Cosmic Axion Background: the QCD axion as a hot relic

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talk @ PASCOS 2021.

[1] In collaboration with R.Z. Ferreira, F. Rompineve, F. D'Eramo, F. Arias-Aragon, J.L. Bernal, L.Merlo.

QCD Axion through $N_{\rm eff}$

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 $\not{CP}$ to zero
  3. $\implies$ Axion mass $m_a \approx 0.57\left(\frac{10^7\,GeV}{f}\right)$ eV

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- Bounds on $f \Leftrightarrow$ bounds on m_a

Axion: constraints

Axions as Hot Relics

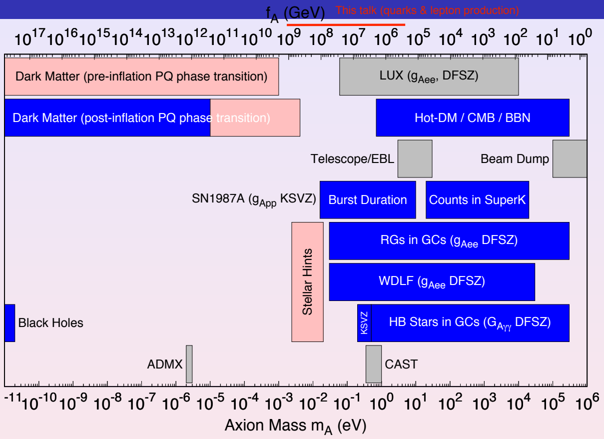
The QCD Axion

Axions via Gluons

Axion via Quarks

Axion via Leptons

Axions via Pions



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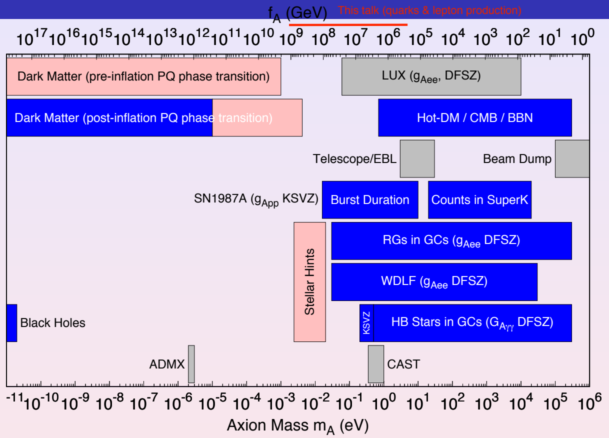

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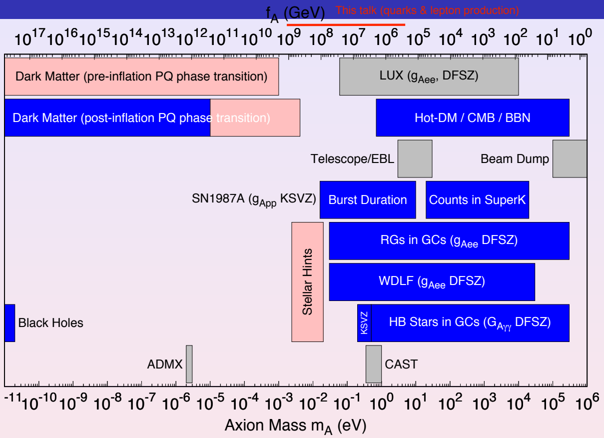

- Caveat: Constraints based on individual couplings with e, γ, nucleons... Expected $\mathcal{O}(1/f)$, but model dependent.
- Small $m_a \ll \mathcal{O}(eV) \implies$ acts as Dark Radiation, visible in CMB (*Cosmic Axion Background*)

QCD Axion

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

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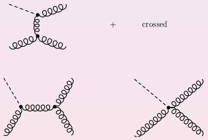

Figure: (Massò et al. Phys.Rev. D66 (2002).).

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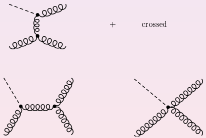

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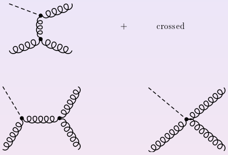

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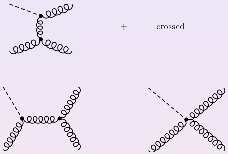

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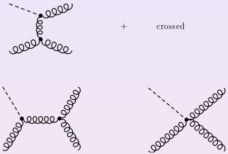

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- Example:
  1. $f = 10^8 GeV \implies T_{DEC} \approx TeV$
  2. $f = 10^9 GeV \implies T_{DEC} \approx 100 TeV$

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- $\boxed{\Delta N_{eff} \approx \frac{13.6}{g_{*,DEC}^{4/3}}}$.

