Dark Matter and New Physics at Neutrino Experiments

Ningqiang Song

宋宁强

Institute of Theoretical Physics, Chinese Academy of Sciences

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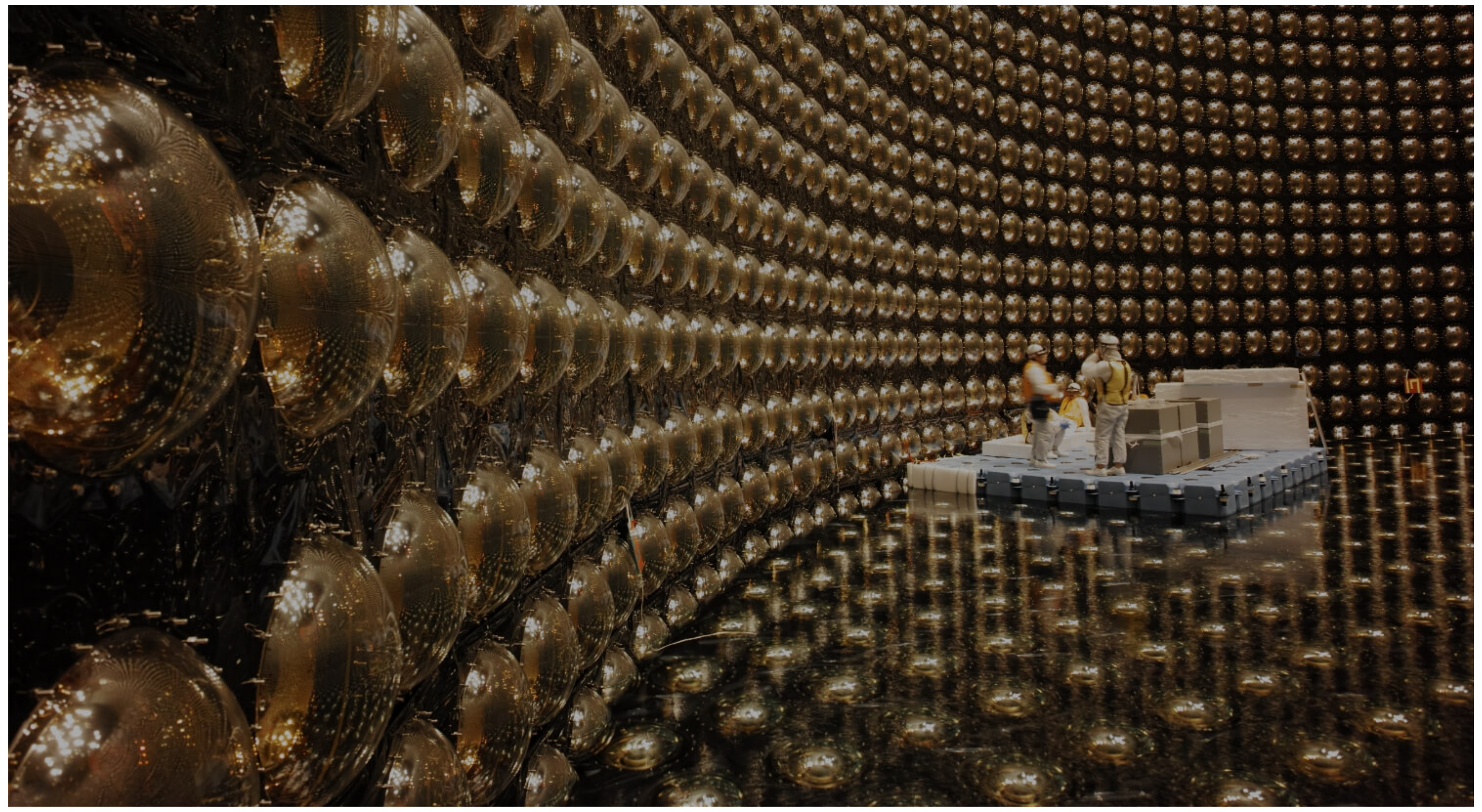
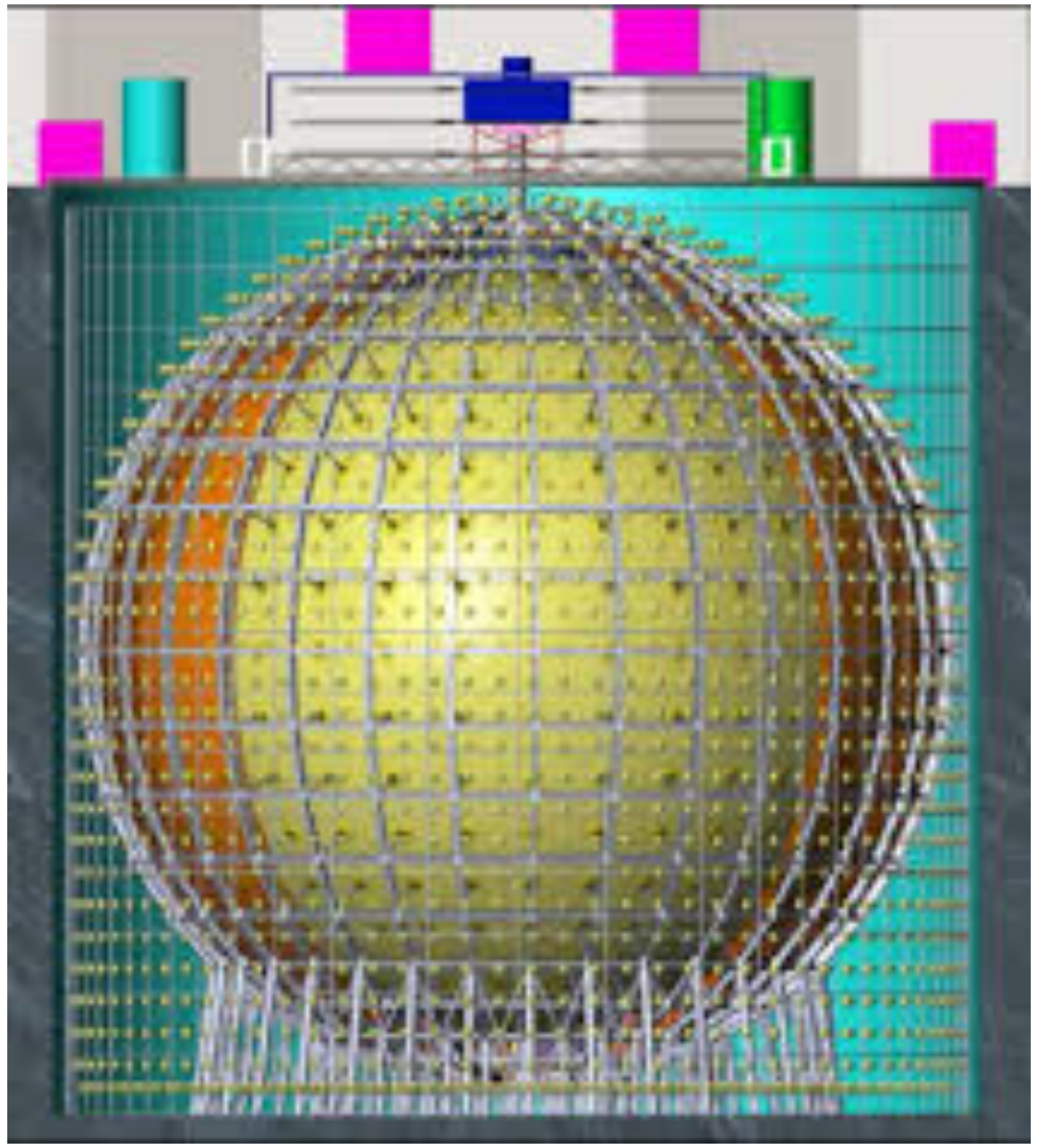
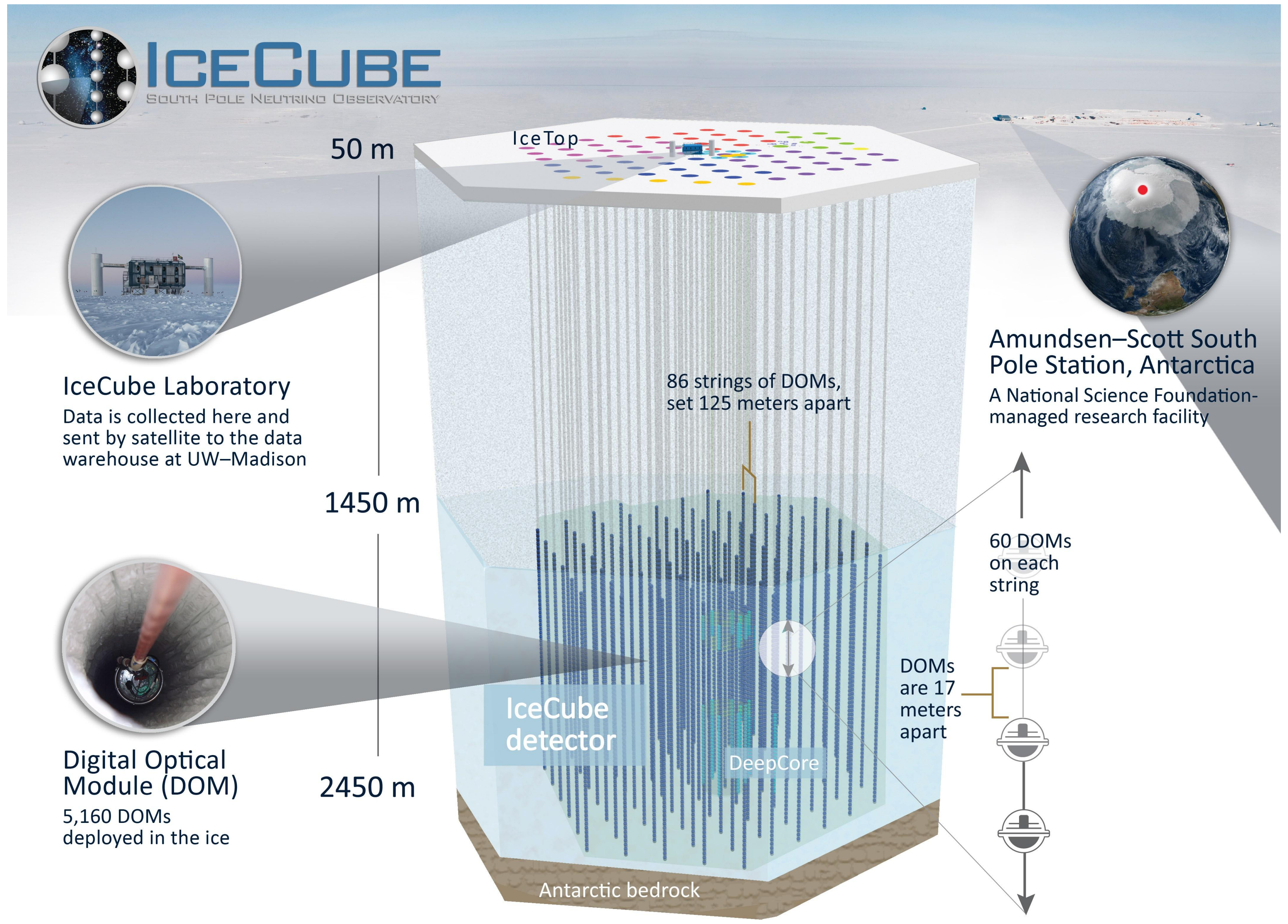
Neutrino Experiments

Super-Kamiokande





JUNO

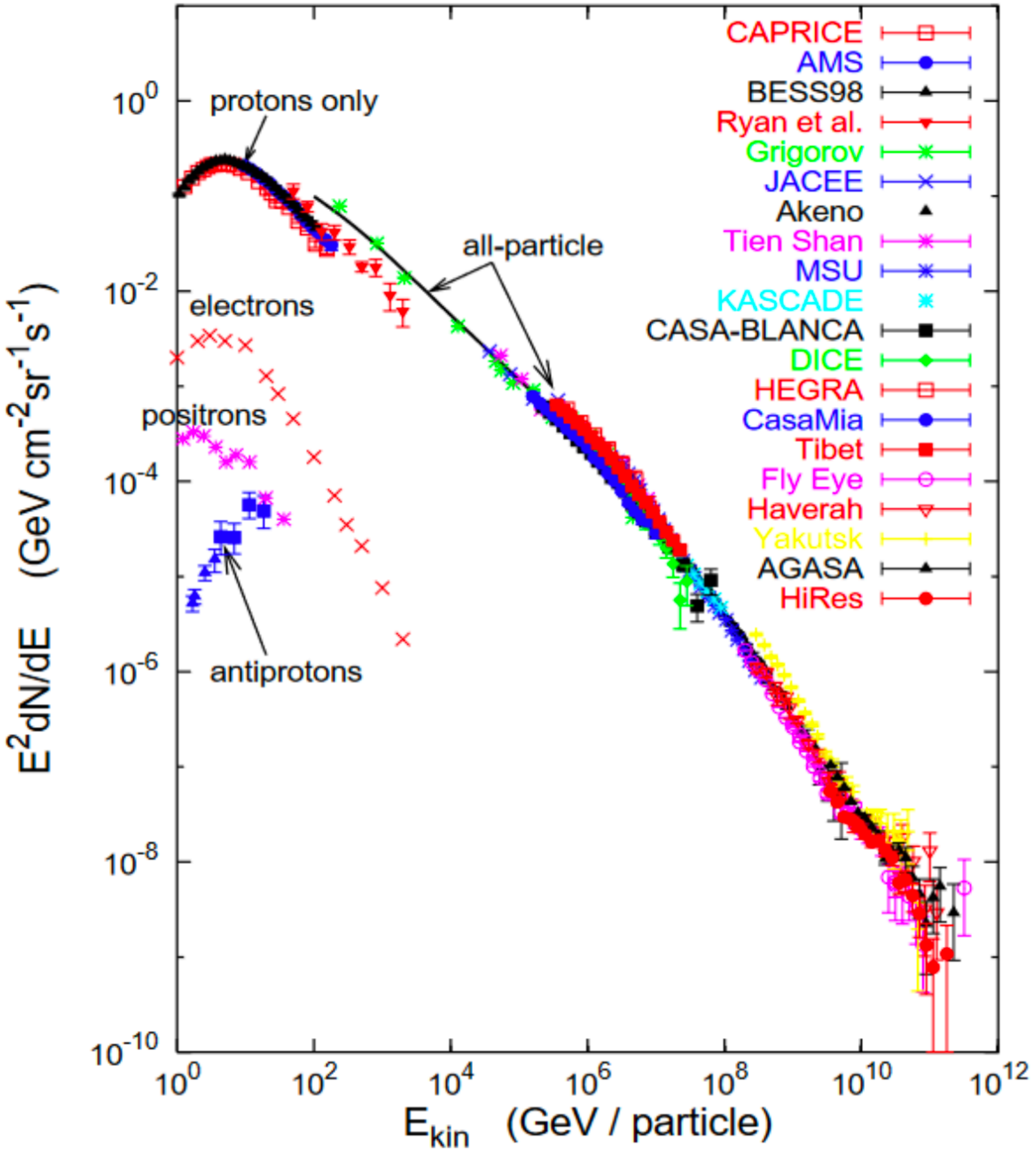


IceCube

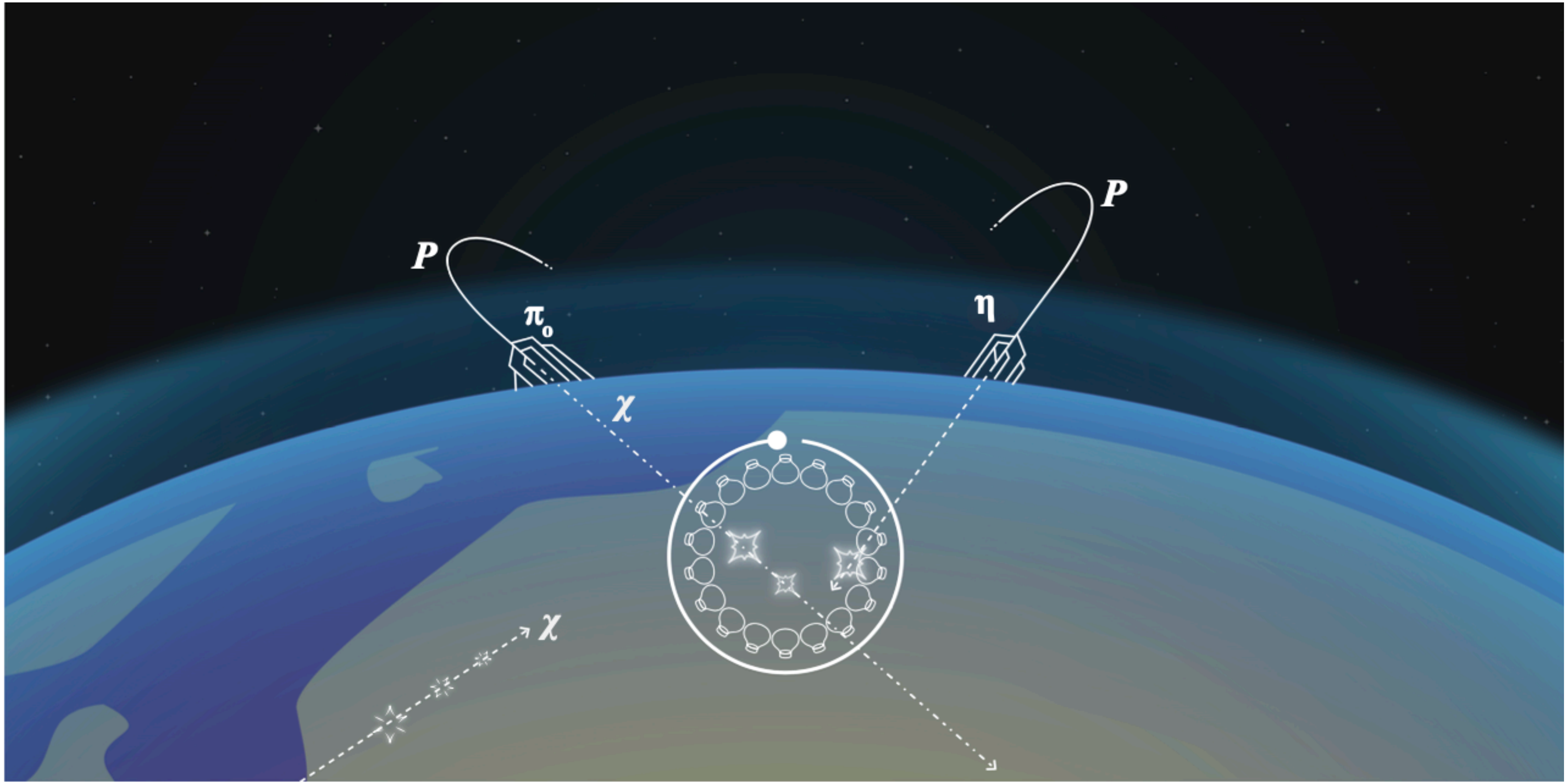
- Large exposure
- Different thresholds

Atmospheric beam dump and new physics

- Heavy neutral leptons
- Hadrophilic dark matter
- Axion-like particles
- Long-lived neutralinos
- Monopoles
- Dark photon
- Millicharged particles
- …



Atmospheric Beam Dump

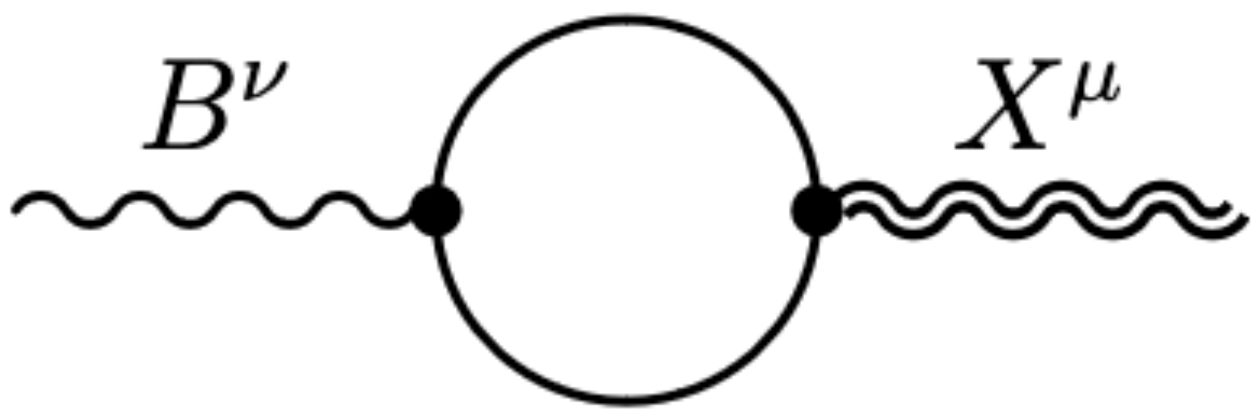


Dark Photon Kinetic Mixing

Extra $U(1)$? $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$

Pospelov' 2008
Ackerman, Buckley, Carrol, Kamionkowsk' 2008
Arkani-Hame, Finkbeine, Slatyer, Weiner' 2008

$$\mathscr{L} = -\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu} - 2\kappa F_{\mu\nu}F'^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}\right) + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - J^\mu A_\mu$$



$$\epsilon = -\frac{g' g_X}{16\pi^2}\sum_i Y_i q_i \ln\frac{M_i^2}{\mu^2} \sim 10^{-1} - 10^{-3}$$

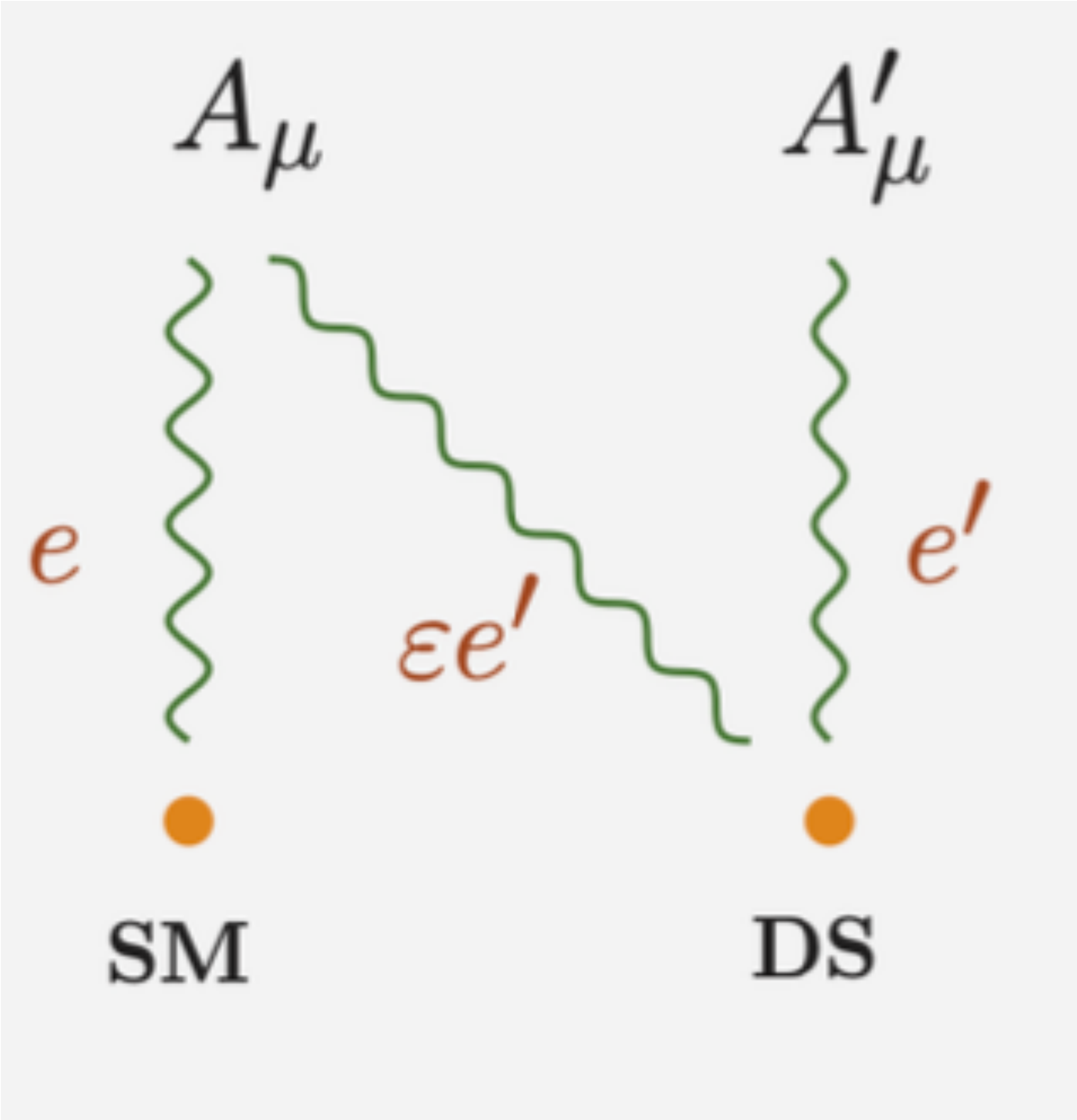
Millicharge Particles

Massless dark photon $\mathcal{L}_0 = -\frac{1}{4}F_{a\mu\nu}F_a^{\mu\nu} - \frac{1}{4}F_{b\mu\nu}F_b^{\mu\nu} - \frac{\varepsilon}{2}F_{a\mu\nu}F_b^{\mu\nu}$ $\mathcal{L} = e\,J_\mu A_b^\mu + e' J'_\mu A_a^\mu$

$$\begin{pmatrix} A_a^\mu \\ A_b^\mu \end{pmatrix} = \begin{pmatrix} \dfrac{1}{\sqrt{1-\varepsilon^2}} & 0 \\ -\dfrac{\varepsilon}{\sqrt{1-\varepsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A'^\mu \\ A^\mu \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}' &= \left[\frac{e'\cos\theta}{\sqrt{1-\varepsilon^2}} J'_\mu + e\left(\sin\theta - \frac{\varepsilon\cos\theta}{\sqrt{1-\varepsilon^2}}\right) J_\mu\right] A'^\mu \\ &+ \left[-\frac{e'\sin\theta}{\sqrt{1-\varepsilon^2}} J'_\mu + e\left(\cos\theta + \frac{\varepsilon\sin\theta}{\sqrt{1-\varepsilon^2}}\right) J_\mu\right] A^\mu \end{aligned}$$

$$\boxed{\mathcal{L}' = e' J'_\mu A'^\mu + \left[-\frac{e'\varepsilon}{\sqrt{1-\varepsilon^2}} J'_\mu + \frac{e}{\sqrt{1-\varepsilon^2}} J_\mu\right] A^\mu}$$



