Asymmetric thermal-relic dark matter

Iason Baldes
Work done in collaboration with Kalliopi Petraki

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(Asymmetric) Dark Matter Freezeout

Assume we have a DM asymmetry

Asymmetry $\eta_D \equiv Y^+ - Y^-$ frozen during freeze-out.
Also define $\epsilon \equiv \eta_D / \eta_B$

Fractional asymmetry

This ratio changes during freezout.

$$r \equiv \frac{Y^-}{Y^+}$$

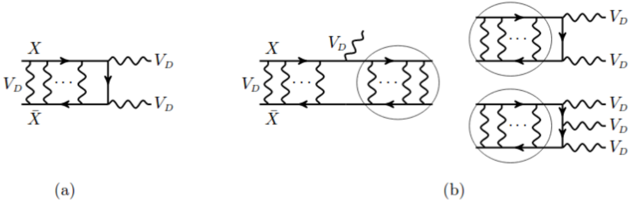
DM mass relation

$$M_{\mathrm{DM}} = \frac{m_p}{\epsilon} \frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{B}}} \left(\frac{1 - r_\infty}{1 + r_\infty} \right)$$

- Graesser, Shoemaker, Vecchi 1103.2771; Iminniyaz, Drees, Chen 1104.5548

New here: Sommerfeld enhancement, bound state formation and unitarity

Vector mediator



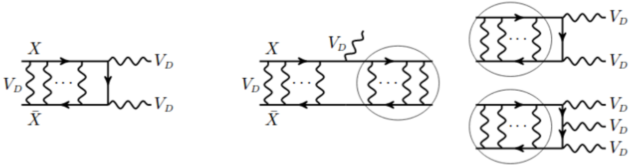
$$\mathcal{L} = \bar{X}(i\not{D} - M_{\mathrm{DM}})X - \frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu}$$

- X denotes the DM particle
- Covariant derivative $D^\mu = \partial^\mu + ig_d V_D^\mu$
- $F_D^{\mu\nu} = \partial^\mu V_D^\nu - \partial^\nu V_D^\mu$, with V_D^μ being the dark photon field
- $\alpha_D \equiv g_d^2/(4\pi)$ being the dark fine-structure constant.

If X carries a particle-antiparticle asymmetry, another field is required to balance the implied $U(1)_D$ charge asymmetry in X.

Vector mediator - Sommerfeld enhancement and bound state formation

Symmetric case: - von Harling, Petraki 1407.7874



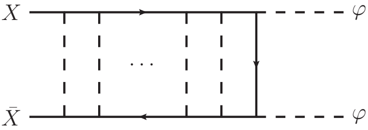
(a) (b)

Here $\sigma v_{\rm rel} = \sigma_0 (S_{\rm ann}^{(0)} + S_{\rm BSF})$. In the Coulomb limit, $S_{\rm ann}^{(0)}$ and $S_{\rm BSF}$ depend only on the ratio $\zeta \equiv \alpha_D / v_{\rm rel}$

$$S_{\rm ann}^{(0)}(\zeta) = \frac{2\pi\zeta}{1-e^{-2\pi\zeta}} \qquad \sigma_0 \equiv \pi\alpha_D^2/M_{\rm DM}^2$$

$$S_{\rm BSF}(\zeta) = \frac{2\pi\zeta}{1-e^{-2\pi\zeta}} \, \frac{\zeta^4}{(1+\zeta^2)^2} \, \frac{2^9}{3} \, e^{-4\zeta\,{\rm arccot}(\zeta)}$$

Scalar mediator

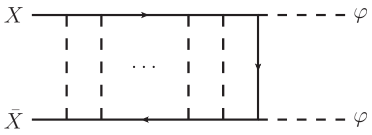


$$\mathcal{L} = \bar{X}(i\partial\!\!\!/ - M_{\rm DM})X + \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - \frac{1}{2}m_\varphi^2\varphi^2 - g_d\ \varphi\bar{X}X$$

- φ is the dark scalar force mediator with mass m_φ
- $\alpha_D \equiv g_d^2/(4\pi)$.

This is a p-wave process. However, as long as $m_\varphi \lesssim \alpha_D M_{\rm DM}/2$, the $X - \bar{X}$ interaction manifests as long range. The velocity suppression is lifted due to the Sommerfeld enhancement!