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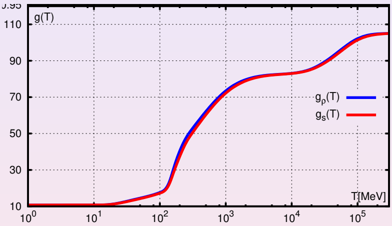

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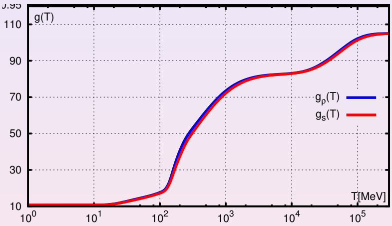

- $$\Delta N_{eff} \approx \frac{13.6}{g_{*,DEC}^{4/3}}$$
- If $T_{DEC} \gg 100$ GeV, $\implies$ $g_{*,DEC} \geq 106.75$
- $\implies$ $\Delta N_{eff} \lesssim 0.027$ (only upper bound!) (marginally detectable, 1 σ, by CMB-Stage 4 experiments)

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

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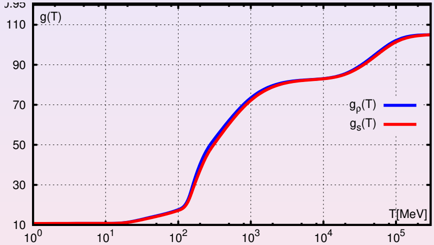

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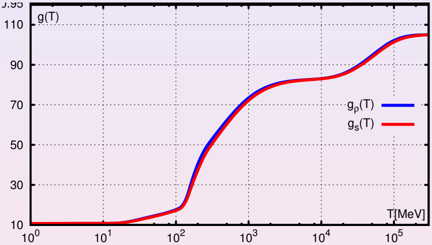

ADVANTAGES:

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)

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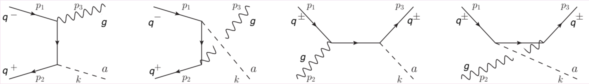

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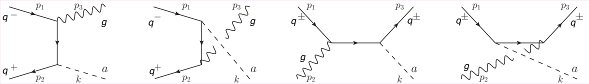

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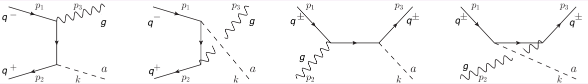

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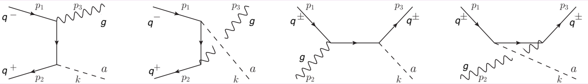

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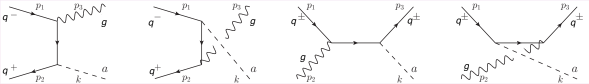

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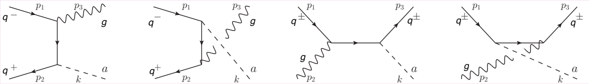

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- Axions produced dominantly via quarks

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

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

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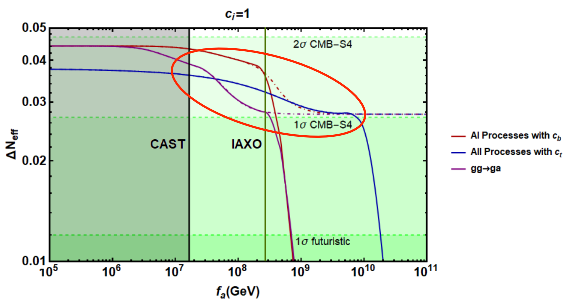
- Solving Boltzmann equations for n_a:

(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)

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

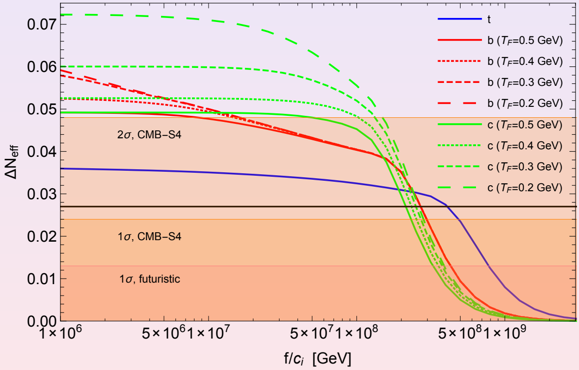

Figure: R.Ferreira & A.N., PRL 2018.

