Hot Axions and the H_0 tension

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talk @ Benasque, Light Scalars, 2019.

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

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

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- Bounds on $f \Leftrightarrow$ bounds on m_a

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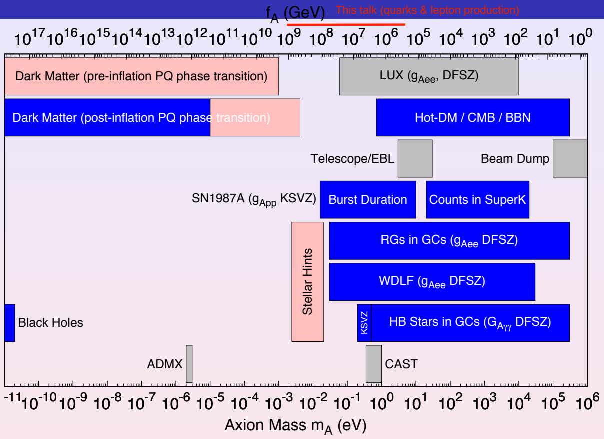

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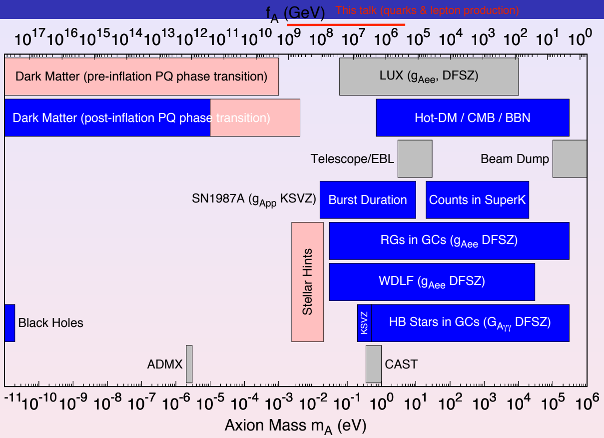

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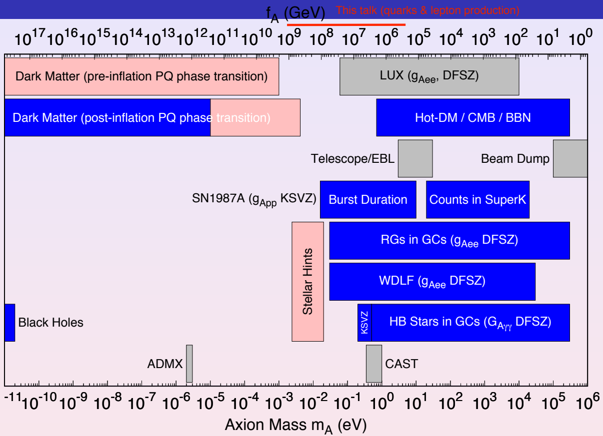

- Caveat: Constraints based on couplings with e, γ, nucleons... Expected $\mathcal{O}(1/f)$, but model dependent.
- Small $m_a \ll \mathcal{O}(eV) \implies$ acts as Radiation, visible in CMB (*Cosmic Axion Background*)

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- Terminology:
  1. If it couples to $G\tilde{G} \implies$ “QCD Axion"
  2. If not: $\implies$ Axion-Like Particle (“ALP")

Cosmic Axion Background via gluons

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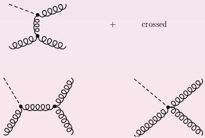

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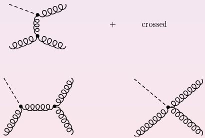

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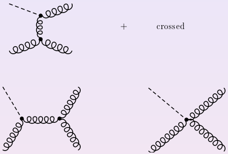

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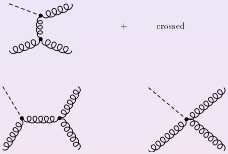

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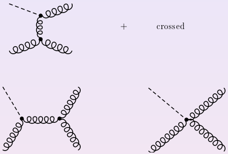

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- Example:
  1. $f = 10^9 GeV \implies T_{DEC} \approx 10 TeV$
  2. $f = 10^{10} GeV \implies T_{DEC} \approx 10^4 TeV$

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

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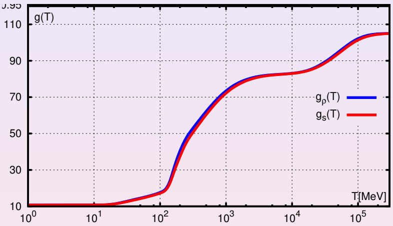

