Cosmic Axion Background: the QCD axion as a hot relic

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QCD Axion through N_{eff}

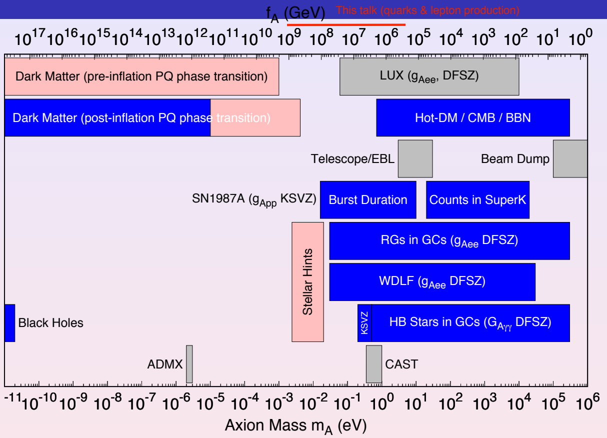
The QCD Axion (a) is a very light particle that

- Solves the "Strong CP problem" via coupling to gluons

$$\mathcal{L}_a = \frac{\alpha_s}{8\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- boundary term sensitive to QCD Instantons,
  1. Induces a potential $V(a) \propto \cos(a/f)$;
  2. $\implies$ Drives $\cancel{CP}$ to zero
  3. $\implies$ Axion mass $m_a \approx 0.57 \left(\frac{10^7\,GeV}{f}\right)$ eV
- Bounds on $f \Leftrightarrow$ bounds on m_a

Axion: constraints



- Caveat: Constraints based on individual couplings with e, γ, nucleons... Expected $\mathcal{O}(1/f)$, but model dependent.
- Small $m_a \ll \mathcal{O}(eV) \implies$ acts as Dark Radiation, visible in CMB (*Cosmic Axion Background*)

QCD Axion

- Axion effective lagrangian:
  1. May couple with continuous shift symmetry with all SM
  2. Only breaking: Instanton-induced (tiny) mass

Cosmic Axion Background via gluons

- Due to $\frac{\alpha_s}{8\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu}$ QCD Axions can be produced by gluon scatterings in the Early Universe
- Can be produced at high T and decouples at $T \lesssim T_{DEC}$ $\rightarrow$ hot relic (dark radiation)

  (M.Turner, 1987; Masso, F. Rota, and G. Zsembinszki, 2003, Salvio, Strumia, Xue, 2014)
- Scattering rate (via gluons) vs. Hubble

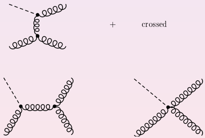


Figure: (Massò et al. Phys.Rev. D66 (2002).).

$$\Gamma_s \equiv \langle \sigma v \rangle \cdot n_g^{EQ} = \left(\frac{\alpha_s}{2\pi f}\right)^2 g_s^2 \cdot T^3 \text{ vs. } H \approx \frac{T^2}{M_{Pl}}.$$

QCD Axion produced via gluons

- Scattering rate (via gluons) vs. Hubble

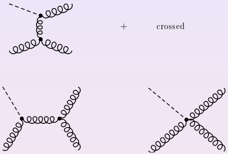


Figure: (Massò et al. Phys.Rev. D66 (2002).).

$$\Gamma_s = \left(\frac{\alpha_s}{2\pi f}\right)^2 g_s^2 T^3 \text{ vs. } H \approx \frac{T^2}{M_{Pl}}.$$

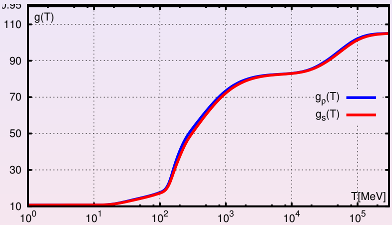
- At $T > T_{DEC} \equiv$ thermal equilibrium
- Example:
  1. $f = 10^8 GeV \implies T_{DEC} \approx TeV$
  2. $f = 10^9 GeV \implies T_{DEC} \approx 100 TeV$

QCD Axion through N_{eff}

- If a particle:
  1. Was in equilibrium at $T > T_{DEC}$
  2. Decouples at some $T \lesssim T_{DEC}$
  3. Has negligible mass
- After decoupling is dark radiation, (if $m \ll \mathcal{O}(0.1 \sim 1 eV)$) (like neutrinos)
- $\implies$ Observable by CMB (and BBN)
  (mostly affects expansion rate, Matter-Radiation equality...)
- Traditionally parameterized by effective neutrino number
- $N_{\mathrm{eff}} = 3.046 + \Delta N_{eff}$
- $\boxed{\Delta N_{eff} \approx \dfrac{13.6}{g_{*,DEC}^{4/3}}}$.

