Prospects of MeV telescopes in probing weak-scale Dark Matter

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Based on: *SciPost Phys. 19, 080 (2025) (arXiv: 2503.04907)*

M. Cirelli, A. Kar

TeV Particle Astrophysics
TeVPA
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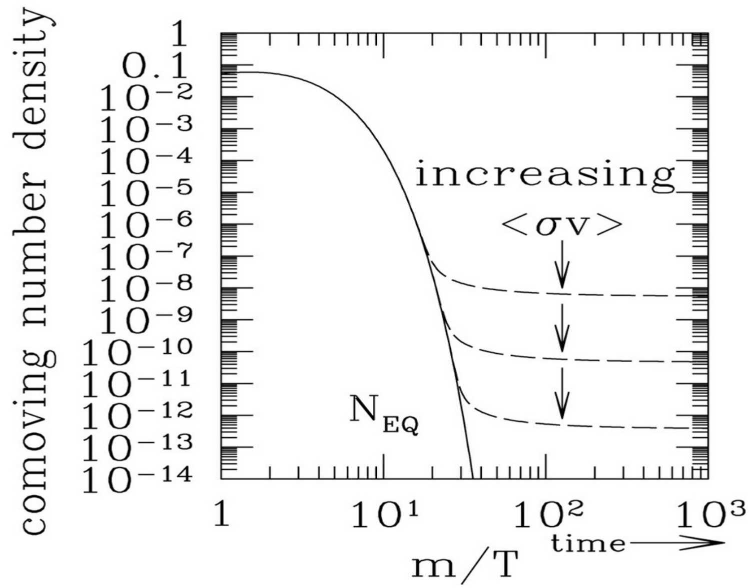
Dark matter : WIMPs

- Dark Matter (DM) exists and provides ~25% of the energy density of the Universe

- Weakly Interacting Massive Particles (WIMPs) : one of the most popular candidates for DM

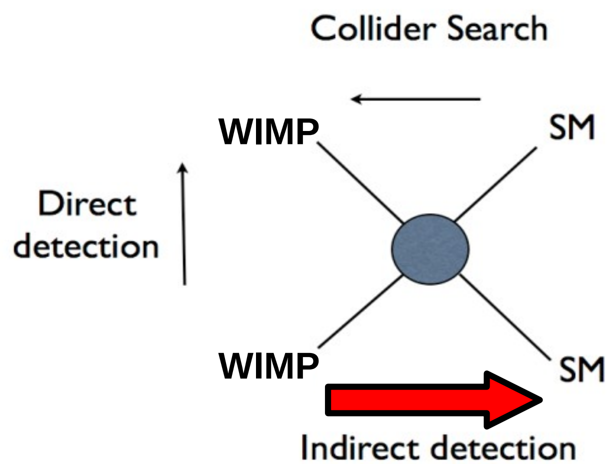
  - Stable, no electric charge, no colors
  - Mass at the weak scale (GeV – TeV)
  - Weak interactions ($\sigma v \sim 10^{-26}\ \mathrm{cm^3 s^{-1}}$) keep WIMPs in thermal equilibrium in the early Universe and provide correct relic abundance through thermal decoupling

$$\Omega_{DM} h^2 = 0.12 \text{ (Obs.)} \qquad \Omega_{DM} h^2 \propto 1/\langle \sigma v \rangle$$



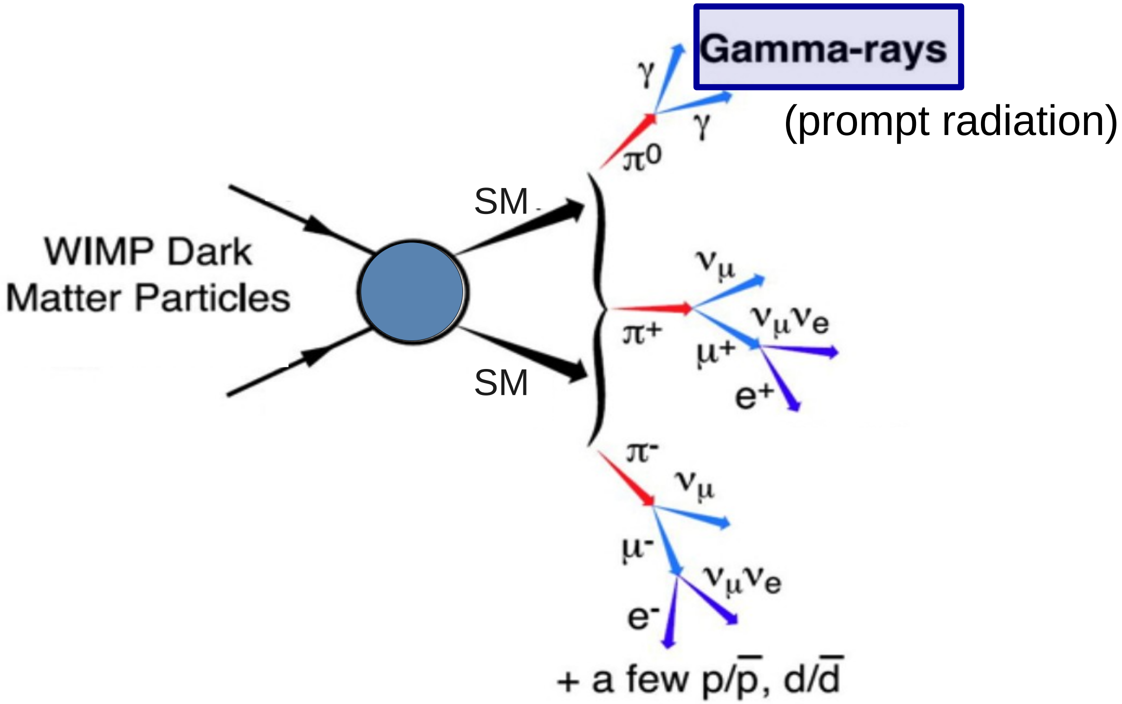
- WIMP searches :

  - Direct detection
  - Collider searches
  - Indirect detection



Searches for WIMP DM in photon observations from the inner Galaxy

- **Photon signals from inner Galaxy:** the observables consist of mainly two types of photon signal



- **Prompt radiation:** High-energy γ- rays are produced directly in the WIMP annihilation process

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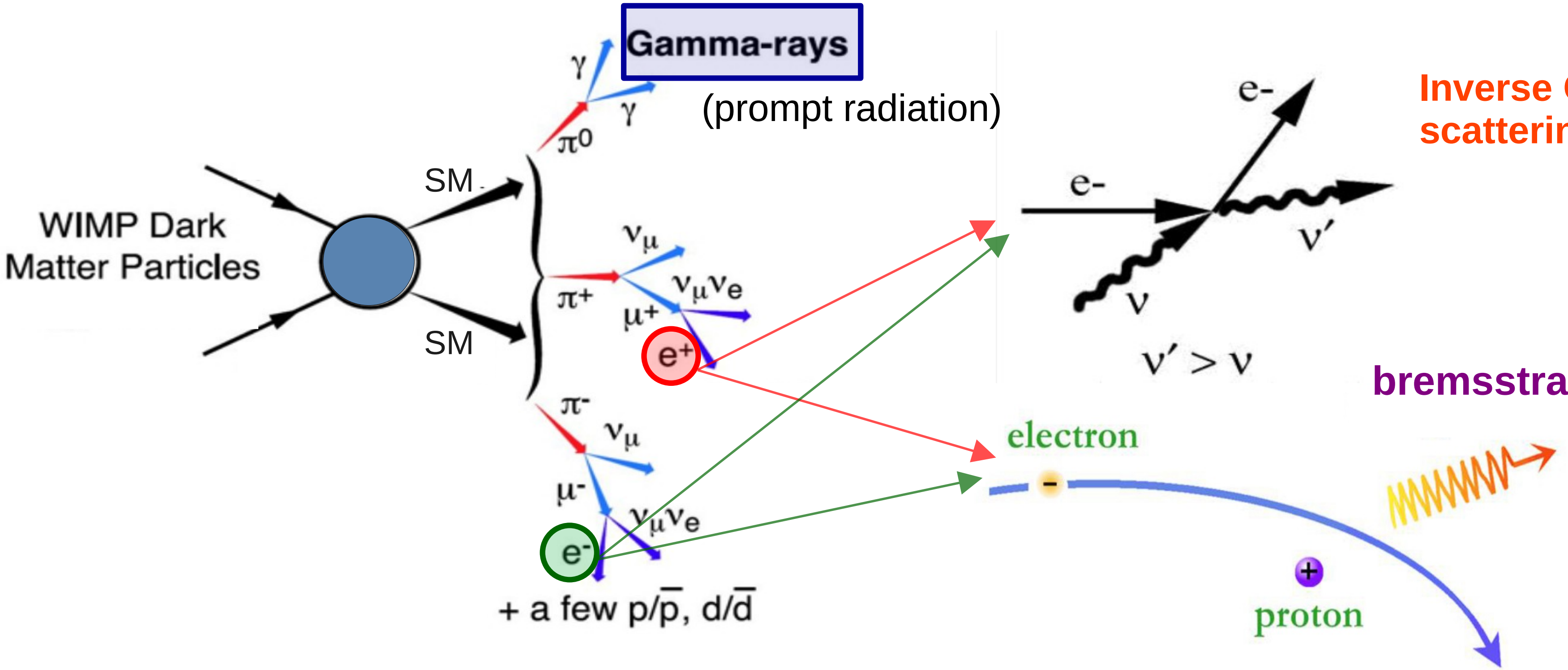
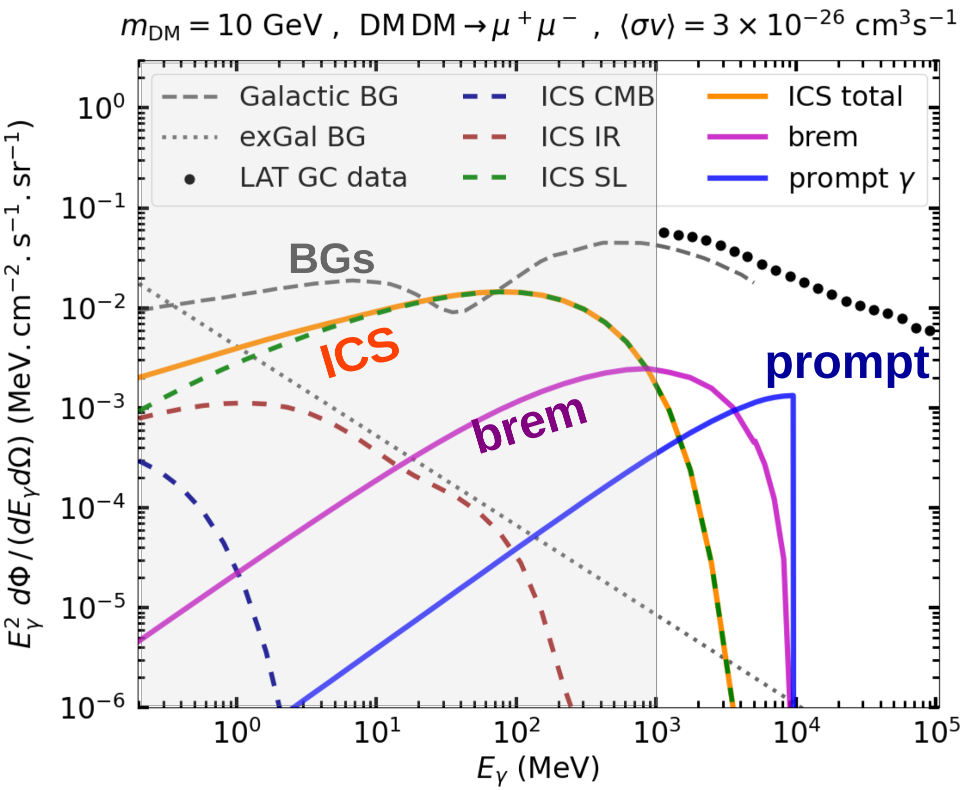
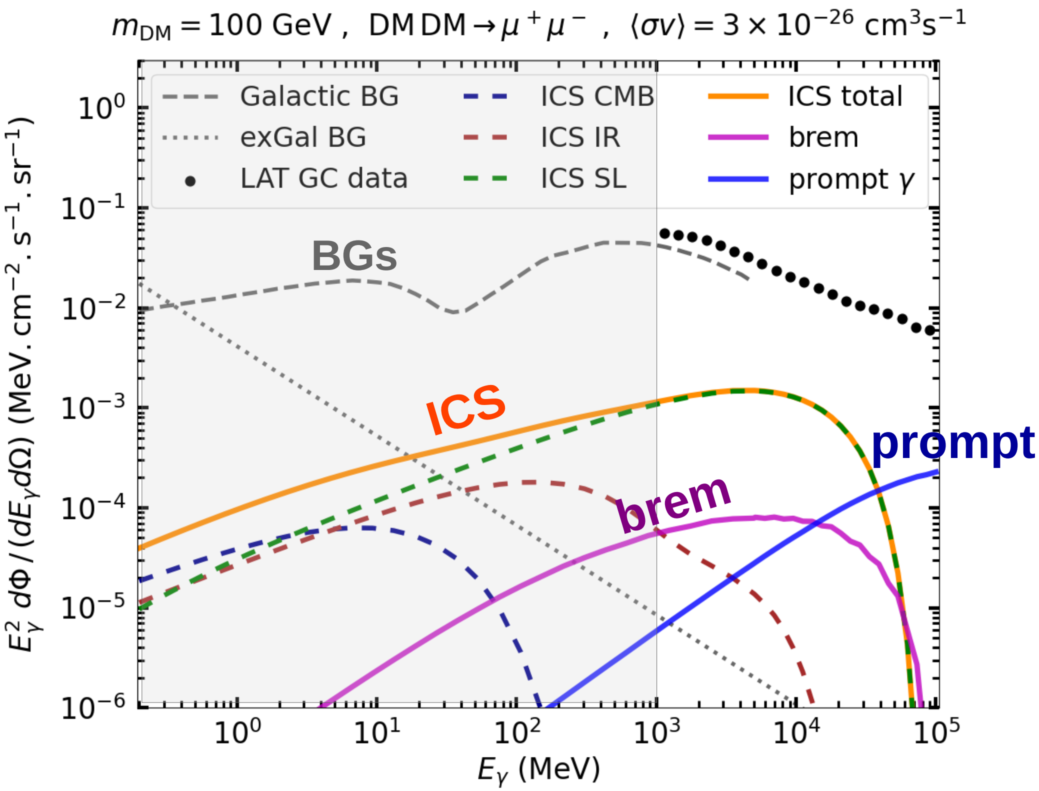


