

# From WIMPs to PBHs: Indirect Detection of Heavy Dark Matter

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In Collaboration with: M. Aghaie, G. Marino & P. Panci

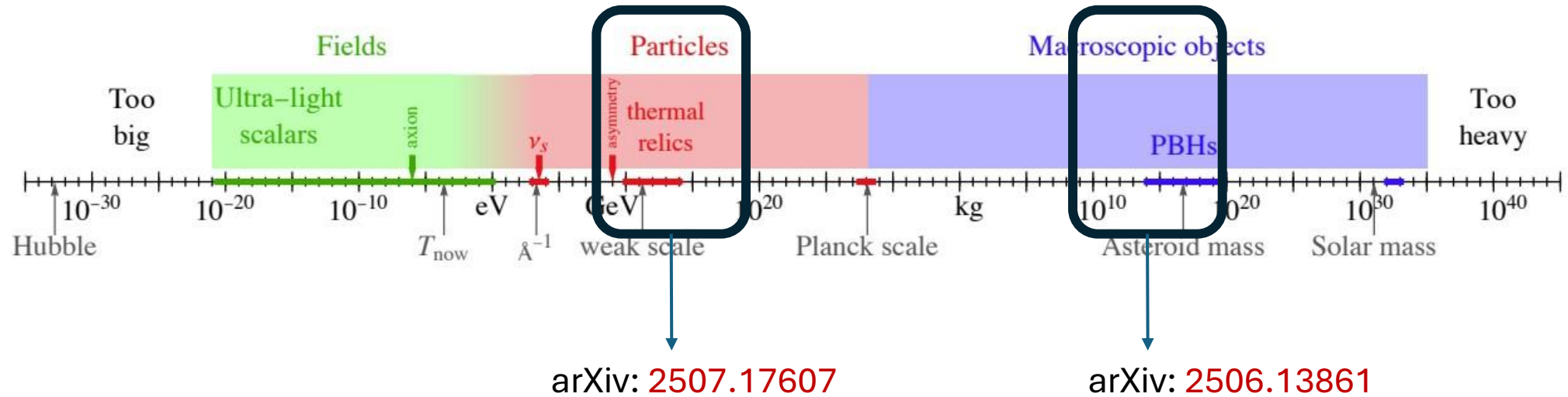
Based on: arXiv:2507.17607

In Collaboration with: G. Marino, P. Panci & M. Zantedeschi

Based on: arXiv:2506.13861

# The Mass Scale of Dark Matter

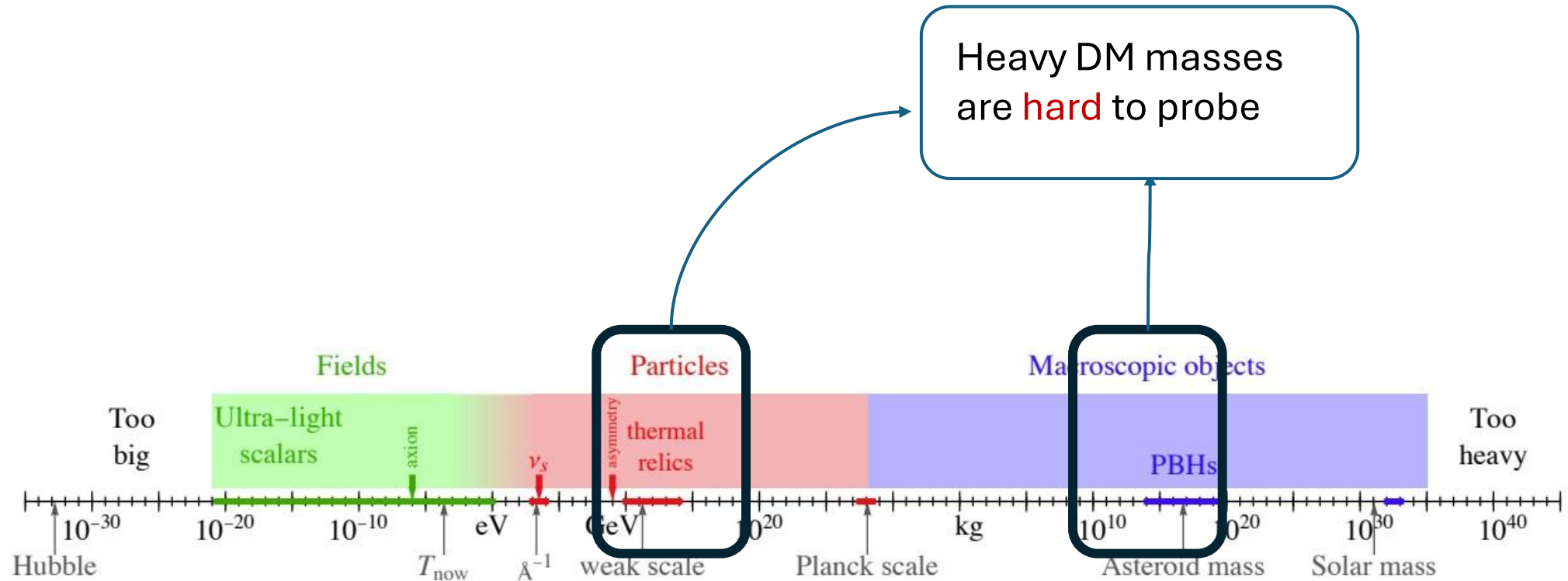
DM: Long Story Short...



- Stable
- Non-Relativistic
- Feebly Interacting with SM

(Plot from arXiv:2406.01705)

# The Mass Scale of Dark Matter



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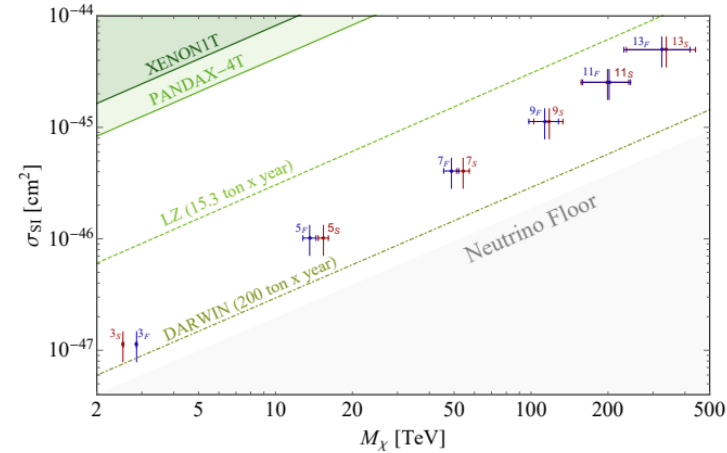
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# How Difficult: the case of WIMPs

From arXiv:2107.09688

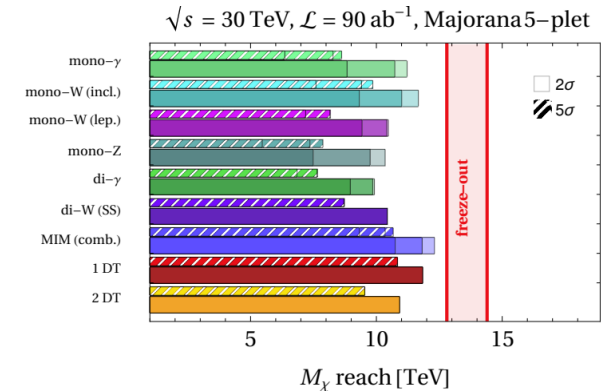
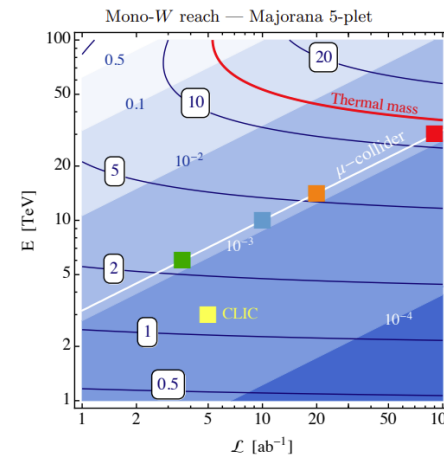
- **Direct Detection:**

**EW multiplets** within the reach of next-generation experiments



- **Collider Searches:**

Will probe small Electroweak Representations in the **future**.  
A final word from a future  $\mu$ -Collider?

