Indirect searches for realistic sub-GeV Dark Matter models in present and upcoming observations

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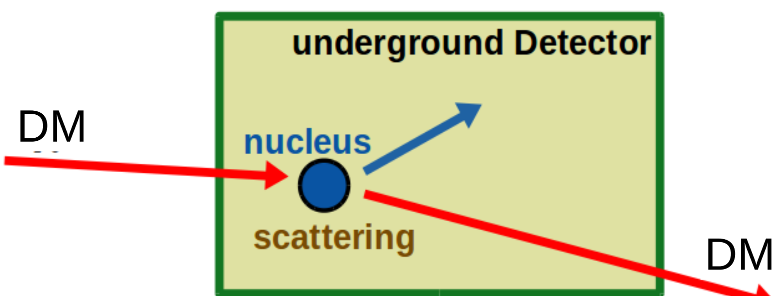
Based on: M. Cirelli, A.K., H. Shaikh; JCAP 01 (2026) 038

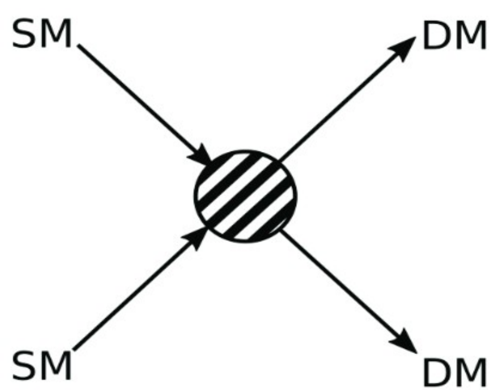
Dark matter

- Dark Matter (DM) exists and provides ∼25% of the energy density of the Universe
- Evidences through gravitational effects:

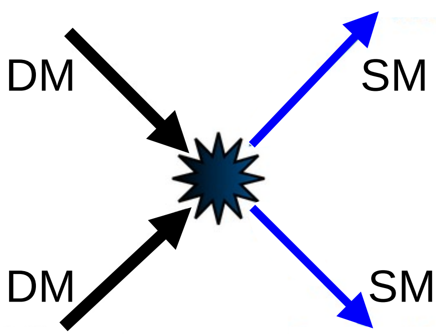
  galactic rotation curves, CMB anisotropy, structure formation, bullet clusters, etc.
- Microscopic natures of DM are still unknown
- It can be composed of a new fundamental particle
  - Massive and Neutral
  - Stable on the cosmological time scale
  - very feebly interacting
  - Cold in nature (non-relativistic at CMB formation)
- Searches for particle DM signals:



Direct detection



Accelerator searches



Indirect detection

Sub-GeV dark matter

- DM can be composed of a light particle with a mass in the range MeV - GeV

  e.g., DM can be coupled to a new light gauge boson (Boehm & Fayet [hep-ph/0305261]) ;
  hidden sector DM (Feng & Kumar [0803.4196])

- Searches for sub-GeV DM particles have drawn recent interest
  - Absence of compelling evidence for usual weak-scale (GeV - TeV) DM in current experiments
  - Motivated theoretical models to predict sub-GeV DM candidates

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- Indirect detection signals are mainly of three kinds:

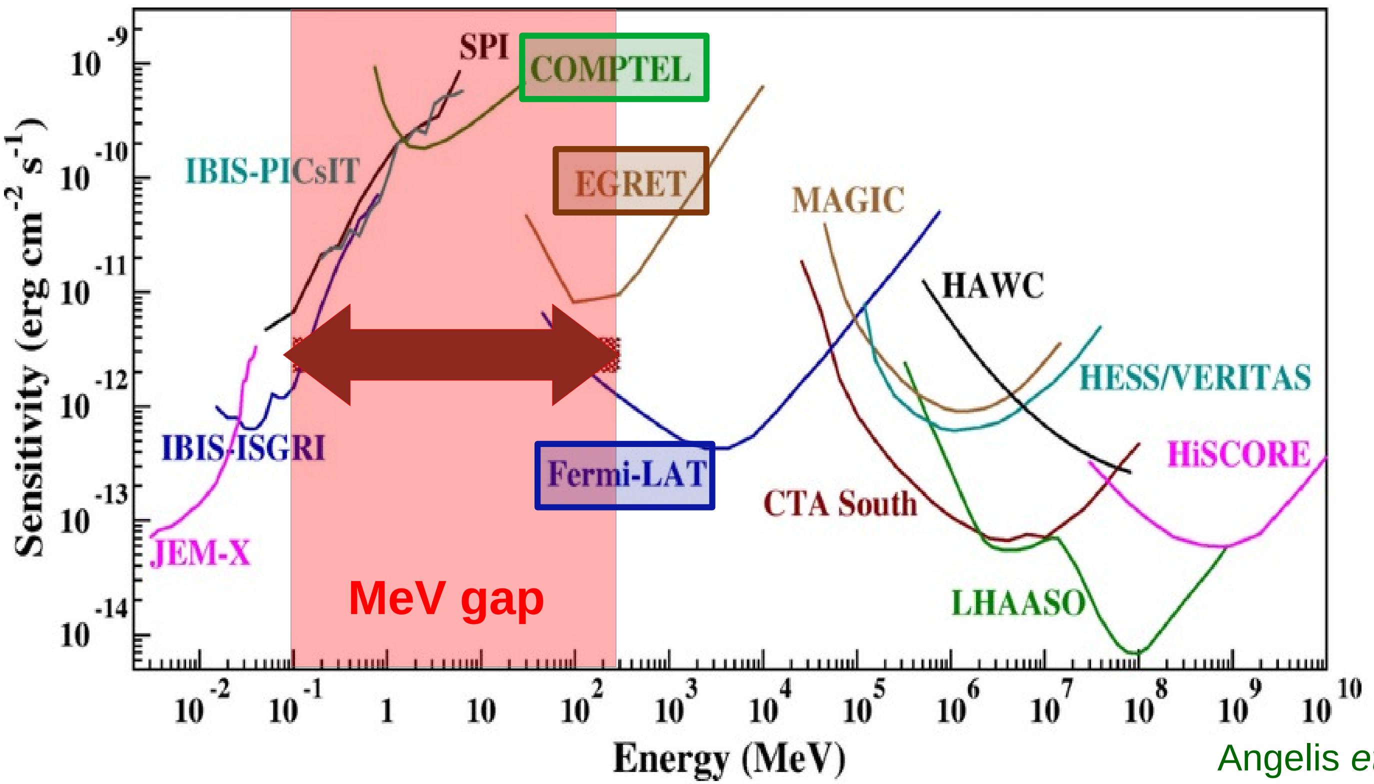
  → MeV - GeV γ - rays emitted as prompt radiation from DM annihilation (in the inner Galaxy)
  (**INTEGRAL, COMPTEL, EGRET, Fermi-LAT**)

  → sub-GeV $e^{\pm}$ from DM annihilation in the Galaxy (cosmic-ray flux near the solar system)
  (**Voyager 1**)

  → X-rays or soft γ- rays emitted as *secondary radiation* from DM induced $e^{\pm}$
  (**NuStar, XMM-Newton, eROSITA, INTEGRAL, COMPTEL**)

Upcoming MeV γ- ray telescopes

- **The difficulty in detecting MeV photon signals:** relatively poor sensitivity of existing telescopes (**COMPTEL**, **EGRET**, **Fermi-LAT**, etc.) in the MeV energy 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, etc.

- **These MeV telescope should play important roles in probing sub-GeV DM signals**

Sub-GeV DM models

- **Indirect searches can be carried out in essentially two ways :**
  - Based on a simplified model, considering one representative annihilation channel at a time (*w/o considering any specific particle physics realization*)

$$\mathrm{DM\,DM} \rightarrow \gamma\gamma,\ e^+e^-,\ \mu^+\mu^-,\ \pi^+\pi^-$$

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  - Based on a specific DM model, with the determined annihilation processes into realistic multiple final states (consisting of light hadronic resonances)

    ➔ *at sub-GeV energies light hadronic resonances (e.g., π, η, K, ρ, ω, ϕ, ...) are the relevant final states of the annihilation*

    ➔ *particularly well motivated for sub-GeV DM searches*

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- Representative sub-GeV DM models: Vector-portal & Scalar-portal models

$$m_{DM} = [\ 1\ \mathrm{MeV} - 1\ \mathrm{GeV}\ ]$$

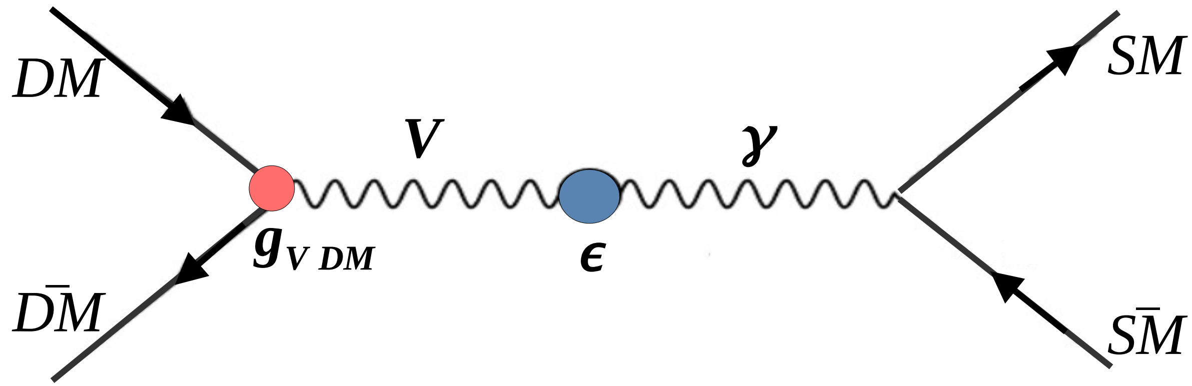
➔ Estimate **all possible prompt and secondary emission signals** related to DM annihilations in the Galaxy

➔ **Indirect detection constraints and future prospects of MeV telescopes (COSI)**

Sub-GeV DM models

- **Vector portal: dark photon portal or kinetic-mixing model**

Dirac fermion



$m_V = 3\, m_{DM}$

$$\langle \sigma v \rangle \propto \epsilon^2 \, \alpha_D \, \frac{m_{\rm DM}^2}{m_V^4} = \frac{y}{m_{\rm DM}^2}\,, \qquad \text{with} \quad y = \epsilon^2 \, \alpha_D \left(\frac{m_{\rm DM}}{m_V} \right)^4$$

where $\alpha_D = g_{V\rm DM}^2/4\pi$

(s-wave annihilation)

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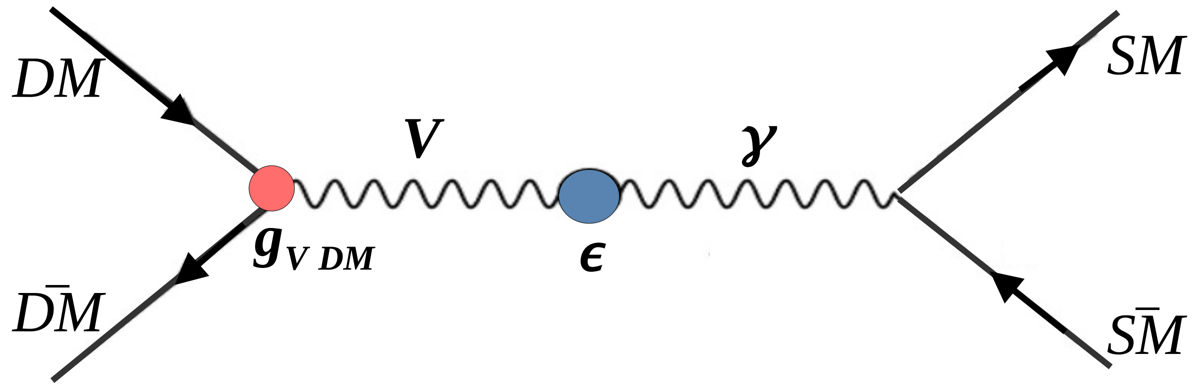

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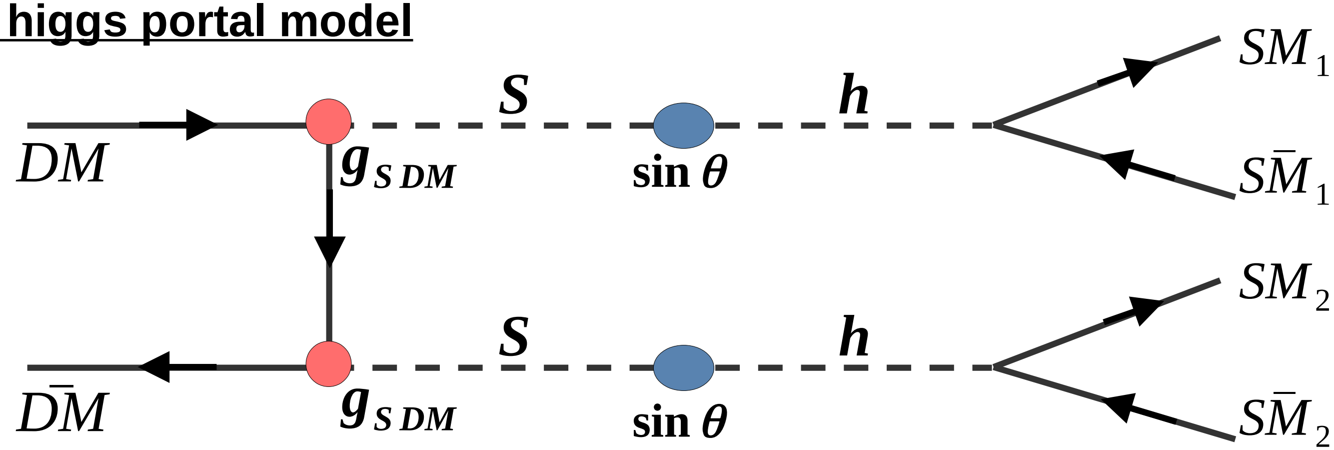
- **Scalar portal: higgs portal model**

