Prospects of probing weak-scale Dark Matter in future MeV telescopes

Arpan Kar

Based on: *[arXiv: 2503.04907]*

M. Cirelli, A. Kar

Dark Tools

Dipartimento di Fisica, Torino

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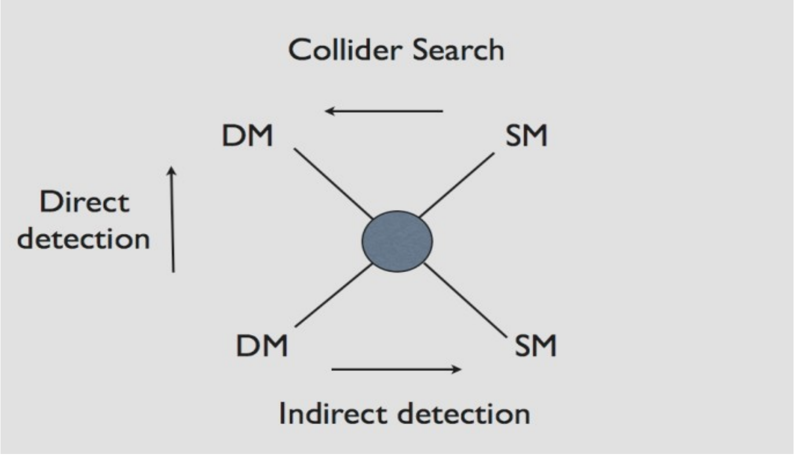
Dark matter : WIMPs

- Dark Matter (DM) exists and provides ∼25% of the energy density of the Universe
- Microscopic natures of DM are still unknown
- Weakly Interacting Massive Particles (WIMPs) : one of the most popular candidates for DM
  - no electric charge, no colors, stable
  - mass at the weak scale **(GeV – TeV)**
  - weak interactions ($\sigma v \sim 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$) keep WIMPs in thermal equilibrium in the early Universe and provide correct relic abundance through thermal decoupling
- WIMP searches :
  - Direct detection
  - Collider searches
  - Indirect detection



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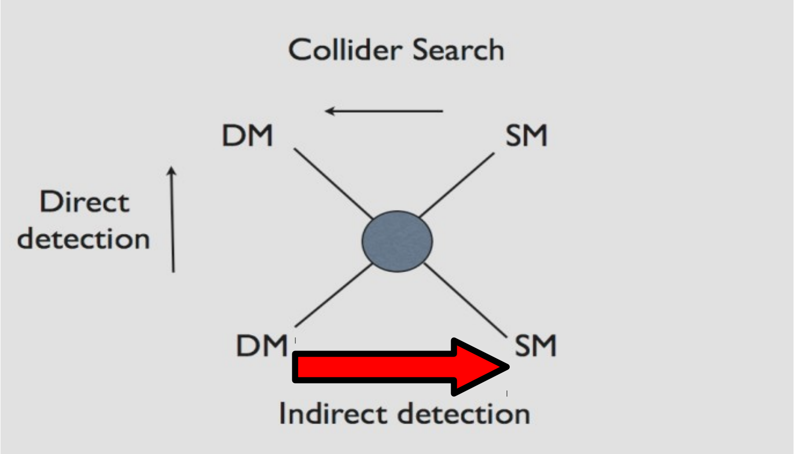
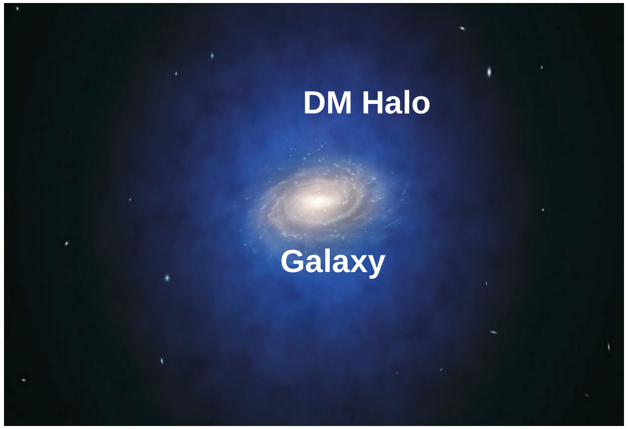
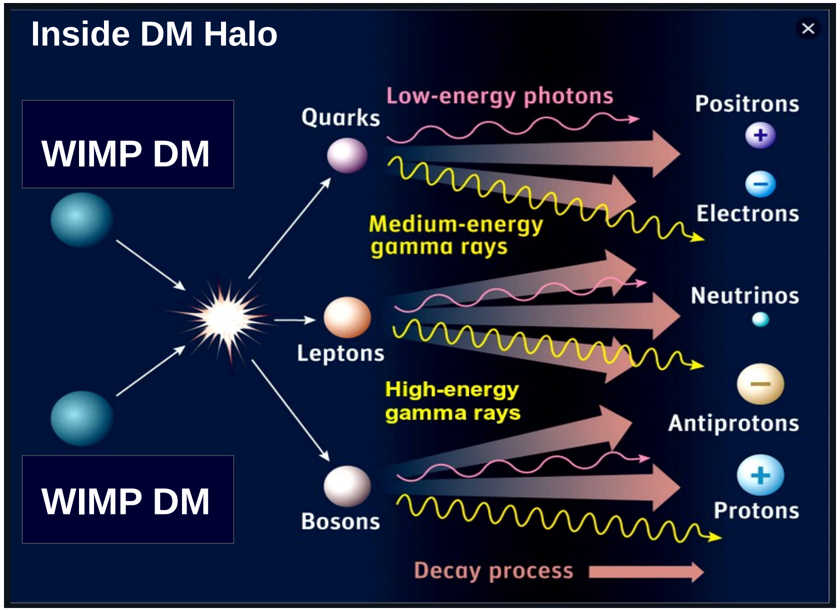


Indirect detection of WIMP DM



- DM is concentrated in the form of halos surrounding different galaxies (including our Galaxy)
  [Evidence: galactic rotation curves]



- Pair-annihilations of WIMP DM particles in such a halo can produce Standard Model particles which cascade further and produce flux of
  γ , e^+ / e^- , $p / \bar{p}$, ν's / $\bar{\nu}$'s , etc.

- Searches using different experiments:

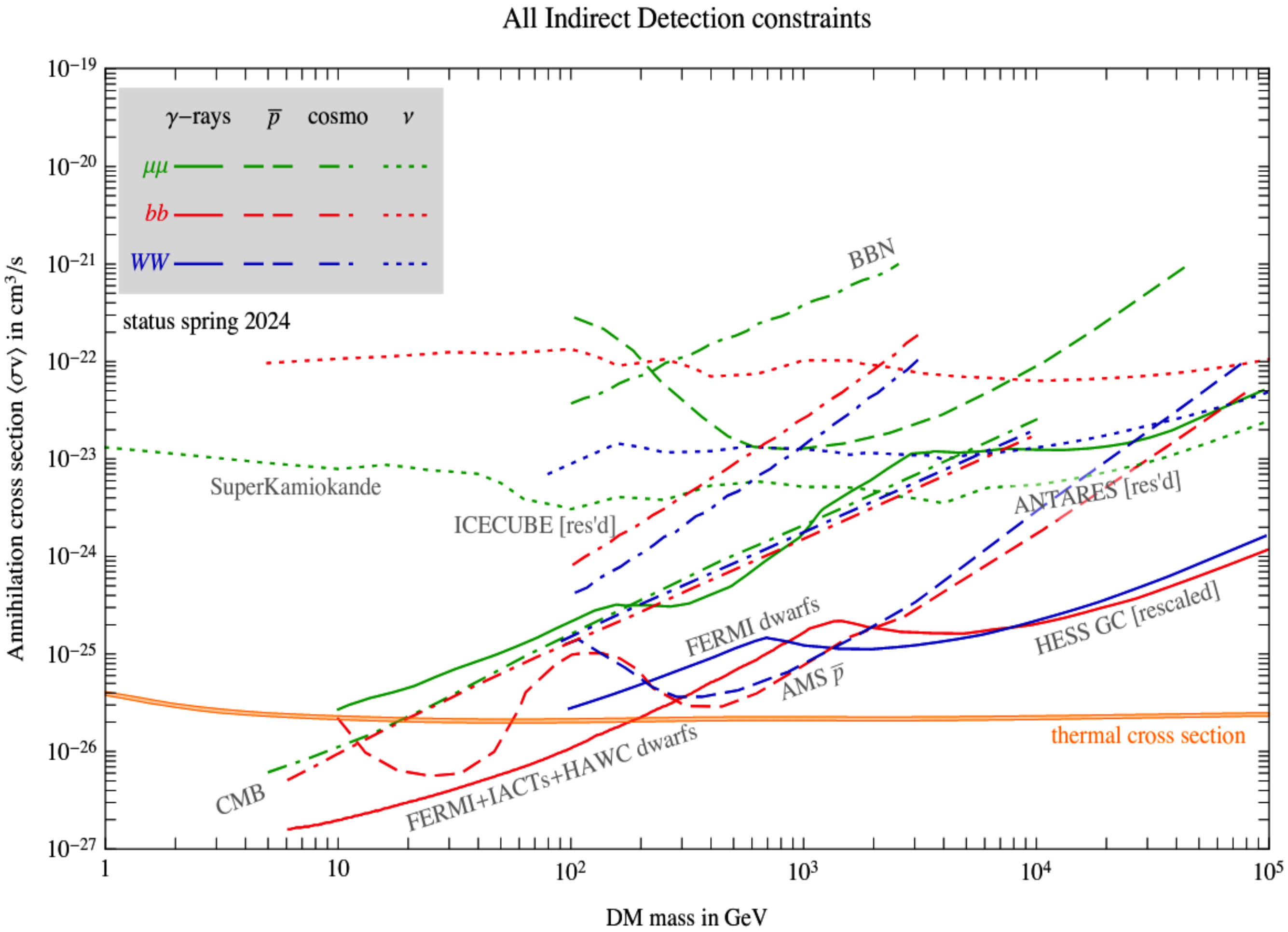
  γ - rays ⇨ Fermi-LAT, H.E.S.S., etc.