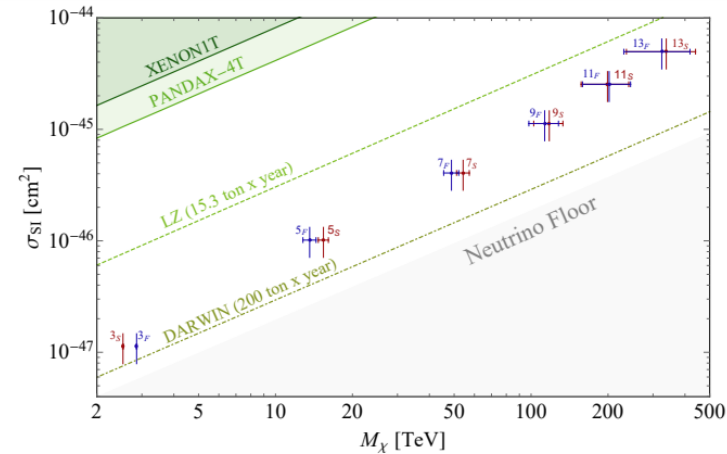


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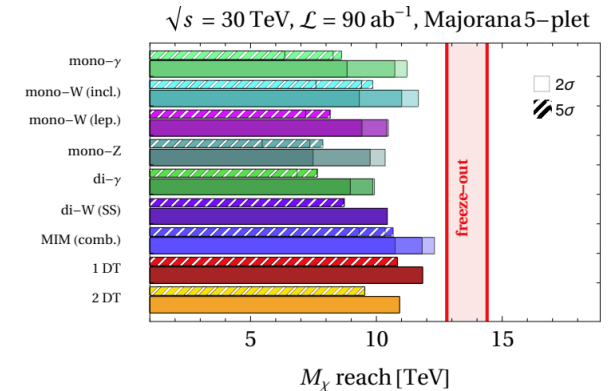
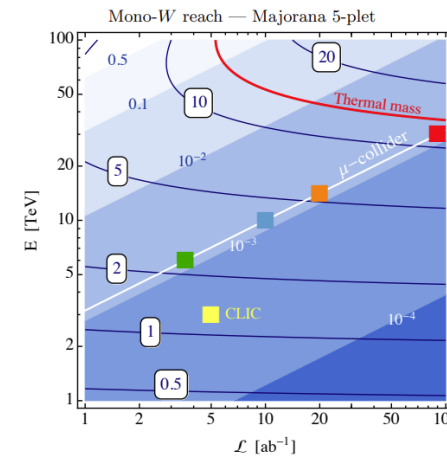
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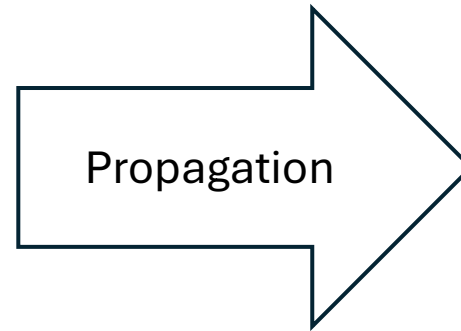
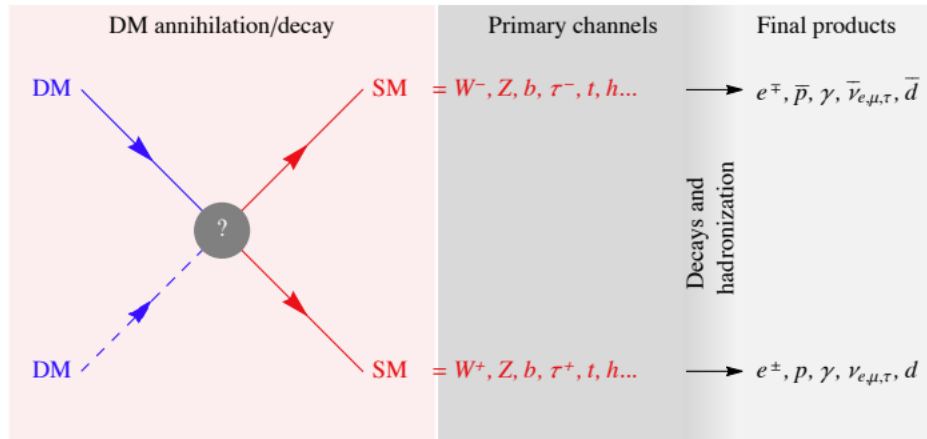


- **Indirect Detection:**

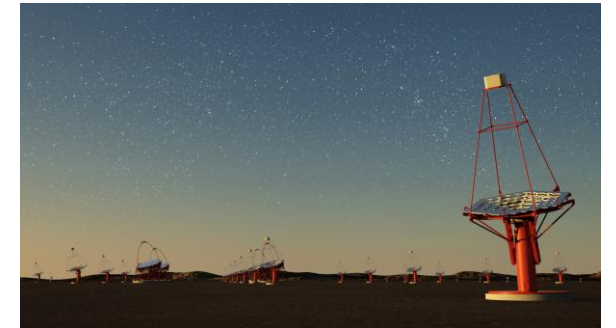
Can already offer valuable information!

# Indirect Detection: from DM to Cosmic Rays

DM annihilation or decay in astrophysical targets



Observation



From arXiv:2406.01705

Stable states  
(**Cosmic rays**)

- $\gamma$ -Rays
- neutrinos
- positrons
- antiprotons
- antideuteron

# Back to WIMPs: Minimal Dark Matter

(arXiv:hep-ph/0512090)

## Minimal Dark Matter

Consider a generic EW multiplet:

$$\chi \equiv \mathbf{1}_c, \left( \begin{array}{c} \chi_1 \\ \chi_2 \\ \dots \\ \chi_n \end{array} \right) \left. \vphantom{\begin{array}{c} \chi_1 \\ \chi_2 \\ \dots \\ \chi_n \end{array}} \right\} SU(2)_{EW} \text{ and } Y. \quad (1)$$

The DM candidate is the neutral component of the n-plet,  $\chi^0$ .

- 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 $Y=0$ )

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

Real Scalar

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

Majorana Fermion

For  $n = 3$  multiplets DM stability is achieved by enforcing a  $Z_2$  symmetry

For  $n \geq 5$  multiplets DM stability comes from an accidental  $Z_2$  symmetry

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For  $n \geq 5$  multiplets DM stability comes from an accidental  $Z_2$  symmetry

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

# MDM & Thermal Freeze-Out

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

DM Abundance is fully controlled by the annihilation cross-section



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

Tree-level cross-section

True but... **Inaccurate!**

Important **Nonperturbative** & **Nonrelativistic** effects modify the annihilation cross-section

- **Sommerfeld Enhancement**
- **Bound State Formation**

# SE & BSF

**Sommerfeld:** Long Range Effects modify the DM wave function

$$\chi^0 \chi^0 \rightarrow V V$$

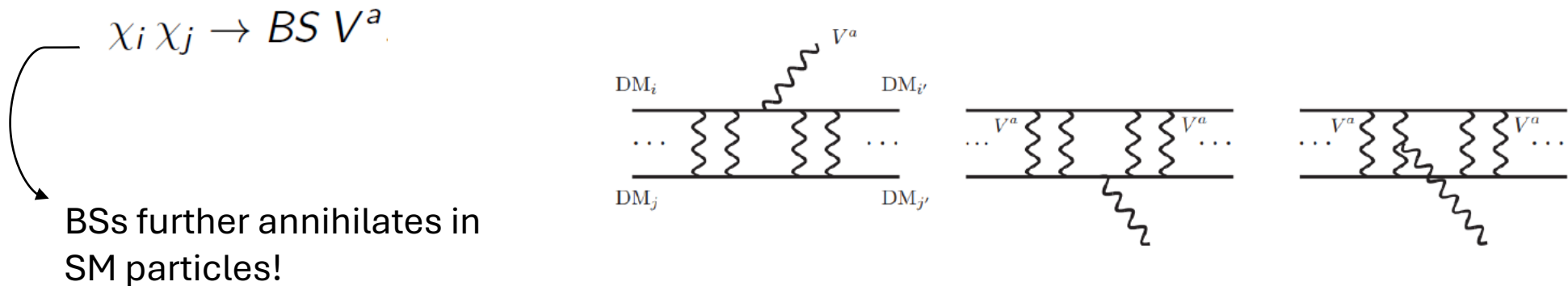
$$-\frac{\nabla^2 \psi}{M_\chi} + V\psi = E\psi$$

