Probing charged lepton flavor violation induced by dark matter

梁锦汉 (Jinhan Liang)
华南师范大学 (South China Normal University)

In collaboration with Yi Liao, Xiao-Dong Ma, Sahabub Jahedi, and Yoshiki Uchida

PRD 113 (2026) 3, L031701
arXiv: 2601.14048, arXiv: 260x.xxxxx

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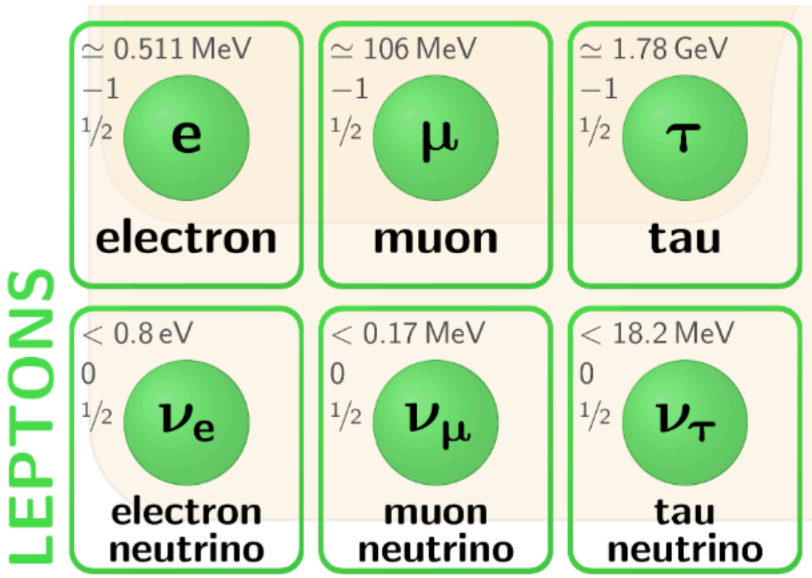
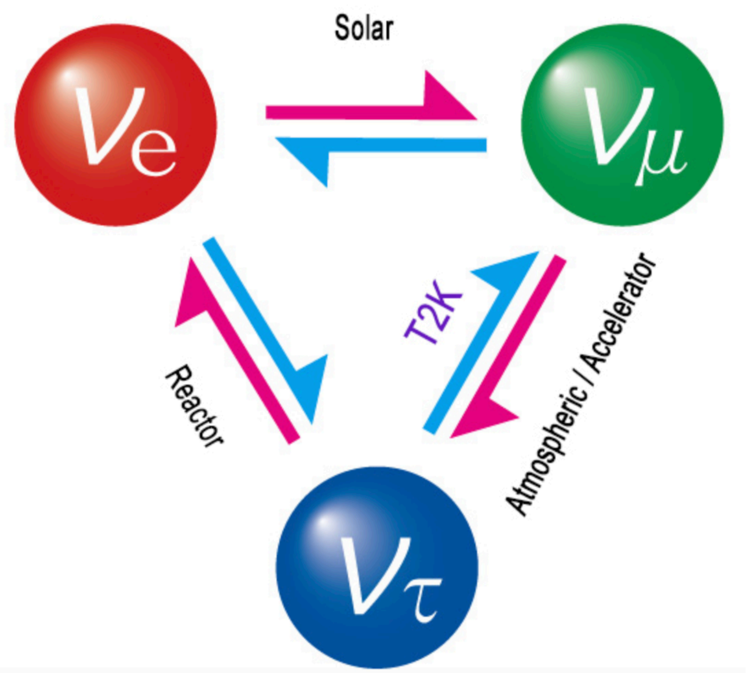
2026.05.17 Nanjing

Outline

- Introduction to charged lepton flavor violation (CLFV) and dark matter (DM)
- Probing CLFV DM via the annihilation process
- Probing CLFV DM via the scattering process
- Summary

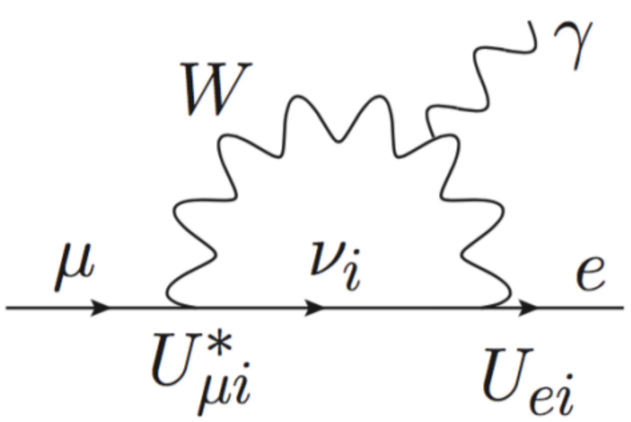
Lepton Flavor violation in the SM





Neutrino oscillations indicate the LFV in the neutrino sector.

Calibbi Lorenzo and Signorelli Giovanni, Riv. Nuovo Cim. 41 (2018) 2, 71-174

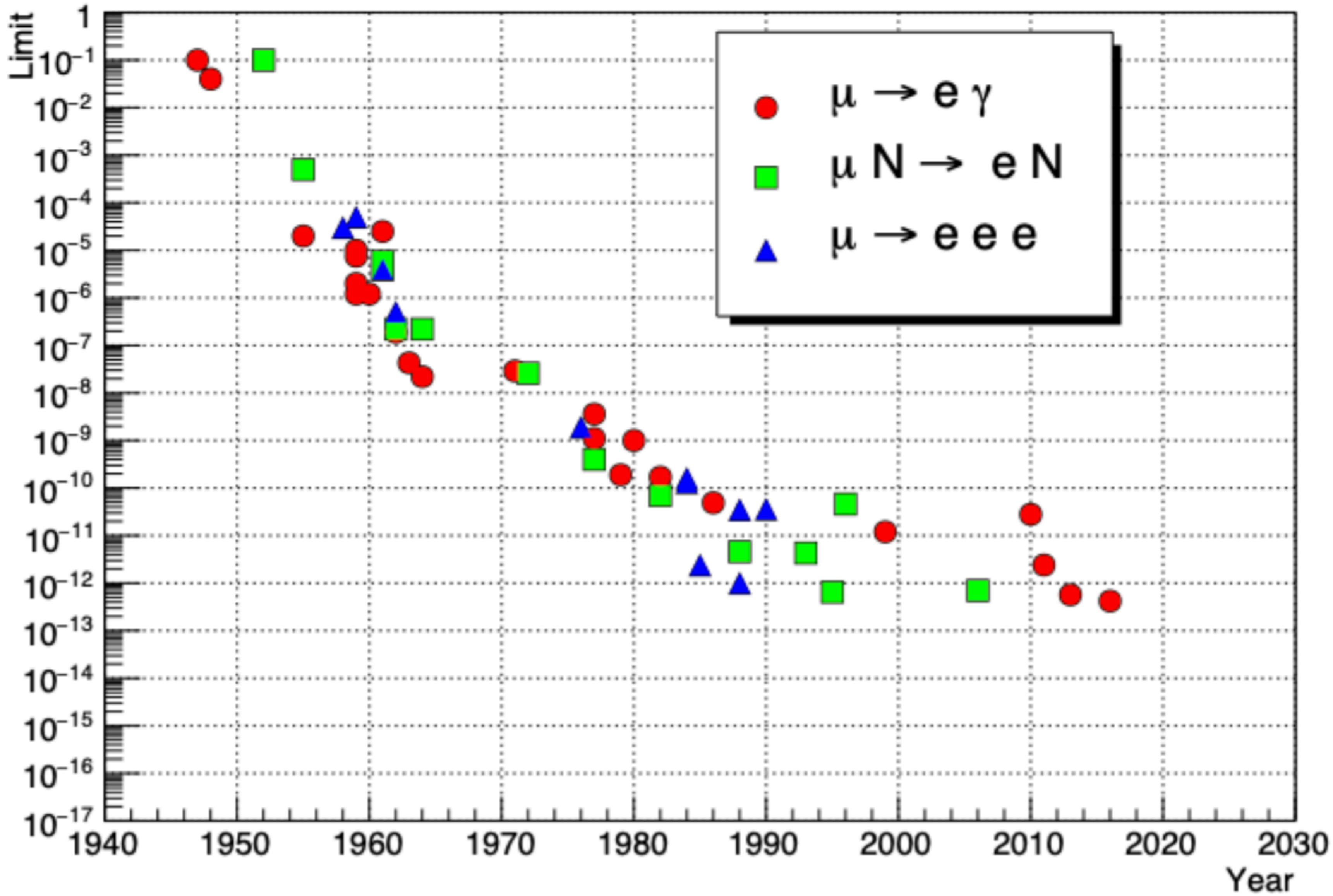


$$\mathrm{BR}(\mu \to e\gamma) \propto \left| \sum U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{M^2_W} \right|^2 \sim 10^{-54}$$

The CLFV is highly suppressed by the GIM mechanism in the SM, which offers a golden channel to search for new physics.

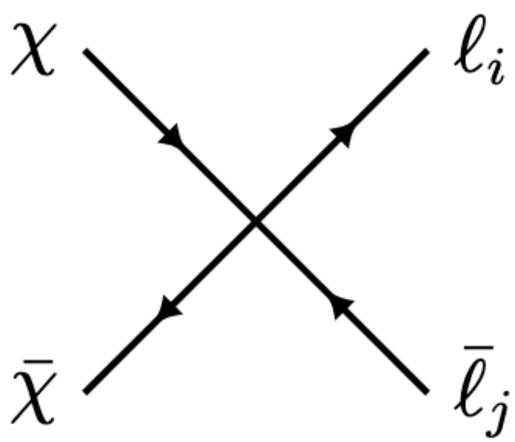
Current experimential sensitivities to CLFV

Calibbi Lorenzo and Signorelli Giovanni, Riv. Nuovo Cim. 41 (2018) 2, 71-174



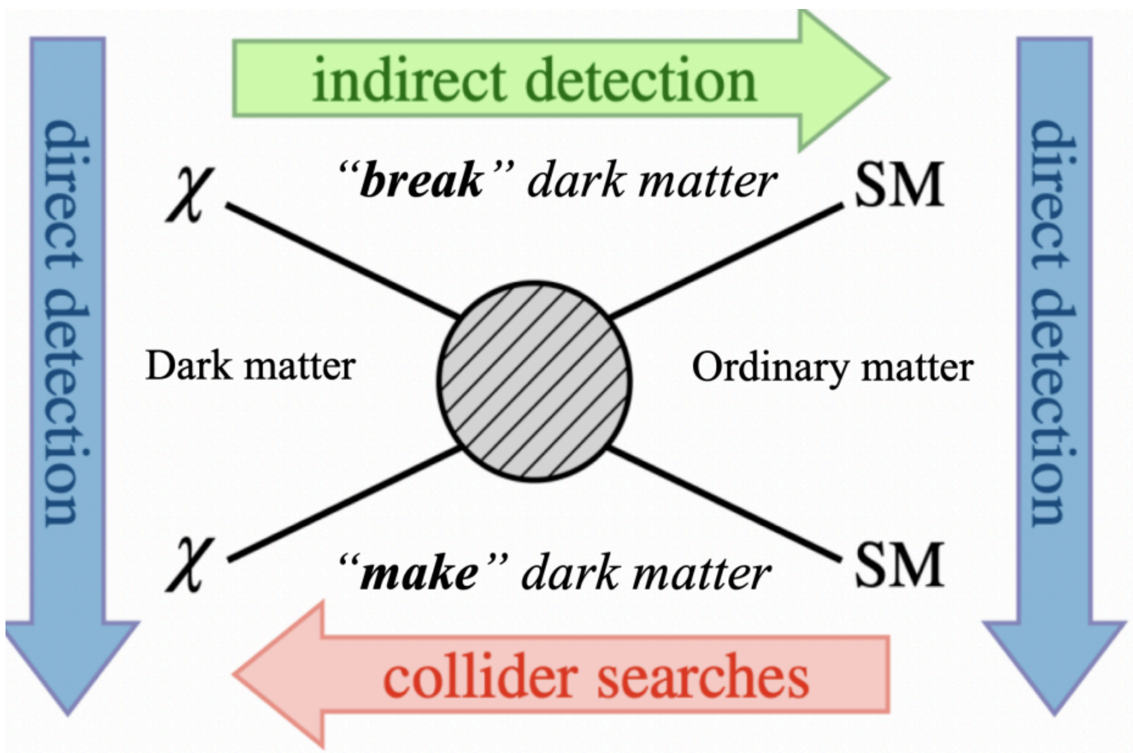
Both the initial- and final-state particles are SM particles

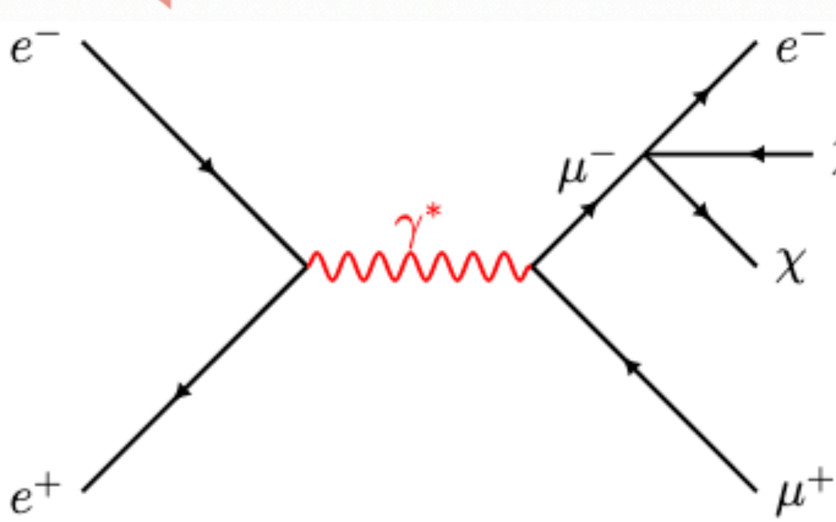
Probing CLFV induced by dark matter

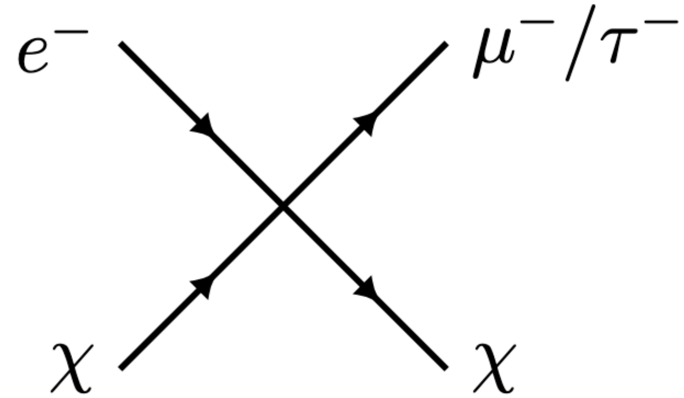


JL, Liao, Ma, arXiv: 2508.05121

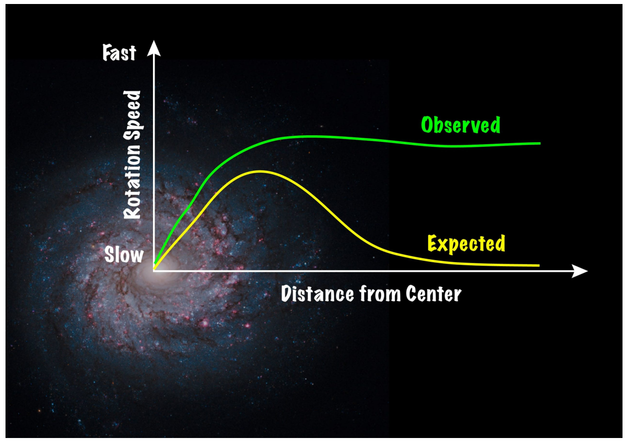
Jahedi, JL, Liao, Ma, Uchida, arXiv: 2601.14048