Scalar mediator - Sommerfeld enhancement



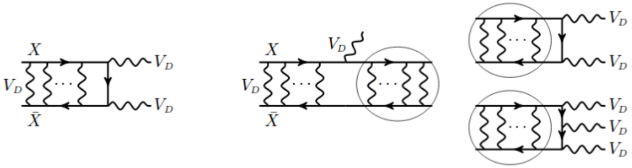
This is a *p*-wave annihilation process

$$\sigma_{\rm ann} v_{\rm rel} = \sigma_1 \, v_{\rm rel}^2 \; S_{\rm ann}^{(1)}$$

$$\sigma_1 = \frac{3\pi\alpha_D^2}{8M_{\rm DM}^2} \qquad\qquad S_{\rm ann}^{(1)}(\zeta) = \frac{2\pi\zeta}{1-e^{-2\pi\zeta}}\,(1+\zeta^2)$$

- As before, $\zeta \equiv \alpha_D / v_{\rm rel}$.
- At $v_{\rm rel} \lesssim \alpha_D$, $\sigma_{\rm ann} v_{\rm rel} \propto 1/v_{\rm rel}$.
- The $v_{\rm rel}^2$ suppression of the perturbative cross-section morphs into an α_D^2 suppression, with $\sigma_{\rm ann} v_{\rm rel} \propto \alpha_D^5$.

Boltzmann Equations - Vector Mediator

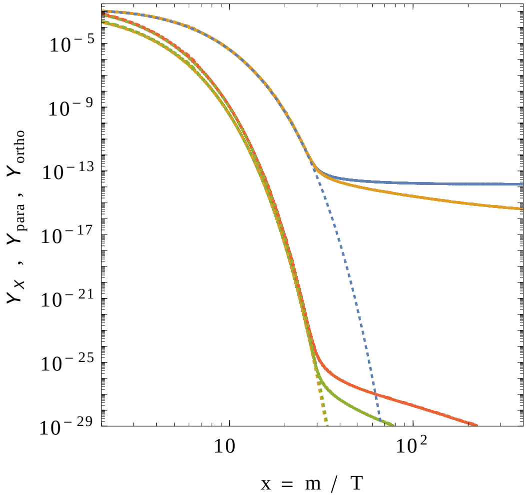


(a) (b)

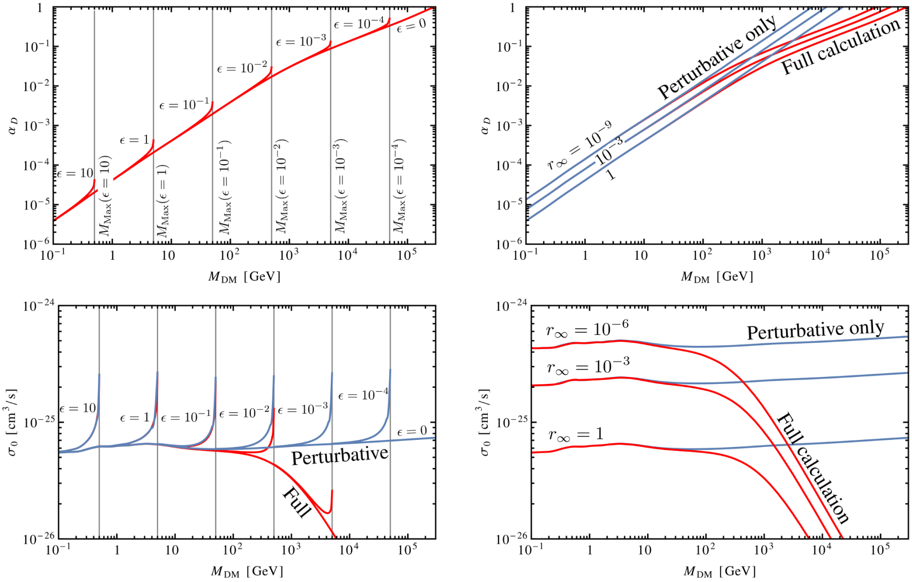
- Three coupled equations, taking into account Y^+ ($Y^- = Y^+ - \eta_D$), and the two bound states $Y_{\uparrow\downarrow}$ and $Y_{\uparrow\uparrow}$.
- At some stage T drops enough so bound state decay becomes quicker than ionization.
- Annihilation through the bound state then becomes significant.
- We take into account the T difference between the visible and dark sectors.

Similarly for the scalar mediator but without the bound states.