  $e^+ / \bar{p}$ ⇨ AMS-02 cosmic-ray, etc.

  ν's / $\bar{\nu}$'s ⇨ Super-K, IceCube, ANTARES etc.

- **Constraints on WIMP annihilation rate and WIMP mass**

Status of Indirect searches of WIMP DM



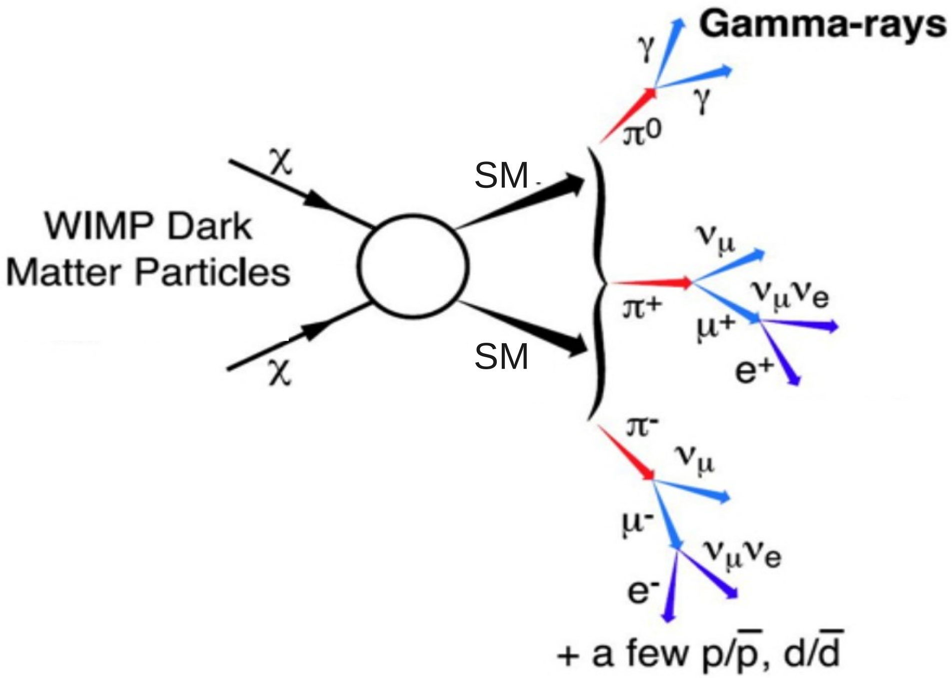
see talk by Marco Cirelli

M. Cirelli, A. Strumia, J. Zupan; (2406.01705)

Constraints on $<\sigma\, v>$ (WIMP pair-annihilation cross-section times velocity) as a function of the WIMP mass

Searches for WIMP DM in photon observations from the Galaxy

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



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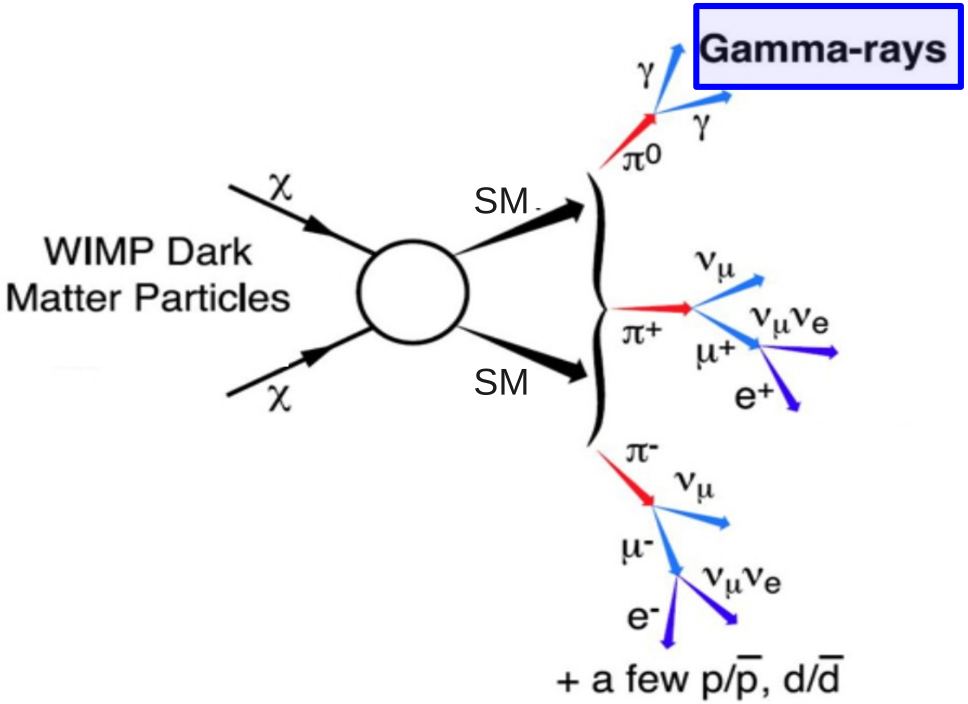

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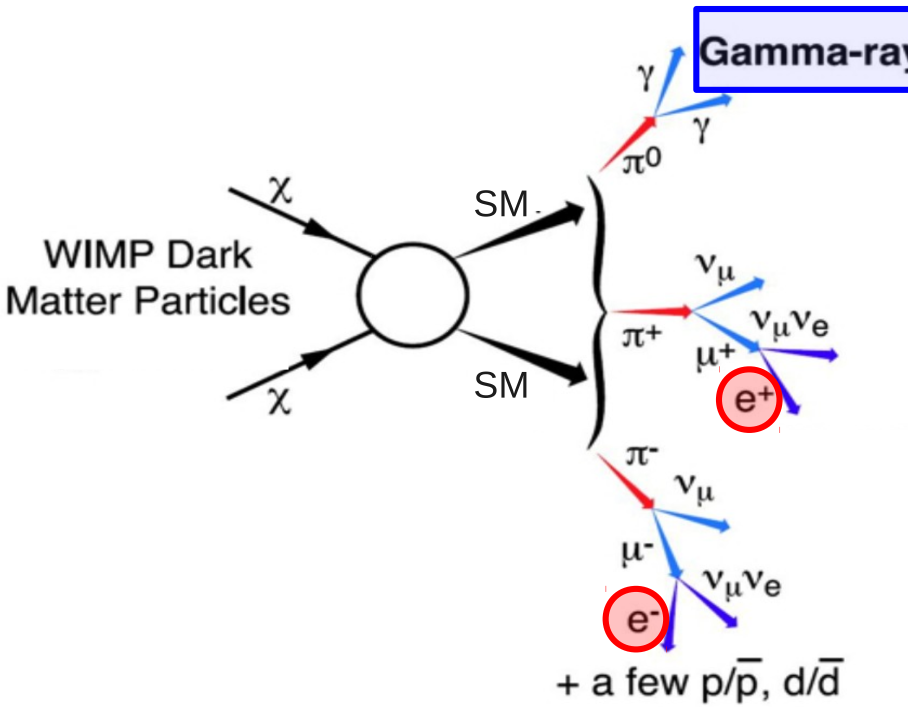

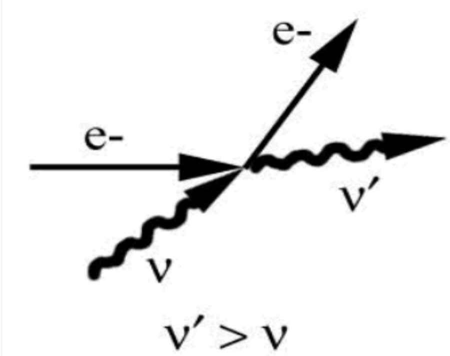

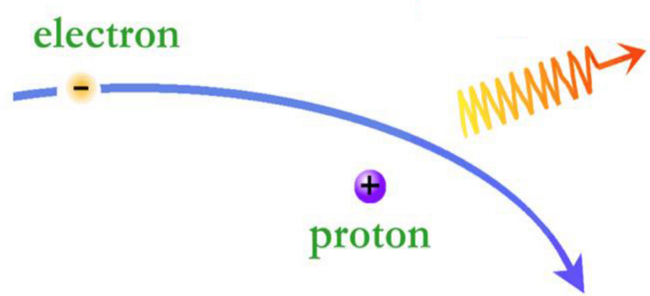

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- **Secondary radiation:** Galactic WIMP annihilations generate abundant energetic $e^{\pm}$, which subsequently emit through **Inverse Compton scattering (ICS)** and **bremsstrahlung**

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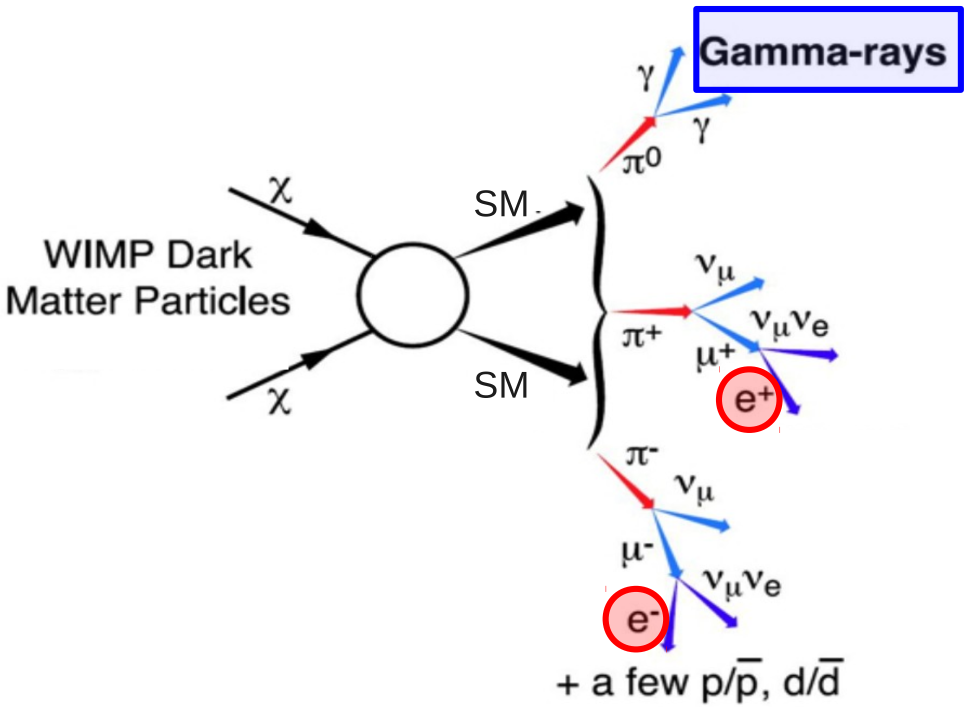

