NOVEL COSMOLOGICAL BOUNDS ON THERMALLY-PRODUCED AXION-LIKE PARTICLES

Luca Caloni
University of Ferrara & INFN

Based on JCAP09(2022)021,
with M. Gerbino, M. Lattanzi and L. Visinelli

PUMA22, 27/09/22

OUTLINE OF THE TALK

- The QCD axion and axion-like particles
- Why cosmology?
- Cosmo-phenomenology of thermal axions
- Analysis and results: cosmological bounds on the axion couplings to photons and gluons
- Conclusions and future perspectives

QCD AXION AND AXION-LIKE PARTICLES

- The QCD axion is a pseudo Nambu-Goldstone boson (PNG) resulting from the SSB of a global U(1) symmetry, introduced to solve the strong CP problem of QCD

[Peccei, Quinn: PRL 38 (1977) 1440–1443] [Weinberg: PRL 40 (1978) 223–226] [Wilczek: PRL 40 (1978) 279–282] [Georgi et al.: Phys. Lett. B 169 (1986) 73–78]

QCD AXION AND AXION-LIKE PARTICLES

- The QCD axion is a pseudo Nambu-Goldstone boson (PNG) resulting from the SSB of a global U(1) symmetry, introduced to solve the strong CP problem of QCD

- Axions are light and weakly coupled

$$g_a \propto m_a \propto \frac{1}{f_a}$$

⇨ difficult to detect directly, but important in the early Universe
⇨ cosmology plays a prominent role in constraining the physics of axions!

[Peccei, Quinn: PRL 38 (1977) 1440–1443] [Weinberg: PRL 40 (1978) 223–226] [Wilczek: PRL 40 (1978) 279–282] [Georgi et al.: Phys. Lett. B 169 (1986) 73–78]

QCD AXION AND AXION-LIKE PARTICLES

- The QCD axion is a pseudo Nambu-Goldstone boson (PNG) resulting from the SSB of a global U(1) symmetry, introduced to solve the strong CP problem of QCD

- Axions are light and weakly coupled

$$g_a \propto m_a \propto \frac{1}{f_a}$$

⇨ difficult to detect directly, but important in the early Universe
⇨ cosmology plays a prominent role in constraining the physics of axions!

- More in general, axion-like particles are PNGs characterized by an anomalous coupling to photons and gluons and are a common prediction of many theories BSM (e.g., string theory). The mass and couplings are decoupled!

[Peccei, Quinn: PRL 38 (1977) 1440–1443] [Weinberg: PRL 40 (1978) 223–226] [Wilczek: PRL 40 (1978) 279–282] [Georgi et al.: Phys. Lett. B 169 (1986) 73–78]

COSMO-PHENOMENOLOGY OF THERMAL AXIONS

- We consider thermal axions in the mass range $[10^{-4}, 100]\ \mathrm{eV}$

COSMO-PHENOMENOLOGY OF THERMAL AXIONS

- We consider thermal axions in the mass range $[10^{-4}, 100]\ \mathrm{eV}$
- Axions decouple at the temperature T_d , when freeze-out takes place: $\Gamma(T_d) \simeq H(T_d)$

COSMO-PHENOMENOLOGY OF THERMAL AXIONS

- We consider thermal axions in the mass range $[10^{-4}, 100]\ \mathrm{eV}$
- Axions decouple at the temperature T_d, when freeze-out takes place: $\Gamma(T_d) \simeq H(T_d)$

Small axion masses

- Light axions contribute to the energy density of radiation

$$\Delta N_{\rm eff} \equiv \frac{\rho_a(m_a = 0)}{\rho_{\nu,\rm mless}} \propto \left(\frac{g_a}{g_\gamma}\right)\left(\frac{T_a}{T_\gamma}\right)^4$$

$$\simeq 0.027 \left(\frac{g_{*s}(T_d)}{106.75}\right)^{-4/3}$$

$$\Delta N_{\rm eff}^{\rm CMB} \equiv \frac{\rho_a(m_a)}{\rho_{\nu,\rm mless}} \propto m_a g_{*s}(T_d)^{1/3}$$

COSMO-PHENOMENOLOGY OF THERMAL AXIONS

- We consider thermal axions in the mass range $[10^{-4}, 100]\ \mathrm{eV}$
- Axions decouple at the temperature T_d, when freeze-out takes place: $\Gamma(T_d) \simeq H(T_d)$

Small axion masses

- Light axions contribute to the energy density of radiation

$$\Delta N_{\rm eff} \equiv \frac{\rho_a(m_a = 0)}{\rho_{\nu,\rm mless}} \propto \left(\frac{g_a}{g_\gamma}\right)\left(\frac{T_a}{T_\gamma}\right)^4$$

$$\simeq 0.027 \left(\frac{g_{*s}(T_d)}{106.75}\right)^{-4/3}$$

$$\Delta N_{\rm eff}^{\rm CMB} \equiv \frac{\rho_a(m_a)}{\rho_{\nu,\rm mless}} \propto m_a g_{*s}(T_d)^{1/3}$$

Large axion masses

- Heavier axions contribute to the energy density of matter

$$\omega_a \simeq m_a n_a h^2 \simeq 0.011 \left(\frac{m_a}{\rm eV}\right) \Delta N_{\rm eff}^{3/4}$$

PRODUCTION OF THERMAL AXIONS

- Effective Lagrangian for the axion (QCD axion recovered for $m_0 = 0\,,\; C_g = 1$):

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \frac{\alpha_s}{8\pi}\frac{C_g}{f_a}\, a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} + \frac{1}{4}g^0_{a\gamma}\, a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

PRODUCTION OF THERMAL AXIONS

- Effective Lagrangian for the axion:

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \frac{\alpha_s}{8\pi}\frac{C_g}{f_a}\, a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} + \frac{1}{4} g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Explicit mass term

PRODUCTION OF THERMAL AXIONS

- Effective Lagrangian for the axion:

Axion-photon coupling

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \frac{\alpha_s}{8\pi}\frac{C_g}{f_a} a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} + \frac{1}{4} g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Explicit mass term

Axion-gluon coupling

PRODUCTION OF THERMAL AXIONS

- Effective Lagrangian for the axion:

Axion-photon coupling

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \frac{\alpha_s}{8\pi}\frac{C_g}{f_a}\, a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} + \frac{1}{4} g^0_{a\gamma}\, a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Explicit mass term

Axion-gluon coupling

- We focus on thermal axions, that are produced in the early Universe from scatterings involving particles in the primordial thermal bath at temperatures >> axion mass

PRODUCTION OF THERMAL AXIONS

- Effective Lagrangian for the axion:

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \frac{\alpha_s}{8\pi}\frac{C_g}{f_a} a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} + \frac{1}{4}g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Explicit mass term: $\frac{1}{2}m_0^2 a^2$

Axion-gluon coupling: $\frac{\alpha_s}{8\pi}\frac{C_g}{f_a} a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i}$

Axion-photon coupling: $\frac{1}{4}g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$

- We focus on thermal axions, that are produced in the early Universe from scatterings involving particles in the primordial thermal bath at temperatures >> axion mass
- We consider production processes involving either the axion-photon or the axion-gluon coupling

PRODUCTION OF THERMAL AXIONS

- Effective Lagrangian for the axion:

Axion-photon coupling

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \frac{\alpha_s}{8\pi}\frac{C_g}{f_a} a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} + \frac{1}{4}g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Explicit mass term

Axion-gluon coupling

- We focus on thermal axions, that are produced in the early Universe from scatterings involving particles in the primordial thermal bath at temperatures >> axion mass

