Axion-Like Electrophilic Portal for Pion Dark Matter

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“The X17 particle, status and new ideas”, ECT*, Trento

26/03/2026

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Based on 2602.02678,
accepted in PRD

Outline

- The SIMP framework
- Electrophilic ALP portal
- A possible answer to the X17 puzzle?

The SIMP framework

The dark matter problem

Astrophysical evidence of **missing mass**:

- Spiral galaxy rotation curves
- Galaxy cluster collisions
- Large scale structure formation
- CMB acoustic peaks
- ...

Credits: ESO

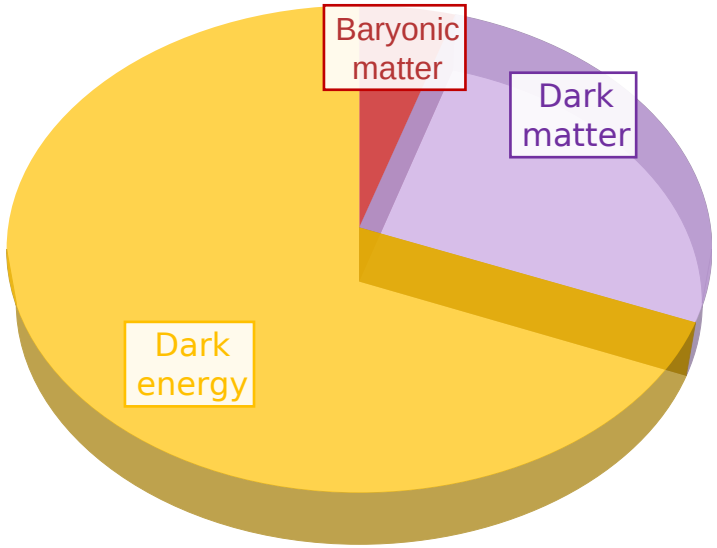
Credits: NASA/CXC/CfA and NASA/STScI

Dark matter properties

- **Pressureless matter:** $\rho_{\mathrm{DM}} \propto a(t)^{-3}$
- **Cold:** Nonrelativistic at matter-radiation equality
- **Sufficiently small self-interactions**
- **Dark:** Weakly interacting with SM particles

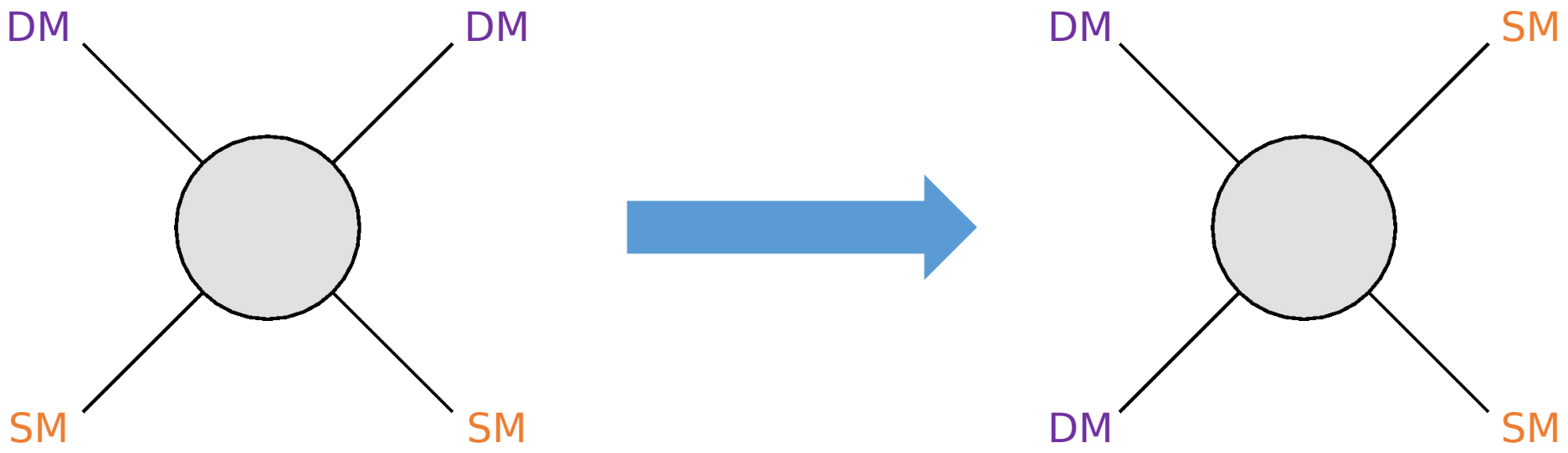
$$\Omega_{\mathrm{DM}} h^2 = 0.1200 \pm 0.0012$$

[Particle Data Group, 2024]



WIMP dark matter

Dark matter as thermal relic after freeze-out



Thermal equilibrium with SM

Decoupling when $\Gamma_{2\to 2} \sim H$

WIMP dark matter

$$m_{\mathrm{DM}} \sim \alpha_{\mathrm{ann}} (T_{\mathrm{eq}} M_{\mathrm{Pl}})^{1/2} \sim \mathrm{TeV}$$

