

Axion Dark Matter from Heavy Quarks

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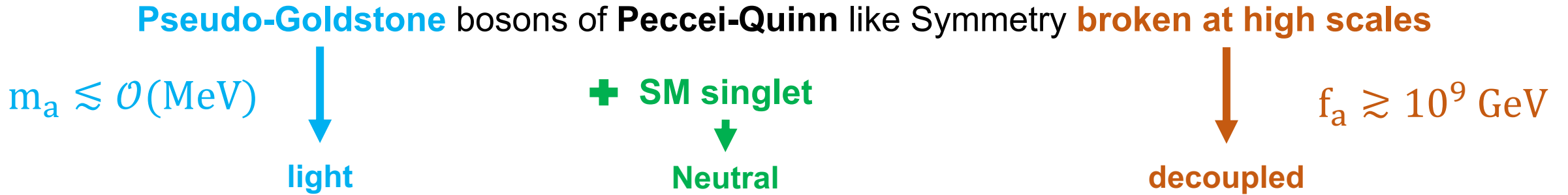
Outlook

- » 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**



- ❖ **Stable** on Cosmological time scales

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

- ❖ 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

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

Ziegler 2303.13353



anomalous coupling to gluons

- Solves Strong CP problem
- Generates the axion mass



Anomalous coupling to photons

- Responsible for axion phenomenology
 - 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

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

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

$$\begin{aligned} C_u^{V,A} &= U_{u_R}^\dagger X_{u_R} U_{u_R} \pm U_{u_L}^\dagger X_{Q_L} U_{u_L}, \\ C_d^{V,A} &= U_{d_R}^\dagger X_{d_R} U_{d_R} \pm U_{d_L}^\dagger X_{Q_L} U_{d_L}, \end{aligned}$$

axions in SM decays

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

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

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

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

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}”

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

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

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

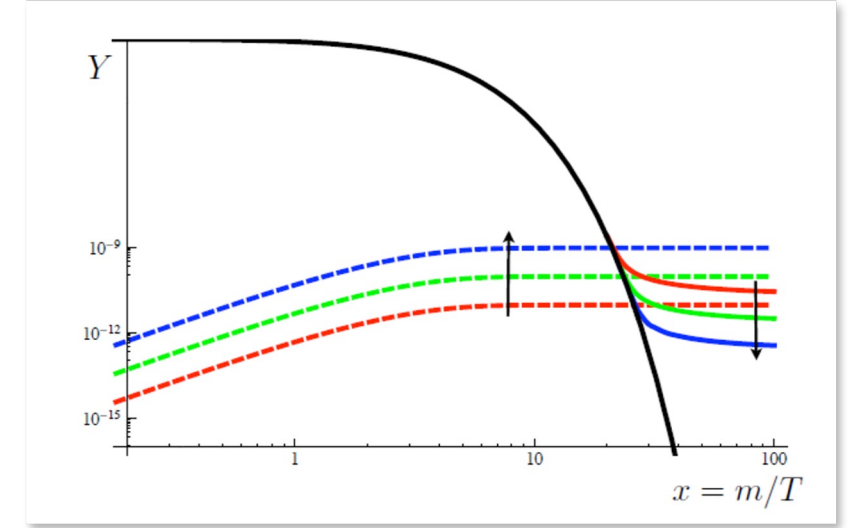
$$\Omega_a h^2|_{\text{mis}} \approx 4 \times 10^{-3} \left(\frac{H_R}{11 \text{ keV}} \right)^{1/2} \left(\frac{f_a \theta_0}{10^{10} \text{ GeV}} \right)^2$$

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

3. 2 to 2 Scatterings: $q_i g(\gamma) \rightarrow q_j a$; $q_i \bar{q}_i \rightarrow g(\gamma) a$

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

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



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,

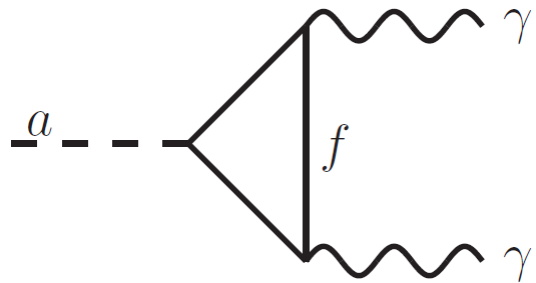
1. Decay into pions ($a \rightarrow \pi \pi \pi$) \longrightarrow $m_a \gtrsim 3 m_\pi$ is already excluded by X – ray observations.
2. Decay into leptons ($a \rightarrow ll$) \longrightarrow Choosing leptophobic axions, they are avoided.
3. Decay into photons ($a \rightarrow \gamma\gamma$) \longrightarrow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

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

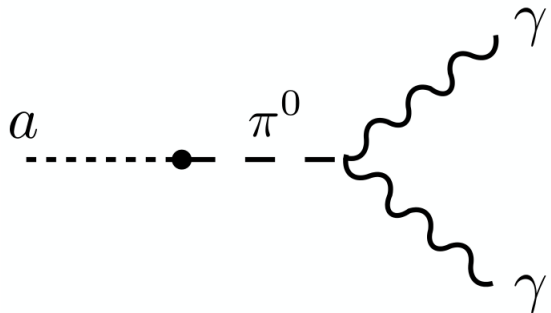
$$\Gamma_{\gamma\gamma} = \frac{\alpha_{\text{em}}^2 m_a^3}{64\pi^3 f_a^2} |C_{\gamma\gamma}^{\text{heavy}} + C_{\gamma\gamma}^{\text{light}}|^2$$