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

**Sommerfeld factor**

$$V = -\alpha_{\text{eff}} \frac{e^{-M_V r}}{r}$$

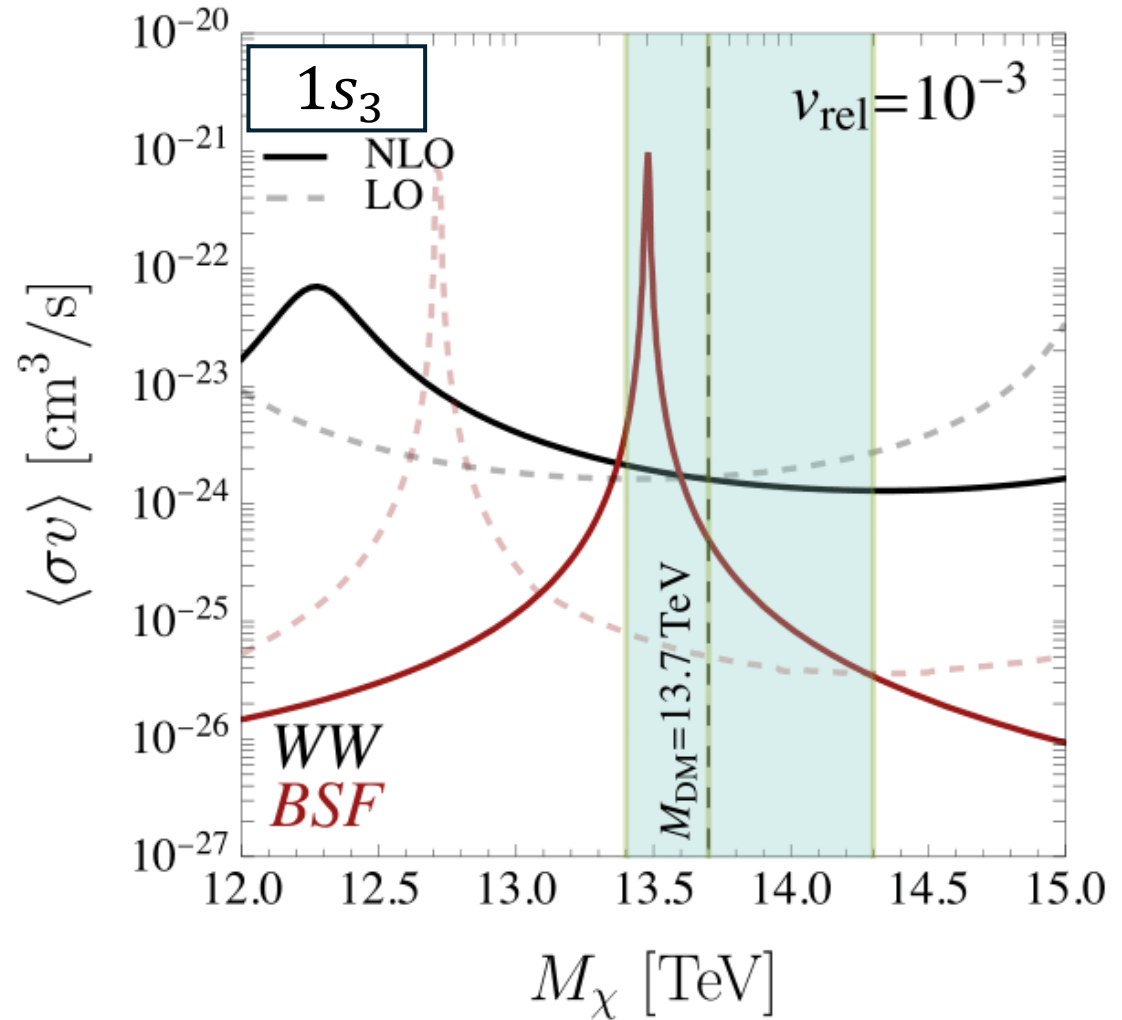
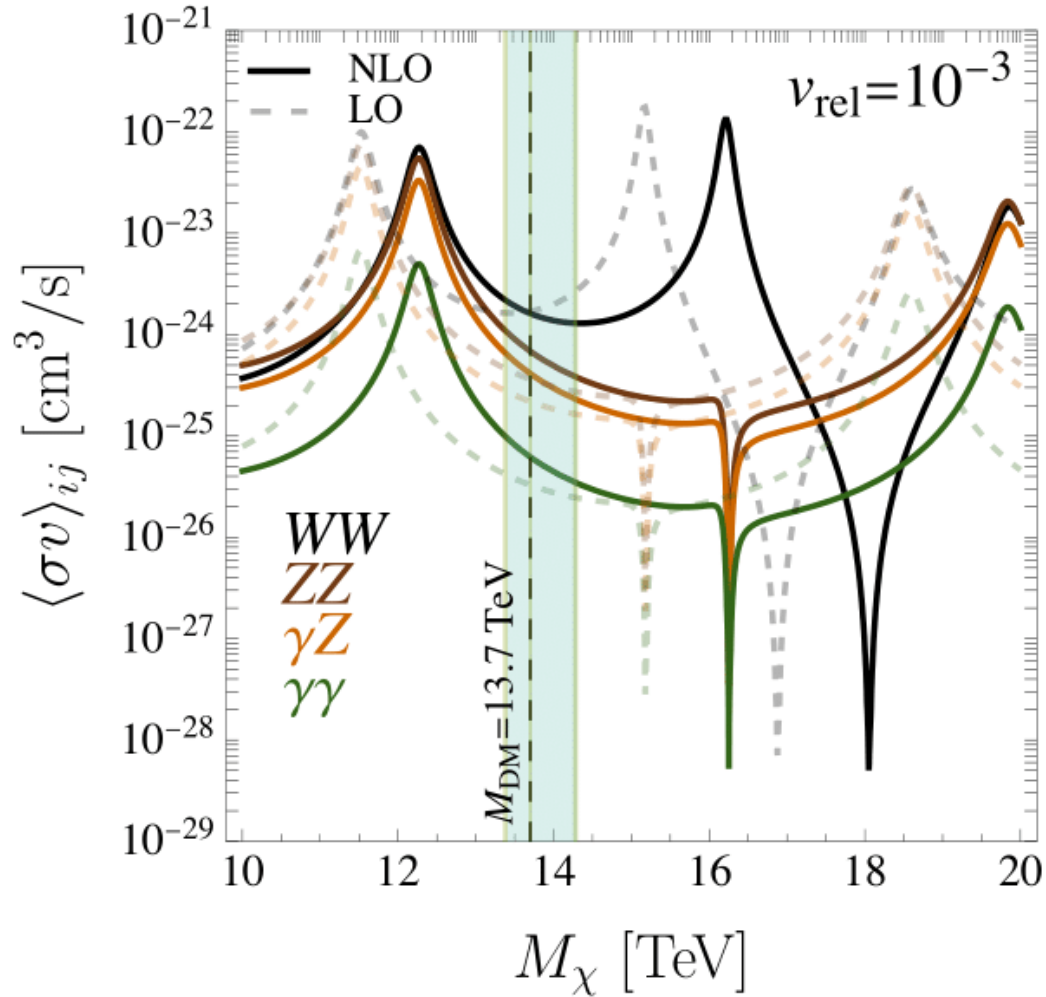
**BSF:** DM forms Bound state via the emission of a gauge boson



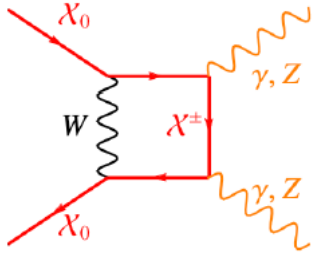
# SE & BSF: 5-Plet Results

Thermal Mass Window @NLO:

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



# Indirect Detection: $\gamma$ - Ray Flux



MDM annihilates in SM gauge bosons producing (in principle) detectable **Cosmic Rays**

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

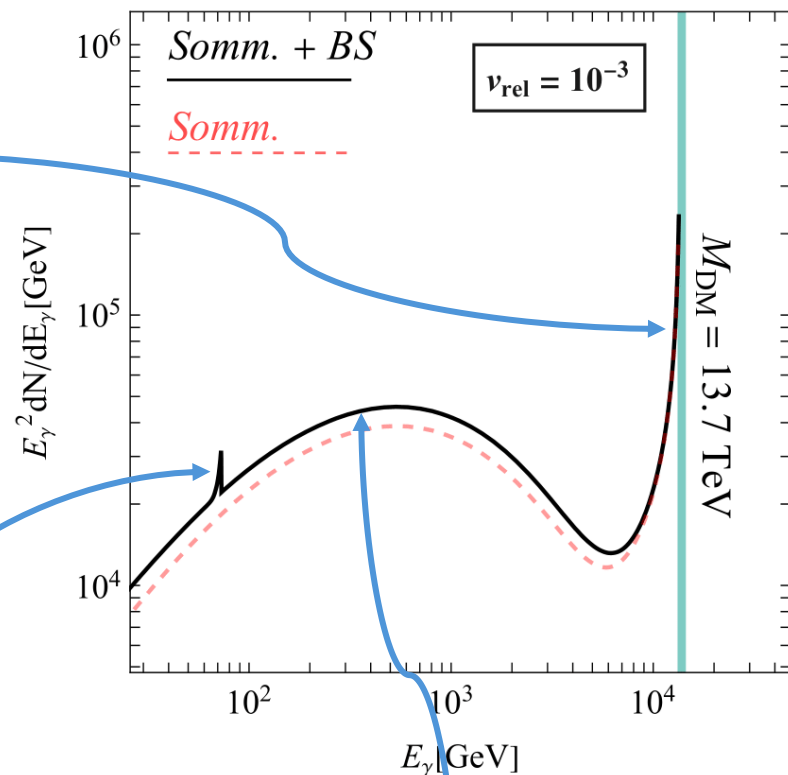
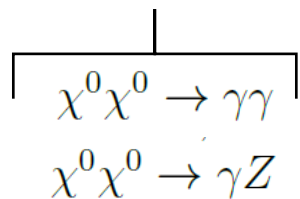
In our case  $\alpha = \gamma$

