Capture and Decay of Wimponioum

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Based on : arXiv:1610.07617
PA, Matthew Baumgart, Patrick J. Fitzpatrick, Emmett Krupczak, Tracy R. Slatyer

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Outline

Sommerfeld Enhancement

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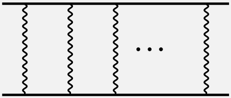
- Forces are mediated by a ladder of mediators being exchanged [0810.0713].



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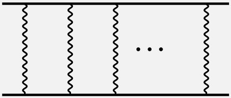

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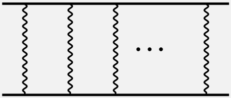

- The pair is described by a joint wavefunction [0903.5307].
- Can have this effect both in the initial and in the final states.

Wino

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$$m_{\chi^\pm} - m_{\chi^0} \approx 0.165\mathrm{GeV} \equiv \delta M$$

- Two electrically-neutral pairs :

$$\begin{pmatrix} \chi^0\chi^0 \\ \chi^\pm\chi^\mp \end{pmatrix}$$

Wino

- Control parameters :

$$\epsilon_\phi = \frac{m_\phi}{\alpha m_\chi}$$

$$\epsilon_v = \frac{v}{\alpha}$$

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- Odd (even) L+S means a symmetric (an anti-symmetric) wavefunction. Can give rise to different selection rules for processes involving $\chi^0\chi^0$ and $\chi^\pm\chi^\mp$.
- For $\chi^0\chi^0$, the total wavefunction should be anti-symmetric.

Wino Potential in Massless Mediator Limit

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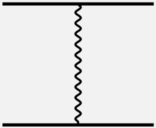
- Leading order contribution to the potential



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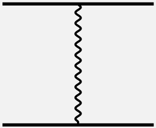

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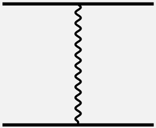

- Different L+S implies different potentials.

$$V(r) = \frac{\alpha_W}{r}\begin{pmatrix} 0 & -\sqrt{2} \\ -\sqrt{2} & -1 \end{pmatrix}, \quad L+S \text{ even}, \qquad V(r) = \frac{\alpha_W}{r}\begin{pmatrix} 0 & 0 \\ 0 & -1 \end{pmatrix}, \quad L+S \text{ odd}.$$

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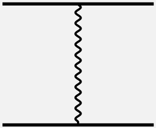

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- The eigenvalues are very important in shaping the spectrum : they determine the interaction strength
- For the $L+S$-even case, the eigenvalues are $\lambda = -2, \lambda = 1$.

Wino Potential with Massive Mediators

- The potential in the broken phase.

$$V_{L+S\,\mathrm{odd}}(r) = \begin{pmatrix} 0 & 0 \\ 0 & 2\delta M - \frac{\alpha}{r} - \alpha_W c_W^2 \frac{e^{-m_Z r}}{r} \end{pmatrix}$$

$$V_{L+S\,\mathrm{even}}(r) = \begin{pmatrix} 0 & -\sqrt{2}\alpha_W \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_W \frac{e^{-m_W r}}{r} & 2\delta M - \frac{\alpha}{r} - \alpha_W c_W^2 \frac{e^{-m_Z r}}{r} \end{pmatrix}$$

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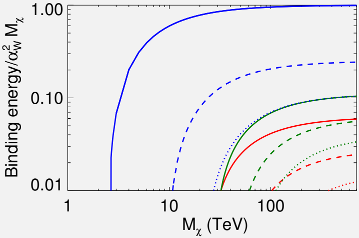
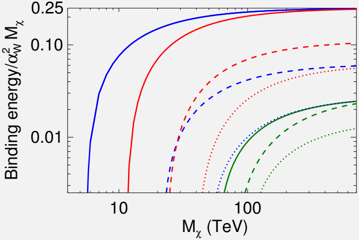
- Numerical methods needed to study the Schrodinger equation.

Wino Potential with Massive Mediator

- SPD
- Solid/Dashed/Dotted : 1st/2nd/3rd bound state to capture to.



