Axion Dark Matter from Heavy Quarks

New perspectives on flavor and symmetries in particle physics

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Based on 2404.12199

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Outlook

- » Axion-like particles
- » Framework
- » Production
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Axion-like particles as Dark Matter

- 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!

Axion EFT

At $E \ll \Lambda_{EWSB}$, 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

anomalous coupling to gluons
- **Solves Strong CP problem**
- **Generates the axion mass**

Anomalous coupling to photons
- **Responsible for axion pheno.**
- **Determines stability**
- **Induces axion-photon conversion**

Diagonal Coupling to fermions
- **Induces axion-nucleon coupling**
- **Allows axion direct detection**

Off-diagonal Coupling to fermions
- **Usually ignored!**
- **Should be included!**
- **Interesting phenomenology**

Framework

At $E \ll \Lambda_{EWSB}$, the most general Effective Lagrangian for a leptophobic anomaly-free ALP

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

At $\Lambda_{EWSB} \ll E \ll \Lambda_{PQ}$, on the other hand, the Lagrangian can be written as

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu X_\psi \psi$$

misalignment between the PQ basis and flavor basis

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

axions in SM decays →

- Relic Abundance
  $b \to s(d) + a, \quad t \to c(u) + a$
- Precision Flavor Experiments
  $K \to \pi + a, \quad B \to K + a$
- SN1987A bound
  $\Lambda \to na, \quad N + N' \to N + N' + a$

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

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

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

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

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

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

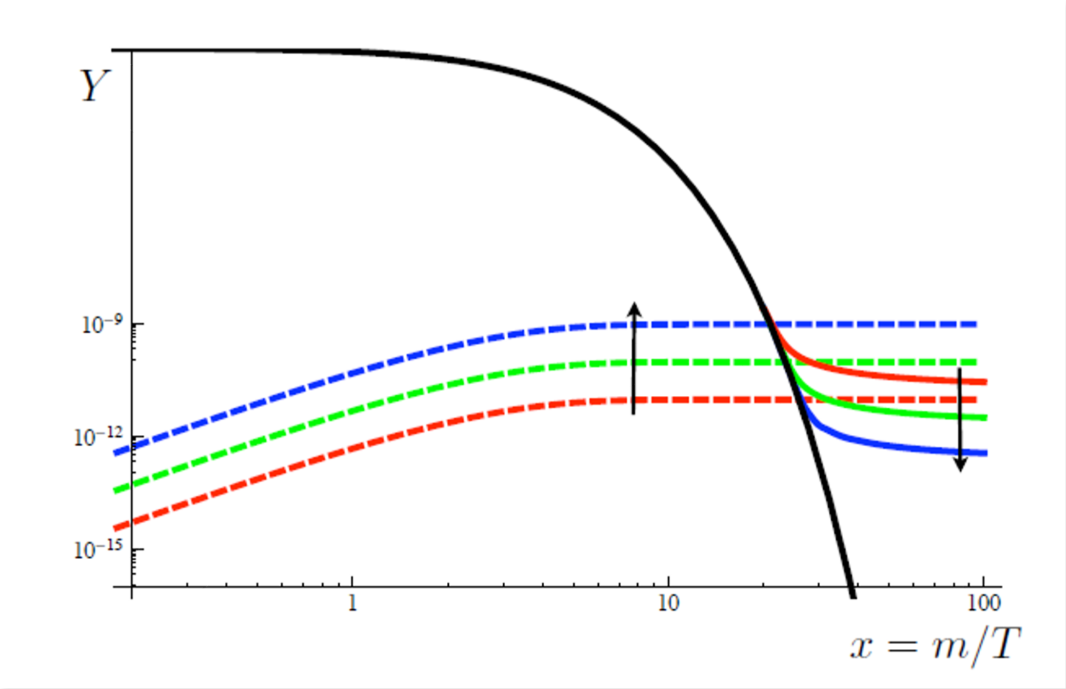
$$U_{u_L} = 1, U_{d_L} = V_{\mathrm{CKM}}$$

Free Parameters: m_a, f_a, α

Free Parameters: m_a, f_a, X

ALP Production: IR Freeze-in

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. Flavor violating decays: $q_i \rightarrow q_j\, a$

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

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

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

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ALP Production: UV Freeze-in

At energies above EWSB, some UV sensitive non-renormalizable operators become important, e.g.

$$\mathcal{L}_{eff} = -C^A_{q_i q_j} \frac{ia}{f_a} \frac{m_{q_i}}{v} h \bar{q}_i P_R q_j \longrightarrow q_i\, h \to q_j\, a$$

The contribution of this process to the relic abundance is,

$$\frac{dY_{\rm UV}}{dT} \simeq \frac{0.4\, M_{\rm Pl}}{g_{*s}\sqrt{g_*}\,\pi^7} \left(\frac{C^A_{q_i,q_j}\, m_{q_i}}{v\, f_a} \right)^2 = \text{constant} \longrightarrow \Omega h^2\big|_{\rm UV} = \frac{m_{q_i} T_R}{3\pi^3 v^2} \Omega h^2\big|_{q_i \to q_j\, a}$$