Dirac fermion



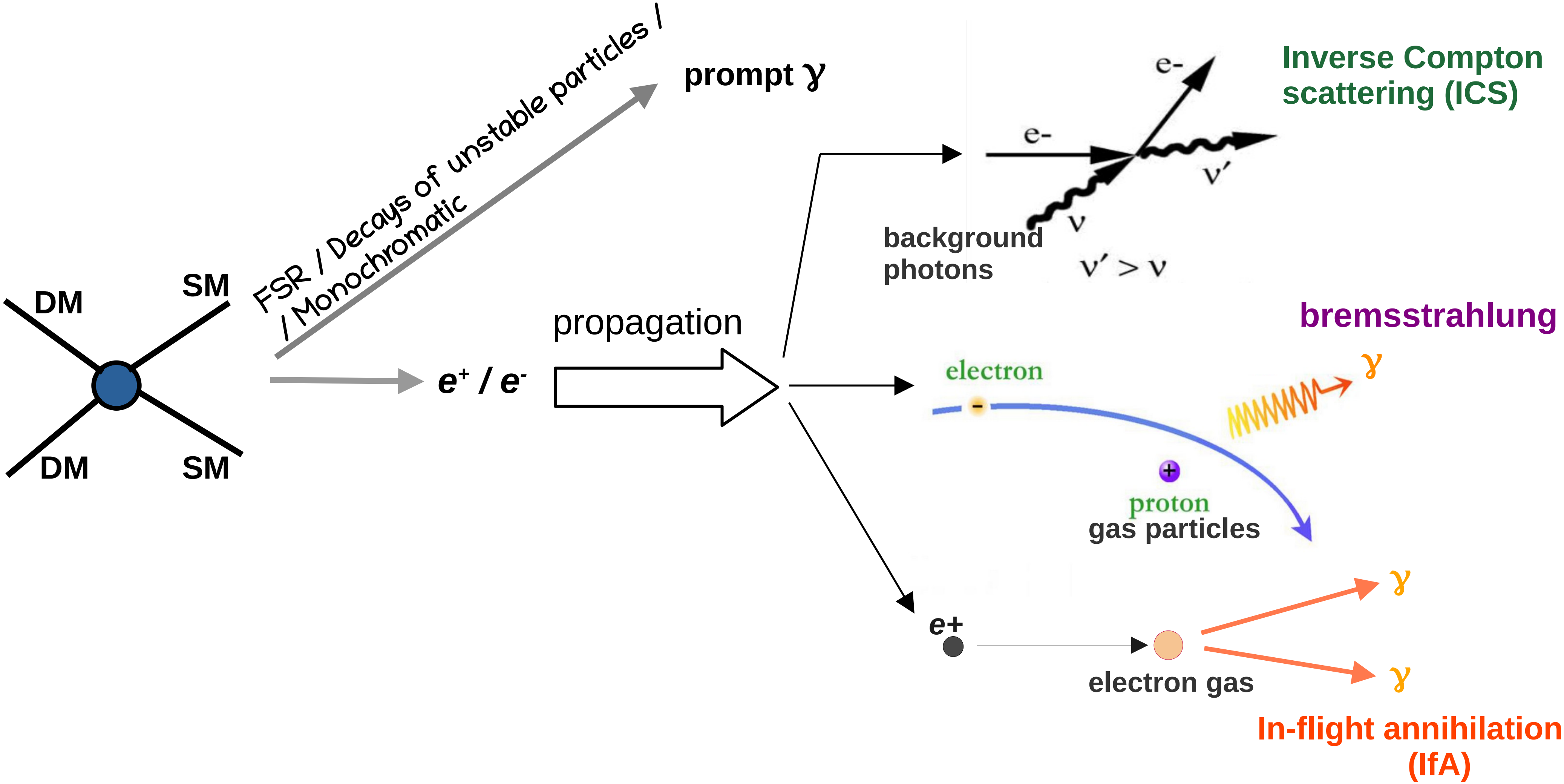
$m_S = m_{DM}/2$

$$\langle \sigma v \rangle = \frac{3\, g_{S\rm DM}^4\, v_{\rm rel}^2}{128\, \pi\, m_{\rm DM}^2}$$

dominating annihilation **(p-wave annihilation)**

$v_{\rm rel}$ = DM relative velocity

Searches for DM in photon observations from the inner Galaxy



- **Prompt radiation:** γ-rays produced directly from DM annihilation
- **Secondary radiation:** photon emissions via **Inverse Compton scattering (ICS)** , **bremsstrahlung** , **In-flight annihilation (IfA)** **produced by DM induced** e^+/e^-

- **Prompt γ - ray flux:**

$$\frac{d\Phi_{\rm prompt}}{dE_\gamma d\Omega} = \frac{\langle \sigma v \rangle}{8\pi \, f_\chi \, m_{\rm DM}^2} \left. \frac{dN_\gamma}{dE_\gamma} \right|_{\rm tot} \frac{J_{\Delta\Omega}}{\Delta\Omega}$$

$\frac{dN_\gamma}{dE_\gamma}$ spectra produced per DM annihilation

HAZMA

Coogan, *et al.*, (1907.11846), (2207.07634)

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

s → line-of-sight (l.o.s.)

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

NFW DM profile :

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

MeV-GeV photons from DM annihilations in the Galaxy

- **Secondary γ - ray flux:**

(s, b, l) → Galactic coordinates

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

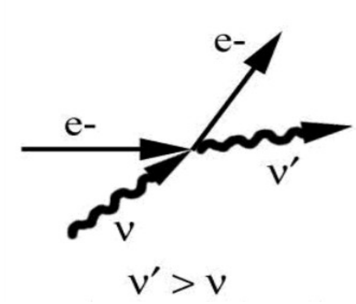
$$\frac{d\Phi_{\rm 2ndary}}{dE_\gamma d\Omega} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \left[\frac{1}{E_\gamma}\int_{l.o.s.} ds \, \frac{j_{\rm 2ndary}(E_\gamma, \vec{x}(s,b,l))}{4\pi}\right]$$

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

From DM annihilation

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

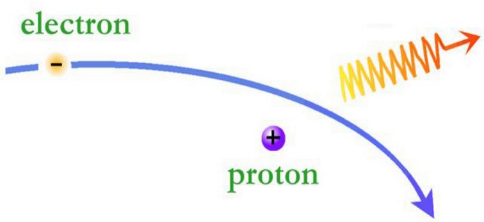
$$\mathcal{P}^i_{\rm ICS}(E_\gamma, E_e, \vec{x}) = c\, E_\gamma \int d\epsilon \, n_i^{\rm ISRF}(\epsilon, \vec{x})\, \sigma_{\rm IC}(\epsilon, E_\gamma, E_e)$$



Inter-Stellar Radiation Field (ISRF) : CMB, Infrared (IR), Starlight (SL)

Buch, *et al.*, (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 DM annihilations in the Galaxy

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

Source function from DM annihilation : $$Q_e(E_e^S, r) = \frac{\langle \sigma v \rangle}{2\, f_\chi\, m_{\rm DM}^2} \left.\frac{dN_e}{dE_e^S}\right|_{\rm tot} \rho_{\rm DM}^2(r)$$

DM density

spectra produced per annihilation

- 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**

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

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

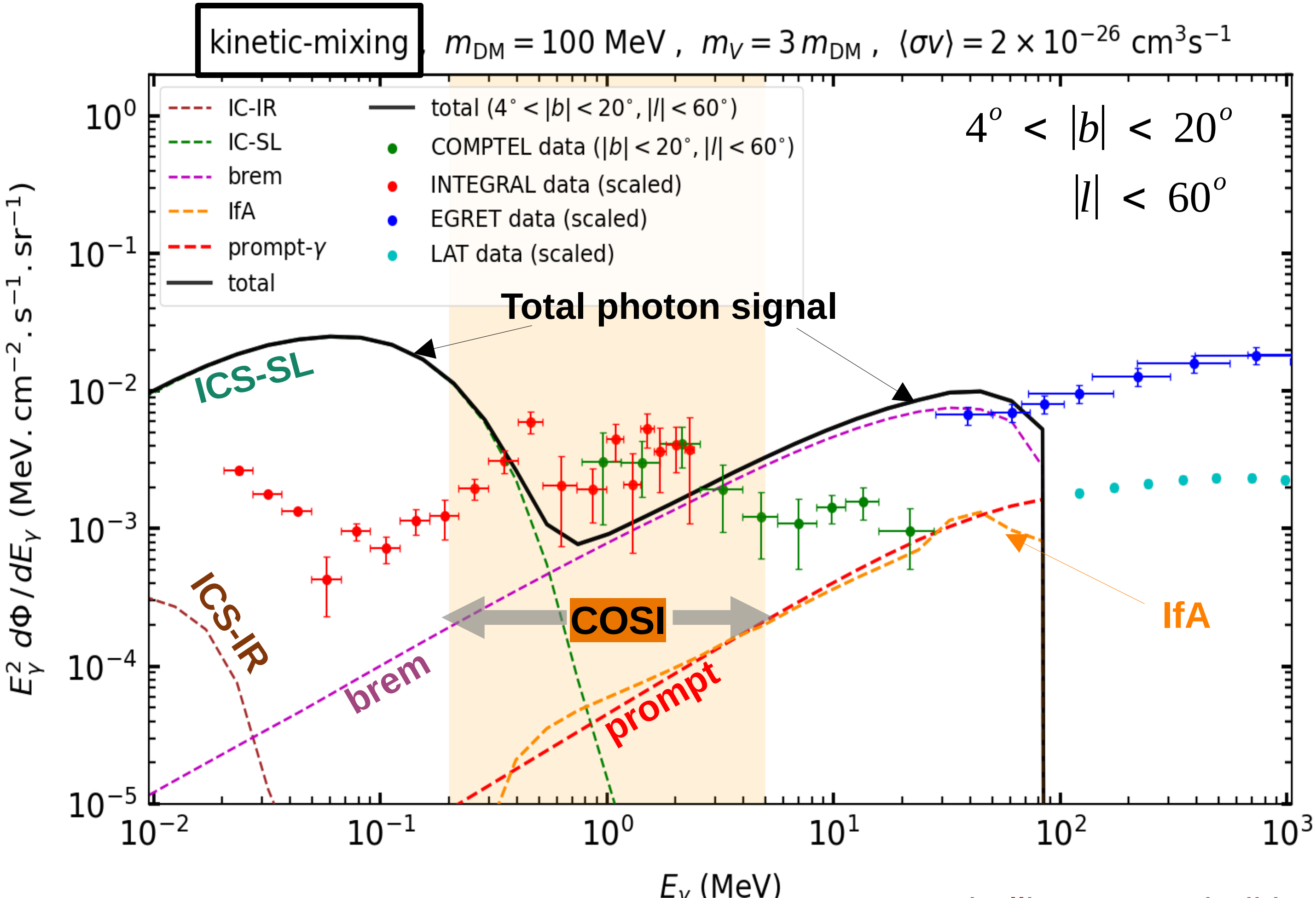
$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_w\right) N_i\right] = Q + \sum_{i<j}\left(c\beta n_{\rm gas}\,\sigma_{j\to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

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

Evoli *et al.*, (1607.07886)