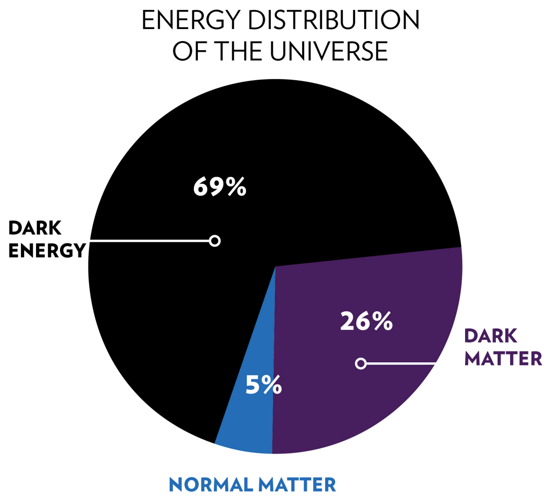




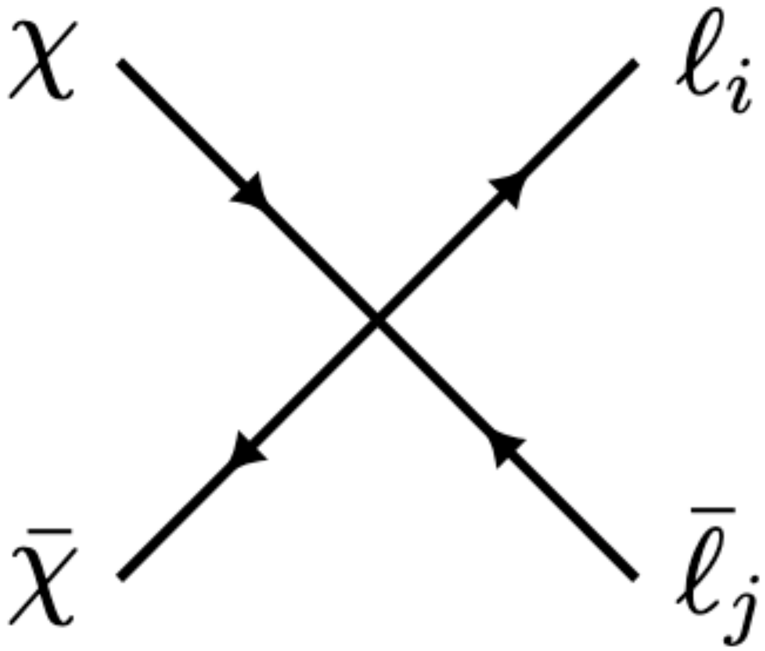


JL, Liao, Ma, arXiv: 260x.xxxxx



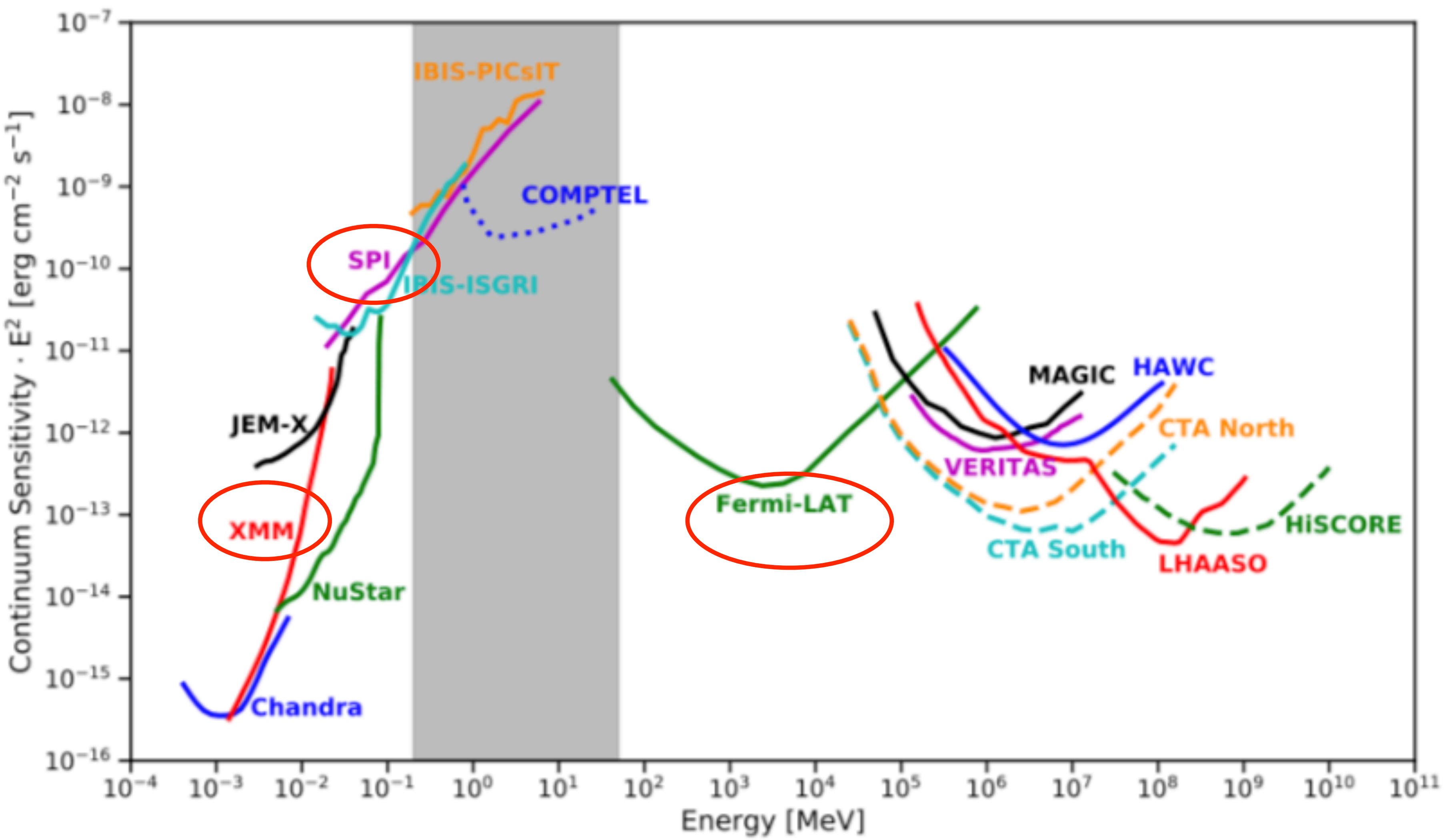


Annihilation process for CLFV DM



Astrophysical photons and electrons/positrons

Lucchetta et al., JCAP 08 (2022) 013



AMS: GeV - TeV

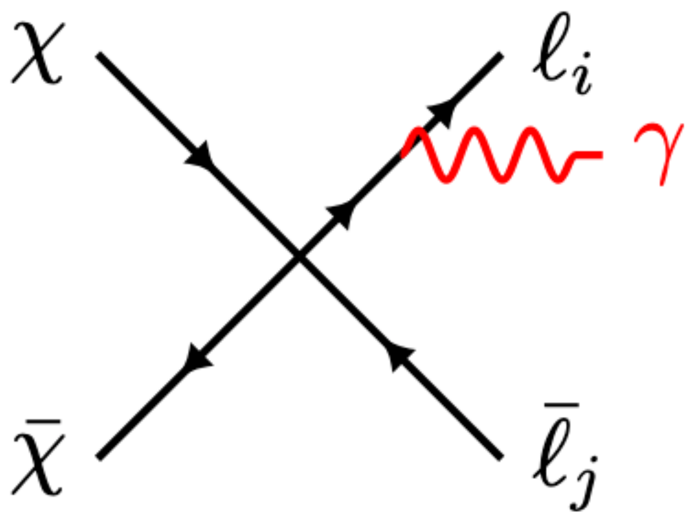
XMM-Newton: keV - 10 keV

INTEGRAL/SPI: 10 keV - 10 MeV

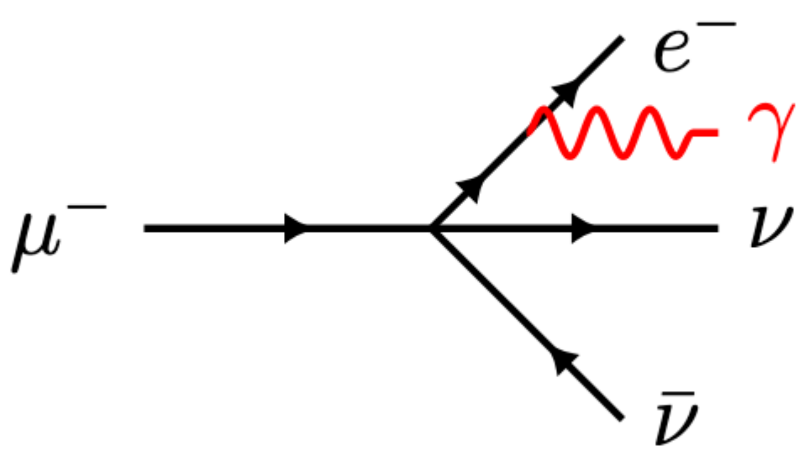
Fermi: 100 MeV - TeV

Astrophysical photons induced by DM annihilation

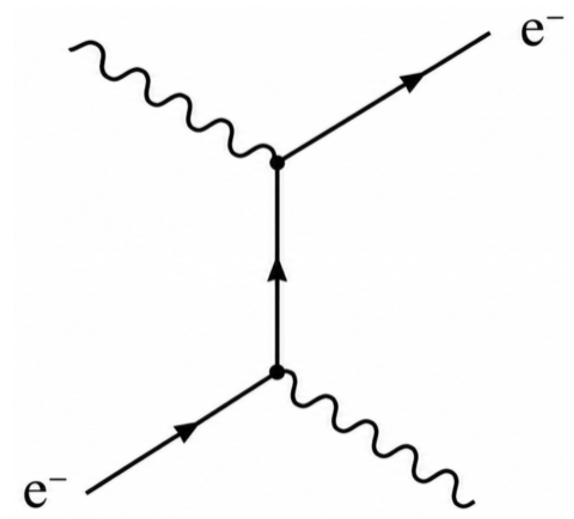
- Final state radiation



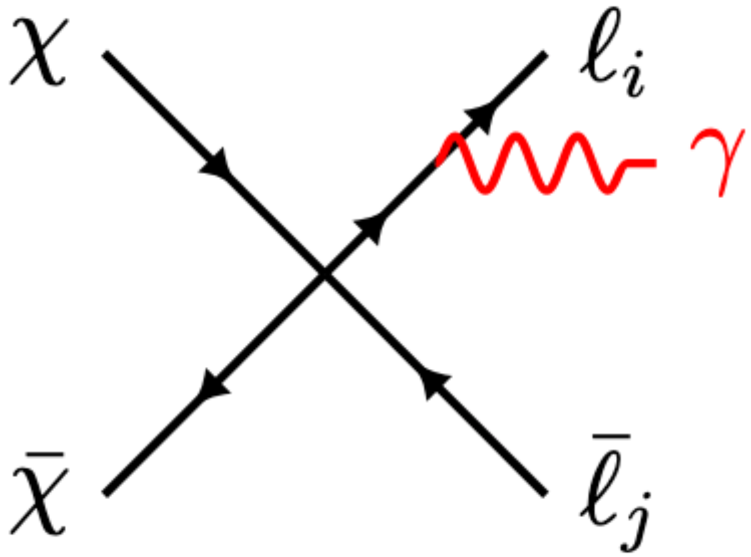
- Radiative decay



- Inverse Compton scattering



Final state radiation



O. Nicrosini and L. Trentadue, Z.Phys.C 39 (1988) 479

$$\frac{dN^{\gamma}_{ij}(x_\gamma, s)}{dx_\gamma} = H_{i,j}(x_\gamma, \hat{s}), \ \hat{s} \equiv (1 - x_\gamma)s$$

$$H_{i,j}(x_\gamma, \hat{s}) = \int_{1-x_\gamma}^{1} \frac{dz}{z} D_i(z, \hat{s}) D_j\left(\frac{1 - x_\gamma}{z}, \hat{s}\right)$$

$i = j \ (i \neq j)$ for LFC (LFV)

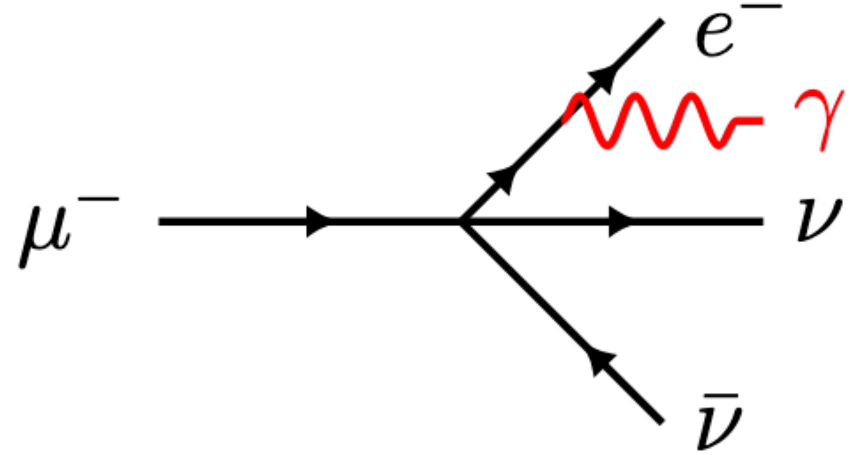
$$H_{i,j}(x_\gamma, \hat{s}) = d(x_\gamma, \hat{s}, m_i) + d(x_\gamma, \hat{s}, m_j)$$

$$d(x_\gamma, \hat{s}, m_\ell) = \frac{\alpha}{2\pi}(\log[\hat{s}/m_\ell^2] - 1)\frac{1 + (1 - x_\gamma)^2}{x_\gamma}$$

$D_i(x, \hat{s})$ denotes the structure function of the lepton i at the scale $\hat{s}$ with a longitudinal momentum fraction of x_γ.

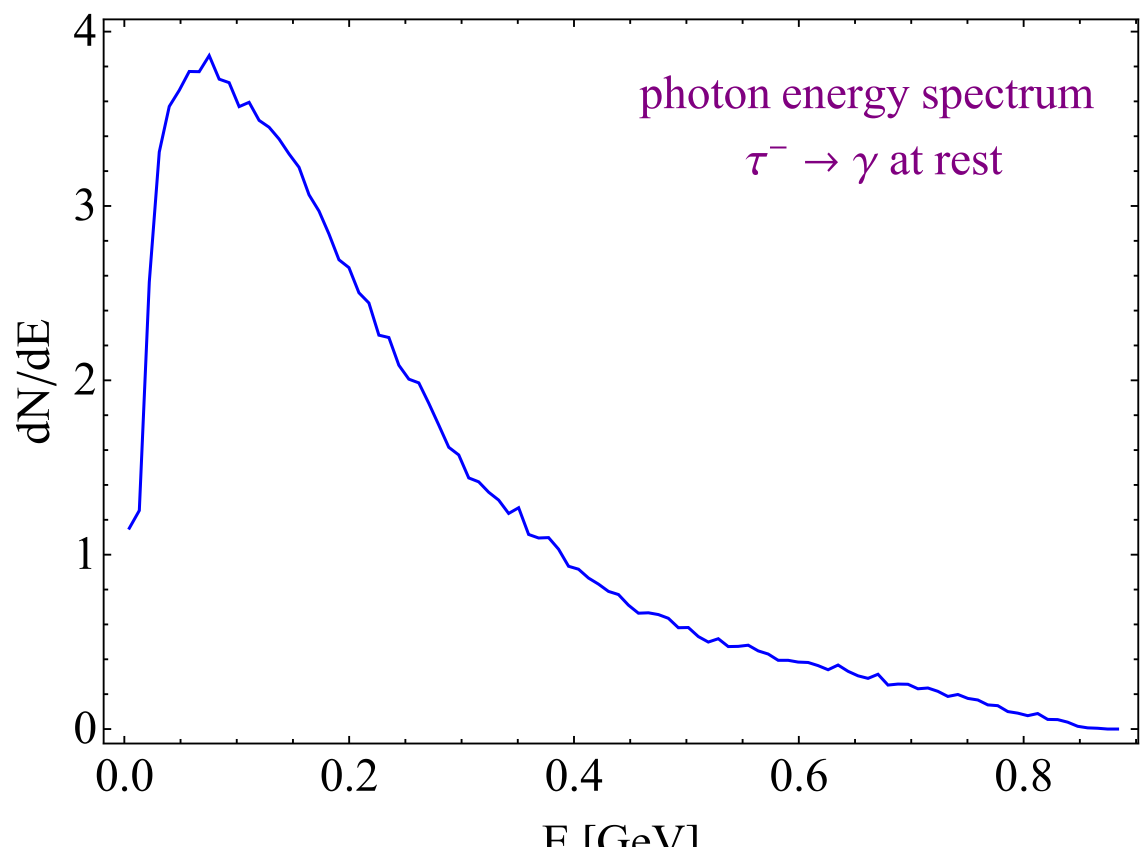
Jahedi, **JL**, Liao, Ma, Uchida, arXiv: 2601.14048

Radiative decay of muons and taus



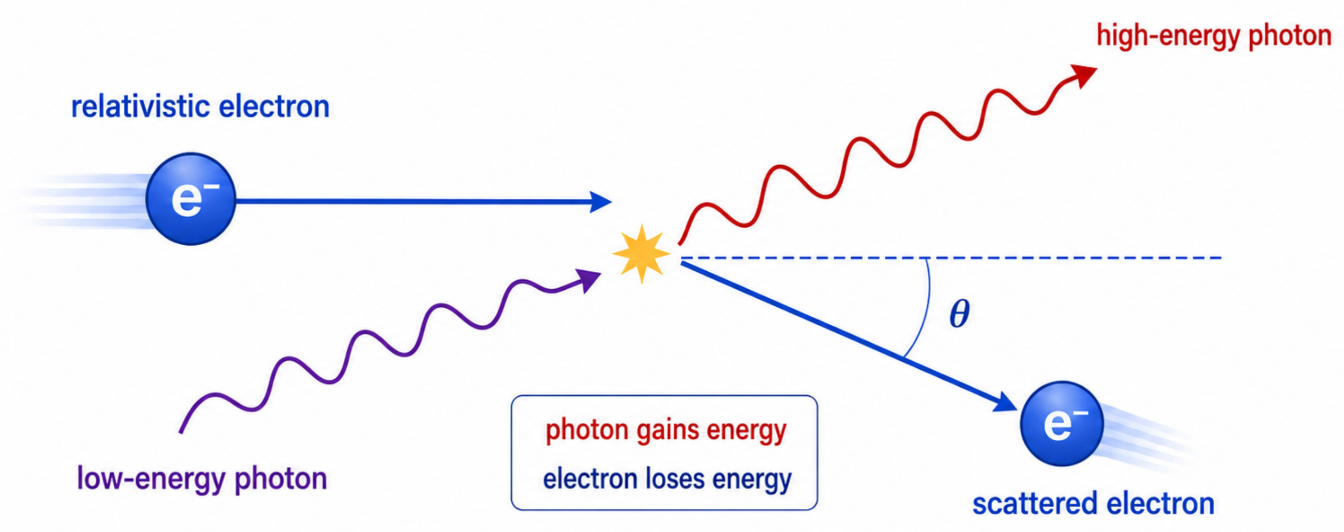
$$\left.\frac{dN_\gamma^{\mu^-\to e^-\bar{\nu}_e\nu_\mu\gamma}}{dE_\gamma}\right|_{E_\mu=m_\mu} = \frac{\alpha(1-x)}{36\pi E_\gamma}\left[12\left(3-2x(1-x)^2\right)\log\left(\frac{1-x}{r}\right)+x(1-x)(46-55x)-102\right]$$