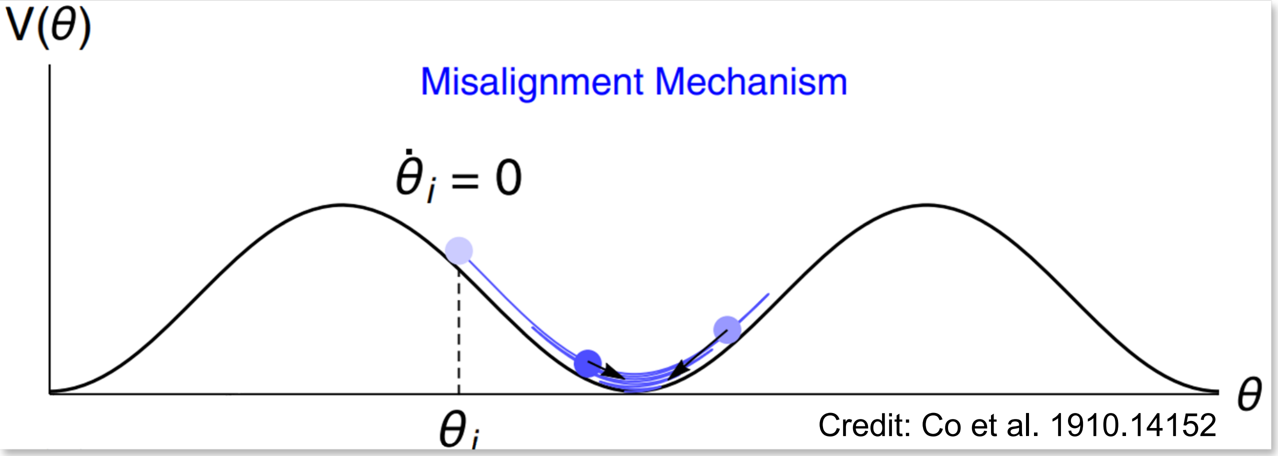
Sticking to the minimal number of free parameters and requiring IR dominated production,

$$T_R < \frac{3\pi^3 v^2}{m_{q_i}}$$

ALP Production: Misalignment Mechanism

In general, axion can be produced also non-thermally via the misalignment mechanism,

$$\ddot{\phi} + 3H(t)\dot{\phi} + m^2\phi = 0$$



where, $H \approx m_a$ sets the onset of the oscillations, however, for the reheating temperature set above

$$T_R < 3\pi^3 v^2/m_{q_i}$$

and for the mass ranges considered in this work, the onset of the oscillations is prior to the T_R, therefore the axion produced via misalignment dilutes away!

$$\Omega_a h^2 = \frac{\theta_i^2 f_a^2 m_a m_a(T_{\rm osc})}{6H_0^2 M_{\rm Pl}^2}\left(\frac{g_{\star,s}(T_0)T_0^3}{g_{\star,s}(T_{\rm osc})T_{\rm osc}^3}\right) \Longrightarrow \Omega_a h^2|_{\rm mis} \approx 4\times 10^{-3}\left(\frac{H_R}{11\,{\rm keV}}\right)^{1/2}\left(\frac{f_a\theta_0}{10^{10}\,{\rm GeV}}\right)^2$$

Stability

For axions with $f_a \gtrsim 10^8$ GeV, stability and long lifetime can be achieved easily. The main decay channels for a generic axion are,

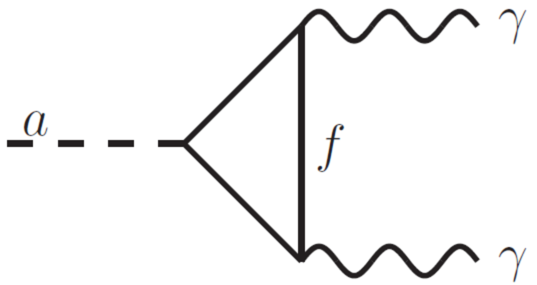
1. Decay into pions ($a \to \pi\,\pi\,\pi$) $\longrightarrow$ $m_a \gtrsim 3\,m_\pi$ *is already excluded by X − ray observations.*
2. Decay into leptons ($a \to ll$) $\longrightarrow$ *Choosing leptophobic axions, they are avoided.*
3. Decay into photons ($a \to \gamma\gamma$) $\longrightarrow$ *It is induced at loop level.*

So, the stability of our DM candidate is determined by di-photon decay, as advertised.

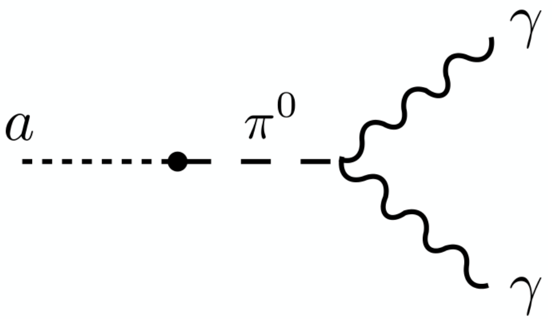
$$\Gamma_{\gamma\gamma} = \frac{\alpha_{\rm em}^2 m_a^3}{64\pi^3 f_a^2}\left|C_{\gamma\gamma}^{\rm heavy} + C_{\gamma\gamma}^{\rm light}\right|^2$$

Stability

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



$$C_{\gamma\gamma}^{\rm heavy} \approx \sum_{i=c,b,t} Q_i^2 C_i \frac{m_a^2}{4m_i^2}$$



$$C_{\gamma\gamma}^{\rm light} \approx \frac{C_u - C_d}{2}\frac{m_a^2}{m_\pi^2} + \frac{\sqrt{2}}{6}(C_u + C_d - C_s)\frac{m_a^2}{m_\eta^2} + \frac{\sqrt{2}}{3}(C_u + C_d + 2C_s)\frac{m_a^2}{m_{\eta'}^2},$$

Chiral Perturbation theory Remark

$$\mathcal{L}_{\chi\rm PT} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{f_\pi^2}{8}{\rm Tr}\left[D_\mu \Sigma D^\mu \Sigma^\dagger\right] + \frac{f_\pi^2}{4}B_0 {\rm Tr}\left[M_q \Sigma^\dagger + {\rm h.c.}\right] - \frac{1}{2}M_0^2 \eta_0^2,$$