Stability

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



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



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

Chiral Perturbation theory Remark

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

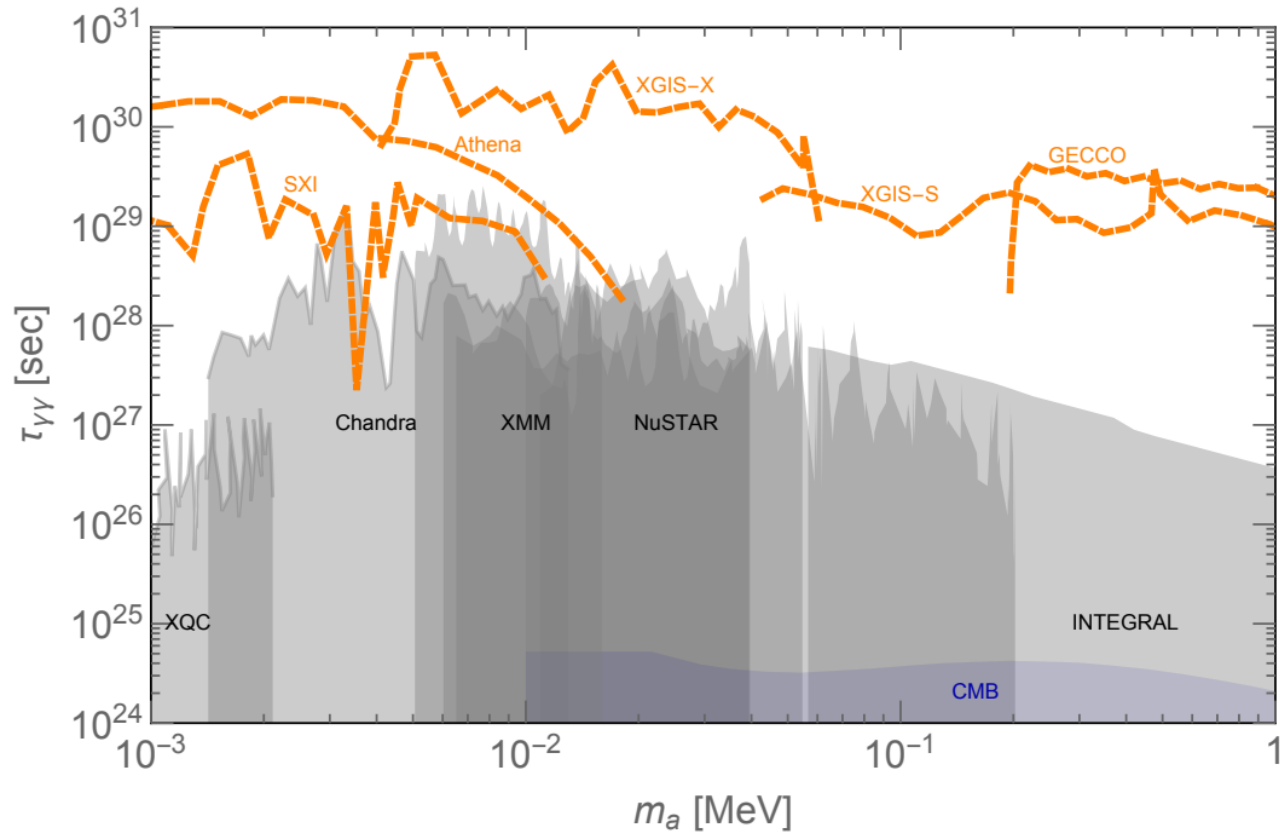
$$\pi^0 \approx \pi_{\text{phys}}^0 + \epsilon \frac{C_u - C_d}{2\sqrt{2}} \frac{m_a^2}{m_a^2 - m_\pi^2} a_{\text{phys}},$$

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

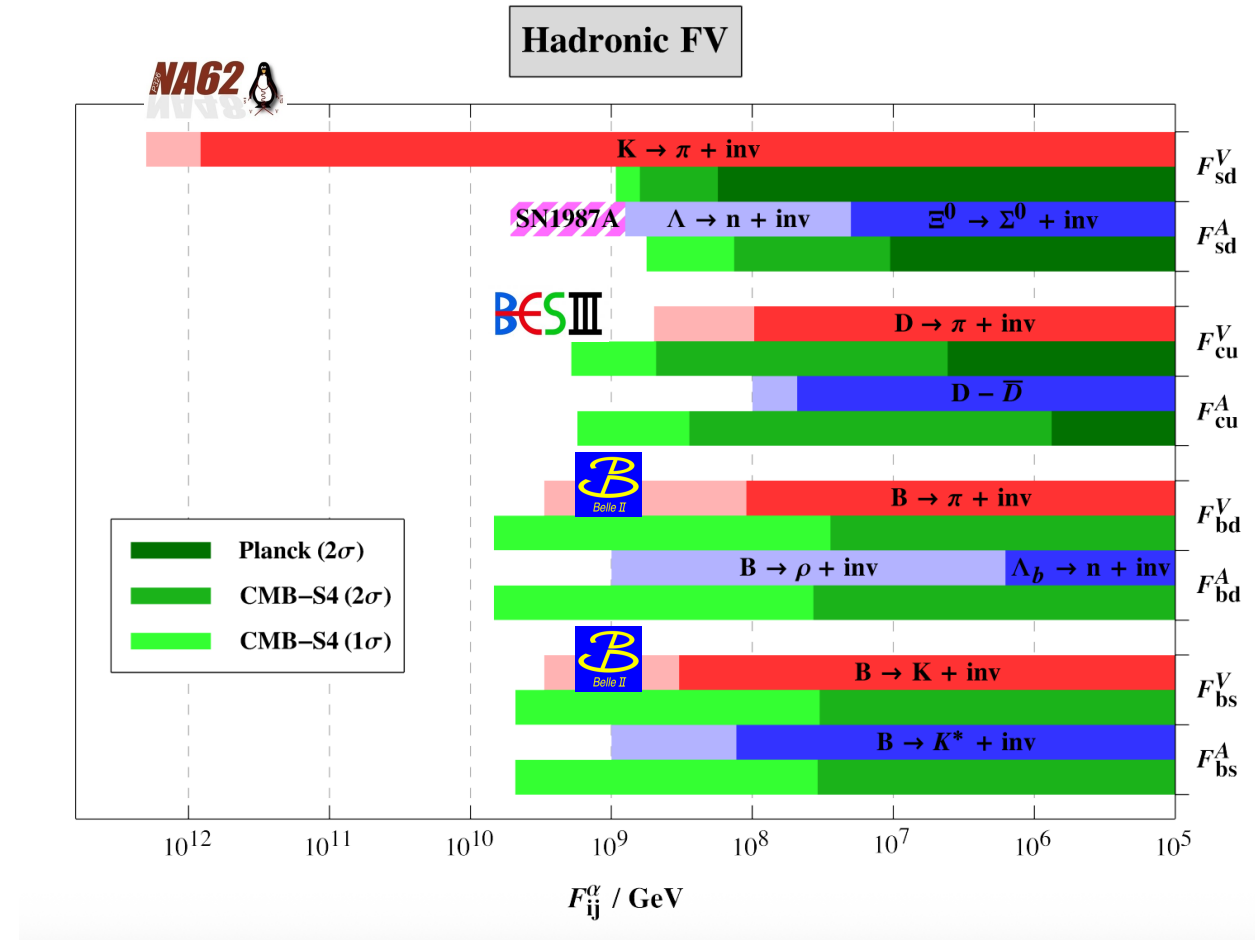
$$\eta_0 \approx \eta'_{\text{phys}} + \epsilon \frac{C_u + C_d + 2C_s}{2\sqrt{6}} \frac{m_a^2}{m_a^2 - m_{\eta'}^2} a_{\text{phys}}$$

