Observable windows for Axions as Hot Relics

Alessio Notari [1]

Universitat de Barcelona

talk @ Workshop on the Standard Model and Beyond, Corfu 2018.

[1] In collaboration with Ricardo Z. Ferreira, F. D'Eramo, J.L. Bernal

QCD Axion through N_{eff}

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

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

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

QCD Axion through N_{eff}

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

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

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

- Integrating by parts: $\mathcal{L}_a = \frac{\alpha_s}{8\pi}\frac{\partial_\mu a}{f}K^\mu$,

$\implies$ continuous shift symmetry $a \to a + c$

QCD Axion through N_{eff}

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

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

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

- Integrating by parts: $\mathcal{L}_a = \frac{\alpha_s}{8\pi} \frac{\partial_\mu a}{f} K^\mu$,

$\implies$ continuous shift symmetry $a \to a + c$

- But: boundary term sensitive to QCD Instantons,
  1. breaks to discrete $\frac{a}{f} \to \frac{a}{f} + 2\pi$.
  2. Induces a mass $m_a \approx \frac{\Lambda^2_{QCD}}{f}$

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

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

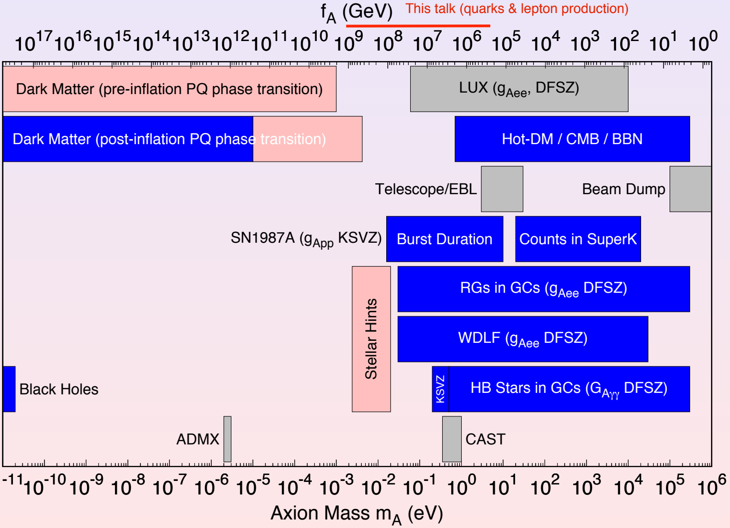
- Integrating by parts: $\mathcal{L}_a = \frac{\alpha_s}{8\pi}\frac{\partial_\mu a}{f} K^\mu$,

  $\implies$ continuous shift symmetry $a \to a + c$

- But: boundary term sensitive to QCD Instantons,
  1. breaks to discrete $\frac{a}{f} \to \frac{a}{f} + 2\pi$.
  2. Induces a mass $m_a \approx \frac{\Lambda^2_{QCD}}{f}$

- Present bounds on $f \implies m_a \ll 0.1 eV$ (or even less)

Axion: constraints



QCD Axion through $N_{\rm eff}$

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

QCD Axion through $N_{\rm eff}$

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

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

QCD Axion production in Early Universe

- 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

QCD Axion production in Early Universe

- 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)

QCD Axion production in Early Universe

- 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

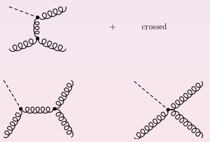


Figure: (Massò et al. Phys.Rev. D66 (2002).).

$$\Gamma_s \equiv \langle \sigma v \rangle \cdot n_g^{EQ} = \left(\frac{\alpha_s}{2\pi f}\right)^2 g_s^2 \cdot T^3$$

QCD Axion production in Early Universe

- 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

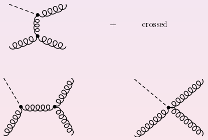


Figure: (Massò et al. Phys.Rev. D66 (2002).).

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

QCD Axion thermalization and decoupling

- Scattering rate (via gluons) vs. Hubble

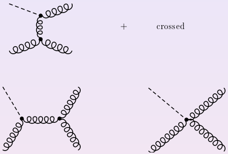


Figure: (Massò et al. Phys.Rev. D66 (2002).).

