

Direct and Indirect searches for Dark Matter-electron interactions in sub-GeV DM models

Arpan Kar



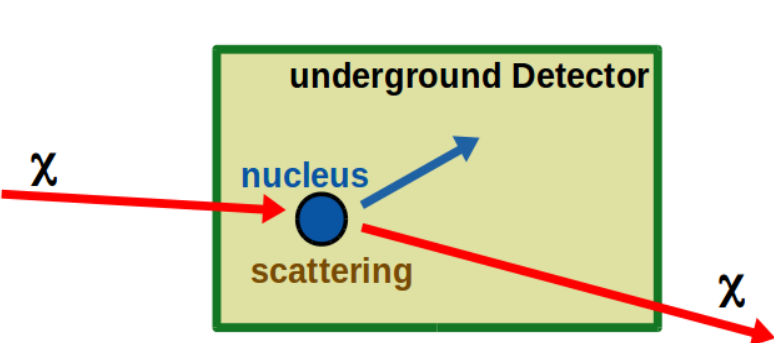
Based on: [M. Cirelli, A. K., A. Letessier-Selvon, H. Lumengo-Kidimbu; \[arXiv:2608.26467\]](#)
[M. Cirelli, A.K., H. Shaikh; JCAP 01 \(2026\) 038](#)

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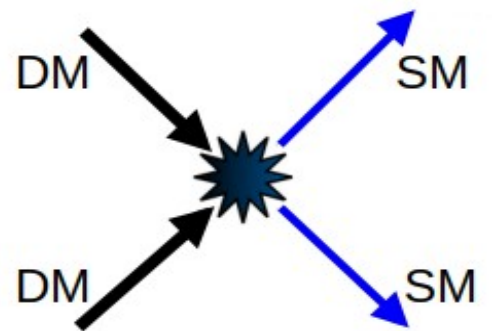
Oct 21 – 22, 2026

Dark matter

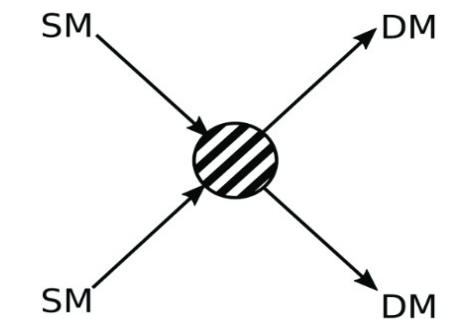
- Existence of Dark Matter (DM) is established gravitationally (provides $\sim 25\%$ of the energy density of the Universe)
- Microscopic natures of DM are still unknown
- It can be composed of a new fundamental particle
 - Massive and Neutral
 - Stable (on the cosmological time scale)
 - very feebly interacting
 - Cold in nature (non-relativistic at CMB formation)
- Searches for particle DM signals:



Direct detection (DD)



Indirect detection (ID)



Accelerator searches

- Searches span many orders of magnitude in mass and interaction strength

Sub-GeV dark matter

- DM can be composed of a light particle with a mass in the range MeV - GeV
- **Why look below a GeV?**
 - Absence of compelling evidence for usual weak-scale (GeV - TeV) DM in current experiments
 - Motivated theoretical models to predict sub-GeV DM candidates
 - E.g., DM can be coupled to a new light gauge boson (Boehm & Fayet [hep-ph/0305261]) ;
 - Hidden sector DM (Feng & Kumar [0803.4196])

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Hidden sector DM (Feng & Kumar [0803.4196])
- Direct detection with **typical nuclear recoil is difficult** due to the threshold of these experiments
- **Two promising search channels :**

Indirect detections

Look for **MeV photons** and **sub-GeV cosmic-ray $e^\pm$** produced by DM annihilation in the Galaxy

Direct detection based on DM-electron scattering

Look for energy deposited when halo **DM scatters on electrons** in a semiconductor

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In a model-independent approach, it is not possible to map the constraints obtained via one strategy onto another one

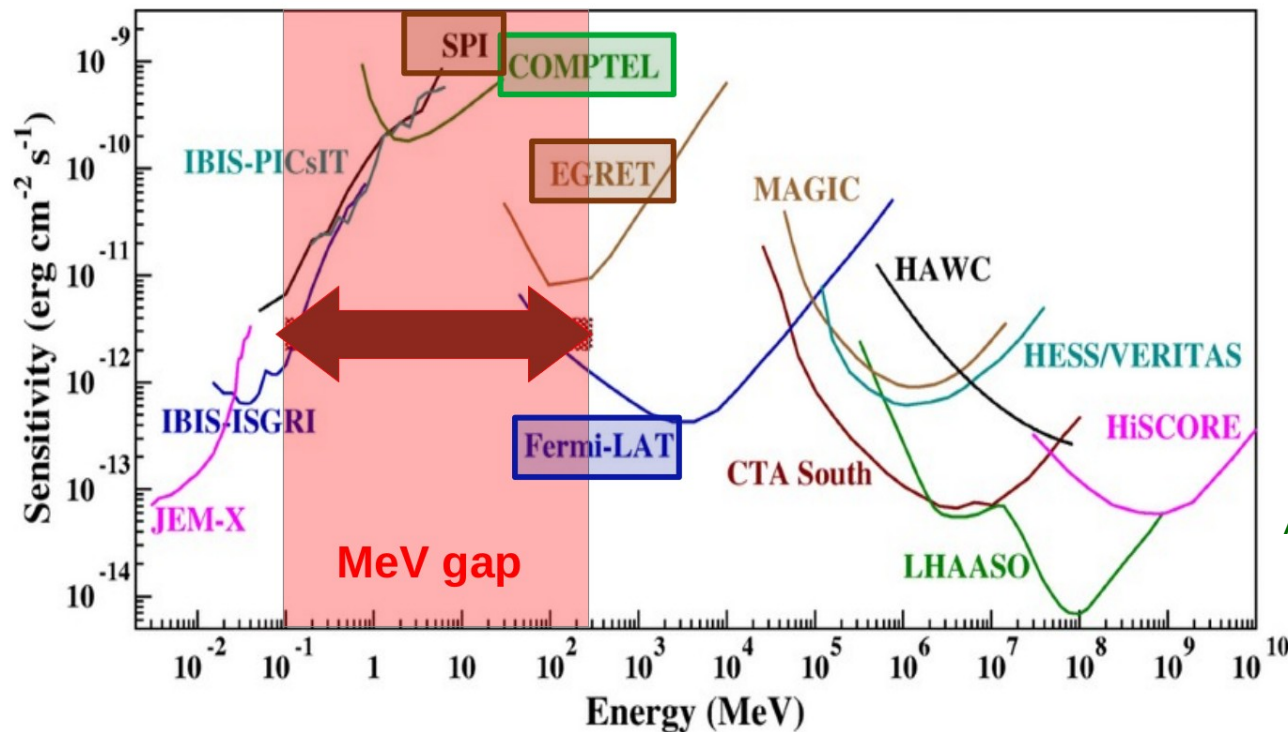
A specified model relates the scattering cross-section to the annihilation rate

 **Compare both probes in the same plane: $\sigma_e - m_{\text{DM}}$ plane**

- **Complementarity:** one channel can cover regions where the other is weak or systematics-limited

Upcoming MeV γ -ray telescopes (a new motivation for MeV-scale DM)

- Relatively poor sensitivity of *existing* photon telescopes 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.
- COSI has already been selected to fly with its scheduled launch in 2027
- COSI has a **wide field-of-view** ($\gtrsim 25\%$ of the sky) with an energy range: $0.2 \text{ MeV} \lesssim E_\gamma \lesssim 5 \text{ MeV}$
- Other upcoming MeV telescopes (like AMEGO) are expected to improve the sensitivity further
- These MeV telescopes should play important roles in probing the sub-GeV DM signals

Direct Detection (DD) of sub-GeV DM based on DM-e scattering

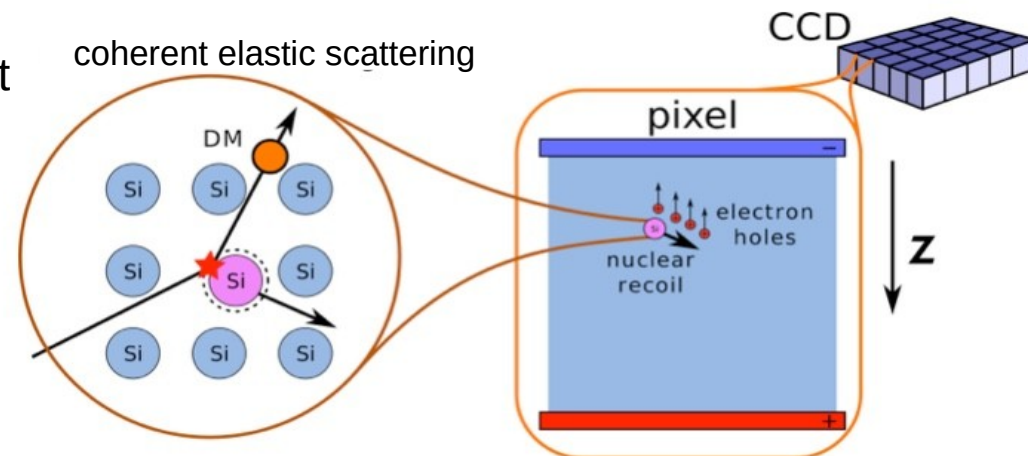
- We focus on the present **DAMIC-M** experiment

→ uses skipper charge-coupled devices (CCDs) to measure possible **DM-e scattering**

- DM-e scattering rate:

$$\frac{dR}{dE_e} = \alpha N_{\text{cell}} \bar{\sigma}_e \frac{m_e^2}{\mu_{\text{DM}e}^2} \left(\frac{\rho_{\odot}^{\text{DM}}}{m_{\text{DM}}} \right) \int \frac{dq}{q^2} \left[\int \frac{f(\mathbf{v}_{\text{DM}})}{v_{\text{DM}}} d^3 v_{\text{DM}} \right] |F_{\text{DM}}(q)|^2 |F_c(q, E_e)|^2$$

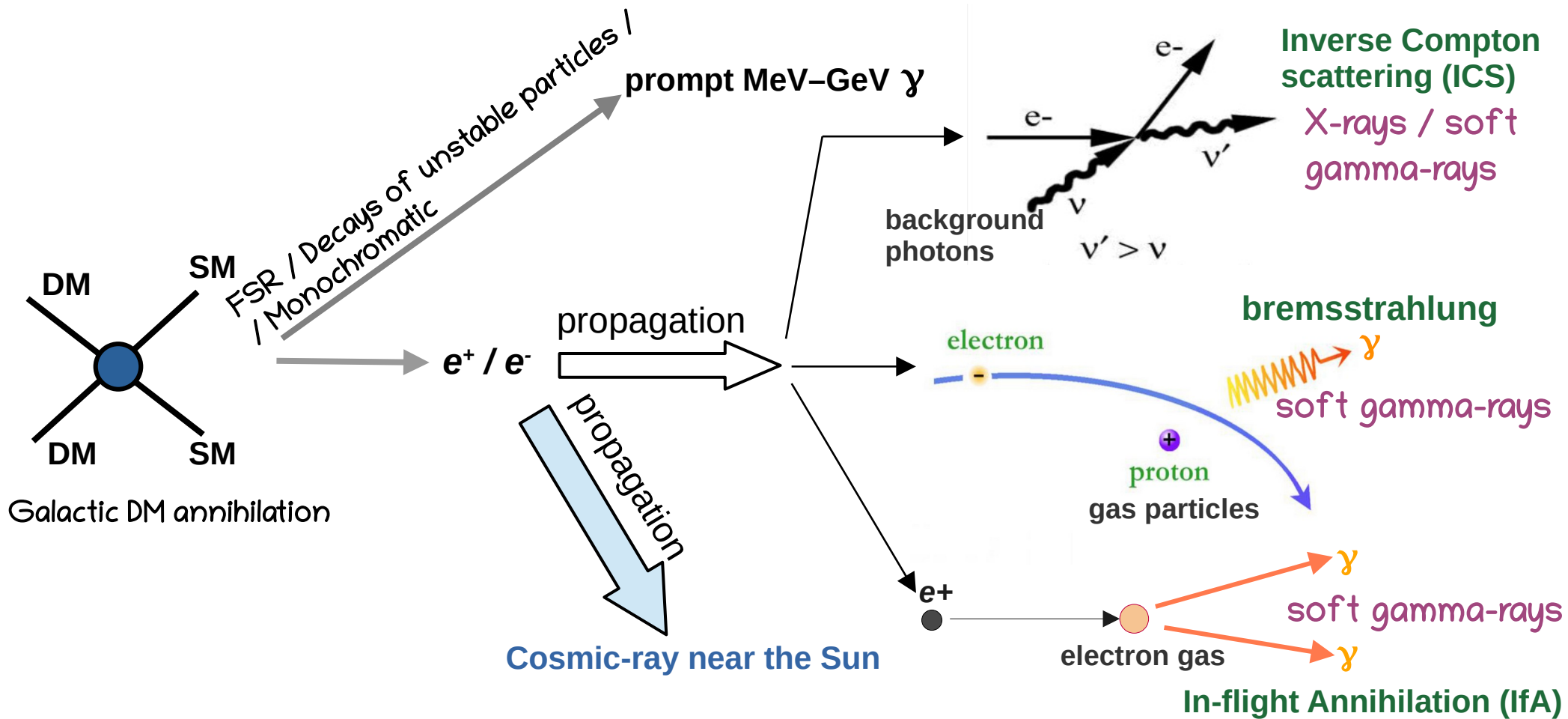
αN_{cell} : number of unit crystal cells
 $\bar{\sigma}_e$: reference scattering cross-section, evaluated at a fixed momentum transfer $q_{\text{ref}} = \alpha m_e$
 $\frac{m_e^2}{\mu_{\text{DM}e}^2}$: local DM density
 $\mu_{\text{DM}e}$: DM-e reduced mass
 $\left(\frac{\rho_{\odot}^{\text{DM}}}{m_{\text{DM}}} \right)$: momentum transfer
 $\int \frac{dq}{q^2}$: velocity distribution of DM particles in the local halo
 $\left[\int \frac{f(\mathbf{v}_{\text{DM}})}{v_{\text{DM}}} d^3 v_{\text{DM}} \right]$: includes crystal form-factor
 $|F_{\text{DM}}(q)|^2 |F_c(q, E_e)|^2$