ΔN_{eff} diluted by $g_{*,DEC}$

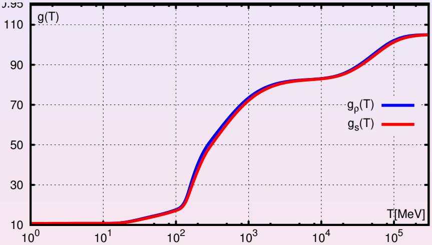
- Abundance ΔN_{eff} diluted if total number of relativistic species in the plasma $g_{*,DEC}$ is large



- $\boxed{\Delta N_{eff} \approx \dfrac{13.6}{g_{*,DEC}^{4/3}}}$
- If $T_{DEC} \gg 100$ GeV, $\Longrightarrow$ $\boxed{g_{*,DEC} \geq 106.75}$
- $\Longrightarrow$ $\Delta N_{eff} \lesssim 0.027$ (only upper bound!) (marginally detectable, 1 σ, by CMB-Stage 4 experiments)

QCD Axion through $N_{\rm eff}$

- If $f \lesssim 10^9$-10^{10} GeV dominant channels can be via quarks & leptons [2] with $T_{DEC} \leq$ Electroweak scale



ADVANTAGES:

1. g_*^{SM} is smaller $\Longrightarrow$ larger N_{eff}
2. Here we are confident on g_*^{SM} $\Longrightarrow$ Precise predictions
3. Lower f $\Longrightarrow$ more accessible by direct searches (CAST, IAXO)

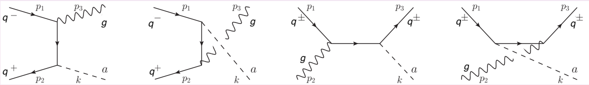
[2] A.N. & R.Z.Ferreira, PRL 2018; D'Eramo, Ferreira, A.N., Bernal JCAP 2018, F. Arias-Aragón et al. JCAP 2021.

QCD Axion through $N_{\rm eff}$

- If a is directly coupled to SM heavy quarks (c, b, t):

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

- Scattering rate (via quarks, *e.g.* $qg \leftrightarrow qa$) vs. Hubble



- If $m_q = 0 \implies$ the vertex vanishes
- Indeed:
  - This coupling can be rotated away $q \to e^{i \frac{c_i a}{2f} \gamma^5} q$
  - But it reappears in the mass term $m_q \bar{q} e^{i \frac{c_i a}{f} \gamma^5} q$

$$\Gamma_s = \left(\frac{c_i}{f}\right)^2 g_s^2 m_q^2 T \cdot e^{-\frac{m_q}{T}} \text{ vs. } H \approx \frac{T^2}{M_{Pl}}$$

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- Ratio peaks at $\boxed{T \approx m_q}$

- Axions produced dominantly via quarks

$$\boxed{1\ \mathrm{GeV} \lesssim T \lesssim 100\mathrm{GeV}}$$

- Range $10^9\mathrm{GeV} \gtrsim f/c_i \gtrsim 10^7\mathrm{GeV}$ [3]
  (partly in tension with SN bounds, if all $c_i = 1$)

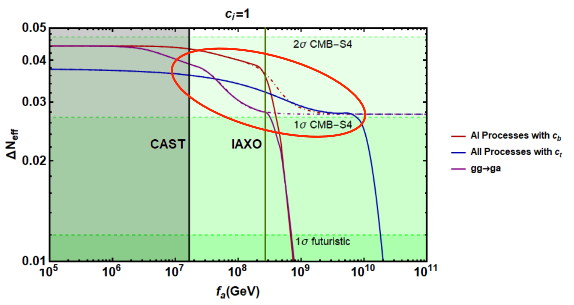
- Interesting for direct detection (*e.g.* IAXO),
  $m_a \approx 10^{-1} \sim 10^{-3} eV$, (+ *Hints from stellar cooling*)

[3] R.Ferreira & A.N., PRL 2018. See also Turner PRL 1987, Brust et al. JHEP 2013, Baumann et al. PRL 2016.

