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

In collaboration with Aoife Bharucha, Felix Brümmer and Nishita Desai

Sophie Mutzel

Centre de Physique Théorique Marseille

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

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

**Lagrangian:**

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

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

\[
\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar{\chi} \rightarrow f\bar{f}v} \right\rangle \left( (n_{\chi}^{\text{eq}}(T))^2 - n_\chi^2 \right) \\
+ \left\langle \sigma_{aa \rightarrow \chi\bar{\chi}v} \right\rangle n_a^2 - \left\langle \sigma_{\chi\bar{\chi} \rightarrow aa v} \right\rangle n_\chi^2
\]

\[
\frac{dn_a}{dt} + 3Hn_a = -\left\langle \sigma_{aa \rightarrow \chi\bar{\chi}v} \right\rangle n_a^2 + \left\langle \sigma_{\chi\bar{\chi} \rightarrow aa v} \right\rangle n_\chi^2 \\
+ \left\langle \Gamma_a \right\rangle \left( n_a^{\text{eq}}(T) - n_a \right) + \sum_{i,j,k} \left\langle \sigma_{ai \rightarrow jk v} \right\rangle \left( n_a^{\text{eq}}(T)n_i^{\text{eq}}(T) - n_a n_i^{\text{eq}}(T) \right)
\]
Coupled Boltzmann equations

\[ \frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi \bar{\chi} \to f \bar{f} V} \right\rangle \left( n_{\chi \text{eq}}(T) \right)^2 \]

\[ + \left( \left\langle \sigma_{aa \to \chi \bar{\chi} V}(T') \right\rangle n_a^2 - \left\langle \sigma_{\chi \bar{\chi} \to aa V}(T') \right\rangle n_\chi^2 \right) \]

\[ \frac{dn_a}{dt} + 3Hn_a = -\left\langle \sigma_{aa \to \chi \bar{\chi} V}(T') \right\rangle n_a^2 + \left\langle \sigma_{\chi \bar{\chi} \to aa V}(T') \right\rangle n_\chi^2 \]

\[ + \left\langle \Gamma_a \right\rangle n_{a \text{eq}}(T) \]

\[ + \sum_{i,j,k} \left\langle \sigma_{ai \to jk V} \right\rangle n_{a \text{eq}}(T) n_{i \text{eq}}^{\text{eq}}(T) \]

\[ \langle \sigma_{aa \to \chi \bar{\chi} V} \rangle (T') n_{a \text{eq}}(T') \simeq H \]

\[ \langle \sigma_{ai \to jk V} \rangle n_i^{\text{eq}} \simeq H \]
Coupled Boltzmann equations

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

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

Results: Reannihilation vs. constraints on our ALP

\[ g_{a\chi} = 10^{-1} \text{ GeV}^{-1} \]
\[ m_\chi = 5 \cdot m_a \]
\[ g_{a\chi} = 10^{-2} \text{ GeV}^{-1} \]
\[ m_\chi = 5 \cdot m_a \]
\[ g_{a\chi} = 10^{-2} \text{ GeV}^{-1} \]
\[ m_\chi = 50 \cdot m_a \]

SLAC E137
- decay into $\gamma\gamma$
- SLAC E137
- decay into $e^+e^-$
- SN1987A
- HB stars

$A T L A S$, $36.1 \text{ fb}^{-1}$

$h \to Z\gamma$ 13 TeV

Resolved ($36.1 \text{ fb}^{-1}$)

$B \to K + \mu^+\mu^-$

$K \to \pi + e^+e^-$
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

- Improve accuracy, in particular in freeze-in but also in reannihilation region, by solving unintegrated Boltzmann equation
- Apply future expected constraints to our model
Conclusion

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Future work

\[ E \left( \partial_t - H p \partial_p \right) f = C \left[ f \right] \]

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