Axion-like Particles as Mediators for Dark Matter: Beyond Freeze-out

In collaboration with Felix Brümmer, Nishita Desai

Based on A. Bharucha, F. Brümmer, N. Desai and S. Mutzel, [arXiv:2209.03932 [hep-ph]], to be published in JHEP

Aoife Bharucha and Sophie Mutzel

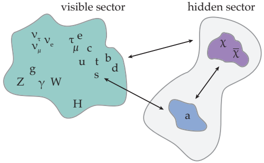
Centre de Physique Théorique Marseille

8th November, 2022
DISCRETE 2022, Baden-Baden

The Model

A new light pseudoscalar a might well be an axion-like particle (ALP), i.e. the pseudo-Goldstone boson of an approx. $\mathrm{U}(1)_{\mathrm{PQ}}$ global symmetry, spontaneously broken at a high scale f_a ($\Rightarrow$ light)

Axion-like particle (a) mediator between the SM fermions (f) and the DM (χ)a $\mathrm{U}(1)_{\mathrm{PQ}}$ charged Dirac fermion



$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - \frac{1}{2}m_a^2 a^2 + ia\sum_f \frac{m_f}{f_a} C_f \bar{f}\gamma_5 f + ia\frac{m_\chi}{f_a} C_\chi \bar{\chi}\gamma_5\chi + a\sum_f C_f \frac{y_f}{\sqrt{2}f_a} h\,\bar{f}i\gamma_5 f + \ldots$$

$g_{a\chi\chi} \equiv C_\chi/f_a$, $g_{aff} \equiv C_f/f_a$, no coupling to gauge bosons at tree-level but couple via loops

- a can emerge naturally from extended Higgs sector $\Rightarrow$ also expect dim-5 couplings
- If a was (DFSZ-like) QCD axion, multiple astrophysical and laboratory constraints (see [DiLuzio'20] for overview). (may be possible to circumvent these constraints by extensive model-building)
- Therefore assume that the a mass is mainly due to some explicitly $\mathrm{U}(1)_{\mathrm{PQ}}$-breaking effect other than the anomaly (no m_a g_{aff} relation and evade constraints)

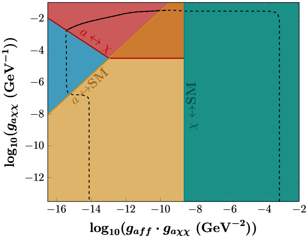
Dark matter generation beyond freeze-out

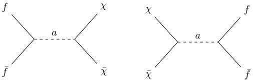
- Scale f_a should be large, $f_a \gg$ TeV $\Rightarrow$ couplings too small to give the correct relic density through freeze-out
- Alternative is that the initial abundance zero after reheating, e.g. freeze-in mechanism: gradually produced by scattering processes in thermal plasma without reaching equilibrium, processes decouple and DM abundance remains constant [Hall et al'10, Bernal et al'17].
- We consider the following possibilities
  - Small $g_{a\chi\chi}$ and g_{aff}, DM produced by IR freeze-in. Either directly via $f\bar{f} \to \chi\bar{\chi}$ or e.g. $f\bar{f} \to ag$ followed by $aa \to \chi\bar{\chi}$ (where the ALP may or may not be in equilibrium with the SM [Bélanger et al'20],) (Note for large $T_{\rm RH}$, dominant process via $2 \to 3$ scattering $f\bar{f} \to h\chi\bar{\chi}$, UV freeze-in i.e. sensitive to the reheating temperature)
  - Intermediate g_{aff}, ALPs not in eq. with SM, but if $g_{a\chi\chi}$ sufficiently large, in eq. with DM $\Rightarrow$ freeze-out from a thermally decoupled dark sector, or to put it simply, decoupled freeze-out (DFO), see [Chu et al'12], and more recently [Hambye'19].
- Let's study how to solve the Boltmann equations in these different cases

