Indirect Detection of the Minimal Dark Matter 5-plet: Present and Future Directions

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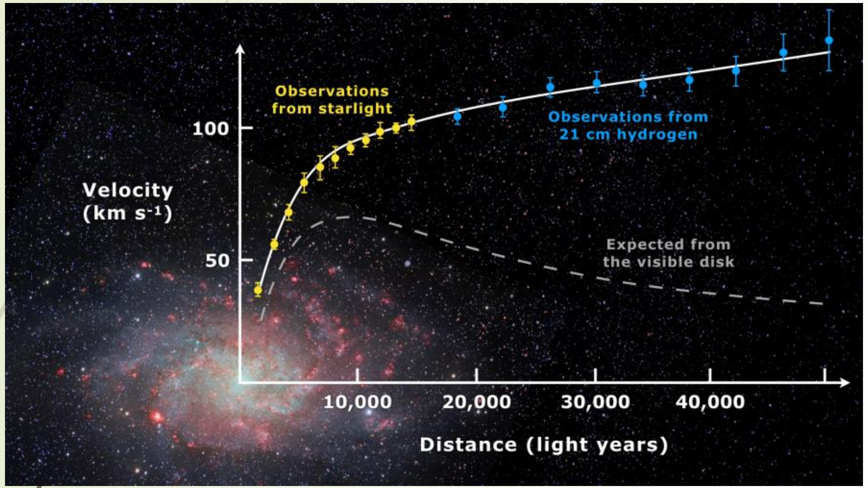
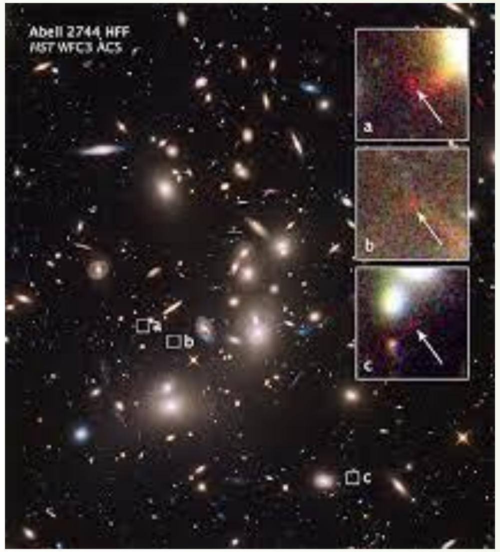
Based on an ongoing project with:

G. Armando, M. Aghaie, S. Bottaro, D. Gaggero, G. Marino & P. Panci

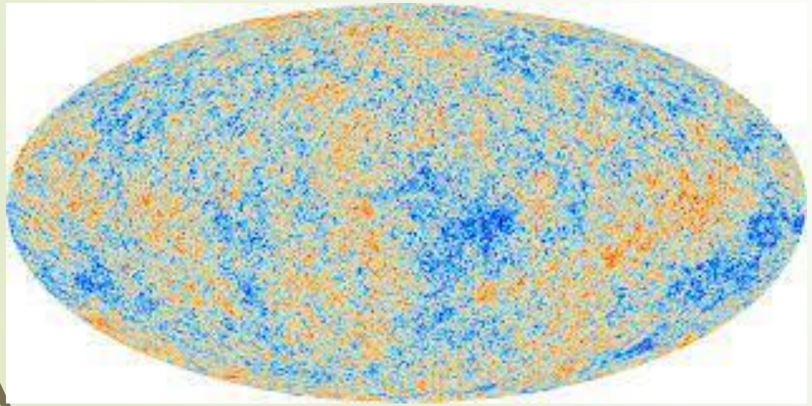
Dark Matter: Motivations at Every Scale

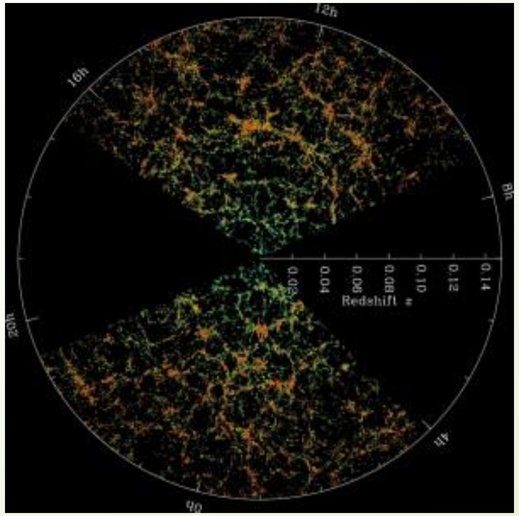


Rotation Curves (~10 kpc)