- **Prompt radiation:** High-energy γ- rays are produced directly in the WIMP annihilation process
- **Secondary radiation:** Galactic WIMP annihilations generate abundant energetic $e^{\pm}$, which subsequently emit through **Inverse Compton scattering (ICS)** , **bremsstrahlung**
  - **Comparatively lower-energetic gamma-rays photons**
  - **Enhanced for the lepton-rich annihilation channels of WIMPs**

e.g., $\mathrm{DM\,DM} \to e^+e^-$, $\mathrm{DM\,DM} \to \mu^+\mu^-$

Prompt and secondary photons from WIMP annihilations in the Galaxy





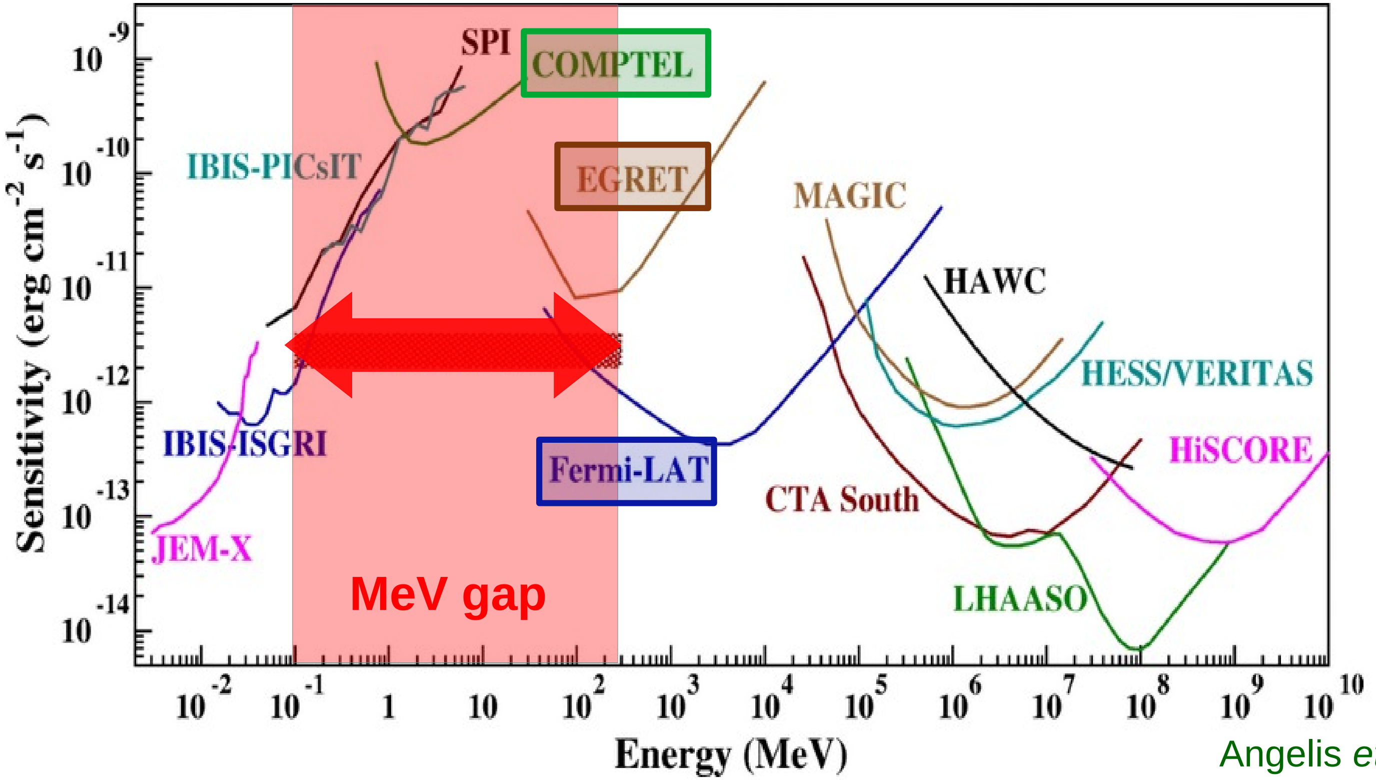
M. Cirelli, A.K.; (SciPost Phys. 19 (2025) 080)

- **Secondary photons from WIMP annihilation in general populate the Sub-GeV energy range**

(MeV - GeV)

MeV Gap and upcoming MeV γ- ray telescopes

- **One potential difficulty for detecting the secondary emissions:** relatively poor sensitivity of existing telescopes (**COMPTEL**, **EGRET**, **Fermi-LAT**, etc.) in the sub-GeV range



Angelis *et al*., (2102.02460)

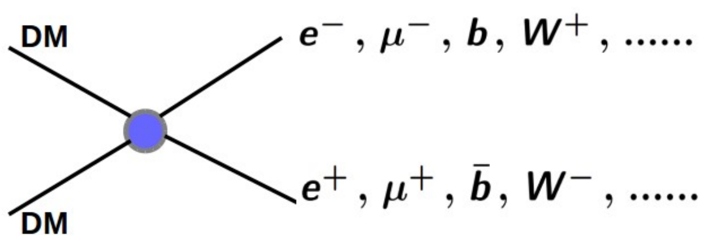
- The upcoming space-based **MeV telescopes** will efficiently fill the **MeV gap** with ***better sensitivity***

  ➔ COSI, AMEGO, e-ASTROGAM, GECCO, AdEPT, PANGU, GRAMS, MAST, …….

- **Potential of these MeV telescopes in probing WIMP DM, based on the secondary emission ?**

MeV-GeV photons from WIMP annihilations in the Galaxy

- Target region for observation: a disk of 10^{o} radius around the galactic Center (GC)
  ➔ same order as the maximum angular width of the MeV telescopes



cascade ⇒

γ flux prompt emission (high energy)

$e^{\pm}$ flux ➡ secondary emission (low energy)

- **Prompt γ - ray emission flux:**

$$\frac{d\Phi_{\rm prompt}}{dE_\gamma d\Omega} = \frac{\langle \sigma v \rangle}{8\pi\, m_{\rm DM}^2} \frac{dN_\gamma}{dE_\gamma} \frac{J_{\Delta\Omega}}{\Delta\Omega}$$

$\frac{dN_\gamma}{dE_\gamma}$ spectra produced per annihilation in a given annihilation channel

$$J_{\Delta\Omega} = \int_{\Delta\Omega} d\Omega \int_{l.o.s.} ds\, \rho_{\rm DM}^2(r(s,\theta))$$

(10^{o} around GC)

s ➔ line-of-sight (l.o.s.)

$d\Omega = 2\pi \sin\theta \, d\theta$

NFW DM profile :

$$\rho_{\rm DM}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$

Salas *et al*., (1906.06133)
Cirelli *et al*., (2406.01705)

MeV-GeV photons from WIMP annihilations in the Galaxy

- **Secondary γ - ray emission flux:**

(s, b, l) → Galactic coordinates

$\cos b \ \cos l = \cos\theta$

$$\frac{d\Phi_{\text{2ndary}}}{dE_\gamma d\Omega} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \left[\frac{1}{E_\gamma}\int_{l.o.s.} ds \, \frac{j_{\text{2ndary}}(E_\gamma, \vec{x}(s,b,l))}{4\pi}\right]$$

$$j_{2ndary} = j_{ICS} + j_{brem}$$

$$j_{\text{ICS}}(E_\gamma, \vec{x}(s,b,l)) = 2\int_{m_e}^{m_{\text{DM}}} dE_e \sum_{i\in\text{ISRF}} \mathcal{P}^i_{\text{ICS}}(E_\gamma, E_e, \vec{x}) \frac{dn_e}{dE_e}(E_e, \vec{x})$$

$$j_{\text{brem}}(E_\gamma, \vec{x}(s,b,l)) = 2\int_{m_e}^{m_{\text{DM}}} dE_e \, \mathcal{P}_{\text{brem}}(E_\gamma, E_e, \vec{x}) \frac{dn_e}{dE_e}(E_e, \vec{x})$$

From DM annihilation

MeV-GeV photons from WIMP annihilations in the Galaxy

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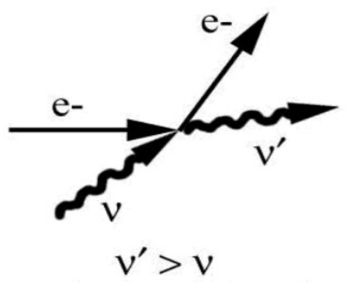
From DM annihilation

$$j_{\rm brem}(E_\gamma, \vec{x}(s,b,l)) = 2\int_{m_e}^{m_{\rm DM}} dE_e \, \mathcal{P}_{\rm brem}(E_\gamma, E_e, \vec{x}) \frac{dn_e}{dE_e}(E_e, \vec{x})$$

$$\mathcal{P}^i_{\rm ICS}(E_\gamma, E_e, \vec{x}) = c\, E_\gamma \int d\epsilon \, n_i^{\rm ISRF}(\epsilon, \vec{x})\, \sigma_{\rm IC}(\epsilon, E_\gamma, E_e)$$



Inter-Stellar Radiation Field (ISRF) : CMB, infrared (IR), starlight (SL)