$\sin\theta = \varepsilon\,,\ \cos\theta = \sqrt{1-\varepsilon^2}$

Fabbrichesi et al arXiv: 2005.01515

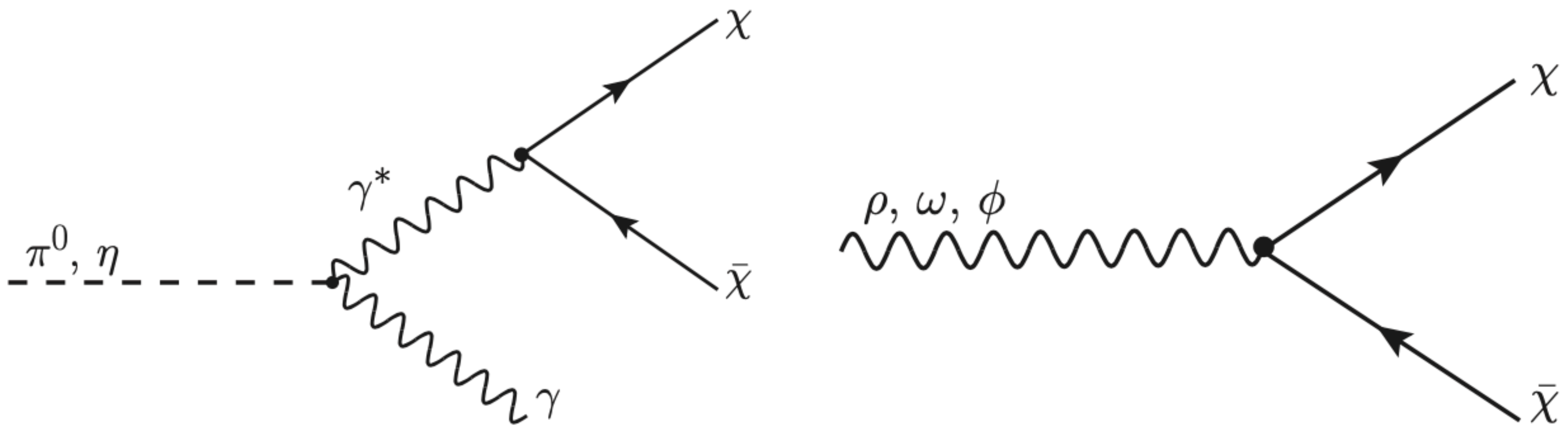
Millicharge Particles from Light Meson Decay

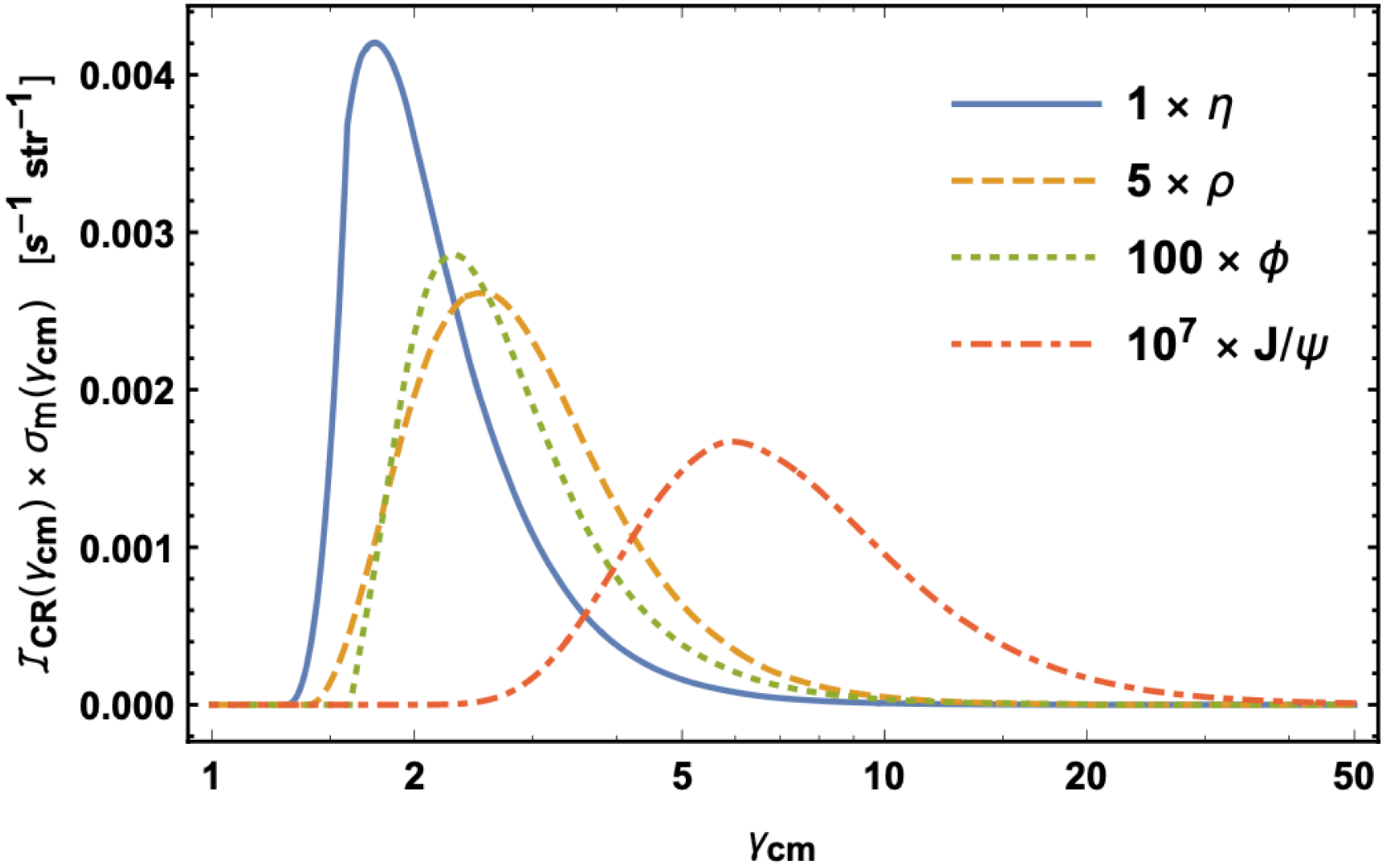
$$\Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}}) = \Omega_{\text{eff}} \int \mathcal{I}_{\text{CR}}(\gamma_{\text{cm}}) \frac{\sigma_{\mathfrak{m}}(\gamma_{\text{cm}})}{\sigma_{\text{in}}(\gamma_{\text{cm}})} P(\gamma_{\mathfrak{m}}|\gamma_{\text{cm}})\, \mathrm{d}\gamma_{\text{cm}}$$

$$\gamma_{\text{cm}} = \frac{1}{2}\sqrt{s}/m_p$$

$$P(\gamma_{\mathfrak{m}}|\gamma_{\text{cm}}) \approx \sum_{\alpha} \frac{1}{\sigma_{\mathfrak{m}}} \times \frac{\mathrm{d}\sigma_{\mathfrak{m}}}{\mathrm{d}x_F} \times \frac{\mathrm{d}x_F^{(\alpha)}}{\mathrm{d}\gamma_{\mathfrak{m}}}$$

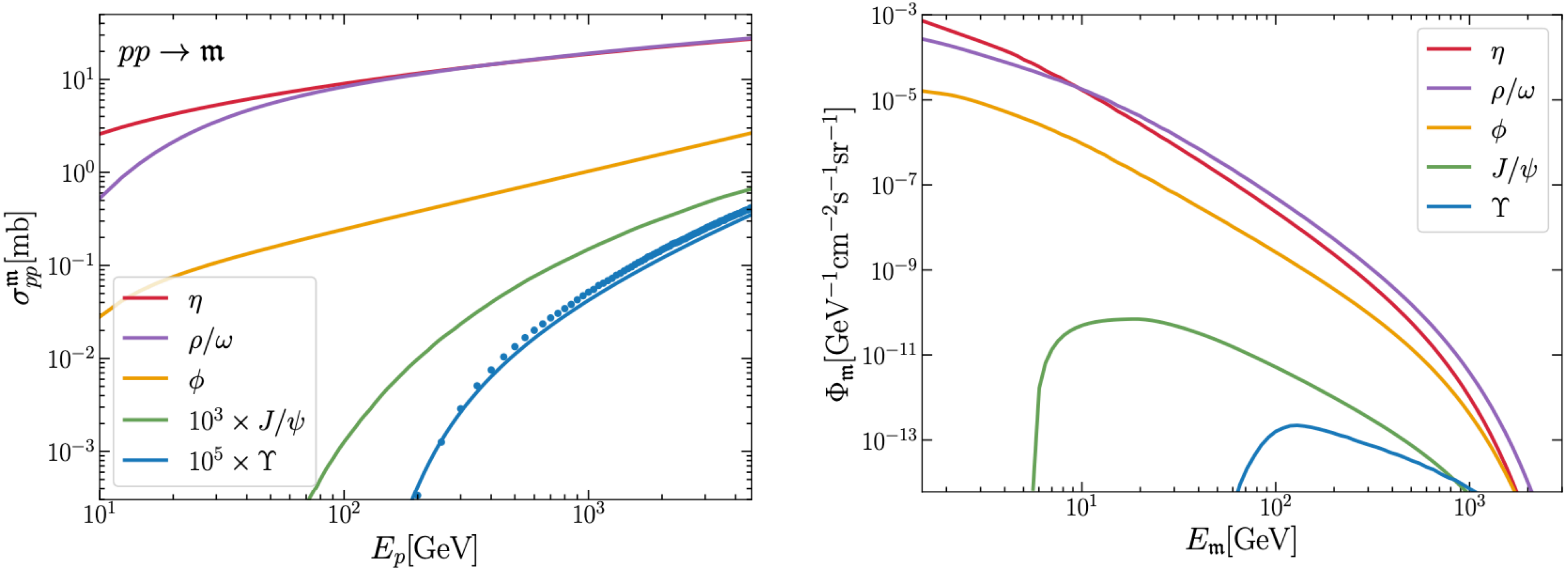
Plestid et al PRD/2002.11732





Millicharge Particles from Upsilon Meson Decay

Pythia8 simulations



Wu, Hardy, **NS**, arXiv: 2406.01668

Millicharge Particles from Proton Bremsstrahlung

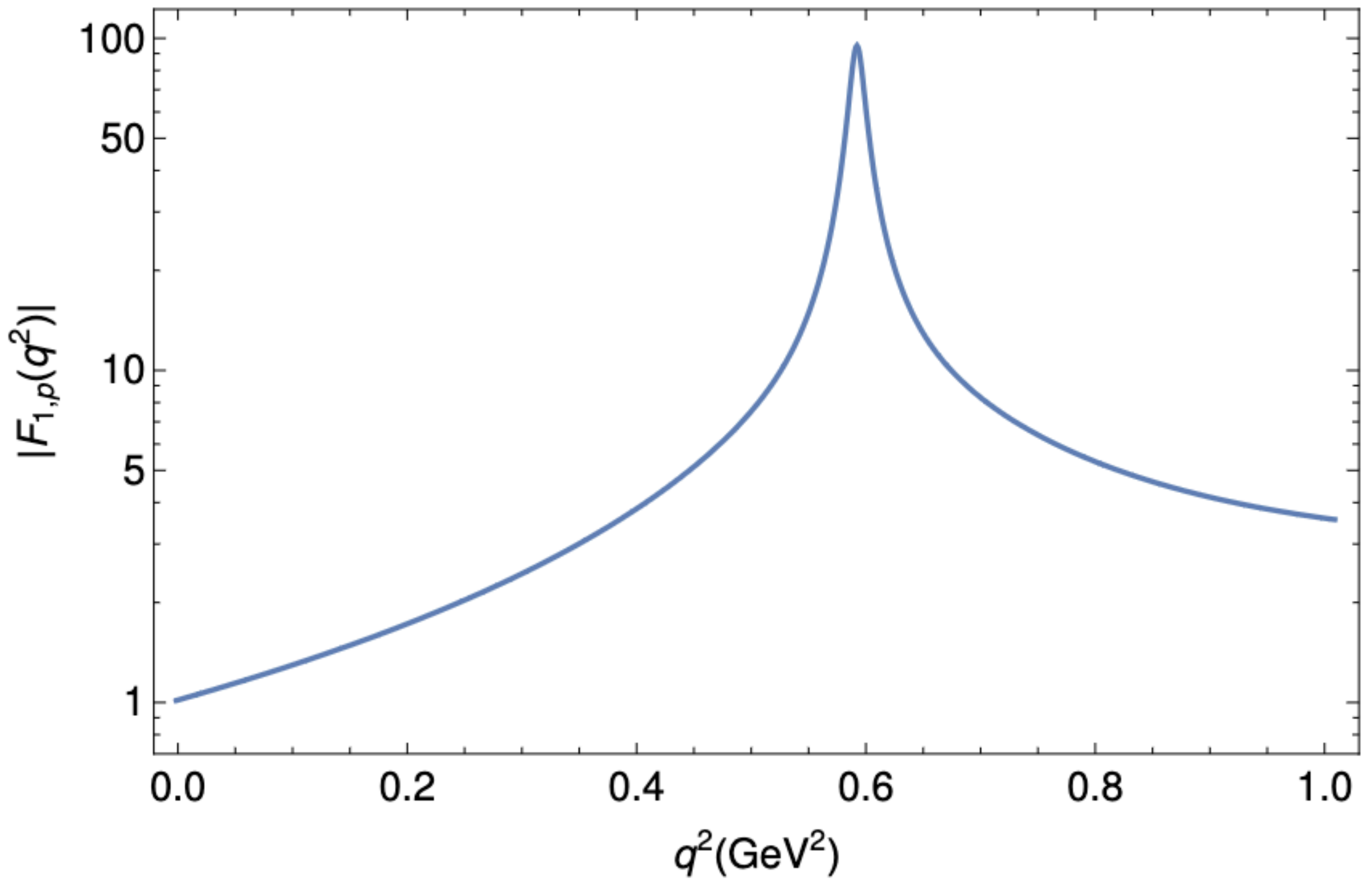
Fermi-Weizsacker-Williams (FWW) approximation with the splitting-kernel approach

$$d\sigma^{\mathrm{PB}}(s) \simeq d\mathscr{P}_{p\to\gamma^* p'} \times \sigma_{pN}(s')$$

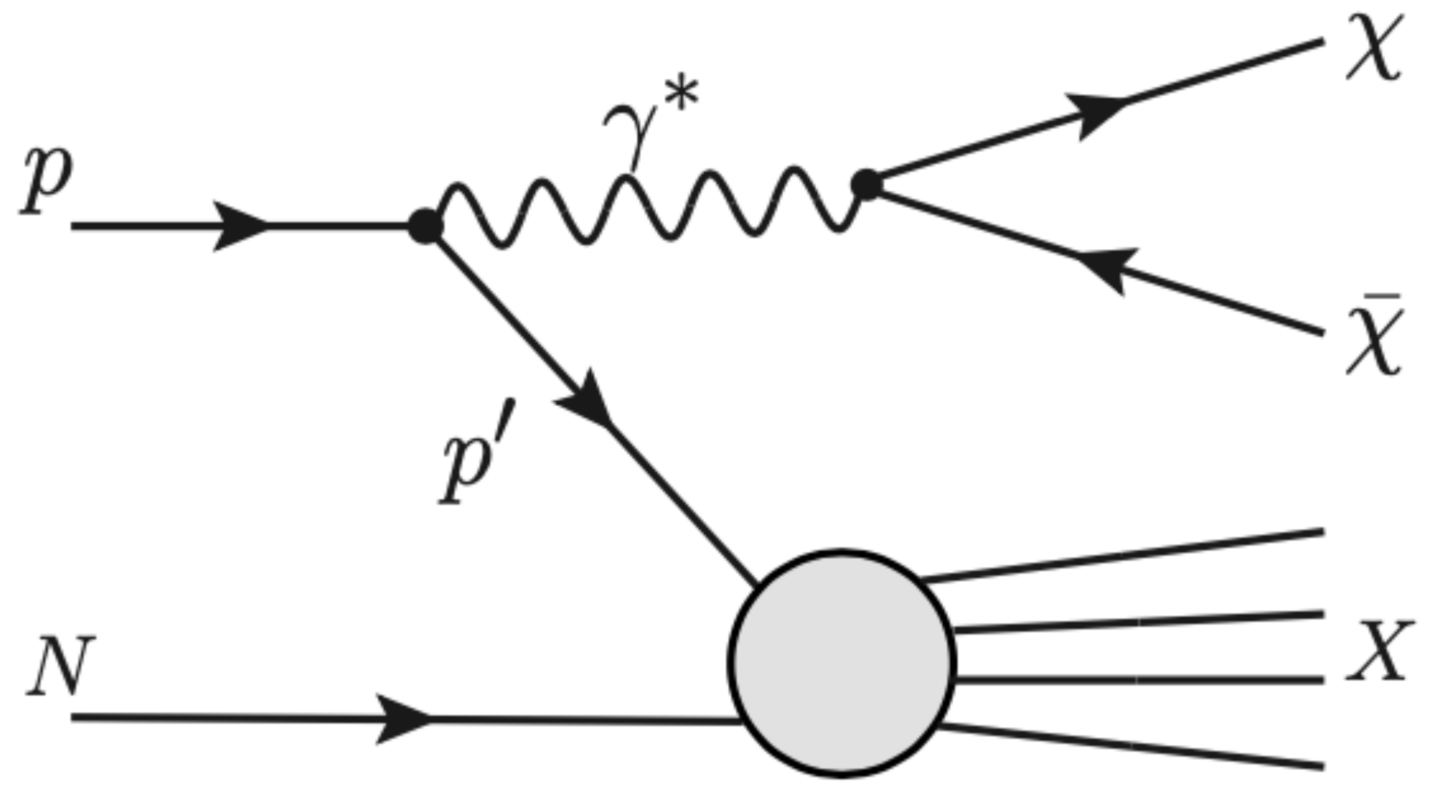
Kernel

$$\frac{d^2\mathcal{P}^{\mathrm{FWW}}_{p\to\gamma^* p}}{dE_k\, d\cos\theta_k} = \left|\mathbf{J}(z,p_T^2)\right| \frac{d^2\mathcal{P}^{\mathrm{FWW}}_{p\to\gamma^* p}}{dz\, dp_T^2} = \left|\mathbf{J}(z,p_T^2)\right| \left|F_V(k)\right|^2 \omega(z,p_T^2)$$

EM form factor



deNiverville et al PRD/1609.01770



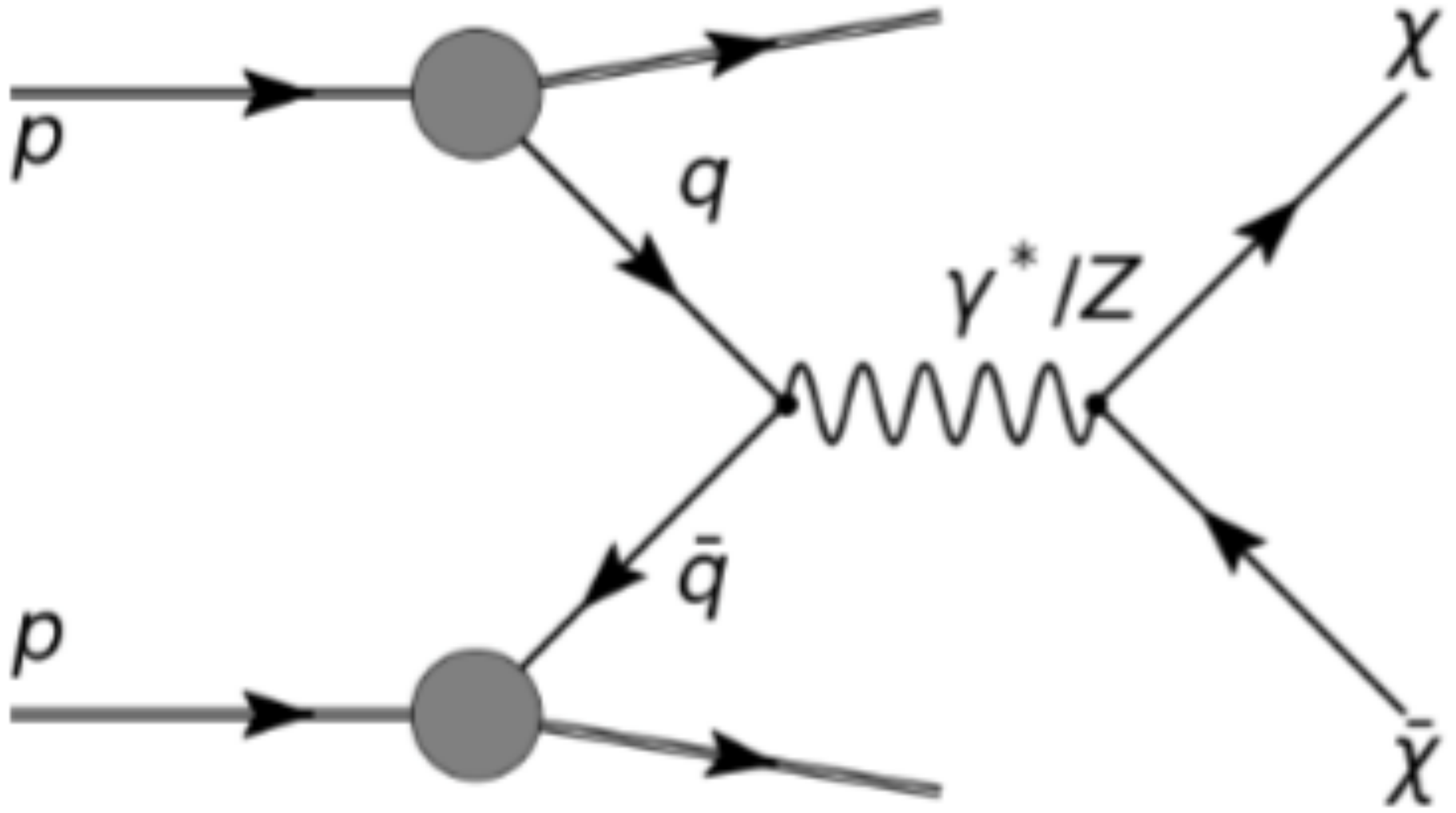
$$\Phi_\chi^{\mathrm{PB}} = \int dE_p \Phi_p \frac{\epsilon^2 e^2}{6\pi^2} \int \frac{dk^2}{k^2} \sqrt{1-\frac{4m_\chi^2}{k^2}} \left(1+\frac{2m_\chi^2}{k^2}\right) \times \int dE_k \frac{1}{\sigma_{pN}} \frac{d\sigma^{\mathrm{PB}}}{dE_k} \frac{\Theta(E_\chi - E_{\mathrm{min}})\Theta(E_{\mathrm{max}} - E_\chi)}{E_{\mathrm{max}} - E_{\mathrm{min}}}$$

