# 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**

arXiv: 2508.05121 (accepted by PRD letter)
arXiv: 2601.14048, arXiv: 260x.xxxxx

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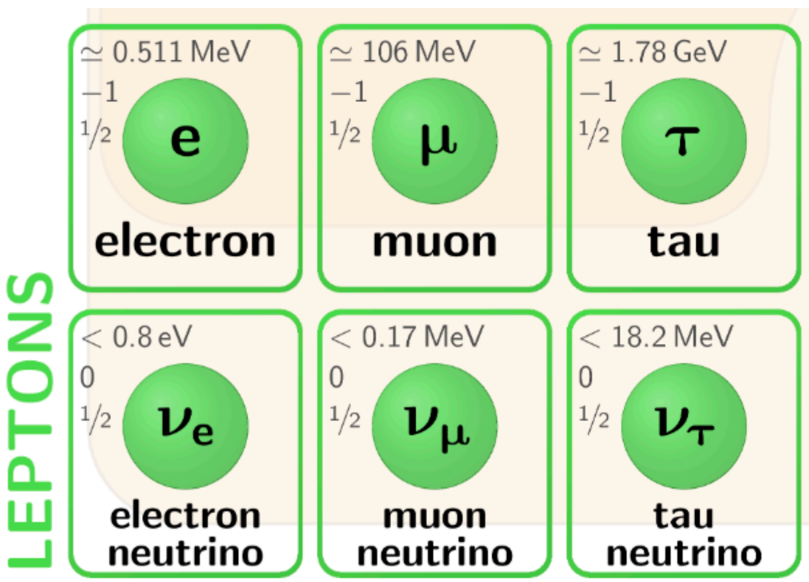
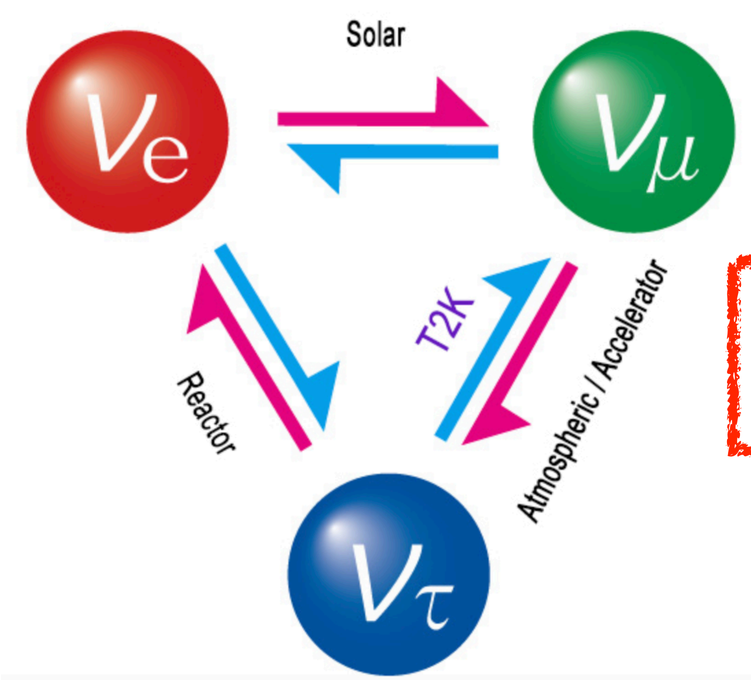
# Outline

- 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

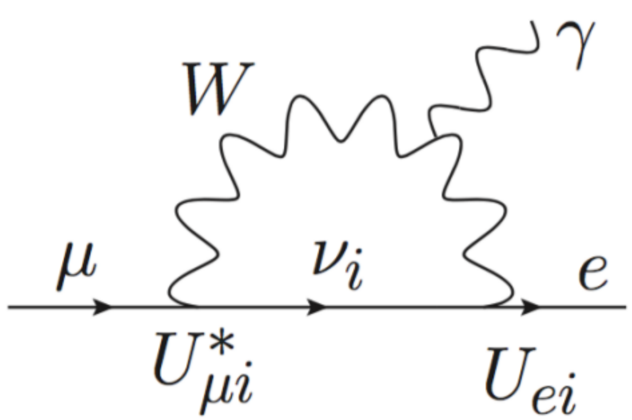
# Lepton Flavor violation in the SM




Neutrino oscillations indicate the LFV in the neutrino sector.

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

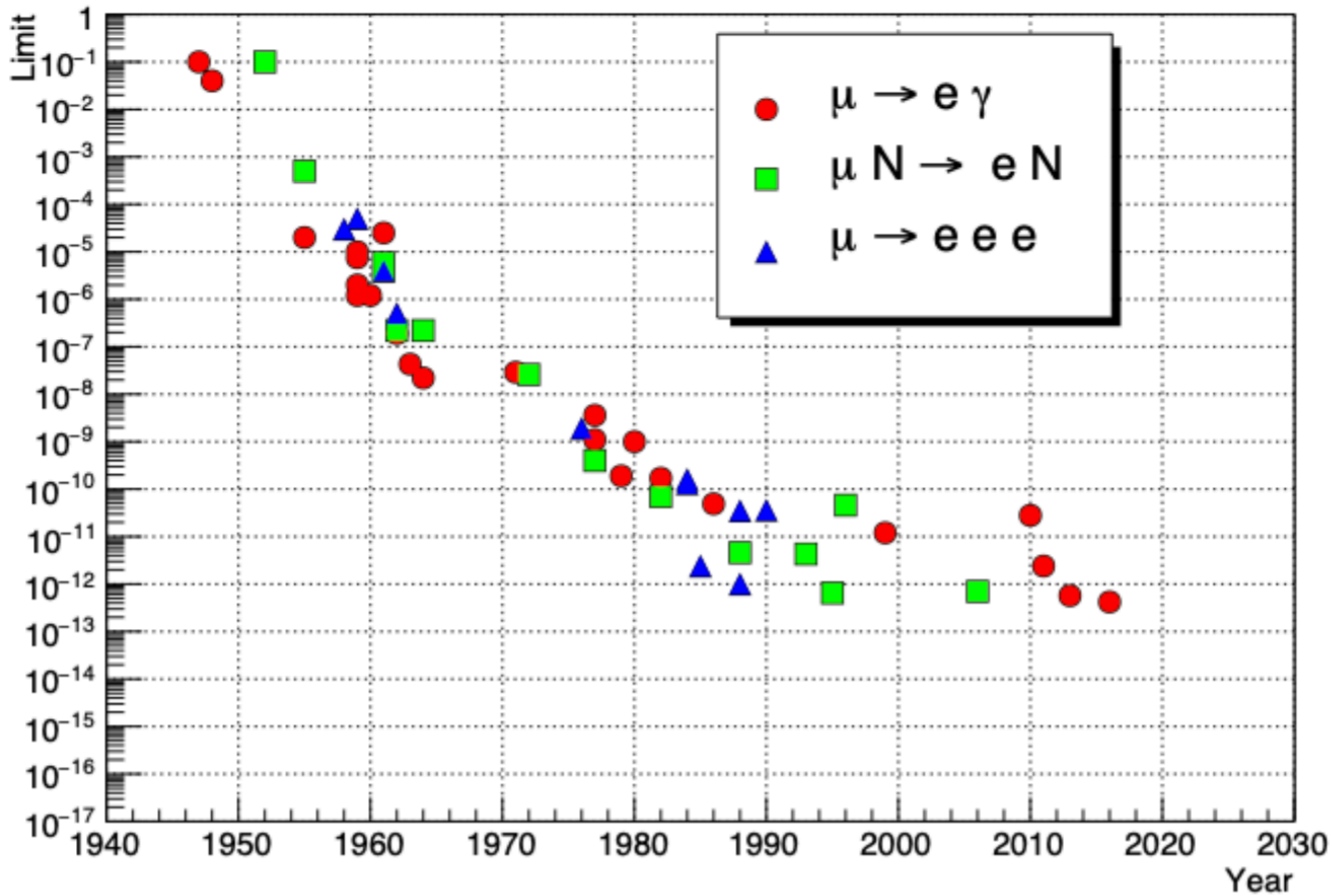



$$\mathrm{BR}(\mu \to e\gamma) \propto \left| \sum U^*_{\mu i} U_{ei} \frac{m^2_{\nu i}}{M^2_W} \right|^2 \sim 10^{-54}$$

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

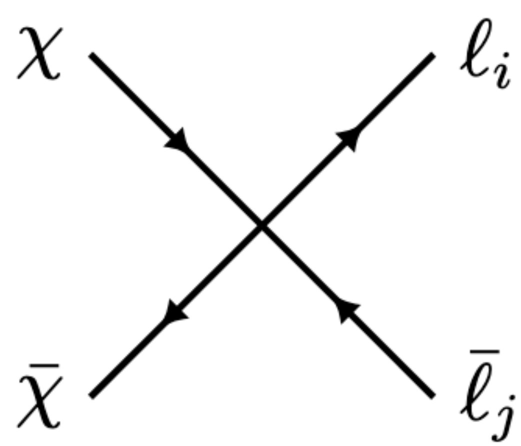
# Current experimential sensitivities to CLFV

