Axion Dark Matter with Flavor-Violating Couplings to Quarks

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Motivations for axions and ALPs

- Axion: solution to the strong CP problem

$$\mathcal{L}_\theta = \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

- Pseudo Nambu-Goldstone Bosons of a spontaneously broken symmetry
- Plausible Dark Matter candidates with several production mechanisms

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

Misalignment

$$\dot{n}_X + 3n_X H \approx g_{B_1} \int \frac{d^3 p_{B_1}}{(2\pi)^3} \frac{f_{B_1} \Gamma_{B_1}}{\gamma_{B_1}}$$

Freeze- In

ALP with Flavor-Violating Couplings

Consider an ALP model with flavor-violating (FV) couplings to SM fermions f

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{2f_a}\bar{f}_i\gamma^\mu(C^V_{f_i,f_j} + C^A_{f_i,f_j}\gamma^5)f_j$$

Features:

- Free parameters: ALP mass m_a , the scale f_a and the FV couplings $C^{V,A}_{q_i,q_j}$.
- Anomaly-free: No couplings to gluons or EW gauge bosons ⟹ Crucial for DM Pheno.

- Leptons: DM scenario considered in arxiv:2209.03371, Panci et al.
- Quarks ⟹ This talk.

ALP with Flavor-Violating Couplings: why?

Theory

Misalignment between the U(1) PQ charges $X_{L,R}$ and the Yukawa matrix

$$V_{\mathrm{CKM}} = U^\dagger_{u_L} U_{d_L}$$

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

Phenomenology

Potentially interesting experimental signatures, for example…

Colliders

$$K \to \pi a$$

Supernovae

$$\Lambda \to n a$$

arxiv: 2012.11632,
Camalich et al.

Indirect probes of high-energy scales f_a (up to 10^{12} GeV)

ALP with Flavor-Violating Couplings: how?

What about the $U_{L,R}$ matrices? Who knows…

A Benchmark case: two-flavor scenario

$$X_{d_R} = \mathrm{diag}(0,1,-1) \xrightarrow{\text{Suitable rotation in a plane}} C^d_{V,A} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin\alpha & \cos\alpha \\ 0 & \cos\alpha & -\sin\alpha \end{pmatrix}$$

$$b - s$$

In this way, 3 parameters only

m_a α f_a

ALP Dark Matter - Stability

Extremely light axion, $m_a < \Lambda_{\text{QCD}}$ $\Longrightarrow$ χPT needed

- Decay into pions: $a \to \pi\pi\pi$ $\longrightarrow$ $m_a \gtrsim 3m_\pi$
- Decay into photons: $a \to \gamma\gamma$

Excluded by X-ray searches

$$\boxed{\tau_{\gamma\gamma} \gtrsim 10^{30}\ \text{sec}}$$

$$\Gamma_{\gamma\gamma} = \frac{4\pi\alpha_{em}^2 m_a^3}{f_a^2}|C_{\gamma\gamma}|^2$$

$$C_{\gamma\gamma} \approx -\frac{1}{16\pi^2}\sum_i \frac{C^A_{ii}\,Q_i^2}{4}\frac{m_a^2}{m_i^2} - \frac{C^A_{ss}}{48\pi^2}\frac{m_a^2}{m_\eta^2 - m_a^2}\,, \quad (\pi^8 - \text{mixing}) \qquad (i = c, b, t)$$

$$C_{\gamma\gamma} \approx -\frac{1}{16\pi^2}\sum_i \frac{C^A_{ii}\,Q_i^2}{4}\frac{m_a^2}{m_i^2} - \frac{C^A_{uu} - C^A_{dd}}{32\pi^2}\frac{m_a^2}{m_\pi^2 - m_a^2}\,, \quad (\pi^3 - \text{mixing}).$$

ALP Dark Matter – Production I

Large f_a → Small couplings → DM produced out of equilibrium from the early Universe thermal bath

