A Selection Rule for Enhanced Dark Matter Annihilation

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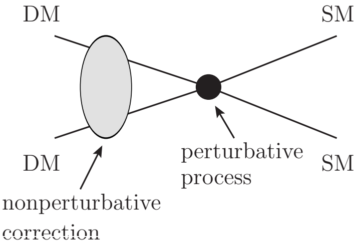
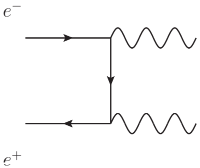
Sommerfeld Effect

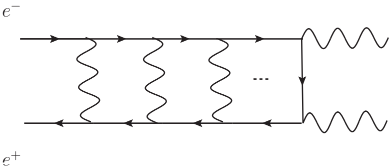


- Sommerfeld effect is a nonperturbative correction to dark matter annihilation.
- An angular momentum and spin based **selection mechanism** in a **multi-level dark matter** model.

Sommerfeld effect

- **SIDM: If the mediator is lighter than the DM $\rightarrow$ Sommerfeld effect.**
- An example in QED:





- Enhanced annihilation rate: $\sigma v_{\rm rel} = S_\ell \times \sigma_0 v_{\rm rel}$
- Present wisdom:
  - *p*-wave annihilation rate is smaller than *s*-wave rate.
  - In a *p*-wave suppressed model, present day annihilation signal will be negligible.

SE can change this scenario!

Sommerfeld effect

- **SIDM: If the mediator is lighter than the DM $\rightarrow$ Sommerfeld effect.**
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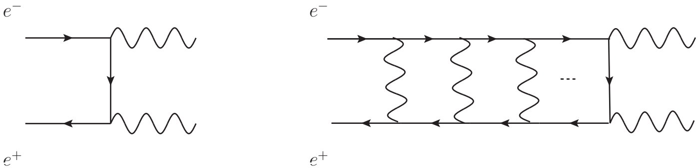

- Enhanced annihilation rate: $\sigma v_{\mathrm{rel}} = S_\ell \times \sigma_0 v_{\mathrm{rel}}$
- Present wisdom:
  - p-wave annihilation rate is smaller than s-wave rate.
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SE can change this scenario!

The dark sector

A dark $U(1)$-symmetric theory with a small breaking term-

$$\mathcal{L} \supset \partial^\mu \phi^\dagger \partial_\mu \phi + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \mathcal{L}_{U(1)-\text{breaking}} \\ + i\overline{\chi}\partial\!\!\!/\chi - M\overline{\chi}\chi - \left(\frac{f}{\sqrt{2}}\phi\overline{\chi}\chi^c + h.c.\right).$$

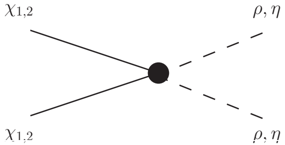
- SSB $\rightarrow \phi \rightarrow v + \rho + i\eta$ and $\chi \rightarrow \chi_1,\ \chi_2$
- New interactions: $-\frac{f}{2}\rho(\bar{\chi}_1\chi_1 - \bar{\chi}_2\chi_2) - \frac{f}{2}\eta(\bar{\chi}_1\chi_2 + \bar{\chi}_2\chi_1)$
- Potential matrix

$$V = \begin{pmatrix} V_\rho & V_\eta \\ V_\eta & V_\rho \end{pmatrix}$$

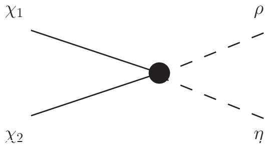
The dark sector

- A 2-level DM system: χ_1 and χ_2

Annihilation



Coannihilation

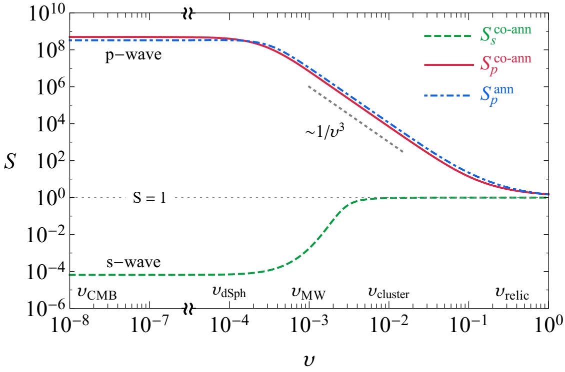


- **Annihilation**: $s-$wave ✗
  $p-$wave ✓

Coannihilation: $s-$wave ✓
$p-$wave ✓

An interesting result: s-wave suppressed and p-wave dominating!

Variation with $v_{\rm rel}$



$S_p \gg 1$ but $S_s \leq 1$!

Indirect detection signal will be produced by p-wave annihilations!

