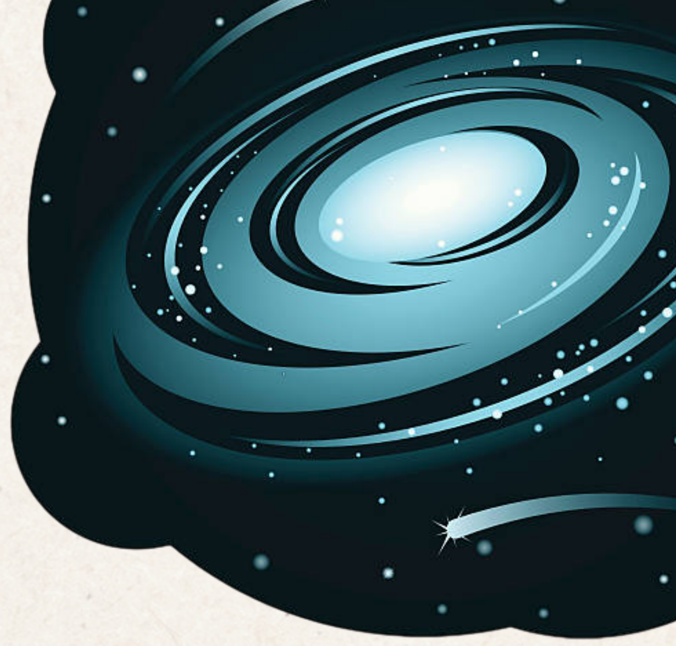
Minimal Dark Matter in the sky



Updated Indirect Detection probes for WIMPs

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TeVPA | 2025

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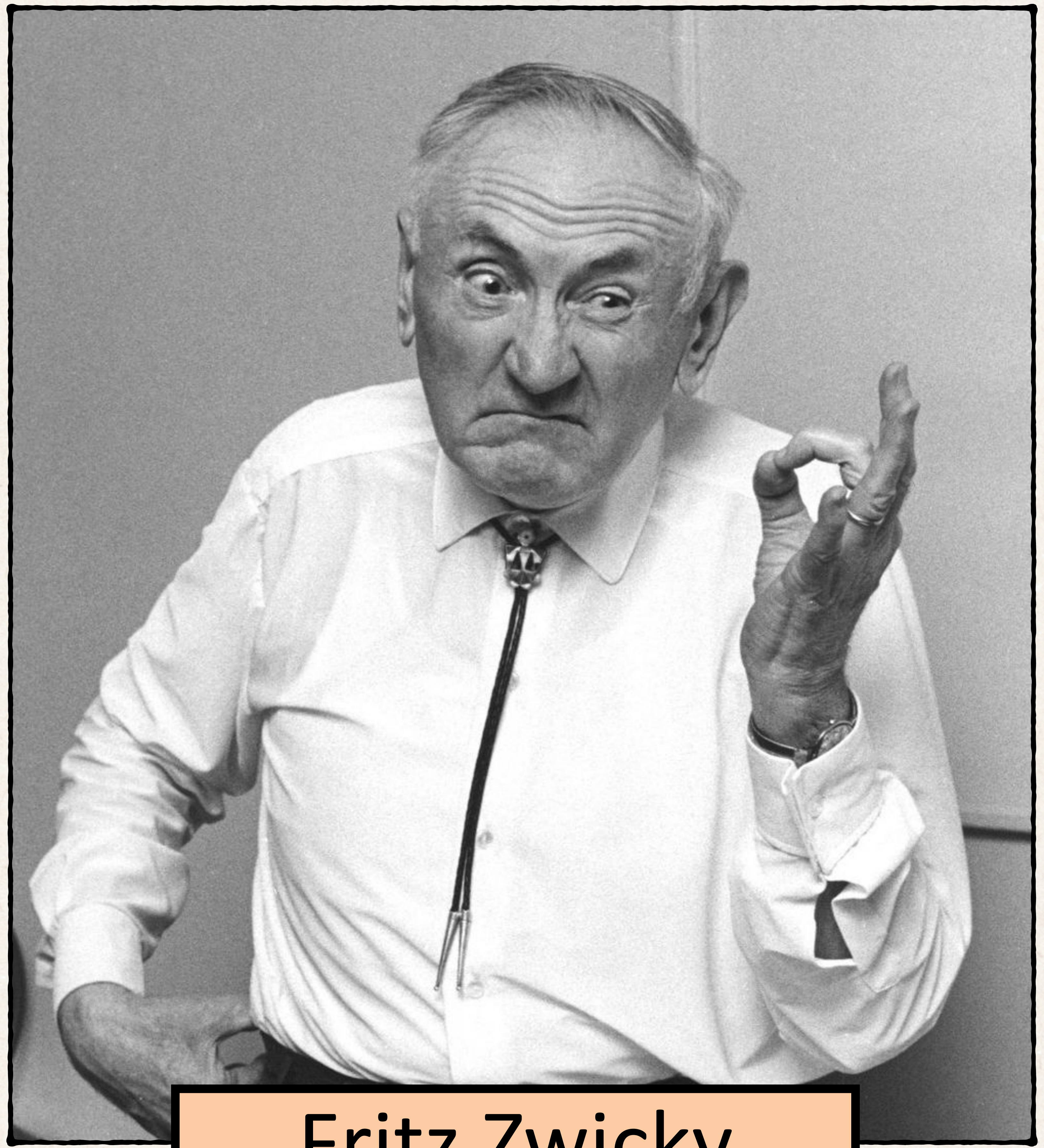
Sezione di Pisa

IN SUPREMÆ DIGNITATIS 1343
UNIVERSITÀ DI PISA

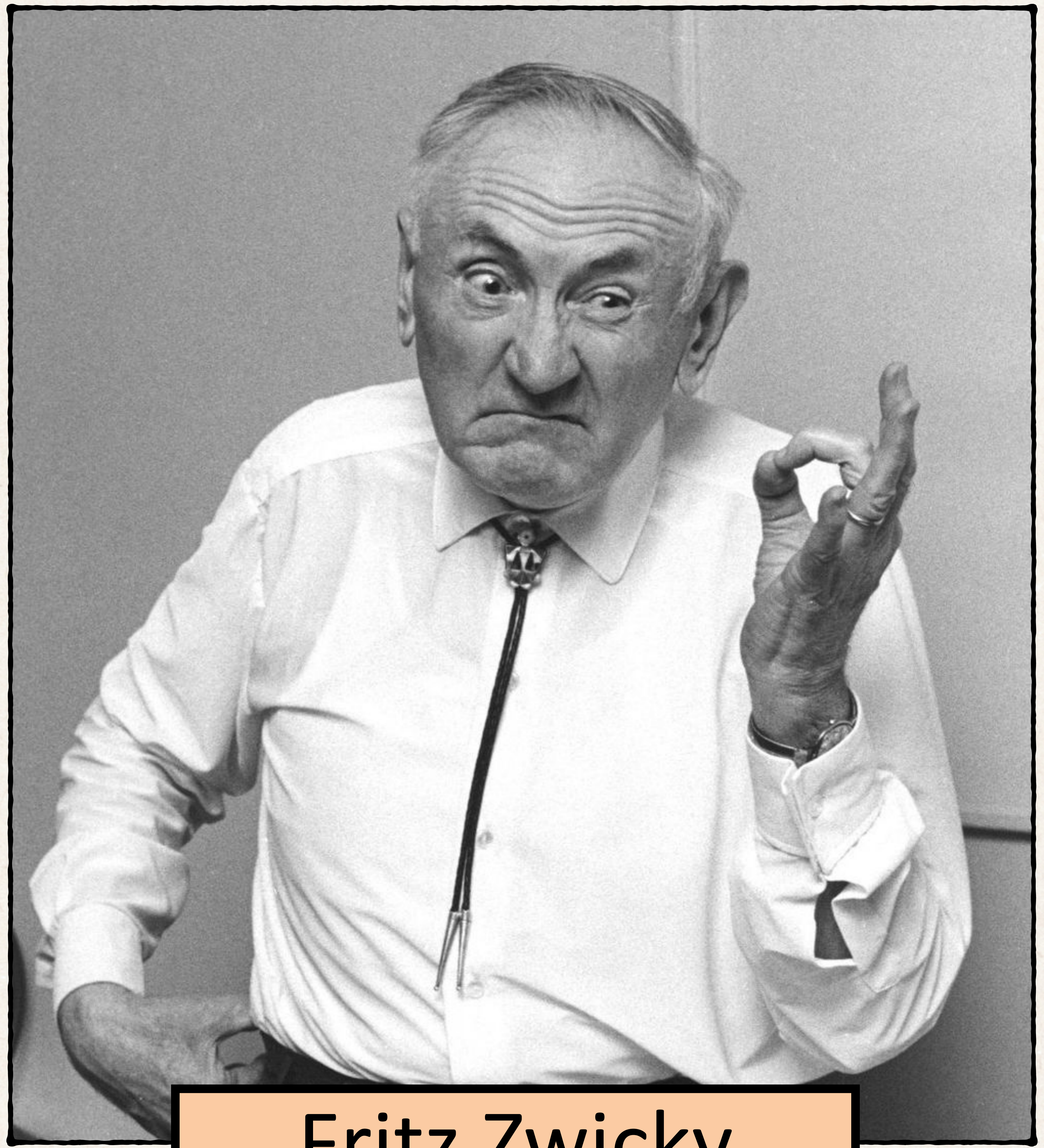
Dark Matter in a nutshell



Fritz Zwicky

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

Dark Matter in a nutshell



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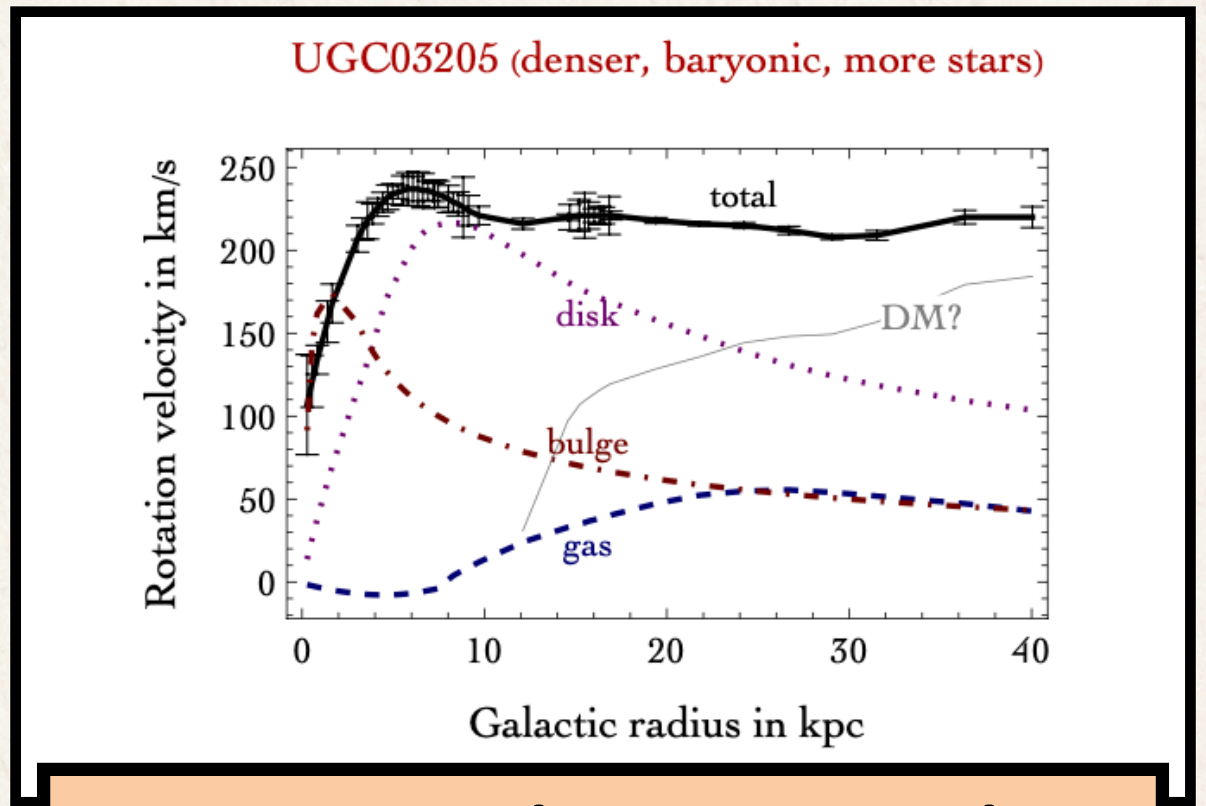
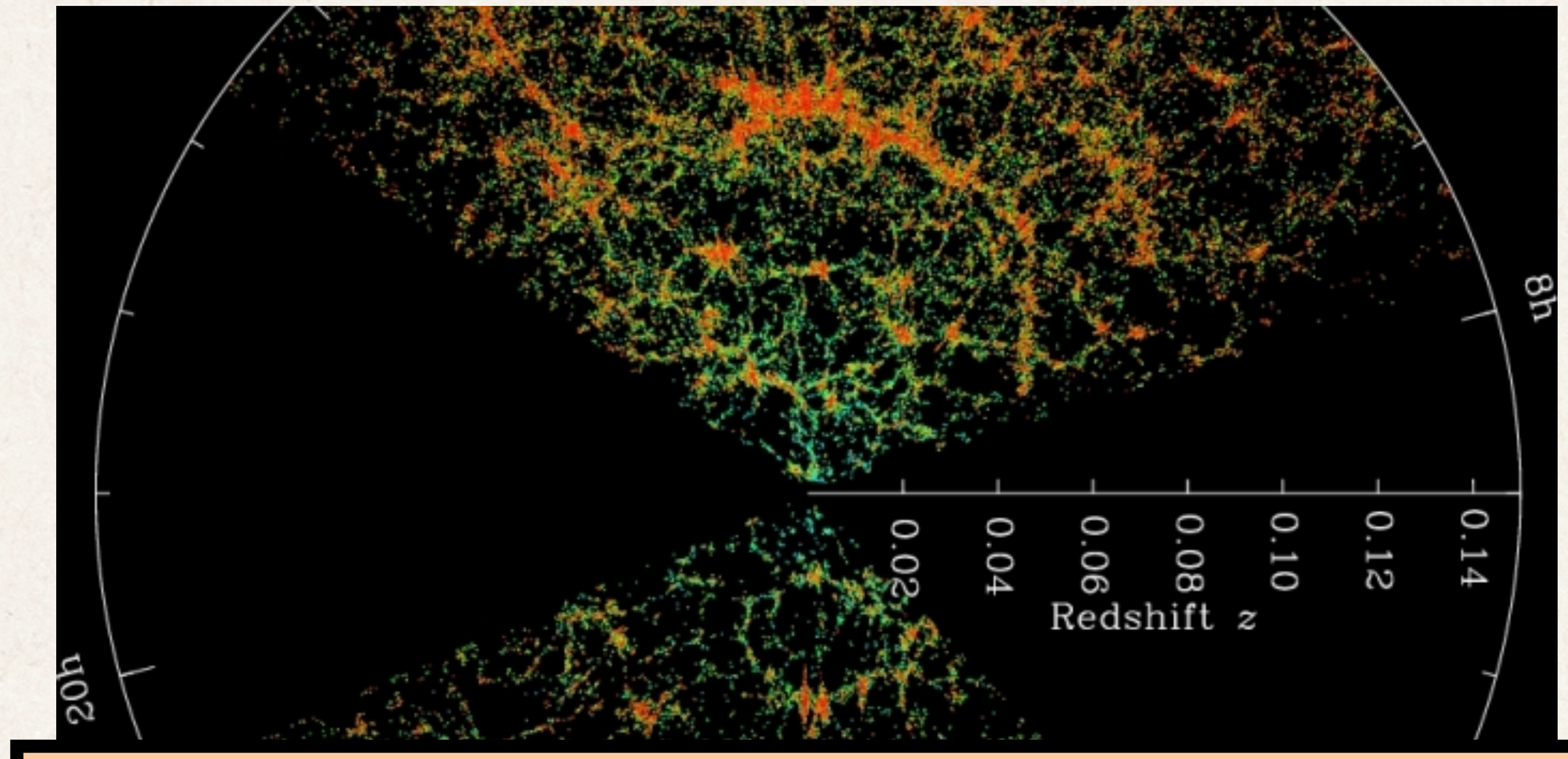
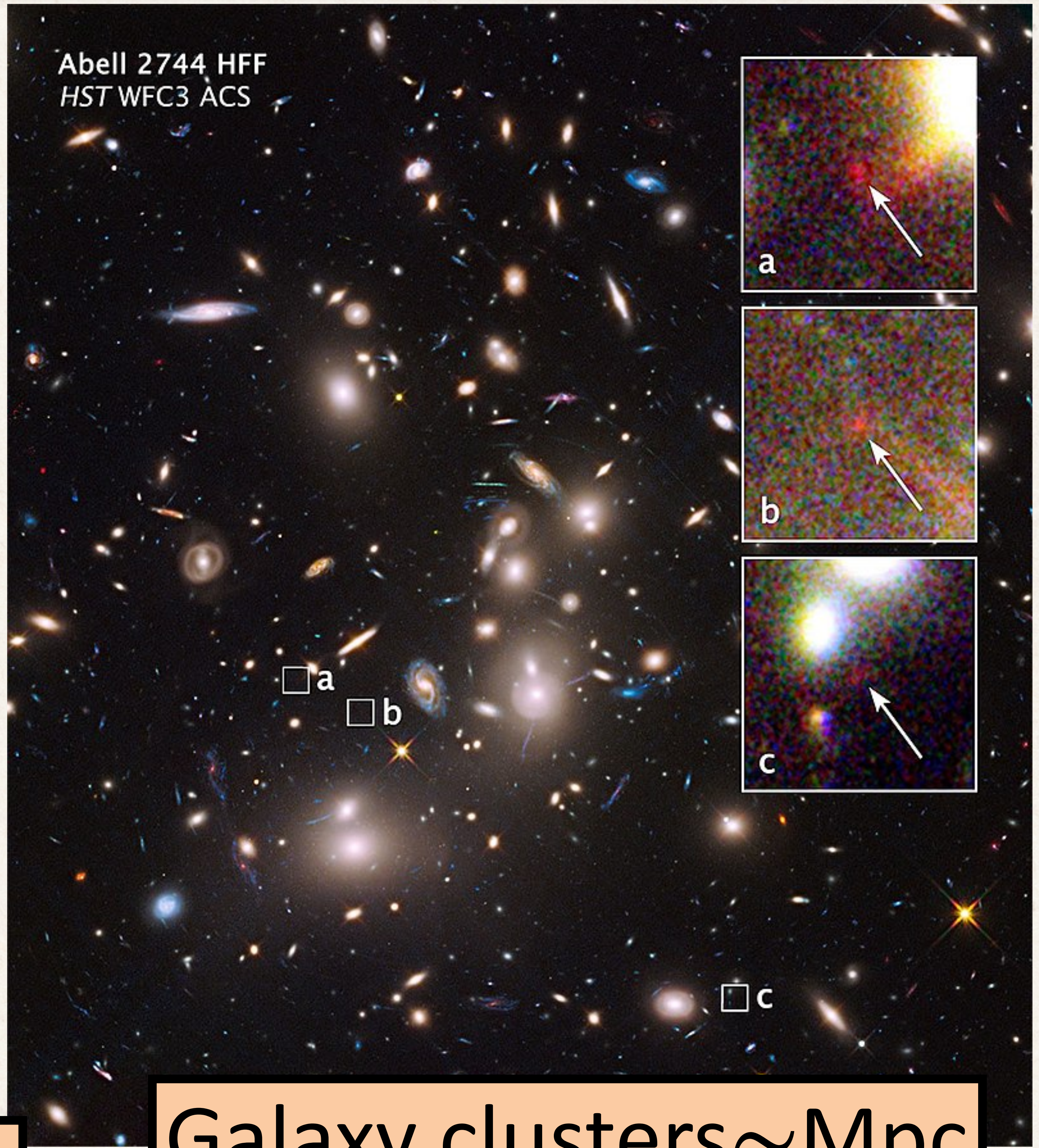


