Indirect Detection probes for MDM 5plet

Giulio Marino

(Università di Pisa, INFN)

In collaboration with: *Armando, Aghaie, Bottaro, Dondarini, Gaggero and Panci*

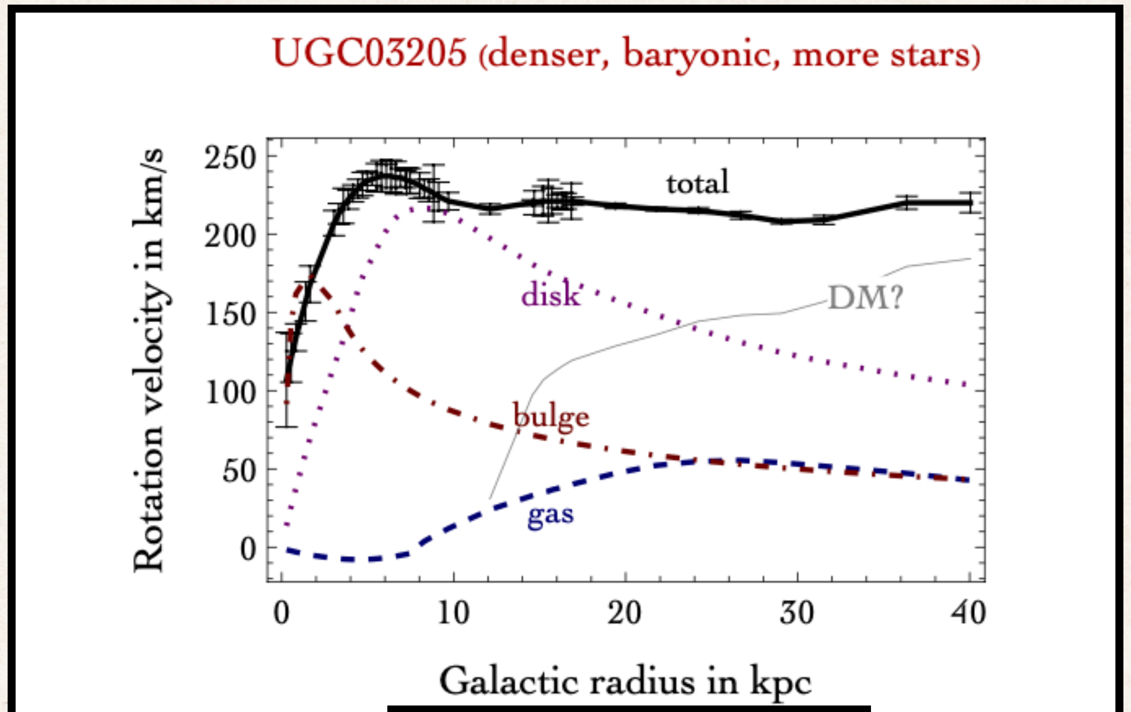
hep-ph/2506.xxxx

INFN PISA
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

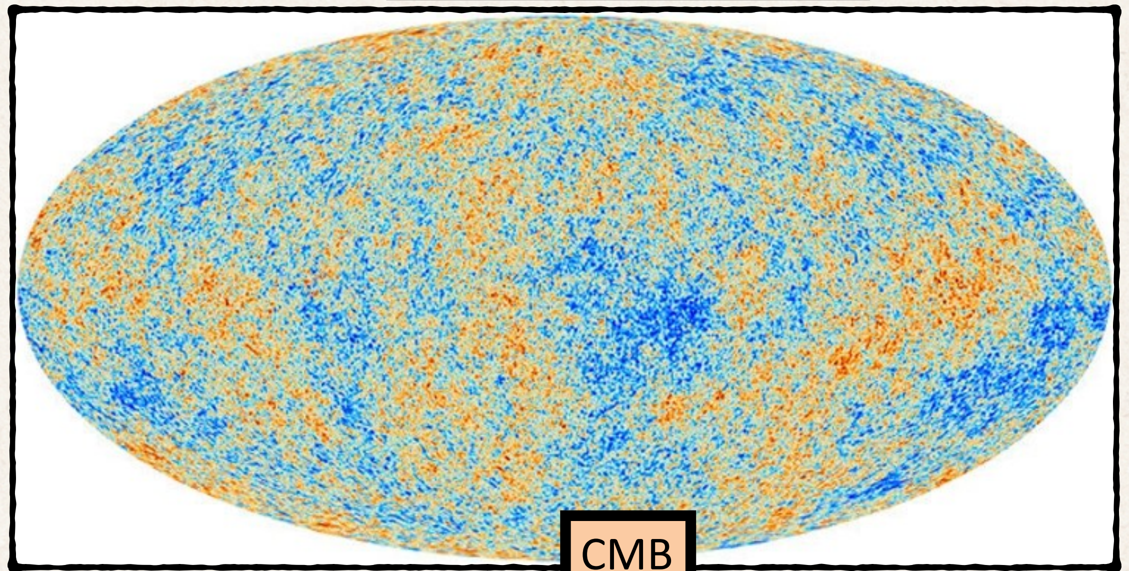
New Frontiers in Theoretical Physics|
Cortona - 2025