DM freeze-in

$$\Omega h^2|_{\rm dec} \approx 0.12 \left(\frac{m_a}{0.1\,{\rm MeV}}\right)\left(\frac{6\times 10^9{\rm GeV}}{f_a/C_{q_iq_j}}\right)^2\left(\frac{m_{q_i}}{\rm GeV}\right)\left(\frac{79}{g^*(m_q)}\right)^{\frac{3}{2}} \qquad q_i \to q_j a$$

$$\Omega h^2|_{\rm scatt} \approx 0.12 \left(\frac{m_a}{0.1\,{\rm MeV}}\right)\left(\frac{2\times 10^9{\rm GeV}}{f_a/C_{qq}}\right)^2\left(\frac{m_q}{\rm GeV}\right)\left(\frac{79}{g^*(m_q)}\right)^{\frac{3}{2}} \qquad q_i\bar{q}_i \to g a, \qquad q_i\, g \to q_i a$$

ALP Dark Matter – Production II

Freeze-In under control? The non-ren. operator

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

$q_i h \rightarrow q_j a$

$$\Omega h^2|_{\mathrm{UV}} = \frac{m_{q_i} T_R}{3\pi^3 v^2} \Omega h^2|_{q_i \rightarrow q_j a}$$

Introduces a dependence on T_R (unknown)

arxiv:0911.1120, Hall et al.

Dominant IR contribution for

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

Scenarios involving the top quark have

$T_R \approx O(10)\,\mathrm{TeV}$ ⇨ UV Dominated

Astro Bounds – Lyman-α

DM produced with large free-streaming length

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

arxiv:2012.01446,
D'Eramo, Lenoci

For lower DM masses the large free streaming length suppresses the matter power spectrum

Conflicts with structure formation: constraints from Ly-α data

Astro Bounds - Supernova

Axion emission through nucleon scattering $\mathrm{N}' = n, p$

$$N + N' \to N + N' + a$$

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

Careful matching
with
Nucleon Chiral Lagrangian

Plus emittivity constraint from SN 1987A:

$$0.61 g_{ap}^2 + g_{an}^2 + 0.53 g_{an} g_{ap} < 8.26 \times 10^{-19}$$
$$g_{ai} \equiv C_i m_i / f_a.$$

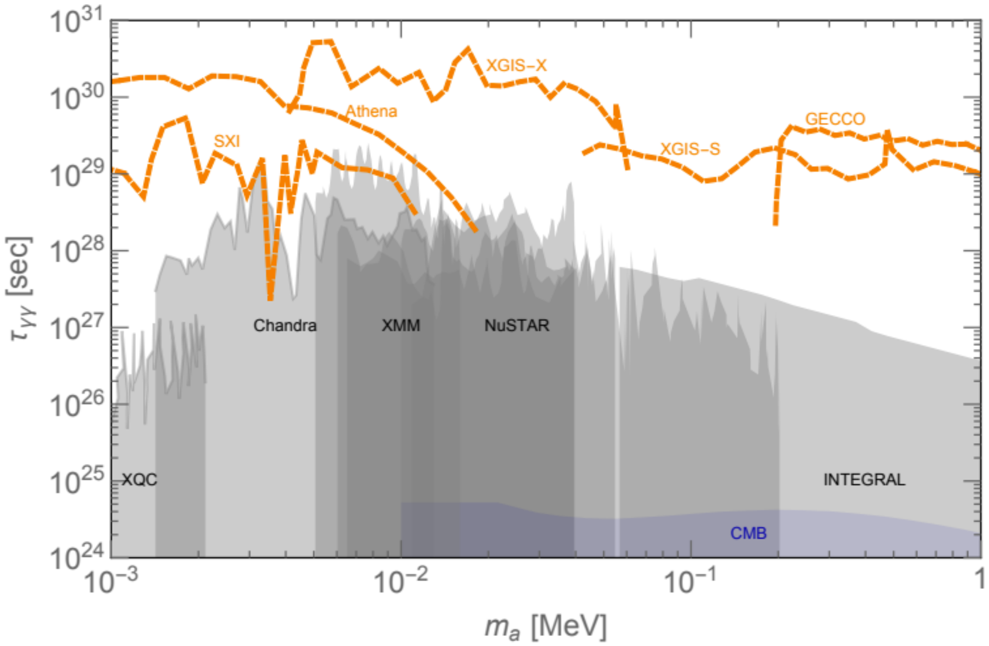
arxiv:1906.11844,
Carenza et al.

