Axion Dark Matter from Heavy Quarks

Alessandro Dondarini

(GGI & INFN, Florence)

Based on: arXiv: 2404.12199 , *Phys.Lett.B* 856 (2024)

Motivations for axions and Axion-Like Particles (ALPs)

- **QCD Axion**: solution to the strong CP problem

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

Axion Like Particles: Typically they do not solve the strong CP problem, but still…

- Pseudo Nambu-Goldstone Bosons of a spontaneously broken symmetry: naturally light scalars
- 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 $C^{V,A}_{q_i,q_j}$.

- Leptons: DM scenario considered in arxiv:2209.03371
- Quarks ⟹ This talk.

ALP with Flavor-Violating Couplings: why?

Theory

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

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

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

Phenomenology

Potentially interesting experimental signatures, for example…

Colliders $K \to \pi a$

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 Simplified scenario: two-flavor scenario

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

Suitable rotation in a plane

$$C^d_{V,A} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin\alpha & \cos\alpha \\ 0 & \cos\alpha & -\sin\alpha \end{pmatrix}$$

$b - s$

A Physical scenario: CKM scenarios

CKM_{Q_L}: $X_{u_R} = X_{d_R} = 0, X_{Q_L} = \mathrm{diag}(1, X, -1-X)$ → $U_{u_L} = 1, U_{d_L} = V_{\rm CKM}$

CKM_{d_R}: $X_{Q_L} = X_{u_R} = 0, X_{d_R} = \mathrm{diag}(1, X, -1-X)$ → $U_{d_R} = V_{\rm CKM}$

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

In this way, 3 parameters only

m_a α / X f_a

ALP Dark Matter - Stability

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

- Decay into pions: $a \to \pi\pi\pi$
- Decay into photons: $a \to \gamma\gamma$

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

$m_a \gtrsim 3 m_\pi$

Excluded by X-ray searches

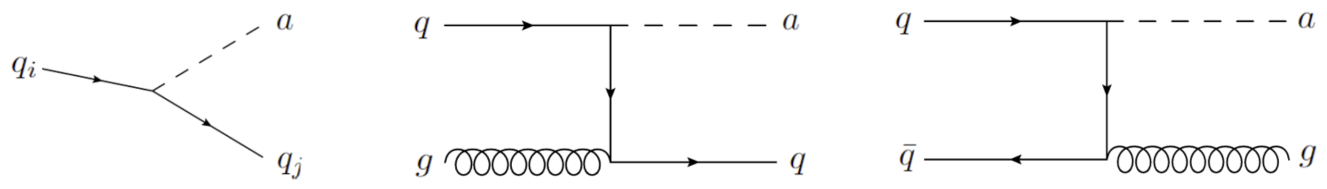
$$C_{\gamma\gamma}^{\rm light} \approx \frac{C_u - C_d}{2}\frac{m_a^2}{m_\pi^2} + \frac{\sqrt{2}}{6}(C_u + C_d - C_s)\frac{m_a^2}{m_\eta^2} + \frac{\sqrt{2}}{3}(C_u + C_d + 2C_s)\frac{m_a^2}{m_{\eta'}^2}\,,$$

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

Axion's lifetime exceeds by far the Age of the Universe!