Rotational curves~kpc



Large Scale Structure~The Universe



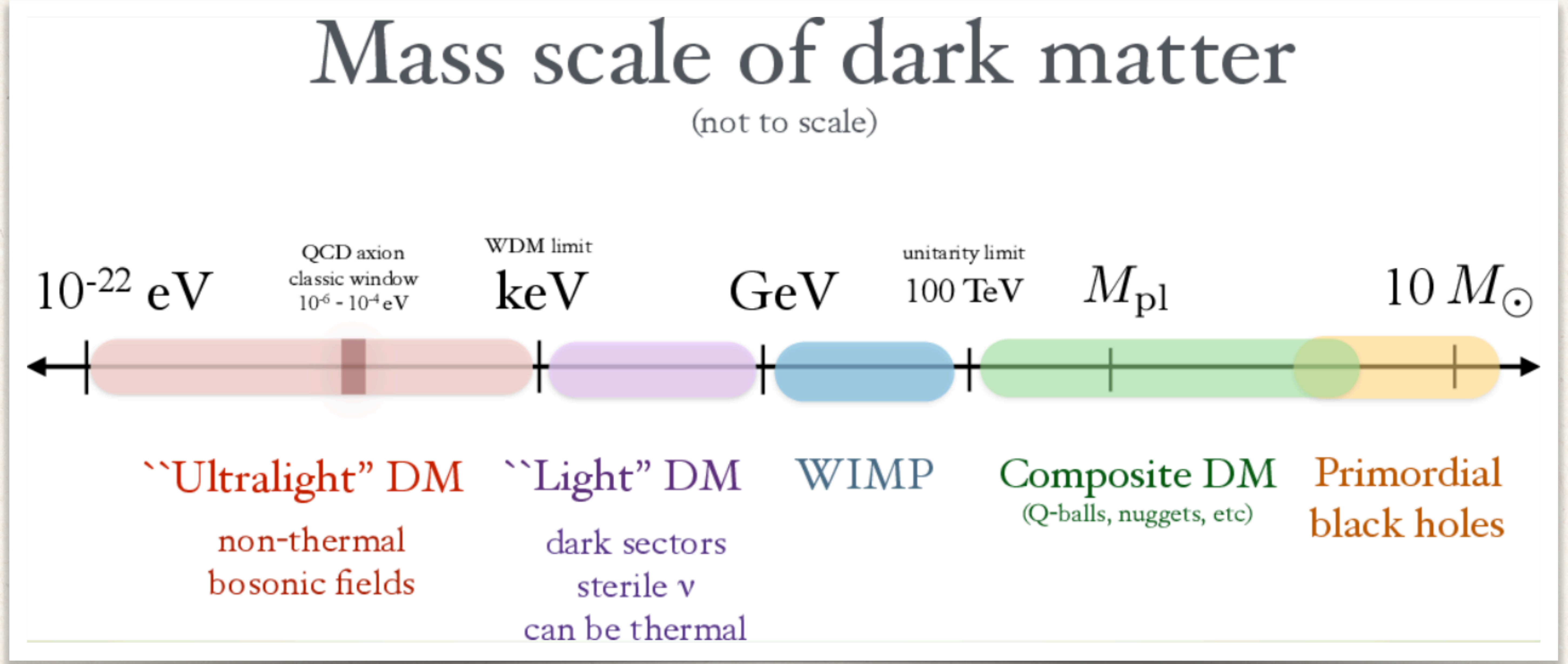
Galaxy clusters~Mpc

[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?

90 order of magnitudes



Stable

Non relativistic

Weakly Interacting

[1] Image: TASI Lectures on Dark Matter models

Dark Matter in a nutshell

90 order of magnitudes

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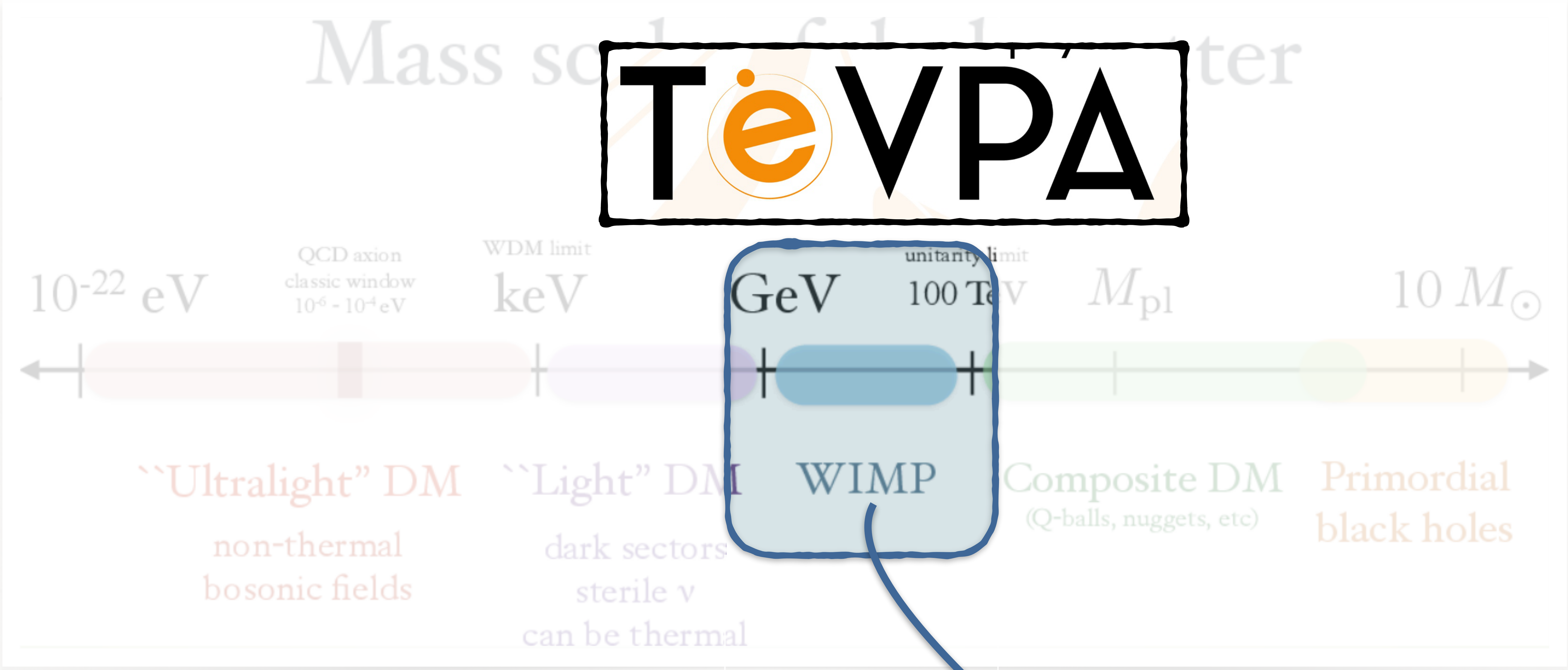


Stable

Non relativistic

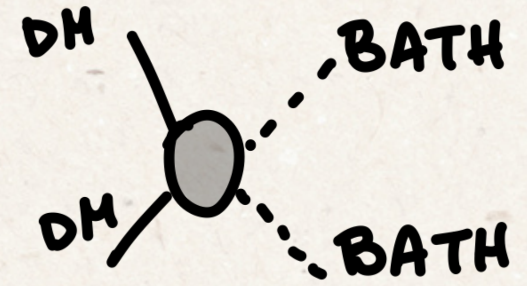
Weakly Interacting

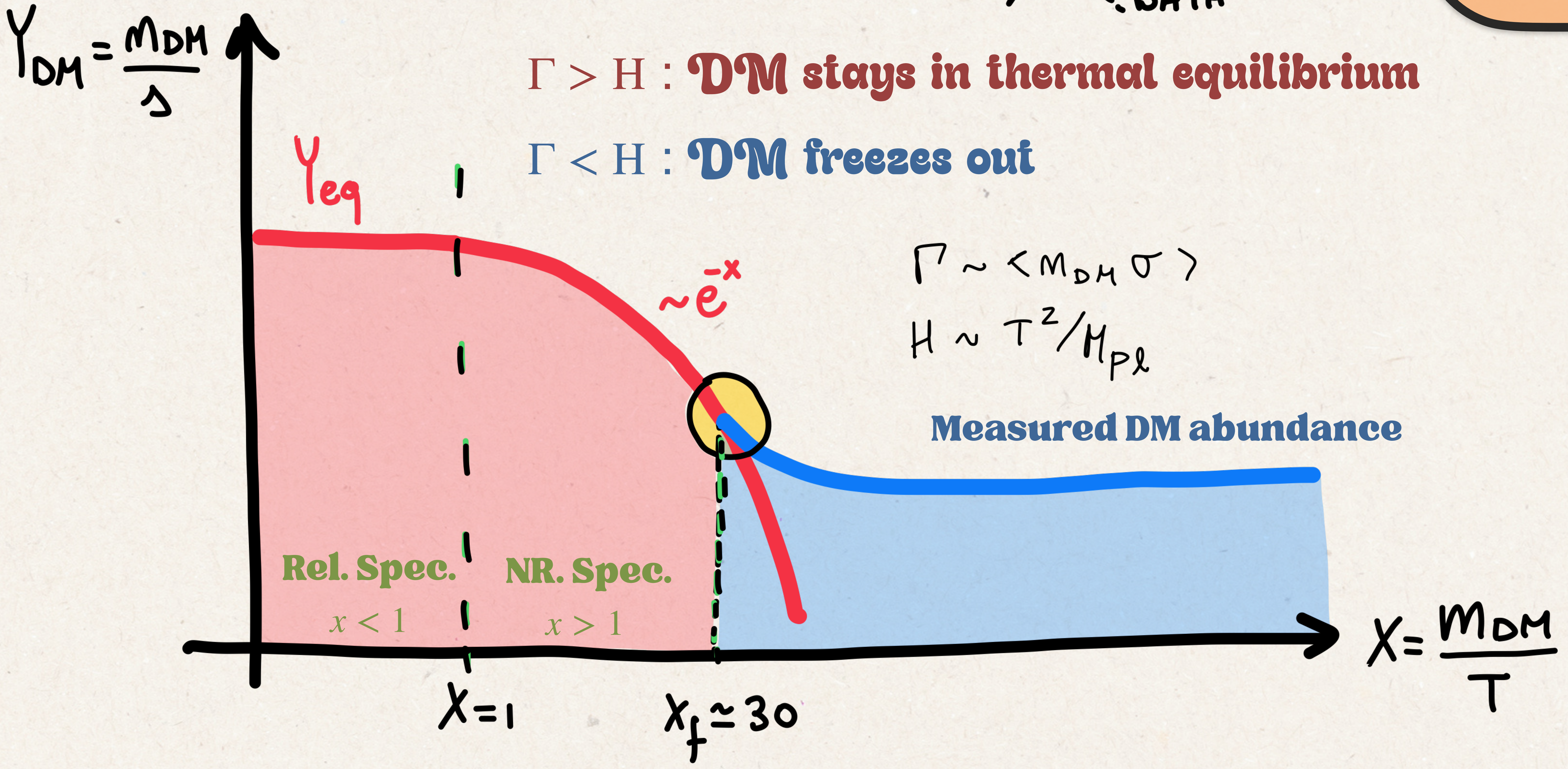
MDM in the sky: updated ID probes: 2507.17607
*Aghaie, Dondarini, **GM**, Panci*

[1] Image: TASI Lectures on Dark Matter models

The WIMP Miracle

DM as a Thermal Relic





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

$$\langle \sigma v \rangle \sim 1\text{pb} \sim 10^{-26}\text{cm}^3\text{s}^{-1}$$

WIMP MIRACLE:

Weak-scale coupling + TeV scale DM

naturally matches the thermal xsec.