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

QCD Axion thermalization and decoupling

- Scattering rate (via gluons) vs. Hubble

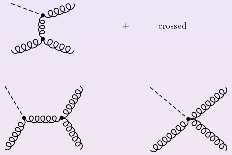


Figure: (Massò et al. Phys.Rev. D66 (2002).).

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

- At $T > T_{DEC} \equiv$ thermal equilibrium

QCD Axion thermalization and decoupling

- Scattering rate (via gluons) vs. Hubble

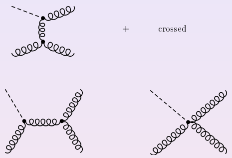


Figure: (Massò et al. Phys.Rev. D66 (2002).).

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

- At $T > T_{DEC} \equiv$ thermal equilibrium
- Example:
  1. $f = 10^9 GeV \implies T_{DEC} \approx 10 TeV$
  2. $f = 10^{10} GeV \implies T_{DEC} \approx 10^4 TeV$

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

QCD Axion through $N_{\rm eff}$

- 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 $n_a \propto a^{-3}$ and $\rho_a \propto a^{-4}$, acts as a hot relic (like neutrinos)
- Affects Matter-Radiation equality (if $m \ll \mathcal{O}(0.1 \sim 1eV)$)
  $\implies$ Observable by CMB (and BBN)

QCD Axion through $N_{\rm eff}$

- 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 $n_a \propto a^{-3}$ and $\rho_a \propto a^{-4}$, acts as a hot relic (like neutrinos)
- Affects Matter-Radiation equality (if $m \ll \mathcal{O}(0.1 \sim 1 eV)$) $\implies$ Observable by CMB (and BBN)
- Traditionally parameterized by effective neutrino number
- $N_{\rm eff} = 3.046 + \Delta N_{eff}$

QCD Axion through $N_{\rm eff}$

- 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 $n_a \propto a^{-3}$ and $\rho_a \propto a^{-4}$, acts as a hot relic (like neutrinos)
- Affects Matter-Radiation equality (if $m \ll \mathcal{O}(0.1 \sim 1eV)$) $\implies$ Observable by CMB (and BBN)
- Traditionally parameterized by effective neutrino number
- $N_{\rm eff} = 3.046 + \Delta N_{eff}$
- $\boxed{\Delta N_{eff} \approx \frac{13.6}{g_{*,DEC}^{4/3}}}$.

QCD Axion through $N_{\rm eff}$

- $$\Delta N_{eff} \approx \frac{13.6}{g_{*,DEC}^{4/3}}$$
- If $T_{DEC} \gg 100 GeV$ we only know
  $$g_{*,DEC} \geq g_{*,DEC}^{SM} = 106.75$$

QCD Axion through $N_{\rm eff}$

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

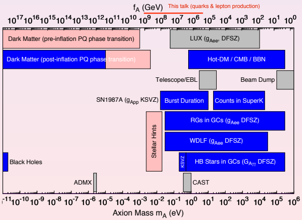
- If $T_{DEC} \gg 100\,GeV$ we only know

  $$g_{*,DEC} \geq g_{*,DEC}^{SM} = 106.75$$

- $\Longrightarrow \Delta N_{eff} \lesssim 0.027$ (only upper bound!)

QCD Axion through N_{eff}

- $$\Delta N_{eff} \approx \frac{13.6}{g_{*,DEC}^{4/3}}$$
- If $T_{DEC} \gg 100 GeV$ we only know
  $$g_{*,DEC} \geq g_{*,DEC}^{SM} = 106.75$$
- $\implies \Delta N_{eff} \lesssim 0.027$ (only upper bound!)