- We consider production processes involving either the axion-photon or the axion-gluon coupling

Primakoff effect, i.e. photon conversion to axions in the presence of charged particles

$$Q + \gamma \to Q + a$$

[Bolz, Brandenburg, Buchmuller: hep-ph/0012052]
[Cadamuro, Redondo: 1110.2895]

PRODUCTION OF THERMAL AXIONS

- Effective Lagrangian for the axion:

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \frac{\alpha_s}{8\pi}\frac{C_g}{f_a} a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} + \frac{1}{4}g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Explicit mass term — Axion-gluon coupling — Axion-photon coupling

- We focus on thermal axions, that are produced in the early Universe from scatterings involving particles in the primordial thermal bath at temperatures >> axion mass

- We consider production processes involving either the axion-photon or the axion-gluon coupling

- Above QCDPT: $g + g \longrightarrow g + a\,, \quad q + \bar{q} \longrightarrow g + a\,, \quad q/\bar{q} + g \longrightarrow q/\bar{q} + a$
- Below QCDPT: $\pi^+\pi^- \longrightarrow \pi^0 + a\,, \quad \pi^+ + \pi^0 \longrightarrow \pi^+ + a\,, \quad \pi^- + \pi^0 \longrightarrow \pi^- + a$

[D'Eramo et al.: 2108.04259] [Di Luzio et al.: 2101.10330]

PRODUCTION OF THERMAL AXIONS

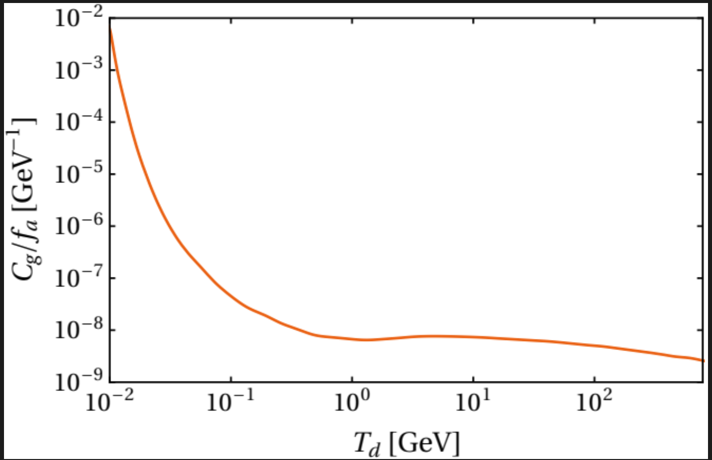
- Effective Lagrangian for the axion:

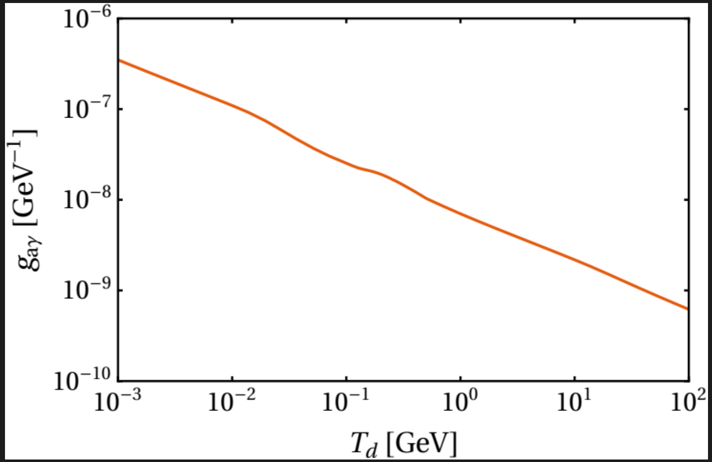
$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \frac{\alpha_s}{8\pi}\frac{C_g}{f_a} a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} + \frac{1}{4}g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Explicit mass term

Axion-gluon coupling

Axion-photon coupling





AXION-PHOTON COUPLING: AXION DECAY INTO PHOTONS

- The axion-photon coupling induces also the decay of axions into a pair of photons, with rate

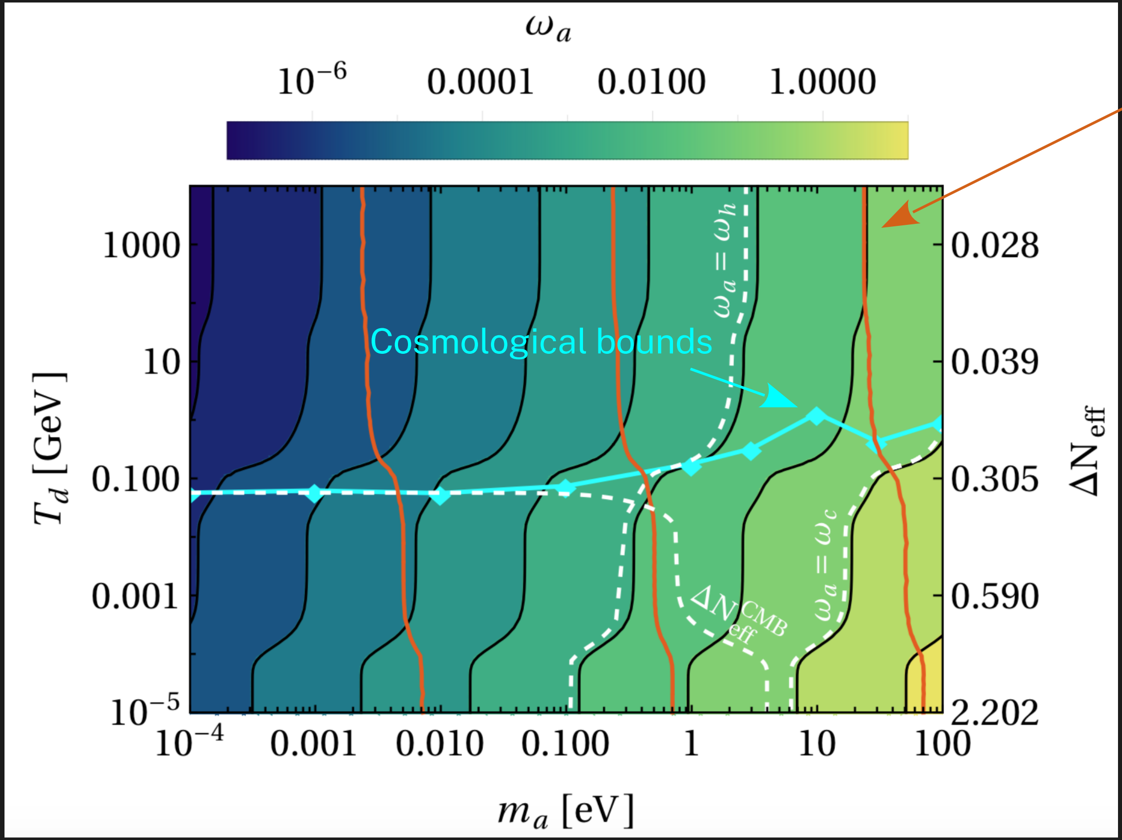
$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi}$$

- The axion is a stable relic over cosmological timescales if the decay time is larger than the current age of the Universe. This leads to the requirement

$$\frac{\Gamma_{a\to\gamma\gamma}}{H_0} \simeq 3.48\times 10^{-2}\left(\frac{g_{a\gamma}}{10^{-7}\,\mathrm{GeV}^{-1}}\right)^2\left(\frac{m_a}{\mathrm{eV}}\right)^3 \ll 1$$

- The decay of axions would be accompanied by a reduction of their cosmological abundance and an injection of photons with energy $= m_a/2$. We do not consider this region of the parameter space in the results

