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Axions and the CMB

A short review of current constraints
and future perspectives

27 October 2016 - Axions and IAXO in Spain - Zaragoza (ES)

Relativistic species and radiation content: $\Delta N_{\rm eff}$

Radiation energy density ρ_r in the early Universe:

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma = \left[1 + 0.2271 N_{\rm eff}\right]\rho_\gamma$$

ρ_γ photon energy density, 7/8 is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

- $N_{\rm eff} \to$ all the radiation contribution not given by photons
- $N_{\rm eff} \simeq 1$ correspond to a single family of active neutrino, in equilibrium in the early Universe
- Active neutrinos: $N_{\rm eff} = 3.046$ [Mangano et al., 2005]
  > 3 due to not instantaneous decoupling for the neutrinos
- $+$ Non Standard Interactions: $3.040 < N_{\rm eff} < 3.059$ [de Salas et al., 2016]
- additional species contribute with $\Delta N_{\rm eff} = N_{\rm eff} - 3.046$:

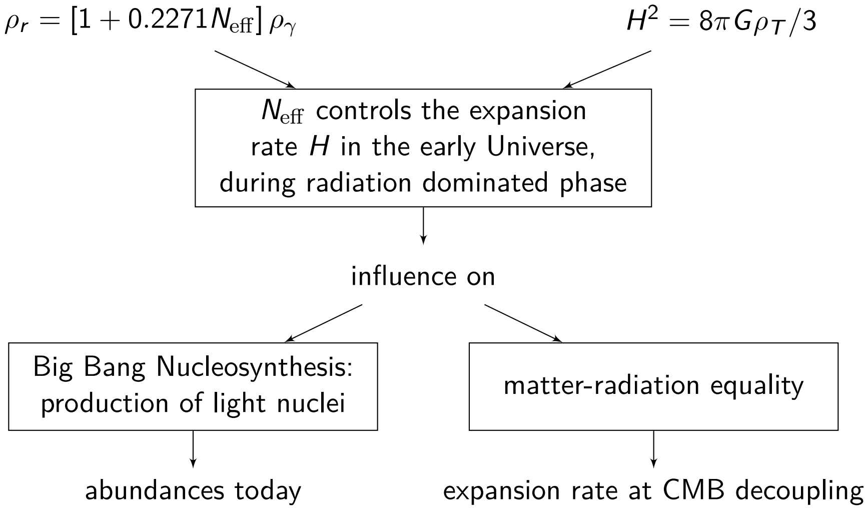
Additional species may be:

light sterile neutrinos

axions (thermally produced ones)

(...insert your candidates here...)

Additional Radiation in the Early Universe



$\rho_r = [1 + 0.2271 N_{\rm eff}]\,\rho_\gamma$

$H^2 = 8\pi G \rho_T / 3$

$N_{\rm eff}$ controls the expansion rate H in the early Universe, during radiation dominated phase

influence on

Big Bang Nucleosynthesis: production of light nuclei

abundances today

matter-radiation equality

expansion rate at CMB decoupling

Additional radiation: Big Bang Nucleosynthesis (BBN)

BBN: production of light nuclei at $t \sim 1\text{s}$ to $t \sim \mathcal{O}(10^2)\text{s}$

temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out

$$\Gamma_{n\leftrightarrow p} \sim G_F^2 T^5 \quad = \quad H \sim \sqrt{g_\star G_N}\, T^2$$

$$\Downarrow$$

$$\boxed{T_{fr} \simeq (g_\star G_N / G_F^4)^{1/6}}$$

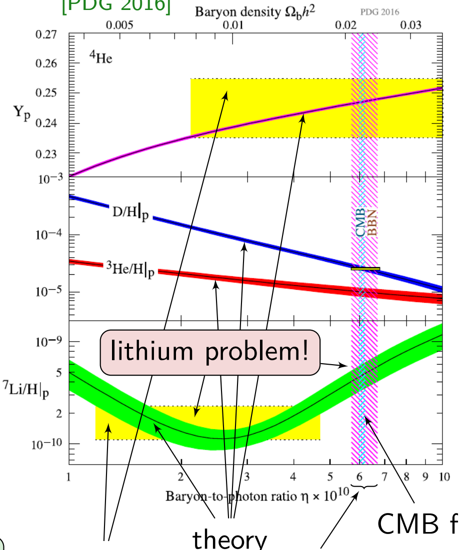
initial $n/p = \exp(-Q/T_{fr}) \simeq 1/6$

after neutron β-decay: $n/p \simeq 1/7$

element abundances depend on n/p

$\hookrightarrow$ new species: larger $g_\star \rightarrow n/p$

[PDG 2016]



lithium problem!