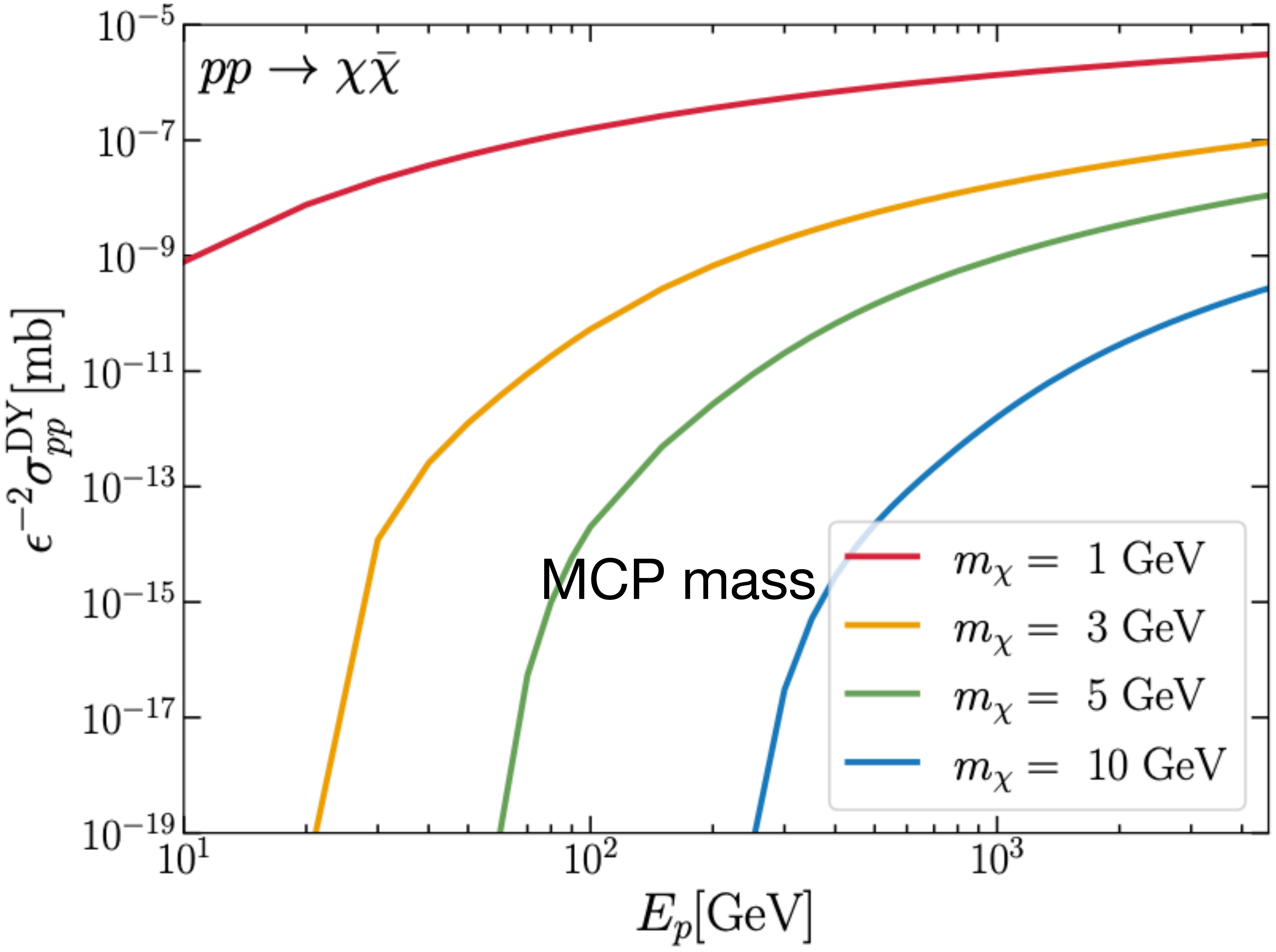
Du et al arXiv: 2211.11469

Du et al arXiv: 2308.05607

Millicharge Particles from Drell-Yan Process

Madgraph simulations





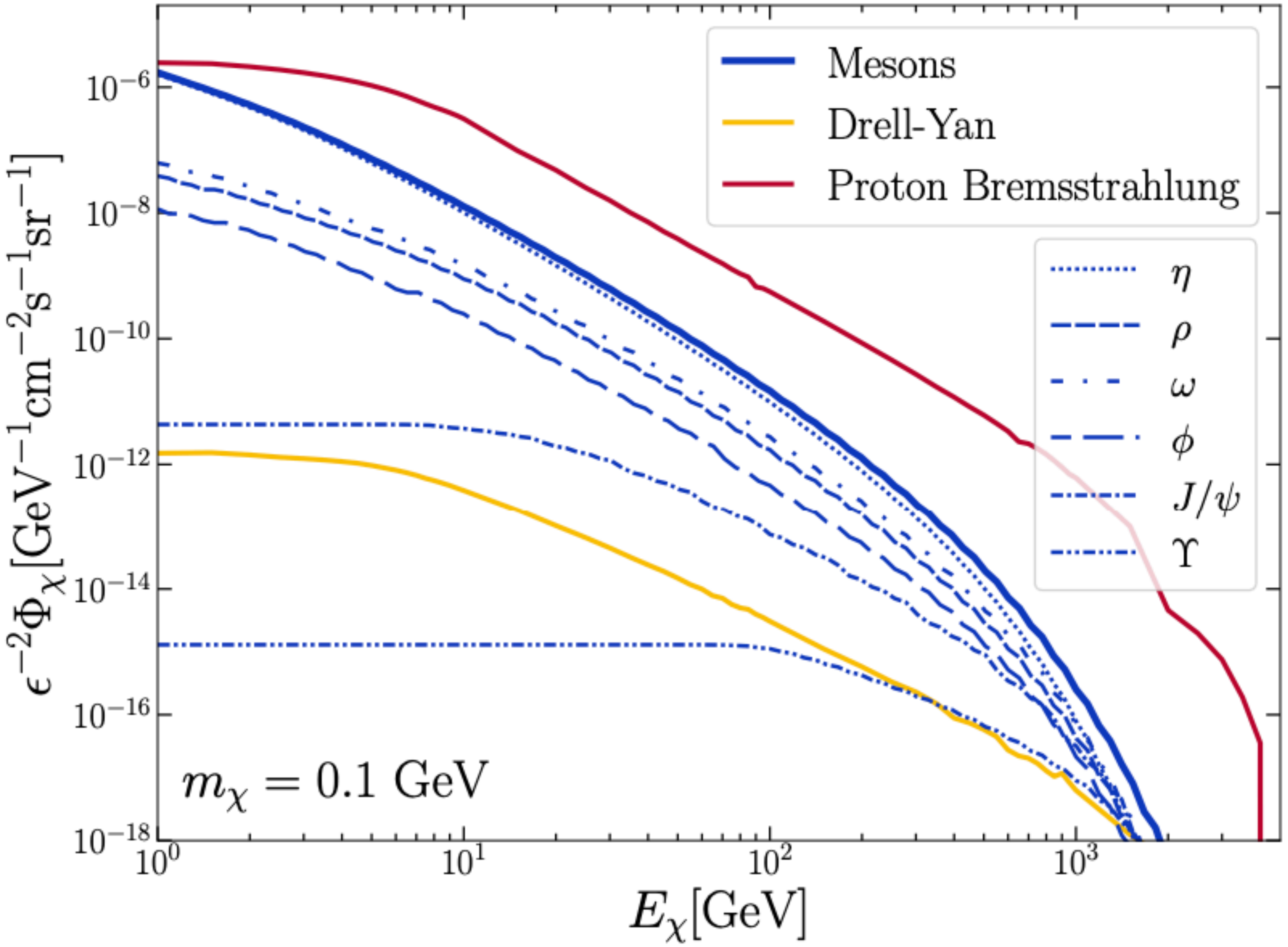
MCP mass

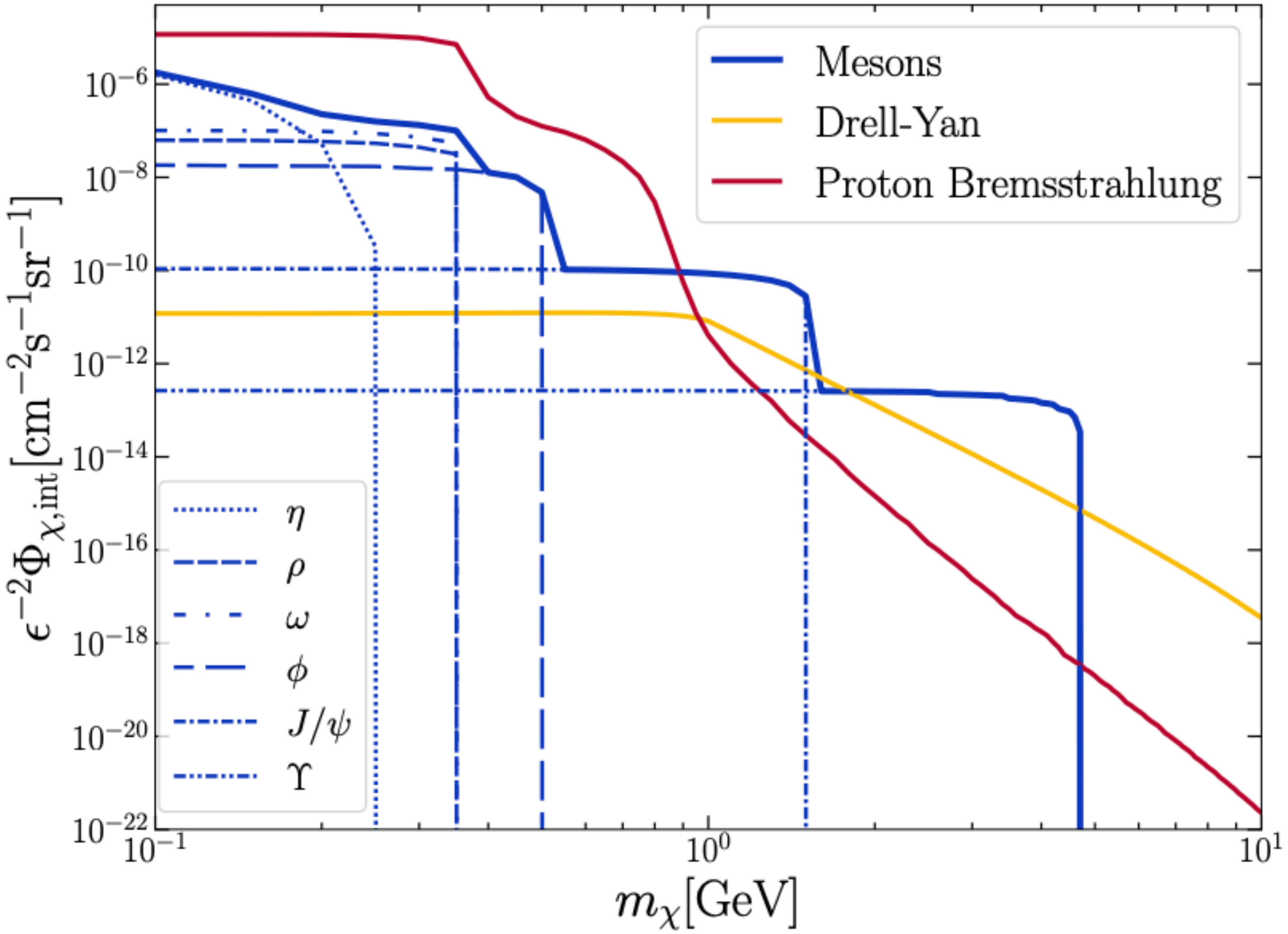
$$\hat{\sigma}\left(q(p_1)\,\bar{q}(p_2) \to l^+ l^-\right) = \frac{4\pi\alpha^2}{3\hat{s}}\,\frac{1}{N_c}\,Q_q^2$$

Wu, Hardy, **NS**, arXiv: 2406.01668

Millicharge Particles Flux

Meson decay+Proton Bremsstrahlung+Drell-Yan

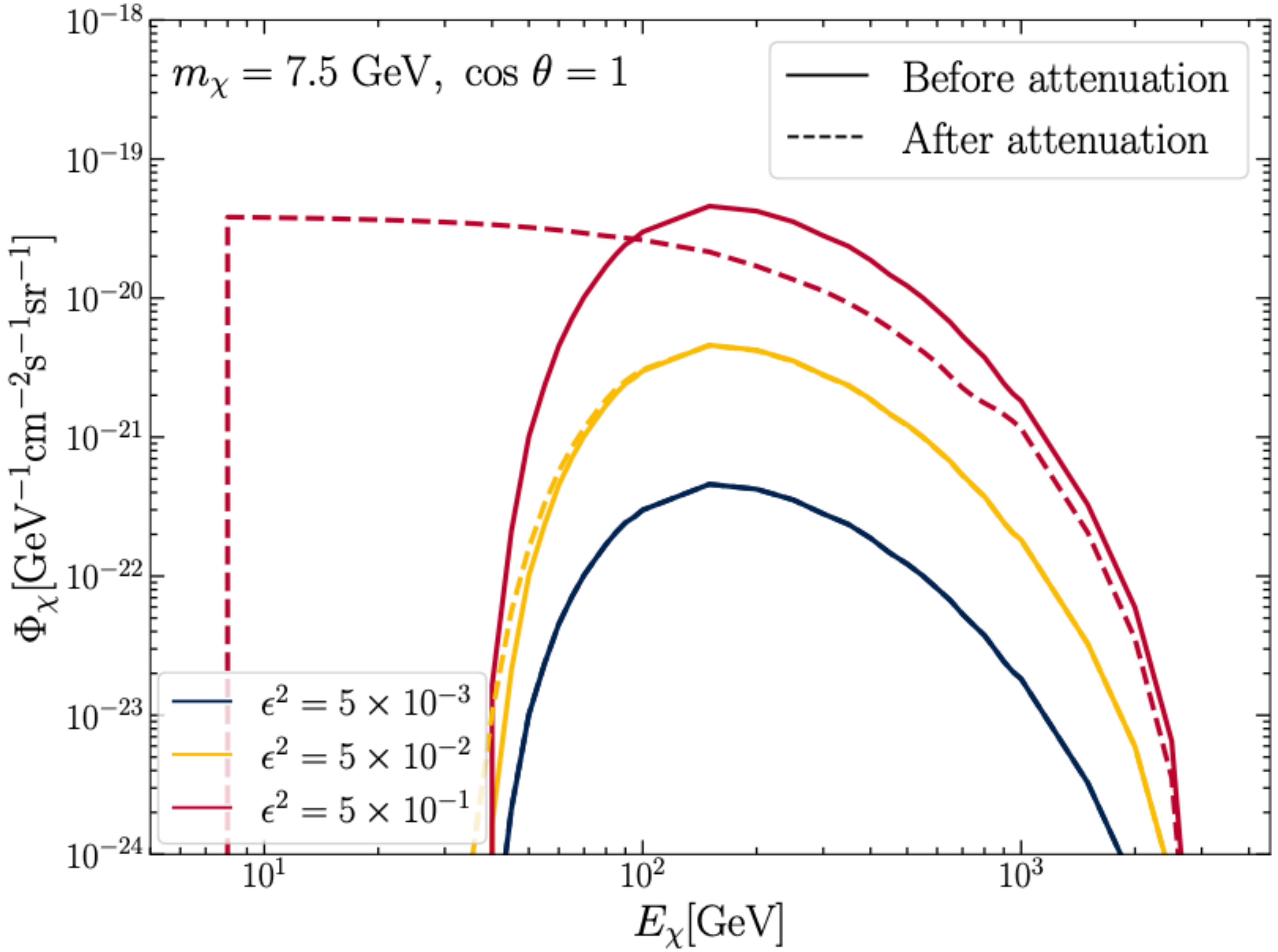




Wu, Hardy, **NS**, arXiv: 2406.01668

Earth Attenuation

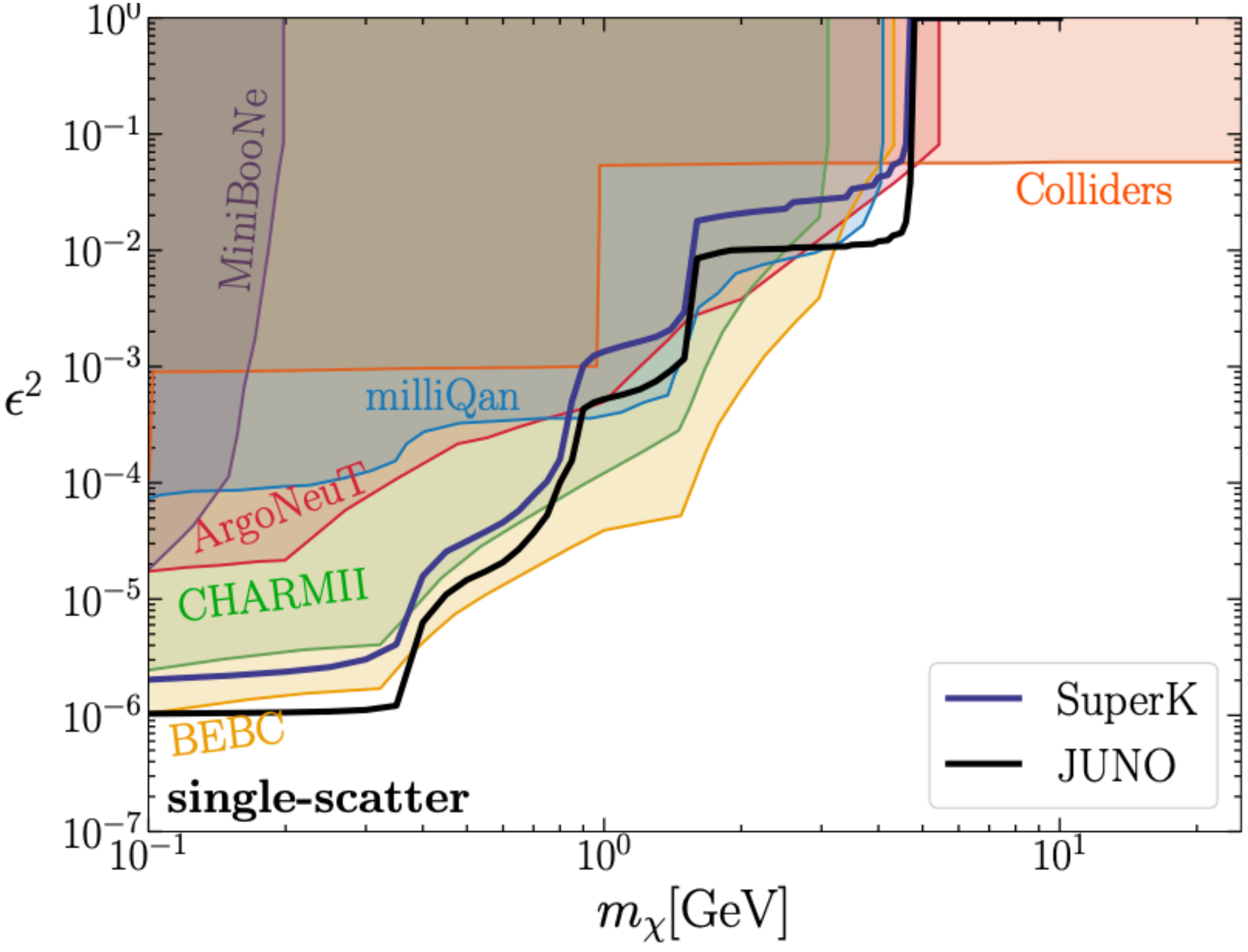
$$-\frac{dE}{dX} = \varepsilon^2 \left(a_{\text{ion.}} + b_{\text{el.-brem.}}\varepsilon^2 E + b_{\text{inel.-brem.}}E + b_{\text{pair}}E + b_{\text{photo-had.}}E\right) \approx \varepsilon^2 \left(a + bE\right)$$



Wu, Hardy, **NS**, arXiv: 2406.01668

For $\epsilon^2 \gtrsim 10^{-2}$, the down-going flux becomes significantly attenuated

Single Scatter Constraint



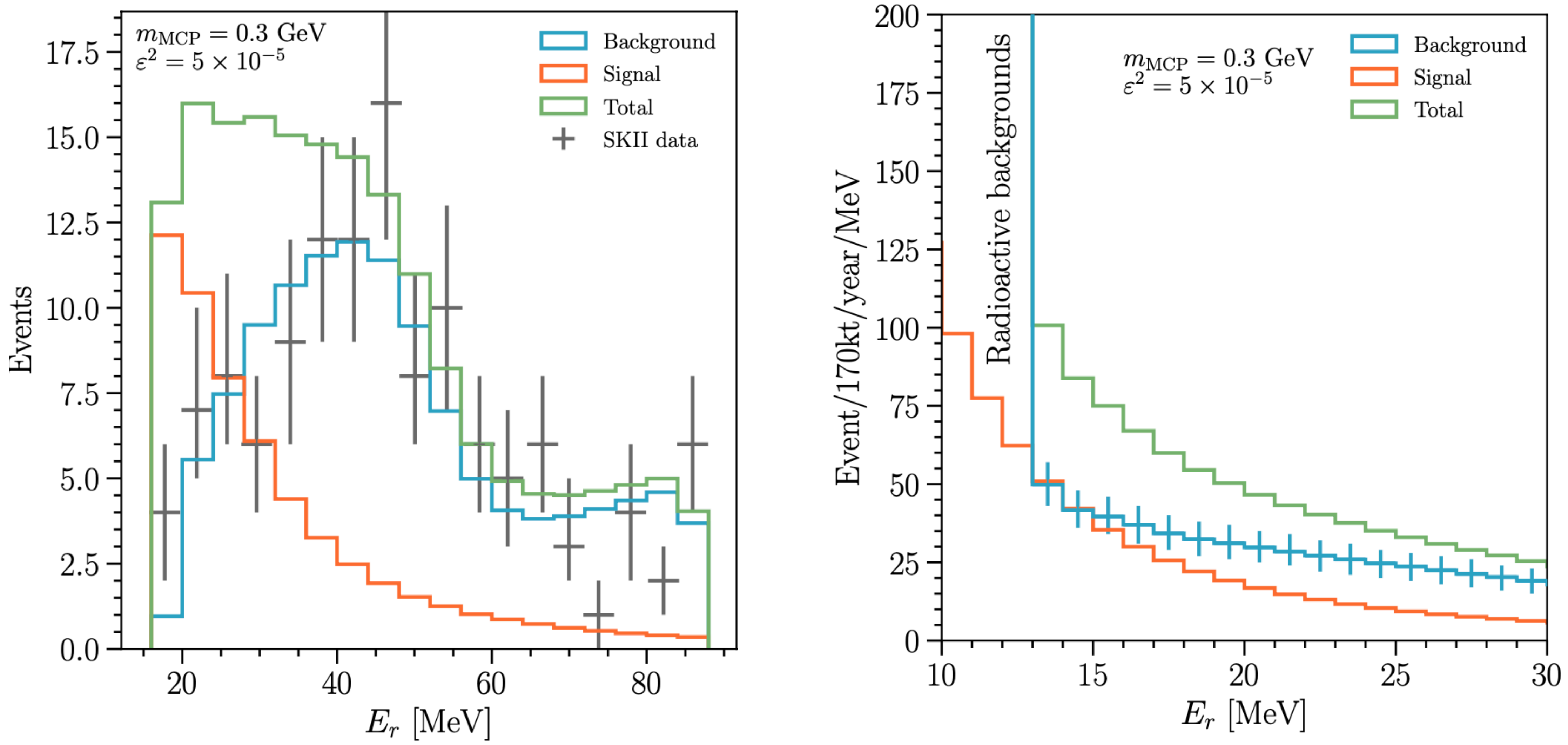
Assuming JUNO 10 MeV threshold+170 kton·yr exposure

Wu, Hardy, **NS**, arXiv: 2406.01668

$$\frac{d\sigma_{\chi e}}{dE_r} = \pi\epsilon^2\alpha^2 \frac{(E_r^2 + 2E_\chi^2)m_e - \left((2E_\chi + m_e)m_e + m_\chi^2\right) E}{E_r^2 m_e^2 \left(E_\chi^2 - m_\chi^2\right)}$$

$$d\sigma_{\chi e}/dE_r \propto 1/E_r^2$$

$$\sigma_{\chi e} \simeq \frac{\pi\alpha_{EM}\epsilon^2}{m_e T_{\min}} = 2.6\times 10^{-25}\epsilon^2\ \mathrm{cm}^2\frac{\mathrm{MeV}}{T_{\min}}$$



Arguelles et al JHEP/2104.13924

Multiple Scatter Constraint

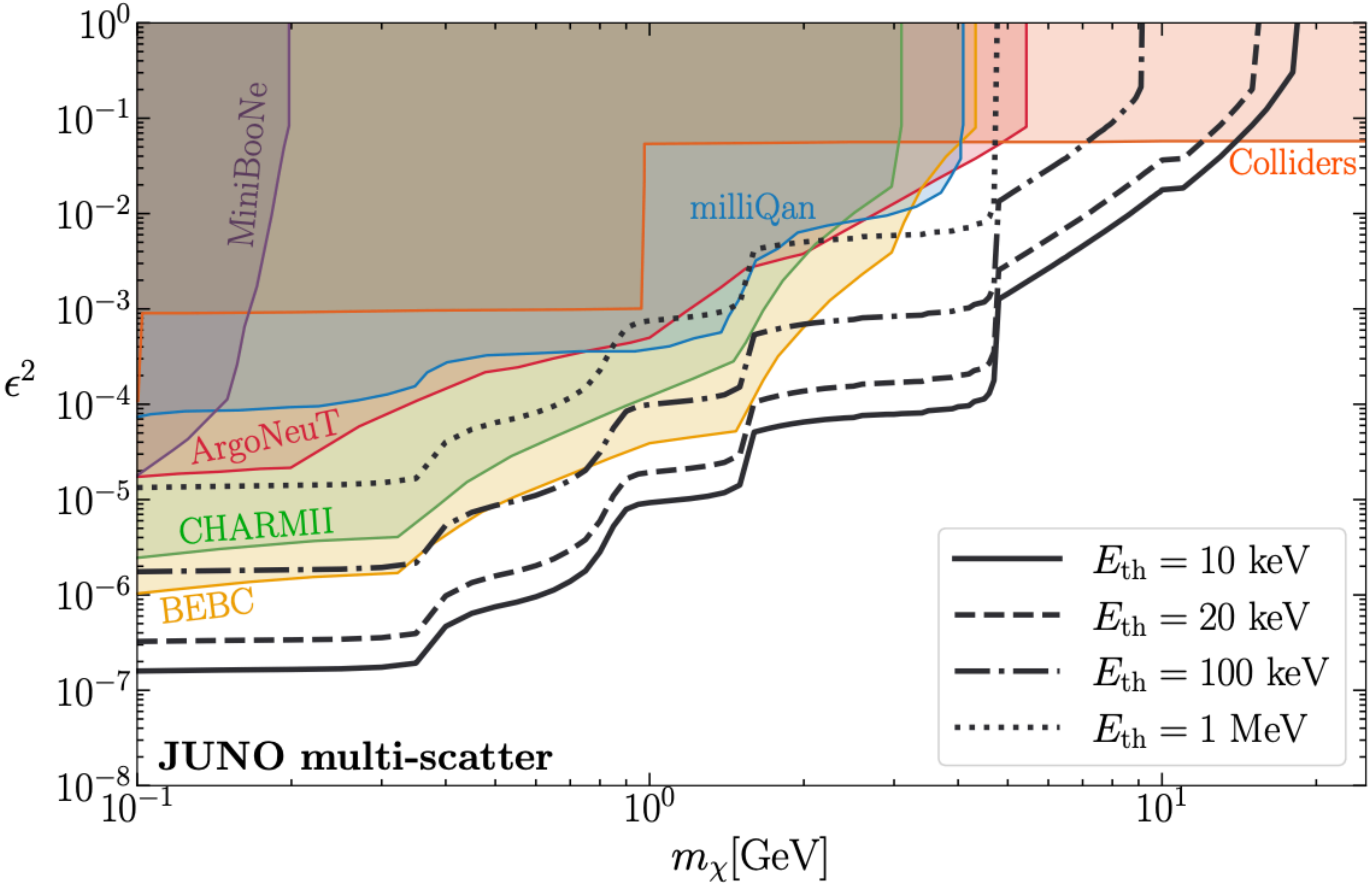
Single scatter probability $$P_1 = 1 - \exp\left(-\frac{L_D}{\lambda(T_{\min})}\right)$$

Multiple scatter probability $$P_{n\geq 2}(T_{\min}) = 1 - \exp\left(-\frac{L_D}{\lambda}\right)\left(1 + \frac{L_D}{\lambda}\right)$$

Number of observed events $$N_{\text{multi}} = N_{\text{single}} P_{n\geq 2}(T_{\min\text{ ,multi}}) / P_1(T_{\min\text{ ,single}})$$

$$N_{\text{single}}\left(m_\chi, \epsilon\right) = N_e T \int_{E_{i,\,\min}}^{E_{i,\,\max}} dE_r \epsilon_D(E_r) \times \int dE_\chi d\Omega \Phi_\chi^D \left(E_\chi, \Omega\right) \frac{d\sigma_{\chi e}}{dE_r}$$

Multiple Scatter Constraint



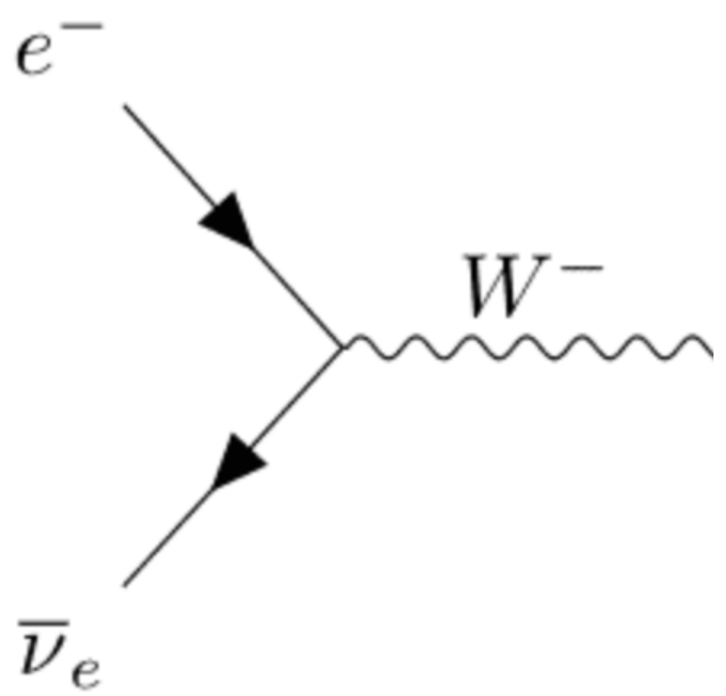
Assuming JUNO 170 kton·yr exposure

Wu, Hardy, **NS**, arXiv: 2406.01668

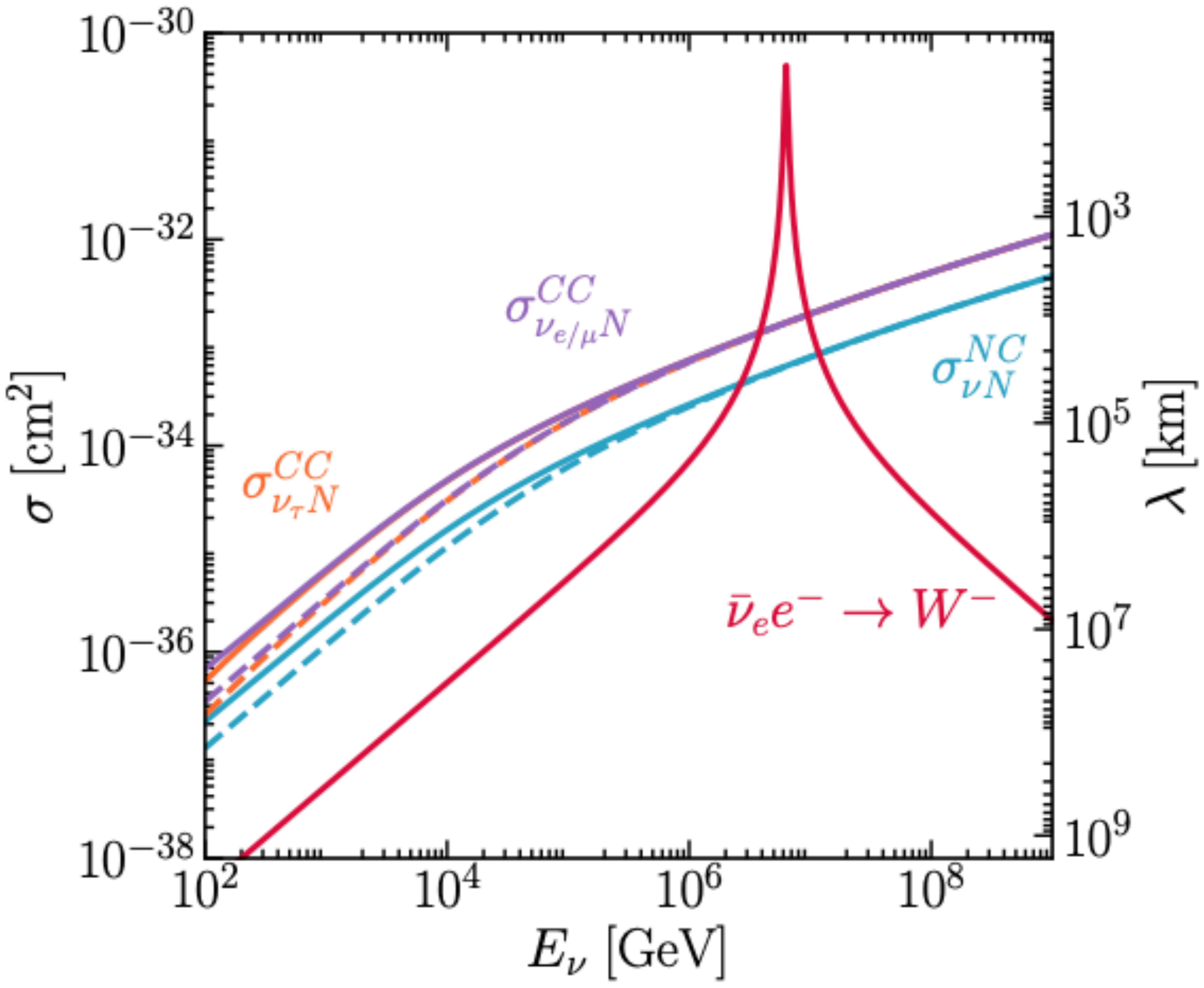
Glashow Resonance (GR)