For heavy DM this is a perfect MIRACLE

DM puzzle ⇔ EW interactions

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

Minimal Dark Matter

The Prototypical WIMP *

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

1. **Neutral under EM.** DM candidate is χ_0
2. **DM Stability.** χ_0 is stable on cosmo scales
3. **No coupling to Z-boson.** Avoid DD bounds

* [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

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Real EW representation

one viable possibility

Y=0 and odd n

for $n \gtrsim 5$ DM stability comes from an accidental $\mathbb{Z}_2$ symmetry

Majorana SU(2)-5plet

* [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

We focus on the

smallest accidentally stable MDM multiplet:

the Majorana 5-plet

Thermal freeze-out fixes M_χ

DM physics is fully predicted !

* [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**

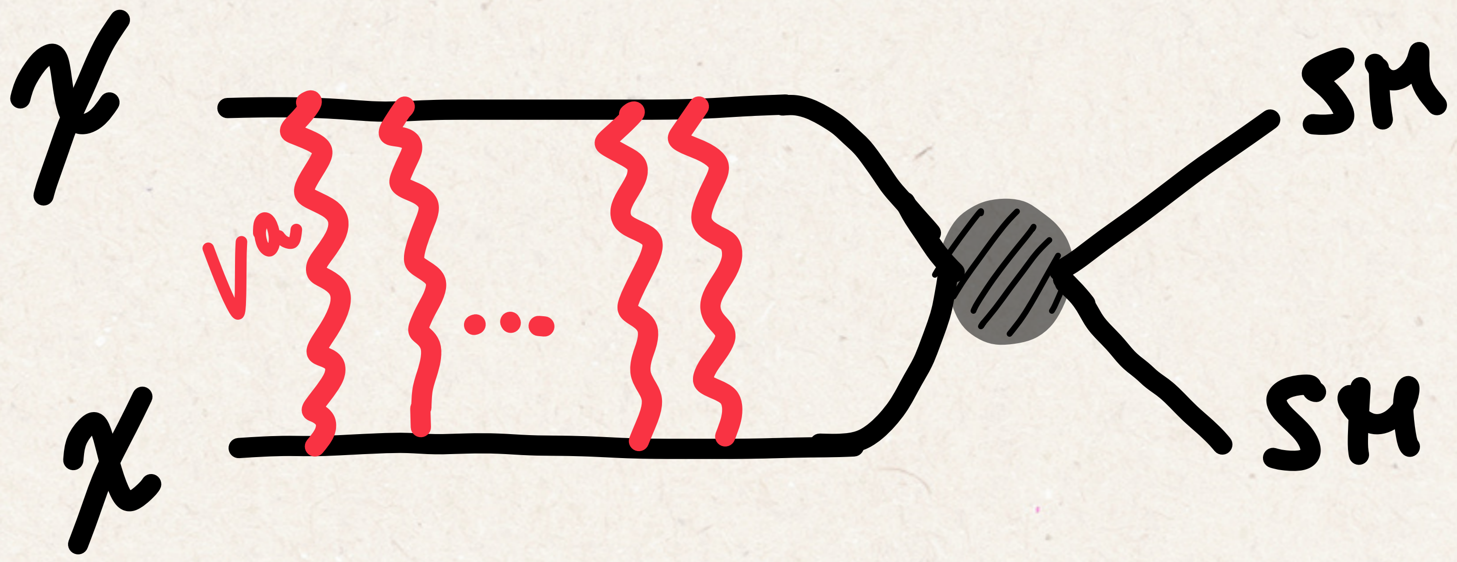
SE and BSF

$$\sigma v_{\text{rel}} = \frac{g_2^4(2n^4 + 17n^2 - 19)}{256\pi g_\chi M_\chi^2}$$ ⇒ However this is inaccurate → **Non perturbative** and **Non-relativistic**

Thermal mass window

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

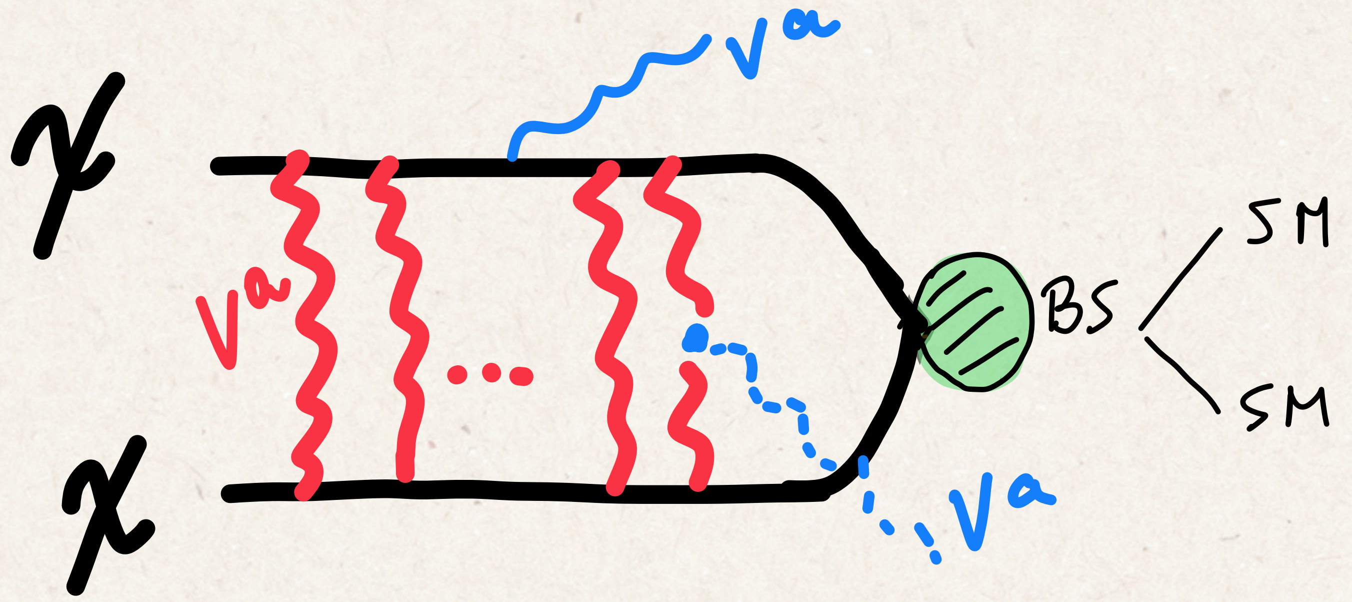
Sommerferld Enhancement †



Long range effects modify the 2-body initial state W.F.

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

Bound State Formation



$${}^1s_3 : E_B \sim 80\ \text{GeV}$$

BS annihilation into SM particles ($f\bar{f}$ and HH^*)

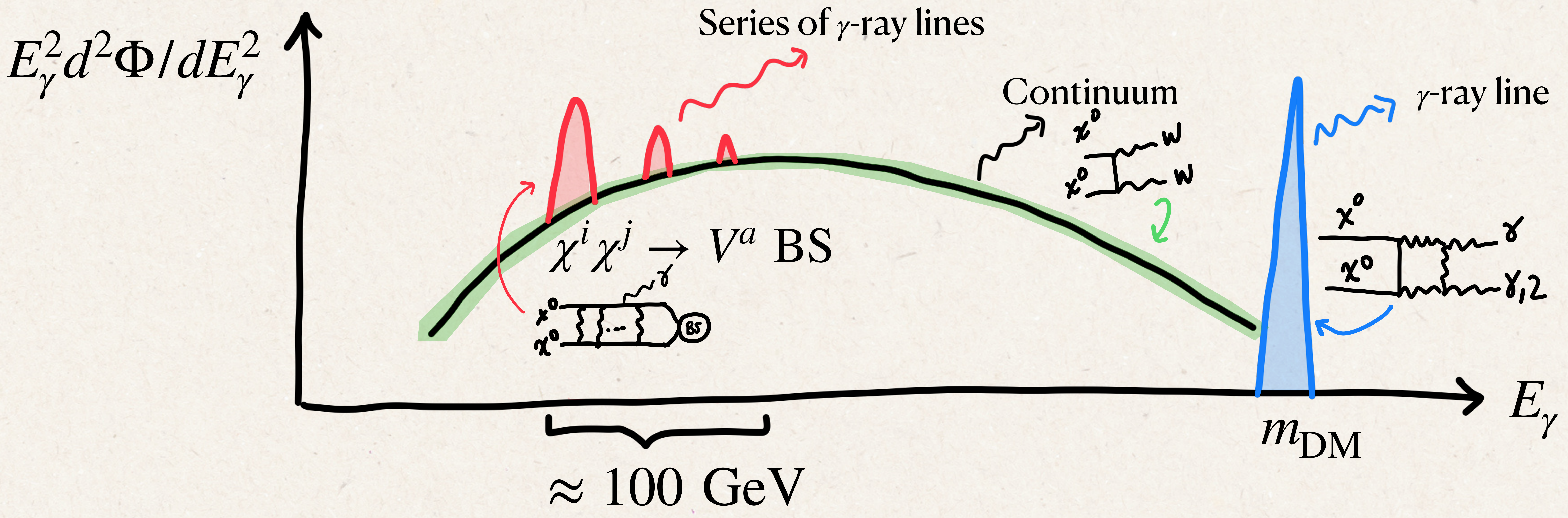
* *[1] NLO electroweak potentials for minimal dark matter and beyond:* ***arXiv:hep-ph/2108.07285***
[2] The Sommerfeld enhancement at NLO and the dark matter unitarity bound: ***arXiv:hep-ph/2305.01680***
† *[3] Non-relativistic pair annihilation of nearly mass degenerate neutralinos and charginos III. Computation of the Sommerfeld enhancements:* ***arXiv:hep-ph/1411.6924***
[4] Capture and Decay of Electroweak WIMPonium: ***arXiv:hep-ph/1610.07617***

Indirect Detection

Can already offer valuable information!

Typical γ-ray flux

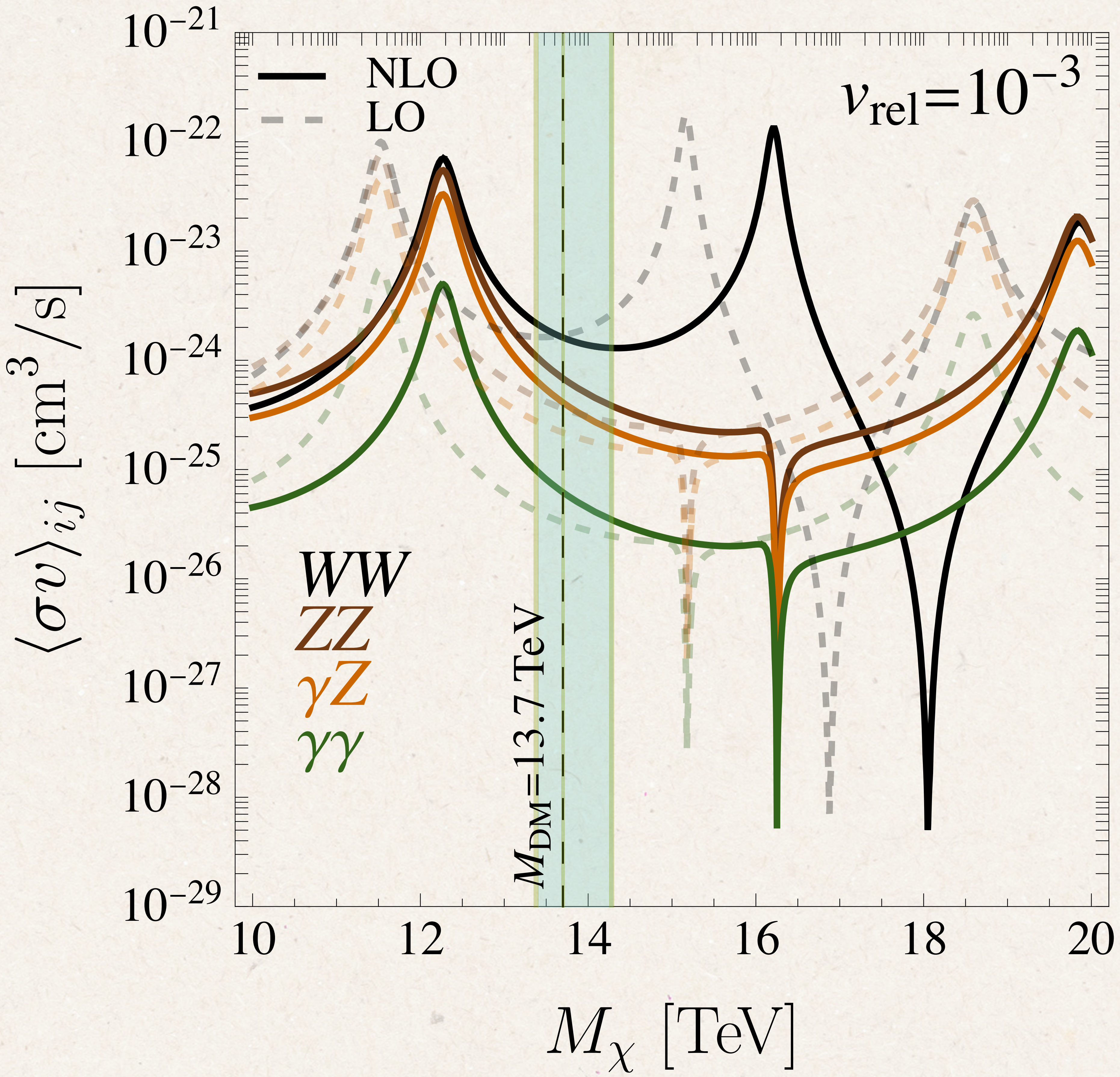
$$\frac{d\Phi}{dE_\gamma d\Omega} = \frac{J(\theta)}{8\pi} \frac{\langle \sigma v \rangle}{M_\chi^2} \frac{d\mathcal{N}}{dE_\gamma}, \qquad \text{where } J(\theta) = \int_{\text{l.o.s.}} ds\, \rho(r(s,\theta))^2,$$