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



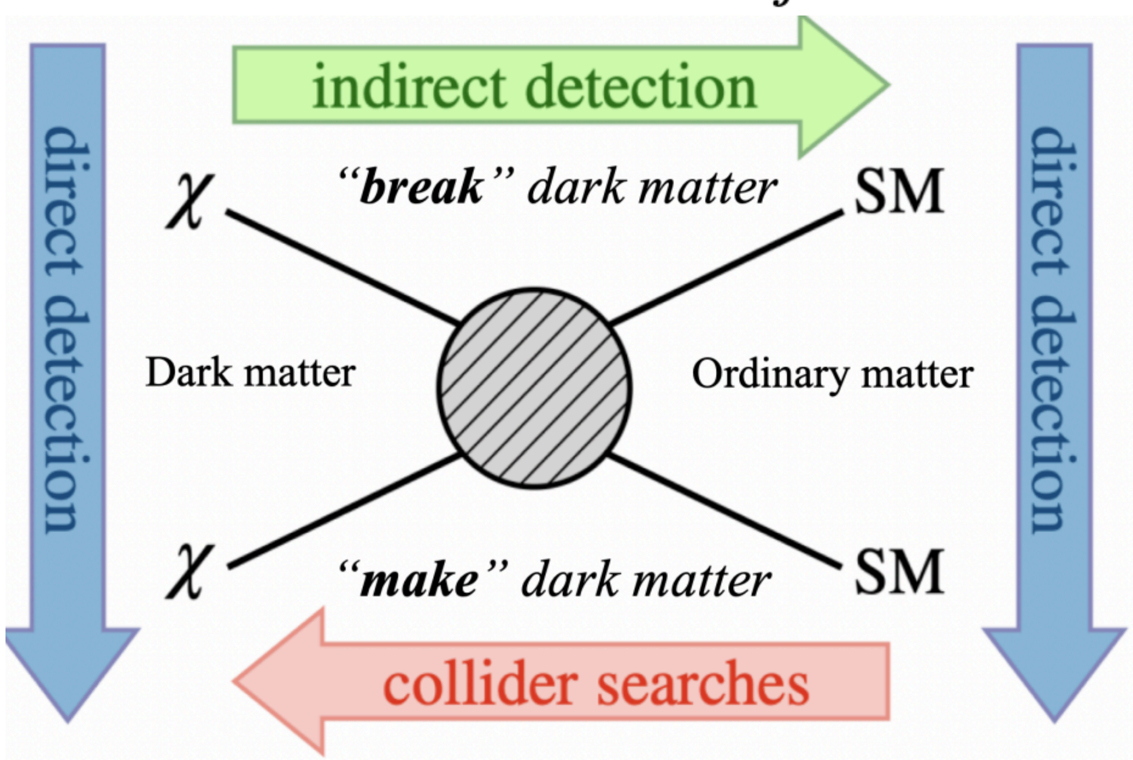

Both the initial- and final-state particles are SM particles

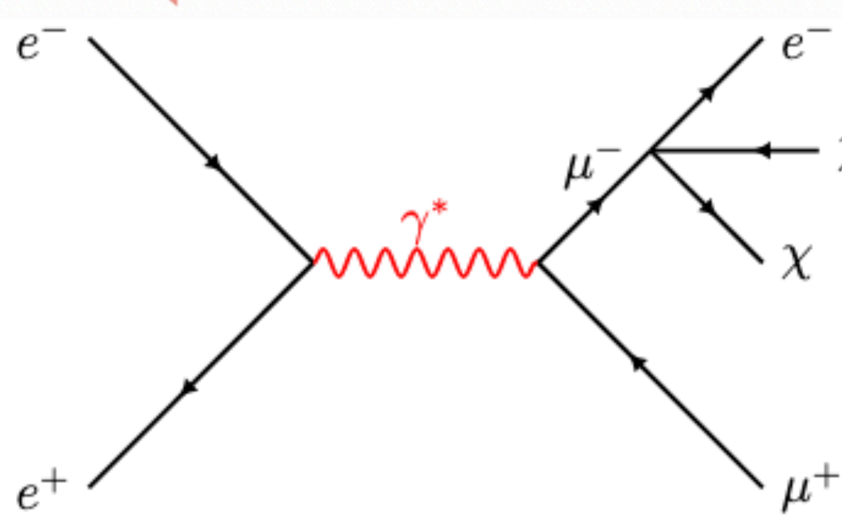
# Probing CLFV induced by dark matter

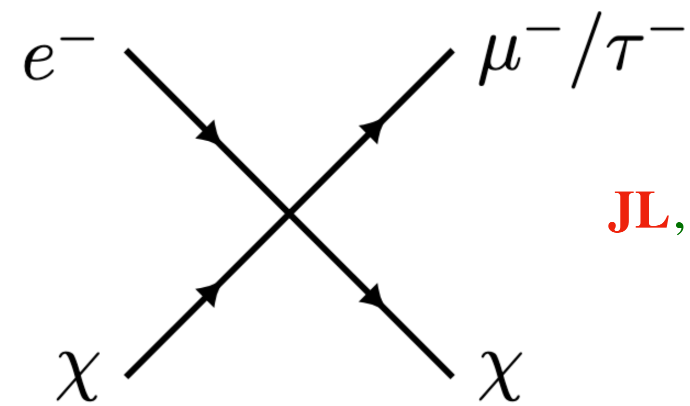



JL, Liao, Ma, arXiv: 2508.05121

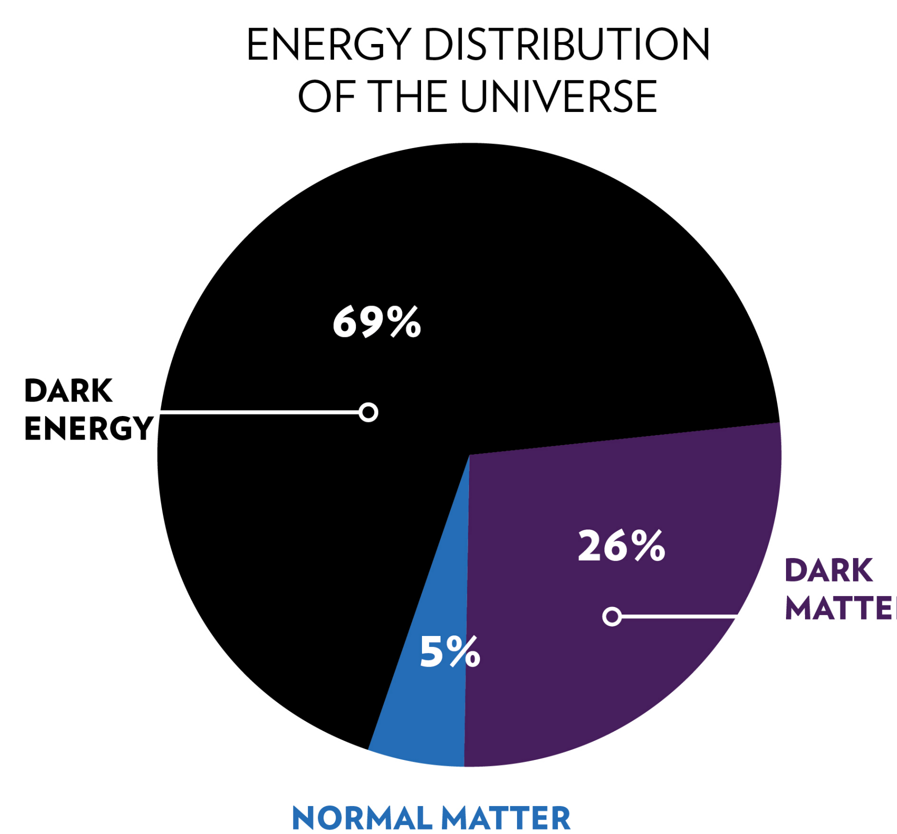
Jahedi, JL, Liao, Ma, Uchida, arXiv: 2601.14048



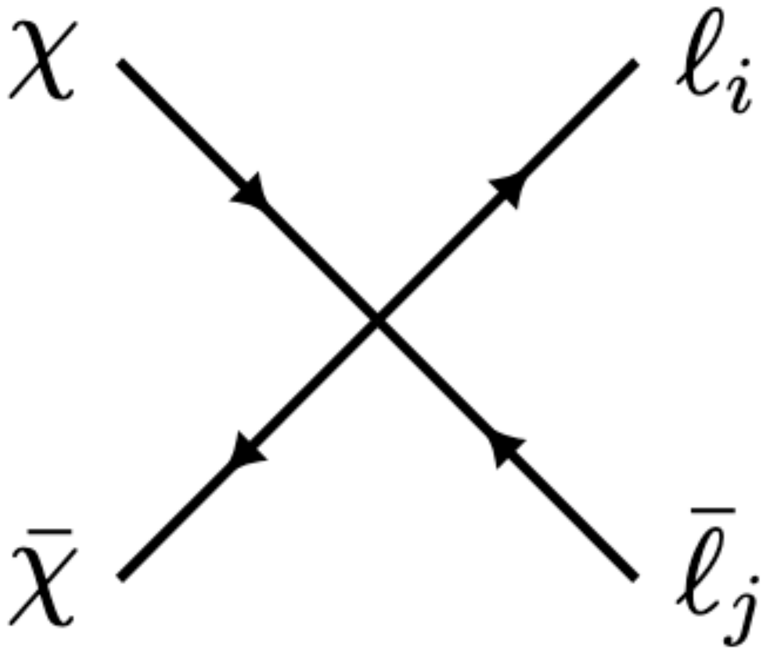




JL, Liao, Ma, arXiv: 260x.xxxxx

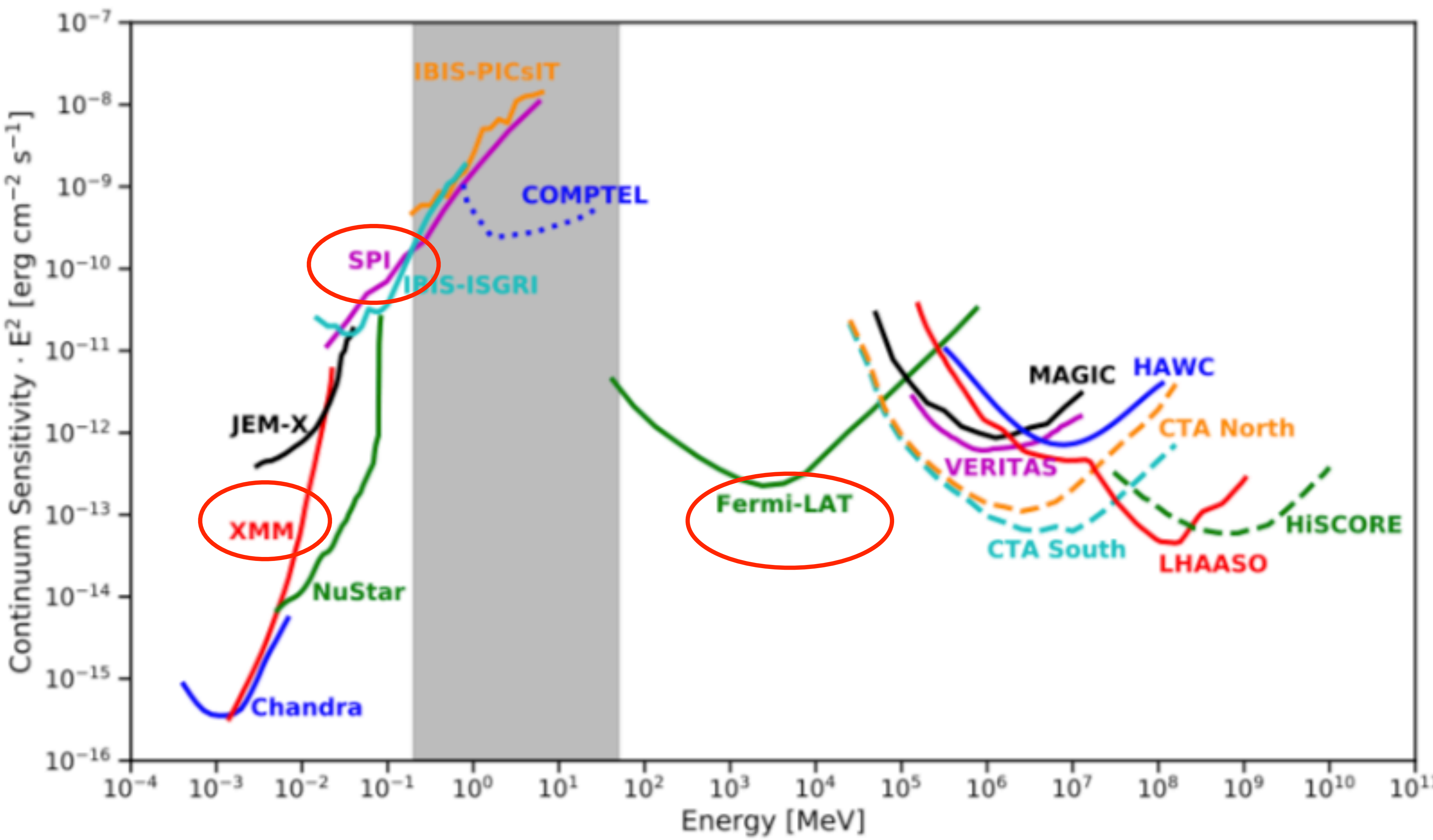


# Annihilation process for CLFV DM



# Astrophysical photons and electrons/positrons

Lucchetta et al., JCAP 08 (2022) 013




AMS: GeV - TeV

XMM-Newton: keV - 10 keV

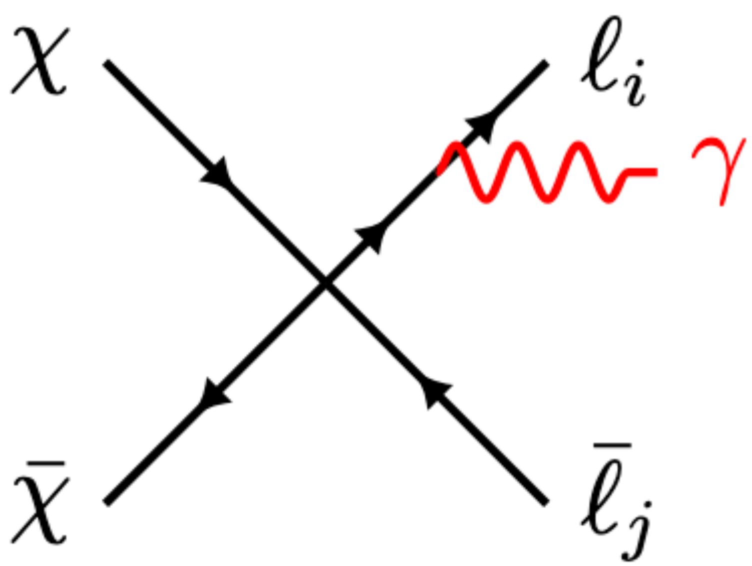
INTEGRAL/SPI: 10 keV - 10 MeV

Fermi: 100 MeV - TeV

# Photons generated 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

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

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

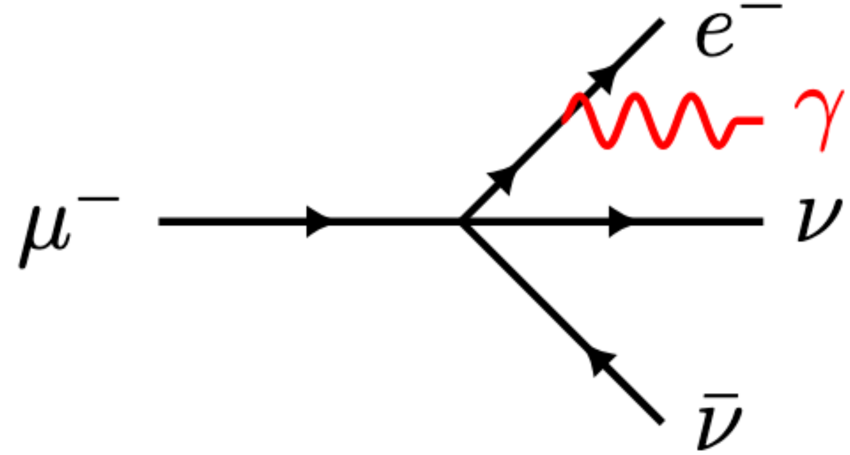
$$H_{i,j}(x_\gamma, \hat{s}) = d(x_\gamma, \hat{s}, m_i) + d(x_\gamma, \hat{s}, m_j)$$