Buch, *et al.*, (PPPC 4 DM, [1505.01049]), (GALPROP)

MeV-GeV photons from WIMP annihilations in the Galaxy

$(s, b, l) \rightarrow$ Galactic coordinates

$\cos b \; \cos l = \cos\theta$

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From DM annihilation

$$j_{\rm brem}(E_\gamma, \vec{x}(s,b,l)) = 2\int_{m_e}^{m_{\rm DM}} dE_e \, \mathcal{P}_{\rm brem}(E_\gamma, E_e, \vec{x}) \frac{dn_e}{dE_e}(E_e, \vec{x})$$

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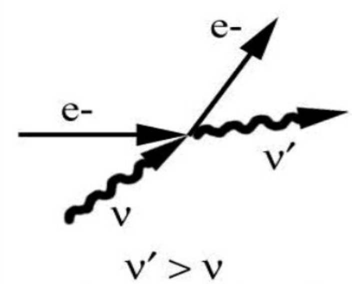

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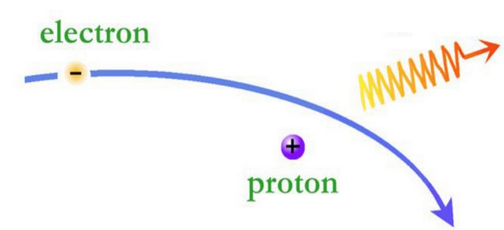

Gas species : ionic, atomic and molecular

MeV-GeV photons from WIMP annihilations in the Galaxy

- **Distribution of WIMP induced $e^{\pm}$ in the galaxy :**

Source function from WIMP annihilation : $Q_e(E_e^S, r) = \frac{\langle \sigma v \rangle}{2 m_{\rm DM}^2} \frac{dN_e}{dE_e^S} \rho_{\rm DM}^2(r)$

DM density

spectra produced per annihilation in a given annihilation channel

- Semi-Analytic : $$\frac{dn_e}{dE_e}(E_e, \vec{x}) = \frac{1}{b_{\rm tot}(E_e, \vec{x})} \int_{E_e}^{m_{\rm DM}} dE_e^S \, Q_e(E_e^S, r)$$

$b_{\rm tot}(E_e, \vec{x})$: total energy loss rate of $e^{\pm}$ ➡ Dominating process near the GC region

- ➔ **ICS on ambient photons**
- ➔ **synchrotron emission in galactic *B*-field**
- ➔ **Coulomb interactions with interstellar gases**
- ➔ **ionization of the same gases**
- ➔ **bremsstrahlung on the same gases**

Buch, *et al.*, (PPPC 4 DM, [1505.01049])

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Buch, *et al.*, (PPPC 4 DM, [1505.01049])

- Full-propagation of $e^{\pm}$:

(spatial difusion, advection/convection, re-acceleration, energy losses, various nuclear processes)

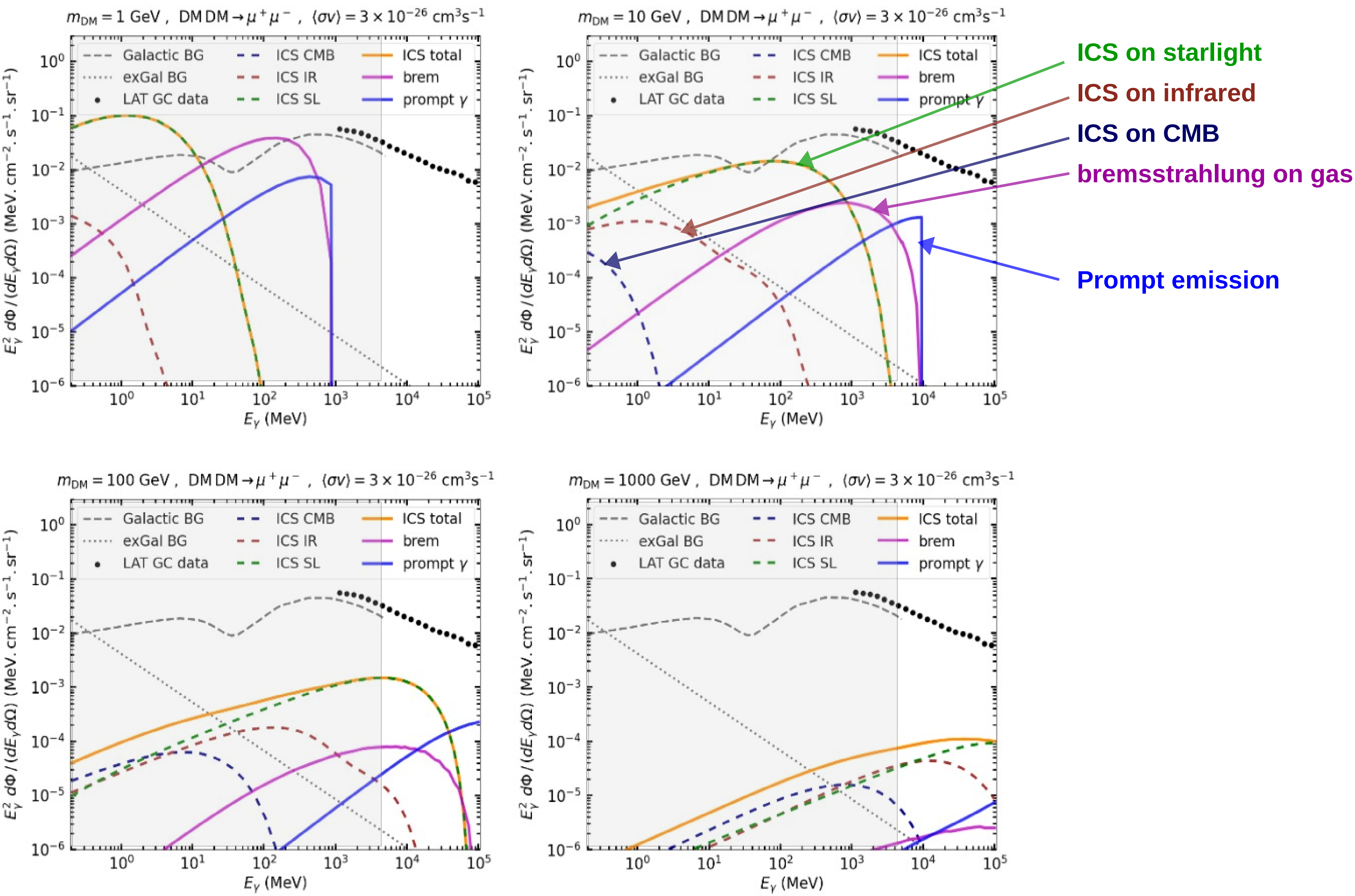
$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N_i\right] = Q + \sum_{i<j}\left(c\beta n_{\rm gas}\, \sigma_{j\to i} + \frac{1}{\gamma \tau_{j\to i}}\right) N_j - \left(c\beta n_{\rm gas}\, \sigma_i + \frac{1}{\gamma \tau_i}\right) N_i$$

$J_i = -D_{ij} \nabla_j N$

Evoli *et al.*, (1607.07886)

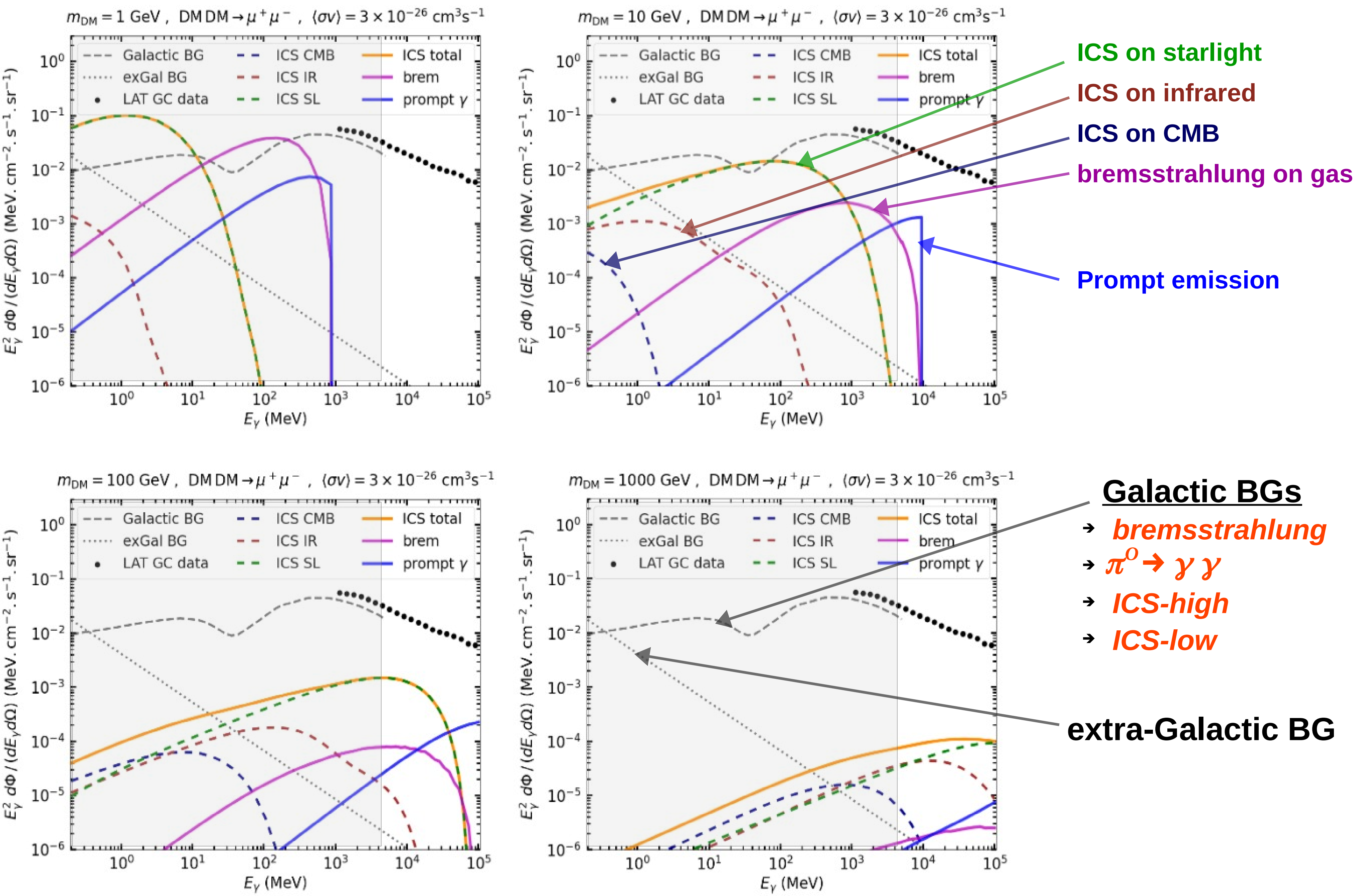
$N_i(\vec{r}, p)$: no. density of e^- / e^+ per momentum *p*