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

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

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

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

Constraints: Astrophysics

Warmness Bound a.k.a WDM

1. Free streaming

$$\lambda_{\rm FS} \simeq 0.1\ {\rm Mpc}\left(\frac{1\ {\rm keV}}{m_\chi}\right) < \lambda_{\rm FS}^{\rm WDM} = \begin{cases} 0.070\,{\rm Mpc} \\ 0.041\,{\rm Mpc} \end{cases}$$

$$m_{\rm WDM} = 3.5\ {\rm keV}$$
$$m_{\rm WDM} = 5.3\ {\rm keV}$$

2. Momentum dispersion

D'Eramo and Lenoci, 2012.01446

$$m_a \gtrsim 10\,{\rm keV}\left(\frac{m_{\rm WDM}}{3.5\,{\rm keV}}\right)^{\frac{4}{3}}\left(\frac{79}{g^*(m_q)}\right)^{\frac{1}{3}}$$

SN1987A: $N + N' \to N + N' + a$

Through a careful matching onto axion-Nucleon Chiral Lagrangian, the following bound is extracted

$$0.61 g_{ap}^2 + g_{an}^2 + 0.53 g_{an} g_{ap} < 8.26 \times 10^{-19}$$

$$g_{ai} \equiv C_i m_i / f_a .$$

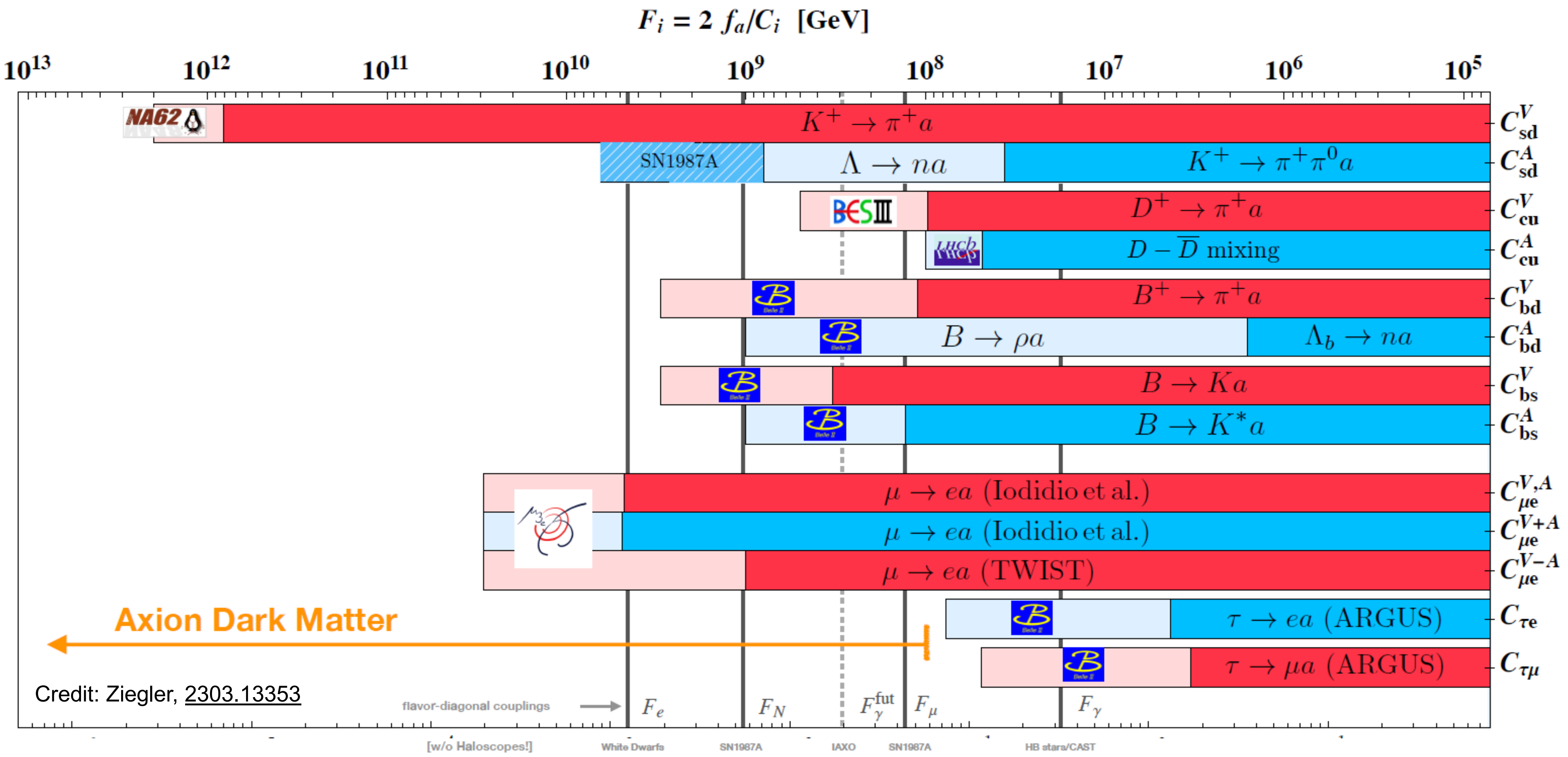
