Axion Dark Matter from Heavy Quarks

Particle Physics at Crossroads

March 2026

Mohammad Aghaie

Postdoctoral Researcher, University of Osaka

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

Based on 2404.12199

UNIVERSITÀ DI PISA

The University of Osaka

Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

Outlook

- Axion-like particles
- Framework
- Production
- Stability
- Constraints
- Results
- Summary

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**

$m_a \lesssim \mathcal{O}(\mathrm{MeV})$ ↓ **light**

✚ **SM singlet** ↓ **Neutral**

↓ **decoupled** $f_a \gtrsim 10^9\ \mathrm{GeV}$

- **Stable** on Cosmological time scales

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

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

These ALPs are great DM candidates but they are invisible!

Mohammad Aghaie · Postdoctoral Researcher · University of Osaka · aghaie.sci@osaka-u.ac.jp

Axion EFT

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

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

Ziegler 2303.13353

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

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

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

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
  $\mathrm{b} \to s(d) + a, \qquad t \to c(u) + a$
- Precision Flavor Experiments
  $\mathrm{K} \to \pi + a, \qquad B \to K + a$
- SN1987A bound
  $\Lambda \to na, \qquad \mathrm{N} + \mathrm{N}' \to N + N' + a$

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

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

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

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 “$\mathrm{CKM}_{\mathrm{dR}}$” and “$\mathrm{CKM}_{\mathrm{QL}}$”

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

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

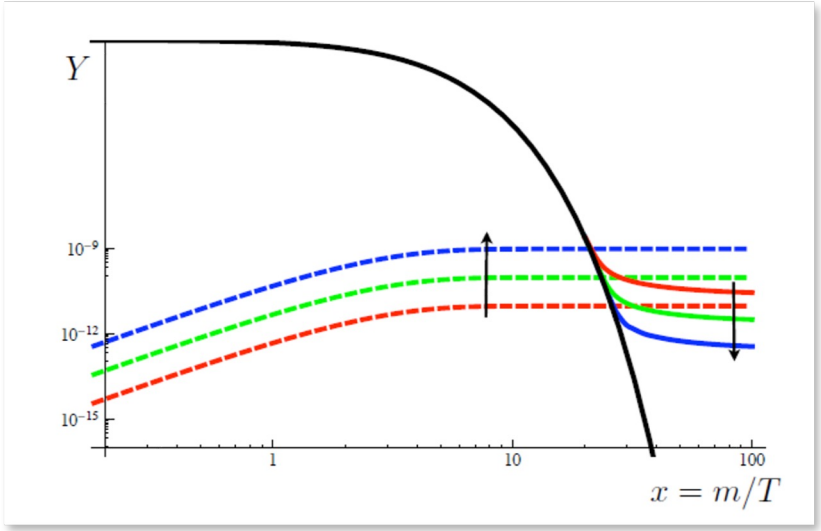
Free Parameters: m_a, f_a, X

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: $q_i \rightarrow q_j\, a$

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

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

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

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,

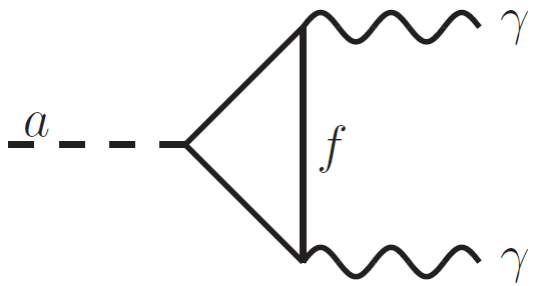
1. Decay into pions ($a \to \pi\,\pi\,\pi$) ⟶ $m_a \gtrsim 3\,m_\pi$ *is already excluded by* $X-$*ray observations.*
2. Decay into leptons ($a \to ll$) ⟶ *Choosing leptophobic axions, they are avoided.*
3. Decay into photons ($a \to \gamma\gamma$) ⟶ *It is induced at loop level.*

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

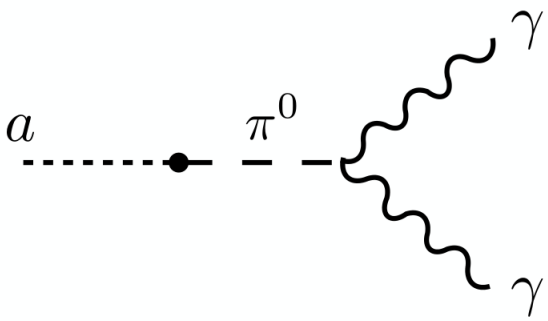
$$\Gamma_{\gamma\gamma} = \frac{\alpha_{\rm em}^2 m_a^3}{64\pi^3 f_a^2} \left| C_{\gamma\gamma}^{\rm heavy} + C_{\gamma\gamma}^{\rm light} \right|^2$$