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

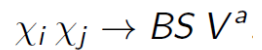
# DM Photon Spectrum

Spectrum @  $M_{DM} = 13.7$  TeV

Spectral **Line** from Sommerfeld

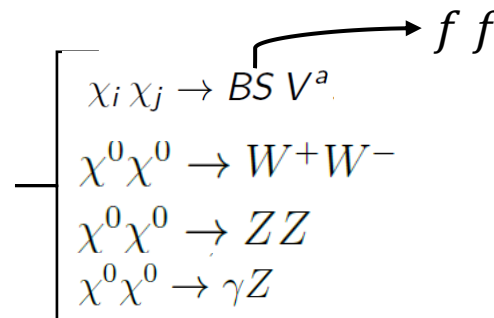
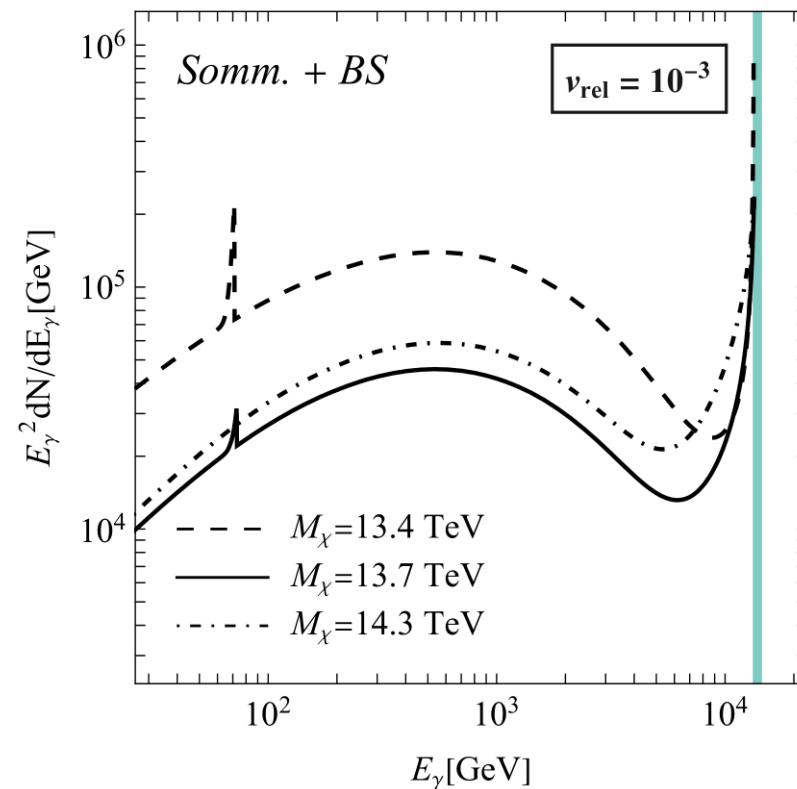


Spectral **Line** from Bound State Formation



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

Spectrum in the Thermal Mass Window



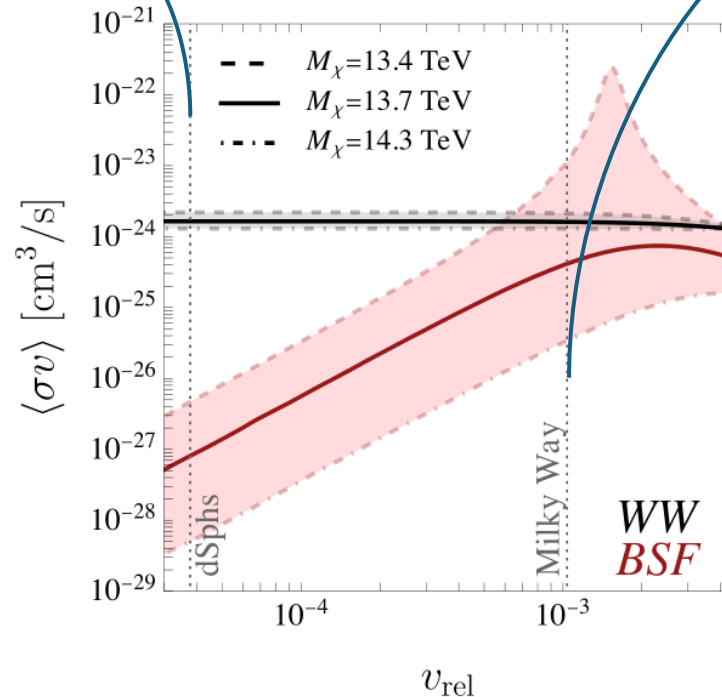
# Choice of the Targets

## 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**)

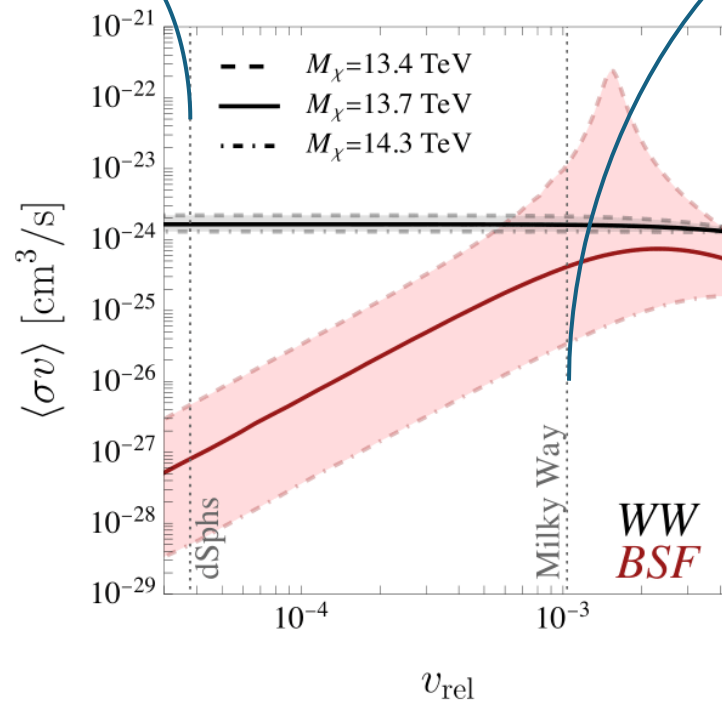
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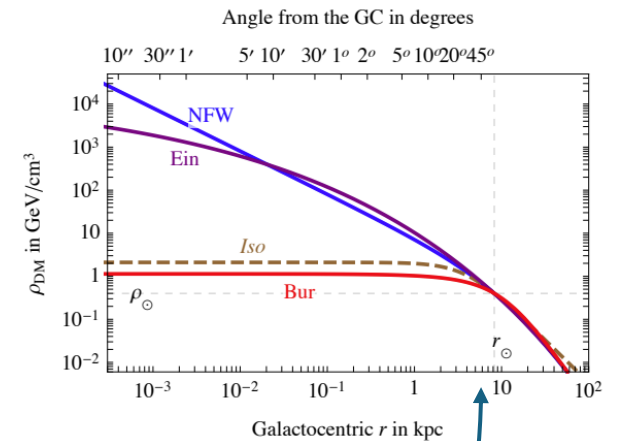
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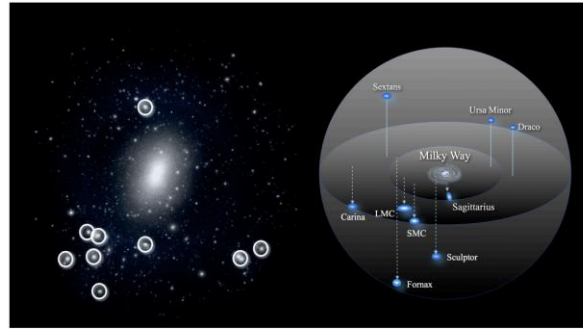


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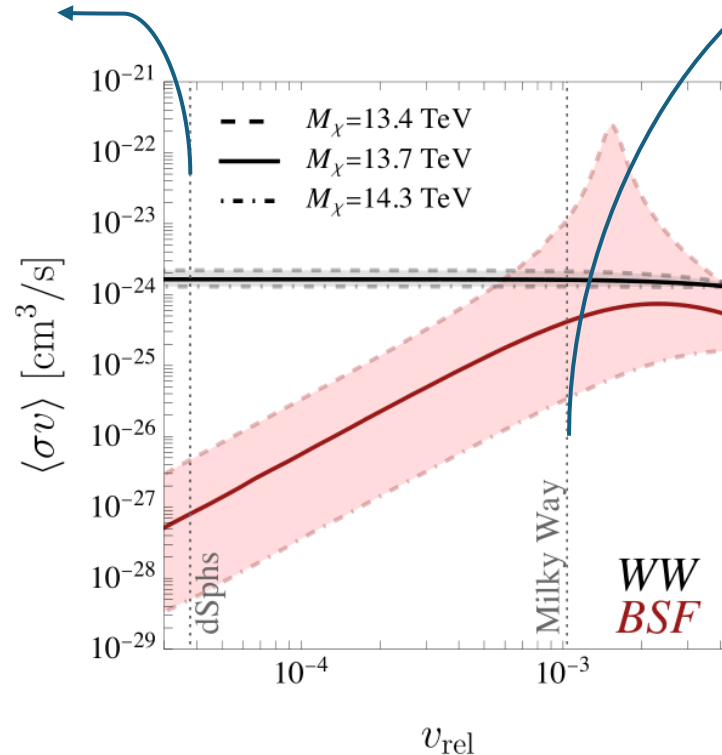
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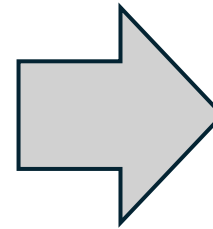
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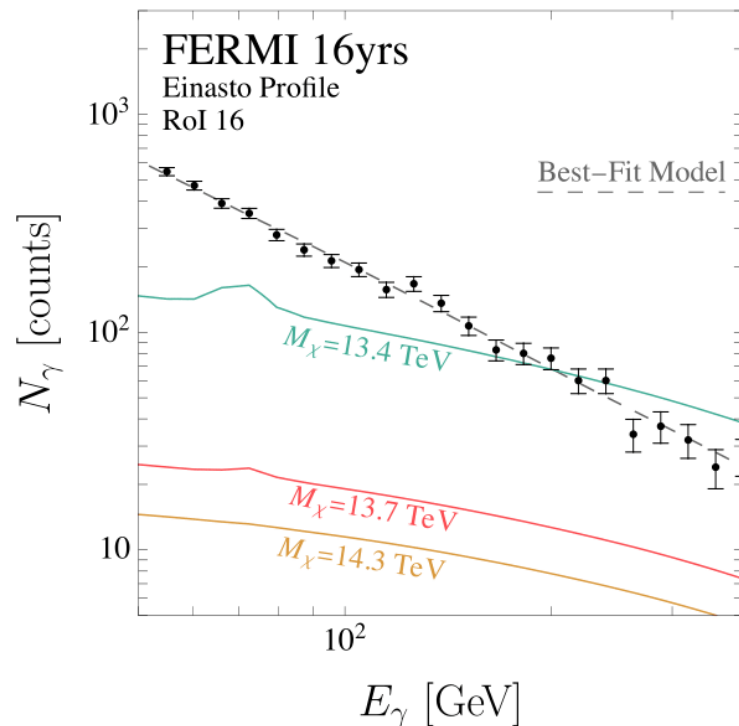