- Present **prototype** already provides stringent limits in the $\bar{\sigma}_e - m_{\text{DM}}$ plane for MeV-scale DM (exposure of ~ 1.3 kg-day) Aggarwal *et al.*, (PRL 135, 071002)

- The future DAMIC-M detector aims at improving these results by up to ~ 3 orders of magnitude Arnquist *et al.*, (SciPost Phys.Proc. 12 (2023) 014)

Indirect Detection (ID) of sub-GeV DM



- **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^-
- **Cosmic-ray near the solar system**

MeV-GeV photons from DM annihilation in the Galaxy

- **Prompt γ - ray flux:**

total velocity-averaged
pair-annihilation cross-section

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

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

Determined by the final state of DM annihilation

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

$s \rightarrow$ line-of-sight (l.o.s.)
 $d\Omega = 2\pi \sin\theta d\theta$

NFW DM profile :

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

MeV-GeV photons from DM annihilation in the Galaxy

● Secondary γ - ray flux:

$(s, b, l) \rightarrow$ Galactic coordinates
 $\cos b \cos l = \cos \theta$

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

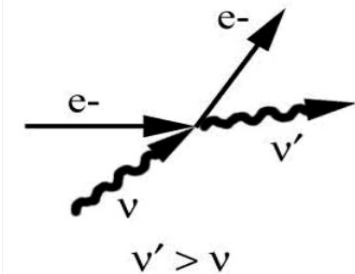
$$j_{\text{ICS}}(E_\gamma, \vec{x}(s, b, l)) = 2 \int_{m_e}^{m_{\text{DM}}} dE_e \sum_{i \in \text{ISRF}} \mathcal{P}_{\text{ICS}}^i(E_\gamma, E_e, \vec{x}) \frac{dn_e}{dE_e}(E_e, \vec{x})$$

From DM annihilation

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

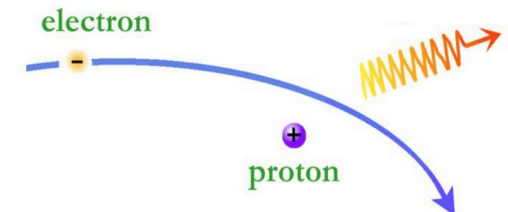
$$\mathcal{P}_{\text{ICS}}^i(E_\gamma, E_e, \vec{x}) = c E_\gamma \int d\epsilon n_i^{\text{ISRF}}(\epsilon, \vec{x}) \sigma_{\text{IC}}(\epsilon, E_\gamma, E_e)$$

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



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

Gas species : Ionic, Atomic and Molecular



Distribution of sub-GeV DM induced $e^\pm$ in the galaxy :

Source function from DM annihilation :

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

total velocity-averaged pair-annihilation cross-section $\langle \sigma v \rangle$
 e^+ / e^- spectra produced per annihilation $\left. \frac{dN_e}{dE_e^S} \right|_{\text{tot}}$
 DM density $\rho_{\text{DM}}^2(r)$

Determined by the final state of annihilation

■ Semi-Analytic :

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

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

■ Full-propagation of $e^\pm$ (Cosmic-rays):

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

$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p} \left[p^2 D_{pp} \frac{\partial}{\partial p} \left(\frac{N_i}{p^2} \right) \right] - \frac{\partial}{\partial p} \left[\dot{p} N_i - \frac{p}{3} (\vec{\nabla} \cdot \vec{v}_w) N_i \right] =$$

$$Q + \sum_{i < j} \left(c \beta n_{\text{gas}} \sigma_{j \rightarrow i} + \frac{1}{\gamma \tau_{j \rightarrow i}} \right) N_j - \left(c \beta n_{\text{gas}} \sigma_i + \frac{1}{\gamma \tau_i} \right) N_i$$

Evoli et al., (1607.07886)

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

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

Sub-GeV DM models

- Representative sub-GeV DM models: **Vector-portal**, **Scalar-portal** models
- Vector portal: dark photon (DP) portal or kinetic-mixing model**

$$\mathcal{L}_D^V = \bar{\chi}(i\gamma^\mu D_\mu - m_{\text{DM}})\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + m_V^2 V_\mu V^\mu + \frac{\epsilon}{2}F_{\mu\nu}V^{\mu\nu}$$

$$\bar{\sigma}_e = \frac{16\pi \alpha \alpha_D \epsilon^2 \mu_{\text{DMe}}^2}{(\alpha^2 m_e^2 + m_V^2)^2}$$

$$F_{\text{DM}}(q) = \begin{cases} 1 & \text{if } m_V \gg \alpha m_e \\ \left(\frac{\alpha m_e}{q}\right)^2 & \text{if } m_V \ll \alpha m_e \end{cases}$$

$$D_\mu = \partial_\mu - ig_D V_\mu$$
$$g_D = \sqrt{4\pi\alpha_D}$$

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▪ Heavy DP: $m_V > m_{\text{DM}}$ ($m_V = 3 m_{\text{DM}}$)

Direct Detection : $F_{\text{DM}}(q) = 1$

Dominating annihilation: $\chi\bar{\chi} \rightarrow V^* \rightarrow f\bar{f}$

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

$$\Rightarrow y = \frac{(q_{\text{ref}}^2 + m_V^2)^2 m_{\text{DM}}^4}{16\pi\alpha m_V^4 \mu_{\text{DMe}}^2} \bar{\sigma}_e$$

$$\Rightarrow \langle\sigma v\rangle \propto \bar{\sigma}_e \quad (\text{for a given mass})$$

direct conversion

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direct conversion

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Direct Detection : $F_{\text{DM}}(q) = 1$
(for the considered mass range)

Dominating annihilation: $\chi\bar{\chi} \rightarrow VV \rightarrow f\bar{f}f'\bar{f}'$

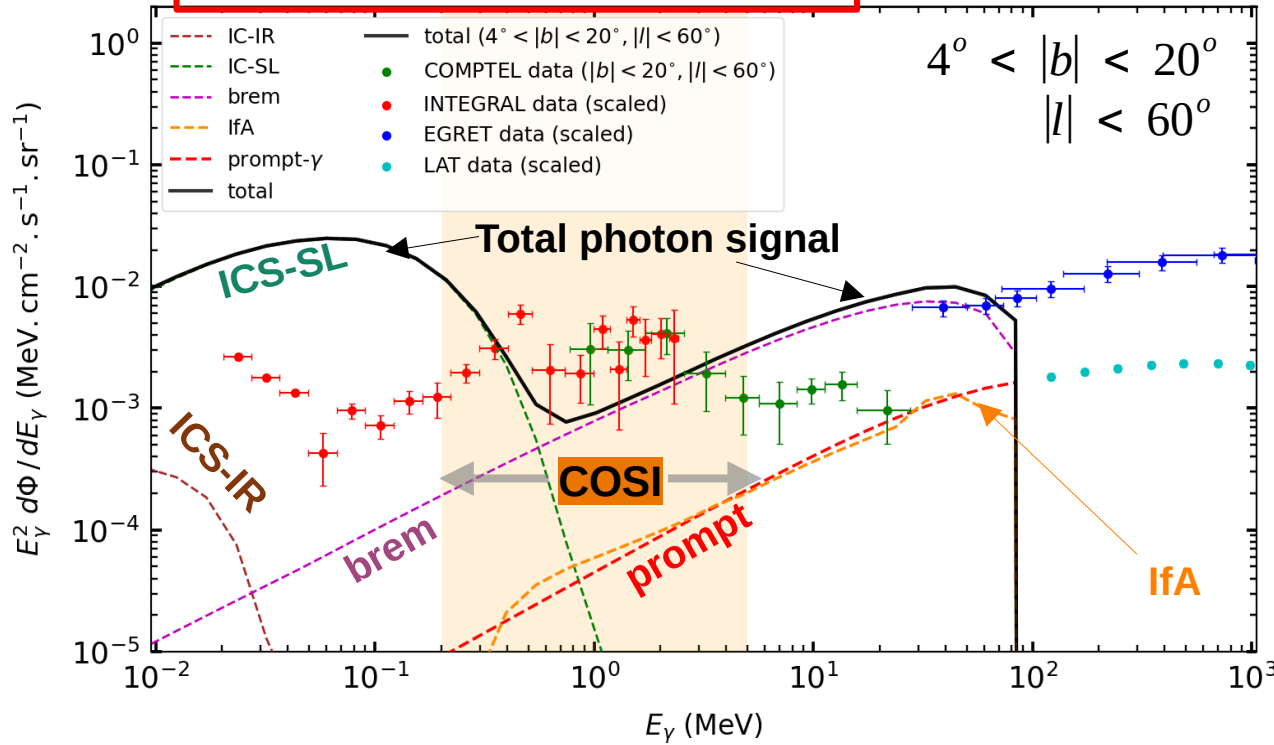
$$\langle\sigma v\rangle \simeq \langle\sigma v\rangle_{VV} \simeq \frac{\pi\alpha_D^2}{m_{\text{DM}}^2} \frac{(1 - m_V^2/m_{\text{DM}}^2)^{3/2}}{(1 - m_V^2/2m_{\text{DM}}^2)^2}$$

$$\Rightarrow \langle\sigma v\rangle \rightarrow \bar{\sigma}_e$$

requires additional info on mixing ϵ

Photon and cosmic-ray signals from sub-GeV DM annihilation in the Galaxy

kinetic-mixing , $m_{\text{DM}} = 100 \text{ MeV}$, $m_V = 3 m_{\text{DM}}$, $\langle \sigma v \rangle = 2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$



