ALP Dark Matter from Heavy Quarks

Invisibles25, CERN

Mohammad Aghaie

PhD Candidate, University of Pisa

In collaboration with,
Armando, Conaci, Dondarini, Matak, Panci, Sinska, Ziegler

Based on 2404.12199

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Why ALP?

- Axion-like particles (ALPs) are compelling dark matter candidates **because**

Pseudo-Goldstone bosons of **Peccei-Quinn** like Symmetry **broken at high scales**

$m_a \lesssim \mathcal{O}(\text{MeV})$ → **light**

+ SM singlet → **Neutral**

$f_a \gtrsim 10^9$ GeV → **decoupled**

- **Stable** on Cosmological time scales

$$1/\Gamma(a \to \gamma\gamma) \simeq 10^{12}\,\text{yrs}\left(\frac{f_a}{10^9\text{GeV}}\right)^2\left(\frac{\text{keV}}{m_a}\right)^3$$

- Easy to Produce in the Early universe via **freeze-in**, freeze-out, misalignment, etc.

These ALPs are great DM candidates but they are invisible!

Why anomaly-free and flavor violating?

At $E \ll \Lambda_{PQ} \propto f_a$, The most general axion coupling to SM is described by the following EFT

$$\mathcal{L}_{\text{eff}} = \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} + C_{a\gamma}\frac{a}{f_a}\frac{\alpha_{\text{em}}}{8\pi}F\tilde{F} + \frac{\partial_\mu a}{2f_a}\sum_i C_i \bar{f}_i\gamma^\mu\gamma_5 f_i + \frac{\partial_\mu a}{2f_a}\sum_{i\neq j}\bar{f}_i\gamma^\mu\left(C^V_{ij} + C^A_{ij}\gamma_5\right)f_j$$

Ziegler 2303.13353

Then, the most general EFT for a leptophobic anomaly-free ALP is

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{2f_a}\bar{q}_i\gamma^\mu\left(C^V_{q_i,q_j} + C^A_{q_i,q_j}\gamma_5\right)q_j$$

Then, the most general EFT for a leptophobic anomaly-free ALP is

$$C_u^{V,A} = U^\dagger_{u_R}X_{u_R}U_{u_R} \pm U^\dagger_{u_L}X_{Q_L}U_{u_L}\,,$$
$$C_d^{V,A} = U^\dagger_{d_R}X_{d_R}U_{d_R} \pm U^\dagger_{d_L}X_{Q_L}U_{d_L}\,,$$

Axions in SM decays → $b \to sa\,,\Lambda \to na, etc$

- Relic Abundance
- Precision Flavor Experiments
- SN1987A bound

Benchmarks

We have considered two classes of models:

"two-flavor scenario"
a single flavor transition at a time
only two flavors charged under PQ,

6 possible scenarios, e.g. "b-s" scenario

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

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

Free Parameters: m_a, f_a, α

"CKM-scenario"
the unitary flavor rotations are given by the CKM
All quark flavors are charged.

possible scenarios are "CKM_{dR}" and "CKM_{QL}"

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

$$U_{u_L} = 1, U_{d_L} = V_{\mathrm{CKM}}$$

Free Parameters: m_a, f_a, X

ALP Production

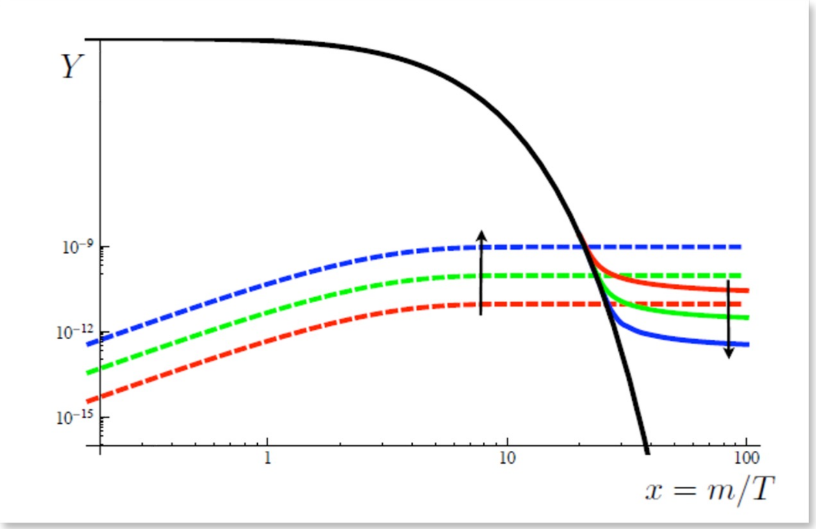
Due to the large decay constant $f_a \geq 10^9$ GeV, the ALP was never in thermal equilibrium with the SM bath. Therefore, it must be produced non-thermally:

1. Misalignment Mechanism $\longrightarrow$ $T_R < 3\pi^3 v^2/m_{q_i}$

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

2. Flavor violating decays: $q_i \to q_j\, a$

3. 2 to 2 Scatterings: $q_i\, g(\gamma) \to q_j\, a$; $q_i\,\overline{q_i} \to g(\gamma)\, a$



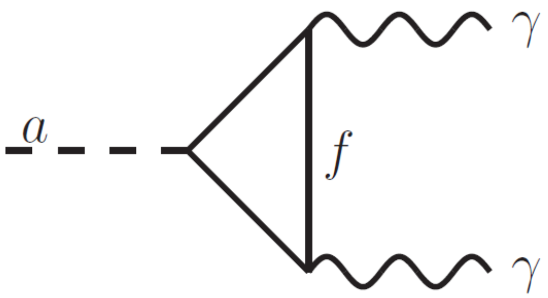
$$\Omega_a h^2|_{\rm dec} \approx 0.12\left(\frac{m x_a}{0.1\,{\rm MeV}}\right)\left(\frac{9.7\times 10^9{\rm GeV}}{f_a/C_{q_iq_j}}\right)^2\left(\frac{m_{q_i}}{\rm GeV}\right)\left(\frac{70}{g_*(m_{q_i})}\right)^{3/2} \quad \text{for decays},$$

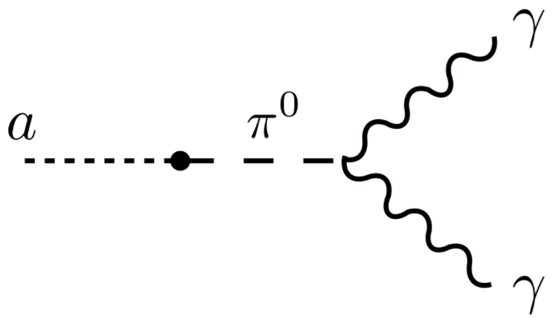
$$\Omega_a h^2|_{\rm scatt} \approx 0.12\left(\frac{m_a}{0.1\,{\rm MeV}}\right)\left(\frac{1.4\times 10^{10}{\rm GeV}}{f_a/C^A_{q_iq_i}}\right)^2\left(\frac{m_{q_i}}{\rm GeV}\right)\left(\frac{70}{g_*(m_{q_i})}\right)^{3/2}\left(\frac{\alpha_s(m_{q_i})}{0.48}\right) \quad \text{for scattering},$$

Stability

For the leptophobic ALPs in our mass range the main decay channel is into photons ($a \to \gamma\gamma$)

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





$$\tau_a \approx 3 \times 10^{26} {\rm sec} \left(\frac{0.1\,{\rm MeV}}{m_a} \right)^7 \left(\frac{f_a/(C_u - C_d)}{10^9\,{\rm GeV}} \right)^2$$

Chiral Perturbation theory Remark

$$\mathcal{L}_{\chi\rm PT} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2} a^2 + \frac{f_\pi^2}{8} {\rm Tr}\left[D_\mu \Sigma D^\mu \Sigma^\dagger \right]$$