When the centre of mass energy is close to W boson mass, $\bar{\nu}_e$-electron interaction is enhanced by the resonant production of W

$$\sigma_{\overline{\nu}_e e}(s) = 24\pi\,\Gamma_W^2\,\mathrm{Br}(W^- \to \overline{\nu}_e + e^-) \times \frac{s/M_W^2}{(s-M_W^2)^2 + (M_W\Gamma_W)^2},$$



Huang, Liu , 1912.02976



Glashow Resonance at IceCube

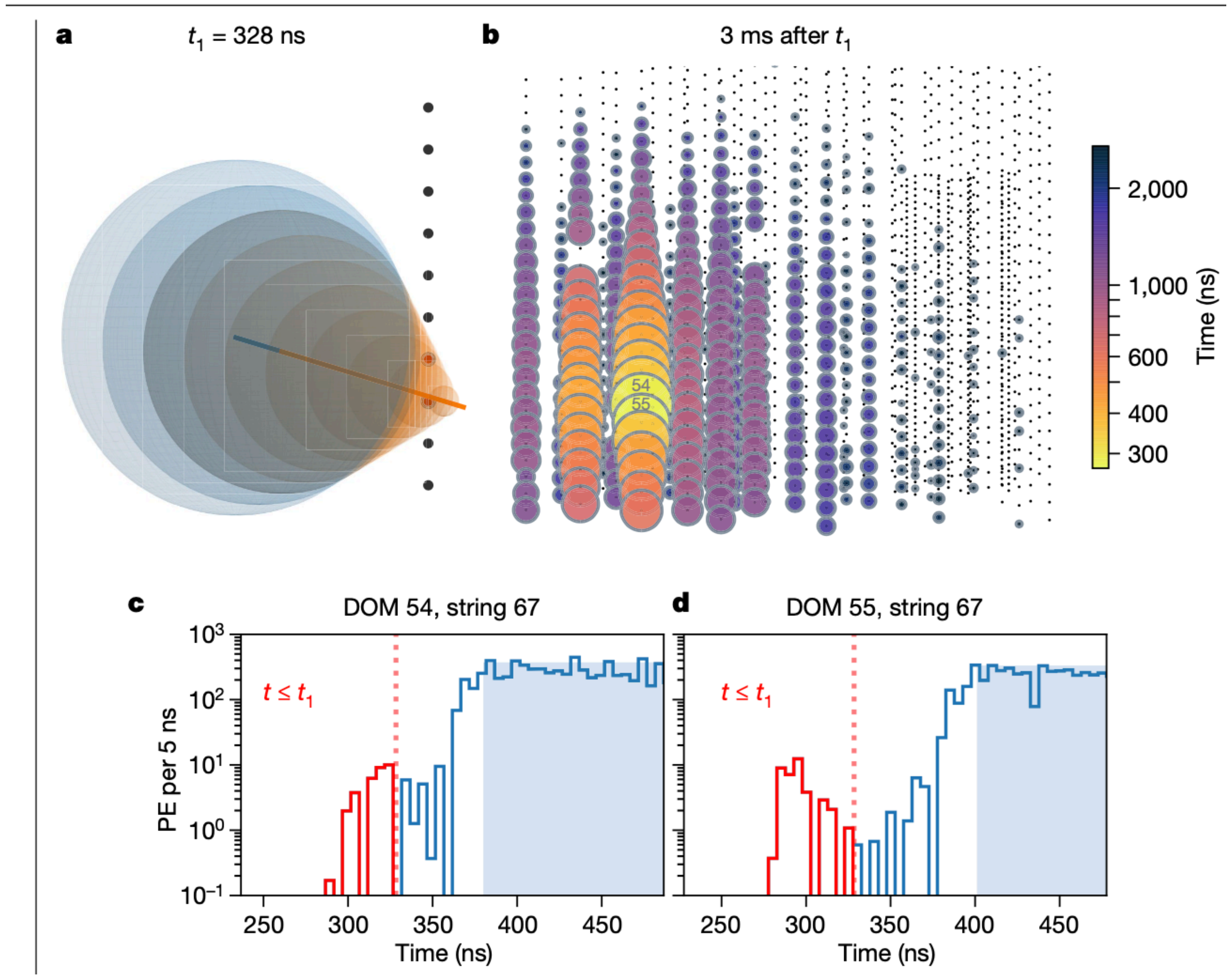
Article | Published: 10 March 2021

Detection of a particle shower at the Glashow resonance with IceCube

The IceCube Collaboration

Nature **591**, 220–224 (2021) | Cite this article

16k Accesses | **63** Citations | **507** Altmetric | Metrics

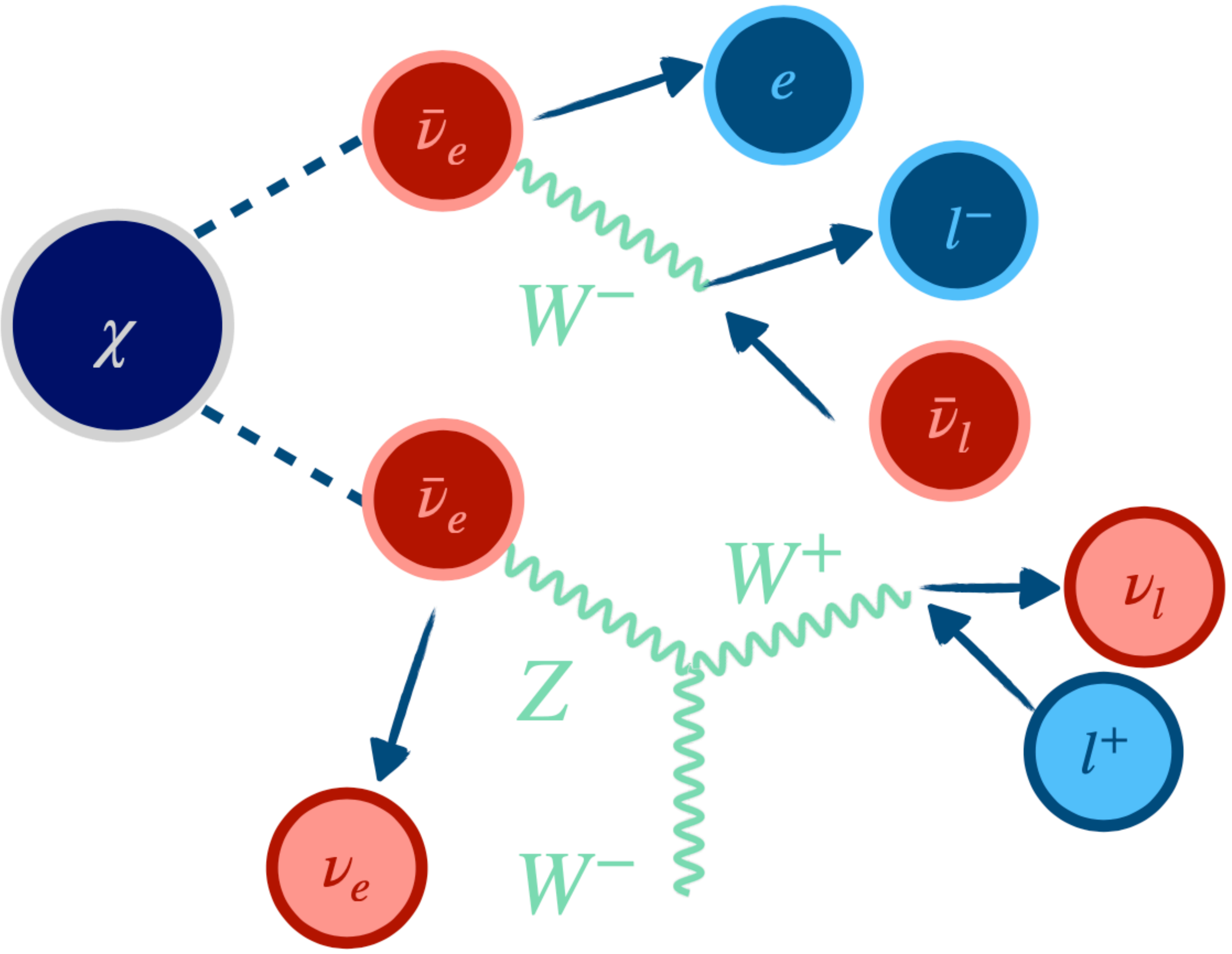


- Glashow resonance candidate was identified with 2.3 σ significance assuming $E^{-2.5}$ spectrum
- The cascade is partially contained (PEPE), with muon early pulses consistent with W decay

Asymmetric Dark Matter Decay

$$\mathcal{O}_{X\to\nu} = \frac{1}{\Lambda^2} X\psi L\Phi\,, \quad \frac{1}{\Lambda^2} X(L\Phi)^2\,, \quad \frac{1}{\Lambda^{3n-1}} \bar{X} l \psi^n$$

$$X \to \bar{\nu},\;\; X \to \bar{\nu}\bar{\nu},\;\; X \to \nu\bar{\nu}\bar{\nu}$$



Credit: Qinrui Liu

Asymmetric Dark Matter Decay

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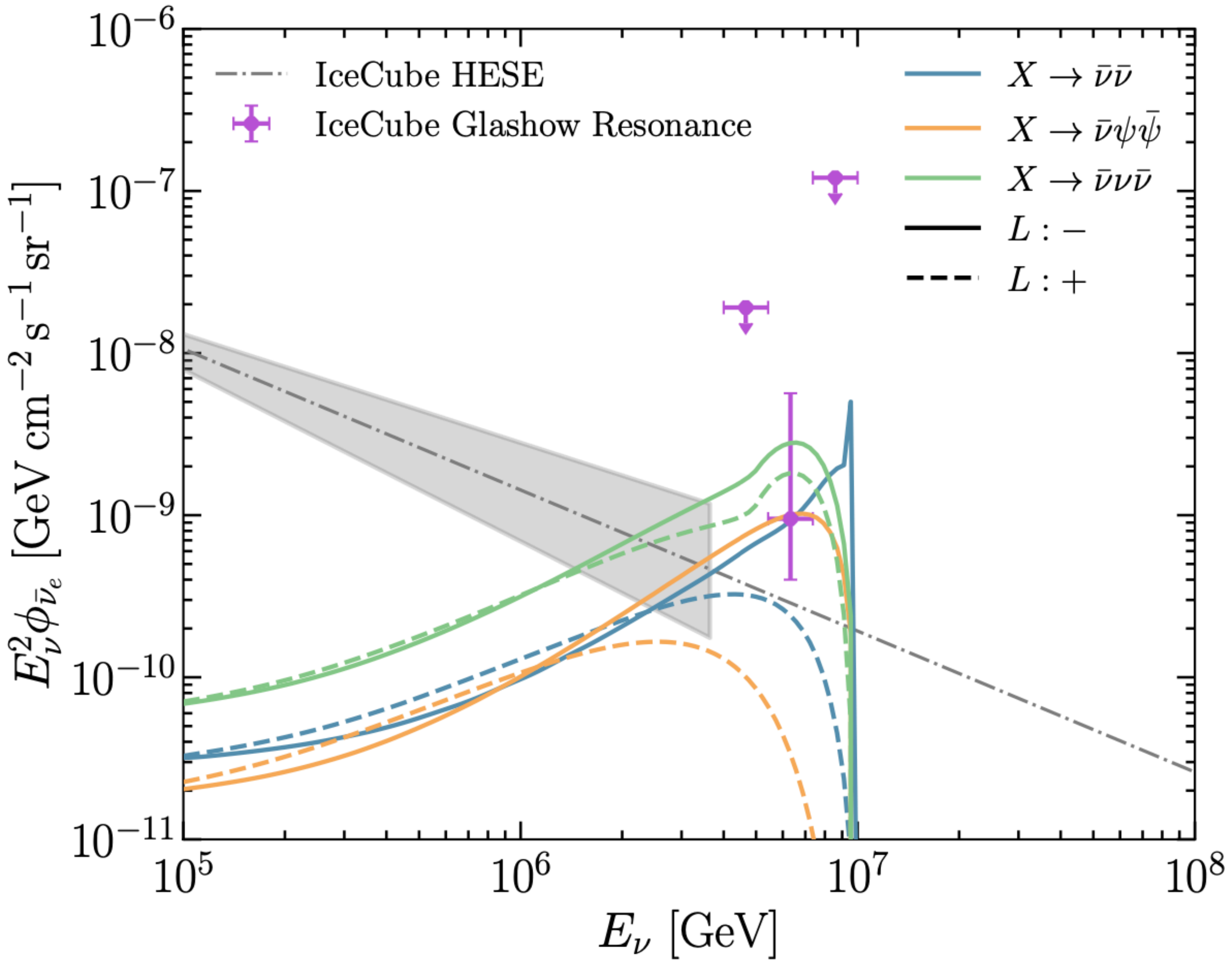
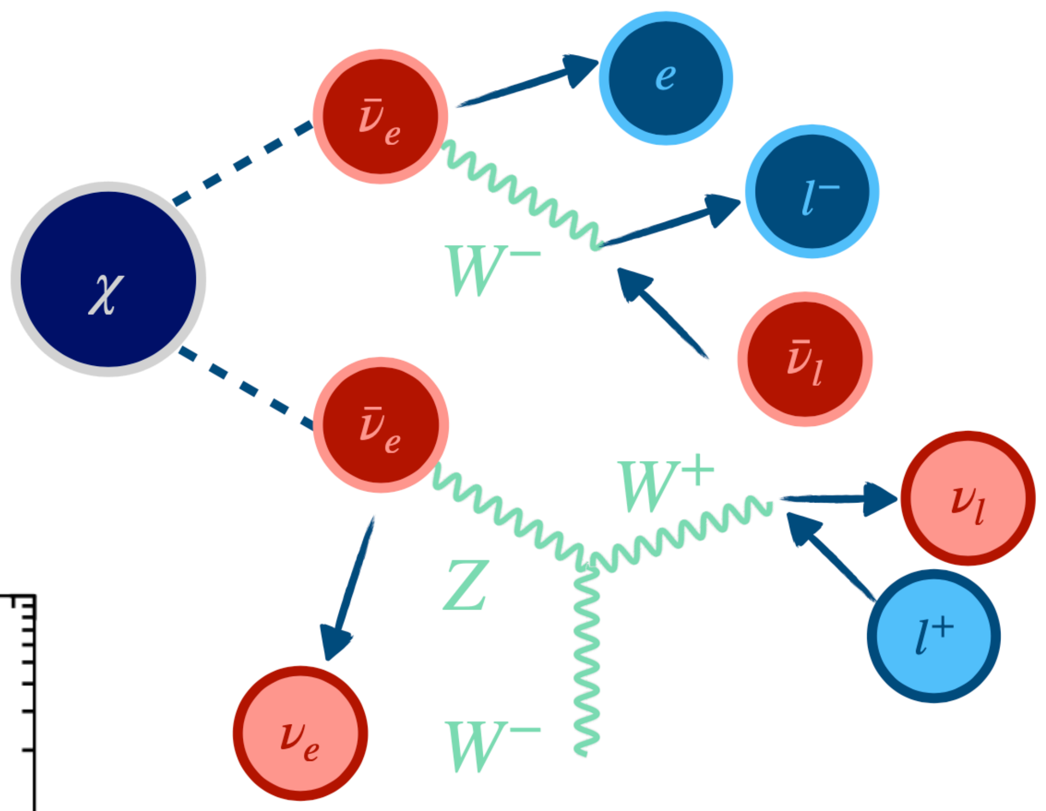
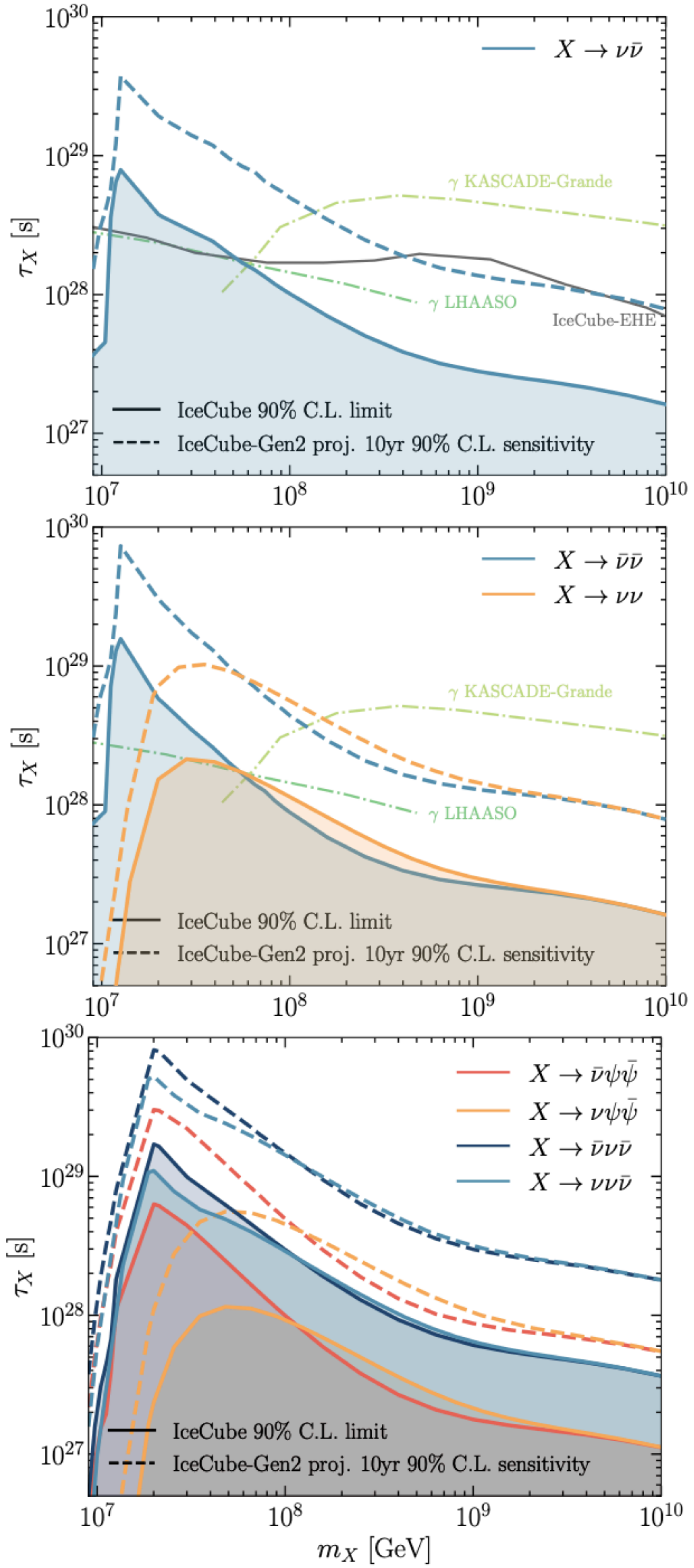
$$X \to \bar{\nu},\ \ X \to \bar{\nu}\bar{\nu},\ \ X \to \nu\bar{\nu}\bar{\nu}$$







Liu, **NS**, Vincent, arXiv: 2406.14602

Summary

- Neutrino experiments could be powerful probes of dark matter thanks to their large exposure

- Search for millicharged particles from atmospheric beam dump at JUNO and SuperK

- Search for heavy dark matter decay at IceCube

谢谢

Heavy neutral leptons

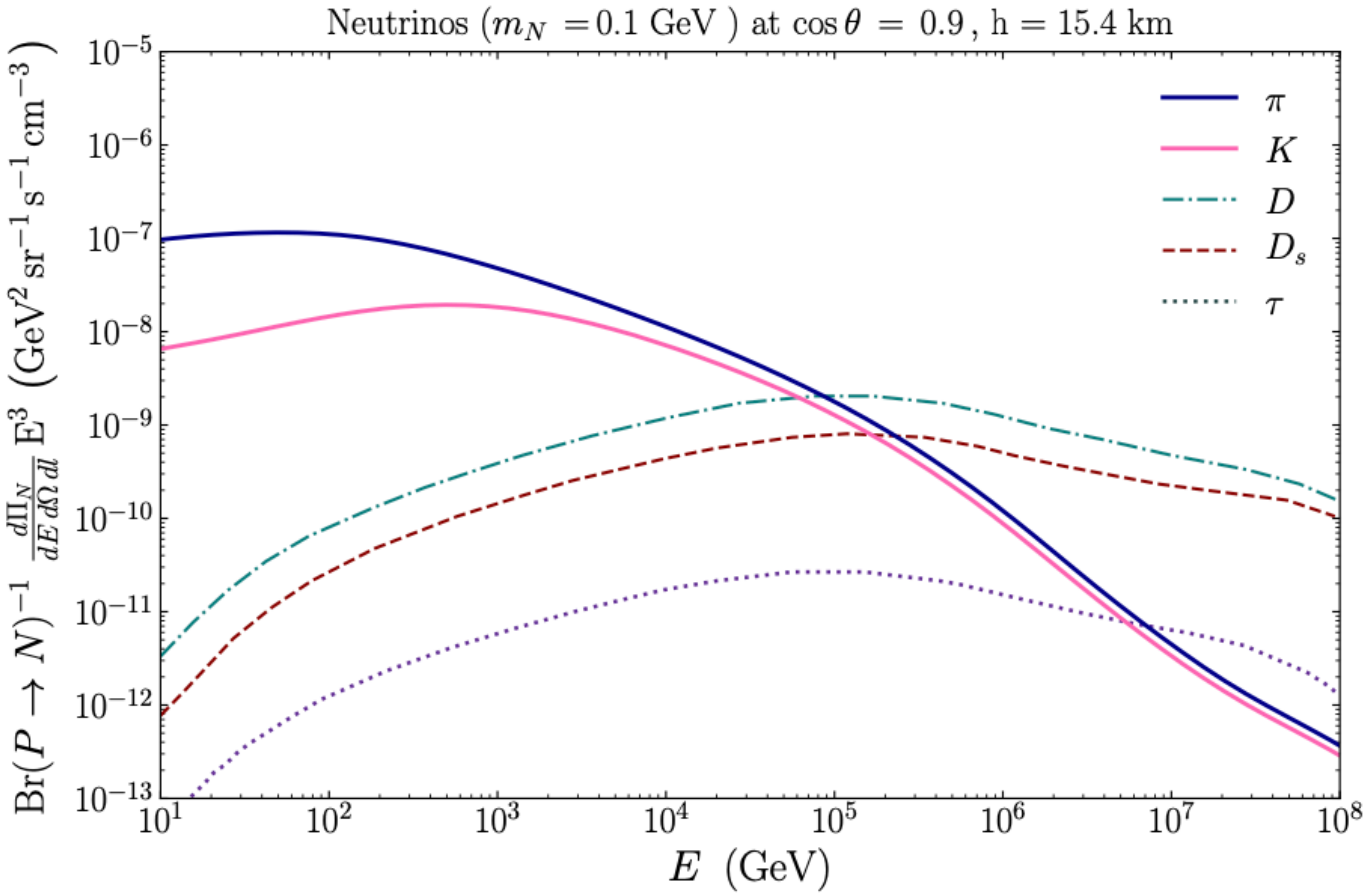
Type-I seesaw $$\mathcal{L}_N = \mathcal{L}_{SM} + \sum_j i\bar{N}_j \gamma^\mu \partial_\mu N_j - \left(Y_{\alpha j} \bar{L}_\alpha \tilde{\Phi} N_j + \frac{m_{N_j}}{2} \bar{N}_j N_j^c \right)$$

Neutrino mass $m_\nu \propto \frac{(Y\nu)^2}{m_N}$ mixing $U_{\alpha j} \propto \frac{Y\nu}{m_N}$