QCD Axion through $N_{\rm eff}$

- $g_{*,DEC}$ is smaller at $\boxed{1\ \mathrm{GeV} \lesssim T \lesssim 100\mathrm{GeV}}$
- Prediction: larger $N_{\rm eff} \lesssim 0.045$ *(*Not just upper bound!*)*
- Solving Boltzmann equations for n_a:

(R.Ferreira & A.N., PRL 2018; F.Arias-Aragon et al. JCAP, 2021)



$$10^9\mathrm{GeV} \gtrsim f/c_i \gtrsim 10^7\mathrm{GeV} \quad , 5\times 10^{-3}\mathrm{eV} \lesssim m_a \lesssim 0.5\mathrm{eV}$$

($c_i = 1$, for QCD Axion)

QCD Axion through $N_{\rm eff}$

Axions as Hot Relics

The QCD Axion

Axions via Gluons

Axion via Quarks

Axion via Leptons

Axions via Pions

- Potentially larger for c-quark: $N_{\rm eff} \lesssim 0.05 - 0.06$ (but uncertain)

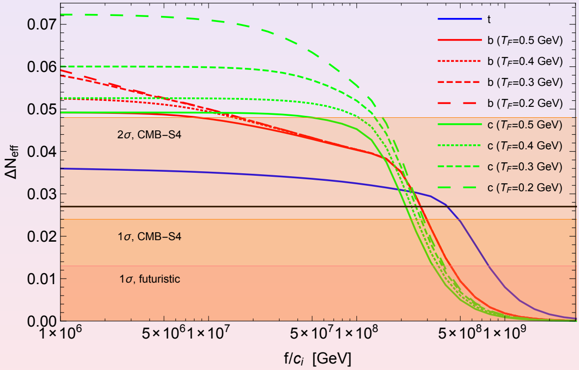
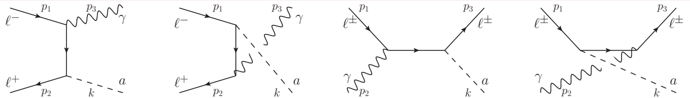


Figure: R.Ferreira & A.N., PRL 2018.

Hot Axions via Leptons

- The same can be done with leptons (μ and τ) [4]
- a-electron uninteresting (strongly constrained)
- Direct coupling to heavy leptons (μ, τ):

$$\mathcal{L}_{a-\ell} = \partial_\mu a \sum_i \frac{c_i}{2f} \bar{\ell}_i \gamma^\mu \gamma^5 \ell_i \,,$$

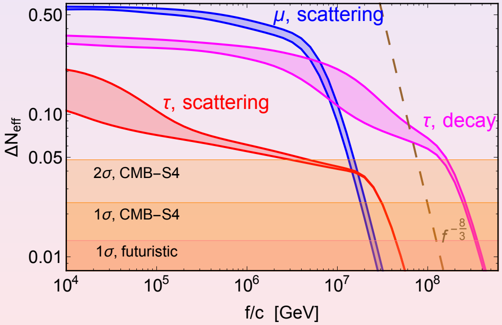


- Slightly smaller f/c_ℓ
- Ratio peaks at $\boxed{T \approx m_\ell}$ $\implies$ Larger N_{eff}

[4] F.D'Eramo, A.N.,R.Z.Ferreira, J.L.Bernal, JCAP 2018.

Hot Axions via Lepton Scatterings

- Smaller $f/c_i \lesssim \text{few} \cdot 10^7$ GeV
- Ratio peaks at $\boxed{T \approx m_\ell}$ $\Longrightarrow$ Larger N_{eff}



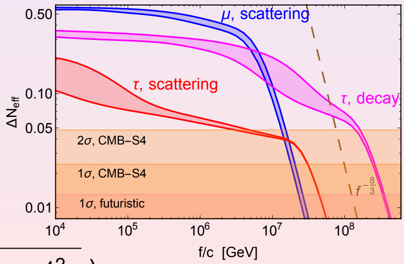
- Caveat: μ scattering constrained by SN cooling at $f/c_\mu \gtrsim 10^8 GeV$ (Bolling et al. PRL 2020, Croon et al. JHEP 2021)

Hot Axions via Lepton Decays

- $a - \ell$ interaction can be flavor non-diagonal

$$\mathcal{L}_{a-\ell} = \partial_\mu a \sum_{\ell \neq \ell'} \bar{\ell}' \gamma^\mu \left(\mathcal{V}_{\ell'\ell} + \mathcal{A}_{\ell'\ell}\gamma^5 \right) \ell + \text{h.c.} \, ,$$

- Decays $\tau \to \mu + a$, $\tau \to e + a$



$(c_{\ell\ell'} \equiv \sqrt{\mathcal{V}^2_{\ell'\ell} + \mathcal{A}^2_{\ell'\ell}}\,)$

- More efficient than scatterings (larger f/c)

Hot Axions via quark Decays

- *a*-quarks interaction can be also flavor non-diagonal

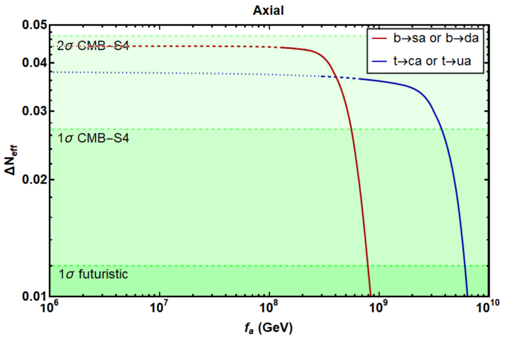


Figure: F.Arias-Aragon et al. JCAP 2021.