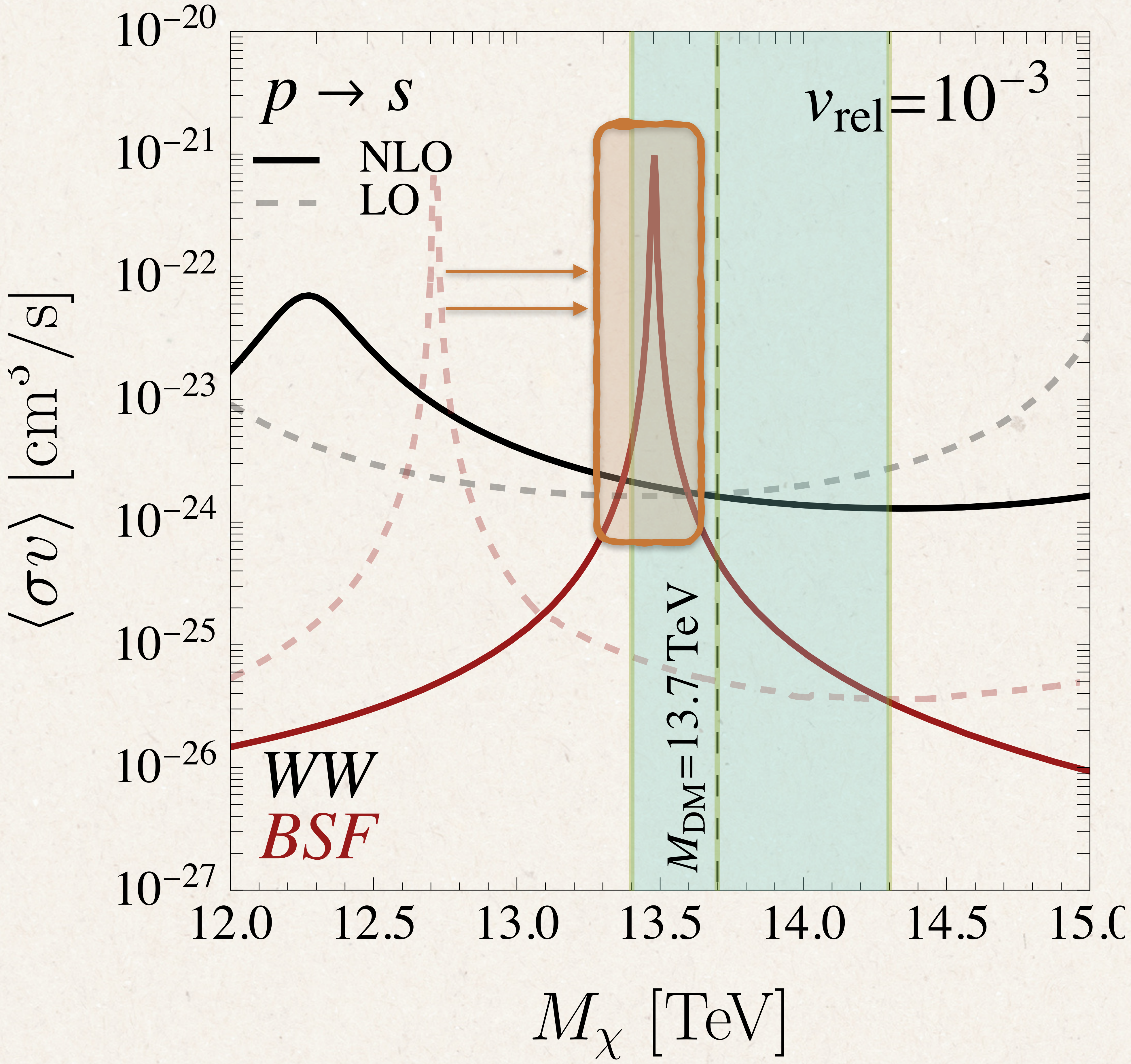


- **Continuum:** Decay and hadronization of heavy EW gauge bosons
- **γ-ray line:** SE boost the loop-induce annihilation into $\gamma\gamma$ and γZ
- **Series of γ-ray lines:** Due to BSF

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

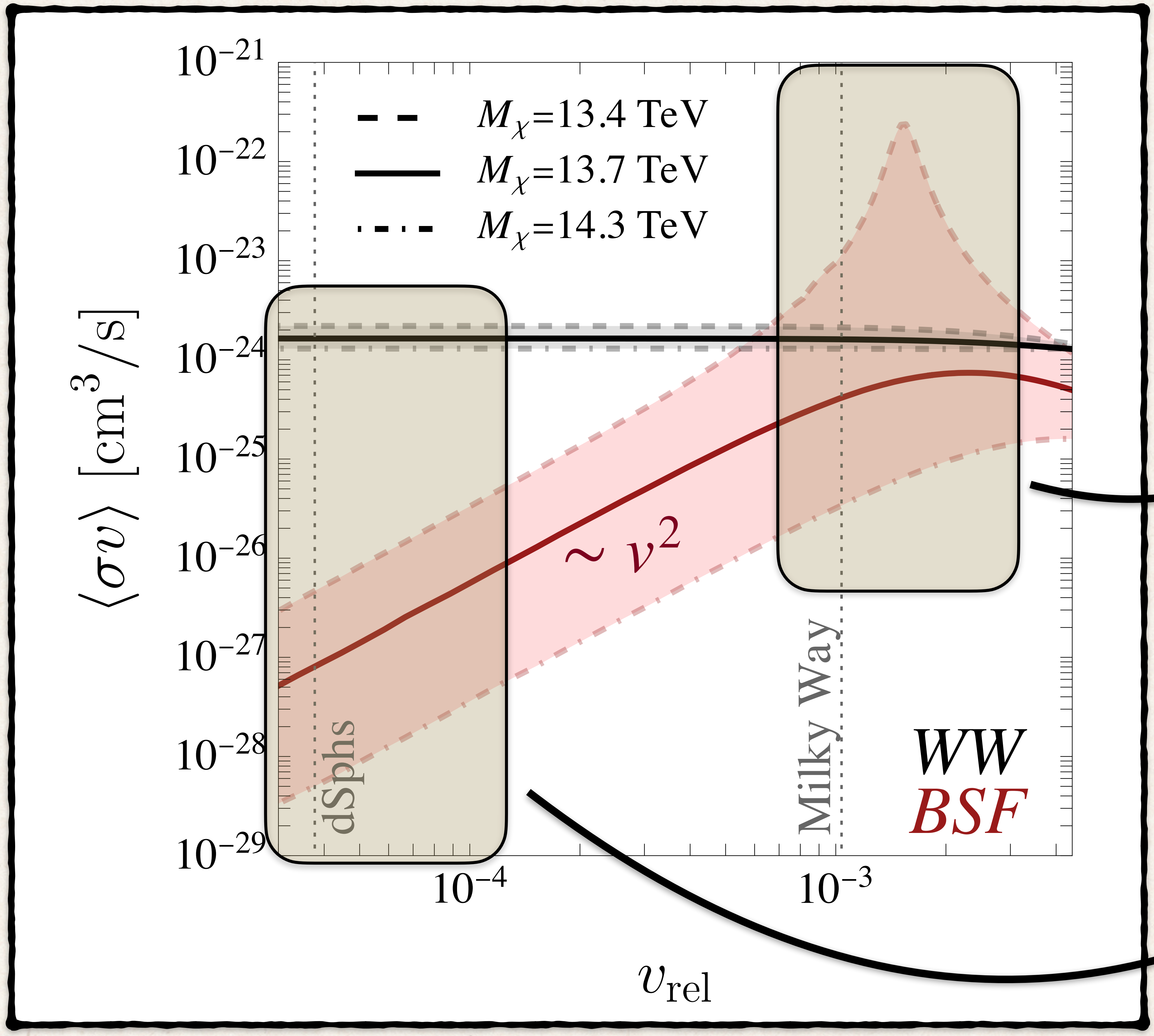
Annihilation cross sections





[1] *Minimal Dark Matter in the sky: updated Indirect Detection probes:* ***arXiv:hep-ph/2507.17607***

Velocity dependence



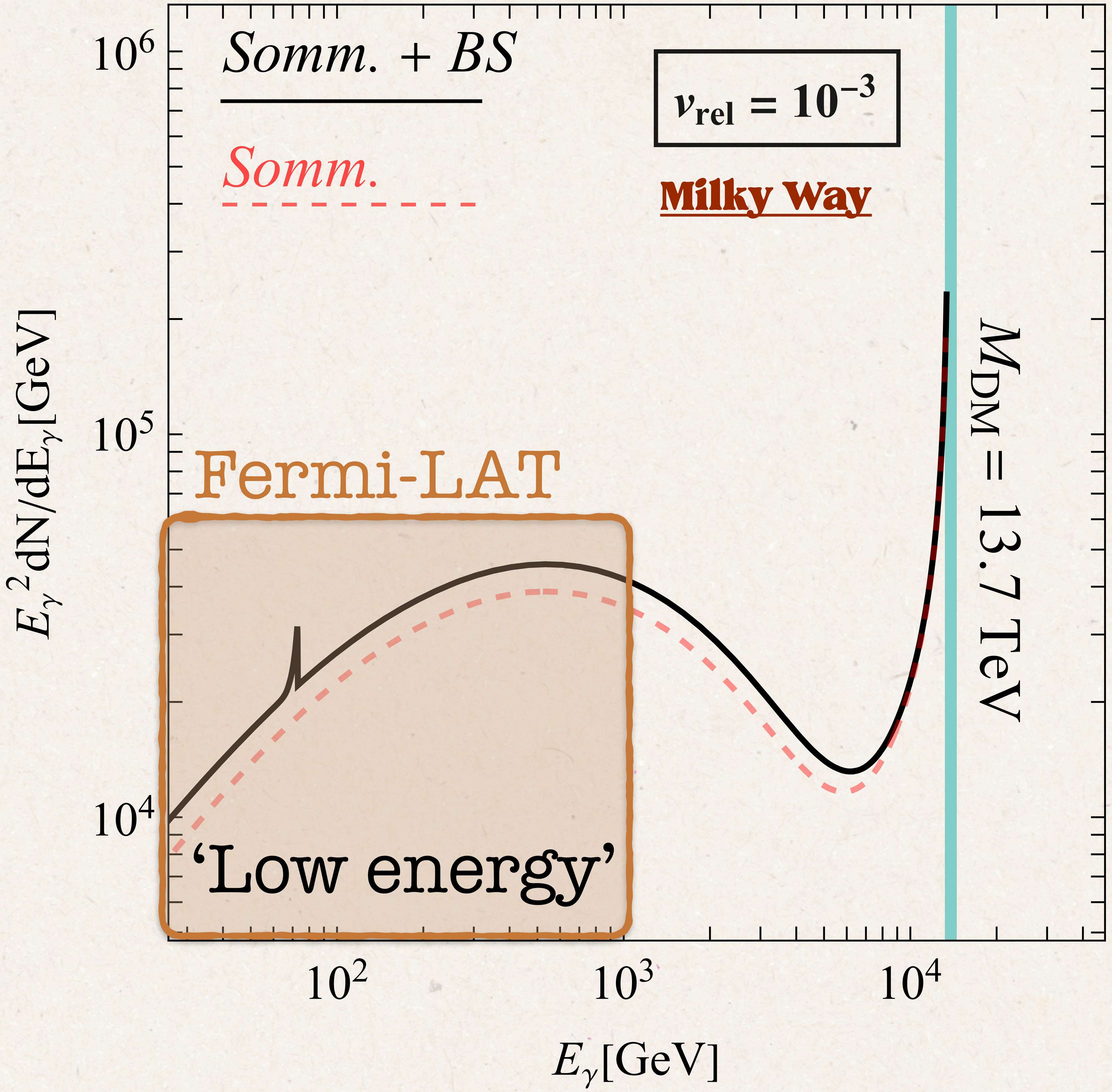
BSF xsec is velocity dependent (p-wave)

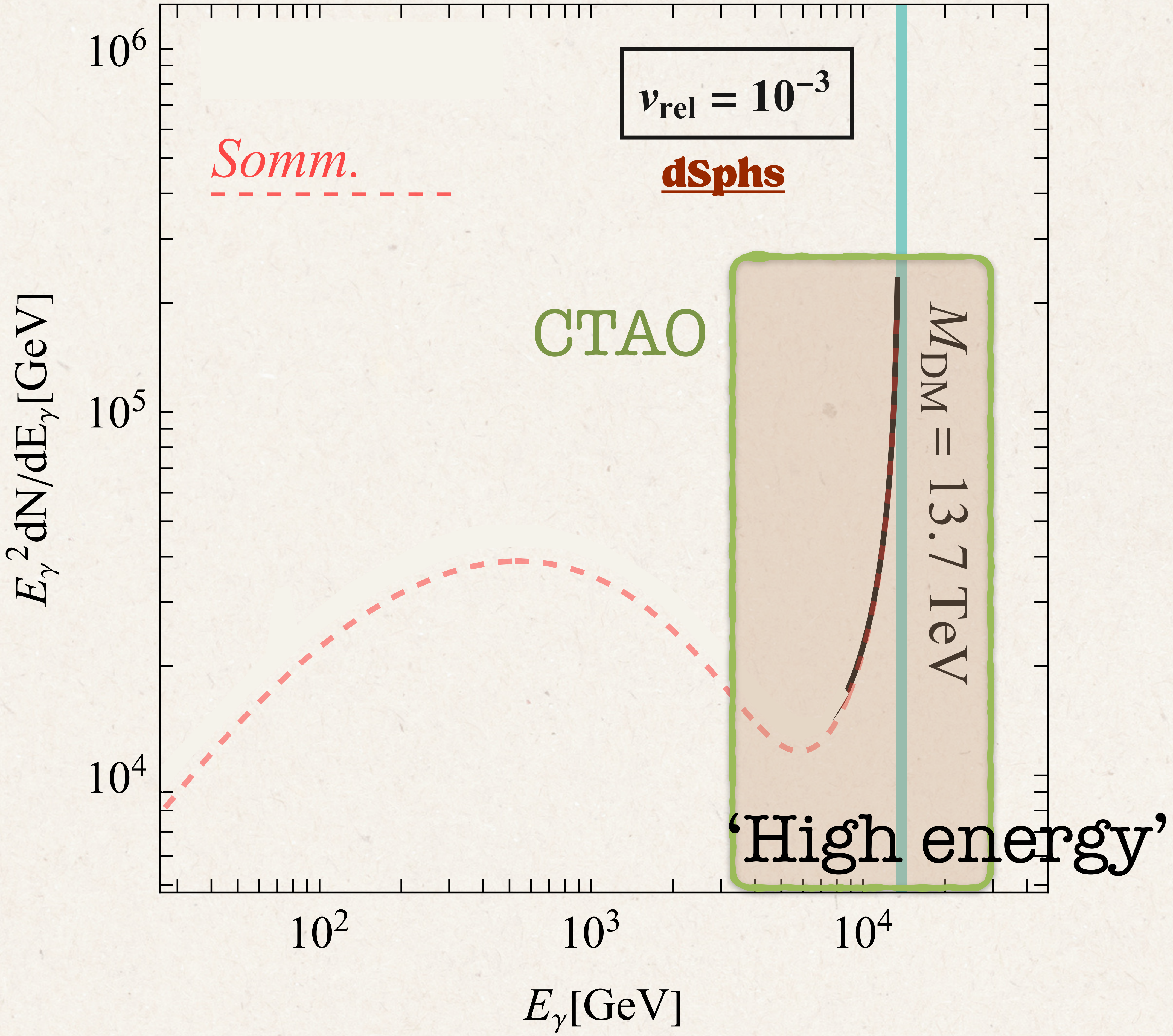
Here BSF is dominant

Here SE dominates

[1] Minimal Dark Matter in the sky: updated Indirect Detection probes: ***arXiv:hep-ph/2507.17607***