Carenza et al. 1906.11844

where the couplings are

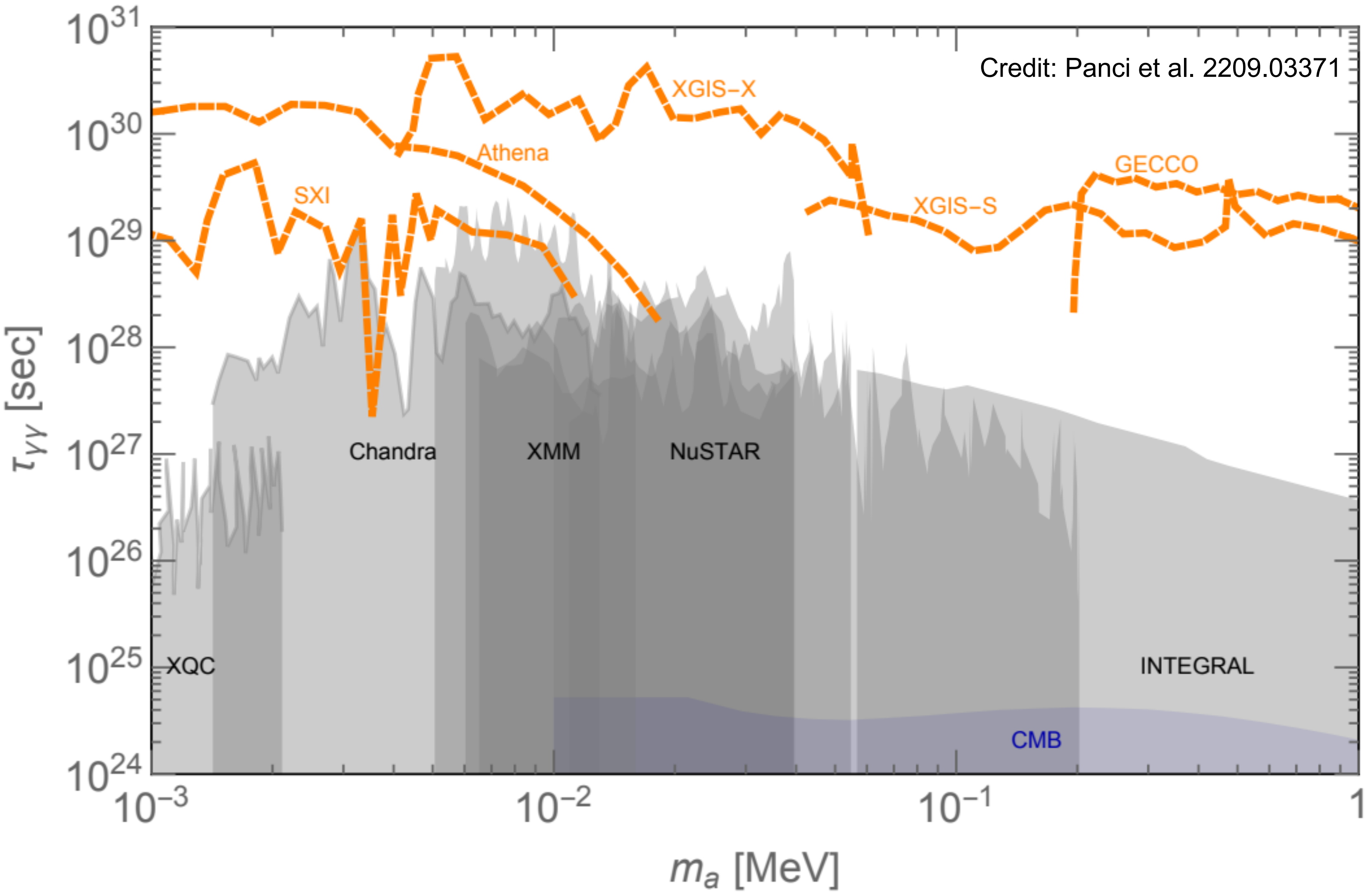
$$\begin{cases} C_p \approx \Delta u\, C_{uu}^A + \Delta d\, C_{dd}^A + \Delta s\, C_{ss}^A \\ C_n \approx \Delta u\, C_{dd}^A + \Delta d\, C_{uu}^A + \Delta s\, C_{ss}^A ; \end{cases}$$

$$\frac{f_a}{C_N} \gtrsim 1.5 \times 10^9\ {\rm GeV}$$

Constraints: Flavor Physics



Constraints: X-Ray Observatories



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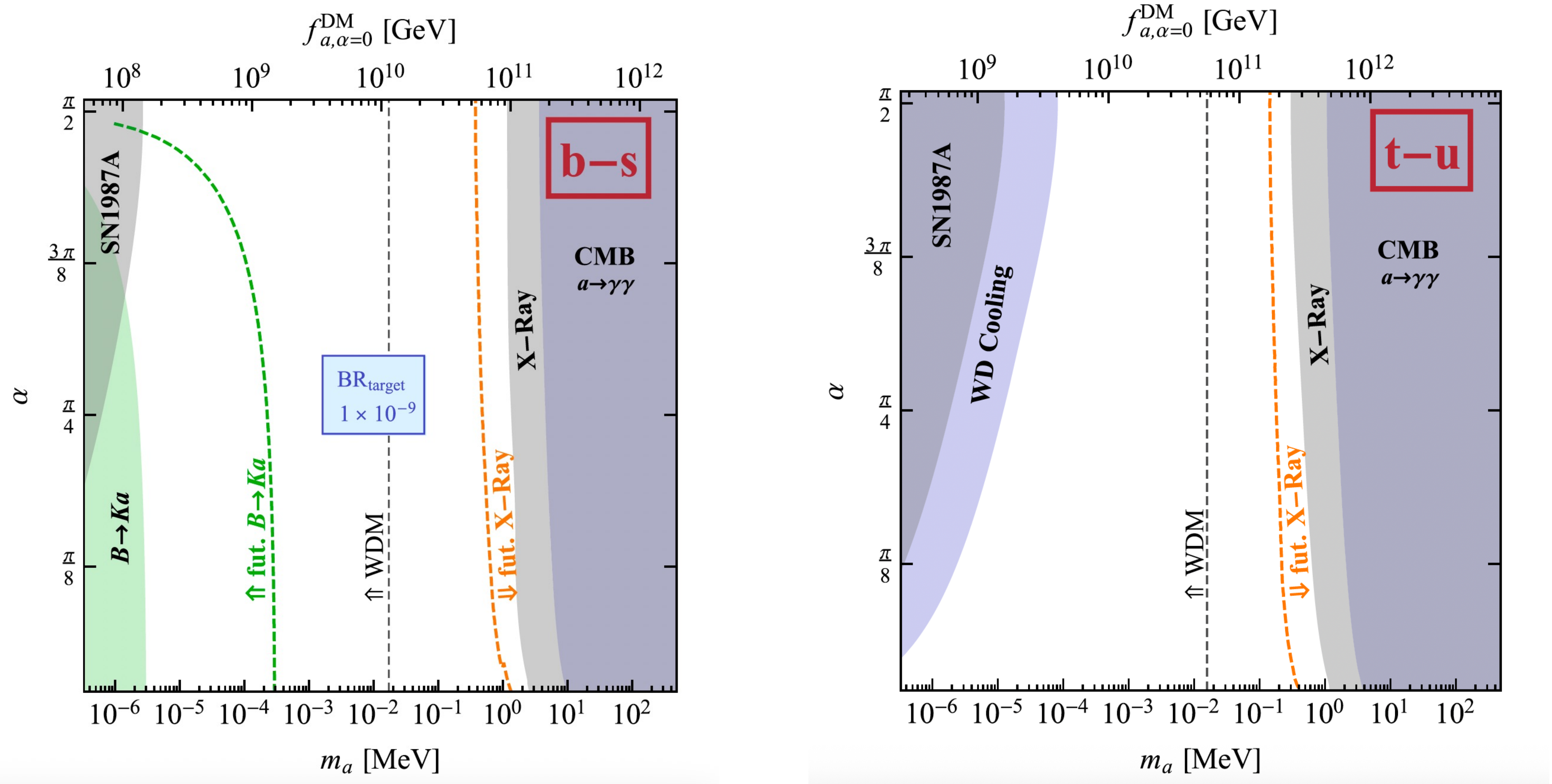
Results: toy models