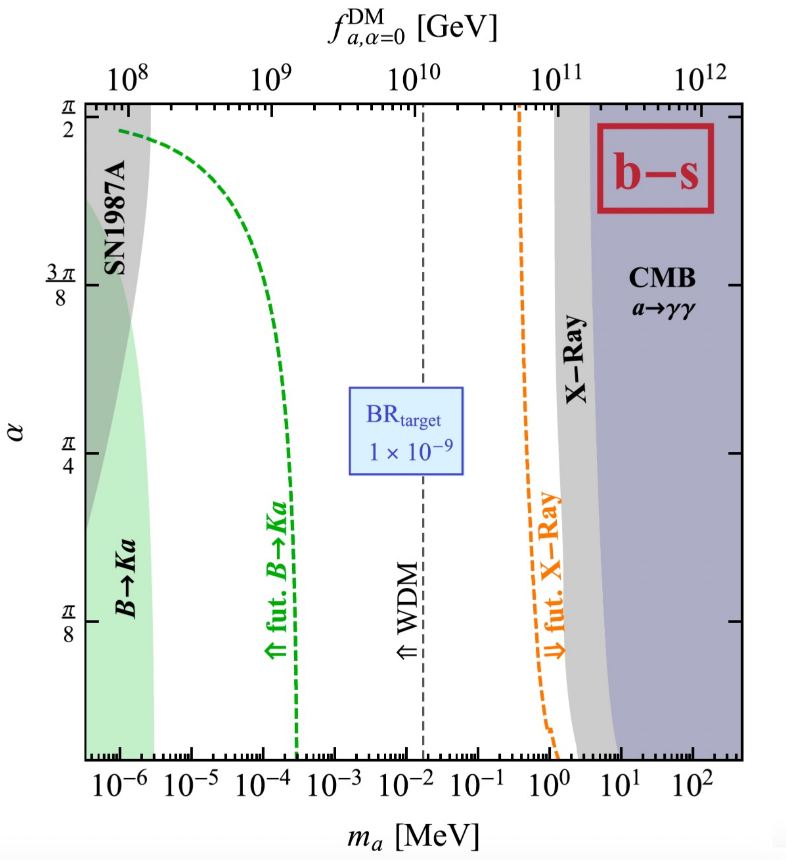
$$+ \frac{f_\pi^2}{4} B_0 {\rm Tr}\left[M_q \Sigma^\dagger + {\rm h.c.} \right] - \frac{1}{2} M_0^2 \eta_0^2,$$

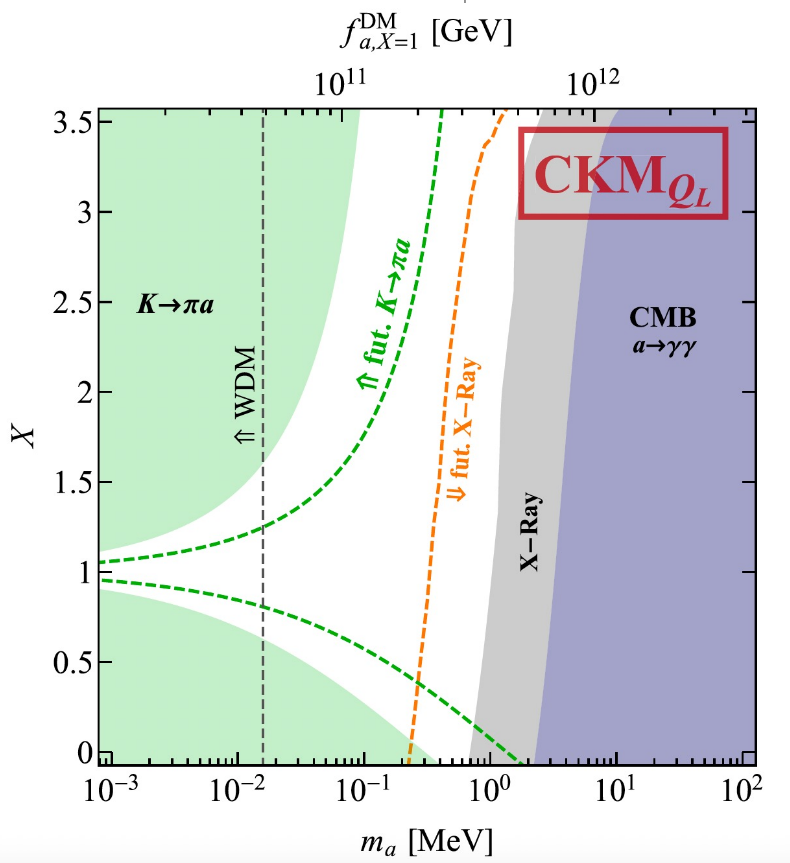
$$\pi^0 \approx \pi^0_{\rm phys} + \epsilon \frac{C_u - C_d}{2\sqrt{2}} \frac{m_a^2}{m_a^2 - m_\pi^2} a_{\rm phys},$$