IN SUPREMÆ DIGNITATIS 1343
UNIVERSITÀ DI PISA

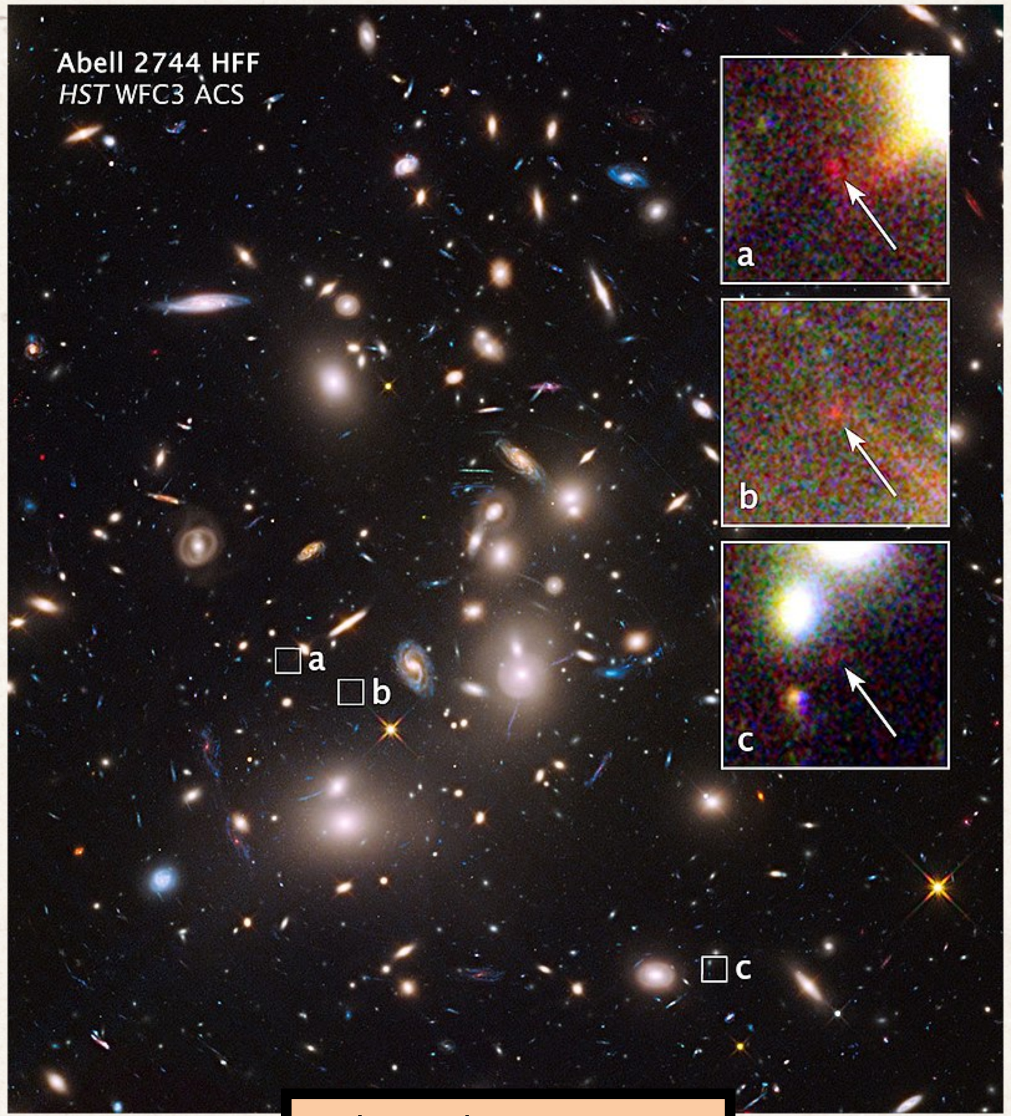
Dark Matter Motivations



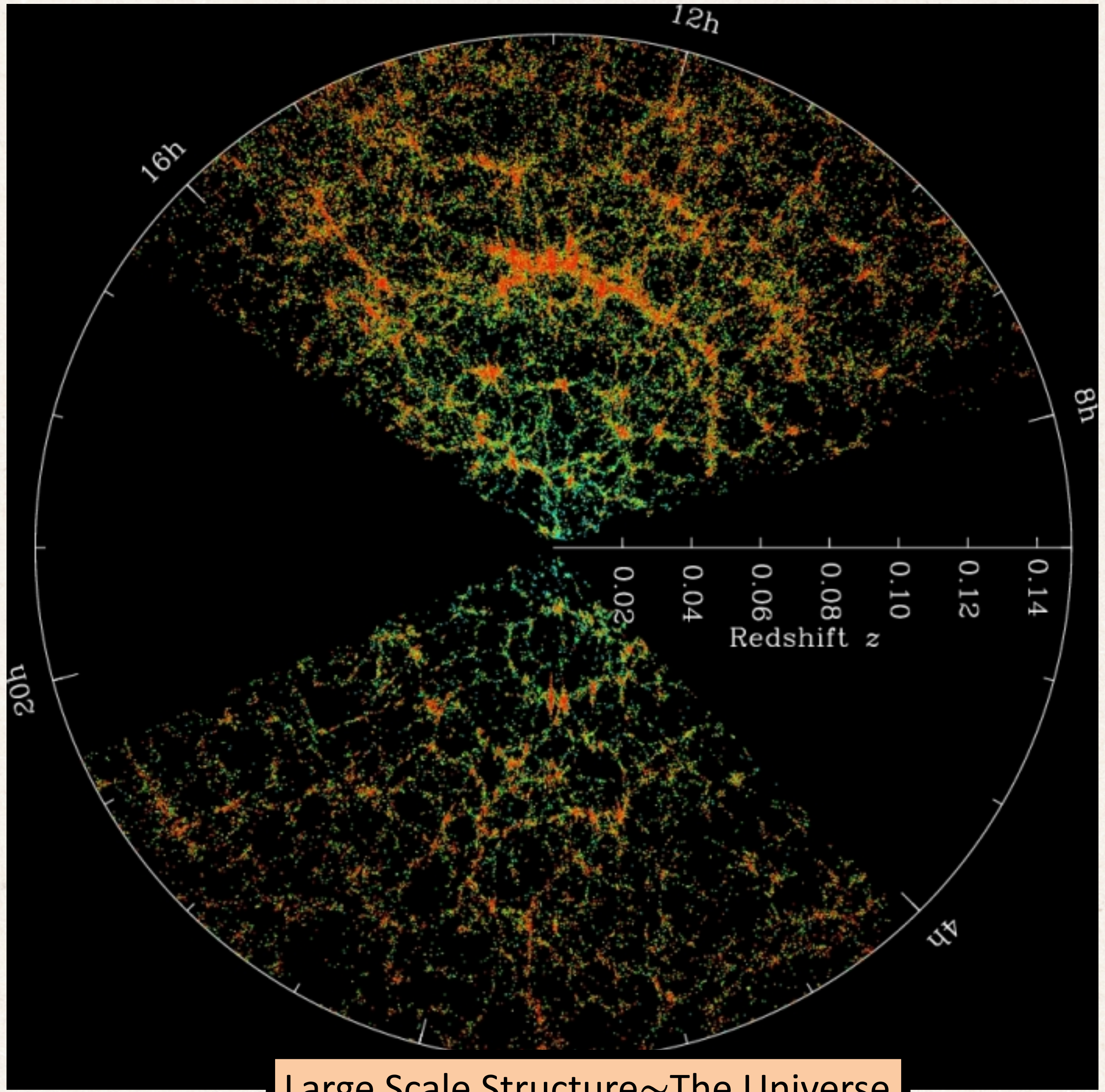
Rotational curves~kpc



CMB



Galaxy clusters~Mpc

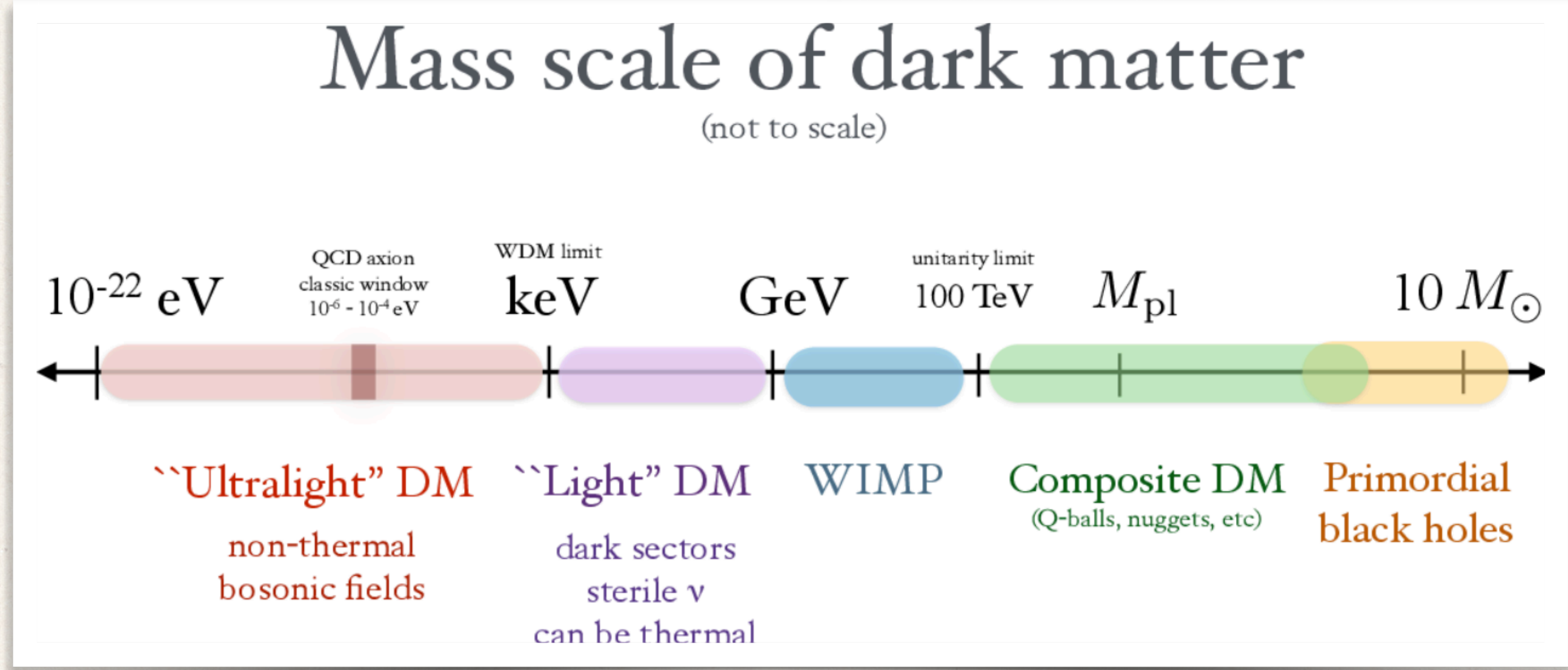


Large Scale Structure~The Universe

[1] LSS Image: Galaxies in the local universe as seen by Sloan Digital Sky Survey

Dark Matter in a nutshell

1. **Unknown microphysics?**
2. **Which DM interactions/ Mass?**
3. **Production Mechanism?**



Stable

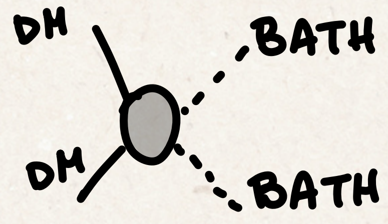
Non relativistic

Weakly Interacting

[1] Image: TASI Lectures on Dark Matter models - 2019

The WIMP Miracle

DM as a Thermal Relic

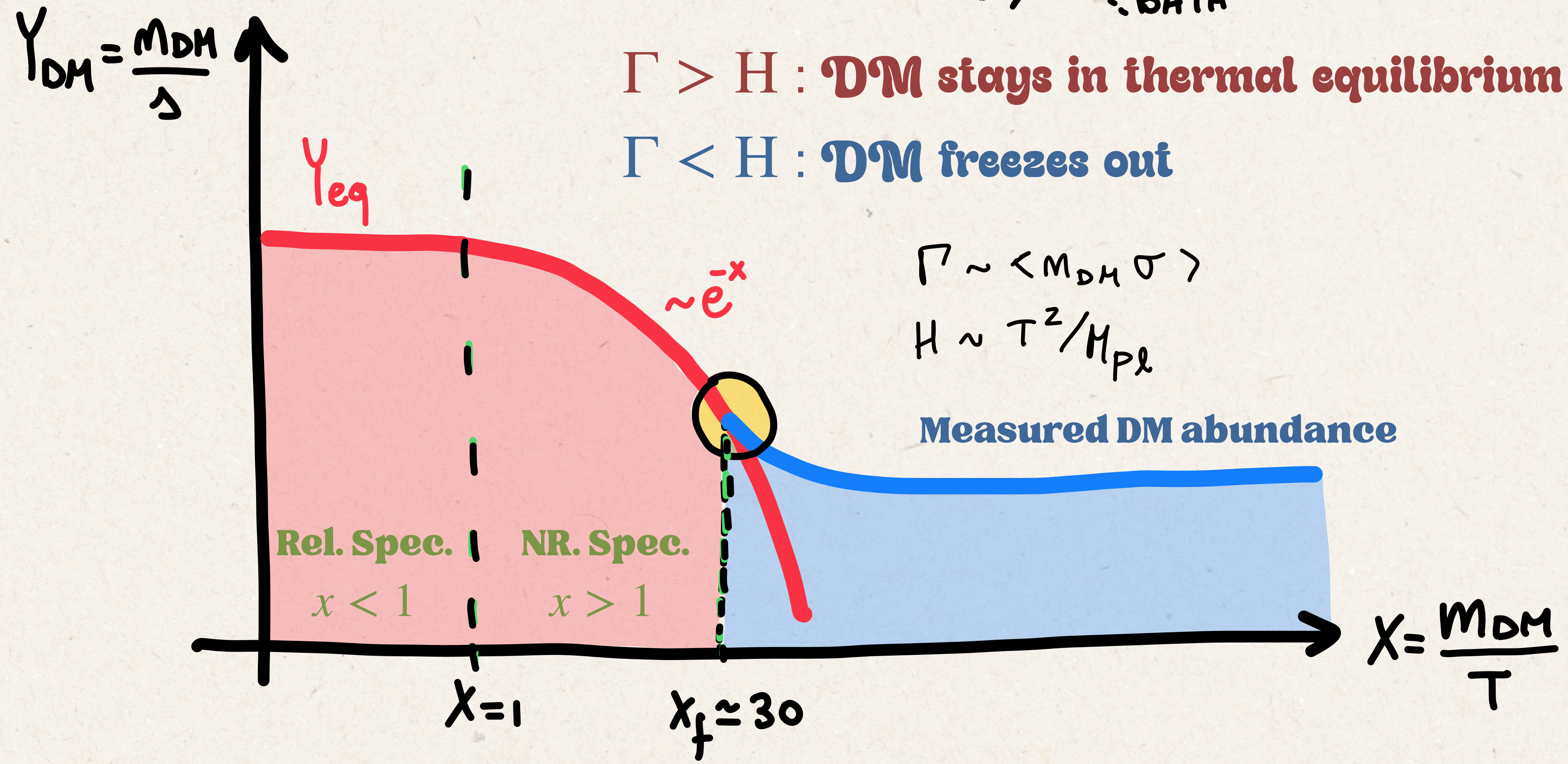


$\Gamma > H$: **DM stays in thermal equilibrium**

$\Gamma < H$: **DM freezes out**

$\Gamma \sim \langle m_{DM} \sigma \rangle$

$H \sim T^2/M_{Pl}$



- Thermal *freeze-out* relies only on one **IR parameter**

→ The xsec $\langle \sigma v \rangle_{\text{cosmo}} \sim 1\text{pb} \sim 10^{-26}\text{cm}^3\text{s}^{-1}$

WIMP MIRACLE:

- Weak-scale coupling + TeV scale DM naturally matches the thermal xsec.

  For heavy DM this is a perfect MIRACLE

(Possible connection to the naturalness of the EW scale)

$$\frac{\Omega_{DM}h^2}{0.110} = \frac{x_{fo}}{25} \frac{2.18\, 10^{-26}\text{cm}^3\text{s}^{-1}}{\sigma_0 + 3\sigma_1/x_{fo}}$$

Minimal Dark Matter

The Prototypical WIMP

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

Requirement: Embedding the χ_0 component in a EW rep. → $Q = T_3 + Y, \quad T_3 = \mathrm{diag}\left(\frac{n+1}{2} - i\right)$

1. **Real EW rep.** with Y=0 and odd n
2. **Complex EW rep.** with arbitrary n and $Y = \pm\left(\frac{n+1}{2} - i\right)$

WIMP Classification

[1] *Minimal Dark Matter:* ***arXiv:hep-ph/0512090***
[2] *Cosmology and Astrophysics of Minimal Dark Matter:* ***arXiv:hep-ph/0706.4071***
[3] *Minimal Dark Matter: Model and results:* ***arXiv:hep-ph/0903.3381***

Minimal Dark Matter

The Prototypical WIMP

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

- No tree-level coupling with Z-boson → Y=0
- For $n \geq 5$ multiplets DM stability comes from an accidental Z_2 symmetry.