MeV-GeV photons from WIMP annihilations in the Galaxy



M. Cirelli, A.K.; (SciPost Phys. 19 (2025) 080)

MeV-GeV photons from WIMP annihilations in the Galaxy



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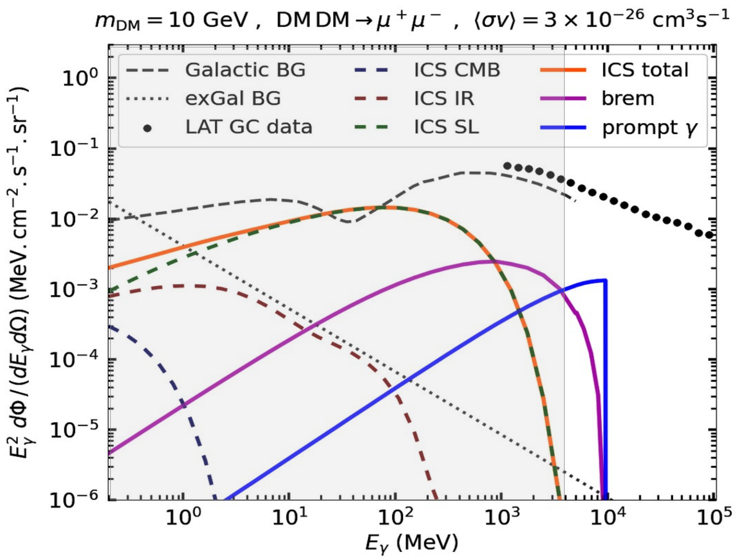
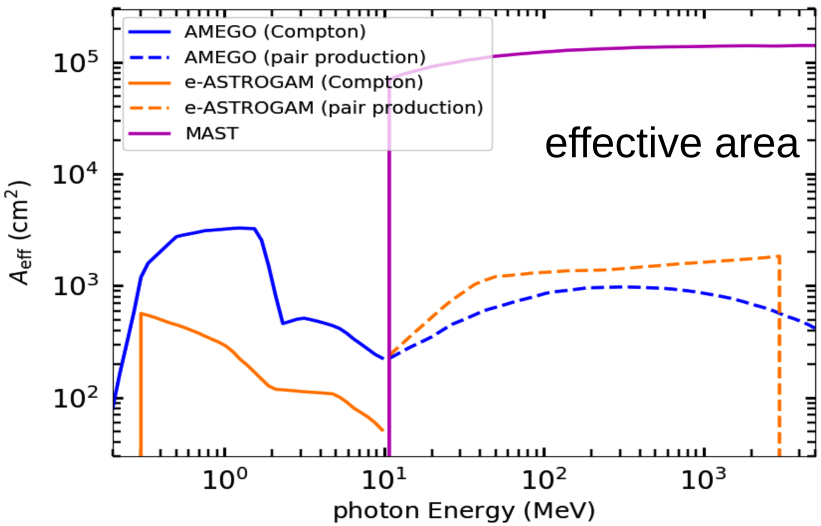
WIMP annihilation signals at the MeV telescopes

- MeV telescopes : **AMEGO, e-ASTROGAM and MAST** **0.2 MeV $\lesssim E_\gamma \lesssim$ 5 GeV**





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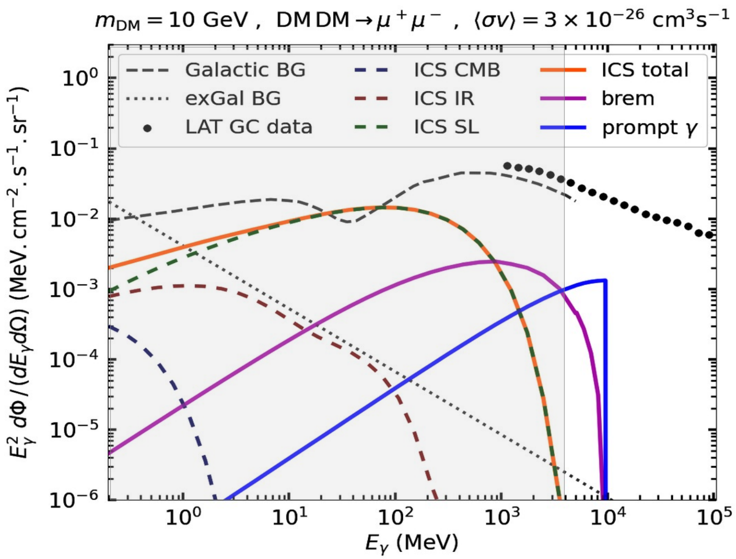
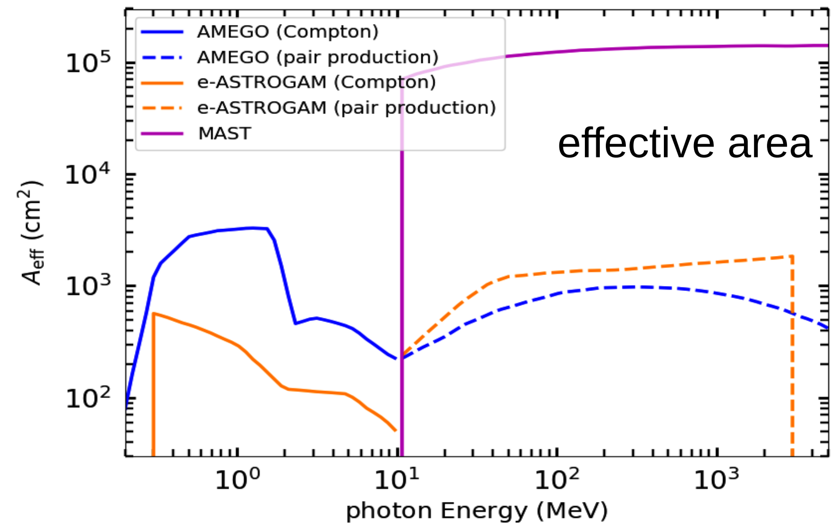




Fisher-projections :

M. Cirelli, A.K.; (SciPost Phys. 19 (2025) 080)

$$\mathcal{F}_{ij} = t_{obs} \int_{E_{min}}^{E_{max}} dE_\gamma A_{eff}(E_\gamma) \int_{\Delta\Omega} d\Omega \left(\frac{1}{\phi_{tot}} \frac{\partial \phi_{tot}}{\partial \theta_i} \frac{\partial \phi_{tot}}{\partial \theta_j} \right)_{\vec{\theta}=\vec{\theta}_{fiducial}}$$

$$\phi_{tot}(\vec{\theta}) = \frac{d\Phi^{SIG}}{dE_\gamma d\Omega}(\Gamma^{SIG}) + \sum_I \theta_I^{BG} \left\{ \frac{d\Phi_{BG}^I}{dE_\gamma d\Omega} \right\}_{fiducial}$$

$$\vec{\theta} = \left[\Gamma^{SIG},\, \theta^{BG}_{brem},\, \theta^{BG}_{\pi^0},\, \theta^{BG}_{ICS_{hi}},\, \theta^{BG}_{ICS_{lo}},\, \theta^{BG}_{e.g.}\right]$$

t_{obs} → observation time

Energy-resolution

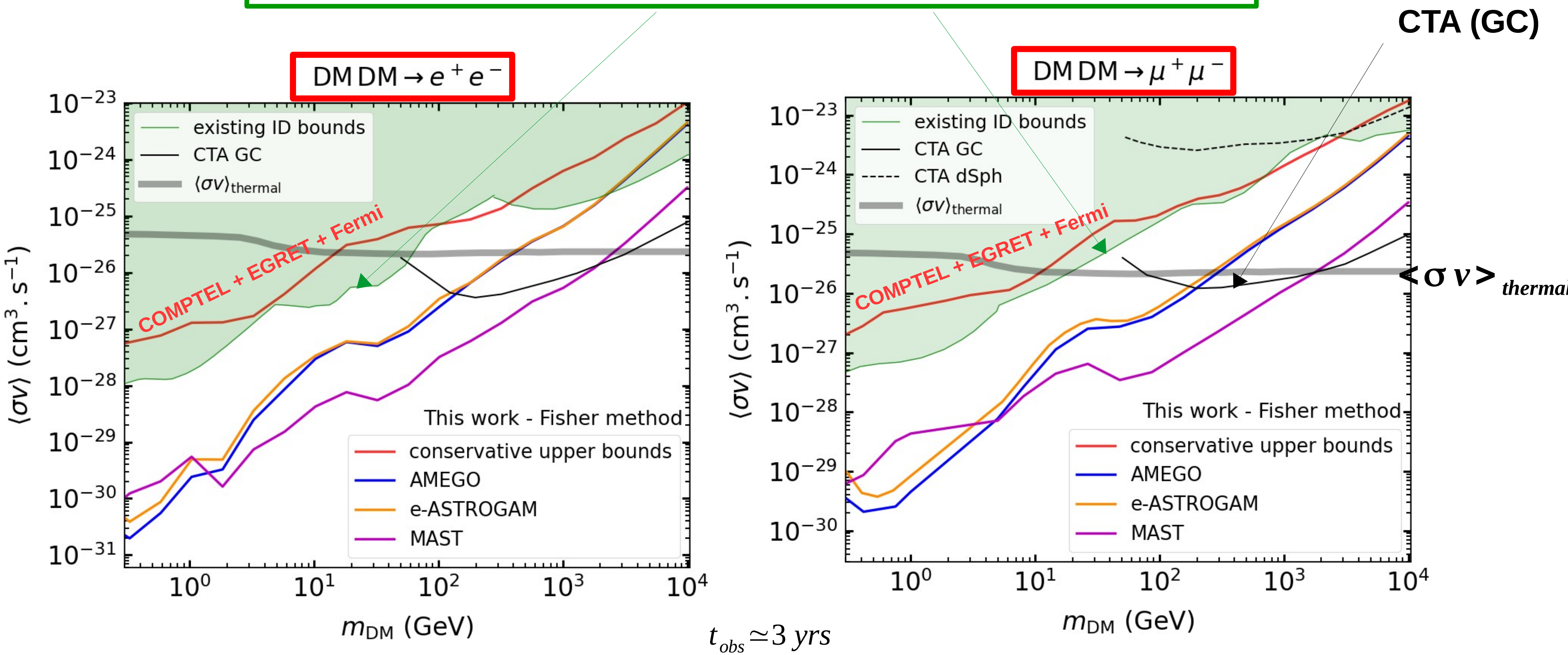
$$\frac{d\Phi}{dE_\gamma d\Omega} = \int dE'_\gamma R_\epsilon(E_\gamma, E'_\gamma) \frac{d\Phi}{dE'_\gamma d\Omega}$$

AMEGO (30%) , e-Astrogam (30%), MAST (30%)

(2σ - projections) $\Gamma^{SIG}_{proj} = 2\sqrt{(\mathcal{F}^{-1})_{11}}$ (scales as $\sqrt{t_{obs}}$)

Projected sensitivities for WIMP (leptonic annihilations)

