Observable windows of the QCD axion through N_{eff}

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Idea:

QCD axion thermalizes between QCD PT and EW PT $\Rightarrow$ observable ΔN_{eff}

Ingredients:

- Tree-level axial coupling with fermions

$$\mathcal{L}_{int} \supset \frac{\partial_\mu a}{2f} \sum_i c_i \bar{q}_i \gamma^\mu \gamma^5 q_i \,,$$

  Present in DFSZ-like axion models (but not in KSVZ models)

- Thermal axion production has been computed in several works but involving scatterings with the gluons and/or at temperatures above the EWPT [Turner 87', Masso 02', Strumia 13', ...] .

- But for $T \simeq m_q$ the dominant processes for axion production are [Turner 87', Baumann et al. 16']

$$q_i + g \to q_i + a, \quad \bar{q}_i + g \to \bar{q}_i + a \quad ,$$
$$q_i + \bar{q}_i \to g + a \,.$$

- The scattering rate for these processes below EWPT is of the order [Turner 87', Baumann et al. 16']

$$\Gamma \propto \left(\frac{g_s c_i}{2}\right)^2 \frac{m_i^2 T}{f^2}$$

which we should compare to $g + g \to g + a$

[Turner 87', Masso 02', Strumia 13']

$$\Gamma \propto \left(\frac{\alpha_s}{2\pi}\right) g_s^2 \frac{T^3}{f^2}$$

- Constraints on the axial couplings are quite week (apart from the electron and the top).
- CMB-S4 will improve these constrains by several orders of magnitude through $N_{\rm eff}$

[Baumann et al. 16'] .

	Current Constraints	
Coupling	Bound [GeV]	Origin
Λ_{ee}	1.2×10^{10}	white dwarfs
$\Lambda_{\mu\mu}$	2.0×10^{6}	stellar cooling
$\Lambda_{\tau\tau}$	2.5×10^{4}	stellar cooling
Λ_{bb}	6.1×10^{5}	stellar cooling
Λ_{tt}	1.2×10^{9}	stellar cooling
$\Lambda^V_{\mu e}$	5.5×10^{9}	$\mu^+ \to e^+ \phi$
$\Lambda_{\mu e}$	3.1×10^{9}	$\mu^+ \to e^+ \phi \gamma$
$\Lambda_{\tau e}$	4.4×10^{6}	$\tau^- \to e^- \phi$
$\Lambda_{\tau \mu}$	3.2×10^{6}	$\tau^- \to \mu^- \phi$
Λ^A_{cu}	6.9×10^{5}	D^0-$\bar{D}^0$
Λ^A_{bd}	6.4×10^{5}	B^0-$\bar{B}^0$
Λ_{bs}	6.1×10^{7}	$b \to s\phi$
Λ_{tu}	6.6×10^{9}	mixing
Λ_{tc}	2.2×10^{9}	mixing

Figure: Constraints on the axial couplings $\Lambda_{ii} = 2f_i$. Taken from Baumann. et al 16'

Observable signal: ΔN_{eff}

N_{eff} is the number of relativistic species defined as

$$\rho_{\text{radiation}} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \mathbf{N}_{\text{eff}}\right]\rho_\gamma, \qquad N_{\text{eff}} = 3.045 \text{ in } \Lambda\text{CDM}$$

Any extra light specie with a relic abundance contributes to N_{eff}. For the axion

$$\Delta N_{\text{eff}} = \frac{\rho_a}{\rho_\nu} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_a}{T_\gamma}\right)^4$$

By entropy conservation, after the axion decouples, particles which become non-relativistic warm up the photons.
Therefore, the ratio depends on the change on the # off relativistic dof

$$\left(\frac{T_a}{T_\gamma}\right)^3 = \frac{g_*(T_{\text{LSS}})}{g_*(T_{\text{dec}})} \quad \Rightarrow \quad \Delta N_{\text{eff}} \simeq \frac{13.56}{g_*(T_{\text{dec}})^{4/3}}$$

Prospects for ΔN_{eff}

From the CMB we constraint Planck 15' :

$$N_{\text{eff}} = 3.15 \pm 0.23$$

But next generation of CMB experiments will give a great improvement

CMB-S4 forecast: $\Delta N_{\text{eff}} \gtrsim 0.025 \ (1\sigma)$
optimistic configuration