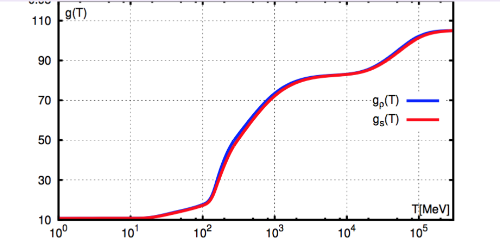
- Let's study $f \lesssim 10^9$ GeV
  $\implies T_{DEC} \leq$ Electroweak scale

QCD Axion through $N_{\rm eff}$

- Below EW scale ($f \lesssim 10^9$ GeV) dominant channels are via quarks & leptons (A.N. & R.Z.Ferreira, PRL 2018)

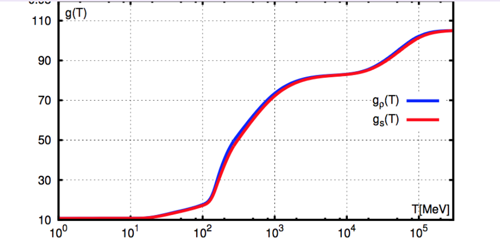
QCD Axion through $N_{\rm eff}$

- Below EW scale ($f \lesssim 10^9$ GeV) dominant channels are via quarks & leptons (A.N. & R.Z.Ferreira, PRL 2018)



QCD Axion through $N_{\rm eff}$

- Below EW scale ($f \lesssim 10^9$ GeV) dominant channels are via quarks & leptons (A.N. & R.Z.Ferreira, PRL 2018)



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)

QCD Axion through $N_{\rm eff}$

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

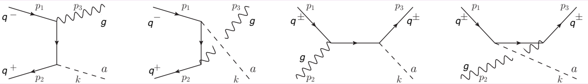
$$\mathcal{L}_{a-q} = \partial_\mu a \sum_i \frac{c_i}{2f} \bar{q}_i \gamma^\mu \gamma^5 q_i \, ,$$

QCD Axion through N_{eff}

- If a is directly coupled to 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

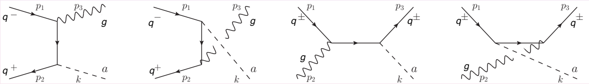


QCD Axion through $N_{\rm eff}$

- If a is directly coupled to 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



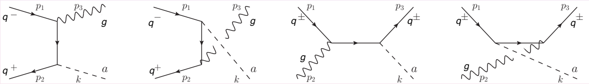
- If $m_q = 0 \implies$ the vertex vanishes

QCD Axion through N_{eff}

- If a is directly coupled to 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



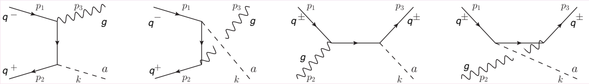
- If $m_q = 0 \implies$ the vertex vanishes
- In fact:
  - This coupling can be rotated away $q \to e^{i\frac{c_i a}{f}\gamma^5} q$
  - But it reappears in the mass term $m_q \bar{q} q$

QCD Axion through N_{eff}

- If a is directly coupled to 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
- In fact:
  - This coupling can be rotated away $q \to e^{i\frac{c_i a}{f}\gamma^5} q$
  - But it reappears in the mass term $m_q \bar{q} q$

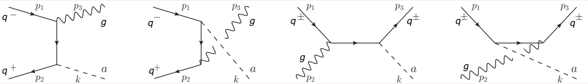
$\Gamma_s = \left(\frac{c_i}{f}\right)^2 g_s^2 m_q^2 T$

QCD Axion through N_{eff}

- If a is directly coupled to 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
- In fact:
  - This coupling can be rotated away $q \to e^{i\frac{c_i a}{f}\gamma^5} q$
  - But it reappears in the mass term $m_q \bar{q} q$

$$\Gamma_s = \left(\frac{c_i}{f}\right)^2 g_s^2 m_q^2 T \cdot e^{-\frac{m_q}{T}}$$

QCD Axion through $N_{\rm eff}$

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

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

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

QCD Axion through $N_{\rm eff}$

- If a is directly coupled to 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
- $\Gamma_s = \left(\frac{c_i}{f}\right)^2 g_s^2 m_q^2 T \cdot e^{-\frac{m_q}{T}}$ vs. $H \approx \frac{T^2}{M_{Pl}}$.

