Shoot for the Stars, Aim for the Axions, 5/10/22

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

OUTLINE OF THE TALK

- Model and production of thermal axions in the early Universe
- Cosmo-phenomenology of thermal axions
- Analysis and results: cosmological bounds on the axion couplings to photons and gluons
- Future perspectives and conclusions

MODEL AND PRODUCTION OF THERMAL AXIONS

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

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

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Explicit mass term

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- 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

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

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

$$\boxed{g_{a\gamma} = g^0_{a\gamma} - \frac{\alpha_{\rm EM}}{3\pi}\frac{C_g}{f_a}\frac{4+z}{1+z} \approx g^0_{a\gamma} - 2.3\times10^{-15}\,\text{GeV}^{-1}\left(\frac{10^{12}\,\text{GeV}}{f_a/C_g}\right)}$$

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Axion-gluon coupling

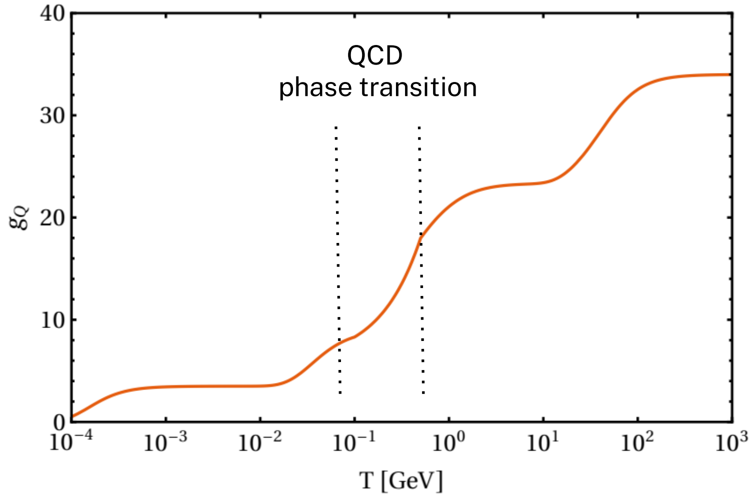
- We focus on thermal axions, that are produced in the early Universe from scatterings involving particles in the primordial thermal bath at temperatures >> axion mass
- We assume that axions are predominantly produced from processes involving either the axion-photon or the axion-gluon coupling
- Axions decouple at the temperature T_d, when freeze-out takes place: $\Gamma(T_d, g_a) \simeq H(T_d)$

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]

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



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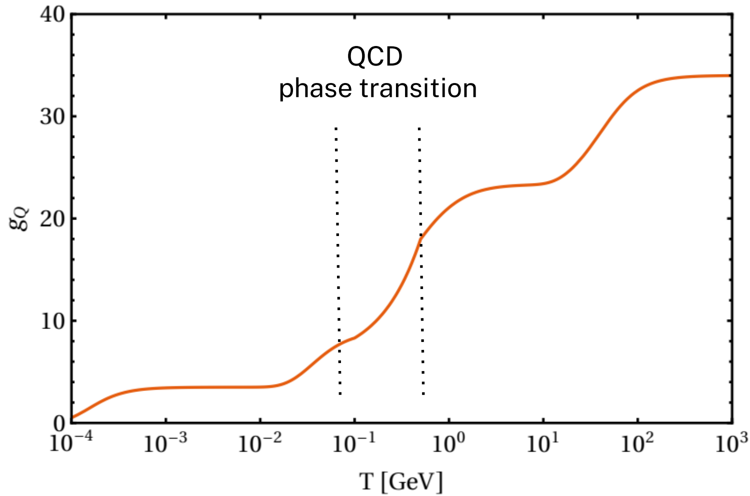

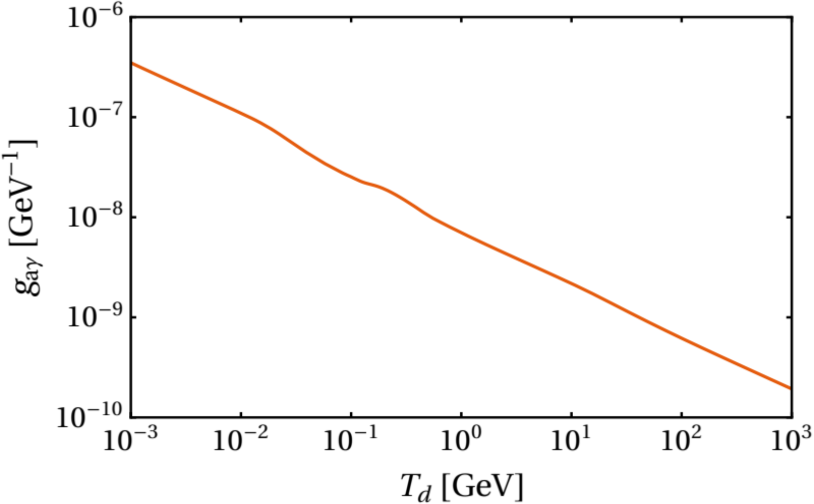

AXION-PHOTON COUPLING: AXION DECAY INTO PHOTONS

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- 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

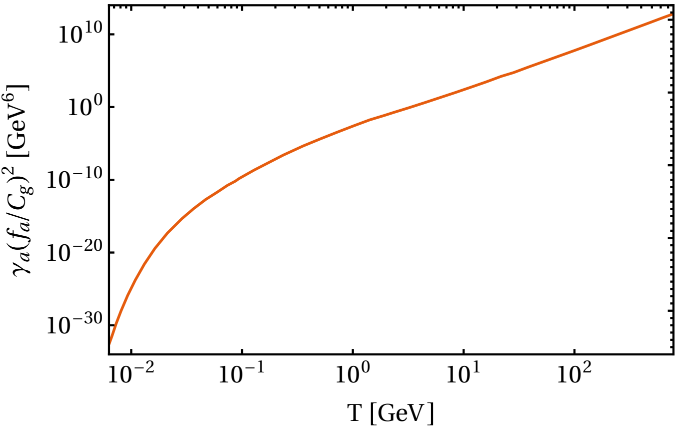
$$\frac{\Gamma_{a\to\gamma\gamma}}{H_0} \simeq 3.48 \times 10^{-2} \left(\frac{g_{a\gamma}}{10^{-7}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{m_a}{\mathrm{eV}}\right)^3 \ll 1$$