Coupled Boltzmann equations

$$\langle \sigma_{aa\to\chi\bar\chi} v\rangle \, (T') \; n_a^{\rm eq}(T') \simeq H$$

$$\langle \sigma_{ai\to jk} v\rangle \; n_i^{\rm eq} \simeq H$$



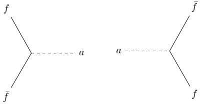


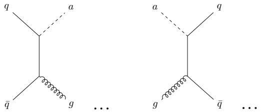
$$\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar\chi\to f\bar f} v \right\rangle \left(\left(n_\chi^{\rm eq}(T)\right)^2 - n_\chi^2 \right)$$

$$+ \langle \sigma_{aa\to\chi\bar\chi} v\rangle \, (T^{(\prime)}) n_a^2 - \langle \sigma_{\chi\bar\chi\to aa} v\rangle \, (T^{(\prime)}) n_\chi^2$$

$$\frac{dn_a}{dt} + 3Hn_a = - \langle \sigma_{aa\to\chi\bar\chi} v\rangle \, (T^{(\prime)}) n_a^2 + \langle \sigma_{\chi\bar\chi\to aa} v\rangle \, (T^{(\prime)}) n_\chi^2$$

$$+ \langle \Gamma_a \rangle \left(n_a^{\rm eq}(T) - n_a \right) + \sum_{i,j,k} \langle \sigma_{ai\to jk} v\rangle \left(n_a^{\rm eq}(T) n_i^{\rm eq}(T) - n_a n_i^{\rm eq}(T) \right)$$

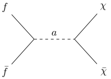




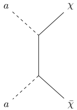
Coupled Boltzmann equations

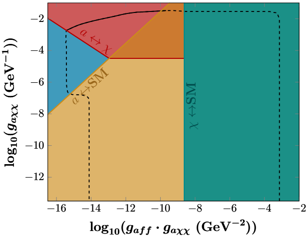
$$\langle \sigma_{aa\to\chi\bar{\chi}} v\rangle \,({\color{red}T'})\; n_a^{\mathrm{eq}}({\color{red}T'}) \simeq H$$

$$\langle \sigma_{ai\to jk} v\rangle \; n_i^{\mathrm{eq}} \simeq H$$



$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar{\chi}\to f\bar{f}} v \right\rangle \overbrace{\left(\left(n_\chi^{\mathrm{eq}}(T)\right)^2\right.} + \underbrace{\langle \sigma_{aa\to\chi\bar{\chi}} v\rangle \,(T) n_a^2}$$

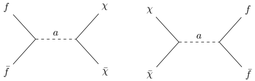


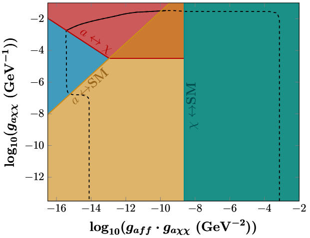


Coupled Boltzmann equations

$$\langle \sigma_{aa\to\chi\bar{\chi}} v\rangle \, ({\color{red}T'}) \; n_a^{\rm eq}({\color{red}T'}) \simeq H$$

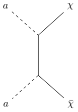
$$\langle \sigma_{ai\to jk} v\rangle \; n_i^{\rm eq} \simeq H$$

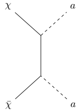




$$\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar{\chi}\to f\bar{f}} v \right\rangle \overbrace{\left((n_\chi^{\rm eq}(T))^2 \right.}\; - \; \overbrace{\left. n_\chi^2 \right)}$$

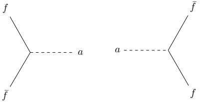
$$+ \underbrace{\langle \sigma_{aa\to\chi\bar{\chi}} v\rangle \, ({\color{red}T'}) n_a^2} - \underbrace{\langle \sigma_{\chi\bar{\chi}\to aa} v\rangle \, ({\color{red}T'}) n_\chi^2}$$

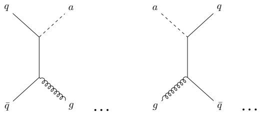




$$\frac{dn_a}{dt} + 3Hn_a = - \overbrace{\langle \sigma_{aa\to\chi\bar{\chi}} v\rangle \, ({\color{red}T'}) n_a^2} + \overbrace{\langle \sigma_{\chi\bar{\chi}\to aa} v\rangle \, ({\color{red}T'}) n_\chi^2}$$

$$+ \langle \Gamma_a \rangle \left(\underbrace{n_a^{\rm eq}(T)} - \underbrace{n_a} \right) + \sum_{i,j,k} \langle \sigma_{ai\to jk} v\rangle \left(\underbrace{n_a^{\rm eq}(T) n_i^{\rm eq}(T)} - \underbrace{n_a n_i^{\rm eq}(T)} \right)$$