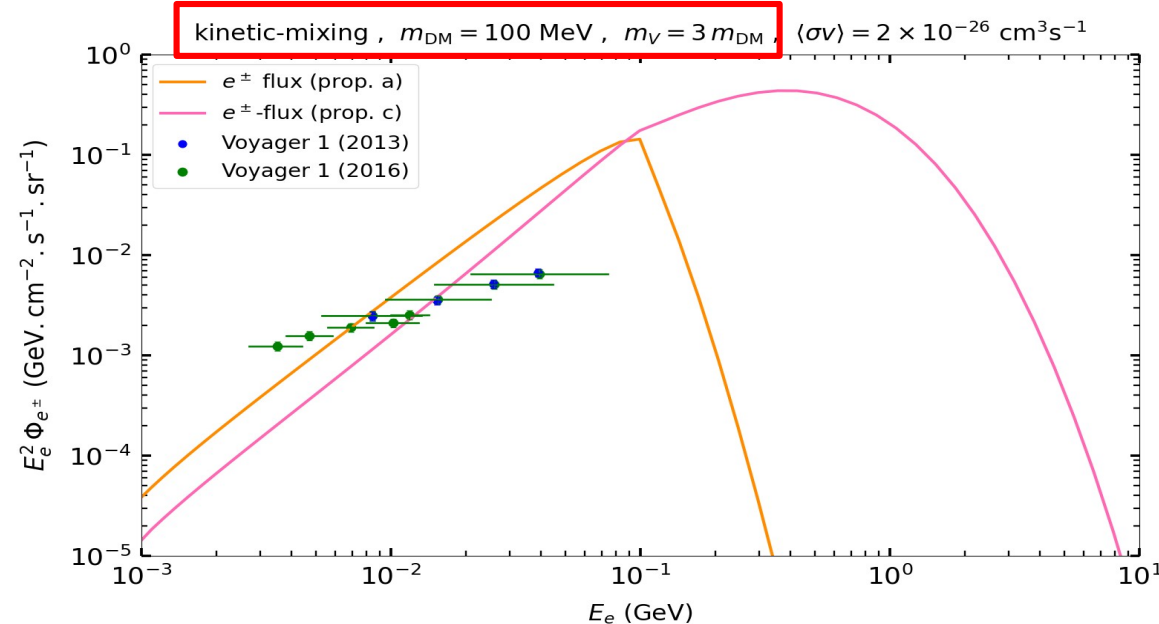
$$\frac{dn_e}{dE_e}(E_e, \vec{x}) = \frac{1}{b_{\text{tot}}(E_e, \vec{x})} \int_{E_e}^{m_{\text{DM}}} dE_e^S Q_e(E_e^S, r)$$

Total photon signal (prompt + secondaries) is estimated masking $|b| \leq 4^\circ$

▪ X-ray / gamma-ray observations:

**INTEGRAL + COMPTEL +
EGRET + Fermi-LAT**

▪ Upcoming MeV gamma-ray observation: **COSI**



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

With two different propagation models

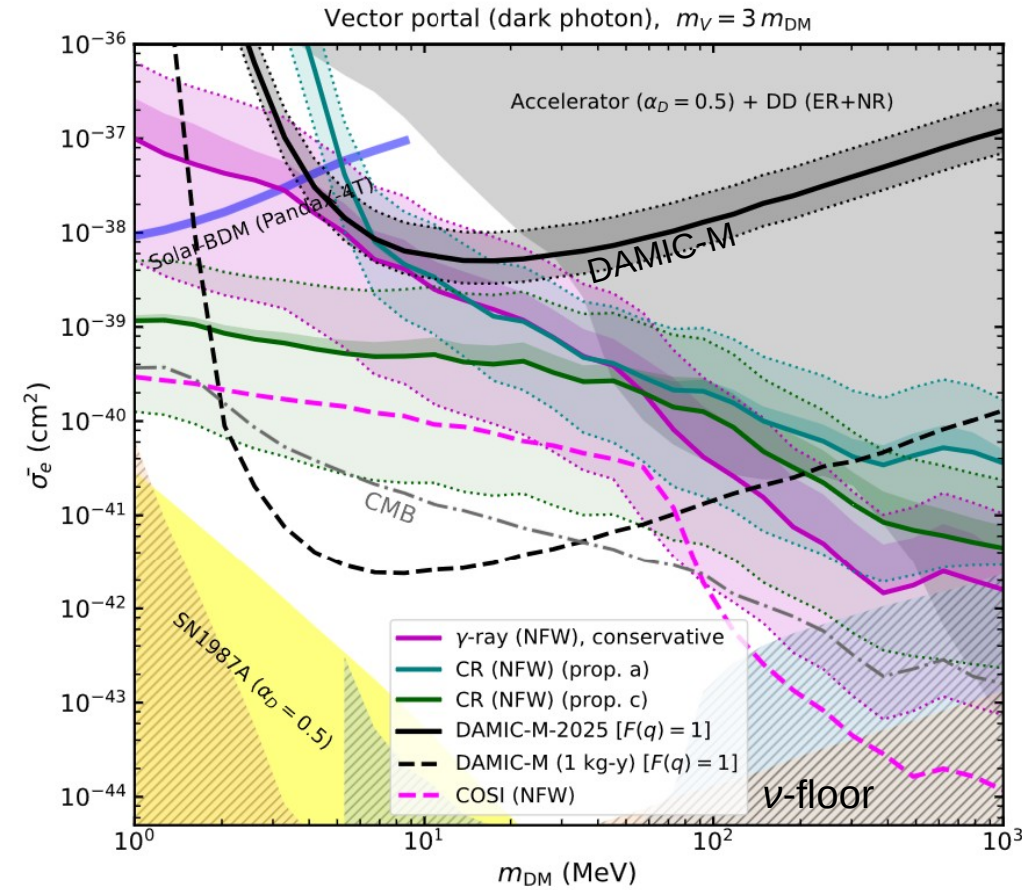
▪ Cosmic-ray observations:

Voyager 1, AMS-02

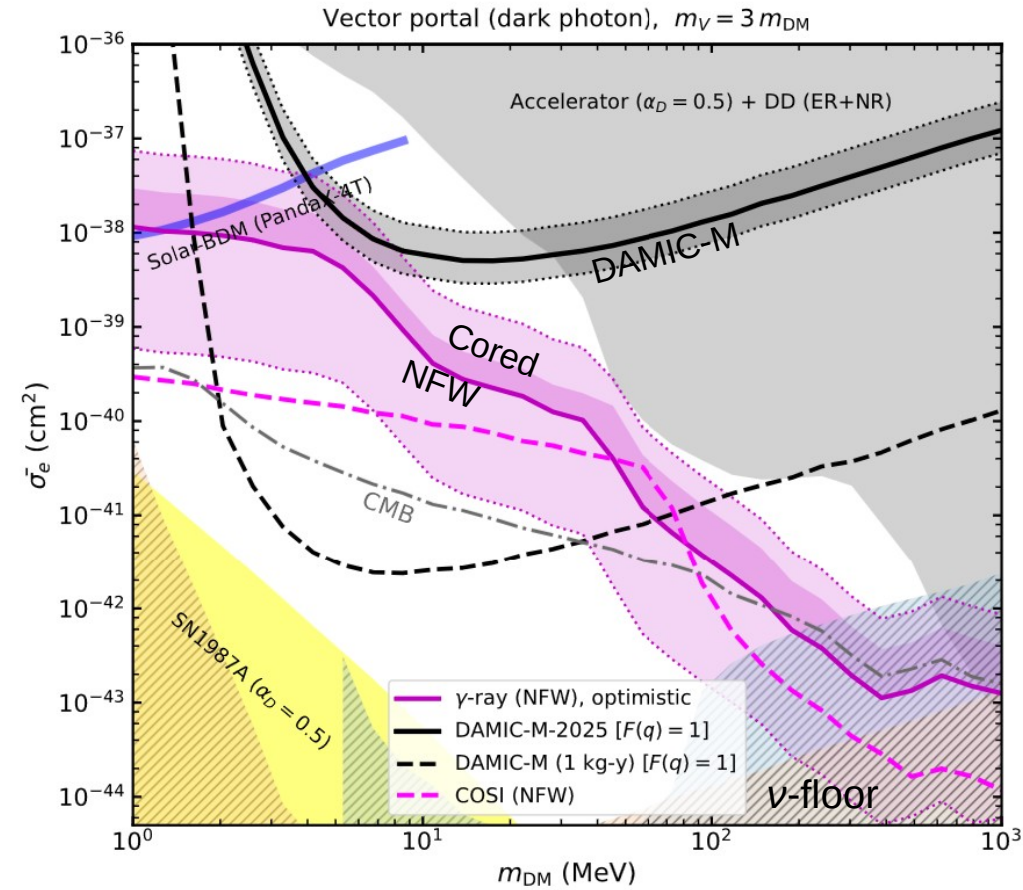
M. Cirelli, A.K. H. Shaikh; (JCAP 01 (2026) 038)

Comparisons of ID and DD constraints in the $\bar{\sigma}_e - m_{DM}$ plane for sub-GeV DM

- Heavy Dark Photon mediator: $m_V > m_{DM}$ ($m_V = 3 m_{DM}$)



ID exclusions obtained under 'conservative approach', comparing DM ID signals directly with observed data

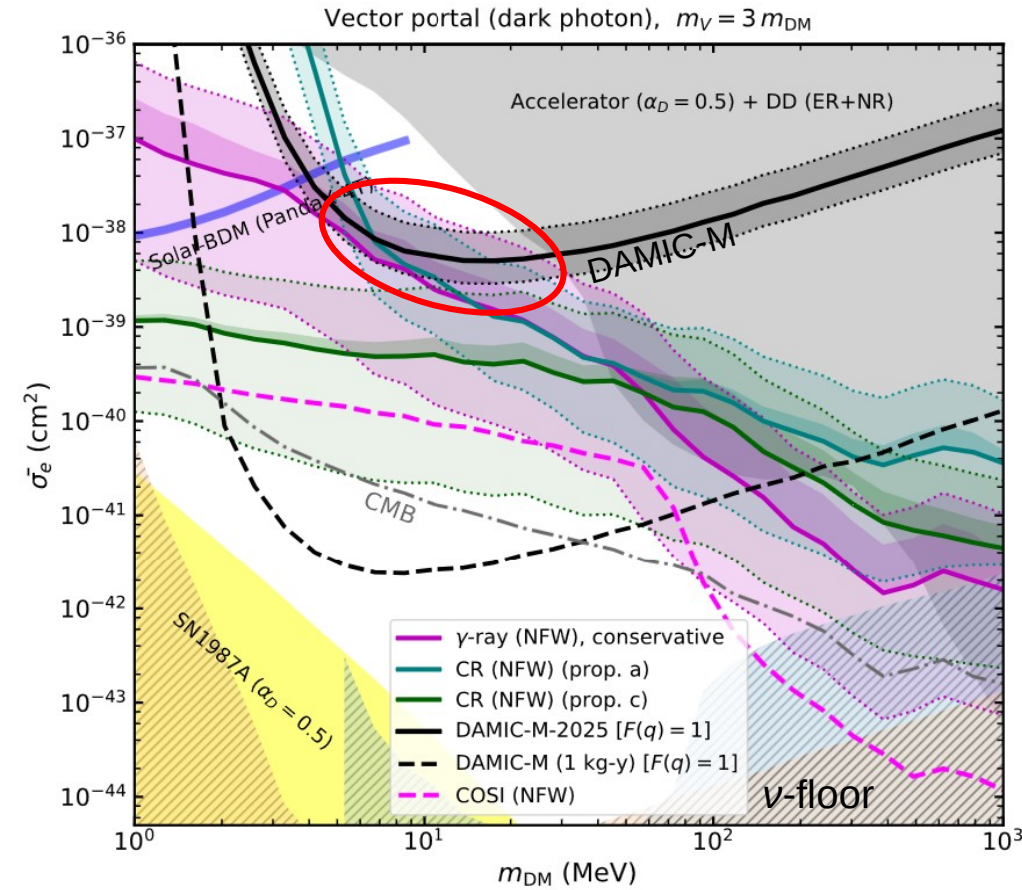


ID exclusions obtained under 'optimistic approach', fitting observed data (X-rays/ γ -rays) with standard astro-BG