Spin-Singlet



Spin Triplet

Capture

- $\chi^0\ \chi^0 \to SM\ SM$

Capture

- $\chi^0 \ \chi^0 \rightarrow SM \ SM$
- $\chi^0 \chi^0 \rightarrow boundstate \rightarrow SM \ SM$

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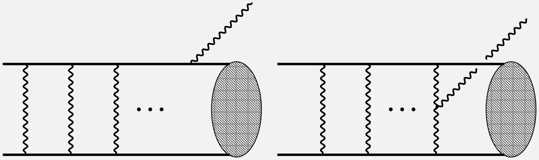
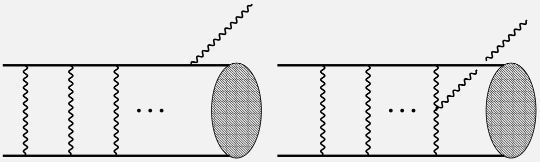


Capture

- $\chi^0\ \chi^0 \to$ *SM SM*
- $\chi^0\chi^0 \to$ *boundstate* $\to$ *SM SM*



$$\sigma v_{\rm rel}\,(\text{continuum} \to \text{bound})\ \text{or}\ \Gamma\,(\text{bound} \to \text{bound})$$
$$= \frac{2\,\alpha}{\pi}\frac{k}{M_\chi^2}\int d\Omega_k \left|\epsilon(\hat{k},\sigma)\cdot\int d^3r\,\left(\psi^*_{f,C}(\mathbf{r})\nabla_{\mathbf{r}}\,\psi_{i,C}(\mathbf{r}) + \frac{\alpha_W\,M_\chi\,e^{-m_W\,r}}{\sqrt{2}}\,\psi^*_{f,C}(\mathbf{r})\,\hat{\mathbf{r}}\,\psi_{i,N}(\mathbf{r})\right)\right|^2$$

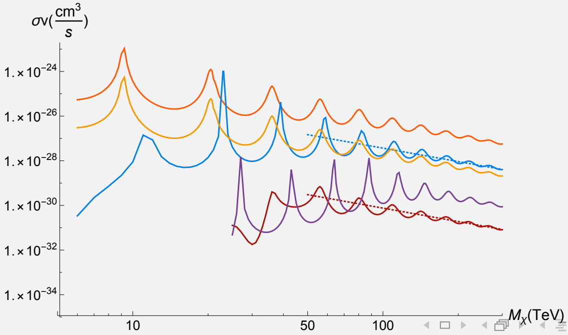
Capture Into Bound State

$$\chi^0\ \chi^0 \to W^{\pm}W^{\mp}, \gamma Z, \gamma\gamma, \qquad \chi^0\ \chi^0 \to \gamma\gamma \tag{1}$$

$$\chi^0\ \chi^0(\mathrm{p-wave}) \to 1S\ \gamma \tag{2}$$

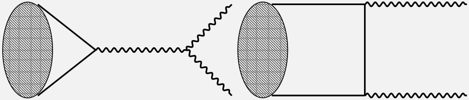
$$\chi^0\ \chi^0(\mathrm{d-wave}) \to 2P\ \gamma \tag{3}$$

$$\chi^0\ \chi^0(\mathrm{s-wave}) \to 2P\ \gamma \tag{4}$$



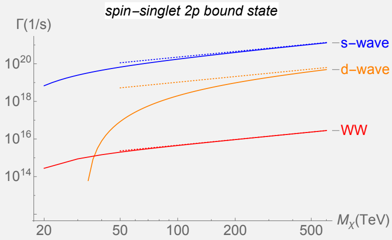
Decay Channels

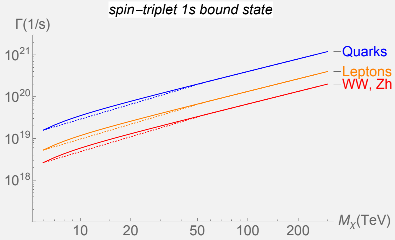
- Captured bound state can decay to lower bound states as well as SM particles.
- Decay Topologies



Decay Rates

- Decay rates : No particularly enhanced rate to photons. Low chances of detection.





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- Eventual decay to photons will be suppressed as well.
- Could the monochromatic photon from capture process be a smoking gun?
- For a benchmark DM mass of 10TeV, we will receive $\sim 10^{-3}$ photon/(yr$*m^2$) with energy 1GeV.