Astro Bounds – X-ray Searches + CMB

$$\tau_{\gamma\gamma} \approx 1.3 \times 10^{27}\,\mathrm{sec} \left(\frac{C_{q_i q_j}}{N_{ll}}\right)^2 \left(\frac{10\,\mathrm{keV}}{m_a}\right)^6 \left(\frac{m_{q_i}}{1\,\mathrm{GeV}}\right) \left(\frac{79}{g^*(m_q)}\right)^{\frac{3}{2}} \left(\frac{0.12}{\Omega h^2}\right) \qquad \text{for FV decay,}$$

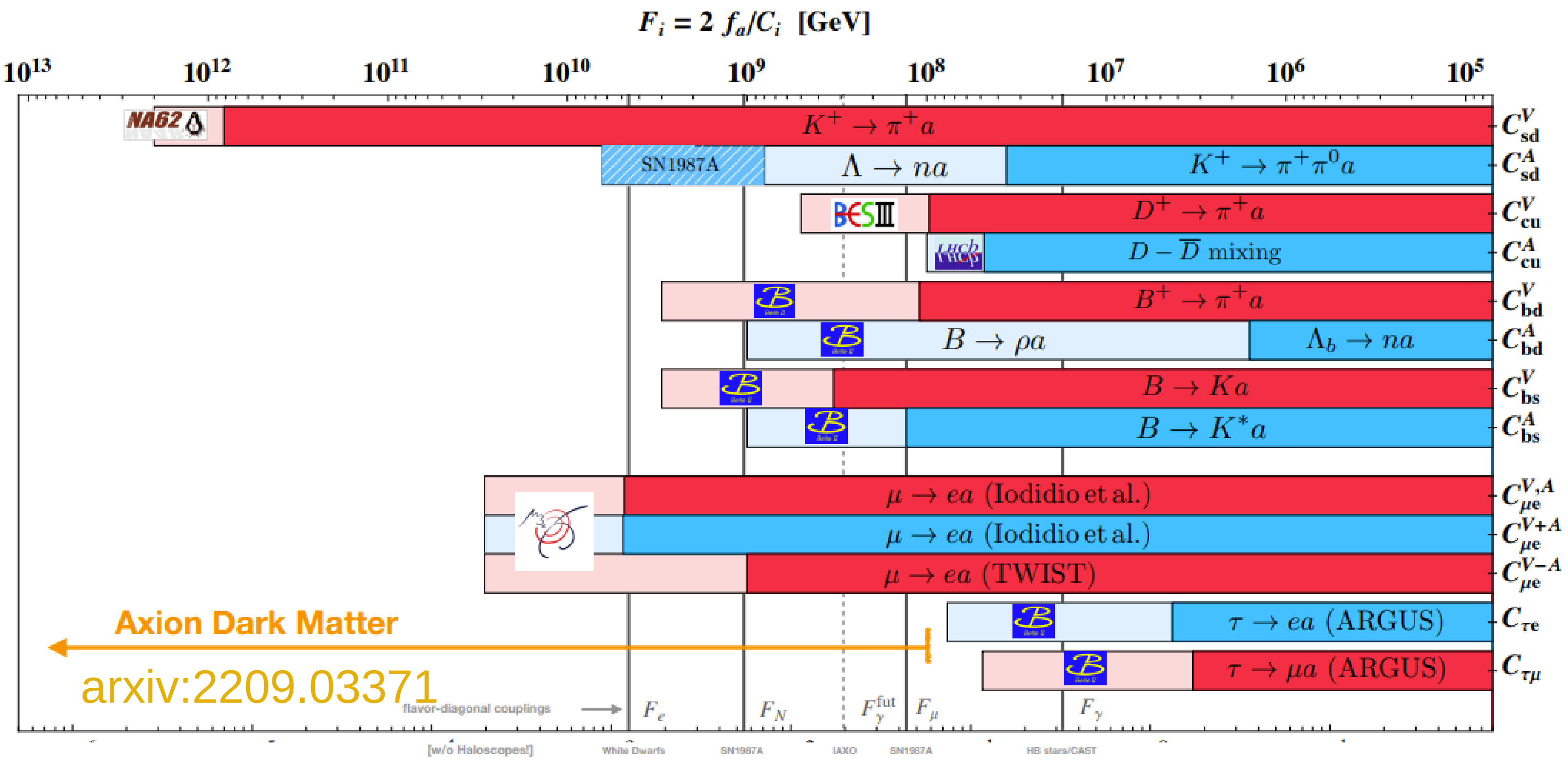
$$\tau_{\gamma\gamma} \approx 1.4 \times 10^{26}\,\mathrm{sec} \left(\frac{C_{qq}}{N_{ll}}\right)^2 \left(\frac{10\,\mathrm{keV}}{m_a}\right)^6 \left(\frac{m_{q_i}}{1\,\mathrm{GeV}}\right) \left(\frac{79}{g^*(m_q)}\right)^{\frac{3}{2}} \left(\frac{0.12}{\Omega h^2}\right) \qquad \text{for diagonal scattering.}$$