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

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

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

# Radiative decay of muons and taus




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

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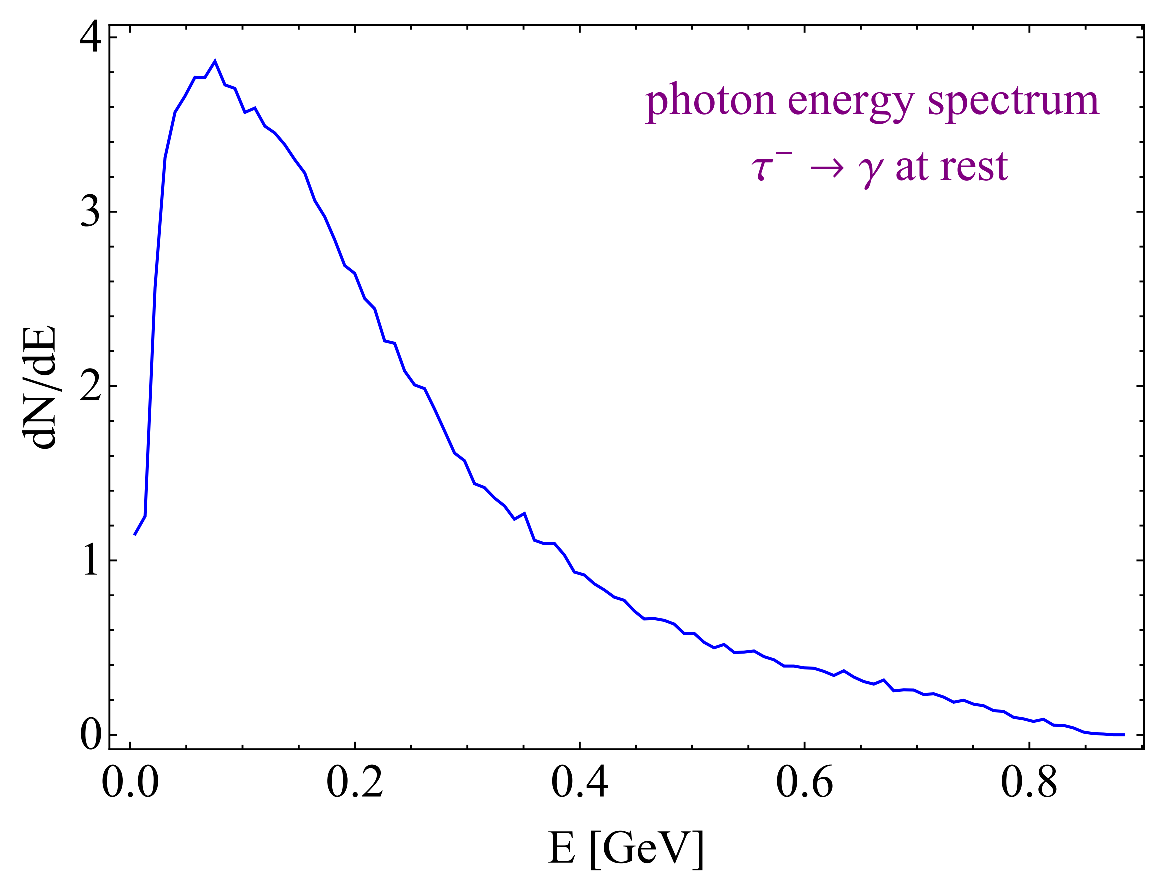
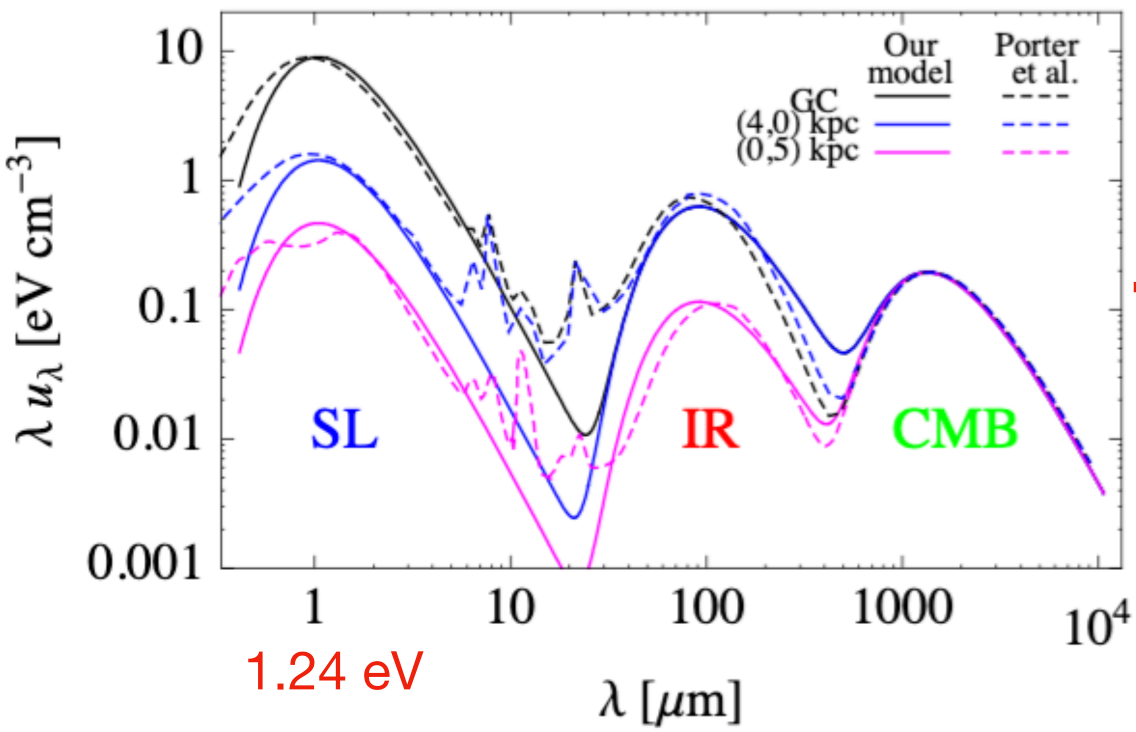
Pythia simulation for tau decay



# Inverse Compton scattering

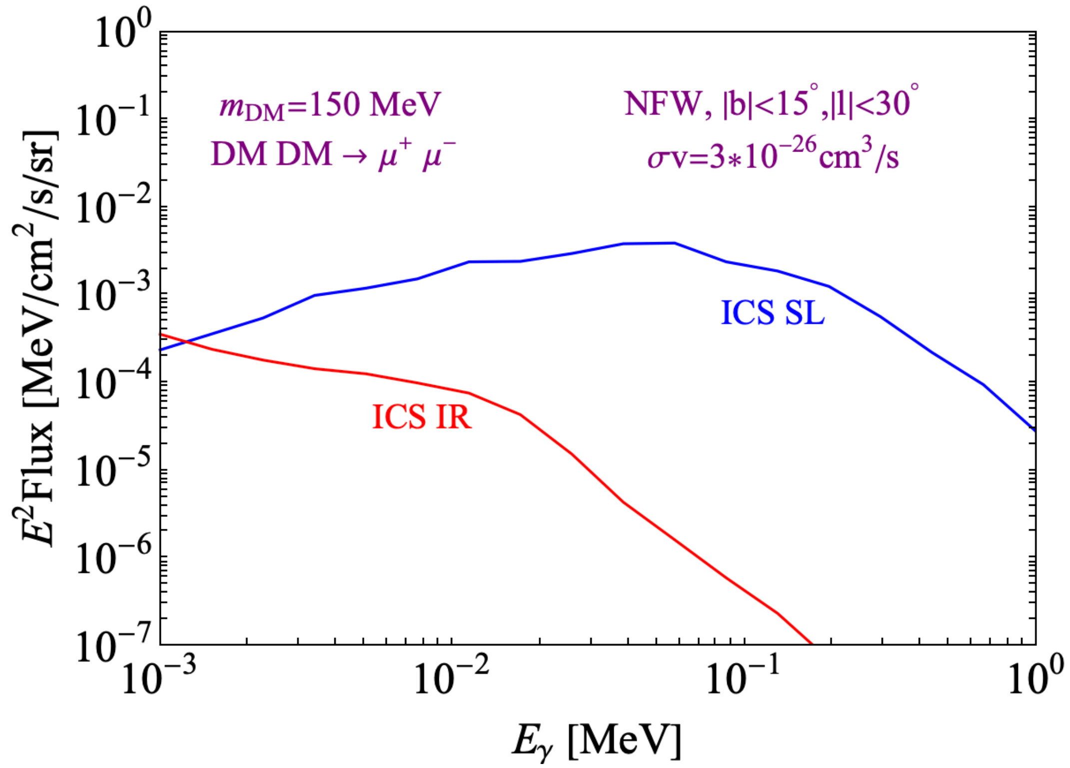
eV scale background photons

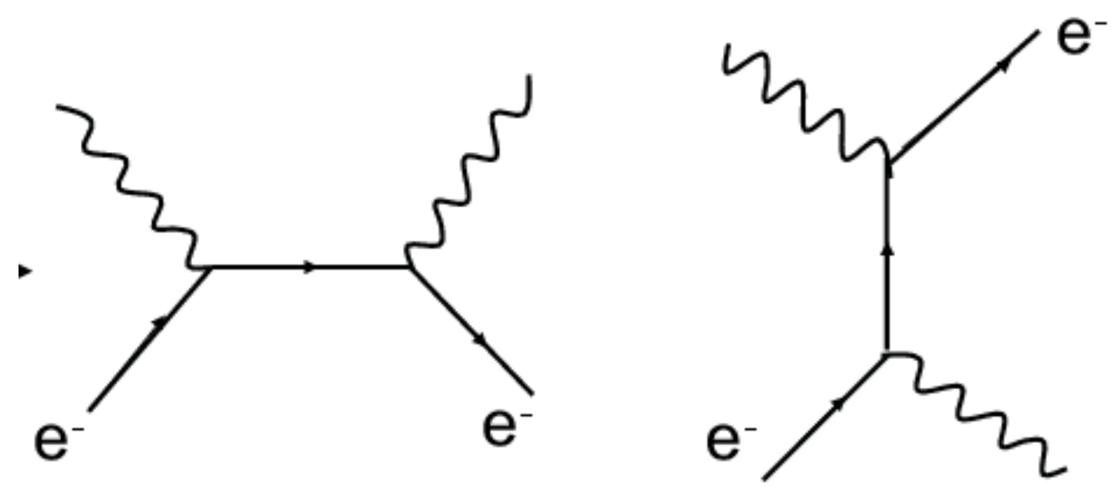



1.24 eV

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

X-ray or gamma-ray

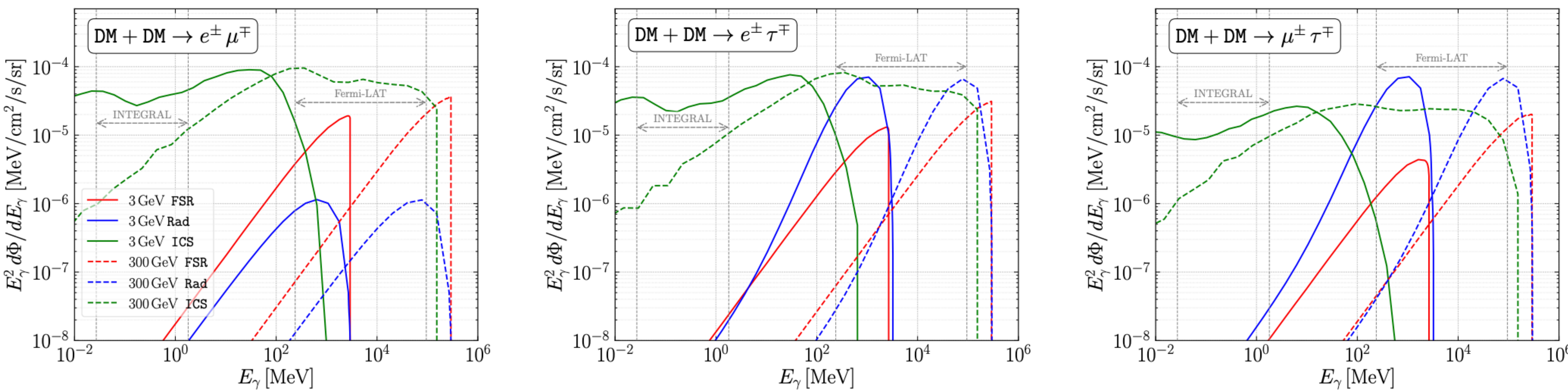



Inverse Compton scattering

# 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 $\tau$-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.

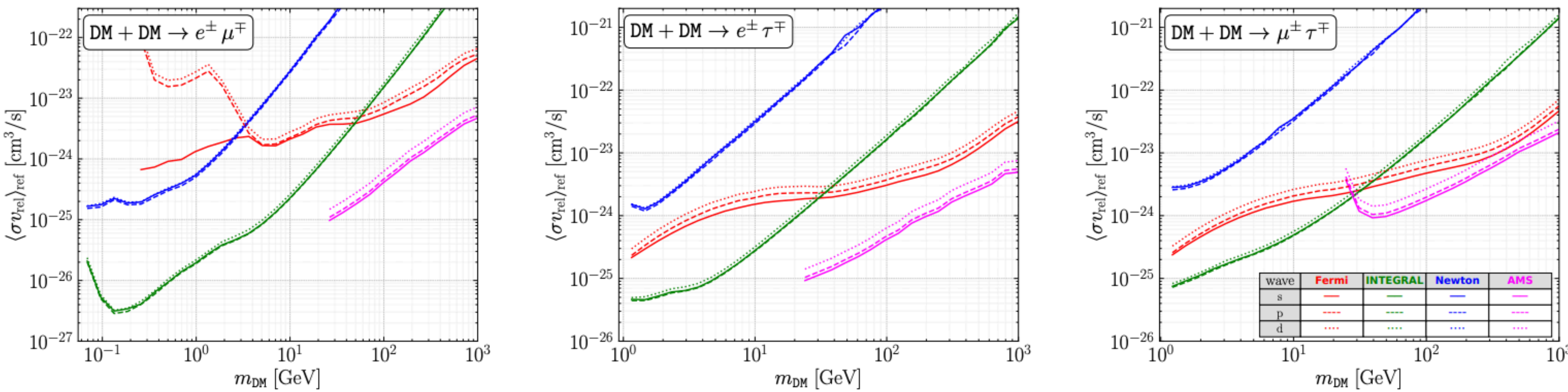
# General constraints on annihilation cross sections

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

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

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

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




(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 $\hat{a}_{2\sigma} \simeq \hat{b}_{2\sigma}\left(v_{\rm ref}^{\rm p}\right)^2 \simeq \hat{d}_{2\sigma}\left(v_{\rm ref}^{\rm d}\right)^4$.