measured

theory

CMB fit

BBN concordance (^{4}He and D/N)

G_F Fermi constant
G_N Newton constant

$Q = 1.293$ MeV neutron–proton mass difference
n_b, n_γ, n, p baryon, photon, neutron, proton density number

$\eta = n_b/n_\gamma$

Helium abundance Y_p

$$Y_p = \frac{\rho(^4\mathrm{He})}{\rho_b} = \frac{2(n/p)}{1+n/p} \simeq 0.25$$

^{4}He is the most stable element

depends on neutron lifetime

$\tau_n = 880.3 \pm 1.1$ s?

small corrections from:

- nucleon mass effects
- radiative processes
- heating of neutrinos from $e^\pm$ annihilations

positive correlation with $N_{\rm eff}$

adding thermal axions means higher Y_p

Measures?

recombination emission lines in extragalactic H II regions
(metal-poor: no star contamination)
(extrapolate to zero-metallicity)

systematics in describing H II regions! T, n_e degeneracy

solved including He λ10830 emission line

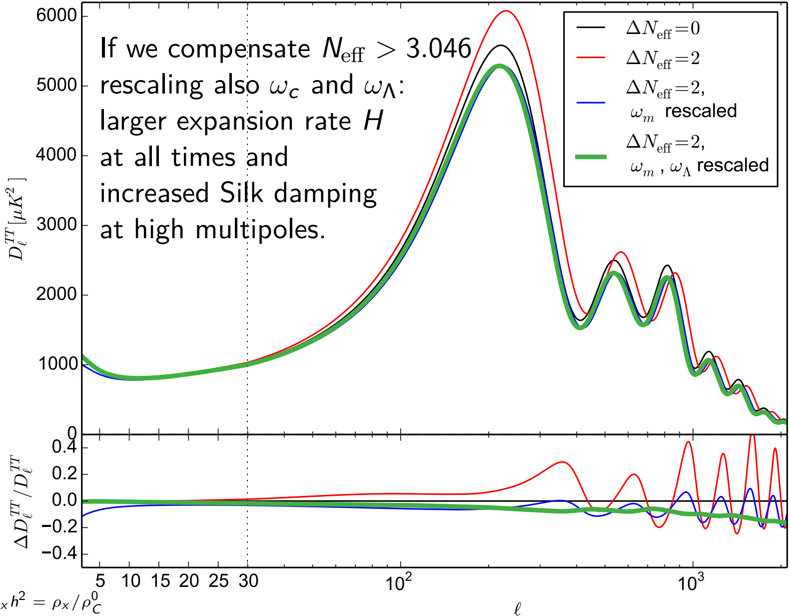
Recent Y_p determinations:

0.2449 ± 0.0040 [Aver et al., 2015]
0.2551 ± 0.0022 [Izotov et al., 2014]
0.2446 ± 0.0029 [Peimbert et al., 2016]

translates in

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

Additional Radiation: Effects on the CMB



If we compensate $N_{\rm eff} > 3.046$ rescaling also ω_c and ω_Λ: larger expansion rate H at all times and increased Silk damping at high multipoles.