# Current Constraints: spectrum at low-energy ( $\sim$ hundreds of GeV)

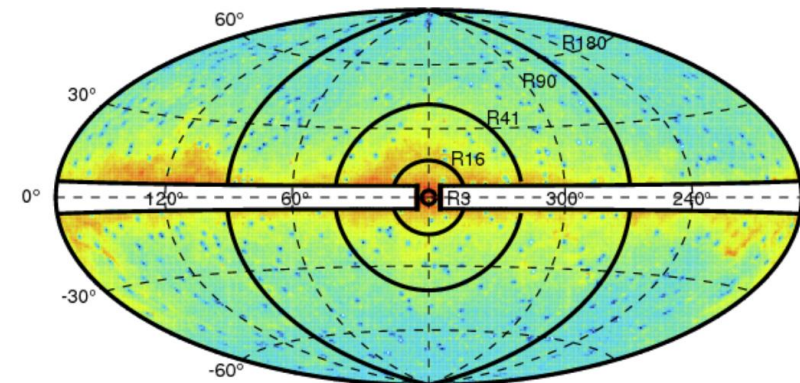
FERMI-LAT measurements of the Galactic Diffuse can set **stringent** constraints on the 5-plet



Exploiting the interplay of BSF continuum & SE



Focus on one **Region of Interest** (RoI): RoI16



Strategy taken from the Fermi-LAT collab. (arXiv:1305.5597)

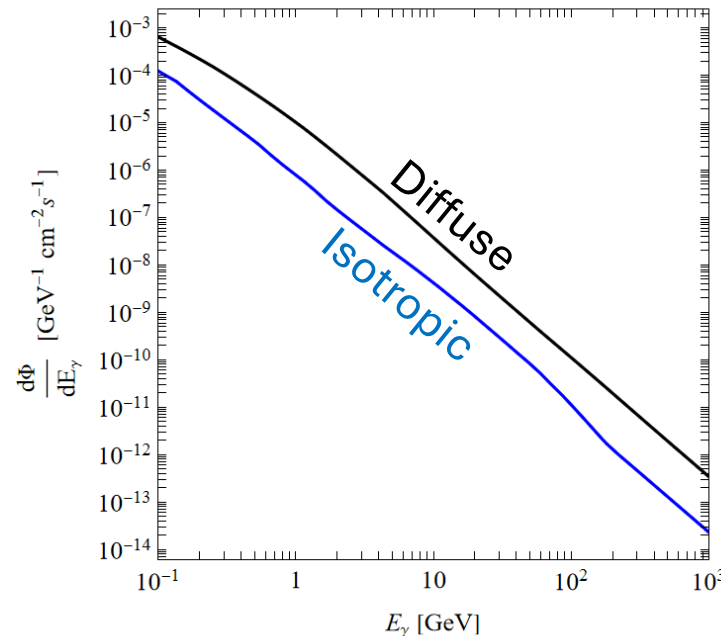
# Background Modelling

$$\frac{d\Phi_{\text{bkg}}^{\text{RoI}}(E_\gamma)}{dE_\gamma}$$

Two relevant components

## Isotropic background

- Photons from unresolved extragalactic sources
- Misclassified cosmic ray emission



## Diffuse background

- $\pi^0$  decay ( $p p \rightarrow \pi^0 + X \rightarrow \gamma\gamma + X$ )
- Bremsstrahlung
- Inverse Compton ( $e \gamma \rightarrow e \gamma$ )

Both of them provided by the FERMI collaboration via template fit!

# Statistical Procedure for the FERMI Analysis

1) From flux to counts

$$N_{\text{DM, bkg}}^i = \text{DRM}_j^i \int_{E_j}^{E_{j+1}} dE_\gamma \frac{d\Phi_{\text{DM, bkg}}^{\text{RoI}}(E_\gamma)}{dE_\gamma} \mathcal{E}^{\text{RoI}}(E_\gamma)$$

Detector Response Matrix  
 (~ Energy Resolution)

Template bkg +  
 photons from DM

Effective exposure (~ Effective  
 Area X Observation Time)

2) Compute the theoretical number of events

$$N_{\text{th}}^i(\kappa, A_{\text{diff}}, A_{\text{iso}}) = A_{\text{diff}} N_{\text{diff}}^i + A_{\text{iso}} N_{\text{iso}}^i + \kappa N_{\text{DM}}^i$$

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

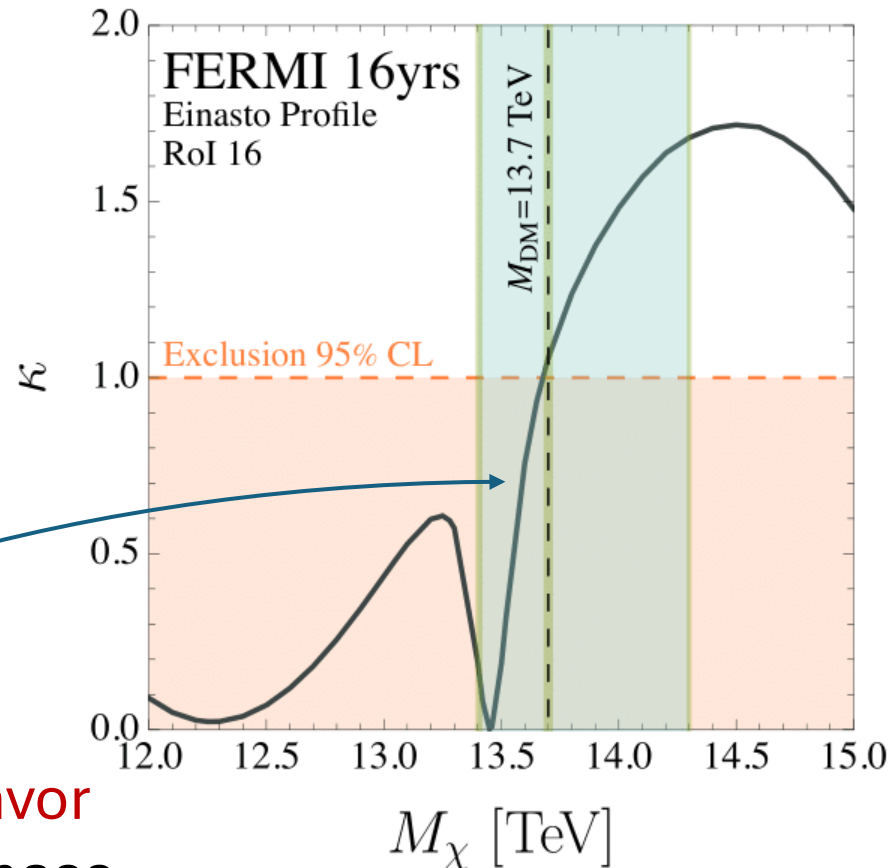
3) Build the (Poissonian) Likelihood

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

# Current Constraints: spectrum at low-energy ( $\sim$ hundreds of GeV)

$$t(\kappa) = 2 \log \left[ \frac{\max_{\kappa, A_{\text{diff}}, A_{\text{iso}}} \tilde{\mathcal{L}}(\kappa, A_{\text{diff}}, A_{\text{iso}})}{\max_{A_{\text{diff}}, A_{\text{iso}}} \tilde{\mathcal{L}}(\kappa, A_{\text{diff}}, A_{\text{iso}})} \right]$$