Decay rate + $\Omega h^2 \approx 0.12$ to fix f_a



From arxiv:2209.03371, Panci et al.

Collider Bounds

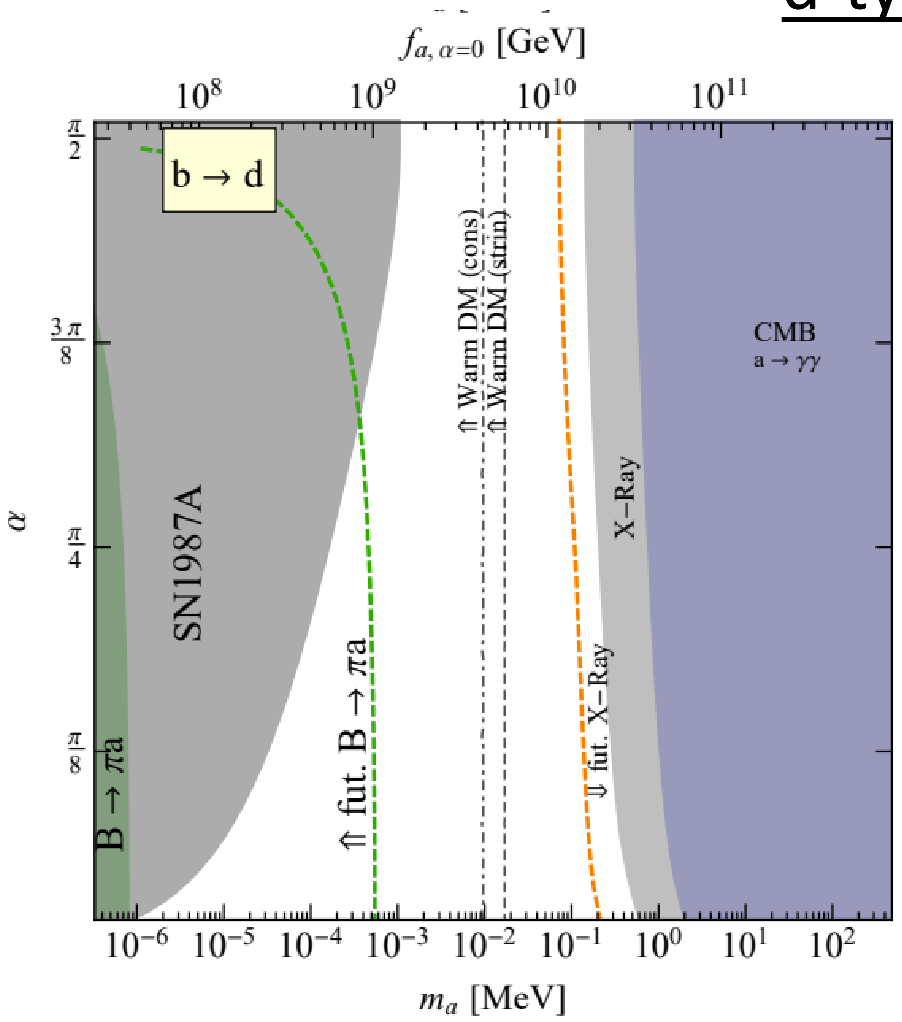


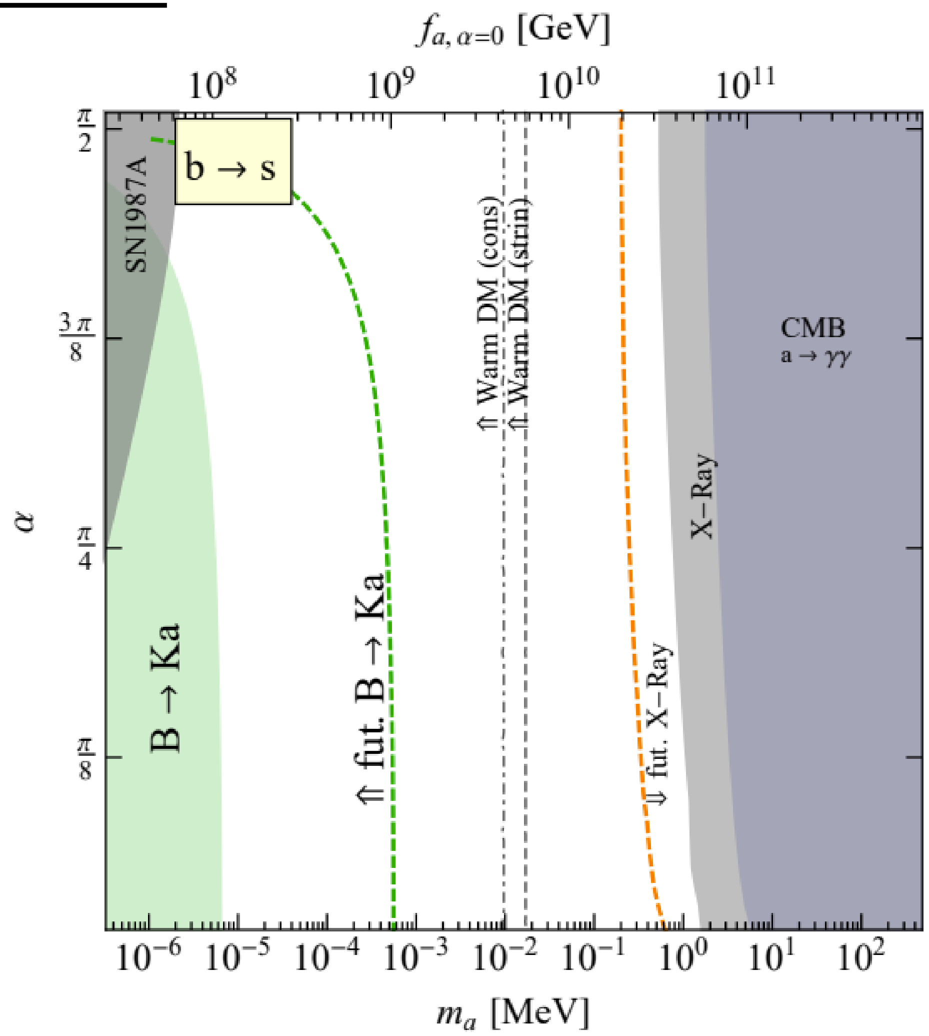
Axion Dark Matter

arxiv:2209.03371

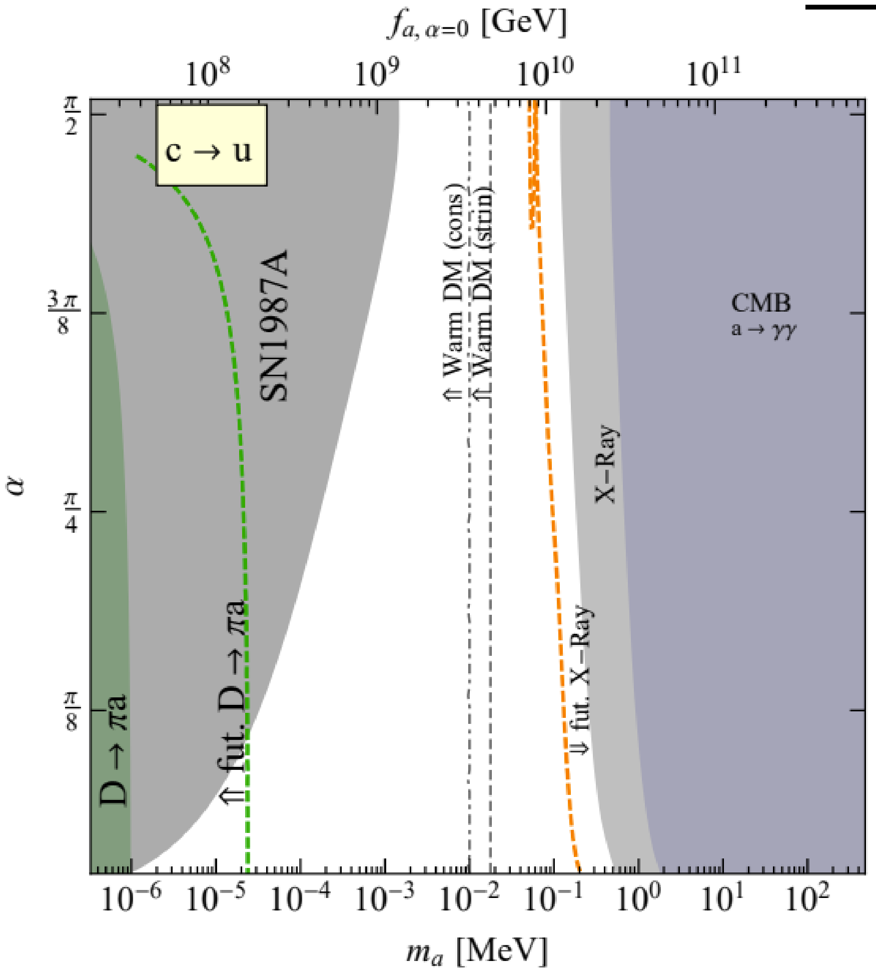