- 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

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

- 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: $\pi^+\pi^- \longrightarrow \pi^0 + a\,, \quad \pi^+ + \pi^0 \longrightarrow \pi^+ + a\,, \quad \pi^- + \pi^0 \longrightarrow \pi^- + a$



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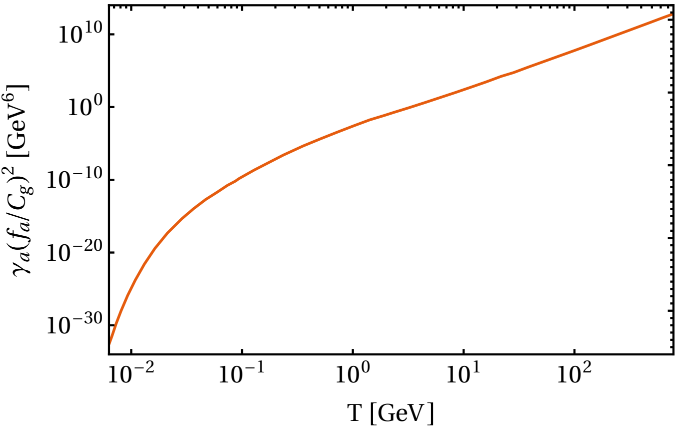

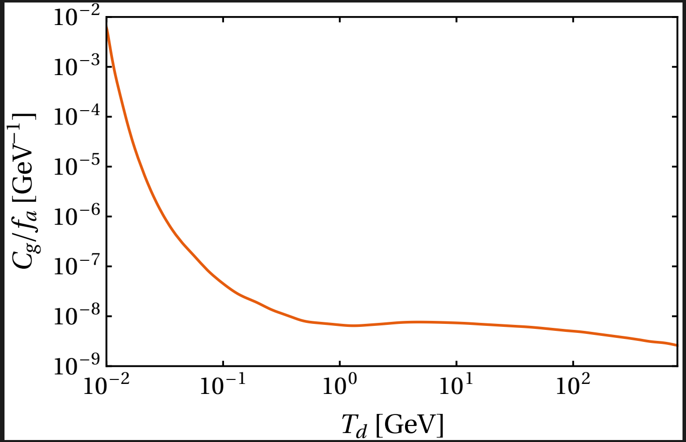

COSMO-PHENOMENOLOGY OF THERMAL AXIONS

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Small axion masses

- Light axions contribute to the energy density of radiation

$$\Delta N_{\rm eff} \equiv \frac{\rho_a(m_a=0)}{\rho_{\nu,\rm mless}} \propto \left(\frac{g_a}{g_\gamma}\right)\left(\frac{T_a}{T_\gamma}\right)^4$$
$$\simeq 0.027\left(\frac{g_{*s}(T_d)}{106.75}\right)^{-4/3}$$

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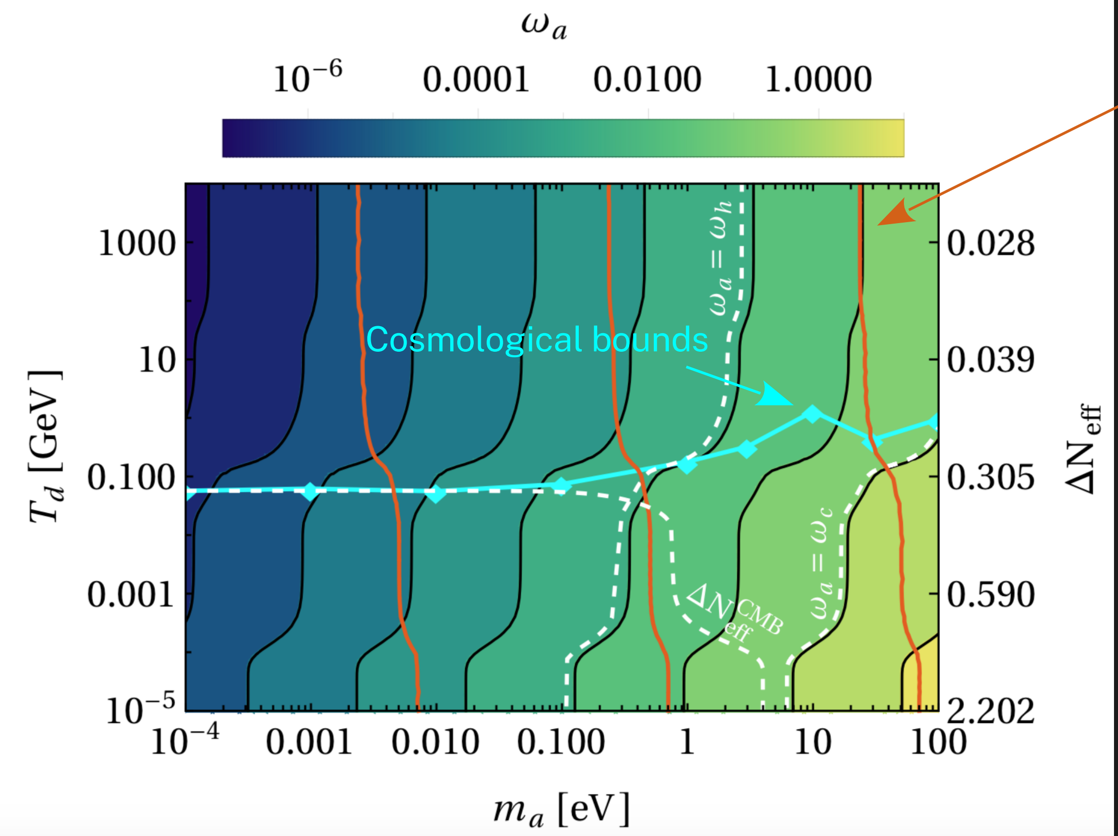
Axion couplings!