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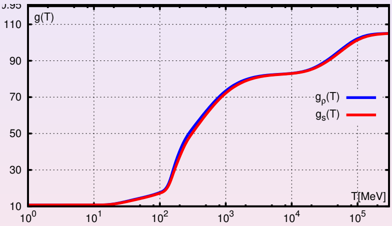

- $$\Delta N_{eff} \approx \frac{13.6}{g_{*,DEC}^{4/3}}$$
- If $T_{DEC} \gg 100$ GeV, $\Longrightarrow$ $g_{*,DEC} \geq 106.75$
- $\Longrightarrow$ $\Delta N_{eff} \lesssim 0.027$ (only upper bound!) (maybe detectable by CMB-Stage 4 experiments)

QCD Axion through N_{eff}

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

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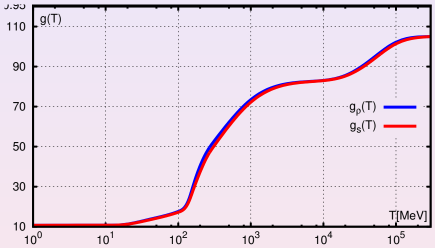

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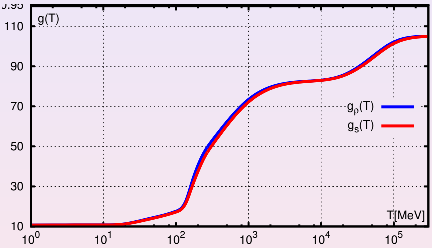

ADVANTAGES:

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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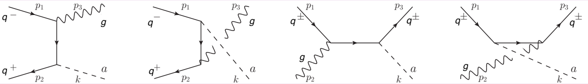

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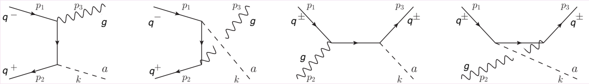

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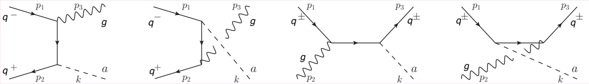

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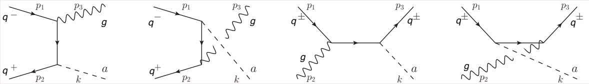

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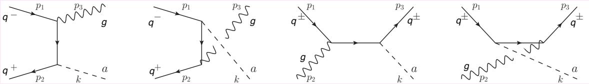

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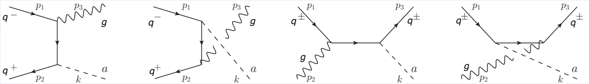

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- Axions/ALPs produced dominantly via quarks

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

- Range $10^9\text{GeV} \gtrsim f/c_i \gtrsim 10^7\text{GeV}$ [3]

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- Tension with SN bounds (for QCD Axion, $c_i = 1$)
- Interesting for direct detection (*e.g.* IAXO), $m_a \approx 10^{-1} \sim 10^{-3} eV$,

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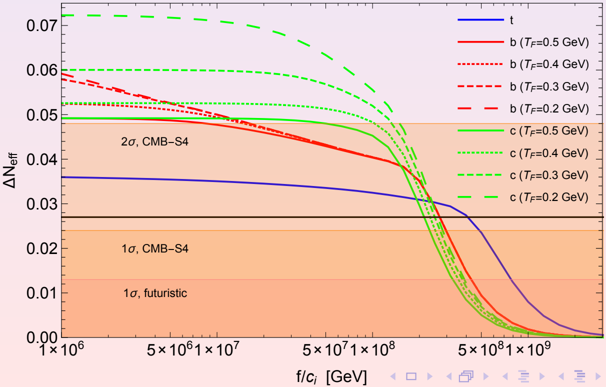
- Solving Boltzmann equations for n_a:



