm^2_{41}, θ_s):

[Hannestad et al., JCAP 07 (2012) 025]



(colors coding ΔN_{eff})

[Mirizzi et al., PRD 86 (2012) 053009]



(L: lepton asymmetry)

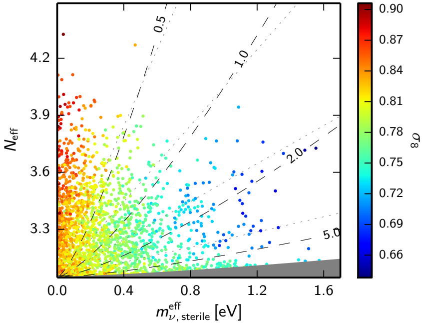
Unless $L \gtrsim \mathcal{O}(10^{-3})$, $\Delta N_{\mathrm{eff}} \simeq 1$

See also: [Saviano et al., PRD 87 (2013) 073006], [Hannestad et al., JCAP 08 (2015) 019]

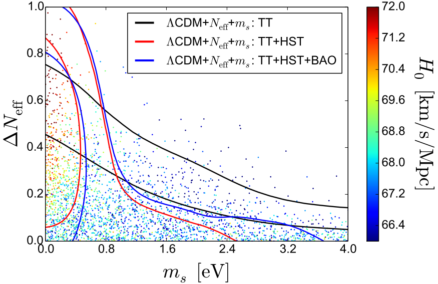
[to be precise: ΔN_{eff} is slightly smaller at CMB decoupling, when the LSν starts to be non-relativistic]

LSν constraints from cosmology

CMB+local: [Planck Collaboration, 2015]



[Archidiacono et al., JCAP 08 (2016) 067]



$\begin{cases} N_{\rm eff} < 3.7 \\ m_s^{\rm eff} < 0.52 \text{ eV} \end{cases}$ (TT+lensing+BAO) $[m_s < 5 \text{ eV}]$

dataset	free $\Delta N_{\rm eff}$ $[m_s < 10 \text{ eV}]$	$\Delta N_{\rm eff} = 1$
(TT)	$N_{\rm eff} < 3.5$	$m_s < 0.66$ eV
(+H_0)	$N_{\rm eff} < 3.9$	$m_s < 0.55$ eV
(+BAO)	$N_{\rm eff} < 3.8$	$m_s < 0.53$ eV

BBN constraints: $N_{\rm eff} = 2.90 \pm 0.22$ (BBN+Y_p) [Peimbert et al., 2016]

Summary: $\Delta N_{\rm eff} = 1$ from LSν incompatible with $m_s \simeq 1$ eV!

TT=Planck 2015 TT + lowTEB

All the constraints are at 2σ CL

Incomplete Thermalization

Active-sterile oscillations in the early Universe:

mixing parameters from SBL data $\Longrightarrow \Delta N_{\rm eff} \simeq 1$

[Hannestad et al., 2012] [Mirizzi et al., 2012]

Many probes constrain $\Delta N_{\rm eff} < 1$. Do we need

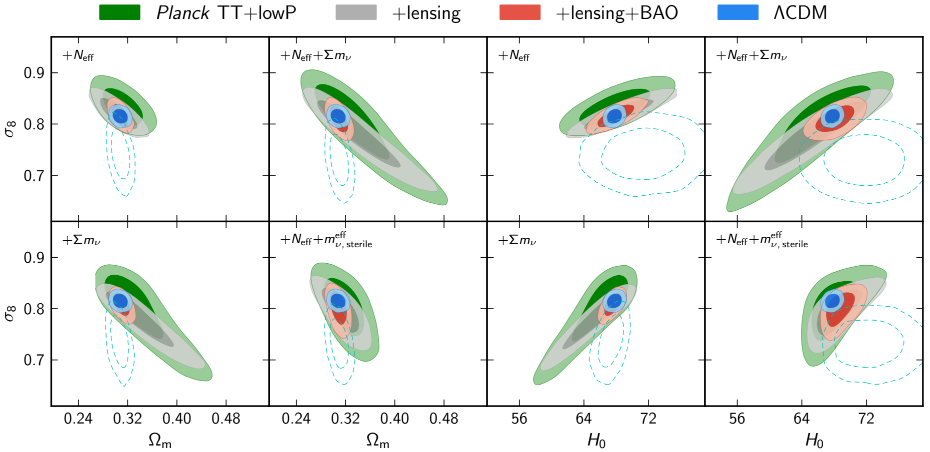
- a mechanism to suppress oscillations and full thermalization of ν_s?
- to compensate $\Delta N_{\rm eff} = 1$ with additional mechanisms in Cosmology?