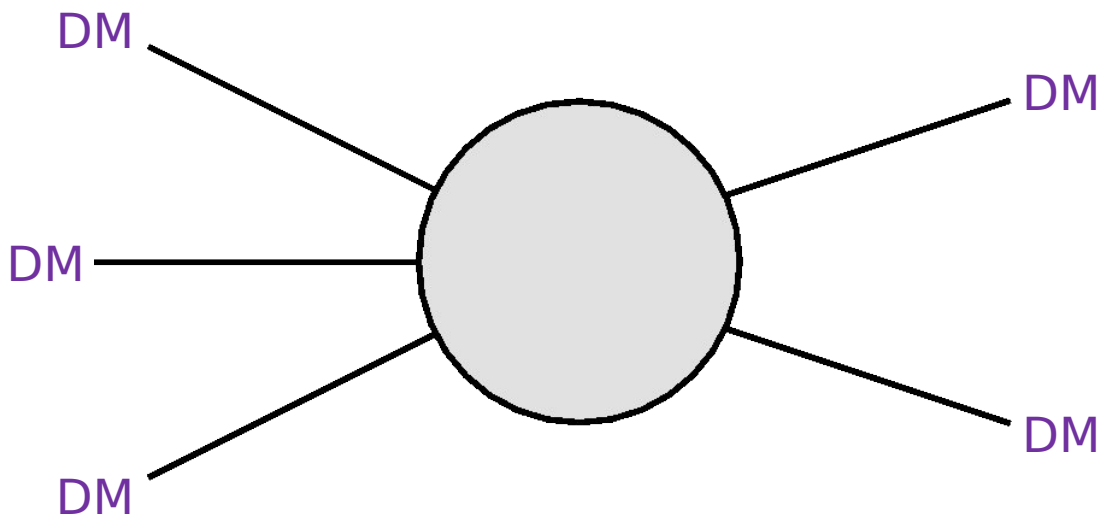
Within reach of current experiments

WIMP framework

- DM interacting with SM through $\mathrm{SU}(2)_{\mathrm{L}}$ gauge interactions
- Weak scale mass
- Able to reproduce observed DM density for $\alpha_{\mathrm{ann}} \gtrsim 1/30$

SIMP dark matter

[Hochberg, Kuflik, Volansky, Wacker, 1402.5143]



Decoupling through 3 → 2
DM to DM annihilations

$$m_{\rm DM} \sim \alpha_{\rm eff} (T_{\rm eq}^2 M_{\rm Pl})^{1/3} \sim 100\,{\rm MeV}$$

SIMP: Strongly Interacting Massive Particle

SIMP dark matter: Motivation

Inconsistencies between ΛCDM N-body simulations and observations

- Core vs cusp problem
- Too-big-to-fail problem

Possible solution: self-interacting DM with [Spergel, Steinhardt, astro-ph/9909386]

$$\sigma(v)/m_{\rm DM} \sim 1 - 10\,{\rm cm}^2/{\rm g}$$

SIMP DM ☑

The SIMPlest model

[Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727]

$\mathrm{Sp}(2\mathrm{N_c})$ gauge theory

$$\mathcal{L}_{\mathrm{SIMP}} = -\frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} + q_i^\dagger i\bar{\sigma}^\mu D_\mu q_i, \quad i = 1, \dots 2N_f$$

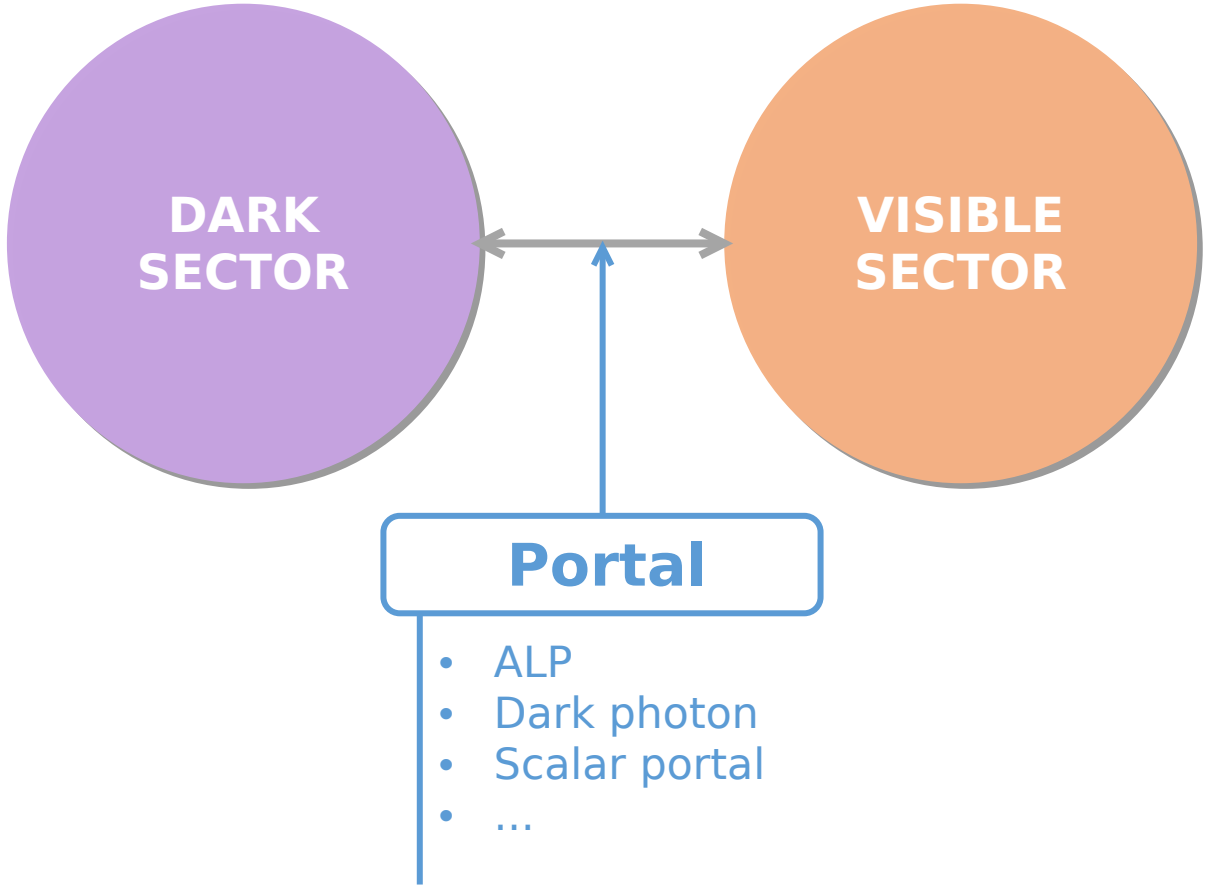
Confinement $\longrightarrow$ $\langle q_i q_j \rangle = \mu^3 (\gamma_{2N_f})_{ij}, \quad \gamma_{2N_f} = i\sigma_2 \otimes \mathbb{1}_{N_f}$