Determining the temperature of the hidden sector-I

Solving the Energy transfer Boltzmann equation we can obtain the HS energy density ρ'. The temperature T' of HS calculated from ρ' via the equation of state:

$$\frac{\partial \rho'}{\partial t} + 3H\left(\rho' + P'\right) = \int \frac{d^3p}{(2\pi)^3} C[f(p,t)] \qquad \text{using} \qquad P' = \tfrac{1}{3}\langle p \tfrac{\partial E}{\partial p}\rangle .$$

where $\rho' + P' = \rho_a + \rho_\chi + P_a + P_\chi$

In our model, complication as not $f\bar{f} \to aa$ (see [Chu et al'12]) but $f\bar{f} \to ag$, $gf \to af$ $+ f\bar{f} \to a$.

Initially for $T' > m_\chi, m_a$ ALPs and DM will be ultra-relativistic, $P' = \rho'/3$, and universe radiation-dominated $\rho \propto T^4$:

$$\frac{\partial \rho'}{\partial t} + 4H\rho' = -H\left(T\frac{\partial \rho'}{\partial T} - 4\rho'\right) = -HT\rho\frac{\partial}{\partial T}\left(\frac{\rho'}{\rho}\right) = \int \frac{d^3p}{(2\pi)^3} C[f(p,t)] .$$

where $\rho' = \rho_a^{\mathrm{eq}}(T') + \rho_{\mathrm{DM}}^{\mathrm{eq}}(T')$ and $P' = P_a^{\mathrm{eq}}(T') + P_{\mathrm{DM}}^{\mathrm{eq}}(T')$

$\Rightarrow$ Here the equation for T' can be solved independently

Determining the temperature of the hidden sector-II

For $T' \lesssim m_a, m_\chi$, HS particles become non-relativistic, and interactions will freeze out $\Rightarrow$ T' determined together with n_χ and n_a. [1]:

$$\rho_\chi = \frac{\rho_\chi^{\rm eq}(T')}{n_\chi^{\rm eq}(T')}\; n_\chi\,, \qquad P_\chi = \frac{P_\chi^{\rm eq}(T')}{n_\chi^{\rm eq}(T')}\; n_\chi = T' n_\chi\;,$$

and similarly for the ALP

The hidden sector equation of state is then given by

$$\rho' + P' = \frac{\rho_\chi^{\rm eq}(T')}{n_\chi^{\rm eq}(T')}\; n_\chi + \frac{\rho_a^{\rm eq}(T')}{n_a^{\rm eq}(T')}\; n_a + T'\,(n_\chi + n_a)\;.$$

$\Rightarrow$ solve three coupled differential equations:

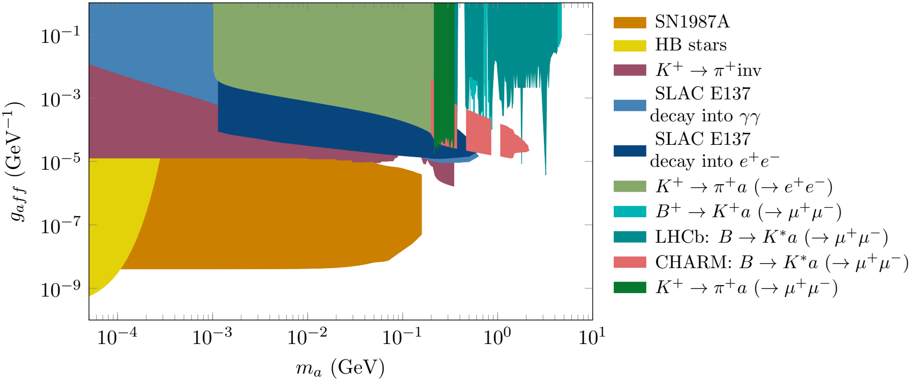
$$z\frac{{\rm d}\rho'}{{\rm d}T'}\frac{{\rm d}T'}{{\rm d}z} = -\,3(\rho'+P') + \frac{1}{H}\int \frac{d^3p}{(2\pi)^3}\, C[f(p,t)]$$