COSMOLOGICAL BOUNDS



Lines of constant

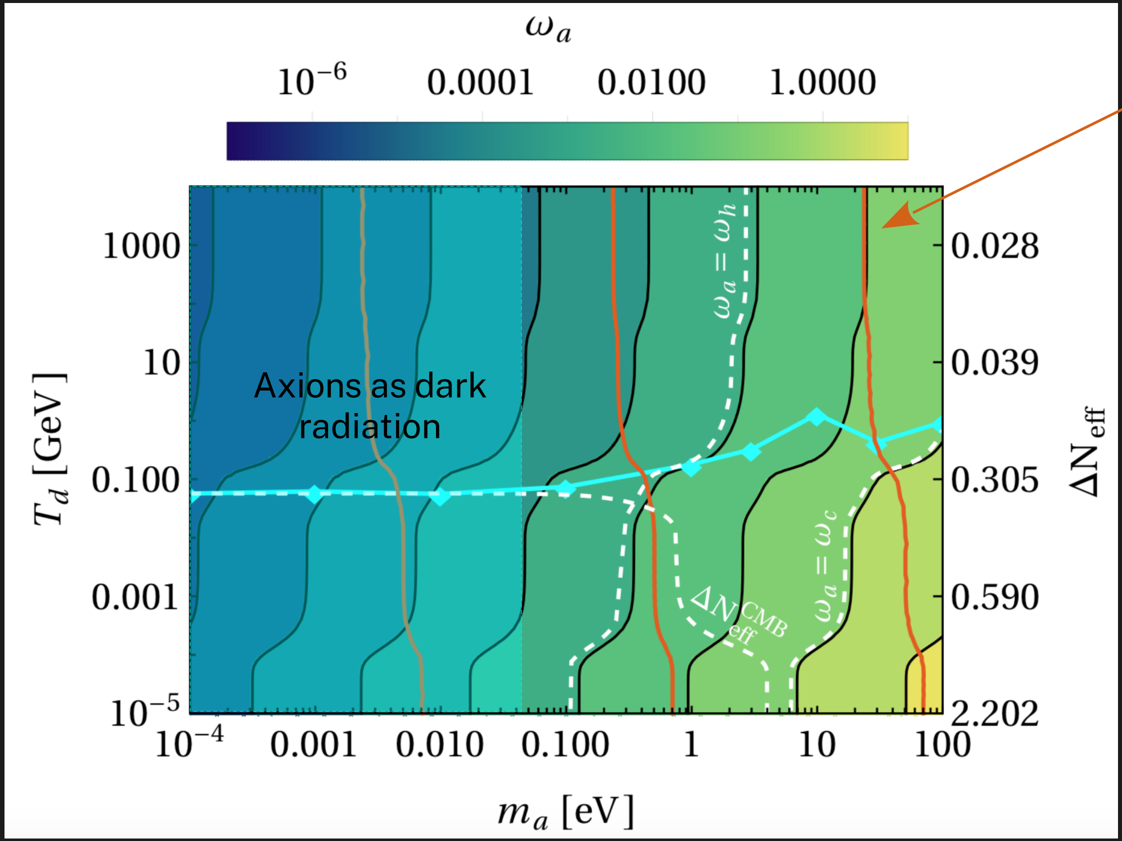
$$\frac{\langle p_{a,\rm rec}\rangle}{m_a} = \{10^2, 1, 10^{-2}\}$$

$$\Lambda\mathrm{CDM} + m_a + \Delta N_{\rm eff}$$

Data:

- CMB: Planck TTTEEE
- BAO: BOSS + 6dF + SDSS

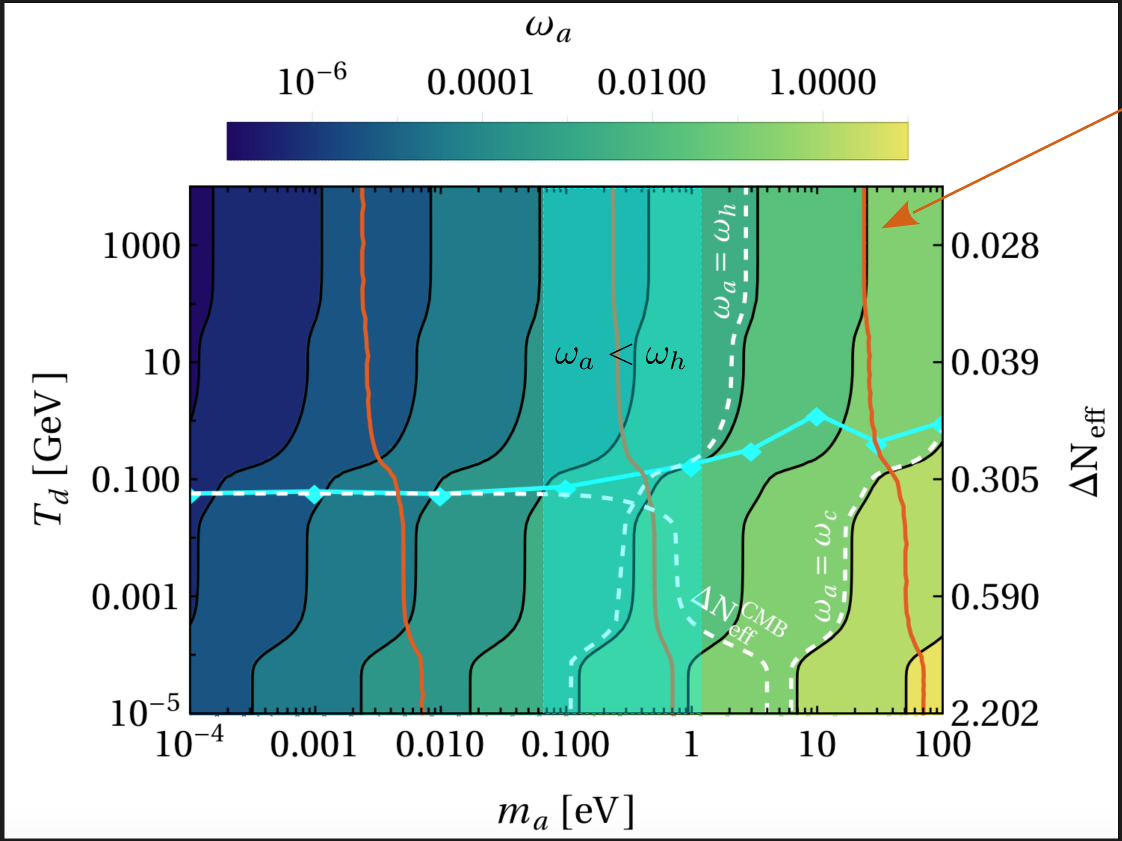
COSMOLOGICAL BOUNDS



Lines of constant

$$\frac{\langle p_{a,\rm rec}\rangle}{m_a} = \{10^2, 1, 10^{-2}\}$$

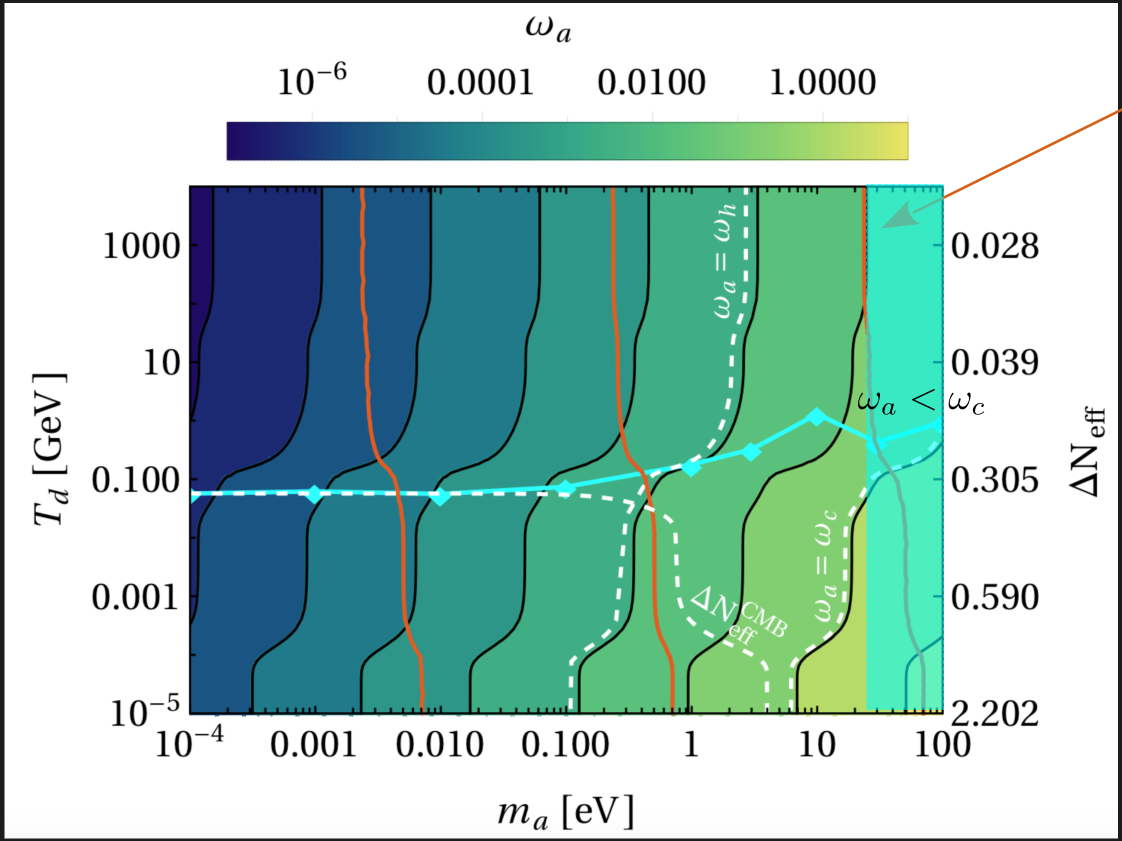
COSMOLOGICAL BOUNDS



Lines of constant

$$\frac{\langle p_{a,\rm rec}\rangle}{m_a} = \{10^2, 1, 10^{-2}\}$$

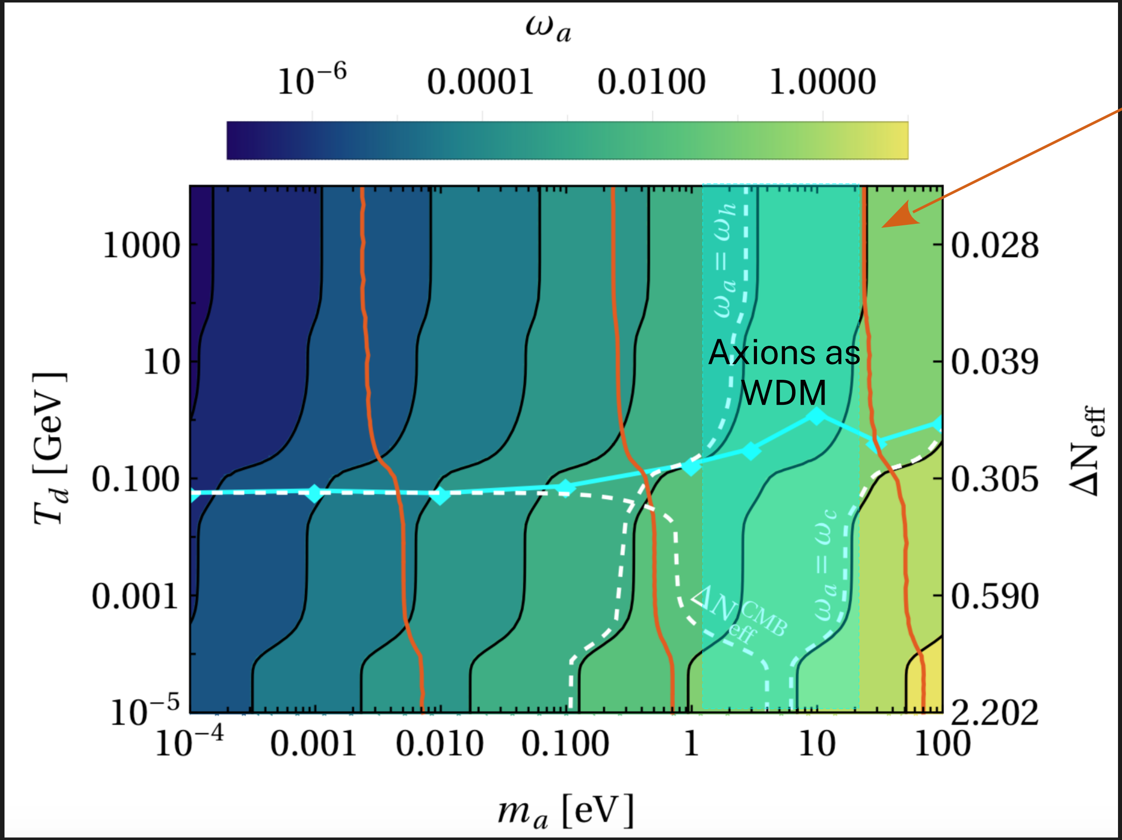
COSMOLOGICAL BOUNDS



Lines of constant

$$\frac{\langle p_{a,\rm rec}\rangle}{m_a} = \{10^2, 1, 10^{-2}\}$$