$\omega_x = \Omega_x h^2 = \rho_x / \rho_C^0$

1. Cosmological Effects of Relativistic Species
    - Parameterization
    - Big Bang Nucleosynthesis
    - Cosmic Microwave Background

2. Cosmological effects of warm massive species
    - Cosmic Microwave Background
    - Matter perturbations

3. Axions in cosmology
    - Non-thermal production
    - Thermal production

4. Current constraints vs future perspectives

5. Conclusions

Impact of non-cold species on the CMB

$$1 + z_{\rm eq} = (\omega_b + \omega_c)/\omega_r$$

independent of m_ν

$$\omega_m^0 = \omega_b^0 + \omega_c^0 + \omega_\nu^0 \text{ today}$$

mass of species relativistic at recombination
affect late time evolution only

small effects on the SW plateau
(cosmic variance, degeneracies...)

Effects on the early ISW effect

$$\frac{\Delta C_\ell}{C_\ell} \simeq -\left(\frac{\sum m_\nu}{0.1 \text{ eV}}\right)\%$$

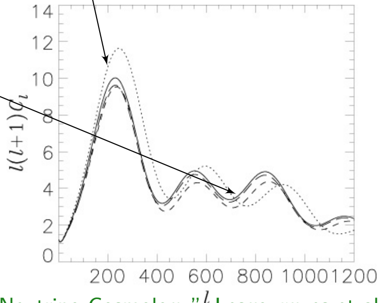
effects on the position of peaks

$$\theta_s = r_s(\eta_{LS})/D_A(\eta_{LS})$$

$$D_A = \int_0^{z_{rec}} \frac{dz}{H(z)}$$

(this effect can be compensated reducing H_0)

degeneracy m_ν–H_0



["Neutrino Cosmology", Lesgourgues et al.]

Free-streaming - I

Non-cold relics $\Longrightarrow$ damping in the perturbations due to free-streaming

Growth equation: $$\ddot{\delta} + \underbrace{\boxed{2H\dot{\delta}}}_{\text{Hubble drag}} - \underbrace{\boxed{c_s^2 k^2 \frac{\delta}{a^2}}}_{\text{pressure}} = \underbrace{\boxed{4\pi G_N \rho\, \delta}}_{\text{gravity}}$$

Jeans scale: pressure=gravity

$$k_J \equiv \sqrt{\frac{4\pi G_N \rho}{c_s^2 (1+z)^2}}$$

$k \quad < \quad k_J$

growth of density perturbations

$k \quad > \quad k_J$

no growth can occur

neutrino free-streaming scale

$$\boxed{k_{fs}(z) \equiv \sqrt{\frac{3}{2}\frac{H(z)}{(1+z)\sigma_{v,\nu}(z)}} \simeq 0.7 \left(\frac{m_\nu}{1\ \mathrm{eV}}\right) \sqrt{\frac{\Omega_M}{1+z}} h/\mathrm{Mpc}}$$

ρ energy density of a given fluid

$\delta = \delta\rho/\rho$ perturbation (single fluid)

c_s sound speed of the fluid

$\sigma_{v,\nu}(z)$ ν velocity dispersion

$H = H(z)$ Hubble factor at redshift z

h reduced Hubble factor today

Free-streaming - II

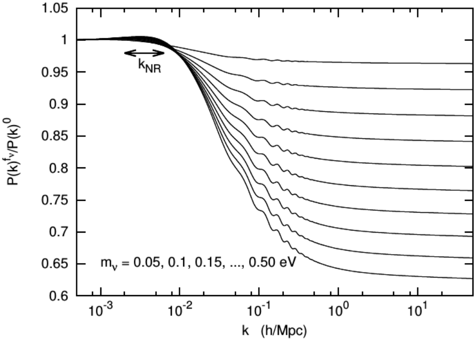
Damping occurs for all $k \gtrsim k_{\rm nr}$

k_{nr}: corresponding
to ν non-relativistic transition

Plot: $\dfrac{P_{m_\nu>0}(k)}{P_{m_\nu=0}(k)}$

- top to bottom: $m_\nu = 0.05$ eV
  to $m_\nu = 0.5$ eV
- $\dfrac{\Delta P}{P} \simeq -\dfrac{8\Omega_\nu}{\Omega_M} \simeq -\dfrac{\sum m_\nu}{0.01\ \mathrm{eV}}\%$