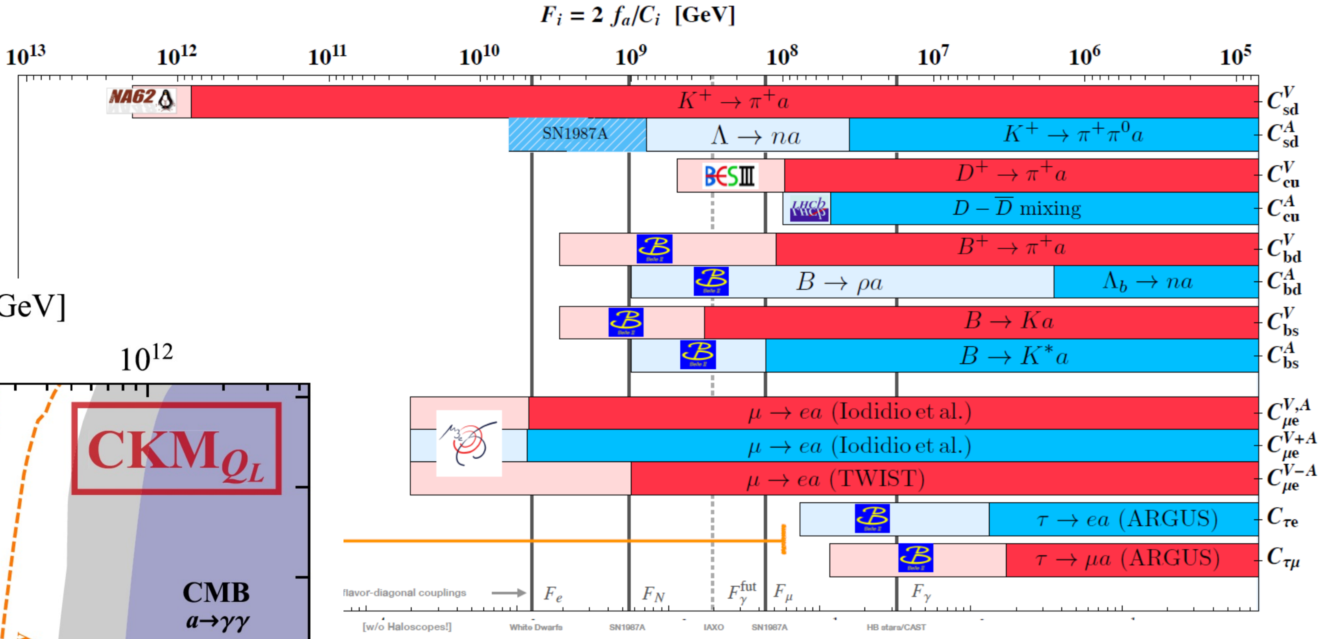
$$\eta_8 \approx \eta_{\rm phys} + \epsilon \frac{C_u + C_d - C_s}{2\sqrt{3}} \frac{m_a^2}{m_a^2 - m_\eta^2} a_{\rm phys},$$

$$\eta_0 \approx \eta'_{\rm phys} + \epsilon \frac{C_u + C_d + 2C_s}{2\sqrt{6}} \frac{m_a^2}{m_a^2 - m_{\eta'}^2} a_{\rm phys}$$

Results







Credit: Ziegler, 2303.13353

Summary

- For a DM ALP, we don't need to start with an anomalous PQ symmetry
- The most general axion EFT possesses non-diagonal coupling to SM fermions
- These FV couplings not only produce the observed relic abundance of DM but also makes the invisible ALP more "Visible!"

  - They can be probed by current and future flavor experiments
    - NA62: up to 10^{12} GeV
    - Belle II: up to 10^{10} GeV

  - The next generation X-ray observatories provide a complementary probe
    - GECCO
    - XGIS-X

Leptophobic ALPs with off-diagonal couplings to SM quarks are great DM candidates!

Thank You!

Mohammad Aghaie

University of Pisa

Department of Physics (E. Fermi)

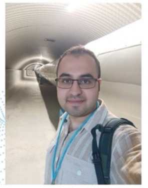
Largo B. Pontecorvo 3, Building C, Room n. 154

Mohammad.AghaieMoghadamOzbak@phd.unipi.it

Quarky Tale of Axion Dark Matter

Mohammad Aghaie[1], 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,

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{2f_a}\bar{q}_i\gamma^\mu\left(C^V_{q_i,q_j} + C^A_{q_i,q_j}\gamma_5\right)q_j, \quad (1)$$

where $C^{V,A}_{q_i,q_j}$ 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:

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

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.,

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

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 $0 \le \alpha \le \frac{\pi}{2}$. This leads to the following form for the axion-quark couplings:

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

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 posess 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 posess 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 $(m_a, \alpha$ 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.,

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

Misalignment?

