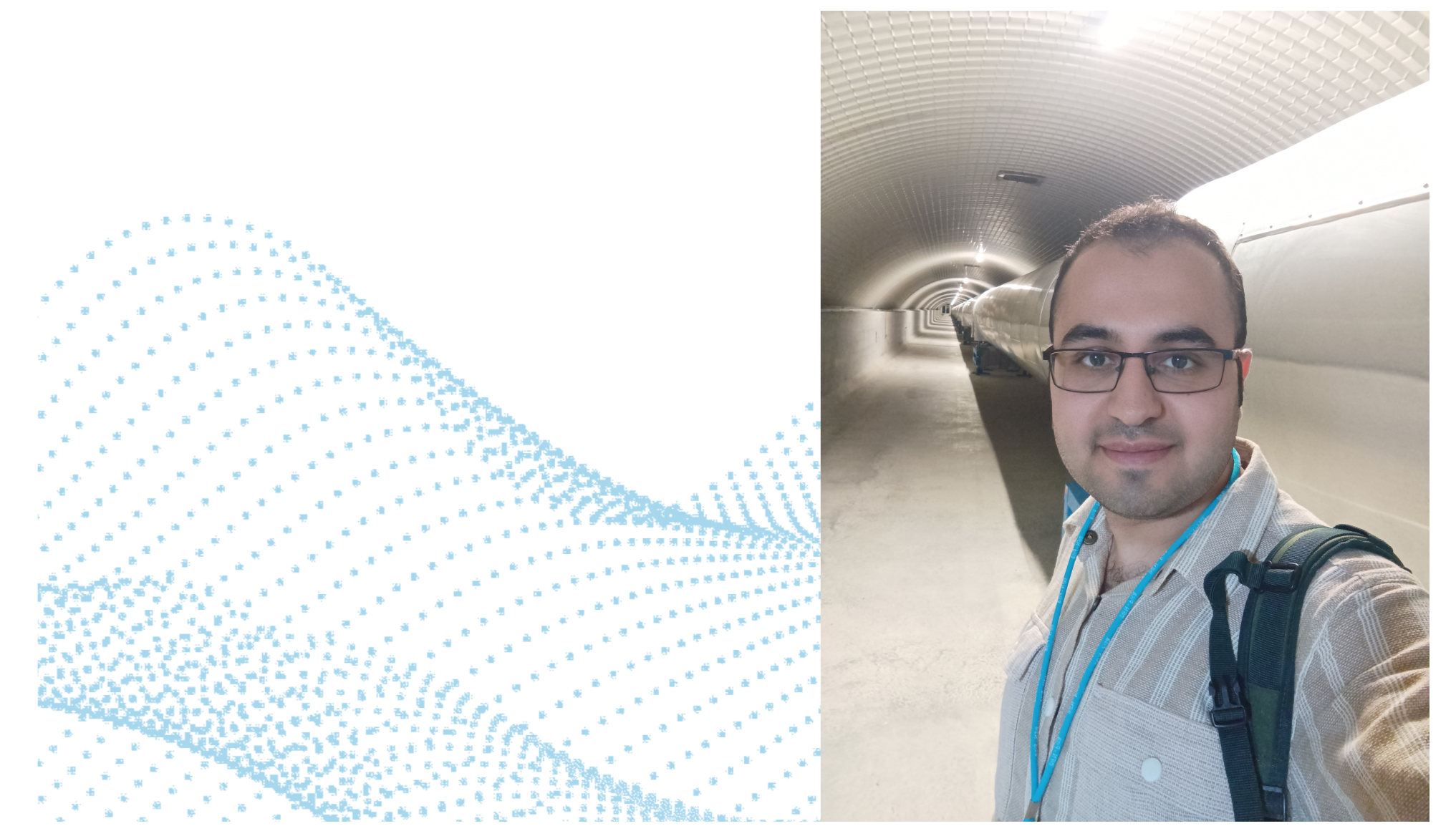


Quarky Tale of Axion Dark Matter

 Mohammad Aghaie¹, G. Armando, A. Conaci, A. Dondarini, P. Maták, P. Panci, Z. Sinská, and R. Ziegler

¹ University of Pisa and INFN, Pisa section


1. Framework

Our DM candidate is an anomaly-free ALP that doesn't talk to leptons, i.e. it only interacts with quarks, and it does so through derivative couplings. All of this is neatly packed into the following minimal effective Lagrangian,

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{2f_a} \bar{q}_i \gamma^\mu (C_{q_i, q_j}^V + C_{q_i, q_j}^A \gamma_5) q_j, \quad (1)$$

where $C_{q_i, q_j}^{V,A}$ are traceless hermitian matrices in flavor space.