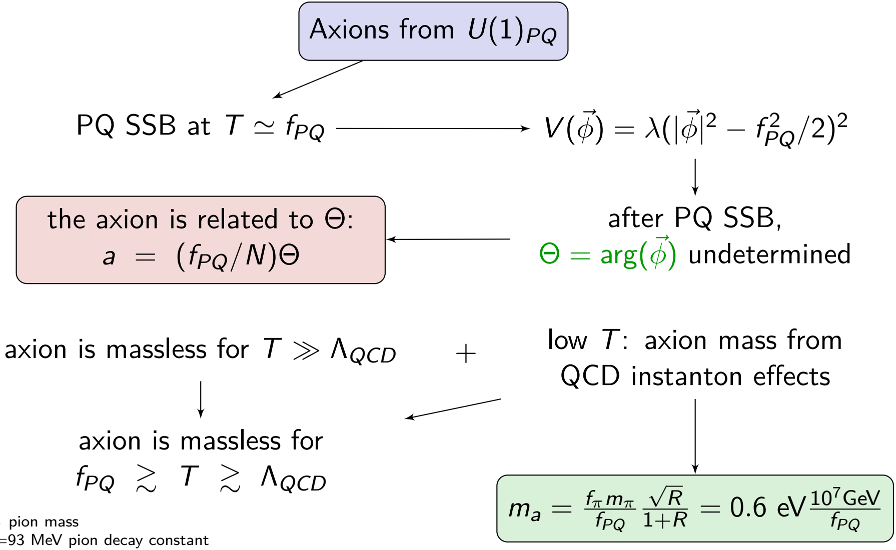
["Neutrino Cosmology", Lesgourgues et al.]
(fixed h, ω_m, ω_b, ω_Λ)



Expected constraints from future surveys:

- Planck CMB + DES: $\sigma(m_\nu) \simeq 0.04$–$0.06$ eV [Font-Ribera et al., 2014]
- Planck CMB + Euclid: $\sigma(m_\nu) \simeq 0.03$ eV [Audren et al., 2013]

Axions during the expansion - I



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

PQ SSB at $T \simeq f_{PQ}$

$V(\vec{\phi}) = \lambda(|\vec{\phi}|^2 - f_{PQ}^2/2)^2$

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

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

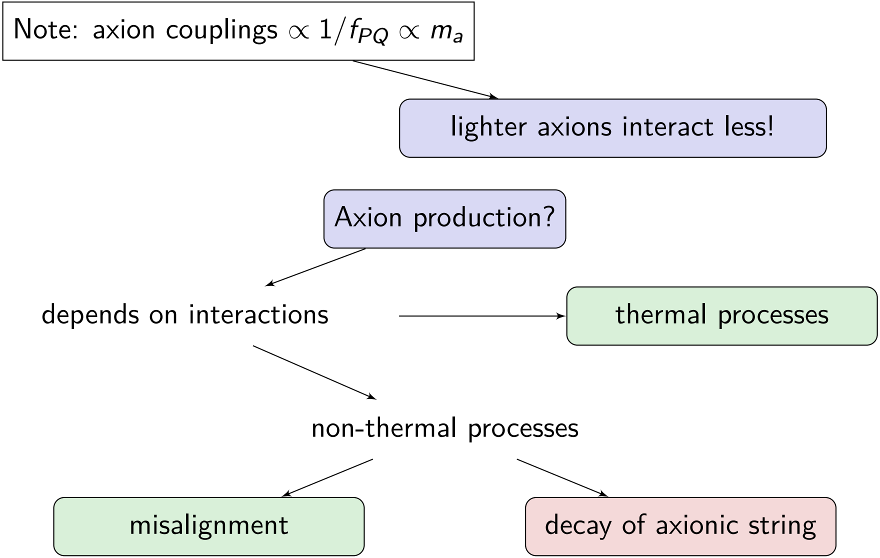
axion is massless for $T \gg \Lambda_{QCD}$ $+$ low T: axion mass from QCD instanton effects

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

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

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

Axions during the expansion - II



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

lighter axions interact less!