Existing constraints: CMB + X-rays + γ-rays + AMS e^{+} + neutrinos

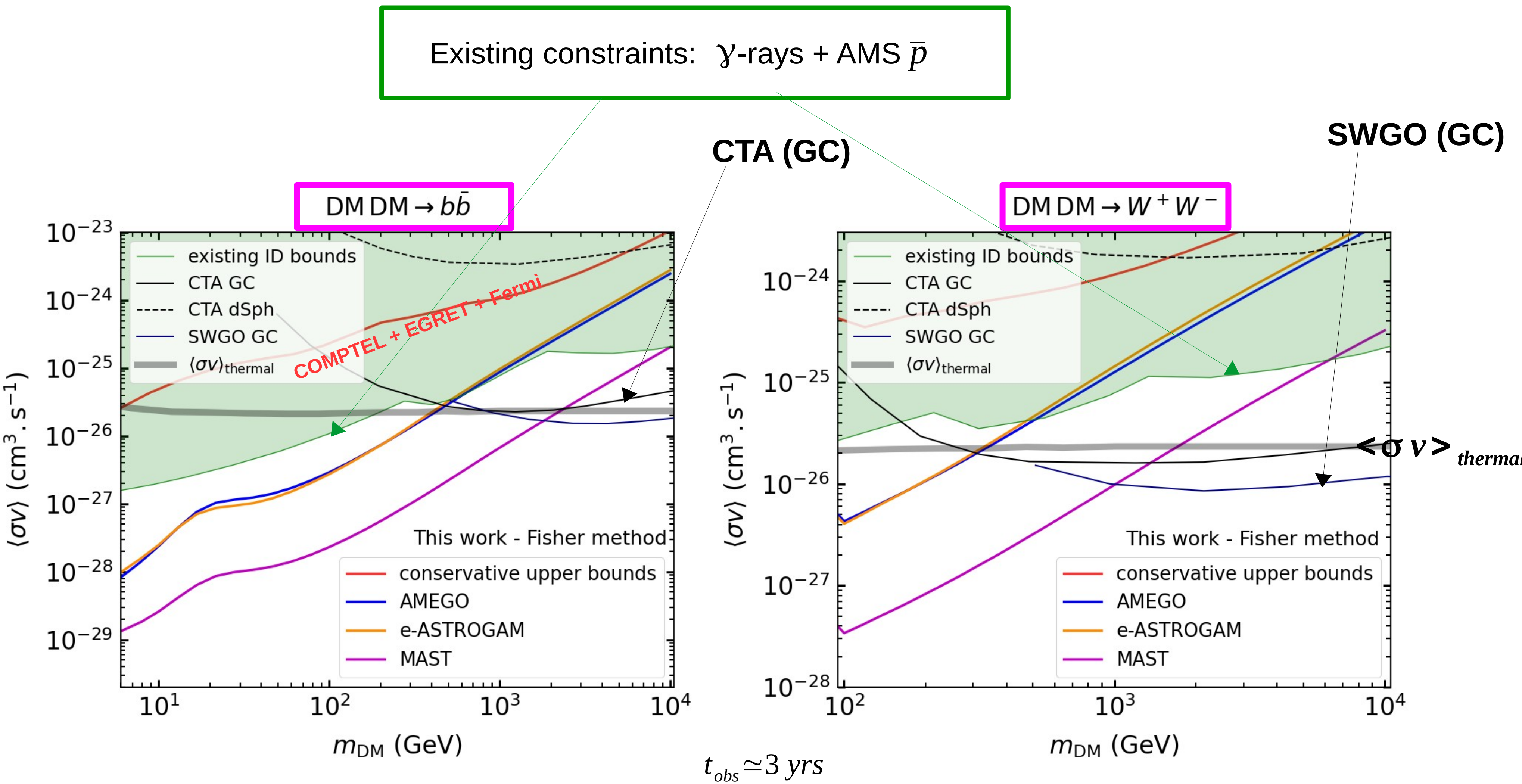


upper-bounds and projected sensitivities of the MeV telescopes AMEGO, e-ASTROGAM and MAST

M. Cirelli, A.K.; (SciPost Phys. 19 (2025) 080)

- **Future space-based MeV gamma-ray telescopes will complement the ground-based high energy gamma-ray instruments in the indirect searches for weak-scale DM**

Projected sensitivities for WIMP (hadronic annihilations)



M. Cirelli, A.K.; (SciPost Phys. 19 (2025) 080)

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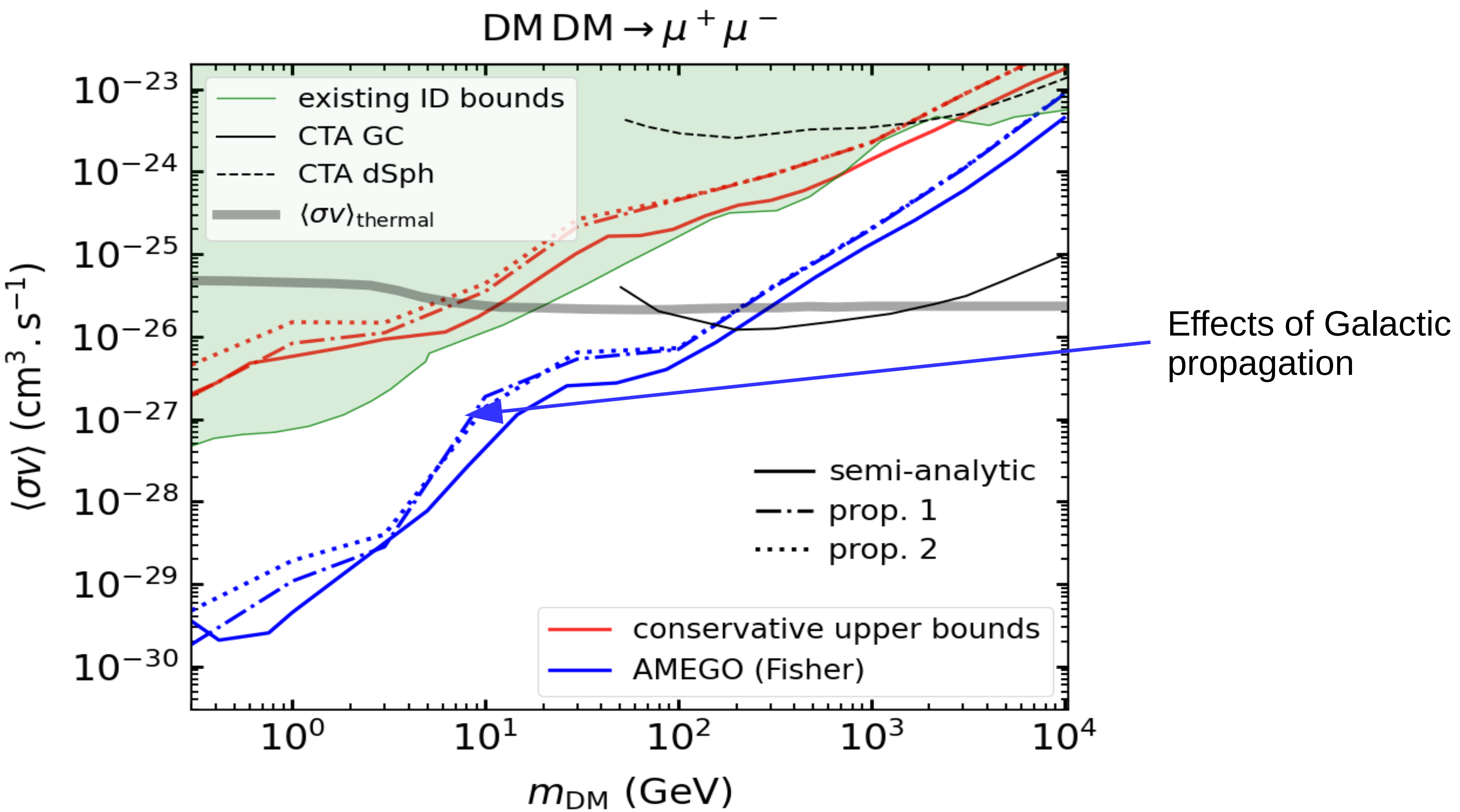
Effects of propagation of $e^{\pm}$ in the Galaxy



projected sensitivities of the MeV telescope AMEGO

Prop. 1 : propagation model from [Strong *et al*., (1008.4330), (1101.1381)]

Prop. 2 : propagation model from [Calore *et al*., (1409.0042)]

} used also to estimate the **secondary photon BGs** towards the GC region

M. Cirelli, A.K.; (SciPost Phys. 19 (2025) 080)

Summary

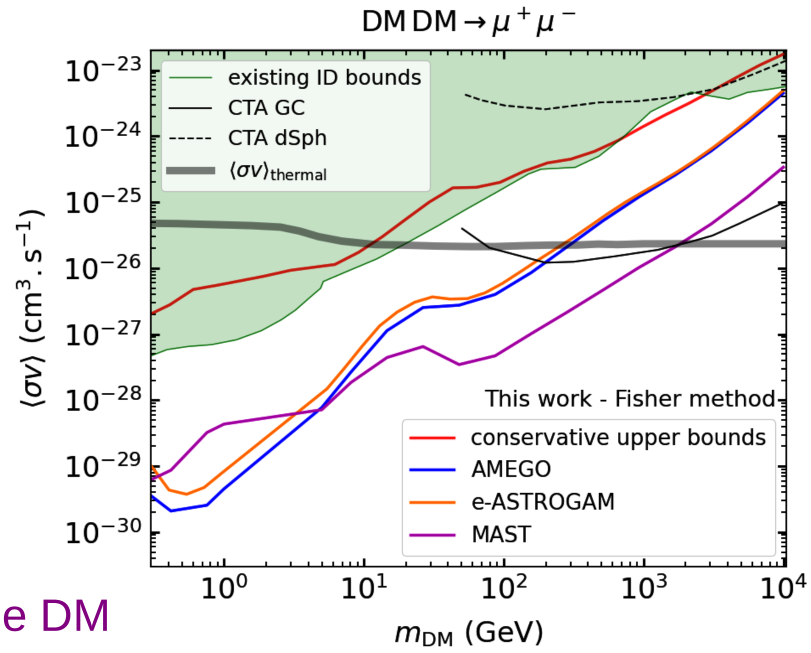
- We explore the potential of the upcoming MeV telescopes in probing the photon signals from weak-scale DM annihilations in the Galaxy

- Low-energy secondary emissions (e.g., ICS and bremsstrahlung) produced by DM induced $e^{\pm}$ significantly enhance the sub-GeV γ- ray signals of weak-scale DM annihilations

  (for lepton-rich annihilation channels)

  ⟹ Significant enhancements in the sensitivity of MeV telescopes in probing weak-scale DM

- Based on such signals, the MeV telescopes will be able to explore a wide area of the m_{DM}- <σv> plane that is yet unconstrained

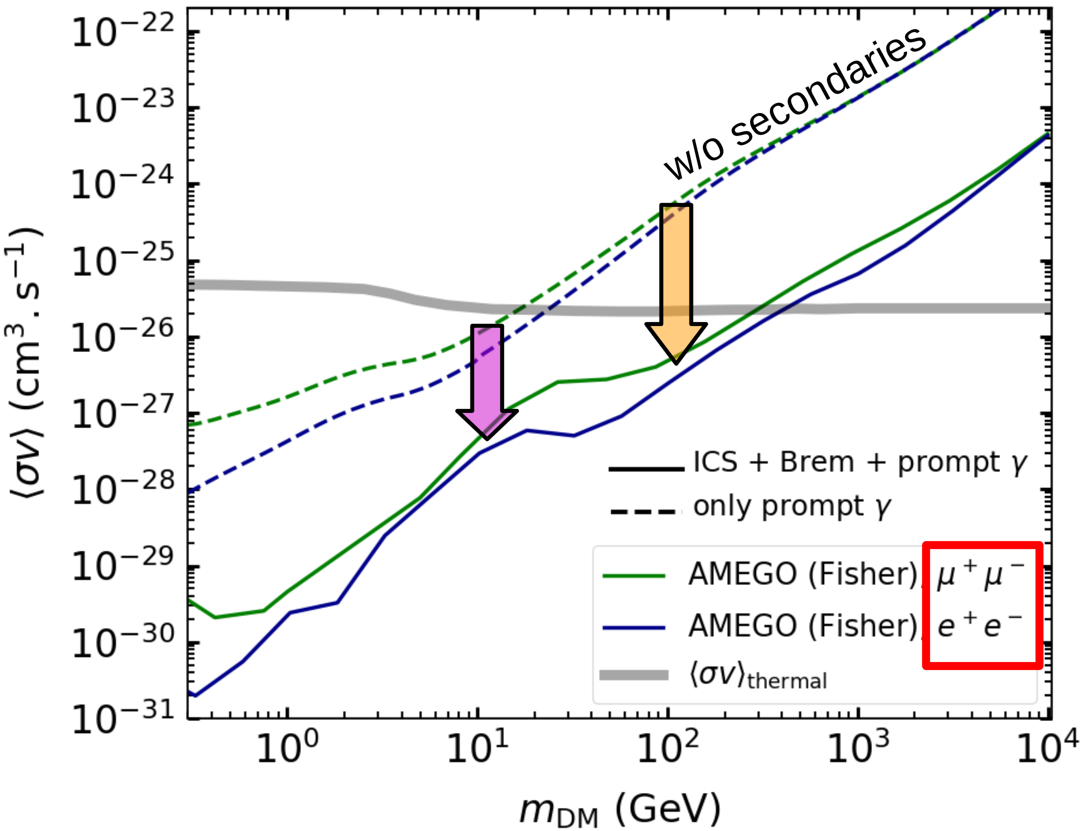


- MeV γ- ray telescopes can efficiently complement the ground-based high energy γ- ray instruments in the indirect searches for weak-scale DM