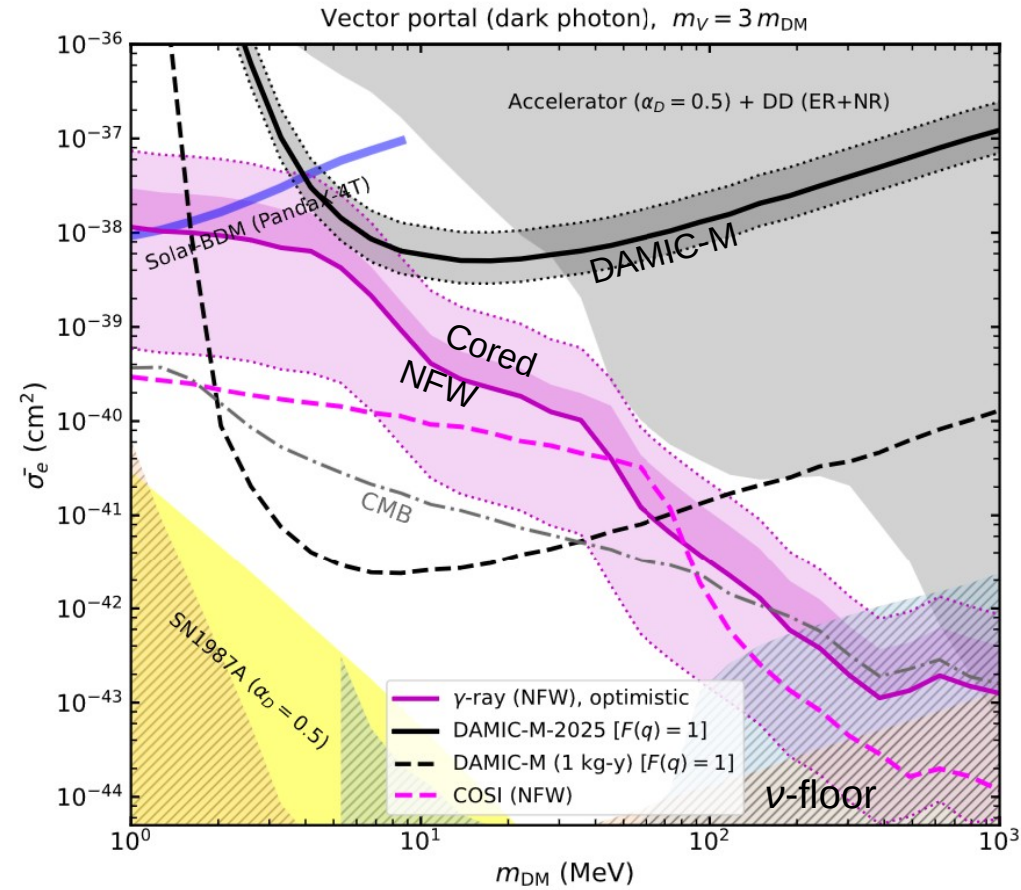
Shaded bands: Variation of $\rho_{\odot}^{DM}$ in the range $[0.2 - 0.7] \text{ GeV cm}^{-3}$
 + corresponding variation in the halo DM profile (to keep M_{DM}^{halo} same)

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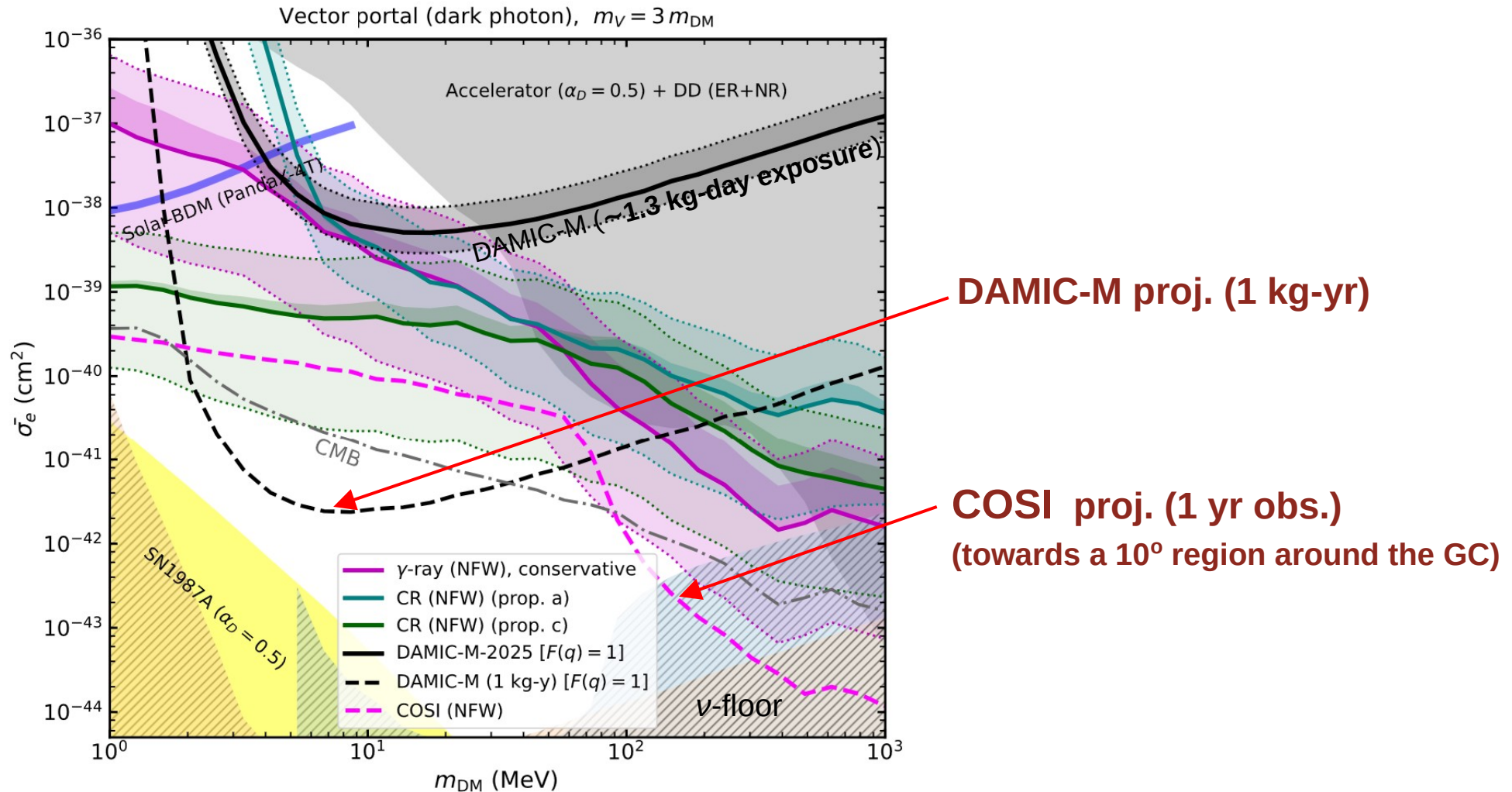


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- Future DAMIC-M will provide a better sensitivity for $2 \text{ MeV} \lesssim m_{DM} \lesssim 80 \text{ MeV}$,
outside this range COSI will provide a better probe (thanks to the secondary photons)

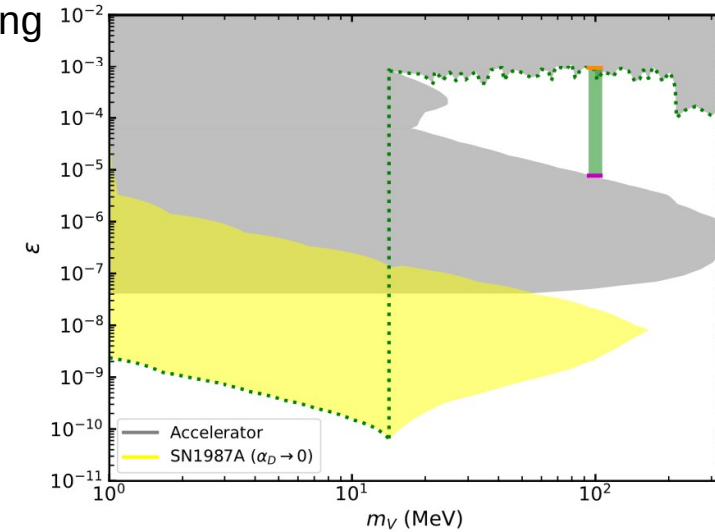
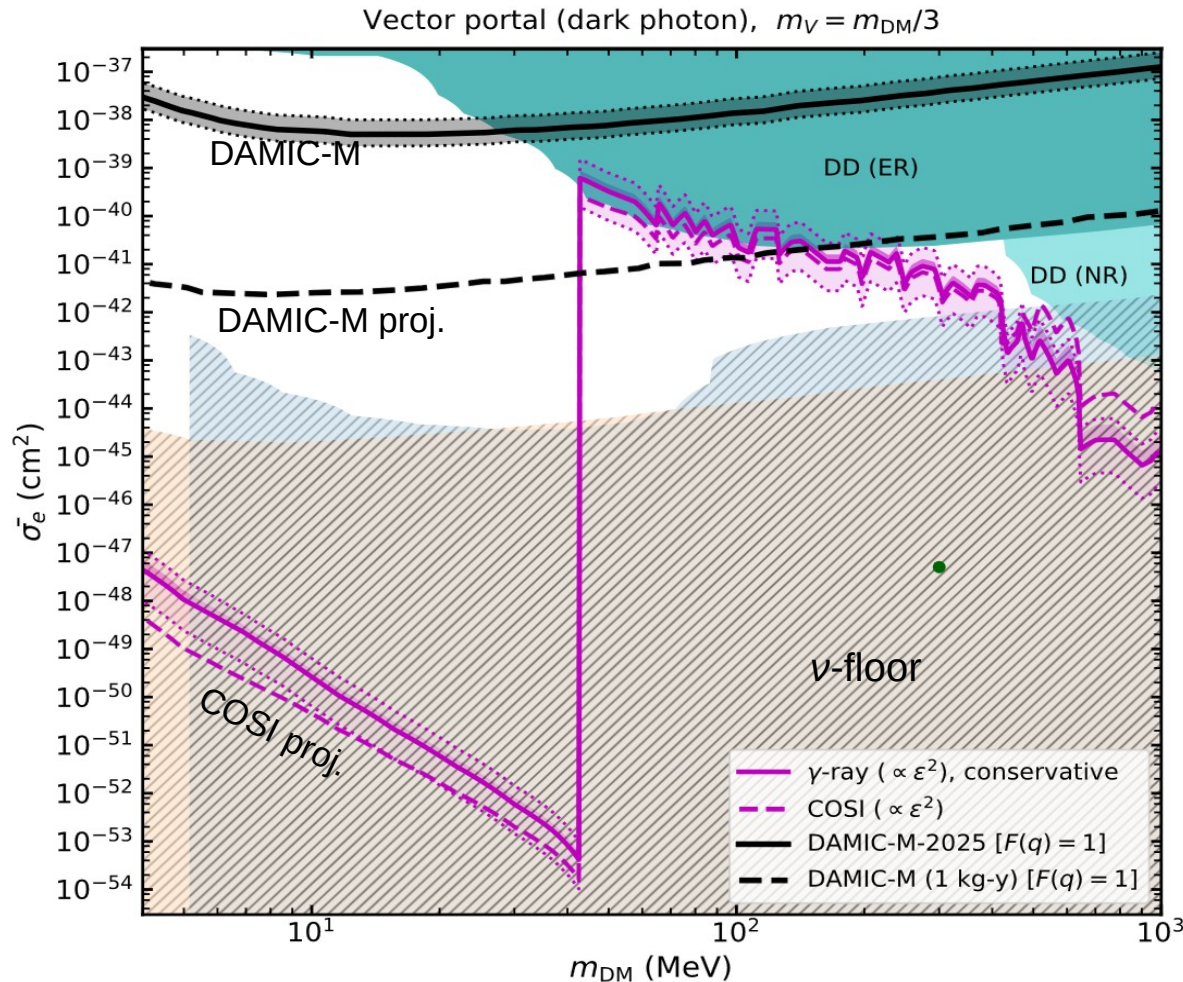
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$$\bar{\sigma}_e = \frac{16\pi\alpha\alpha_D\epsilon^2\mu_{DMe}^2}{(\alpha^2 m_e^2 + m_V^2)^2}$$

Conversion of ID bounds on $\langle\sigma v\rangle \rightarrow \bar{\sigma}_e$ requires additional info on mixing