Requirement: Embedding the χ_0 component in a EW rep. → $Q = T_3 + Y, \quad T_3 = \text{diag}\left(\frac{n+1}{2} - i\right)$

1. **Real EW rep.** with Y=0 and odd n
2. **Complex EW rep.** with arbitrary n and $Y = \pm\left(\frac{n+1}{2} - i\right)$

WIMP Classification

[1] Minimal Dark Matter: **arXiv:hep-ph/0512090**

[2] Cosmology and Astrophysics of Minimal Dark Matter: **arXiv:hep-ph/0706.4071**

[3] Minimal Dark Matter: Model and results: **arXiv:hep-ph/0903.3381**

Real WIMPs

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

1. **Neutral under EM.** DM candidate is χ_0
2. **DM Stability.** For such multiplets χ_0 is automatically the lightest
3. **No coupling to Z-boson.** Y=0 and odd n

DM physics is fully predicted !

[1] Minimal Dark Matter: arXiv:hep-ph/0512090

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
- The tree-level cross-section: $\sigma v_{\rm rel} = \frac{g_2^4(2n^4 + 17n^2 - 19)}{256\pi g_\chi M_\chi^2}$
- However this is inaccurate → **Non perturbative** and **Non-relativistic** effects modify the cross section

Sommerferld Enhancement

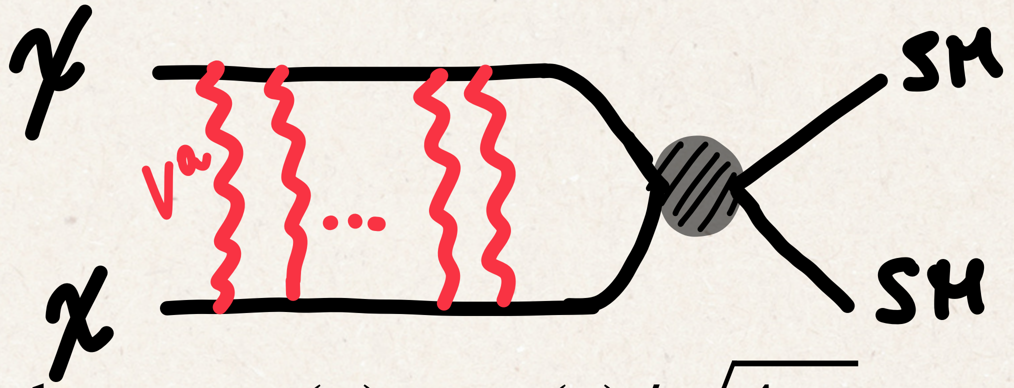
Bound State Formation

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

[1] NLO electroweak potentials for minimal dark matter and beyond: **arXiv:hep-ph/2108.07285**
[2] The Sommerfeld enhancement at NLO and the dark matter unitarity bound: **arXiv:hep-ph/2305.01680**

SE and BSF

1 Sommerfeld $\chi^0\chi^0 \to V^a V^a$



- $\sigma_{\rm NR}$ can receive large non-perturbative corrections (low vel. Enhanced)

$$\sigma \to S\ \sigma_{\rm pert}$$

- Long Range effects modify the DM wave function of the 2-body DM-DM initial state $\psi(\mathbf{r}) = u(r)/\sqrt{4\pi r}$

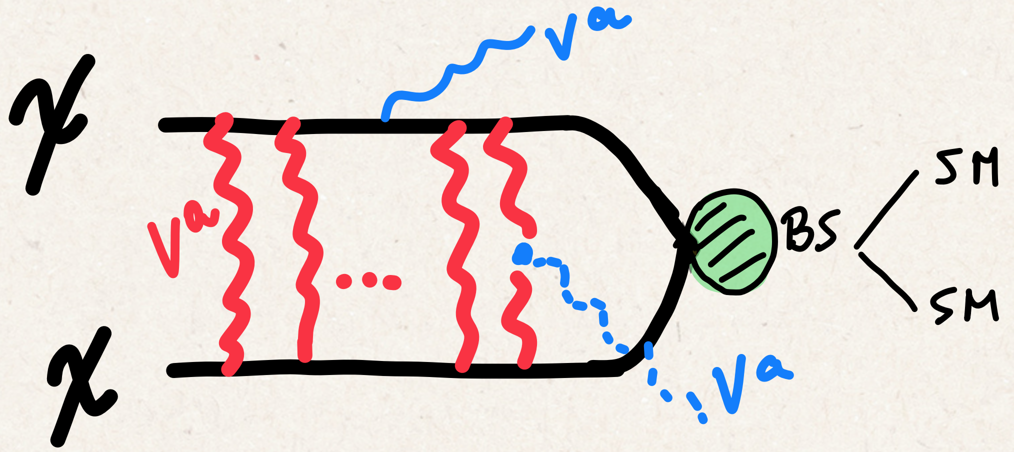
$$S = \left|\frac{u(\infty)}{u(0)}\right|^2 = \frac{2\pi\alpha/v_{\rm rel}}{1 - e^{-2\pi\alpha/v_{\rm rel}}}$$

Not so easy...

broken phase, NLO corrections, ecc...

2 BSF $\chi^0\chi^0 \to V^a\ \mathrm{BS}$

- The same long-range potential is also responsible for BSF.
- ${}^1s_3 : E_B \sim 80\ \mathrm{GeV}$
- BS annihilation with a rate $\Gamma_{\rm ann} \sim \alpha_2^5 M_\chi$ into SM particles ($f\bar{f}$ and HH^*)



[1] Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos III. Computation of the Sommerfeld enhancements: ***arXiv:hep-ph/1411.6924***
[2] Capture and Decay of Electroweak WIMPonium: ***arXiv:hep-ph/1610.07617***

Detection Strategies

1 **Direct Detection**

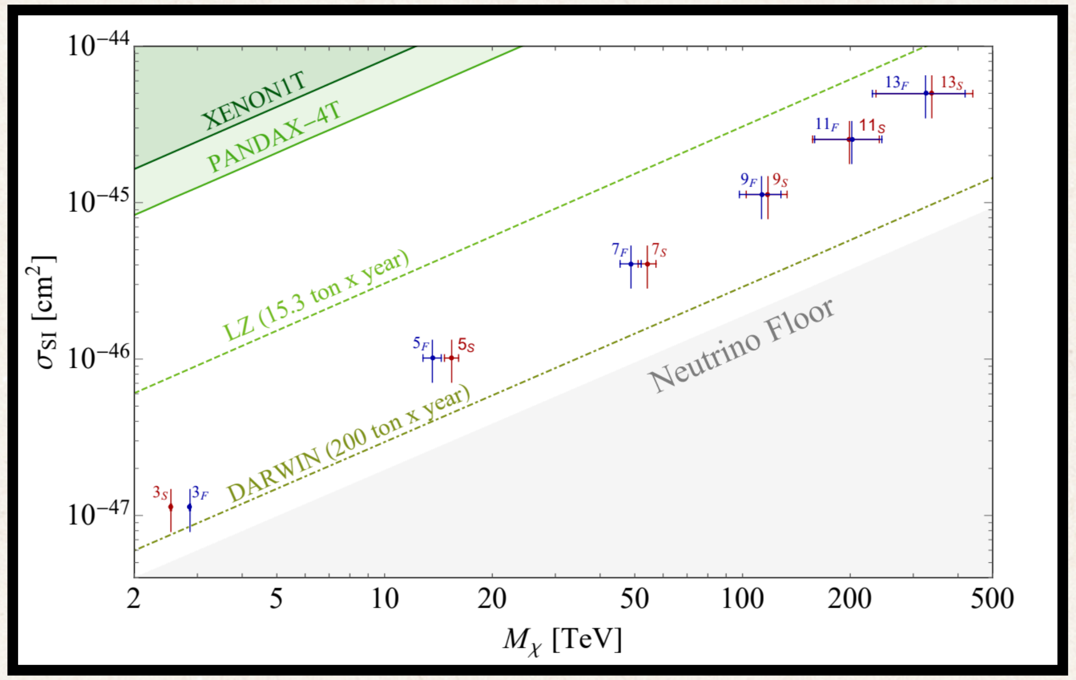
- EW multiplets within the reach of next generation experiments

