Minimal Dark Matter

Quick review, constraints, generalisations

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Main literature for this talk

[1] M. Cirelli, N. Fornengo and A. Strumia, *Minimal dark matter*, Nucl. Phys. B **753** (2006) 178, `hep-ph/0512090`

[2] M. Cirelli, A. Strumia and M. Tamburini, *Cosmology and Astrophysics of Minimal Dark Matter*, Nucl. Phys. B **787** (2007) 152, `0706.4071`

[3] M. Cirelli, T. Hambye, P. Panci, F. Sala and M. Taoso, *Gamma ray tests of Minimal Dark Matter*, JCAP **1510** (2015) no.10, 026, `1507.05519`

[4] E. Del Nobile, M. Nardecchia and P. Panci, *Millicharge or Decay: A Critical Take on Minimal Dark Matter*, JCAP **1604** (2016) no.04, 048, `1512.05353`

[5] A. Mitridate, M. Redi, J. Smirnov and A. Strumia, *Cosmological Implications of Dark Matter Bound States*, JCAP **1705** (2017) no.05, 006, `1702.01141`

[6] E. Del Nobile, talk at *Origin of Mass 2017*

Motivation and set-up

- Stability through *accidental* symmetries, not global ad-hoc symmetries (R-symmetry in SUSY, Kaluza-Klein parity, ...).
- *Minimal* set of assumptions:
  1. add just DM multiplet $\mathcal{X}$, no extra gauge symmetries;
  2. choose quantum numbers that automatically ensure absolute stability, with cut-off M_P;
  3. $SU(3)_C$ neutral, strong constraints on dark baryons (colliders, Earth heat flow, ...);
  4. tree level vector current of DM candidate with Z vanishes: $\rightsquigarrow Y(\mathcal{X}) = 0$;
  5. electric charge $Q(\mathcal{X}) = 0$.
- Mass M of $\mathcal{X}$ is the only free parameter, fixed by relic abundance.

  (For scalar DM, there could be extra potential terms, $V(H, \mathcal{X})$: assume them to be small)

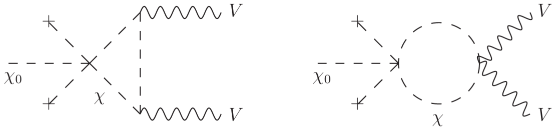
Candidates

Quantum numbers			DM can decay into	DD bound?	Stable?
$\mathrm{SU}(2)_\mathrm{L}$	$\mathrm{U}(1)_Y$	Spin			
2	1/2	S	EL	$\times$	$\times$
2	1/2	F	EH	$\times$	$\times$
3	0	S	HH^*	$\surd$	$\times$
3	0	F	LH	$\surd$	$\times$
3	1	S	HH, LL	$\times$	$\times$
3	1	F	LH	$\times$	$\times$
4	1/2	S	HHH^*	$\times$	$\times$
4	1/2	F	(LHH^*)	$\times$	$\times$
4	3/2	S	HHH	$\times$	$\times$
4	3/2	F	(LHH)	$\times$	$\times$
5	0	S	(HHH^*H^*)	$\surd$	$\times$
5	0	F	$-$	$\surd$	$\surd$
5	1	S	$(HH^*H^*H^*)$	$\times$	$\times$
5	1	F	$-$	$\times$	$\surd$
5	2	S	$(H^*H^*H^*H^*)$	$\times$	$\times$
5	2	F	$-$	$\times$	$\surd$
6	1/2, 3/2, 5/2	S	$-$	$\times$	$\surd$
7	0	S	$-$	$\surd$	~~$\surd$~~
8	1/2, 3/2 ...	S	$-$	$\times$	$\surd$

The scalar 7-plet is unstable

- An originally overlooked operator leads to unsuppressed decay.
- For decay DM $\to$ SM, need to break $\mathbb{Z}_2$: need one or three $\mathcal{X}$ fields.
- You can always build a singlet or triplet out of 3 odd $SU(2)_L$ representations.
  Ex.: $\mathbf{3}^3 : \ \square\square \times \square\square \times \square\square = \square\square + \dots$
  $\mathbf{5}^3 : \ \square\square\square\square \times \square\square\square\square \times \square\square\square\square = \cdot + \dots$
- If $\mathcal{X}$ is scalar, you can contract it with HH.