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

Constraints

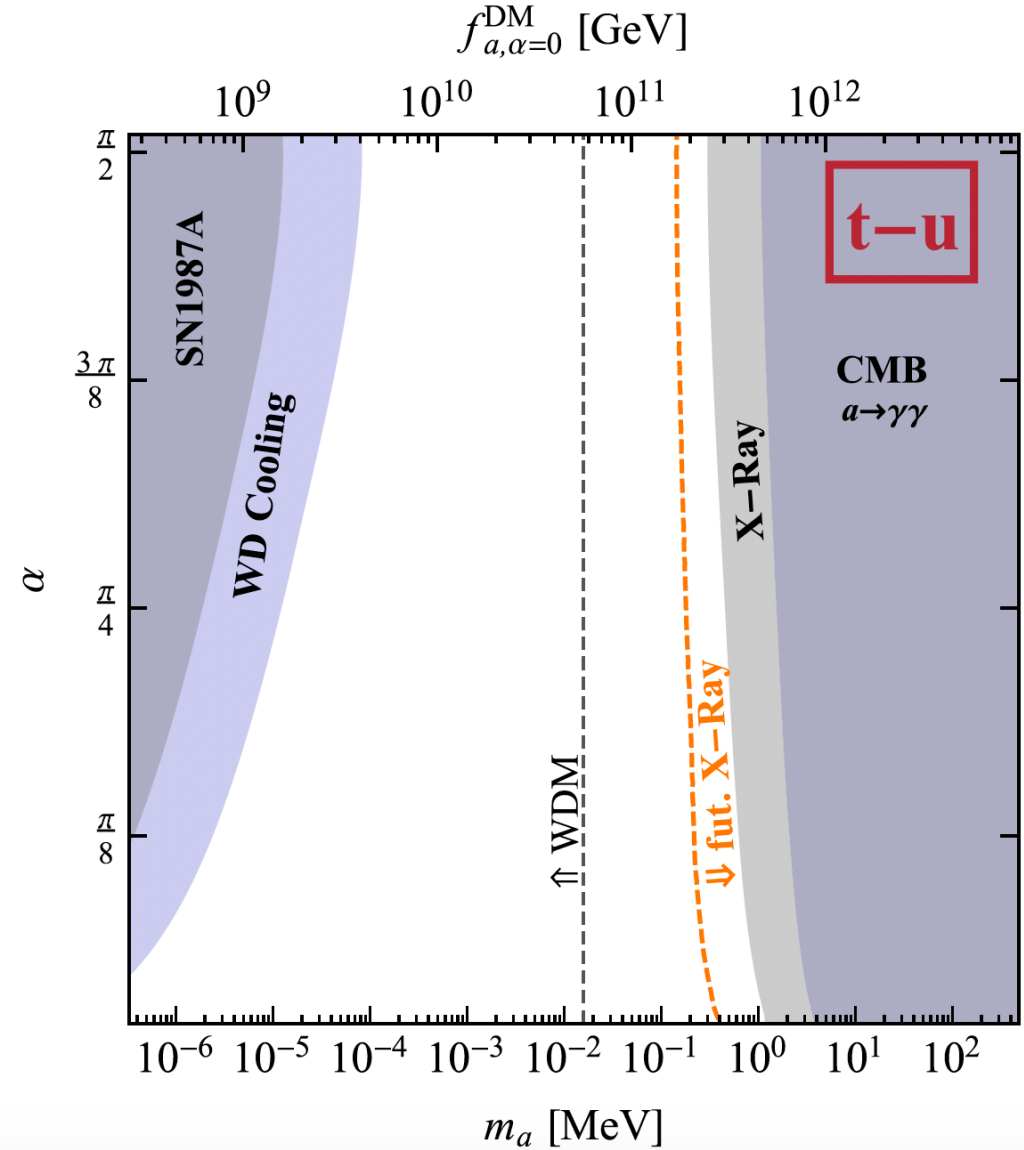
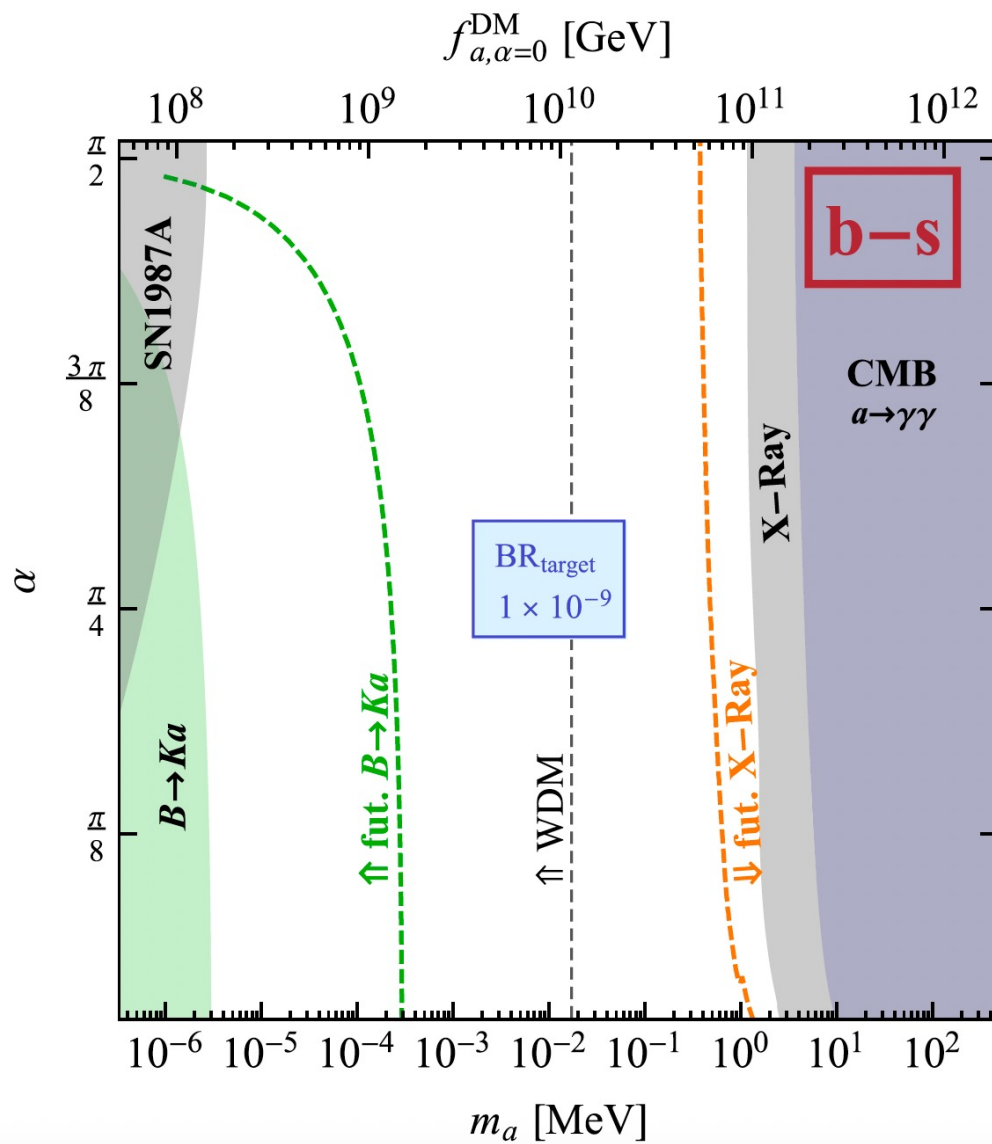