That means that if the axion decouples:

- above EWPT

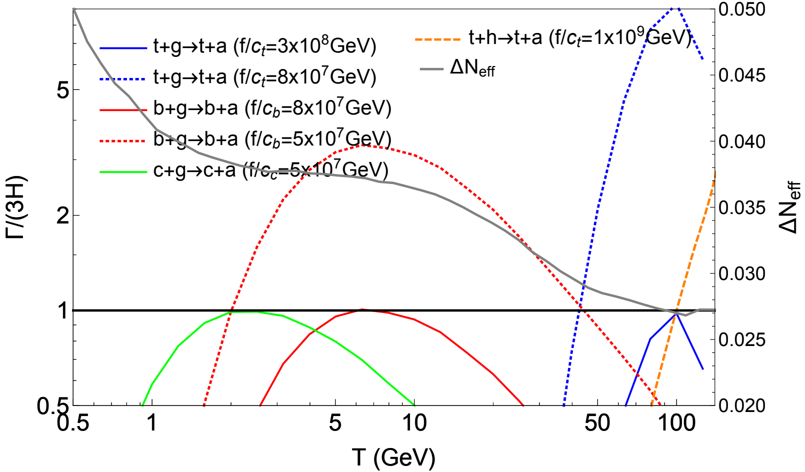
$$\Delta N_{\text{eff}} \lesssim 0.027 \qquad \text{(unobservable)}$$

Result depends on the number of extra dof at $T \gtrsim$ TeV.

- below EWPT

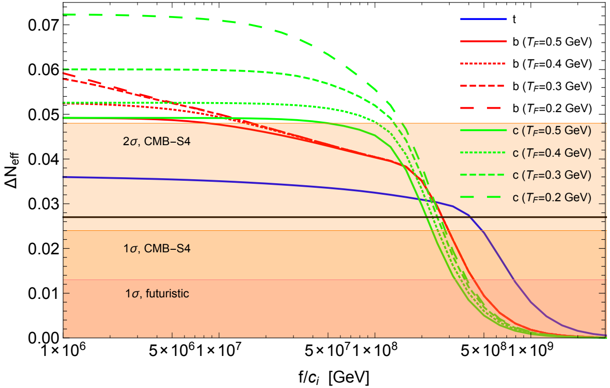
$$\Delta N_{\text{eff}} \gtrsim 0.027 \qquad \text{(potentially observable)}$$

relativistic dof is more known, so, for a given f/c_i, results are more predictive.


t+g→t+a (f/c_t=3x10^8GeV)
t+g→t+a (f/c_t=8x10^7GeV)
b+g→b+a (f/c_b=8x10^7GeV)
b+g→b+a (f/c_b=5x10^7GeV)
c+g→c+a (f/c_c=5x10^7GeV)
t+h→t+a (f/c_t=1x10^9GeV)
ΔN_eff
Γ/(3H)
ΔN_eff
T (GeV)
0.5
1
2
5
0.5
1
5
10
50
100
0.020
0.025
0.030
0.035
0.040
0.045
0.050

Results

- t-quark: $0.027 \leq \Delta N_{\text{eff}} \leq 0.036$ for $10^6\,\text{GeV} \lesssim f/c_t \lesssim 4 \times 10^8\,$GeV
- b-quark: $0.027 \leq \Delta N_{\text{eff}} \leq 0.047$ for $10^7\,\text{GeV} \lesssim f/c_b \lesssim 3 \times 10^8\,\text{GeV}$
- c-quark: $0.027 < \Delta N_{\text{eff}} \lesssim \mathcal{O}(0.1)$ for $f/c_c \lesssim (2-3) \times 10^8\,\text{GeV}$



Conclusions

- The axion can thermalize and decoupled below the EWPT for $f/c_i < 10^9$ GeV and affect $\Delta N_{\text{eff}} > 0.027$.
- The change in ΔN_{eff} is within the sensitivity of CMB-S4. A wide region of parameter space for many axion models will be probed.
- Window of f/c_i probed might overlap with CAST and IAXO. If there is a direct detection and a cosmological signal we would get information on the precise value of g_* at those temperatures.