[2]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_{eff}

- If a is directly coupled to 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
- $\Gamma_s = \left(\frac{c_i}{f}\right)^2 g_s^2 m_q^2 T \cdot e^{-\frac{m_q}{T}}$ vs. $H \approx \frac{T^2}{M_{Pl}}$.
- Ratio peaks at $\boxed{T \approx m_q}$

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

QCD Axion through $N_{\rm eff}$

- If a is directly coupled to 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
- $\Gamma_s = \left(\frac{c_i}{f}\right)^2 g_s^2 m_q^2 T \cdot e^{-\frac{m_q}{T}}$ vs. $H \approx \frac{T^2}{M_{Pl}}$.
- Ratio peaks at $\boxed{T \approx m_q}$
- Axions produced dominantly via quarks

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

(for $10^7\mathrm{GeV} \lesssim f/c_i \lesssim 10^9\mathrm{GeV}$) [2]

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

QCD Axion through $N_{\rm eff}$

- If a is directly coupled to 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
- $\Gamma_s = \left(\frac{c_i}{f}\right)^2 g_s^2 m_q^2 T \cdot e^{-\frac{m_q}{T}}$ vs. $H \approx \frac{T^2}{M_{Pl}}$.
- Ratio peaks at $\boxed{T \approx m_q}$
- Axions produced dominantly via quarks

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

(for $10^7\mathrm{GeV} \lesssim f/c_i \lesssim 10^9\mathrm{GeV}$) [2]

- Range interesting for direct detection (*e.g.* IAXO), $m_a \approx 10^{-2} \sim 10^{-3} eV$,

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

QCD Axion through $N_{\rm eff}$

- If a is directly coupled to 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
- $\Gamma_s = \left(\frac{c_i}{f}\right)^2 g_s^2 m_q^2 T \cdot e^{-\frac{m_q}{T}}$ vs. $H \approx \frac{T^2}{M_{Pl}}$.
- Ratio peaks at $\boxed{T \approx m_q}$
- Axions produced dominantly via quarks

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

(for $10^7\mathrm{GeV} \lesssim f/c_i \lesssim 10^9\mathrm{GeV}$) [2]

- Range interesting for direct detection (*e.g.* IAXO), $m_a \approx 10^{-2} \sim 10^{-3} eV$, (+ Hints from stellar cooling)

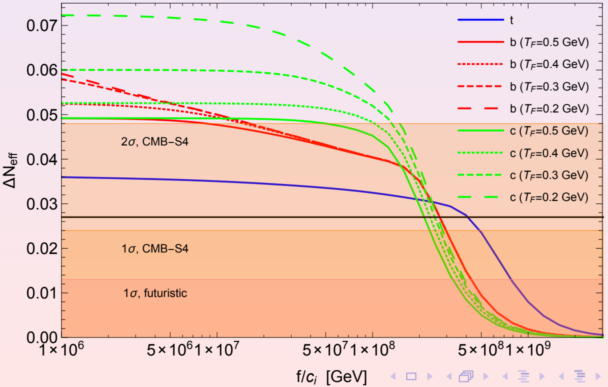
[2] R.Ferreira & A.N., PRL 2018. See also Turner PRL 1987, Brust et al. JHEP 2013, Baumann et al. PRL 2016.

QCD Axion through $N_{\rm eff}$

- $g_{*,DEC}$ is smaller at $\boxed{1\ \mathrm{GeV} \lesssim T \lesssim 100\mathrm{GeV}}$
- Prediction: larger $N_{\rm eff} \lesssim 0.05 - 0.06$
  *(*Not just upper bound!*)*

QCD Axion through N_{eff}

- $g_{*,DEC}$ is smaller at $\boxed{1\text{ GeV} \lesssim T \lesssim 100\text{GeV}}$
- Prediction: larger $N_{\text{eff}} \lesssim 0.05 - 0.06$ *(*Not just upper bound!*)*
- Solving Boltzmann equations for n_a:



Hot Axions via lepton scatterings

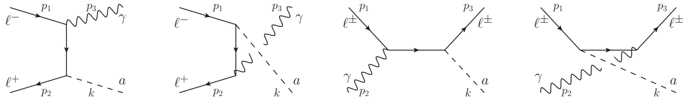
- The same can be done with leptons (μ and τ) [3]
- *a*-electron uninteresting (strongly constrained)

[3] arxiv:, F.D'Eramo, A.N.,R.Z.Ferreira, J.L.Bernal

Hot Axions via lepton scatterings

- The same can be done with leptons (μ and τ) [3]
- *a*-electron uninteresting (strongly constrained)
- Direct coupling to heavy leptons (μ, τ):

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

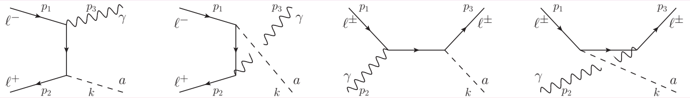


[3] arxiv:, F.D'Eramo, A.N.,R.Z.Ferreira, J.L.Bernal

Hot Axions via lepton scatterings

- The same can be done with leptons (μ and τ) [3]
- *a*-electron uninteresting (strongly constrained)
- Direct coupling to heavy leptons (μ, τ):

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



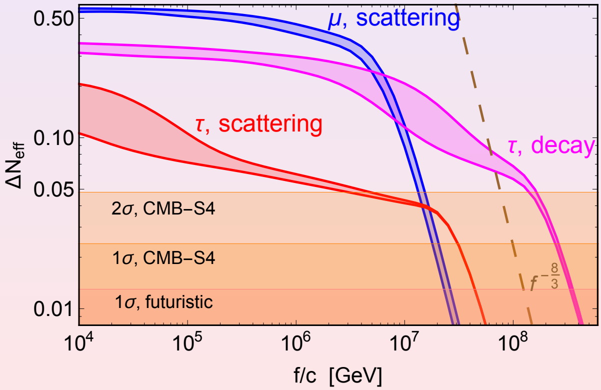
- Slightly smaller f/c_ℓ
- Ratio peaks at $\boxed{T \approx m_\ell}$ $\Longrightarrow$ Larger N_{eff}

[3] arxiv:, F.D'Eramo, A.N.,R.Z.Ferreira, J.L.Bernal

Hot Axions via lepton scatterings

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

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

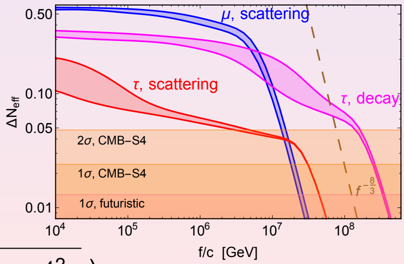
- Decays $\tau \to \mu + a$, $\tau \to e + a$

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



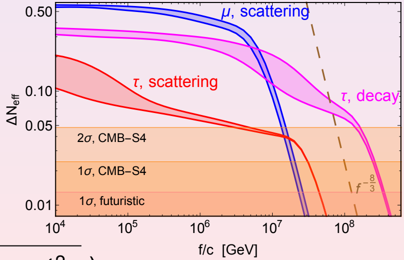
$$\left(c_{\ell\ell'} \equiv \sqrt{\mathcal{V}_{\ell'\ell}^2 + \mathcal{A}_{\ell'\ell}^2} \right)$$

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



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

- More efficient than scatterings (larger f/c)

H_0 tension

- Planck CMB data (2015 and recent 2018)
- Measured H_0 in tension with direct local measurements from SN

H_0 tension

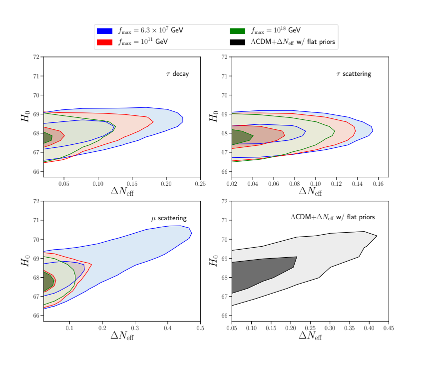
- Planck CMB data (2015 and recent 2018)
- Measured H_0 in tension with direct local measurements from SN
  - $H_0 = 67.27 \pm 0.60$ km s^{-1} Mpc^{-1} (CMB)
  - $H_0 = 73.52 \pm 1.62$ km s^{-1} Mpc^{-1} (SN)
- Tension at 3.6σ (3.46σ including BAO)