# CLFV DM interaction EFT operators

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

| | |
|---|---|
| **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** | |
| $\tilde{\mathcal{O}}^{\mathtt{S},ij}_{\ell X1} = (\overline{\ell_i}\ell_j)X^\dagger_{\mu\nu}X^{\mu\nu}$ | $\tilde{\mathcal{O}}^{\mathtt{S},ij}_{\ell X2} = (\overline{\ell_i}\ell_j)X^\dagger_{\mu\nu}\tilde{X}^{\mu\nu}$ |
| $\tilde{\mathcal{O}}^{\mathtt{P},ij}_{\ell X1} = (\overline{\ell_i}i\gamma_5\ell_j)X^\dagger_{\mu\nu}X^{\mu\nu}$ | $\tilde{\mathcal{O}}^{\mathtt{P},ij}_{\ell X2} = (\overline{\ell_i}i\gamma_5\ell_j)X^\dagger_{\mu\nu}\tilde{X}^{\mu\nu}$ |
| $\tilde{\mathcal{O}}^{\mathtt{T},ij}_{\ell X1} = \frac{i}{2}(\overline{\ell_i}\sigma^{\mu\nu}\ell_j)(X^\dagger_{\mu\rho}X^\rho_\nu - X^\dagger_{\nu\rho}X^\rho_\mu)$ (✗) | $\tilde{\mathcal{O}}^{\mathtt{T},ij}_{\ell X2} = \frac{1}{2}(\overline{\ell_i}\sigma^{\mu\nu}\gamma_5\ell_j)(X^\dagger_{\mu\rho}X^\rho_\nu - X^\dagger_{\nu\rho}X^\rho_\mu)$(✗) |

# 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 $\sigma$ $[\lvert C_i^j\rvert^2]$ | Leading-order $\sigma v_{\rm rel}$ $[\lvert C_i^j\rvert^2]$ |
|---|---|---|
| | **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** | |
| $\mathcal{O}_{\ell\chi1}^{\mathtt{S},ij}(\mathcal{O}_{\ell\chi1}^{\mathtt{P},ij})$ | $\frac{\sqrt{\kappa_f\rho_+\rho_-}}{16\pi s}\rho_-,$ | $\frac{m_\chi^2}{8\pi}(1-\eta_{ij})^2v_{\rm rel}^2.$ |
| $\mathcal{O}_{\ell\chi2}^{\mathtt{S},ij}(\mathcal{O}_{\ell\chi2}^{\mathtt{P},ij})$ | $\frac{\sqrt{\rho_+\rho_-}}{16\pi s\sqrt{\kappa_f}}\rho_-,$ | $\frac{m_\chi^2}{2\pi}(1-\eta_{ij})^2.$ |
| $\mathcal{O}_{\ell\chi1}^{\mathtt{V},ij}(\mathcal{O}_{\ell\chi1}^{\mathtt{A},ij})$ | $\frac{\sqrt{\rho_+\rho_-}}{48\pi s^2\sqrt{\kappa_f}}(3-\kappa_f)\rho_+(3s-\rho_-),$ | $\frac{m_\chi^2}{2\pi}(1-\eta_{ij})^2(2+\eta_{ij}).$ |
| $\mathcal{O}_{\ell\chi2}^{\mathtt{V},ij}(\mathcal{O}_{\ell\chi2}^{\mathtt{A},ij})$ | $\frac{\sqrt{\rho_+\rho_-}}{48\pi s^2\sqrt{\kappa_f}}\{3s[2\kappa_f\rho_+ + (1-\kappa_f)\rho_-] - (3-\kappa_f)\rho_+\rho_-\},$ | $\frac{m_\chi^2}{2\pi}\eta_{ij}(1-\eta_{ij})^2$ $+\frac{m_\chi^2}{24\pi}(1-\eta_{ij})(4-5\eta_{ij}+7\eta_{ij}^2)v_{\rm rel}^2.$ |
| $\mathcal{O}_{\ell\chi1}^{\mathtt{T},ij}(\mathcal{O}_{\ell\chi2}^{\mathtt{T},ij})$ | $\frac{\sqrt{\rho_+\rho_-}}{12\pi s^2\sqrt{\kappa_f}}\{3s[(3-2\kappa_f)\rho_+ + \kappa_f\rho_-] - 2(3-\kappa_f)\rho_+\rho_-\},$ | $\frac{2m_\chi^2}{\pi}(1-\eta_{ij})^2(1+2\eta_{ij}).$ |
| | **Vector DM case A** | |
| $\mathcal{O}_{\ell X}^{\mathtt{S},ij}(\mathcal{O}_{\ell X}^{\mathtt{P},ij})$ | $\frac{\sqrt{\rho_+\rho_-}}{1512\pi m_X^4\sqrt{\kappa_f}}(3-2\kappa_f+3\kappa_f^2)\rho_-,$ | $\frac{1}{12\pi}(1-\eta_{ij})^2.$ |
| $\mathcal{O}_{\ell X1}^{\mathtt{T},ij}(\mathcal{O}_{\ell X2}^{\mathtt{T},ij})$ | $\frac{\sqrt{\rho_+\rho_-}}{1728\pi m_X^4 s\sqrt{\kappa_f}}\{3s[2(2\kappa_f-\kappa_f^2)\rho_+ + (3-4\kappa_f+\kappa_f^2)\rho_-] - 2(3-\kappa_f^2)\rho_+\rho_-\},$ | $\frac{1}{18\pi}(1-\eta_{ij})^2(1+2\eta_{ij}).$ |
| $\mathcal{O}_{\ell X1}^{\mathtt{V},ij}(\mathcal{O}_{\ell X1}^{\mathtt{A},ij})$ | $\frac{\sqrt{\rho_+\rho_-}}{4320\pi m_X^4 s^2\sqrt{\kappa_f}}\{15s^3[(\kappa_f-\kappa_f^2)\rho_+ + \kappa_f^2\rho_-]$ $-5s^2[3(\kappa_f-\kappa_f^2)\rho_+^2 + 3\kappa_f^2\rho_-^2 + 4\kappa_f\rho_+\rho_-]$ $+10s[(3-2\kappa_f)\rho_+ + (\kappa_f+\kappa_f^2)\rho_-]\rho_+\rho_- - (15-10\kappa_f+3\kappa_f^2)\rho_+^2\rho_-^2\},$ | $\frac{4m_X^2}{9\pi}(1-\eta_{ij})^4(1+\eta_{ij}).$ |
| $\mathcal{O}_{\ell X2}^{\mathtt{V},ij}(\mathcal{O}_{\ell X2}^{\mathtt{A},ij})$ | $\frac{\sqrt{\kappa_f\rho_+\rho_-}}{864\pi m_X^4}\{3s[(1-\kappa_f)\rho_+ + \kappa_f\rho_-] - (1+2\kappa_f)\rho_+\rho_-\},$ | $\frac{m_X^2}{27\pi}(1-\eta_{ij})^2(2+\eta_{ij})v_{\rm rel}^2.$ |
| $\mathcal{O}_{\ell X3}^{\mathtt{V},ij}(\mathcal{O}_{\ell X3}^{\mathtt{A},ij})$ | $\frac{\sqrt{\kappa_f\rho_+\rho_-}}{432\pi m_X^2 s}\{3s[2\kappa_f\rho_+ + (1-\kappa_f)\rho_-] - (3-\kappa_f)\rho_+\rho_-\},$ | $\frac{m_X^2}{18\pi}\eta_{ij}(1-\eta_{ij})^2v_{\rm rel}^2$ $+\frac{m_X^2}{108\pi}(1-\eta_{ij})(2-\eta_{ij}+2\eta_{ij}^2)v_{\rm rel}^4.$ |
| $\mathcal{O}_{\ell X4}^{\mathtt{V},ij}(\mathcal{O}_{\ell X4}^{\mathtt{A},ij})$ | $\frac{\sqrt{\kappa_f\rho_+\rho_-}}{3456\pi m_X^4}(3-2\kappa_f+3\kappa_f^2)\rho_+(3s-\rho_-),$ | $\frac{m_X^2}{36\pi}(1-\eta_{ij})^2(2+\eta_{ij})v_{\rm rel}^2.$ |
| $\mathcal{O}_{\ell X5}^{\mathtt{V},ij}(\mathcal{O}_{\ell X5}^{\mathtt{A},ij})$ | $\frac{\sqrt{\kappa_f\rho_+\rho_-}}{864\pi m_X^4}(2-\kappa_f)\rho_+(3s-\rho_-),$ | $\frac{2m_X^2}{27\pi}(1-\eta_{ij})^2(2+\eta_{ij})v_{\rm rel}^2.$ |
| $\mathcal{O}_{\ell X6}^{\mathtt{V},ij}(\mathcal{O}_{\ell X6}^{\mathtt{A},ij})$ | $\frac{\sqrt{\rho_+\rho_-}}{432\pi m_X^2 s\sqrt{\kappa_f}}(3-\kappa_f)\rho_+(3s-\rho_-),$ | $\frac{2m_X^2}{9\pi}(1-\eta_{ij})^2(2+\eta_{ij}).$ |
| | **Vector DM case B** | |
| $\tilde{\mathcal{O}}_{\ell X1}^{\mathtt{S},ij}(\tilde{\mathcal{O}}_{\ell X1}^{\mathtt{P},ij})$ | $\frac{\sqrt{\rho_+\rho_-}}{288\pi\sqrt{\kappa_f}}(3+2\kappa_f+3\kappa_f^2)\rho_-,$ | $\frac{m_X^4}{3\pi}(1-\eta_{ij})^2.$ |
| $\tilde{\mathcal{O}}_{\ell X2}^{\mathtt{S},ij}(\tilde{\mathcal{O}}_{\ell X2}^{\mathtt{P},ij})$ | $\frac{\sqrt{\kappa_f\rho_+\rho_-}}{36\pi}\rho_-,$ | $\frac{2m_X^4}{9\pi}(1-\eta_{ij})^2v_{\rm rel}^2.$ |
| $\tilde{\mathcal{O}}_{\ell X1}^{\mathtt{T},ij}(\tilde{\mathcal{O}}_{\ell X2}^{\mathtt{T},ij})$ | $\frac{\sqrt{\rho_+\rho_-}}{1728\pi s\sqrt{\kappa_f}}\{3s[2(3\kappa_f-\kappa_f^2)\rho_+ + (3+\kappa_f^2)\rho_-] - 2(3+6\kappa_f-\kappa_f^2)\rho_+\rho_-\},$ | $\frac{m_X^4}{18\pi}(1-\eta_{ij})^2(1+2\eta_{ij}).$ |

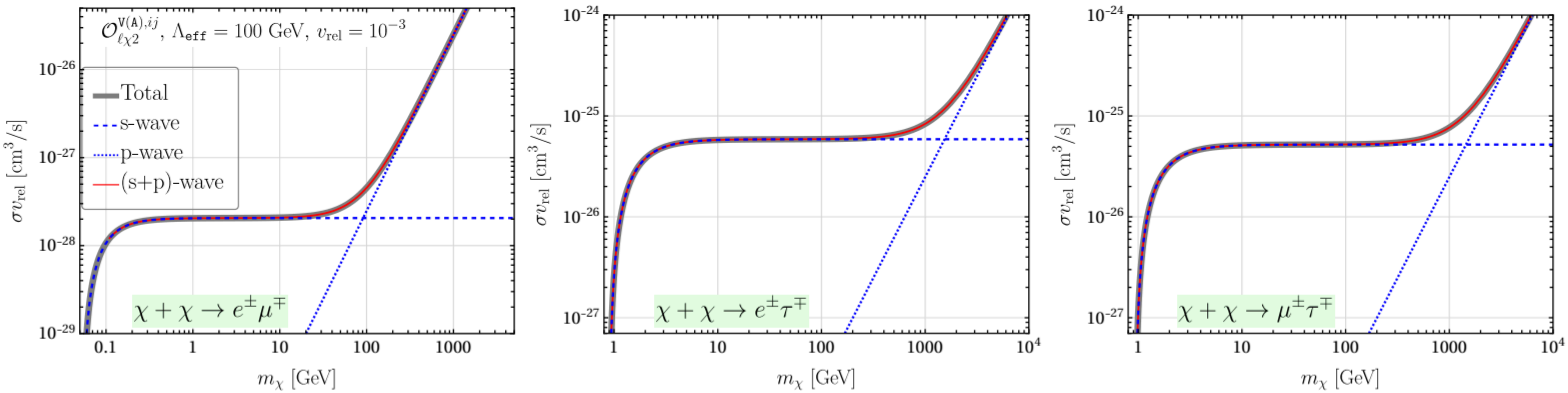
Leading term is suppressed by a mass fraction

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

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

# Annihilation cross section

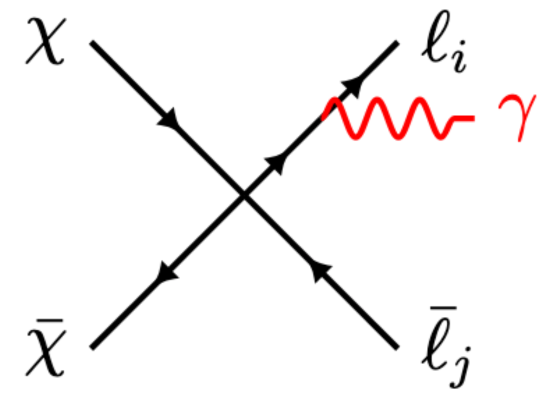
$$\sigma v_{\rm rel} = \frac{m_\chi^2}{2\pi}\eta_{ij}(1-\eta_{ij})^2 + \frac{m_\chi^2}{24\pi}(1-\eta_{ij})(4-5\eta_{ij}+7\eta_{ij}^2)v_{\rm rel}^2$$




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 $m_{\rm DM} \gtrsim m_{\mu(\tau)}/v_{\rm rel}$.