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

$$\Omega_a h^2|_{\text{mis}} \approx 4\times10^{-3}\left(\frac{H_R}{11\text{keV}}\right)^{1/2}\left(\frac{f_a\theta_0}{10^{10}\,\text{GeV}}\right)^2. \quad (5)$$

Freeze-in

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

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

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,

$$\Omega_a h^2|_{\text{dec}} \approx 0.12\left(\frac{m_a}{0.1\,\text{MeV}}\right)\left(\frac{9.7\times10^9\,\text{GeV}}{f_a/C_{q_iq_j}}\right)^2 \times\left(\frac{m_{q_i}}{\text{GeV}}\right)\left(\frac{70}{g_*(m_{q_i})}\right)^{3/2} \quad (6)$$

$$\Omega_a h^2|_{\text{scatt}} \approx 0.12\left(\frac{m_a}{0.1\,\text{MeV}}\right)\left(\frac{1.4\times10^{10}\,\text{GeV}}{f_a/C^A_{q_iq_i}}\right)^2 \times\left(\frac{m_{q_i}}{\text{GeV}}\right)\left(\frac{70}{g_*(m_{q_i})}\right)^{3/2}\left(\frac{\alpha_s(m_{q_i})}{0.48}\right) \quad (7)$$

Clean. Predictive. Freeze-in at its finest!

For the dark matter mass around ~ 100 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. :

$$\mathcal{L}_{\text{eff}} = -C^A_{q_iq_j}\frac{ia}{f_a}\frac{m_{q_i}}{v}H\overline{Q}_i q_{Rj}$$

   This operator leads to UV-sensitive processes such as $\bar{q}_i q_j \to h\,a$. 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.

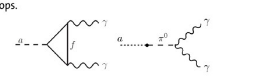
3. Axion stability

With f_a fixed, it's time to check where in the $(m_a, \alpha$ 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 lifetime alone, they come from X-ray searches looking for DM decays. We need to be extra careful. We design our axion to be:

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

So, in our benchmarks, the axion decays to photons ($a \to \gamma\gamma$) 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:

$$\Gamma_{\gamma\gamma} = \frac{\alpha^2_{\text{em}}m_a^3}{64\pi^3 f_a^2}\left|C^{\text{heavy}}_{\gamma\gamma} + C^{\text{light}}_{\gamma\gamma}\right|^2$$

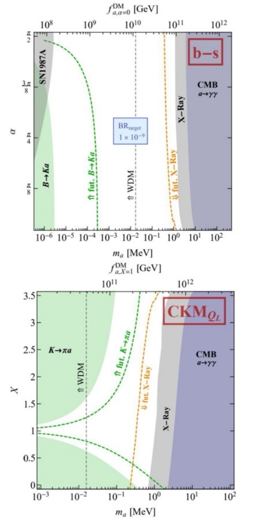
Then, the axion lifetime is

$$\tau_a \approx 3\times10^{28}\,\text{sec}\left(\frac{0.1\,\text{MeV}}{m_a}\right)^7\left(\frac{f_a/(C_u - C_d)}{10^{10}\,\text{GeV}}\right)^2$$

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 repruce the observed relic abundance of the DM, one needs to check its viablity in the light of current existing experiments.