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- a suppression factor due to the potential eigenvalues : $e^{-4n\lambda_i/\lambda_f}$.
- In wino model $\lambda_i/\lambda_f = 2$. Other representations have a better ratios.
- Stronger attractive potential for captured state means less suppression.
- For generic group representation, or other groups and mediator masses the capture rate can easily dominate direct annihilation. [1702.01141]

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- For our wino model, capture into bound states does not affect the annihilation rate calculation significantly; mainly due to the group theory argument and the form of the potential. This can change for different gauge group and representations in minimal extensions of SM
- Other minimal models can have more relevant contribution from processes involving bound state.

Back-up Slides

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Sommerfeld Enhancement

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$$\epsilon_v = \frac{v}{\alpha}$$

- ϵ_v measures how relativistic the particle is, considering the interaction strength.
- For a relevant effect, both these should be smaller than 1.
- DM is non-relativistic today. Hence, such non-relativistic effects can be quite important.

The bound state Spectrum in The Symmetric Limit

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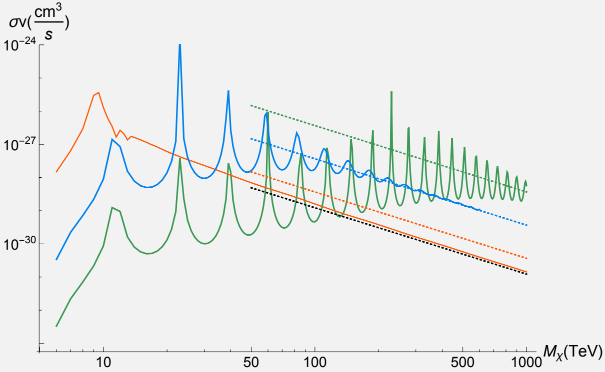
	Spin-Singlet Spectrum	Spin-Triplet Spectrum
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{144}$		6D
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{100}$	5P	5D
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{64}$	4P	4S 4D
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{36}$	3P 6D	3S 3D
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{25}$	5D	5P
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{16}$	4S 2P 4D	2S 4P
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{9}$	3S 3D	3P
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = \frac{1}{4}$	2S	1S 2P
$\left\lvert\frac{E_n}{M_\chi \alpha_W^2}\right\rvert = 1$	1S	

Capture Into Bound State

- Capture from $\chi^0\ \chi^0$ (p-wave) to deepest bound state.
- $v = 10^{-2}$, $v = 10^{-3}$, $v = 10^{-4}$



- Small mass : small velocity has lower rate (p-wave). High mass : small velocity has higher rate (coloumbic prediction).

Capture Into Bound State

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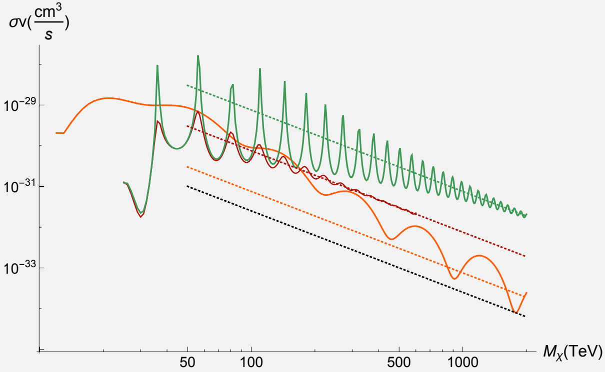

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Numerical Method I

[1411.6924]

$$\Psi(\mathbf{r})_a = \sum_L \frac{[u_L(r)]_a}{r} A_{L\,a} P_L(\cos\theta).$$

$$f_a(x) = \sqrt{\frac{\pi x}{2}} J_{L+\frac{1}{2}}(\hat{k}_a x)$$

$$g_a(x) = -\sqrt{\frac{\pi x}{2}} \left[Y_{L+\frac{1}{2}}(\hat{k}_a x) - i\,J_{L+\frac{1}{2}}(\hat{k}_a x)\right]$$