The γ ray spectrum





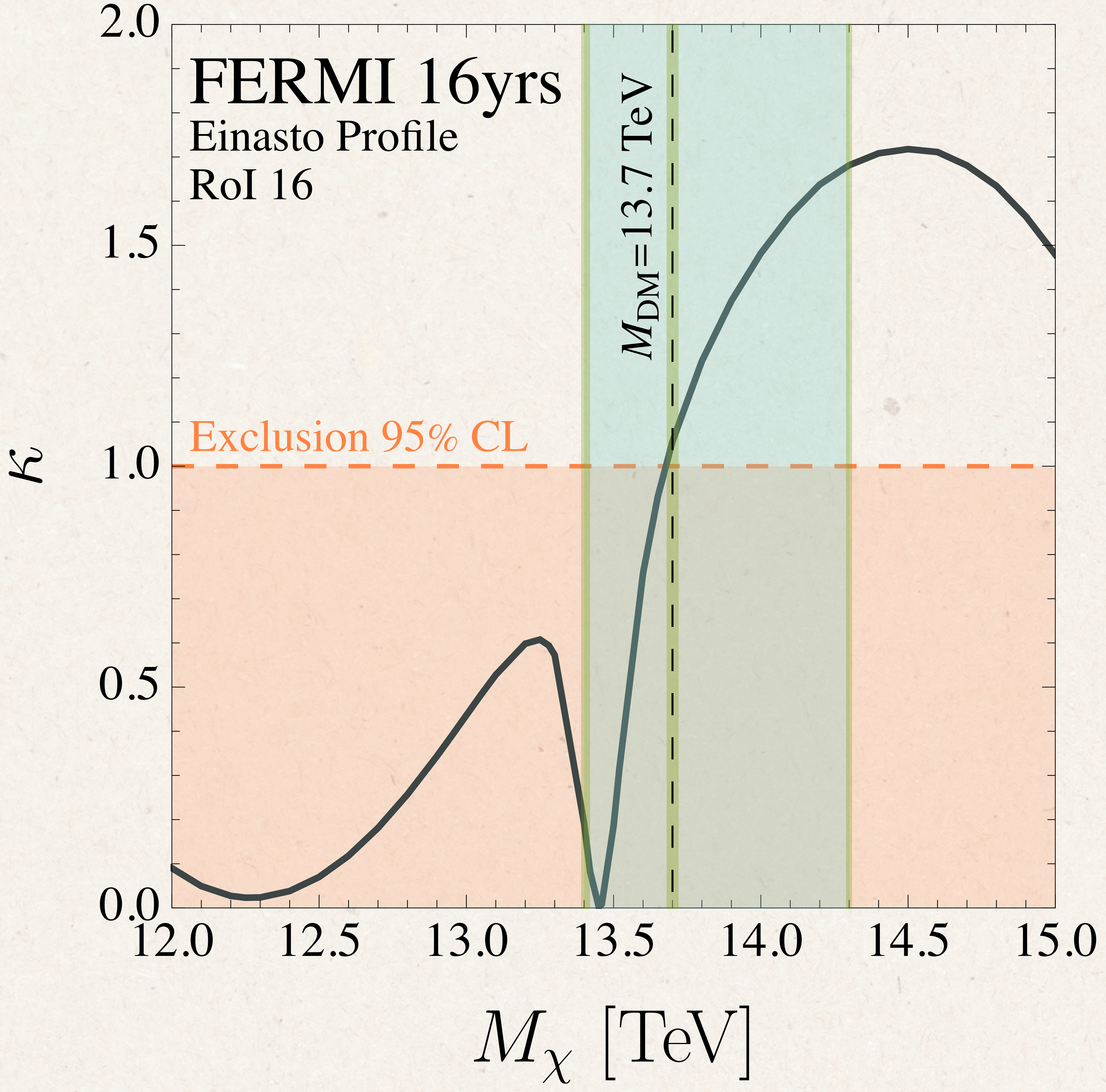
[1] *Minimal Dark Matter in the sky: updated Indirect Detection probes:* ***arXiv:hep-ph/2507.17607***

Fermi-LAT

- **16 yrs of data** + **Masking (Galactic plane + sources)**
- Energy window $E_\gamma \in [25,398]$ GeV
- We use the Fermi-LAT template for astro bkg modeling:
  - Galactic diffuse (A_{diff})
  - Isotropic emission (A_{iso})

- No free parameters in the theory: $\langle \sigma v \rangle \rightarrow \kappa \langle \sigma v \rangle$

Changes of the DM profile can still mitigate the exclusion



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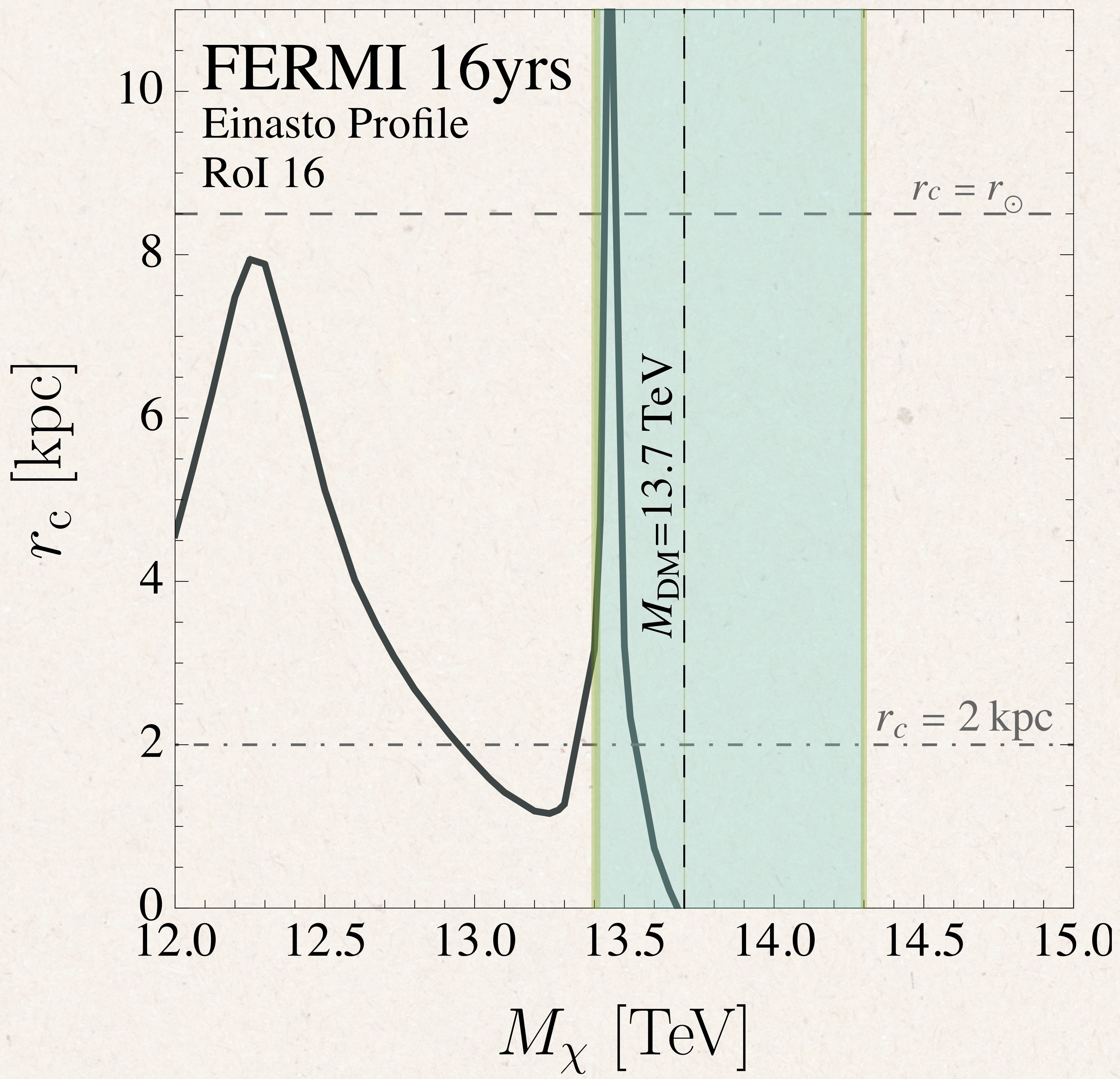
Fermi-LAT

The exclusion depend on the uncertainty in the DM density profile near the GC

Results:

1) The big exclusion at 13.5 TeV is due to the BSF xsec peak
2) 13.4 TeV $\lesssim M_\chi \lesssim$ 13.6 TeV are robustly excluded by Fermi-LAT observation of the Galactic diffuse emission
3) For 13.7 TeV we find a border-line exclusion since any r_c are needed to raise κ to unity



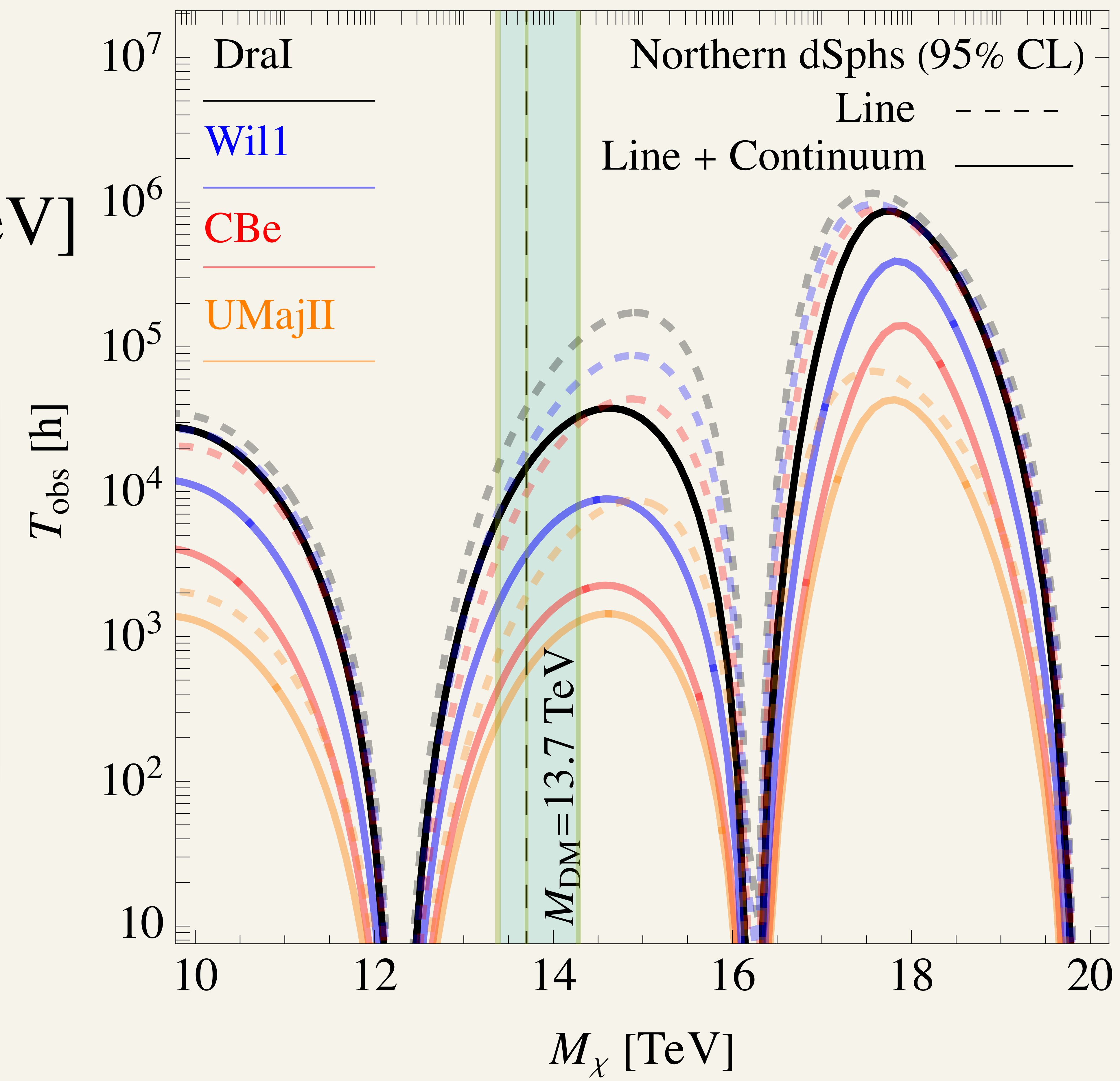
[1] Minimal Dark Matter in the sky: updated Indirect Detection probes: **arXiv:hep-ph/2507.17607**

Cerenkov Telescope Array

- **No current data! near soon... stay tuned :)**
- We consider 20 energy bins spanning $E_\gamma \in [25\ \mathrm{GeV}, 160\ \mathrm{TeV}]$

Results:

1) Best sensitivity $\Rightarrow T_{\mathrm{obs}}^{\mathrm{UMajII}} \simeq 600\ \mathrm{h}$ for $M_{\mathrm{DM}} = 13.7\ \mathrm{TeV}$
2) The other ultra-faint dSphs pose weaker bounds because the impact of the J-factor systematics
3) Including the continuum leads to a ~ 3 better sensitivity (UMajII)



[1] Minimal Dark Matter in the sky: updated Indirect Detection probes: ***arXiv:hep-ph/2507.17607***

Take Home message

- 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 $Y = 0$

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

Majorana Fermion

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

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.

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

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

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

Sommerferld Enhancement

Bound State Formation

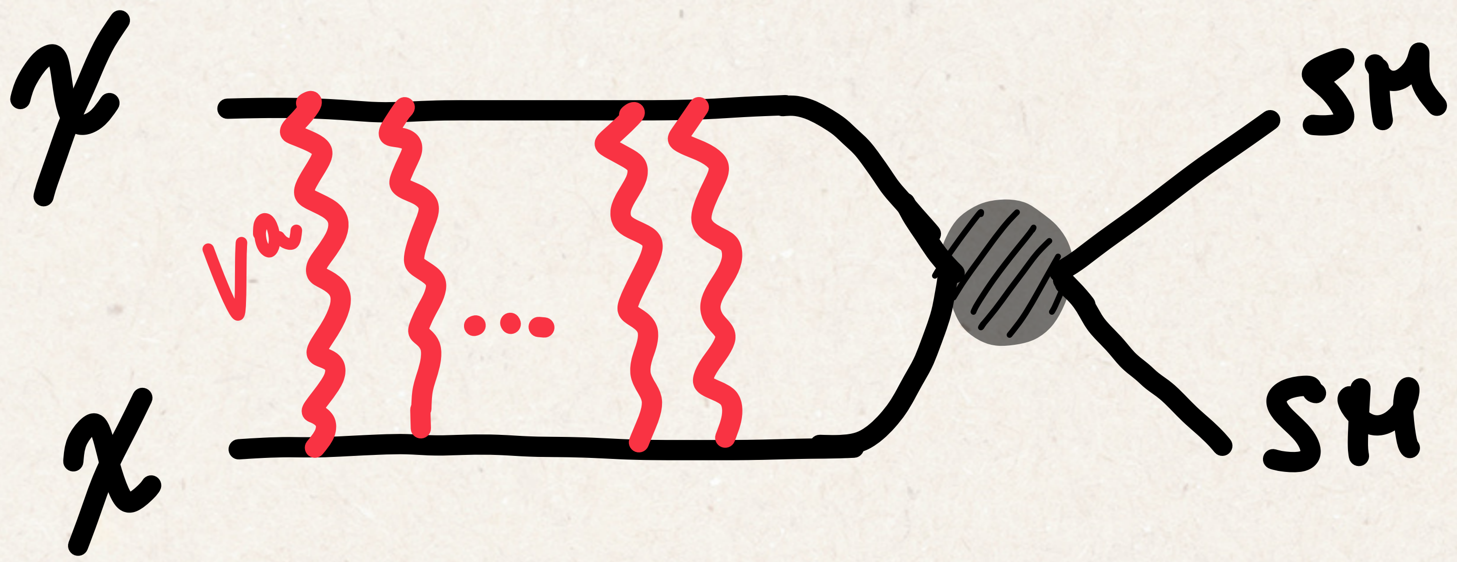
Thermal mass window

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

* [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** $\chi^0\chi^0 \to V^a V^a$