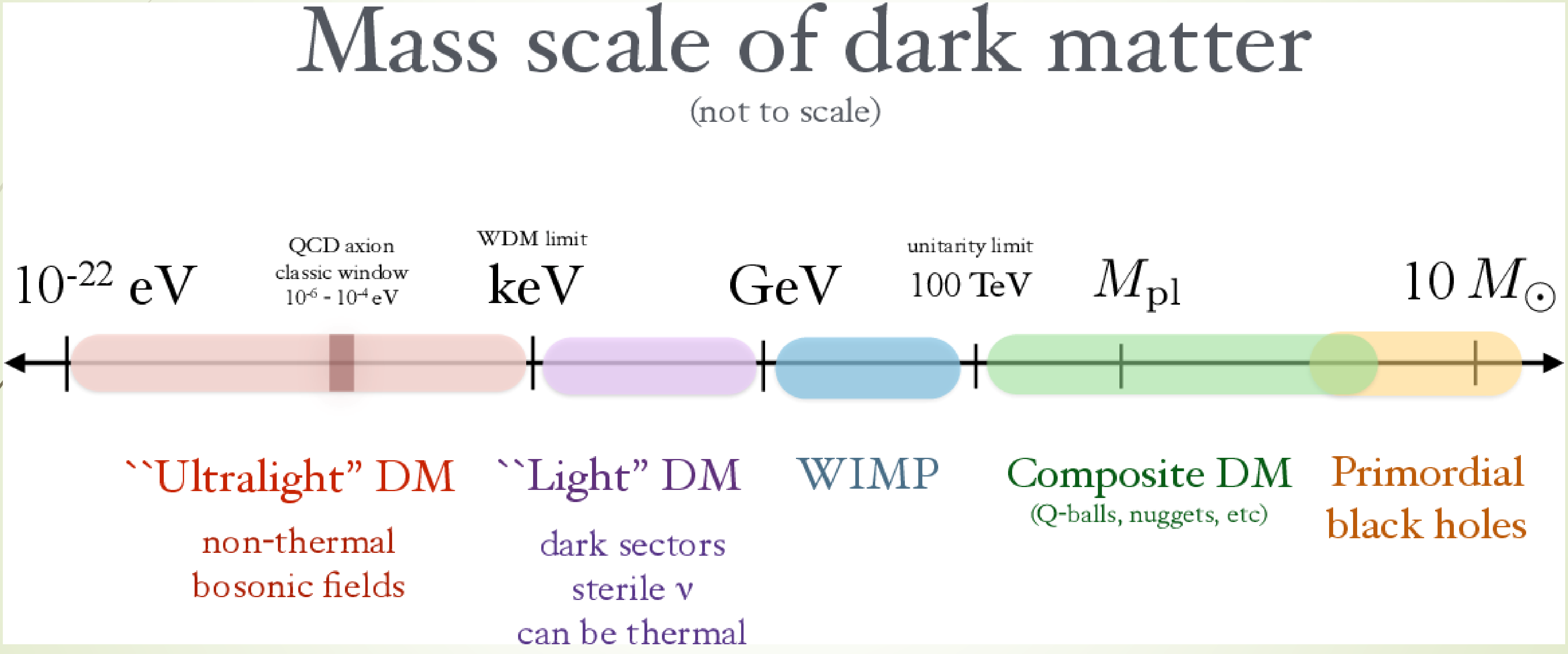
Clusters of Galaxies (~few Mpc)





CMB & Large Scale Structures (~the Universe)

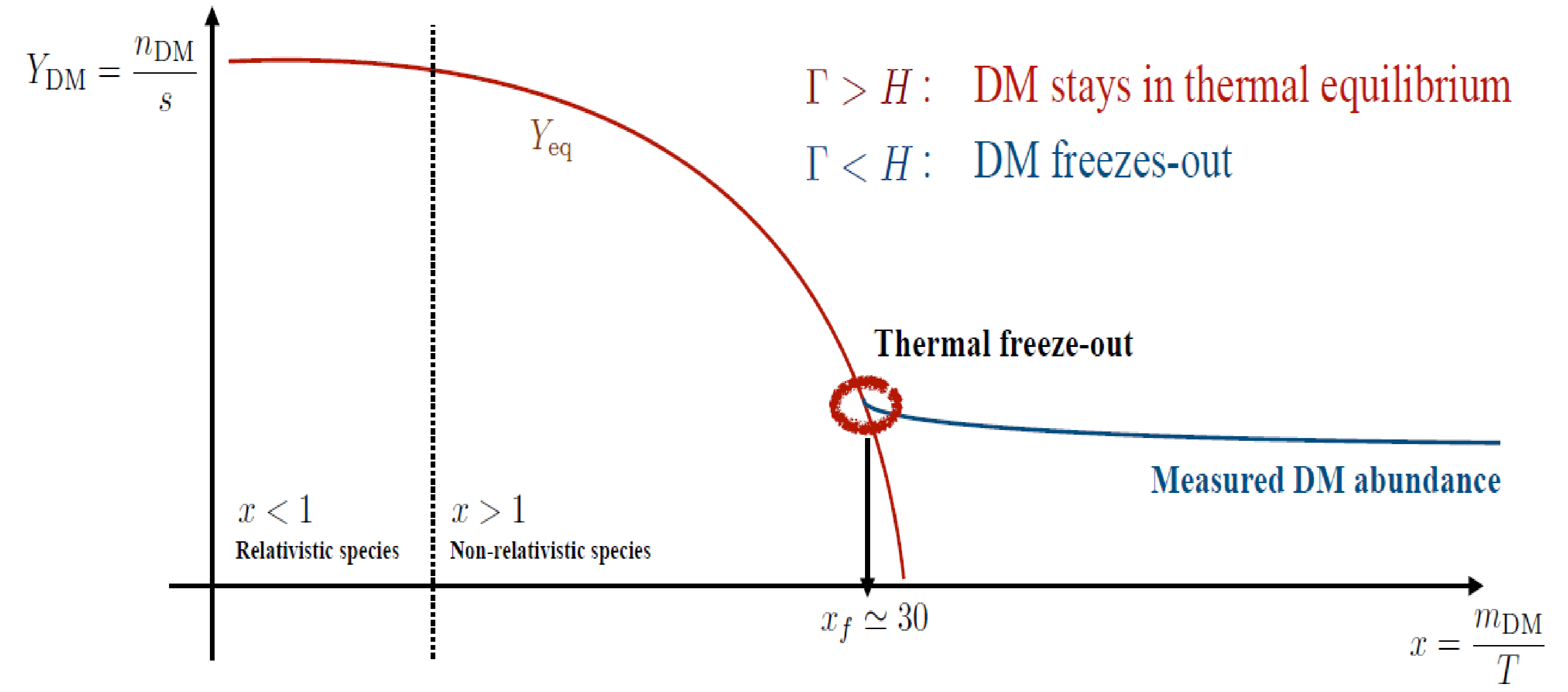
...Uknown Microphysics: Which DM Interactions/Mass? (and Production Mechanism?)