- More efficient than scatterings (larger $f/c \lesssim 10^{10}$ GeV)

Axion-Pion coupling

- DFSZ model: couples to u-type and d-type quarks,
- KSVZ model: no coupling to SM fermions

$$\textbf{DFSZ}: \quad c_u^0 = \frac{1}{3}\cos^2(\beta)\,, \quad c_d^0 = \frac{1}{3}\sin^2(\beta)\,,$$

$$\textbf{KSVZ}: \quad c_u^0 = c_d^0 = 0\,,$$

- Coupling to pions:

$$\mathcal{L}_{a\pi} = \frac{c_{a\pi}}{f_\pi}\frac{\partial_\mu a}{f}\left[2\partial^\mu\pi^0\pi^+\pi^- - \pi_0\left(\partial^\mu\pi^+\pi^- - \pi^+\partial^\mu\pi^-\right)\right],$$

where

$$c_{a\pi} = -\frac{1}{3}c_u^0 - c_d^0 - \frac{1-z}{1+z}\,. \qquad z \equiv \frac{m_u}{m_d} \simeq 0.47^{+0.06}_{-0.07},$$

$$\textbf{KSVZ}: \quad c_{a\pi} \simeq 0.12^{+0.023}_{-0.018}\,,$$

$$\textbf{DFSZ}: \quad c_{a\pi} \simeq 0.12^{+0.023}_{-0.018} - \frac{1}{9}\cos(2\beta)\,.$$

CMB Bounds on DFSZ

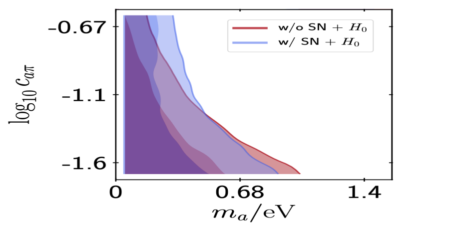


Figure: Constraints due to pion production Planck 18 + BAO (+ Pantheon + SH0ES H_0)

For DFSZ-II: muon production is also relevant for $c_{a\pi} \lesssim \mathcal{O}(0.1)$:

DFSZ-I	Planck 18+BAO (+SN+H_0)
$c_{a\pi} = 0.225$	$m_a \leq 0.20$ (0.29) eV
$c_{a\pi} = 0.0225$	$m_a \leq 0.84$ (0.82) eV

DFSZ-II	Planck 18+BAO (+SN+H_0)
$c_{a\pi} = 0.225$	$m_a \leq 0.20$ (0.29) eV
$c_{a\pi} = 0.0225$	$m_a \leq 0.60$ (0.61) eV

Caveat! Pion cross-section calculation should break down at $T \gtrsim 60$ MeV (Di Luzio et al. 2021, arXiv 2101.10330.)

Conclusions

1. If $f \lesssim \mathcal{O}(10^9)$ GeV, coupling with quarks and leptons (with $c_i = \mathcal{O}(1)$) dominates over $\frac{\alpha_s}{8\pi}\frac{a}{f}G\tilde{G}$
2. Efficiency peaks at $\boxed{T \approx m_f}$
3. For quarks (t, b): $N_{eff} \lesssim 0.05$ (*measurable at 2σ by CMB S4*) (*maybe higher for c-quark?)
4. For leptons (τ): $N_{eff} \lesssim 0.3$ (*measurable by CMB S4*)
5. Non-diagonal couplings $\Longrightarrow$ production via Decays more efficient $(f \lesssim \mathcal{O}(10^{10})$ GeV$)$
6. Large N_{eff} (~ 0.3) could alleviate H_0 tension
7. Pion production bound on DFSZ axion: $m_a \lesssim 0.2$ eV (at large $c_{a\pi}$), but relaxed $m_a \lesssim 0.6 - 0.8$ eV for small $c_{a\pi}$

   (*Caveat: Pion cross-section calculation should break down at $T \gtrsim 60$ MeV (Di Luzio et al. 2021))
8. Future CMB experiments will tell in a few years, plus direct detection (*e.g.* IAXO)