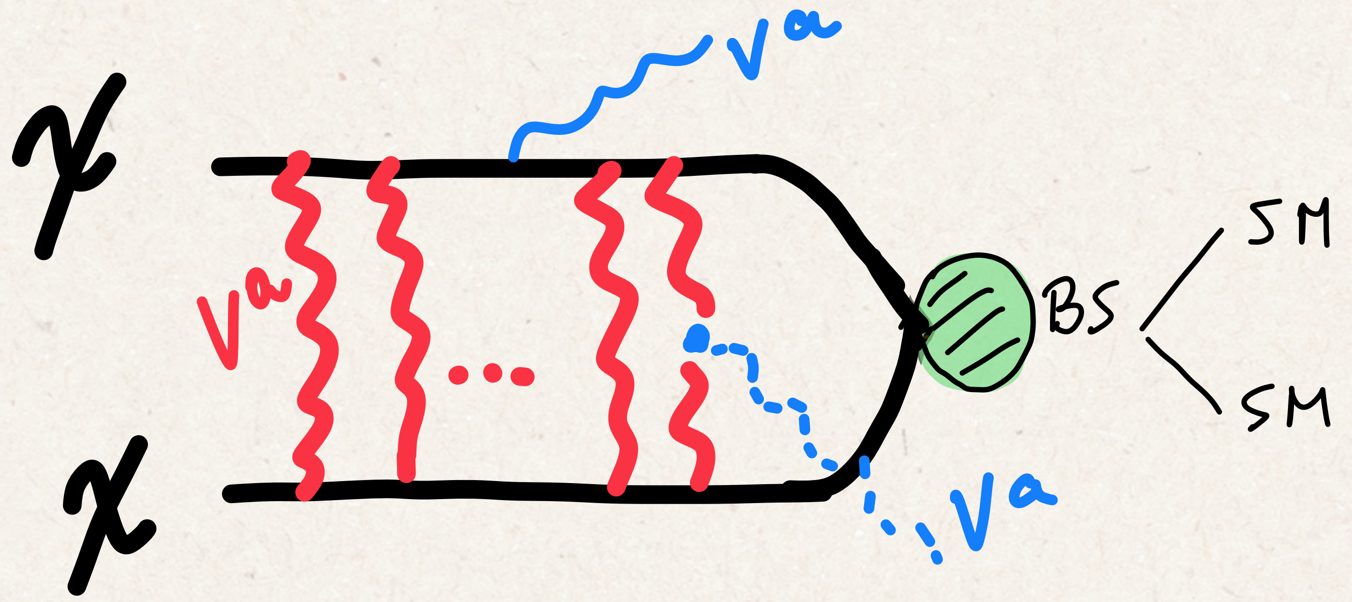
- Long range effects modify the wave function of the 2-body DM-DM initial state
- $\sigma_{\rm NR}$ can receive large non-perturbative corrections (low vel. Enhanced)

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

Not so easy... *

broken phase, NLO corrections, ecc...

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



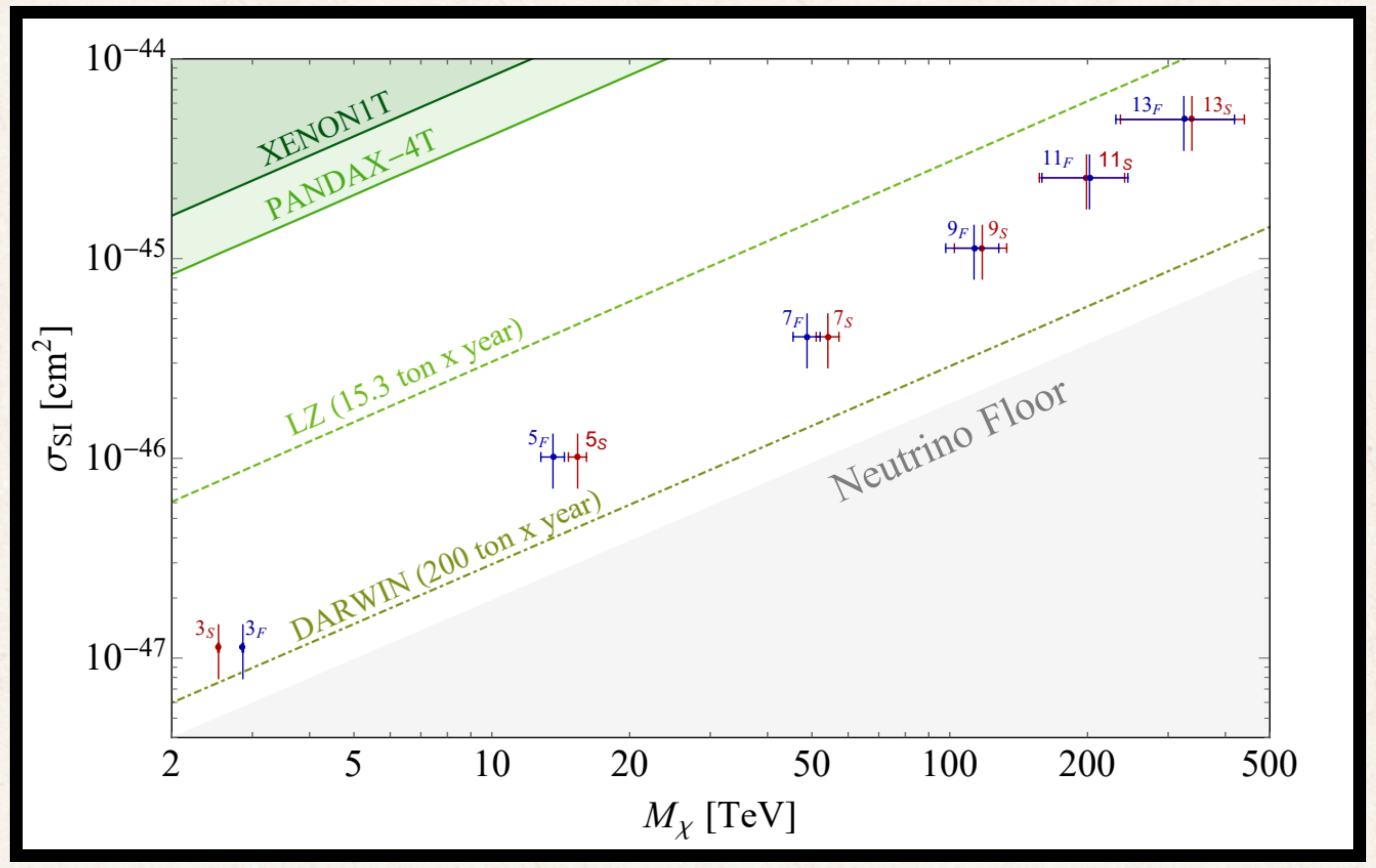
- The same long-range potential is also responsible for BSF.
- ${}^1S_3 : E_B \sim 80\ \mathrm{GeV}$
- BS annihilation with a rate $\Gamma_{\rm ann} \sim \alpha_2^5 M_\chi$ into SM particles ($f\bar{f}$ and HH^*)

* [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**

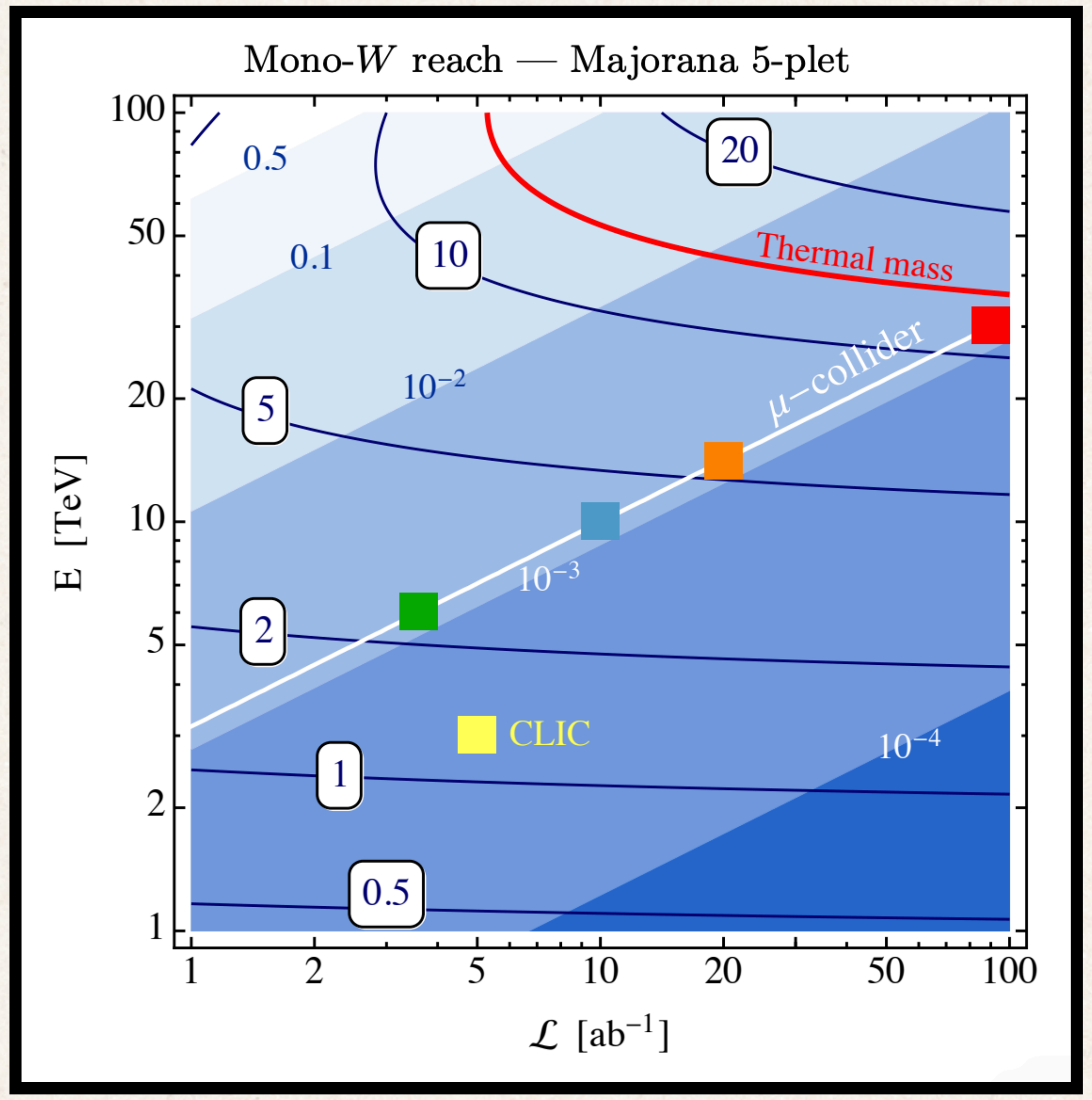
- EW multiplets within the reach of next generation experiments (~30 yrs)



2 **Collider searches**

- Will probe small multiplets in the future ($\gtrsim$ 50 yrs) !

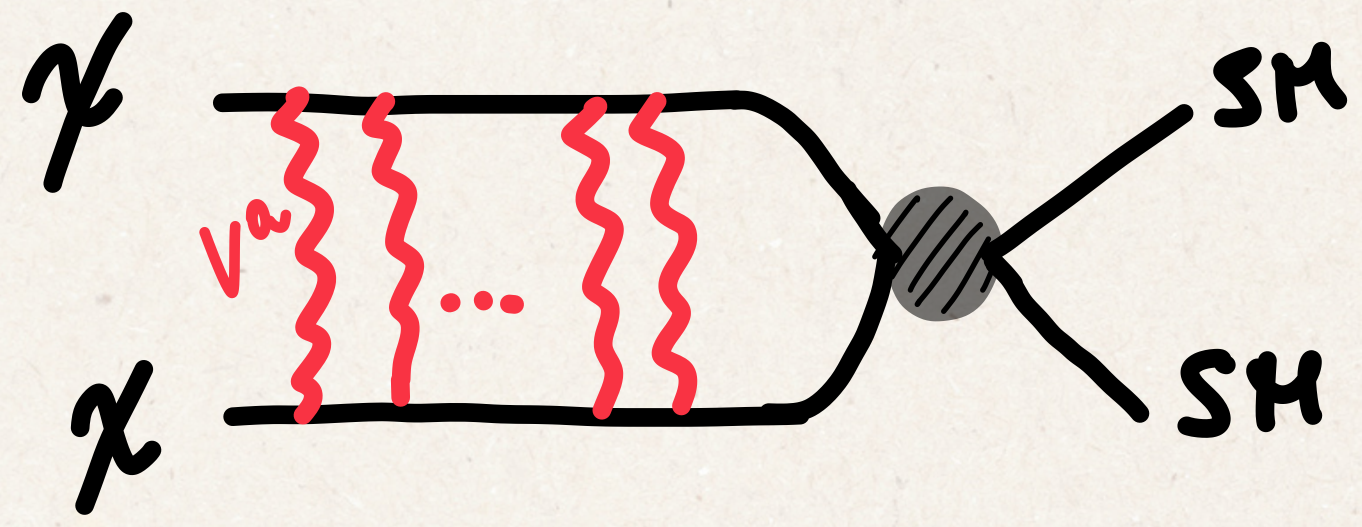
Futuristic μC???



* [1] Closing the window on WIMP Dark Matter: **arXiv:hep-ph/2107.09688**

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)

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

- 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 $V = -\alpha/r$

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

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

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

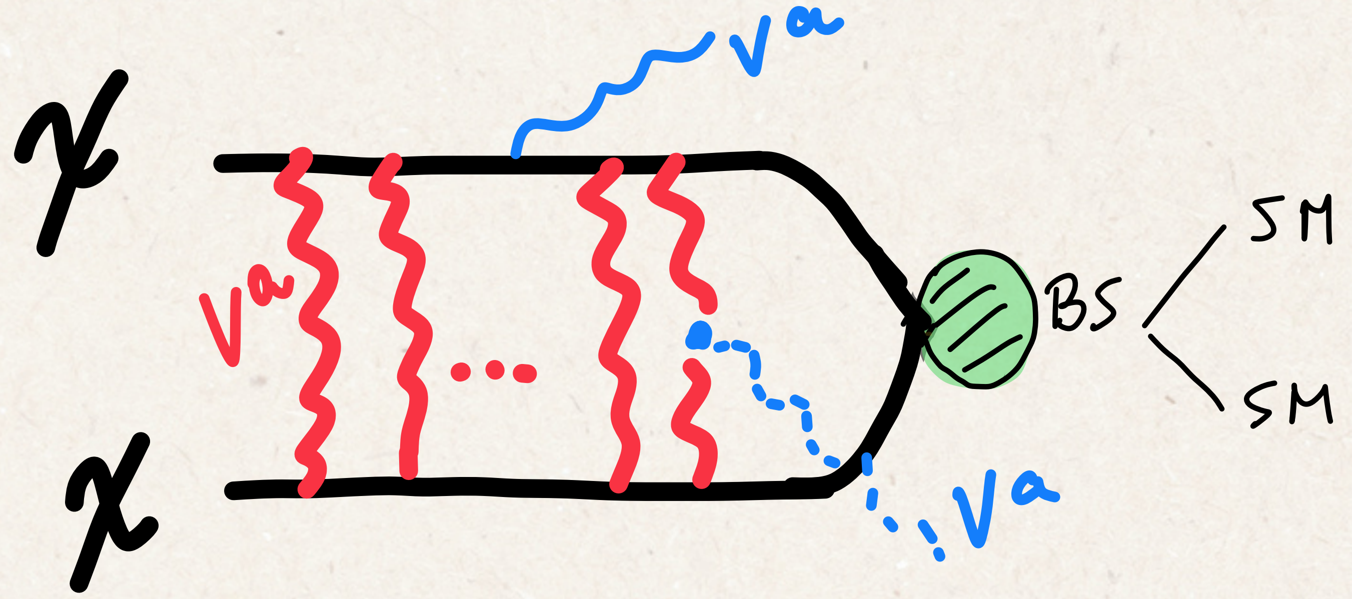
Not so easy...