from arxiv:2303.13353, Ziegler

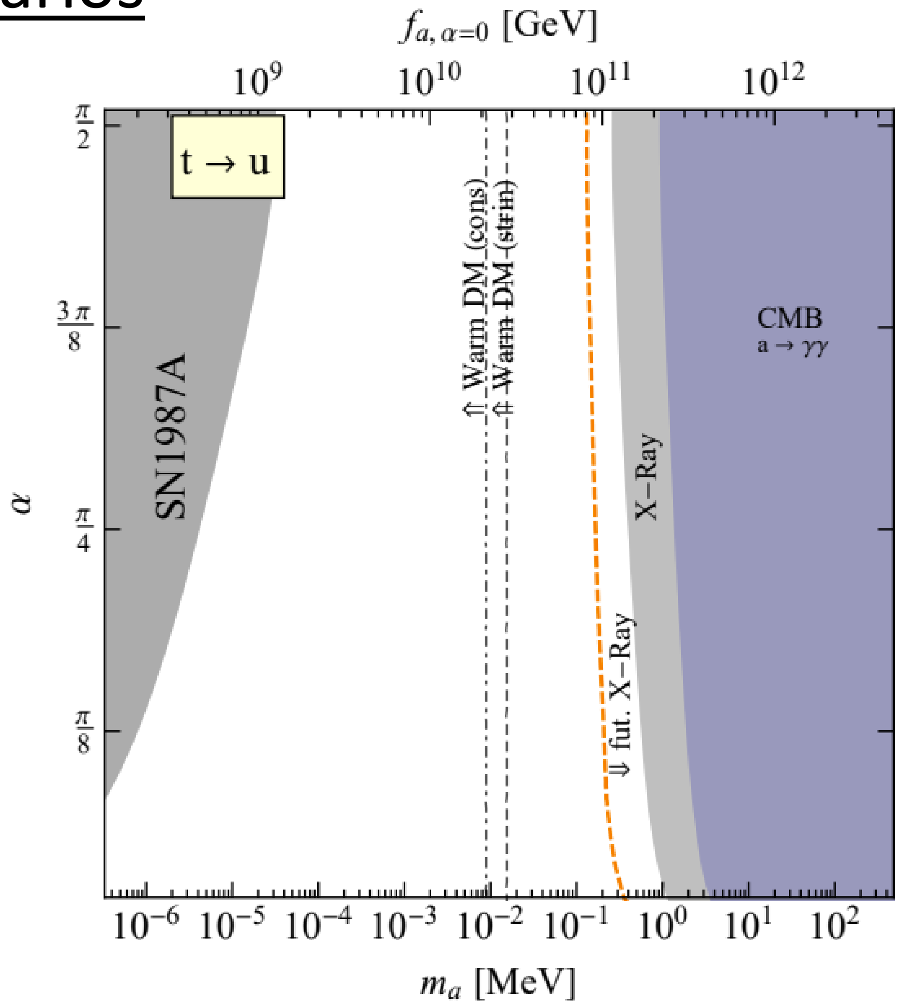
d-type scenarios





u-type scenarios





Conclusions

- Axions and ALPs are interesting candidates from a phenomenological point of view.
- An ALP that is also a DM candidate meets specific requirements , especially from Cosmology.
- Flavor Violating couplings to fermions: more parameters but also more pheno.
- For ALPs coupled to quarks, QCD dynamics improves DM stability: weaker constraints.
- Less testable than ALP coupled to leptons. Can future collider and X-ray searches cover more parameter space?