$$Hz\frac{{\rm d}n_\chi}{{\rm d}z} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar\chi\to f\bar f} v\right\rangle (T) n_\chi^{\rm eq}(T)^2 + \sum_{i,j,k} \langle \sigma_{\chi\bar\chi i\to jk} v^2\rangle\; n_i^{\rm eq}\;(n_\chi^{\rm eq})^2$$
$$+\, \langle \sigma_{aa\to\chi\bar\chi} v\rangle\,(T') n_a^2 - \langle \sigma_{\chi\bar\chi\to aa} v\rangle\,(T') n_\chi^2$$

$$Hz\frac{{\rm d}n_a}{{\rm d}z} + 3Hn_a = \langle \Gamma_a\rangle\; n_a^{\rm eq}(T) + \sum_{i,j,k} \left\langle \sigma_{ia\to jk} v\right\rangle (T) n_a^{\rm eq}(T) n_i^{\rm eq}(T)$$
$$-\, \langle \sigma_{aa\to\chi\bar\chi} v\rangle\,(T') n_a^2 + \langle \sigma_{\chi\bar\chi\to aa} v\rangle\,(T') n_\chi^2$$

[1] Kinetic equilibrium is maintained (due to efficient $\chi a \to \chi a$ scattering)

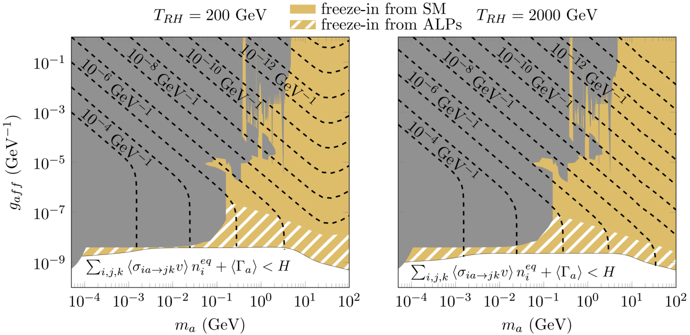
Constraints on our ALP

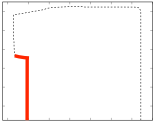


- Revisit constraints from electron beam dumps, rare B and K decays, astrophysics, dark matter searches and cosmology.
- In particular, for our specific ALP scenario we (re)calculate and improve beam dump, flavour and supernova constraints.

Freeze-in vs. constraints on our ALP

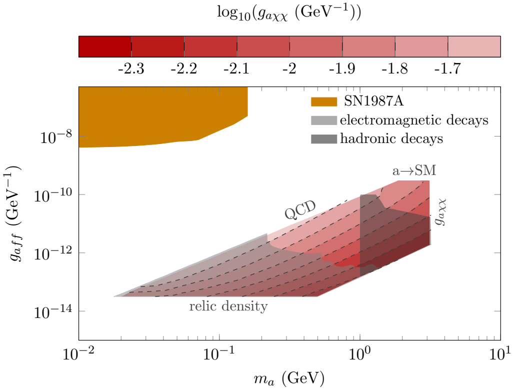
$m_\chi / m_a = 10$

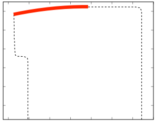




DFO vs. constraints on our ALP

$m_\chi / m_a = 10$

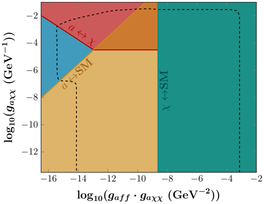




- Tiny g_{aff} $\Rightarrow$ ALP relatively long lived $\Rightarrow$ Consequences for BBN
- For $m_a \lesssim 2m_\mu$ constraints are very similar, see [Kawasaki et al.'20] for very long-lived ALPs with sub-GeV m_a excluding $\tau_a \sim 10^3 - 10^5$ s
- For $2m_\mu \lesssim m_a \lesssim 1$ GeV, EM bounds probably apply too, llifetimes not excluded.
- For hadronic decays $\tau \sim 0.1$ s can be excluded, see [Kawasak et al'17]
- ALPs decaying into photons can re-equilibrate with the SM, see [Millea et al'15], excluding much shorter lifetimes, but these should be alleviated as our dark sector is at T', to be studied in more detail