⚠ The Flavor-violating couplings are not just allowed, they're expected!

In our model Flavor-violating (FV) axion couplings naturally emerge from the misalignment between the Peccei-Quinn (PQ) charge matrices and the Standard Model (SM) Yukawas:

$$C_q^{V,A} = U_{q_R}^\dagger X_{q_R} U_{q_R} \pm U_{q_L}^\dagger X_{q_L} U_{q_L}. \quad (2)$$

The catch? Their exact size depends on the UV flavor model!

We play another game here: assuming ALPs make up dark matter and were produced via freeze-in, we fix the size of the FV couplings by demanding they yield the observed relic abundance.

Bottom line: Rare FV decays become a direct window into DM physics, potentially even within experimental reach.

Benchmark Scenarios: Axions Speak Flavor!

We explore two classes of flavor-violating ALP scenarios based on PQ charge structures and flavor rotations:

i. Two Flavor Scenario

In this family of models only two quark flavors gain PQ charges, e.g.,

$$X_{d_R} = \text{diag}(0, 1, -1), \quad X_{u_R} = X_{Q_L} = 0$$

The corresponding unitary rotation matrix is limited to a rotation within the same flavor sector, specifically, a 2-3 rotation by an angle α , where $0 \leq \alpha \leq \frac{\pi}{2}$. This leads to the following form for the axion-quark couplings:

$$C_d^V = C_d^A = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin \alpha & \cos \alpha \\ 0 & \cos \alpha & -\sin \alpha \end{pmatrix}, \quad C_u^V = C_u^A = 0. \quad (3)$$

We refer to this configuration as the “*bs* scenario”. One can similarly construct benchmark scenarios for the *bd*, *cu*, *sd*, *tu*, and *tc* sectors.

ii. CKM-like Scenarios

For our second class of models, we identify the unitary flavor rotations directly with the CKM matrix. Within this setup, we explore two simple but insightful benchmark scenarios:

• **CKM_{Q_L}:** Only left-handed quarks possess PQ charges and the CKM is coming entirely from the down-quark sector,

$$X_{Q_L} = \text{diag}(1, X, -1 - X), \quad X_{u_R} = X_{d_R} = 0, \\ U_{Q_L} = \mathbb{1}, \quad U_{d_L} = V_{\text{CKM}}.$$

• **CKM_{d_R}:** Only right-handed quarks possess PQ charges and the CKM matrix shows up in the right-handed quark sector,

$$X_{Q_L} = X_{u_R} = 0, \quad X_{d_R} = \text{diag}(1, X, -1 - X), \\ U_{d_R} = V_{\text{CKM}}.$$

These scenarios are considered to be representative for the phenomenology of more realistic models, where flavor-rotations are determined by the same dynamics that explain fermion mass hierarchies, which may be the PQ symmetry itself.

Just 3 Ingredients

Our recipe is simple: Since each model depends on just three key parameters: $\{f_a, m_a, \alpha \text{ or } X\}$.

Fixing the relic abundance, we can fix one parameter, e.g. f_a ! Then, it's all about exploring the allowed parameter space $(m_a, \alpha \text{ or } X)$ space under current experimental constraints!

2. Axion Production

Axions are often produced via non-thermal production mechanism such as the **misalignment mechanism**, but that comes with extra free parameters like reheating temperature (T_{RH}) and UV headaches.

Instead, we keep it minimal — IR all the way! The trick is to keep T_{RH} low enough, e.g.,

$$T_R < \frac{3\pi^3 v^2}{m_{q_i}} \rightarrow H_R < 11 \text{keV} \left(\frac{\text{GeV}}{m_{q_i}} \right)^2, \quad (4)$$

Misalignment?

Yeah, it's there... but it's not running the show!

$$\Omega_a h^2|_{\text{mis}} \approx 4 \times 10^{-3} \left(\frac{H_R}{11 \text{keV}} \right)^{1/2} \left(\frac{f_a \theta_0}{10^{10} \text{GeV}} \right)^2. \quad (5)$$

Freeze-in

For $f_a \gtrsim 10^8 \text{ GeV}$, axions never reach thermal equilibrium. Instead, they are produced through:

- **Flavor-violating decays:** $q_i \rightarrow q_j a$
- **Flavor-conserving scatterings:** $q_i g(\gamma) \rightarrow q_i a, \quad q_i q_i \rightarrow g(\gamma) a$

This leads to axion dark matter via the **freeze-in** mechanism. The total relic abundance is: $\Omega_a h^2 = \Omega_a h^2|_{\text{dec}} + \Omega_a h^2|_{\text{scatt}}$