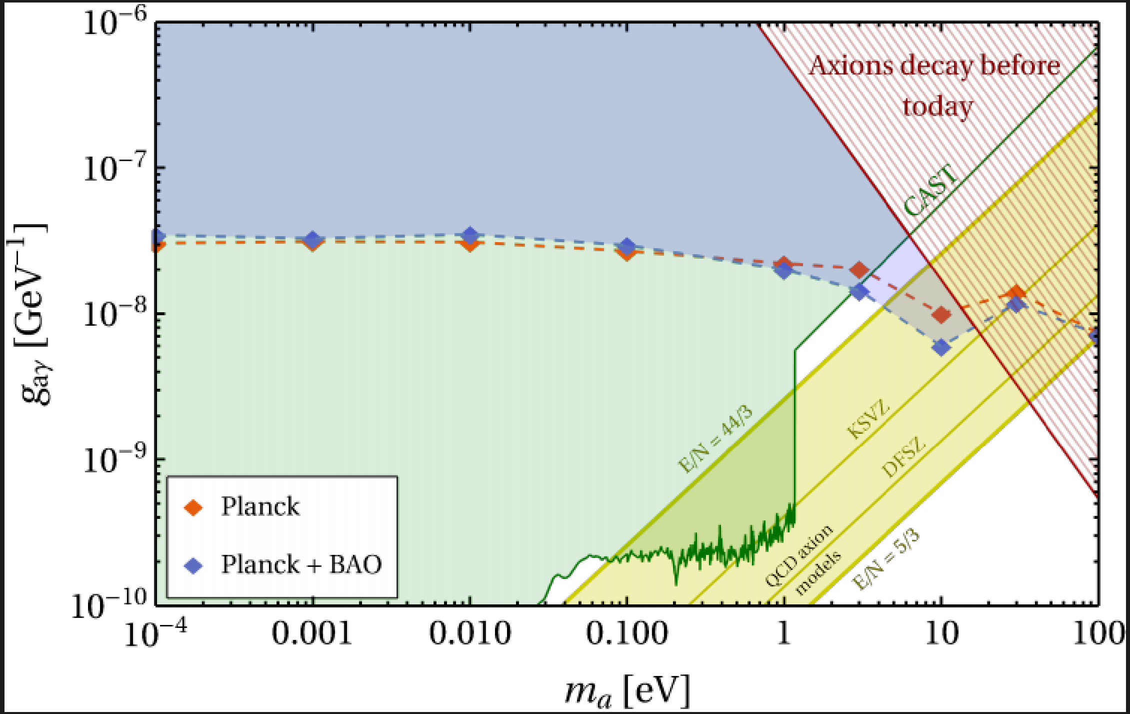
COSMOLOGICAL BOUNDS



Lines of constant

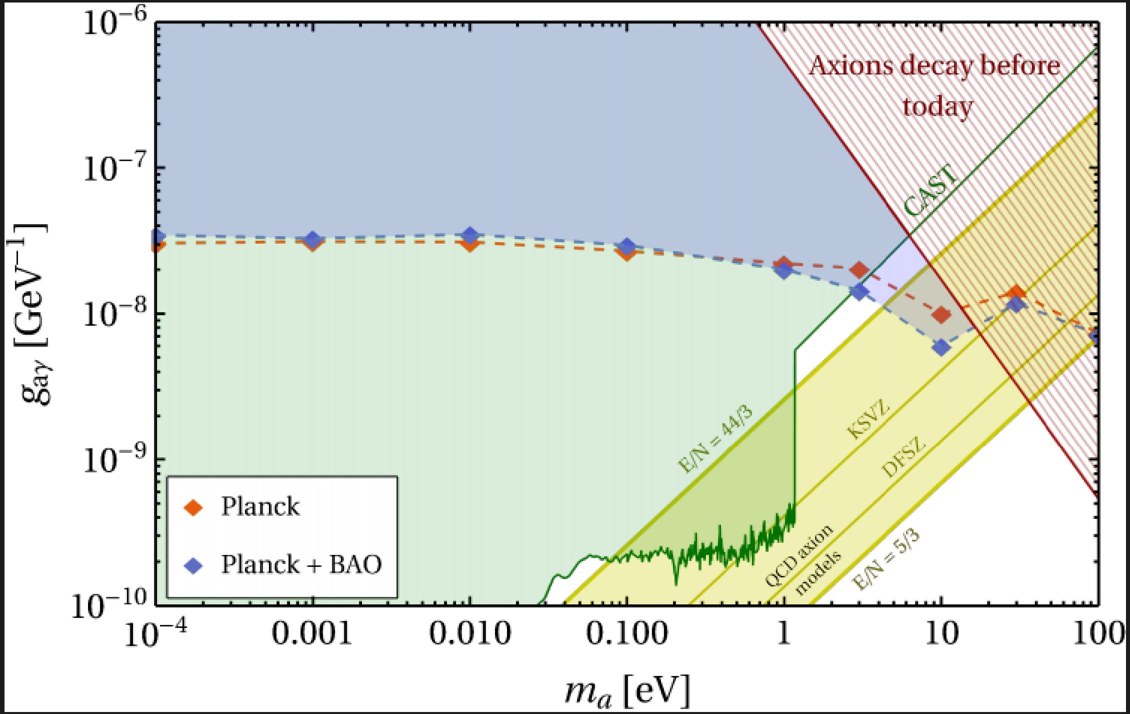
$$\frac{\langle p_{a,\rm rec}\rangle}{m_a} = \{10^2, 1, 10^{-2}\}$$

BOUNDS ON THE AXION-PHOTON COUPLING



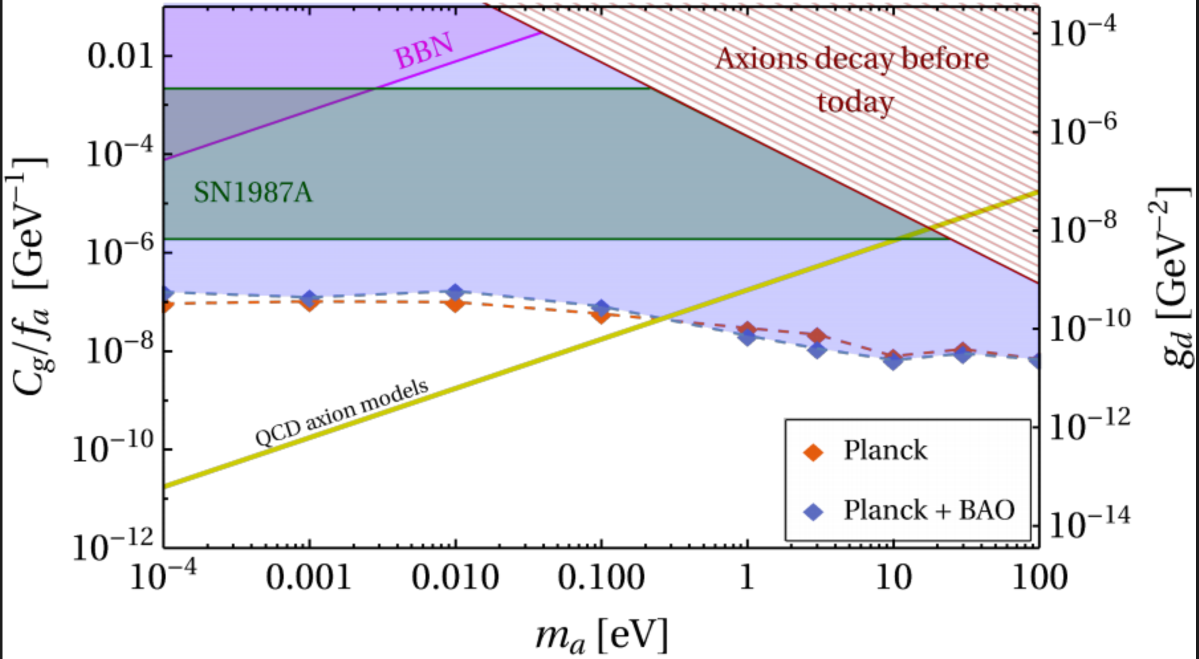
- Bounds stronger than those from CAST for $m_a > 3$ eV

BOUNDS ON THE AXION-PHOTON COUPLING



- Bounds stronger than those from CAST for $m_a > 3$ eV
- Stronger bounds from stellar evolution, but <u>the cosmological constraints are independent and complementary</u>