Pythia simulation for tau decay



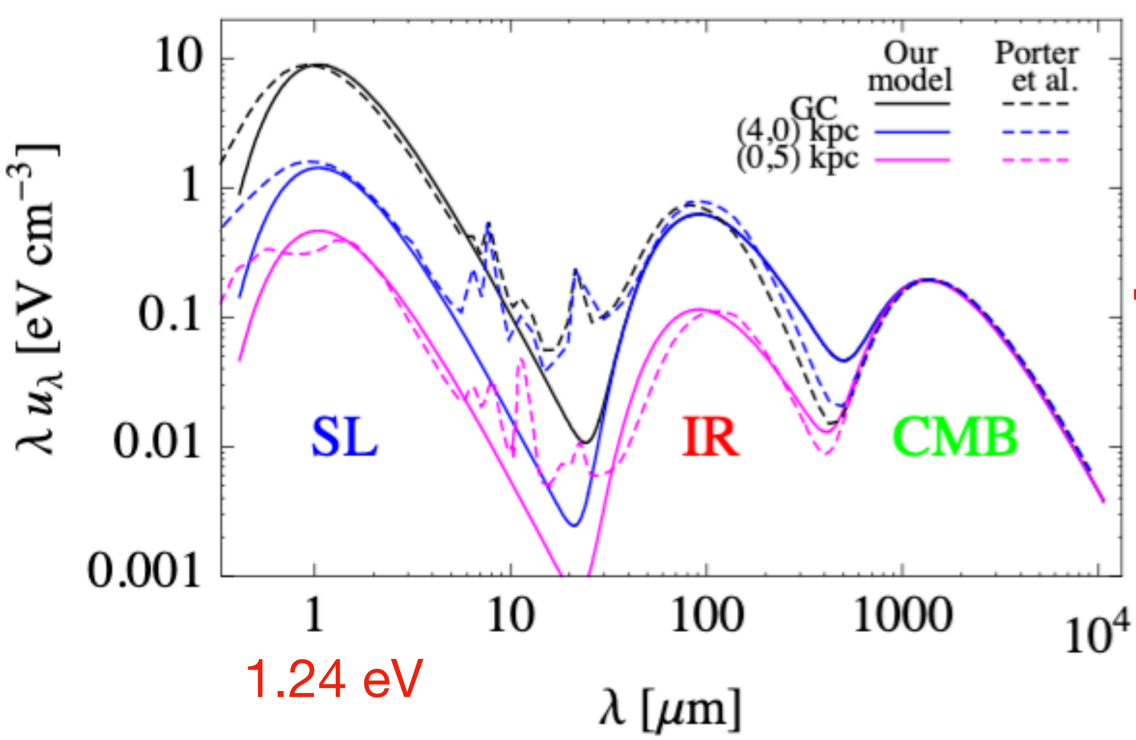
Inverse Compton scattering

Inverse Compton Scattering



A low-energy photon scatters off a relativistic electron and emerges with higher energy.

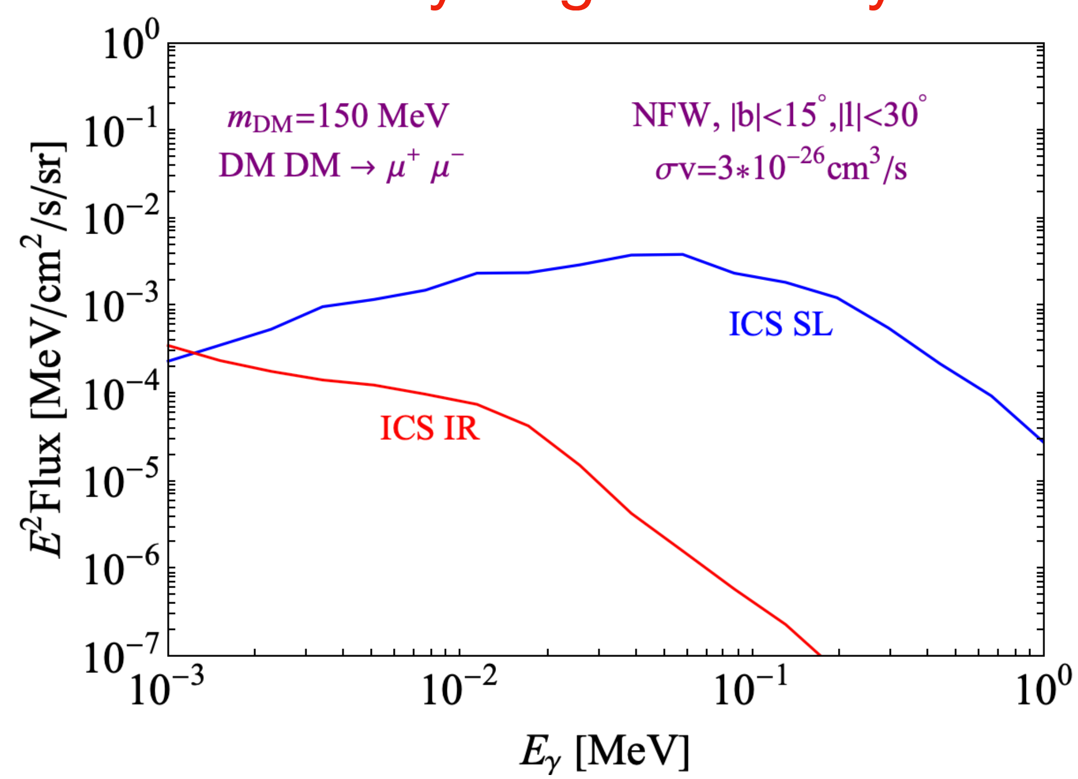
eV scale background photons



1.24 eV

ICS

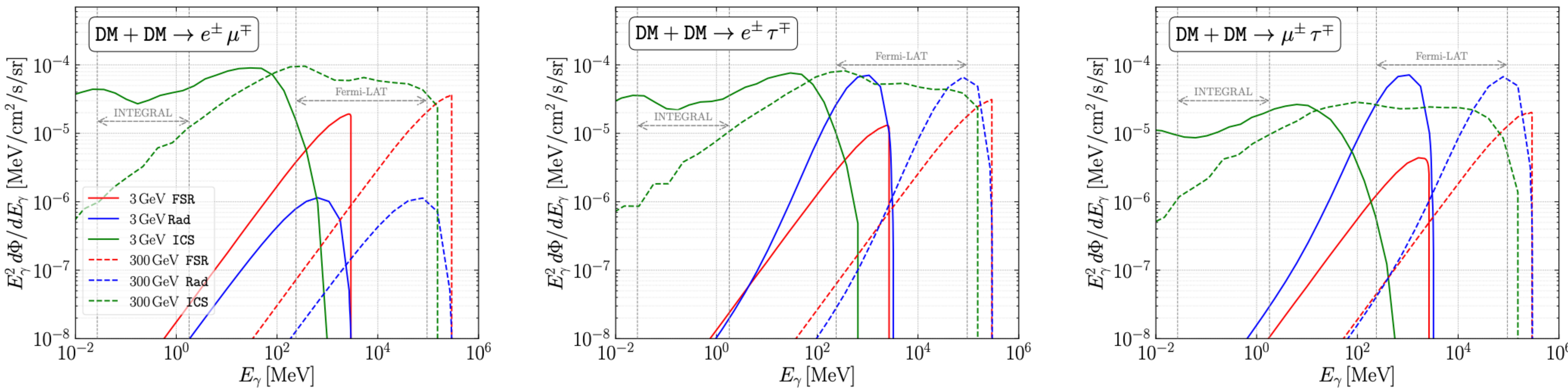
X-ray or gamma-ray



Cirelli, Panci, Nucl.Phys.B 821 (2009) 399-416

Photon fluxes from different contributions

Jahedi, **JL**, Liao, Ma, Uchida, arXiv: 2601.14048



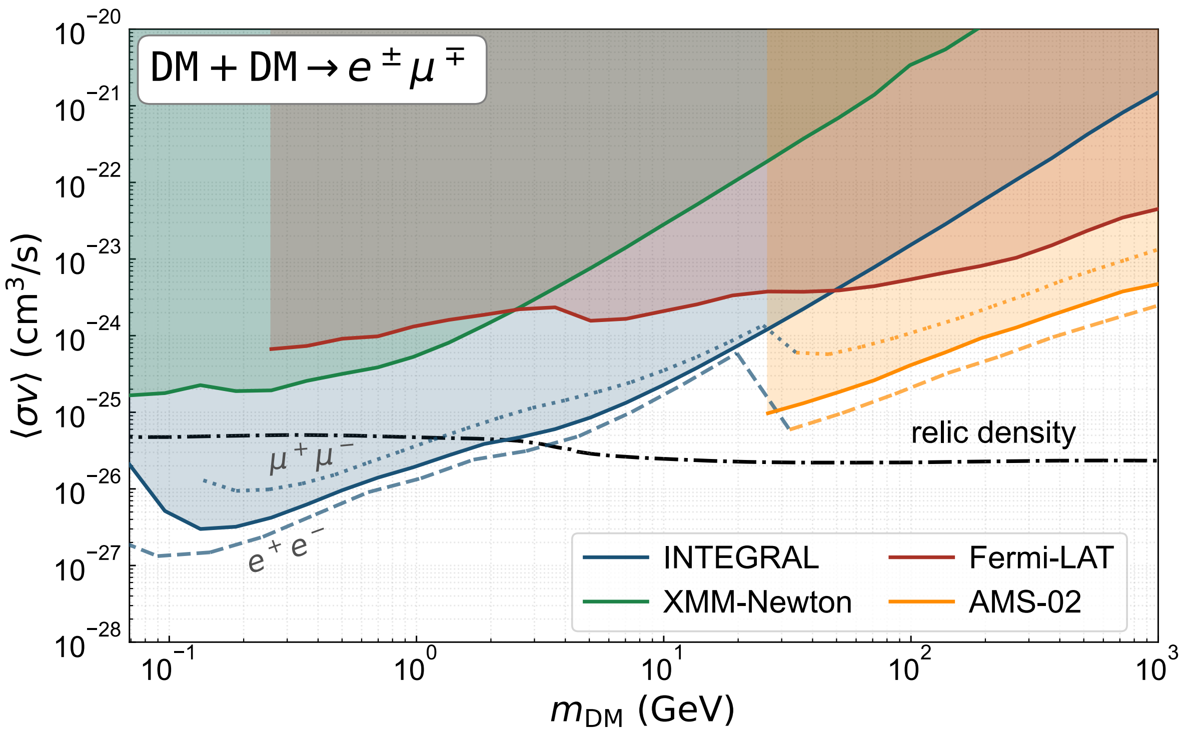
(1) In the low-energy region, the ICS contribution is dominant for all three channels.

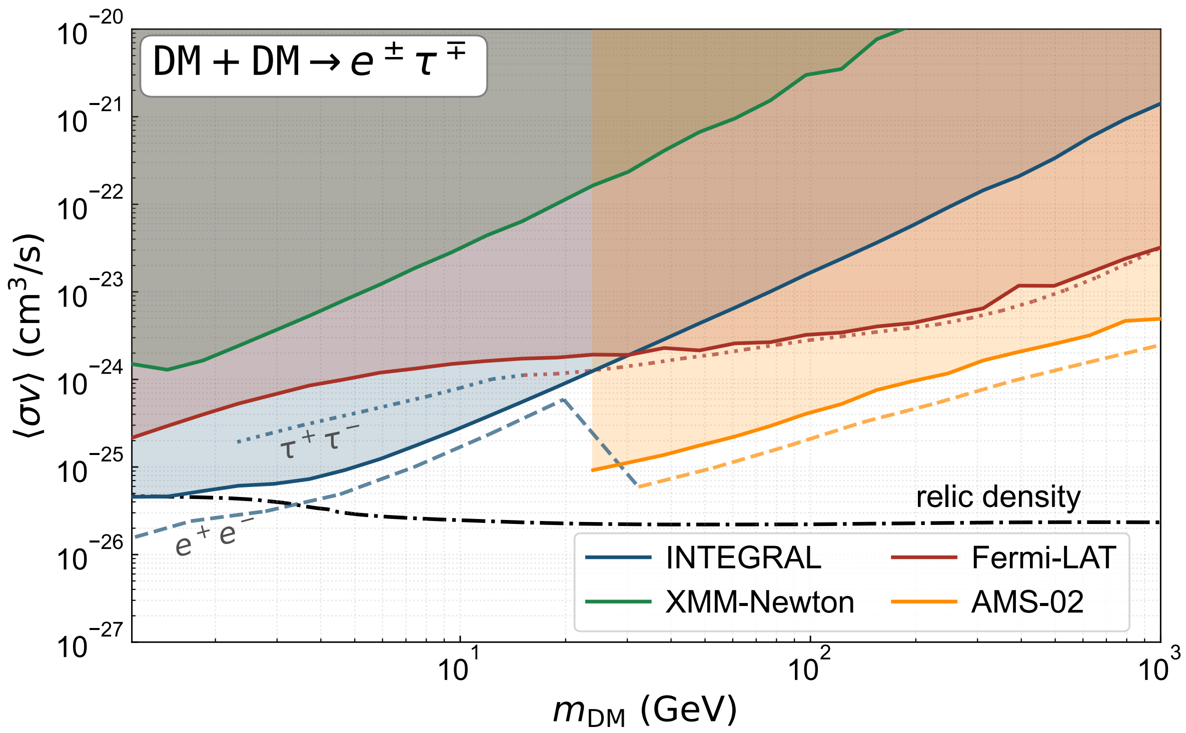
(2) In the high-energy region:

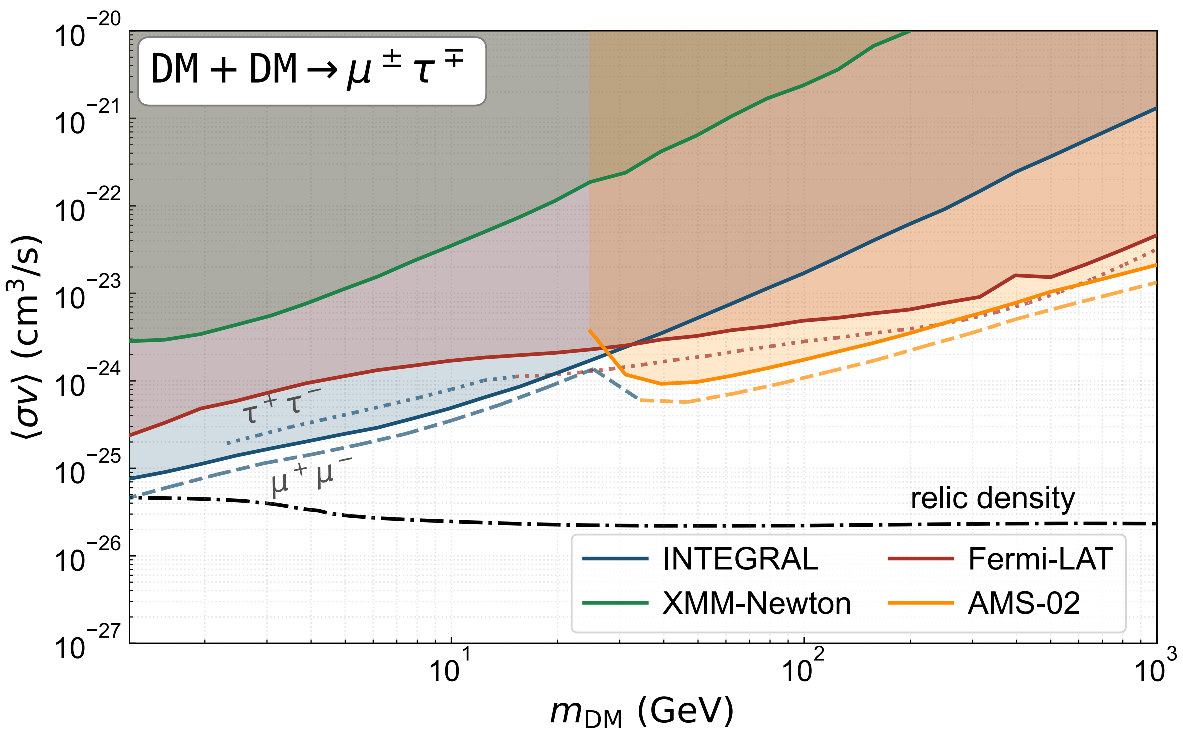
a. For the τ-related channel ($e\tau$, $\mu\tau$), the RAD contribution is dominant.

b. For the $e\mu$ channel, the FSR (ICS) contribution is dominant for light (heavy) DM.