M. Cirelli, A.K., A. Letessier-Selvon,
H. Lumengo-Kidimbu; (2608.26467)

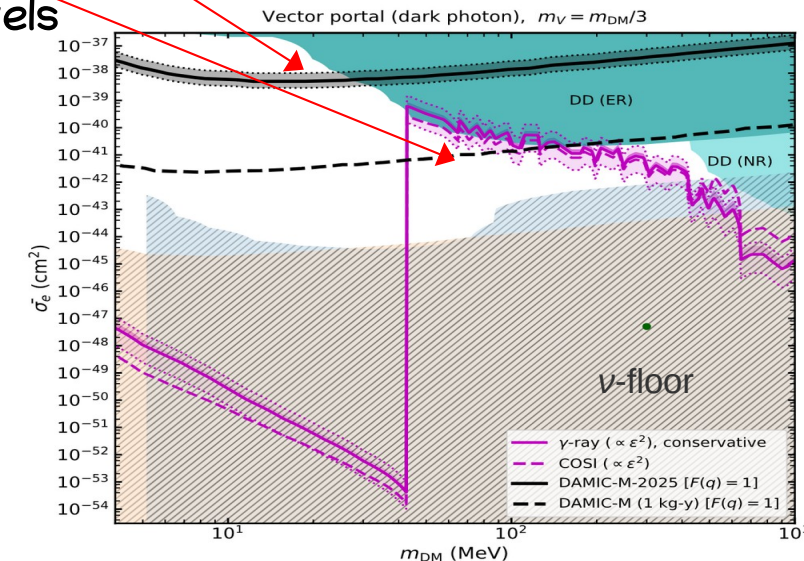
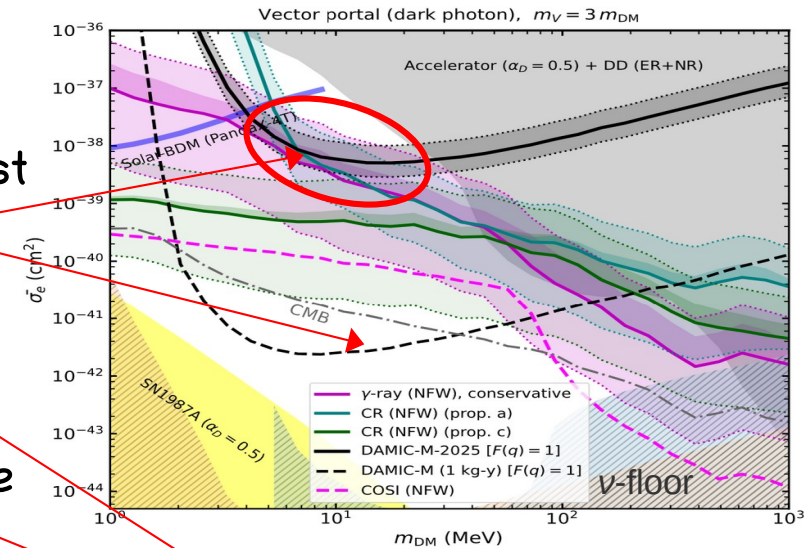
Summary

- We combine direct detection (DD) and indirect detection (ID) searches of DM to analyze their complementarity in probing the parameter space (in the $\bar{\sigma}_e - m_{DM}$ plane) of sub-GeV DM

DD: DM-e scattering in DAMIC-M

ID: X-ray / MeV gamma-ray telescopes + Cosmic-ray obs.

- The complementarity between DAMIC-M and ID works best for the vector-portal model, especially with $m_V > m_{DM}$
- For the case $m_V < m_{DM}$ (e.g., $m_V = m_{DM} / 3$), the DAMIC-M bound is much weaker than ID bounds/projections
 - future DAMIC-M can provide a comparatively better probe
- ID observations often constrain the DM- e scattering at levels below the ν -floor, which the DD bounds cannot access
- Present ID bounds (thanks to secondary photons) already reach the level of (or overcome) existing bounds like the CMB bound
- Both COSI and future DAMIC will probe new unconstrained parameter space for these sub-GeV DM models



Backup slides

Upcoming MeV telescope Compton Spectrometer and Imager (COSI)

- Key features:

- High-resolution spectroscopy (energy resolution $\lesssim 4\%$)
- Direct imaging over a **wide field-of-view ($\gtrsim 25\%$ of the sky)**
- An effective suppression for the background events



MeV satellite mission COSI

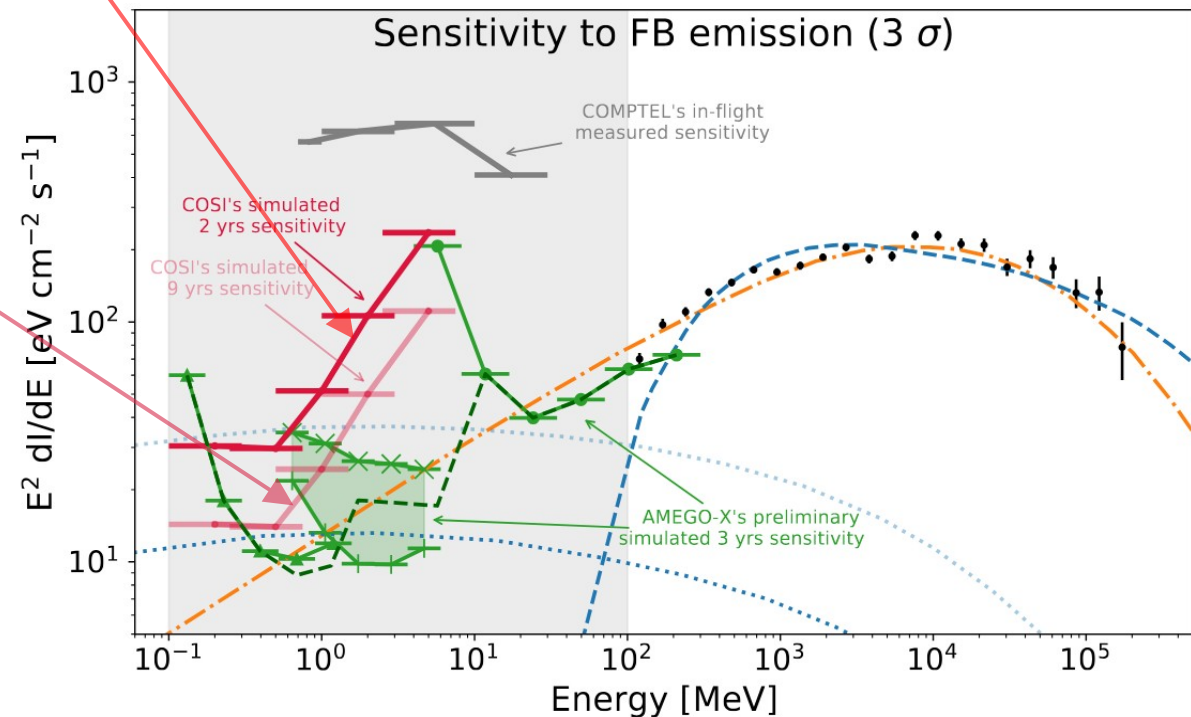
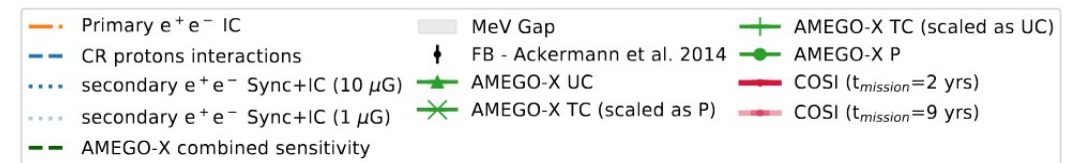
- Energy range: **$0.2 \text{ MeV} \lesssim E_\gamma \lesssim 5 \text{ MeV}$**

- 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 estimate COSI prospects for probing new parameter space of the sub-GeV DM models

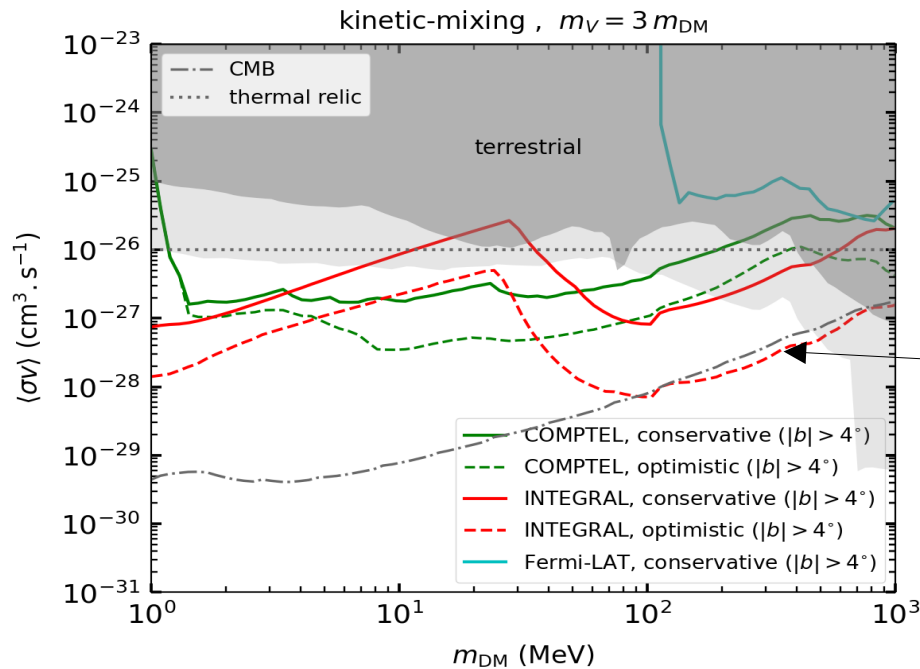
- Other upcoming MeV telescopes (like AMEGO) are expected to improve the sensitivity



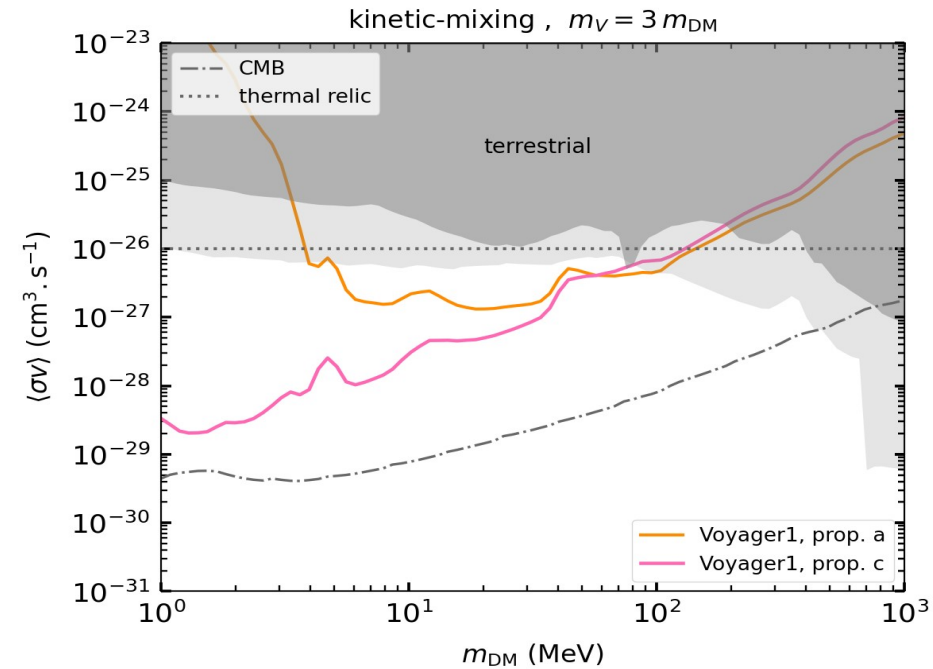
Negro, et al., (2111.10362)

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

- Heavy Dark Photon mediator: $m_V > m_{DM}$ ($m_V = 3 m_{DM}$)