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

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

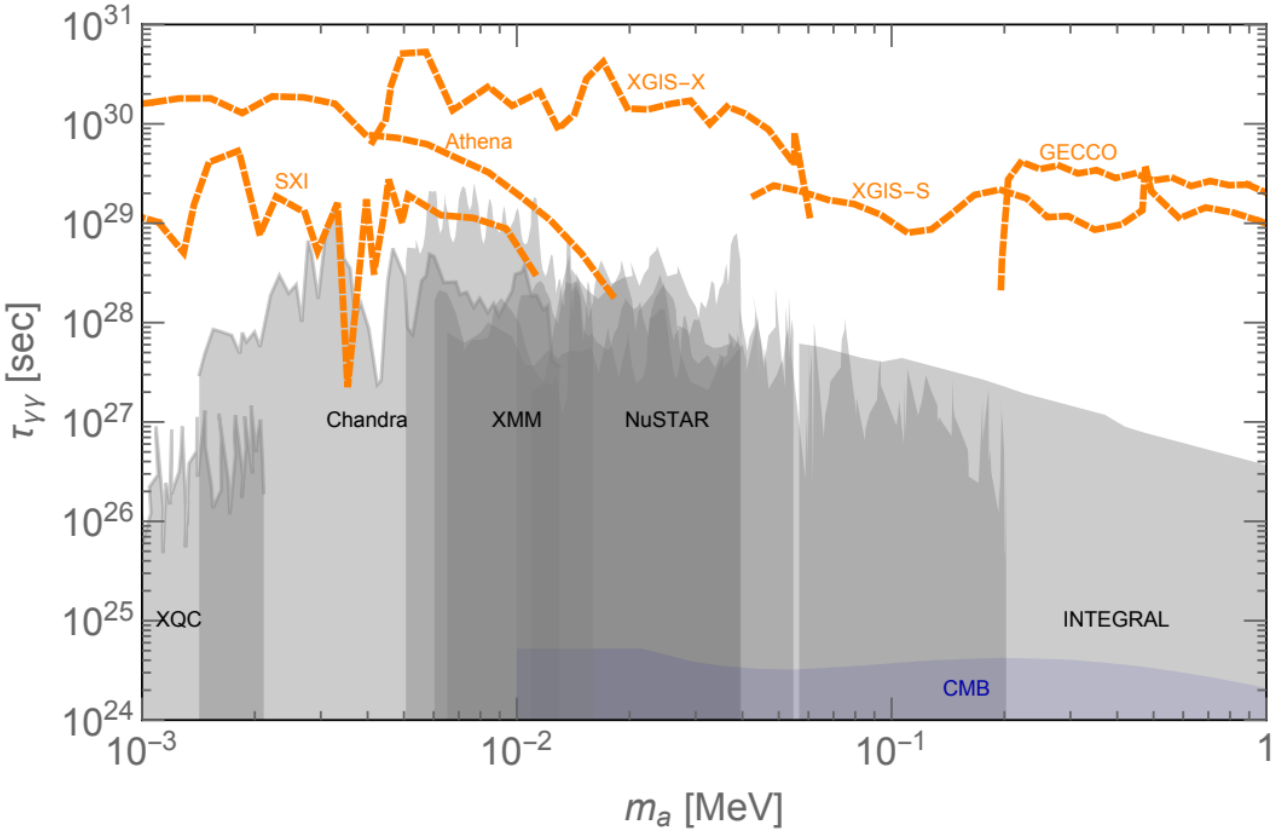
$$\pi^0 \approx \pi^0_{\rm phys} + \epsilon \frac{C_u - C_d}{2\sqrt{2}} \frac{m_a^2}{m_a^2 - m_\pi^2} a_{\rm phys},$$

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

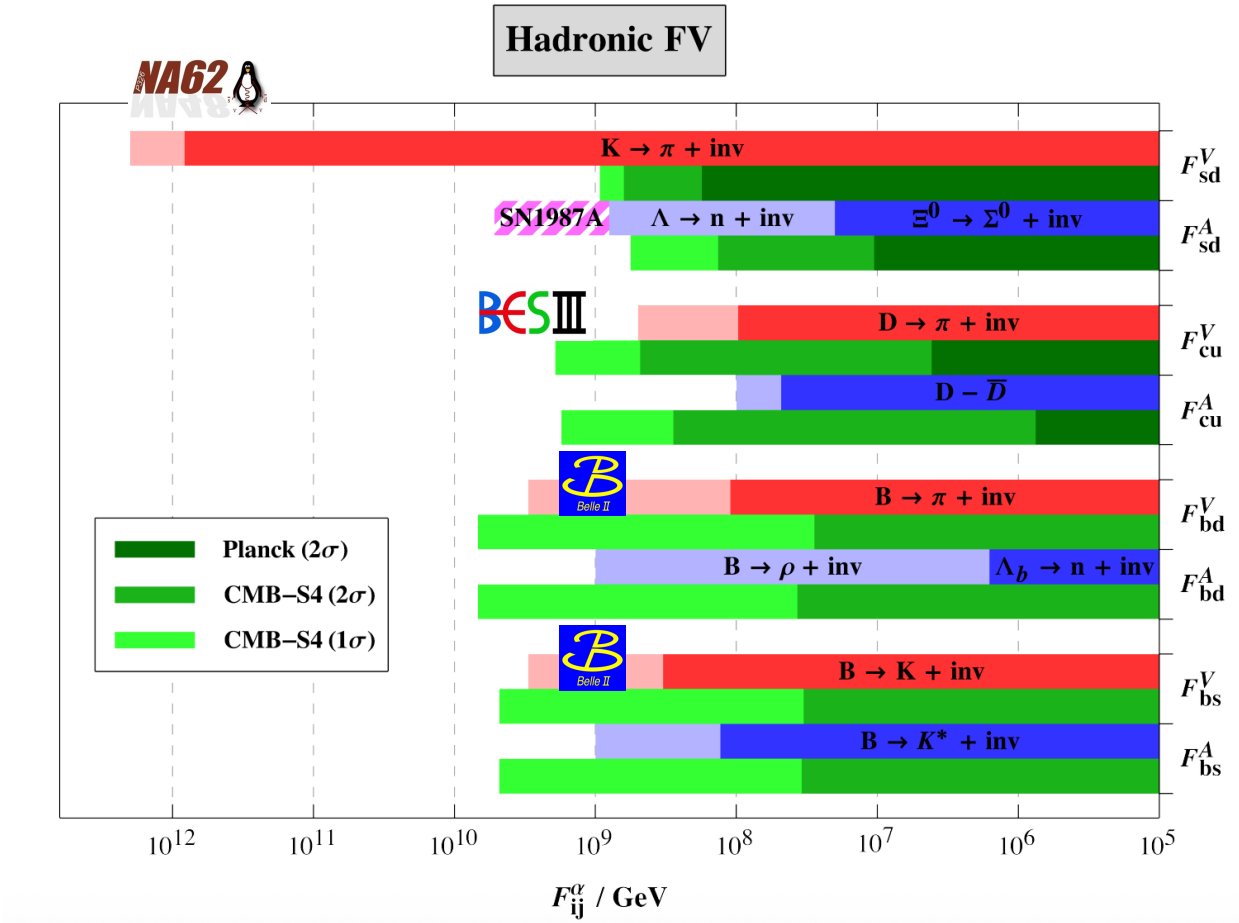
$$\eta_0 \approx \eta'_{\rm phys} + \epsilon \frac{C_u + C_d + 2C_s}{2\sqrt{6}} \frac{m_a^2}{m_a^2 - m_{\eta'}^2} a_{\rm phys}$$