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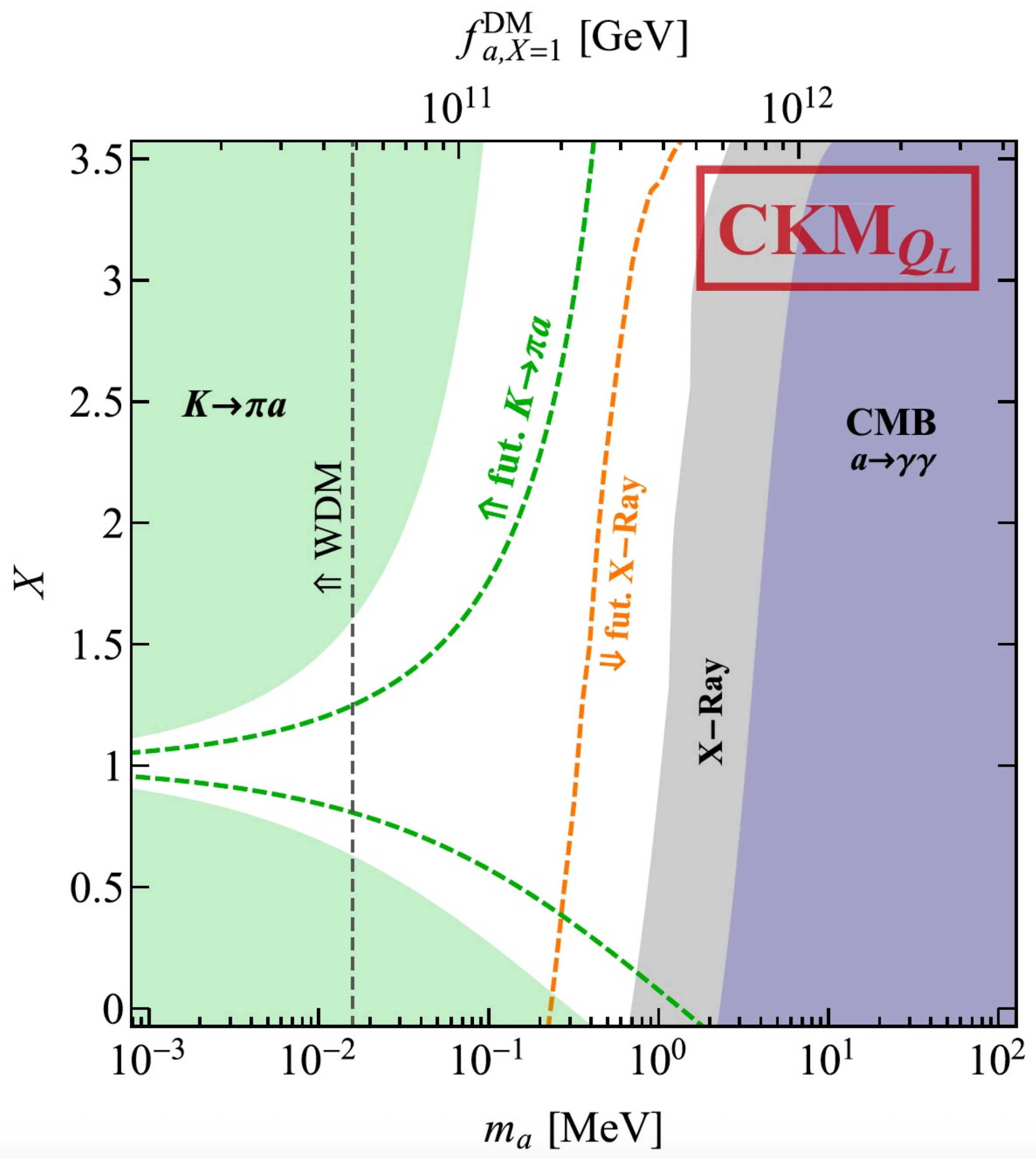
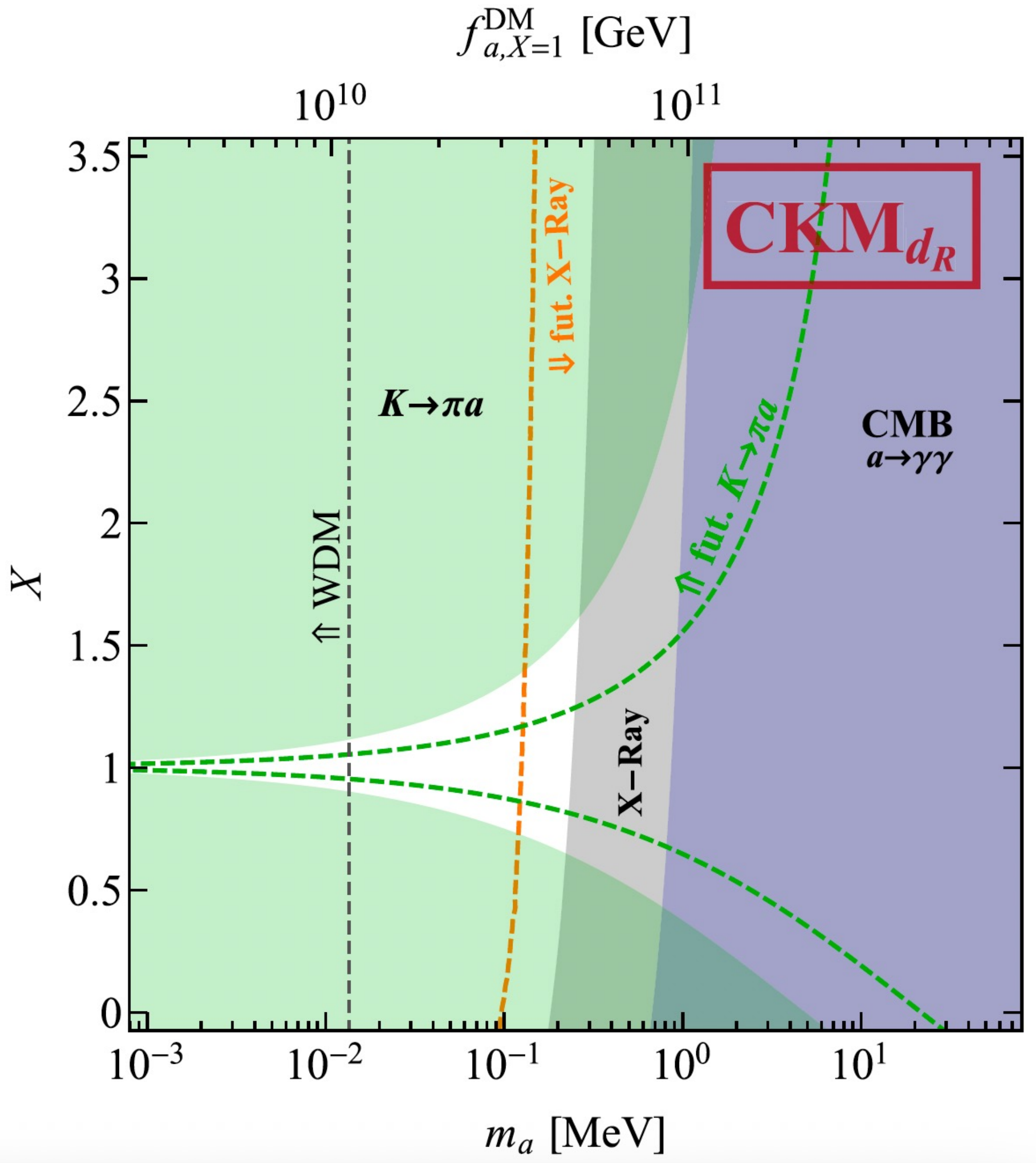
Results: CKM Scenarios