$$\pi_5(SU(2N_f)/Sp(2N_f)) = \mathbb{Z}, \quad N_f \geq 2$$

$$\mathcal{L}_{\mathrm{WZW}} = \frac{2N_c}{15\pi^2 f_\pi^5} \varepsilon^{\mu\nu\rho\sigma} \mathrm{Tr}[\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi]$$

SIMP dark matter: Thermalisation

3 → 2 annihilations heat up the DM bath → **Cannibalisation**



WIMP vs SIMP dark matter

WIMP DM

- Decouples through $2 \to 2$ annihilations

  DM + DM → SM + SM
- Thermal equilibrium guaranteed by

  DM + SM → DM + SM
- Reproduces the observed relic density just by exploiting SM weak interactions: “WIMP miracle”
- $m_{DM} = \mathcal{O}(\mathrm{TeV})$

SIMP DM

- Decouples through $3 \to 2$ annihilations

  DM + DM + DM → DM + DM
- Need for a portal to ensure thermal equilibrium with the SM bath
- Reproduces the observed relic density via dark sector interactions
- $m_{DM} = \mathcal{O}(100\ \mathrm{MeV})$
- Provides a solution to inconsistencies in astrophysical N-body simulations

Electrophilic ALP portal

Electrophilic ALP portal

[VF, Guo, Landini, Mescia, 2602.02678]

$\mathrm{Sp}(2\mathrm{N_c})$ gauge theory with 4 Weyl fermions

$$\mathcal{L}_{\rm DM} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + q^\dagger i\bar{\sigma}^\mu D_\mu q - \frac{1}{2}(e^{i\vartheta} M_{ij} q_i q_j + \text{h.c.}) \qquad M_{ij} = m(\gamma_{2N_f})_{ij}$$

coupled to an electrophilic ALP

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - g_{ae} a \bar{e} i\gamma_5 e$$

In a ChPT description, setting $U = e^{2i\frac{\pi^a \lambda^a}{f_\pi}}(\gamma_{2N_f})$

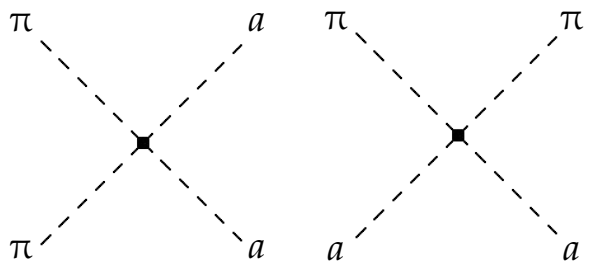
$$\mathcal{L} = \frac{f_\pi^2}{16}\mathrm{Tr}[\partial_\mu U^\dagger \partial^\mu U] - \frac{f_\pi^2}{8} B_0 \,\mathrm{Tr}[e^{i(\vartheta + a/f_a)} MU + \text{h.c.}] + \mathcal{L}_{\rm WZW}$$

Coupling to the dark sector

$$\mathcal{L}_{aq} = -\frac{1}{2}\left(e^{i(\vartheta + a/f_a)} M_{ij} q_i q_j + \text{h.c.}\right)$$

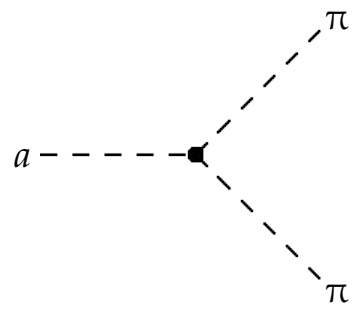
$\vartheta = 0$

$$\mathcal{L} \supset \frac{m_\pi^2}{4 f_a^2} a^2 \pi^a \pi^a$$



$\vartheta \neq 0$

$$\mathcal{L} \supset \frac{m_\pi^2 \tan\vartheta}{2 f_a} a \pi^a \pi^a$$



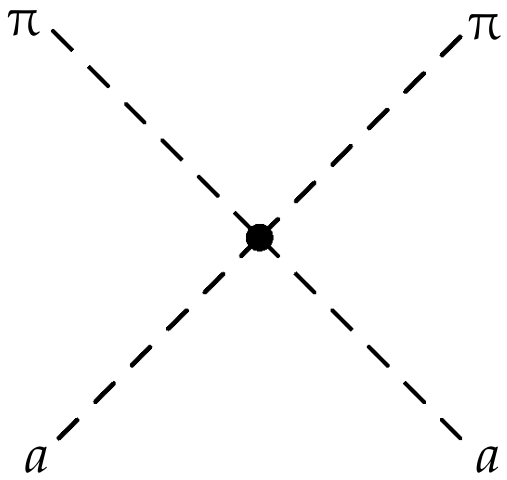
Thermalisation

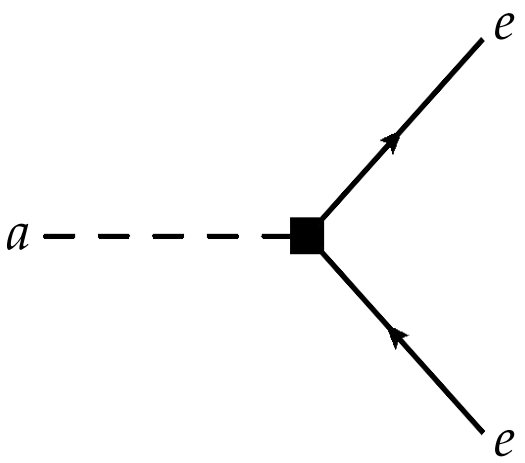
Two-step thermalisation:

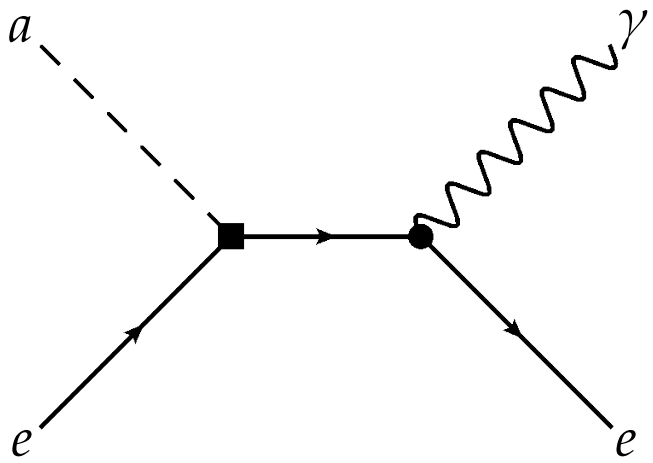
1. Dark pions ↔ ALP via $\pi a \to \pi a$
2. ALP ↔ Electrons via $a \to e^+e^-$ and $ae^\pm \to \gamma e^\pm$

$$\gamma_{ae}^{\rm eq} = \frac{T}{32\pi^4}\int_{(m_a+m_e)^2}^{+\infty} {\rm d}s\,\sqrt{s}K_1\left(\frac{\sqrt{s}}{T}\right)\int {\rm d}t\,\frac{\overline{|\mathcal{M}_{ae}|^2}}{8\pi s}$$

$$\overline{|\mathcal{M}_{ae}|^2} = 8\pi\alpha_{\rm em}g_{ae}^2\frac{t^2+m_a^4}{s(s+t-m_a^2)}$$





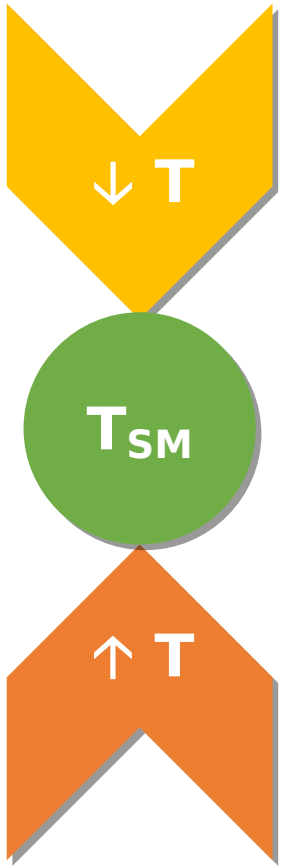


$$\sigma v(\pi a \to \pi a) = \frac{m_\pi^4\sqrt{m_a^4-2m_a^2(m_\pi^2+s)+(m_\pi^2-s)^2}}{8\pi f_a^4(s^2-(m_\pi^2-m_a^2)^2)}$$

$$\Gamma_a = \frac{g_{ae}^2 m_a}{8\pi}\sqrt{1-\frac{4m_e^2}{m_a^2}}$$

$$\langle\sigma v(ae^\pm \to \gamma e^\pm)\rangle = \frac{\gamma_{ae}^{\rm eq}}{n_a^{\rm eq}n_e^{\rm eq}}$$

Thermalisation: constraints



Hubble expansion

Elastic scatterings

3π → 2π annihilations

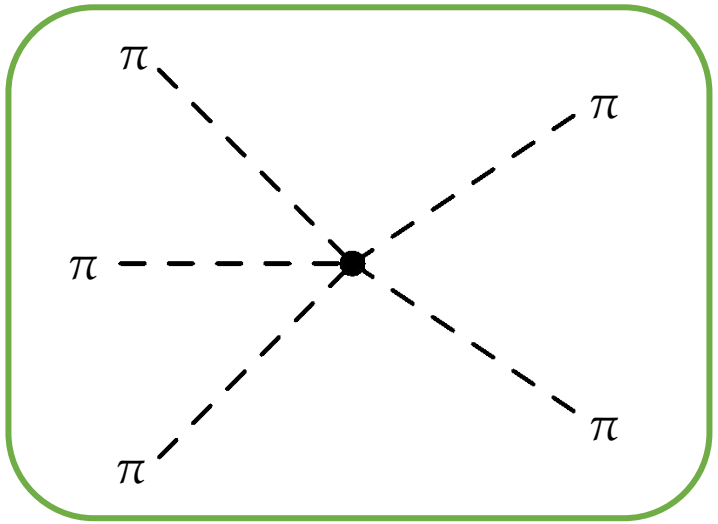
$$T_{\rm dec} \simeq m_\pi \left(\frac{\sqrt{5\pi g_\rho} f_a^4}{m_\pi^3 M_{\rm Pl}} \right)^{1/4}$$