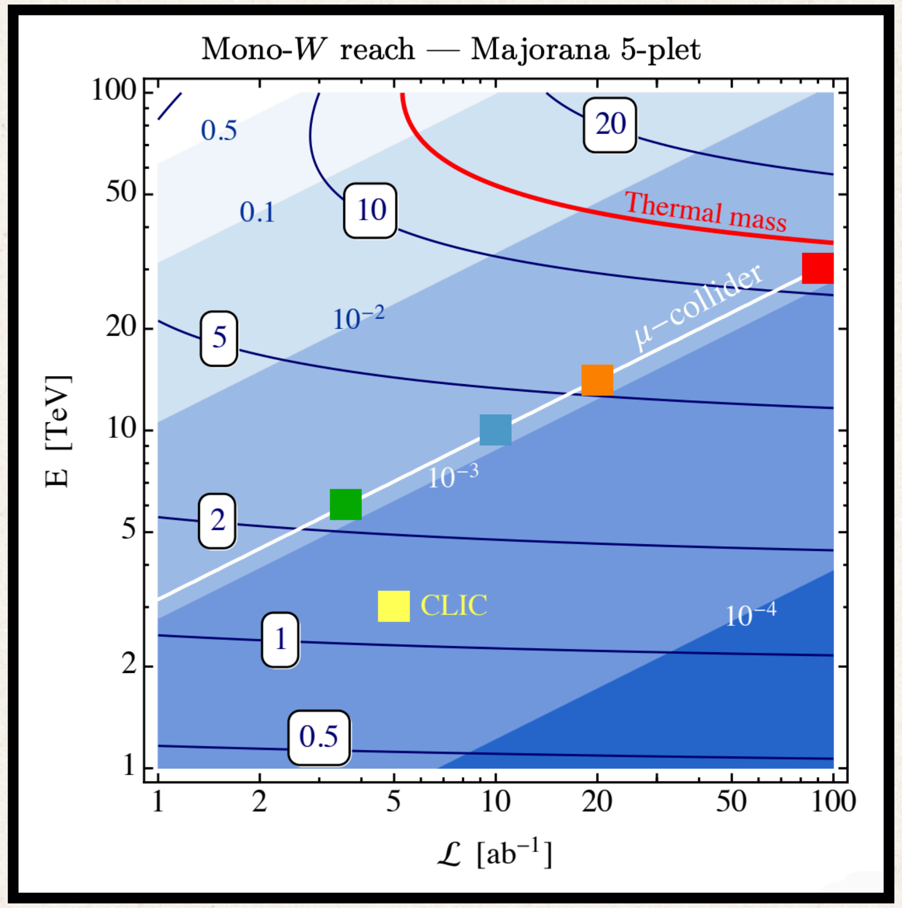
2 **Collider searches**

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

3 **Indirect Detection**

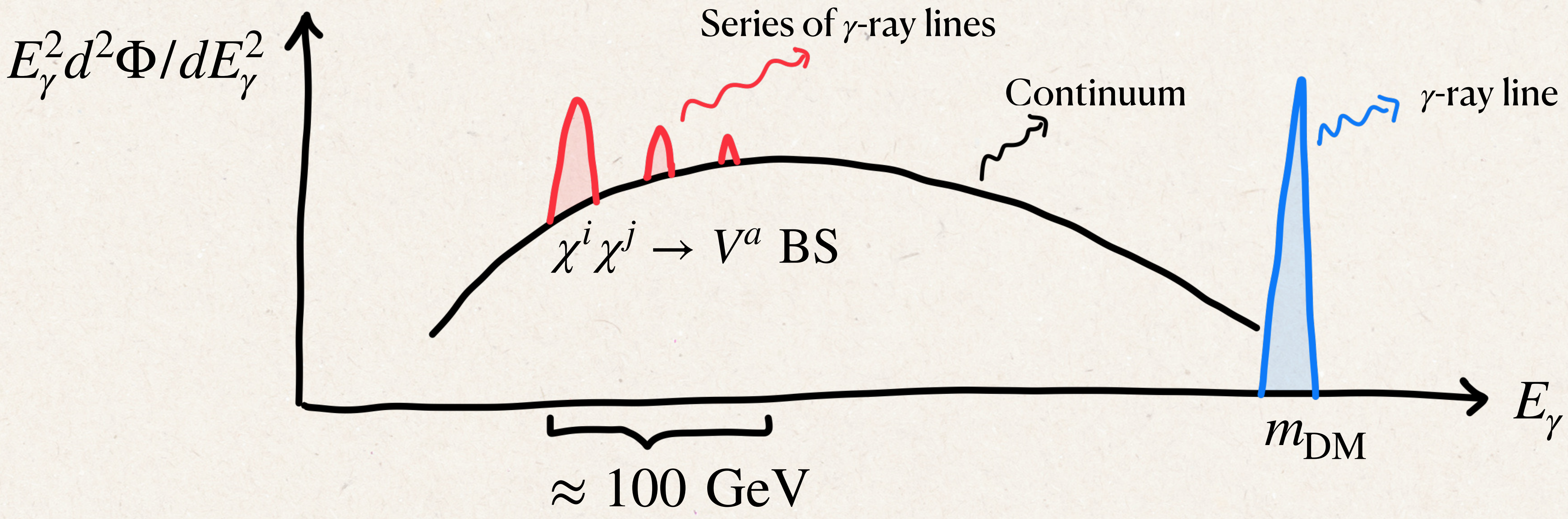
- Can already offer valuable information!





Typical γ-ray flux

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



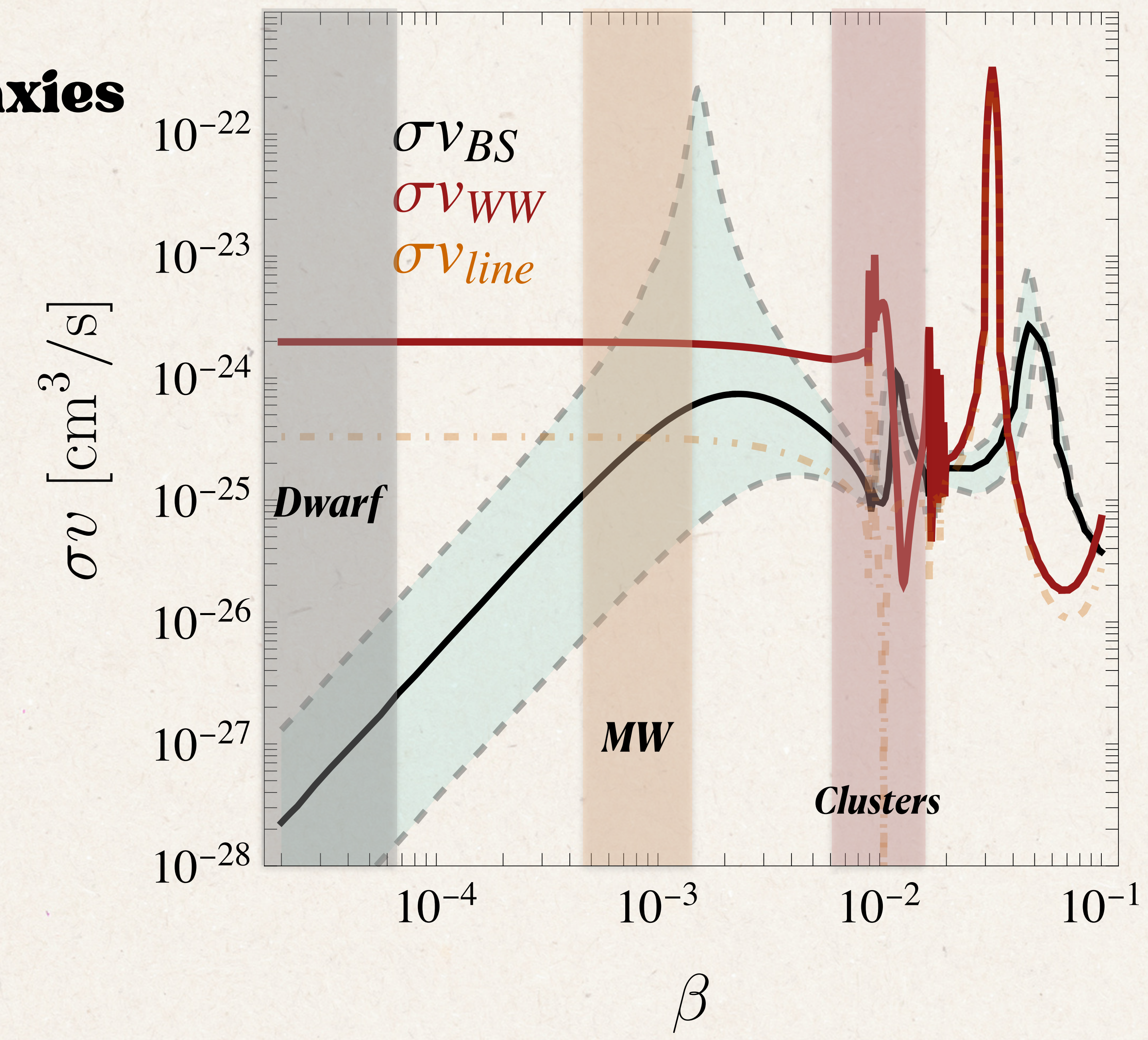
- **Continuum:** Decay and hadronization of heavy EW gauge bosons
- **γ-ray line:** SE boost the loop-induce annihilation into $\gamma\gamma$ and γZ
- **Series of γ-ray lines:** Due to BSF

SMOKING GUN: Heavy EW multiplets are like atoms emitting in γ-rays

Choice of the Targets

1 Dwarf Spheroidal Galaxies

- DM dominated targets
- More robust predictions for the DM density profile.
- **But...** Small velocity dispersion → BSF is suppressed

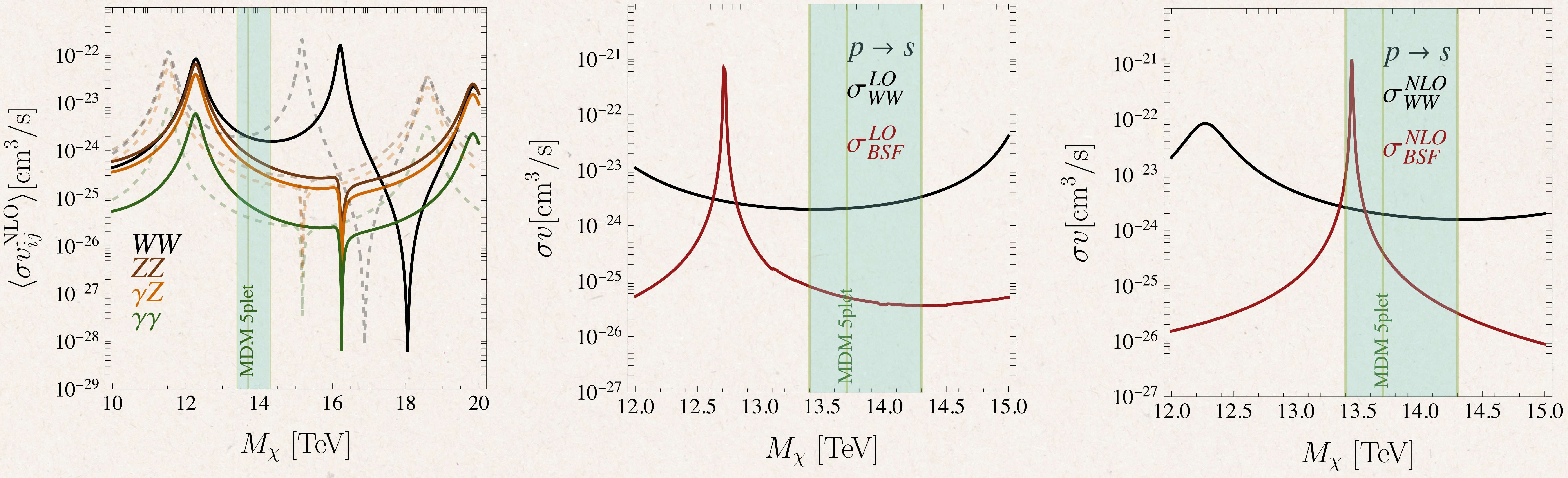


2 Our Galaxy

- Large velocity dispersion → enhanced BSF
- Possibly large DM signals
- Large baryonic density (more foreground, **uncertain DM profile**)

[1] Indirect detection probes of Minimal Dark Matter 5-plet: ***arXiv:hep-ph/2506.xxxx***