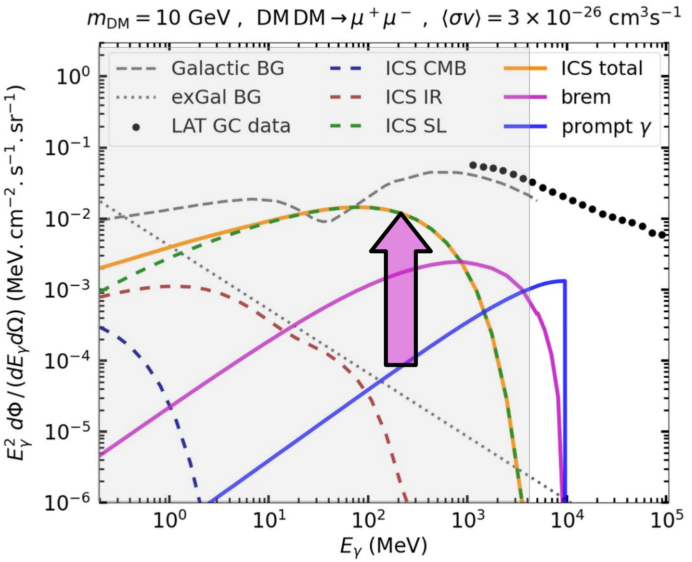
- Add an important tool in the indirect searches of weak-scale DM

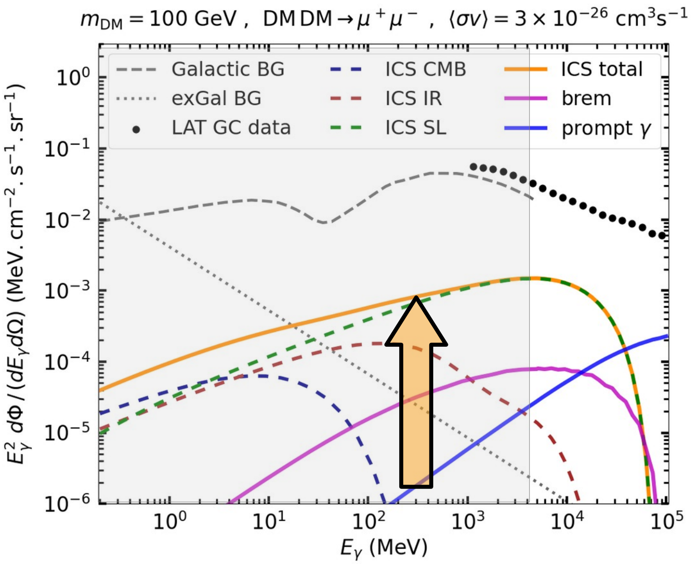
Backup slides

Importance of considering the secondary signals for WIMPs



projected sensitivities of the MeV telescope AMEGO





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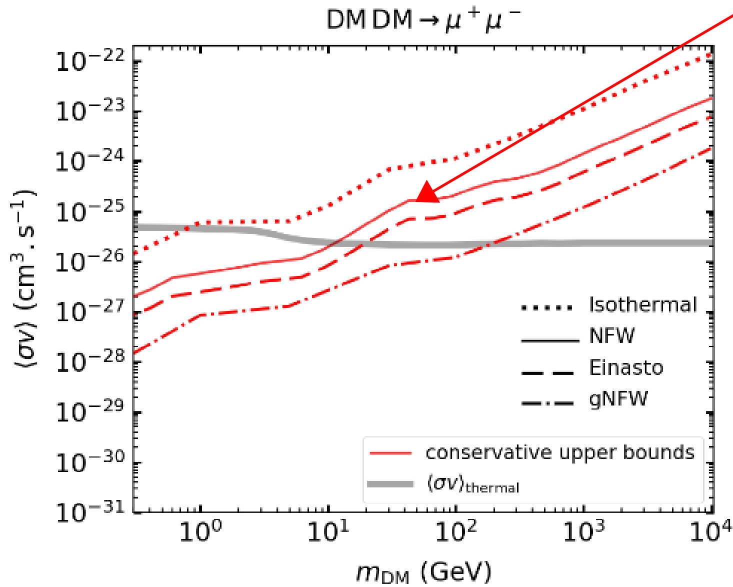
Impact of the choice of DM profile

NFW: $$\rho_{\rm DM}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$$



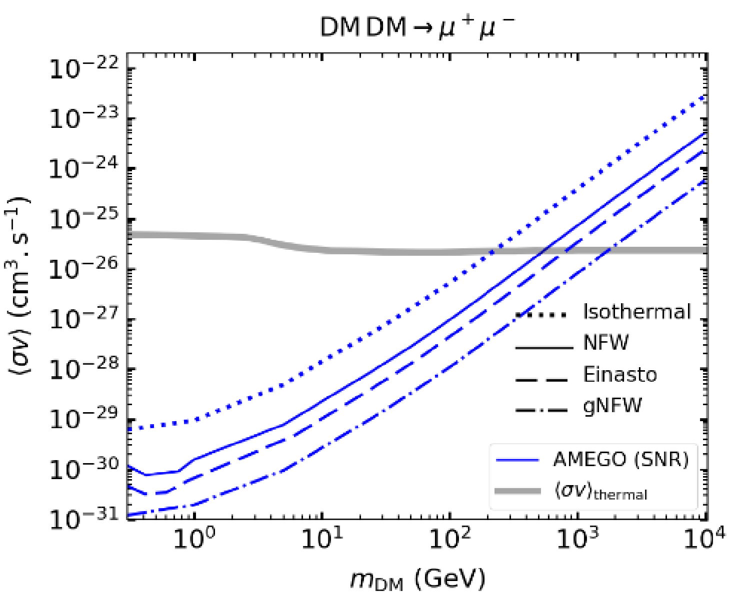
Einasto: $$\rho_{\rm DM}^{\rm Ein}(r) = \rho_0 \exp\left\{-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right\}$$

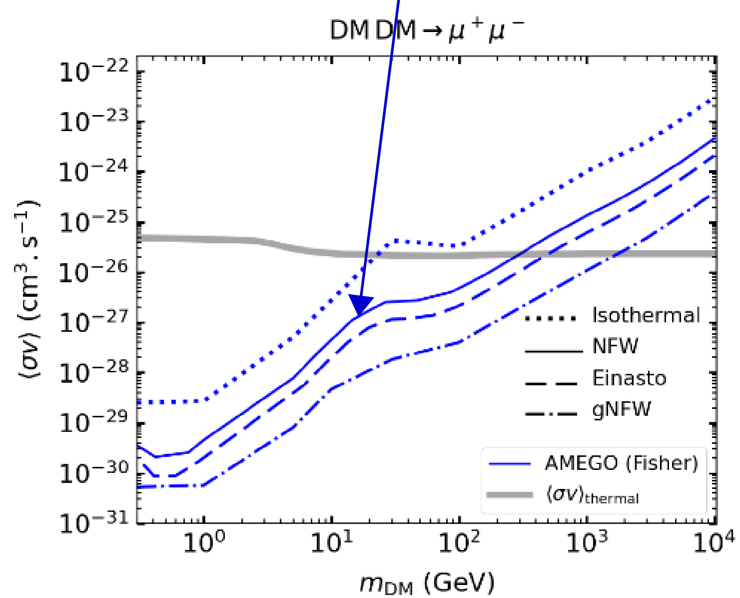
$\alpha = 0.18$

gNFW: $$\rho_{\rm DM}^{\rm gNFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$

$\gamma = 1.3$

Isothermal (cored): $$\rho_{\rm DM}^{\rm Iso}(r) = \frac{\rho_0}{1+\left(\frac{r}{r_s}\right)^2}$$





Salas *et al*., (1906.06133)

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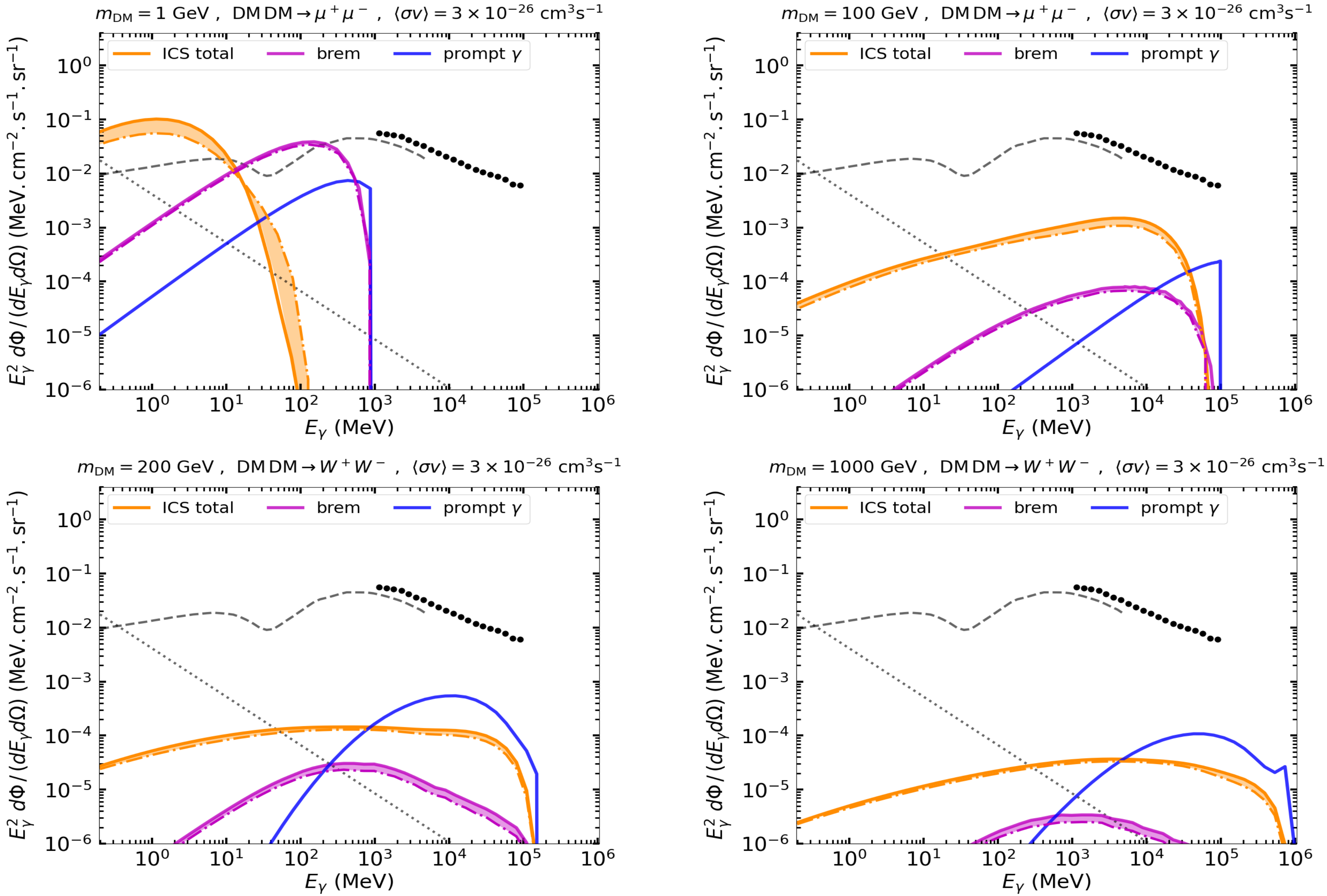
ISRF models