1) broken phase
2) NLO corrections

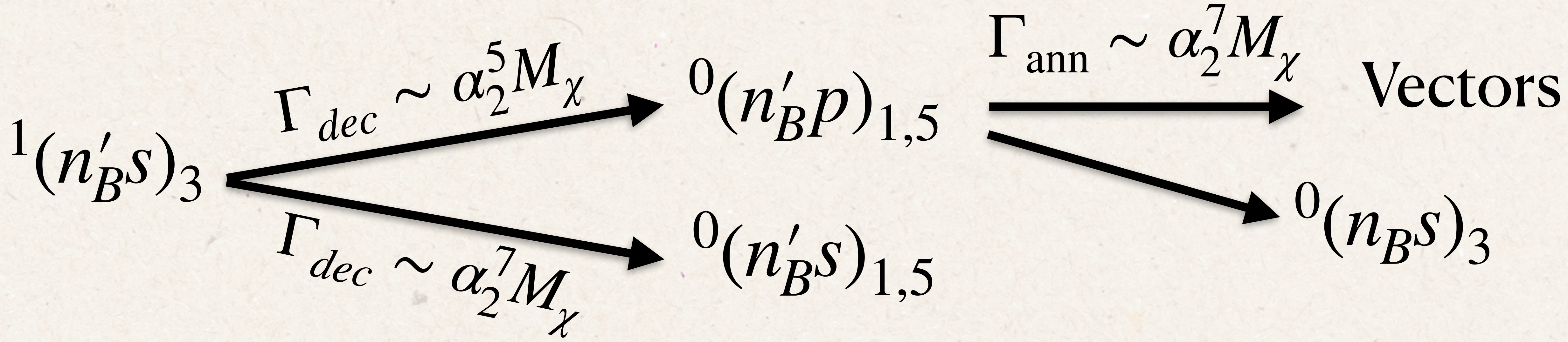
[1] Minimal Dark Matter: **arXiv:hep-ph/0512090**

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 $\chi_i\chi_j \to V^a + \text{BSF}$
- 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 $\Gamma_{\text{ann}} \sim \alpha_2^5 M_\chi$ into SM particles ($f\bar{f}$ and HH^*)



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

Spectrum

$$\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}E_\gamma} = \frac{1}{\langle\sigma v\rangle^{\mathrm{NLL}}_{\mathrm{line}}}\left(\left.\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}E_\gamma}\right|_{\mathrm{Cont}} + \left.\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}E_\gamma}\right|_{\mathrm{BS-line}} + \left.\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}E_\gamma}\right|^{\mathrm{NLL}}_{\mathrm{line}}\right)$$

1 **Continuum**

$$\left.\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}E_\gamma}\right|_{\mathrm{Cont}} = \langle\sigma v\rangle_{1s3}\sum_{i=\{q,\ell,h\}}\mathrm{BR}_i\frac{\mathrm{d}N^i_\gamma}{\mathrm{d}E_\gamma}(M_\chi) + \langle\sigma v\rangle_{WW}\frac{\mathrm{d}N^W_\gamma}{\mathrm{d}E_\gamma}(M_\chi) + \frac{\langle\sigma v\rangle^{\mathrm{NLL}}_{\mathrm{line}}}{\tan^2\theta_w}\frac{\mathrm{d}N^Z_\gamma}{\mathrm{d}E_\gamma}(M_\chi)\ ,$$

2 **BSF line**

$$\left.\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}E_\gamma}\right|_{\mathrm{BS-line}} = \frac{1}{2}\langle\sigma v\rangle_{1s3}\frac{\mathrm{d}N^\gamma_\gamma}{\mathrm{d}E_\gamma}(E_b)$$

3 **Endpoint**

$$\left.\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}E_\gamma}\right|^{\mathrm{NLL}}_{\mathrm{line}} = \langle\sigma v\rangle^{\mathrm{NLL}}_{\mathrm{line}}\Big(2\delta(E_\gamma - M_\chi) + \mathcal{E}^{\mathrm{NLL}}(E_\gamma)\Big)\ ,$$

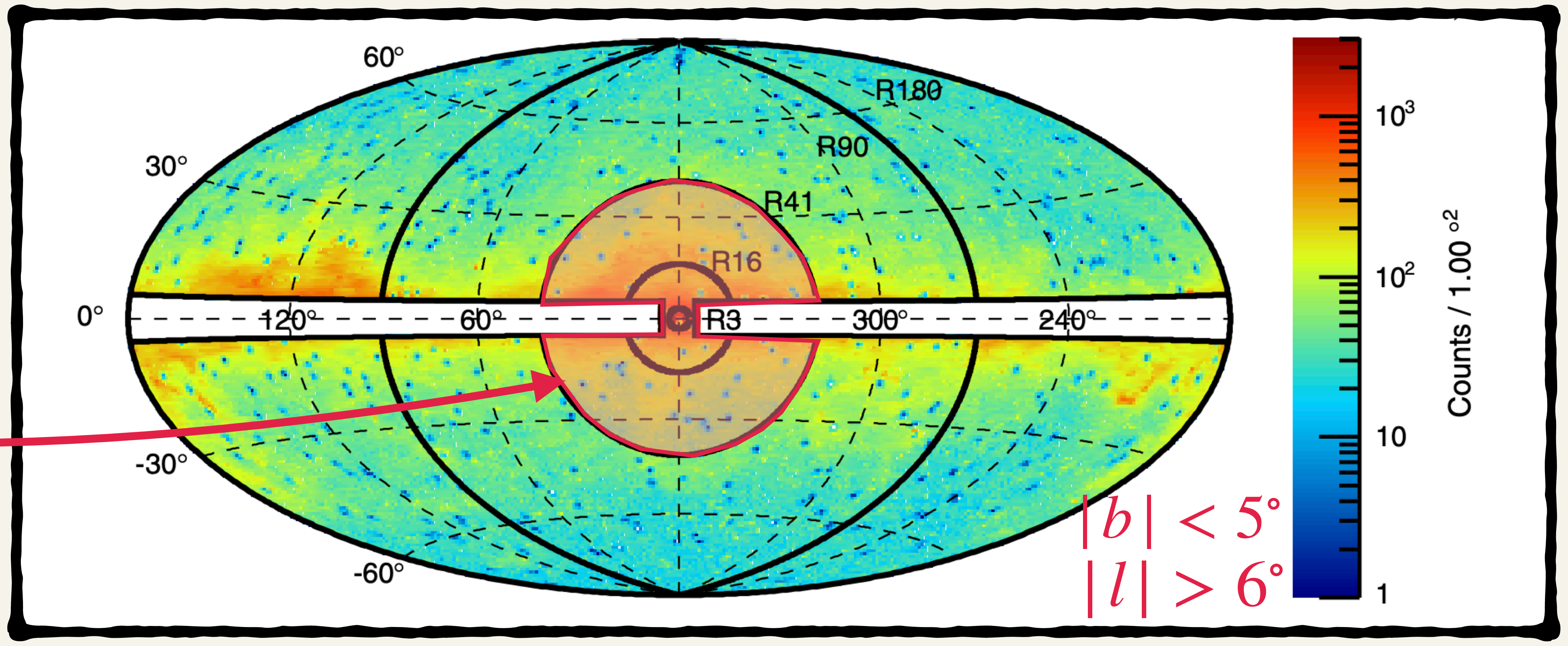
Choice of the Targets

1 Galactic Halo (Fermi-LAT)

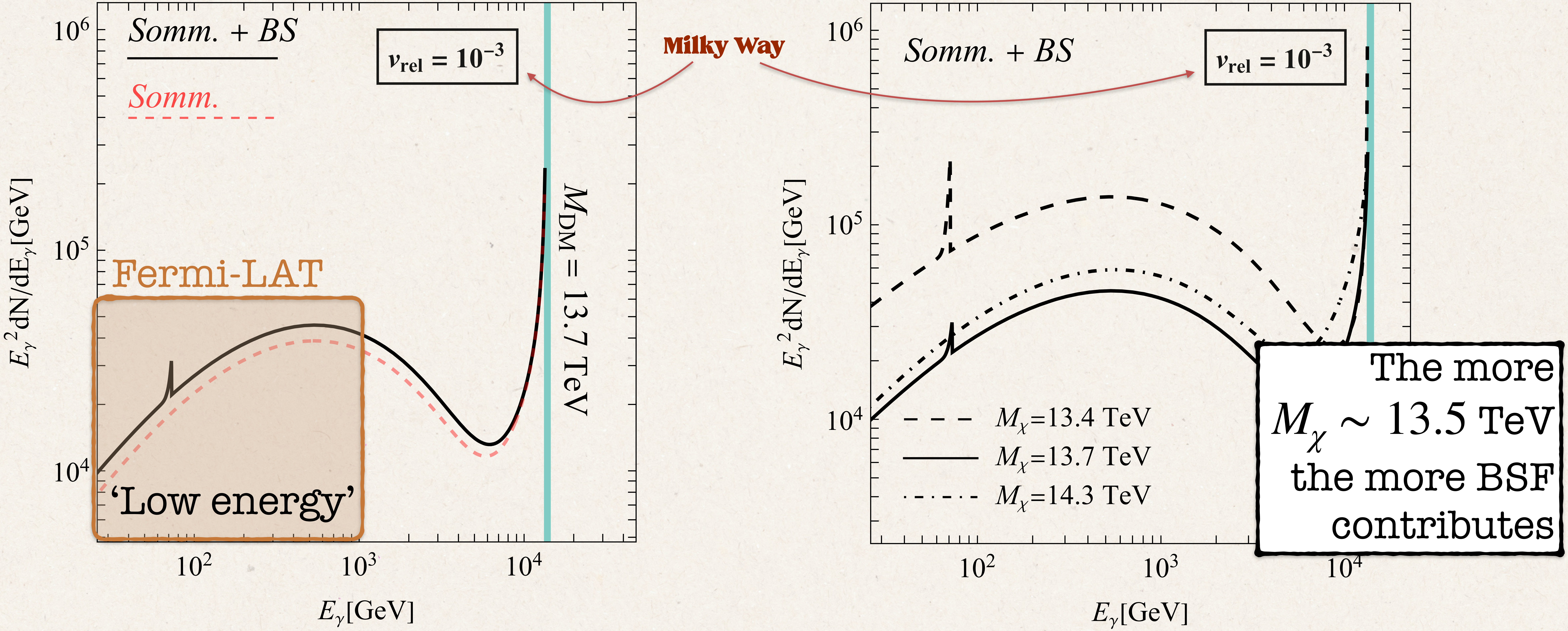
- We focus on a specific RoI:
  - The presence of a γ-ray line at E_b well within Fermi-LAT
  - Large angular size to mitigate DM density profile uncertainties
  - But not so large as to introduce template fit mismodelling for the galactic diffuse emission
  - J factor uncertainties well under control
- We identify the RoI 16 as the optimal fiducial region.
- It optimizes the SNR for an Einasto profile

2 Dwarf Spheroidal Galaxies (CTAO)

- DM-dominated with low astro bkg. ⇒ Robust constraints
- Less luminosity
- We focus on a sample of dSphs located in the northern hemisphere: (Draco I, Willman I, Coma Berenices and Ursa Major II)



The γ ray spectrum



[1] Minimal Dark Matter in the sky: updated Indirect Detection probes: **arXiv:hep-ph/2507.17607**

CTAO Analysis

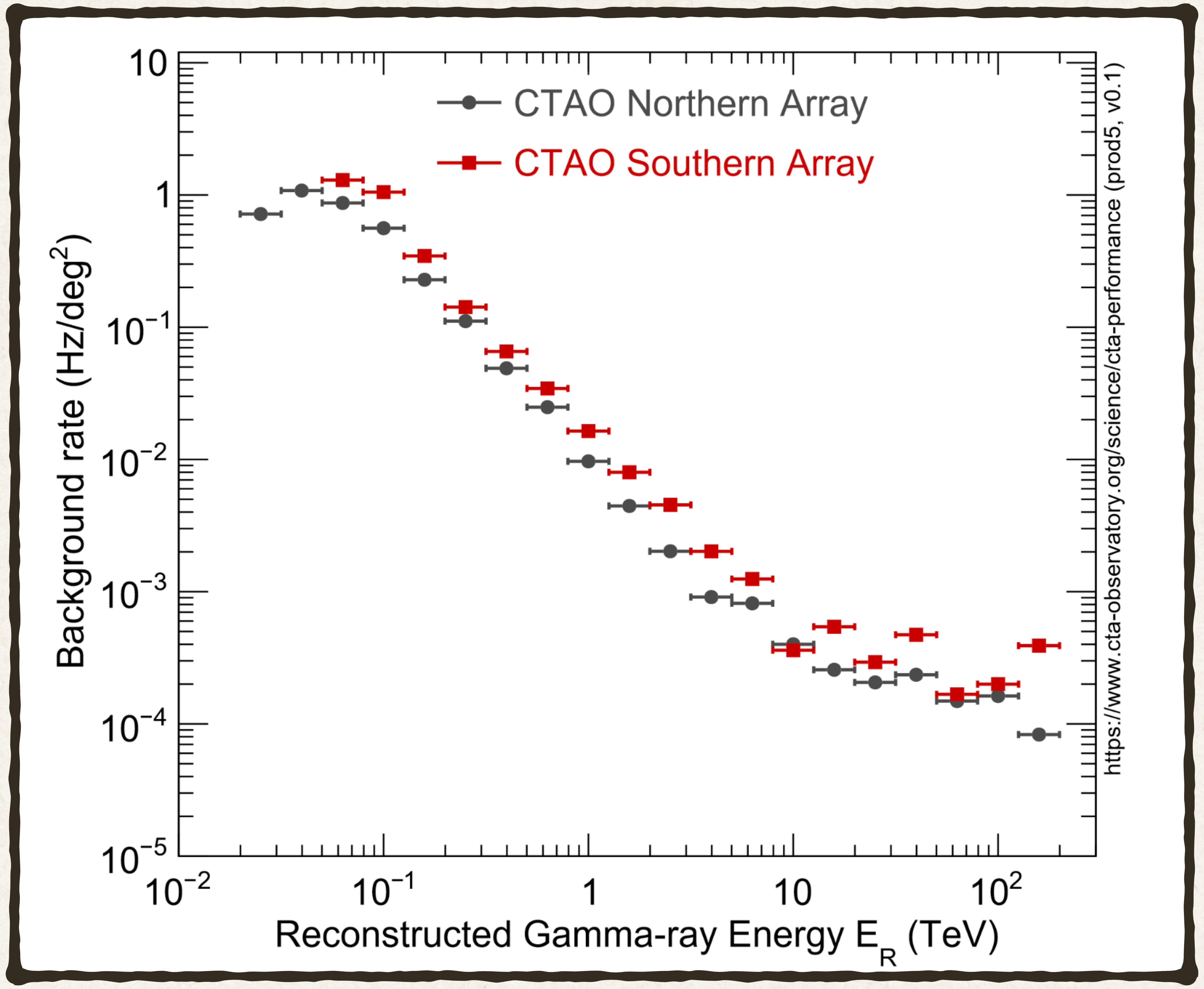
- **No current data! near soon... stay tuned :)**
- We consider 20 energy bins spanning $E_\gamma \in [25\ \text{GeV}, 160\ \text{TeV}]$
- Northern hemisphere and RoI with $\Delta\theta_{\text{dPhs}} = 0.5^\circ$

