Updated cosmological bounds on ALPs with full phase-space analysis

N. Barbieri[a], L. Caloni[b], M. Gerbino[a], M. Lattanzi[a] and L. Visinelli[c,d]

[a]INFN sezione di Ferrara
[b]Universidade de Coimbra
[c]Università degli Studi di Salerno
[d]INFN sezione di Napoli (gruppo collegato di Salerno)





contact email:
nicola.barbieri@unife.it

TeV Particle Astrophysics Valencia 2025 TeVPA

Abstract

We present updated constraints on the coupling of thermally-produced axion-like particles with leptons and photons, derived from recent cosmic microwave background (CMB) and baryon acoustic oscillation (BAO). We improve upon previous studies by using a more accurate axion distribution function obtained from solving the full Boltzmann equation, thereby incorporating spectral distortions arising from a non-instantaneous decoupling. Thanks to a proper and careful assessment of the impact of different choices of priors, we also enhance the robustness of the bound derived from this analysis. Our analysis provides constraints based on the latest available observational data and includes forecasts for next-generation CMB experiments.

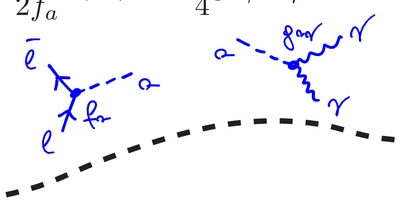
Outline of the work

1 Phenomenological model

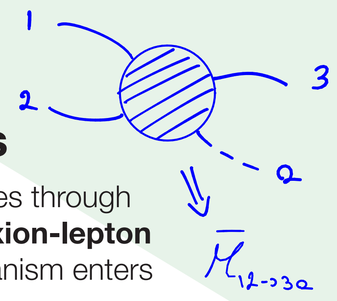
The **QCD axion** arises as the pNGB of the additional $\mathrm{U}(1)$ symmetry required by the PQ mechanism to solve the strong CP problem. Along with the QCD axions, **other light particles** with similar properties could arise from various extensions of the SM.

We work under the assumption that, below the energy scale f_a at which the global symmetry is spontaneously broken, the ALP field, a, is described by an effective field theory. The **low-energy interactions** that we consider are captured by the Lagrangian

$$\mathcal{L}_a \supset \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{1}{2}m_a^2 a^2 + c_\ell \frac{\partial_\mu a}{2f_a}\bar{\ell}\gamma^\mu\gamma^5\ell + \frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$



2 Computation of collision integrals for different production mechanisms

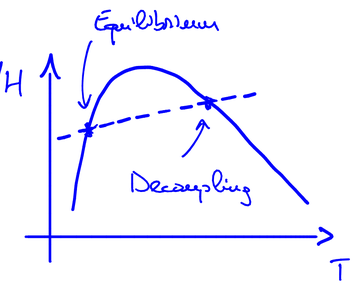


In this work, we focus on the production of axion-like particles through $2 \to 2$ scatterings of the type $1 + 2 \to 3 + a$, arising from **axion-lepton** and **axion-photon** photon interactions. The different mechanism enters the Boltzmann equation through the collision integral

$$\mathcal{C}_a(k,T) = \frac{1}{2E_k}\int d\Pi_1 d\Pi_2 d\Pi_3 (2\pi)^4 \delta^{(4)}(P_1 + P_2 - P_3 - K) \times \left|\overline{\mathcal{M}}_{12\to 3a}(s,t,u)\right|^2 f_1 f_2 (1 \mp f_3)$$

For each production channel considered, the collision integral were numerically evaluated using the `VEGAS` algorithm from the `PyCUBA` library.

3 Numerical solution to the full Boltzmann equation



Axions' **distribution function** can be obtained from the integration of the full Boltzmann equation (in dimensionless variables)

$$\frac{d\mathcal{F}_a(q,x)}{d\log x} = \frac{\mathcal{C}_a(q,x)}{H(x)}\left(1 - \frac{1}{3}\frac{d\log g_{*s}}{d\log x}\right)\left[1 - \frac{\mathcal{F}_a(q,x)}{\mathcal{F}_a^{\mathrm{eq}}(q,x)}\right]$$