$$\frac{1}{\Lambda}\chi^3 H^2$$



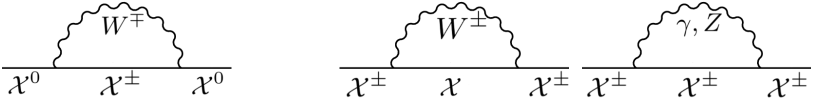
The neutral particle is the lightest

- Canonical kinetic and mass terms:

$$\mathscr{L}_{Y=0} = \mathscr{L}_{\rm SM} + \begin{cases} \frac{1}{2}\overline{\mathcal{X}} i \not{D} \mathcal{X} + \frac{M}{2}\mathcal{X}^{\mathsf{T}} C^{-1} \mathcal{X} & \text{for Majorana } \mathcal{X}, \\ \frac{1}{2}(D^\mu \mathcal{X})^\dagger (D_\mu \mathcal{X}) - \frac{M^2}{2}\mathcal{X}^{\mathsf{T}}\mathcal{X} - V(\mathcal{X}, H) & \text{for real scalar } \mathcal{X} \end{cases}$$

$$\mathscr{L}_{Y\neq 0} = \mathscr{L}_{\rm SM} + \begin{cases} \overline{\mathcal{X}}(i\not{D} - M)\mathcal{X} & \text{for Dirac } \mathcal{X}, \\ (D^\mu \mathcal{X})^\dagger (D_\mu \mathcal{X}) - M^2 \mathcal{X}^\dagger \mathcal{X} - V(\mathcal{X}, H) & \text{for complex scalar } \mathcal{X} \end{cases}$$

- At tree level, no mass splitting (except possible terms $V(H, \mathcal{X})$ for scalar $\mathcal{X}$)
- Loop corrections:



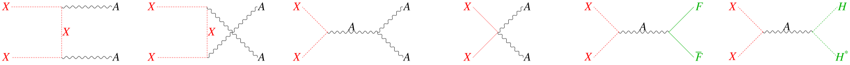
- The result is that, for $Y = 0$, the state with $Q = 0$ is the lightest:

$$M(\mathcal{X}^Q) - M(\mathcal{X}^0) \simeq \alpha_W Q^2 m_W \sin^2\frac{\theta_W}{2} = Q^2 \cdot 166 \text{ MeV}$$

- This small positive splitting makes the neutral candidate stable.

Relic density

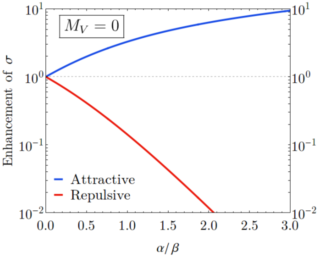
- Freeze-out only possible scenario: at early times $\mathcal{X}$ was in thermal equilibrium with SM.
- At tree level, annihilation channels are

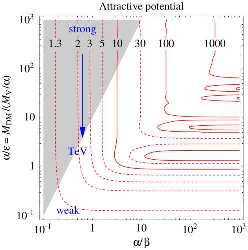


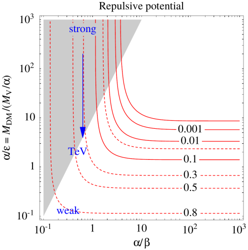
- To get the right relic abundance, $M \sim \mathcal{O}(\text{TeV})$: for the 5-plet, 4.4 TeV.
- *Caveat*: For $T/M \sim 1/25$, velocity at freeze-out is $\beta \sim 1/5$ comparable to $\pi\alpha_W \sim 1/10 \rightsquigarrow$ Sommerfeld enhancement

Relic density: Sommerfeld enhancement

- **Sommerfeld enhancement**: at low DM kinetic energies, long range Coulomb forces are relevant ($M \gg m_W, m_Z$).
- Wavefunction of $\mathcal{X}$ is modified even at long range, is not a plane wave: study with Schrödinger equation. Use the static Yukawa potential, and compute annihilation cross section for all $\mathcal{X}^i, \mathcal{X}^j$.
- "Non-perturbative" effect: it corresponds to resumming many perturbative diagrams.
- Effect: enhance cross section for attractive potentials.

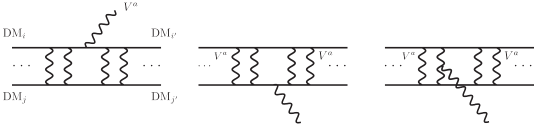


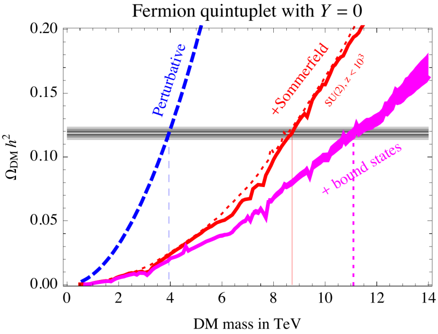




Relic density: formation of bound states

- $\mathcal{X}^i - \mathcal{X}^j$ system can form a **bound state** with the emission of a weak boson if the binding energy plus the initial kinetic energy is $> M_V$. This state will in turn decay, after possible transitions between energy levels.