Credit: Panci et al. 2209.03371

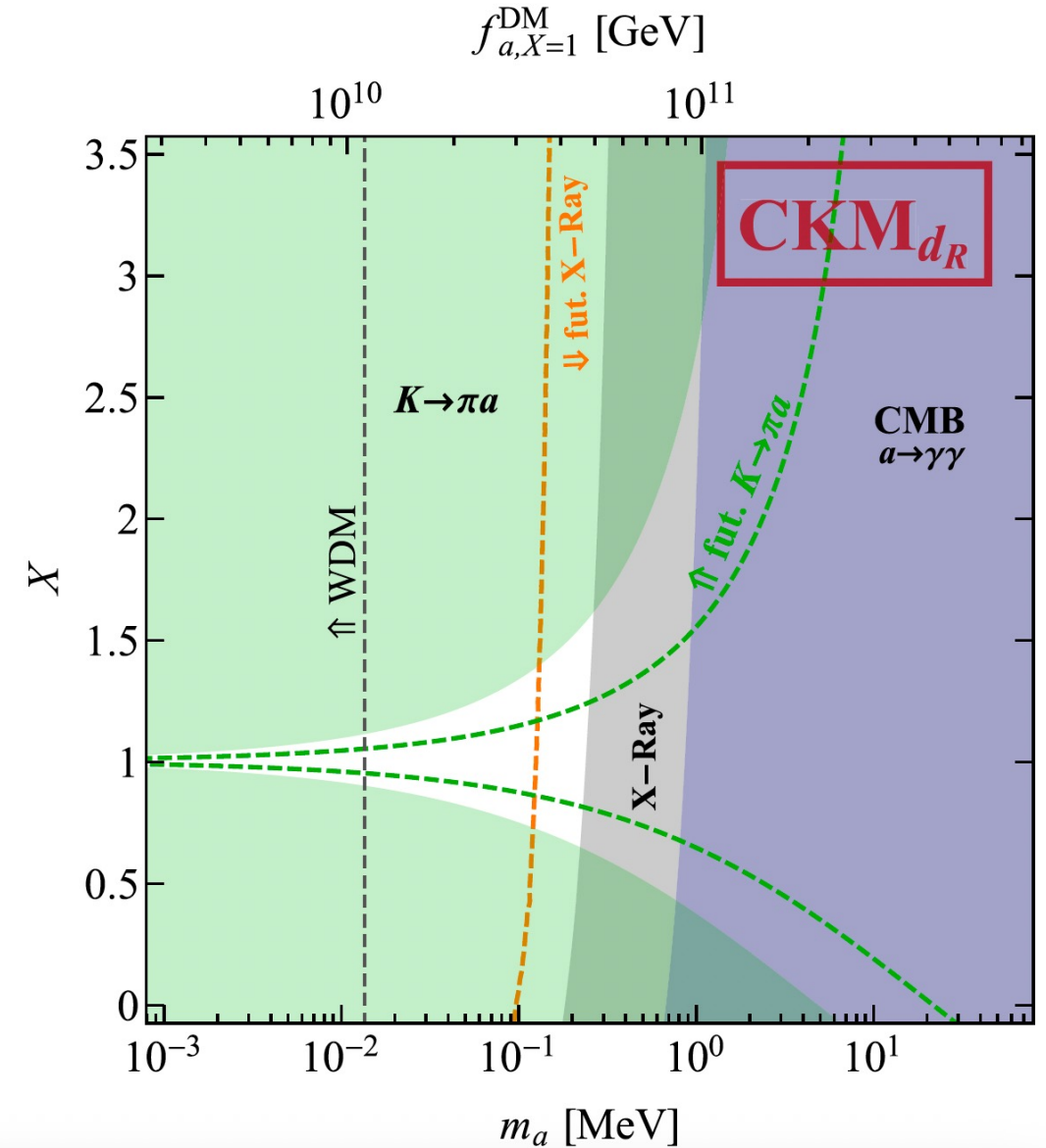
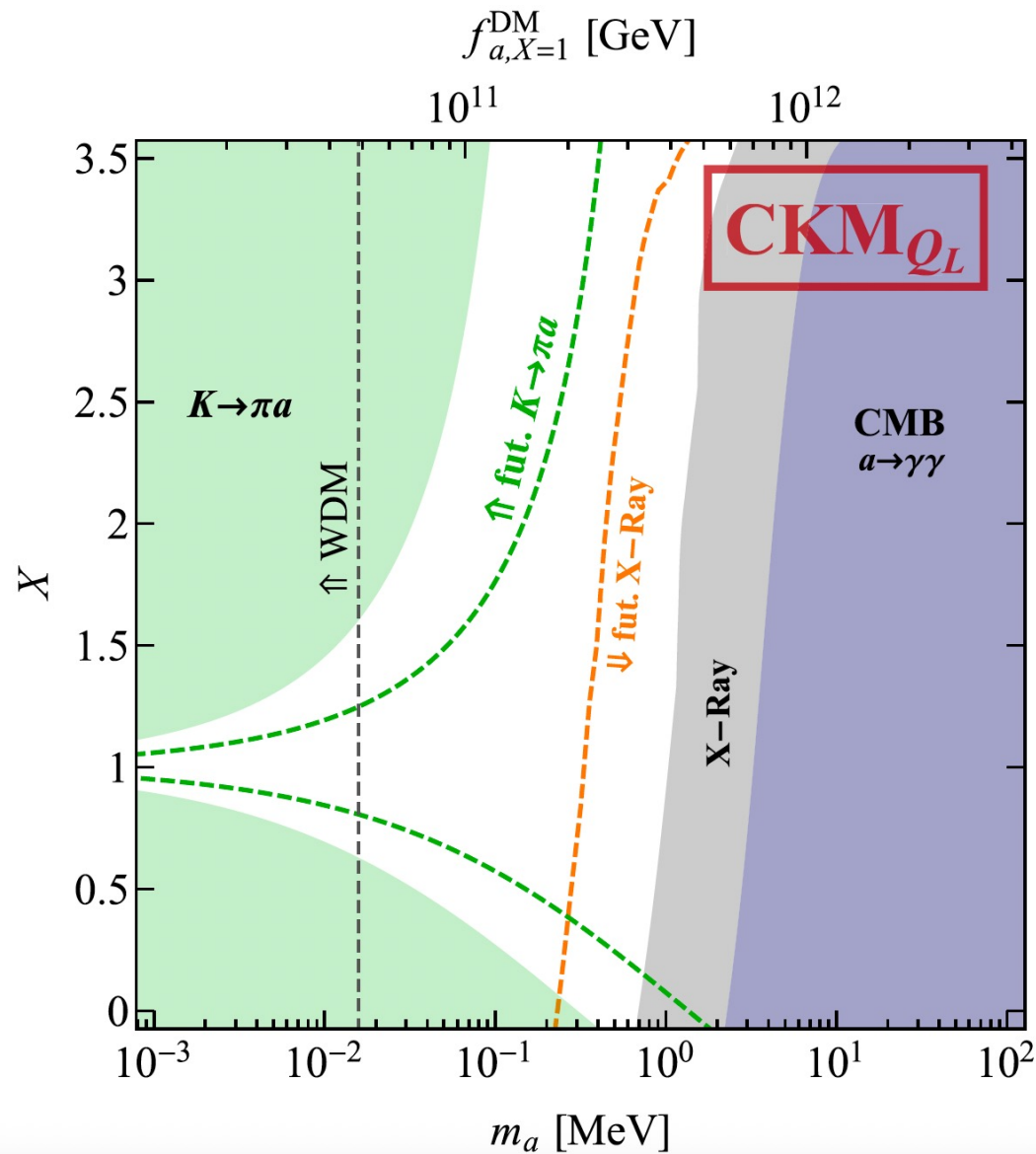


Credit: D'Eramo and Yun, 2111.12108

Results: toy models



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 in SM FV 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

Thank You!