Backup Slides

A chiral Lagrangian for ALP and Mesons

$$
\begin{aligned}
\mathcal{L}_{\text{light}} = {} & \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \bar{\Psi}(i\not{D} - M_q)\Psi \\
& + \frac{\partial_\mu a}{2f_a}\bar{\Psi}\gamma^\mu \widetilde{k}_L \left(1-\gamma^5\right)\Psi + \frac{\partial_\mu a}{2f_a}\bar{\Psi}\gamma^\mu \widetilde{k}_R \left(1+\gamma^5\right)\Psi \\
& \Psi \equiv (u,d,s)^T .
\end{aligned}
$$

Effective symmetry

$$\mathrm{SU(3)_L} \otimes \mathrm{SU(3)_R}$$

with

$$\Sigma = \exp\left(i\sqrt{2}\lambda_a \cdot \pi^a / f_\pi\right)$$

$$D_\mu \Sigma = \partial_\mu \Sigma + ieA_\mu\left[Q,\Sigma\right] + i\frac{\partial_\mu a}{f_a}\left(\widetilde{k}_L\Sigma - \Sigma\widetilde{k}_R\right)$$

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

ALP Dark Matter – Production III

Non thermal mechanisms are also allowed

Misalignment $m_a \approx H$

$$\Omega h^2|_{\rm mis} \approx 0.015 \left(\frac{H_R}{0.64{\rm keV}}\right)^{\frac{1}{2}} \left(\frac{f_a \theta_0}{4\times 10^{10}\ {\rm GeV}}\right)^2$$

Negligible

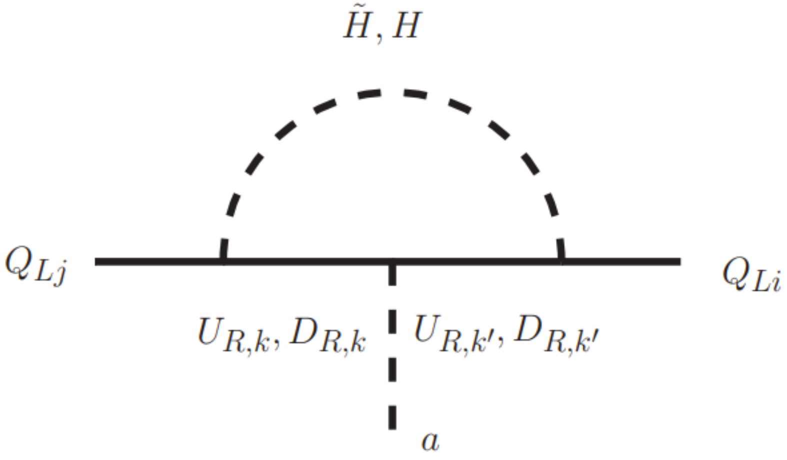
In our mass range, onset of oscilations prior to reheating: diluted mis. contribution.

Additional Bounds? Too weak!

- Collider Bound for the Top Scenario:

$$\Delta c^V_{sd}(\mu) = \frac{y_t^2}{64\pi^2}\log\frac{f_a}{\mu}\left[2V^*_{ts}V_{td}(c^V_{tt}+c^A_{tt}) - \sum_k V^*_{ks}V_{td}(c^V_{u_k t} - c^A_{u_k t}) - \sum_k V^*_{ts}V_{kd}(c^V_{tu_k} - c^A_{tu_k})\right],$$

arxiv: 2002.04623
Camalich et al.



Combined with NA62 is only able to probe $f_a \approx 10^7$ GeV

- Supernova Bound: $\Lambda \rightarrow n\ a$ is only able to probe $f_a \approx 10^3$ GeV

$$F^V_{sd} \gtrsim 7.1 \times 10^9 \ \mathrm{GeV}$$

arxiv: 2012.11632,
Camalich et al.