Axion production?

depends on interactions

thermal processes

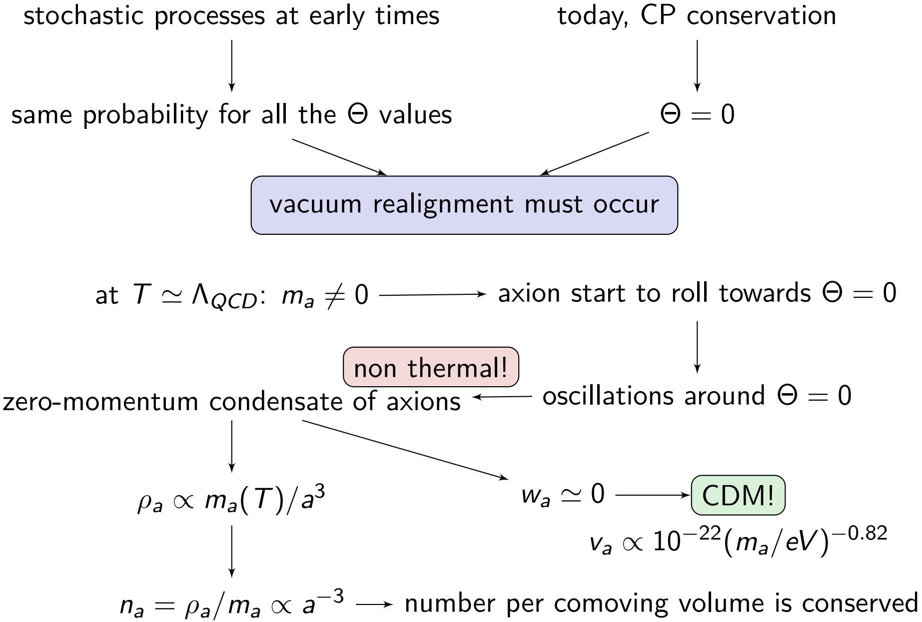
non-thermal processes

misalignment

decay of axionic string

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

CDM from misalignment of the initial Θ - I



stochastic processes at early times

same probability for all the Θ values

today, CP conservation

$\Theta = 0$

vacuum realignment must occur

at $T \simeq \Lambda_{QCD}$: $m_a \neq 0$ ⟶ axion start to roll towards $\Theta = 0$

oscillations around $\Theta = 0$

zero-momentum condensate of axions

non thermal!

$\rho_a \propto m_a(T)/a^3$

$w_a \simeq 0$ ⟶ CDM!

$v_a \propto 10^{-22}(m_a/eV)^{-0.82}$

$n_a = \rho_a/m_a \propto a^{-3}$ ⟶ number per comoving volume is conserved

CDM from misalignment of the initial Θ - II

initial angle? → energy density depends on initial Θ_1 value

$$\text{assume } \langle\bar\Theta_1\rangle^2 = \int_{-\pi}^{\pi} d\bar\Theta_1 \bar\Theta_1^2/2\pi = \mathcal{O}(1)$$

$$\boxed{\Omega_a h^2 = 0.85 \cdot 10^{\pm 0.4} \Lambda_{200}^{-0.7} (m_a/10^{-5}\ \text{eV})^{-1.18}}$$

for $\langle\bar\Theta_1\rangle = \mathcal{O}(1)$, axions can be all the DM if $m_a \gtrsim 10^{-5}$ eV

did inflation occur? —yes→ all the universe is within the same inflationary patch → same Θ_1

[Kolb&Turner]

full calculation:

$$\boxed{\Omega_a h^2 = 0.13 \cdot 10^{\pm 0.4} \Lambda_{200}^{-0.7} f(\bar\Theta_1) \bar\Theta_1^2 (m_a/10^{-5}\ \text{eV})^{-1.18}}$$

measure $\Omega_a h^2$, m_a to obtain Θ_1!