COSMOLOGICAL BOUNDS



Cosmological bounds

Lines of constant

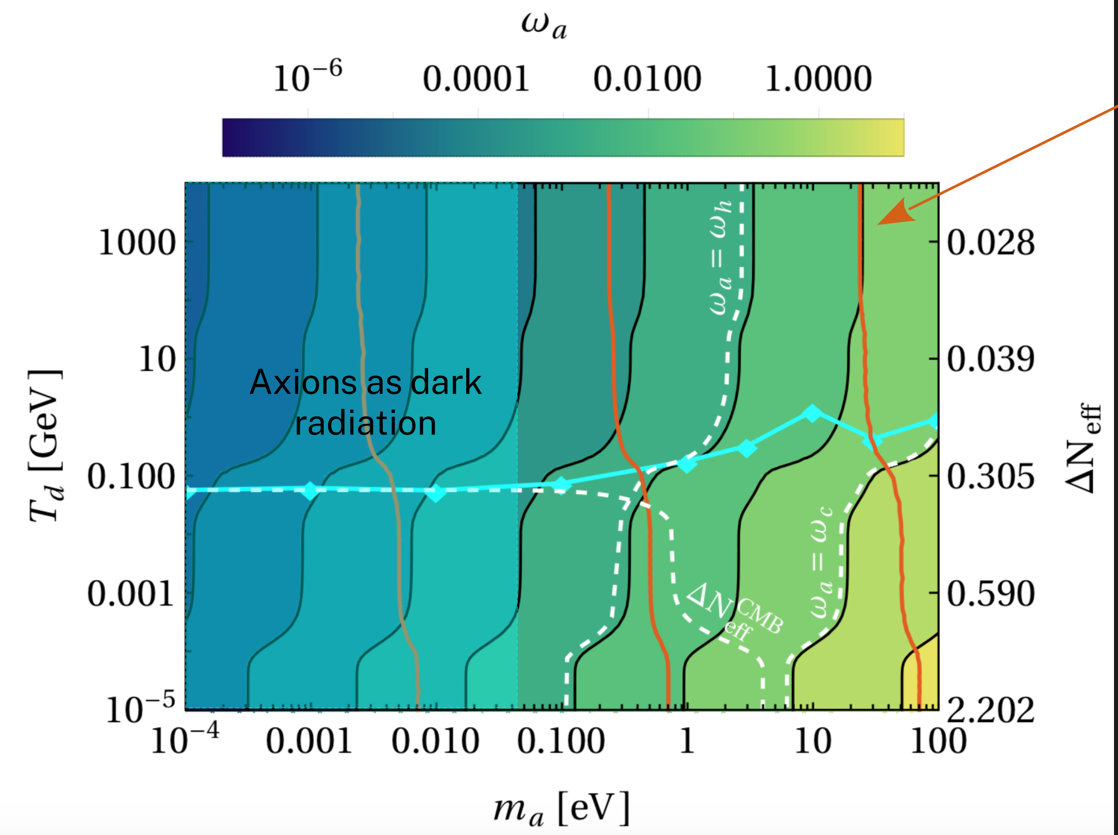
$$\frac{\langle p_{a,\text{rec}} \rangle}{m_a} = \{10^2, 1, 10^{-2}\}$$

$$\Lambda\text{CDM} + m_a + \Delta N_{\text{eff}}$$

Data:

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

COSMOLOGICAL BOUNDS



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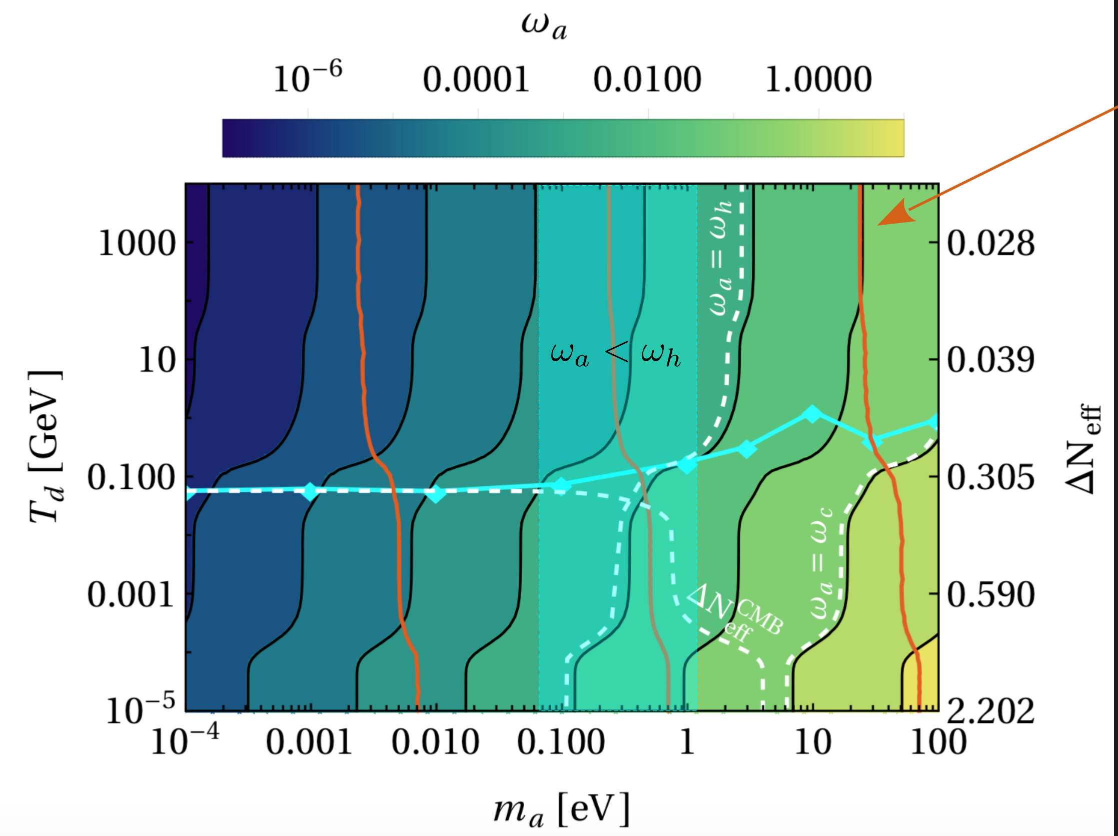