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

Constraints

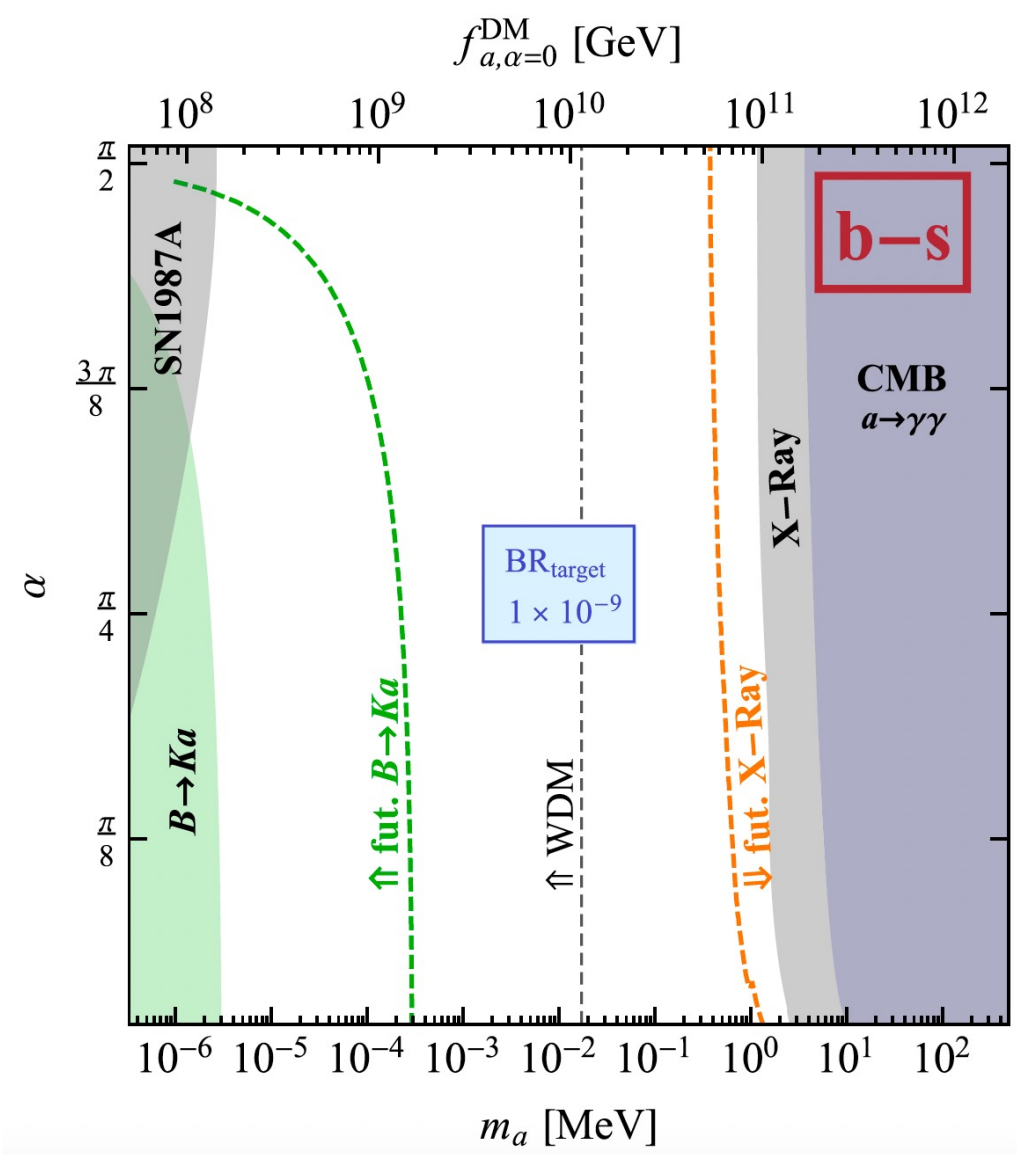


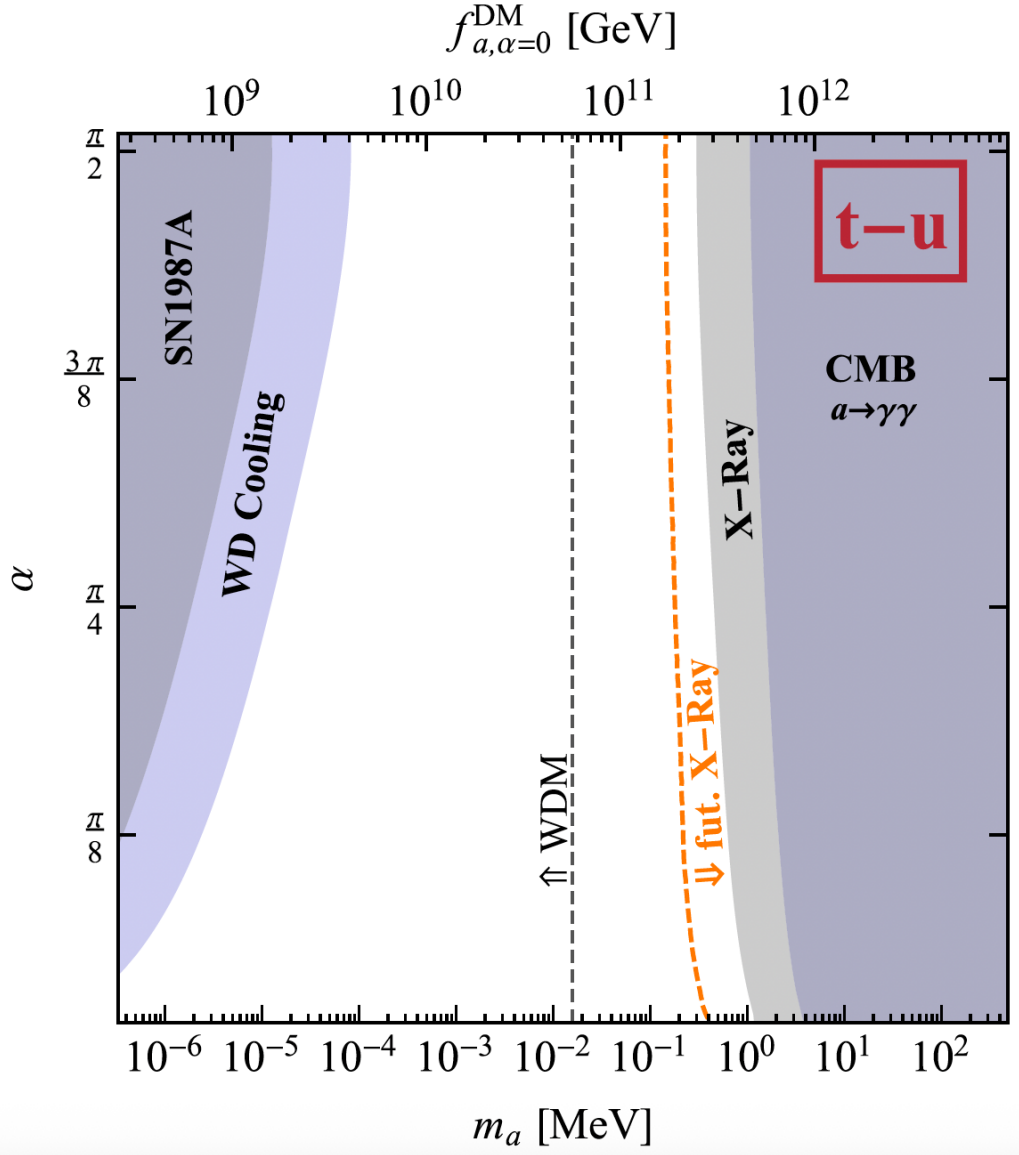
Credit: Panci et al. 2209.03371



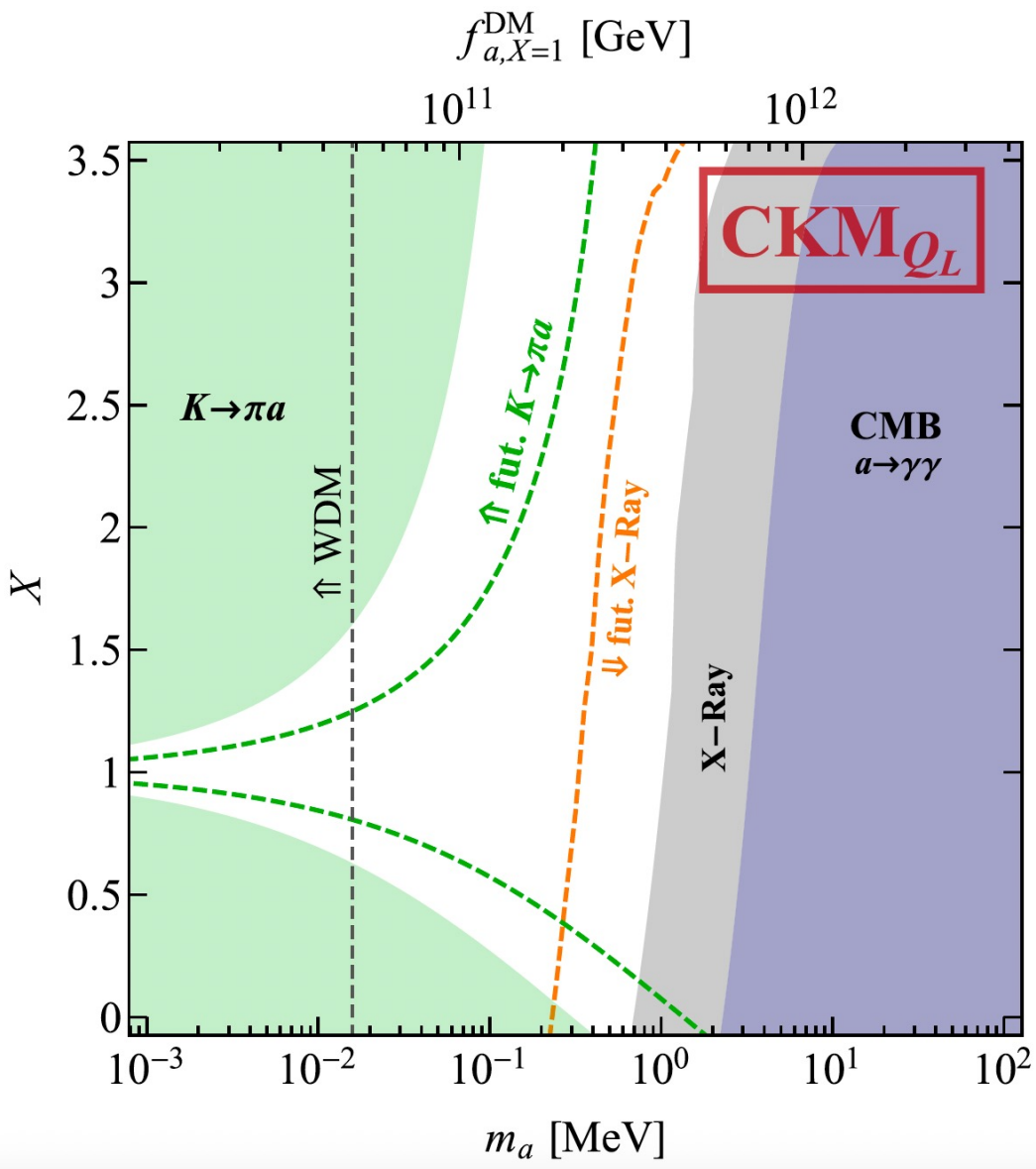
Credit: D'Eramo and Yun, 2111.12108

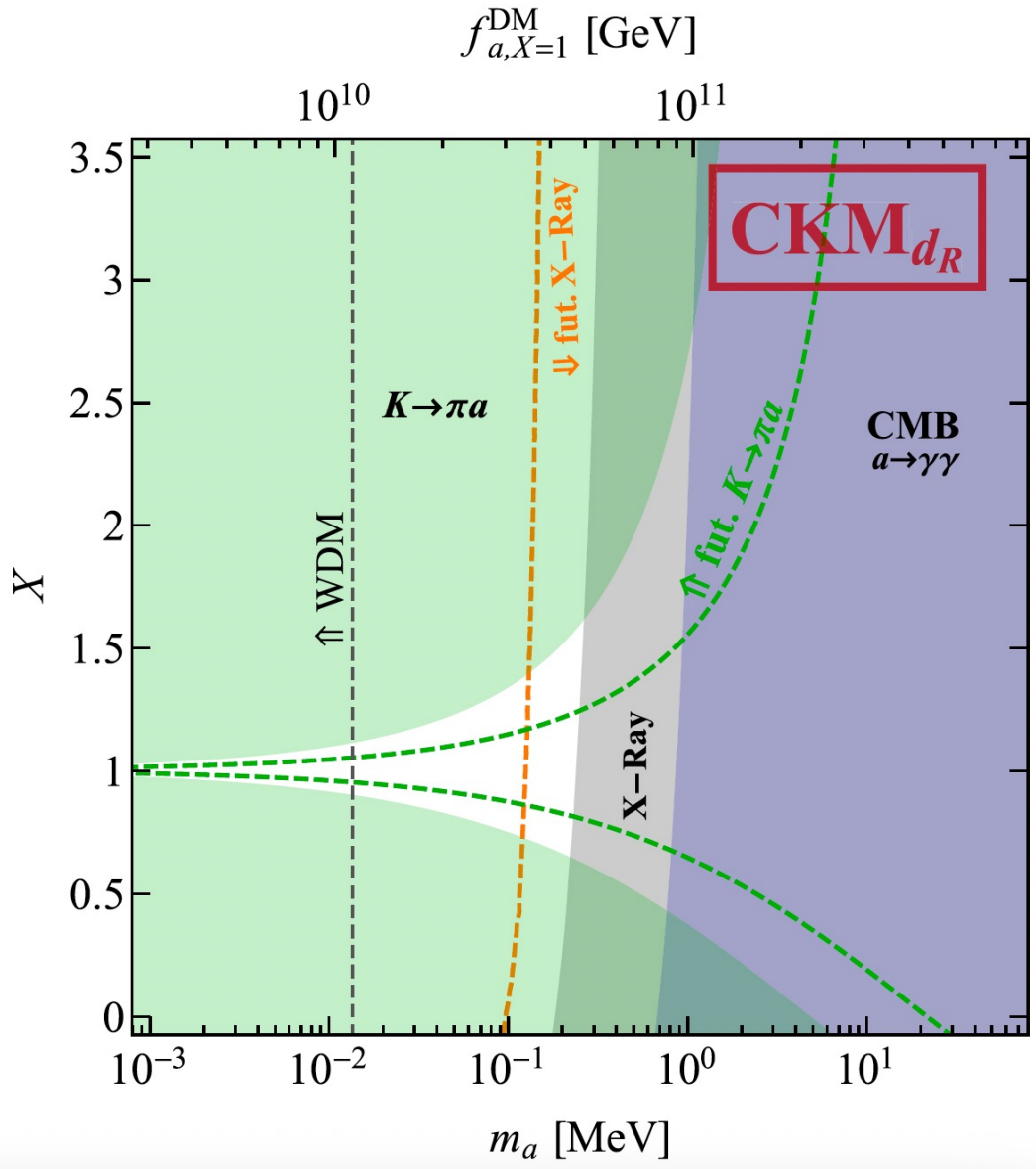
Results: toy models





Results: CKM Scenarios





Mohammad Aghaie · Postdoctoral Researcher · University of Osaka · aghaie.sci@osaka-u.ac.jp

Summary

- Axion-like particles with off-diagonal coupling to SM fermions are considered.
- These couplings which are mostly ignored, open up interesting phenomenology
    - production via freeze-in
    - bounds from Precision Flavor Experiments
    - bounds SN1987A bound
- The absence of anomalous coupling to photons enhanced the stability of the ALP
- This family of ALPs are able to reproduce the observed relic abundance of the dark matter
- Significant portion of the allowed parameter space is going to be probed by future precision flavor experiments and future X-ray observatories.

Thank You!