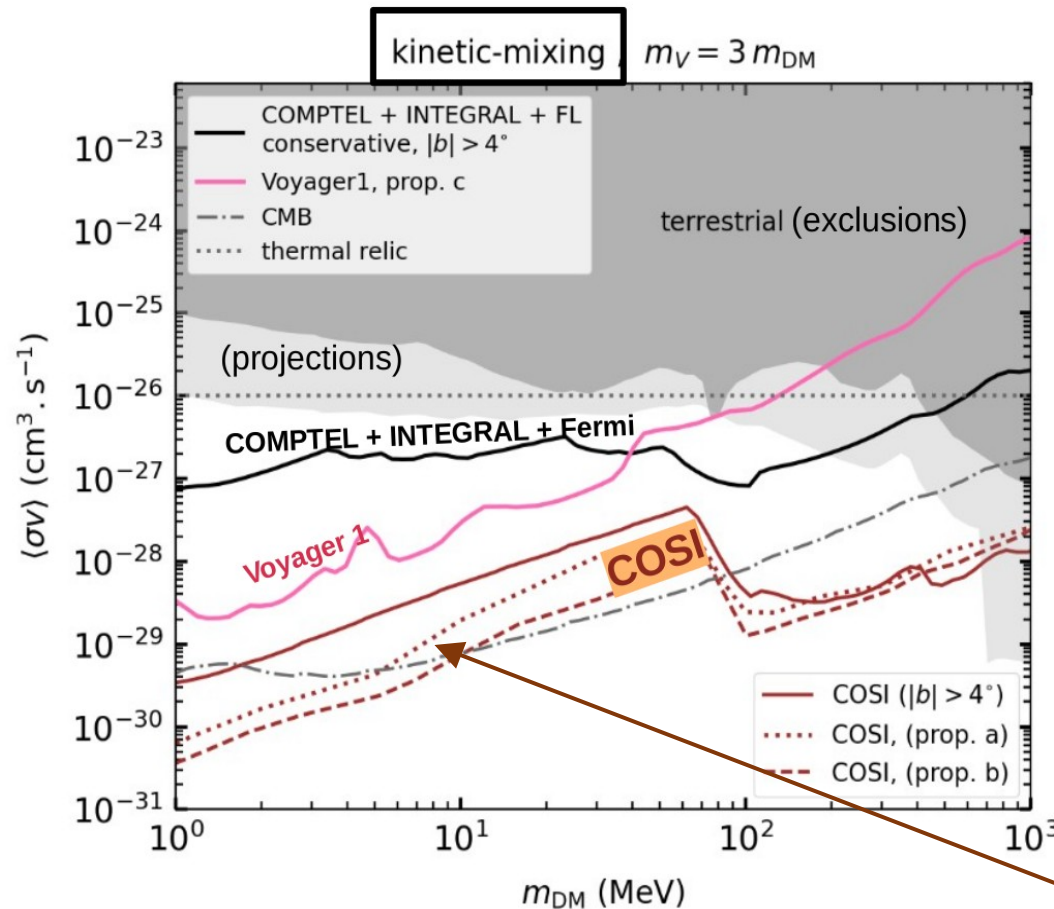
Existing X-ray & MeV gamma-rays observations



Existing Cosmic-ray observations

COSI projections for sub-GeV DM models

- Heavy Dark Photon mediator: $m_V > m_{DM}$ ($m_V = 3 m_{DM}$)



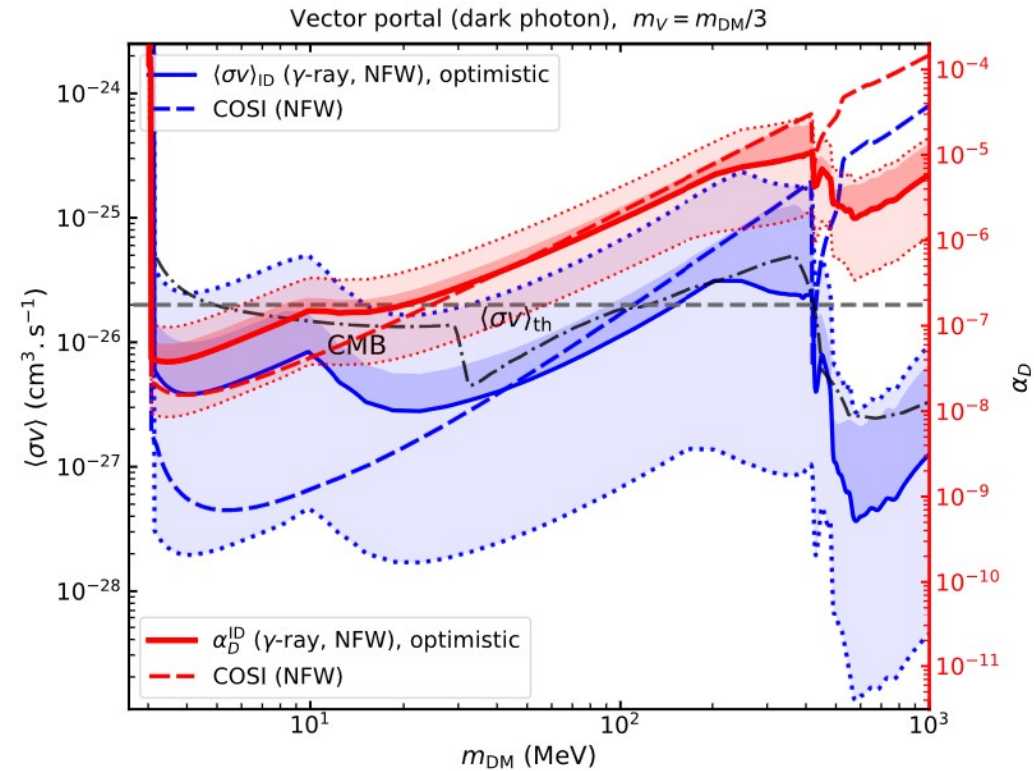
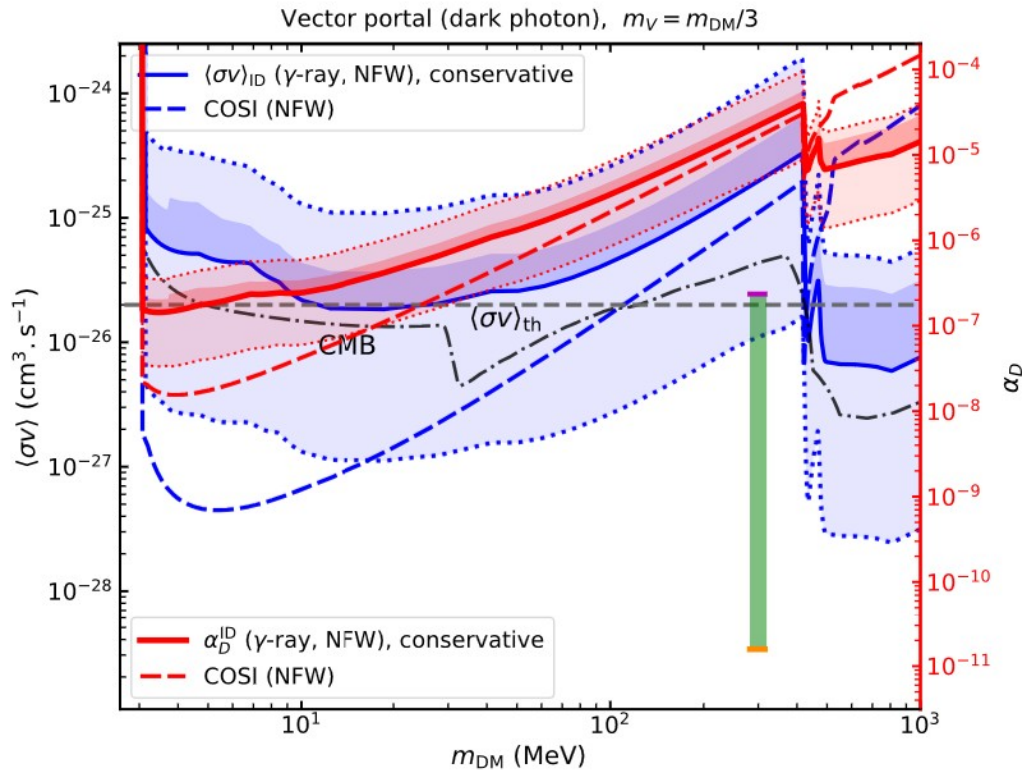
M. Cirelli, A.K. H. Shaikh;
(JCAP 01 (2026) 038)

Effects of Galactic propagation of $e^\pm$

Considering propagation models used to estimate the secondary photon BGs for COSI sensitivity towards the GC region

Indirect detection bounds on sub-GeV DM models using MeV telescopes

- Light Dark Photon mediator: $m_V < m_{DM}$ ($m_V = m_{DM} / 3$)

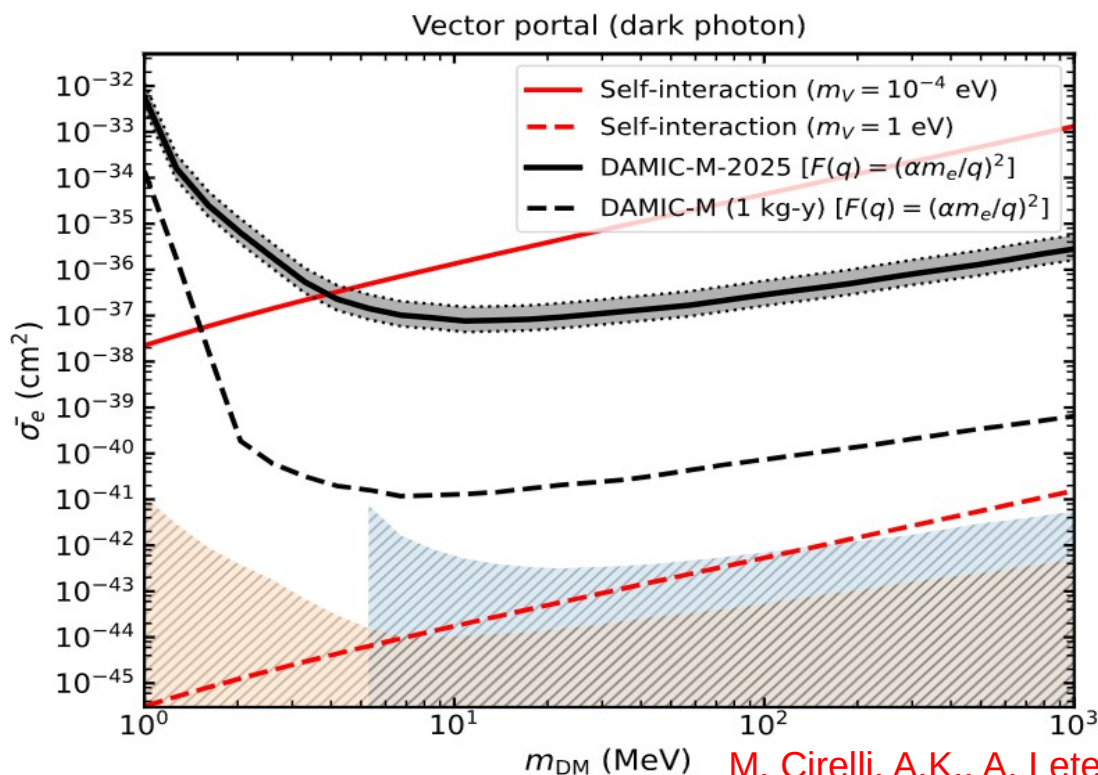


Fitting existing photon data with standard astro-BG

Bounds from existing X-ray & MeV gamma-rays observations and COSI projection

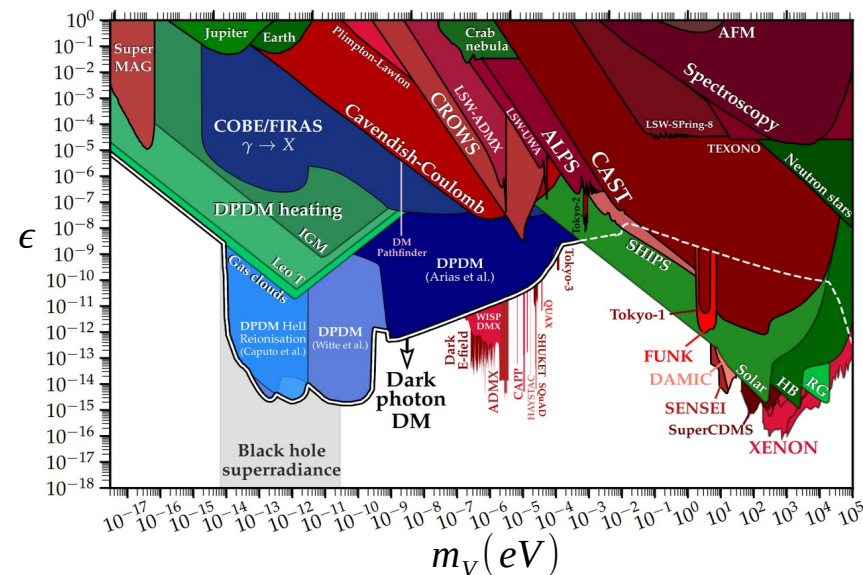
Bounds on sub-GeV DM models for very light mediator

- **Very light DP mediator: $m_V \ll 1$ KeV**



$$\bar{\sigma}_e = \frac{16\pi \alpha \alpha_D \epsilon^2 \mu_{\text{DMe}}^2}{(\alpha^2 m_e^2 + m_V^2)^2}$$