Meson and lepton decay

$$M \to l + N$$

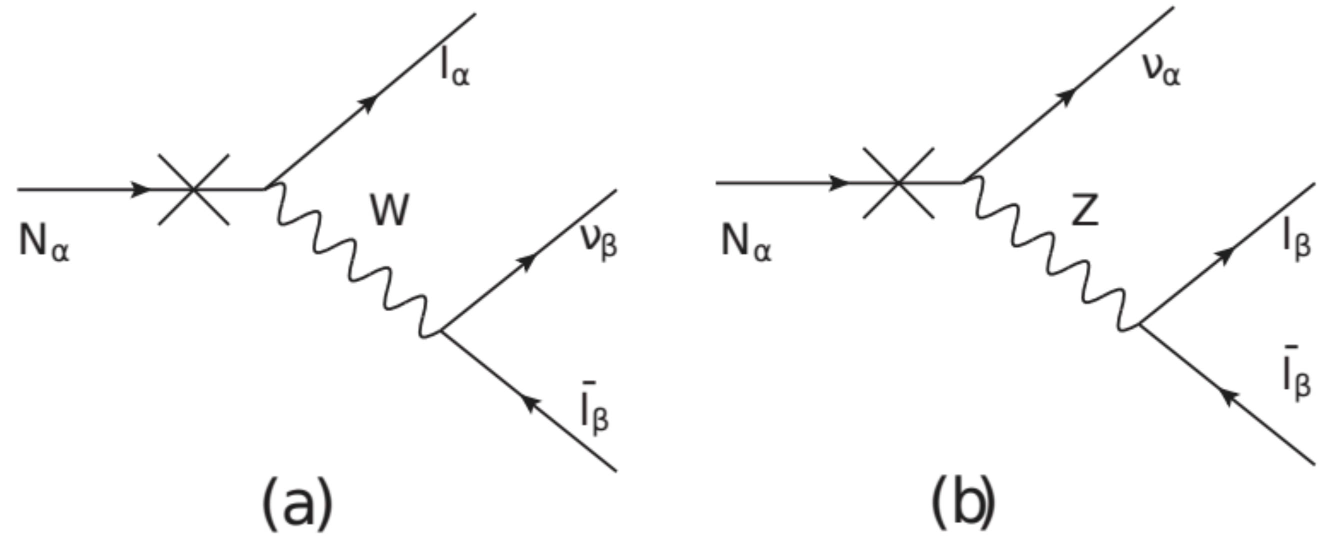
$$\tau \to l + \nu + N$$

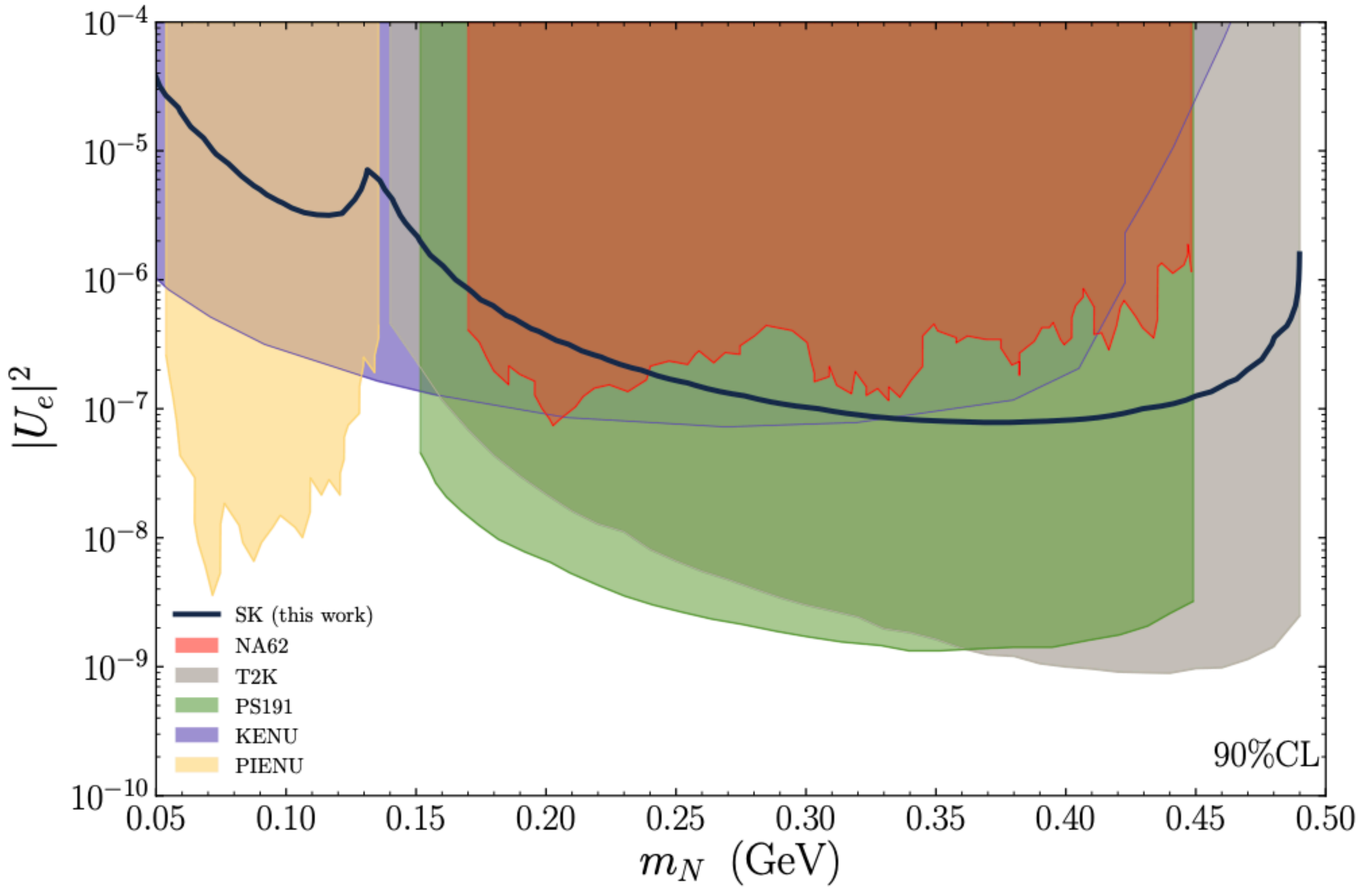


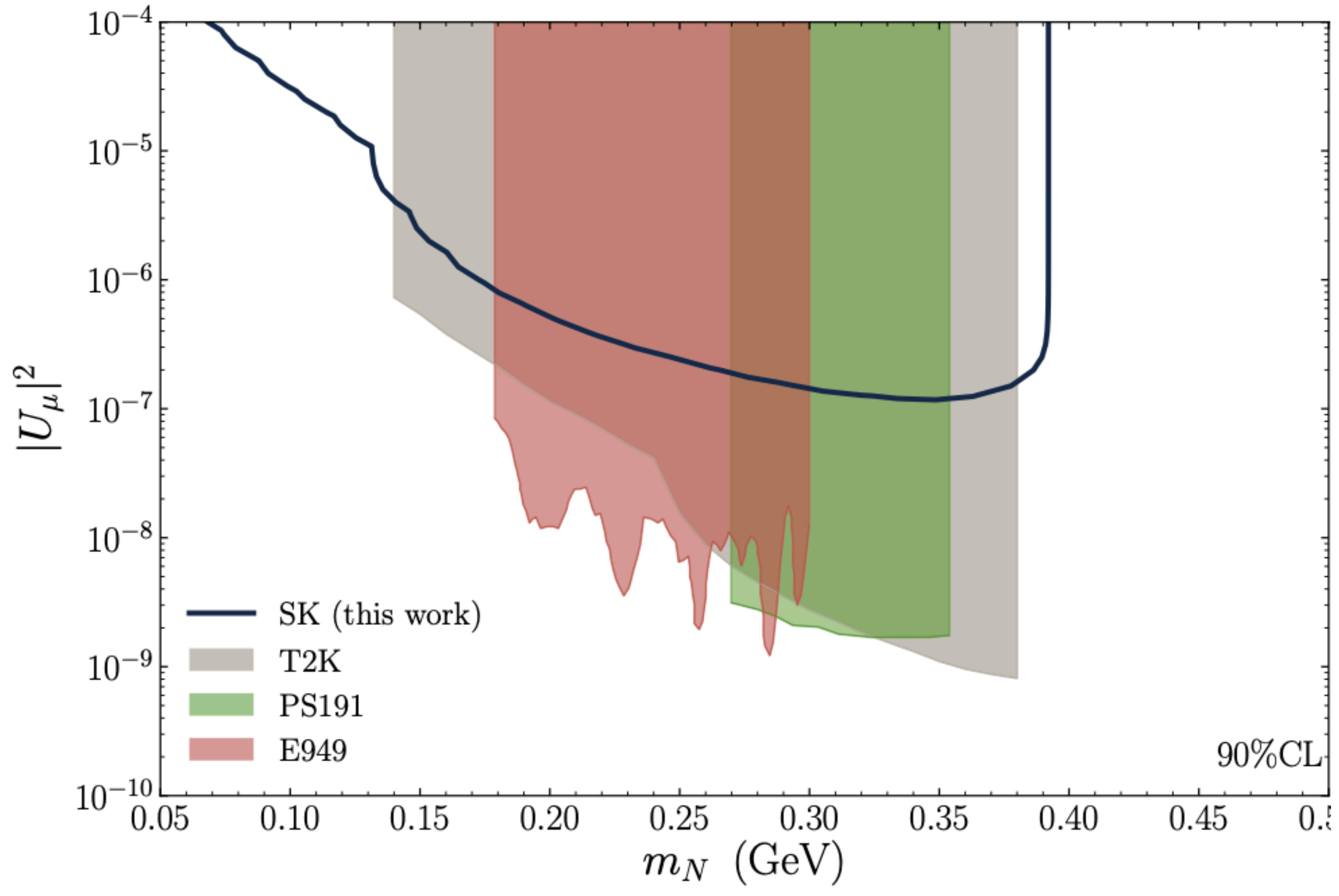
Coloma et al EPJC/1911.09129

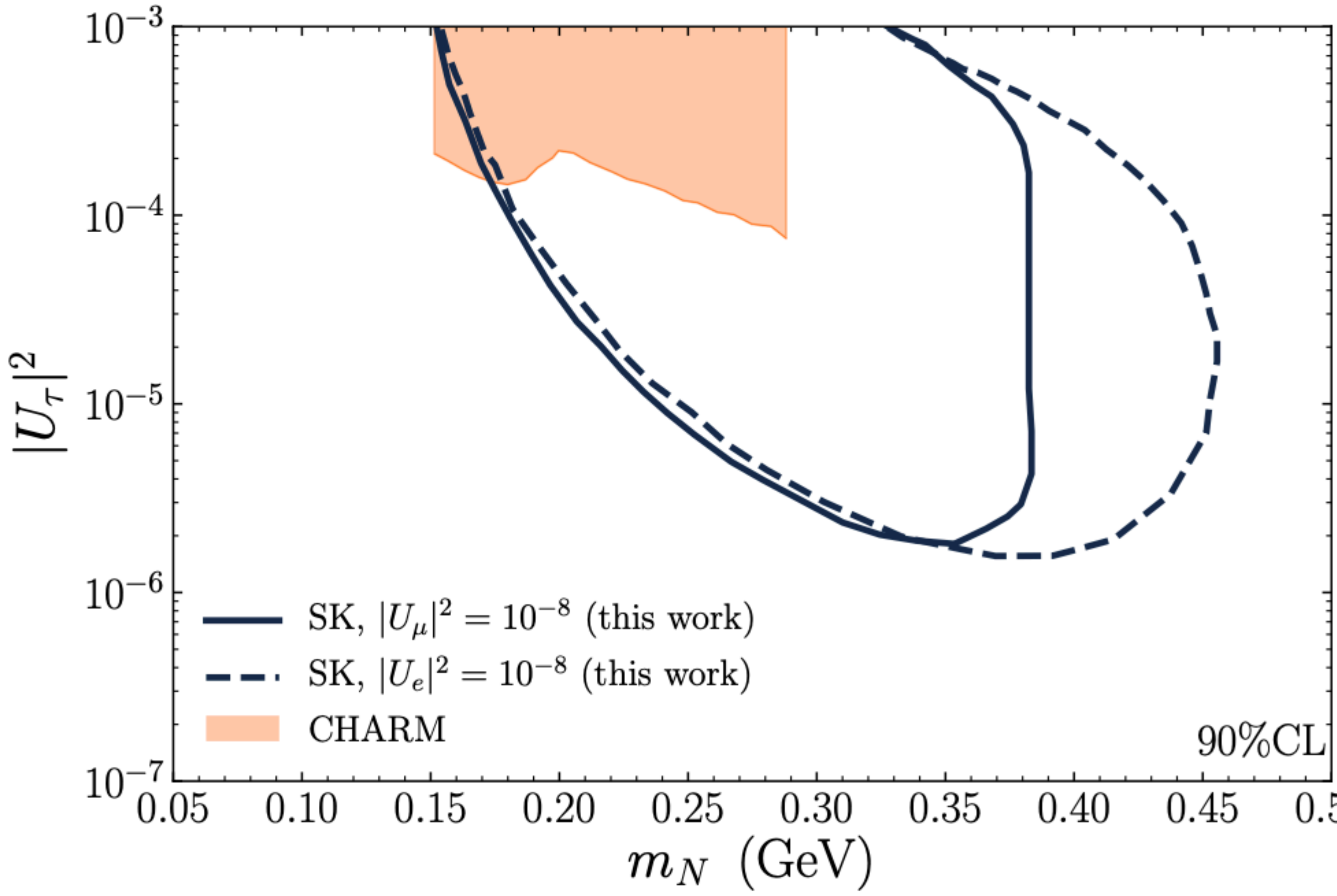
Heavy neutral leptons

Heavy neutral lepton decay to electron/muon at neutrino detectors









Coloma et al EPJC/1911.09129

Hydrophilic dark matter

$$\mathcal{L} \supset i\overline{\chi}(\not{D} - m_\chi)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2$$
$$- \left(g_\chi S \overline{\chi}_L \chi_R + g_u S \overline{u}_L u_R + h.c.\right),$$

Meson decay

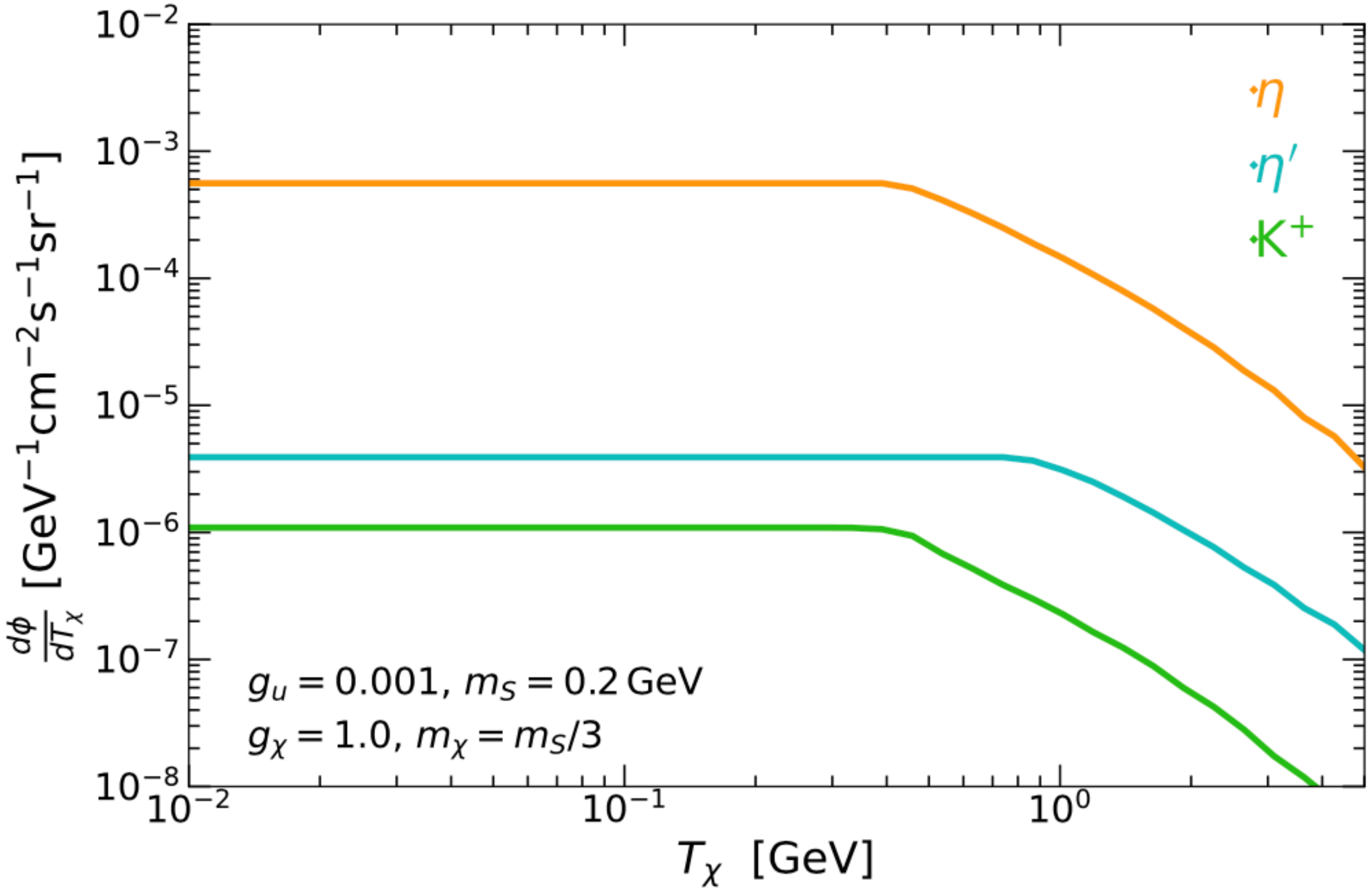
$\eta \rightarrow \pi^0 + S$

$\eta' \rightarrow \pi^0 + S$

$K^+ \rightarrow \pi^+ + S$

$S \rightarrow 2\chi$

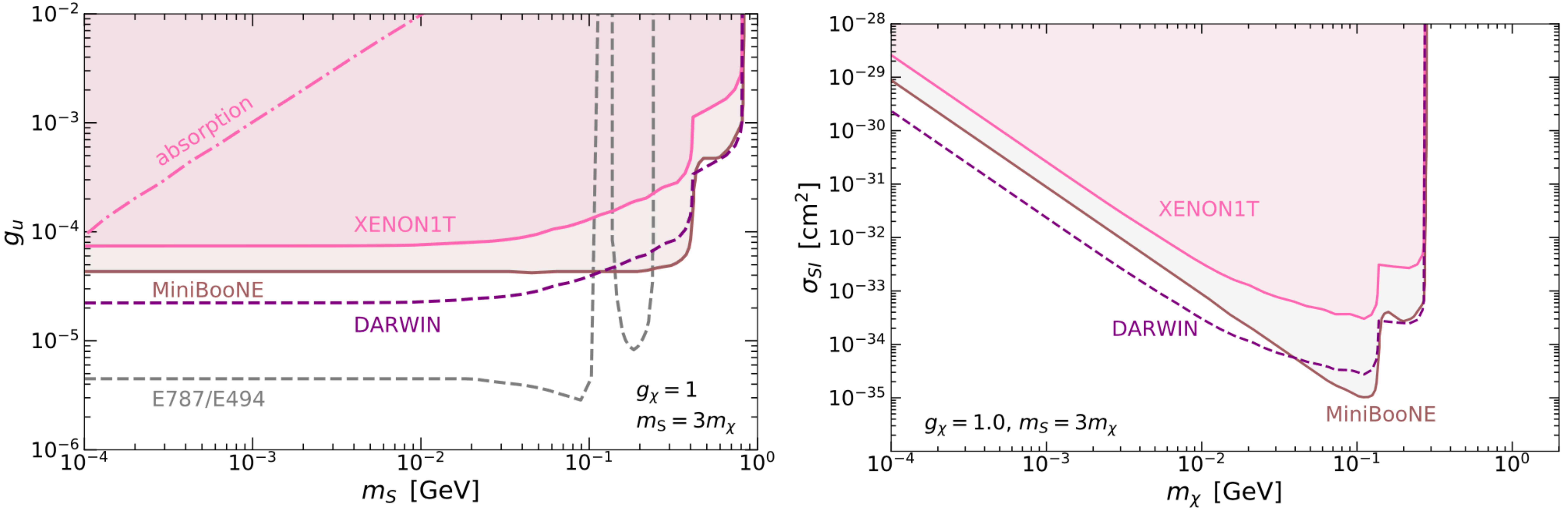
Arguelles et al PLB/2203.12630



Hydrophilic dark matter

$S \to 2\chi$

Dark matter scatters at neutrino and dark matter detectors

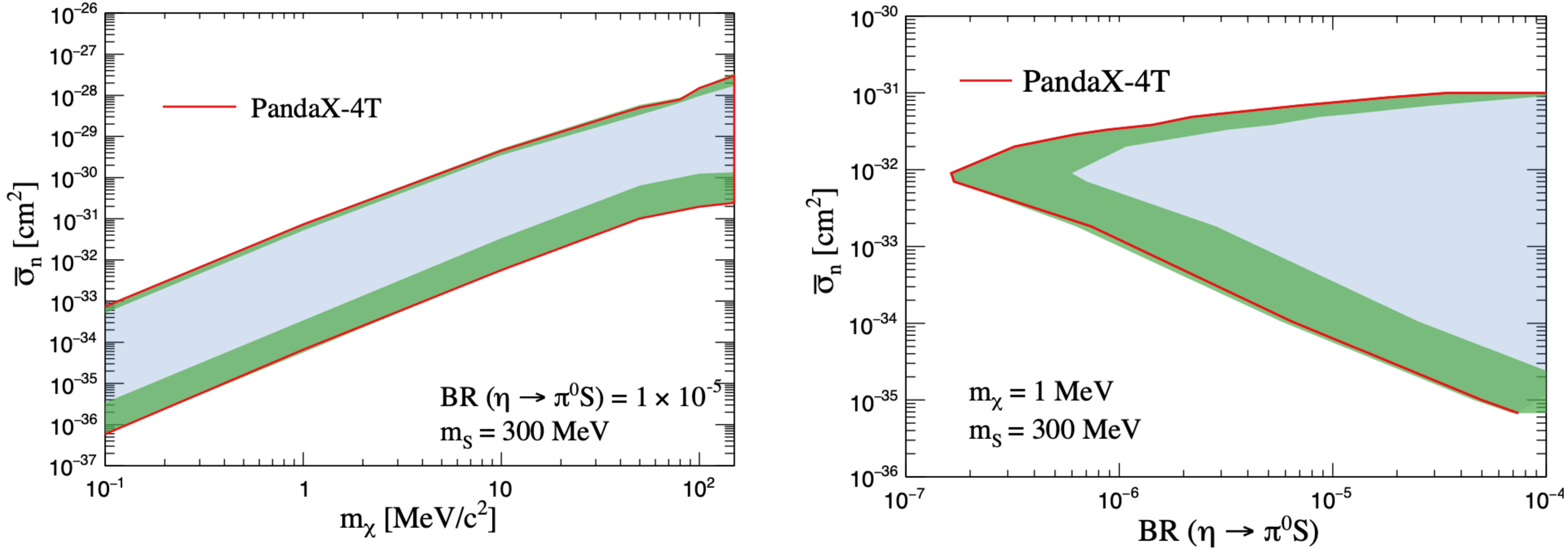


Arguelles et al PLB/2203.12630

Hydrophilic dark matter

Including both elastic and quasi-elastic scattering in the overburden

$$\chi(k) + A\,(p_A) \rightarrow \chi\,(k') + X(\rightarrow n + Y)$$



PandaX PRL/2301.03010

Su et al PRD/2006.11837

Axion-like particles

$$\mathcal{L} \supset -i g_{a\mu\mu} a \bar{\mu} \gamma_5 \mu$$

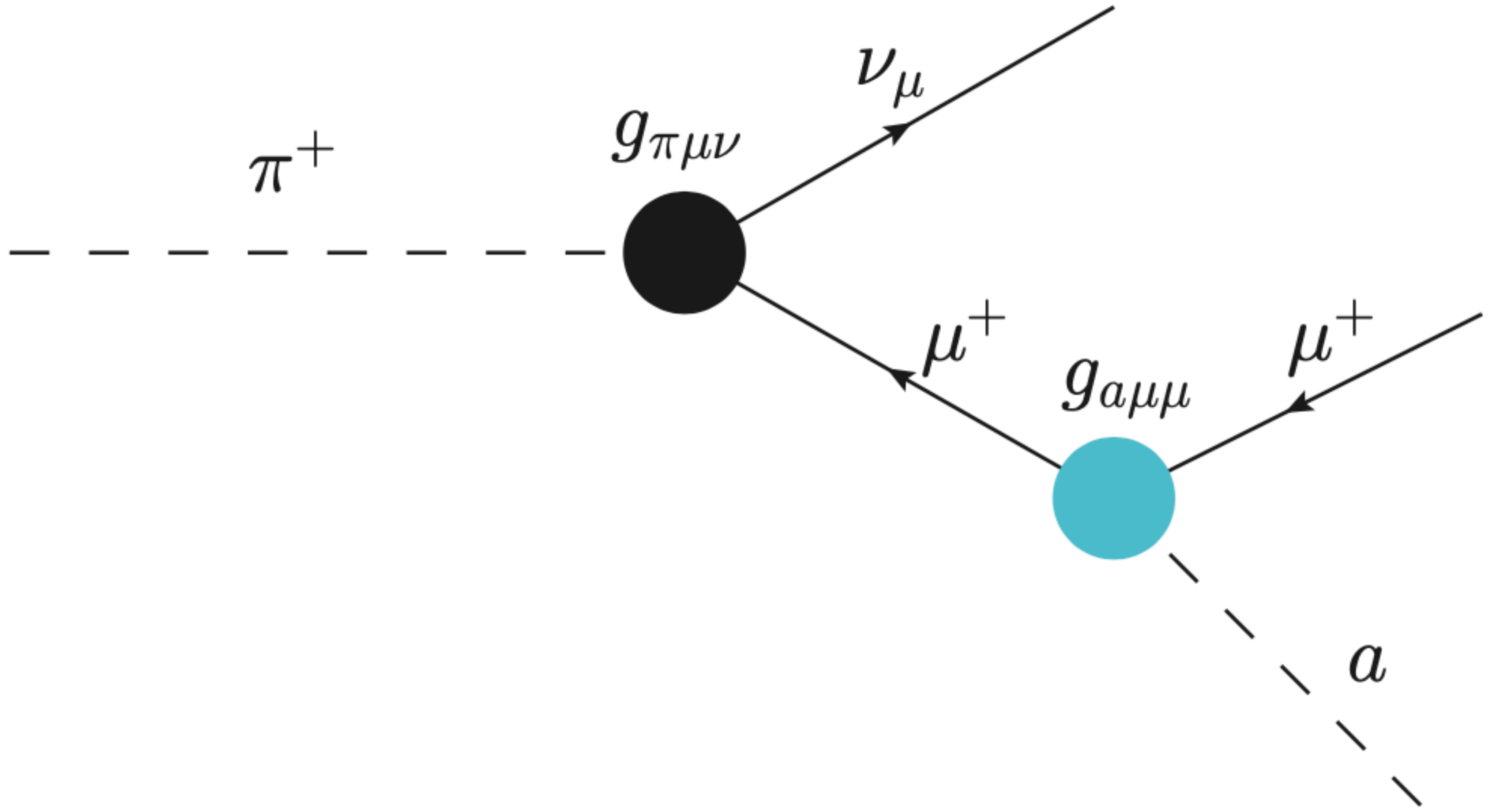
$$\mathcal{L}_{\text{loop}} \supset -\frac{1}{4} g^{\text{eff}}_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$g^{\text{eff}}_{a\gamma\gamma} = \frac{g_{a\mu\mu}\alpha}{m_\mu \pi} \left[1 - \frac{4m_\mu^2}{m_a^2} \arcsin^2 \left(\frac{m_a}{2m_\mu} \right) \right]$$

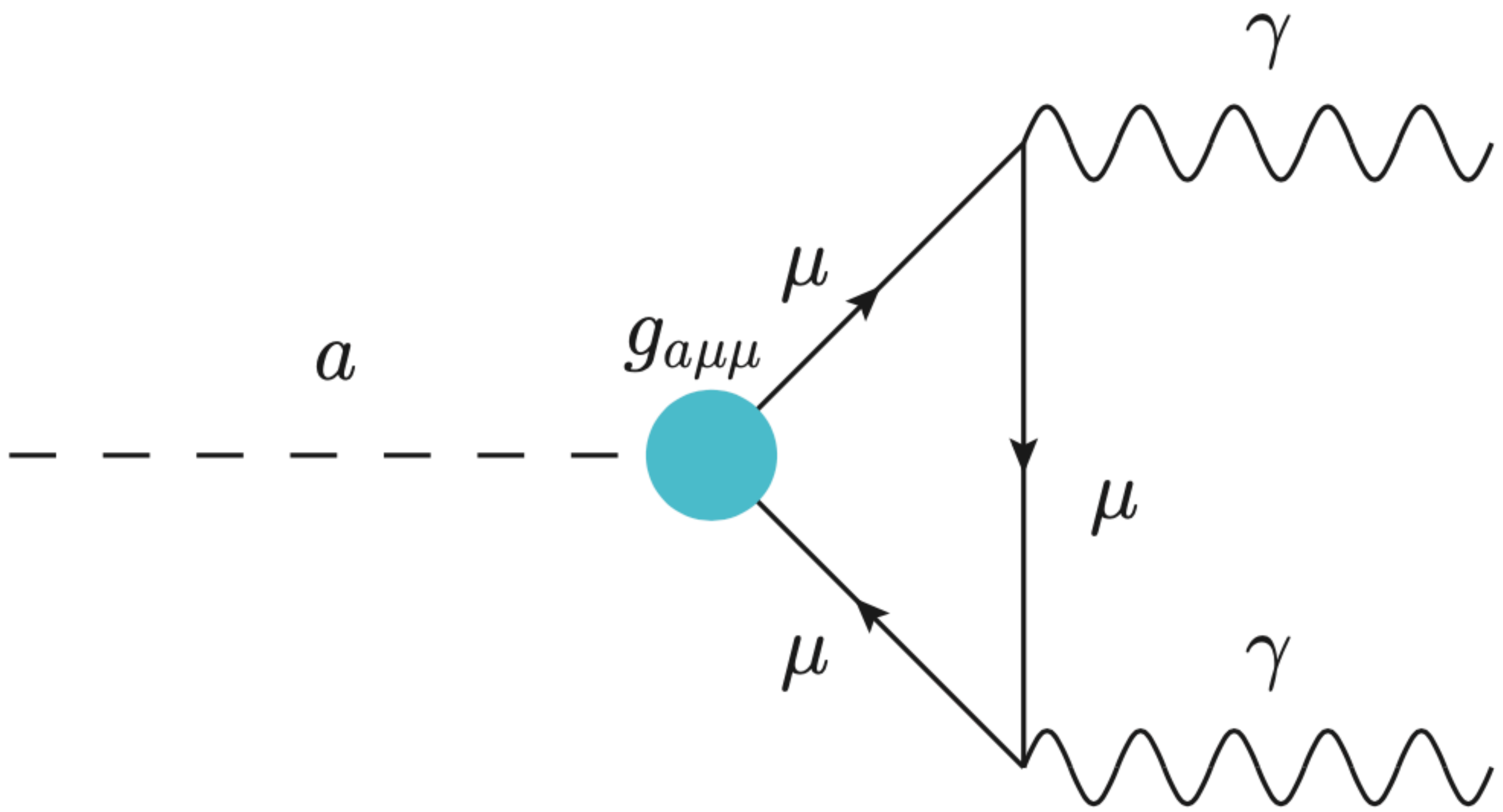
$$\tau_a = \Gamma^{-1}_{a\to\gamma\gamma} = \frac{64\pi}{(g^{\text{eff}}_{a\gamma\gamma})^2 m_a^3}$$