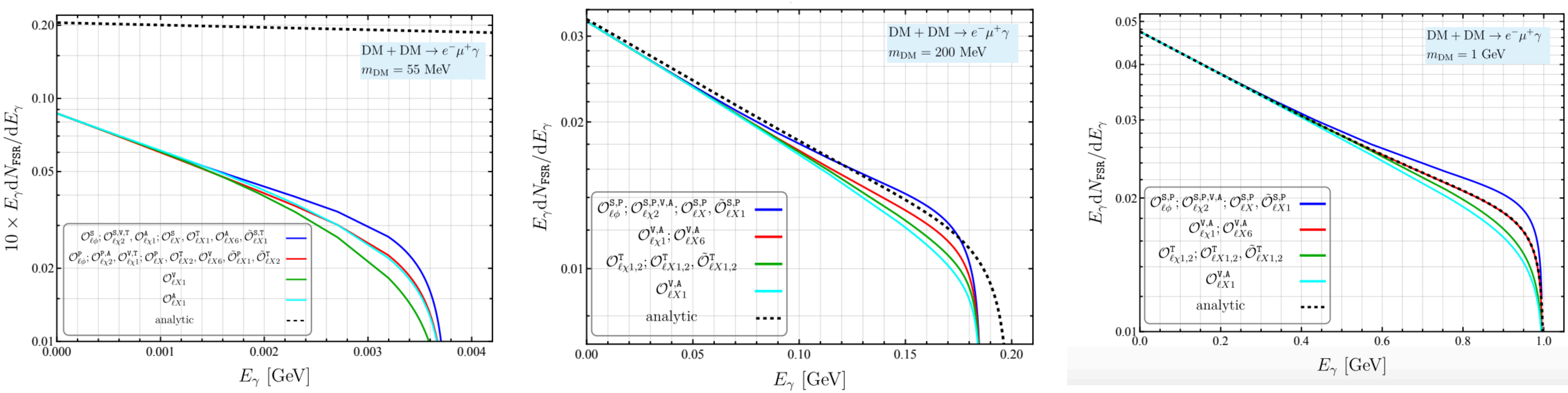
Jahedi, **JL**, Liao, Ma, Uchida, arXiv: 2601.14048

# FSR for different operators




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

Increasing DM mass →




Dashed: structure function method

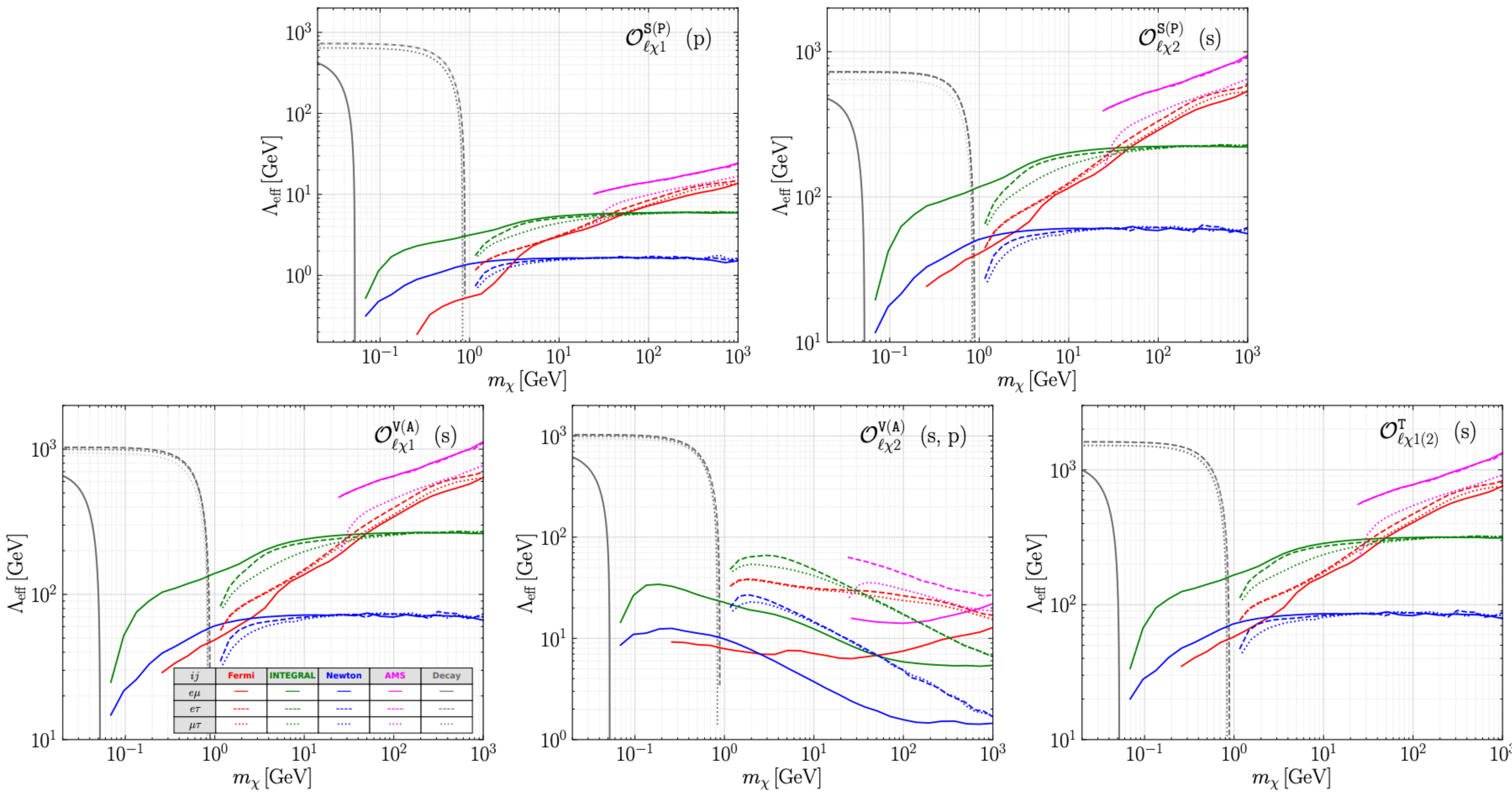
Solid: numerically integrate over the phase space

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

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

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

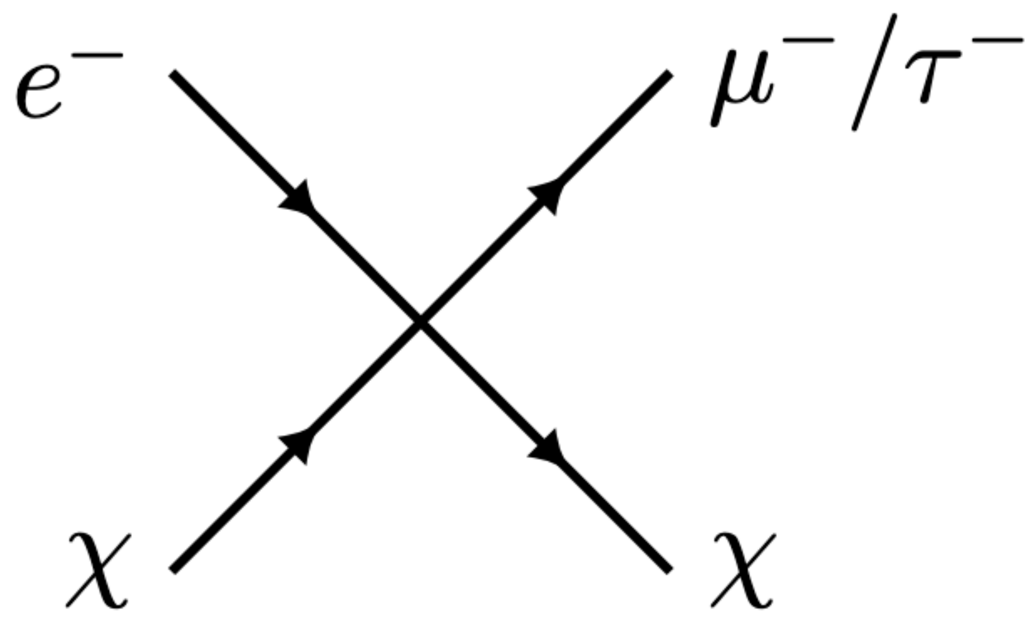
# Constraints on EFT operators



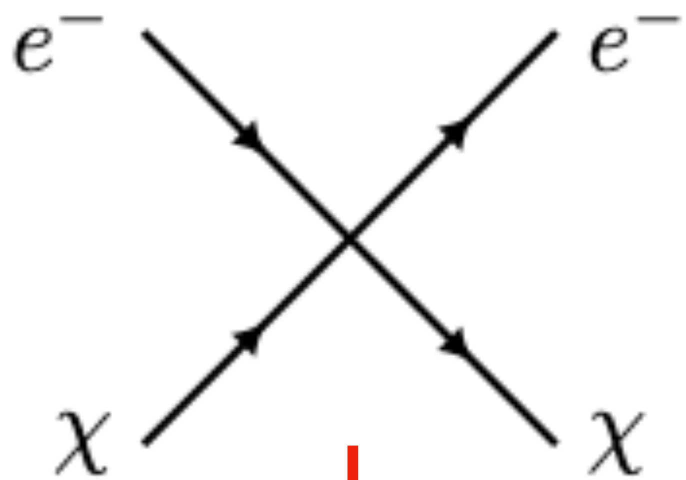

The constraints can reach about 1 TeV (tens of GeV) for s- (p-) wave operators.