BOUNDS ON THE AXION-GLUON COUPLING



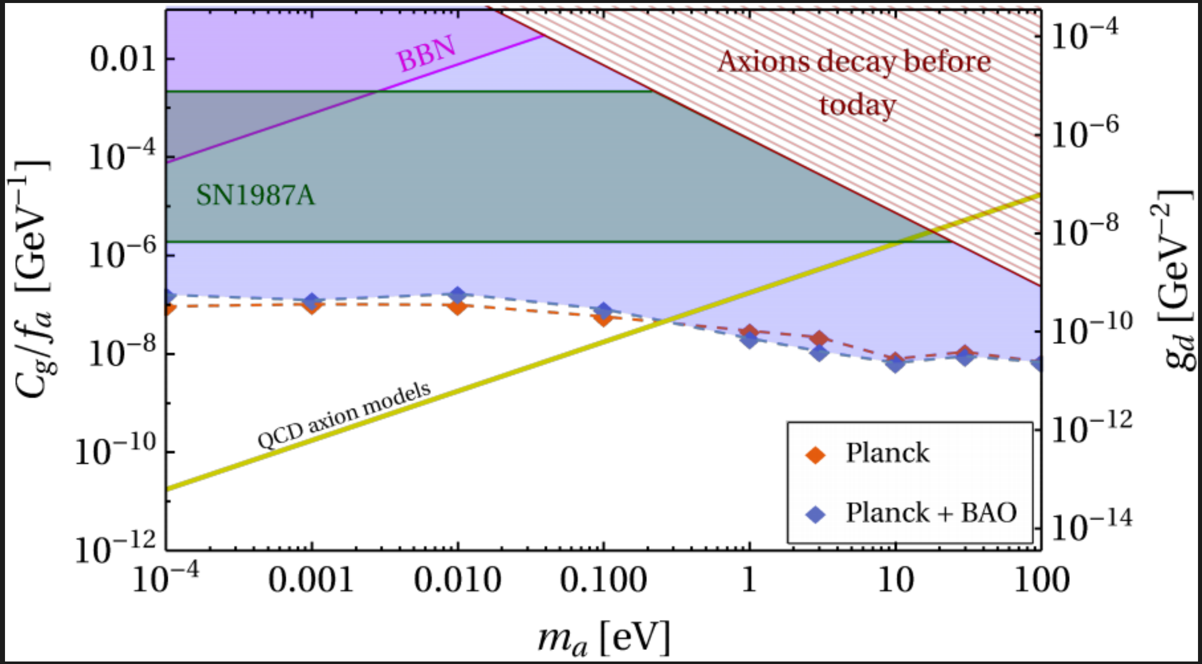
- Electric dipole moment of the neutron:

$$d_n = g_d a_0 \cos(m_a t)\,, \quad g_d = \frac{C_{an\gamma}}{m_n}\frac{C_g}{f_a}$$

[Pospelov, Ritz: hep-ph/9904483]

[Graham, Rajendran: 1306.6088]

BOUNDS ON THE AXION-GLUON COUPLING



- NOTE: cosmology constrains C_g/f_a while SN constrain g_d

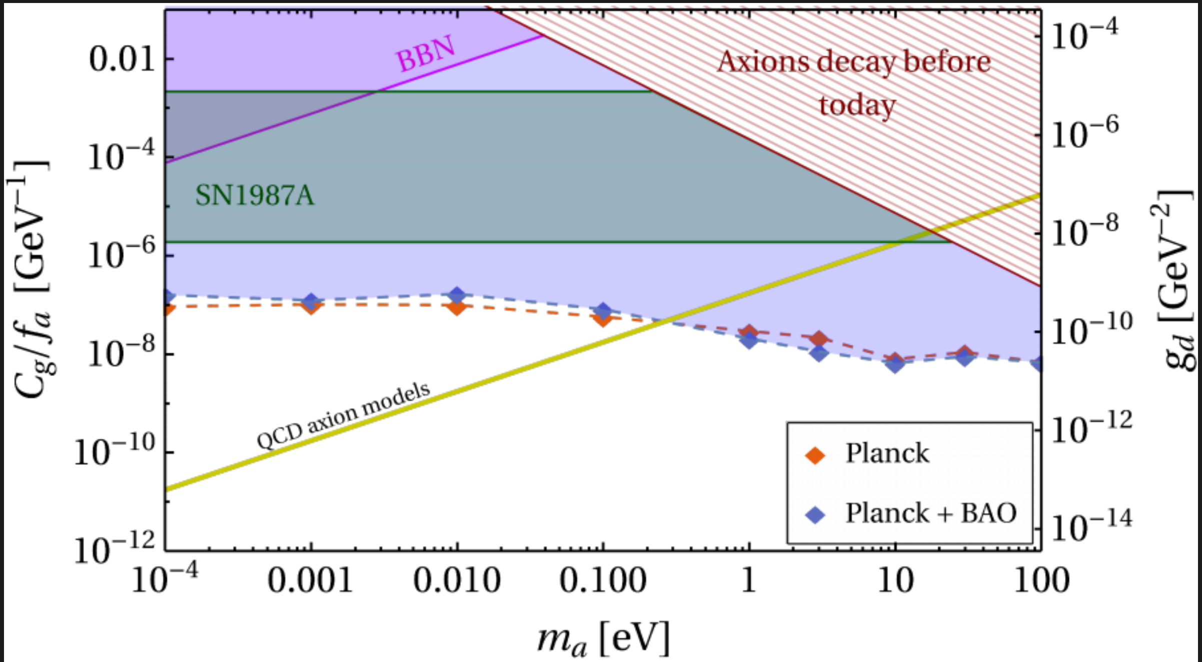
- Electric dipole moment of the neutron:

$$d_n = g_d a_0 \cos(m_a t)\,, \quad g_d = \frac{C_{an\gamma}}{m_n}\frac{C_g}{f_a}$$

[Pospelov, Ritz: hep-ph/9904483]

[Graham, Rajendran: 1306.6088]

BOUNDS ON THE AXION-GLUON COUPLING



- NOTE: cosmology constrains C_g/f_a while SN constrain g_d
- KSVZ (QCD) axion:

$$f_a > 2 \times 10^7 \text{ GeV} \Rightarrow m_a < 0.3 \text{ eV}$$

- Electric dipole moment of the neutron:

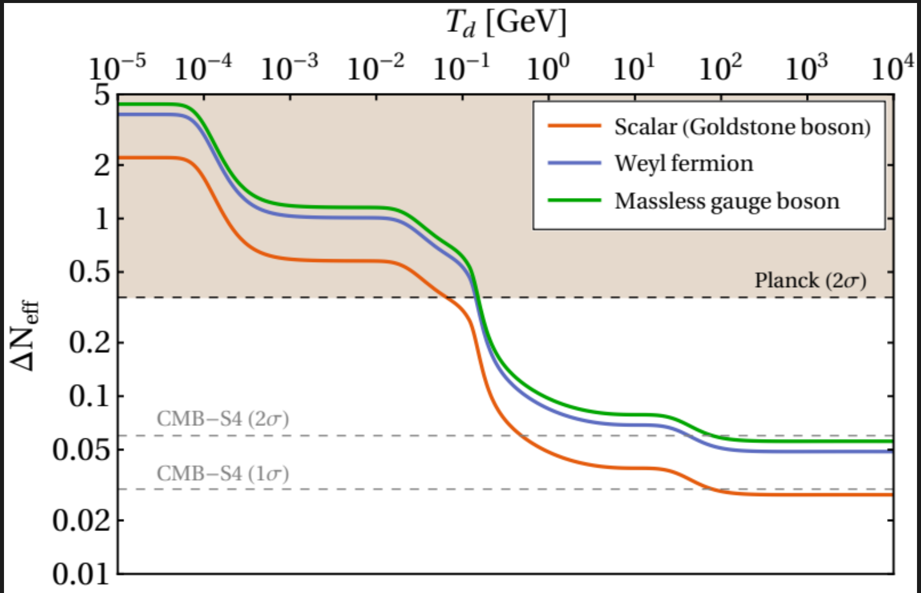
$$d_n = g_d a_0 \cos(m_a t)\,, \qquad g_d = \frac{C_{an\gamma}}{m_n}\frac{C_g}{f_a}$$

[Pospelov, Ritz: hep-ph/9904483]

[Graham, Rajendran: 1306.6088]

FUTURE PERSPECTIVES

- For light axions, behaving as dark radiation ($m_a \lesssim 10^{-2}\,\mathrm{eV}$) CMB-S4 will allow us to probe (at 95% CL)



$$\frac{C_g}{f_a} \lesssim 8 \times 10^{-9}\ \mathrm{GeV}^{-1}$$

$$g_{a\gamma} \lesssim 10^{-8}\ \mathrm{GeV}^{-1}$$

CONCLUSIONS

- We have derived cosmological constraints on thermal axions
- Assuming that the production of axions is dominated by either axion-photon or axion-gluon processes, we have derived bounds on the couplings as a function of the axion mass
- The bounds on the axion-photon coupling are competitive with those from the CAST collaboration for axion masses > 3 eV
- The bounds on the axion-gluon coupling are stronger than those derived from SN1987A energy loss consideration
- Future perspectives: - small scale CMB data (ACT)
  - future CMB experiments (CMB-S4)

Thanks for your attention!