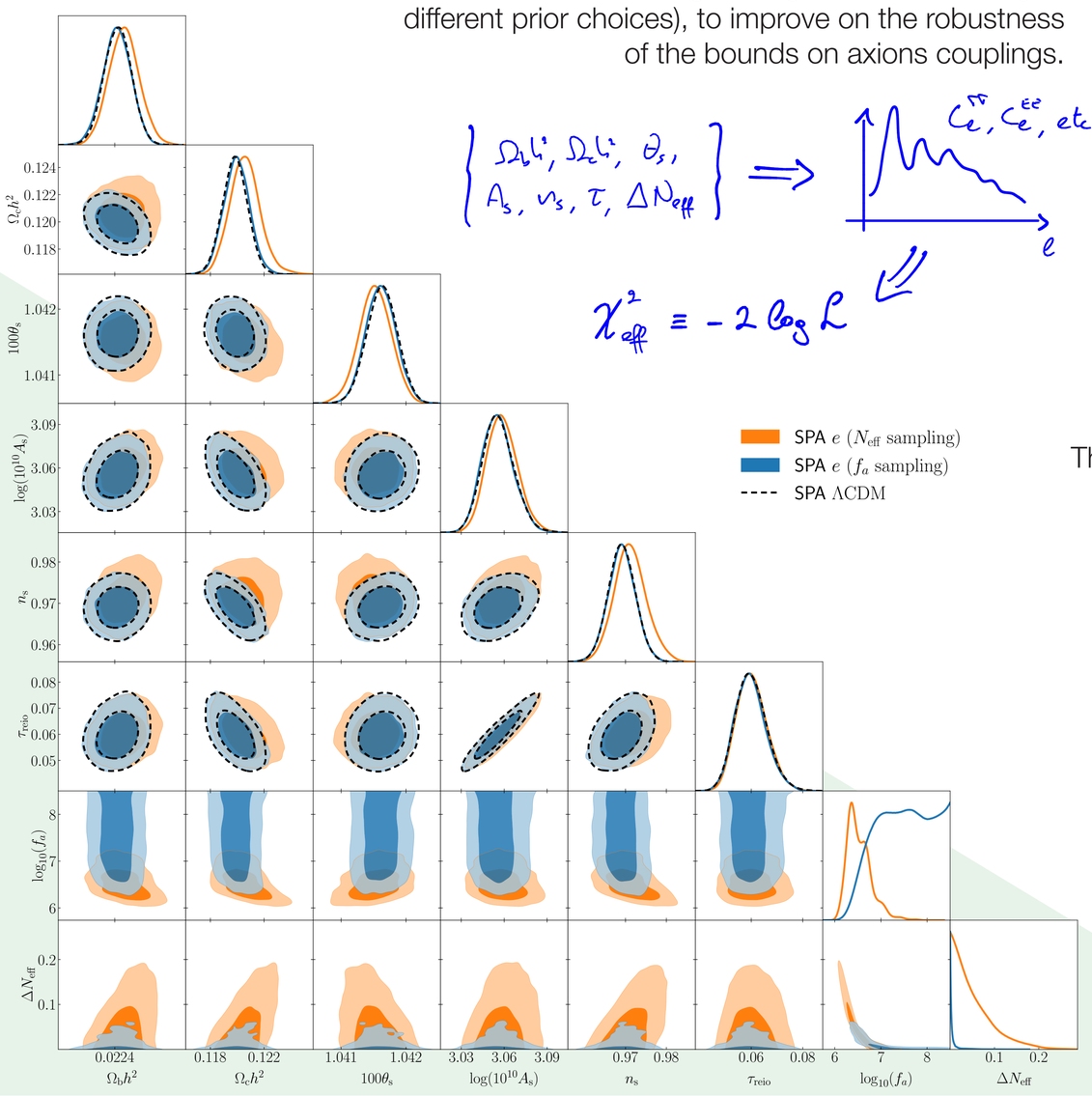
Light axions contributes as a **dark radiation** component that potentially adds up to N_{eff}. This excess is parameterized by the deviation from the value expected within the SM

$$\Delta N_{\mathrm{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{15}{2\pi^4}\frac{g_a}{T^4}\int_0^\infty dk\, k^3 f_a(k,T)$$

4 Implementation in a Boltzmann and subsequent MCMC analysis

We use `CLASS` Boltzmann solver implementation of non-cold dark matter to model the axions with some modifications at the interface level to dinamically generate PSDs for a given value of axions coupling.

MCMC analysis ha been carried out within the `Cobaya` framework. We adopted different sampling strategies (corresponding to different prior choices), to improve on the robustness of the bounds on axions couplings.



Results (preliminary)

Comparison between different sampling strategies on the electron production channel. ΔN_{eff} sampling turns out to be that with the least informative prior.

$$\log_{10} f_a > 6.55 \ (\log_{10} f_a \text{ sampling})$$
$$\log_{10} f_a > 6.18 \ (\Delta N_{\mathrm{eff}} \text{ sampling})$$

SPA at 95% CL

Constraints from current cosmological data

The data set considered for this section is a combination of **Planck 2018** data (low ℓs region, cutted at high ℓs), **ACT DR6** and **SPT-3G D1** (SPA), with BAO from **DESI DR2** (SPA-B). Lensing from all the three CMB experiment has been considered. 95% CL bounds are

Data set	e ch.	μ ch.	τ ch.	Primakoff ch.
SPA	$\log_{10} f_a > 6.18$	$\log_{10} f_a > 6.94$	$\log_{10} f_a > 4.79$	$\log_{10} g_{a\gamma} < -7.66$
SPA-B	$\log_{10} f_a > 6.10$	$\log_{10} f_a > 6.83$	$\log_{10} f_a > 4.25$	$\log_{10} g_{a\gamma} < -7.51$

Forecasts for future CMB experiments

Based on a noise model for a combined **Litebird+SO LAT joint analysis** (LSO). For SO LAT we used publicly available noise models for temperature, polarization and lensing (LSO-L). Instead, for Litebird we computed white noise with a gaussian beam from last istrumental specification officially released. 95% CL forecasts are

	ΔN_{eff}	$\log_{10} f_a$		ΔN_{eff}	$\log_{10} f_a$
LSO	< 0.058	> 6.34	LSO-L	< 0.034	> 6.52

Essential bibliography:

[1] L. Caloni et al., *JCAP* **09** (2022) 021
[2] F. D'Eramo and A. Lenoci, *Phys.Rev.D* **110** (2024) 11
[3] E. Camphuis et al. (SPT-3G Collaboration), arxiv:2506.20707 [astro-ph.CO] (2025)

European Research Council
Established by the European Commission
INFN FERRARA