Reference

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

Back up slides

ALP Stability – Light Quarks

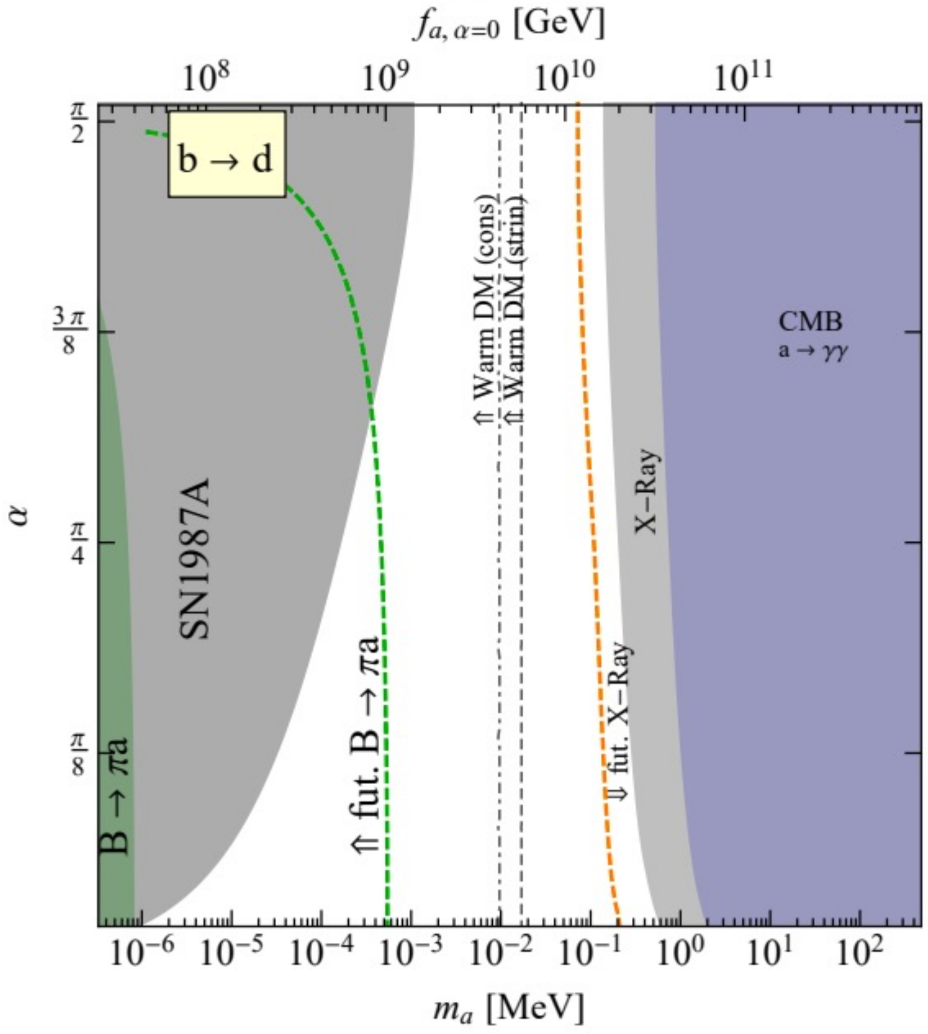
At energies below a few GeV, the effective Lagrangian for the three light quarks $\Psi = (u, d, s)$,

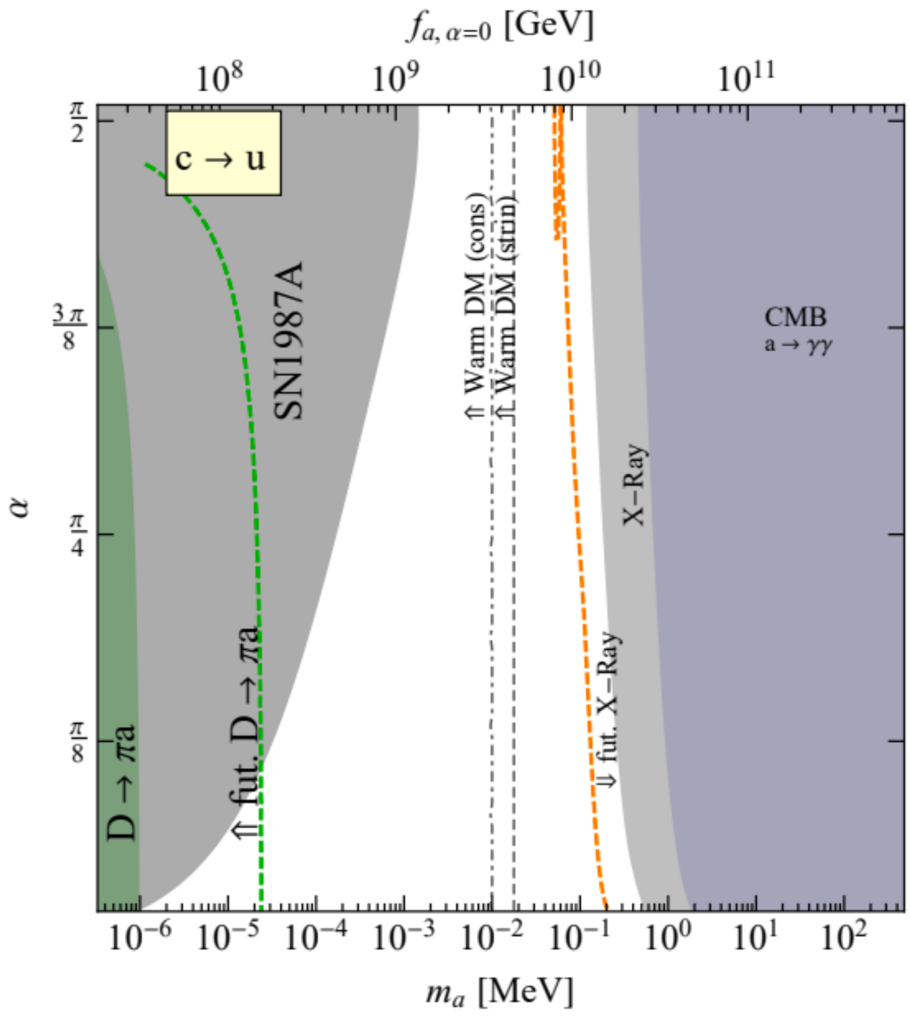
$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{m_a^2}{2}a^2 + \bar{\Psi}(i\not{D} - M_q)\Psi + \frac{\partial^\mu a}{f_a}\bar{\Psi}\gamma^\mu(k_L P_L + k_R P_R)\Psi$$