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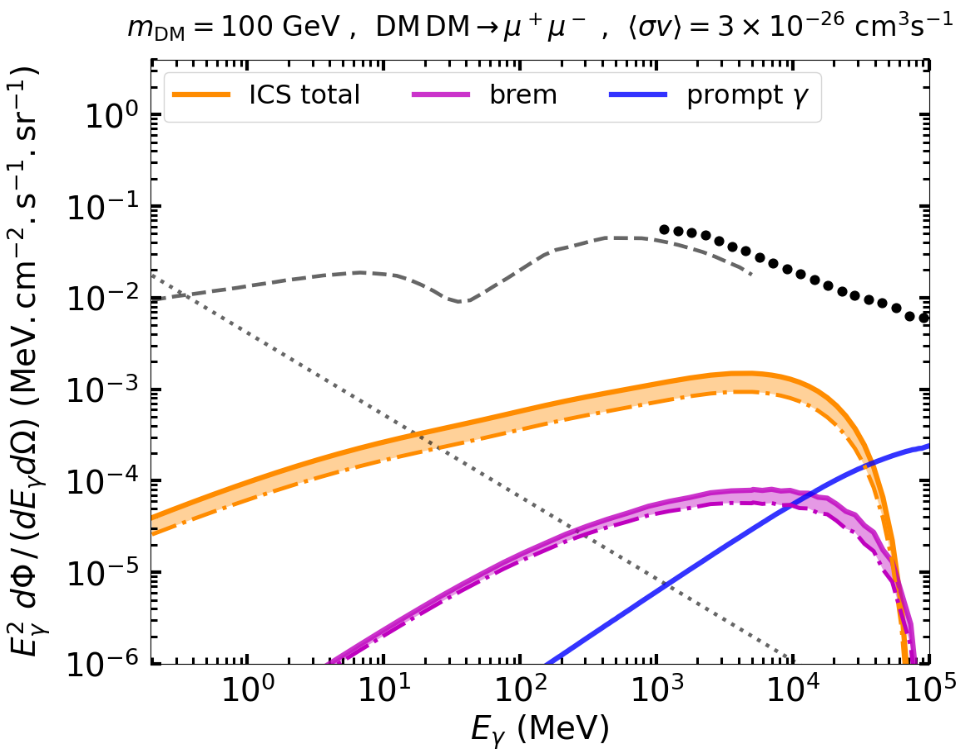
ISRF model 1 (solid lines):

Buch, *et al.*, (PPPC 4 DM, [1505.01049]), (GALPROP)

ISRF model 2 (dashed-dotted lines):

Porter, *et al.*, (astro-ph/0507119) (used in DRAGON)

Galactic B-field models

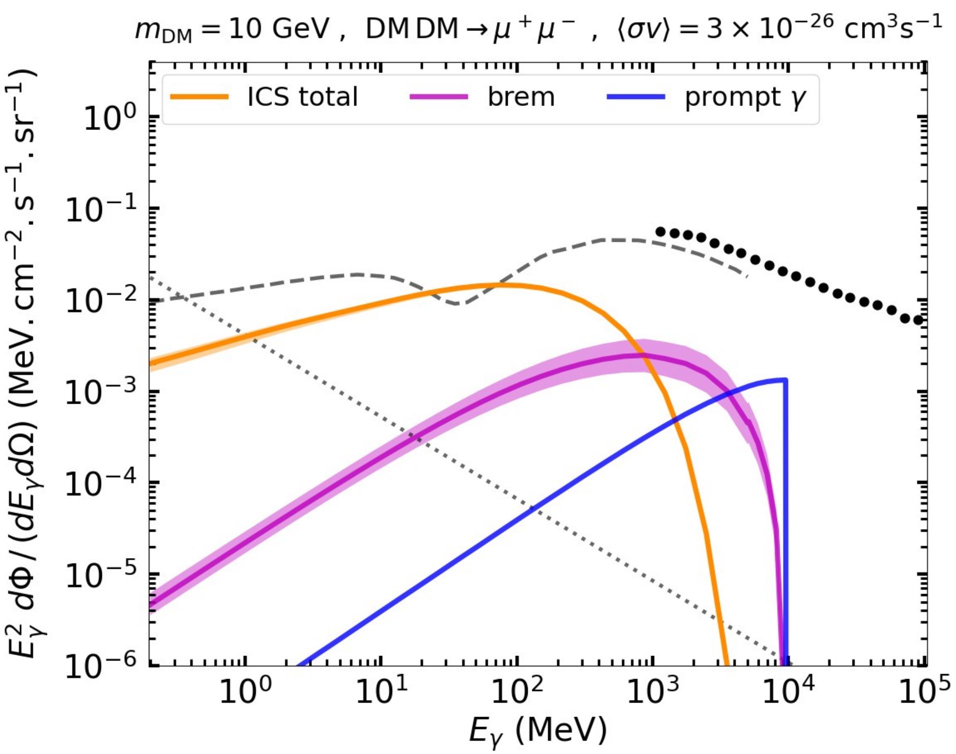


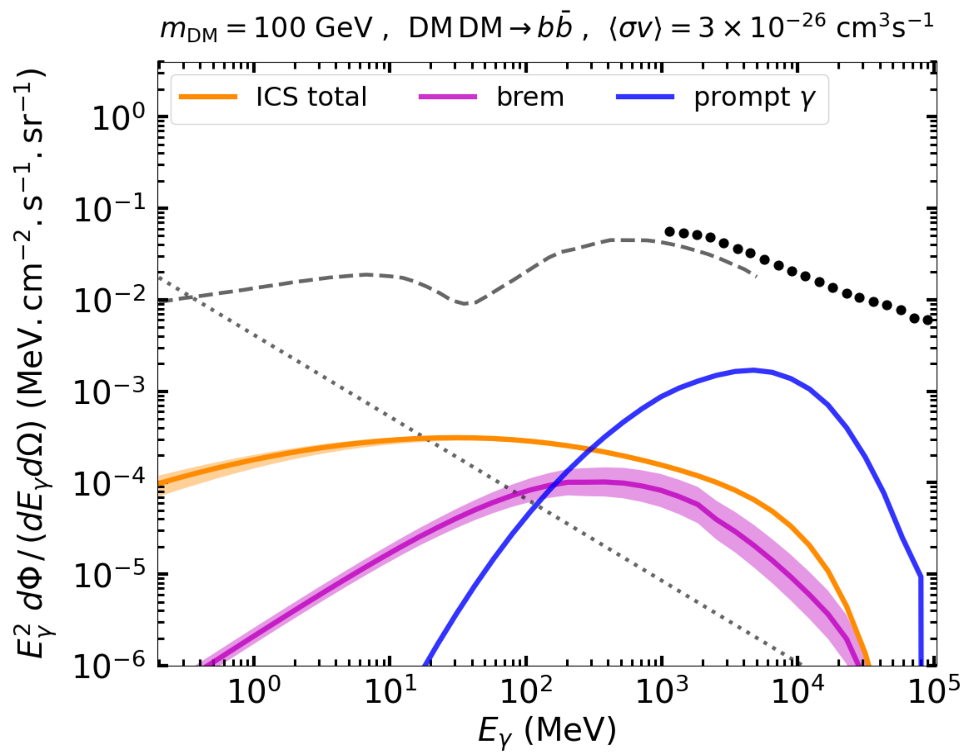
Different Galactic B-field models from:

Buch, *et al.*, (PPPC 4 DM, [1505.01049])