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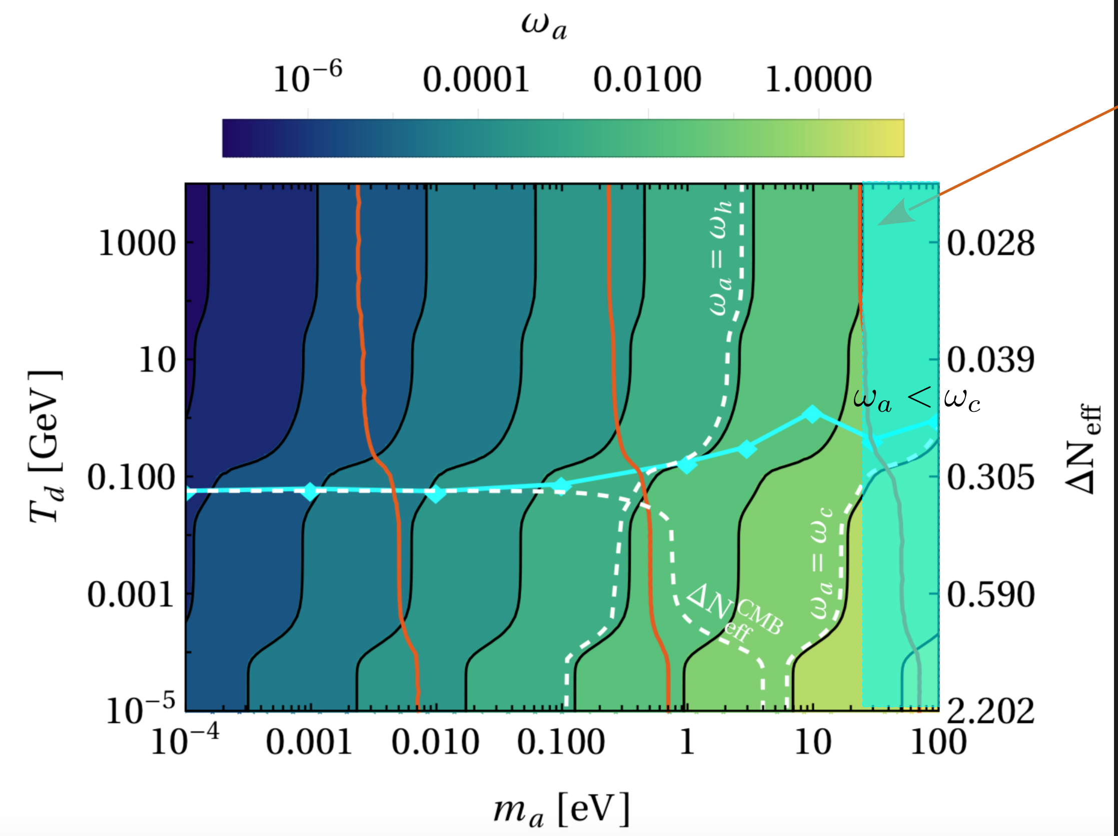

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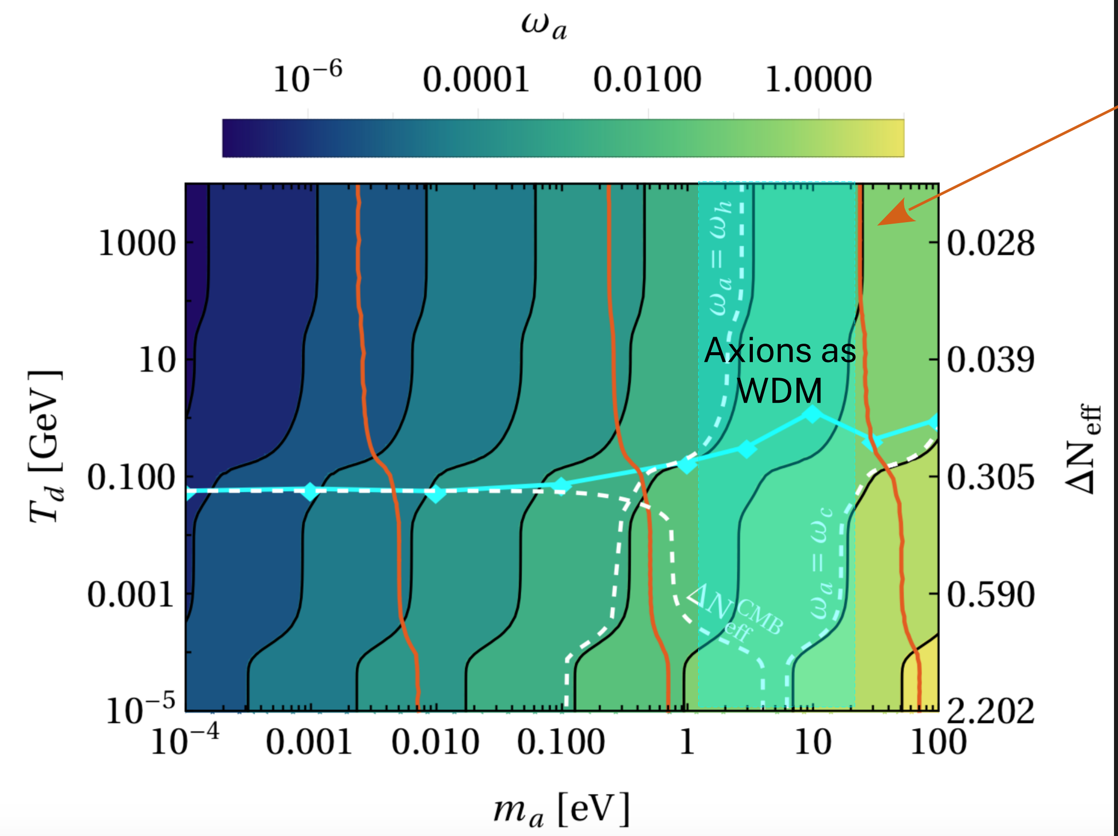