Annihilation cross sections



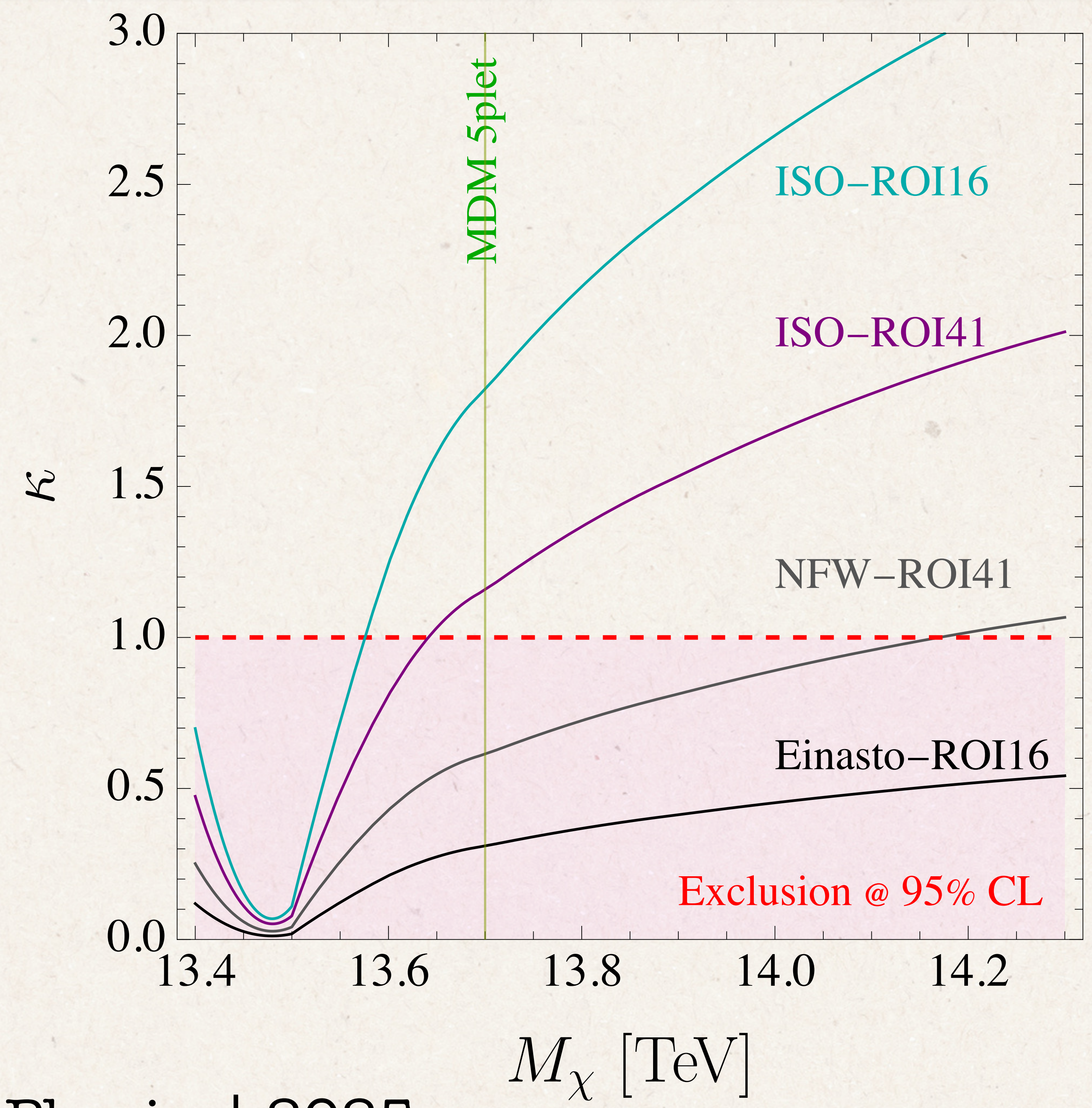
Here $\beta = 10^{-3}$

[1] *Indirect detection probes of Minimal Dark Matter 5-plet:* ***arXiv:hep-ph/2506.xxxx***

Fermi-LAT

- We use the diffuse γ-ray data from MW halo as measured by FERMI
- We put constraints on κ parameter $\langle \sigma v \rangle \rightarrow \kappa \langle \sigma v \rangle$
- We adopt two strategies:
  1. **Line-like searches:** when BSF dominates (at the left-edges of the thermal mass window)
  2. **Continuum-like searches:** when SE dominates (moving to the right edge)
- We focus on the RoI 16 and RoI 41 in order to reduce uncertainties in the DM profile

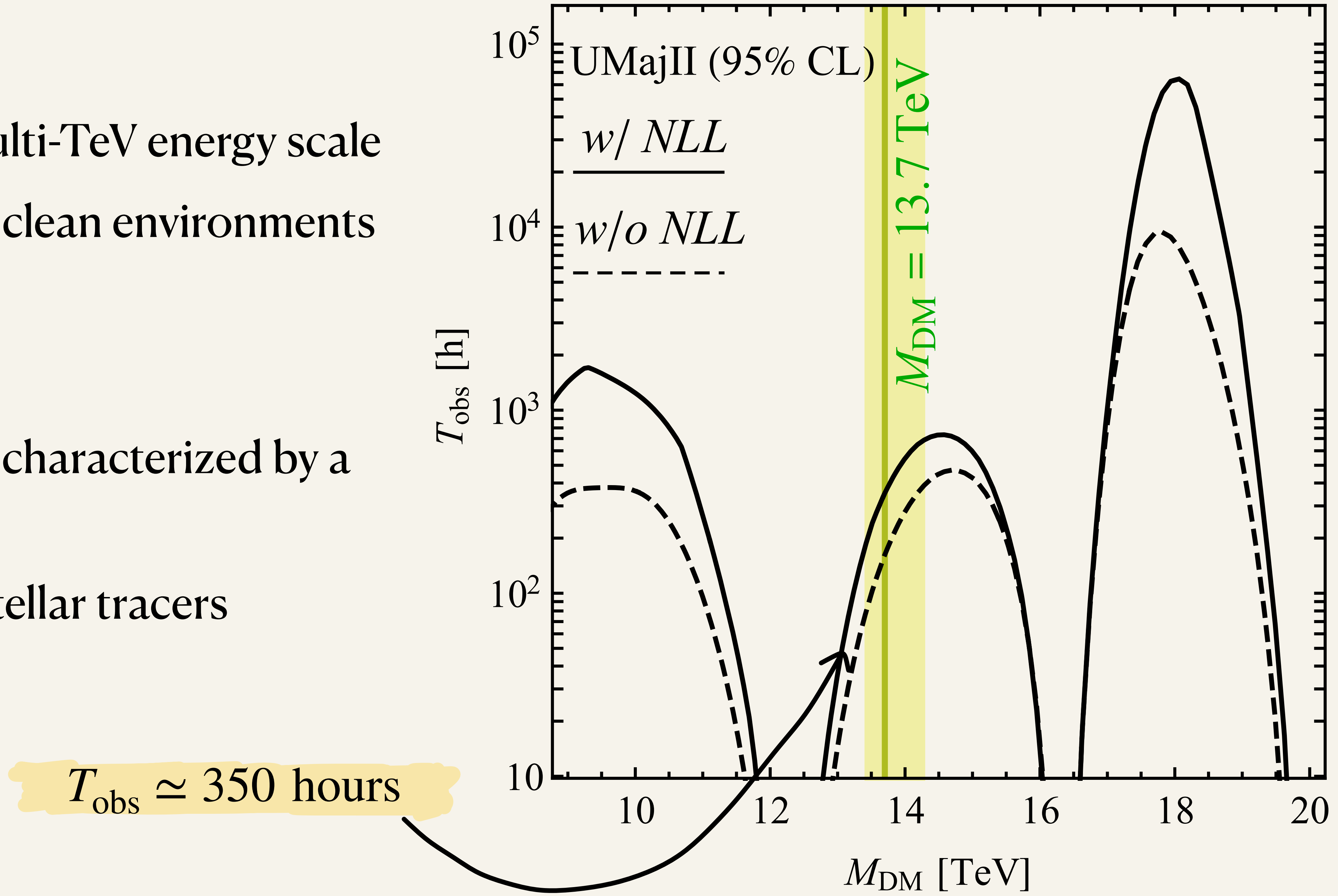
Changes of the DM profile can still mitigate the exclusion



[1] *Indirect detection probes of Minimal Dark Matter 5-plet:* ***arXiv:hep-ph/2506.xxxx***

Cerenkov Telescope Array

- CTA is maximally sensitive to γ-rays at the multi-TeV energy scale
- We compute the CTA sensitivity towards the clean environments
- Sensitivity to high energy spectral features
- **Two Dwarf selections:**
  - 1)Classical-Dwarf: DRACO very clean and characterized by a relative large J-factor
  - 2) URSA-MajorII large J-factor but fewer stellar tracers



[1] Indirect detection probes of Minimal Dark Matter 5-plet: **arXiv:hep-ph/2506.xxxx**

Conclusions

- Minimal Dark Matter is the prototype model of WIMP:
  → huge predictivity, few parameters
- Dark Matter as a WIMP remains one of the main motivation for NP at the multi-TeV scale

Take Home Message:

- 5-plet shows smoking-gun signatures for the ID
- Present data on the galactic diffuse can already place stringent constraints on the MDM 5-plet, particularly on the continuum from BSF
- CTA will be able to probe the model in the next decades by pointing the detectors towards dSphs (Few hour needed!)

thank you

it was a pleasure!

backup slides

State of the Art

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}

Real WIMPs

Odd n and $Y = 0$

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

Majorana Fermion

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

Real Scalar

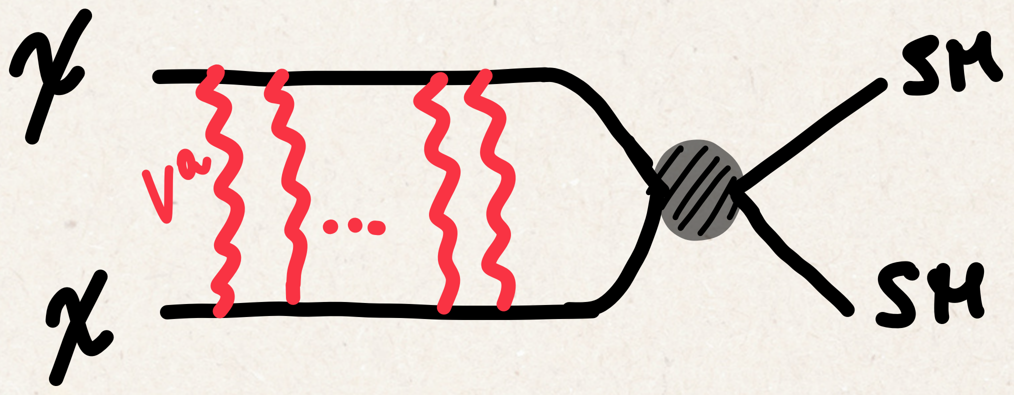
- For $n = 3$ multiplets DM stability is achieved by enforcing a Z_2 symmetry;
- For $n \geq 5$ multiplets DM stability comes from an accidental Z_2 symmetry.