M. Cirelli, A.K.; (SciPost Phys. 19 (2025) 080)

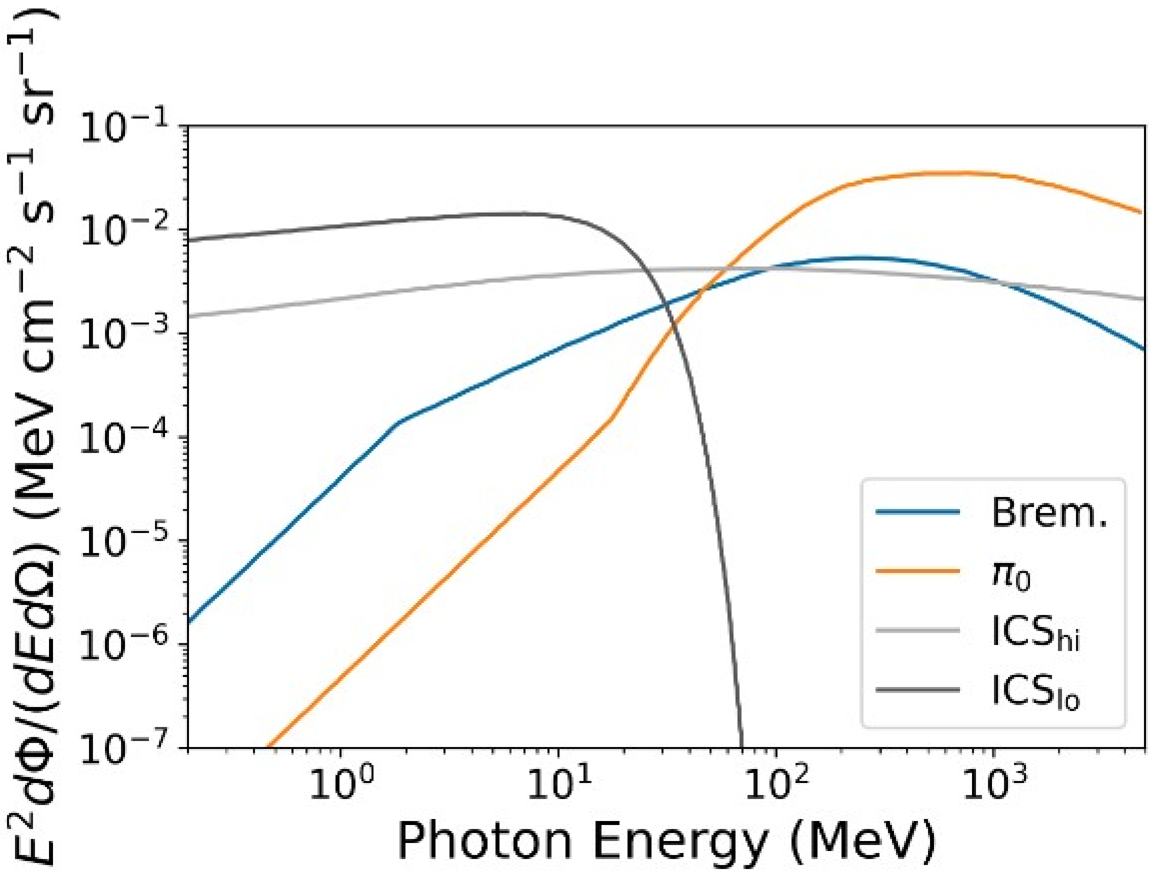
Galactic gas map models





M. Cirelli, A.K.; (SciPost Phys. 19 (2025) 080)

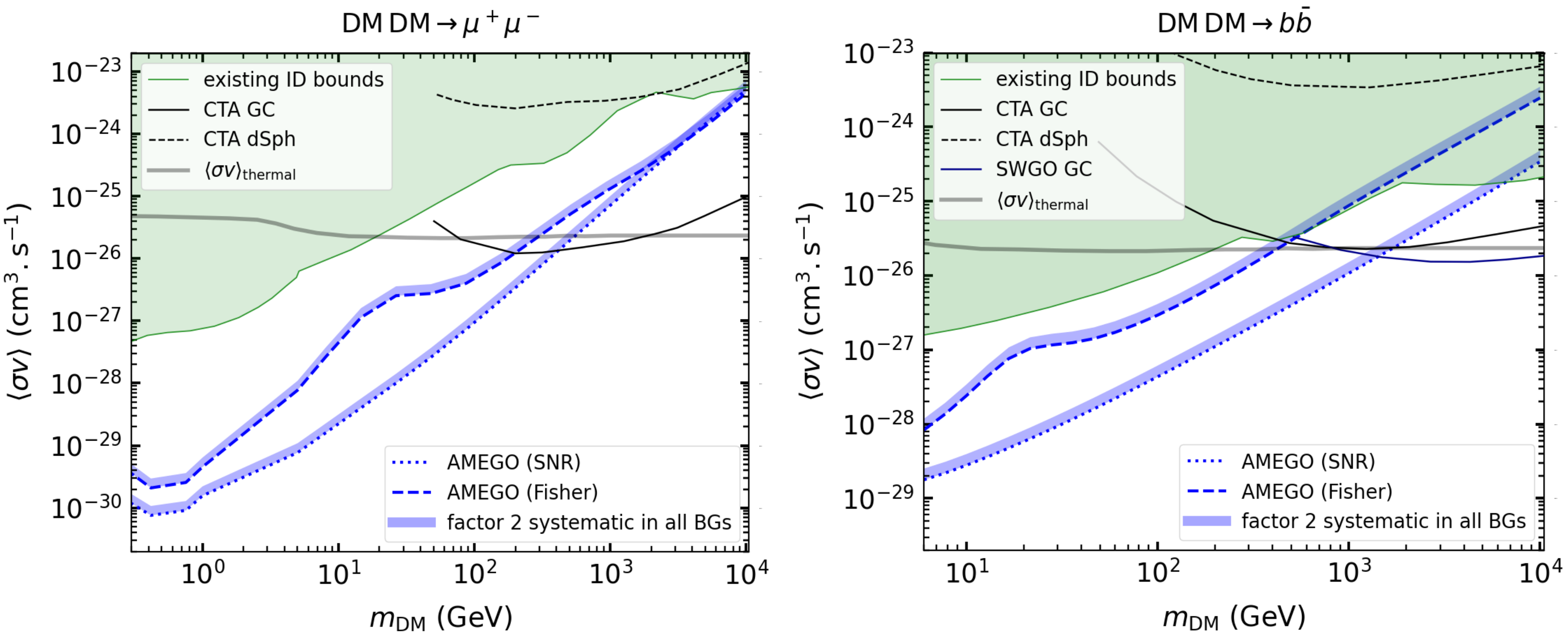
Photon backgrounds from the inner Galaxy



O'Donnell *et al.*, (2411.00087)

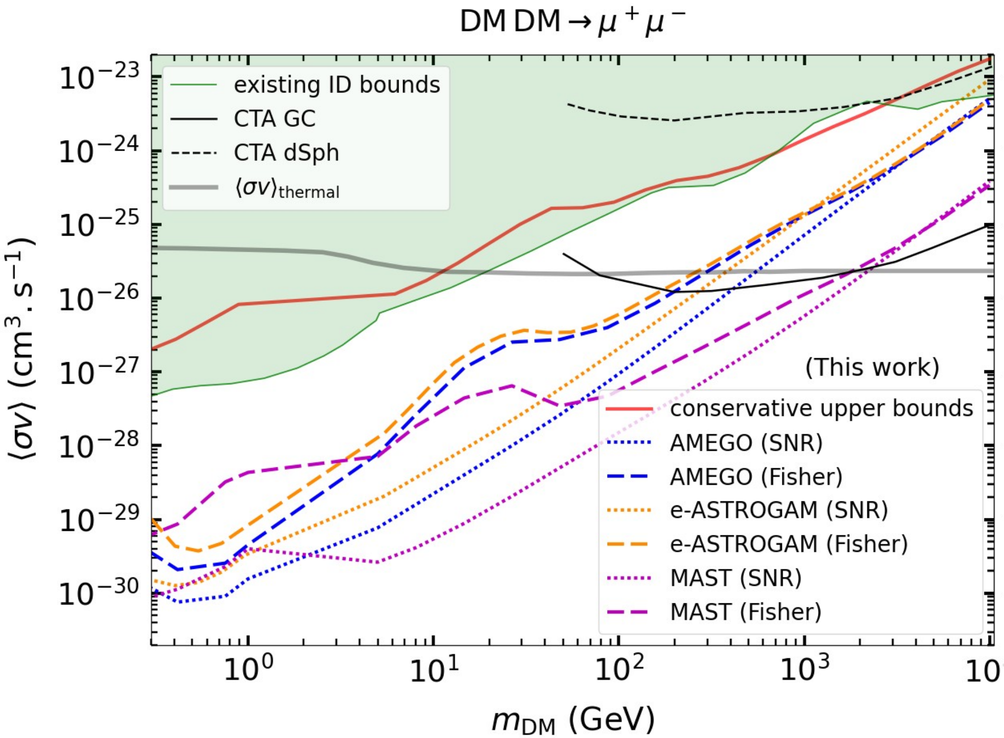
Galactic photon backgrounds from a region of 10^o radius around the GC

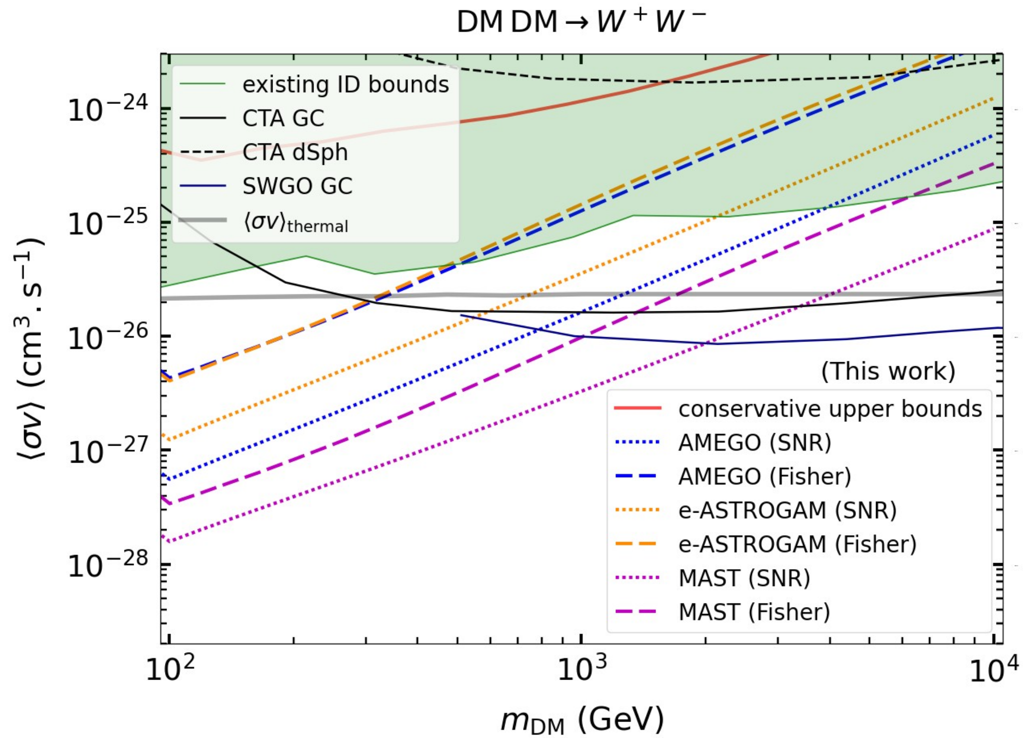
Systematic uncertainties in the backgrounds



M. Cirelli, A.K.; (SciPost Phys. 19 (2025) 080)

Signal-to-noise ratio and Fisher methods





Fisher-projections :

$$\mathcal{F}_{ij} = t_{\rm obs} \int_{E_{\rm min}}^{E_{\rm max}} dE_\gamma A_{\rm eff}(E_\gamma) \int_{\Delta\Omega} d\Omega \left(\frac{1}{\phi_{\rm tot}} \frac{\partial \phi_{\rm tot}}{\partial \theta_i} \frac{\partial \phi_{\rm tot}}{\partial \theta_j} \right)_{\vec{\theta}=\vec{\theta}_{\rm fiducial}}$$

$$\phi_{\rm tot}(\vec{\theta}) = \frac{d\Phi^{\rm SIG}}{dE_\gamma d\Omega}(\Gamma^{\rm SIG}) + \sum_I \theta_I^{\rm BG} \left\{ \frac{d\Phi^I_{\rm BG}}{dE_\gamma d\Omega} \right\}_{\rm fiducial}$$

$$\vec{\theta} = \left[\Gamma^{\rm SIG},\, \theta^{\rm BG}_{\rm brem},\, \theta^{\rm BG}_{\pi^0},\, \theta^{\rm BG}_{\rm ICS_{hi}},\, \theta^{\rm BG}_{\rm ICS_{lo}},\, \theta^{\rm BG}_{\rm e.g.} \right]$$

$$\Gamma^{\rm SIG}_{\rm proj} = 2\sqrt{(\mathcal{F}^{-1})_{11}}$$

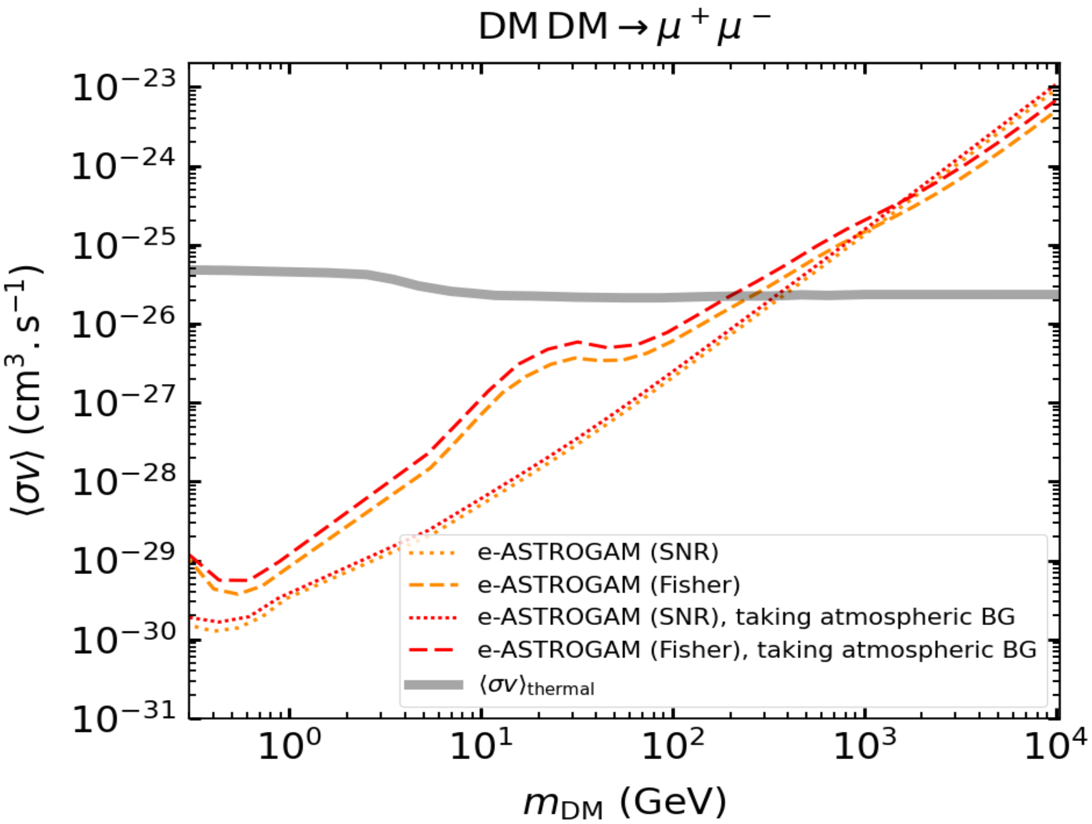
signal-to-noise ratio (SNR) :

$$\frac{N_\gamma\big|_{\rm DM}}{\sqrt{N_\gamma\big|_{\rm BG}}} \geq 5$$

$$N_\gamma = t_{\rm obs} \int_{E_{\rm min}}^{E_{\rm max}} dE_\gamma A_{\rm eff}(E_\gamma) \int_{\Delta\Omega} d\Omega \frac{d\Phi}{dE_\gamma d\Omega}$$

M. Cirelli, A.K.; (2503.04907v1)

Atmospheric backgrounds



M. Cirelli, A.K.; (SciPost Phys. 19 (2025) 080)