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

Photon signals from sub-GeV DM annihilation in the inner Galaxy

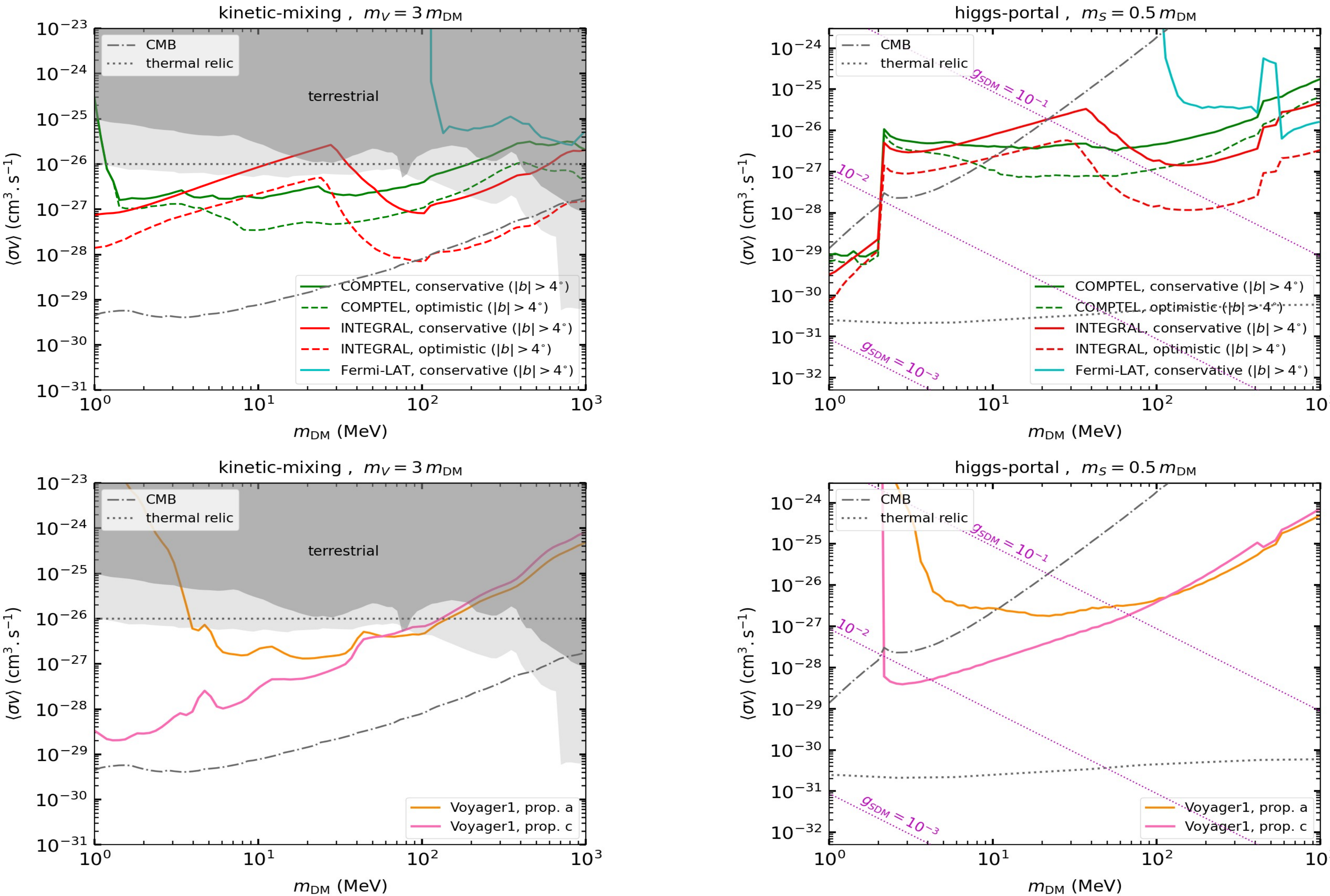


M. Cirelli, A.K. H. Shaikh; (JCAP 01 (2026) 038)

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

- Total photon signal (prompt + secondaries) are estimated **masking** $|b| \leqslant 4^o$
  - ➔ excludes most of the signal coming from the Galactic plane (a conservative estimate)

Indirect detection bounds on sub-GeV DM models using existing data



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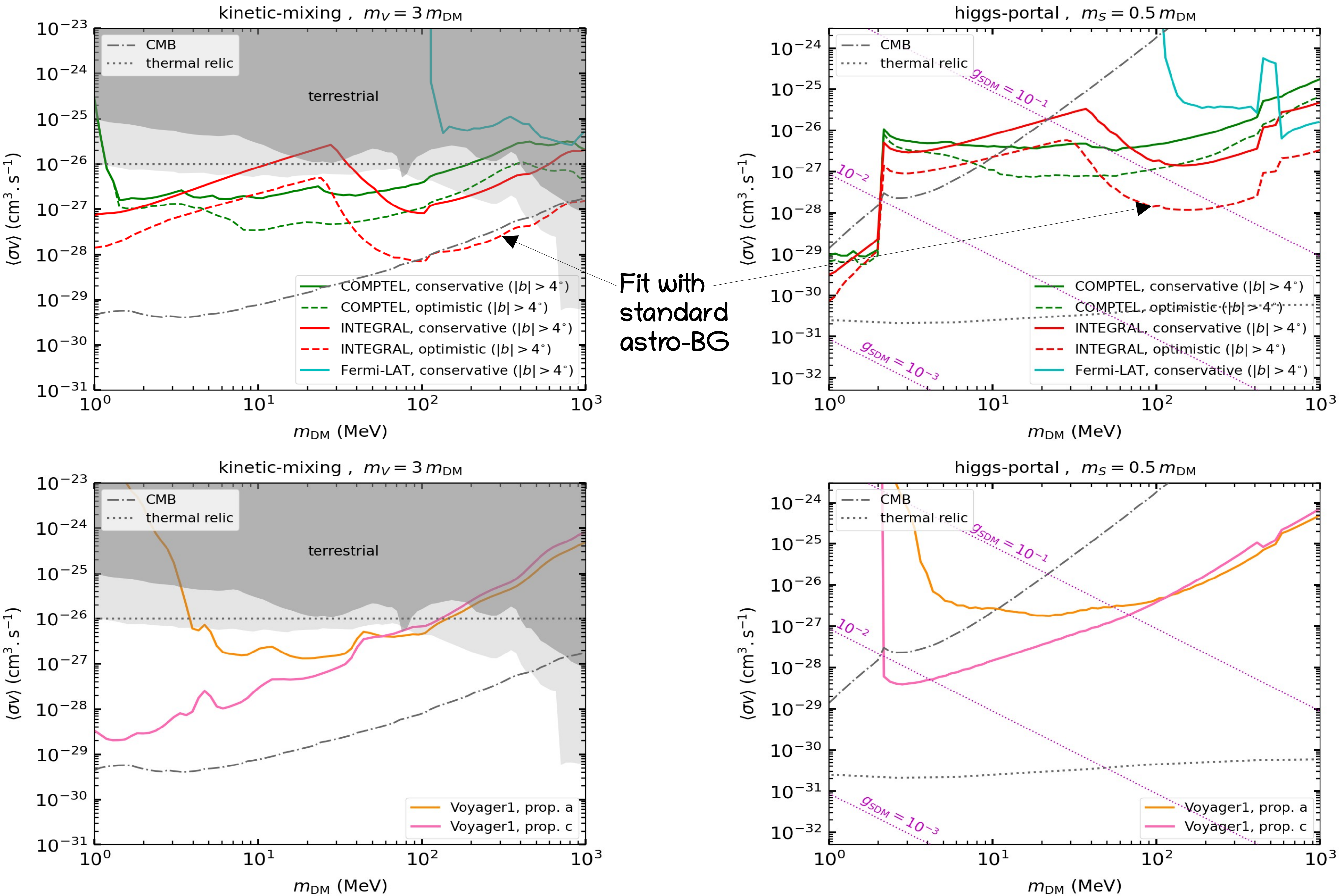

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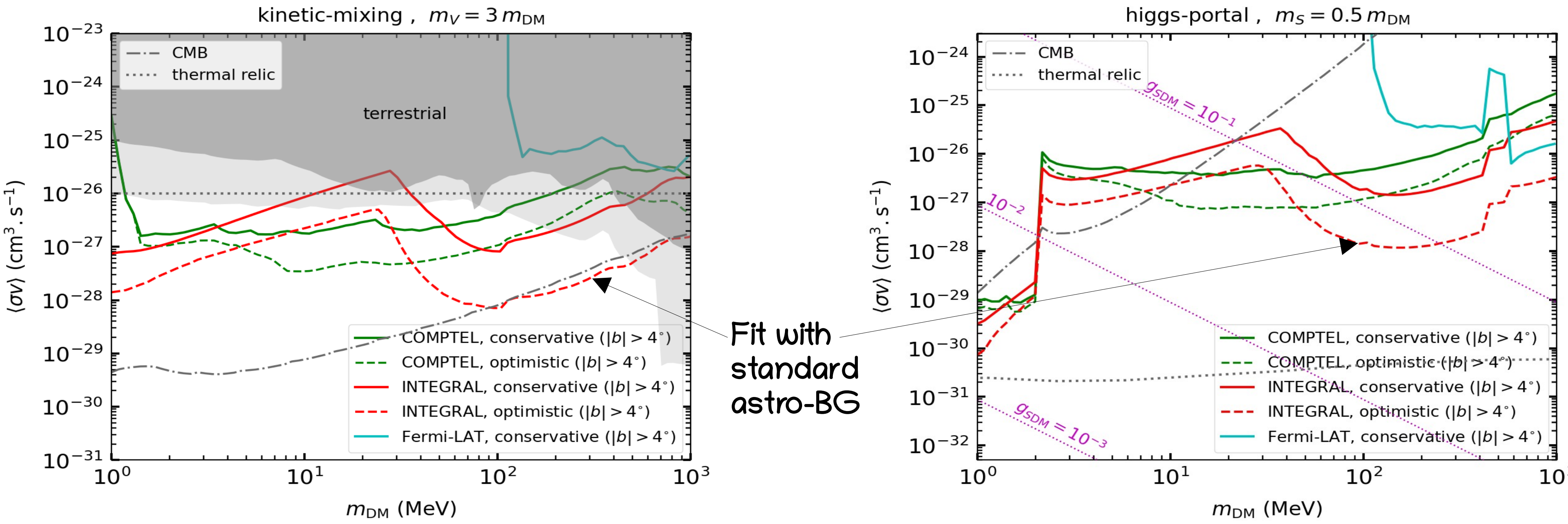