AXIONS AND AXION-LIKE PARTICLES

- The QCD axion is a pseudo Nambu-Goldstone boson (PNG) resulting from the SSB of a global U(1) symmetry, introduced to solve the strong CP problem of QCD. More in general, axion-like particles are PNGs characterized by an anomalous coupling to photons and gluons and are a common prediction of many theories BSM
- Effective axion Lagrangian below the energy scale f_a (at which the symmetry is broken):

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_0^2 a^2 + \frac{\alpha_s}{8\pi}\frac{C_g}{f_a}\, a G^i_{\mu\nu}\tilde{G}^{\mu\nu,i} + \frac{1}{4}g^0_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- The axion-gluon term can be reabsorbed by a field-dependent axial rotation of the quark fields ($q \to e^{i\gamma_5 \frac{a}{2f_a} Q_a} q$), such that the effective mass squared reads $(z = m_u/m_d)$

$$m_a^2 = m_0^2 + \left(\frac{C_g}{f_a}\right)^2 F_\pi^2 m_\pi^2 \frac{z}{(1+z)^2} \approx m_0^2 + \left(5.8\,\mu\text{eV}\,\frac{10^{12}\,\text{GeV}}{f_a/C_g}\right)^2$$

and the effective coupling of the axion with the photon is (for QCD axions, $g^0_{a\gamma} \propto 1/f_a$)

$$g_{a\gamma} = g^0_{a\gamma} - \frac{\alpha_{\text{EM}}}{3\pi}\frac{C_g}{f_a}\frac{4+z}{1+z} \approx g^0_{a\gamma} - 2.3\times 10^{-15}\,\text{GeV}^{-1}\left(\frac{10^{12}\,\text{GeV}}{f_a/C_g}\right)$$

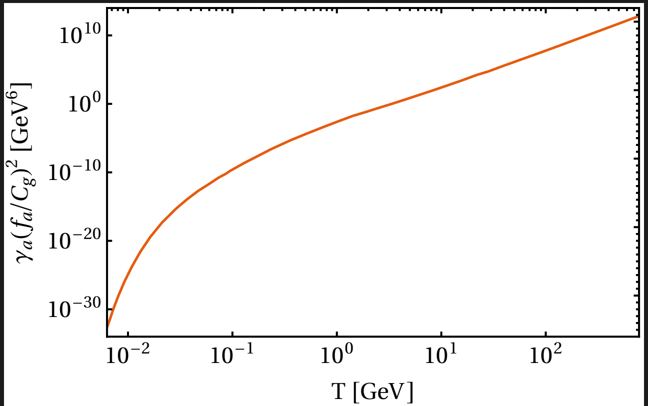
[Peccei, Quinn: PRL 38 (1977) 1440–1443] [Wilczek: PRL 40 (1978) 279–282] [Georgi et al.: Phys. Lett. B 169 (1986) 73–78.]

AXION-GLUON COUPLING

- We adopt the results of [D'Eramo et al.: 2108.04259], where the axion production rate has been computed for T > 2 GeV and T < 62 MeV (at T > 62 MeV chiral perturbation theory breaks down and the calculation for the axion-pion scattering rates is not reliable anymore, see [Di Luzio et al.: 2101.10330]). At intermediate T, it has been obtained by interpolating between the two regimes

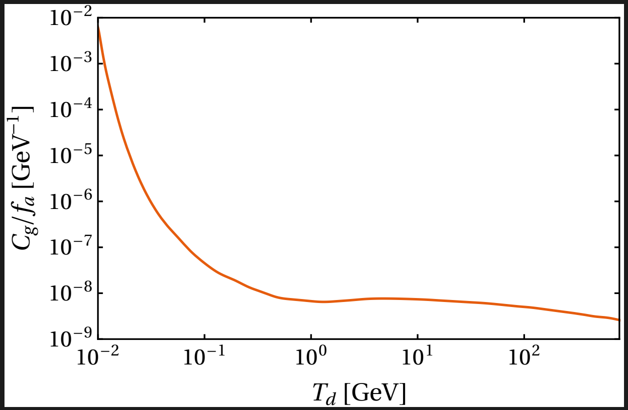
Relevant processes:

- Above QCDPT: $g + g \longrightarrow g + a\,, \quad q + \bar{q} \longrightarrow g + a\,, \quad q/\bar{q} + g \longrightarrow q/\bar{q} + a$
- Below QCDPT: $\pi^+\pi^- \longrightarrow \pi^0 + a\,, \quad \pi^+ + \pi^0 \longrightarrow \pi^+ + a\,, \quad \pi^- + \pi^0 \longrightarrow \pi^- + a$



Freeze-out:

$$H(T_d) \simeq \Gamma \equiv \frac{\gamma}{n_a^{\rm eq}(T_d)}$$



AXION-PHOTON COUPLING

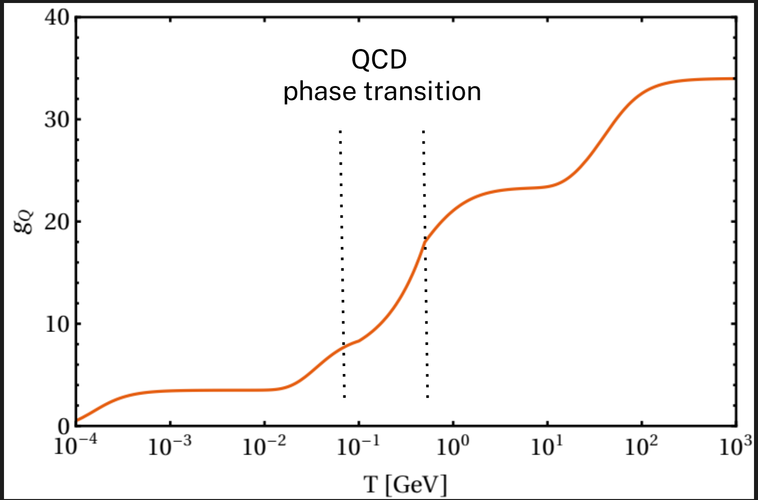
- The leading contribution to axion production is the Primakoff effect, i.e. photon conversion to axions in the presence of charged particles