Interplay with IAXO

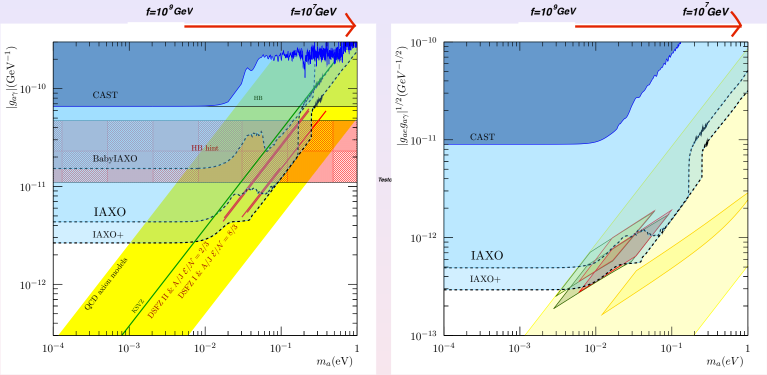


Figure: Physics potential of the International Axion Observatory (IAXO)

$$10^9\mathrm{GeV} \gtrsim f/c_i \gtrsim 10^7\mathrm{GeV}$$

$$5 \times 10^{-3}\mathrm{eV} \gtrsim m_a \gtrsim 0.5\mathrm{eV} \qquad (c_i = 1, \text{ for QCD Axion})$$

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- The same can be done with leptons (μ and τ) [4]
- *a*-electron uninteresting (strongly constrained)

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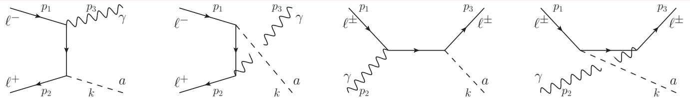

[4] F.D'Eramo, A.N.,R.Z.Ferreira, J.L.Bernal, JCAP 2018.

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):

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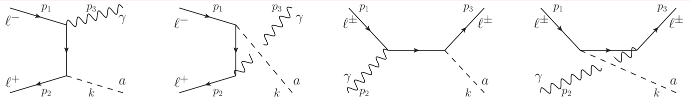
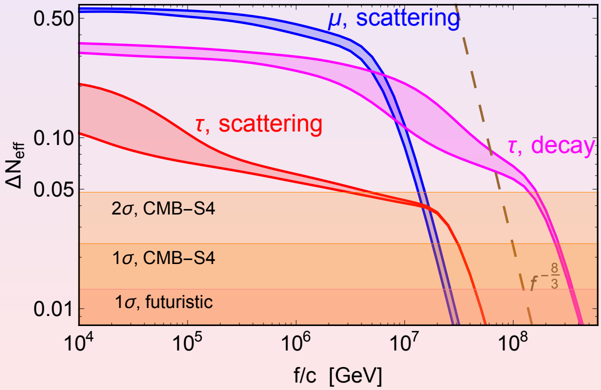


- Slightly smaller f/c_ℓ
- Ratio peaks at $\boxed{T \approx m_\ell}$ $\implies$ Larger N_{eff}

[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}



Hot Axions via Lepton Decays

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

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

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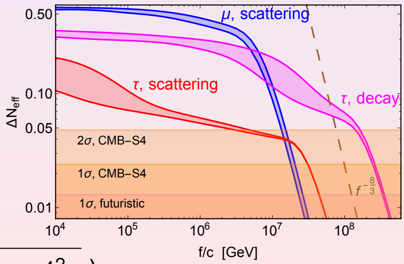

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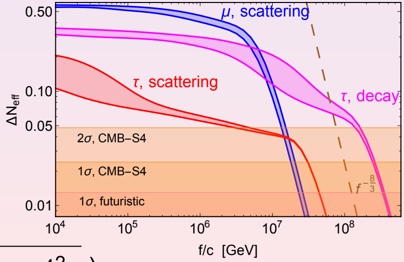

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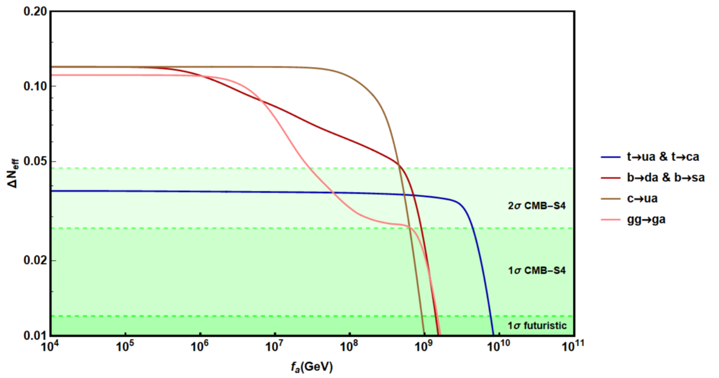

Figure: Preliminary.