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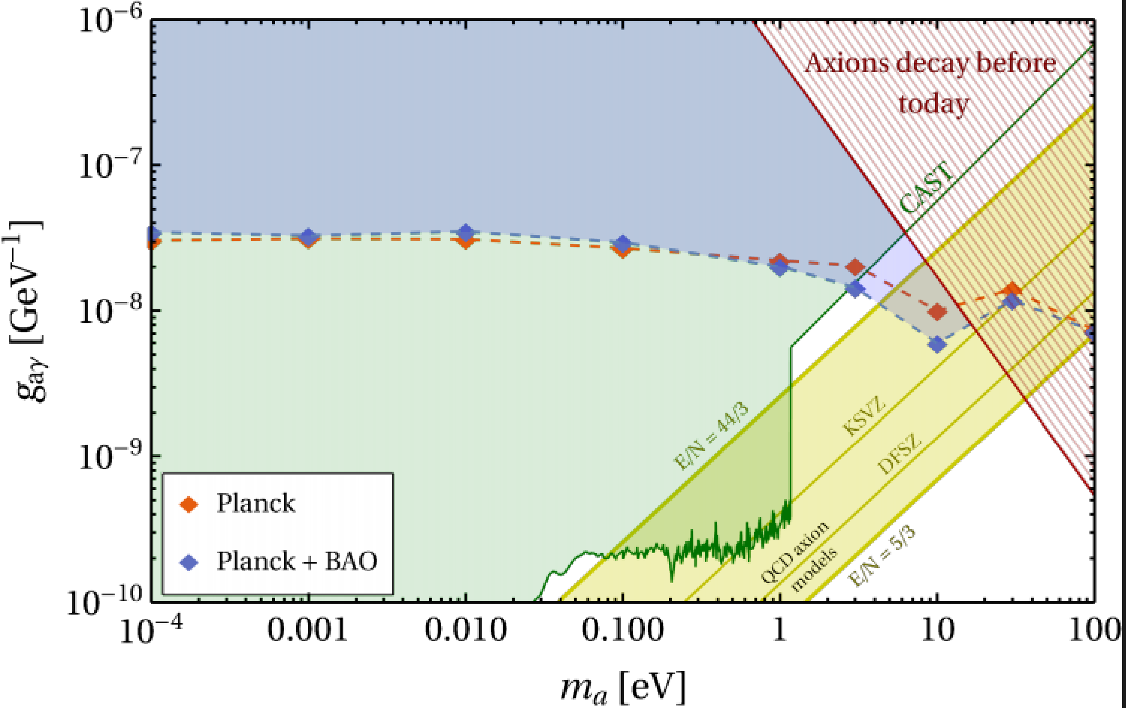

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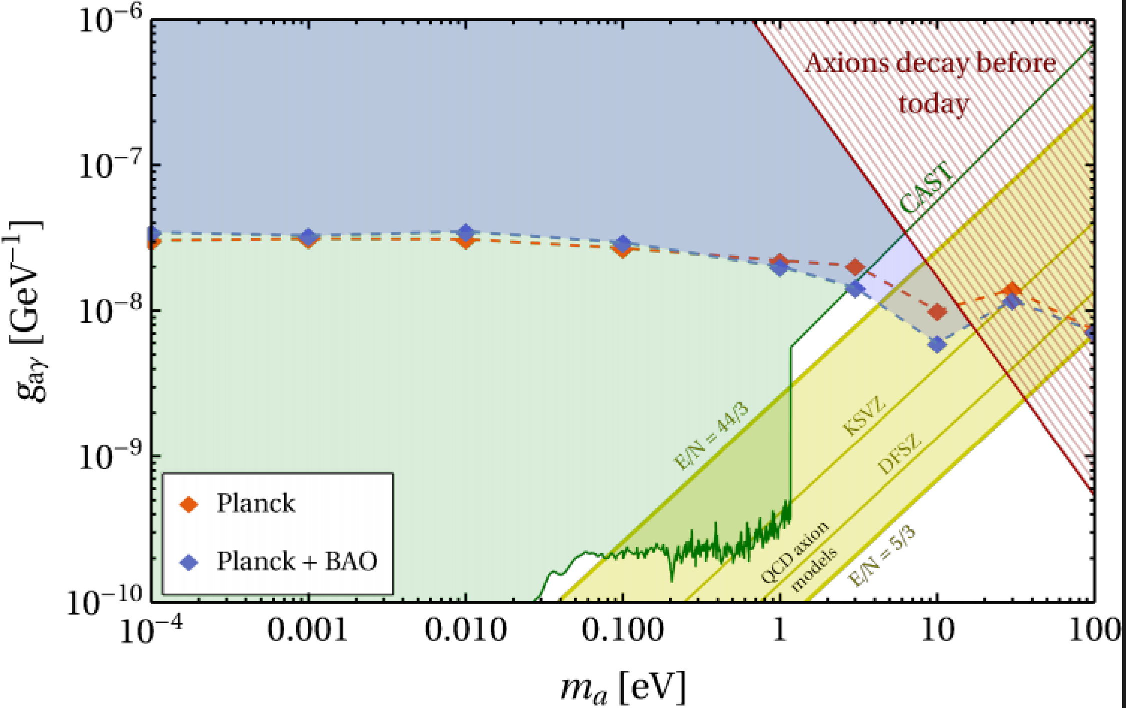
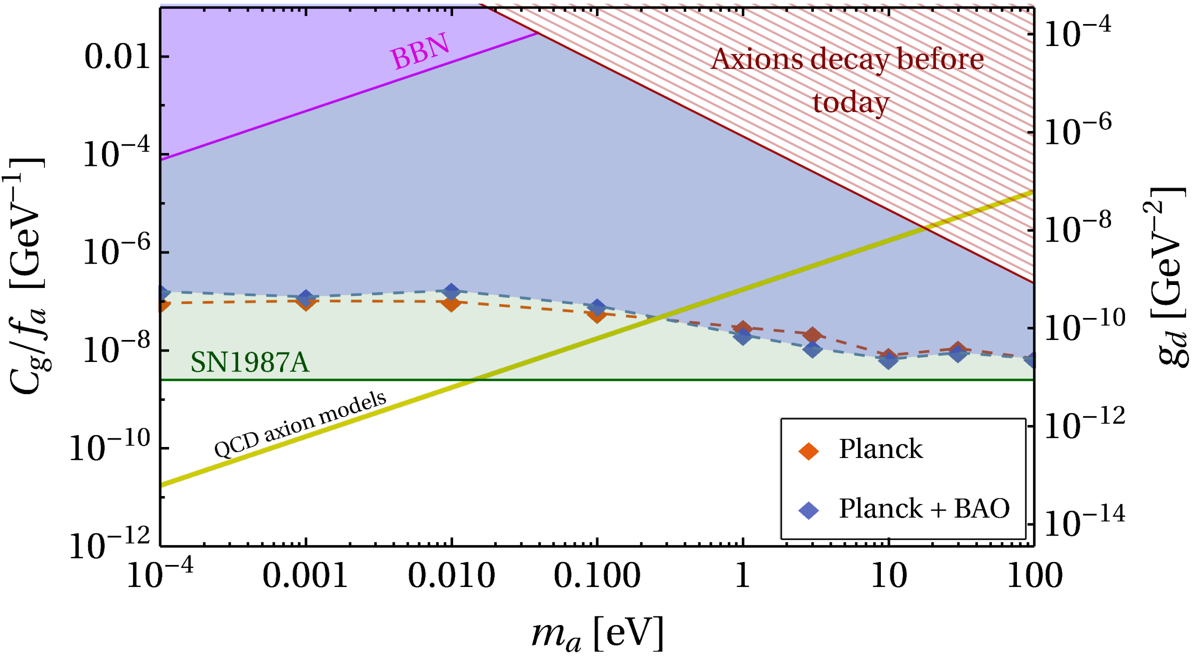