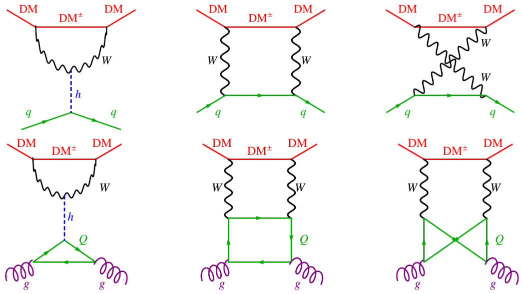
Direct Detection

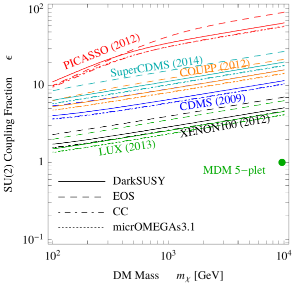
- Avoid strong SI bounds $\Longrightarrow$ Tree level vector current with Z must vanish or be suppressed:

$$\mathcal{L}^Z = \frac{g}{c_W} Z_\mu \left(\overline{\psi}_i \gamma^\mu (g_V^Z - g_A^Z \gamma^5)\psi_i\right) , \quad g_V^Z = \frac{T^3}{2} - s_W^2 Q , \quad g_A^Z = \frac{T^3}{2}$$

For $Q(\mathcal{X}^0) = 0$ (DM candidate), need $T^3(\mathcal{X}^0) = 0$, therefore $\boxed{Y(\mathcal{X}) = 0}$

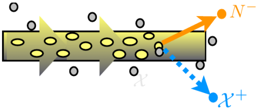
- Loop-induced interactions: [Cirelli, Del Nobile, Panci, 1307.5955]

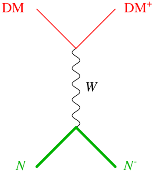


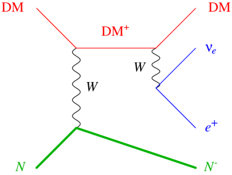


Accumulator ring for charged current interaction

- Producing directly $\mathcal{X}$ requires a collision energy a bit larger than the one at LHC.
- Different possibility: accelerate protons or nuclei to $\Delta M \ll E \ll M$.
- DM $\mathcal{X}^0$ acts as a diffuse target: look for production and decay of $\mathcal{X}^\pm$.



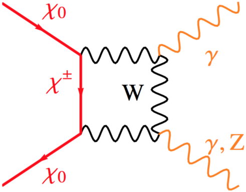




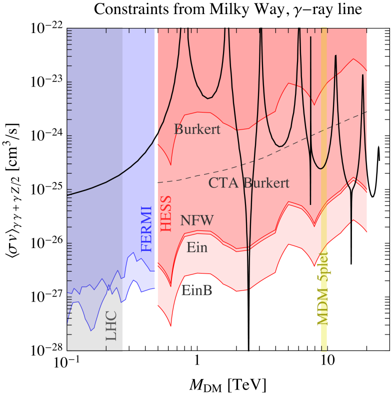
- Problem: difficult to disentangle from beam-related background.
  $\mathcal{X}^\pm$ has a free path $\tau \simeq 44/(n^2-1)$ cm (unfortunately, $\Delta M > m_\pi$ and BR($\mathcal{X}^\pm \to \mathcal{X}^0\pi^\pm) = 98\%$), so the decay tracks are not displaced.

Indirect detection: γ-ray lines

- At 1-loop, $\mathcal{X}^0\mathcal{X}^0 \to \gamma\gamma,\ \gamma Z$ is a signal for γ-ray searches.
- FERMI-LAT satellite, and HESS terrestrial telescope: observations of the Galactic Centre (Milky Way).

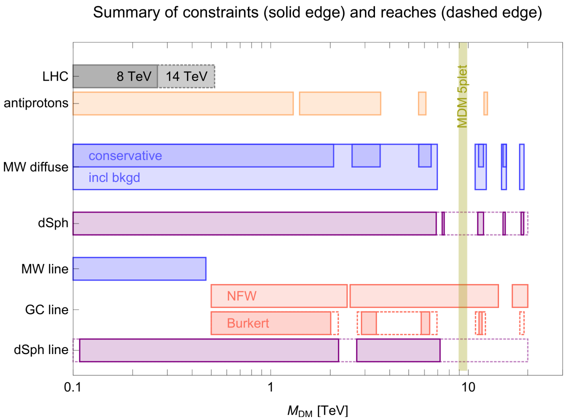


etc.



- Strong bound, but keep in mind the uncertainty on profile. In $0.3^\circ < \theta < 1^\circ$ around GC (HESS), J-factor changes of 2-3 orders of magnitude.