Constraints on LFV DM annihilation



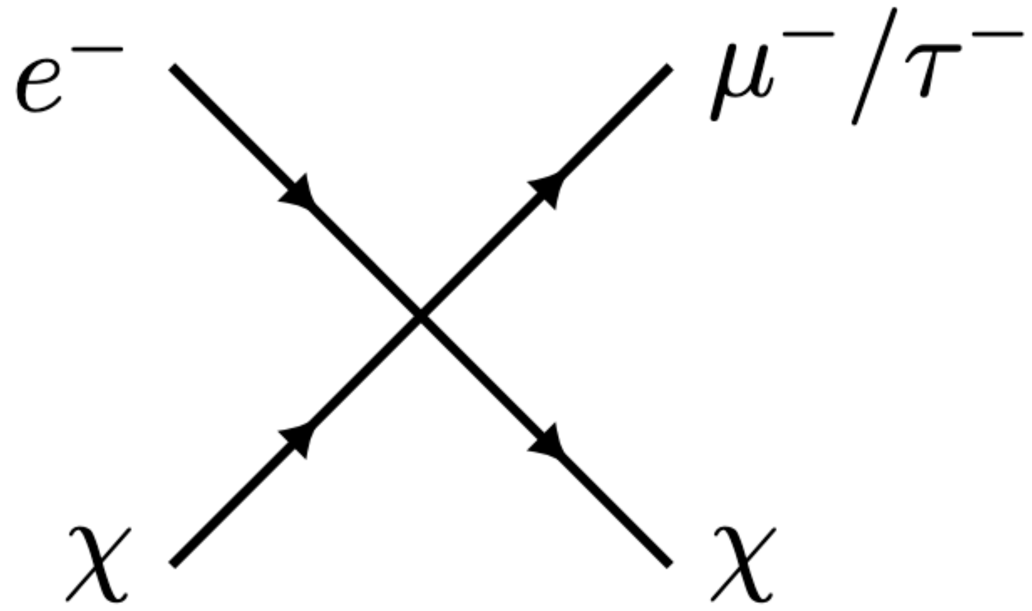




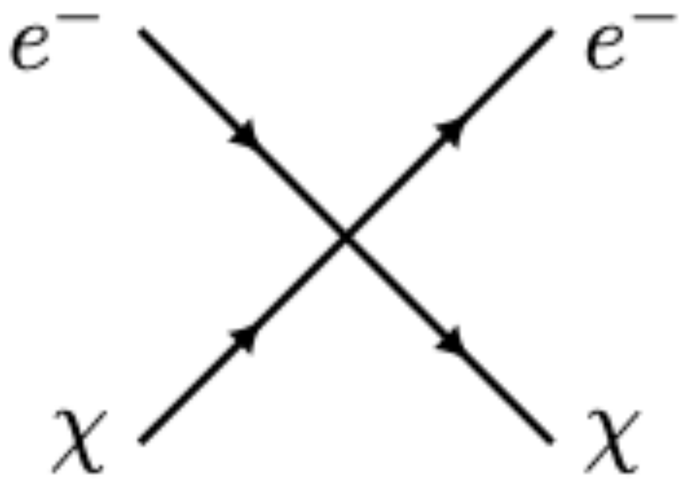
(1) INTEGRAL (AMS) provides the most stringent constraint at low (high) DM masses

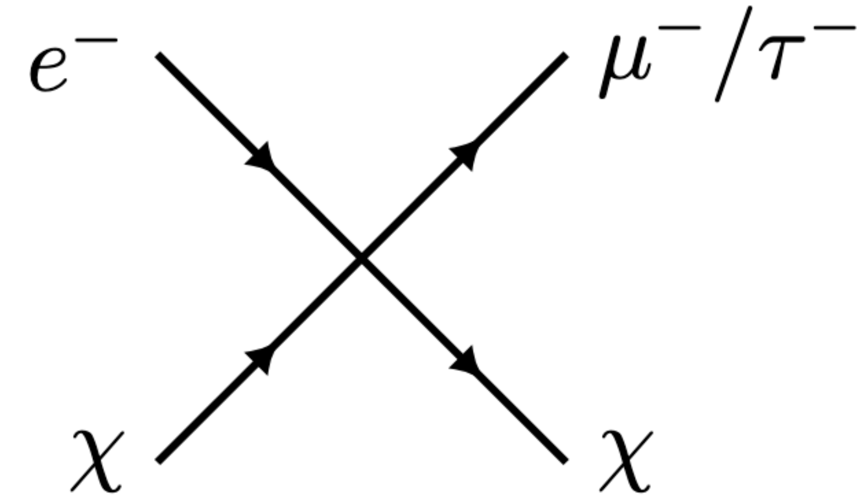
(2) The LFV ij constraints are between the corresponding LFC ii and jj constraints for a given experiment

Scattering process for CLFV DM

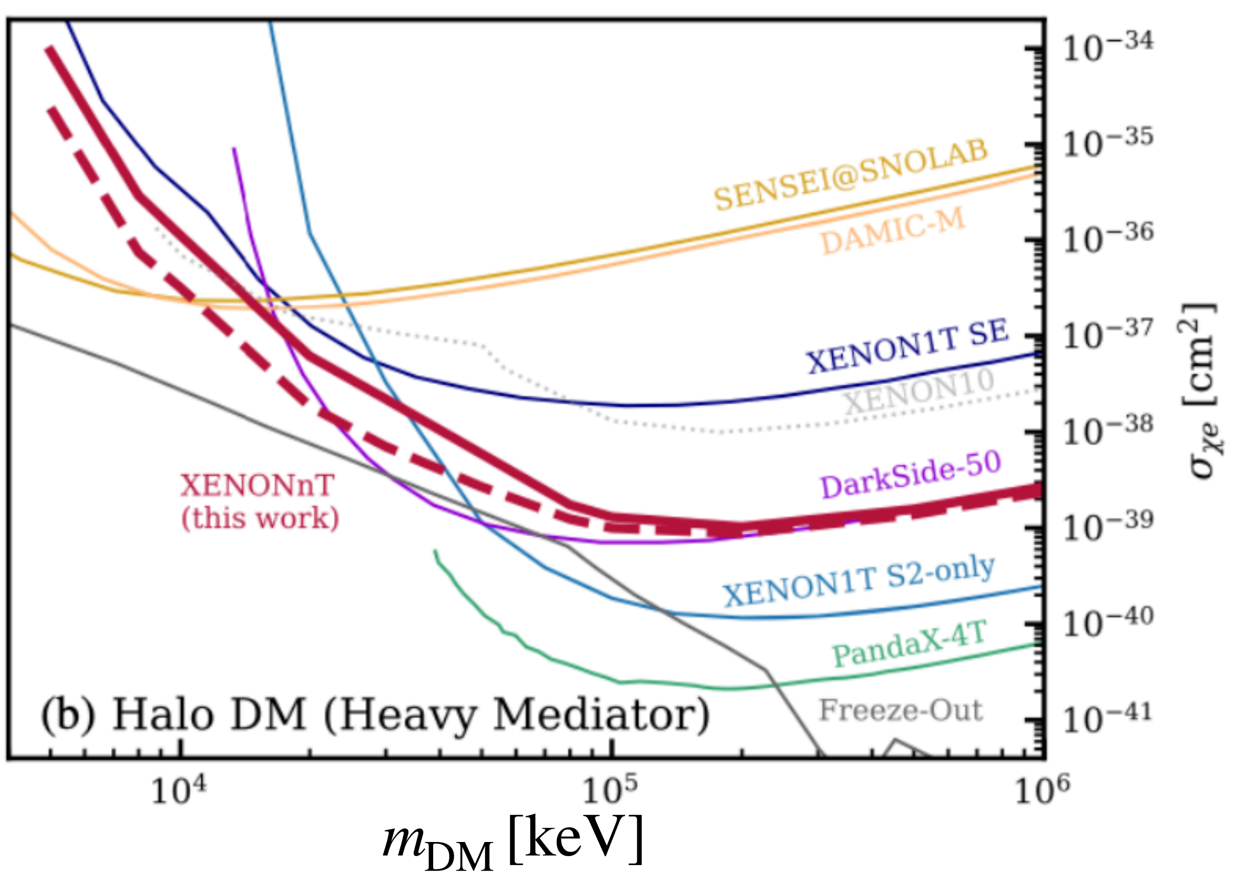


Direct detection on DM-electron interaction





XENON Collaboration, Phys.Rev.Lett. 134 (2025) 16, 161004



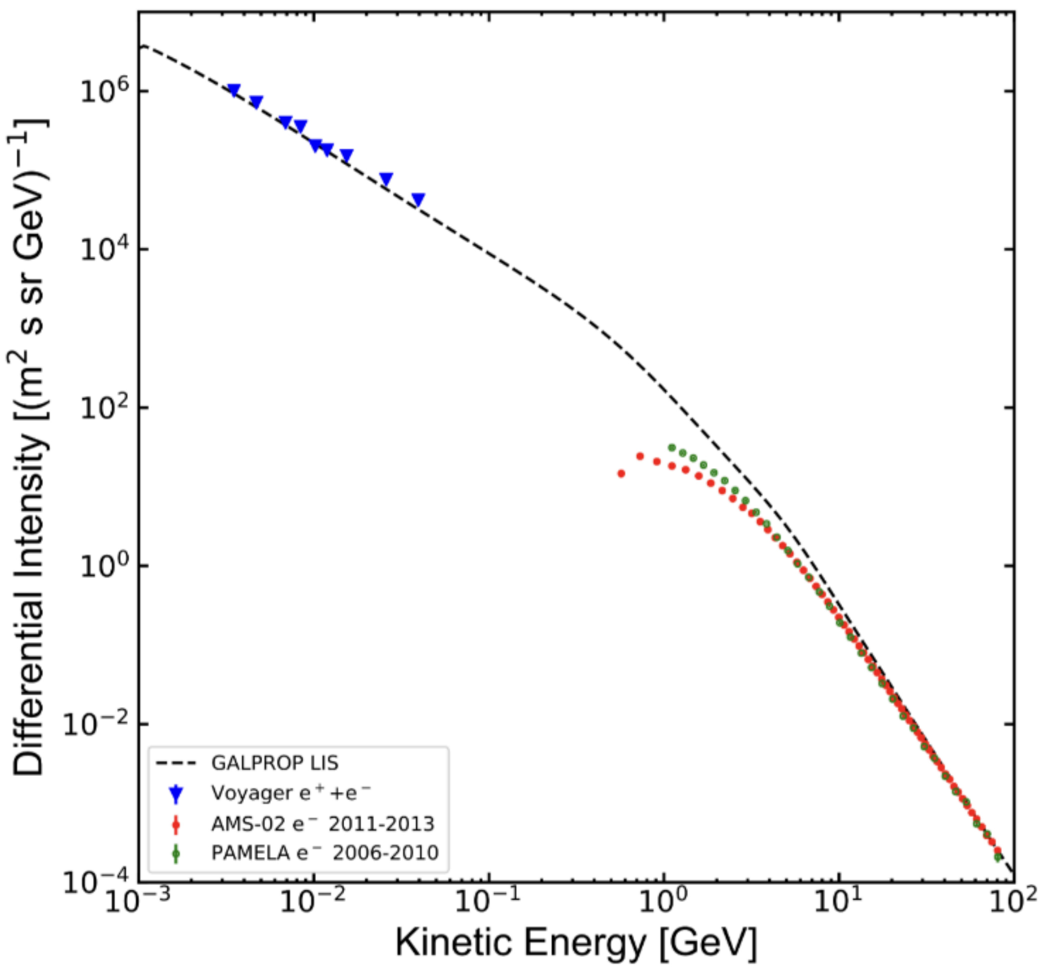
Stringent constraints for the LFC case

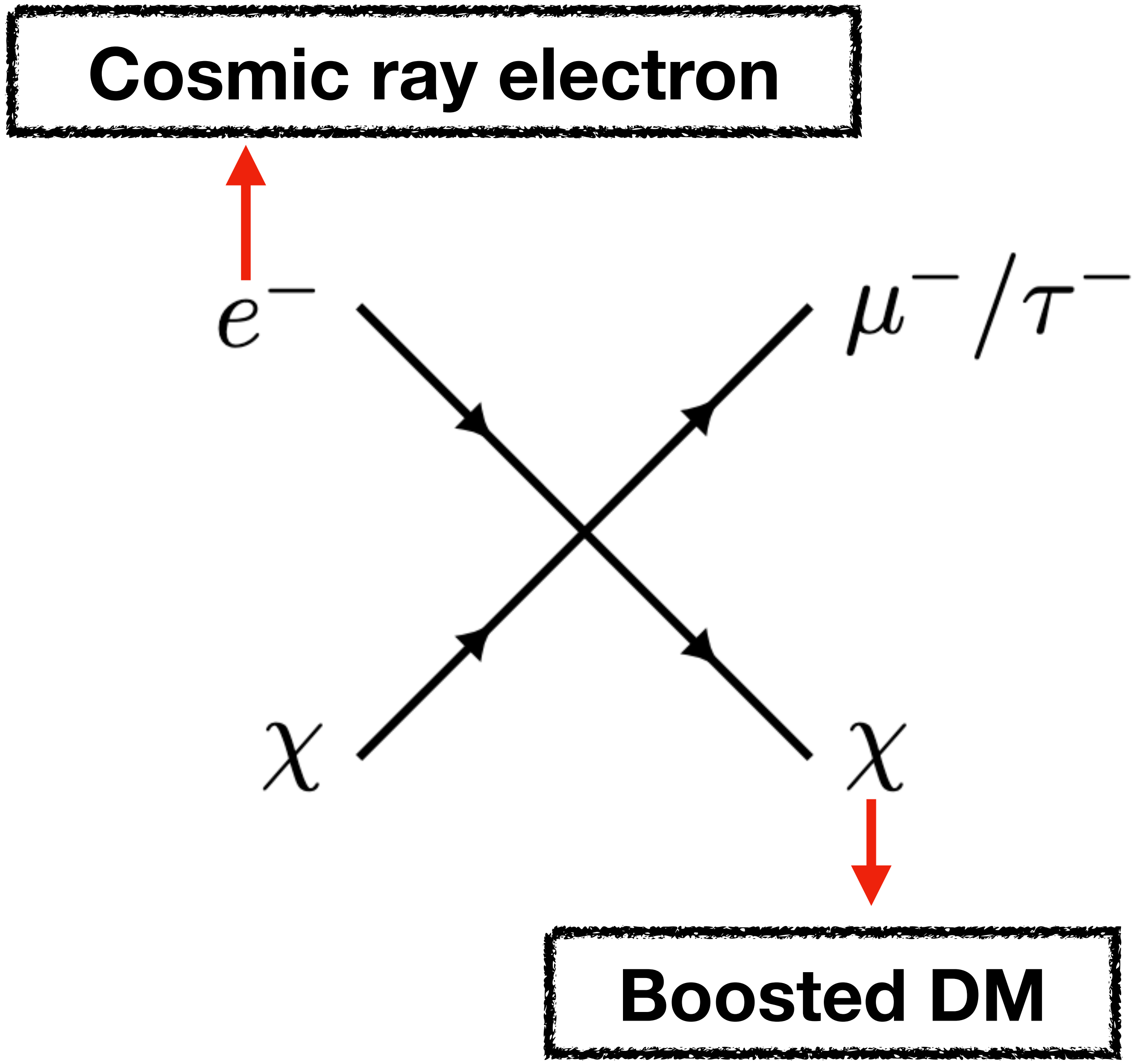
For the LFV case, no constraints since halo DM is too slow to overcome the mass gap.

$$v_{\rm DM} \simeq 10^{-3} c$$

Cosmic ray boosted DM

Boschini et al., Astrophys.J. 854 (2018) 2, 94

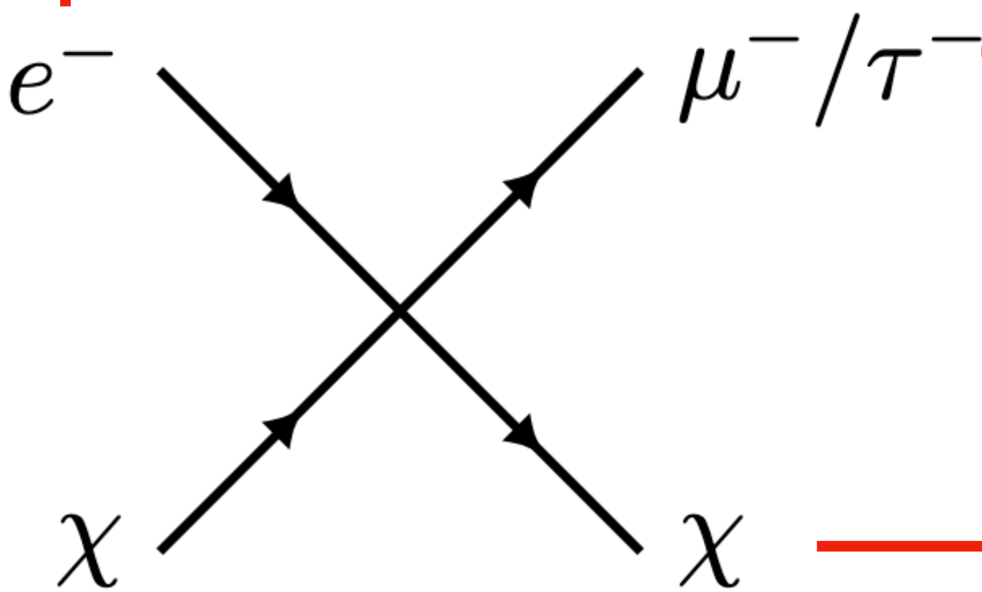




High-energy electrons allow the final-state DM particles to reach energies up to tens of GeV.