$$T_{\rm f.o.} > T_{\rm dec}$$

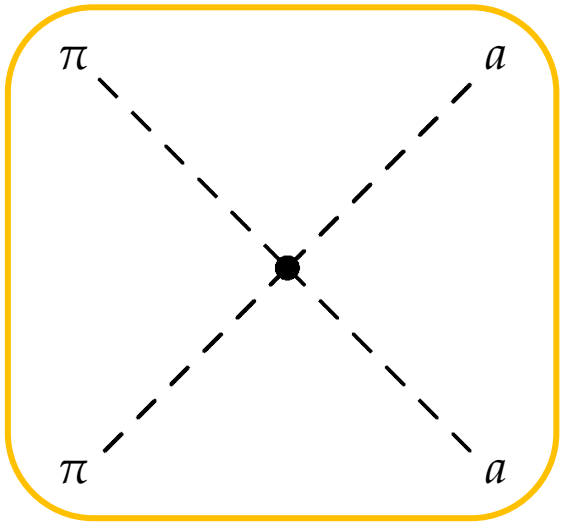
Thermalisation condition

Freeze-out: relevant processes

Two processes reducing the DM density



From $\mathscr{L}_{\mathrm{WZW}}$



From $\mathscr{L}_{a\pi}$

$$\langle \sigma v^2 \rangle_{3\pi \to 2\pi} = \frac{5\sqrt{5}}{2\pi^5 x_f^2} \frac{(2N_c)^2 m_\pi^5}{f_\pi^{10}} \frac{t^2}{N_\pi^3}$$

$$\langle \sigma v \rangle (\pi\pi \to aa) \simeq \frac{m_\pi^2}{64\pi N_\pi f_a^4} \sqrt{1 - \frac{m_a^2}{m_\pi^2}}$$

Freeze-out: Boltzmann equation

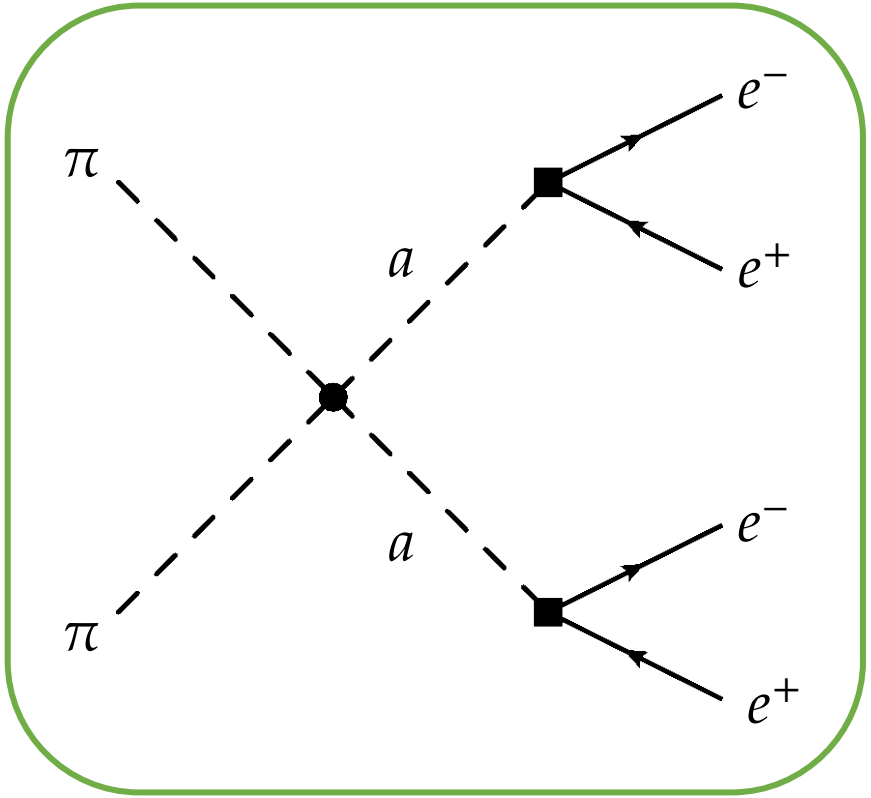
$$\dot{n}_\pi + 3Hn_\pi = -(n_\pi^3 - n_\pi^2 n_\pi^{\mathrm{eq}})\langle \sigma v^2 \rangle_{3\pi \to 2\pi}$$

$$n_\pi^{\mathrm{eq}} = \frac{N_\pi m_\pi^2 T}{2\pi^2} K_2\left(\frac{m_\pi}{T}\right)$$