[Di Valentino et al.,PRD 90 (2014) 043534] – including axionic string decay contribution

$$\boxed{\Omega_a h^2 = 0.119 \pm 0.003 = \Omega_{cdm} h^2 \text{ and } m_a = 81.5 \pm 1.6\,\mu\text{eV (CMB only)}}$$

$\Lambda_{200} = \Lambda_{QCD}/200$ MeV $\bar\Theta_1 \ll H$ initial value of Θ $f(\bar\Theta_1)$ from anharmonic effects $10^{\pm 0.4}$ from theoretical uncertainties

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)

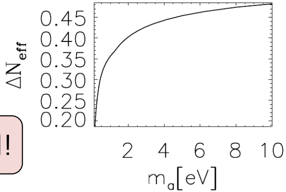
d.o.f. at decoupling $g_{\star S}(T_D)$

same order of n_γ, n_ν

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

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

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



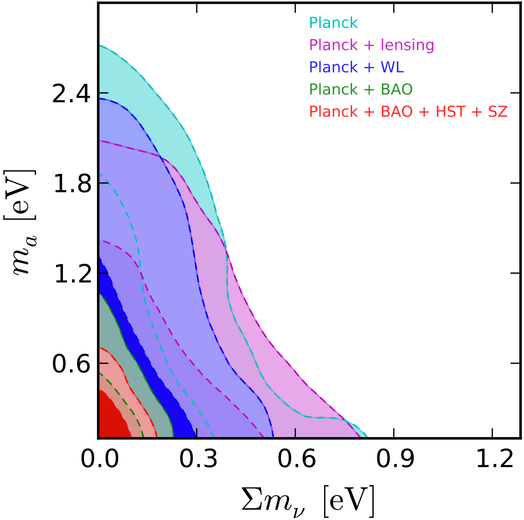
hot: cannot be total DM!

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 ΔN_{eff}

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

↓

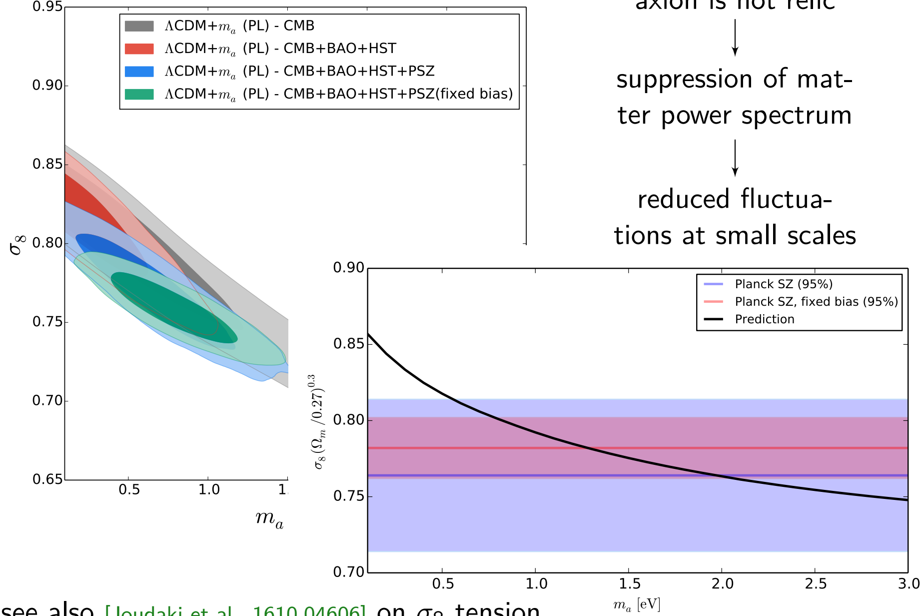
not complete degeneracy

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

↓

reduced fluctuations at small scales

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

CMB-stage IV forecasts

present

based on Planck measurements

[Planck Collaboration, 2015]

95%

$M_\nu < 0.72$ eV (PlanckTT+lowP)

$M_\nu < 0.49$ eV (PlanckTTTEEE+lowP)

$M_\nu < 0.17$ eV (+BAO)

$M_\nu < 0.12$ eV (+Lyman-α)

[Palanque-Delabrouille et al., 2015]

68%

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

$N_{\rm eff} = 2.99 \pm 0.20$ (PlanckTTTEEE+lowP)

$N_{\rm eff} = 3.04 \pm 0.18$ (+BAO)

future

need more precision:
use more detectors ($\mathcal{O}(10^4)$)
to measure more modes

68%

$\sigma(M_\nu) = 0.140$ eV (LiteBird alone)

$\sigma(M_\nu) = 0.045$ eV (Core alone)

$\sigma(N_{\rm eff}) = 0.20$ (LiteBird alone)

$\sigma(N_{\rm eff}) = 0.051$ (Core alone)

[Errard et al., JCAP 03 (2016) 052]

Note:

LiteBird launch > 2024
Core launch > 2028

Meanwhile:
stage III experiments,
baloon experiments...