Multiple signatures of CLFV scattering

Cosmic ray cooling
Additional energy loss for CR electrons
AMS

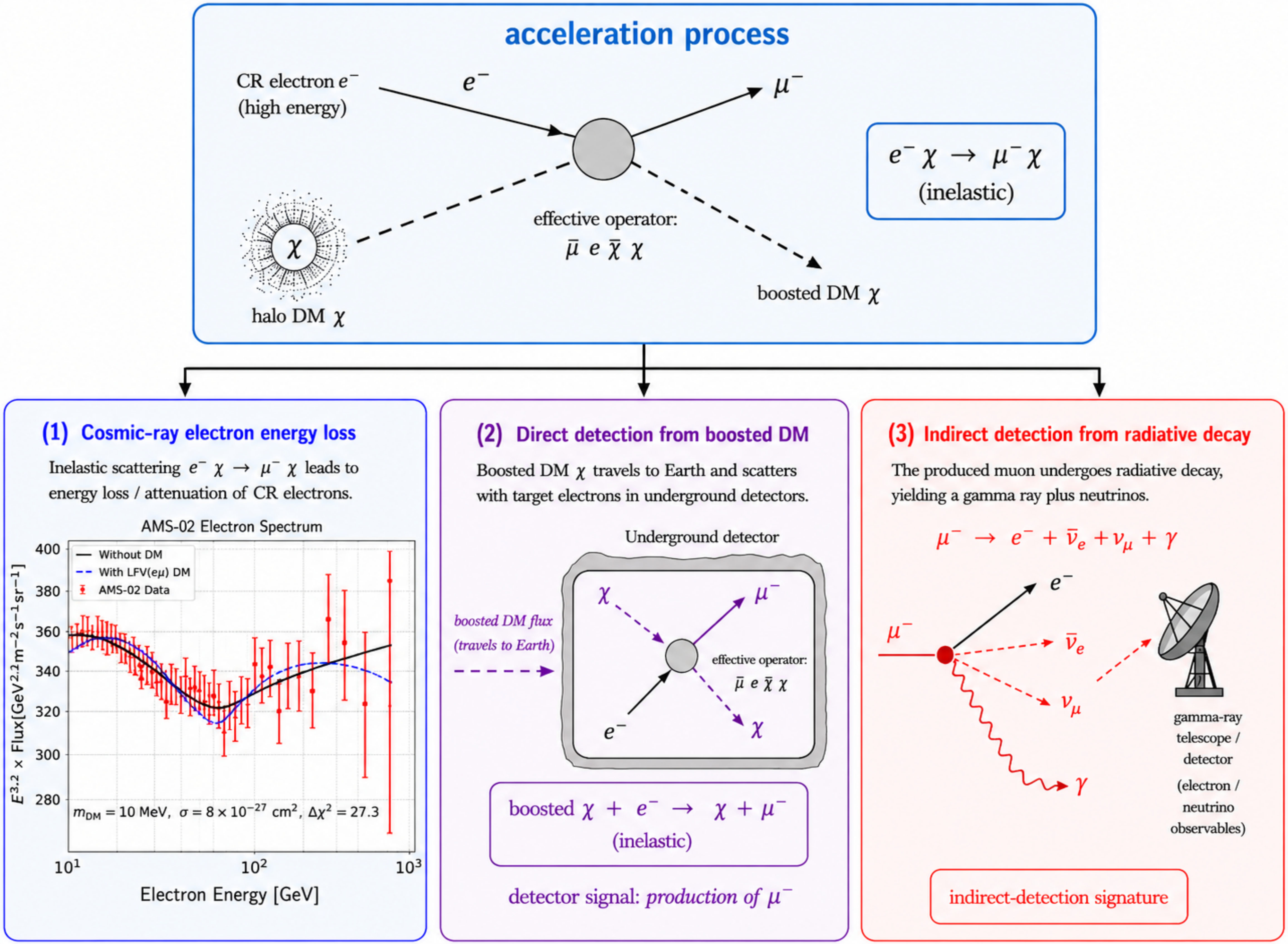


JL, Liao, Ma, arXiv: 260x.xxxxx

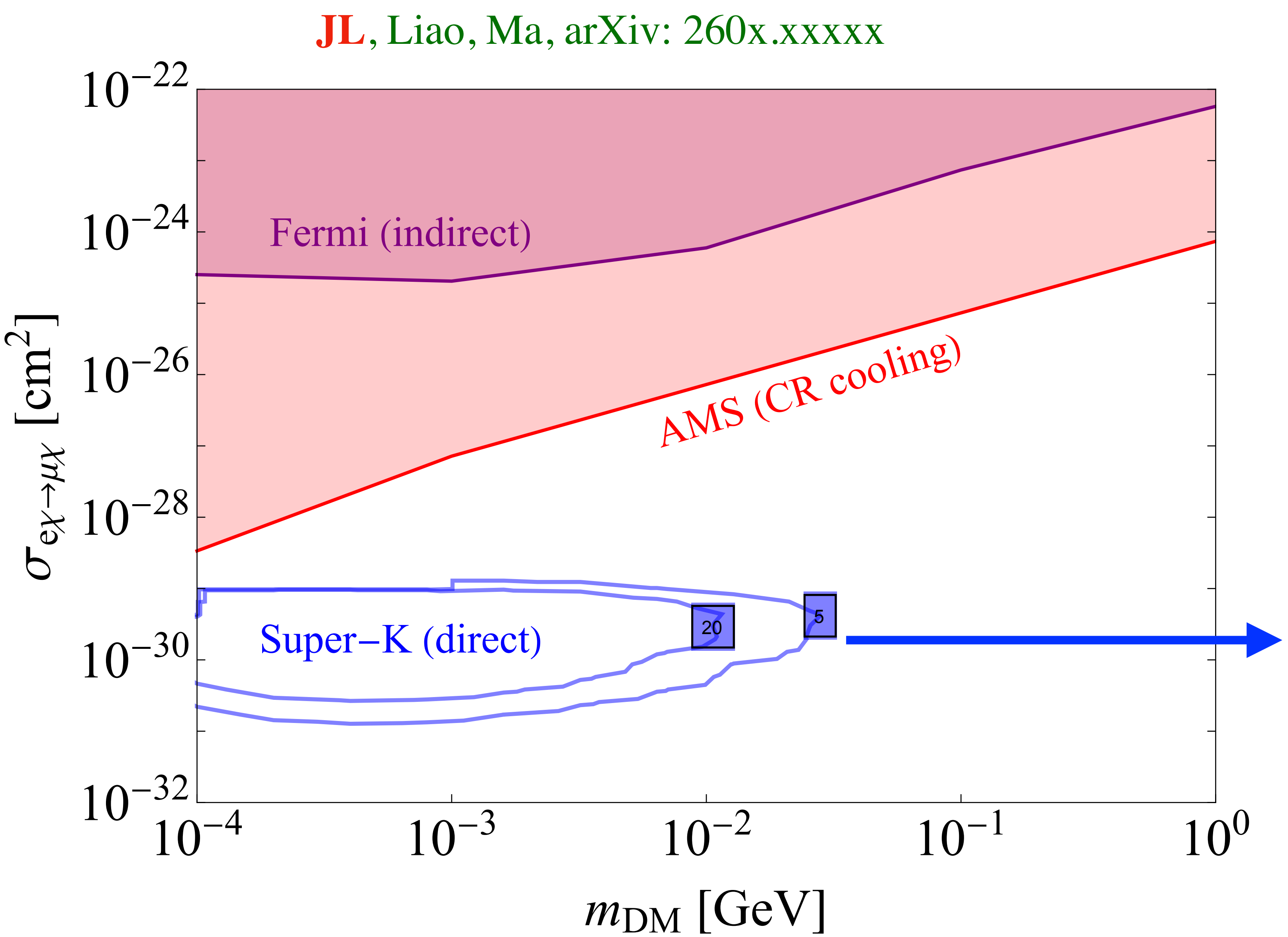
Indirect detection
Radiative decay
High-energy photon at Fermi-LAT

Direct detection
Boosted DM
Single muon at Super-K

Multiple signatures of CLFV scattering



Constraints on CLFV scattering cross section



Isotropic assumption:

$d\sigma/dz^* = C$

$E_\mu > 1.33$ GeV **:**

reduce atmosphere neutrino backgrounds

(1) The CR cooling and direct detection provide complementary constraints on LFV scattering cross sections.

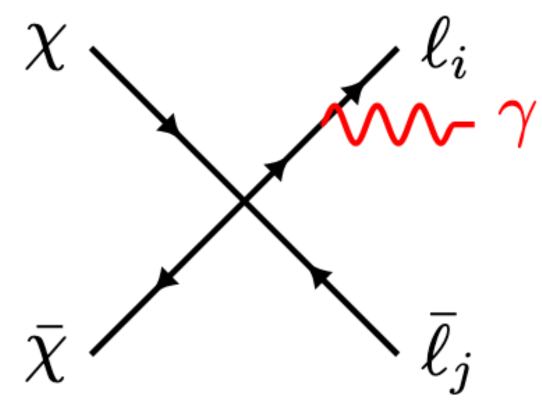
(2) The indirect detection constraint is weak due to the tiny radiative decay branching ratio for muons.

Summary

- CLFV process is a golden channel to search for new physics. However the DM-induced CLFV is forbidden in direct detection due to the mass threshold.
- We present limits on LFV annihilation from INTEGRAL, XMM-Newton, Fermi, and AMS-02, where INTEGRAL (AMS-02) provides the strongest bounds at low (high) DM masses.
- Using CR-boosted DM, we derive constraints on LFV scattering from CR cooling, indirect detection, and direct detection. For the $e\mu$ channel, CR cooling and direct detection offer complementary sensitivities to the LFV scattering cross section.

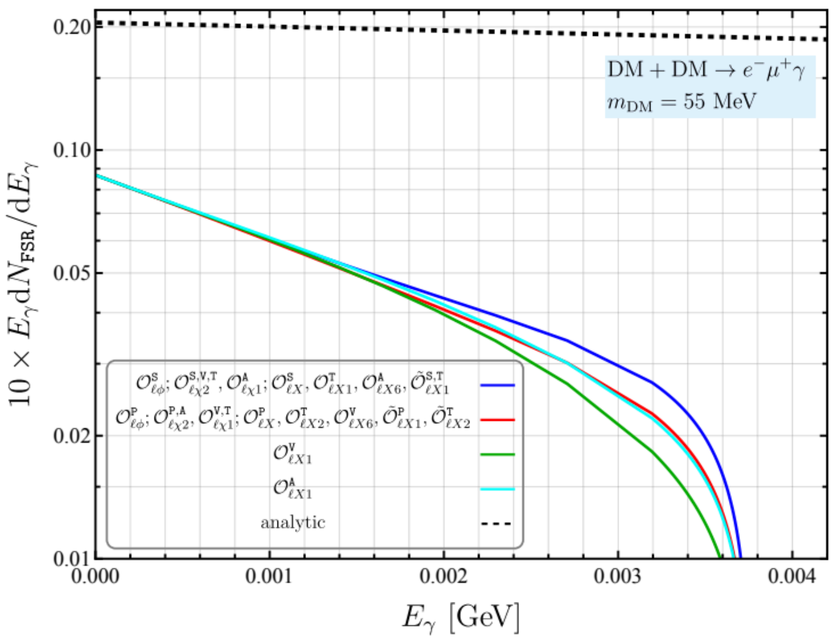
Backup

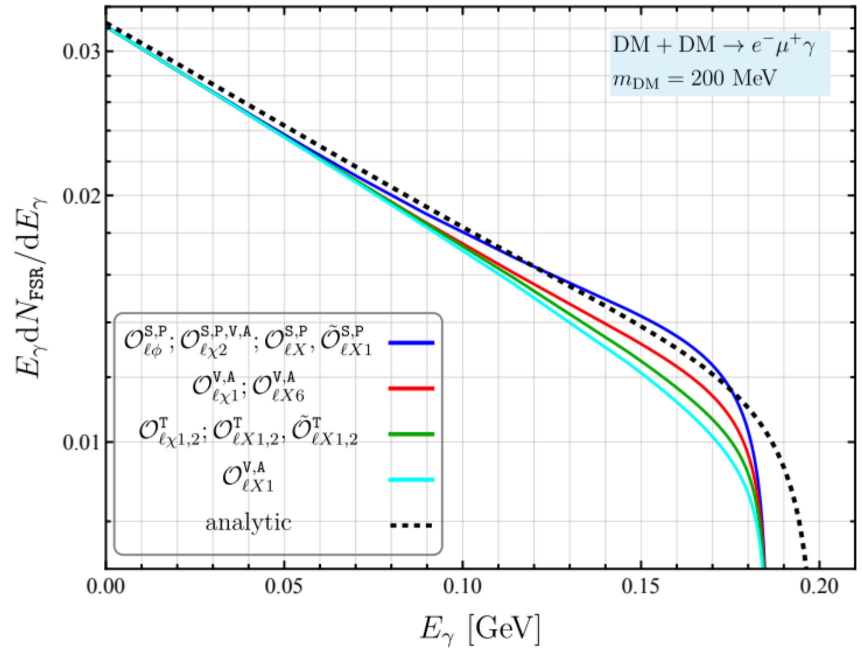
FSR for different operators

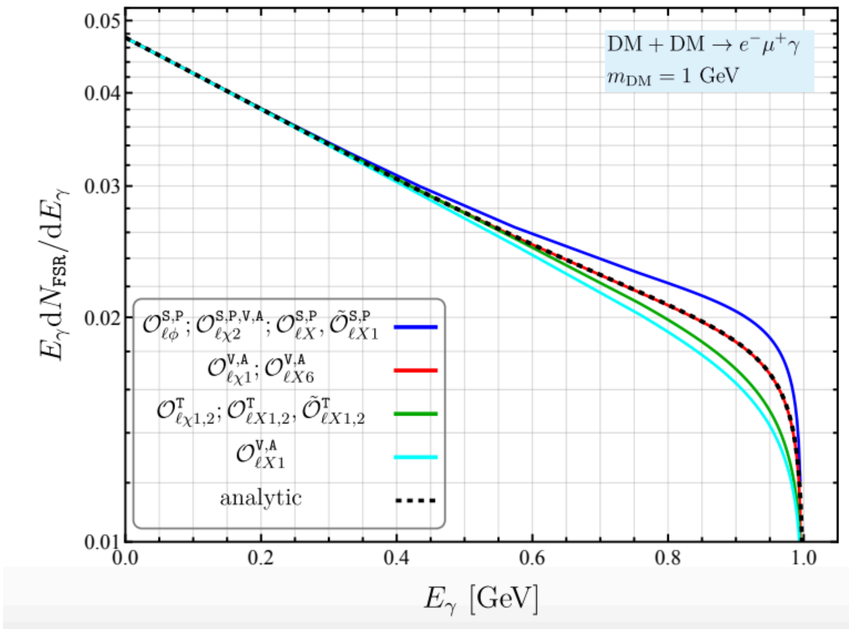


$$\mathtt{DM} + \mathtt{DM} \to e^{\mp}\mu^{\pm}\gamma$$

Increasing DM mass







Dashed: structure function method

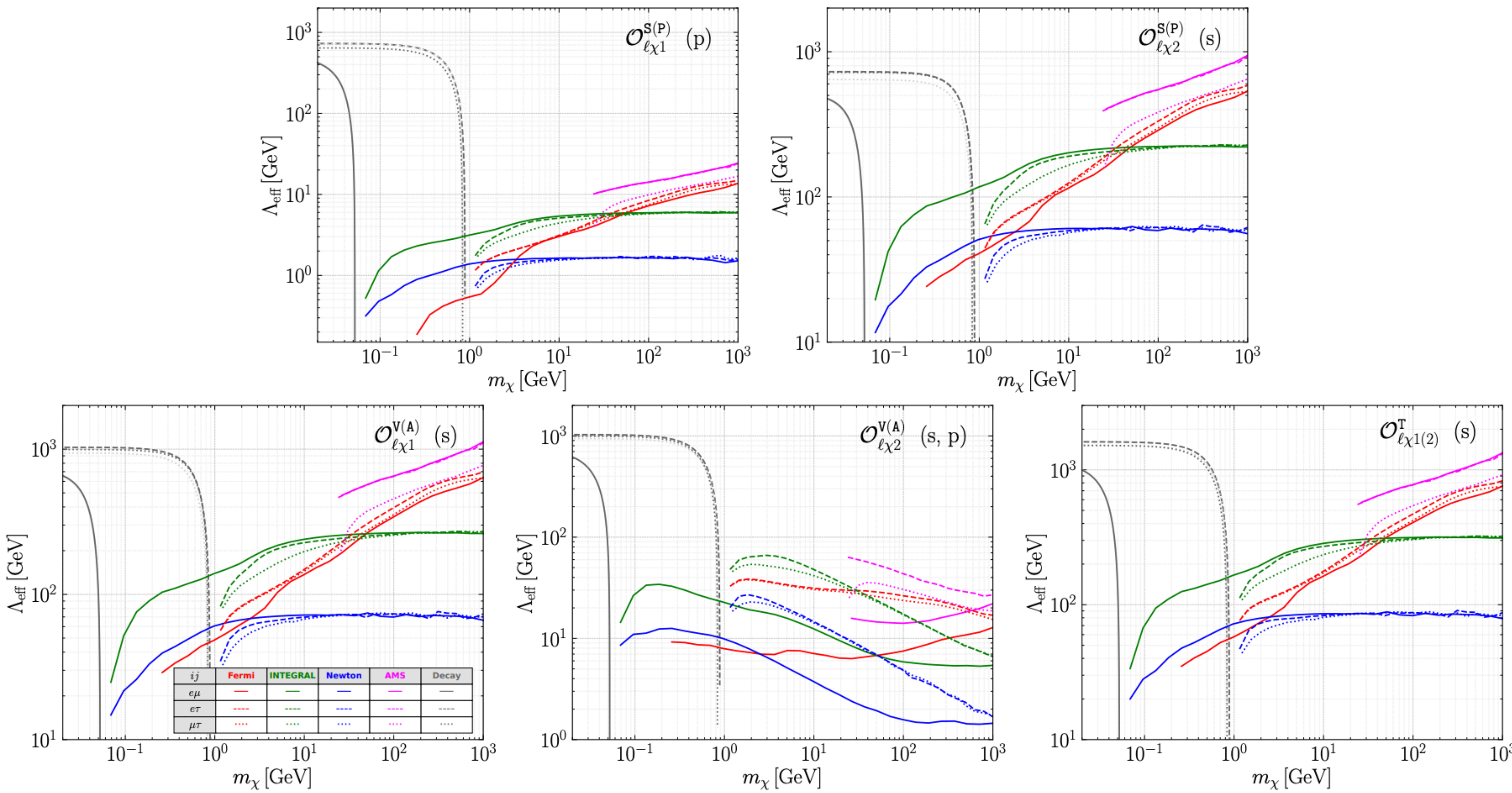
Solid: numerically integrate over the phase space

(1) The analytic formula agrees very well with the direct numerical calculation when $m_{\mathtt{DM}} \gg (m_i + m_j)/2$ and $E_\gamma \lesssim E_{\mathtt{DM}}/2$.