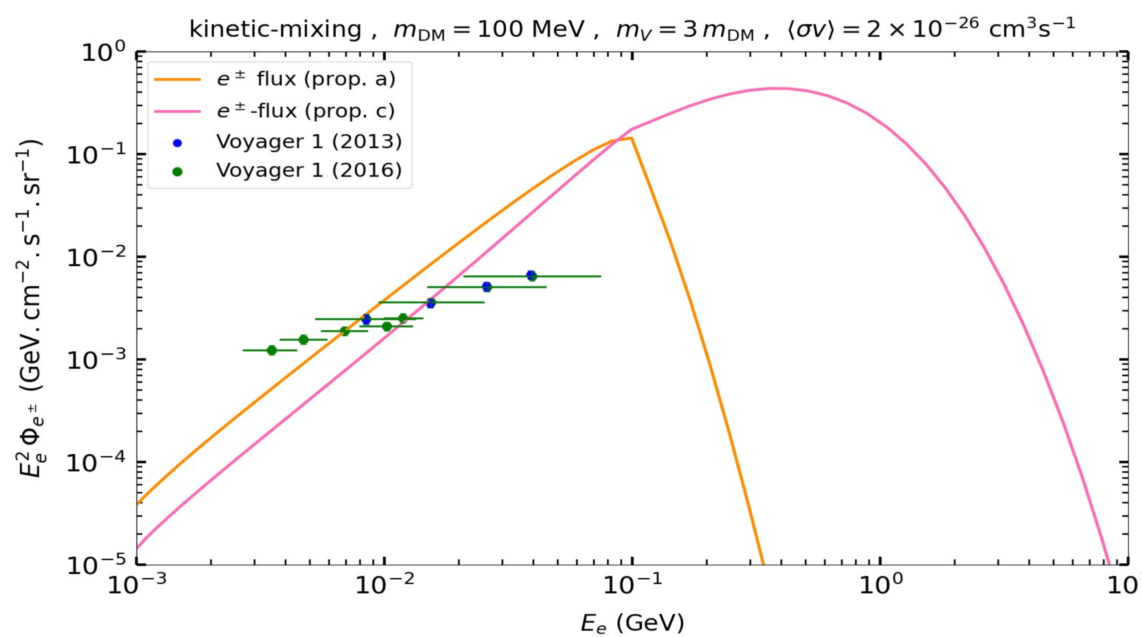

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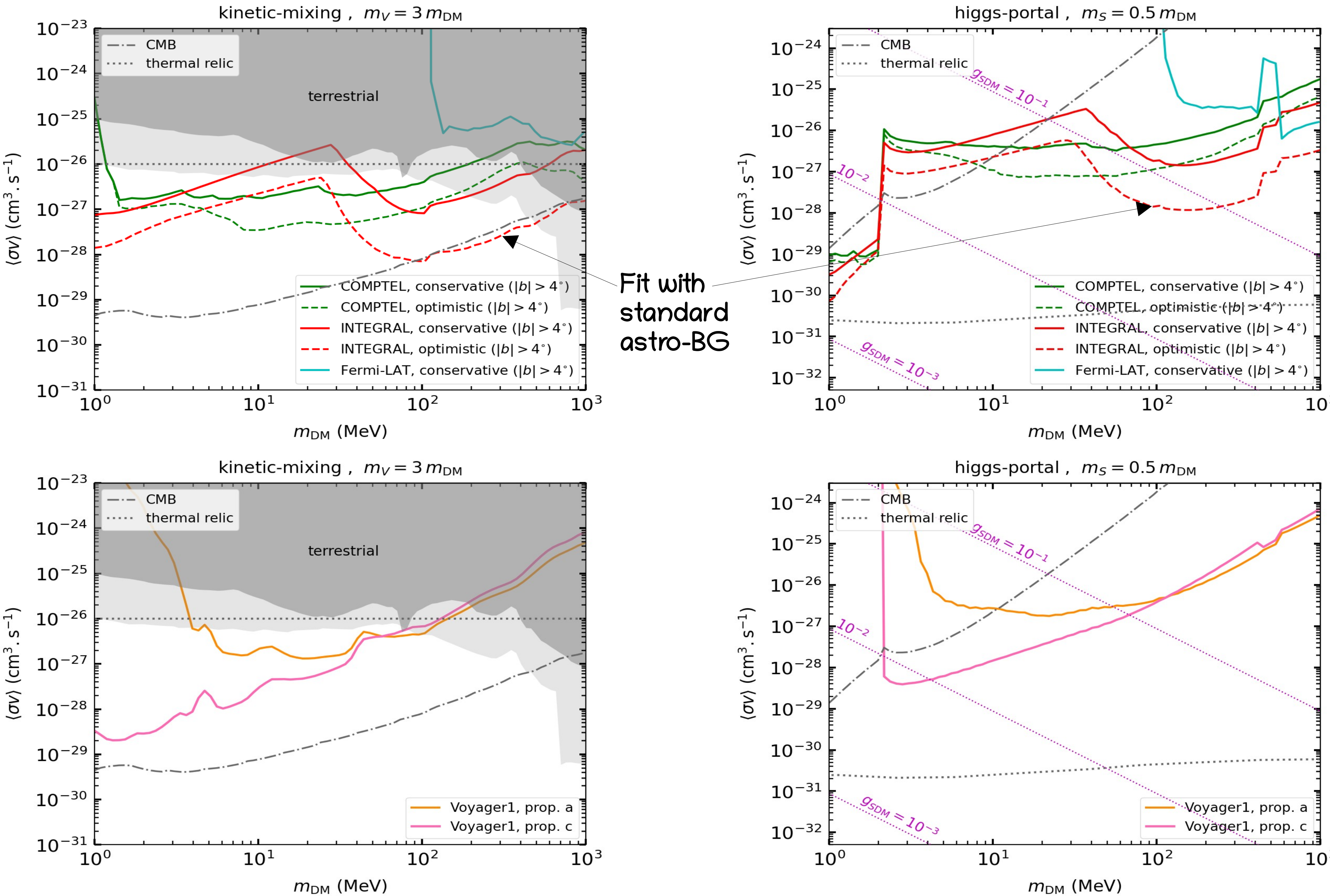

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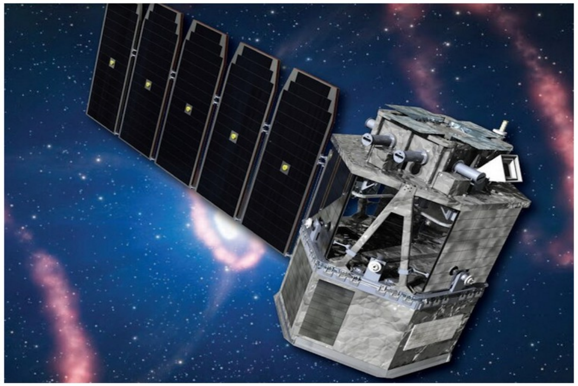
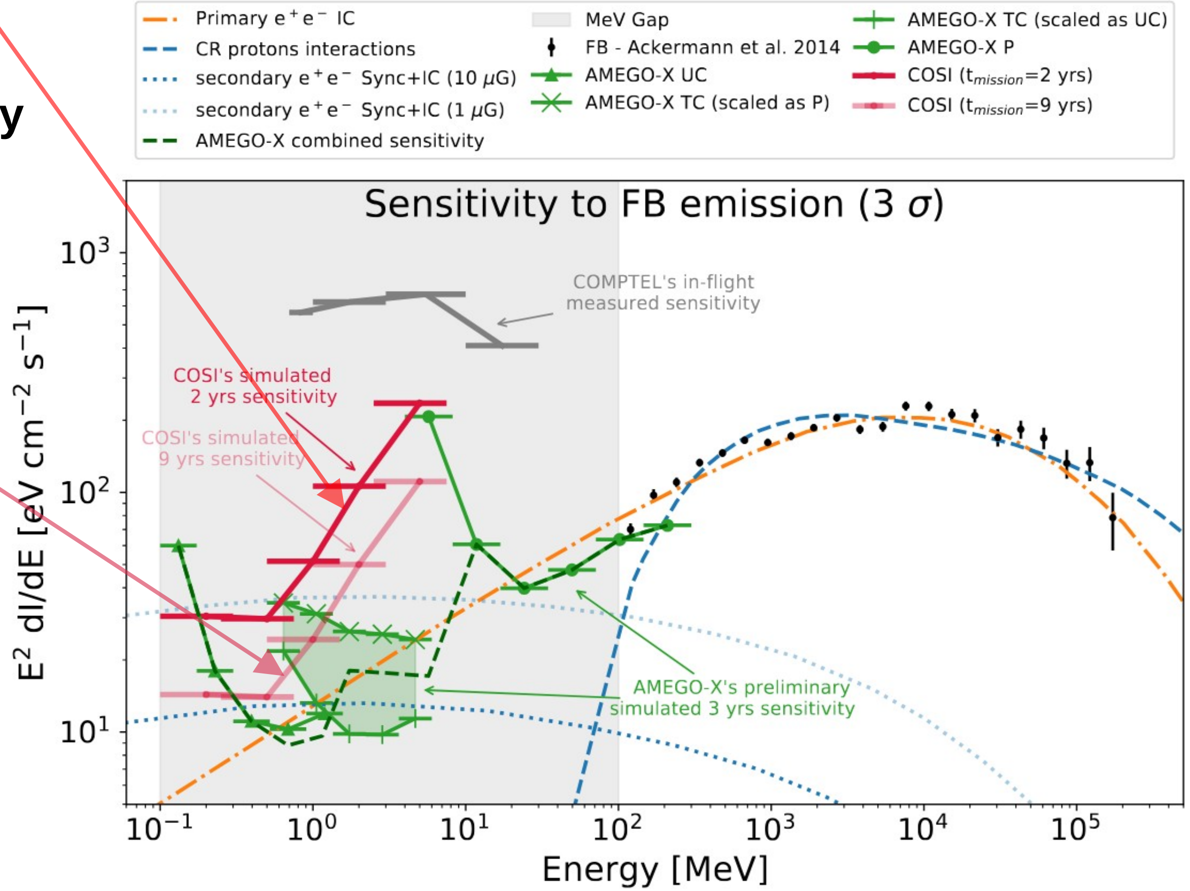
Upcoming MeV telescope Compton Spectrometer and Imager (COSI)

- Key features:
  - ➔ High-resolution spectroscopy (energy resolution ≲ 4%)
  - ➔ Direct imaging over a **wide field-of-view (≳ 25% of the sky)**
  - ➔ An effective suppression for the background events



MeV satellite mission COSI

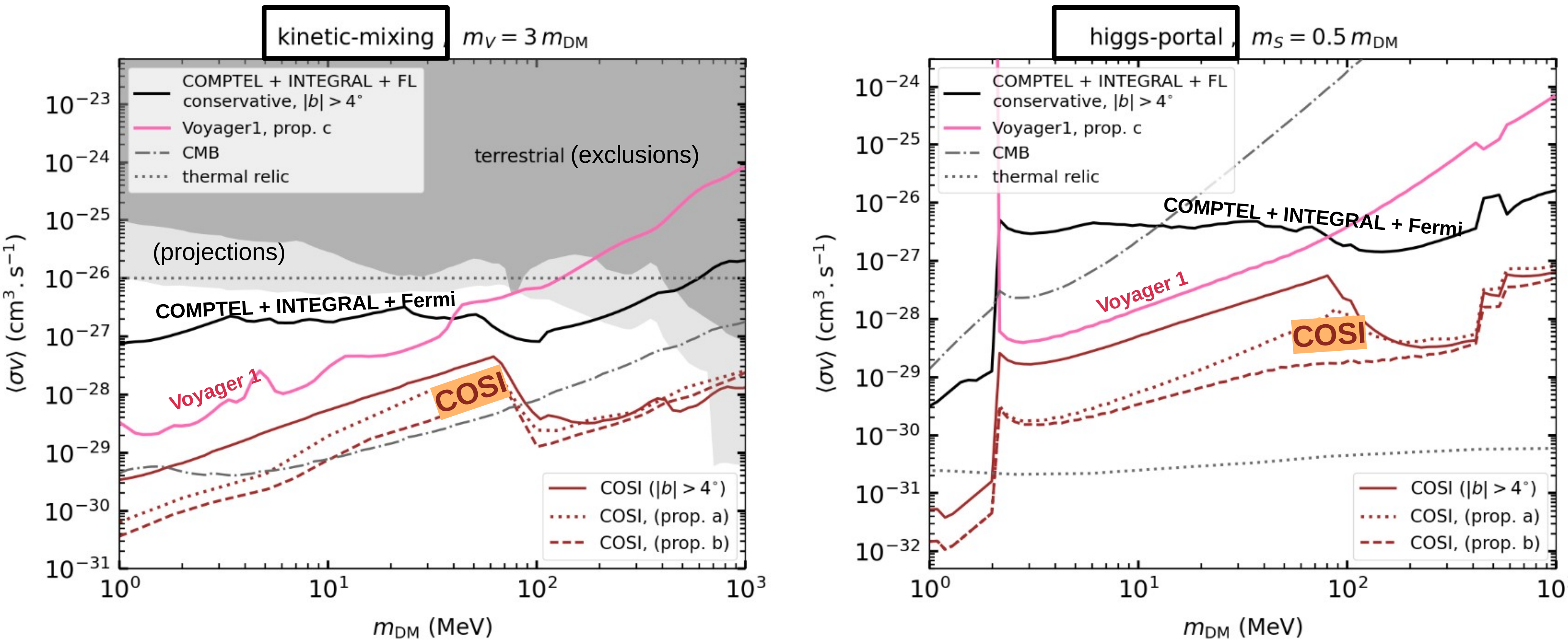
- Energy range: **0.2 MeV ≲ E_γ ≲ 5 MeV**
- **COSI has already been selected to fly with its scheduled launch in 2027**
- Nominal mission lifetime is ~2 yrs, but a longer duration is likely
- We evaluate the COSI prospects for probing new parameter space of the sub-GeV DM models
- Other upcoming MeV telescopes (like AMEGO) are expected to improve the sensitivity



Negro, *et al.*, (2111.10362)

COSI projections for sub-GeV DM models

target region for observation: a 10° radius around the Galactic Center



Upper-bounds and 3σ-projected sensitivities (1 yr obs. time) of the MeV telescope COSI

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COSI *projections for sub-GeV DM models*

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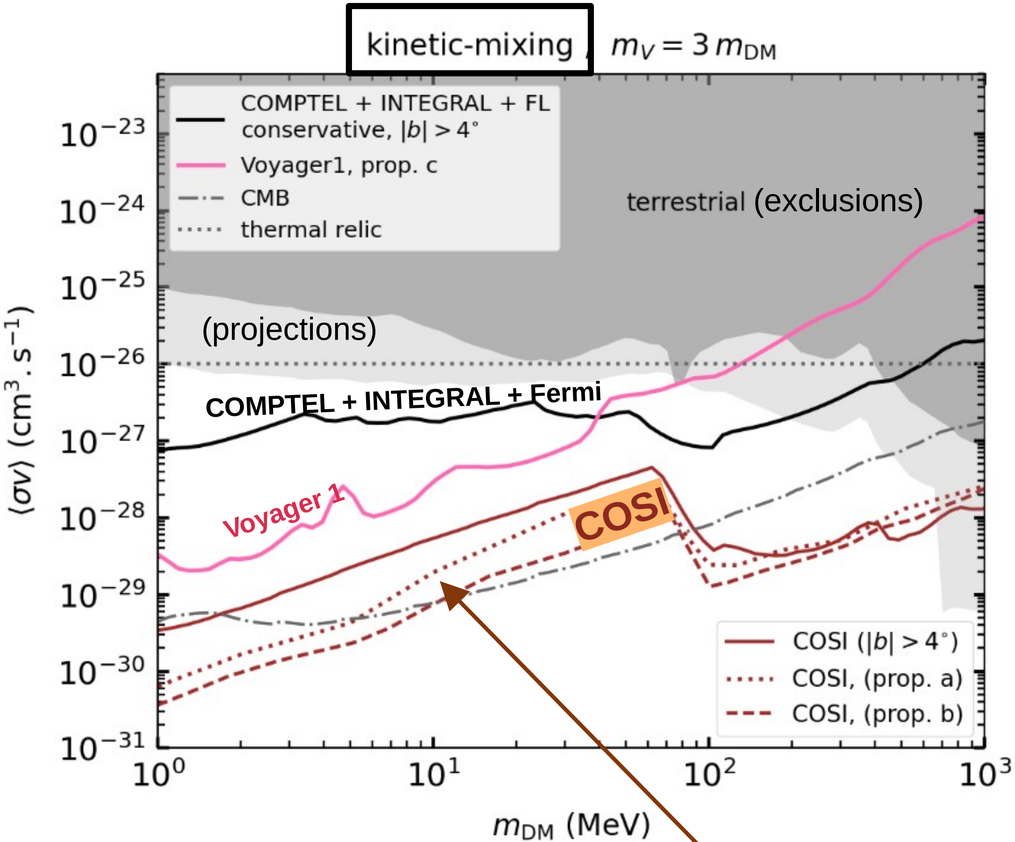