- Stable
- Non-Relativistic
- Weakly Interacting

(Plot from TASI Lectures 2019)

DM as a Thermal Relic: Freeze-Out



$$\frac{\Omega_{DM} h^2}{0.110} = \frac{z_{fo}}{25} \frac{2.18\ 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\sigma_0 + 3\sigma_1/z_{fo}}$$

«WIMP MIRACLE»

Weak-scale coupling + **TeV scale** DM naturally reproduces the thermal xsec!

(+ connection to the naturalness of the EW scale)

The Prototypical WIMP

a.k.a. Minimal Dark Matter (arXiv:hep-ph/0512090)

Minimal Dark Matter

Consider a generic EW multiplet:

$$\chi \equiv \mathbf{1}_c, \begin{pmatrix} \chi_1 \\ \chi_2 \\ \cdots \\ \chi_n \end{pmatrix} \Big\} SU(2)_{EW} \text{ and } Y. \qquad (1)$$

The DM candidate is the neutral component of the n-plet, χ^0.

- DM stability: DM is the lightest component of the multiplet
- Still Allowed: DM cannot have tree-level couplings to the Z boson
  ⇒ strong limits from Direct Detection
- Free parameter: the DM mass. Can be fixed by requiring the correct relic abundance!

A closer look to real WIMPs (odd n and Y=0)

$$\mathscr{L}_s = \frac{1}{2}(D_\mu \chi)^2 - \frac{1}{2}M_\chi^2\chi^2 - \frac{\lambda_H}{2}\chi^2|H|^2 - \frac{\lambda_\chi}{4}\chi^4$$

Real Scalar

$$\mathscr{L}_f = \frac{1}{2}\chi\,(i\bar{\sigma}^\mu D_\mu - M_\chi)\,\chi\,,$$

Majorana Fermion

For $n = 3$ multiplets DM stability is achieved by enforcing a Z2 symmetry

For $n \geq 5$ multiplets DM stability comes from an accidental Z2 symmetry

We focus on the smallest accidentally stable MDM multiplet: the **Majorana 5-plet**

MDM & Thermal Freeze-Out

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = \langle \sigma v_{\rm rel} \rangle (n_{\rm eq}^2 - n_{\rm DM}^2)$$

DM Abundance is fully controlled by the annihilation cross-section

$$\sigma v_{\rm rel} = \frac{g_2^4(2n^4 + 17n^2 - 19)}{256\pi g_\chi M_\chi^2}$$

Tree-level cross-section

True but… Inaccurate!

Important Nonperturbative & Nonrelativistic effects modify the annhilation cross-section

- Sommerfeld Enhancement
- Bound State Formation

SE & BSF

Sommerfeld: Long Range Effects modify the DM wave function

$$\chi^0 \chi^0 \to V\, V$$

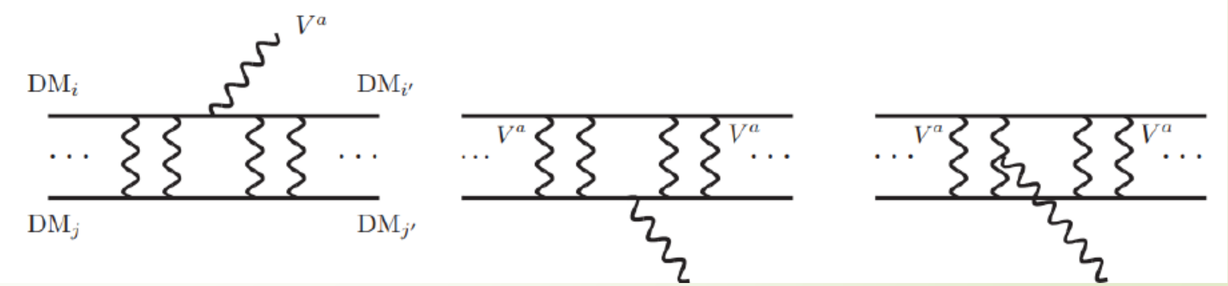
$$S = \left| \frac{u(\infty)}{u(0)} \right|^2 \Rightarrow \langle \sigma v_{rel} \rangle = S \langle \sigma v_{rel} \rangle_0$$

Sommerfeld factor

BSF: DM forms Bound state via the emission of a gauge boson

$$\chi_i\, \chi_j \to BS\, V^a$$

BSs further annihilates in SM particles!