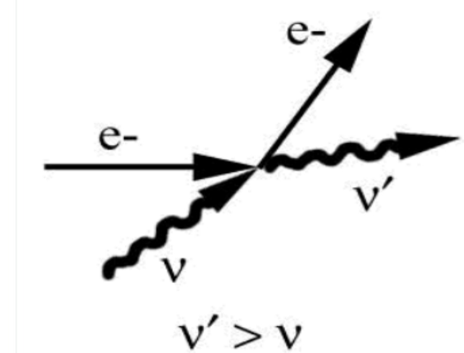

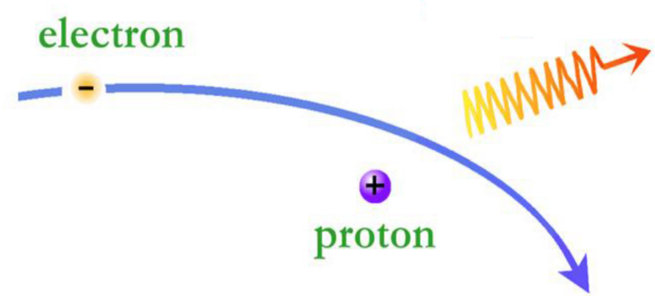

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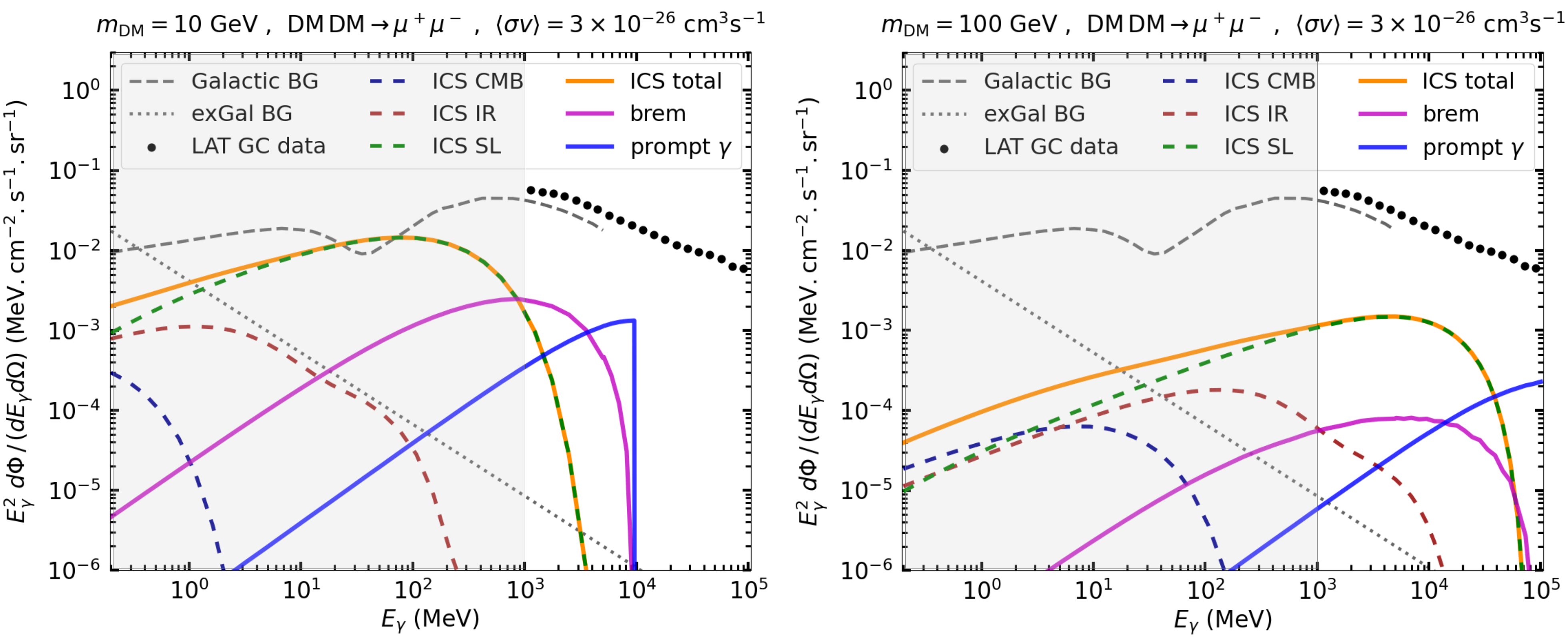
- **Secondary radiation:** Galactic WIMP annihilations generate abundant energetic $e^{\pm}$, which subsequently emit through **Inverse Compton scattering (ICS)** and **bremsstrahlung**
  - Comparatively lower-energetic gamma-rays photons
  - Enhanced for WIMPs annihilating into lepton-rich annihilation channels

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

Prompt and secondary photons from WIMP annihilations in the Galaxy

- The prompt emission signal from WIMP DM received by far most of the attention, mainly because:
  - ➔ Prompt emission concentrates at high-energy (above GeV)
  - ➔ Availability of various high-energy gamma-ray telescopes
    (Existing: Fermi-LAT, H.E.S.S, etc.) (Upcoming: CTA, SWGO, etc.)

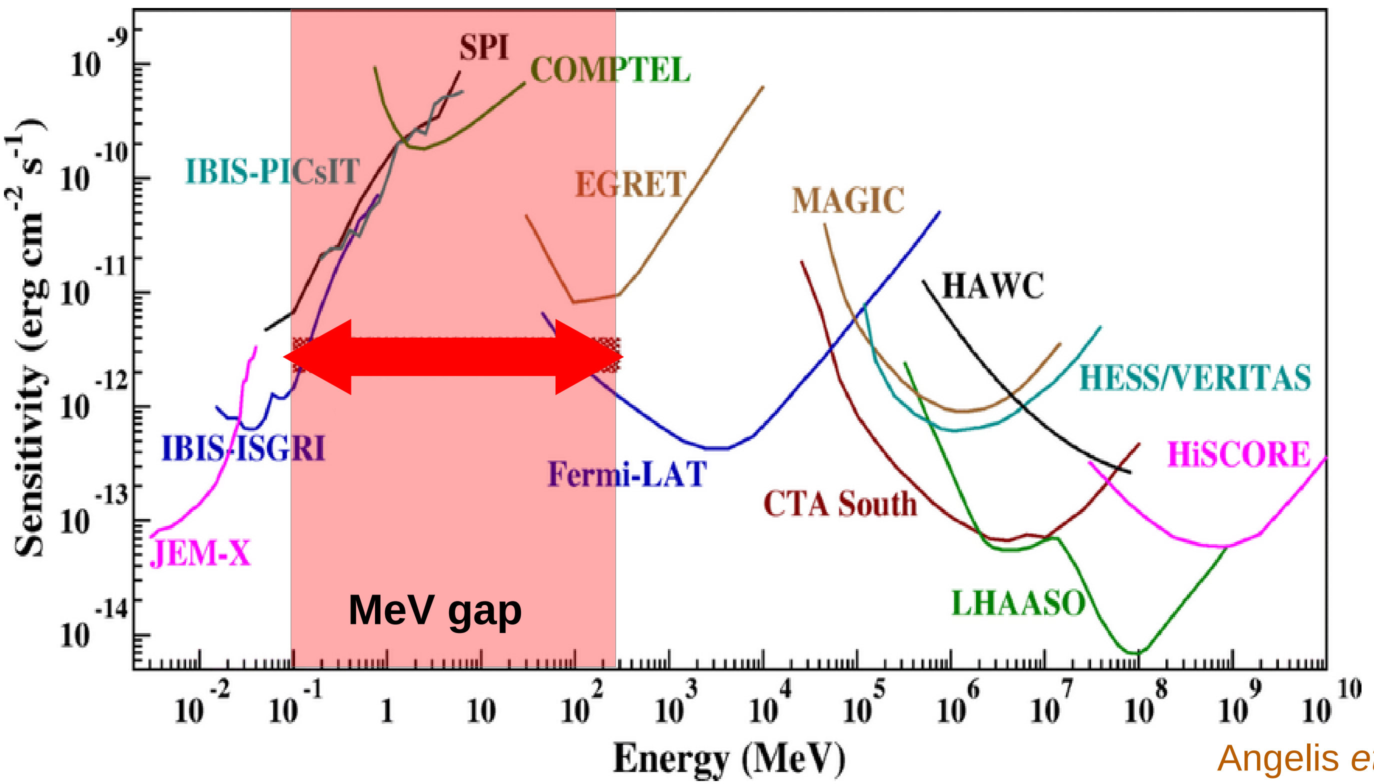


M. Cirelli, A.K.; (2503.04907)

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

MeV Gap and upcoming MeV missions

- **One potential difficulty for detecting the secondary emissions:** relatively poor sensitivity of past and existing telescopes 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, …….