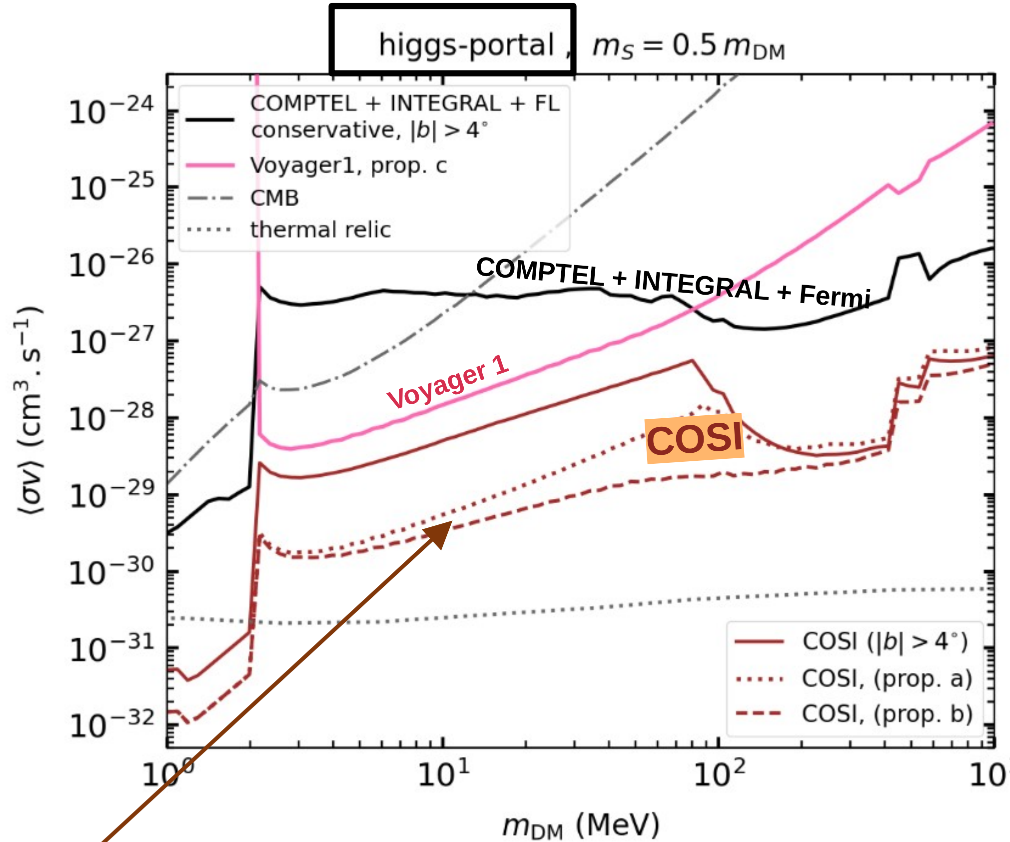

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Effects of Galactic propagation of e±

Propagation models from [Orlando *et al*., (1712.07127)] } used to estimate the secondary photon BGs for COSI sensitivity towards the GC region

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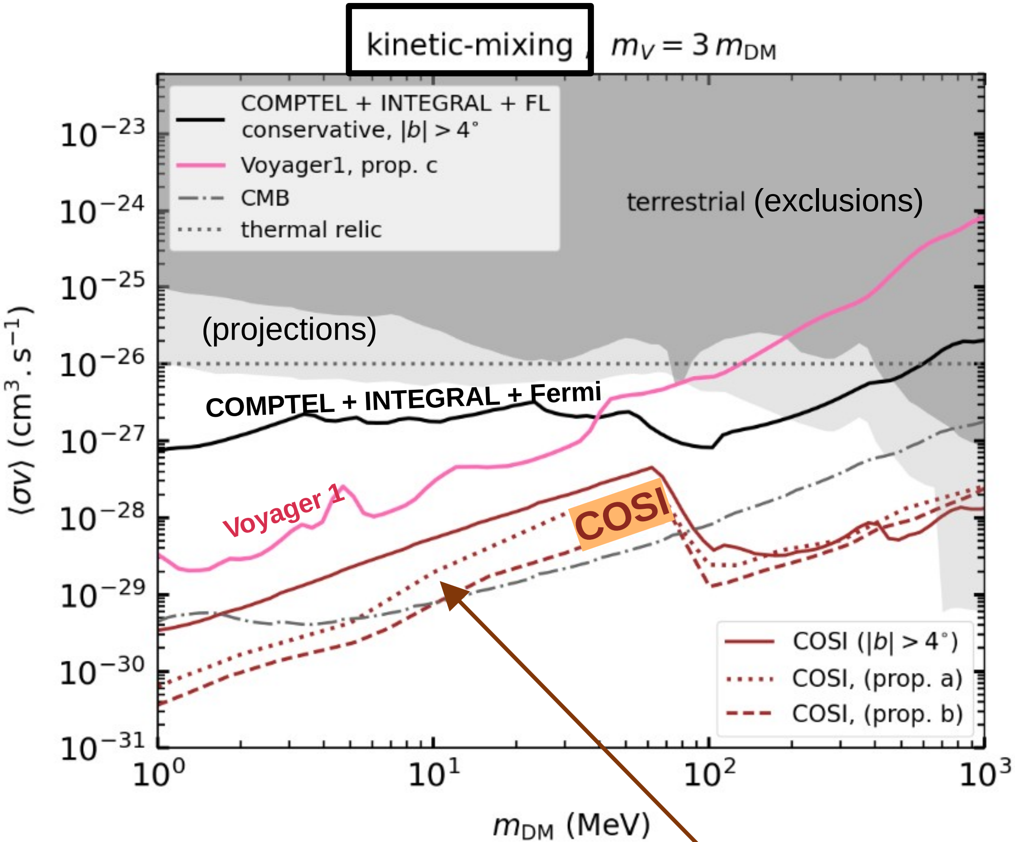

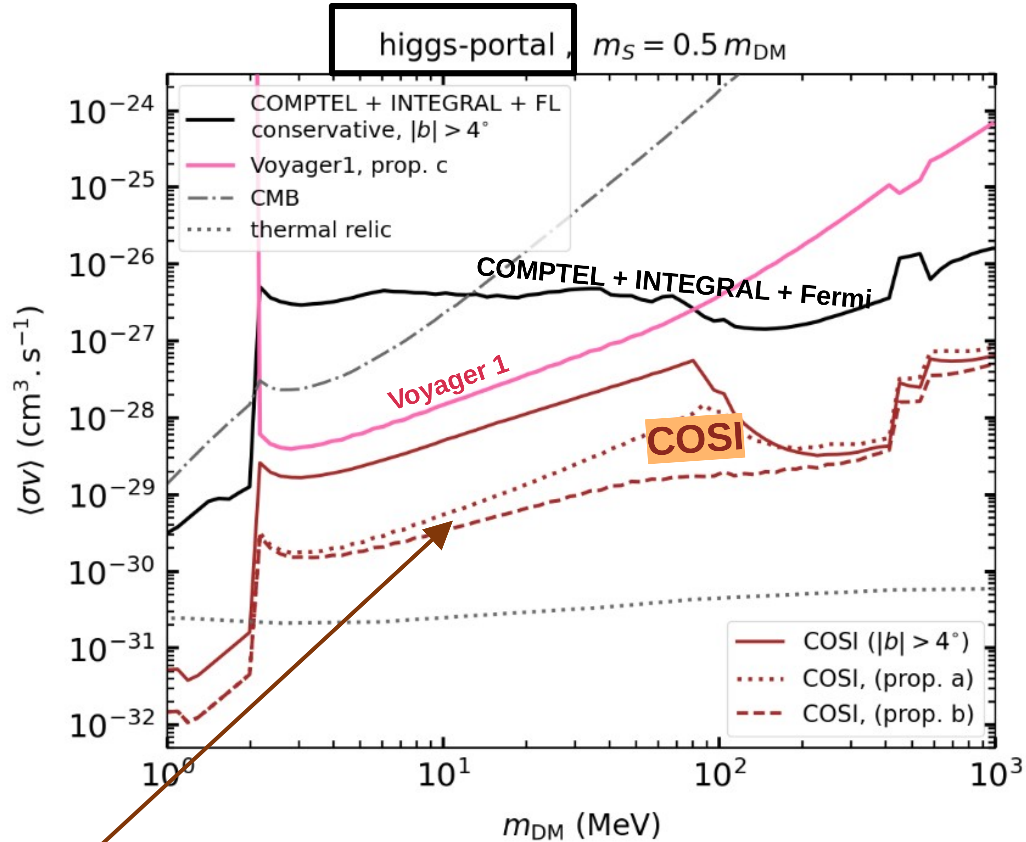

Upper-bounds and 3σ-projected sensitivities (1 yr obs. time) of the MeV telescope COSI

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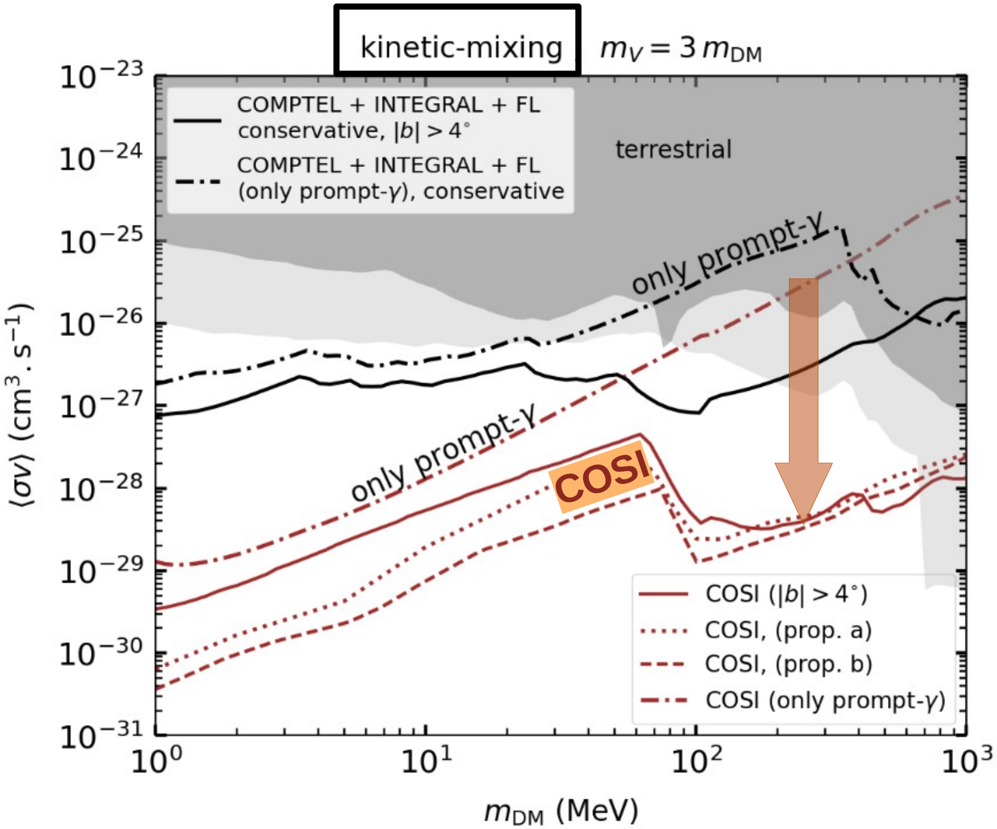
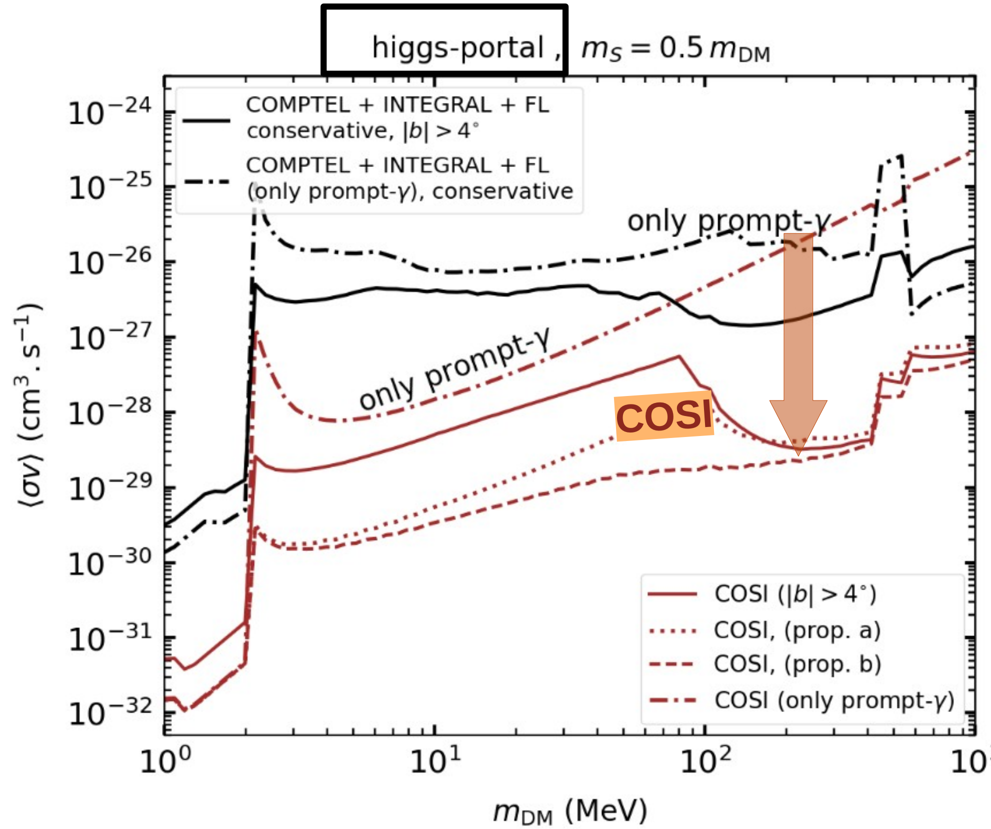
Effects of Galactic propagation of $e^{\pm}$