Caputo *et al.*, (2105.04565)



M. Cirelli, A.K., A. Letessier-Selvon, H. Lumengo-Kidimbu; (2608.26467)

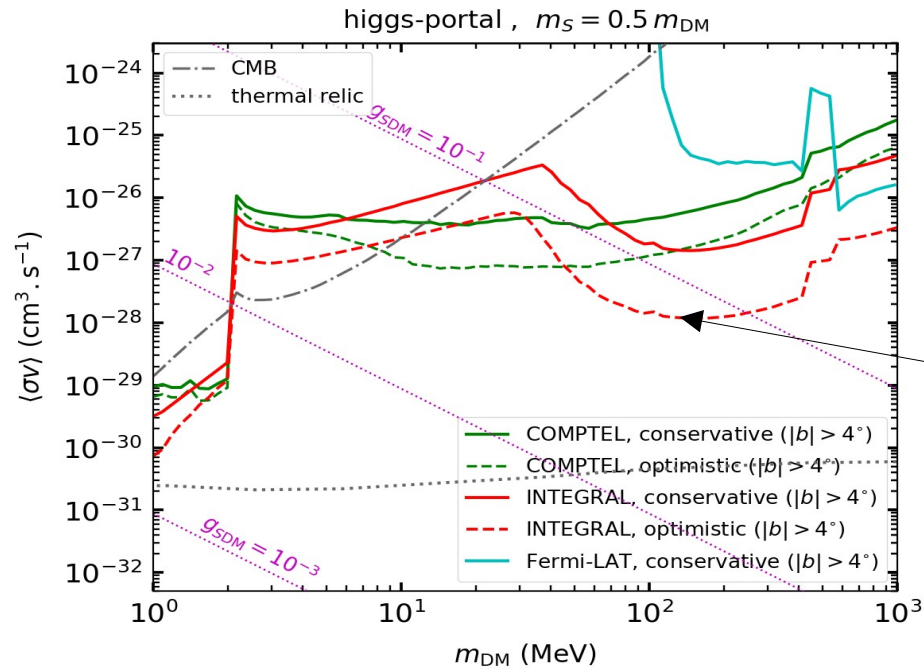
- Indirect detection bounds in this case should be very weak
Dominating annihilation: $\chi\bar{\chi} \longrightarrow VV$
- In this case, DAMIC-M provides one of the leading constraints in probing the DM interactions
- A strong bound (on α_D) arises from DM self-interaction (SIDM) : [Knapen et al., \(1709.07882\)](#)

$$\frac{\sigma_{\text{SIDM}}}{m_{\text{DM}}} \simeq \frac{\alpha_D^2 \pi}{m_{\text{DM}}^3 v_{\text{DM}}^4} (\log R^2 - 1) \lesssim 1 \frac{\text{cm}^2}{\text{g}}$$

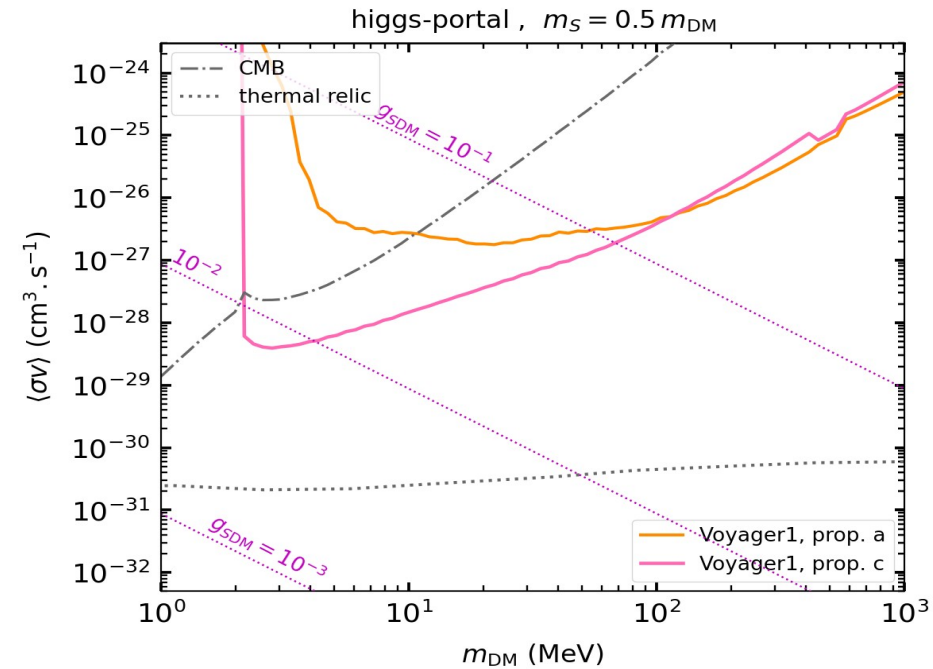
$$R = m_{\text{DM}} v_{\text{DM}} / m_V$$

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

- Scalar portal model: $m_S < m_{DM}$ ($m_S = m_{DM} / 2$)



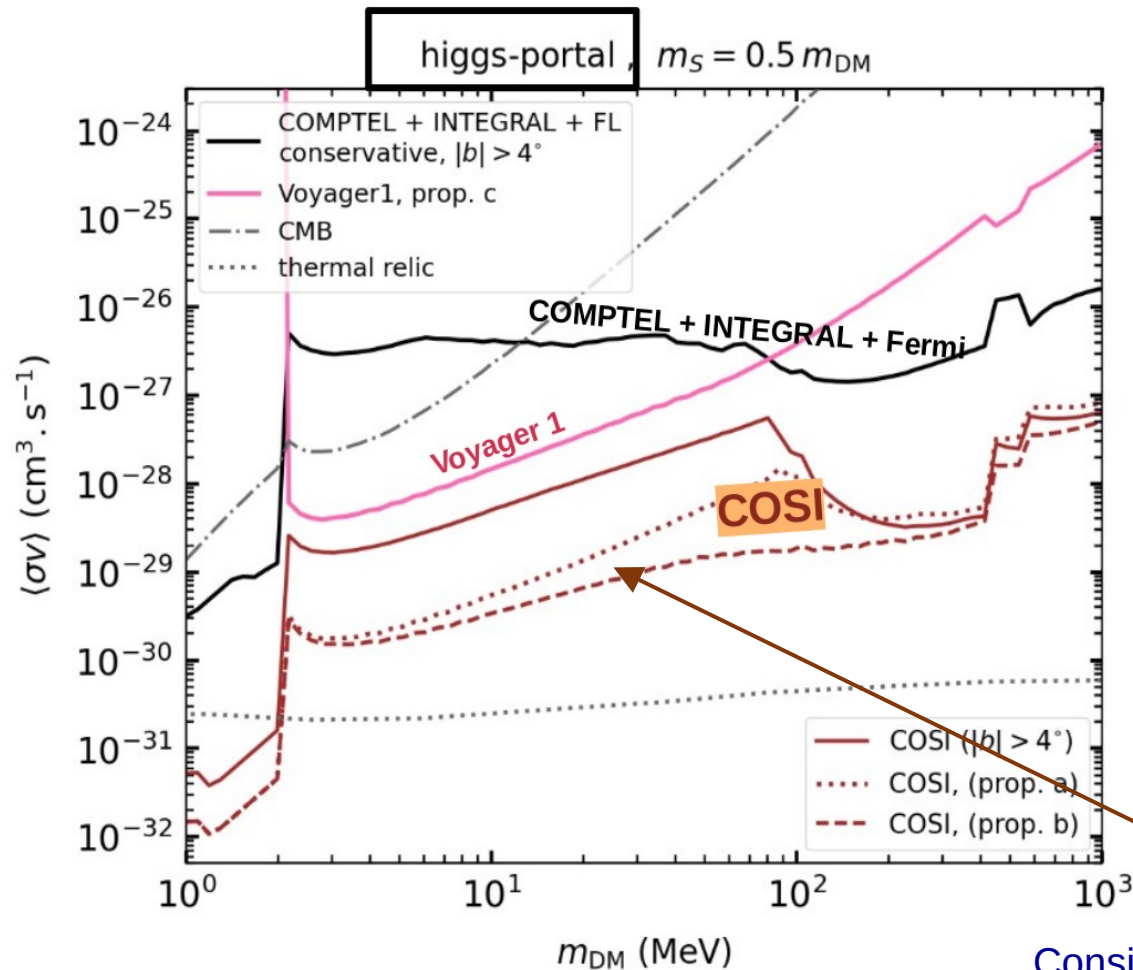
Existing X-ray & MeV gamma-rays observations



Existing Cosmic-ray observations

COSI projections for sub-GeV DM models

- Scalar portal model: $m_S < m_{DM}$ ($m_S = m_{DM} / 2$)



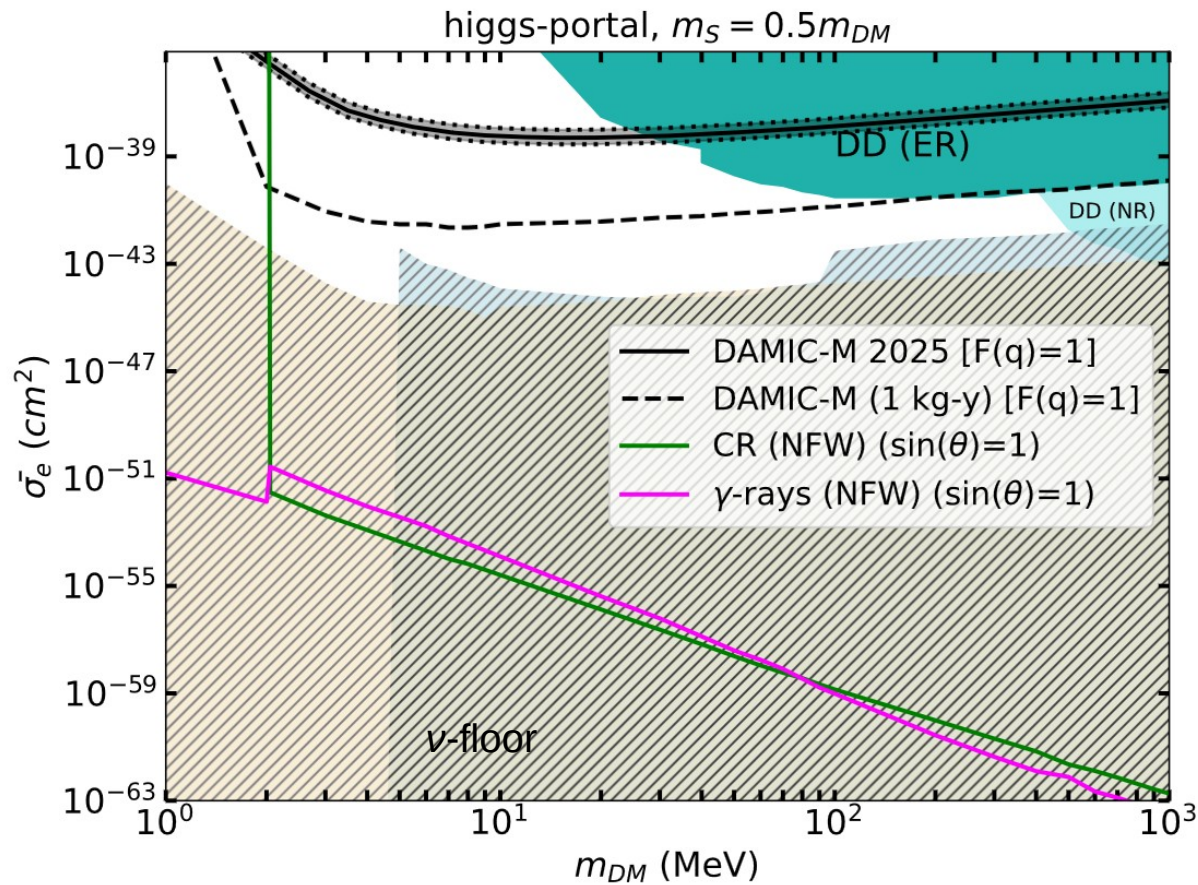
M. Cirelli, A.K. H. Shaikh;
(JCAP 01 (2026) 038)