Conclusion

What we have done



- Our simple framework of an axion-like particle mediating DM leads to various alternative DM genesis scenarios
- Performed a detailed numerical calculation of full region of parameter space giving the correct relic density in various regimes, in particular DFO regime non-trivial
- Brand-new calculation of constraints (normally constraints for ALPs for photon coupling) to verify if these regions of parameter space are allowed

Future work

$$E\left(\partial_t - Hp\partial_p\right) f = C\left[f\right]$$

- Improve accuracy, in particular in sequential freeze-in region, by solving unintegrated Boltzmann equation
- Assess the potential sensitivity of future experiments to the region of interest

Determining the HS equation of state

$$3(\rho' + P') = 3(\rho_a + \rho_\chi + P_a + P_\chi) \ .$$

Radiation dominated $3(\rho' + P') = 4\rho'$, we can change variables using $\frac{\partial}{\partial t} \approx -HT\frac{\partial}{\partial T}$

$$\frac{\partial \rho'}{\partial t} + 4H\rho' = -H\left(T\frac{\partial \rho'}{\partial T} - 4\rho'\right) = -HT\rho\frac{\partial}{\partial T}\left(\frac{\rho'}{\rho}\right) = \int \frac{d^3p}{(2\pi)^3} C[f(p,t)] \, .$$

- $T' > m_\chi, m_a$

$$\rho' = \rho_a^{\mathrm{eq}}(T') + \rho_{\mathrm{DM}}^{\mathrm{eq}}(T') \qquad P' = P_a^{\mathrm{eq}}(T') + P_{\mathrm{DM}}^{\mathrm{eq}}(T')$$

- $T' \lesssim m_\chi$

$$\rho_\chi = \left(\frac{\rho}{n}\right)_\chi^{\mathrm{eq}}(T') \; n_\chi \qquad P_\chi = \left(\frac{P}{n}\right)_\chi^{\mathrm{eq}}(T') \; n_\chi = T' n_\chi \ ,$$

- $T' \lesssim m_a$

$$3(\rho' + P') = 3\left[\left(\frac{\rho}{n}\right)_\chi^{\mathrm{eq}}(T') \; n_\chi + \left(\frac{\rho}{n}\right)_a^{\mathrm{eq}}(T') \; n_a + T'\,(n_\chi + n_a)\right] \ .$$

Boundaries of DFO region

- **Relic density** For connector couplings, g_{aff}, which are too small, the hidden sector does not become sufficiently populated. Although $g_{a\chi\chi}$ might be large enough to establish equilibrium between the hidden sector particles, $n_\chi^{\rm eq}(T')$ can never reach the amount of DM density observed today. This is indicated by the lower boundary.
- ***a*** $\leftrightarrow$ **SM** On the other hand, if the connector coupling g_{aff} is too large, the interactions between the hidden sector and the SM become strong enough to establish thermal equilibrium. Depending on the hidden sector coupling, the DM is then either produced by freeze-in (see section **??**) or thermal freeze-out. We remark that the numerical solution close to the transition between the freeze-in and the DFO regime is challenging and we chose this upper boundary conservatively.
- $\boldsymbol{g_{a\chi\chi}}$ The DM-mediator interaction is (cf. eq. (**??**))

$$C_\chi \frac{m_\chi}{f_a} a\bar{\chi}\gamma_5\chi \equiv g_{a\chi\chi} m_\chi a\bar{\chi}\gamma_5\chi\,. \tag{1}$$

  Our effective theory is valid only below the scale f_a. Thus, the reheating temperature T_{RH} should be below this scale to safely ignore UV contributions. On the other hand, T_{RH} has to be higher than m_χ. We consequently need a hierarchy $f_a \gtrsim T_{RH} \gtrsim m_\chi$, i.e. small $g_{a\chi\chi} = C_\chi/f_a$, and this is the reason why the DM (the ALP for a fixed mass ratio) should not be too heavy.
- **QCD** Finally, we employ a perturbative description of the strong interactions, only convergent at high enough energies. The DM abundance should therefore be set by interactions happening at temperatures before the QCD phase transition. In practice, we set the upper boundary labelled "QCD" by requiring that the χ-particles freeze out at temperatures above the threshold $T_{\rm pert} = 600$ MeV.