To keep things simple, we use the dominant process only and assume constant degrees of freedom during freeze-in. This way, we get clean, analytic expressions for each contribution,

$$\Omega_a h^2|_{\text{dec}} \approx 0.12 \left(\frac{m_a}{0.1 \text{MeV}} \right) \left(\frac{9.7 \times 10^9 \text{GeV}}{f_a / C_{q_i, q_j}} \right)^2 \\ \times \left(\frac{m_{q_i}}{\text{GeV}} \right) \left(\frac{70}{g_*(m_{q_i})} \right)^{3/2} \quad (6)$$

$$\Omega_a h^2|_{\text{scatt}} \approx 0.12 \left(\frac{m_a}{0.1 \text{MeV}} \right) \left(\frac{1.4 \times 10^{10} \text{GeV}}{f_a / C_{q_i, q_i}^A} \right)^2 \\ \times \left(\frac{m_{q_i}}{\text{GeV}} \right) \left(\frac{70}{g_*(m_{q_i})} \right)^{3/2} \left(\frac{\alpha_s(m_{q_i})}{0.48} \right) \quad (7)$$

Clean. Predictive. Freeze-in at its finest!

For the dark matter mass around $\sim 100 \text{ keV}$, we hit the observed relic abundance for a decay constant of about

$$f_a \sim 10^{10} \text{ GeV}.$$

These results have two main caveats:

1. **UV Freeze-In:** Freeze-in isn't always just an IR story! At high temperatures (above the electroweak scale), higher dimension operators kick in, e.g.:

$$\mathcal{L}_{\text{eff}} = -C_{q_i, q_j}^A \frac{i a m_{q_i}}{f_a v} H \bar{Q}_i q_j R_j$$

This operator leads to UV-sensitive processes such as $\bar{q}_i q_j \rightarrow h a$. This contribution depends on T_R , but just like in misalignment, we can shut it down by keeping T_R low.

2. **higher-order QCD corrections:** Due to the large value of the strong coupling near the GeV scale, neglecting higher-order QCD corrections is not a reliable approximation. Therefore, we consider our leading-order results to be valid up to $\mathcal{O}(1)$ uncertainties, which, however, have only a mild impact on the relevant model parameter f_a .

3. Axion stability

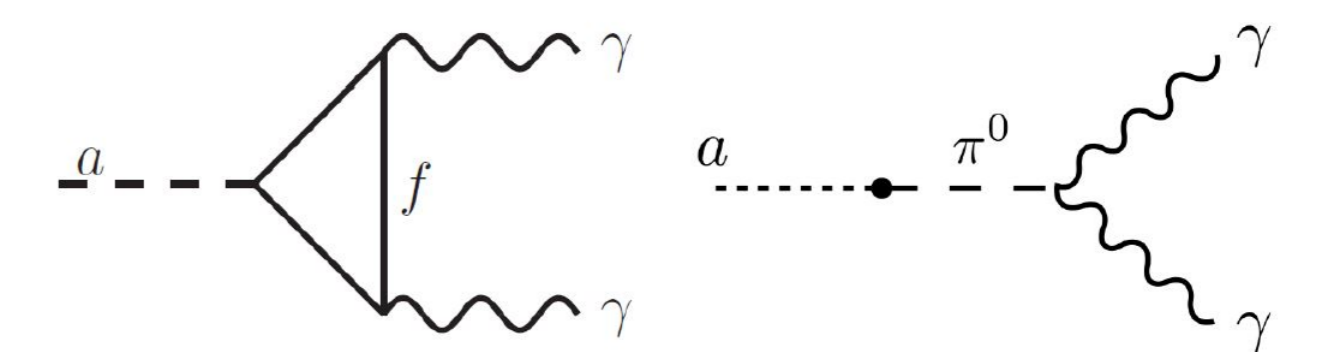
With f_a fixed, it's time to check where in the $(m_a, \alpha \text{ or } X)$ space our axion is a stable DM candidate.

For large f_a , the axion interactions are super weak, so it lives a loooong time. However, the strongest bounds don't come from life-

time alone, they come from X-ray searches looking for DM decays. We need to be extra careful. We design our axion to be:

- **Light** ($m_a < m_\pi$) \rightarrow No decays into pions.
- **Leptophobic** \rightarrow No tree-level decays into light leptons.
- **Anomaly-free** \rightarrow No tree-level axion–photon coupling. However, these interactions are induced at the loop level.

So, in our benchmarks, the axion decays to photons ($a \rightarrow \gamma\gamma$) via quark loops.