Mohammad Aghaie

Postdoctoral Researcher

University of Osaka

Department of Graduate Sciences, Building H #723

Machikaneyama-cho 1-18, Toyonaka, Osaka 560-0043, Japan

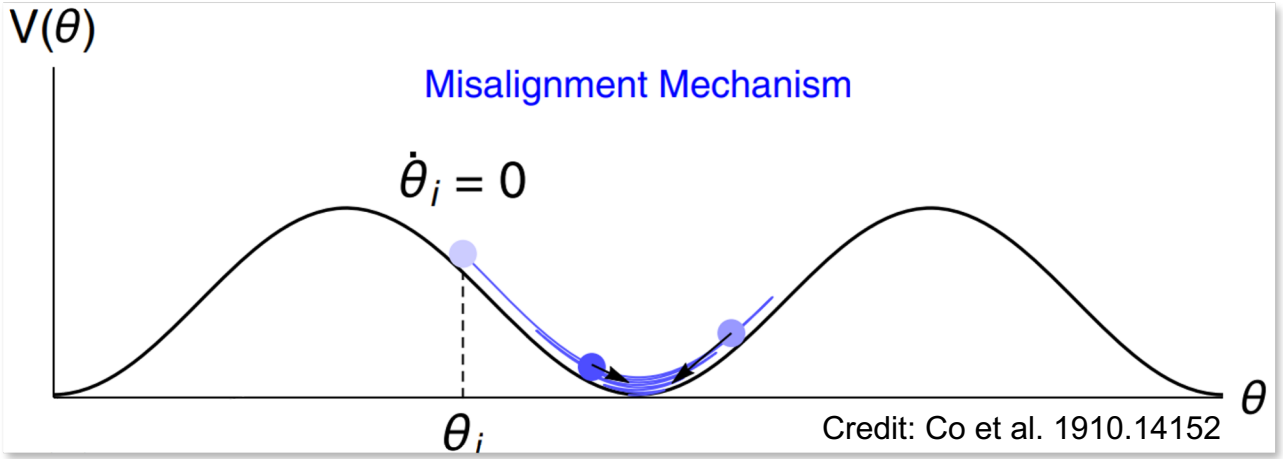
aghaie.sci@osaka-u.ac.jp

Back up slides

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

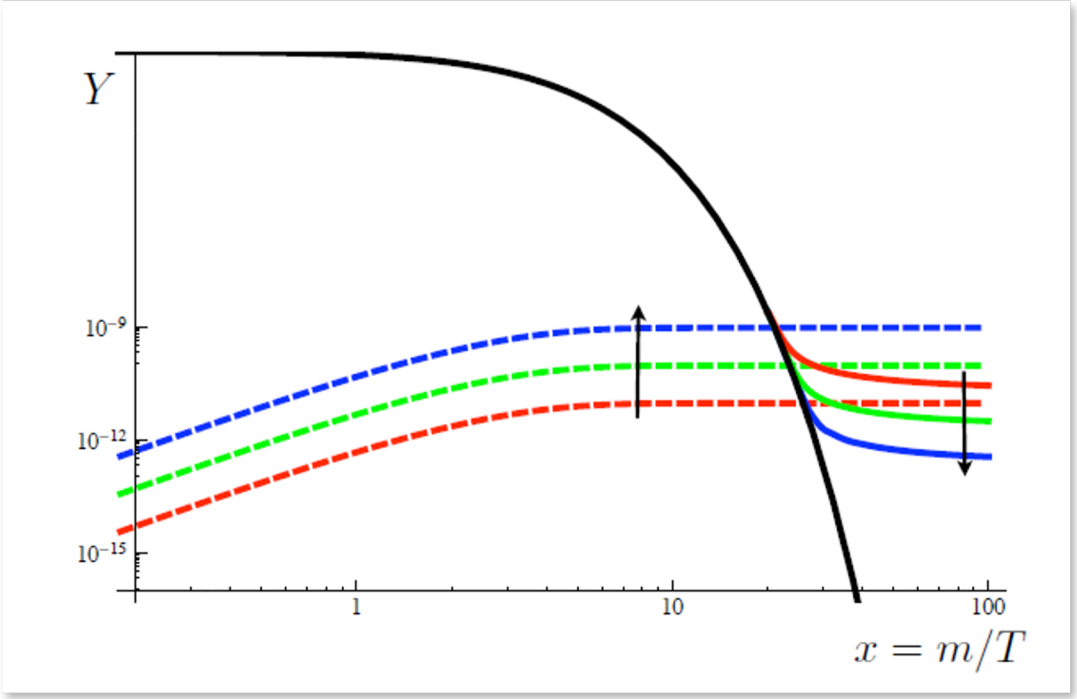
$$T_R < 3\pi^3 v^2 / m_{q_i}$$

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!

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

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: $q_i\, g(\gamma) \rightarrow q_j\, a$; $\quad q_i\, \overline{q_i} \rightarrow g(\gamma)\, a$

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

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

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,

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

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 Stability – Light Quarks

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

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

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

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

Constraints: Astrophysics

Warmness Bound a.k.a WDM

1. Free streaming

$$\lambda_{\rm FS} \simeq 0.1\ {\rm Mpc}\left(\frac{1\ {\rm keV}}{m_\chi}\right) < \lambda_{\rm FS}^{\rm WDM} = \begin{cases} 0.070\,{\rm Mpc} & m_{\rm WDM} = 3.5\ {\rm keV} \\ 0.041\,{\rm Mpc} & m_{\rm WDM} = 5.3\ {\rm keV} \end{cases}$$