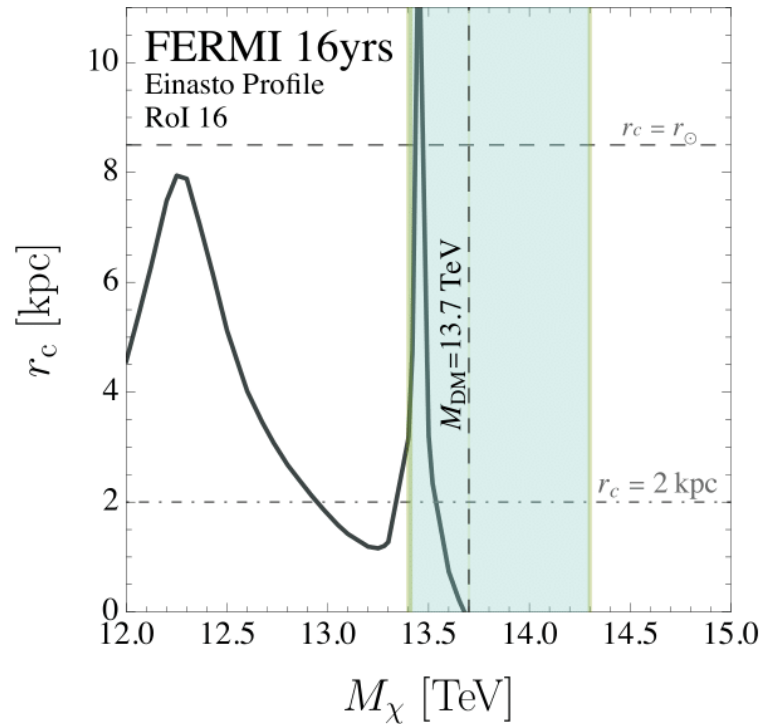
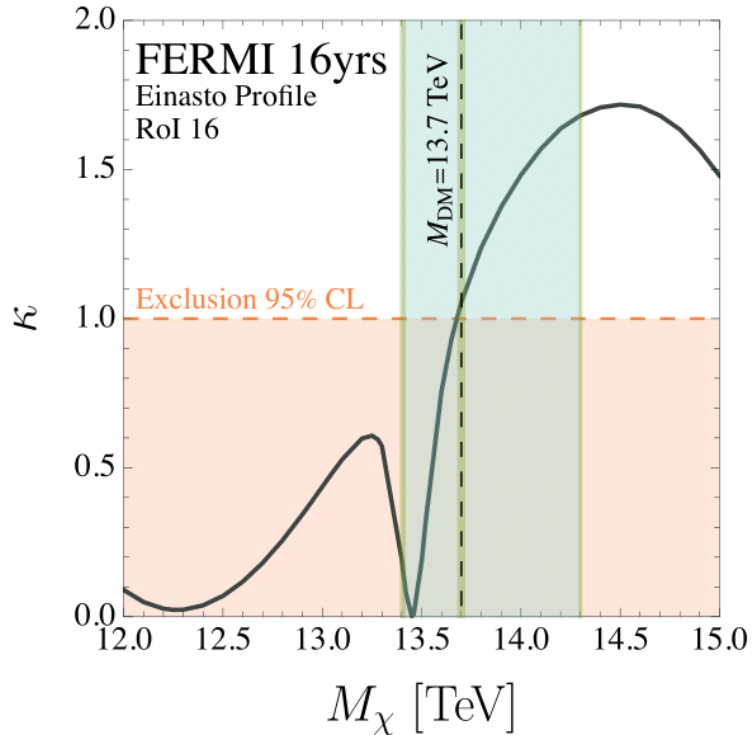
Extract the upper limit on the rescaling parameter  $\kappa$  from the **Test Statistics** ( $t(\kappa) = 2.71$  for 95% C.L.)



Fermi-LAT measurements **disfavor** the **lower edge** of the thermal mass window!

# Current Constraints: spectrum at low-energy ( $\sim$ hundreds of GeV)

At which **core size** does the 5-plet escape exclusion?

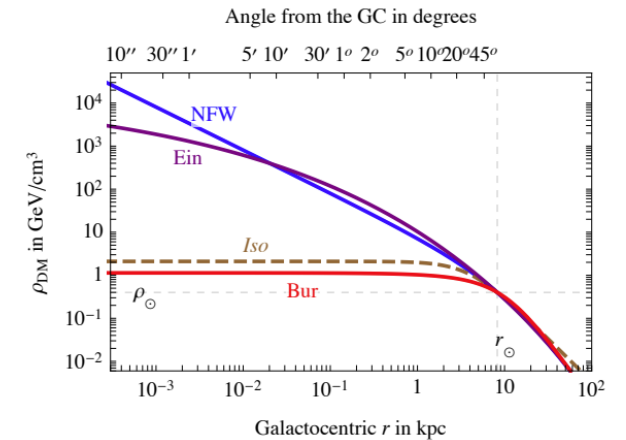
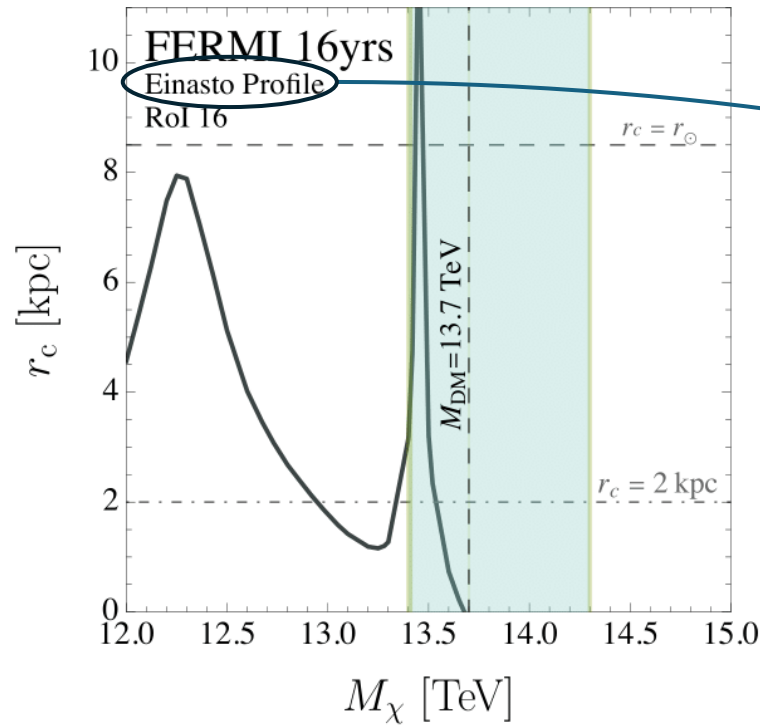
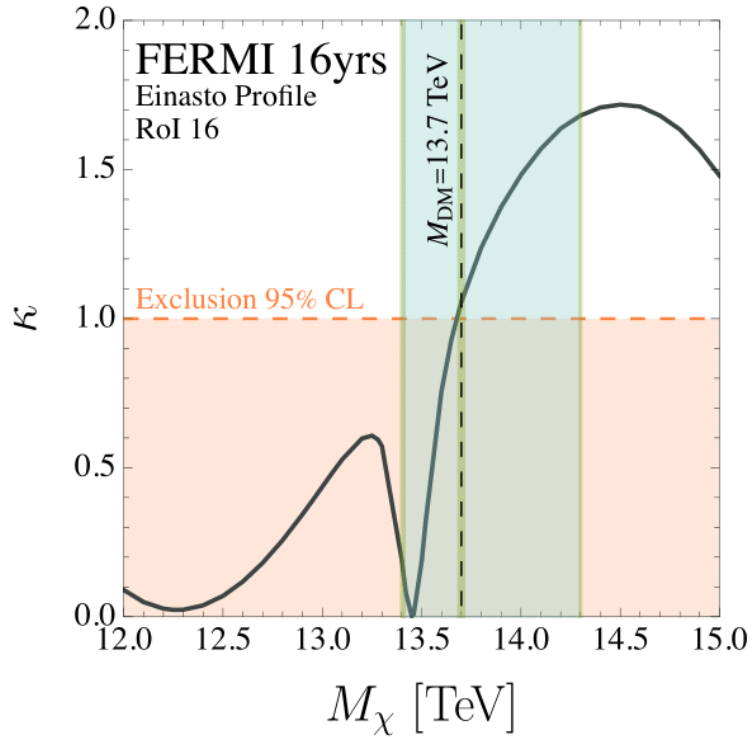


How **robust** is the exclusion?

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

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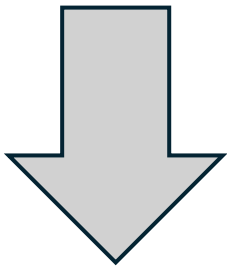
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# Future Constraints: spectrum at high-energy ( $\sim$ tens of TeV)

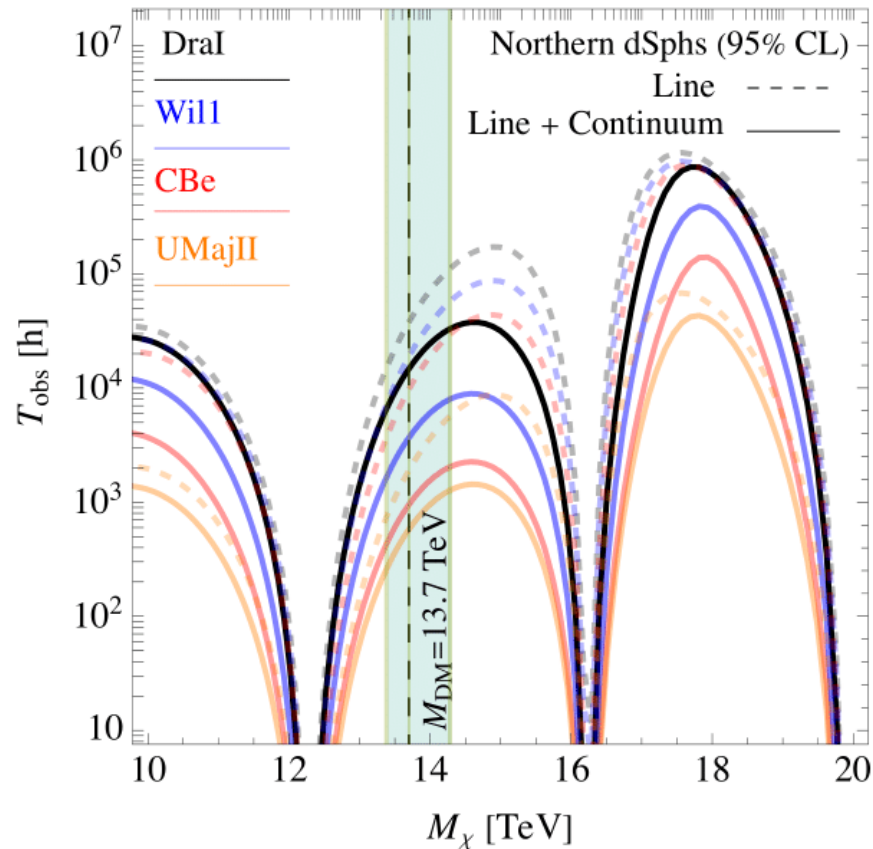
The forthcoming Cerenkov Telescope Array (CTA) will explore the multi-TeV range with unprecedented resolution