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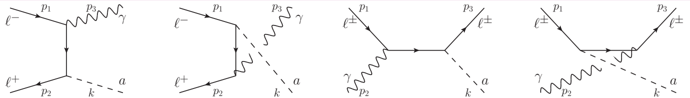

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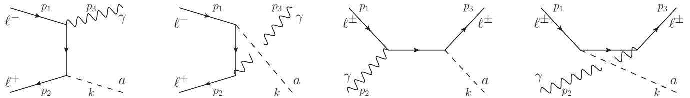
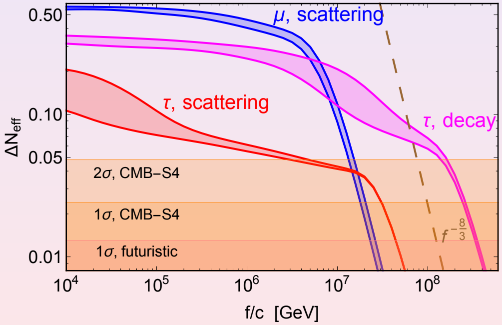


- Slightly smaller f/c_ℓ
- Ratio peaks at $\boxed{T \approx m_\ell}$ $\Longrightarrow$ Larger N_{eff}

[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 $\tau \to \mu + a$, $\tau \to e + a$

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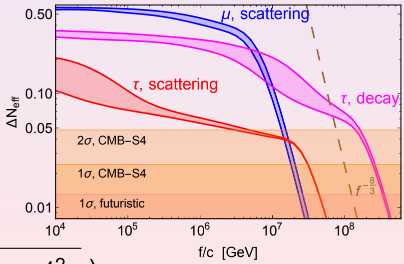

$\left(c_{\ell\ell'} \equiv \sqrt{\mathcal{V}^2_{\ell'\ell} + \mathcal{A}^2_{\ell'\ell}} \right)$

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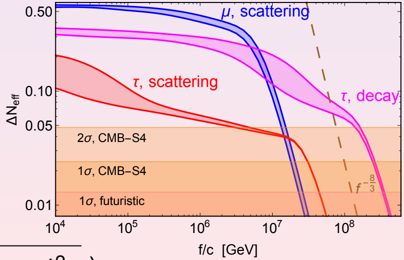

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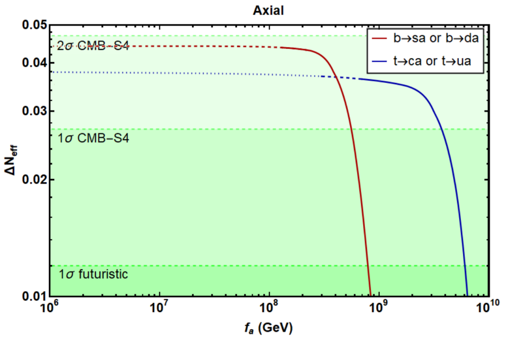

Figure: F.Arias-Aragon et al. JCAP 2021.

- 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

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

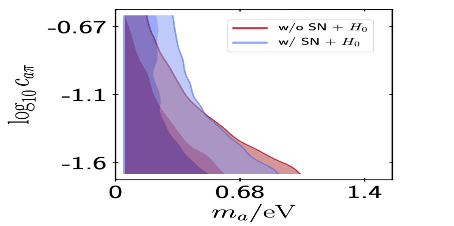

Figure: Constraints due to pion production Planck 18 + BAO (+ Pantheon + SH0ES H_0)

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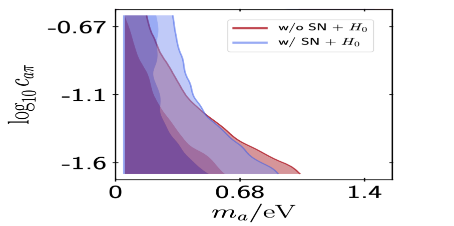

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For DFSZ-II: muon production is also relevant for $c_{a\pi} \lesssim \mathcal{O}(0.1)$:

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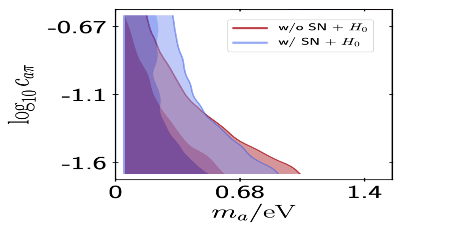

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Conclusions

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8. Future CMB experiments will tell in a few years, plus direct detection (*e.g.* IAXO)