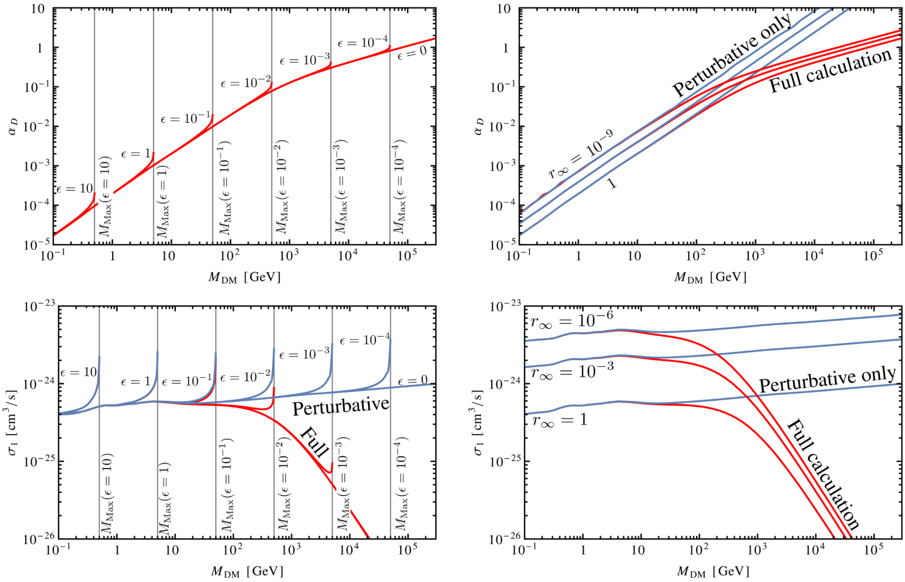
Relic abundance - Example



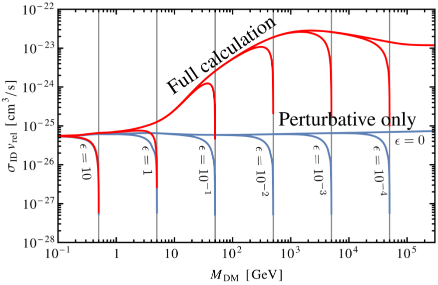
Required couplings/cross-section - vector mediator

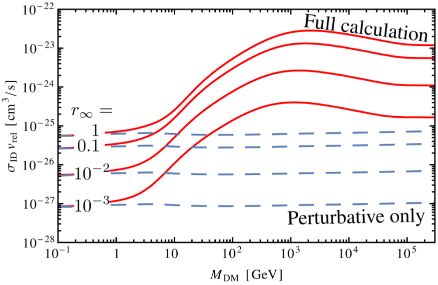


Required couplings - scalar mediator



Indirect detection - vector mediator



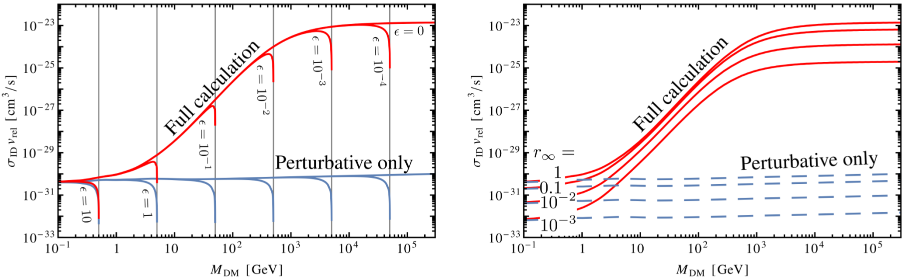


The effective cross-section for indirect detection signals,

$$\sigma_{\rm ID} v_{\rm rel} = \left[\frac{4 r_\infty}{(1+r_\infty)^2}\right] \sigma_{\rm inel} v_{\rm rel}.$$

We have used $v_{\rm rel} = 10^{-3}$, which is relevant for indirect searches in the Milky Way.