- More efficient than scatterings (larger $f/c \lesssim 10^{10}$ GeV)
- Survives better SN bounds for QCD Axion (with $c_i = 1$)

H_0 tension

- Planck CMB data (2015 and recent 2018)

- Measured H_0 in tension with direct local measurements from SN [5]

[5] Planck 2018 results. VI. Cosmological parameters. Bernal, Verde & Riess JCAP 2016. Riess et al. Astrophys. J., 2018.

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  - $H_0 = 67.27 \pm 0.60$ km s^{-1} Mpc^{-1} (CMB)
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- Recently (Riess et al. 2019) claim: $H_0 = 74.03 \pm 1.42$ km s^{-1} Mpc^{-1} (SN) $\implies$ 4.4σ(!)

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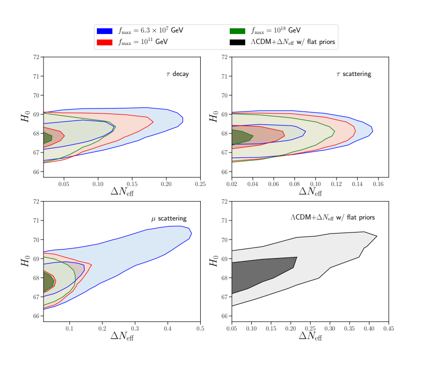

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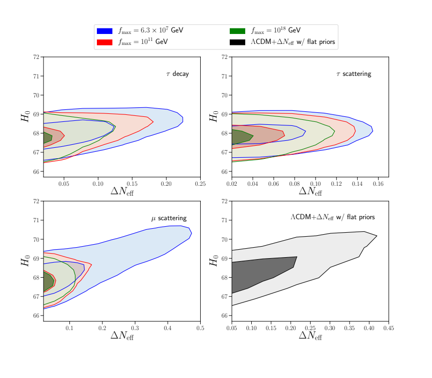

- Flat prior on $\log(f/c_i) \implies$ some prior dependence
- ALPs from μ scatterings can significantly increase H_0

Hot axions and H_0 tension

- Tension remains, but can be alleviated to $3.6\sigma \to 3\sigma$

Model	Coupling	Prior $(f/c)_{\rm max}$ [GeV]	H_0 [km s^{-1} Mpc^{-1}]	Tension (σ)
ΛCDM+$\Delta N_{\rm eff}$	μ scattering	3×10^7	$68.0^{+0.8}_{-0.7}\,(^{+2.3}_{-1.1})$	3.06 (2.75*)
		10^{11}	$67.8^{+0.6}_{-0.5}\,(^{+1.4}_{-1.1})$	3.36
		10^{18}	$67.7^{+0.5}_{-0.4}\,(^{+1.2}_{-1.0})$	3.38
	τ decay	6.3×10^7 GeV	$68.1^{+0.6}_{-0.5}\,(^{+1.2}_{-1.0})$	3.18
		10^{11}	$67.8^{+0.6}_{-0.5}\,(^{+1.2}_{-0.9})$	3.35
		10^{18}	$67.7^{+0.5}_{-0.4}\,(^{+1.1}_{-0.9})$	3.39
	τ scattering	5×10^8	$68.0^{+0.5}_{-0.5}\,(^{+1.0}_{-1.0})$	3.25
		10^{11}	$67.8^{+0.5}_{-0.5}\,(^{+1.1}_{-1.0})$	3.33
		10^{18}	$67.7^{+0.5}_{-0.5}\,(^{+1.1}_{-0.9})$	3.39
	Flat prior on N_{eff}	-	$68.3^{+0.8}_{-0.7}\,(^{+1.8}_{-1.2})$	2.93
ΛCDM	No coupling	-	$67.7^{+0.5}_{-0.4}\,(^{+0.9}_{-0.9})$	3.46

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- Tension with new Riess et al. 2019 SN claim, alleviated to $4.4\sigma \rightarrow 3.7\sigma$

Conclusions

1. If $f \lesssim \mathcal{O}(10^9)$ GeV, coupling with quarks and leptons (with $c_i = \mathcal{O}(1)$) dominates over $\frac{\alpha_s}{8\pi}\frac{a}{f}G\tilde{G}$
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7. Future CMB experiments will tell in a few years about the Axion (and H_0)
8. Interplay with direct detection (*e.g.* IAXO)