Some ideas (an incomplete list!):

- large lepton asymmetry [Foot et al., 1995; Mirizzi et al., 2012; many more]
- new neutrino interactions [Bento et al., 2001; Dasgupta et al., 2014; Hannestad et al., 2014; Saviano et al., 2014; Archidiacono et al. 2016; many more]
- entropy production after neutrino decoupling [Ho et al., 2013]
- very low reheating temperature [Gelmini et al., 2004; Smirnov et al., 2006]
- time varying dark energy components [Giusarma et al., 2012]
- larger expansion rate at the time of ν_s production [Rehagen et al., 2014]

Solving both σ_8 and H_0 Tension?

[Planck Collaboration, 2015]



dashed: local measurements – ΛCDM model, ΛCDM + $\nu_{a,s}$ models: full cosmological dataset

H_0 increases ⇒ σ_8 increases (and viceversa)!
The correlations do not help.

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The Strong CP problem

CP violation is permitted in QCD

effective periodic strong
CP-violating term Θ

Θ is an input of the SM

must be measured, cannot be predicted

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not observed! → Θ is small ($\lesssim 10^{-10}$)

why so small (or zero), if it can be between 0 and 2π?

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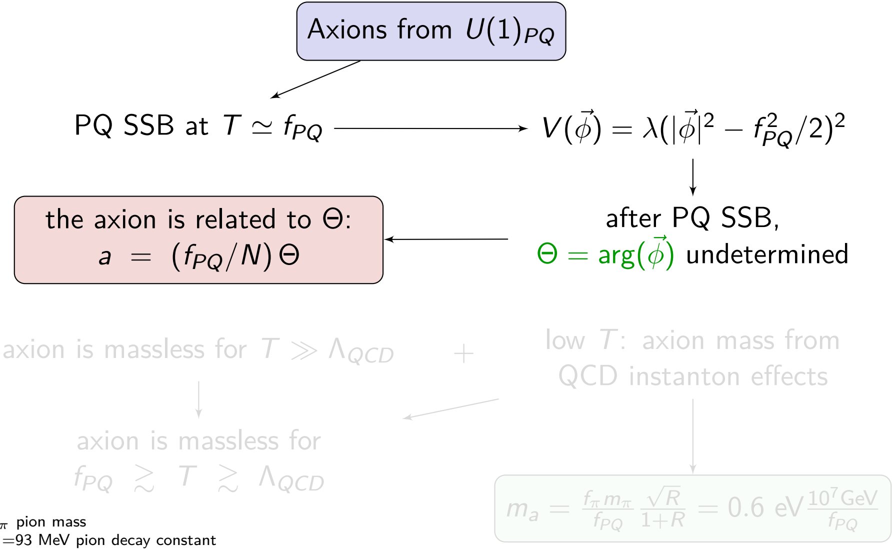
[Peccei&Quinn, 1977]

Possible solution: Θ is a field, corresponding to a new spontaneously broken symmetry $U(1)_{\rm PQ}$

Axions during the expansion - I



Axions from $U(1)_{PQ}$

PQ SSB at $T \simeq f_{PQ}$ $\longrightarrow$ $V(\vec{\phi}) = \lambda(|\vec{\phi}|^2 - f_{PQ}^2/2)^2$

after PQ SSB,
$\Theta = \arg(\vec{\phi})$ undetermined

the axion is related to Θ:
$a = (f_{PQ}/N)\,\Theta$

axion is massless for $T \gg \Lambda_{QCD}$ + low T: axion mass from QCD instanton effects

axion is massless for
$f_{PQ} \gtrsim T \gtrsim \Lambda_{QCD}$

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

m_π pion mass
f_π=93 MeV pion decay constant
N color anomaly of the PQ symmetry
$R = 0.553 \pm 0.043$ up-to-down quark masses ratio
PQ SSB = spontaneous symmetry breaking of PQ symmetry