$$H = \sqrt{\frac{4\pi^3 g_\rho}{45}} \frac{T^2}{M_{\mathrm{Pl}}}$$

$$m_\pi \sim 100\,\mathrm{MeV} - 1\,\mathrm{GeV}$$

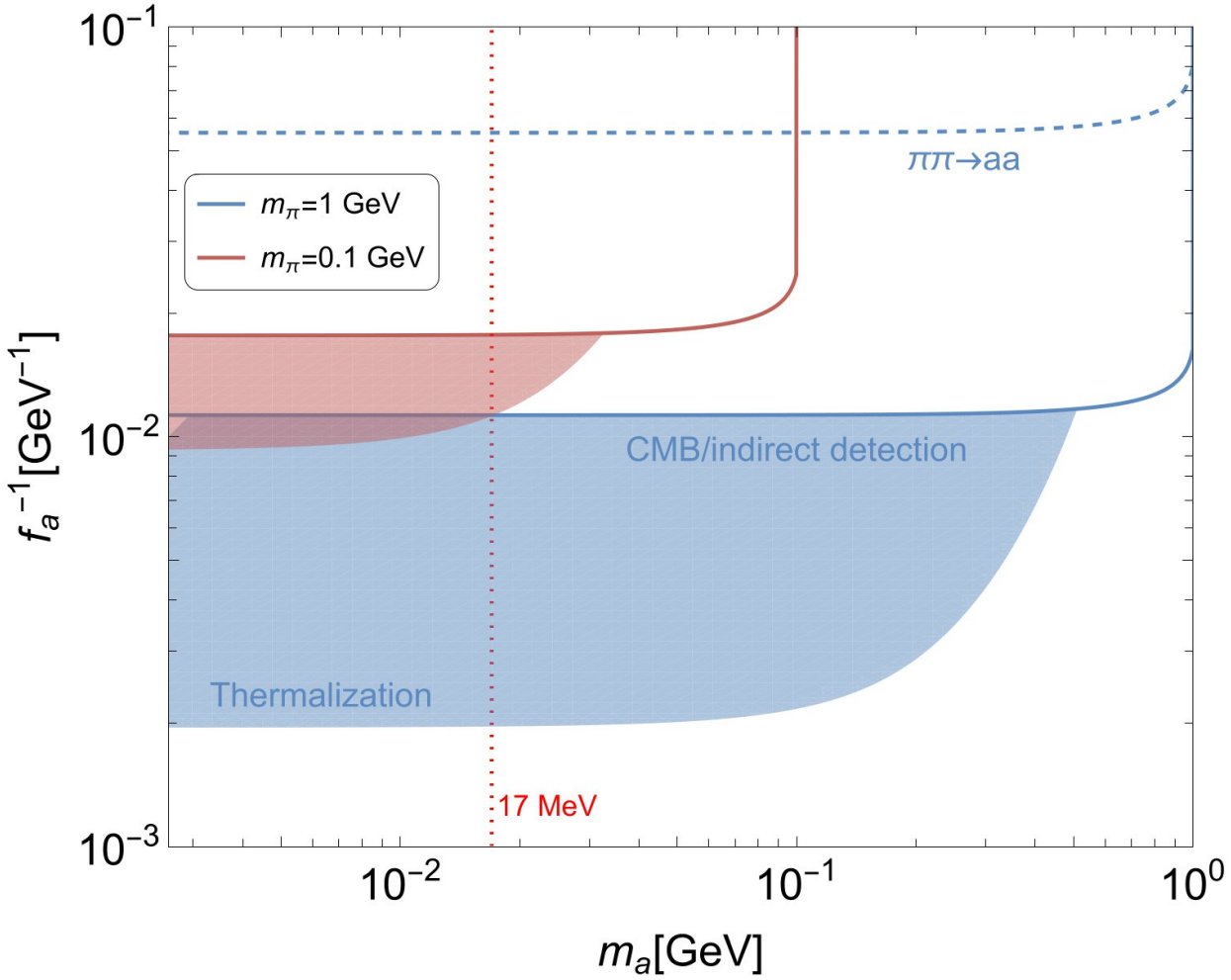
CMB constraints



The CMB anisotropies are affected

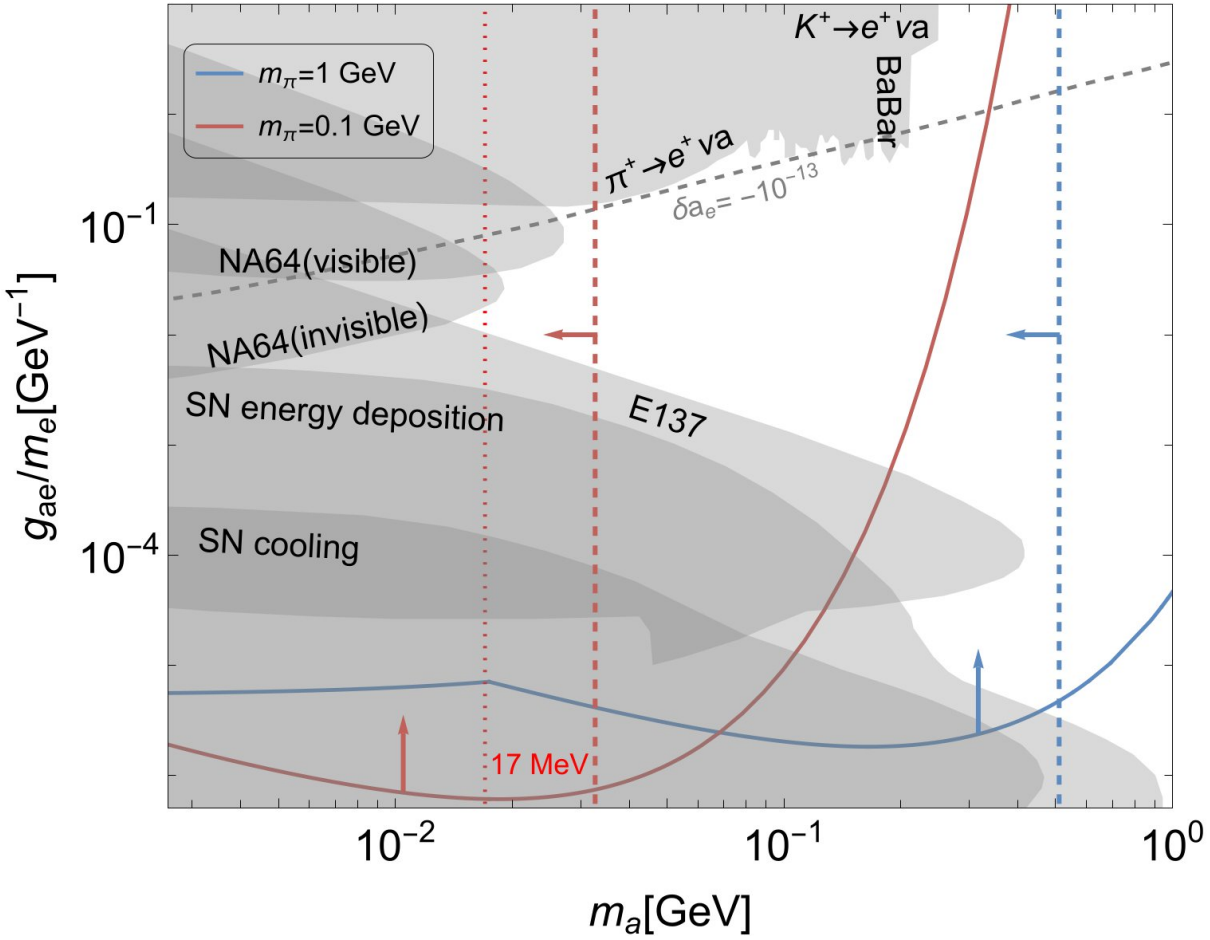
Constraints: Thermalisation and CMB

[Cirelli, Strumia, Zupan, 2406.01705]
[Slatyer, 1506.03811]