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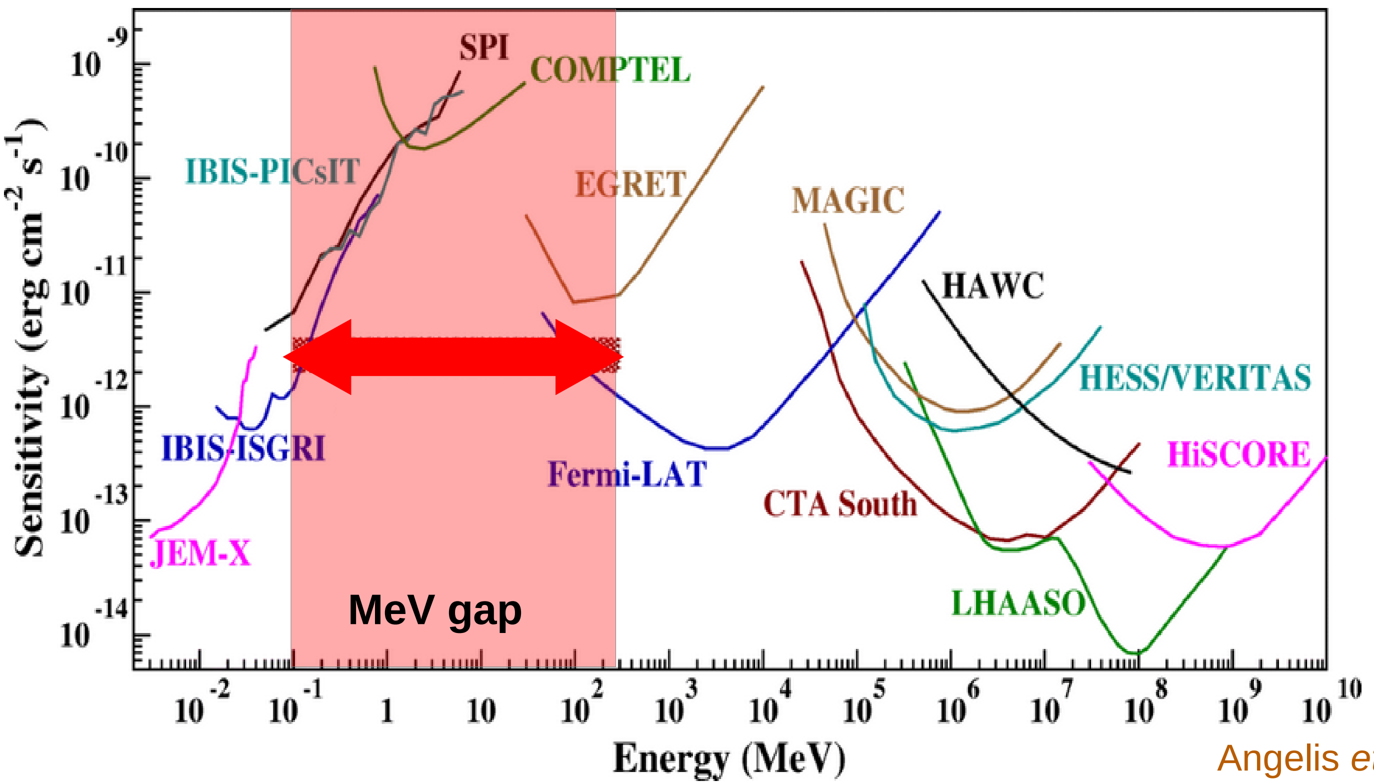

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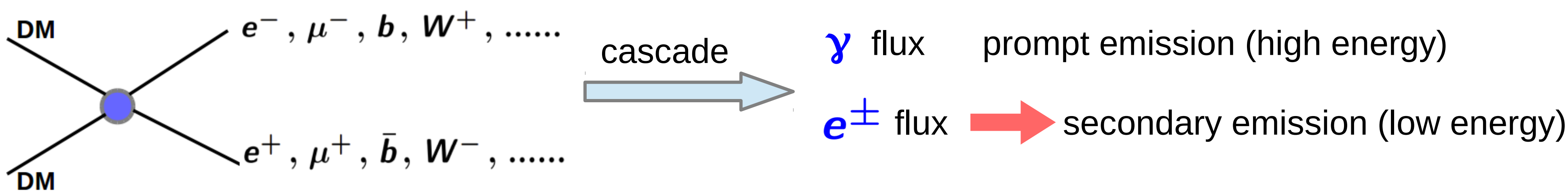
- **Potential of these MeV telescopes in probing WIMP DM, based on the secondary emission?**

MeV-GeV photons from WIMP annihilations in the Galaxy

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



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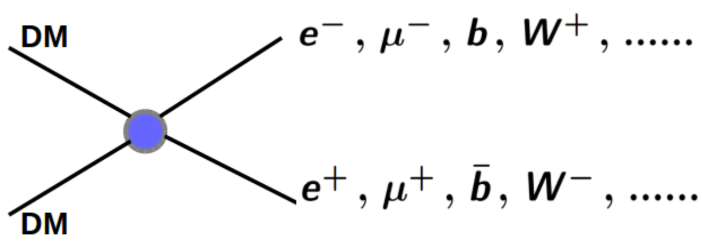

cascade

γ flux prompt emission (high energy)

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

- **<u>Prompt γ - ray emission flux:</u>**

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

$\frac{dN_\gamma}{dE_\gamma}$ 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° 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

(s, b, l) → Galactic coordinates

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

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

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

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

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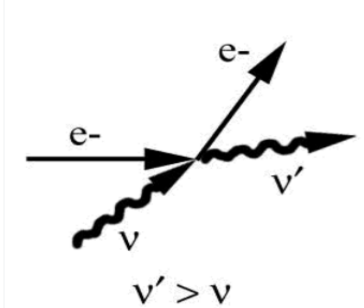
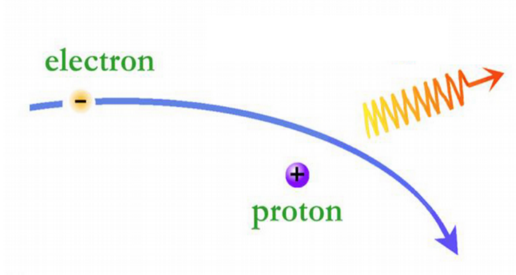
$$j_{\text{ICS}}(E_\gamma, \vec{x}(s,b,l)) = 2\int_{m_e}^{m_{\text{DM}}} dE_e \sum_{i\in\text{ISRF}} \mathcal{P}^i_{\text{ICS}}(E_\gamma, E_e, \vec{x}) \frac{dn_e}{dE_e}(E_e, \vec{x})$$

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

From DM annihilation





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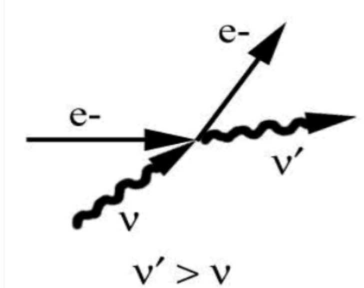
$$j_{\rm ICS}(E_\gamma, \vec{x}(s,b,l)) = 2\int_{m_e}^{m_{\rm DM}} dE_e \sum_{i\in{\rm ISRF}} \mathcal{P}^i_{\rm ICS}(E_\gamma, E_e, \vec{x}) \frac{dn_e}{dE_e}(E_e, \vec{x})$$

From DM annihilation

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

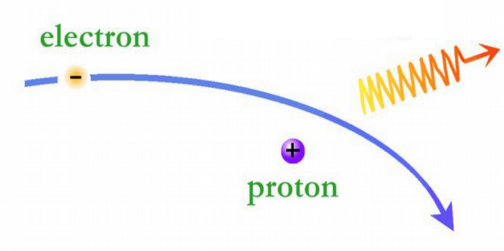
$$\mathcal{P}^i_{\rm ICS}(E_\gamma, E_e, \vec{x}) = c\, E_\gamma \int d\epsilon\, n_i^{\rm ISRF}(\epsilon, \vec{x})\, \sigma_{\rm IC}(\epsilon, E_\gamma, E_e)$$



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

J. Buch, M. Cirelli, G. Giesen, M. Taoso, (PPPC 4 DM, [1505.01049]) , (GALPROP)

$$\mathcal{P}_{\rm brem}(E_\gamma, E_e, \vec{x}) = c\, E_\gamma \sum_i n_i(\vec{x}) \frac{d\sigma_i^{\rm brem}}{dE_\gamma}(E_e, E_\gamma)$$



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 ($\rho_{\rm DM}^2(r)$)

spectra produced per annihilation in a given annihilation channel ($\frac{dN_e}{dE_e^S}$)

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- 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 $e^{\pm}$

- ➔ **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**

J. Buch, M. Cirelli, G. Giesen, M. Taoso, (PPPC 4 DM, [1505.01049])

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- Full-propagation of e± :