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

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



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



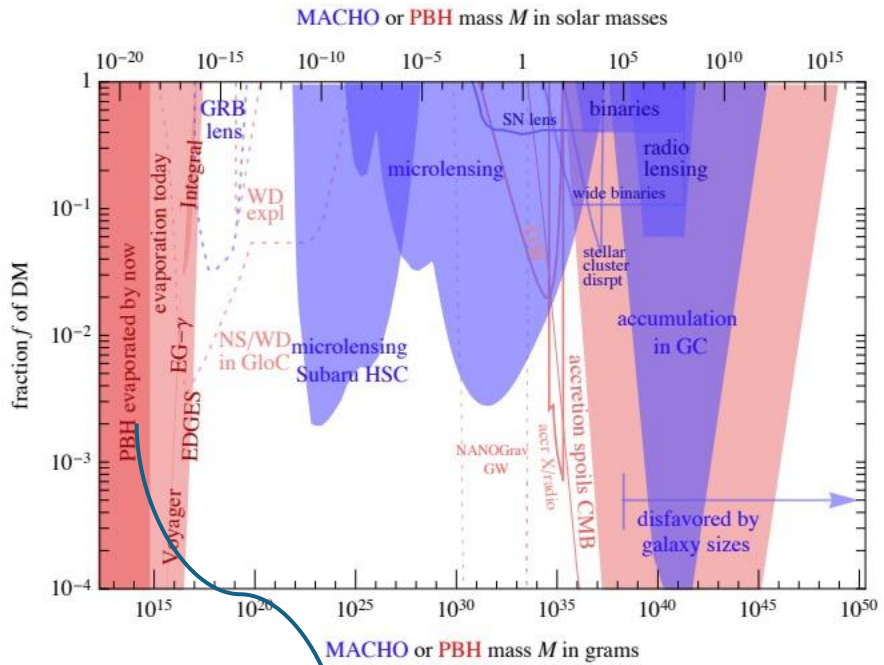
Observation Time Forecasts for **Northern** Dwarf Spheroidal Galaxies (CTA will obtain these data first!)

**Lesson:**  $\gamma$ - ray **continuum** matters!

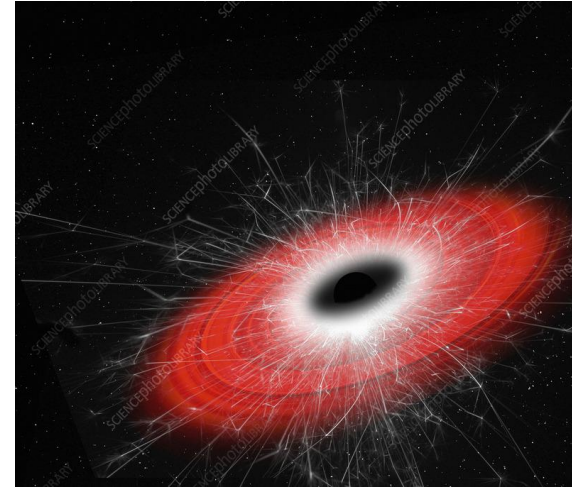
# Part II

# Evaporating Memory Burdened PBHs

The Standard Picture:



$$T_{\text{BH}} = 1/(8\pi GM)$$



BHs emit thermal radiation at the Hawking temperature

$$\begin{cases} \tau_{\text{SC}} \simeq S r_g \\ S = 2\pi M r_g \end{cases}$$

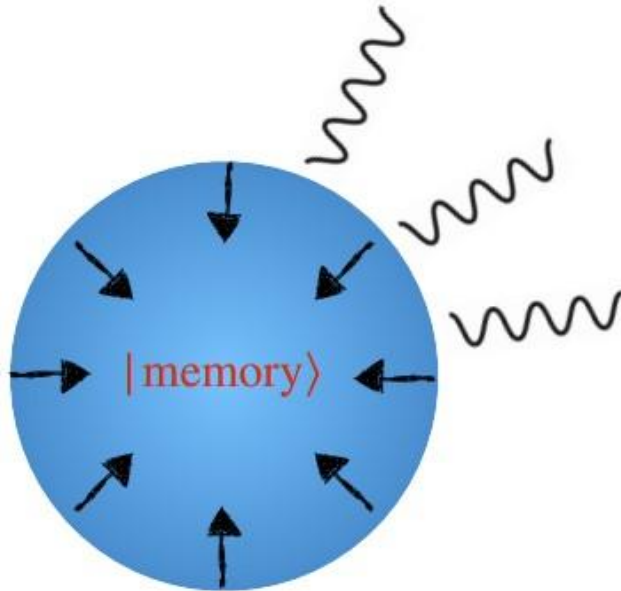
Can be shorter than  $\tau_U$ ! SO:

PBHs with masses below about  $10^{15}$  g are too unstable to be DM

But...

# Memory Burden Effect in BHs in a Nutshell

...Hawking's argument is  
semiclassical

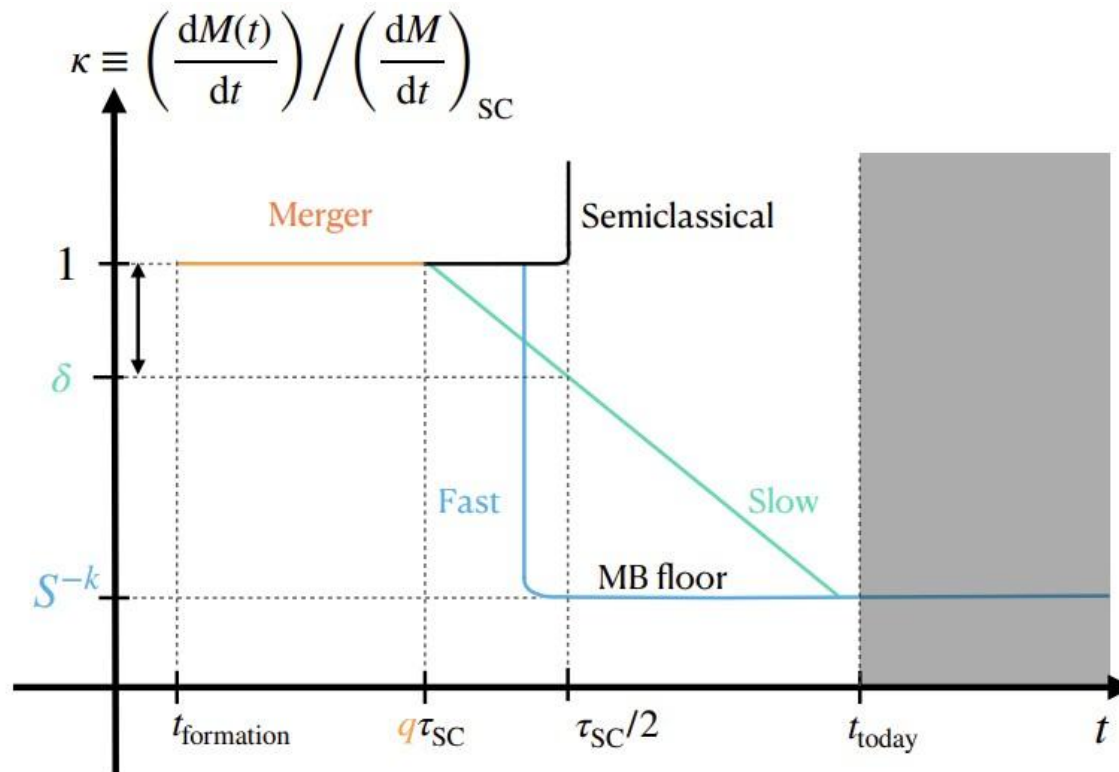


From M. Zantedeschi's talk at PLANCK 2025

- 1) BHs are **high capacity systems** for storing information (and they are not the only ones!)
- 2) Information is stored in **gapless memory modes**: no energy cost for storage (Goldstones from Symmetry Breaking)
- 3) As the BH emits (Hawking Evaporation), **memory modes acquire energy**: altering/ releasing information becomes increasingly expensive.
- 4) **Backreaction**: The system resists its decay.