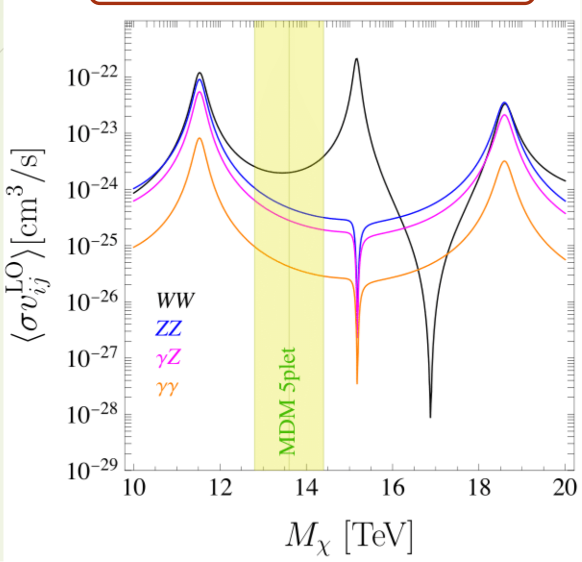
$$S(z) = S_{\mathrm{ann}}(z) + \left[\frac{\sigma_0}{\langle \sigma_I v_{\mathrm{rel}} \rangle} + \frac{g_\chi^2 \sigma_0\, M_\chi^3}{2 g_I\, \Gamma_{\mathrm{ann}}} \left(\frac{1}{4\pi z} \right)^{3/2} e^{-z\, E_{B_I}/M_\chi} \right]^{-1}$$