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

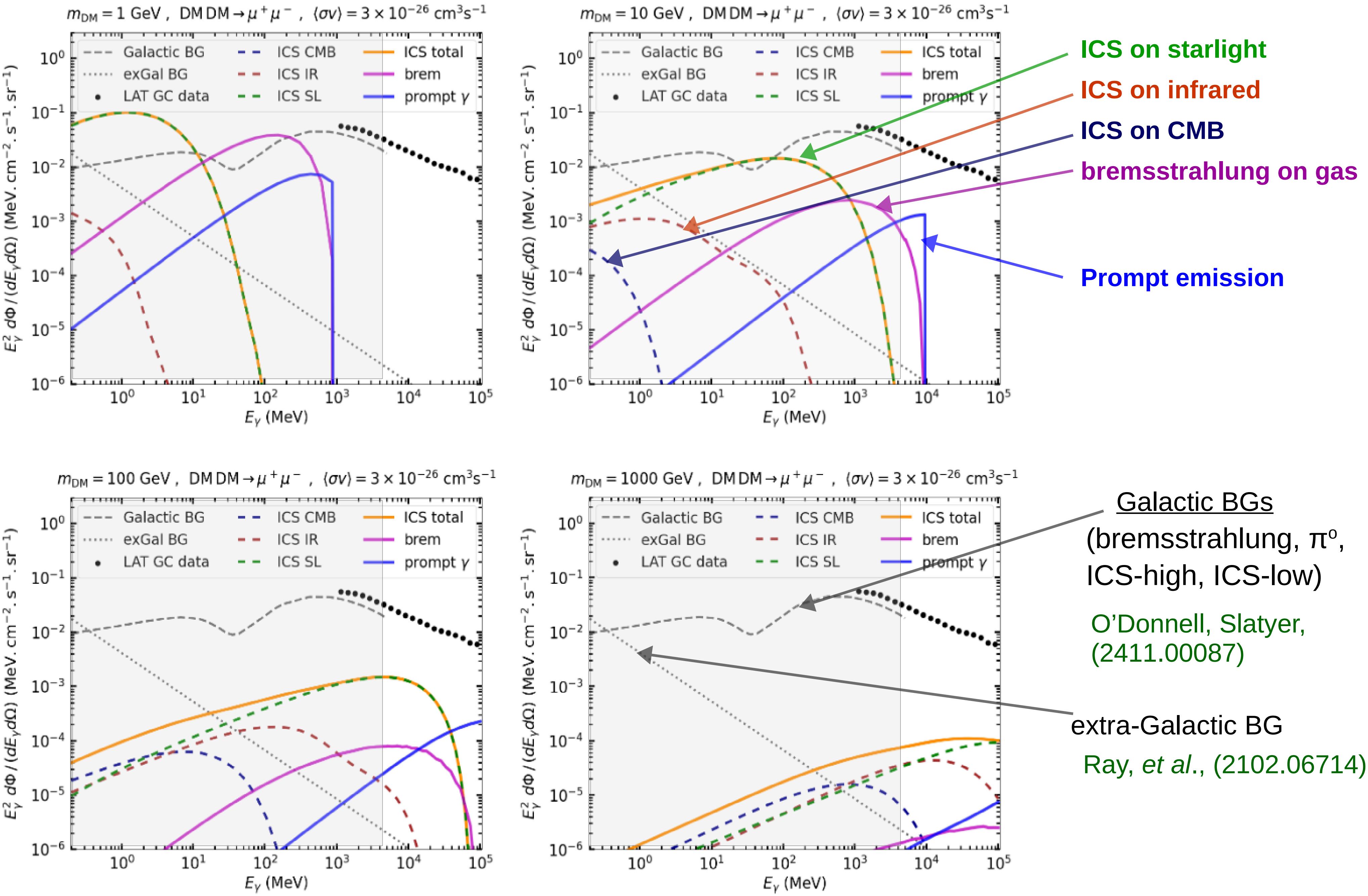
$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N_i\right] =$$
$$Q + \sum_{i<j}\left(c\beta n_{\rm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

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

Evoli *et al.*, (1607.07886)

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

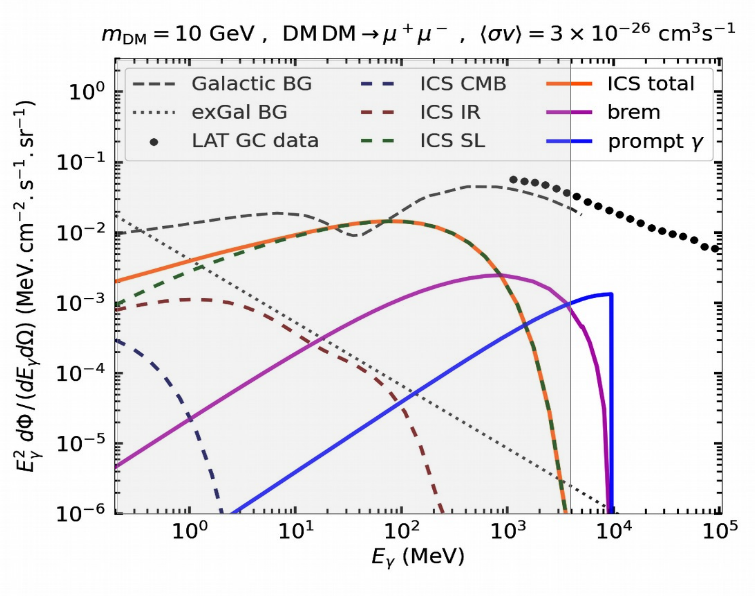
MeV-GeV photons from WIMP annihilations in the Galaxy

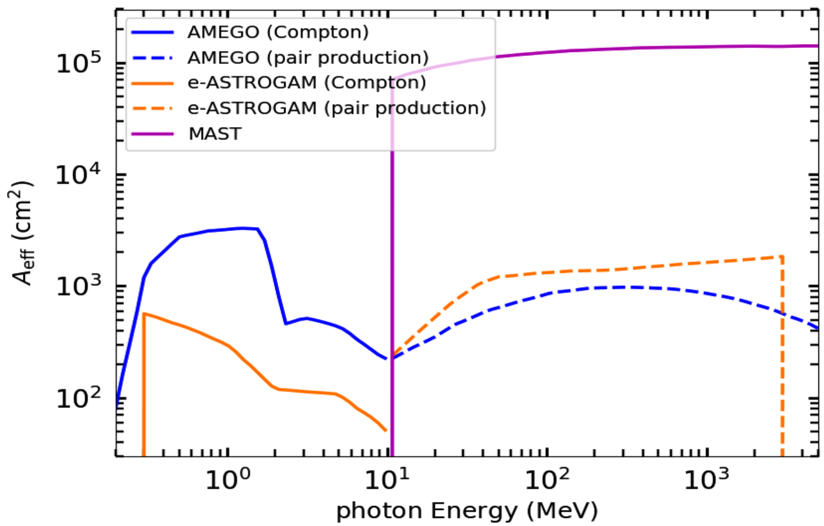


M. Cirelli, A.K.; (2503.04907)

WIMP annihilation signals at the MeV telescopes

- MeV telescopes : **AMEGO, e-ASTROGAM and MAST**





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

Fisher-projections :

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

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

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

t_{obs} → observation time

Energy-resolution

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

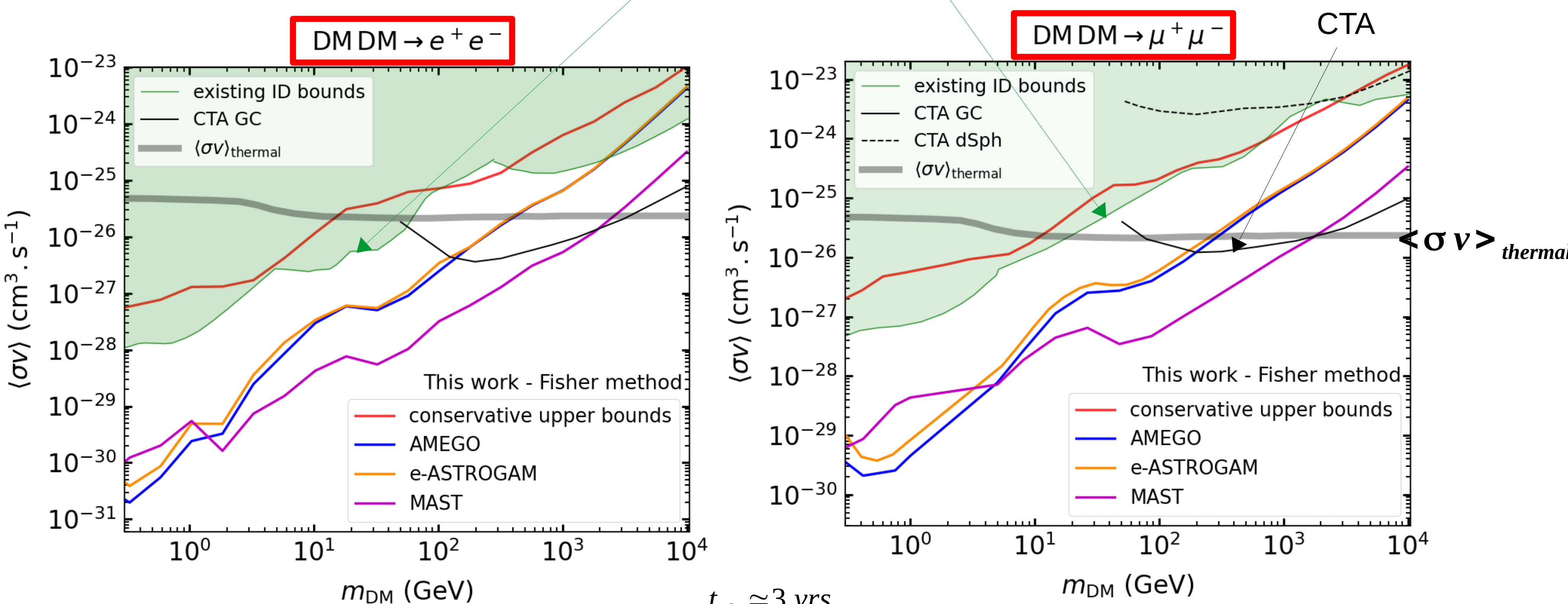
AMEGO (30%) , e-Astrogam (30%), MAST (30%)

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

(2σ - projections)

Projected sensitivities for WIMP (leptonic annihilations)