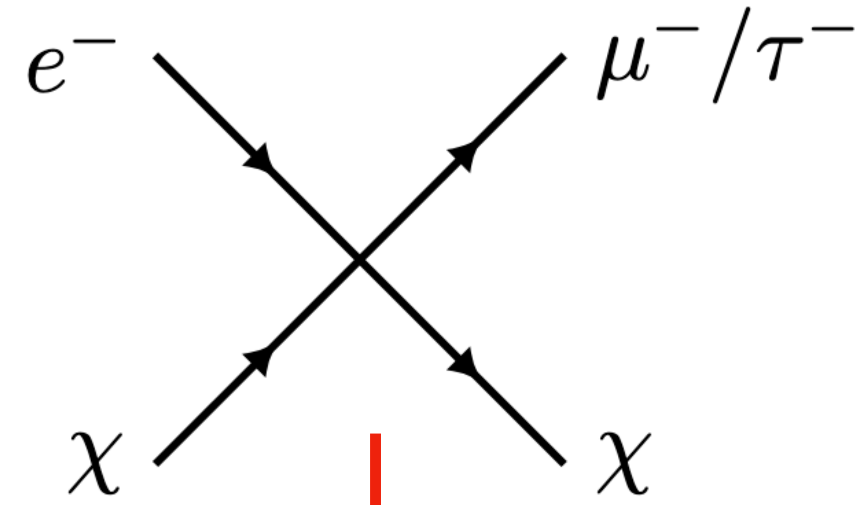
Jahedi, **JL**, Liao, Ma, Uchida, arXiv: 2601.14048

# Scattering process for CLFV DM

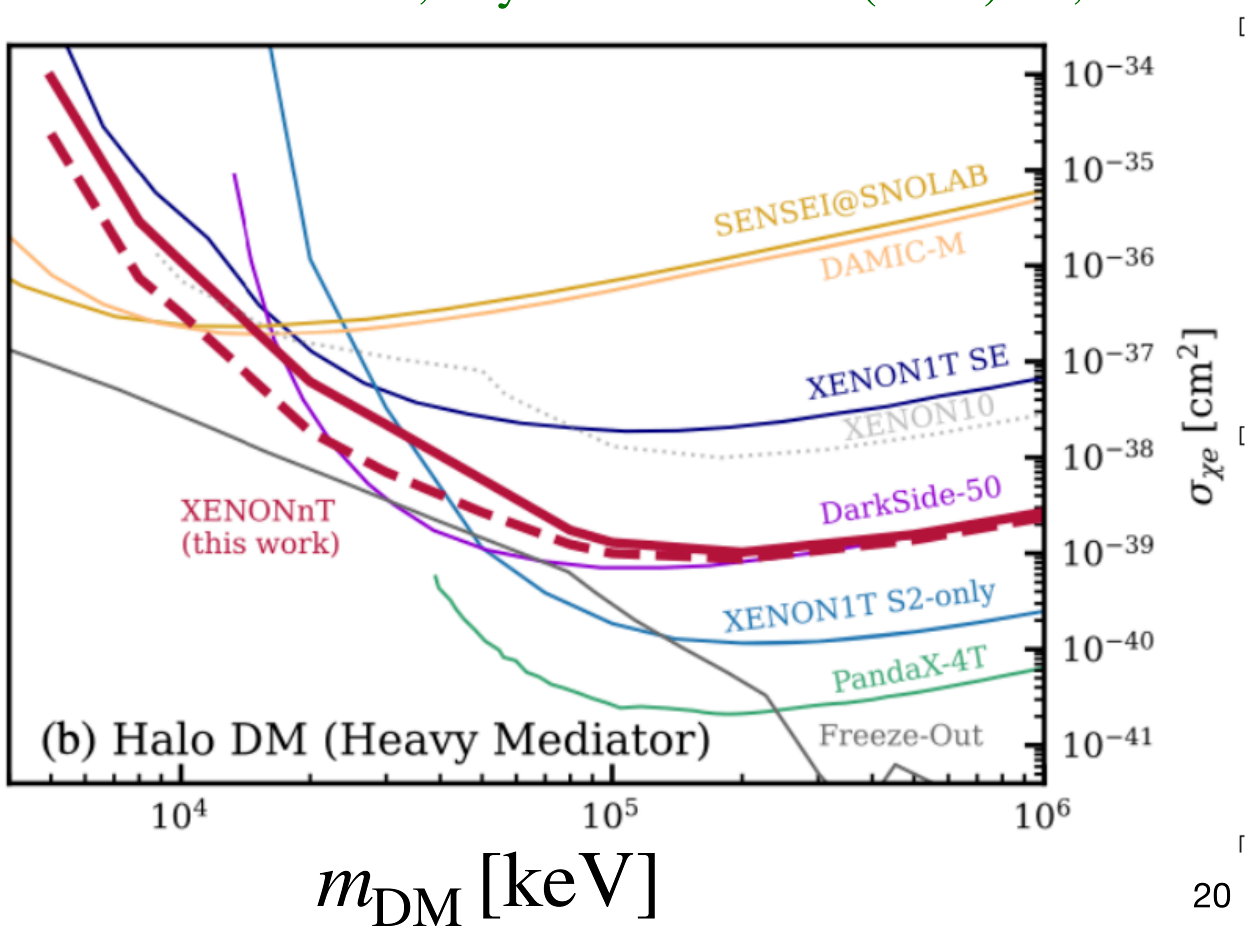


# Direct detection on DM-electron interaction




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

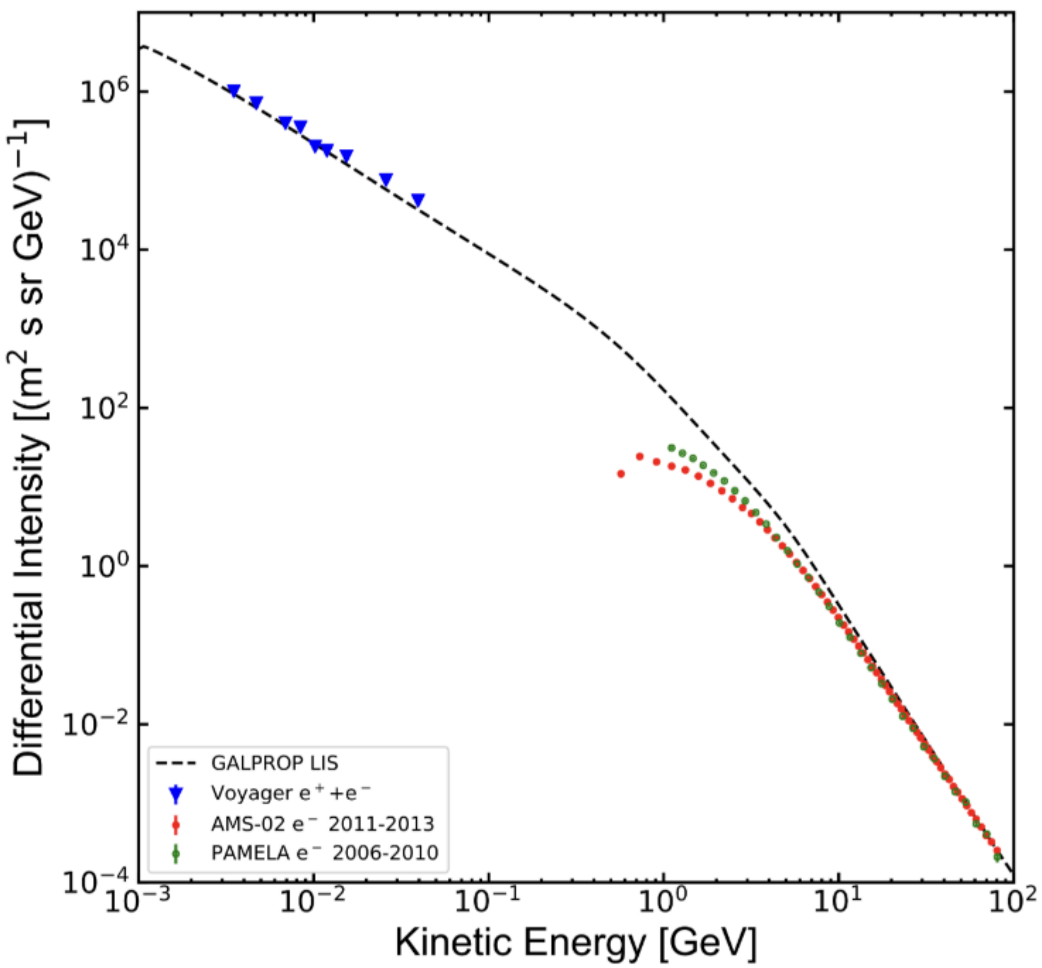


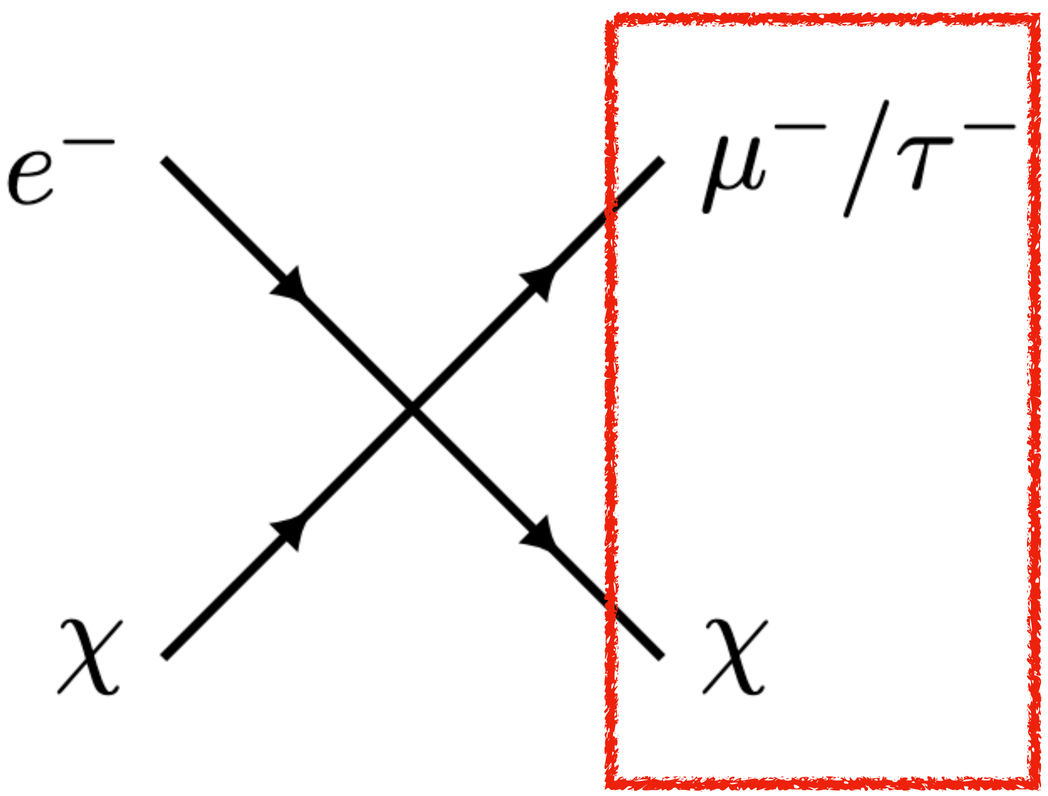

No constraints since halo DM is too slow to overcome the mass gap.

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

# Probing CLFV scattering process

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



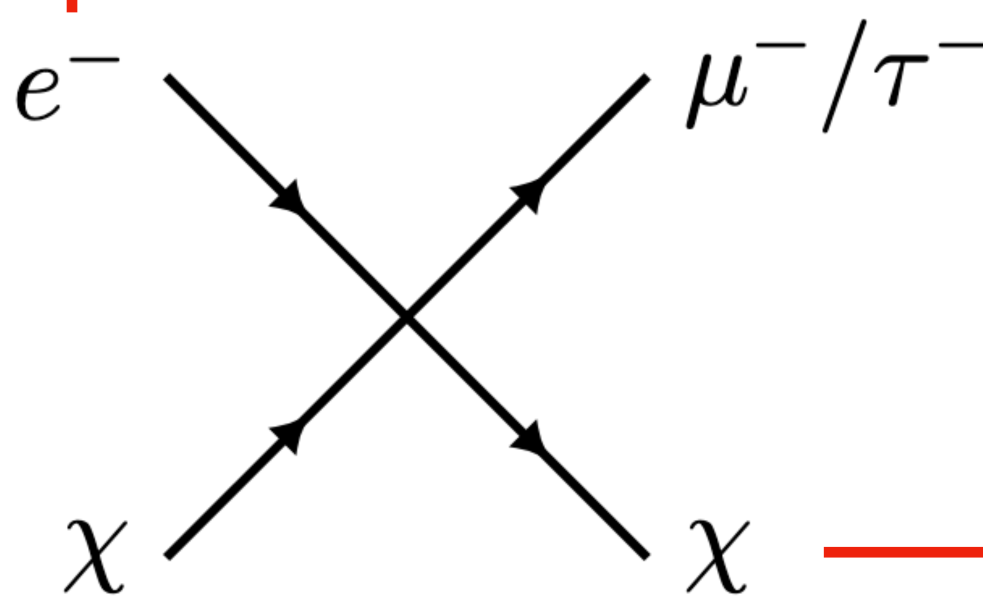




High-energy electrons allow final-state particles to reach energies up to tens of GeV.