SE & BSF: Results

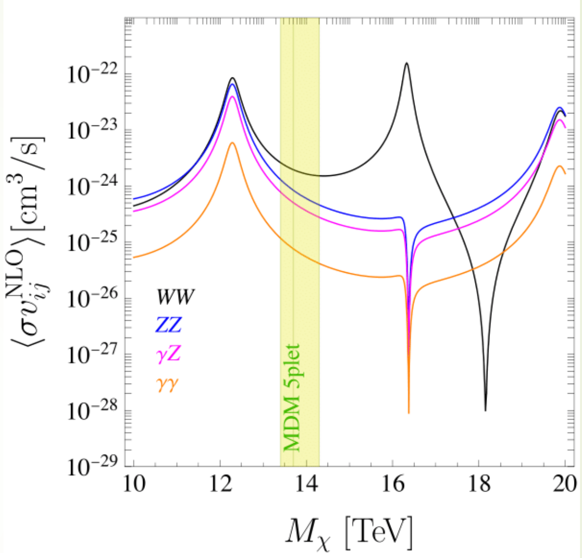
$M_{\rm DM} = 13.6 \pm 0.8$ TeV

$M_{\rm DM} = 13.7^{+0.6}_{-0.3}$ TeV

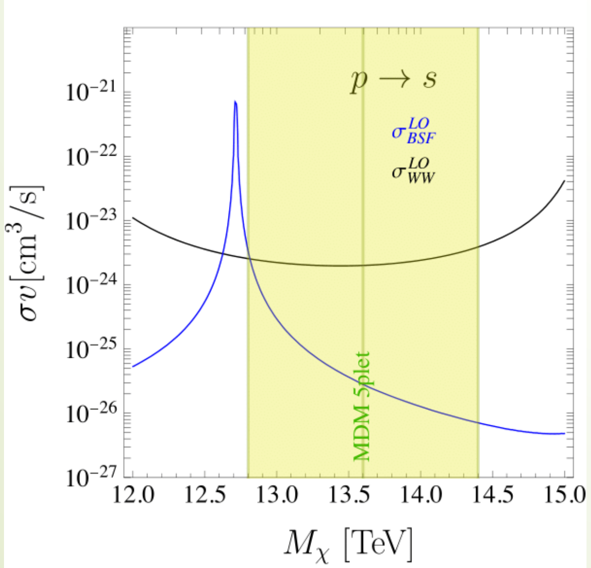
LO



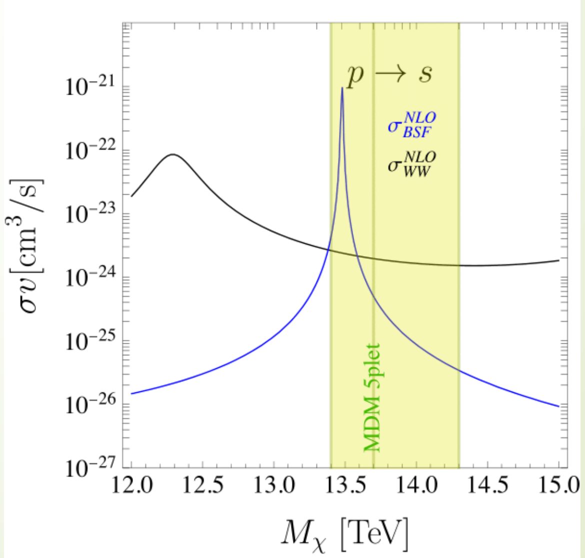
NLO



LO



NLO

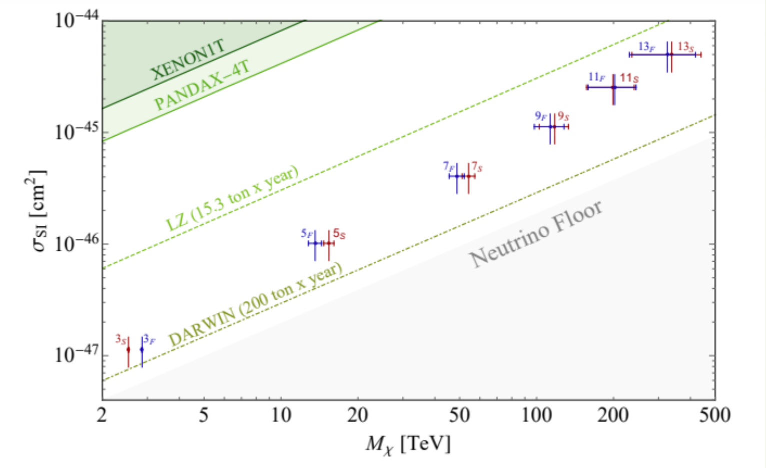


MDM: Detection Strategies

From arXiv:2107.09688

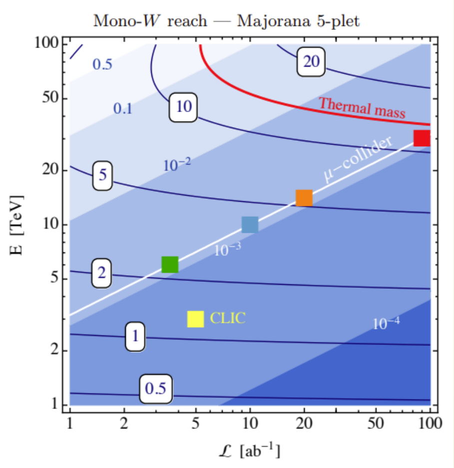
- Direct Detection:

EW multiplets within the reach of next-generation experiments



- Collider Searches:

Will probe small multiplets in the future. A final word from a future μ-Collider?



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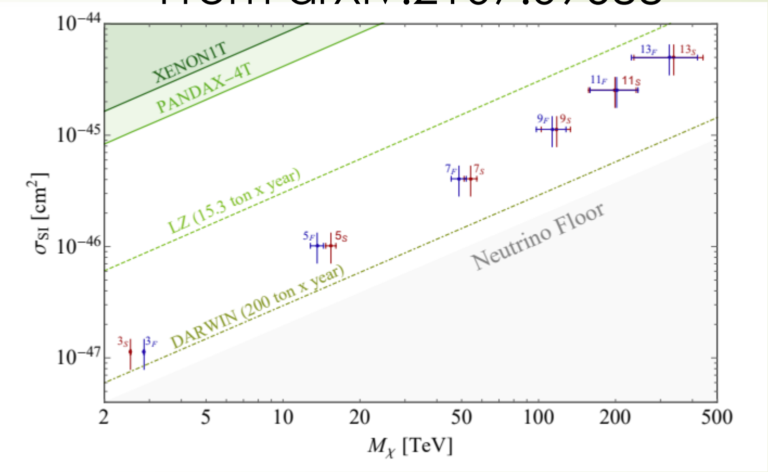

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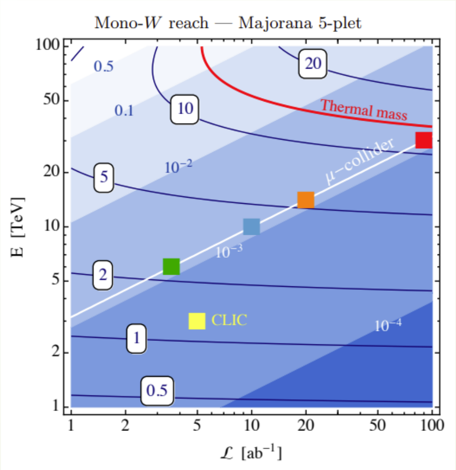


- Indirect Detection:

Can already offer valuable information!