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



$t_{obs} \simeq 3\ yrs$

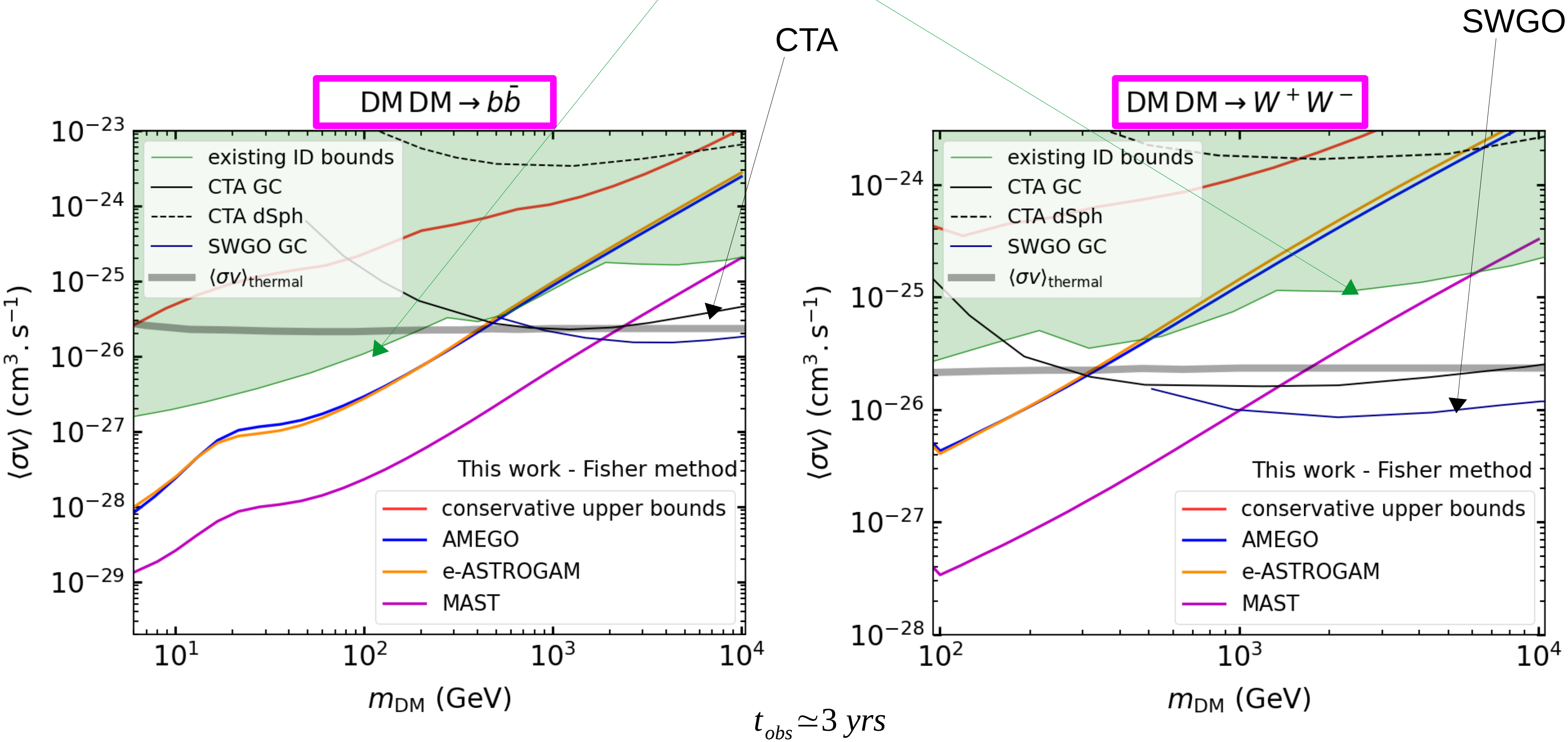
upper-bounds and 2σ-projected sensitivities of the near-future MeV telescopes AMEGO, e-ASTROGAM and MAST

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

- **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)

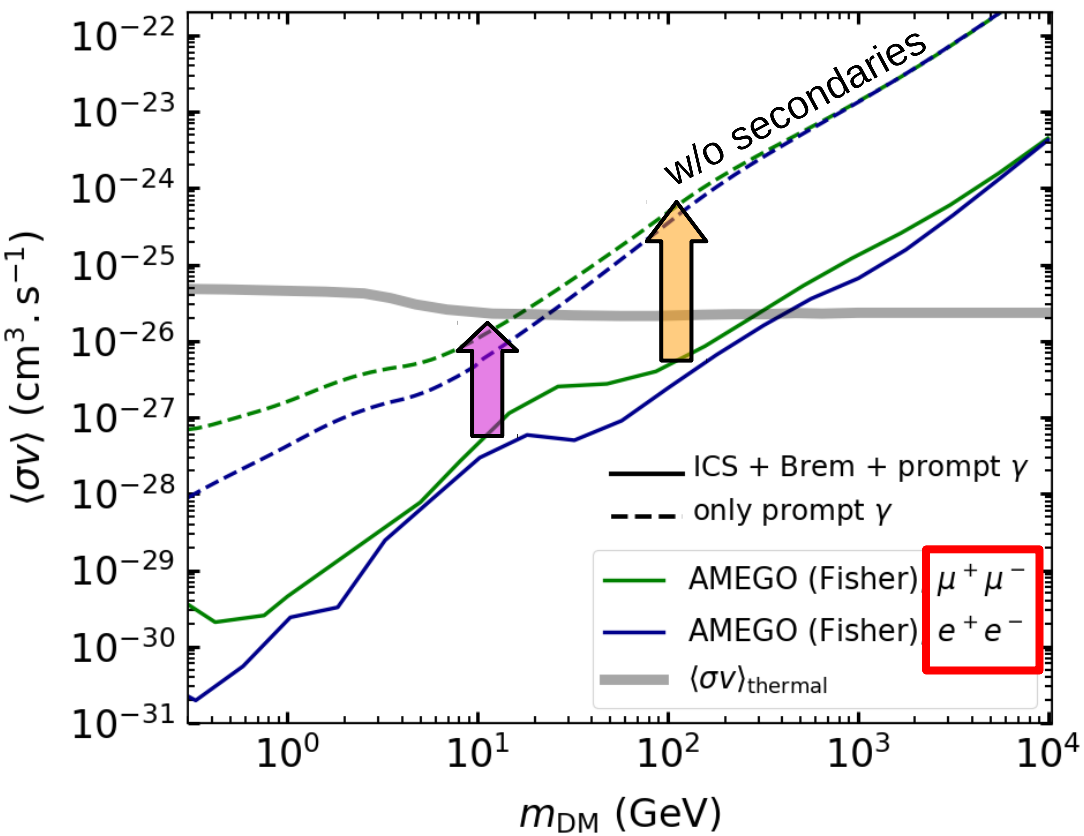
Existing constraints: γ-rays, AMS $\bar{p}$, ...



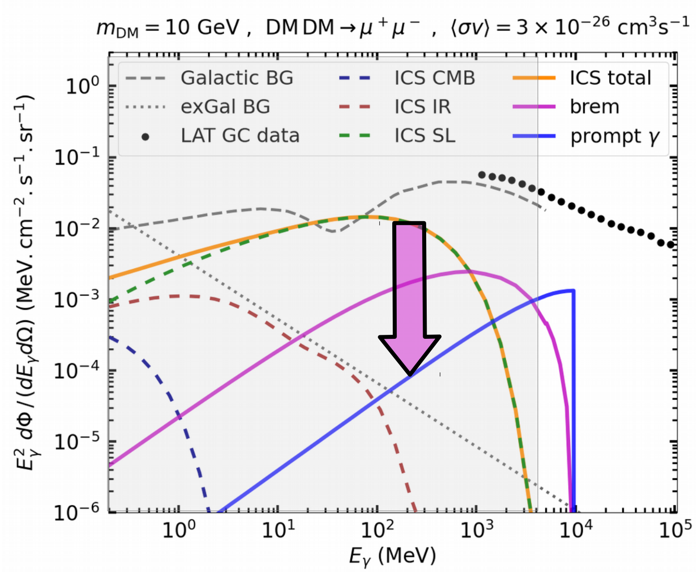
upper-bounds and 2σ-projected sensitivities of the MeV telescopes AMEGO, e-ASTROGAM and MAST

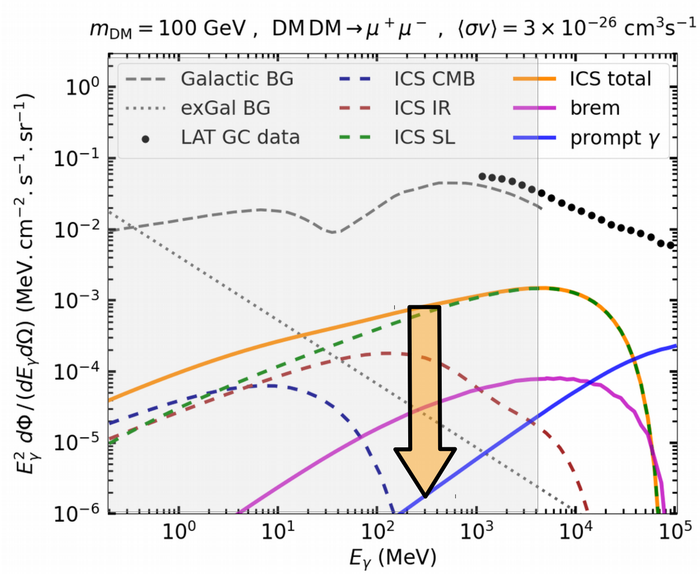
M. Cirelli, A.K.; (2503.04907)