Summary

- The most general axion EFT possesses non-diagonal coupling to SM particle fermions.
- DM Axions with flavor-violating couplings can be produced by SM decays

- 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

- Also, they can modify star cooling
  - Supernoavae
  - White Dwarfs

Back up slides

ALP Stability – Light Quarks

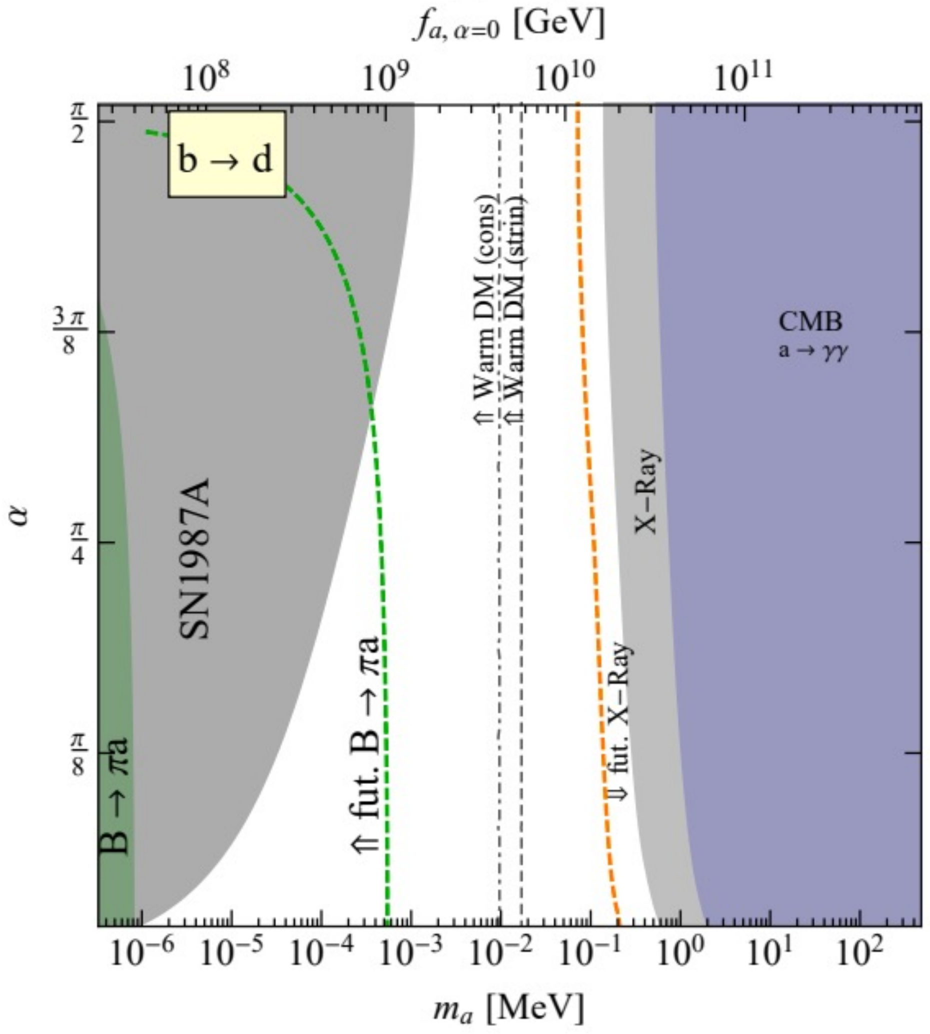
At energies below a few GeV, the effective Lagrangian for the three light quarks $\Psi = (u, d, s)$,

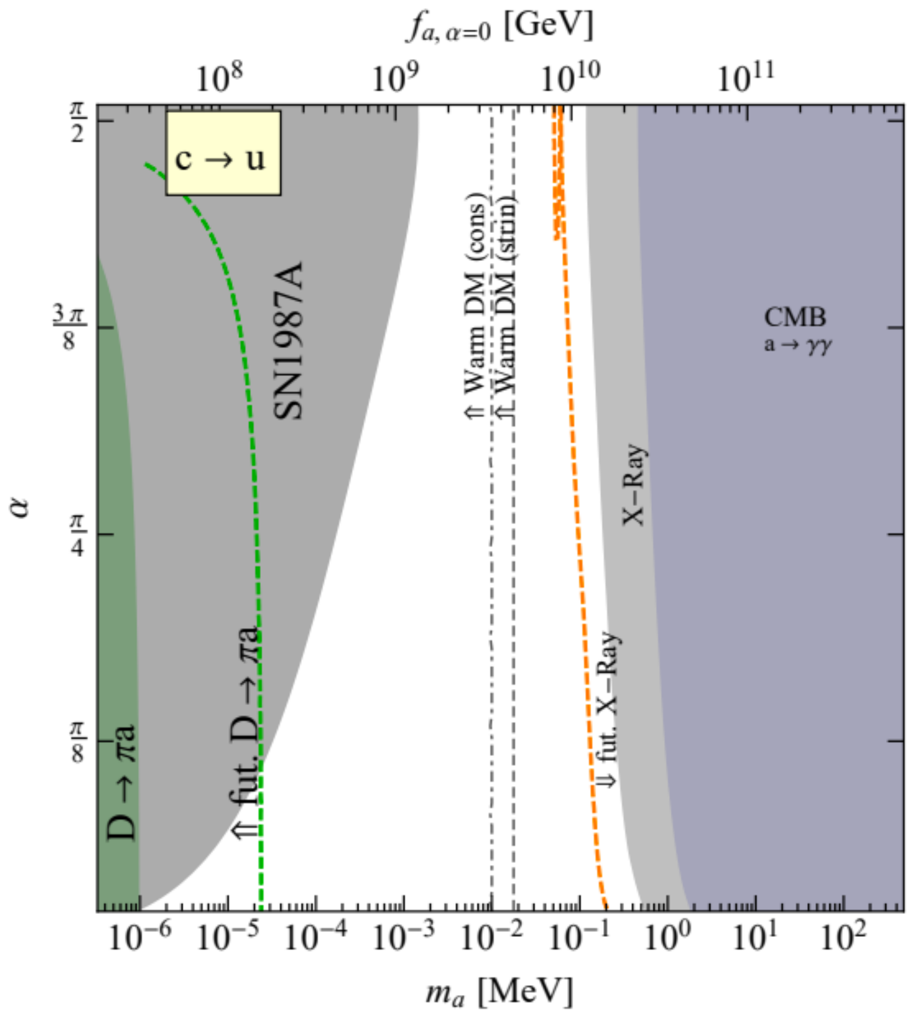
$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial^\mu a)(\partial_\mu a) - \frac{m_a^2}{2}a^2 + \bar{\Psi}(i\not{D} - M_q)\Psi + \frac{\partial^\mu a}{f_a}\bar{\Psi}\gamma^\mu(k_L P_L + k_R P_R)\Psi$$