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

ALP Dark Matter – Production I



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

DM freeze-in

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

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

Constraints

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

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

Conflict with structure formation: constraints from Ly-α data

Astro Bounds - Supernova

Axion emission from hot stellar objects subtracts energy

$$N + N' \to N + N' + a \qquad N' = n, p$$

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

Careful matching with Nucleon Chiral Lagrangian

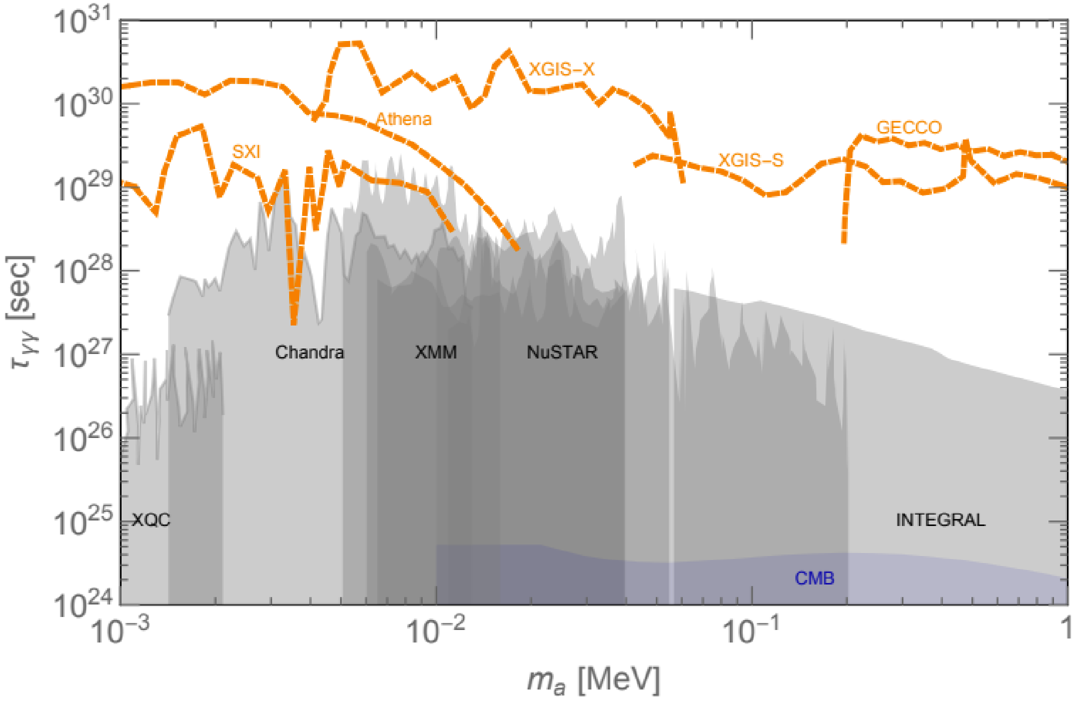
Emittivity constraint from SN 1987A:

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

arxiv:1906.11844

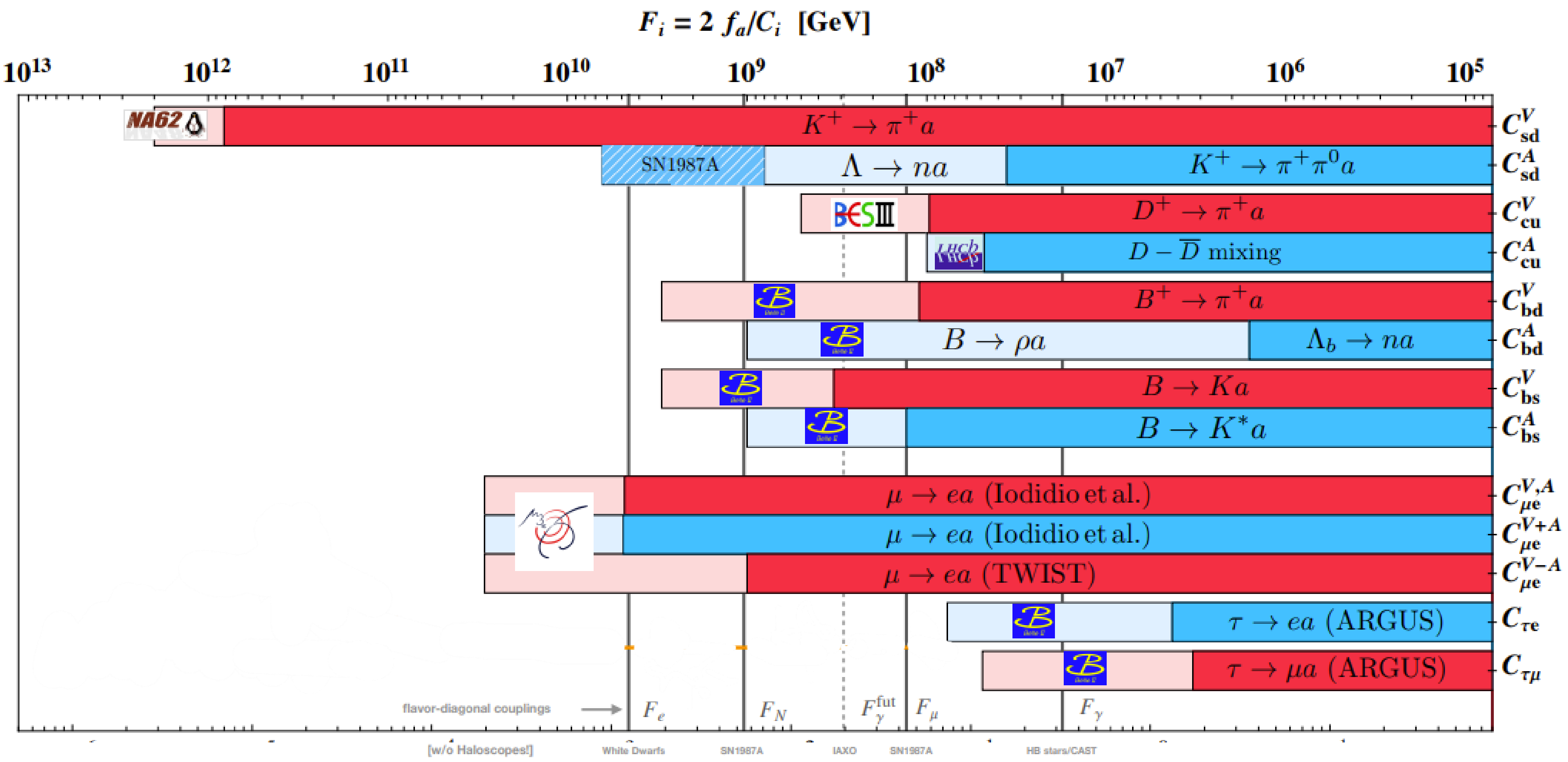
Astro Bounds – X-ray Searches + CMB

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



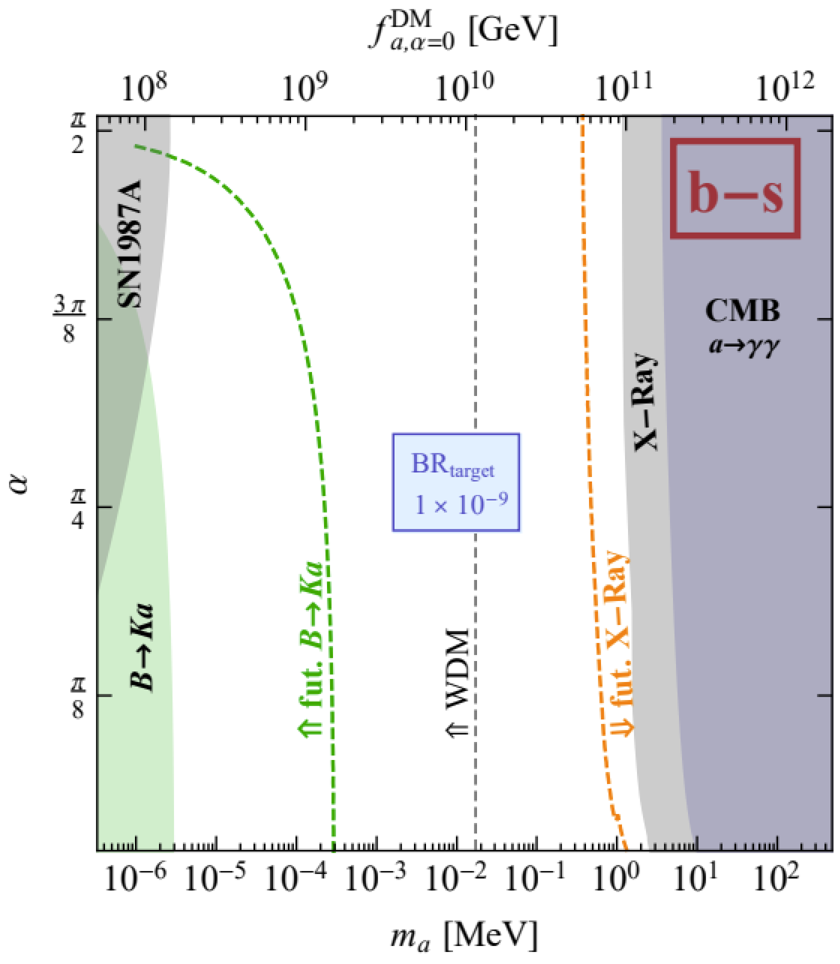
From arxiv:2209.03371

Collider Bounds

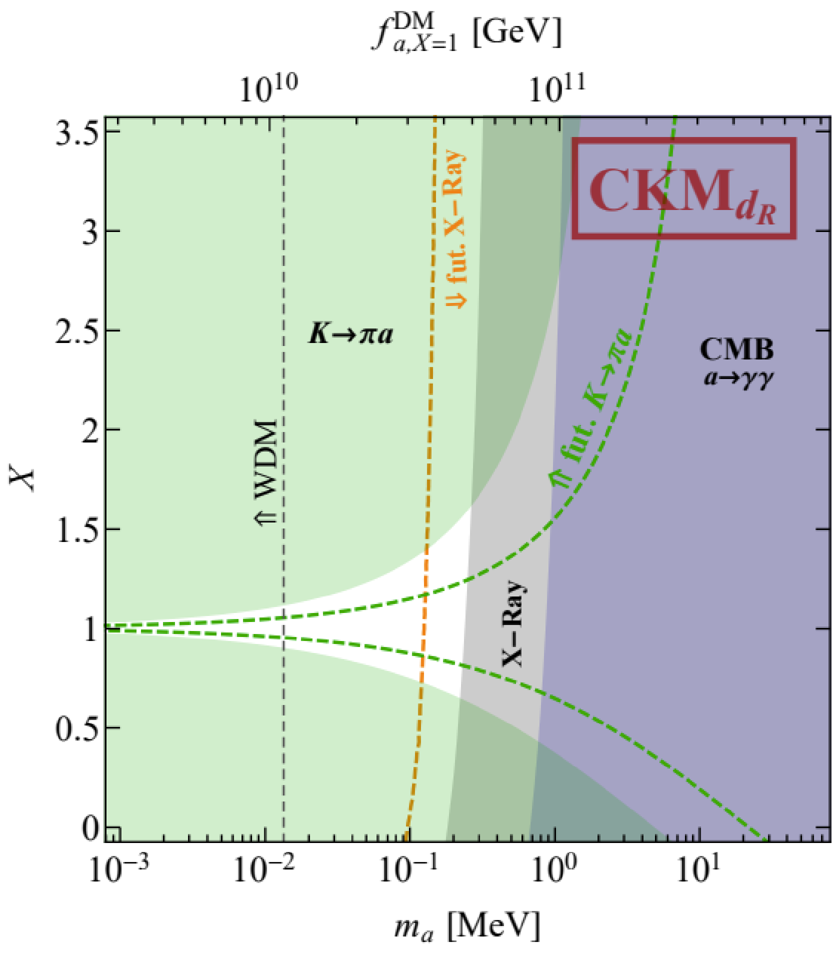


from arxiv:2303.13353

Results: Mass vs Coupling Plane



Poorely Constrained…



Constarined by X-Rays and Collider!

Conclusions

- Axions and ALPs are interesting candidates from a phenomenological point of view.
- An ALP that is also a DM candidate meets additional constraints (stability, production, astrophysical bounds…)
- Flavor Violating couplings to fermions: a bridge between Flavor & DM.
- Concrete Benchmark Scenarios will be tested by the interplay of future X-Rays and Collider searches

Backup Slides

A chiral Lagrangian for ALPs and Mesons

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

Effective symmetry

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

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

with

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

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

ALP Dark Matter – Production II

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

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

$q_i h \to q_j a$

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

Introduces a dependence on T_R (unknown)

arxiv:0911.1120

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

ALP Dark Matter – Production III

Non thermal mechanisms are also allowed

Misalignment $m_a \approx H$

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

Negligible