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

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

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

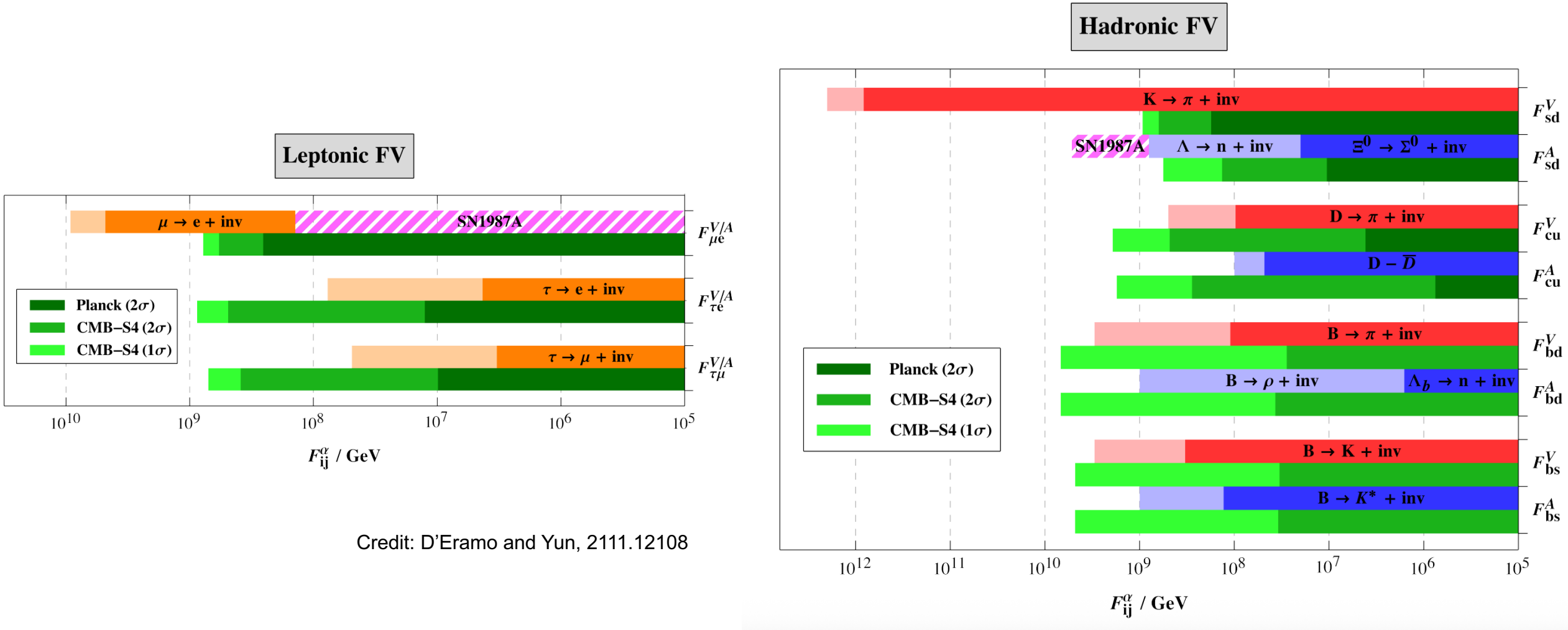
Carenza et al. 1906.11844

where the couplings are

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

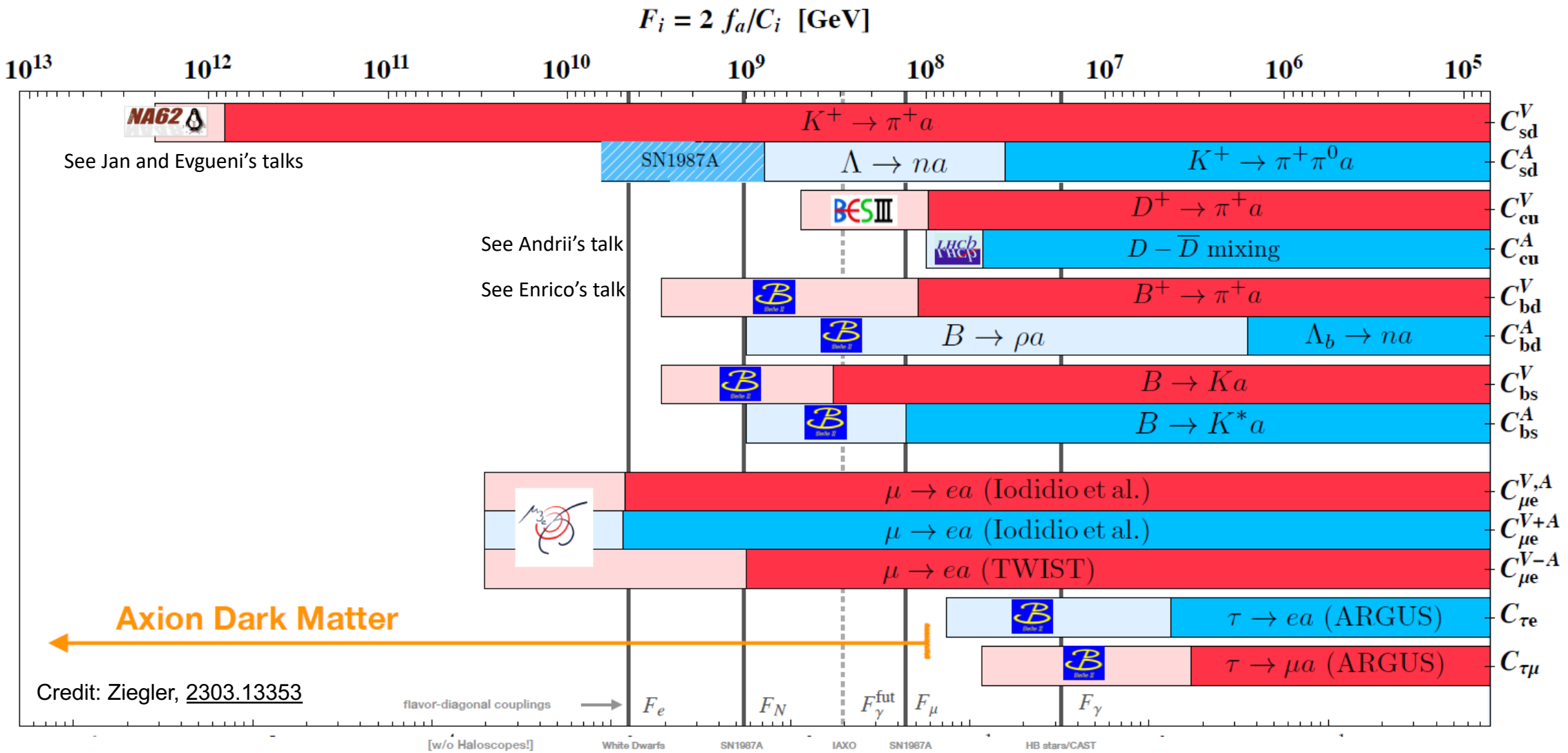
$$\frac{f_a}{C_N} \gtrsim 1.5 \times 10^9\ {\rm GeV}$$