Importance of considering the secondary signals for WIMPs



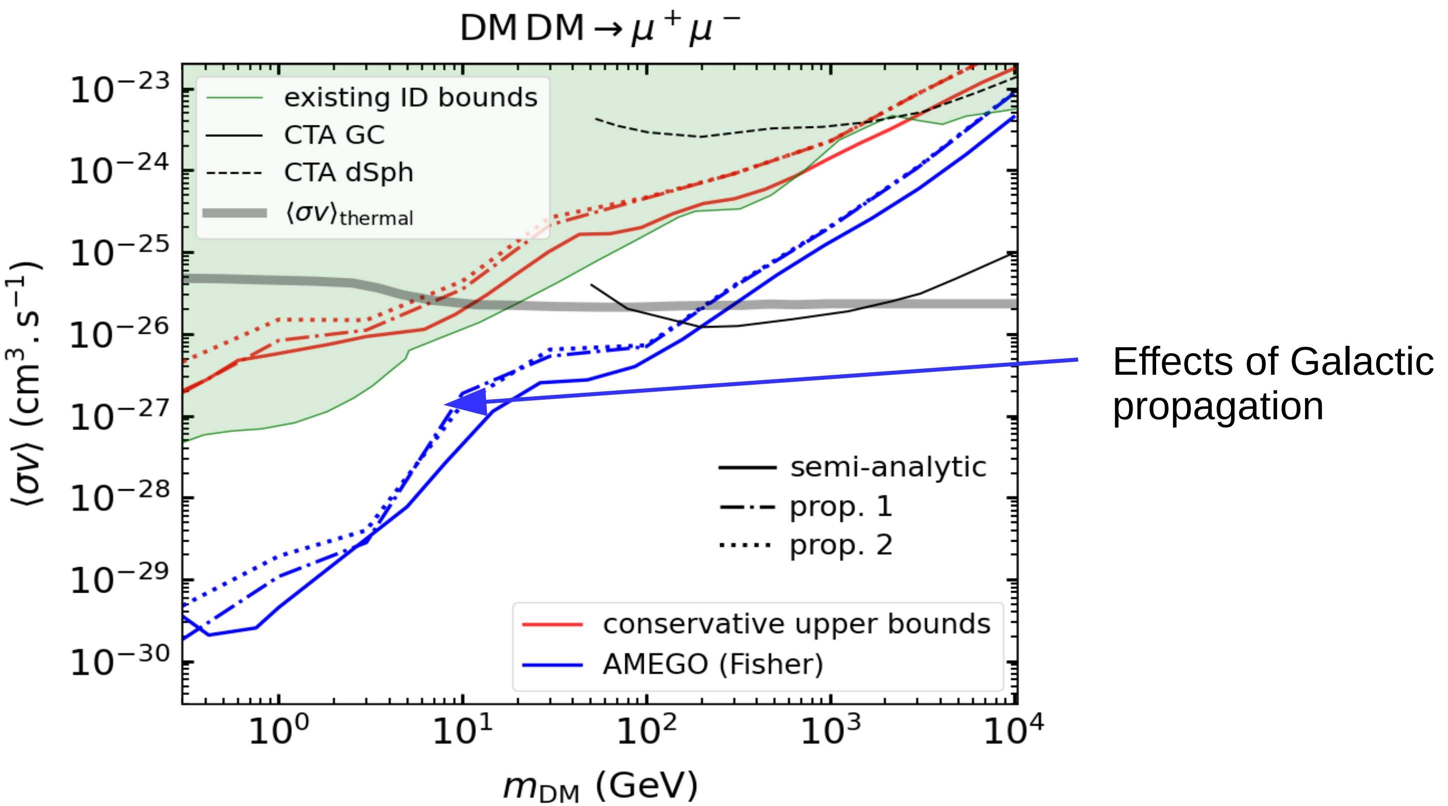
2σ-projected sensitivities of the MeV telescope AMEGO





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

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



2σ-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)]

M. Cirelli, A.K.; (2025)

Summary

- We explored the potential of **upcoming MeV telescopes** (e.g., AMEGO, e-ASTROGAM, MAST) in probing the photon signals from **WIMP DM annihilations** in the inner Galaxy

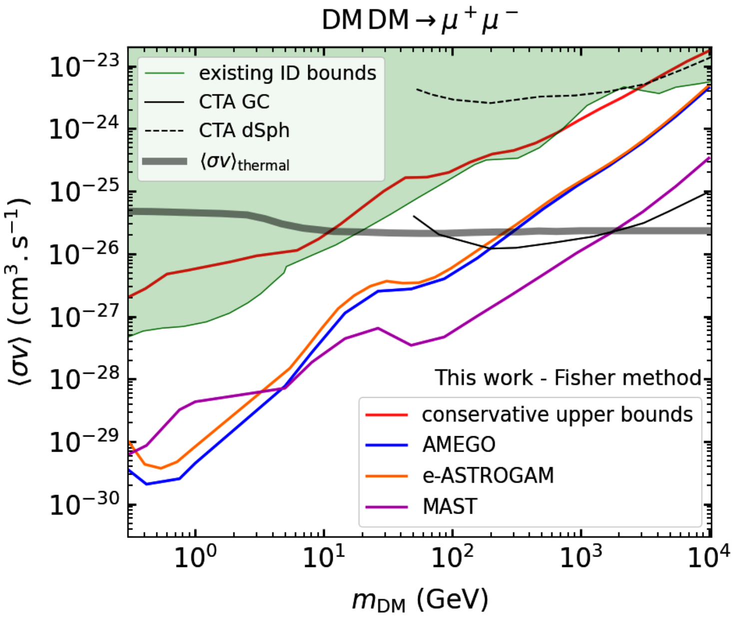
- Low-energy secondary emissions (e.g., ICS and bremsstrahlung) produced by DM induced $e^{\pm}$ significantly enhance the sub-GeV γ- ray signals of WIMP DM annihilations
  (for lepton-rich annihilation channels)

  ➡ 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**

  ➔ can probe GeV scale DM with <σv> ~2-3 orders of magnitude smaller than the current bounds

  ➔ can probe thermally-produced DM with a mass up to the TeV range

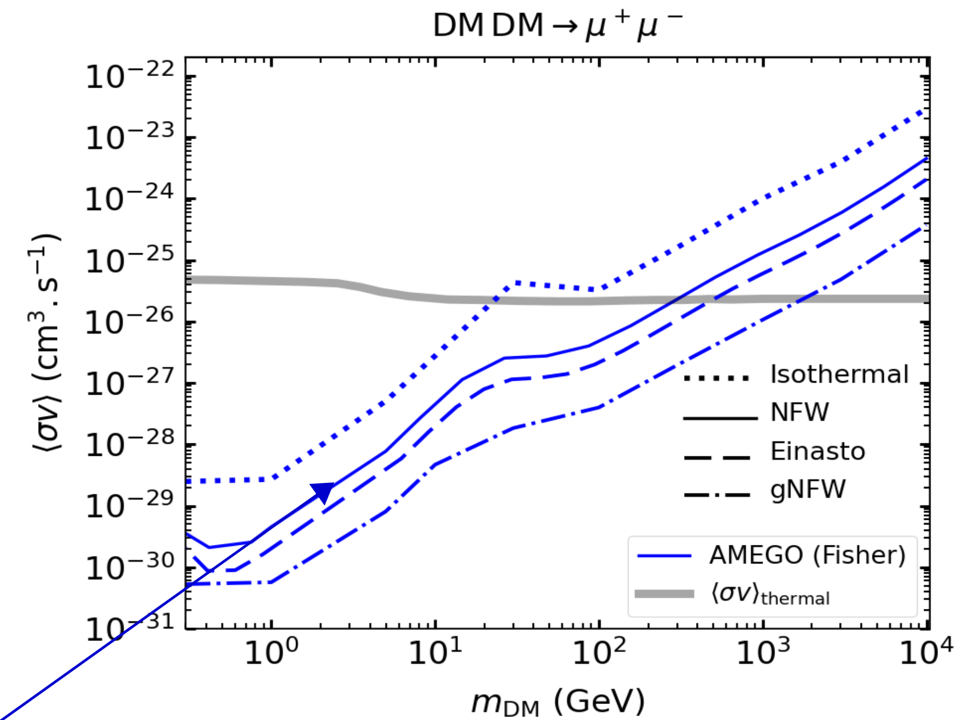


- **MeV *γ*-ray telescopes can efficiently complement the ground-based high energy *γ*-ray instruments in the indirect searches for weak-scale DM**

- **Can add an important tool in the indirect searches of weak-scale DM**

Backup slides

Impact of the choice of DM profile



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

Einasto: $$\rho_{\rm DM}^{\rm Ein}(r) = \rho_0 \exp\left\{-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha}-1\right)\right\}$$ $\alpha = 0.18$

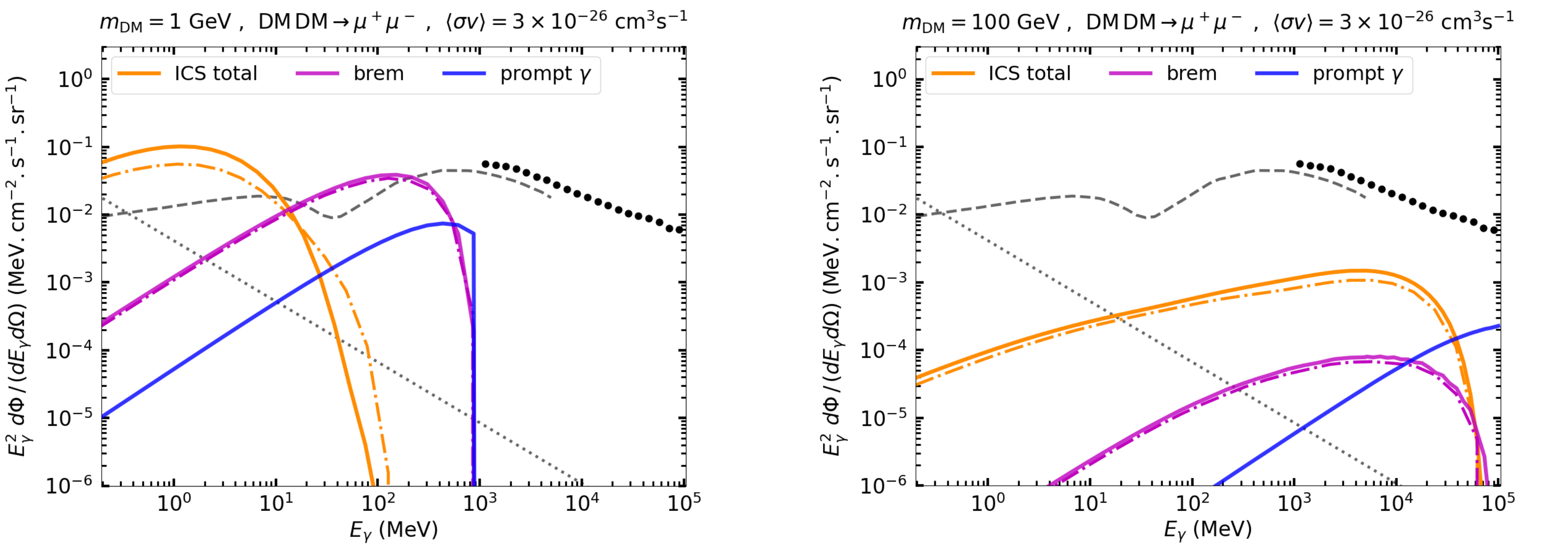
gNFW: $$\rho_{\rm DM}^{\rm gNFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$ $\gamma = 1.3$