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

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

SE and BSF

1 Sommerfeld $\chi^0\chi^0 \to V^aV^a$



- σ_{NR} can receive large non-perturbative corrections (low vel. Enhanced)

$$\sigma \to S\ \sigma_{\text{pert}}$$

- Relevant for cosmology and indirect detection where DM is non-relativistic
- DM couples to a mediator particle with $M_V \ll M_\chi \to$ The interaction is long range
- Long Range effects modify the DM wave function of the 2-body DM-DM initial state $\psi(\mathbf{r}) = u(r)/\sqrt{4\pi r}$

In the unbroken regime and for a Coulomb like potential $V = -\alpha/r$

$$-u''/M_\chi - \alpha u/4\pi r = Eu$$

$$u'(\infty)/u(\infty) \simeq iMv_{\text{rel}}/2$$

$$S = \left|\frac{u(\infty)}{u(0)}\right|^2 = \frac{2\pi\alpha/v_{\text{rel}}}{1 - e^{-2\pi\alpha/v_{\text{rel}}}}$$

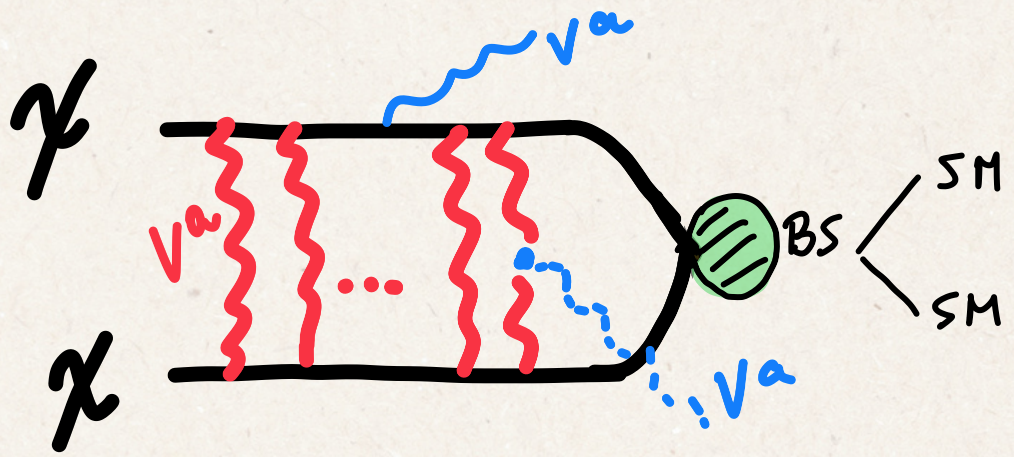
Not so easy…

1) broken phase
2) NLO corrections

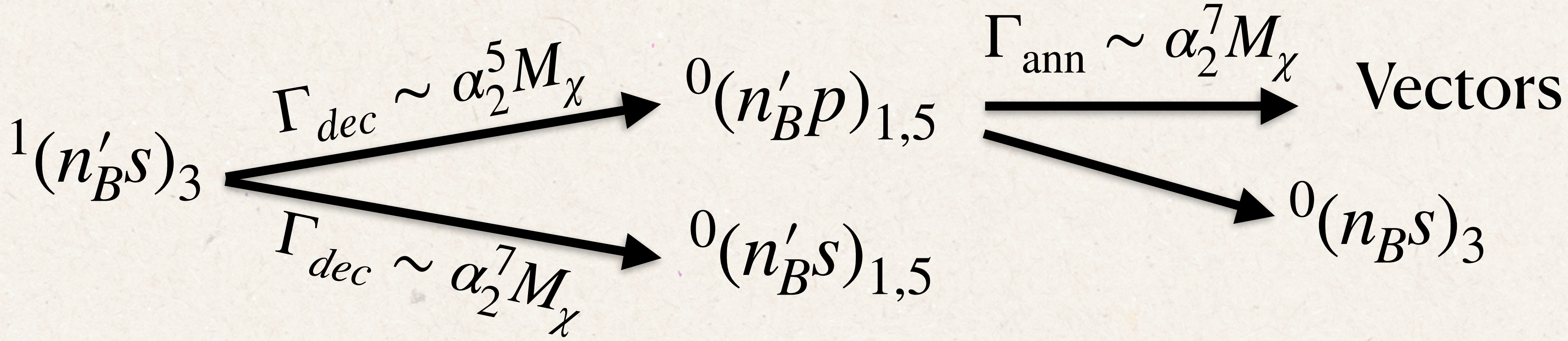
[1] *Minimal Dark Matter:* ***arXiv:hep-ph/0512090***

SE and BSF

2 BSF $\chi^0\chi^0 \to V^a$ BS

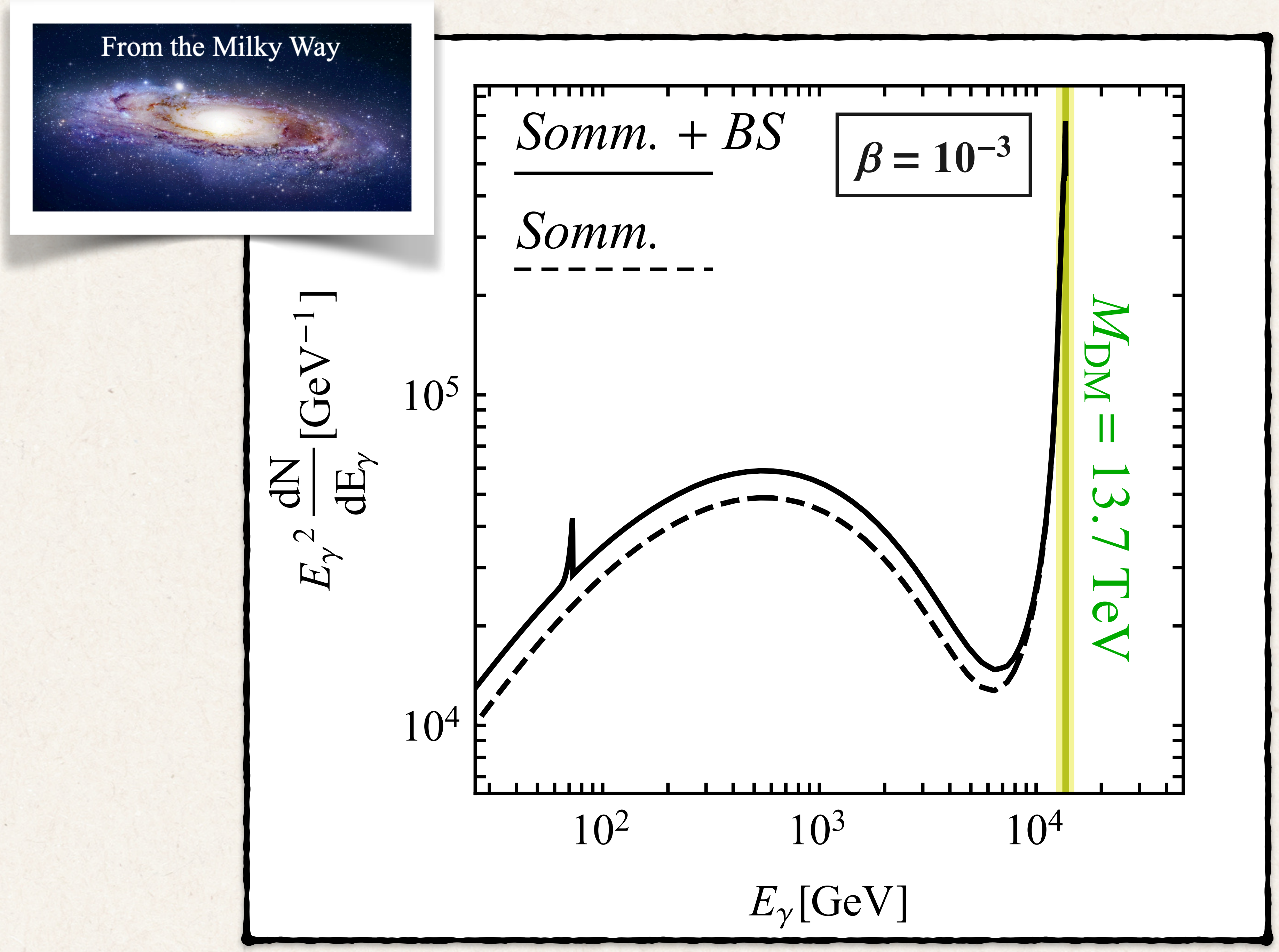


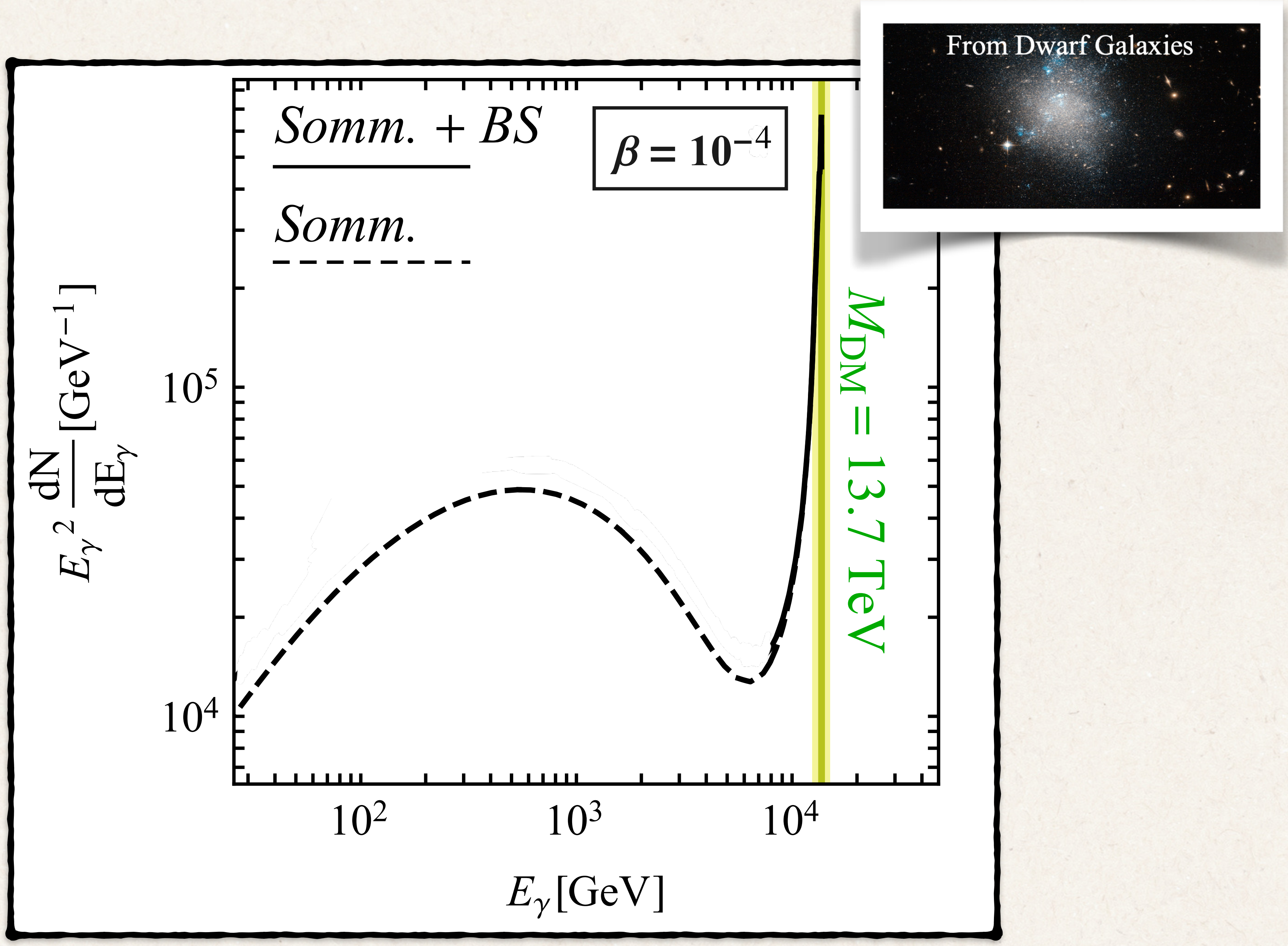
- The same long-range potential is also responsible for BSF.
- At leading order the capture occurs via $\chi_i\chi_j \to V^a + \mathrm{BSF}$
- In the electric dipole approx $\Delta L = 1$ and $\Delta S = 0$, $E_B \sim \alpha_2^2 M_\chi$
- The dominant SBF channel consists in $p \to s$ transitions with $S = 1$ and principal quantum number ${}^1(n_B s)_3$
- Once formed they annihilate with a rate $\Gamma_{\mathrm{ann}} \sim \alpha_2^5 M_\chi$ into SM particles ($f\bar{f}$ and HH^*)