Explanation in terms of particle exchange symmetry

- **Coannihilation**: Two states $|\chi_1\chi_2\rangle$ & $|\chi_2\chi_1\rangle$ are related

$$|\chi_1\chi_2\rangle = (-1)^{\ell+s}|\chi_2\chi_1\rangle$$

- Their equations can be combined together into a single equation with an effective potential

$$V_{\text{eff}} = V_\rho + (-1)^{\ell+s} V_\eta$$

- For coannihilation, $\ell = 0, s = 1$

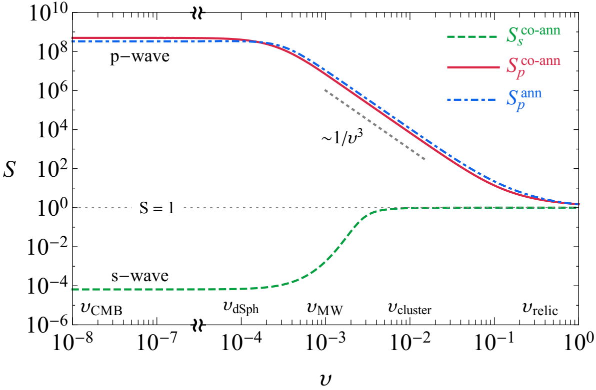
$$V_{\text{eff}} = V_\rho - V_\eta$$

- For $\ell = 1, s = 1$

$$V_{\text{eff}} = V_\rho + V_\eta$$

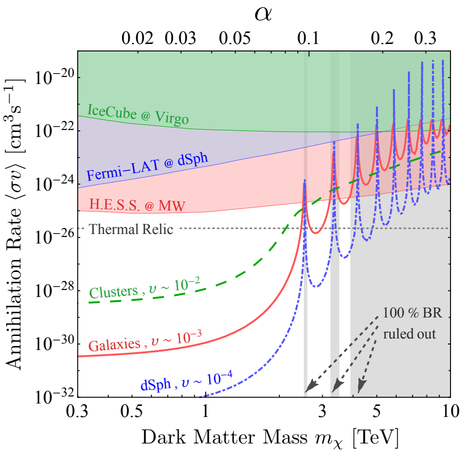
Explanation in terms of particle exchange symmetry

$$V_{\text{eff}}^{\ell=0} = -\frac{\alpha e^{-m_\rho r}}{r} + \frac{\alpha e^{-m_\eta r}}{r}, \quad V_{\text{eff}}^{\ell=1} = -\frac{\alpha e^{-m_\rho r}}{r} - \frac{\alpha e^{-m_\eta r}}{r}.$$



Results

Predicted ***p*-wave** annihilation rates from various sources-



Summary & conclusion

- Contrary to our expectation, the S_p dominates over S_s in a large region of the parameter space.
- The velocity-dependence of S_p is $\sim 1/v^3$ in the intermediate region.
- Particle exchange symmetry $\implies$ A selection mechanism.
- This opens up a new area of model-building and phenomenology allowing enhanced annihilation signals in specific sources, e.g., MW-like galaxies and clusters.
- Future directions: more than two DM particles, repulsive interaction from vector particle mediation, multiple mediators etc.

Back-ups

α-scaling of ladder graphs.

- Typical momentum exchange is NR dynamics is $|\mathbf{p}| \sim \alpha M \implies p^0 \sim \frac{|\mathbf{p}|^2}{2M} \sim \alpha^2 M/2\,.$
- One photon exchange graph: $\sim \frac{\alpha}{|\mathbf{q}|^2} \sim \frac{1}{\alpha}\,.$
- Two photon exchange graph: $\sim \alpha^2 . \frac{1}{\alpha^2}\frac{1}{\alpha^2} . \frac{1}{\alpha^2}\frac{1}{\alpha^2} . \alpha^2 . \alpha^3 \sim \frac{1}{\alpha}\,.$

Yukawa and Hulthén potentials: $V_Y = -\frac{\alpha e^{-mr}}{r} \sim V_H = -\frac{\alpha \delta e^{-\delta r}}{1 - e^{-\delta r}}\,.$

Back-ups

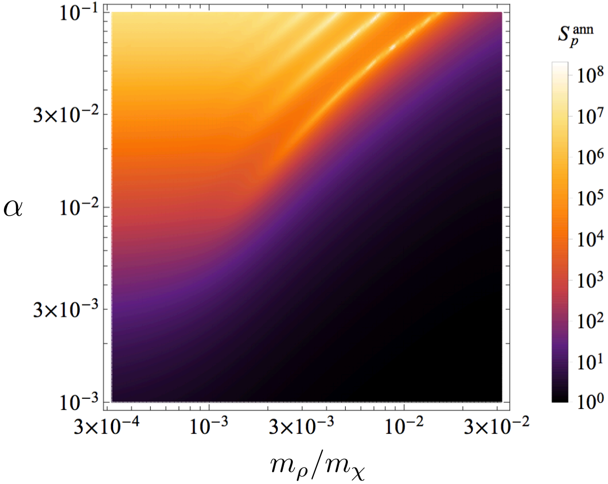
NFW profile: $\rho(r) = \dfrac{\rho_0}{\dfrac{r}{r_s}\left(1+\dfrac{r}{r_s}\right)^2}$.

Einasto profile: $\rho(r) = \rho_0 e^{-Ar^{\alpha}}$.

Star formation rate in dwarfs $\rightarrow 0.02 - 0.2\ M_{\odot}\mathrm{yr}^{-1}$.

To solve CC problem $\rightarrow 4 - 5\ M_{\odot}\mathrm{yr}^{-1}$.

Back-ups


10^{-1}
3×10^{-2}
α
10^{-2}
3×10^{-3}
10^{-3}
3×10^{-4}
10^{-3}
3×10^{-3}
10^{-2}
3×10^{-2}
m_ρ/m_χ
S_p^{ann}
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0

Explanation in terms of particle exchange symmetry

- If A and B are two fermions

$$|AB\rangle = (-1)^{\ell+s}|BA\rangle$$

- $(-1)^{\ell}$ from orbital angular momentum,
- $(-1)^{s+1}$ from spin,
- (-1) from Wick exchange of spinors.
- In case of scalars,

$$|AB\rangle = (-1)^{\ell}|BA\rangle$$