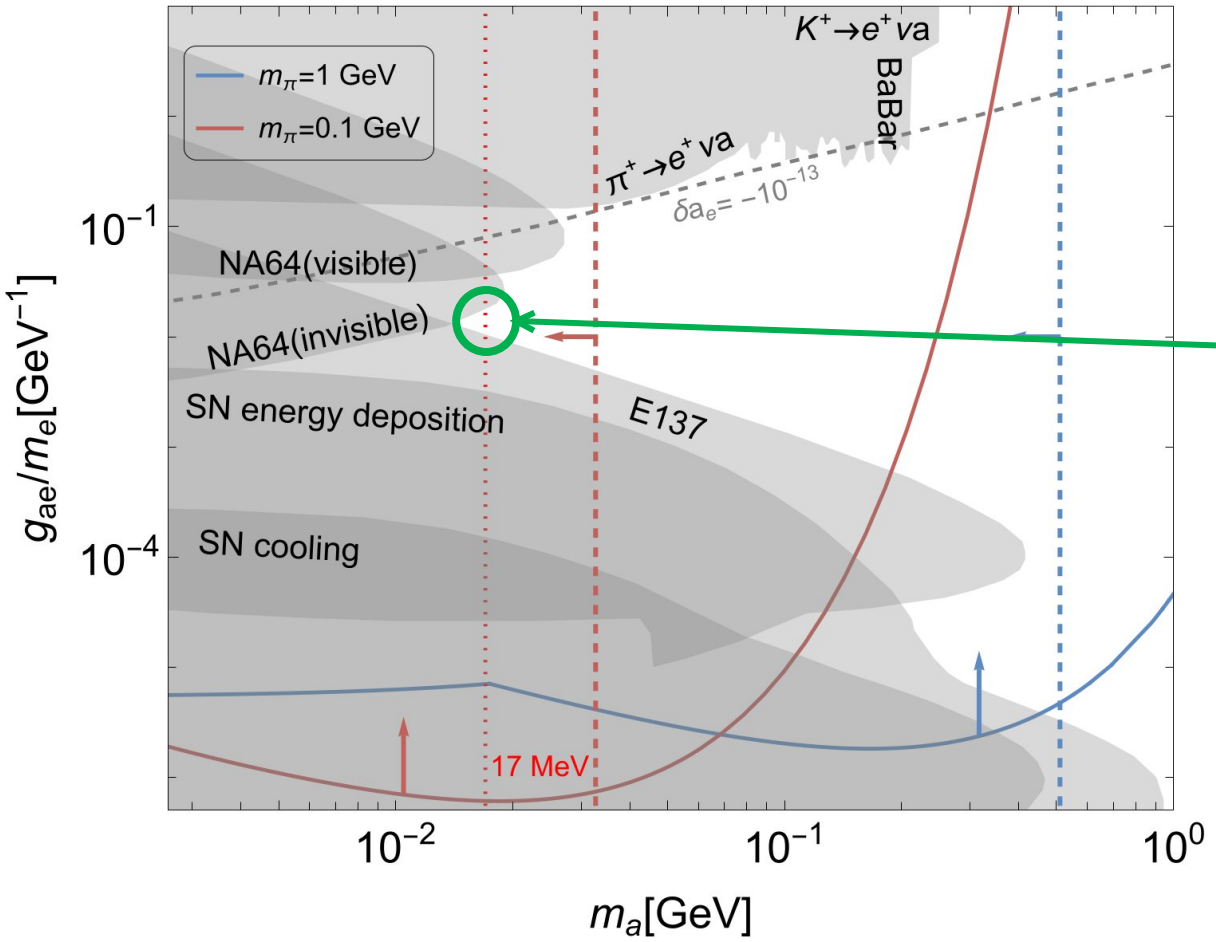
Constraints: Laboratory

[Banerjee et al. (NA64), 1912.11389]
[Lees et al. (BaBar), 1406.2980]
[Eichler at al. (SINDRUM), Phys. Rev. Lett B 175, 101]
[Poblaguev et al., hep-ex/0204006]



A possible answer to the X_{17} puzzle?

Electrophilic ALP X_{17}



$m_a \sim 17\,\mathrm{MeV}$ allowed by constraints!