Constraints: Flavor Physics vs CMB

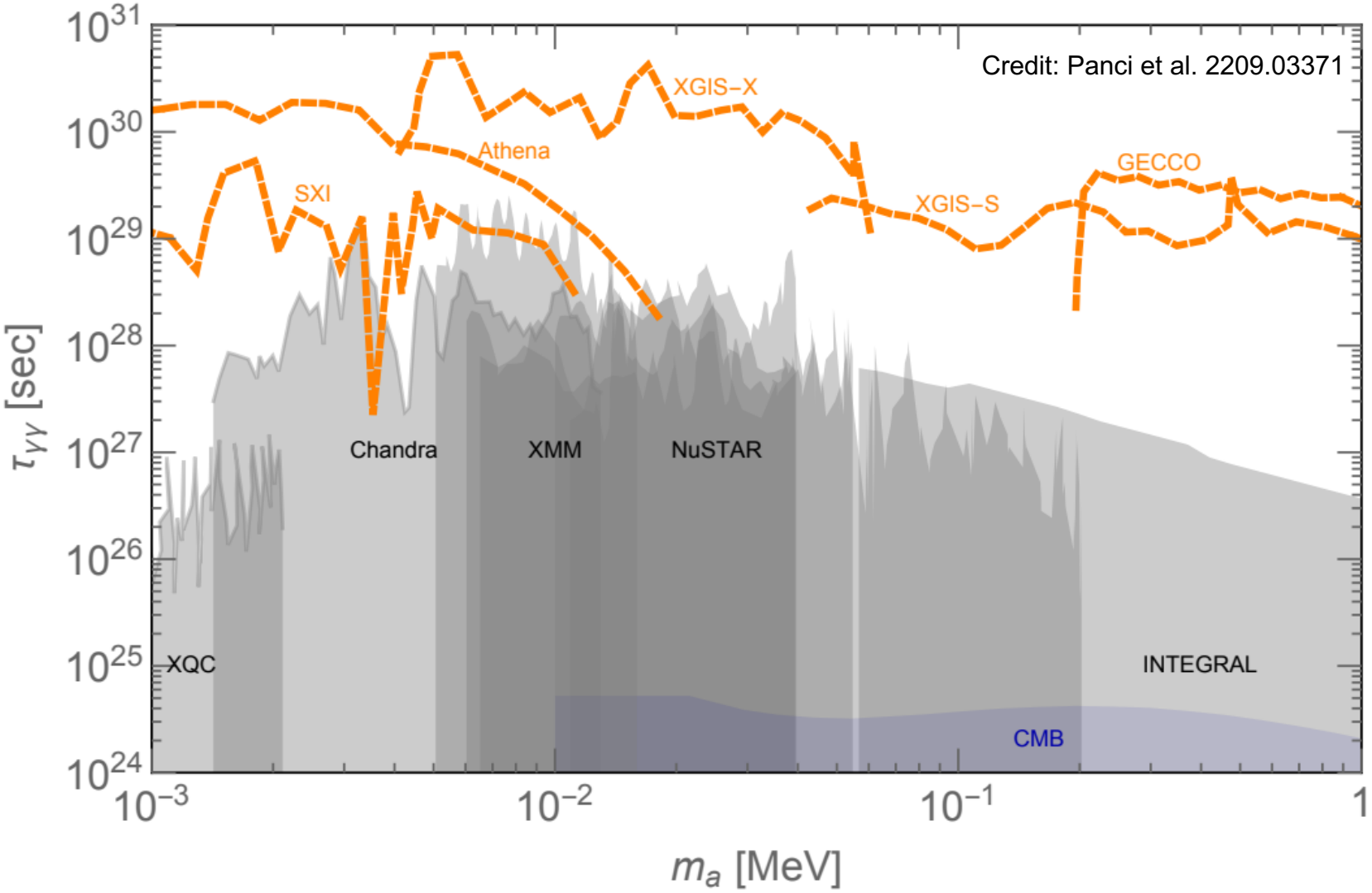
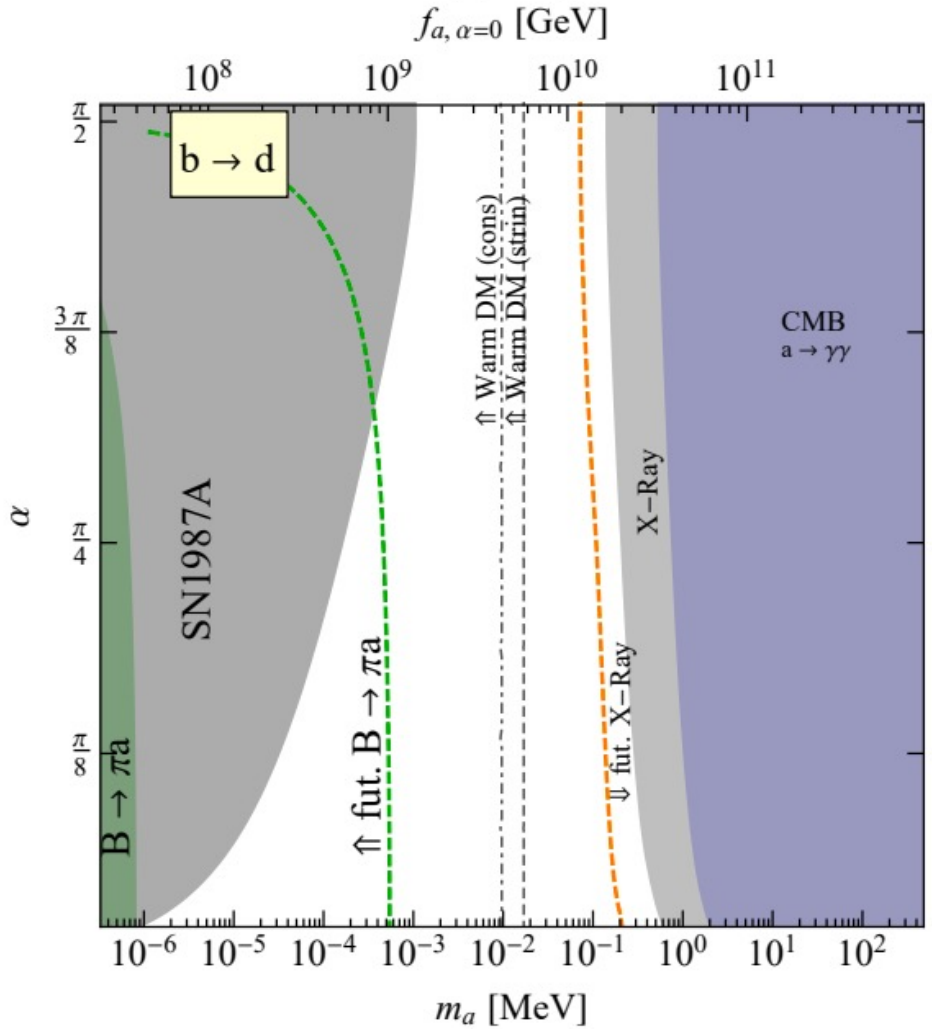
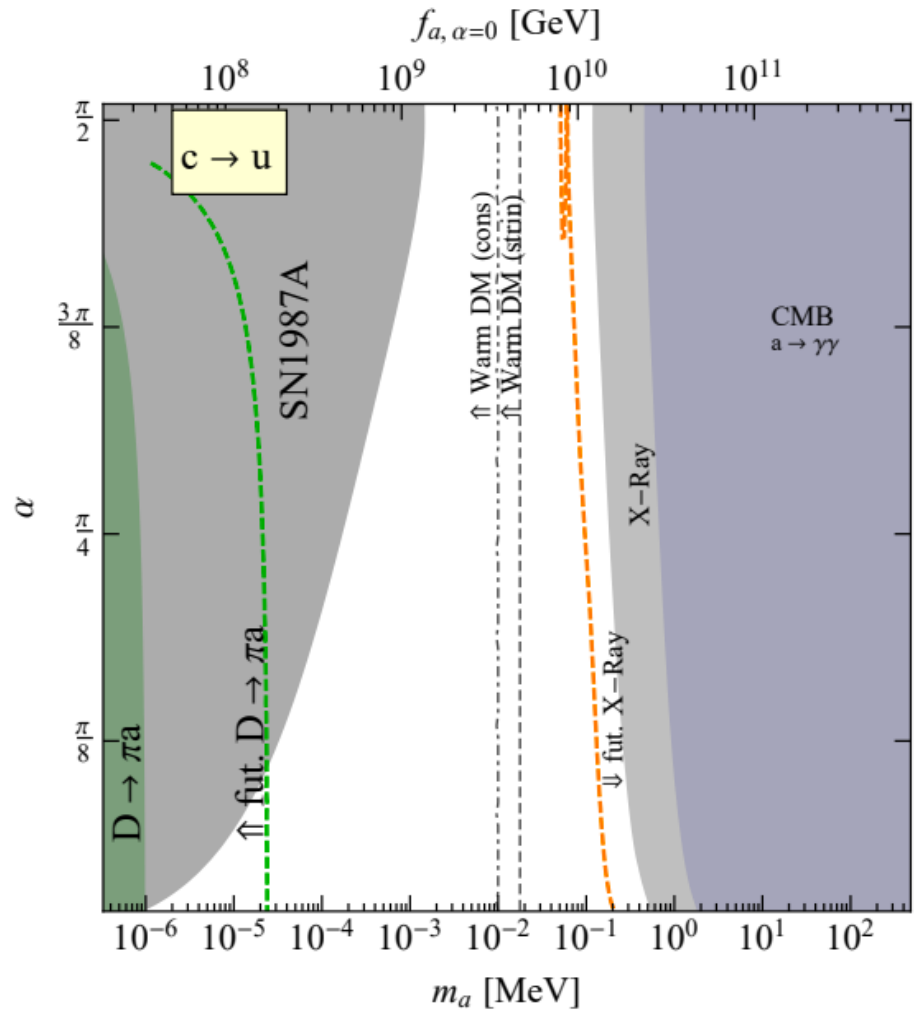


Credit: D'Eramo and Yun, 2111.12108

Constraints: Flavor Physics



Constraints: X-Ray Observatories



Results: More toy models