H_0 vs N_{eff}

- It is known that $\Delta N_{eff} > 0$ correlates with a higher Hubble constant H_0 from CMB

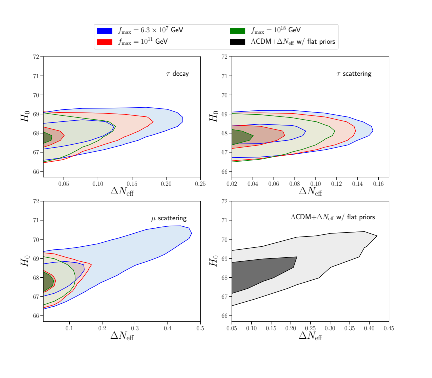
H_0 vs N_{eff}

- It is known that $\Delta N_{eff} > 0$ correlates with a higher Hubble constant H_0 from CMB



H_0 vs N_{eff}

- It is known that $\Delta N_{eff} > 0$ correlates with a higher Hubble constant H_0 from CMB



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

Hot axions and H_0 tension

- Tension remains, but can be alleviated to 3σ level

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

Conclusions

- If $f \lesssim \mathcal{O}(10^9)$ GeV, coupling with quarks and leptons (with $c_i = \mathcal{O}(1)$) dominates over $\frac{\alpha_s}{8\pi}\frac{a}{f}G\tilde{G}$
- Efficiency peaks at $\boxed{T \approx m_f}$

Conclusions

- If $f \lesssim \mathcal{O}(10^9)$ GeV, coupling with quarks and leptons (with $c_i = \mathcal{O}(1)$) dominates over $\frac{\alpha_s}{8\pi}\frac{a}{f}G\tilde{G}$
- Efficiency peaks at $\boxed{T \approx m_f}$
- For quarks $(t, b, c) \implies N_{eff} \lesssim 0.05 - 0.07$ (measurable at 2σ by CMB S4)
- For leptons $(\mu, \tau) \implies N_{eff} \lesssim 0.6 - 0.15$ (measurable by CMB S4)
- Non-diagonal couplings $\implies$ production via Decays at slightly higher f/c_i

Conclusions

- If $f \lesssim \mathcal{O}(10^9)$ GeV, coupling with quarks and leptons (with $c_i = \mathcal{O}(1)$) dominates over $\frac{\alpha_s}{8\pi}\frac{a}{f}G\tilde{G}$
- Efficiency peaks at $\boxed{T \approx m_f}$
- For quarks $(t, b, c) \implies N_{eff} \lesssim 0.05 - 0.07$ (measurable at 2σ by CMB S4)
- For leptons $(\mu, \tau) \implies N_{eff} \lesssim 0.6 - 0.15$ (measurable by CMB S4)
- Non-diagonal couplings $\implies$ production via Decays at slightly higher f/c_i
- μ production can alleviate H_0 tension to 3σ level

Conclusions

- If $f \lesssim \mathcal{O}(10^9)$ GeV, coupling with quarks and leptons (with $c_i = \mathcal{O}(1)$) dominates over $\frac{\alpha_s}{8\pi}\frac{a}{f}G\tilde{G}$
- Efficiency peaks at $\boxed{T \approx m_f}$
- For quarks $(t, b, c) \implies N_{eff} \lesssim 0.05 - 0.07$ (measurable at 2σ by CMB S4)
- For leptons $(\mu, \tau) \implies N_{eff} \lesssim 0.6 - 0.15$ (measurable by CMB S4)
- Non-diagonal couplings $\implies$ production via Decays at slightly higher f/c_i
- μ production can alleviate H_0 tension to 3σ level
- Future CMB experiments will tell in a few years about the Axion (and H_0)