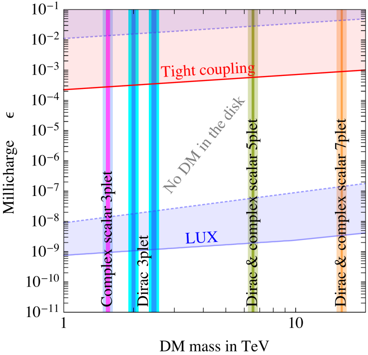
Constraints on 5-plet



- Constraints on the only viable candidate, the fermion 5-plet, are stringent.
- *Were the assumptions truly minimalistic?*

Millicharged MDM

- We made the assumption that electric charge $Q(\mathcal{X}) = 0$.
  Actually it is enough $Y = \varepsilon \neq 0, \varepsilon \ll 1 \Longrightarrow Q = \varepsilon$, for DM to be dark.
- No theoretical problem. Electric charge conservation automatically ensures DM stability.

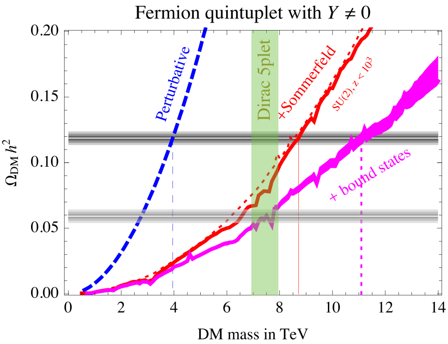


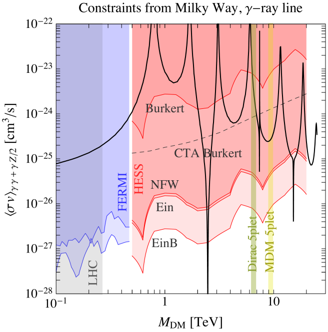
- High ε: tight coupling DM-baryons at recombination.
- Intermediate ε: DM would have been evacuated from Milky Way because of magnetic shielding.
- Below LUX bounds, em interaction is negligible.

- Conclusion: $Q = \varepsilon > 0$ is allowed for very small ε, so that em interactions do not matter and pheno is the same as for $Q = 0$, except that. . .

Millicharged MDM: Majorana → Dirac 5plet

- Having $Y \neq 0$, the DM candidate is complex, not real:
  - Relic abundance for $\mathcal{X}^\varepsilon$ is $\frac{1}{2}$ the one for $\mathcal{X}^0$ (there is also $\mathcal{X}^{-\varepsilon}$) $\Rightarrow$ Lower M
  - Annihilation occurs half of the times: $\mathcal{X}^{+\varepsilon}$ has to meet $\mathcal{X}^{-\varepsilon}$ to annihilate $\Rightarrow$ weaker bounds by factor 2.


Fermion quintuplet with $Y \neq 0$


Constraints from Milky Way, γ−ray line

All bounds to be multiplied by 2

- Consequences of $Q = \varepsilon$:
  - forbids dangerous operators, rescuing some MDM candidates;
  - ensures absolute DM stability with *local* $U(1)_{\rm em}$;
  - wrt to real DM: implies lower M, and weaker ID bounds by factor 2.

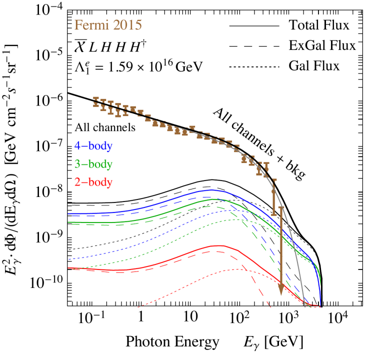
Lowering the cutoff

- Other assumption: choose quantum numbers that automatically ensure absolute stability, with cut-off M_P.
- Can we lower the cut-off?

- 5-plet candidate with a cut-off $\Lambda < M_P$: dim. 6 operator induce decay of DM on cosmological times.

$$\frac{1}{\Lambda^2}\overline{\mathcal{X}}LHHH^\dagger\,, \quad \frac{1}{\Lambda^2}\overline{\mathcal{X}}\sigma_{\mu\nu}LW^{\mu\nu}H\,.$$

- 4-, 3-, 2- body DM decays: fewer-body decays pay a factor v^2/M^2.
- Stronger constraint from γ-ray continuum. Fix M with relic, find lower bound on Λ.



Conclusions

- DM could be charged under the SM gauge group.
- Stability can be ensured by *accidental* symmetry, for some specific quantum numbers.
- Only minimal candidate: neutral component $\mathcal{X}^0$ of a fermion 5-plet with a $M = 11$ TeV.
- γ-ray observations put this model under serious pressure.
- Less minimal assumptions widen the range of possibilities:
  - Millicharged DM: with $Q < 10^{-9}$, absolute stability (other viable candidates, e.g. Dirac 3-plet);
  - Lower cut-off below M_P: possible signatures from DM decays, with handle on new physics scale.