(2) Different EFT operators share a similar FSR spectrum.

Jahedi, **JL**, Liao, Ma, Uchida, arXiv: 2601.14048

Constraints on EFT operators



The constraints can reach about 1 TeV (tens of GeV) for s- (p-) wave operators.

Jahedi, **JL**, Liao, Ma, Uchida, arXiv: 2601.14048

Annihilation cross section

$$\sigma v_{\rm rel} = \hat{a} + \hat{b}\, v_{\rm rel}^2 + \hat{d}\, v_{\rm rel}^4 + \cdots$$

Operator	Total cross section σ $[\vert C_i^j\vert^2]$	Leading-order $\sigma v_{\rm rel}$ $[\vert C_i^j\vert^2]$
	Scalar DM case	
$\mathcal{O}_{\ell\phi}^{\mathtt{S},ij}(\mathcal{O}_{\ell\phi}^{\mathtt{P},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{8\pi s^2\sqrt{\kappa_f}}\rho_-$,	$\frac{1}{4\pi}(1-\eta_{ij})^2$.
$\mathcal{O}_{\ell\phi}^{\mathtt{V},ij}(\mathcal{O}_{\ell\phi}^{\mathtt{A},ij})$	$\frac{\sqrt{\kappa_f\rho_+\rho_-}}{24\pi s^2}\rho_+(3s-\rho_-)$,	$\frac{m_\phi^2}{12\pi}(1-\eta_{ij})^2(2+\eta_{ij})v_{\rm rel}^2$.
	Fermion DM case	
$\mathcal{O}_{\ell\chi 1}^{\mathtt{S},ij}(\mathcal{O}_{\ell\chi 1}^{\mathtt{P},ij})$	$\frac{\sqrt{\kappa_f\rho_+\rho_-}}{16\pi s}\rho_-$,	$\frac{m_\chi^2}{8\pi}(1-\eta_{ij})^2 v_{\rm rel}^2$.
$\mathcal{O}_{\ell\chi 2}^{\mathtt{S},ij}(\mathcal{O}_{\ell\chi 2}^{\mathtt{P},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{16\pi s\sqrt{\kappa_f}}\rho_-$,	$\frac{m_\chi^2}{2\pi}(1-\eta_{ij})^2$.
$\mathcal{O}_{\ell\chi 1}^{\mathtt{V},ij}(\mathcal{O}_{\ell\chi 1}^{\mathtt{A},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{48\pi s^2\sqrt{\kappa_f}}(3-\kappa_f)\rho_+(3s-\rho_-)$,	$\frac{m_\chi^2}{2\pi}(1-\eta_{ij})^2(2+\eta_{ij})$.
$\mathcal{O}_{\ell\chi 2}^{\mathtt{V},ij}(\mathcal{O}_{\ell\chi 2}^{\mathtt{A},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{48\pi s^2\sqrt{\kappa_f}}\{3s[2\kappa_f\rho_+ + (1-\kappa_f)\rho_-] - (3-\kappa_f)\rho_+\rho_-\}$,	$\frac{m_\chi^2}{2\pi}\eta_{ij}(1-\eta_{ij})^2$ $+\frac{m_\chi^2}{24\pi}(1-\eta_{ij})(4-5\eta_{ij}+7\eta_{ij}^2)v_{\rm rel}^2$.
$\mathcal{O}_{\ell\chi 1}^{\mathtt{T},ij}(\mathcal{O}_{\ell\chi 2}^{\mathtt{T},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{12\pi s^2\sqrt{\kappa_f}}\{3s[(3-2\kappa_f)\rho_+ + \kappa_f\rho_-] - 2(3-\kappa_f)\rho_+\rho_-\}$,	$\frac{2m_\chi^2}{\pi}(1-\eta_{ij})^2(1+2\eta_{ij})$.
	Vector DM case A	
$\mathcal{O}_{\ell X}^{\mathtt{S},ij}(\mathcal{O}_{\ell X}^{\mathtt{P},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{1512\pi m_X^4\sqrt{\kappa_f}}(3-2\kappa_f+3\kappa_f^2)\rho_-$,	$\frac{1}{12\pi}(1-\eta_{ij})^2$.
$\mathcal{O}_{\ell X1}^{\mathtt{T},ij}(\mathcal{O}_{\ell X2}^{\mathtt{T},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{1728\pi m_X^4 s\sqrt{\kappa_f}}\{3s[2(2\kappa_f-\kappa_f^2)\rho_+ + (3-4\kappa_f+\kappa_f^2)\rho_-] - 2(3-\kappa_f^2)\rho_+\rho_-\}$,	$\frac{1}{18\pi}(1-\eta_{ij})^2(1+2\eta_{ij})$.
$\mathcal{O}_{\ell X1}^{\mathtt{V},ij}(\mathcal{O}_{\ell X1}^{\mathtt{A},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{4320\pi m_X^4 s^2\sqrt{\kappa_f}}\{15s^3[(\kappa_f-\kappa_f^2)\rho_+ + \kappa_f^2\rho_-]$ $-5s^2[3(\kappa_f-\kappa_f^2)\rho_+^2 + 3\kappa_f^2\rho_-^2 + 4\kappa_f\rho_+\rho_-]$ $+10s[(3-2\kappa_f)\rho_+ + (\kappa_f+\kappa_f^2)\rho_-]\rho_+\rho_- - (15-10\kappa_f+3\kappa_f^2)\rho_+^2\rho_-^2\}$,	$\frac{4m_X^2}{9\pi}(1-\eta_{ij})^4(1+\eta_{ij})$.
$\mathcal{O}_{\ell X2}^{\mathtt{V},ij}(\mathcal{O}_{\ell X2}^{\mathtt{A},ij})$	$\frac{\sqrt{\kappa_f\rho_+\rho_-}}{864\pi m_X^4}\{3s[(1-\kappa_f)\rho_+ + \kappa_f\rho_-] - (1+2\kappa_f)\rho_+\rho_-\}$,	$\frac{m_X^2}{27\pi}(1-\eta_{ij})^2(2+\eta_{ij})v_{\rm rel}^2$.
$\mathcal{O}_{\ell X3}^{\mathtt{V},ij}(\mathcal{O}_{\ell X3}^{\mathtt{A},ij})$	$\frac{\sqrt{\kappa_f\rho_+\rho_-}}{432\pi m_X^2 s}\{3s[2\kappa_f\rho_+ + (1-\kappa_f)\rho_-] - (3-\kappa_f)\rho_+\rho_-\}$,	$\frac{m_X^2}{18\pi}\eta_{ij}(1-\eta_{ij})^2 v_{\rm rel}^2$ $+\frac{m_X^2}{108\pi}(1-\eta_{ij})(2-\eta_{ij}+2\eta_{ij}^2)v_{\rm rel}^4$.
$\mathcal{O}_{\ell X4}^{\mathtt{V},ij}(\mathcal{O}_{\ell X4}^{\mathtt{A},ij})$	$\frac{\sqrt{\kappa_f\rho_+\rho_-}}{3456\pi m_X^4}(3-2\kappa_f+3\kappa_f^2)\rho_+(3s-\rho_-)$,	$\frac{m_X^2}{36\pi}(1-\eta_{ij})^2(2+\eta_{ij})v_{\rm rel}^2$.
$\mathcal{O}_{\ell X5}^{\mathtt{V},ij}(\mathcal{O}_{\ell X5}^{\mathtt{A},ij})$	$\frac{\sqrt{\kappa_f\rho_+\rho_-}}{864\pi m_X^4}(2-\kappa_f)\rho_+(3s-\rho_-)$,	$\frac{2m_X^2}{27\pi}(1-\eta_{ij})^2(2+\eta_{ij})v_{\rm rel}^2$.
$\mathcal{O}_{\ell X6}^{\mathtt{V},ij}(\mathcal{O}_{\ell X6}^{\mathtt{A},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{432\pi m_X^2 s\sqrt{\kappa_f}}(3-\kappa_f)\rho_+(3s-\rho_-)$,	$\frac{2m_X^2}{9\pi}(1-\eta_{ij})^2(2+\eta_{ij})$.
	Vector DM case B	
$\tilde{\mathcal{O}}_{\ell X1}^{\mathtt{S},ij}(\tilde{\mathcal{O}}_{\ell X1}^{\mathtt{P},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{288\pi\sqrt{\kappa_f}}(3+2\kappa_f+3\kappa_f^2)\rho_-$,	$\frac{m_X^4}{3\pi}(1-\eta_{ij})^2$.
$\tilde{\mathcal{O}}_{\ell X2}^{\mathtt{S},ij}(\tilde{\mathcal{O}}_{\ell X2}^{\mathtt{P},ij})$	$\frac{\sqrt{\kappa_f\rho_+\rho_-}}{36\pi}\rho_-$,	$\frac{2m_X^4}{9\pi}(1-\eta_{ij})^2 v_{\rm rel}^2$.
$\tilde{\mathcal{O}}_{\ell X1}^{\mathtt{T},ij}(\tilde{\mathcal{O}}_{\ell X2}^{\mathtt{T},ij})$	$\frac{\sqrt{\rho_+\rho_-}}{1728\pi s\sqrt{\kappa_f}}\{3s[2(3\kappa_f-\kappa_f^2)\rho_+ + (3+\kappa_f^2)\rho_-] - 2(3+6\kappa_f-\kappa_f^2)\rho_+\rho_-\}$,	$\frac{m_X^4}{18\pi}(1-\eta_{ij})^2(1+2\eta_{ij})$.

Leading term is suppressed by a mass fraction

$$\kappa_f \equiv 1 - 4m_{\rm DM}^2/s \qquad \rho_\pm \equiv s - (m_i \mp m_j)^2 \qquad \eta_{ij} \equiv \max[m_i^2, m_j^2]/(4m_{\rm DM}^2)$$

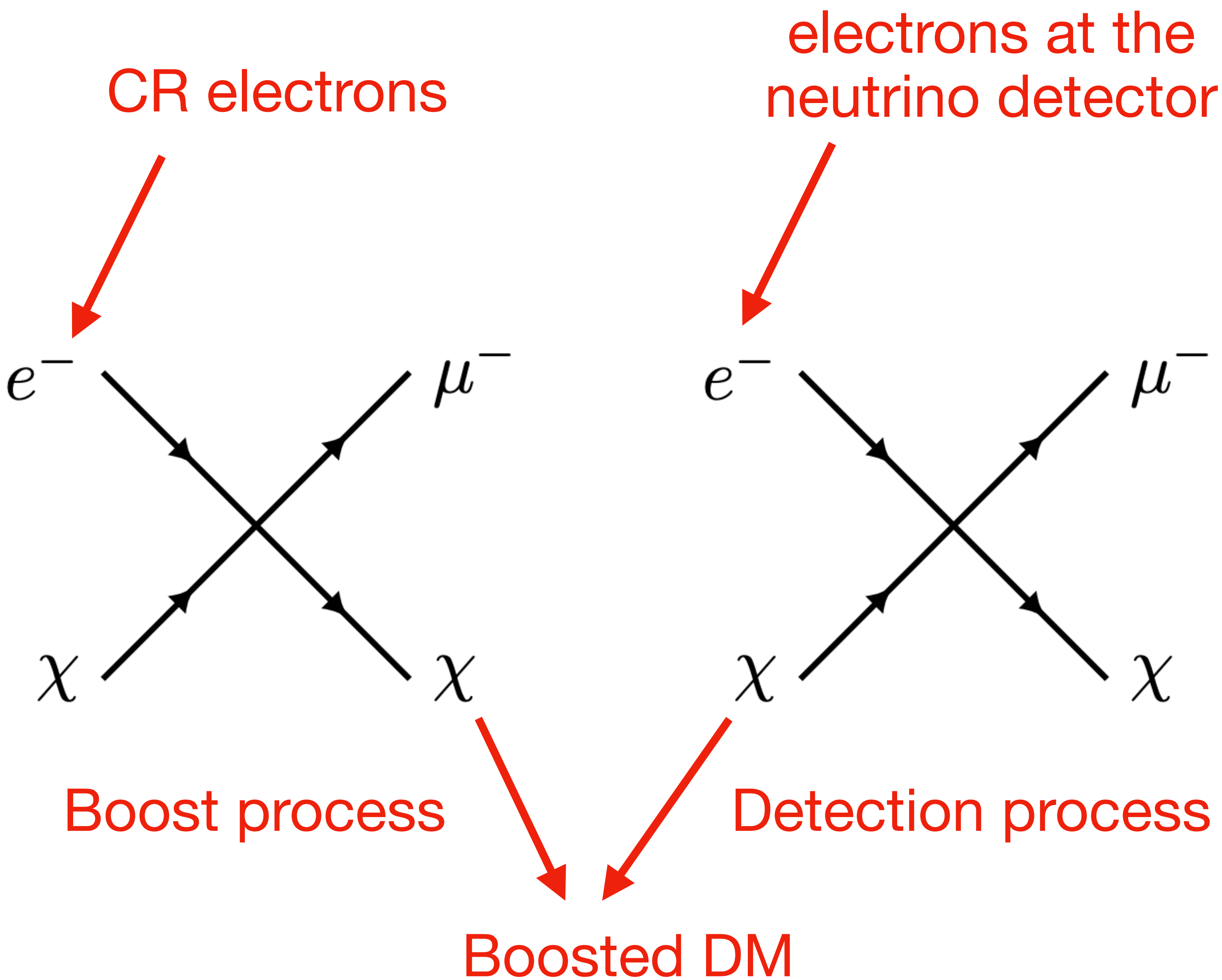
Jahedi, JL, Liao, Ma, Uchida, arXiv: 2601.14048