From DM to Cosmic Rays

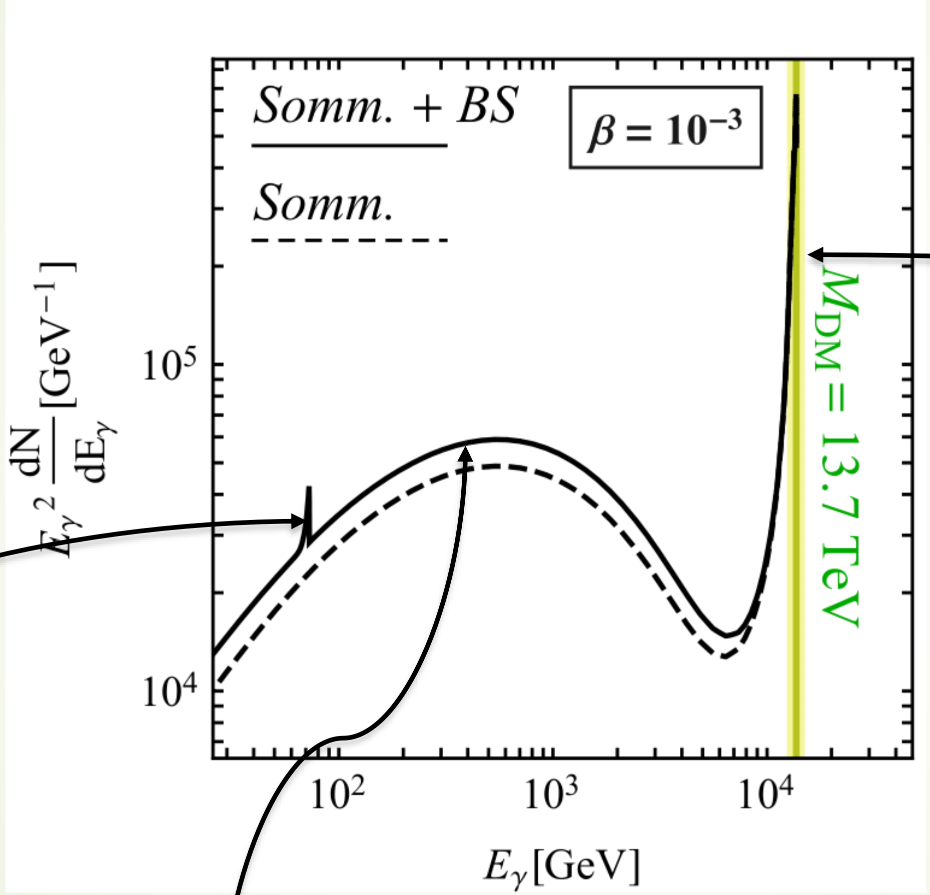
In our case $\alpha = \gamma$

$$\left.\frac{d\Phi}{dE_\alpha}\right|_{ann} = \frac{r_\odot}{2}\left(\frac{\rho_\odot}{M_\chi}\right)^2 \int_{\text{l.o.s}} \frac{ds}{r_\odot}\left(\frac{\rho_{\rm DM}(s)}{\rho_\odot}\right)^2 \left(\sum_f \langle\sigma v\rangle_f \frac{dN^{(f)}}{dE_\alpha}\right)$$

Astrophysics — Particle physics

The annhilation products can shower/decay/hadronize in stable SM particles (photons in our case)

DM Photon Spectrum



Spectral **Line** from Sommerfeld

$\chi^0\chi^0 \to \gamma\gamma$ $\chi^0\chi^0 \to \gamma Z$

Spectral **Line** from Bound State Formation

$\chi_i \chi_j \to BS\ V^a$

Photon **continuum** from Sommerfeld and Bound State Formation

$f\ f$

$\chi_i \chi_j \to BS\ V^a$

$\chi^0\chi^0 \to W^+W^-$

$\chi^0\chi^0 \to ZZ$

$\chi^0\chi^0 \to \gamma Z$

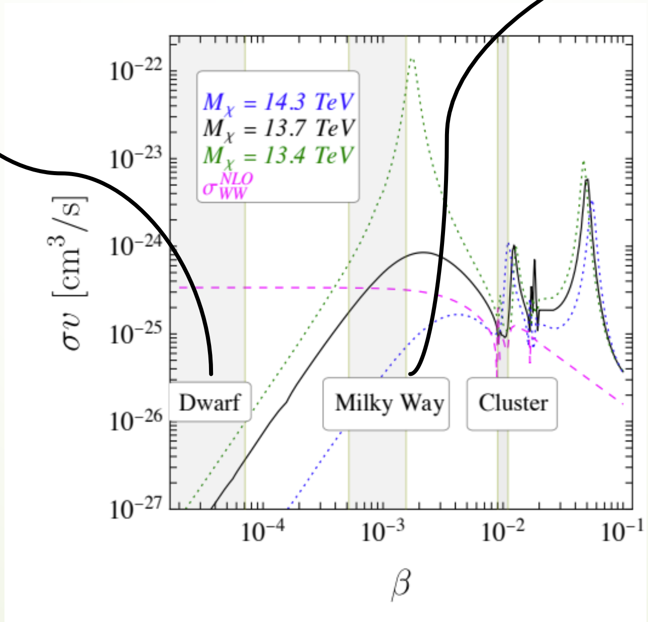
Choice of the Targets

Dwarf Spheroidal Galaxies

- DM dominated targets
- More robust predictions for the DM density profile

But…

- Small Velocity dispersion (suppressed BSF)