Cheung et al PRD/2208.05111

$$\pi^+ \to \mu^+ + \nu_\mu + a$$



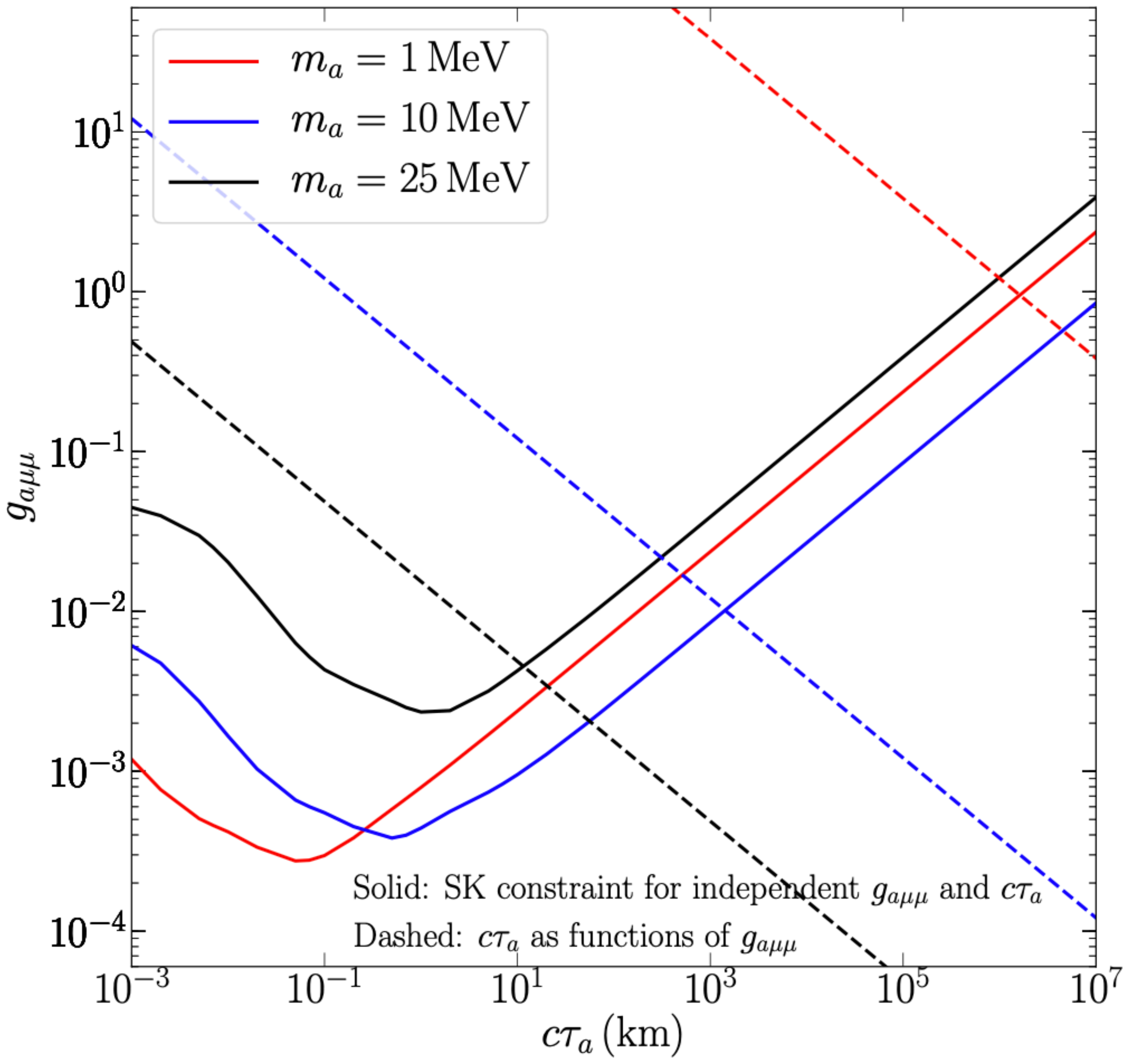
$$m_a < 2m_\mu \qquad a \to \gamma + \gamma$$

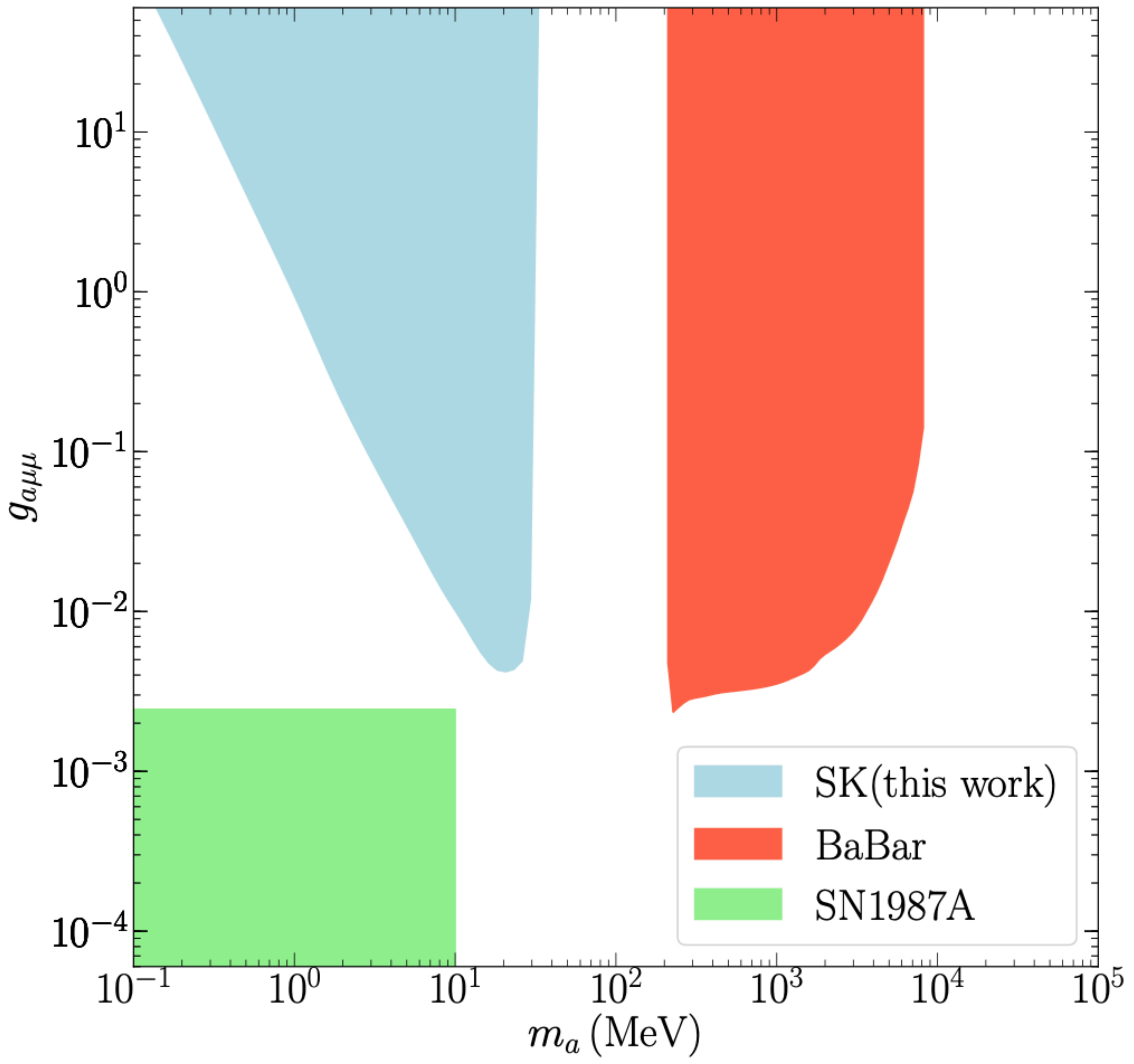


Axion-like particles

Two electron-like Chenrekov rings at neutrino detectors

$$a \rightarrow \gamma + \gamma$$

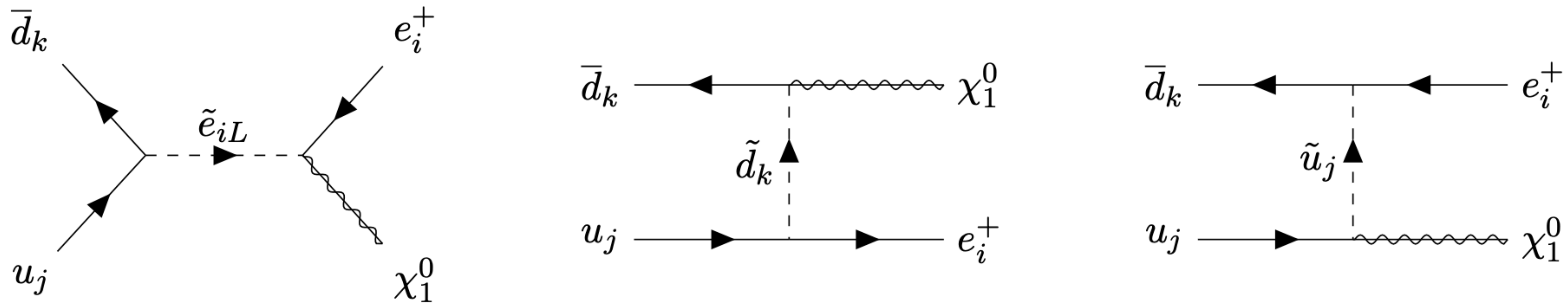




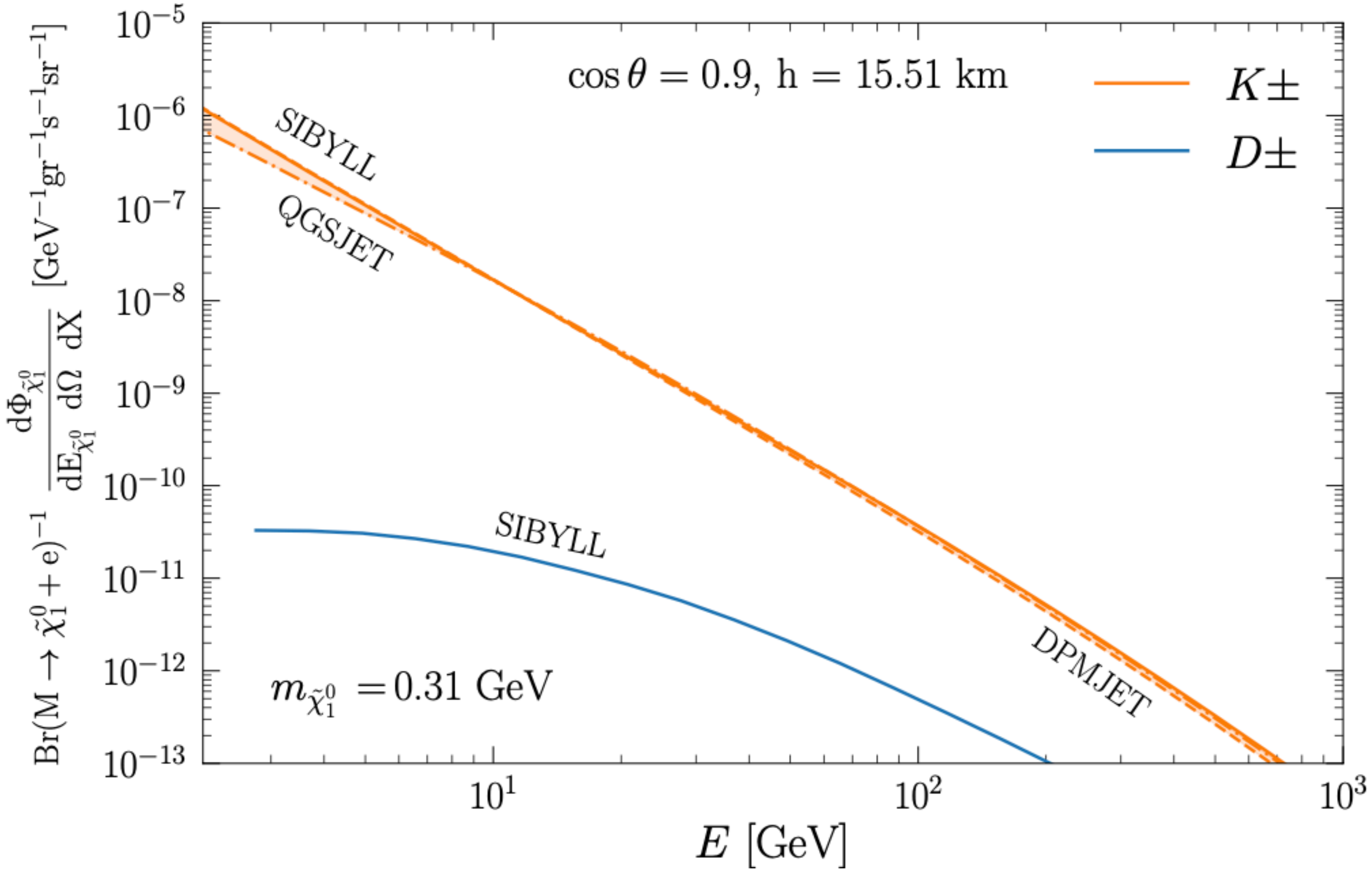
Cheung et al PRD/2208.05111

Long-lived neutralinos

$$\mathcal{L} \supset \lambda'_{ijk} \widehat{L}_i \widehat{Q}_j \widehat{D}^c_k$$



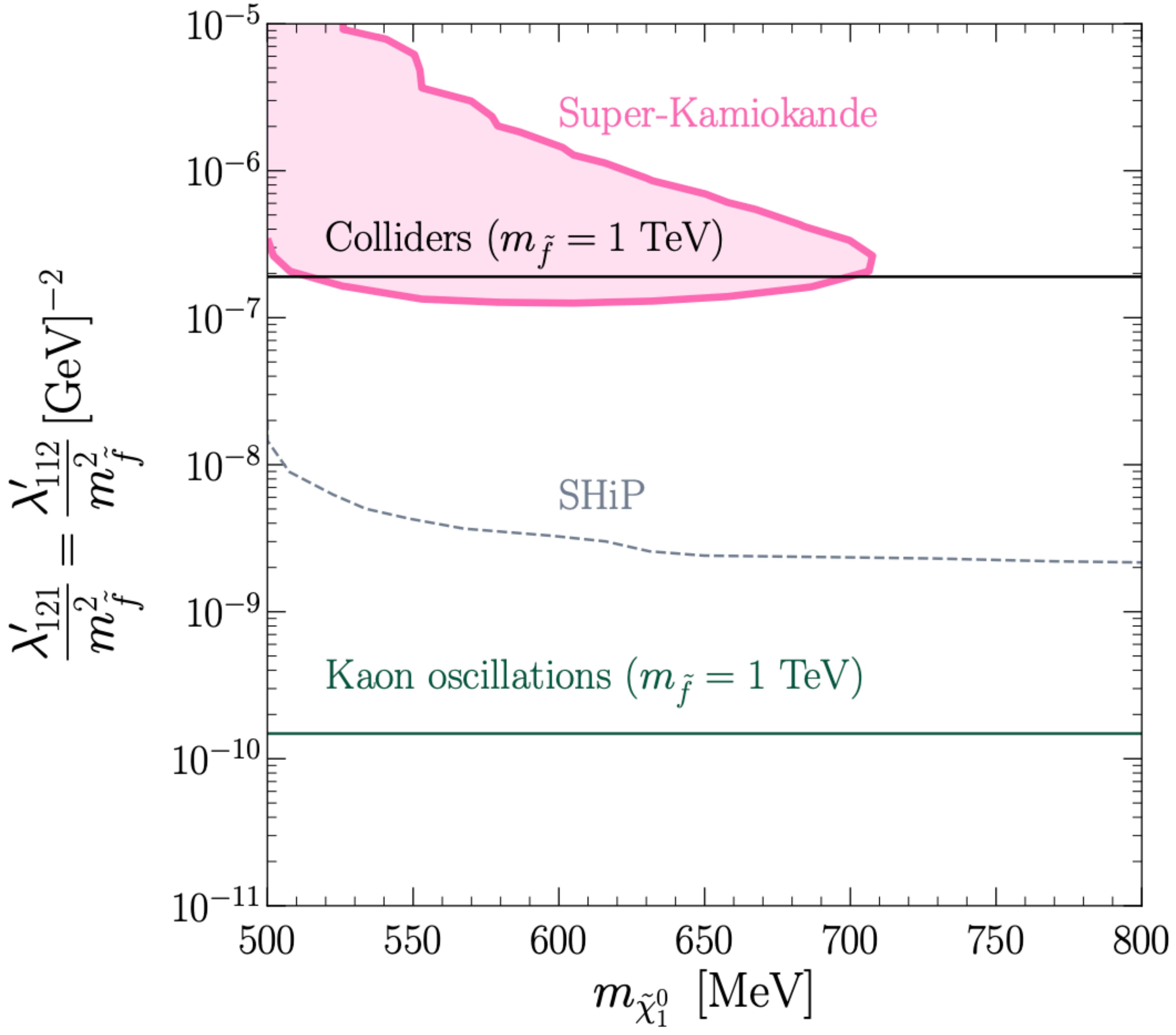
	RPV coupling	Production	Decay mode
B1	$\lambda'_{121}, \lambda'_{112}$	$D^\pm \xrightarrow{\lambda'_{121}} e^\pm + \tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \xrightarrow{\lambda'_{121}} K_S^0 + \nu_e$ $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{121}} K^{*0} + \nu_e$ $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{112}} K^{(*)+} + e^-$ $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{112}} K_S^0 + \nu_e$ $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{112}} K^{*0} + \nu_e$
B2	$\lambda'_{112}, \lambda'_{111}$	$K^\pm \xrightarrow{\lambda'_{112}} e^\pm + \tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \xrightarrow{\lambda'_{111}} \pi^+ + e^-$ $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{111}} \pi^0 + \nu_e$