- + heavy quarks? Easy, just use perturbation theory!
 - + Light quarks? Time to call in the chiral perturbation theory.
- Then, the total decay rate is given by:

$$\Gamma_{\gamma\gamma} = \frac{\alpha_{\text{em}}^2 m_a^3}{64\pi^3 f_a^2} |C_{\gamma\gamma}^{\text{heavy}} + C_{\gamma\gamma}^{\text{light}}|^2$$

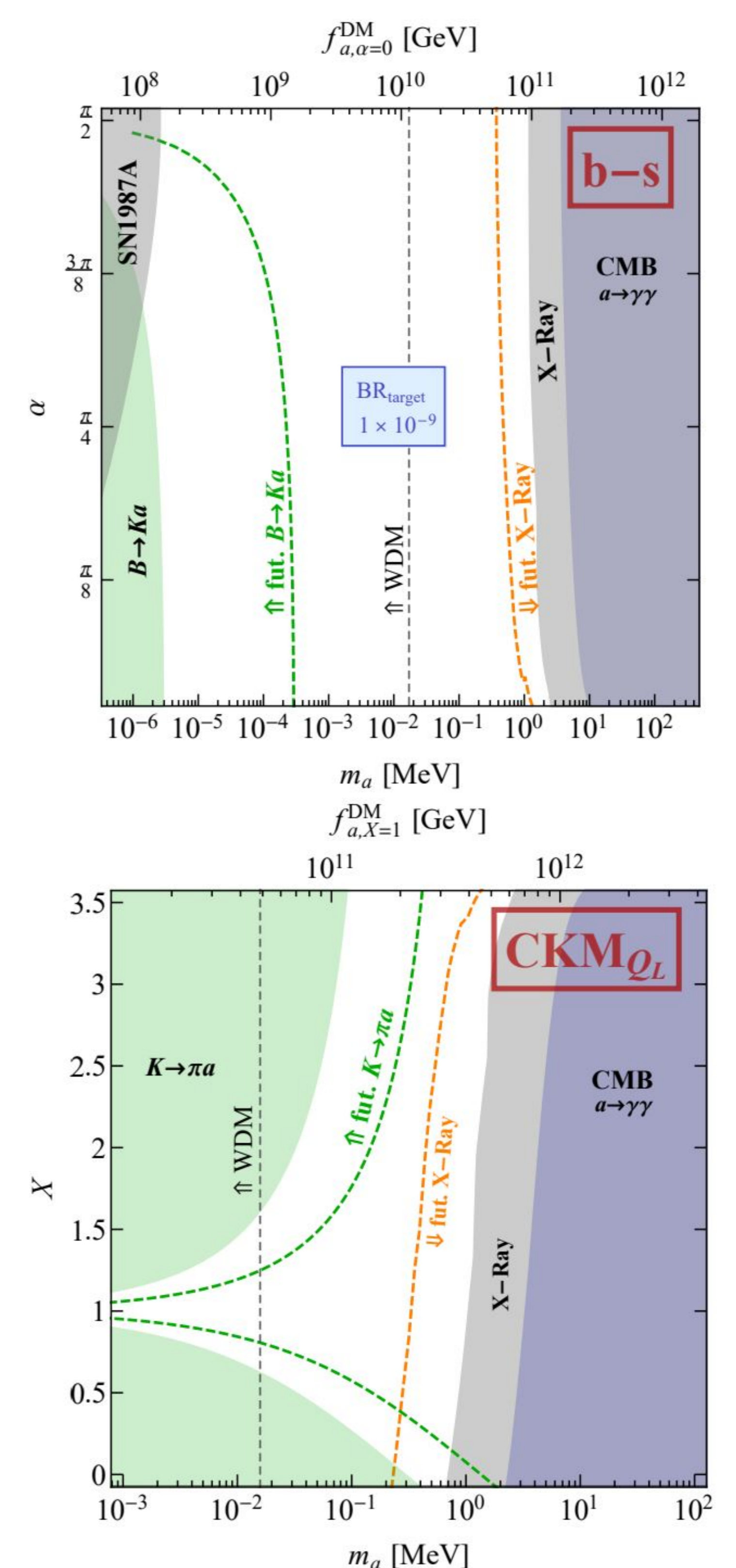
Then, the axion lifetime is

$$\tau_a \approx 3 \times 10^{28} \text{ sec} \left(\frac{0.1 \text{ MeV}}{m_a} \right)^7 \left(\frac{f_a / (C_u - C_d)}{10^{10} \text{ GeV}} \right)^2$$

which easily beats the age of the Universe and stays well below the X-ray limits — right where we want to be!

4. Results

Eventually, having a stable DM candidate that is able to reproduce the observed relic abundance of the DM, one needs to check its viability in the light of current existing experiments.



Reference



Aghaie et al., *Axion Dark Matter from Heavy Quarks*, arXiv:2404.12199