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

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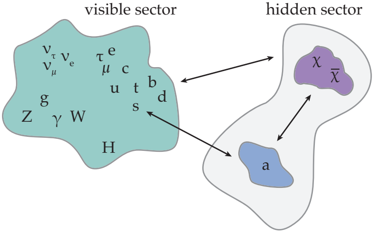
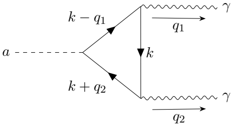
The Model

Axion-like particle (a) mediator between the SM fermions (f)
and the DM (χ), a Dirac fermion



Do not consider coupling to gauge bosons at tree-level but can couple via loops, e.g.

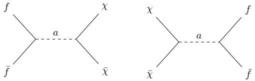


Lagrangian:

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

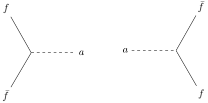
$g_{a\chi\chi} \equiv C_\chi / f_a$ (hidden sector coupling), $g_{aff} \equiv C_f / f_a$ (connector coupling)

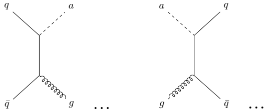
Coupled Boltzmann equations



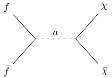
$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar{\chi}\to f\bar{f}} v \right\rangle \left(\left(n_\chi^{\mathrm{eq}}(T)\right)^2 - n_\chi^2 \right) + \langle \sigma_{aa\to\chi\bar{\chi}} v \rangle n_a^2 - \langle \sigma_{\chi\bar{\chi}\to aa} v \rangle n_\chi^2$$

$$\frac{\mathrm{d}n_a}{\mathrm{d}t} + 3Hn_a = -\langle \sigma_{aa\to\chi\bar{\chi}} v \rangle n_a^2 + \langle \sigma_{\chi\bar{\chi}\to aa} v \rangle n_\chi^2 + \langle \Gamma_a \rangle \left(n_a^{\mathrm{eq}}(T) - n_a \right) + \sum_{i,j,k} \left\langle \sigma_{ai\to jk} v \right\rangle \left(n_a^{\mathrm{eq}}(T) n_i^{\mathrm{eq}}(T) - n_a n_i^{\mathrm{eq}}(T) \right)$$



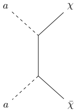


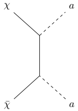
Coupled Boltzmann equations

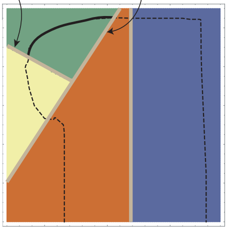


$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar\chi\to f\bar f}\, v \right\rangle \overbrace{\left(n_\chi^{\mathrm{eq}}(T)\right)^2}$$

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

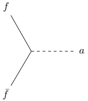


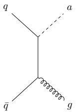




$$\frac{\mathrm{d}n_a}{\mathrm{d}t} + 3Hn_a = -\overbrace{\langle \sigma_{aa\to\chi\bar\chi}\, v\rangle\, ({\color{red}T'}) n_a^2} + \overbrace{\langle \sigma_{\chi\bar\chi\to aa}\, v\rangle\, ({\color{red}T'}) n_\chi^2}$$

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





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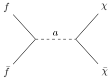
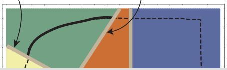
[Chu, Hambye, Tytgat. JCAP, 2012], [Hambye, Tytgat, Vandecasteele, Vanderheyden. Phys. Rev. D, 2019], [Bélanger, Delaunay, Pukhov, Zaldivar. Phys. Rev. D, 2020]

Coupled Boltzmann equations



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

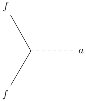


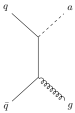
$$\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar\chi\to f\bar f} v \right\rangle \; \overbrace{\left(n_\chi^{\rm eq}(T)\right)^2}$$

Hidden sector and visible sector thermally decoupled, $T' \ll T$

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

Need to solve system of 3 (unfortunately stiff) coupled differential equations





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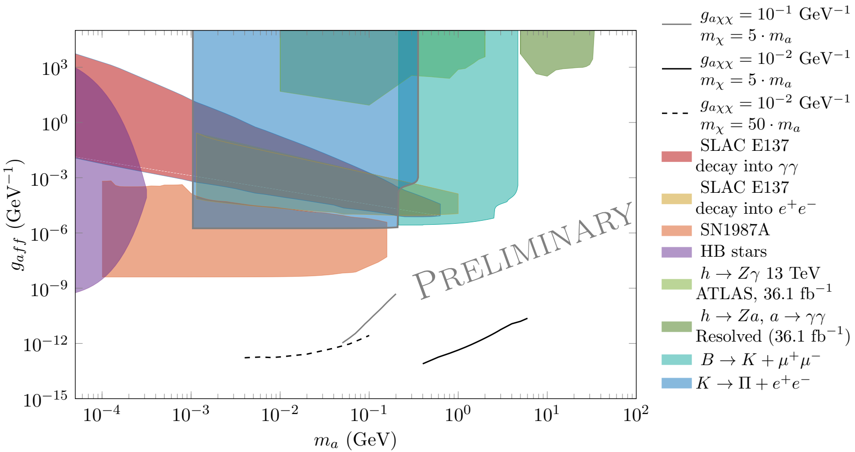
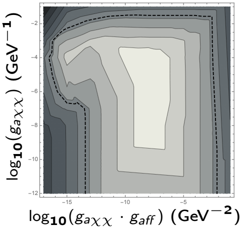
Results: Reannihilation vs. constraints on our ALP



Conclusion

What we have done



- Our simple 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 reannihilation 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 freeze-in but also in reannihilation region, by solving unintegrated Boltzmann equation
- Apply future expected constraints to our model

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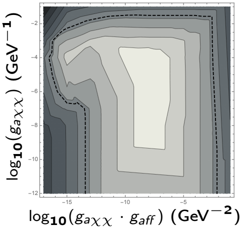

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Exciting time for axions! We look forward to seeing the impact of future experimental results on our model!