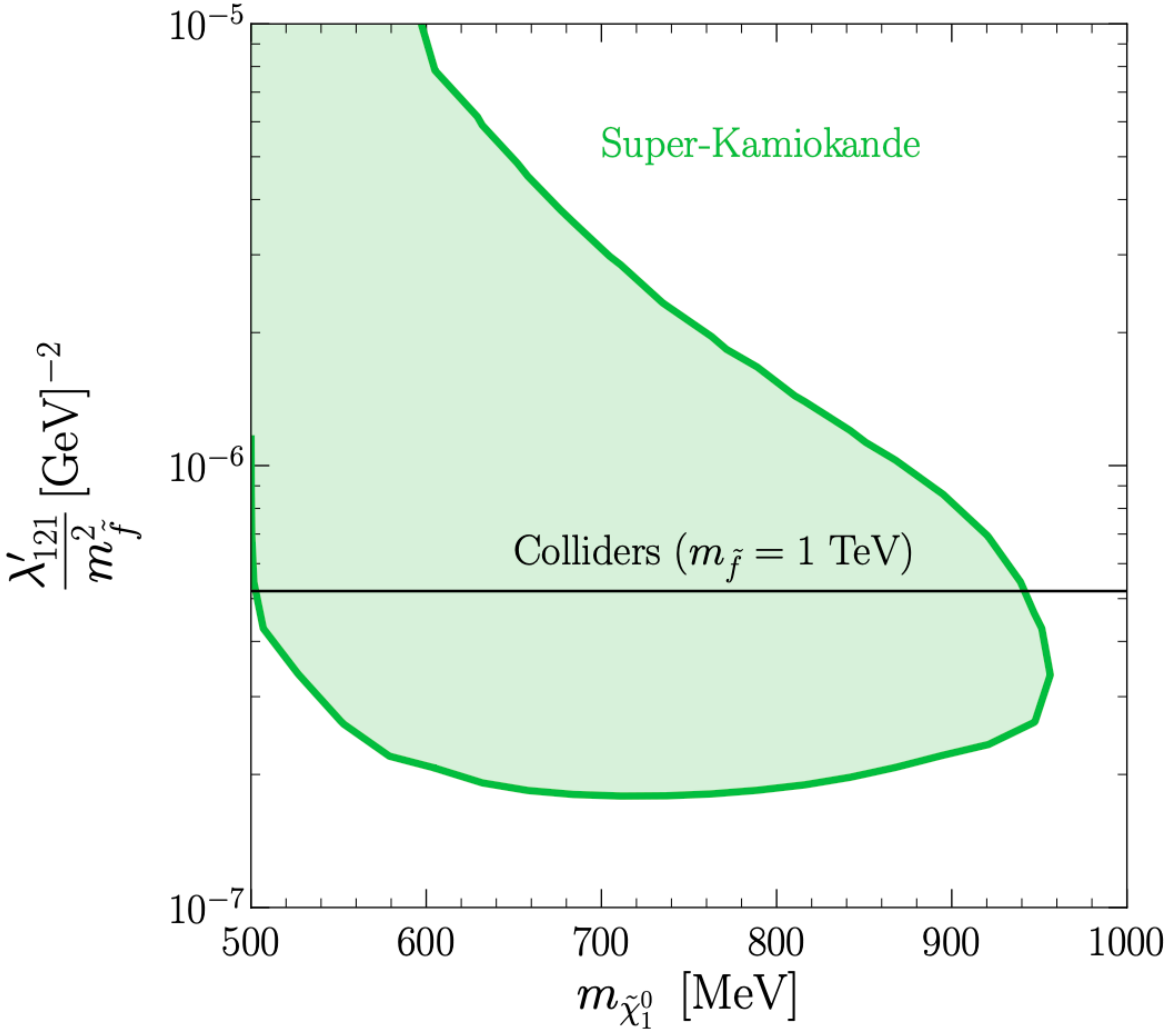


Cheung et al PRD/2208.05111

Long-lived neutralinos

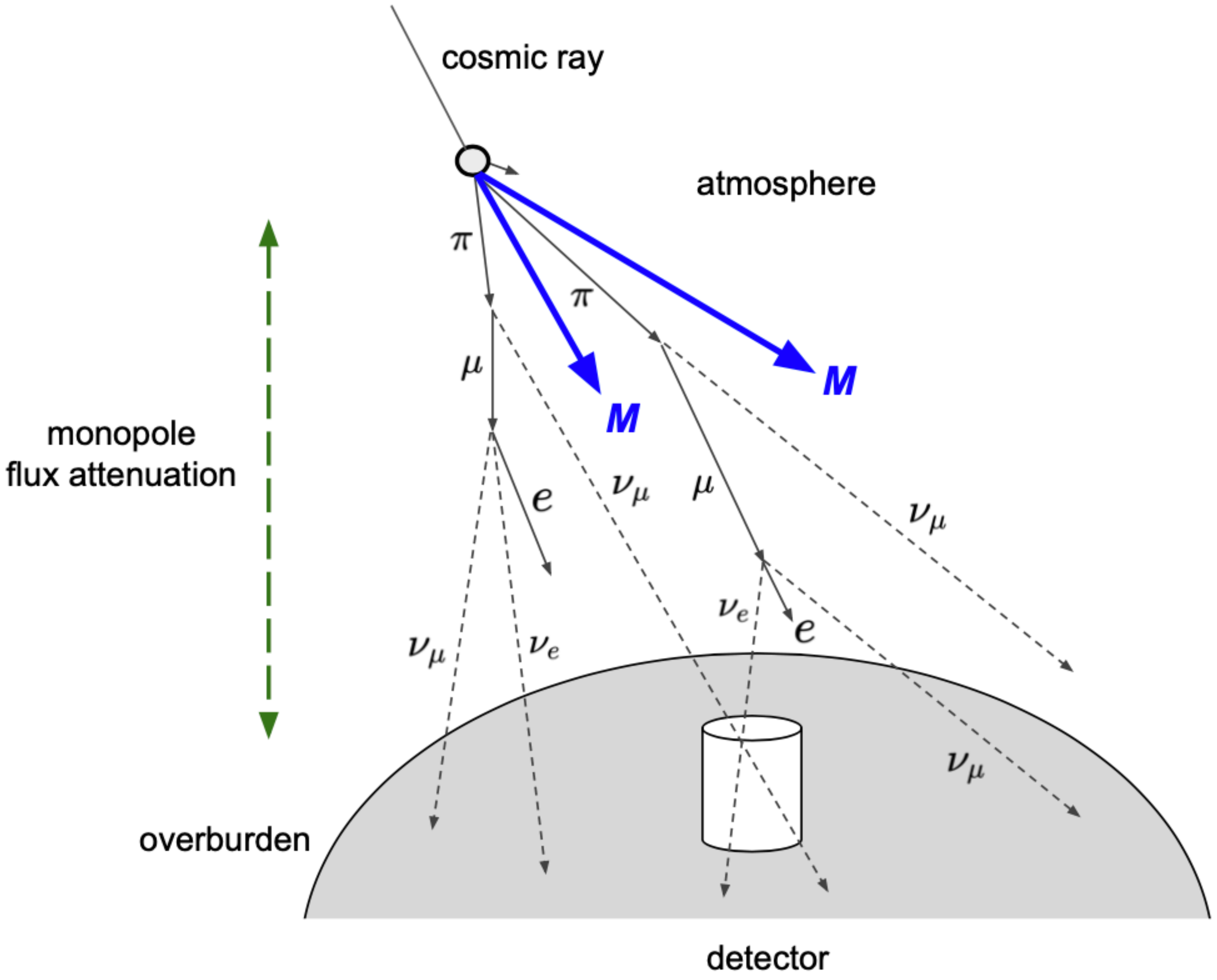
Benchmark 1





Candia et al PRD/2107.02804

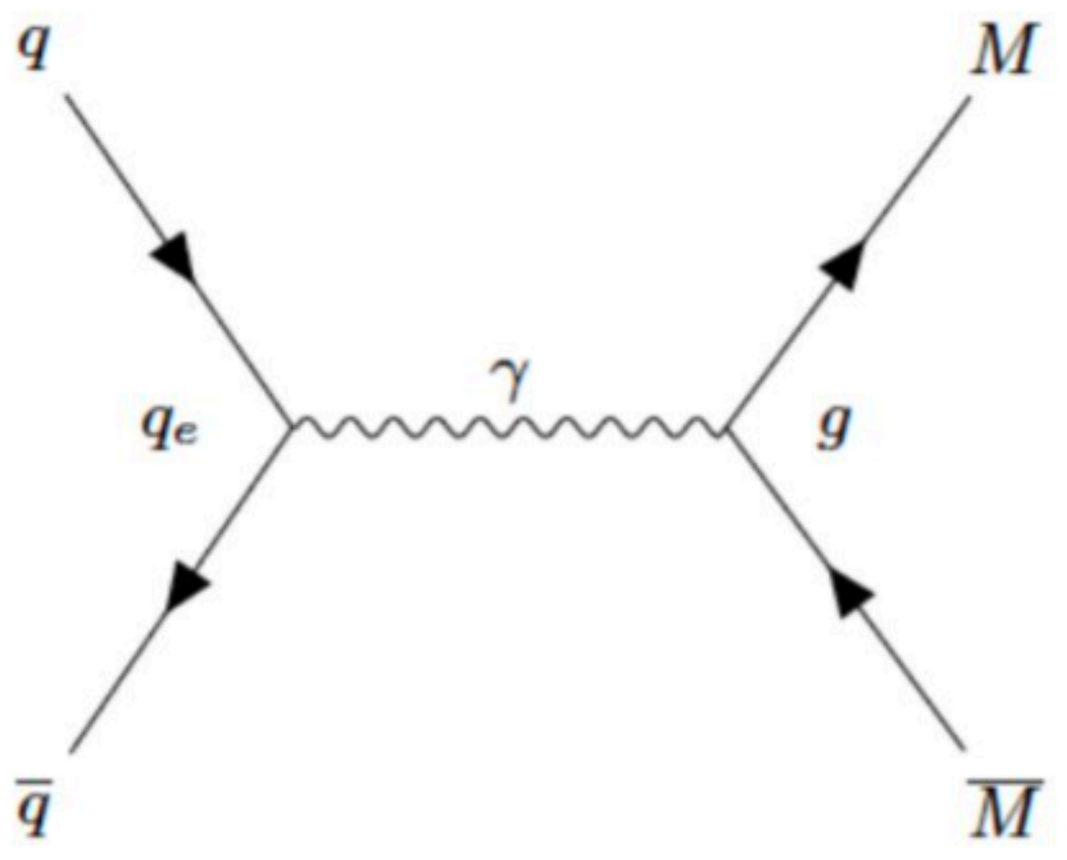
Magnetic monopoles



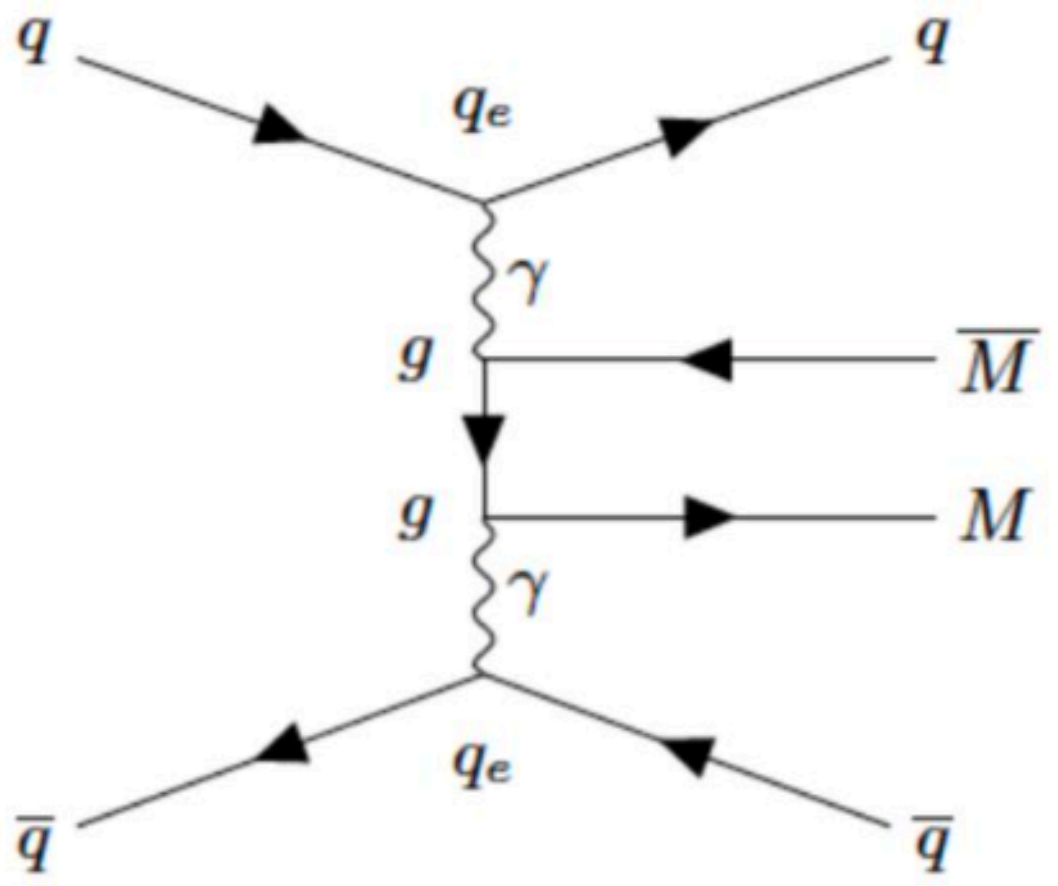
Iguro et al PRL/2111.12091

$$\sigma(pp \to M\overline{M}) = \kappa \times \sigma_{\text{sim}}$$

Drell-Yan

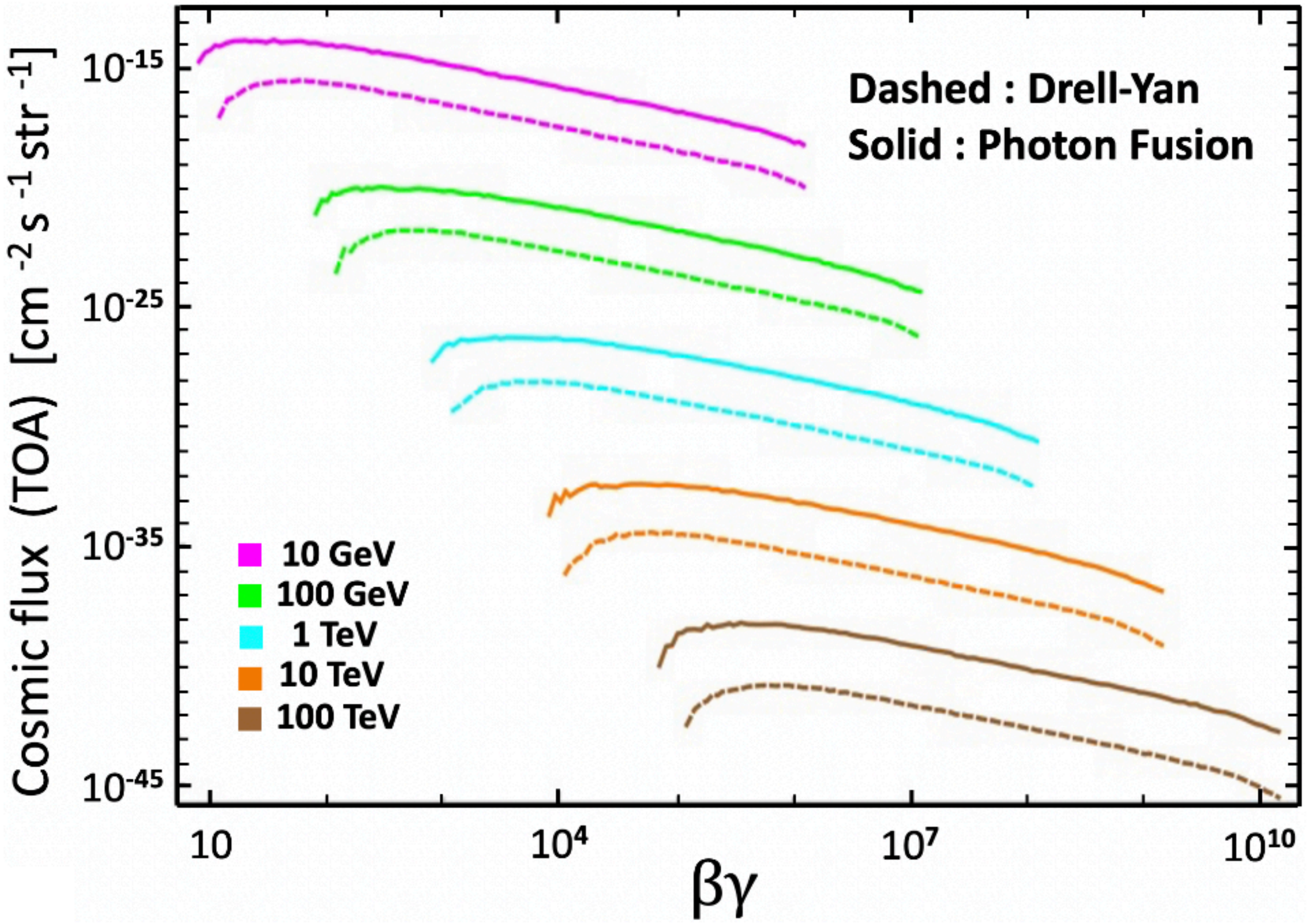


photon-fusion

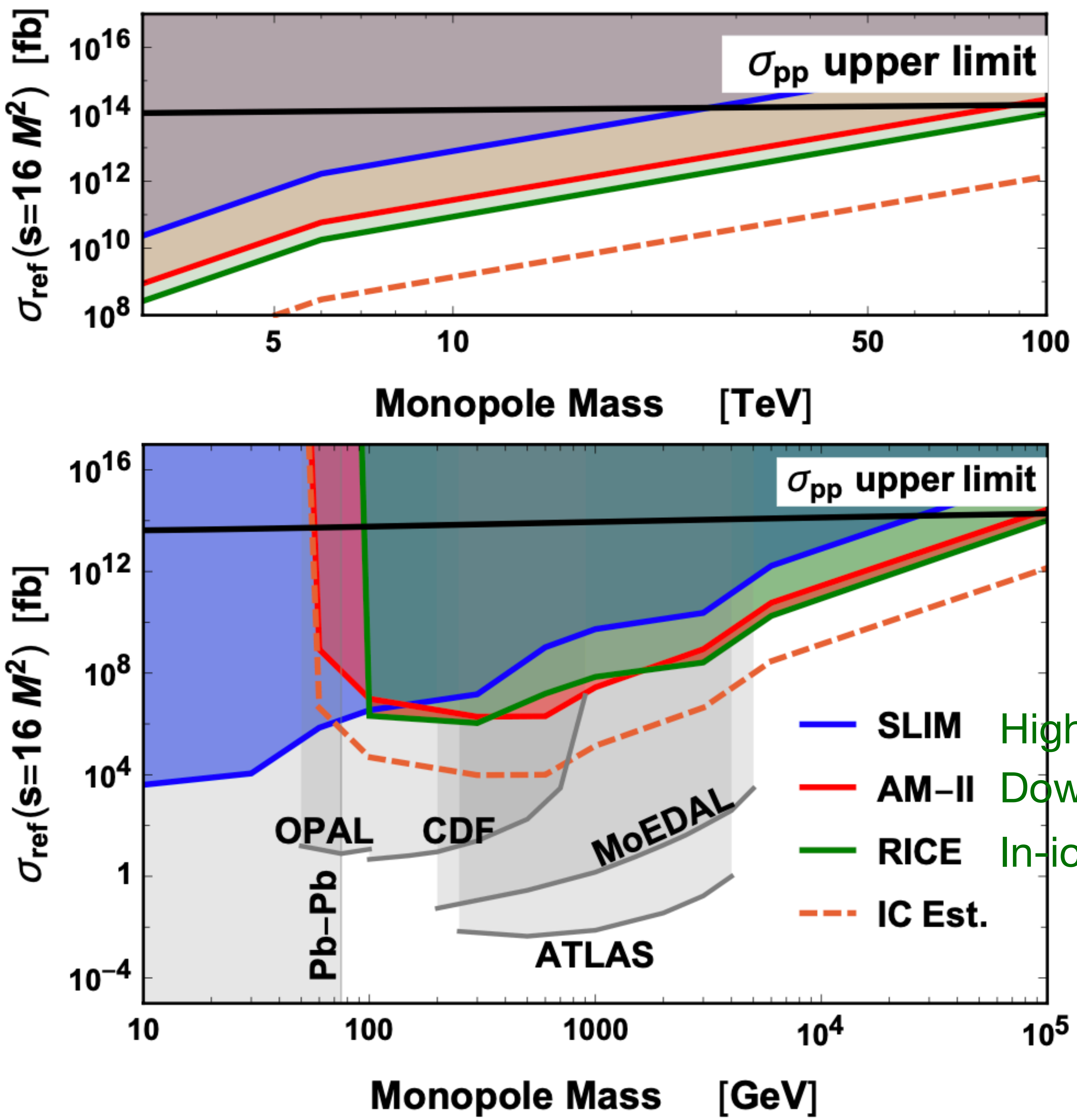


Magnetic monopoles

$$\sigma(pp \rightarrow M\overline{M}) = \kappa \times \sigma_{\text{sim}}$$



Iguro et al PRL/2111.12091



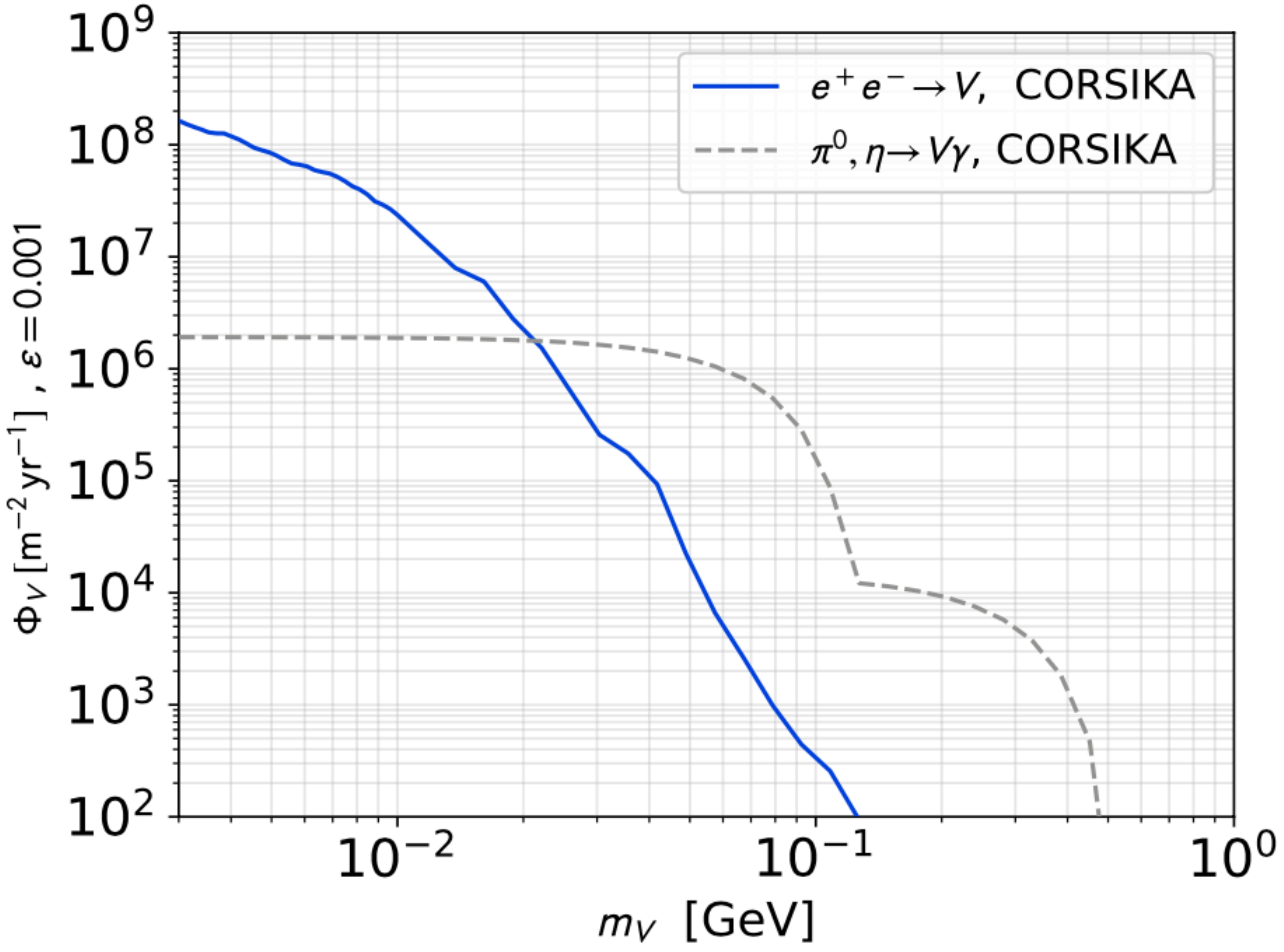
High elevation NTD
Downgoing tracks
In-ice radio

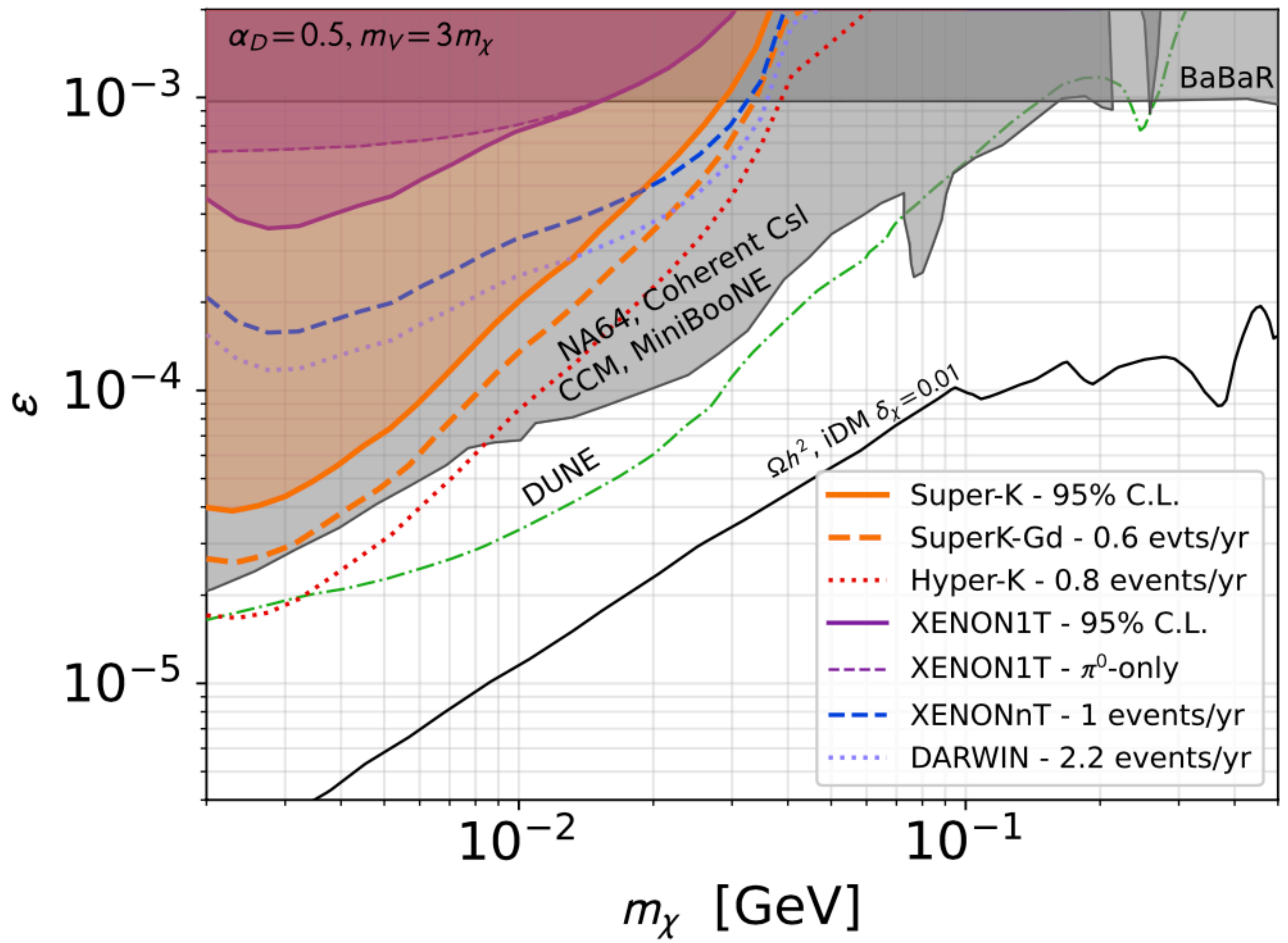
Dark photon

$$\mathcal{L} \supset -V_\mu \left(e\varepsilon \mathcal{J}^\mu_{\rm em} + g_D \mathcal{J}^\mu_D\right)$$

$$\mathcal{J}^\mu_D = -i\,\overline{\chi}_2\gamma^\mu\chi_1$$

$$\sigma_{\rm res} = \frac{2\pi^2\varepsilon^2\alpha_{\rm em}}{m_e}\delta(E_+ - \frac{m_V^2}{2m_e}) \equiv \tilde{\sigma}_{\rm res}\,\delta(E_+ - E_{\rm res})$$





Luc Darmé PRD/2205.09773

Millicharge particles from light meson decay

$$\Phi_\chi(\gamma_\chi) = 2\sum_{\mathfrak{m}} \mathrm{BR}(\mathfrak{m}\to\chi\bar{\chi}) \int \mathrm{d}\gamma_{\mathfrak{m}} \Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}}) P(\gamma_\chi|\gamma_{\mathfrak{m}})$$

Vector mesons $\rho, \omega, \phi, J/\psi$ decay to MCP pairs

$$\frac{\mathrm{BR}\left(\mathfrak{m}\to\chi\bar{\chi}\right)}{\mathrm{BR}\left(\mathfrak{m}\to\mu^+\mu^-\right)} = \epsilon^2\sqrt{\frac{m_{\mathfrak{m}}^2-4m_\chi^2}{m_{\mathfrak{m}}^2-4m_\mu^2}}$$

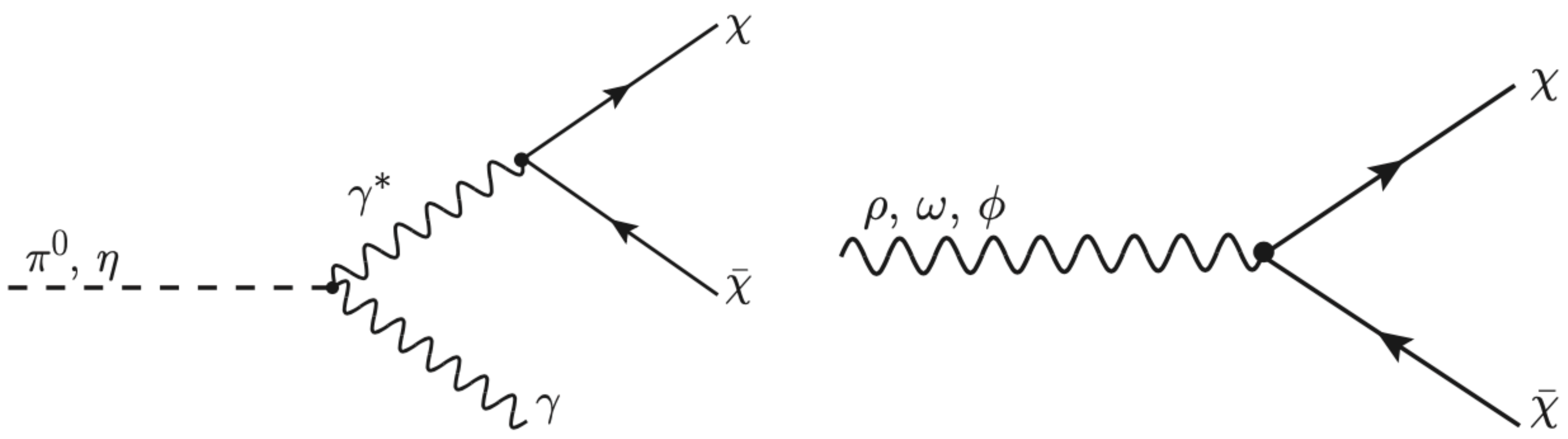
$$P\left(E_\chi|E_{\mathfrak{m}}\right) = \frac{1}{\Gamma_{\mathfrak{m}}}\frac{d\Gamma_{\mathfrak{m}}}{dE_\chi} = \frac{1}{E_\chi^+ - E_\chi^-}$$

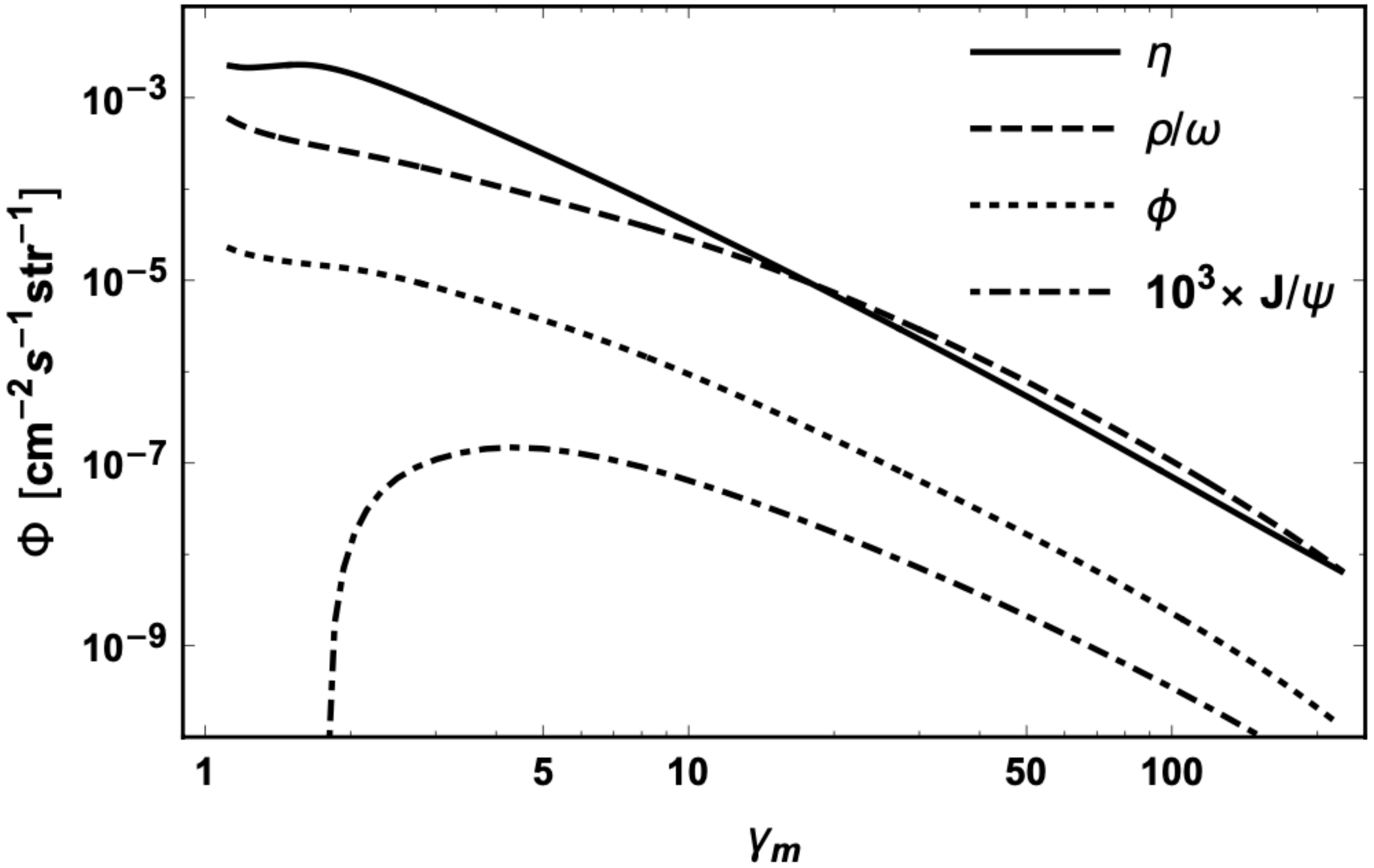
η decay to MCP pairs+photon

$$\mathrm{BR}\left(\eta\to\gamma\chi\chi\right) = 2\epsilon^2\alpha\mathrm{BR}(\eta\to\gamma\gamma)I^{(3)}\left(\frac{m_\chi^2}{m_\eta^2}\right)$$

$$\frac{1}{\Gamma_\eta}\frac{d\Gamma_\eta}{dz} = \frac{m_\eta - z}{72z^3F_1(m_\chi)}F_2\left(z, m_\chi\right)$$