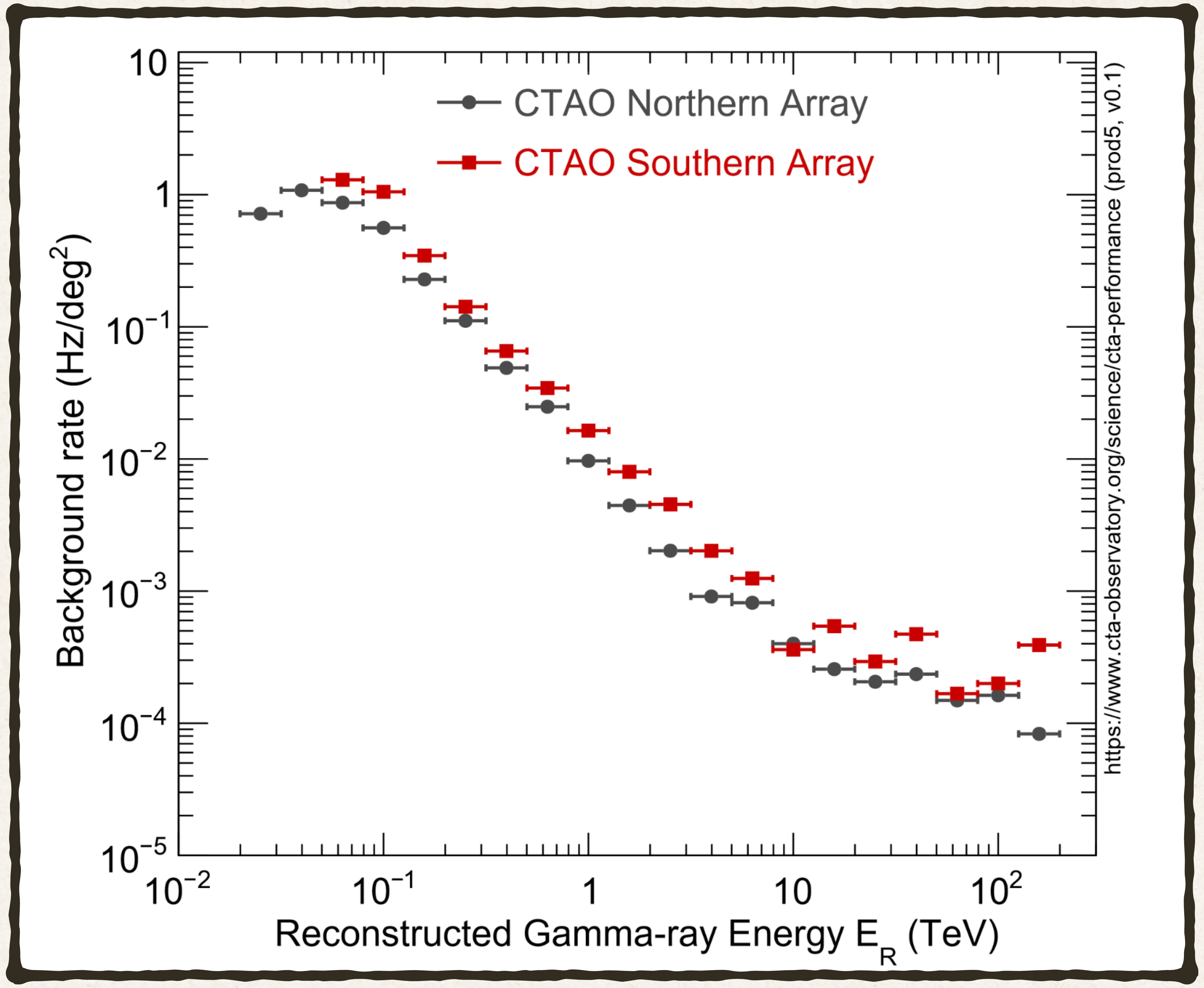
$$N^i_{bkg} = T_{\text{obs}} \frac{\Delta\Gamma^i_{\text{bkg}}}{\Delta\Omega} \Delta\Omega_{\text{dSphs}} \text{ where } \Delta\Omega_{\text{dSphs}} \approx 2.4 \times 10^{-4} \text{sr}$$

$$N^i_{\text{DM}} = T_{\text{obs}} \int_{E_i}^{E_{i+1}} dE' \ \frac{d\Gamma_{\text{DM}}(E')}{dE'}$$

$$\frac{d\Gamma_{\text{DM}}(E')}{dE'} = \int_0^{M_\chi} dE_\gamma \frac{d\Phi_{\text{DM}}(E_\gamma)}{dE_\gamma} \mathscr{A}(E_\gamma) R(E_\gamma, E')$$

CTAO Analysis





https://www.ctao.org/

CTAO Analysis

We fix $\kappa = 1$ in order to determine $T_{\rm obs}$ and we define a poissonian likelihood:

$$\mathscr{L}(T_{\rm obs}) = \prod_{i=1}^{\mathscr{N}} \frac{N^i_{\rm th}(T_{\rm obs})^{N^i{\rm obs}(T_{\rm obs})}}{N^i{}_{\rm obs}(T_{\rm obs})!} e^{-N^i{\rm th}(T_{\rm obs})} \equiv \prod_{i=1}^{\mathscr{N}} \mathscr{L}_i(T_{\rm obs}),$$

We add also the systematic uncertainty of the J-factor as

$$\mathscr{L}_{\rm sys}(T_{\rm obs}) = \prod_{i=1}^{\mathscr{N}} \max_J \left[\mathscr{L}_i(T_{\rm obs}) \times \mathscr{L}^J\right]$$

with $\mathscr{L}^J = \dfrac{1}{\ln(10) J_{\rm obs}} \mathscr{G}(\log_{10} J \,|\, \log_{10} J_{\rm obs})$

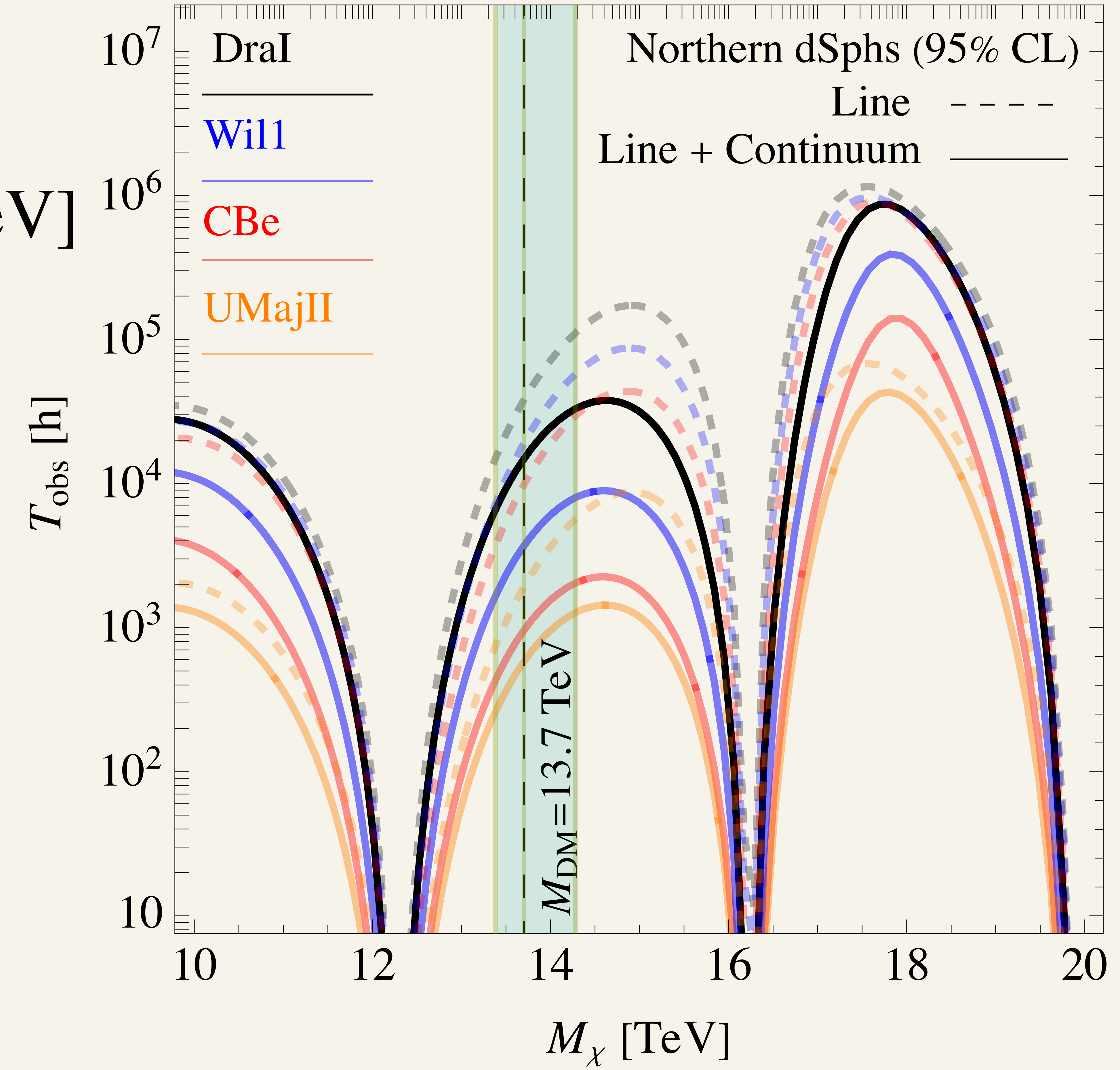
$$\mathrm{TS}(T_{\rm obs}) = -2 \ln \left(\mathscr{L}_{\rm sys}(T_{\rm obs}) / \mathscr{L}^0_{\rm sys}(T_{\rm obs}) \right),$$

Cerenkov Telescope Array

- **No current data! near soon... stay tuned :)**
- We consider 20 energy bins spanning $E_\gamma \in [25\ \text{GeV}, 160\ \text{TeV}]$

Results:

1) Best sensitivity $\Rightarrow T_{\text{obs}}^{\text{UMajII}} \simeq 600\ \text{h}$ for $M_{\text{DM}} = 13.7\ \text{TeV}$
2) The sharp variation are due to the ann. xsec peak
3) The other ultra-faint dSphs pose weaker bounds because the impact of the J-factor systematics
4) Including the continuum leads to a ~ 3 better sensitivity (UMajII)



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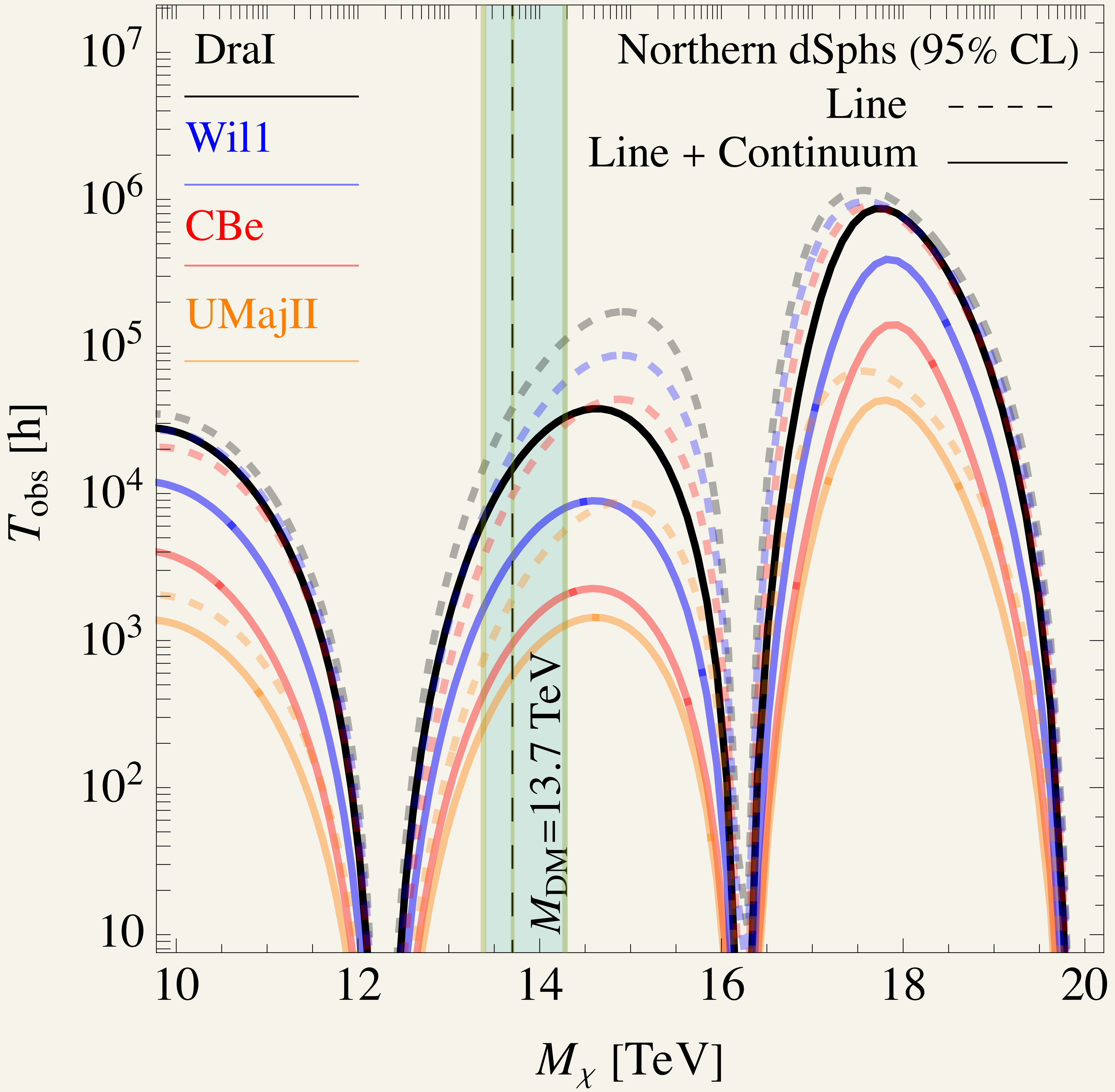
Cerenkov Telescope Array

Systematic uncertainties have a greater impact on line only analysis ⇒ a sharp feature affect less bins in the spectrum.

As a result, the systematic uncertainty from the J-factor leads to a stronger penalization of the sensitivity compared to continuum searches, where the deviation with respect to the background only hypothesis is distributed over a larger number of bins. As a consequence, we find that in the line-only case, the CTAO sensitivity across the various dSphs tends to be comparable, despite the differences in the central values of the J-factors



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