- Bounds stronger than those from CAST for $m_a > 3\ \mathrm{eV}$
- Stronger bounds from stellar evolution, but the cosmological constraints are independent and complementary

BOUNDS ON THE AXION-GLUON COUPLING



- 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]

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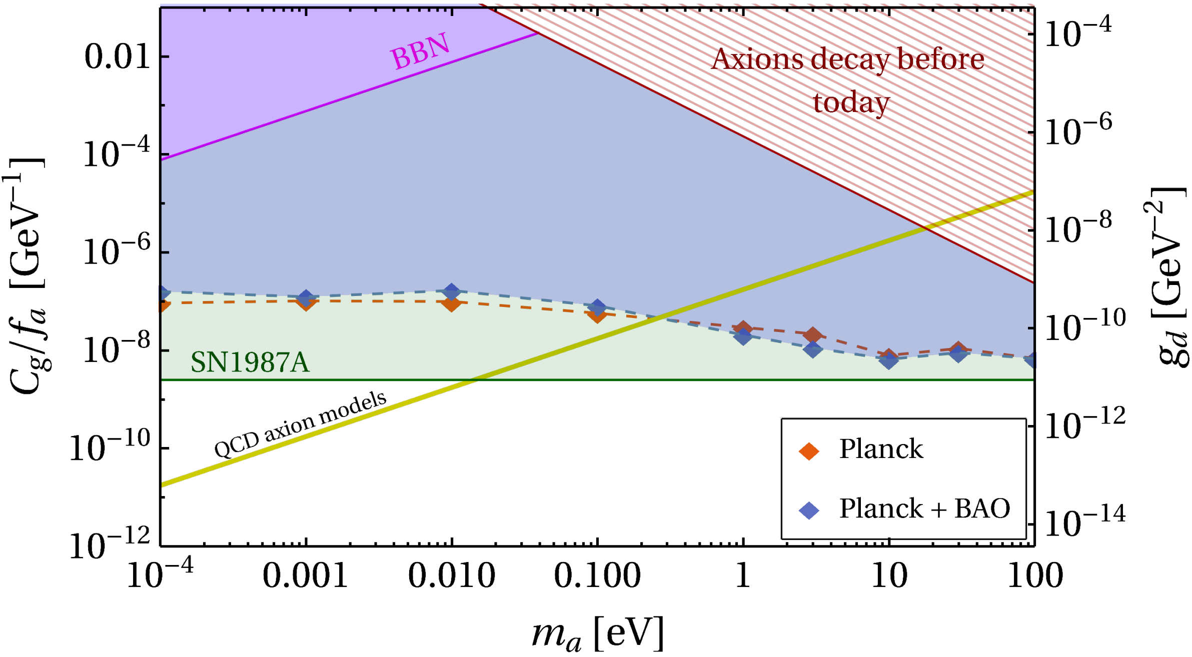

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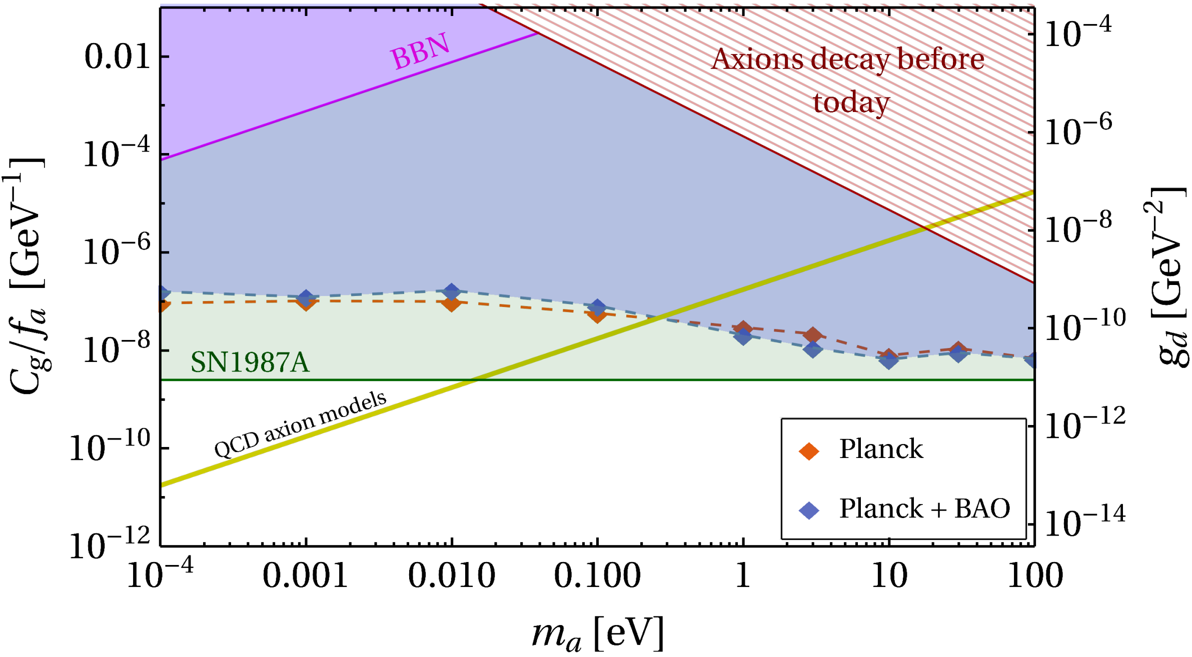