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

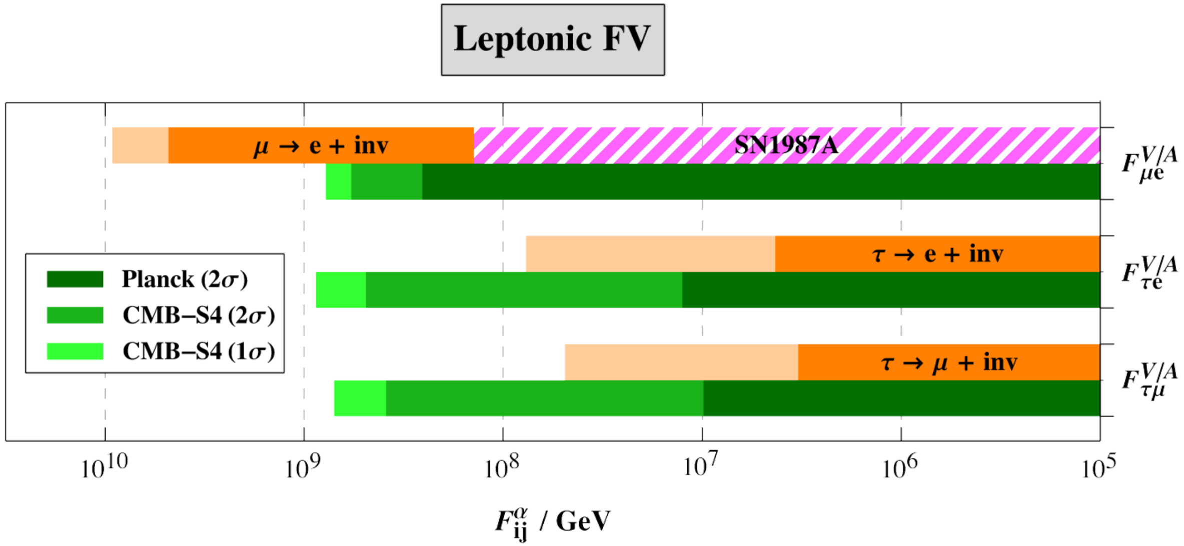
$$\Sigma = \exp\left(i\sqrt{2}\Phi/f_\pi\right) \quad \Phi = \begin{pmatrix} \pi^0 + \frac{\eta_8}{\sqrt{3}} & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{\eta_8}{\sqrt{3}} & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta_8 \end{pmatrix} + \sqrt{\frac{2}{3}}\eta_0\mathbb{1}$$

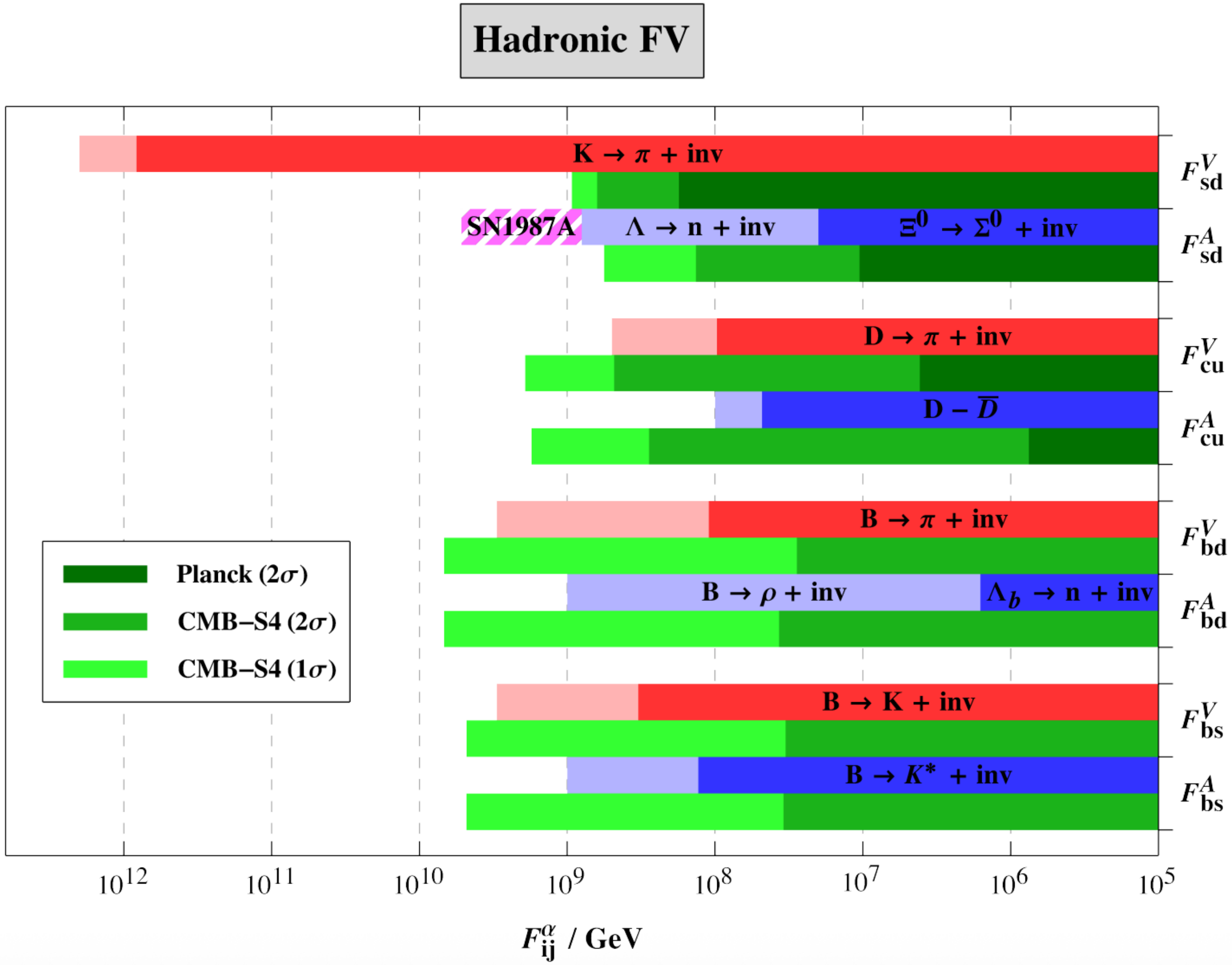
Results: More toy models





Constraints: Flavor Physics vs CMB





Credit: D'Eramo and Yun, 2111.12108