Effects of Galactic propagation of $e^\pm$

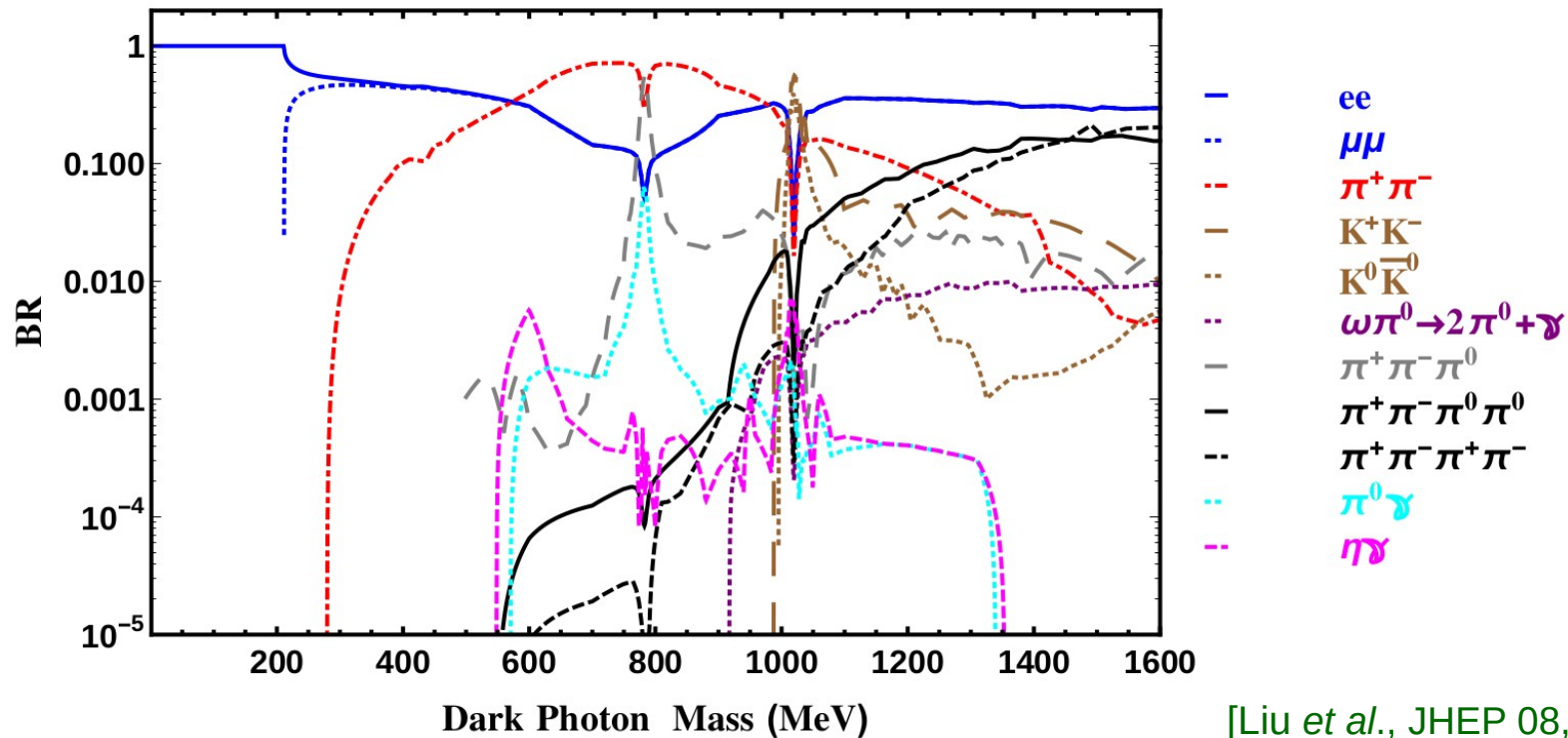
Considering propagation models used to estimate the secondary photon BGs for COSI sensitivity towards the GC region

Comparisons of ID and DD constraints in the $\bar{\sigma}_e - m_{DM}$ plane for sub-GeV DM

- Scalar portal model: $m_S < m_{DM}$ ($m_S = m_{DM} / 2$)



Branching ratios for the dark photon decay



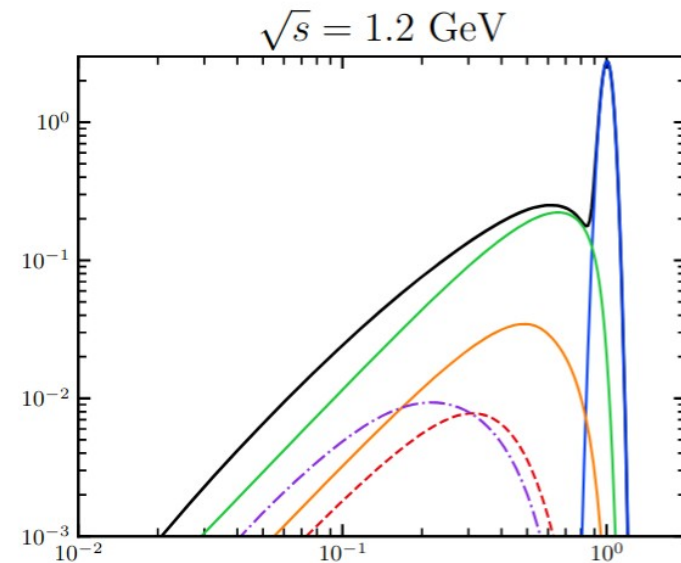
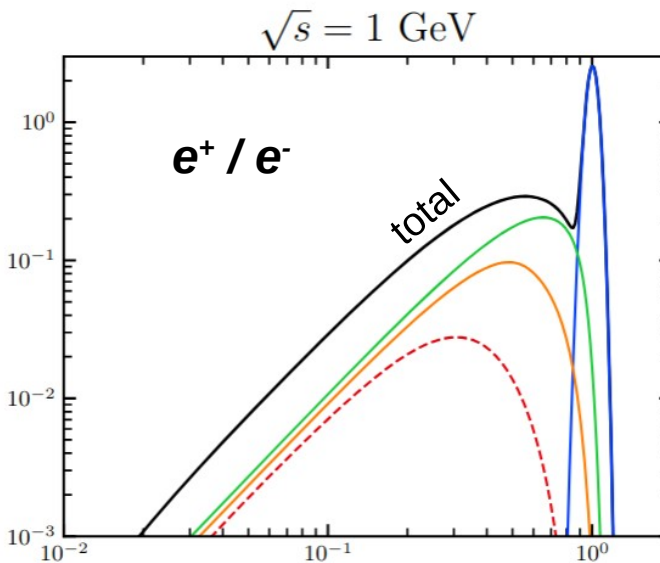
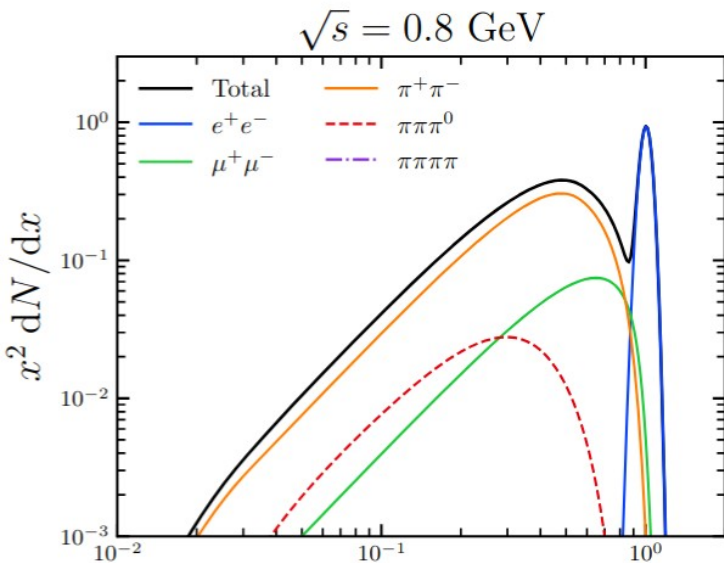
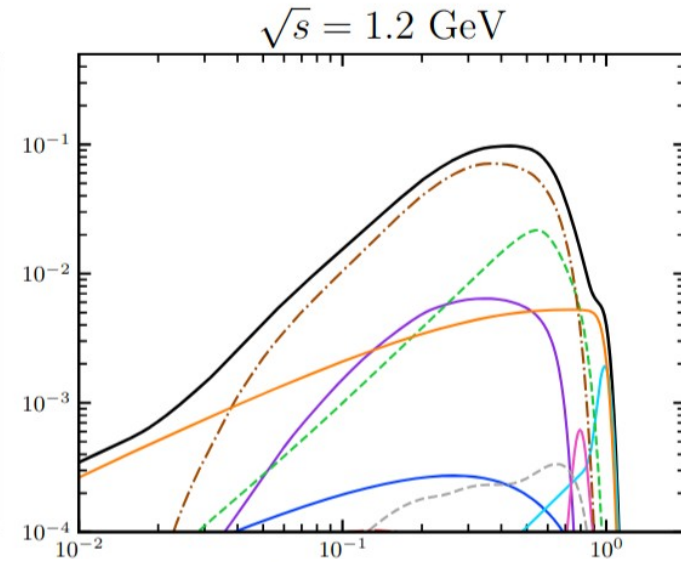
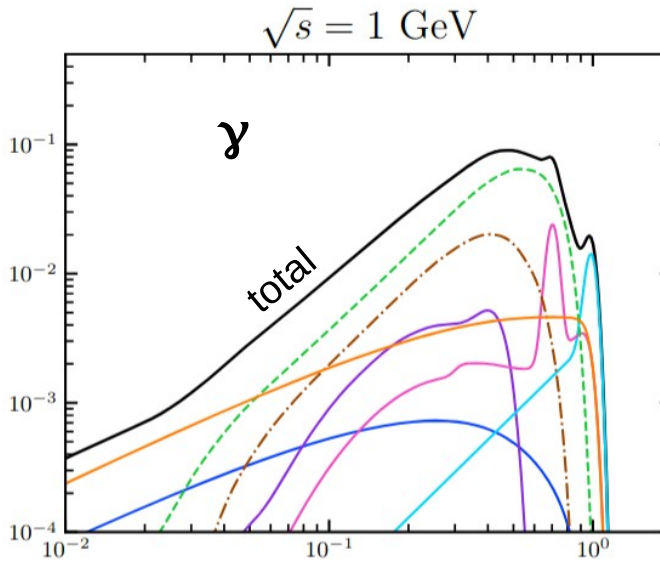
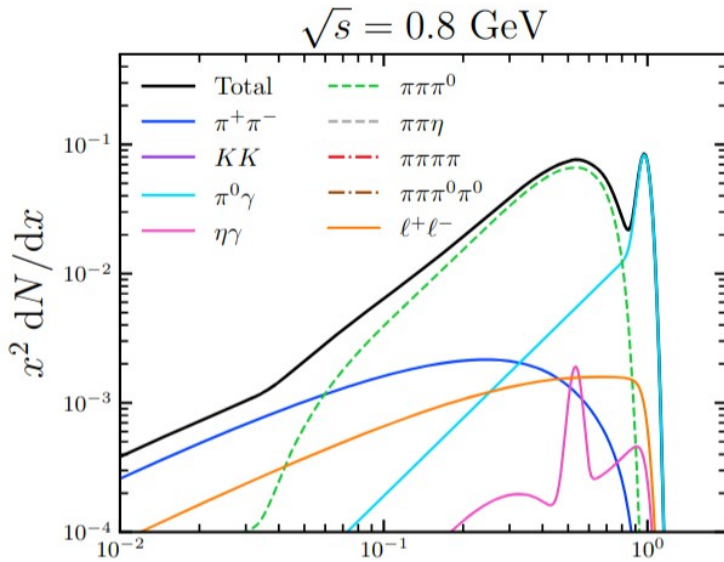
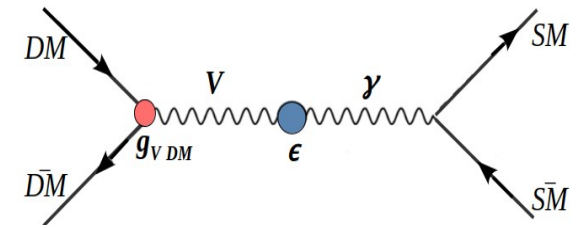
Branching ratios for a vector with kinetic-mixing couplings to the SM

- These models include DM annihilation 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 DM annihilation
 - particularly well motivated for sub-GeV DM searches

Sub-GeV DM models

kinetic-mixing model

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



$$x = 2E_i / \sqrt{s}$$

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