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Back up slides

ALP Production: Misalignment Mechanism

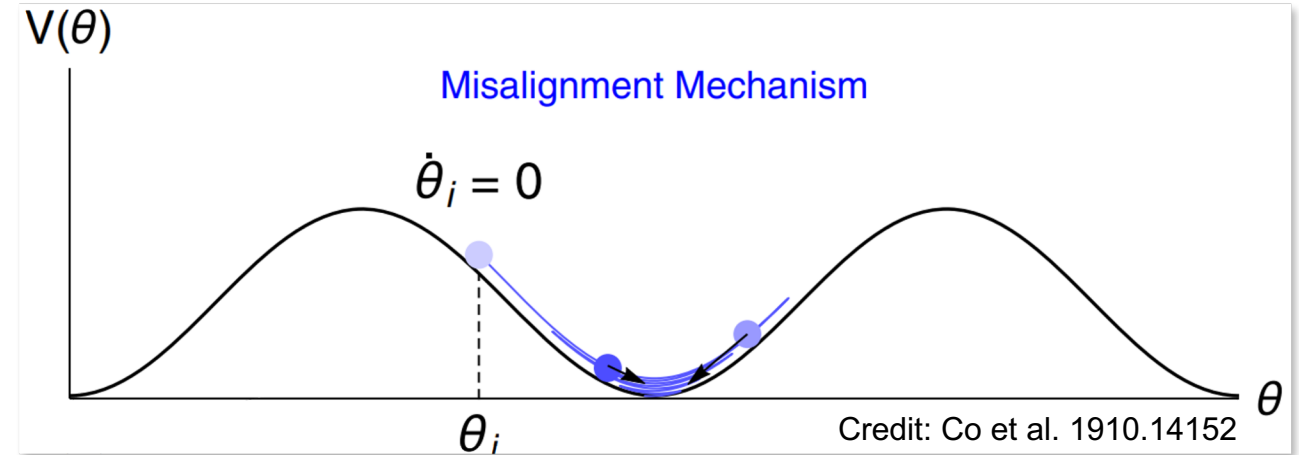
In general, axion can be produced also non-thermally via the misalignment mechanism,

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

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!