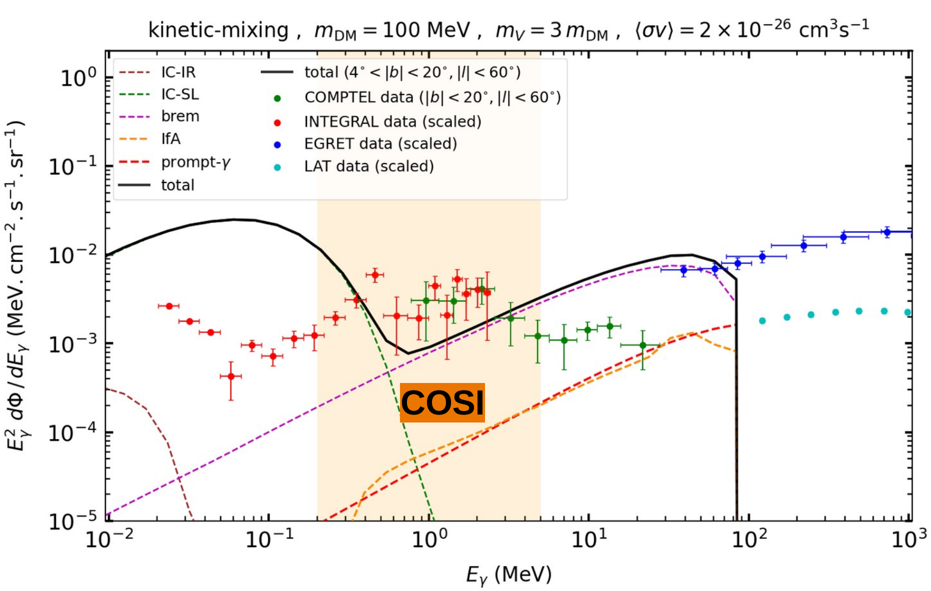
Propagation models from [Orlando *et al*., (1712.07127)] } used to estimate the secondary photon BGs for COSI sensitivity towards the GC region

- For both sub-GeV DM models, COSI can in principle probe a region of the parameter space that lies well beyond the reach of the existing indirect search or terrestrial experiments

Importance of considering the secondary signals for sub-GeV DM models







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Summary

- The combined bound on **realistic sub-GeV DM models** from existing X-ray and γ-ray observations turn out to be significantly stronger compared to the terrestrial constraints

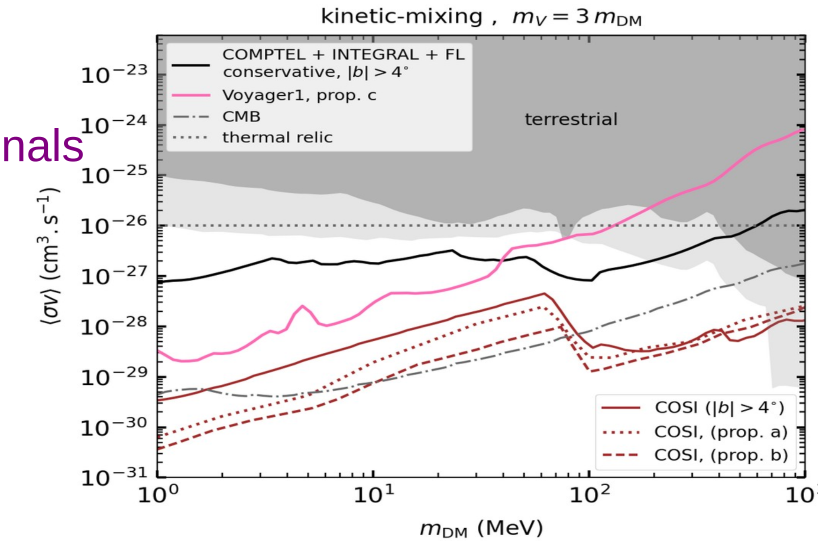
  (can reach at the level of the CMB constraint considering Std. astrophysical backgrounds)

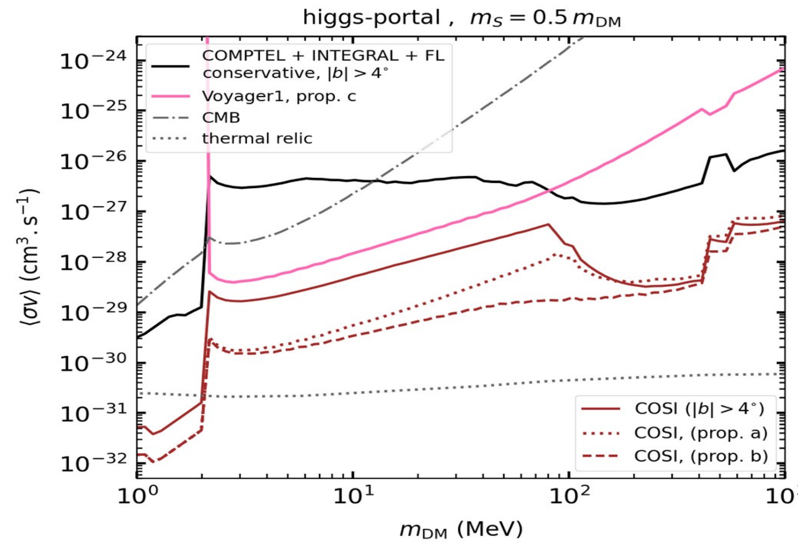
  - Inclusions of the possible **secondary emissions** from sub-GeV DM annihilation in the Galaxy enhance the signals

- We estimate the projected sensitivity of the upcoming MeV telescope COSI in probing **the sub-GeV DM models**

- COSI can probe **new regions of parameter space for these models** that lie **beyond the reach of the existing** indirect search or terrestrial experiments

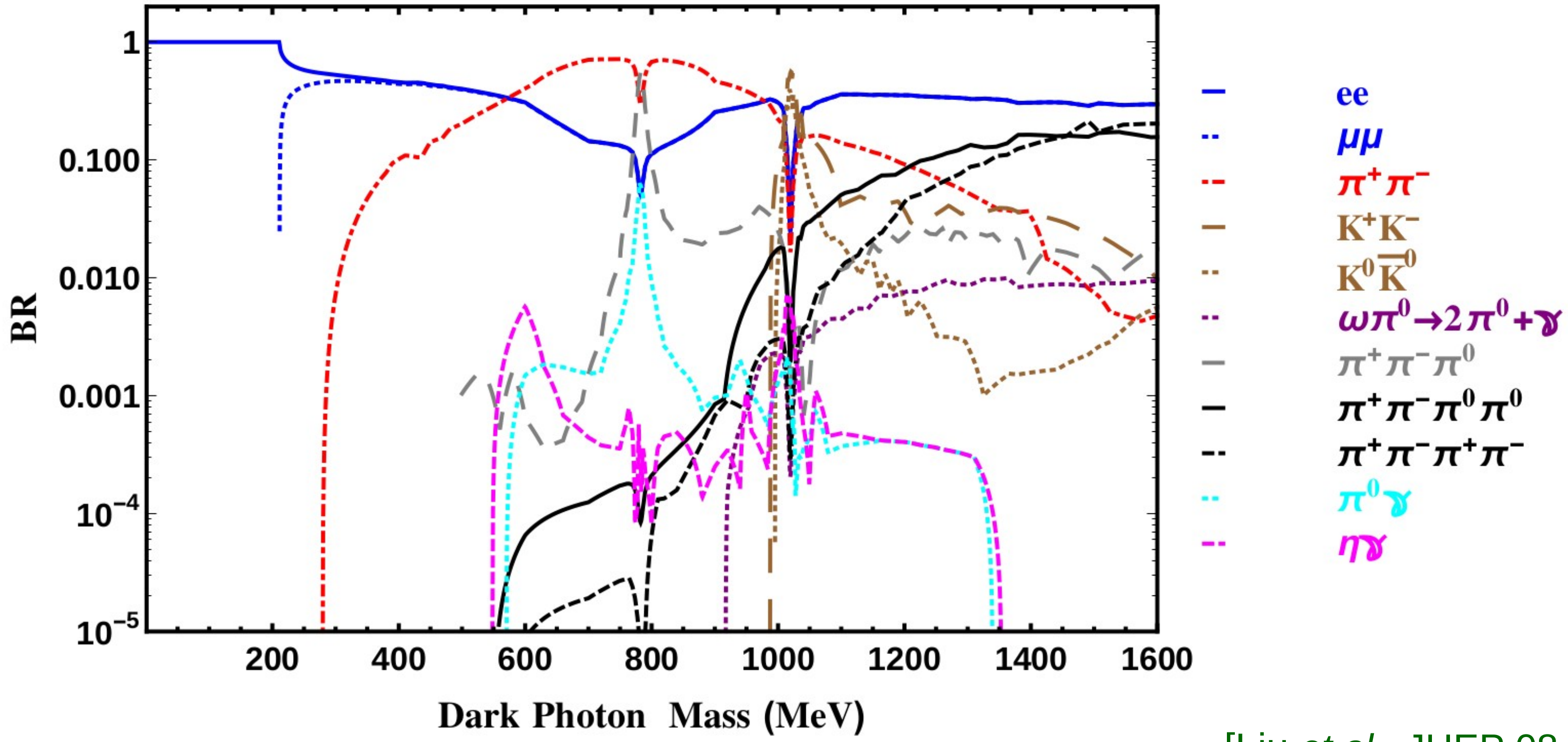
- Upcoming space-based MeV telescopes (COSI, AMEGO, e-ASTROGAM, ...) are going to play crucial roles in probing sub-GeV DM interactions





Backup slides

Branching ratios for the dark photon decay

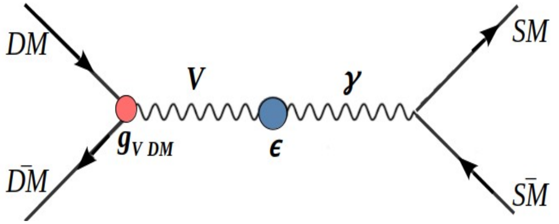


[Liu *et al*., JHEP 08, 050 (2015)]

