Smoking-Gun Signatures for Indirect Detection from Bound State Formation of Electroweak Multiplets

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Electroweak Multiplets as Dark Matter

- Minimal Dark Matter (MDM): first proposed in 2005
  [M. Cirelli, N. Fornengo, A. Strumia, 2005, arXiv:hep-ph/0512090]

- Consider a generic Electroweak (EW) multiplet:

$$\chi \equiv \mathbf{1}_C, \begin{pmatrix} \chi_1 \\ \chi_2 \\ \dots \\ \chi_n \end{pmatrix} \Bigg\} SU(2)_{EW} \text{ and } Y$$

  The neutral component χ_0 is the Dark Matter (DM) candidate

- Consider real representations with $Y = 0$ and odd n

- DM mass fixed by requiring correct relic abundance $\rightarrow$ no free parameters in the theory: **FULLY PREDICTIVE**

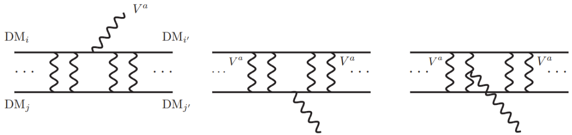
  $\rightarrow$ For the fermion 5-plet, $M_\chi = 13.6$ TeV

Non-Perturbative Effects and Phenomenology

- Sommerfeld Enhancement: In the non-relativistic limit, a long-range (attractive) potential between two DM particles distorts the two-body wavefunction, enhancing the annihilation cross section

$$\langle \sigma v \rangle \xrightarrow{\text{SE}} R \times \langle \sigma v \rangle, \qquad R = \left| \frac{\psi(\infty)}{\psi(0)} \right|^2$$

- The exchange of long range forces can lead to the Formation of Bound States through the emission of a gauge boson: $\chi_i \, \chi_j \to BS \; V$

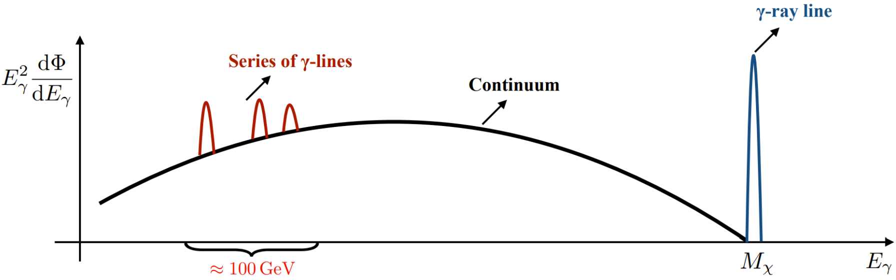


see e.g. 1702.01141

$\to$ Get an additional photon line with $E_\gamma \sim 100$ GeV

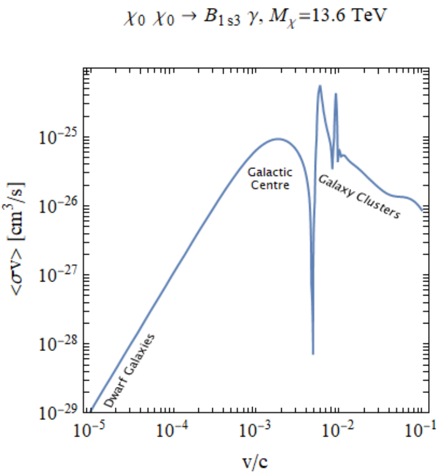
Bound States Formation

- Can get multiple lines for bound states with different binding energies



- Multiple line search can be extremely promising to discover/rule-out the candidate! But where to look?

Bound States Formation



- Larger relative velocity gives a more distinct signature $\rightarrow$ galaxy clusters

Summary & Outlook

- Electroweak Multiplets as WIMP candidates have no free parameters: extremely predictive!
- Phenomenology affected by non-perturbative effects: Sommerfeld Enhancement and the formation of Bound States
- Bound States give rise to distinctive features in the photon spectrum: smoking-gun signatures
- Consider available data e.g. Fermi-LAT to perform a correlated statistical analysis

Thank you for listening!