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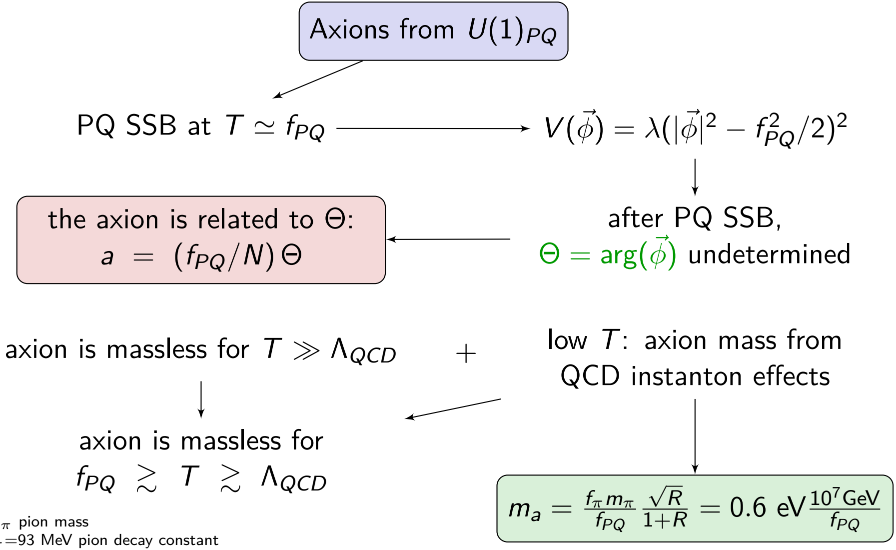

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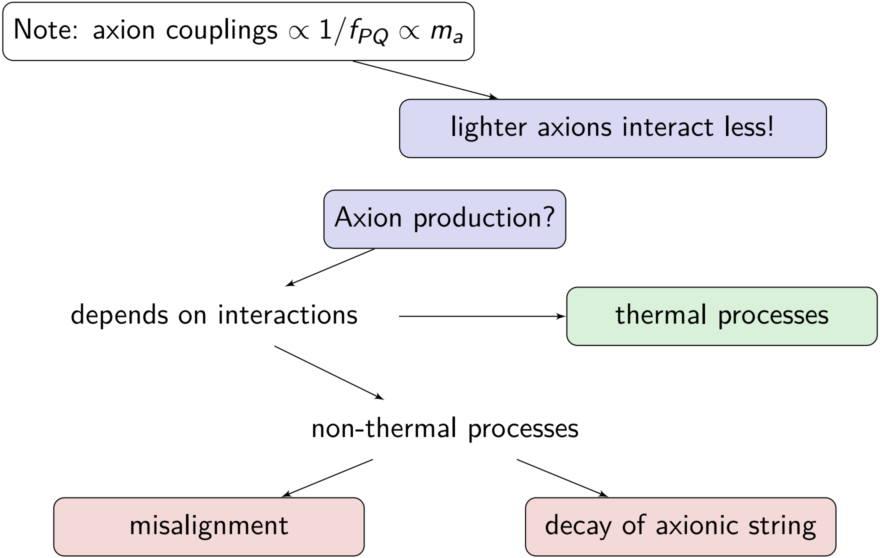
Axions during the expansion - II

[Archidiacono et al., JCAP 05 (2015) 050]



Note: axion couplings $\propto 1/f_{PQ} \propto m_a$

lighter axions interact less!