# Probing CLFV scattering process

**Cosmic ray cooling**
Additional energy loss for CR electrons
AMS

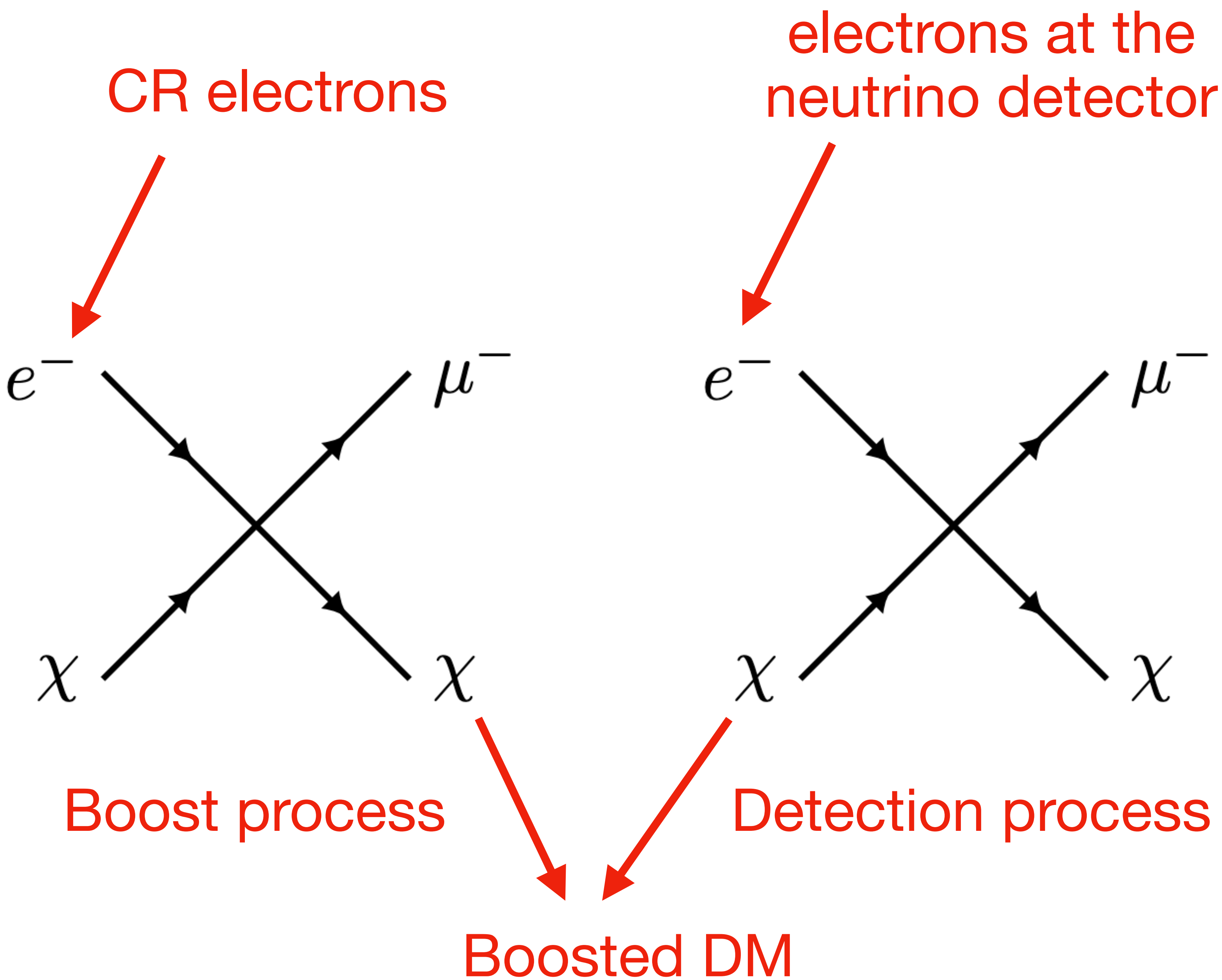
**Indirect detection**
Radiative decay
High energy photon at Fermi-LAT




**Direct detection**
Boosted DM
Single muon at Super-K

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

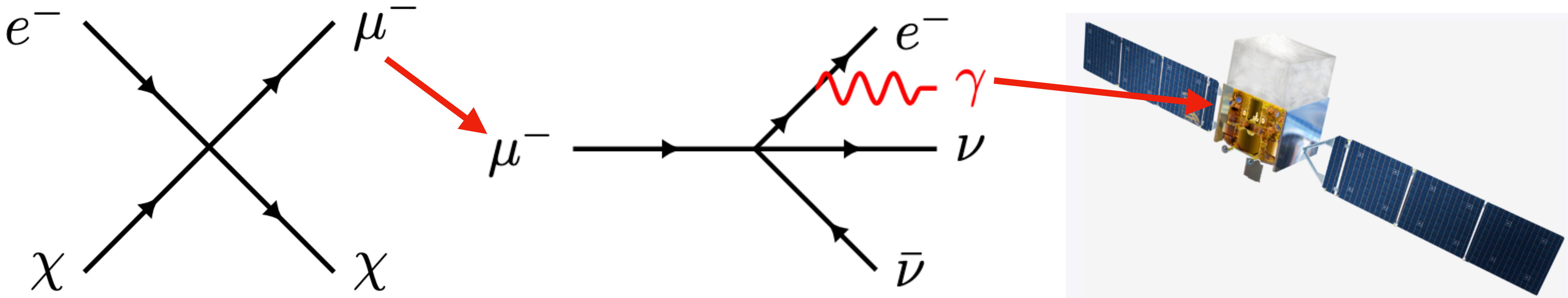
# Direct detection for the scattering process