$$[u_L(x)]_a = f_a(x)\,\alpha_a(x) - g_a(x)\,\beta_a(x)$$

$$N'_{ab} = \delta_{ab} + \left(\frac{g'_a}{g_a} + \frac{g'_n}{g_b}\right) N_{ab} - N_{ac}\frac{\hat{V}_{cd}}{E}N_{db}$$

$$\tilde{\alpha}' = \left(-\frac{g'_a}{g_a}\delta_{ab} + \frac{\hat{V}_{ac}}{E}N_{cb}\right)\tilde{\alpha}_b.$$

$$\tilde{\alpha}_1(x_f) = 1,$$
$$\tilde{\alpha}_2(x_f) = 0.$$

Numerical Method II

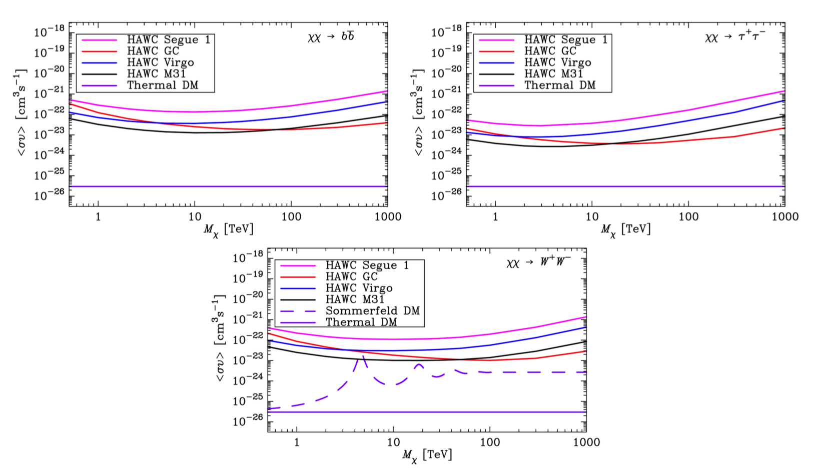
- $z \equiv m_\chi \alpha_W r$; rewrite the Schrodinger equation for each $L+S$ combination.

$$\begin{pmatrix} -\partial_z^2 + \frac{L(L+1)}{z^2} & -\sqrt{2}\frac{e^{-\epsilon_\phi z}}{z} \\ -\sqrt{2}\frac{e^{-\epsilon_\phi z}}{z} & -\partial_z^2 + \epsilon_\delta^2 + \frac{L(L+1)}{z^2} - \frac{c_W^2 e^{-\frac{\epsilon_\phi}{c_W} z}}{z} - \frac{s_W^2}{z} \end{pmatrix} \begin{pmatrix} u_N(z) \\ u_C(z) \end{pmatrix} = \epsilon_v^2 \begin{pmatrix} u_N(z) \\ u_C(z) \end{pmatrix}$$

- Use a basis of functions solving a Schrodinger equation with the proper Coulomb potential.
- A basis of $N = 15$ Coulomb wavefunction is used for neutral/charged part.

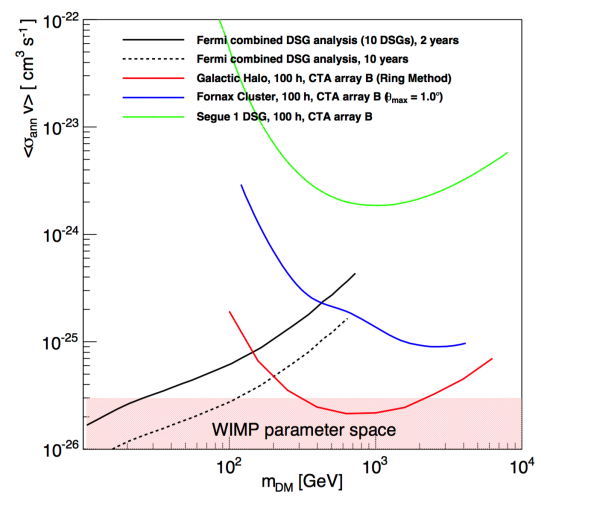
Bounds from HAWC

[1508.04352]



Bounds from CTA

[1208.5356]



Photon Production from a Quintuplet Model

[1702.01141]