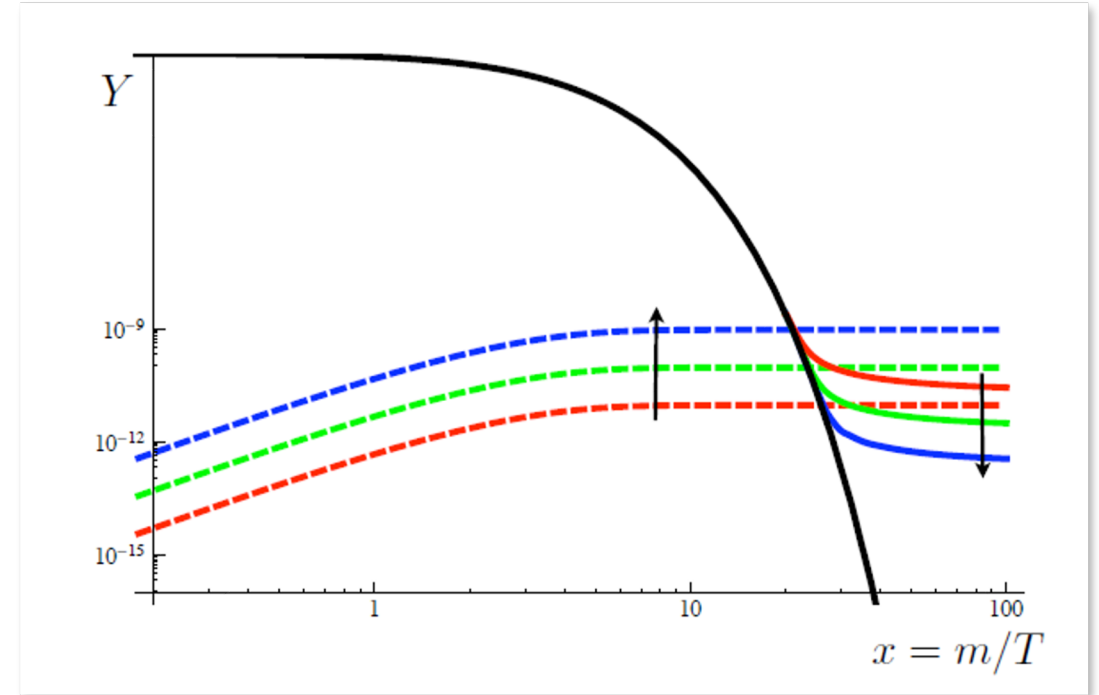


$$\Omega_a h^2 = \frac{\theta_i^2 f_a^2 m_a m_a(T_{\text{osc}})}{6H_0^2 M_{\text{Pl}}^2} \left(\frac{g_{\star,s}(T_0) T_0^3}{g_{\star,s}(T_{\text{osc}}) T_{\text{osc}}^3} \right) \longrightarrow \Omega_a h^2|_{\text{mis}} \approx 4 \times 10^{-3} \left(\frac{H_R}{11 \text{ keV}} \right)^{1/2} \left(\frac{f_a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

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: $q_i g(\gamma) \rightarrow q_j a$; $q_i \bar{q}_i \rightarrow g(\gamma) a$



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

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

ALP Production: UV Freeze-in

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

$$\mathcal{L}_{eff} = -C_{q_i q_j}^A \frac{ia}{f_a} \frac{m_{q_i}}{v} h \bar{q}_i P_R q_j \longrightarrow q_i h \rightarrow q_j a$$

The contribution of this process to the relic abundance is,

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

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 $\Psi = (u, d, s)$,

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

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

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

Constraints: Astrophysics

Warmness Bound a.k.a WDM

1. Free streaming

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

$$m_{\text{WDM}} = 3.5 \text{ keV}$$

$$m_{\text{WDM}} = 5.3 \text{ keV}$$

2. Momentum dispersion

D'Eramo and Lenoci, 2012.01446

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

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

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

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

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

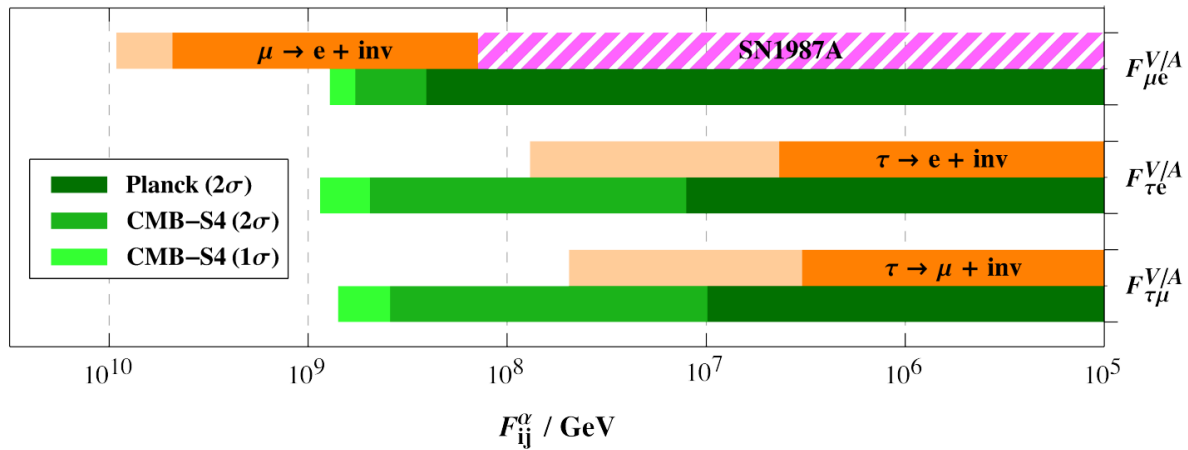
Carenza et al. 1906.11844

where the couplings are $\left\{ \begin{array}{l} C_p \approx \Delta u C_{uu}^A + \Delta d C_{dd}^A + \Delta s C_{ss}^A \\ C_n \approx \Delta u C_{dd}^A + \Delta d C_{uu}^A + \Delta s C_{ss}^A \end{array} \right.$