Coupling to SM quarks

Explanation of X_{17} anomaly in ATOMKI → **ALP coupling to SM quarks**

Effects:

- **No effect on cosmology** → Dominated by 3 → 2 annihilations
- **Thermalisation improves**
- **CMB constraints unaffected**

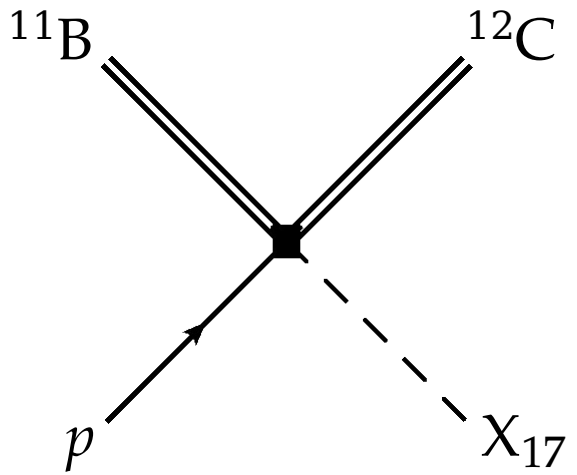
Good compatibility ☑

Pseudoscalar X_{17}

Process	$S^\pi = 0^+$	$S^\pi = 0^-$	$S^\pi = 1^+$	$S^\pi = 1^-$
^{8}Be(18.15) $\rightarrow^8$ Be	/	1	0, 2	1
^{8}Be(17.64) $\rightarrow^8$ Be	/	1	0, 2	1
^{4}He(21.01) $\rightarrow^4$ He	/	0	1	/
^{4}He(20.21) $\rightarrow^4$ He	0	/	/	1
^{12}C(17.23) $\rightarrow^{12}$ C	1	/	1	0, 2

Forbidden by ^{12}C transition

Direct proton capture?



Conclusions

- **SIMP framework** → Dark pion DM
- **Electrophilic ALP portal**: rich phenomenology
  - $\vartheta = 0 \rightarrow m_a \lesssim m_{DM}$
    - **ALP as possible pseudoscalar X_{17} candidate**
  - $\vartheta \neq 0 \rightarrow m_a \gtrsim m_{DM}$
    - **Complementary parameter space**
- **Consistent with PADME observations**
- **Viable extension explaining the ATOMKI anomaly**

Thank you!

BACKUP

ALP UV model

The ALP can either be

- The pseudo-Goldstone boson of a broken $\mathrm{U}(1)_{\mathrm{GB}}$ symmetry
- A generic pseudoscalar

In the pGB scenario

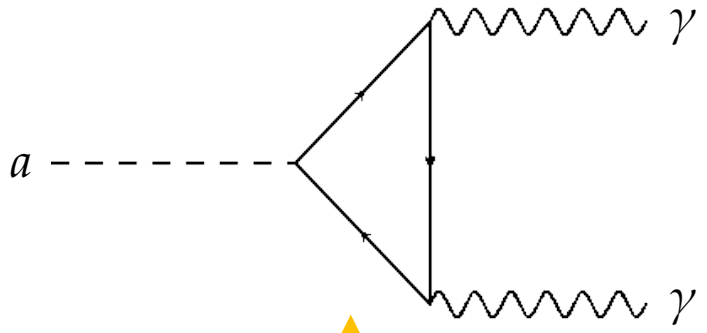
$$\mathcal{L} \supset -m_e \bar{e}_L e_R e^{iC_e a/f_a} + \mathrm{h.c.}$$

from Yukawa with $\mathrm{U}(1)_{\mathrm{GB}}$-charged scalars

$$\frac{C_e}{f_a} = \frac{g_{ae}}{m_e}$$

Coupling to photons

No UV contribution to ALP-photon coupling



Performing a field redefinition

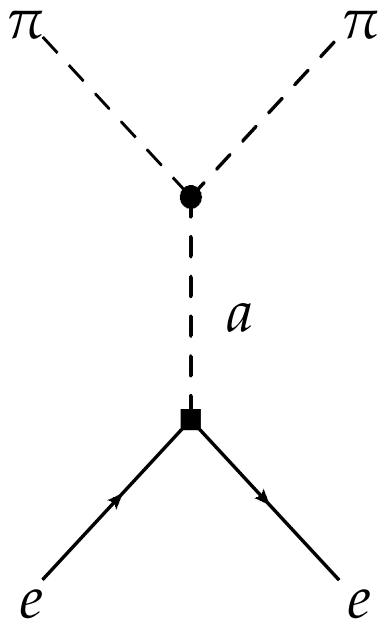
$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + C_e \frac{\partial_\mu a}{2 f_a} \bar{e}\gamma^\mu\gamma_5 e + \frac{C_e}{f_a}\frac{\alpha_{\rm em}}{4\pi} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Manifestly shift-invariant

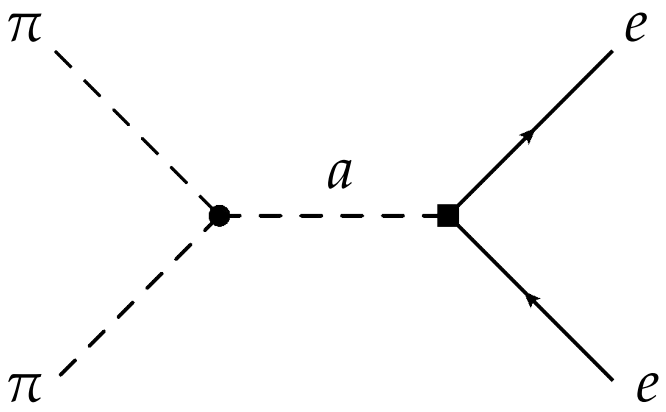
Same effective coupling

The $\vartheta \neq 0$ case

$$\mathcal{L}_{a\pi} \supset \frac{m_\pi^2 \tan\vartheta}{2f_a} a\pi^a\pi^a$$



$$\sigma v(\pi e^\pm \to \pi e^\pm) \simeq \frac{g_{ae}^2 m_\pi^2 p_e^2 \tan^2\vartheta}{8\pi m_a^4 f_a^2}$$



$$\langle \sigma v(\pi\pi \to e^+e^-) \rangle \overset{m_a \gg m_\pi}{\simeq} \frac{g_{ae}^2 m_\pi^4 \tan^2\vartheta}{4\pi N_\pi m_a^4 f_a^2}$$