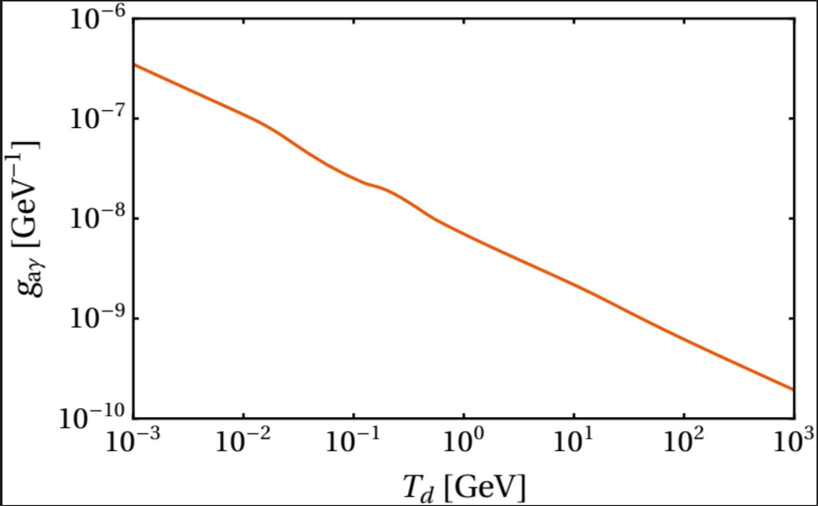
[Bolz, Brandenburg, Buchmuller: hep-ph/0012052]
[Cadamuro, Redondo: 1110.2895]

$$\Gamma_{Q\gamma\to Qa} \simeq \frac{\alpha_{\rm EM} g_{a\gamma}^2 \pi^2}{36\zeta(3)} \left[\log\left(\frac{T^2}{m_\gamma^2}\right) + 0.82\right] n_Q$$

Freeze-out:
$H(T_d) \simeq \Gamma$

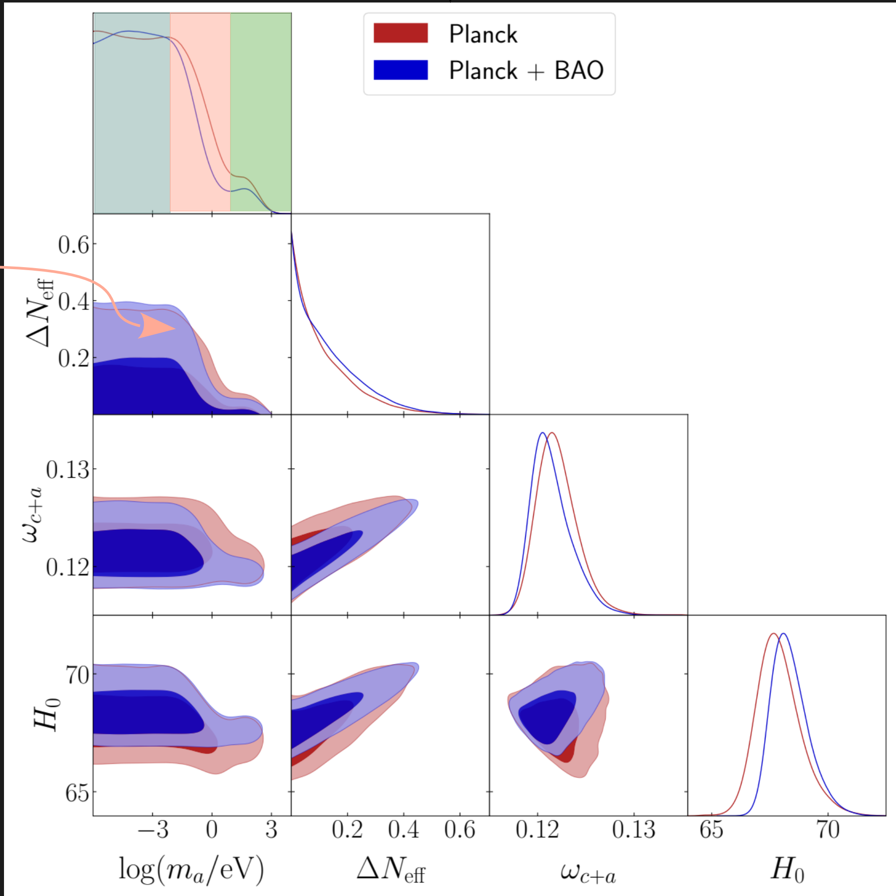
$$g_{a\gamma} \simeq 10^{-8} \times \frac{\sqrt{g_*}}{g_Q} \left(\frac{T_d}{\rm GeV}\right)^{-1} \, {\rm GeV}^{-1}$$



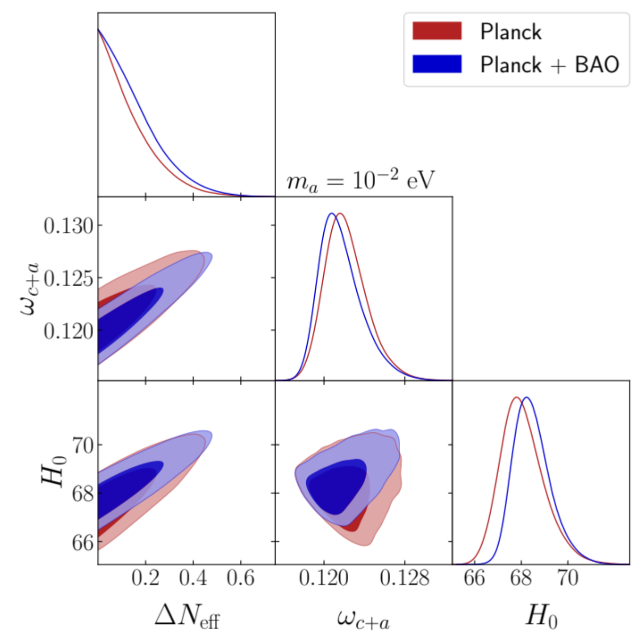


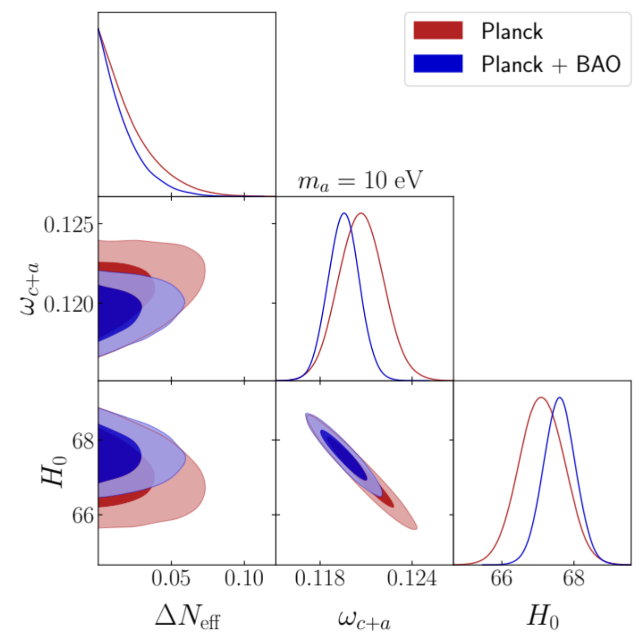
COSMOLOGICAL ANALYSIS AND RESULTS

- Axions behave as hot DM ⟹ mostly constrained by $\Delta N_{\rm eff}$ (flat distribution)
- Increasing the axion mass, we are increasing the abundance of hot DM. Hence, axions must decouple earlier (cut-off in the distribution)
- At masses > 10 eV, axions behave as CDM. The second peak in the 1D distribution of the axion mass corresponds to values of the axion masses that satisfy the cosmological constraints on the abundance of CDM



FIXED AXION MASS





- For light axions, the bound on $\Delta N_{\rm eff}$ is weaker when including BAO data. Heavier axions are instead better constrained with BAO