- NOTE: cosmology constrains C_g/f_a while SN constrain g_d

- KSVZ (QCD) axion:

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

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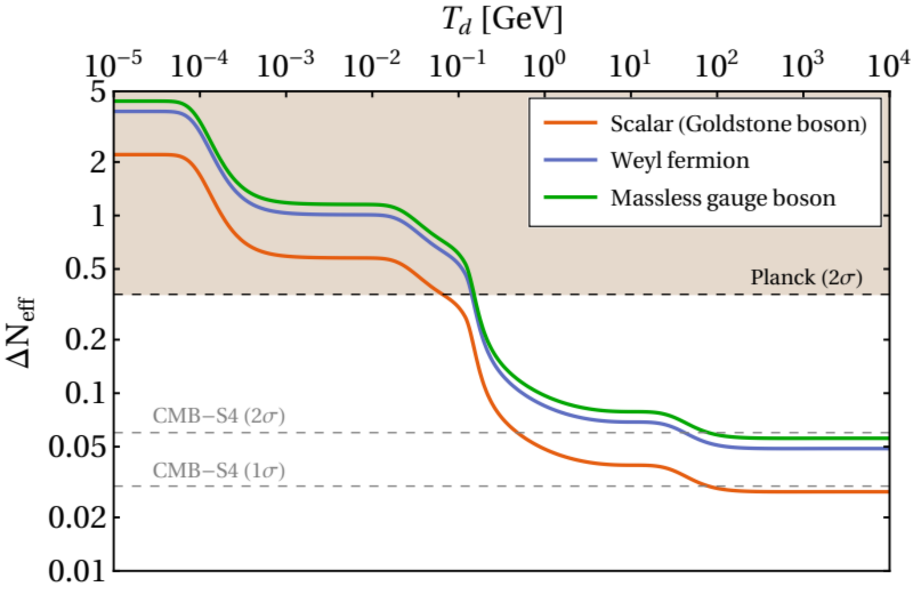
FUTURE PERSPECTIVES

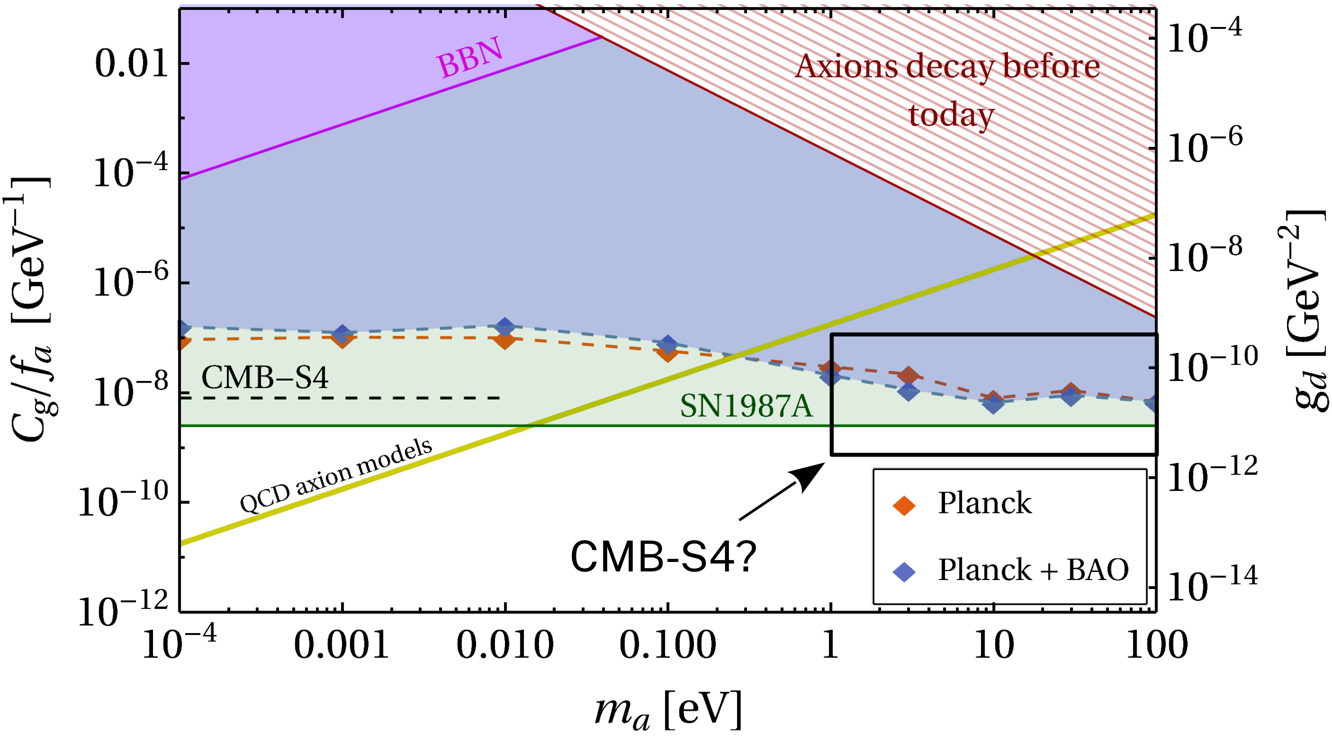
- For light axions, behaving as dark radiation ($m_a \lesssim 10^{-2}\,\mathrm{eV}$) CMB-S4 will allow us to probe (at 95% CL)