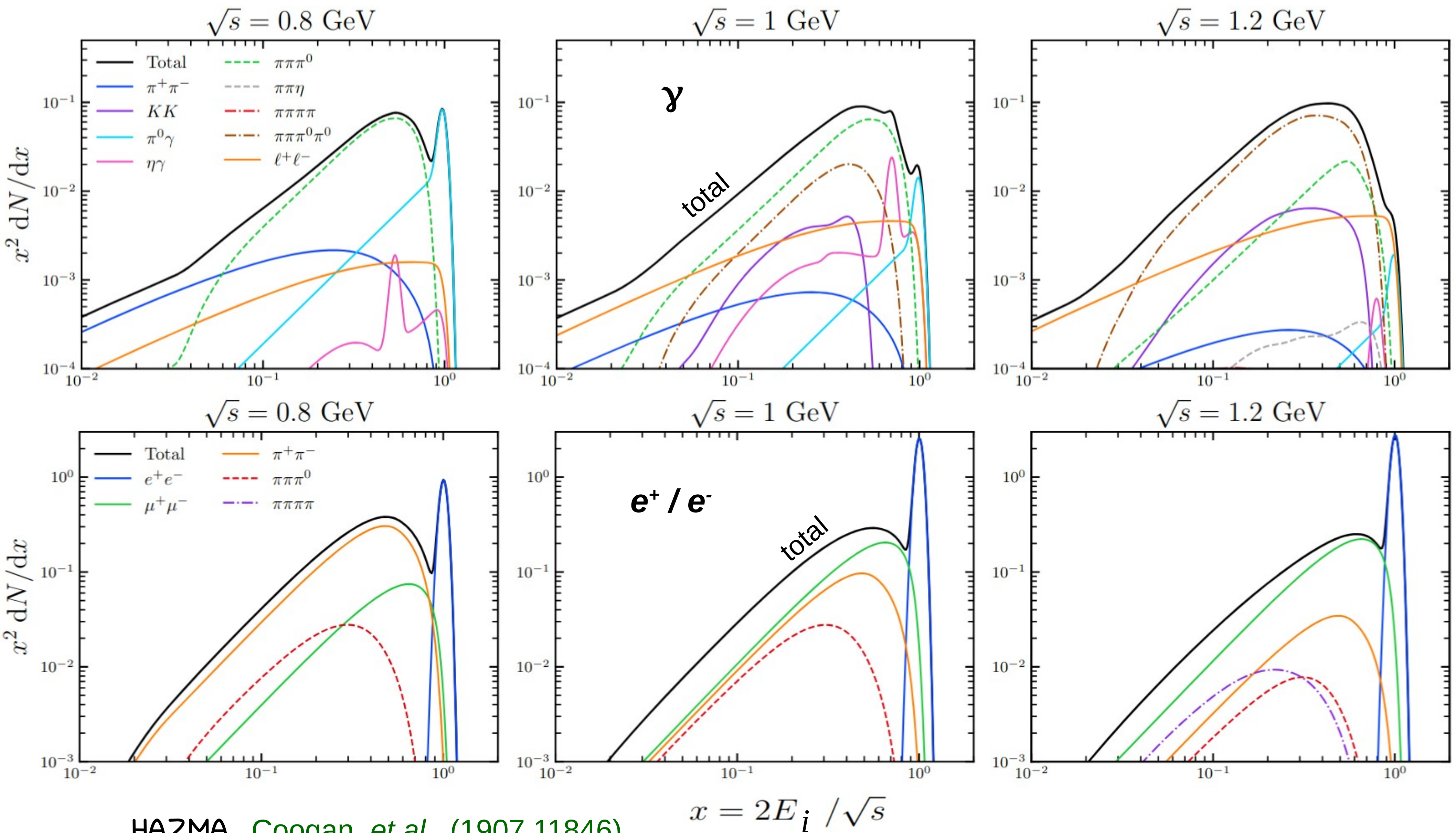
Branching ratios for a vector with kinetic-mixing couplings to the SM

Sub-GeV DM models

- **kinetic-mixing model**



$$\sqrt{s} \simeq 2\, m_{DM}$$



HAZMA Coogan, *et al.*, (1907.11846)
(2207.07634)

MeV-GeV photons from DM annihilations in the Galaxy

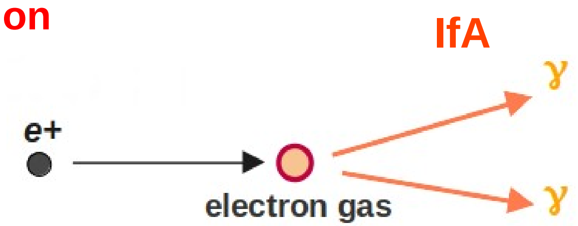
- Secondary emission via **In-flight annihilation (IfA) of DM induced *e*⁺**

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

$$\boxed{j_{2ndary} = j_{ICS} + j_{brem} + \boldsymbol{j_{IfA}}}$$

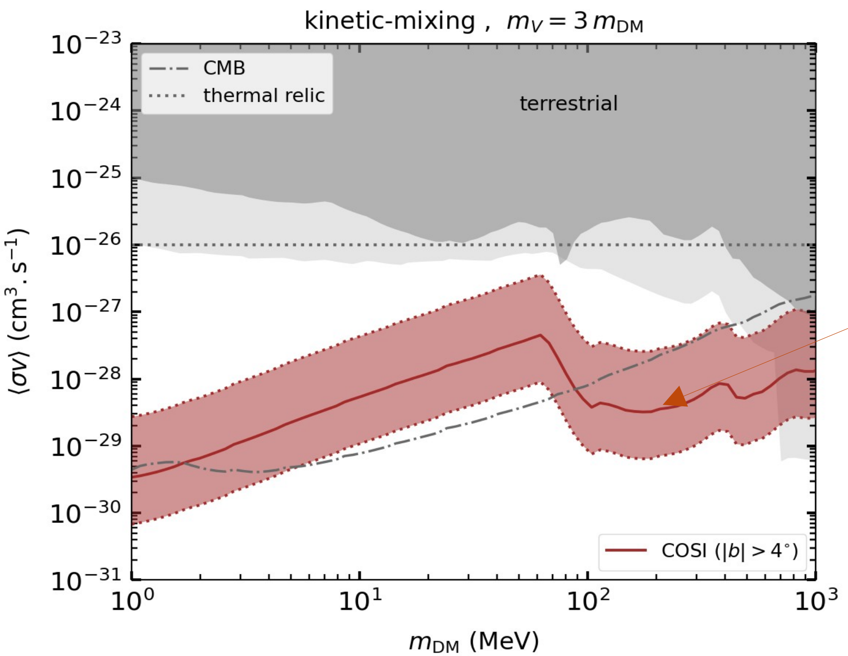
e^+ from sub-GeV DM annihilation

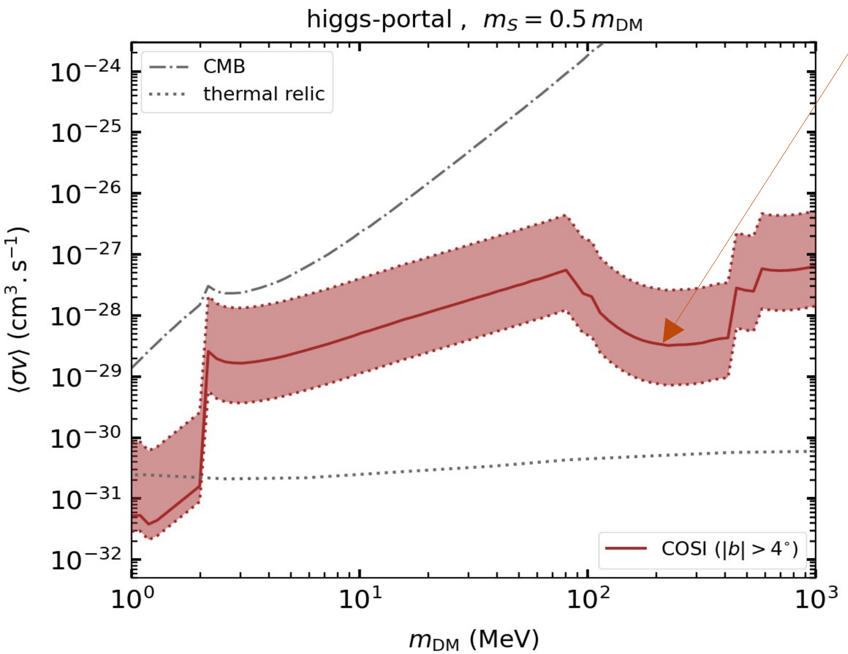
$$j_{\rm IfA}(E_\gamma, \vec{x}(s,b,l)) = \int_{m_e}^{m_{\rm DM}} dE_e\, \boxed{\mathcal{P}_{\rm IfA}(E_\gamma, E_e, \vec{x})}\, \boxed{\frac{dn_e}{dE_e}(E_e, \vec{x})}$$



$$\mathcal{P}_{\rm IfA}(E_\gamma, E_e, \vec{x}) = c\, E_\gamma\, \underbrace{n_{e^-}(\vec{x})}_{\text{Galactic electron density}}\, \beta_e\, \frac{d\sigma^{\rm IfA}}{dE_\gamma}(E_e, E_\gamma)$$

Impact of the choice of DM profile (for sub-GeV DM models)





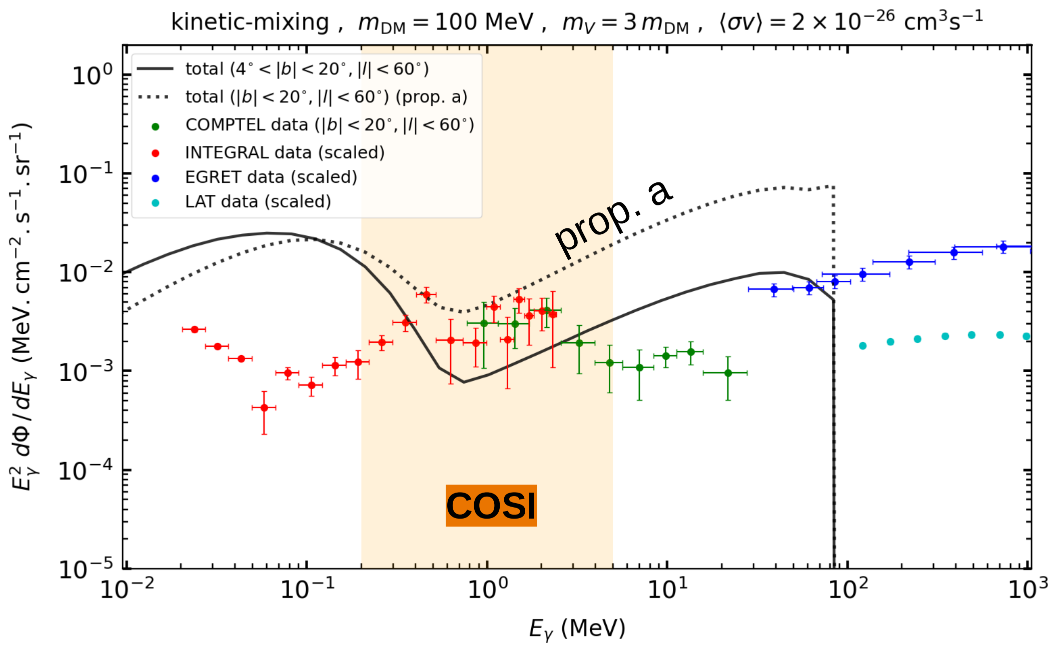
NFW: $$\rho_{DM}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$$

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

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

M. Cirelli, A.K. H. Shaikh; (JCAP 01 (2026) 038)

Effects of including Galactic propagation of $e^{\pm}$



M. Cirelli, A.K. H. Shaikh; (JCAP 01 (2026) 038)

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

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

Solved using DRAGON

spatial diffusion

$$D(\rho) = D_0\ \beta_e\ (\rho/\rho_0 GV)^\delta$$

$$\rho = p_e/e \qquad \beta_e = v_e/c$$

$$D_{pp} = \frac{4}{3}\frac{1}{\delta(4-\delta^2)(4-\delta)}\frac{v_A^2 p^2}{D}$$

v_A → **reacceleration**

v_w → Galactic wind **(convection)**

$R_{Gal} = 20\,kpc$

$z_{Gal} = 4\,kpc$

prop. a: $D_0 \simeq 1.5\times 10^{29}\,cm^2/s,\ \ \delta \simeq 1/3,\ \ \rho_0 \simeq 40\,GV,\ \ v_A \simeq 9\,km/s$

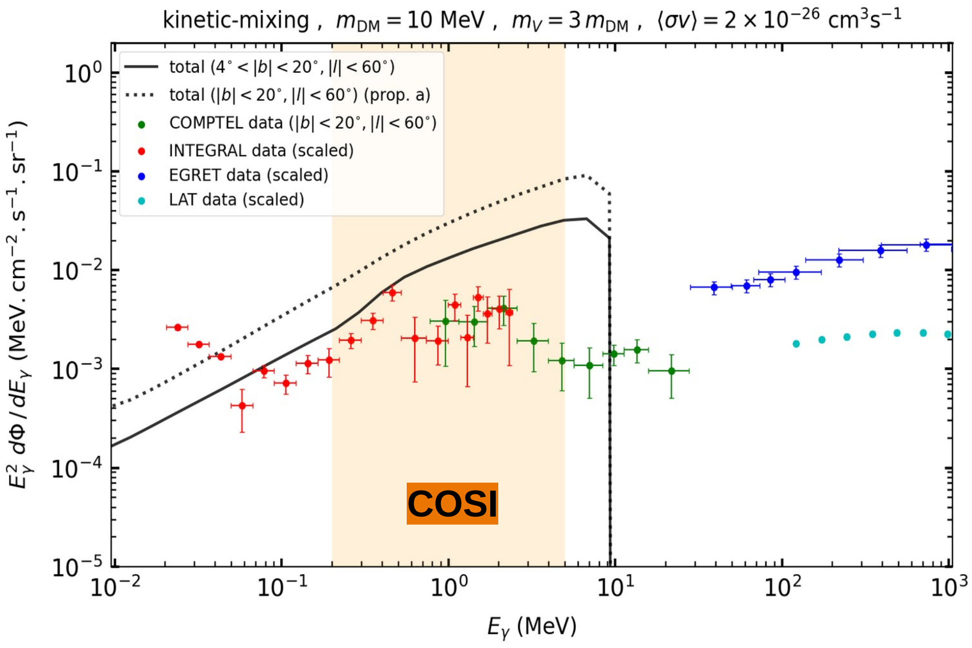
prop. b: $D_0 \simeq 4.3\times 10^{28}\,cm^2/s,\ \ \delta \simeq 0.4,\ \ \rho_0 \simeq 4\,GV,\ \ v_A \simeq 30\,km/s$