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

Salas *et al*., (1906.06133)

Cirelli *et al*., (2406.01705)

ISRF models



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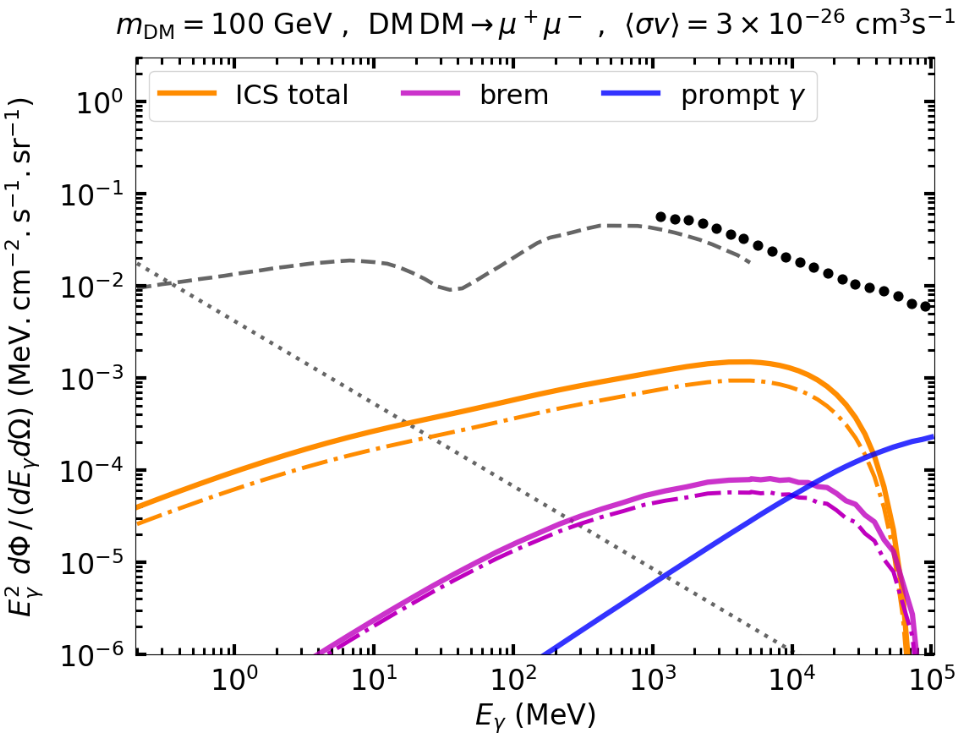
ISRF model 1 (solid lines):

J. Buch, M. Cirelli, G. Giesen, M. Taoso, (PPPC 4 DM, [1505.01049]) , (GALPROP)

ISRF model 2 (dashed-dotted lines):

T. Porter, A. W. Strong, (astro-ph/0507119) (used in DRAGON)

B-field models



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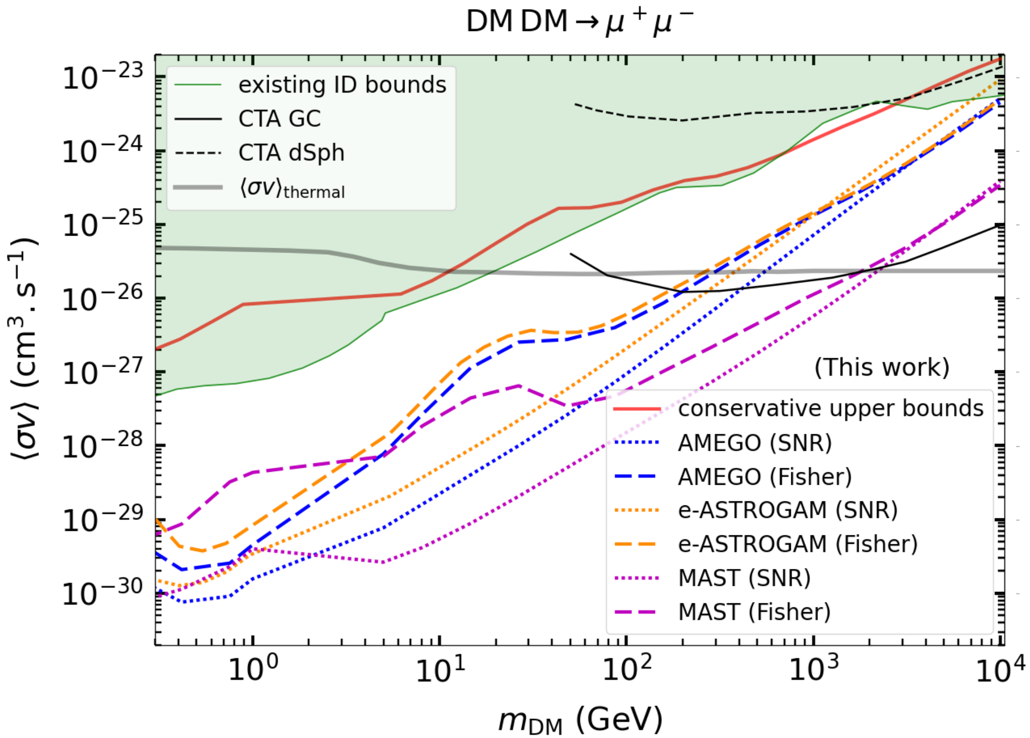
Different Galactic B-field models from:

J. Buch, M. Cirelli, G. Giesen, M. Taoso, (PPPC 4 DM, [1505.01049])

Signal-to-noise ratio and Fisher methods



Fisher-projections :

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

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

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

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

SNR :

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

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

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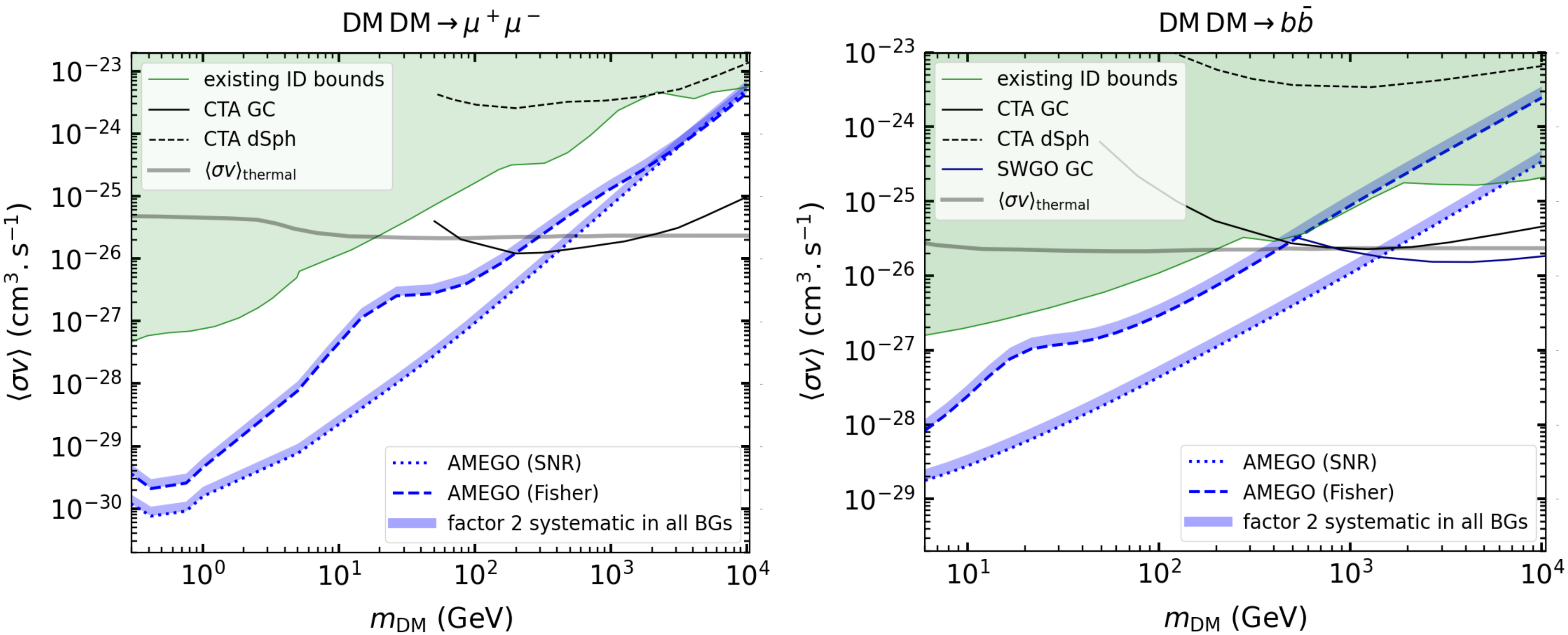
Systematic uncertainties in the backgrounds



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