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

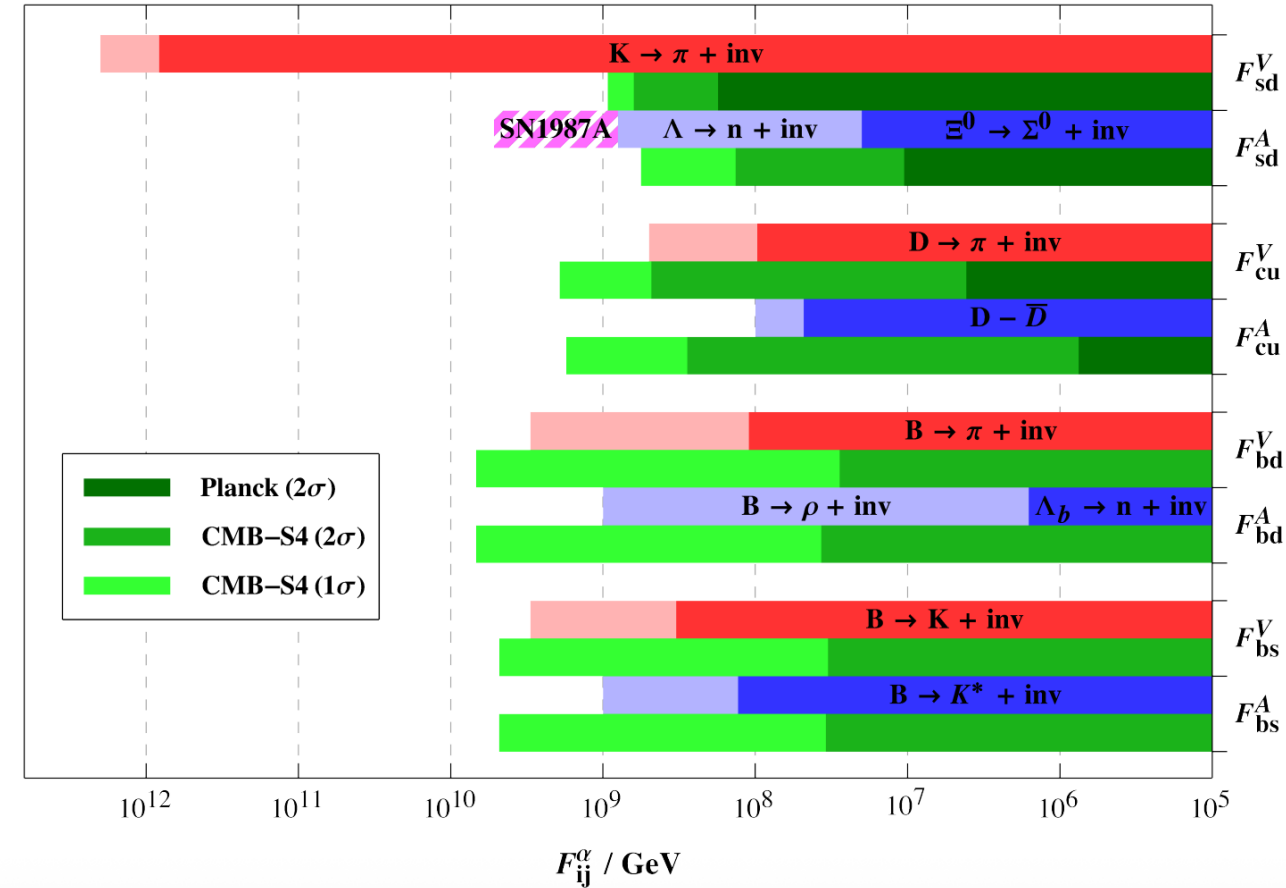
Constraints: Flavor Physics vs CMB

Leptonic FV

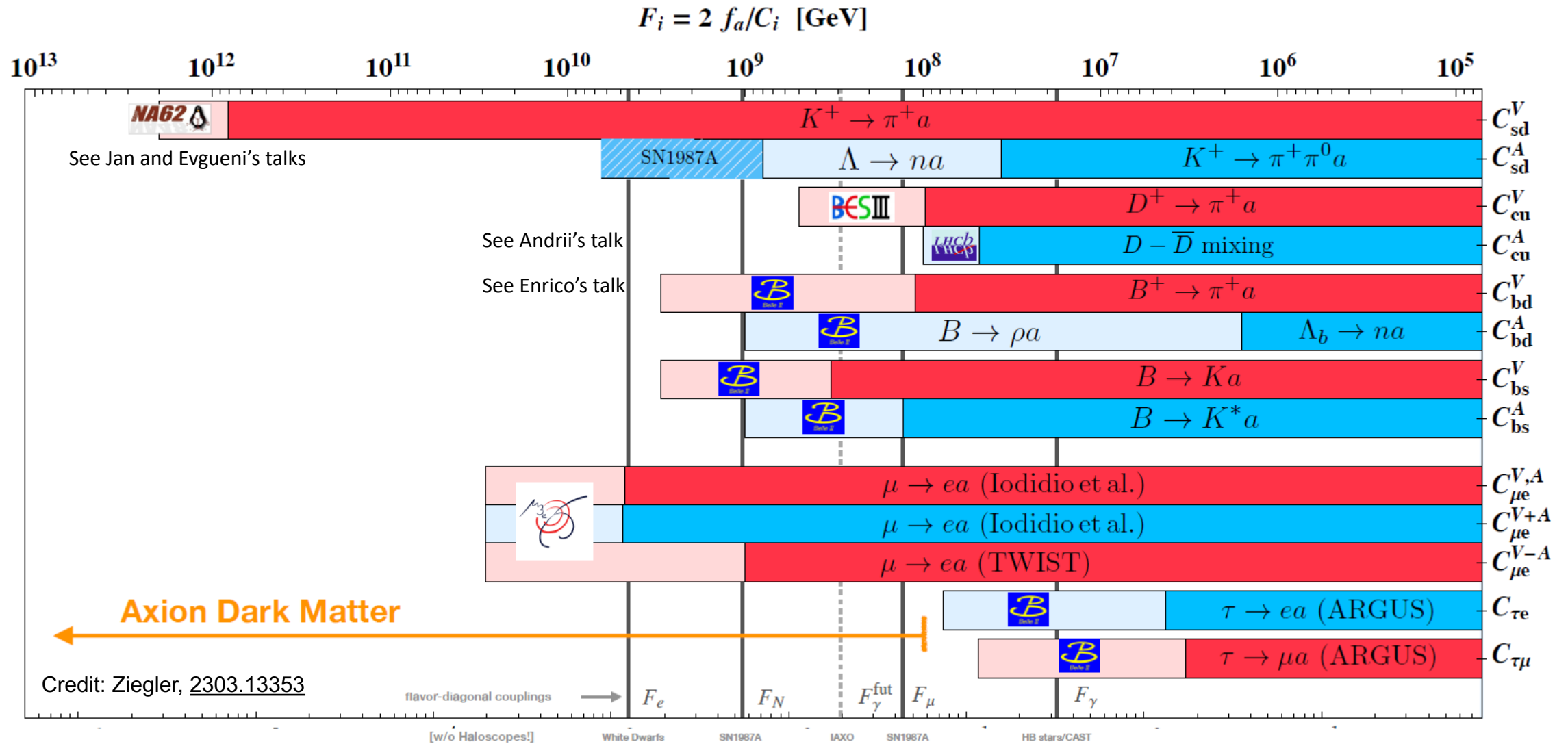