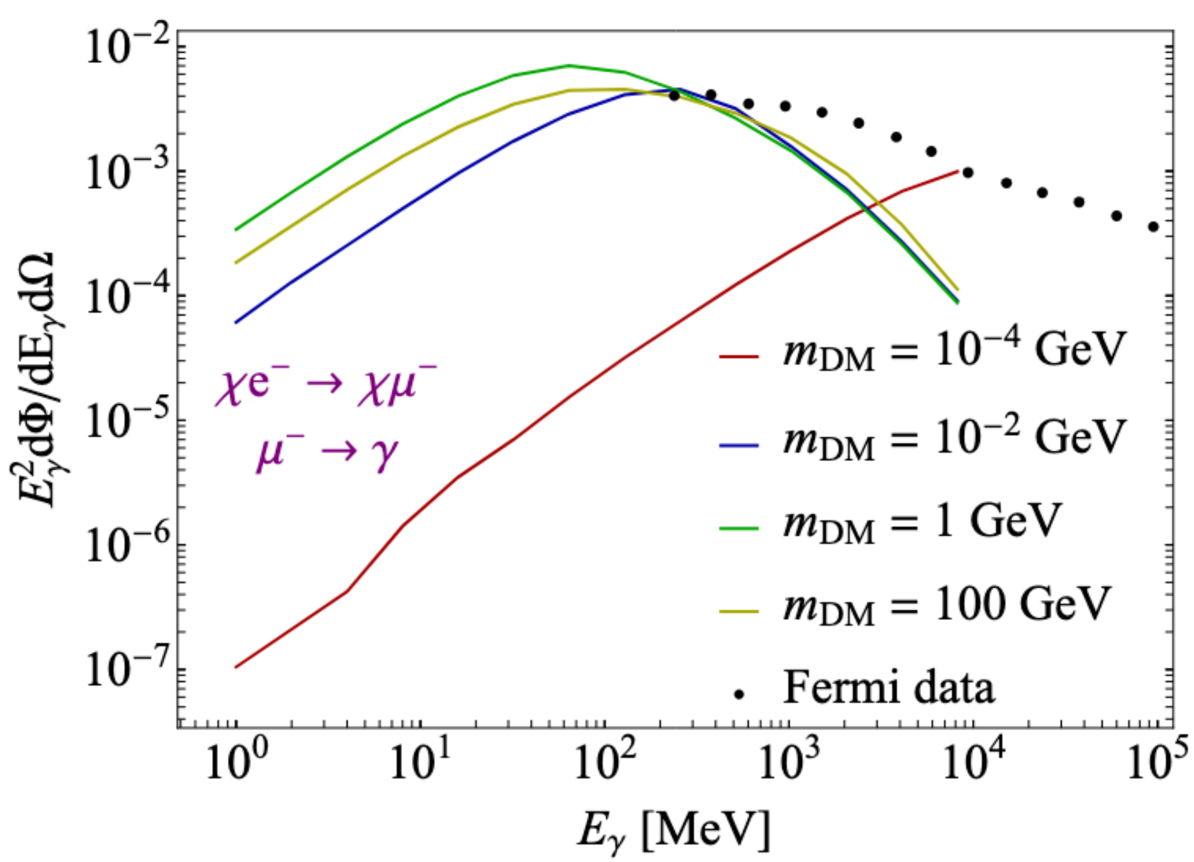

Super-K

# Indirect detection for the scattering process

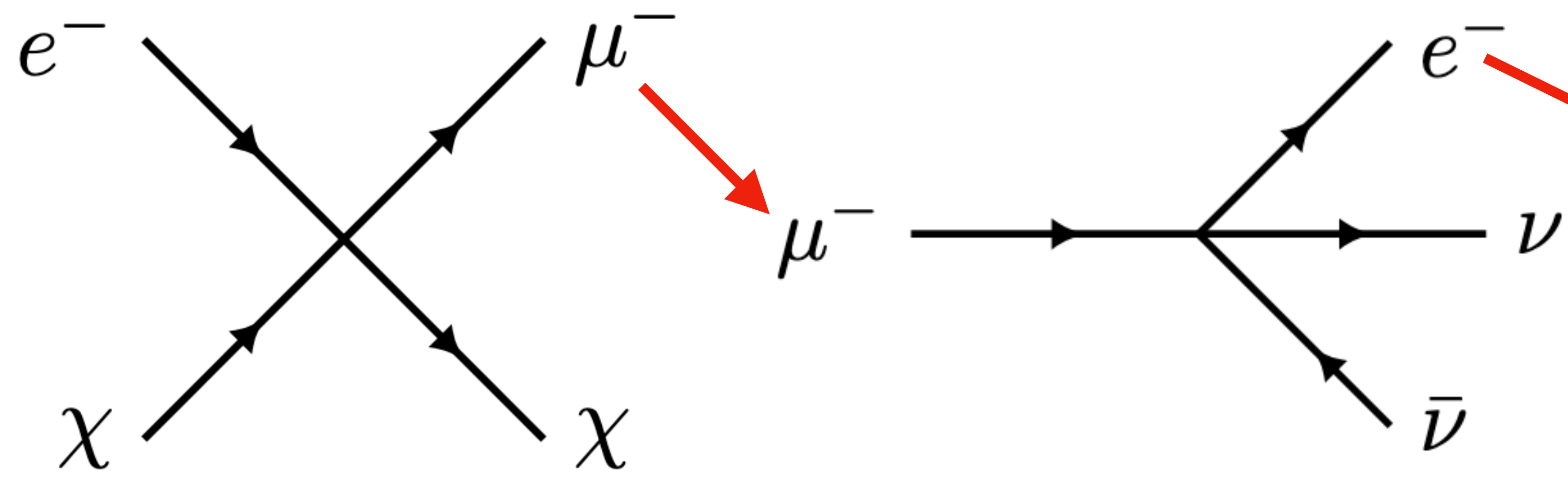
Fermi-LAT




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



# Cosmic ray cooling for the scattering process



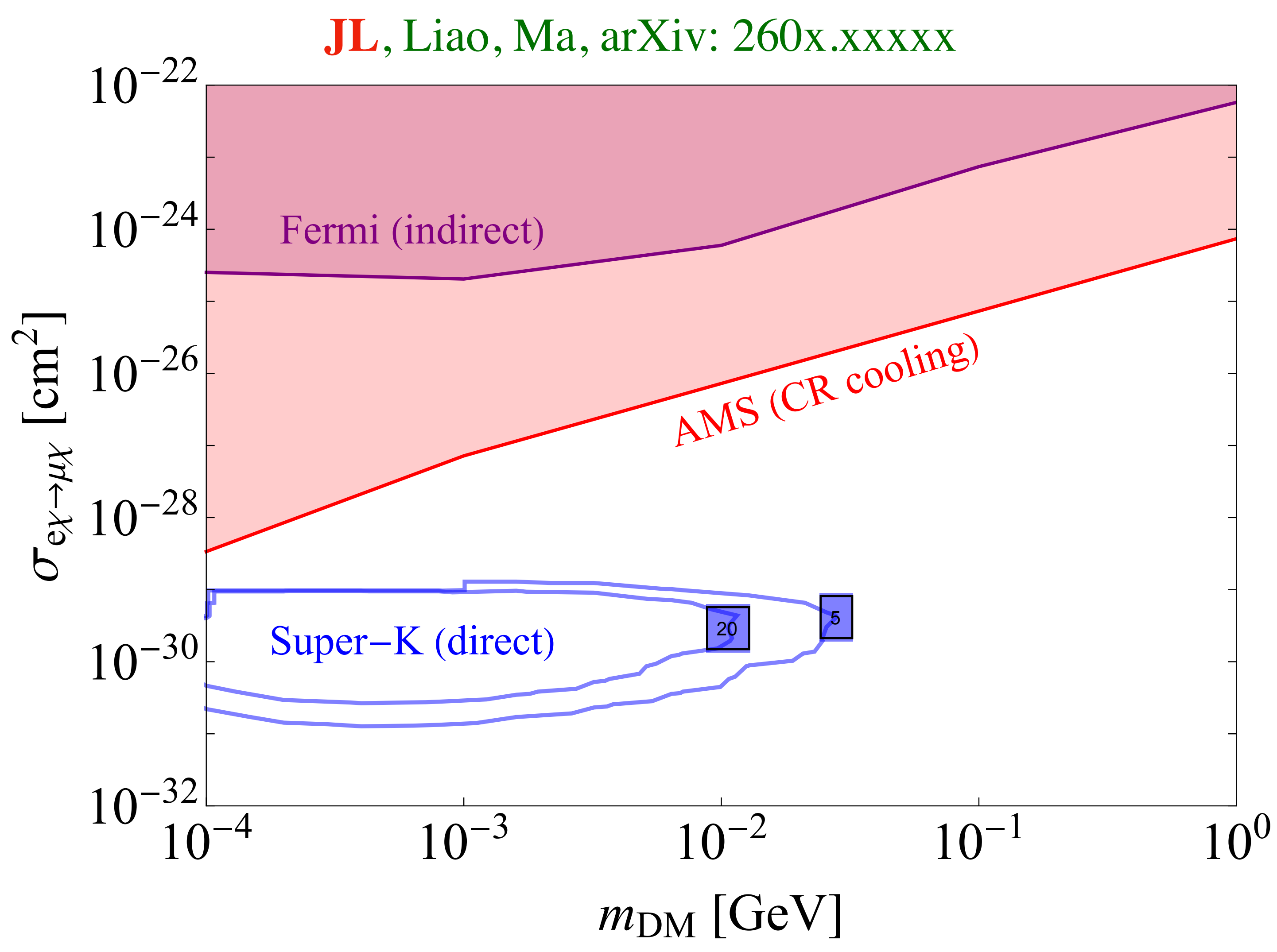

AMS


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

# Constraints on CLFV scattering cross section




$$d\sigma/dz^* = C$$

(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

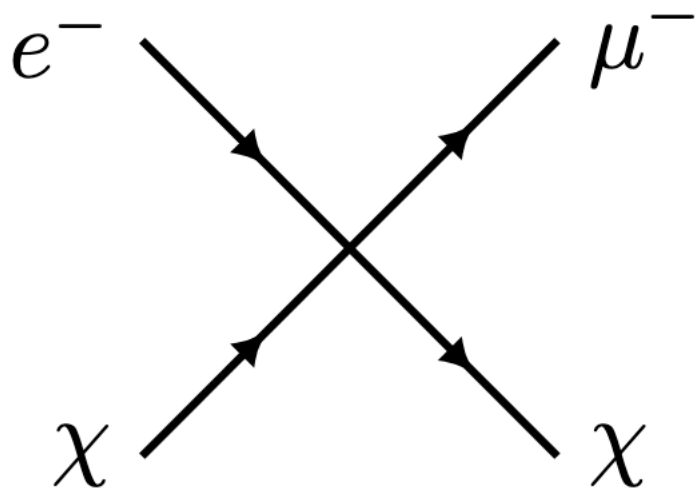
- We present limits on LFV annihilation from INTEGRAL, XMM-Newton, Fermi, and AMS-02, where INTEGRAL (AMS-02) provides the strongest bounds at low (high) DM masses.

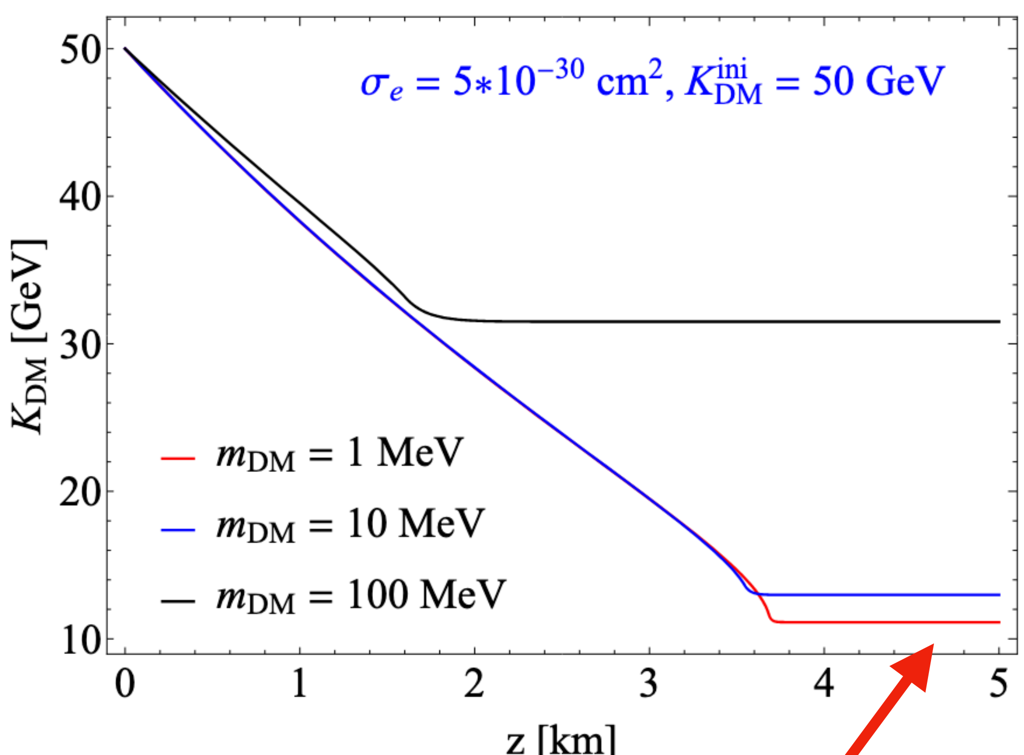
- We then translate these results into constraints on the effective scales of the EFT operators, which can be probed from a few tens of GeV up to the TeV scale.

- 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

# Earth shielding and daily modulation



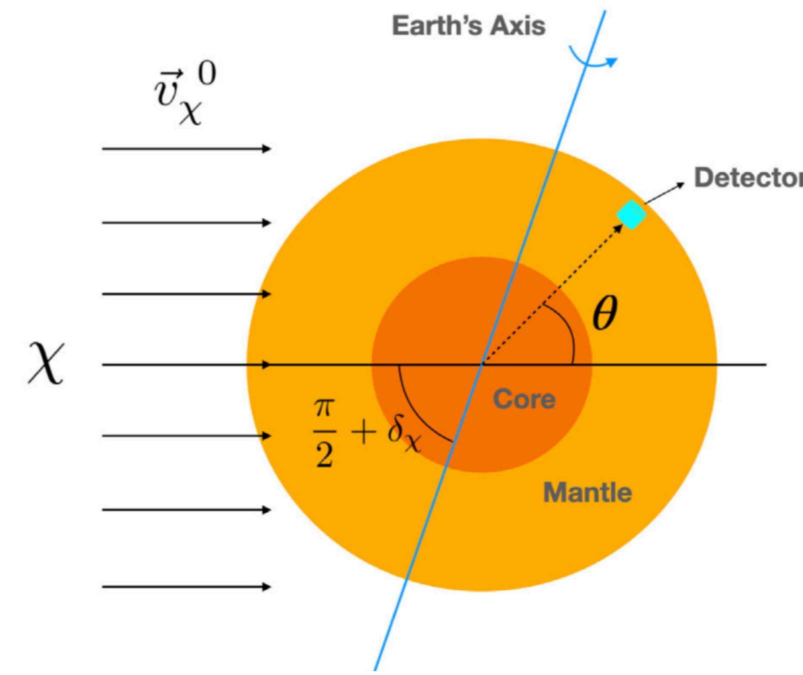



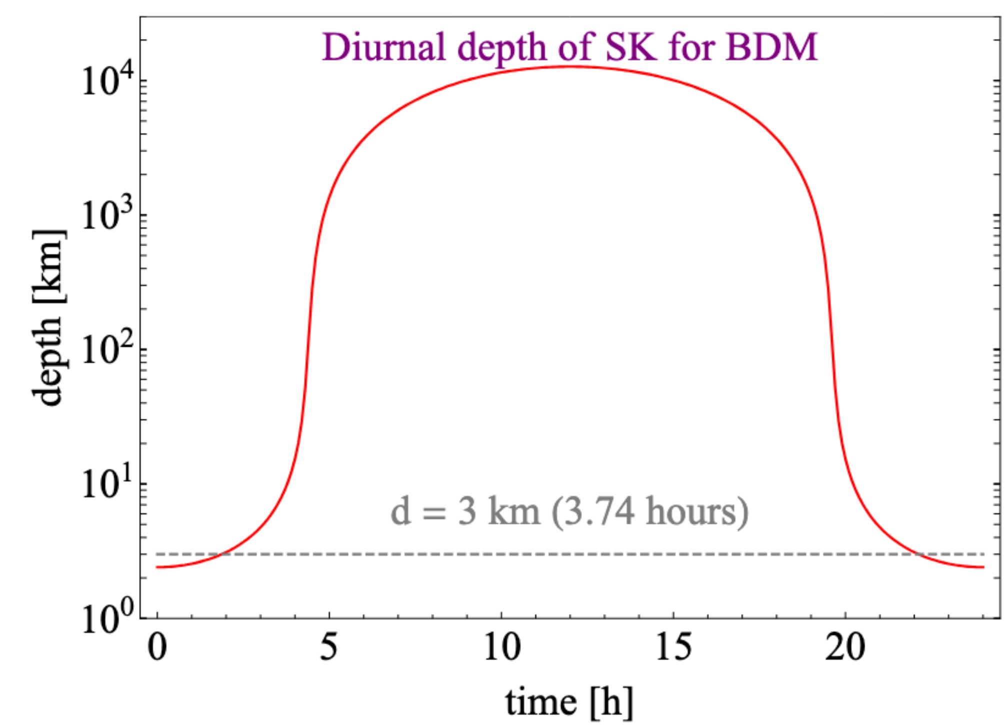

$$E_\chi^{\rm min} = \frac{m_\mu^2 - m_e^2 + 2m_\mu m_\chi}{2m_e}$$

DM energy threshold for LFV scattering

**JL**, Liao, Ma, arXiv: 2512.xxxxx

Chen et al., PhysRevD.107.033006



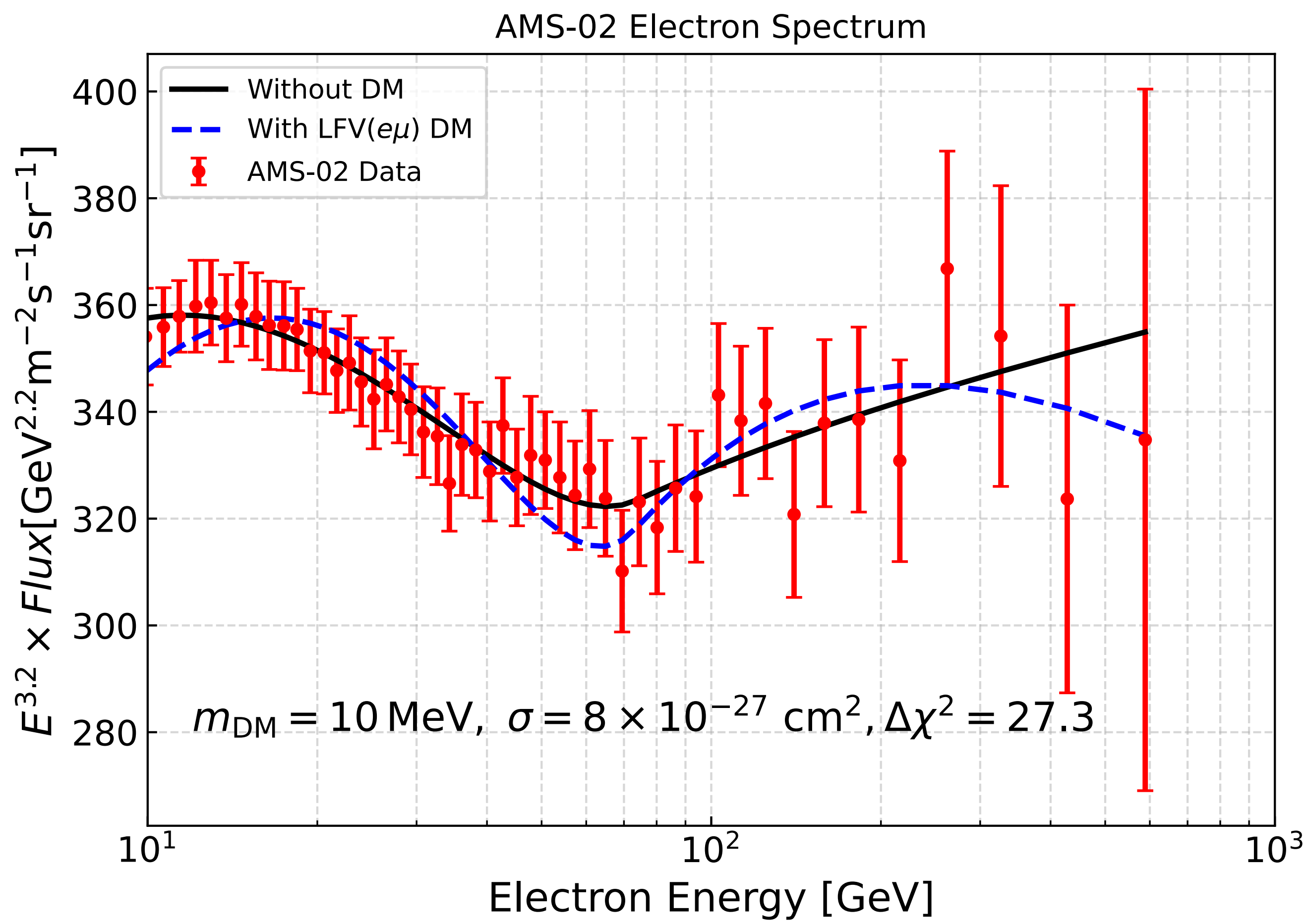




Backgrounds can be effectively reduced using angle and timing cuts.

# 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

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

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

The energy injected into CRs cannot be arbitrarily large.