Plestid et al PRD/2002.11732



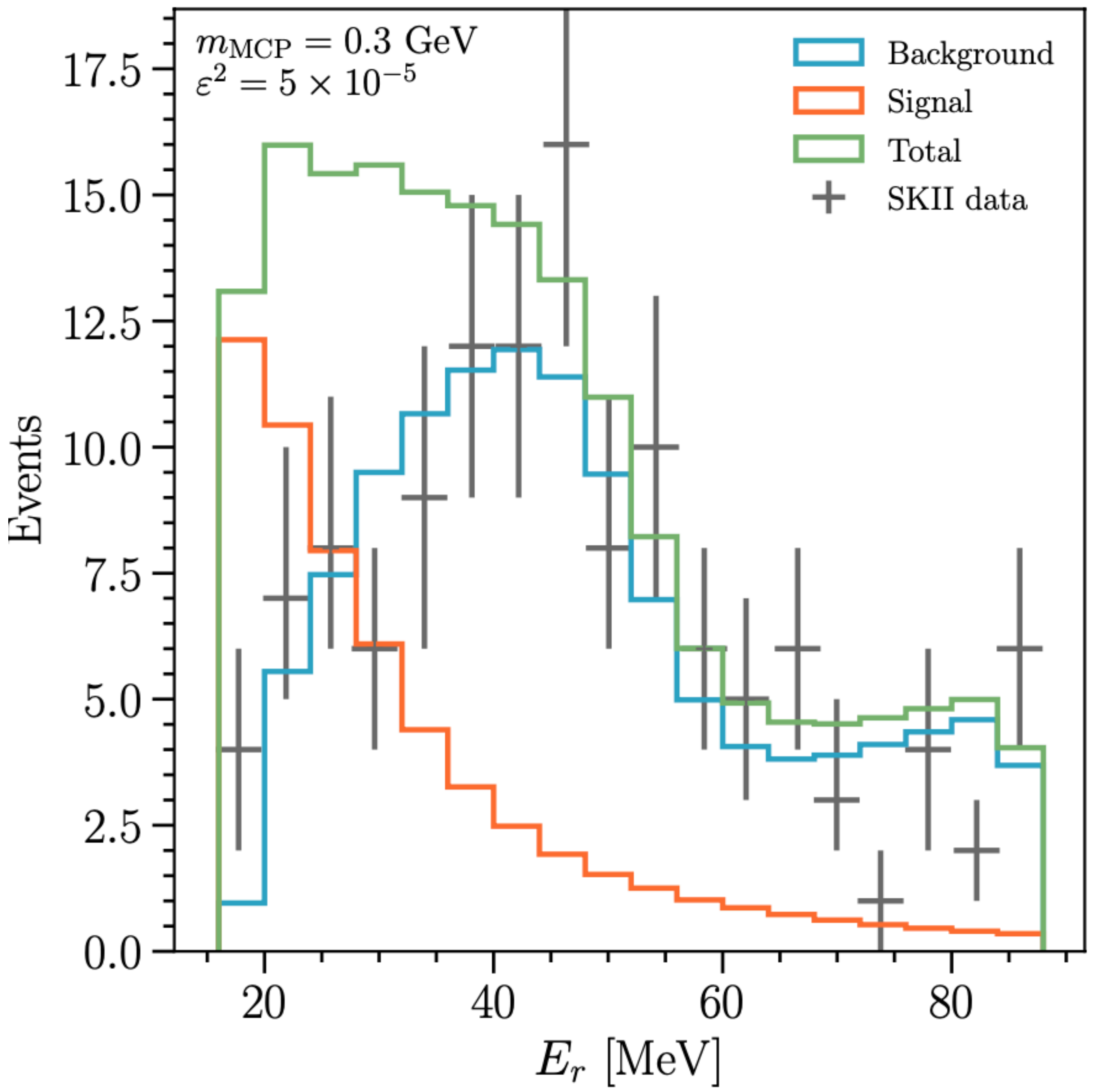


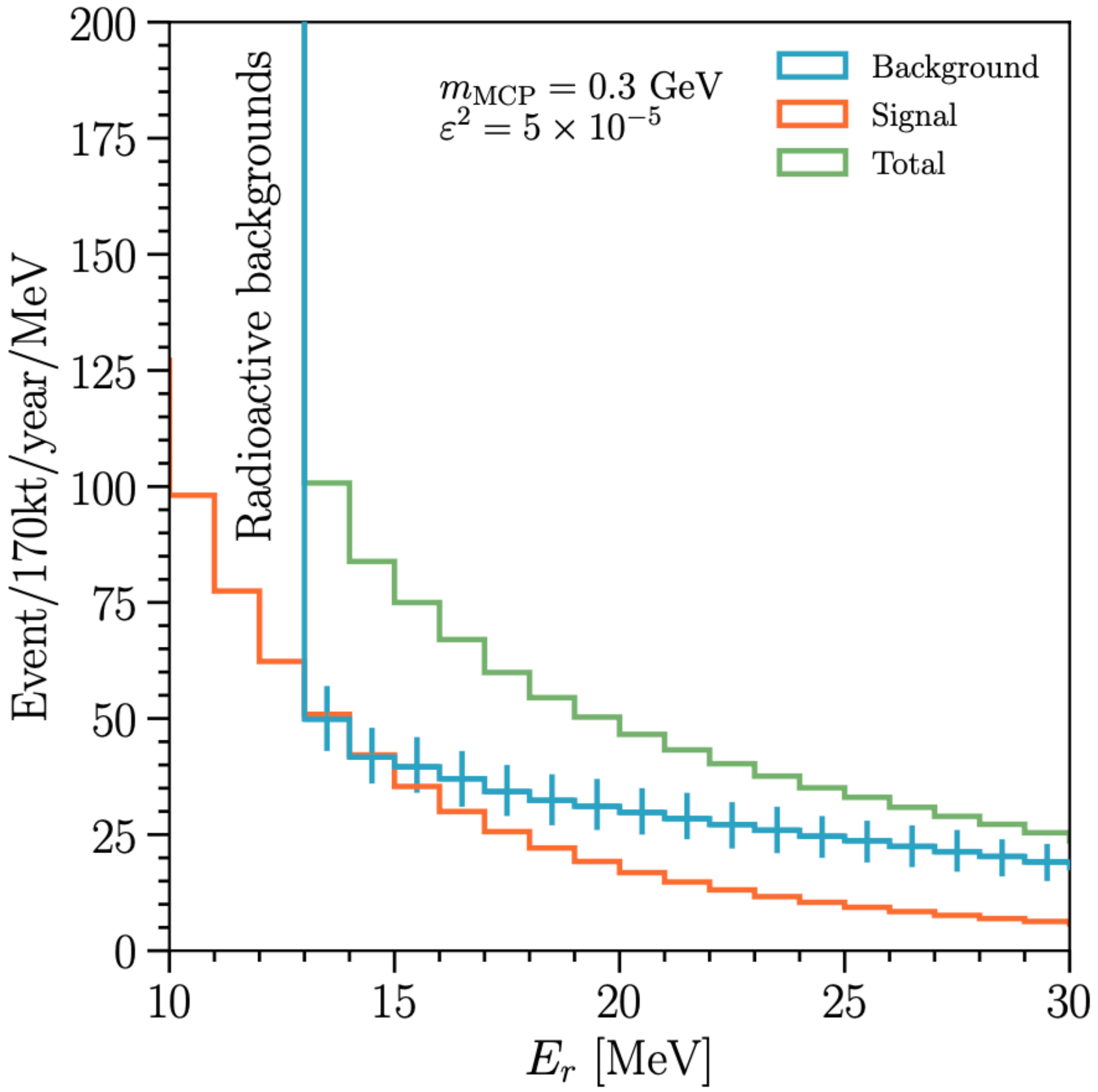
Single scatter

Elastic scattering $$\frac{d\sigma_{\chi e}}{dE_r} = \pi\epsilon^2\alpha^2 \frac{(E_r^2 + 2E_\chi^2)m_e - \left((2E_\chi + m_e)m_e + m_\chi^2\right)E_r}{E_r^2 m_e^2 \left(E_\chi^2 - m_\chi^2\right)}$$

$$d\sigma_{\chi e}/dE_r \propto 1/E_r^2 \qquad \sigma_{\chi e} \simeq \frac{\pi\alpha_{EM}\epsilon^2}{m_e T_{\min}} = 2.6\times10^{-25}\epsilon^2\ \mathrm{cm}^2\frac{\mathrm{MeV}}{T_{\min}}$$

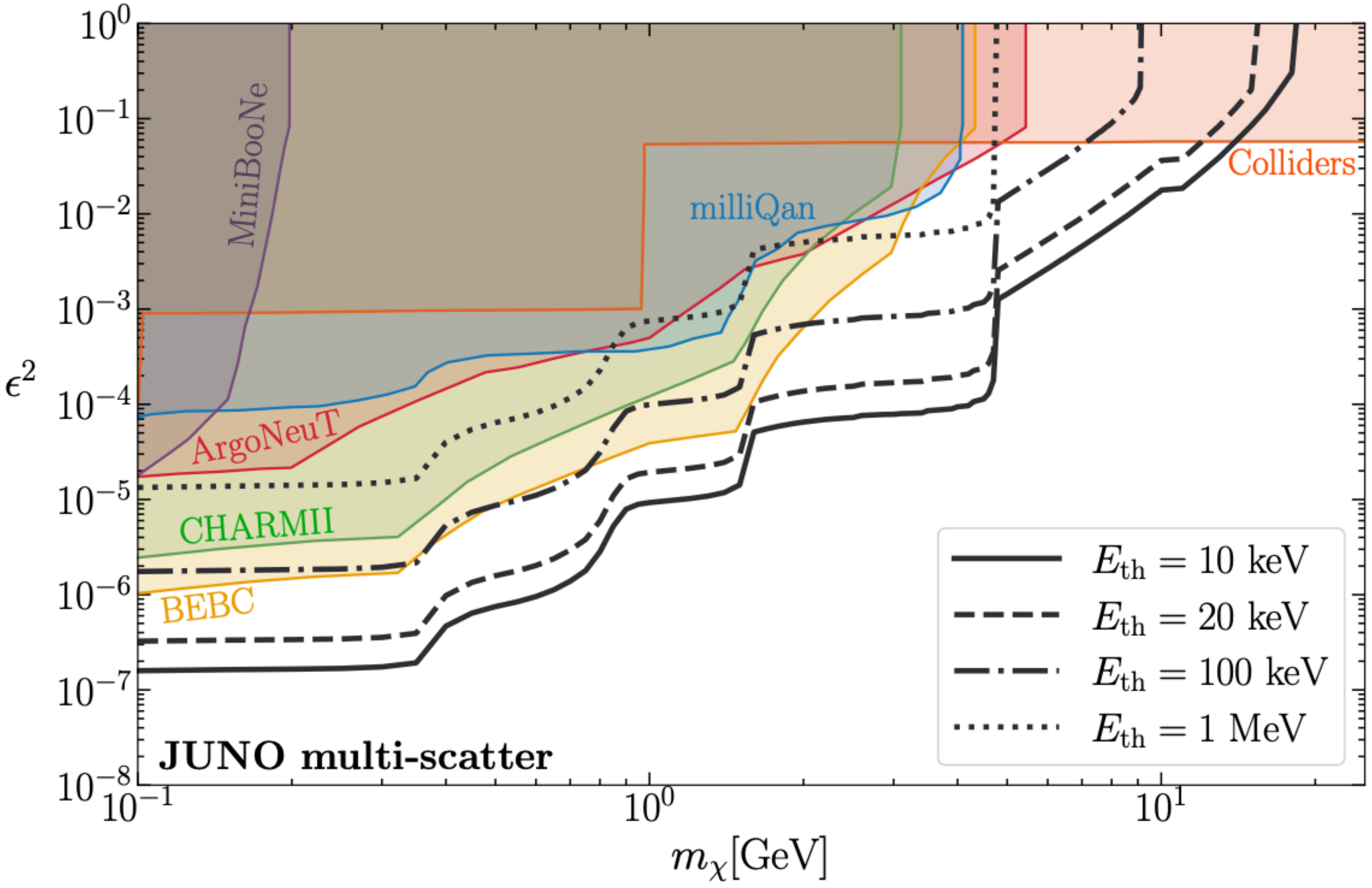
$$N_i\left(m_\chi, \epsilon\right) = N_e T \int_{E_{i,\min}}^{E_{i,\max}} dE_r \epsilon_D(E_r) \times \int dE_\chi d\Omega \Phi_\chi^D\left(E_\chi, \Omega\right)\frac{d\sigma_{\chi e}}{dE_r}$$

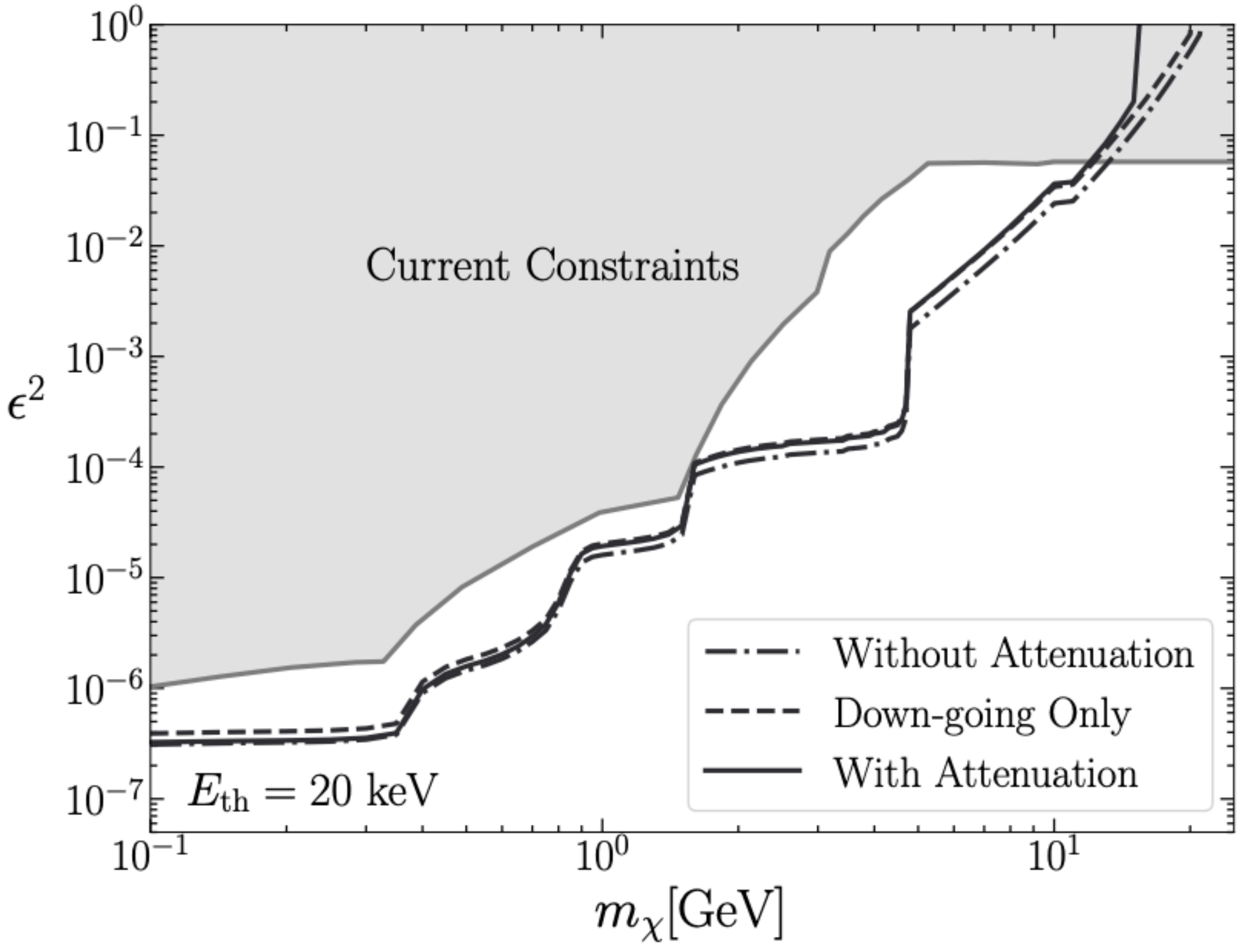




Arguelles et al JHEP/2104.13924

Multiple scatter constraint

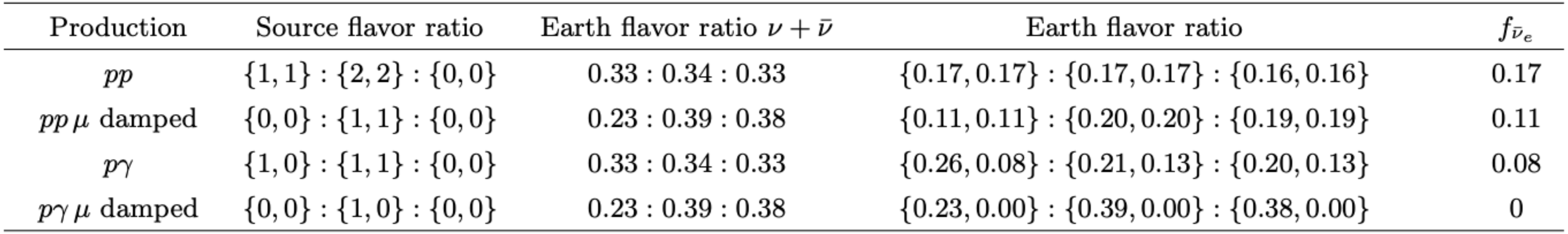




Assuming JUNO 170 kton·yr exposure

Wu, Hardy, **NS**, arXiv: 2406.01668

Degeneracies at the high energy neutrino sources



Production	Source flavor ratio	Earth flavor ratio $\nu+\bar{\nu}$	Earth flavor ratio	$f_{\bar{\nu}_e}$
pp	$\{1,1\}:\{2,2\}:\{0,0\}$	$0.33:0.34:0.33$	$\{0.17,0.17\}:\{0.17,0.17\}:\{0.16,0.16\}$	0.17
$pp\,\mu$ damped	$\{0,0\}:\{1,1\}:\{0,0\}$	$0.23:0.39:0.38$	$\{0.11,0.11\}:\{0.20,0.20\}:\{0.19,0.19\}$	0.11
$p\gamma$	$\{1,0\}:\{1,1\}:\{0,0\}$	$0.33:0.34:0.33$	$\{0.26,0.08\}:\{0.21,0.13\}:\{0.20,0.13\}$	0.08
$p\gamma\,\mu$ damped	$\{0,0\}:\{1,0\}:\{0,0\}$	$0.23:0.39:0.38$	$\{0.23,0.00\}:\{0.39,0.00\}:\{0.38,0.00\}$	0

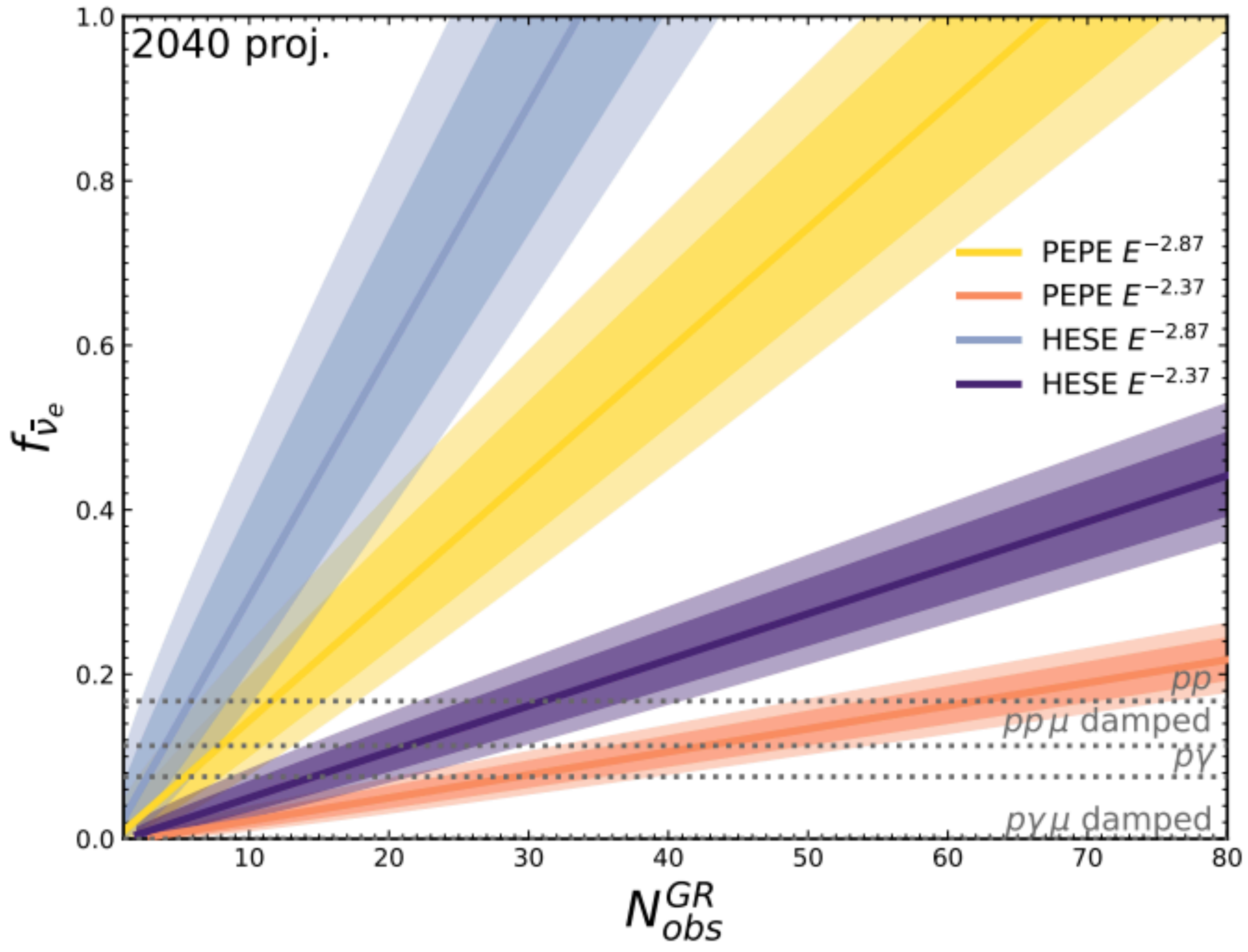
- $p\gamma$ produces more neutrinos than antineutrinos $p+\gamma \to \Delta^+ \to \pi^+ + n$, if μ damped, no antineutrinos are produced
- pp produces equal amount of neutrinos and antineutrinos $p+p \to n_\pi\ [\pi^0+\pi^+ +\pi^-]$, which holds even if μ damped
- pp is indistinguishable from $p\gamma$ if only $\nu+\bar{\nu}$ is analyzed

Event-wise Glashow Resonance Identification

- GR cascade (W hadronic decay, e, τ leptonic decay) indistinguishable from NC DIS. However, NC cascades are less energetic
- GR track without cascade at interaction vertex distinguishable from ν_μ CC
- $2\,\% \leq f_{\bar{\nu}_e} \leq 72\,\%$ with 4.6 years of PEPE, $f_{\bar{\nu}_e} \leq 51\,\%$ with 7.5 years of HESE, assuming hard spectrum
- *pp separated from $p\gamma$ at more than 2 σ significance regardless of flux assumption*

See also 2303.13706

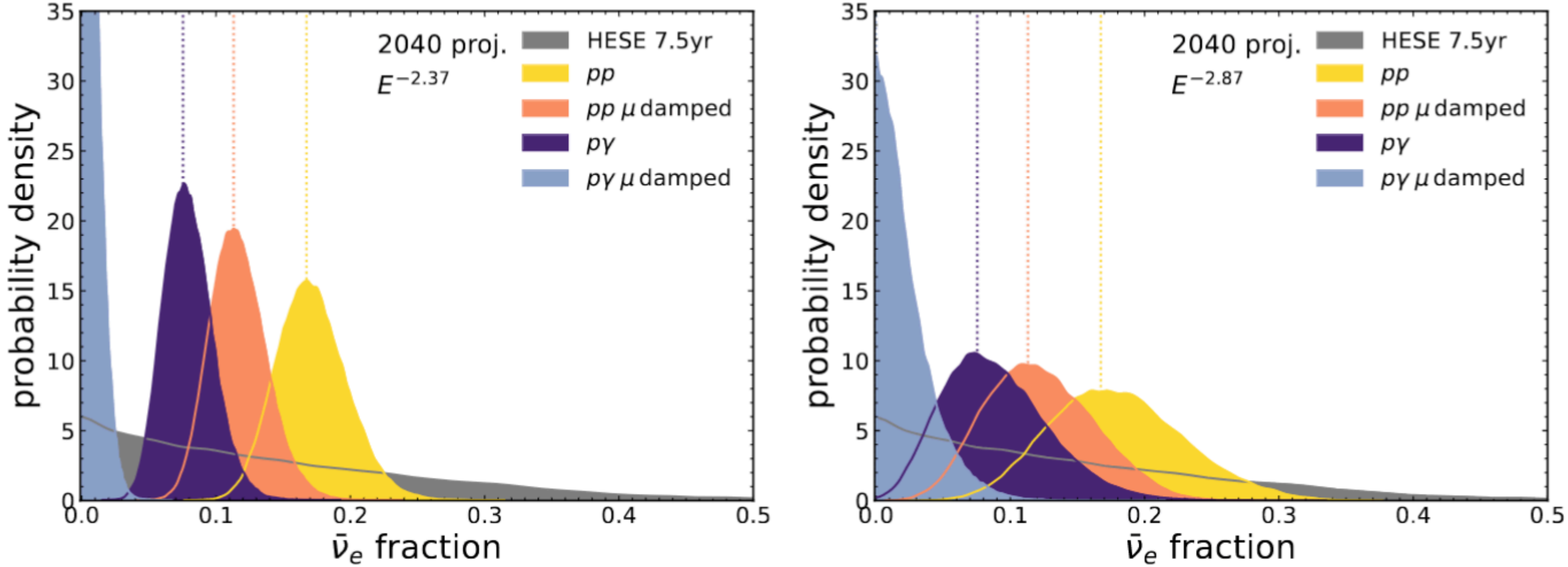
All future ν telescopes

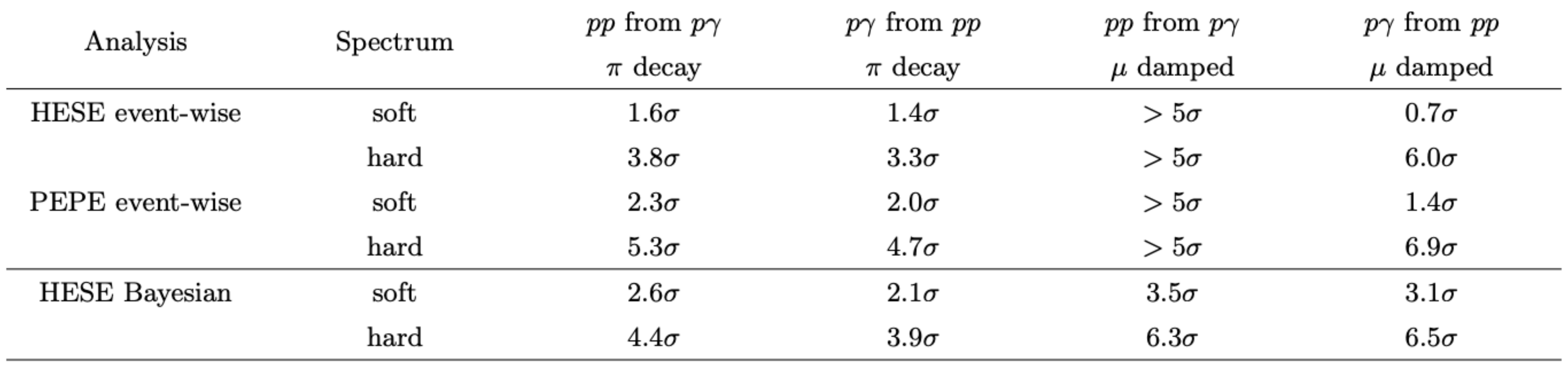


Liu, **NS**, Vincent, PRD/2304.06068

Statistical Analysis of GR

Assuming event-wise identification not possible, consider only contained events





Analysis	Spectrum	pp from $p\gamma$ π decay	$p\gamma$ from pp π decay	pp from $p\gamma$ μ damped	$p\gamma$ from pp μ damped
HESE event-wise	soft	1.6σ	1.4σ	$> 5\sigma$	0.7σ
	hard	3.8σ	3.3σ	$> 5\sigma$	6.0σ
PEPE event-wise	soft	2.3σ	2.0σ	$> 5\sigma$	1.4σ
	hard	5.3σ	4.7σ	$> 5\sigma$	6.9σ
HESE Bayesian	soft	2.6σ	2.1σ	3.5σ	3.1σ
	hard	4.4σ	3.9σ	6.3σ	6.5σ

Liu, **NS**, Vincent, PRD/2304.06068