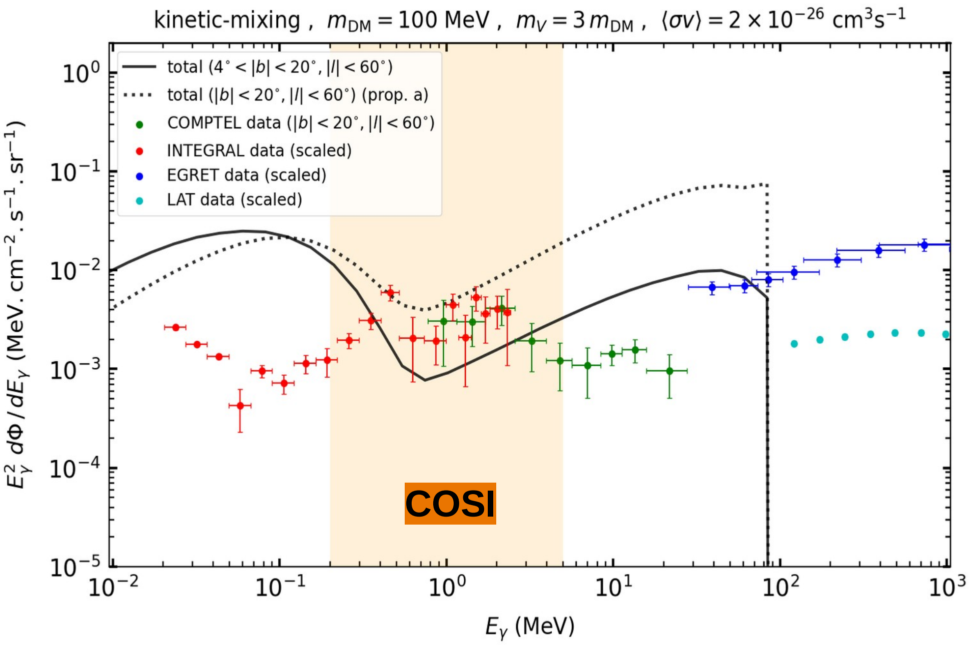
$v_w \simeq 12.4\,km/s,\ \ dv_w/dz \simeq 10.2\,km/s/kpc$

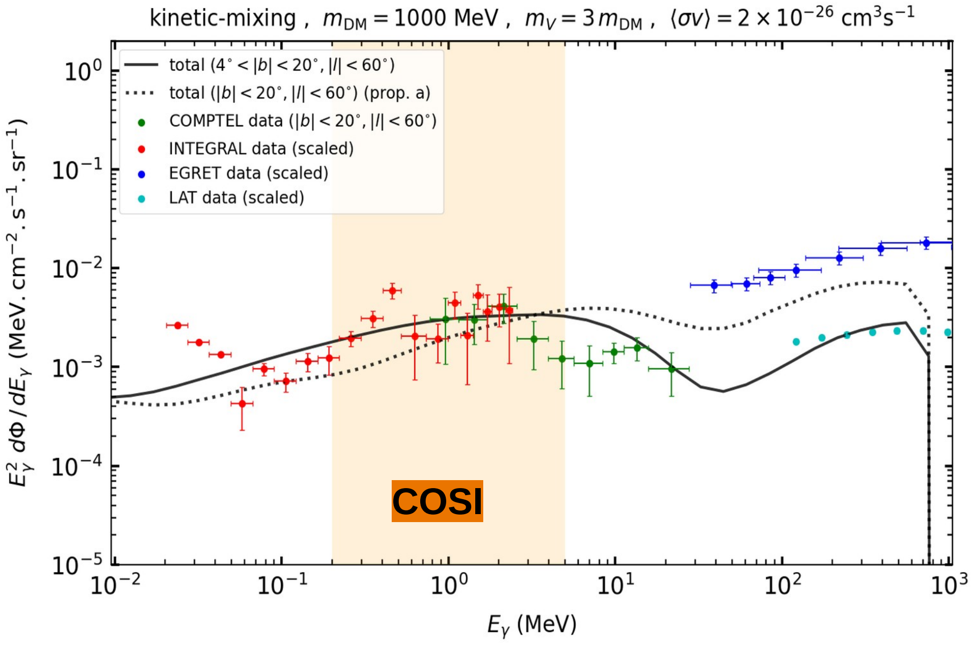
[Orlando *et al.*, (1712.07127)]

- ➔ These models are used to estimate the Galactic secondary photon BGs
- ➔ Such BGs are then used to estimate the COSI sensitivity towards the GC region

Effects of including Galactic propagation of e±



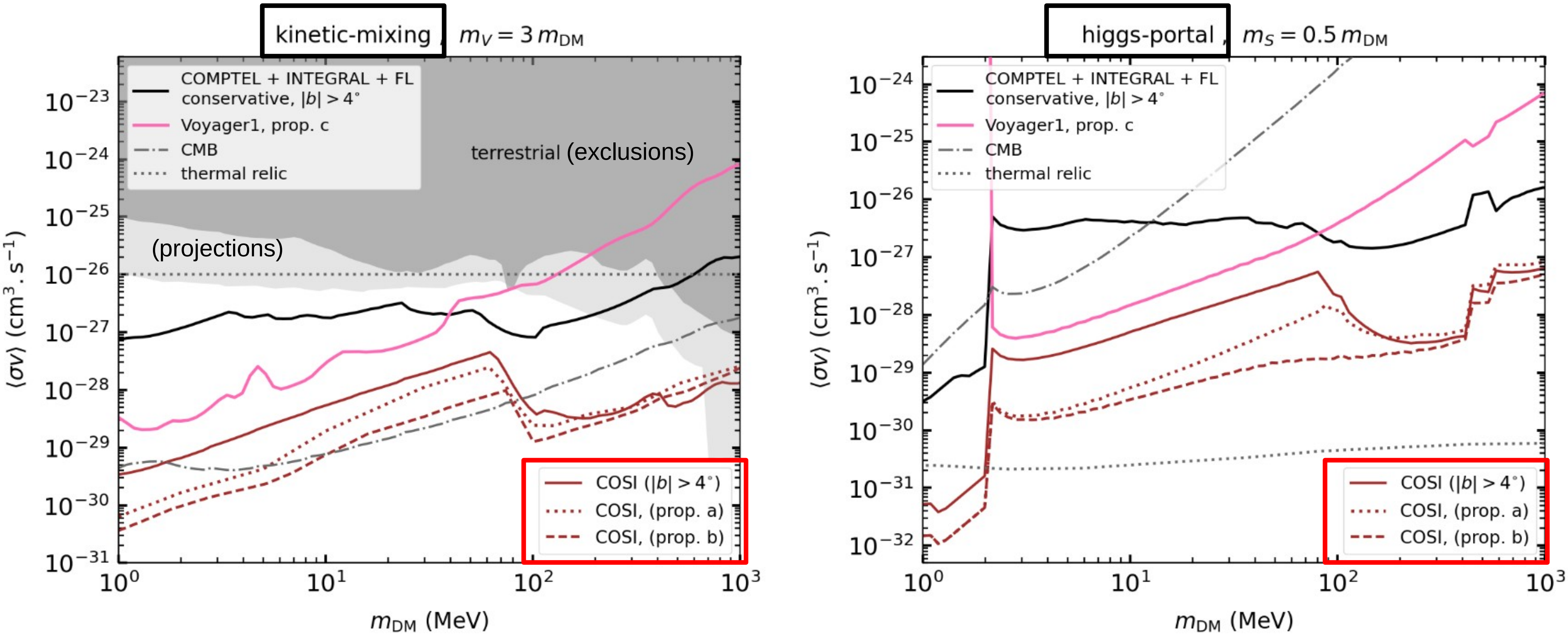




M. Cirelli, A.K. H. Shaikh; (JCAP 01 (2026) 038)

COSI *projections for sub-GeV DM models*

target region for observation: a 10° radius around the Galactic Center



Upper-bounds and 3σ-projected sensitivities (1 yr obs. time) of the MeV telescope COSI

M. Cirelli, A.K. H. Shaikh; (JCAP 01 (2026) 038)

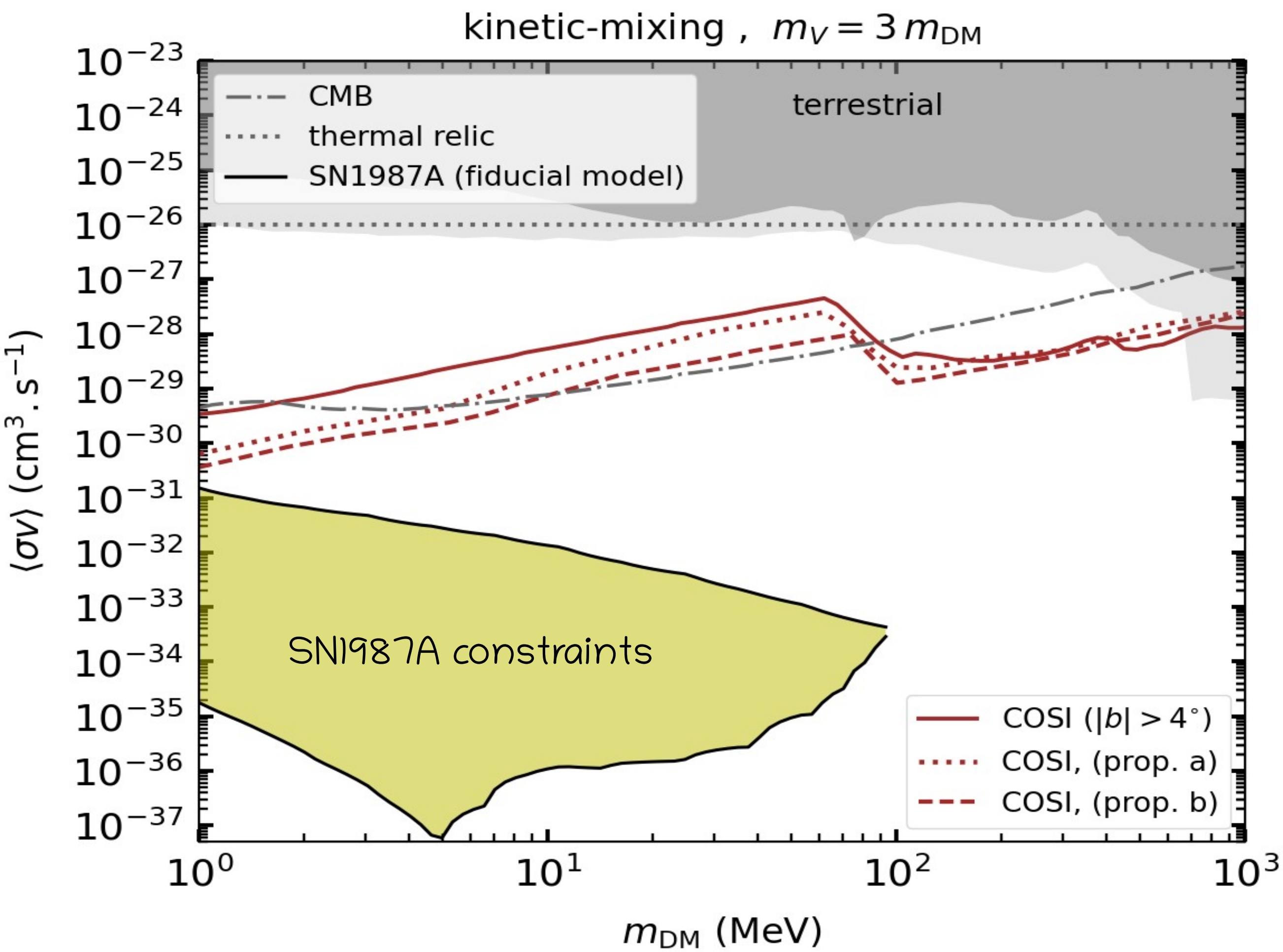
prop. a: $D_0 \simeq 1.5 \times 10^{29}\, cm^2/s,\ \delta \simeq 1/3,\ \rho_0 \simeq 40\, GV,\ v_A \simeq 9\, km/s$

prop. b: $D_0 \simeq 4.3 \times 10^{28}\, cm^2/s,\ \delta \simeq 0.4,\ \rho_0 \simeq 4\, GV,\ v_A \simeq 30\, km/s$
$v_w \simeq 12.4\, km/s,\ dv_w/dz \simeq 10.2\, km/s/kpc$

prop. c: $D_0 \simeq 4.3 \times 10^{28}\, cm^2/s,\ \delta \simeq 0.4,\ \rho_0 \simeq 4\, GV,\ v_A \simeq 42\, km/s$
$v_w \simeq 12.4\, km/s,\ dv_w/dz \simeq 10.2\, km/s/kpc$

models from [Orlando *et al.*, (1712.07127)]

SN1987A constraints on sub-GeV DM models



SN1987A constraints obtained using [Chang *et al*., (1803.00993)]