Credit: D'Eramo and Yun, 2111.12108

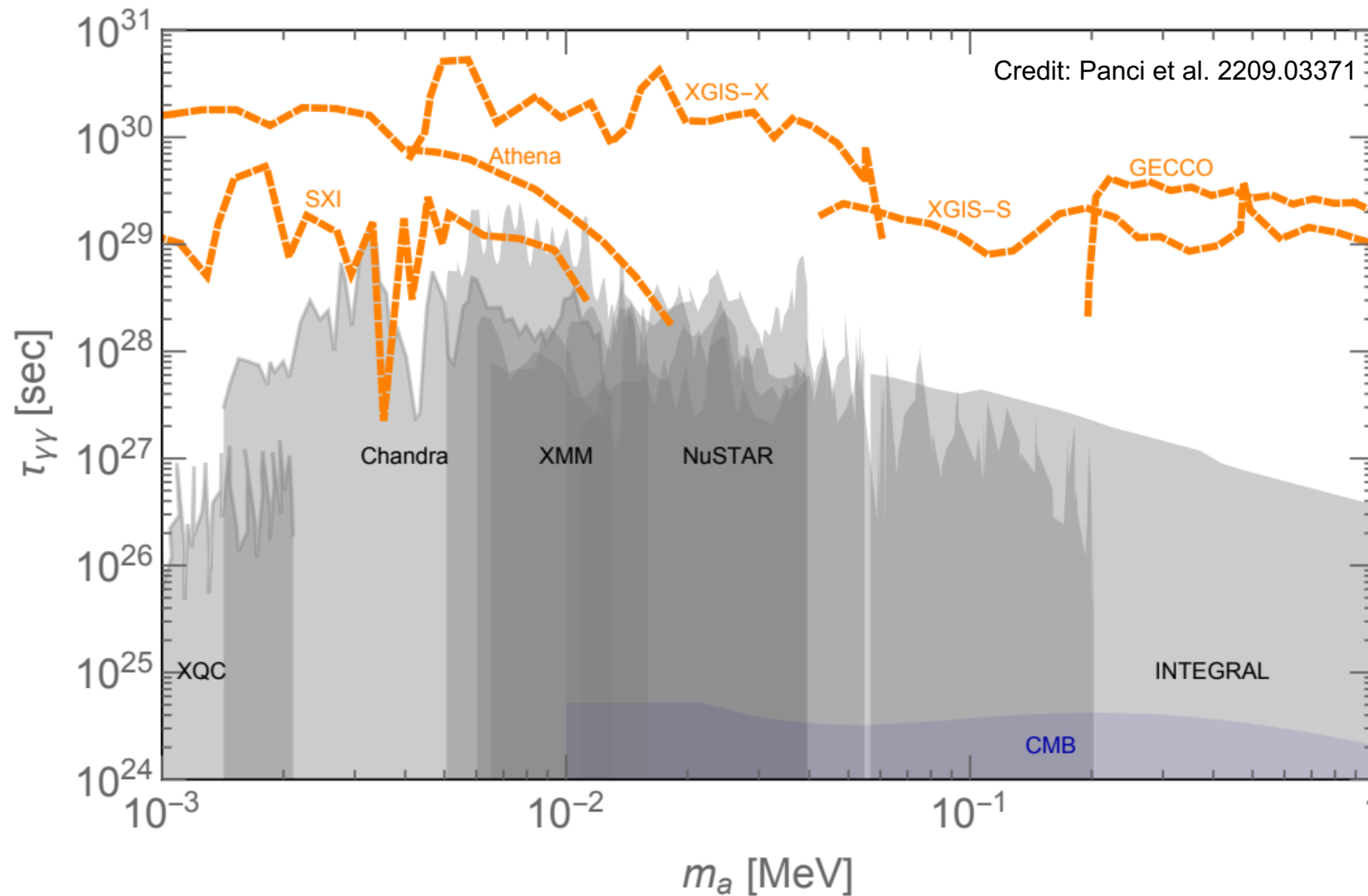
Hadronic FV



Constraints: Flavor Physics



Constraints: X-Ray Observatories



Results: More toy models