[1] *Minimal Dark Matter:* ***arXiv:hep-ph/0512090***

From DM to Cosmic Rays



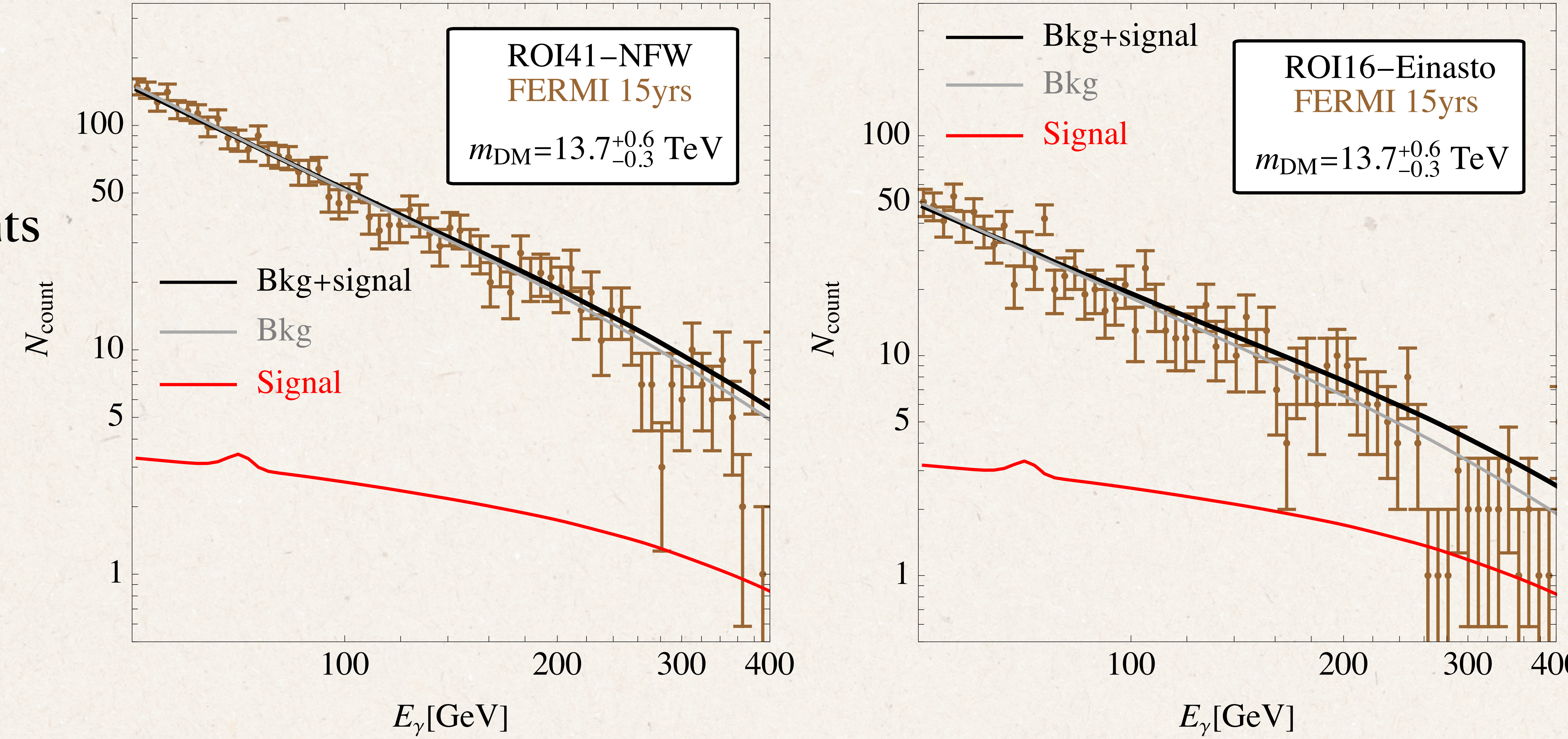


[1] Indirect detection probes of Minimal Dark Matter 5-plet: ***arXiv:hep-ph/2506.xxxx***

Current Constraints

Fermi-LAT : $E_\gamma \sim \mathcal{O}(100\ \text{GeV})$

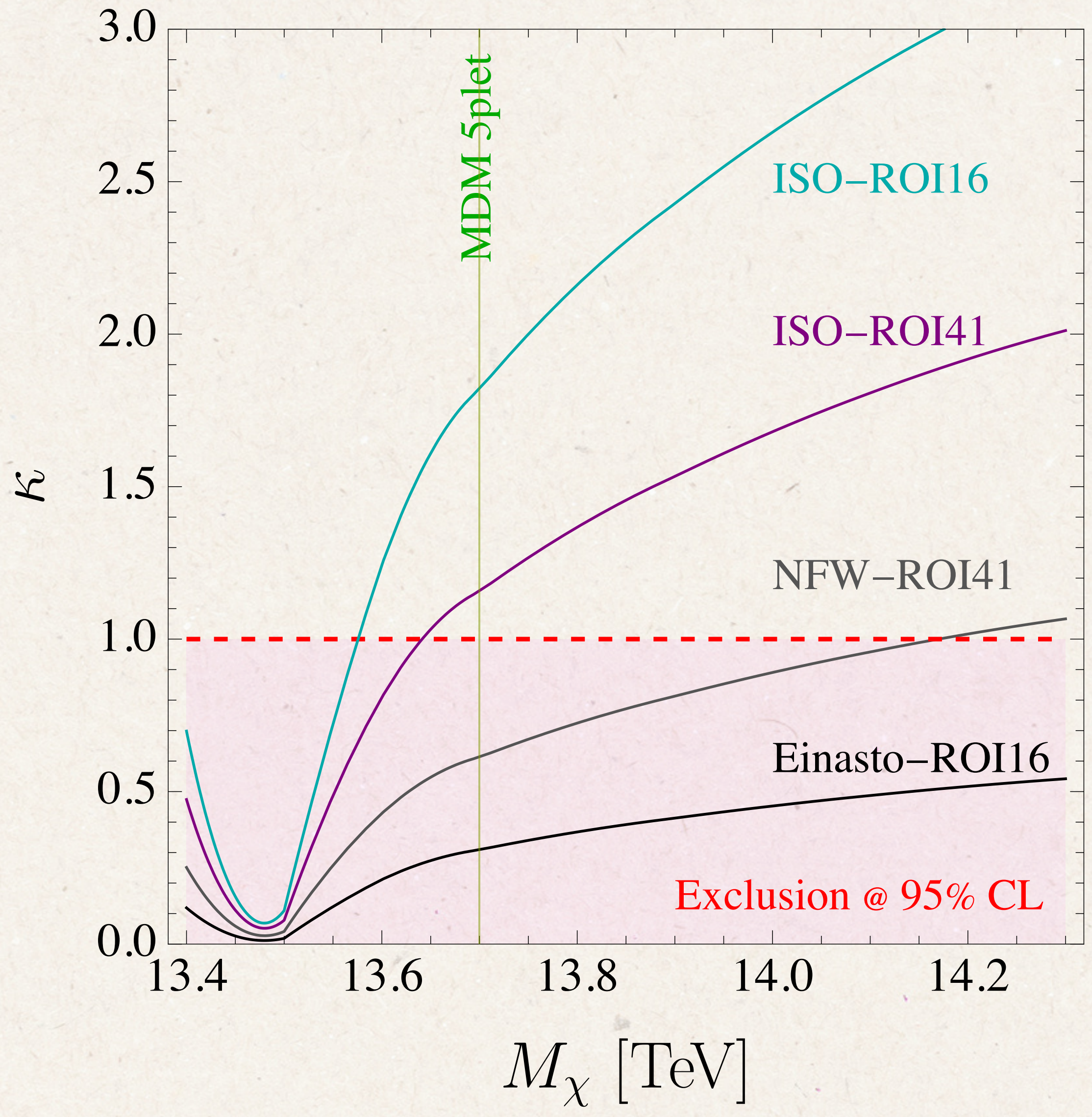
- Measurements of the Galactic Diffuse can set stringent constraints on the 5-plet
- We focus on the RoI 16 and RoI 41
- Exploiting the interplay of BSF continuum and SE



[1] Indirect detection probes of Minimal Dark Matter 5-plet: **arXiv:hep-ph/2506.xxxx**