$$\mathcal{L}_{\chi\text{PT}} = \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{m_a^2}{2}a^2 + \frac{f_\pi^2}{8}\text{Tr}\left[\text{D}^\mu\Sigma\,\text{D}_\mu\Sigma^\dagger\right] + \frac{\text{f}_\pi^2}{4}\text{B}_0\,\text{Tr}\left[\text{M}_\text{q}\Sigma^\dagger + \text{h.c.}\right] - \frac{1}{2}\text{M}_0^2\eta_0^2$$

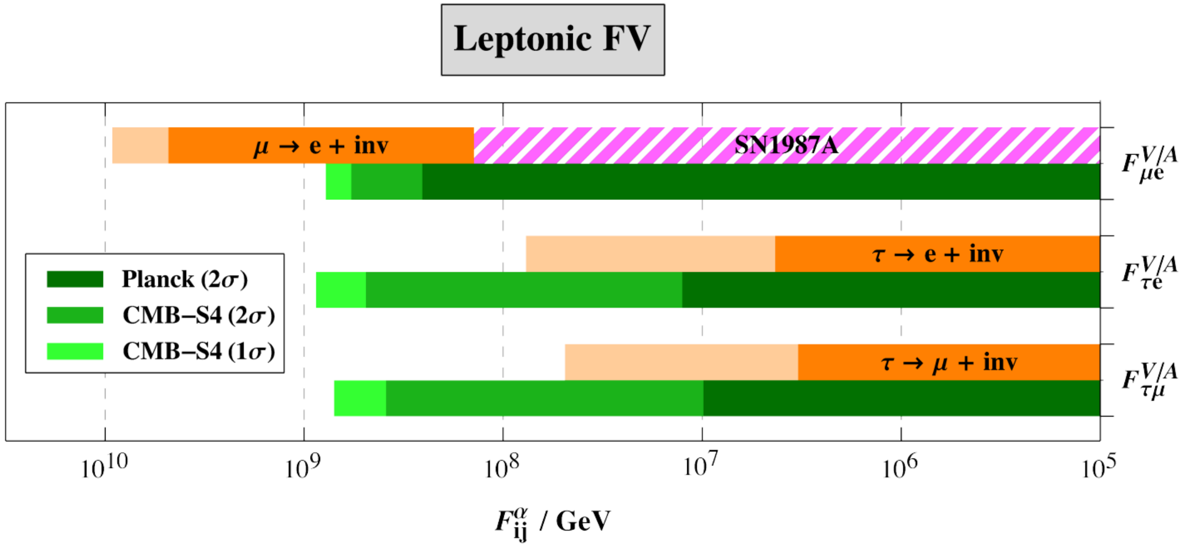
$$\Sigma = \exp\left(i\sqrt{2}\Phi/f_\pi\right) \quad \Phi = \begin{pmatrix} \pi^0 + \frac{\eta_8}{\sqrt{3}} & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{\eta_8}{\sqrt{3}} & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta_8 \end{pmatrix} + \sqrt{\frac{2}{3}}\eta_0\mathbb{1}$$

Results: More toy models





Constraints: Flavor Physics vs CMB



Credit: D'Eramo and Yun, 2111.12108