Our Galaxy

- Large Velocity dispersion (enhanced BSF)
- Possibly large DM signals

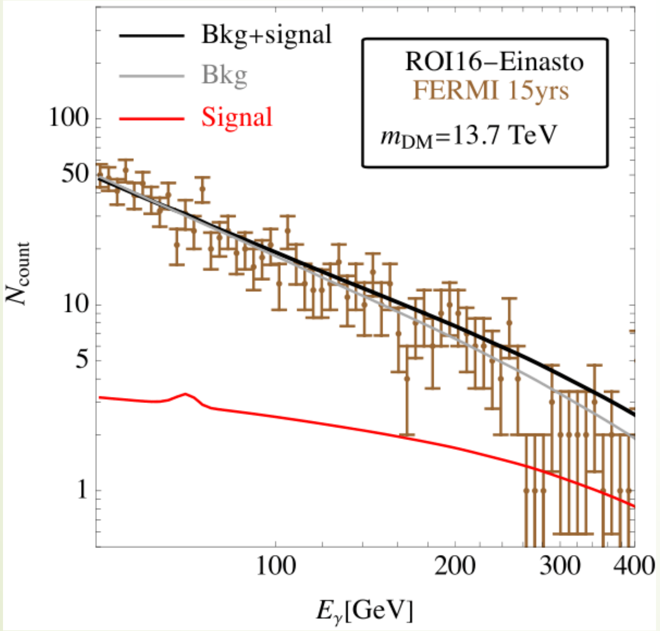
But…

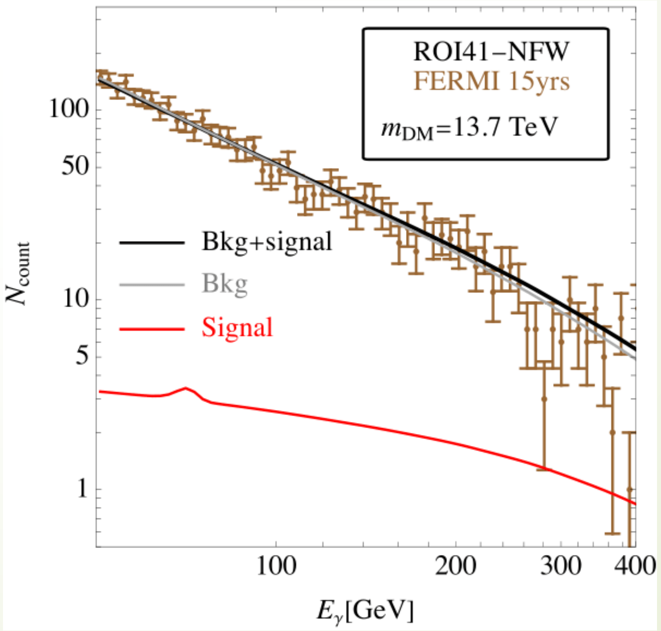
Large Baryonic Density (more foreground, uncertain DM profile)

Current Constraints: spectrum at low-energy (~ hundreds of GeV)

FERMI-LAT measurements of the Galactic Diffuse can set stringent constraints on the 5-plet

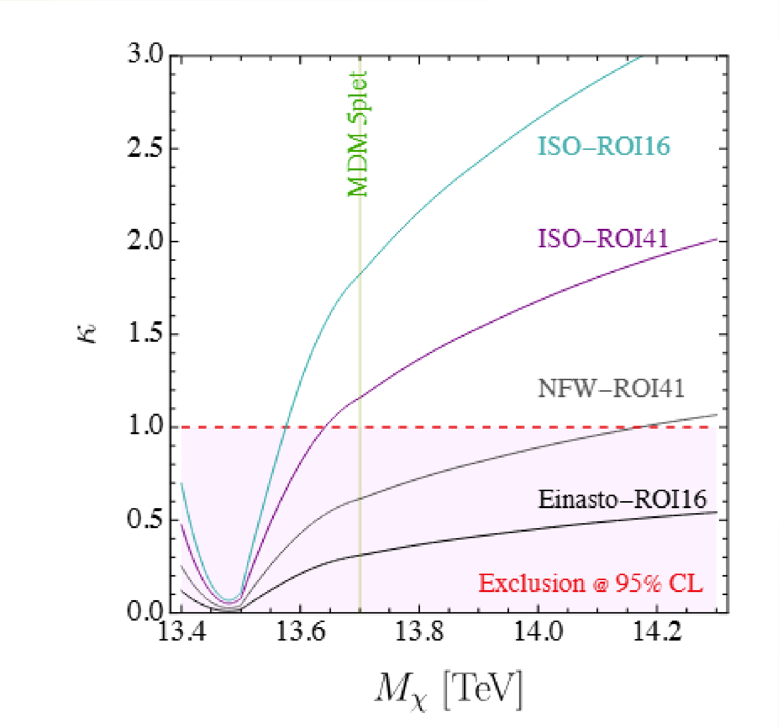
Exploiting the interplay of BSF continuum & SE





Focus on two Regions of Interest (ROIs)

Current Constraints: spectrum at low-energy (~ hundreds of GeV)



$$\mathcal{L}(\kappa, A_{\rm diff}) = \prod_{i=1}^{\mathcal{N}} \frac{(N^i_{\rm th}(\kappa, A_{\rm diff}))^{N^i_{\rm obs}}}{N^i_{\rm obs}!} e^{-N^i_{\rm th}(\kappa, A_{\rm diff})}$$

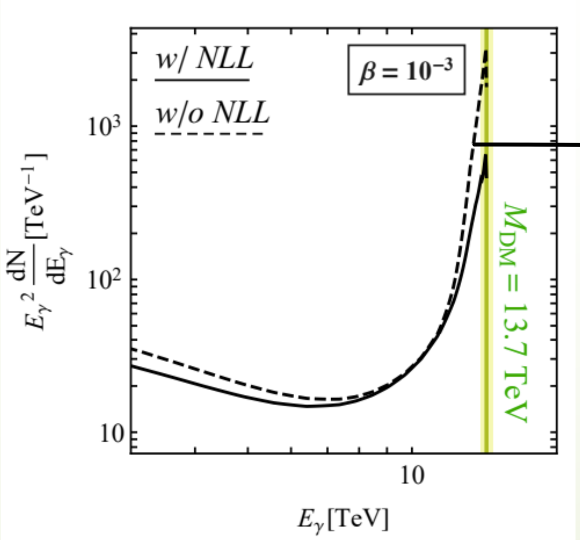
Extract the upper limit on the rescaling parameter

$$\langle \sigma v \rangle \rightarrow \kappa \langle \sigma v \rangle$$

Extreme Changes of the DM profile can still mitigate the exclusion!