$M_\nu = \Sigma m_\nu$

Large scale structures surveys

gravitational lensing scattering of CMB photons during their path $\longrightarrow$ CMB measurements can be used to reconstruct lensing potential

problem! lensing reconstructed from CMB (T,E) in 2σ tension with lensing potential from CMB trispectrum

solution: use cross-correlation with high-z galaxy surveys to remove lensing and obtain primordial CMB (LSST, DESI, Euclid, ...)

present

[Planck Collaboration, 2015]

95%

$M_\nu < 0.72$ eV (PlanckTT+lowP)

$M_\nu < 0.49$ eV (PlanckTTTEEE+lowP)

$M_\nu < 0.17$ eV (+BAO)

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$N_{\rm eff} = 3.04 \pm 0.18$ (+BAO)

$M_\nu = \Sigma m_\nu$

future

68%

$\sigma(M_\nu) = 0.048$ eV (LiteBird+LSST)

$\sigma(M_\nu) = 0.034$ eV (Core+LSST)

$\sigma(M_\nu) = 0.021$ eV (Core+DESI)

$\sigma(M_\nu) = 0.016$ eV (Core+DESI+Euclid)

$\sigma(N_{\rm eff}) = 0.086$ (LiteBird+LSST)

$\sigma(N_{\rm eff}) = 0.036$ (Core+LSST)

$\sigma(N_{\rm eff}) = 0.035$ (Core+DESI)

$\sigma(N_{\rm eff}) = 0.033$ (Core+DESI+Euclid)

[Errard et al., JCAP 03 (2016) 052]

[Lesgourgues@CERN, 17/05/2016]

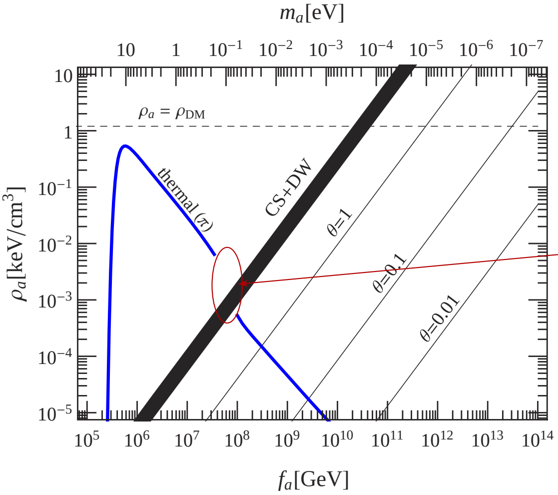
And for the axions?

[Archidiacono et al., JCAP 1505 (2015) 050]

Euclid-like experiments will be able to detect a thermal axion

provided that $m_a \gtrsim 0.15$ eV

complementary to IAXO range $m_a \lesssim 0.2$ eV!



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

(less efficient interactions with unconfined quarks and gluons)

Conclusions

- axions may influence universe evolution
- different behavior depending on production mechanism
- non-thermal production (misalignment, axionic string decay)
  - cold dark matter
  - can be all the dark matter
- thermal production
  - hot dark matter
  - similar to neutrinos
  - influence on BBN, CMB, large scale structures
  - possible solution to σ_8 problem **?**
- more knowledge from future experiments
  - CMB → stronger constraints on $N_{\rm eff}$
    - exclude thermal axions **?**
  - large scale structures to put stronger constraints on the mass
  - measure thermal axion mass provided that $m_a \gtrsim 0.1$ eV
  - but such thermal axion cannot exist if $\Delta N_{\rm eff} \lesssim 0.2$

Thank you for the attention