Indirect detection - scalar mediator



The effective cross-section for indirect detection signals,

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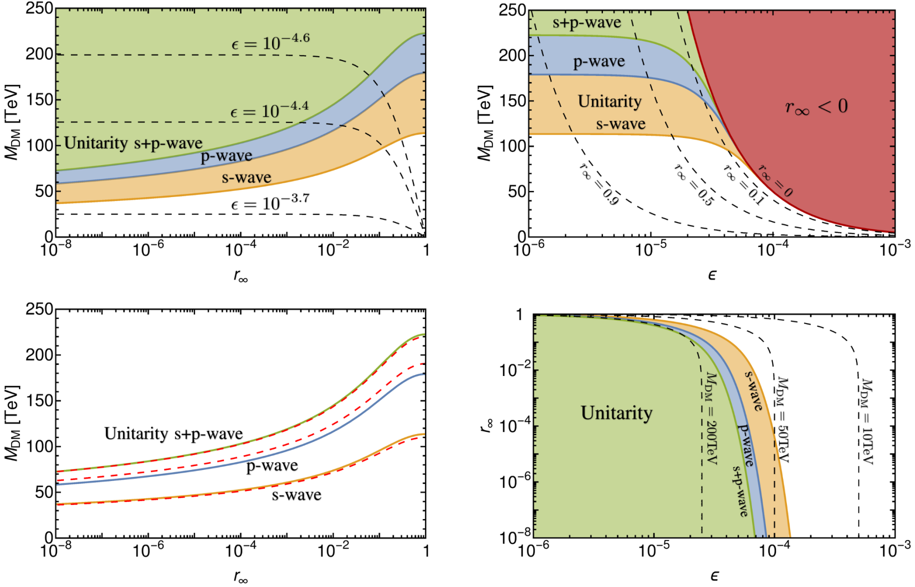
Unitarity constraint

In the non-relativistic regime

$$\sigma^{(J)}_{\rm inel}\, v_{\rm rel} \leqslant \sigma^{(J)}_{\rm uni}\, v_{\rm rel} = \frac{4\pi(2J+1)}{M^2_{\rm DM}\, v_{\rm rel}}$$

- Note that with SE $\sigma v_{\rm rel} \propto 1/v_{\rm rel}$, meaning there is no need to insert an arbitrary $v_{\rm rel}$ on the RHS of the inequality, as would be the case if naively using $\sigma v_{\rm rel} \sim \alpha_D^2/M^2_{\rm DM}$ or $\sigma v_{\rm rel} \sim \alpha_D^2 M^2_{\rm DM}/m^4_{\rm med}$.
- We obtain some $\alpha_{\rm uni}$ above which the unitarity constraint is violated. However, $\sigma v_{\rm rel}$ is based on a perturbative calculation - the relevant approximations will break down before this.
- The $\sigma^{(J)}_{\rm uni}\, v_{\rm rel} \propto 1/v_{\rm rel}$ behaviour indicates that to approach the unitarity limit, the cross section will necessarily display some long range $1/v_{\rm rel}$ behaviour, at least in the types of scenarios explored here.

Unitarity constraint - Results



Approaching Unitarity constraint implies a long range interaction

In the non-relativistic regime

$$\sigma^{(J)}_{\mathrm{inel}}\, v_{\mathrm{rel}} \leqslant \sigma^{(J)}_{\mathrm{uni}}\, v_{\mathrm{rel}} = \frac{4\pi(2J+1)}{M^2_{\mathrm{DM}}\, v_{\mathrm{rel}}}$$

- Interaction mediated by a heavy force carrier of mass $m_{\mathrm{med}} \gtrsim M_{\mathrm{DM}}$.
- $\sigma v_{\mathrm{rel}} \sim \alpha_D^2 M_{\mathrm{DM}}^2 / m_{\mathrm{med}}^4$.
- Realising unitarity limit $\alpha_D^{\mathrm{uni}} \sim (m_{\mathrm{med}}/M_{\mathrm{DM}})^2/\sqrt{v_{\mathrm{rel}}} \gtrsim m_{\mathrm{med}}/M_{\mathrm{DM}} \gtrsim 1$.
- This implies $m_{\mathrm{med}} \lesssim \alpha_D^{\mathrm{uni}} M_{\mathrm{DM}}$.
- That is range of the interaction between two DM particles, m_{med}^{-1}, is comparable or larger than their Bohr radius, $(\alpha_D^{\mathrm{uni}} M_{\mathrm{DM}}/2)^{-1}$.
- Interaction manifests as long-range, thereby contradicting the original premise of a contact-type interaction.

Conclusions

- Asymmetric DM scenarios require a slightly larger annihilation cross section.
- We have calculated the required α_D in some simple example scenarios including Sommerfeld enhancement and bound state formation.
- We have explored the unitarity constraint.
- This is a first step needed in order to constrain these models experimentally.

Thanks.