Future Constraints: spectrum at high-energy (~ tens of TeV)

The forthcoming Cerenkov Telescope Array (CTA) will explore the multi-TeV range with unprecedented resolution



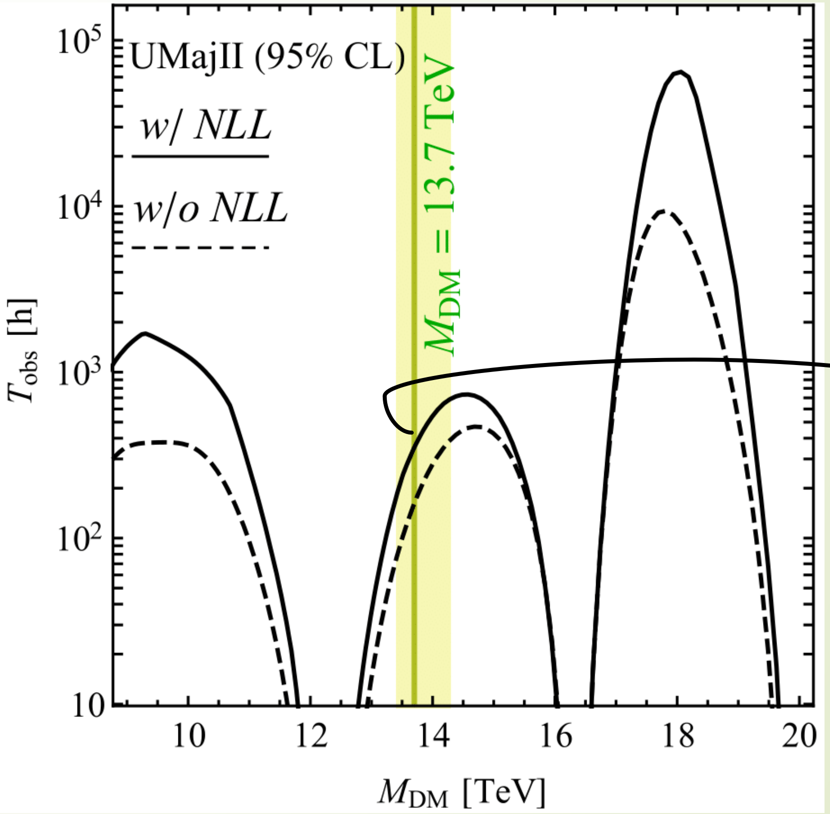
Sensitivity to high-energy spectral features

Future Constraints: spectrum at high-energy (~ tens of TeV)

$$\mathcal{L}_{sys}(\kappa) = \prod_{i=1}^{\mathcal{N}} \max_J \left[\mathcal{L}_i(\kappa) \times \mathcal{L}^J\right],$$

$$\mathcal{L}^J = \frac{1}{\ln(10) J_{\rm obs}} \mathcal{G}(\log_{10} J | \log_{10} J_{\rm obs}, \sigma_{\log_{10} J_j})$$

Extract the upper limit on the observation time (including the systematic error on the J-factor!)



$T_{\rm obs} \simeq 350$ hours

Conclusions

- Dark Matter as a WIMP remains one of the main motivation for new physics at the multi-TeV scale.
- Minimal Dark Matter is the prototype model of WIMP: huge predictivity,few parameters.
- The photon spectrum of the 5-plet shows smoking-gun signatures for the detection.
- Present data on the galactic diffuse can already place stringent constraints on the MDM 5-plet, particularly on the continuum from BSF.
- Future Telescopes such as CTA will be able to probe the model in the next decades by pointing the detectors towards dSphs (Few hours needed!)

A closer look to real WIMPs (odd n and Y=0)

$$\mathscr{L}_{\mathrm{s}} = \frac{1}{2}\left(D_\mu \chi\right)^2 - \frac{1}{2}M_\chi^2\chi^2 - \frac{\lambda_H}{2}\chi^2|H|^2 - \frac{\lambda_\chi}{4}\chi^4$$

Real Scalar

$$\mathscr{L}_{\mathrm{f}} = \frac{1}{2}\chi\left(i\bar{\sigma}^\mu D_\mu - M_\chi\right)\chi\,,$$

Majorana Fermion

For $n = 3$ multiplets DM stability is achieved by enforcing a Z2 symmetry

For $n \geq 5$ multiplets DM stability comes from an accidental Z2 symmetry

But… Higher Dimensional Z2-breaking operators are expected

$$\mathscr{L}_{\mathrm{s}} \supset \frac{C_1^{(s)}}{\Lambda_{\mathrm{UV}}^{n-4}}\chi(H^\dagger H)^{\frac{n-1}{2}} + \frac{C_2^{(s)}}{\Lambda_{\mathrm{UV}}^{n-4}}\chi W_{\mu\nu}W^{\mu\nu}(H^\dagger H)^{\frac{n-5}{2}} + \cdots + \frac{C_w^{(s)}}{\Lambda_{\mathrm{UV}}^{n-4}}\chi(W_{\mu\nu}W^{\mu\nu})^{\frac{n-1}{4}} + \frac{C_{3\chi}^{(s)}}{\Lambda_{\mathrm{UV}}}\chi^3 H^\dagger H,$$

$$\mathscr{L}_{\mathrm{f}} \supset \frac{C_1^{(f)}}{\Lambda_{\mathrm{UV}}^{n-3}}(\chi H L)(H^\dagger H)^{\frac{n-3}{2}} + \frac{C_2^{(f)}}{\Lambda_{\mathrm{UV}}^{n-3}}(\chi\sigma^{\mu\nu}HL)W_{\mu\nu}(H^\dagger H)^{\frac{n-5}{2}} + \cdots + \frac{C_w^{(f)}}{\Lambda_{\mathrm{UV}}^{n-3}}(\chi H L)(W_{\mu\nu}W^{\mu\nu})^{\frac{n-3}{4}} + \frac{C_{3\chi}^{(f)}}{\Lambda_{\mathrm{UV}}^{3}}\chi^3 HL$$

MDM: State of the Art

From arXiv:2107.09688

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}

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Focus on the Fermionic 5-plet: pure accidental stability