CLFV DM interaction EFT operators

$\mathrm{SU}(3)_c \otimes \mathrm{U}(1)_{em}$

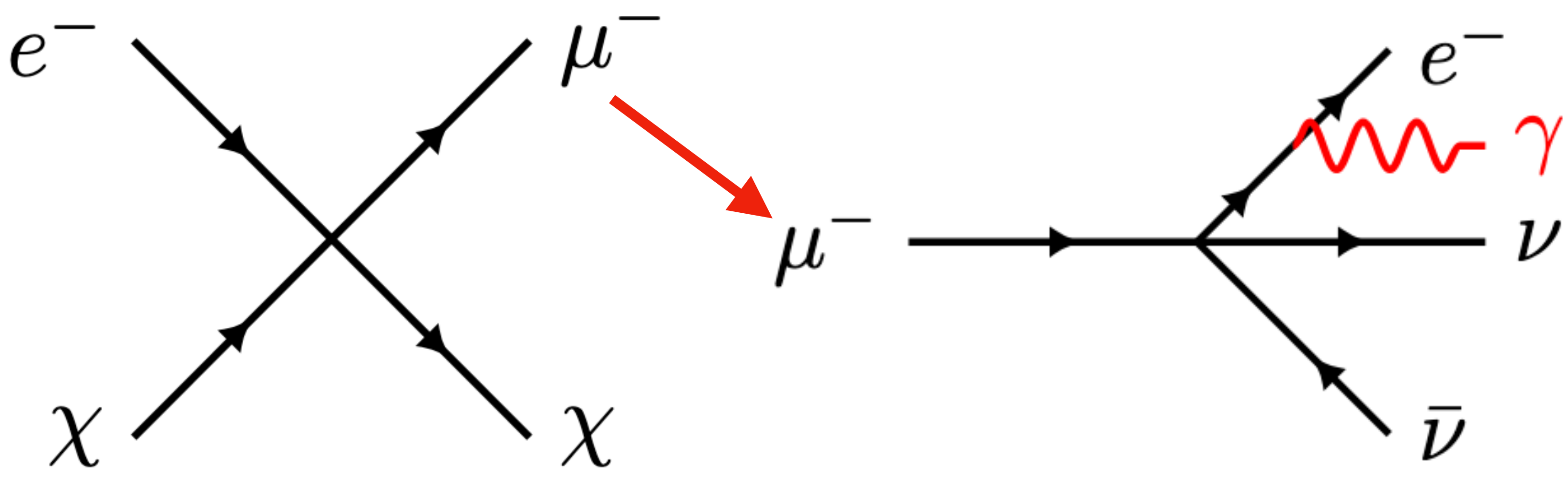
Scalar DM case	
$\mathcal{O}^{\mathtt{S},ij}_{\ell\phi} = (\overline{\ell_i}\ell_j)(\phi^\dagger\phi)$	$\mathcal{O}^{\mathtt{P},ij}_{\ell\phi} = (\overline{\ell_i}i\gamma_5\ell_j)(\phi^\dagger\phi)$
$\mathcal{O}^{\mathtt{V},ij}_{\ell\phi} = (\overline{\ell_i}\gamma^\mu\ell_j)(\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi)$(✗)	$\mathcal{O}^{\mathtt{A},ij}_{\ell\phi} = (\overline{\ell_i}\gamma^\mu\gamma_5\ell_j)(\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi)$(✗)
Fermion DM case	
$\mathcal{O}^{\mathtt{S},ij}_{\ell\chi1} = (\overline{\ell_i}\ell_j)(\overline{\chi}\chi)$	$\mathcal{O}^{\mathtt{P},ij}_{\ell\chi1} = (\overline{\ell_i}i\gamma_5\ell_j)(\overline{\chi}\chi)$
$\mathcal{O}^{\mathtt{S},ij}_{\ell\chi2} = (\overline{\ell_i}\ell_j)(\overline{\chi}i\gamma_5\chi)$	$\mathcal{O}^{\mathtt{P},ij}_{\ell\chi2} = (\overline{\ell_i}\gamma_5\ell_j)(\overline{\chi}\gamma_5\chi)$
$\mathcal{O}^{\mathtt{V},ij}_{\ell\chi1} = (\overline{\ell_i}\gamma^\mu\ell_j)(\overline{\chi}\gamma_\mu\chi)$ (✗)	$\mathcal{O}^{\mathtt{A},ij}_{\ell\chi1} = (\overline{\ell_i}\gamma^\mu\gamma_5\ell_j)(\overline{\chi}\gamma_\mu\chi)$(✗)
$\mathcal{O}^{\mathtt{V},ij}_{\ell\chi2} = (\overline{\ell_i}\gamma^\mu\ell_j)(\overline{\chi}\gamma_\mu\gamma_5\chi)$	$\mathcal{O}^{\mathtt{A},ij}_{\ell\chi2} = (\overline{\ell_i}\gamma^\mu\gamma_5\ell_j)(\overline{\chi}\gamma_\mu\gamma_5\chi)$
$\mathcal{O}^{\mathtt{T},ij}_{\ell\chi1} = (\overline{\ell_i}\sigma^{\mu\nu}\ell_j)(\overline{\chi}\sigma_{\mu\nu}\chi)$(✗)	$\mathcal{O}^{\mathtt{T},ij}_{\ell\chi2} = (\overline{\ell_i}\sigma^{\mu\nu}\ell_j)(\overline{\chi}\sigma_{\mu\nu}\gamma_5\chi)$ (✗)
Vector DM case A	
$\mathcal{O}^{\mathtt{S},ij}_{\ell X} = (\overline{\ell_i}\ell_j)(X^\dagger_\mu X^\mu)$	$\mathcal{O}^{\mathtt{P},ij}_{\ell X} = (\overline{\ell_i}i\gamma_5\ell_j)(X^\dagger_\mu X^\mu)$
$\mathcal{O}^{\mathtt{T},ij}_{\ell X1} = \frac{i}{2}(\overline{\ell_i}\sigma^{\mu\nu}\ell_j)(X^\dagger_\mu X_\nu - X^\dagger_\nu X_\mu)$(✗)	$\mathcal{O}^{\mathtt{T},ij}_{\ell X2} = \frac{1}{2}(\overline{\ell_i}\sigma^{\mu\nu}\gamma_5\ell_j)(X^\dagger_\mu X_\nu - X^\dagger_\nu X_\mu)$(✗)
$\mathcal{O}^{\mathtt{V},ij}_{\ell X1} = \frac{1}{2}[\overline{\ell_i}\gamma_{(\mu}i\overleftrightarrow{D_{\nu)}}\ell_j](X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$	$\mathcal{O}^{\mathtt{A},ij}_{\ell X1} = \frac{1}{2}[\overline{\ell_i}\gamma_{(\mu}\gamma_5 i\overleftrightarrow{D_{\nu)}}\ell_j](X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$
$\mathcal{O}^{\mathtt{V},ij}_{\ell X2} = (\overline{\ell_i}\gamma_\mu\ell_j)\partial_\nu(X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$	$\mathcal{O}^{\mathtt{A},ij}_{\ell X2} = (\overline{\ell_i}\gamma_\mu\gamma_5\ell_j)\partial_\nu(X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu)$
$\mathcal{O}^{\mathtt{V},ij}_{\ell X3} = (\overline{\ell_i}\gamma_\mu\ell_j)(X^\dagger_\rho\overleftrightarrow{\partial_\nu}X_\sigma)\epsilon^{\mu\nu\rho\sigma}$	$\mathcal{O}^{\mathtt{A},ij}_{\ell X3} = (\overline{\ell_i}\gamma_\mu\gamma_5\ell_j)(X^\dagger_\rho\overleftrightarrow{\partial_\nu}X_\sigma)\epsilon^{\mu\nu\rho\sigma}$
$\mathcal{O}^{\mathtt{V},ij}_{\ell X4} = (\overline{\ell_i}\gamma^\mu\ell_j)(X^\dagger_\nu i\overleftrightarrow{\partial_\mu}X^\nu)$(✗)	$\mathcal{O}^{\mathtt{A},ij}_{\ell X4} = (\overline{\ell_i}\gamma^\mu\gamma_5\ell_j)(X^\dagger_\nu i\overleftrightarrow{\partial_\mu}X^\nu)$(✗)
$\mathcal{O}^{\mathtt{V},ij}_{\ell X5} = (\overline{\ell_i}\gamma_\mu\ell_j)i\partial_\nu(X^{\mu\dagger}X^\nu - X^{\nu\dagger}X^\mu)$(✗)	$\mathcal{O}^{\mathtt{A},ij}_{\ell X5} = (\overline{\ell_i}\gamma_\mu\gamma_5\ell_j)i\partial_\nu(X^{\mu\dagger}X^\nu - X^{\nu\dagger}X^\mu)$(✗)
$\mathcal{O}^{\mathtt{V},ij}_{\ell X6} = (\overline{\ell_i}\gamma_\mu\ell_j)i\partial_\nu(X^\dagger_\rho X_\sigma)\epsilon^{\mu\nu\rho\sigma}$(✗)	$\mathcal{O}^{\mathtt{A},ij}_{\ell X6} = (\overline{\ell_i}\gamma_\mu\gamma_5\ell_j)i\partial_\nu(X^\dagger_\rho X_\sigma)\epsilon^{\mu\nu\rho\sigma}$(✗)
Vector DM case B	
$\tilde{\mathcal{O}}^{\mathtt{S},ij}_{\ell X1} = (\overline{\ell_i}\ell_j)X^\dagger_{\mu\nu}X^{\mu\nu}$	$\tilde{\mathcal{O}}^{\mathtt{S},ij}_{\ell X2} = (\overline{\ell_i}\ell_j)X^\dagger_{\mu\nu}\tilde{X}^{\mu\nu}$
$\tilde{\mathcal{O}}^{\mathtt{P},ij}_{\ell X1} = (\overline{\ell_i}i\gamma_5\ell_j)X^\dagger_{\mu\nu}X^{\mu\nu}$	$\tilde{\mathcal{O}}^{\mathtt{P},ij}_{\ell X2} = (\overline{\ell_i}i\gamma_5\ell_j)X^\dagger_{\mu\nu}\tilde{X}^{\mu\nu}$
$\tilde{\mathcal{O}}^{\mathtt{T},ij}_{\ell X1} = \frac{i}{2}(\overline{\ell_i}\sigma^{\mu\nu}\ell_j)(X^\dagger_{\mu\rho}X^\rho_\nu - X^\dagger_{\nu\rho}X^\rho_\mu)$ (✗)	$\tilde{\mathcal{O}}^{\mathtt{T},ij}_{\ell X2} = \frac{1}{2}(\overline{\ell_i}\sigma^{\mu\nu}\gamma_5\ell_j)(X^\dagger_{\mu\rho}X^\rho_\nu - X^\dagger_{\nu\rho}X^\rho_\mu)$(✗)

Direct detection for the scattering process

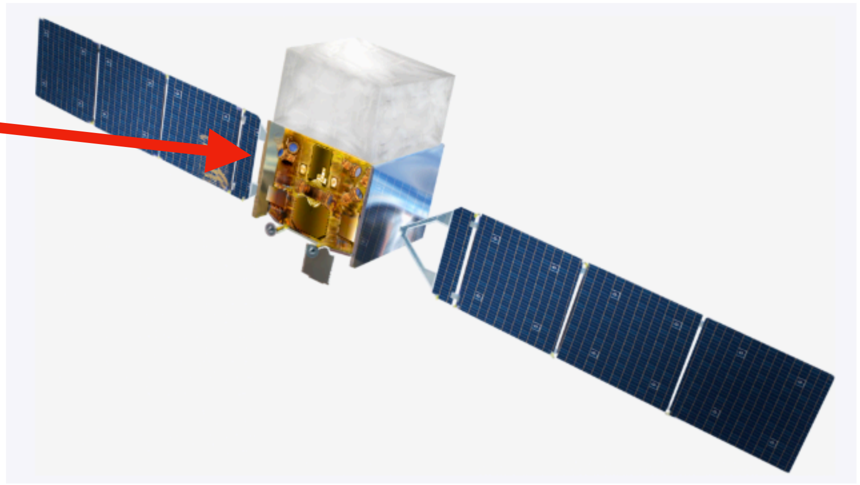


Super-K

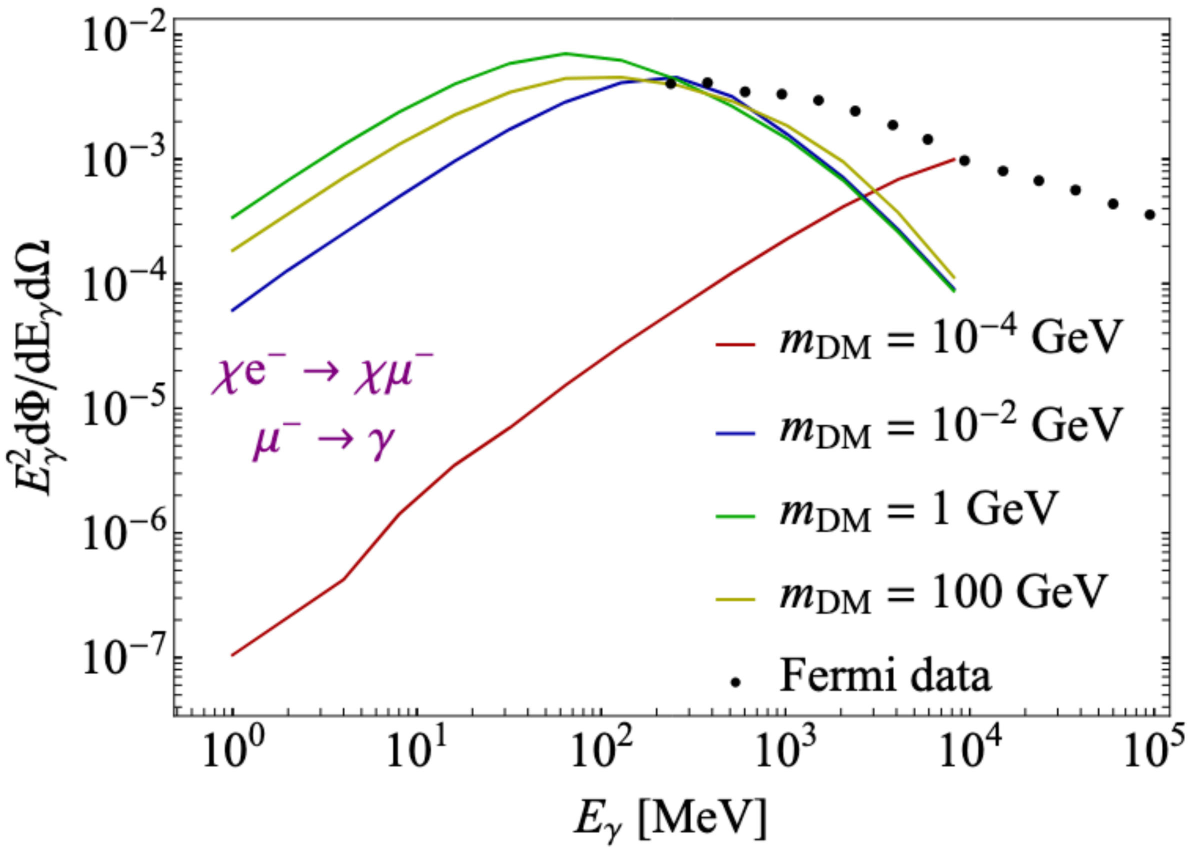
Indirect detection for the scattering process



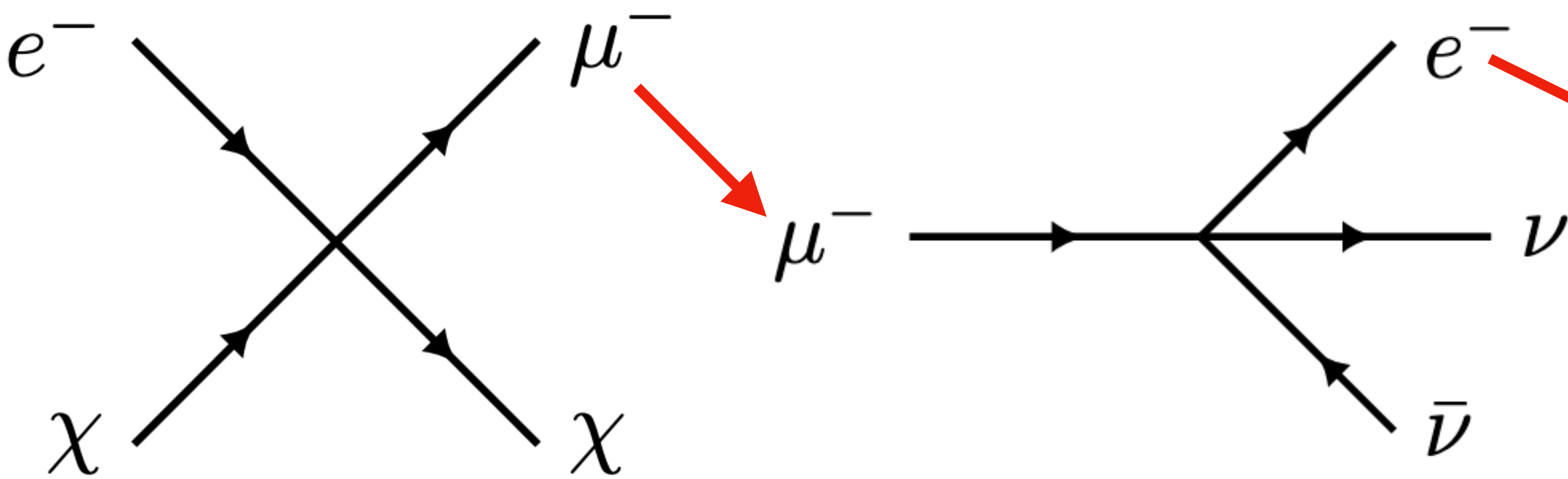
Fermi-LAT



JL, Liao, Ma, arXiv: 260x.xxxxx



Cosmic ray cooling for the scattering process



AMS

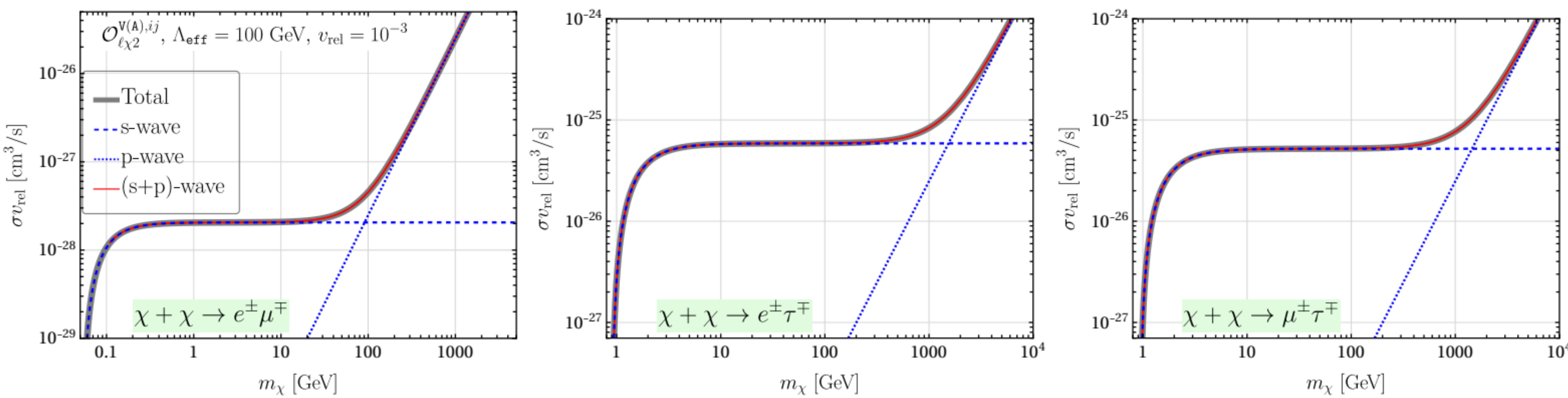
A fraction of the cosmic-ray electron energy is transferred to DM and neutrinos, causing additional energy loss.

$$\frac{dE_e}{dt}(E_e, m_{\rm DM}) = \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_{m_\mu}^{E_\mu^{\rm max}} dE_\mu \frac{d\sigma}{dE_\mu}(E_e, m_{\rm DM}) \int_{m_e}^{E_e^{\rm max}} dE'_e (E_e - E'_e) \frac{dN}{dE'_e}(E_\mu)$$

JL, Liao, Ma, arXiv: 260x.xxxxx

Annihilation cross section

$$\sigma v_{\rm rel} = \frac{m_\chi^2}{2\pi}\eta_{ij}(1-\eta_{ij})^2 + \frac{m_\chi^2}{24\pi}(1-\eta_{ij})(4-5\eta_{ij}+7\eta_{ij}^2)v_{\rm rel}^2$$



The s-wave contribution is valid only when the DM mass is below $m_{\mu(\tau)}/v_{\rm rel}$, whereas the p-wave contribution becomes significant when $m_{\mathtt{DM}} \gtrsim m_{\mu(\tau)}/v_{\rm rel}$.