Axion production?

depends on interactions

thermal processes

non-thermal processes

misalignment

decay of axionic string

see also: [D. Marsh, Phys.Rept. 643 (2016) 1-79]

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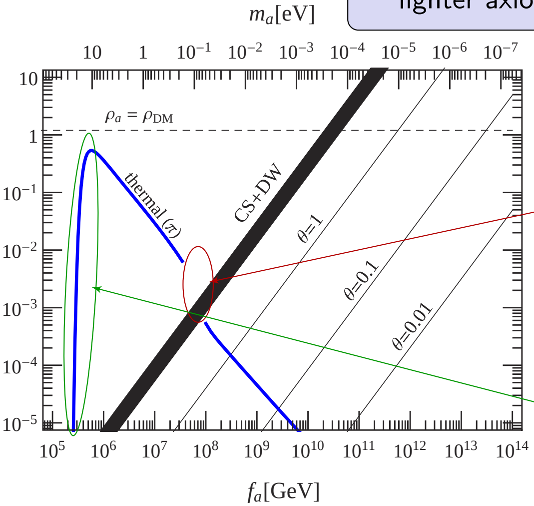


drop when $T_{fr} \simeq \Lambda_{QCD}$

(less efficient interactions with unconfined quarks and gluons + entropy dilution)

Axion rapidly decays $a \to 2\gamma$ and disappears

Thermal production

thermal process $\pi + \pi \to \pi + a$

a singly produced

other processes:
$Q + \pi \to Q + a$
$N + \pi \to N + a$

relativistic at production

hot dark matter

decoupling $T_D(f_{PQ})$ from $\Gamma(T_D) = H(T_D)$ (numerically)

d.o.f. at decoupling $g_{\star S}(T_D)$

same order of n_γ, n_ν

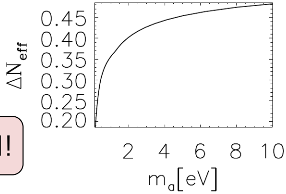
axion number density

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

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

density parameter

$$\omega_a = \Omega_a h^2 \propto m_a n_a \propto m_a / g_{\star S}(T_D)$$



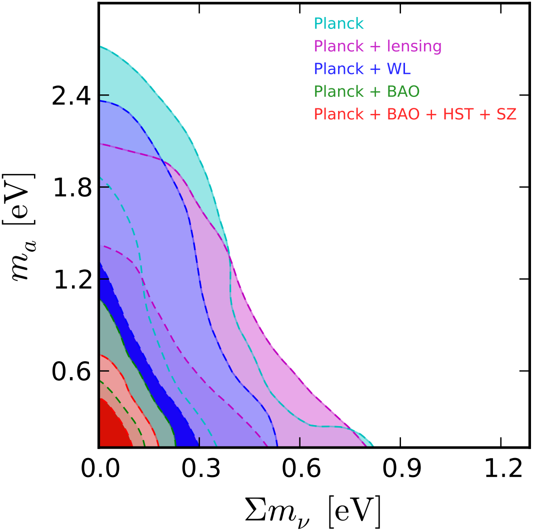
hot: cannot be total DM!

calculations valid for $m_a \gtrsim 0.1$ eV

Q quarks, N nucleons
T_0 CMB temperature today
$n_{\gamma\,(\nu)}$ number density of photons (neutrinos)

Constraints - I

[di Valentino et al., PLB 752 (2016) 182]



thermal axion behavior is
similar to massive neutrinos

↓

degeneracy
$\sum m_\nu - m_a$

but different contributions to $\Delta N_{\rm eff}$

($\Delta N_{eff,a}$ depends on m_a)

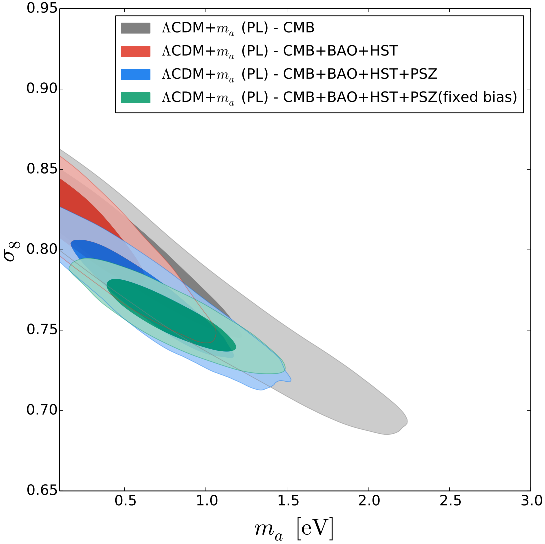
↓

not complete degeneracy

Stronger constraint:
$m_a < 0.529$ eV (95%)