Essence of Memory Burden: *The memory stored in a configuration resists its decay.*

# Practical Take-Home Messages for Pheno



Three relevant scenarios can occur:

- 1) **Merging** memory-burdened PBHs
- 2) **Slow** transition to the MB phase
- 3) **Fast** transition to the MB phase (most popular in the literature)

- 1) Backreaction **stabilizes** the BH:

$$\tau \simeq S^{1+k} r_g$$

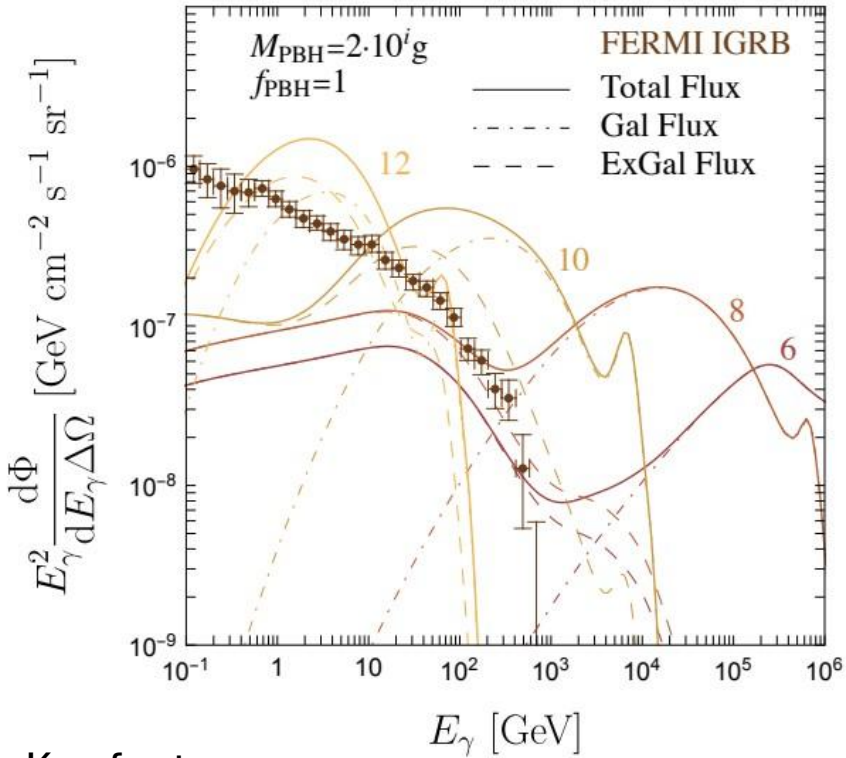
- 2) MB can kick at latest around **half-mass semiclassical evaporation time**

$$\left. \begin{aligned} q &= \frac{\Delta M}{M} \\ \tau_{\text{MB}} &\simeq q \tau_{\text{SC}} \end{aligned} \right\} q \leq 1/2$$

- 3) Transition to the MB phase is **not instantaneous** ( $\delta \equiv$  width)

# Consequences for Indirect Detection: Fluxes

Photon fluxes for the merger case



Key features:

- 1) Galactic  $\gamma$ -rays are absorbed above  $\sim 10^6$  GeV (mainly **PP** from CMB photons)
- 2) ExGal  $\gamma$ -rays are absorbed above  $\sim 10$  TeV (mainly **PP** from EBL/CMB photons)
- 3) Universal Low-Energy **EM cascade** from PP+ICS processes

The spectra...

$$\frac{d^2 N_i}{dE dt} = \xi \frac{d^2 N_i^{\text{SC}}}{dE dt}$$

with  $\xi^{\text{decay}} = \max(S^{-k}, \delta \tau_{\text{SC}}/2t)$  for  $t \gtrsim \tau_{\text{SC}}/2$ ,

$$\xi^{\text{merger}} = \frac{R_{\text{PBH}}(f_{\text{PBH}}, t) q \tau_{\text{SC}}}{f_{\text{PBH}} \rho_{\text{DM},0}} M_{\text{PBH}},$$

...and the fluxes

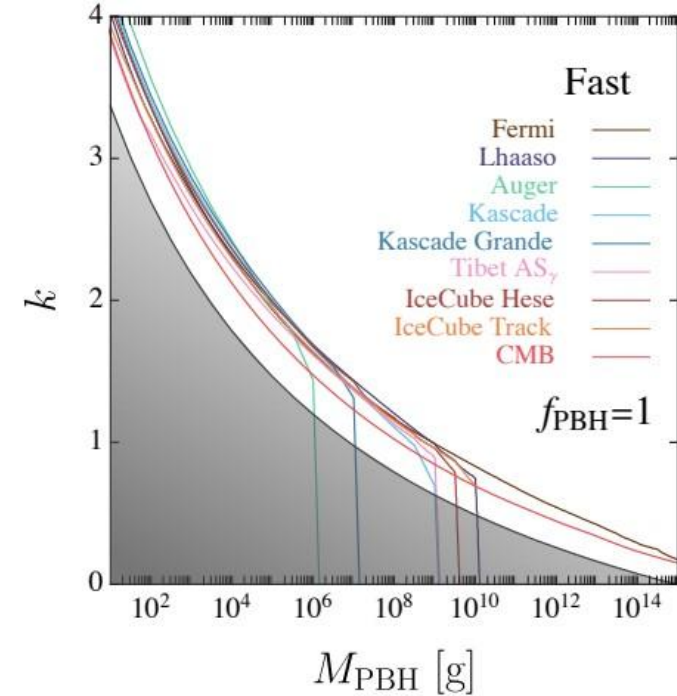
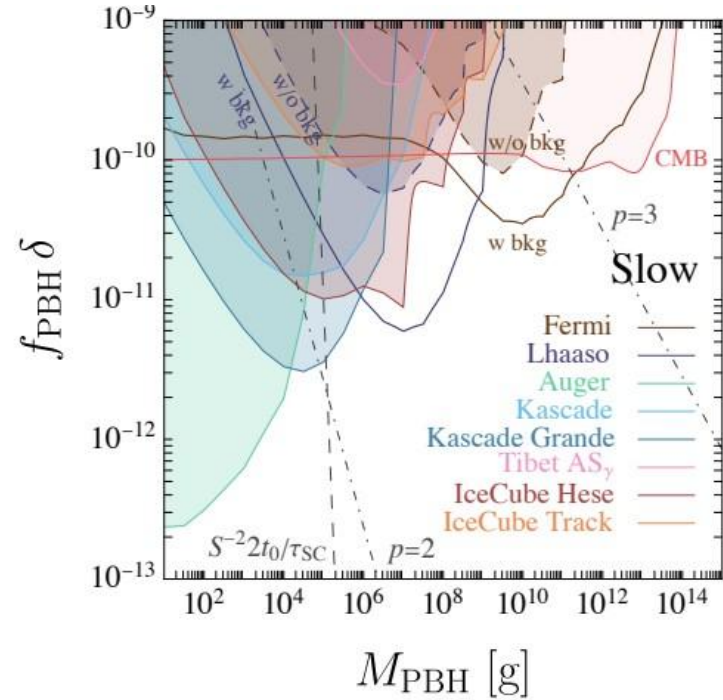
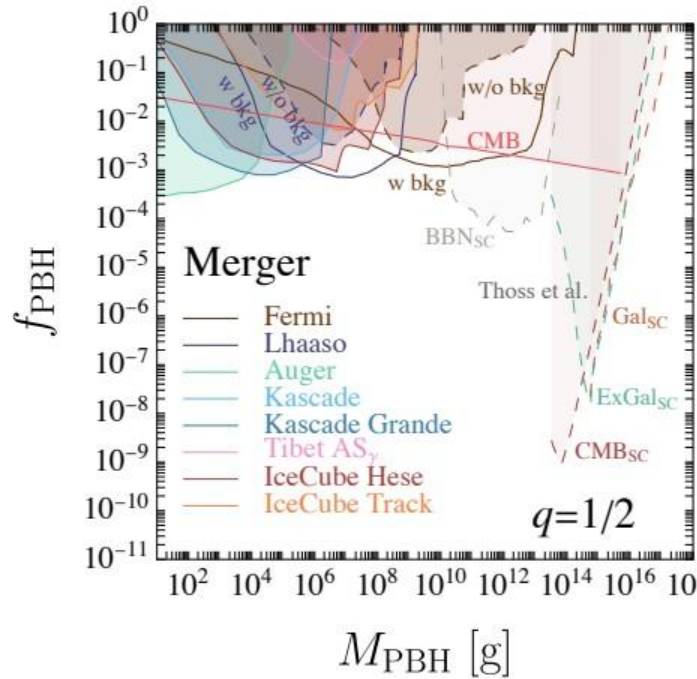
Galactic

$$\frac{d\Phi_{i,\text{gal}}}{dE_i \Delta\Omega} = \frac{1}{4\pi} \frac{f_{\text{PBH}}}{M_{\text{PBH}}} \frac{d^2 N_i}{dE dt} \bar{J}, \quad \text{with } \bar{J} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_0^\infty ds \rho_{\text{DM}}(r(s, \psi)) e^{-\tau_i(E_i, s)}$$

Extra-Galactic (**Isotropic**)

$$\frac{d\Phi_{\gamma,\text{egal}}^{\text{att}}}{dE_\gamma} = \frac{f_{\text{PBH}}}{M_{\text{PBH}}} \rho_{\text{DM},0} \int_0^{z_{\text{max}}} \frac{dz}{H(z)} \frac{d^2 N_\gamma(E_\gamma(1+z))}{dE_\gamma dt} e^{-\tau_\gamma(E_\gamma, z)}$$

# Final Constraints



$$\mathcal{L}(\mu) \equiv \begin{cases} \prod_i \mathcal{P}_i(d|\mu) & \text{for } \mu > d \\ 1 & \text{for } \mu \leq d \end{cases}$$

Performed both **Background-Agnostic** and **Background-Inclusive** (where possible!) analyses for several experiments (LHAASO, FERMI-LAT, Auger, Cascade...)

# Conclusions

## ID of WIMPs:

- ▶ 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.

## ID of Memory Burdened PBHs:

- ▶ Memory Burden inhibits the decay of PBHs. Three scenarios considered: Merger, Slow and Fast transitions.
- ▶ Stringent, Dominant constraints from  $\gamma$ -rays and UHE photons: including the bkg enhances sensitivities!