Jahedi, **JL**, Liao, Ma, Uchida, arXiv: 2601.14048

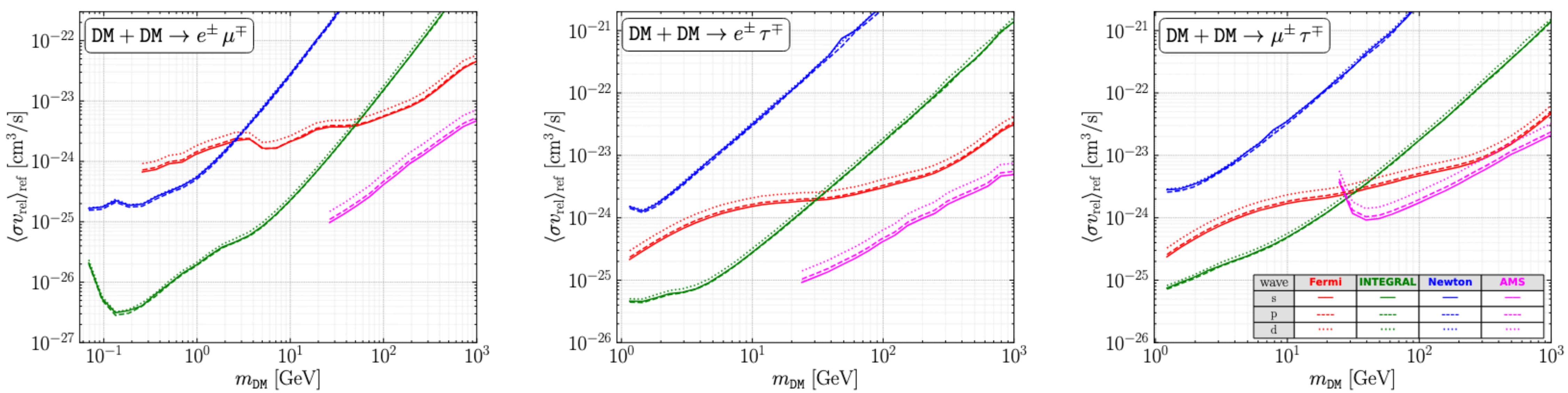
General constraints on annihilation cross sections

$$\sigma v_{\rm rel} = \hat{a} + \hat{b}\, v_{\rm rel}^2 + \hat{d}\, v_{\rm rel}^4 + \cdots \longrightarrow \langle \sigma v_{\rm rel}\rangle(r) \equiv \int d^3\vec{v}_1 f(r,\vec{v}_1) \int d^3\vec{v}_2 f(r,\vec{v}_2)\sigma v_{\rm rel}$$

$$= \hat{a} + 6\hat{b}\, v_0^2(r) + 60\hat{d}\, v_0^4(r) + \cdots$$

Jahedi, JL, Liao, Ma, Uchida, arXiv: 2601.14048

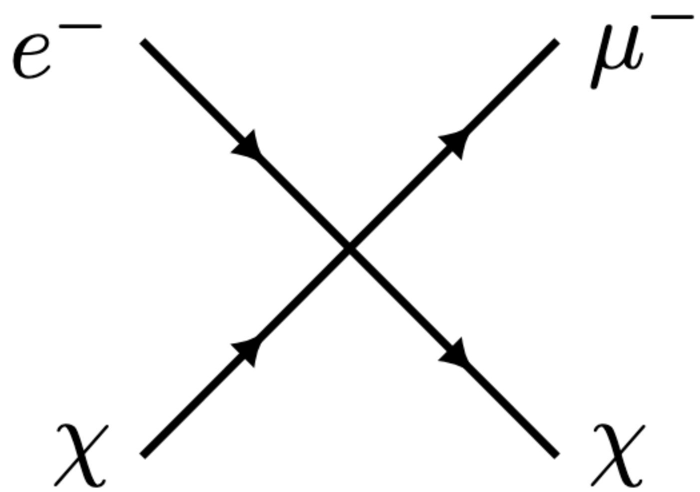
$$\boxed{\langle \sigma v_{\rm rel}\rangle_{\rm ref} \equiv \hat{a}_{2\sigma}, \hat{b}_{2\sigma}(v_{\rm ref}^{\rm p})^2, \hat{d}_{2\sigma}(v_{\rm ref}^{\rm d})^4 \qquad v_{\rm ref}^{\rm p} \simeq 1.4\times 10^{-3}, v_{\rm ref}^{\rm d} \simeq 1.7\times 10^{-3}}$$



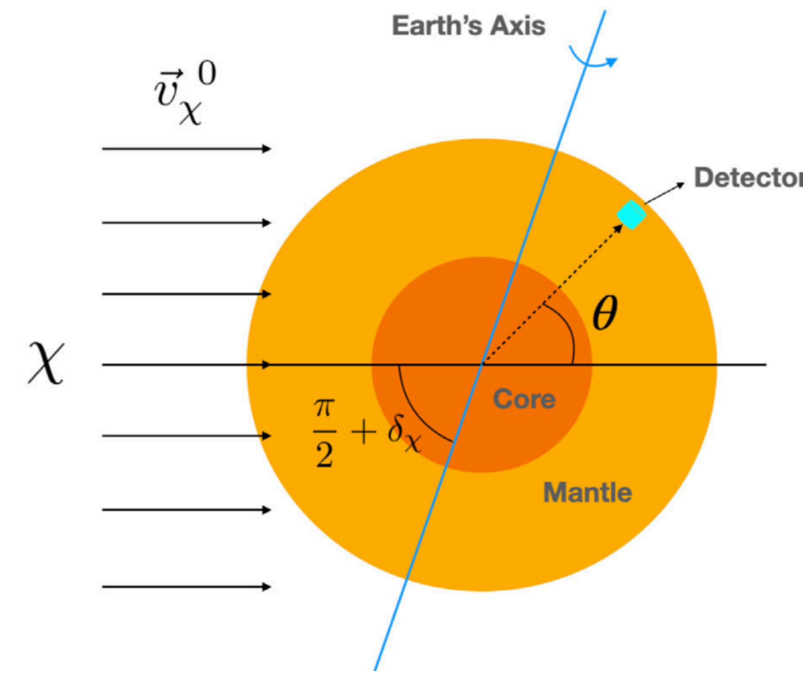
(1) INTEGRAL (AMS) provides the most stringent constraint at low (high) DM masses.

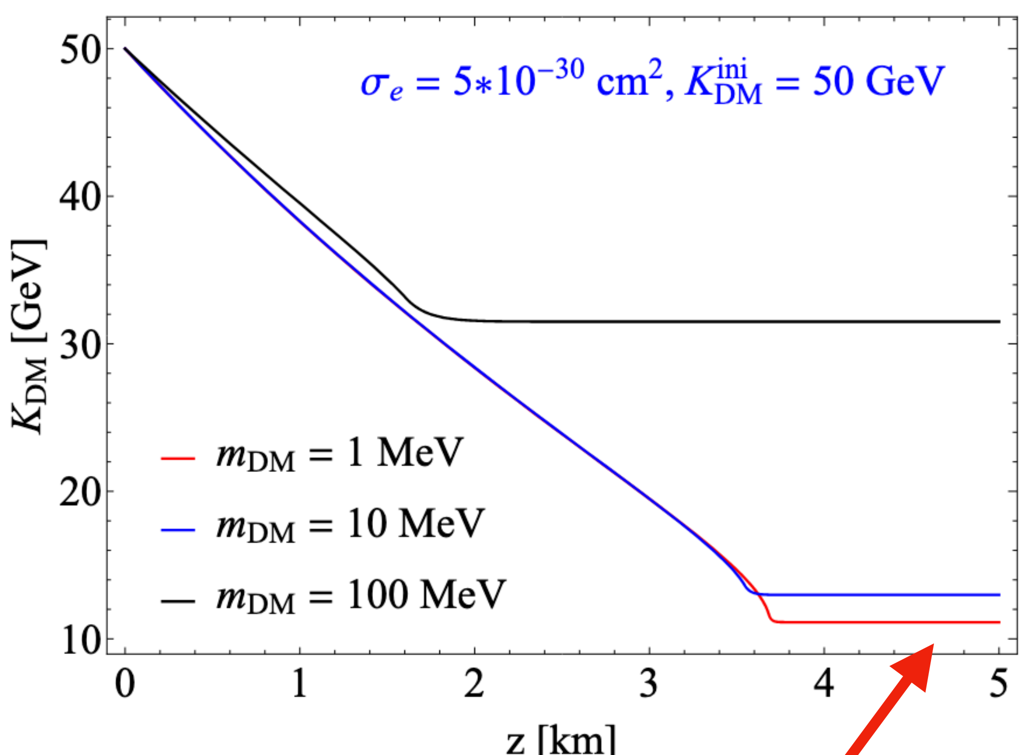
(2) The constraints for the s, p, and d wave cases can be approximately rescaled by global factors, giving $\hat{a}_{2\sigma} \simeq \hat{b}_{2\sigma}\left(v_{\rm ref}^{\rm p}\right)^2 \simeq \hat{d}_{2\sigma}\left(v_{\rm ref}^{\rm d}\right)^4$.

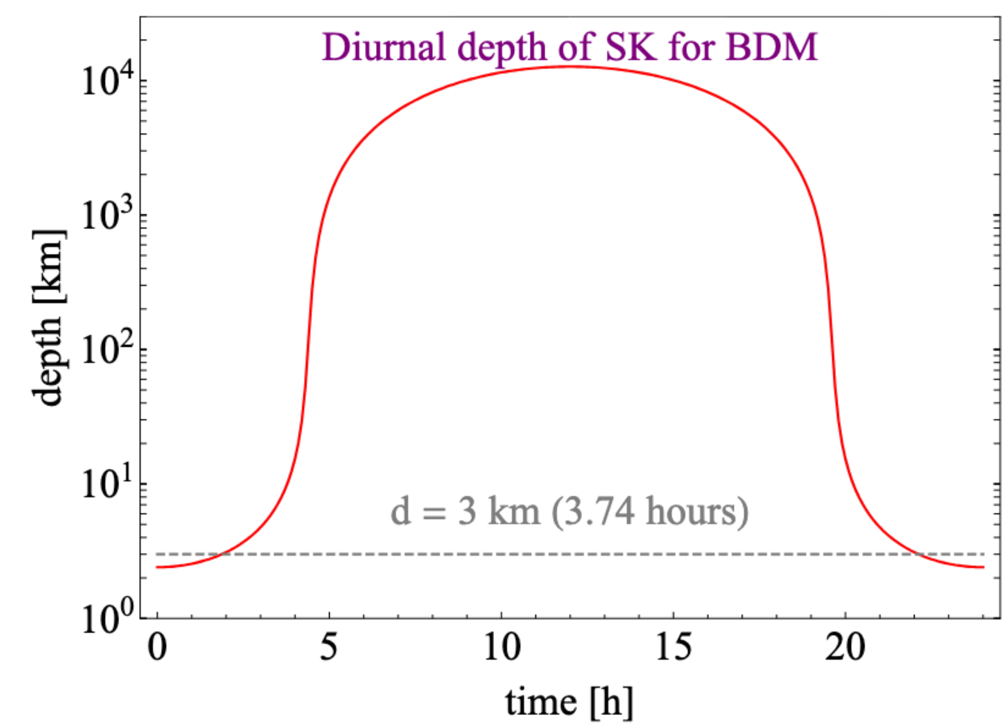
Earth shielding and daily modulation



Chen et al., PhysRevD.107.033006







$$E_\chi^{\rm min} = \frac{m_\mu^2 - m_e^2 + 2m_\mu m_\chi}{2m_e}$$

DM energy threshold for LFV scattering

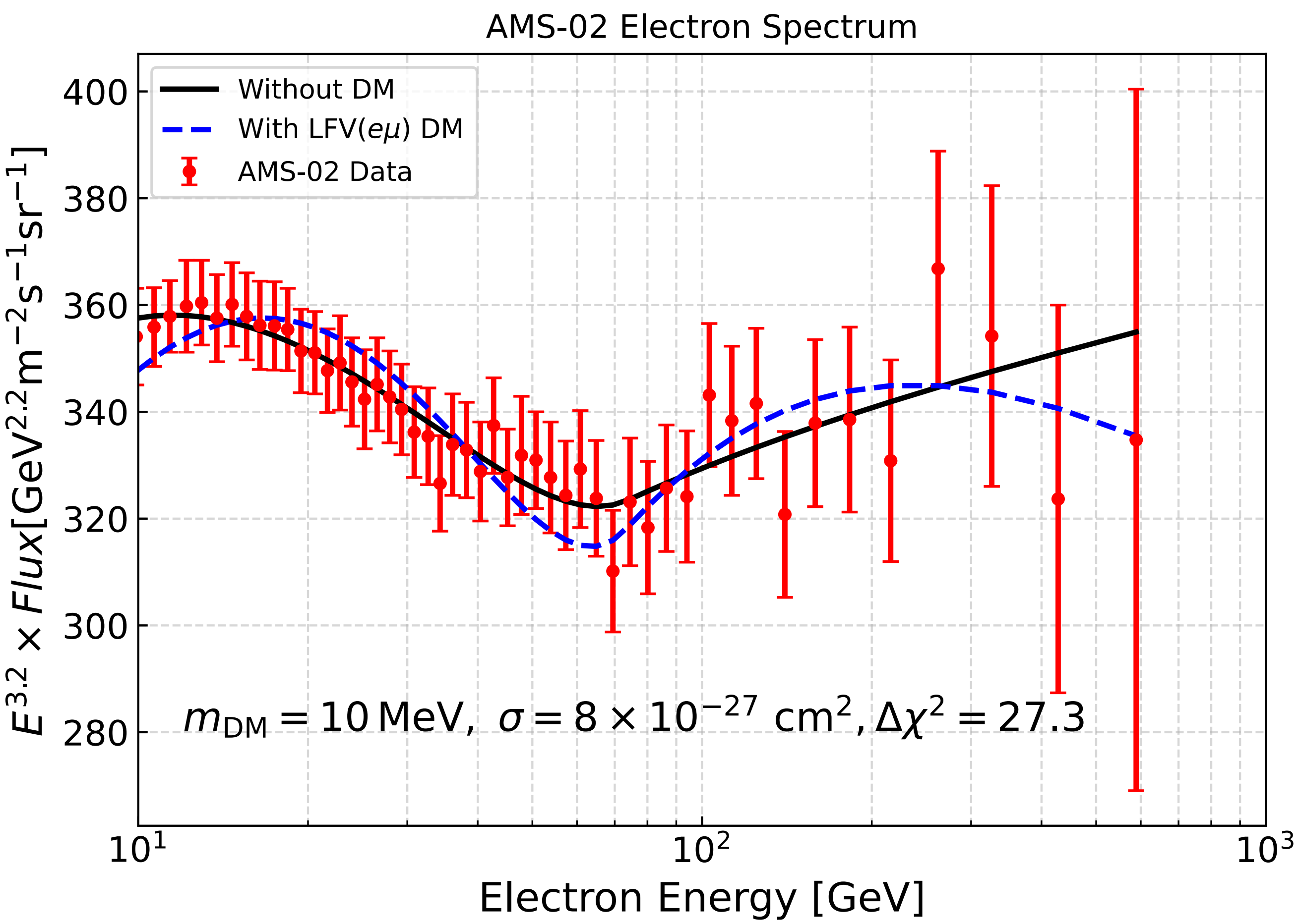
JL, Liao, Ma, arXiv: 2512.xxxxx

Backgrounds can be effectively reduced using angle and timing cuts.

Cosmic ray cooling for the scattering process

$$\frac{dE_e}{dt}(E_e, m_{\rm DM}) = \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_{m_\mu}^{E_\mu^{\rm max}} dE_\mu \frac{d\sigma}{dE_\mu}(E_e, m_{\rm DM}) \int_{m_e}^{E_e^{\rm max}} dE'_e (E_e - E'_e) \frac{dN}{dE'_e}(E_\mu)$$

JL, Liao, Ma, arXiv: 2512.xxxxx



Cappiello et al., Phys.Rev.D 99 (2019) 6, 063004

$$N(E) = \int_E^\infty dE' \frac{Q(E')}{dE'/dt} \times \exp\left(-\int_E^{E'} \frac{dE''}{(dE''/dt)\, T_{\rm esc}(E'')}\right)$$

$$\Delta\chi^2_{\rm mod} = \Delta\chi^2 + \frac{\mathrm{Log}_{10}\left(\int dE\, Q(E) / \int dE\, Q_0(E)\right)^2}{(\Delta Q)^2}$$

The energy injected into CRs cannot be arbitrarily large.