Current Constraints

Fermi-LAT : $E_\gamma \sim \mathcal{O}(100 \text{ GeV})$



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

↓ *Extract the upper limit on the rescaling parameter*

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

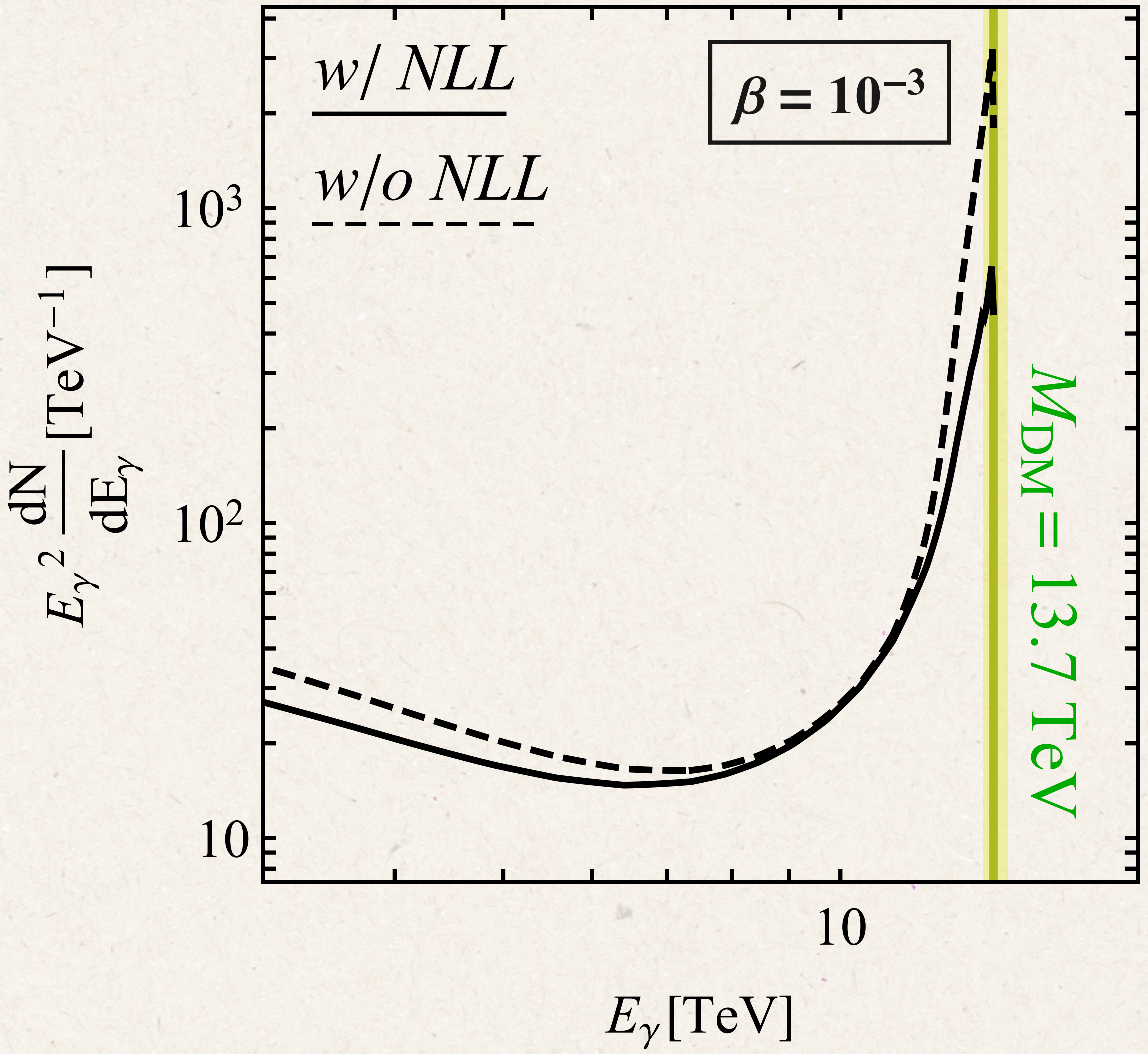
Changes of the DM profile can still mitigate the exclusion

[1] *Indirect detection probes of Minimal Dark Matter 5-plet:* ***arXiv:hep-ph/2506.xxxx***

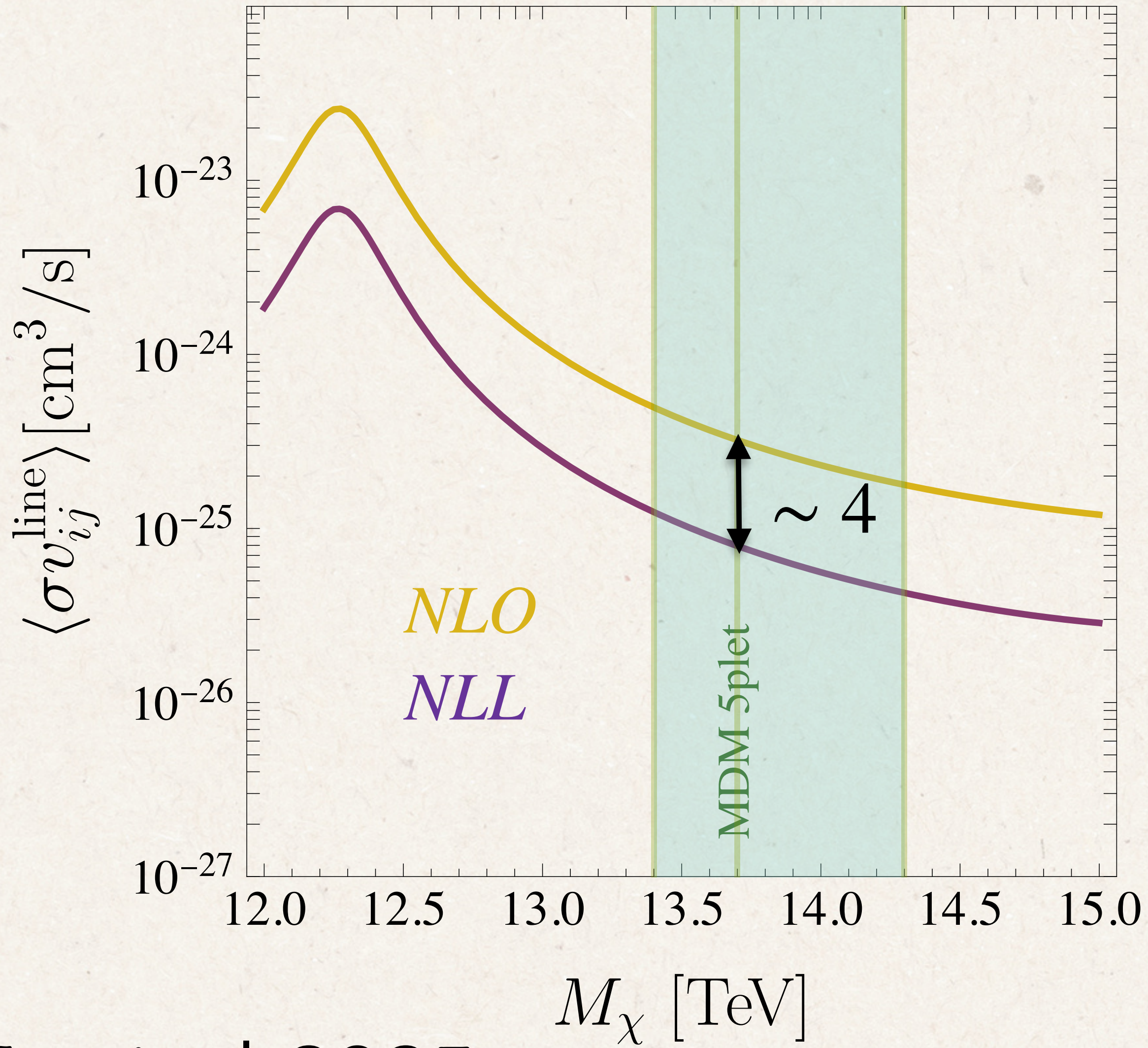
Future Constraints

Cerenkov Telescope Array (CTA): $E_\gamma \sim \mathcal{O}(10\ \text{TeV})$

- The forthcoming CTA will explore the multi-TeV range with unprecedented resolution



Sensitivity to high energy spectral features



[1] *Indirect detection probes of Minimal Dark Matter 5-plet:* ***arXiv:hep-ph/2506.xxxx***

Future Constraints

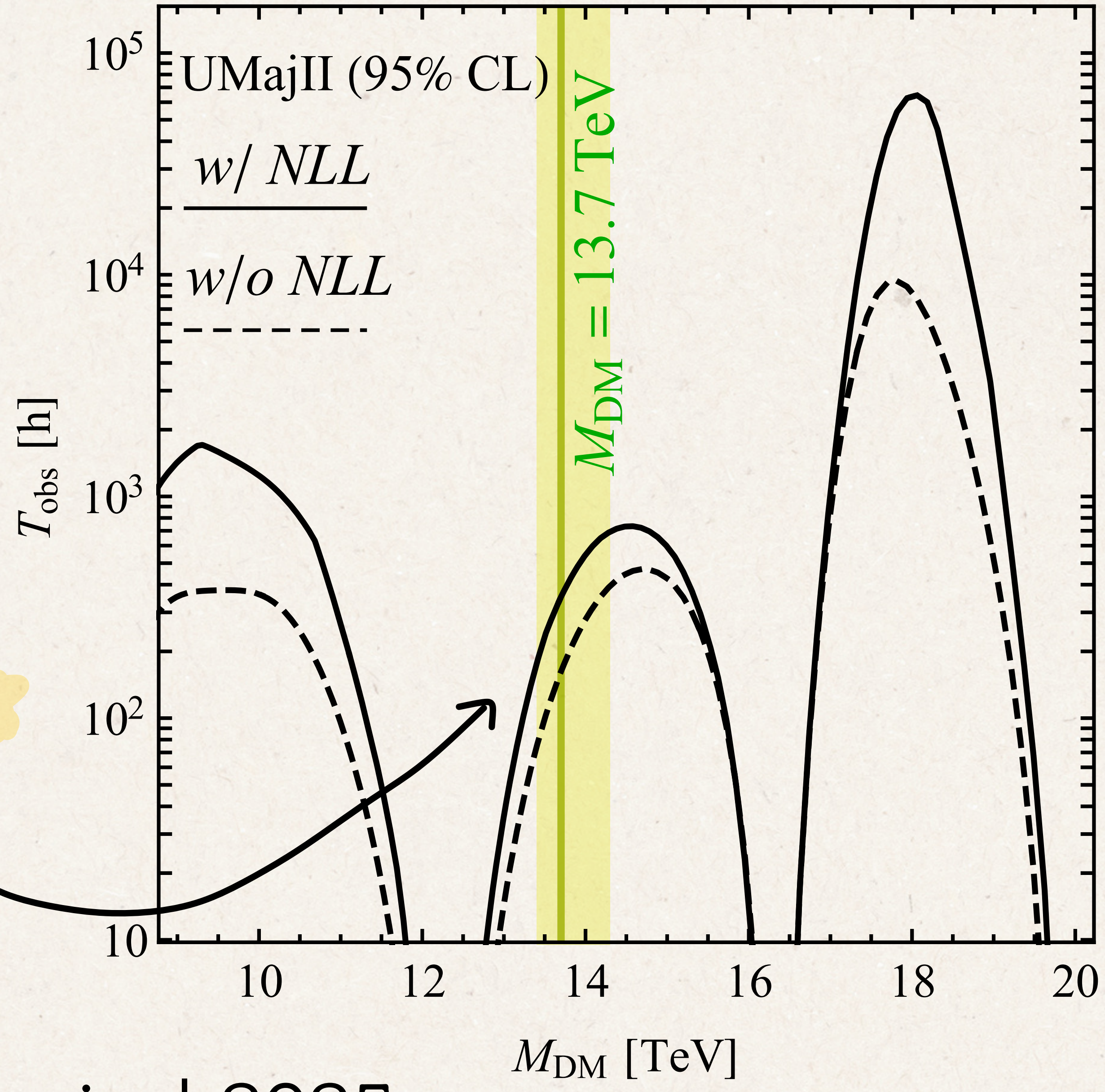
Cerenkov Telescope Array (CTA): $E_\gamma \sim \mathcal{O}(10\ \mathrm{TeV})$

$$\mathcal{L}_{\mathrm{sys}}(\kappa) = \prod_{i=1}^{\mathcal{N}} \max_{\mathrm{J}}[\mathcal{L}_{\mathrm{i}}(\kappa) \times \mathcal{L}^{\mathrm{J}}]$$

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

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

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



[1] Indirect detection probes of Minimal Dark Matter 5-plet: **arXiv:hep-ph/2506.xxxx**