Backup Slides

Electroweak Multiplets as Dark Matter

$$\boxed{\mathcal{L}_f = \frac{1}{2}\bar{\chi}(i\not{D} - M_\chi)\chi, \quad \chi = \chi^c} \qquad \text{(fermion)}$$

$$\mathcal{L}_s = \frac{1}{2}(D_\mu\chi)^2 - \frac{1}{2}M_\chi^2\chi^2 - \frac{\lambda_H}{2}\chi^2\,|H|^2 - \frac{\lambda_\chi}{4}\chi^4 \qquad \text{(scalar)}$$

$$D_\mu = \partial_\mu + ig_2 W_\mu^a T^a$$

- The DM mass is fixed by requiring that the WIMP make up the whole DM content of the Universe $\rightarrow$ TeV scale DM
- DM stability is obtained accidentally: no renormalisable operators break $\mathcal{Z}_2$ symmetry

DM Stability

- In an Effective Field Theory (EFT), can have operators of arbitrarily high dimensions suppressed by powers of a cut-off energy, Λ_{UV}

- For n=3, have fast DM decay at the renormalisable level

$$\mathcal{L} \supset \lambda_3 \chi H L$$

- For $n > 3$, have an accidental $\mathcal{Z}_2$ symmetry explicitly broken by operators with $d \geq 5$

$$\mathcal{L}_{EFT} \supset \frac{C_1}{\Lambda_{\mathrm{UV}}^{n-3}} (\chi H L)(H^\dagger H)^{\frac{n-3}{2}} + ... + \frac{C_{3\chi}}{\Lambda_{\mathrm{UV}}^3} \chi^3 H L$$

A sufficiently large Λ_{UV} makes sure these operators are sufficiently suppressed $\rightarrow$ DM is stable

DM Tests

- These non-perturbative effects are very important both for the computation of the DM mass...

DM spin	EW n-plet	M_χ (TeV)	$(\sigma v)^{J=0}_{\rm tot}/(\sigma v)^{J=0}_{\rm max}$	$\Lambda_{\rm Landau}/M_{\rm DM}$	$\Lambda_{\rm UV}/M_{\rm DM}$
Real scalar	3	2.53 ± 0.01	–	2.4×10^{37}	$4 \times 10^{24}*$
	5	15.4 ± 0.7	0.002	7×10^{36}	3×10^{24}
	7	54.2 ± 3.1	0.022	7.8×10^{16}	2×10^{24}
	9	117.8 ± 15.4	0.088	3×10^{4}	2×10^{24}
	11	199 ± 42	0.25	62	1×10^{24}
	13	338 ± 102	0.6	7.2	2×10^{24}
Majorana fermion	3	2.86 ± 0.01	–	2.4×10^{37}	$2 \times 10^{12}*$
	5	13.6 ± 0.8	0.003	5.5×10^{17}	3×10^{12}
	7	48.8 ± 3.3	0.019	1.2×10^{4}	1×10^{8}
	9	113 ± 15	0.07	41	1×10^{8}
	11	202 ± 43	0.2	6	1×10^{8}
	13	324.6 ± 94	0.5	2.6	1×10^{8}

- ...and for the observational tests:
  $\rightarrow$ Collider Searches out of reach
  $\rightarrow$ Direct Detection only at loop-level: $\sigma_{\rm DD} \lesssim 10^{-45}{\rm cm}^2$
  $\rightarrow$ Turn to Indirect Detection

Indirect Detection

- Procedure:
  1) Calculate DM annihilation cross section
  2) Calculate flux of stable SM particles: photons and neutrinos
  3) Compare with the observed flux

- For each DM annihilation channel, the final state (primary channel) can then decay into other SM particles (secondary channel)

$$\frac{d\Phi_\gamma}{d\Omega\ dE} = \underbrace{\frac{1}{2}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{M_\chi}\right)^2 \int_{\text{l.o.s.}} \frac{ds}{r_\odot}\left(\frac{\rho_{\text{DM}}(s)}{\rho_\odot}\right)^2}_{\text{Astrophysics}} \underbrace{\sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE}}_{\text{Particle Physics}}$$

Expected Photon Flux