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

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

FUTURE PERSPECTIVES



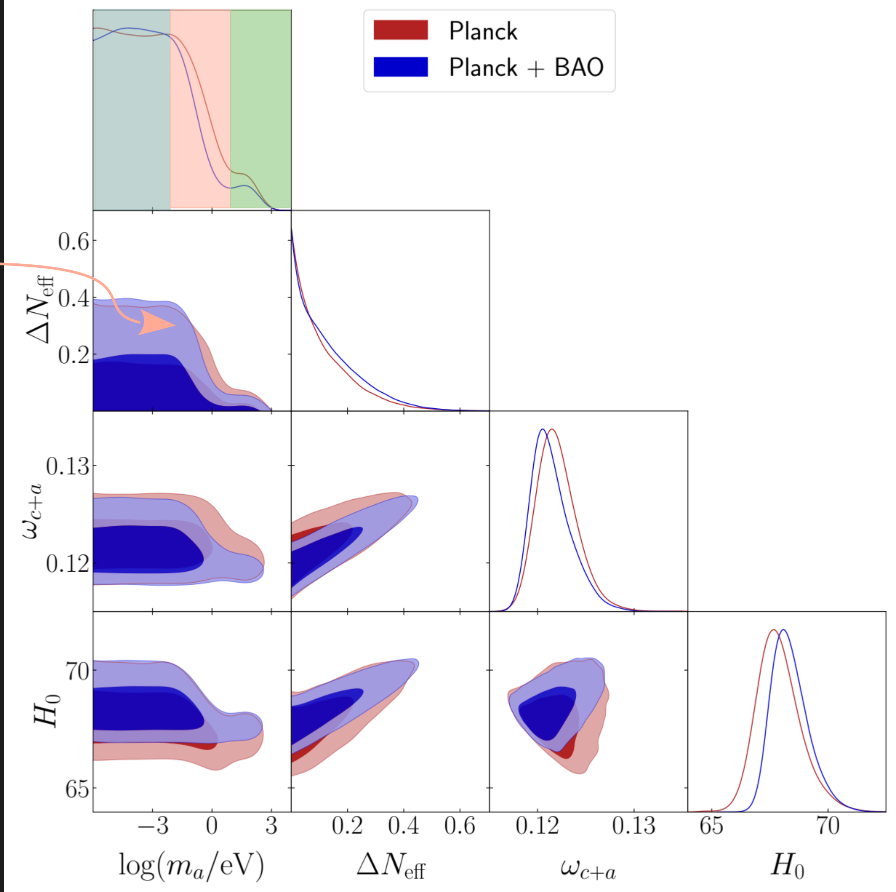
CONCLUSIONS

- 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 stronger with those from the CAST collaboration for axion masses > 3 eV
- The bounds on the axion-gluon coupling are still weaker than those from SN1987A, but interesting perspectives for next-generation cosmological surveys

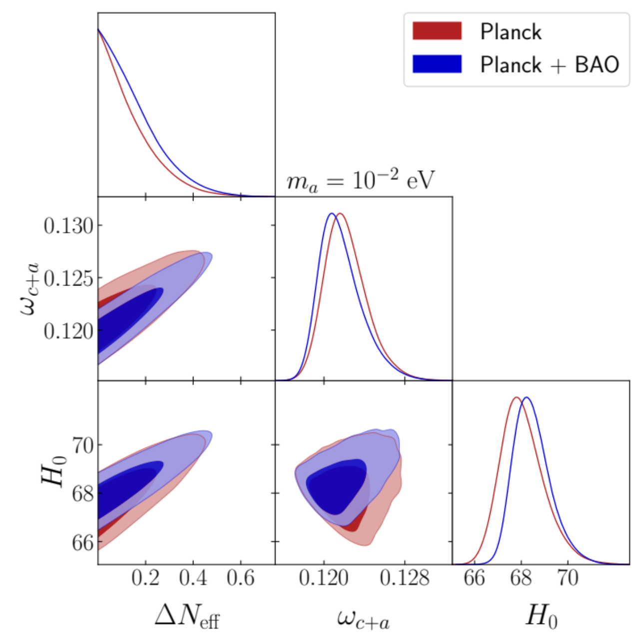
Thanks for your attention!

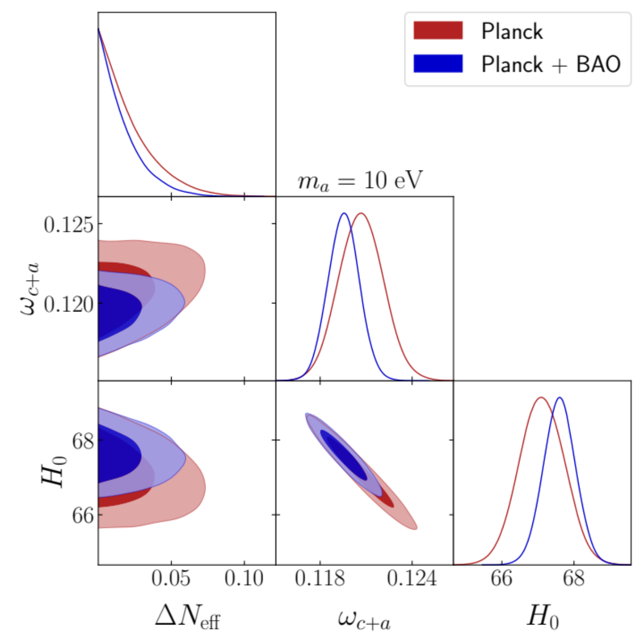
COSMOLOGICAL ANALYSIS AND RESULTS

- Axions behave as hot DM $\Longrightarrow$ 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