Constraints - II

[Di Valentino et al., PRD 91 (2015) 123505]



axion is hot relic

↓

suppression of matter power spectrum

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reduced fluctuations at small scales

see also [Joudaki et al., 1610.04606] on σ_8 tension

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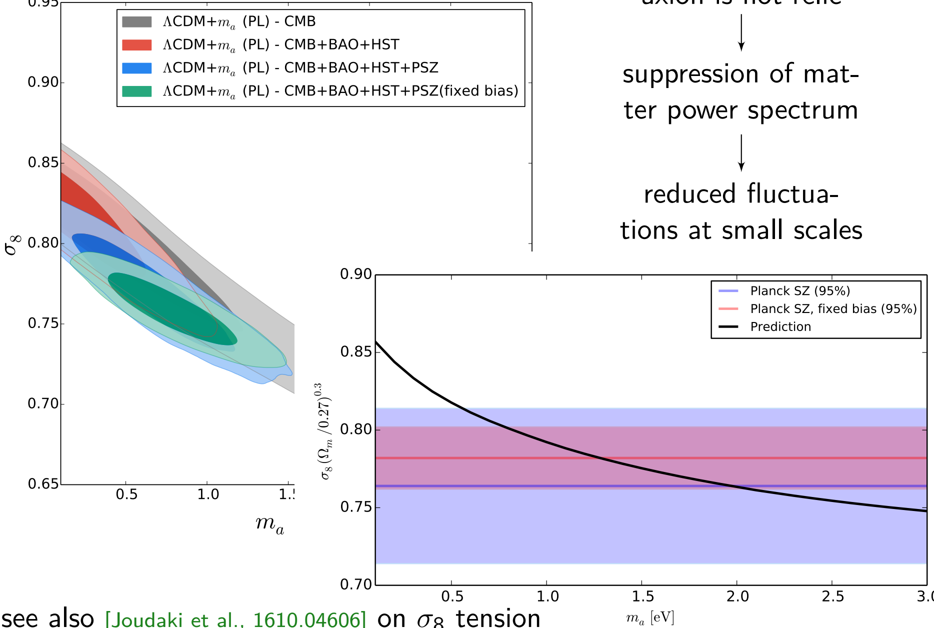

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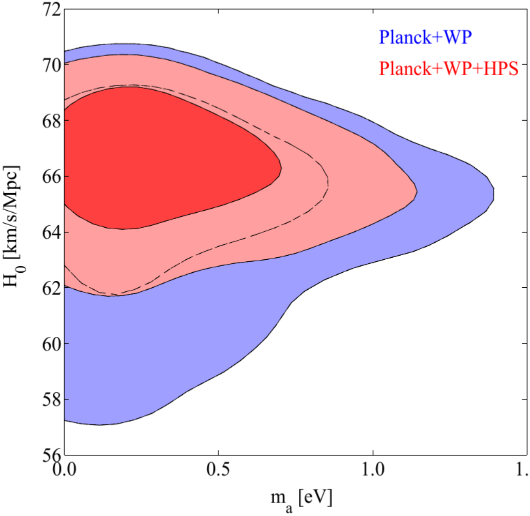

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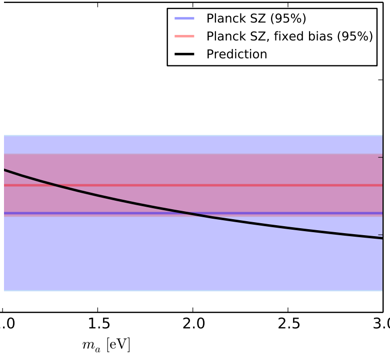

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Not completely clear.

If yes, problems in early universe!

More new physics to be discovered?

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Is there an axion?

If yes, study it using CMB data!

DM may be thermal + non-thermal axions/axion-like particles

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