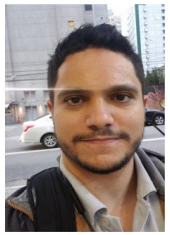
Fermionic Absorption DM

Shao-Feng Ge

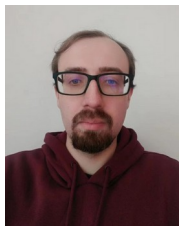
gesf@sjtu.edu.cn


马凯


马小东


Pedro Pasquini


盛杰


Oleg Titov

SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [Phys.Rev.Lett. 129 (2022) 16, 161804]

SFG, Pedro Pasquini, Jie Sheng [JHEP 05 (2022) 088]

SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [JHEP 11 (2023) 190]

SFG, Oleg Titov [Phys.Rev.D 110 (2024) 055003]

Kai Ma, **SFG**, Lin-Yun He, Ning Zhou [2405.16878 [hep-ph]]

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

李政道研究所 Tsung-Dao Lee Institute

October 12, 2024 @ 紫金山论坛

Outline

Tsung-Dao Lee Institute

1) Thresholds in DM search

2) **Direct Detection with Atomic & Nuclear Effects**

SFG, Pedro Pasquini, Jie Sheng [JHEP 05 (2022) 088]

PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [Phys.Rev.Lett. 129 (2022) 16, 161804]

SFG, Oleg Titov [Phys.Rev.D 110 (2024) 055003]

3) **Astro & Cosmo Constraints**

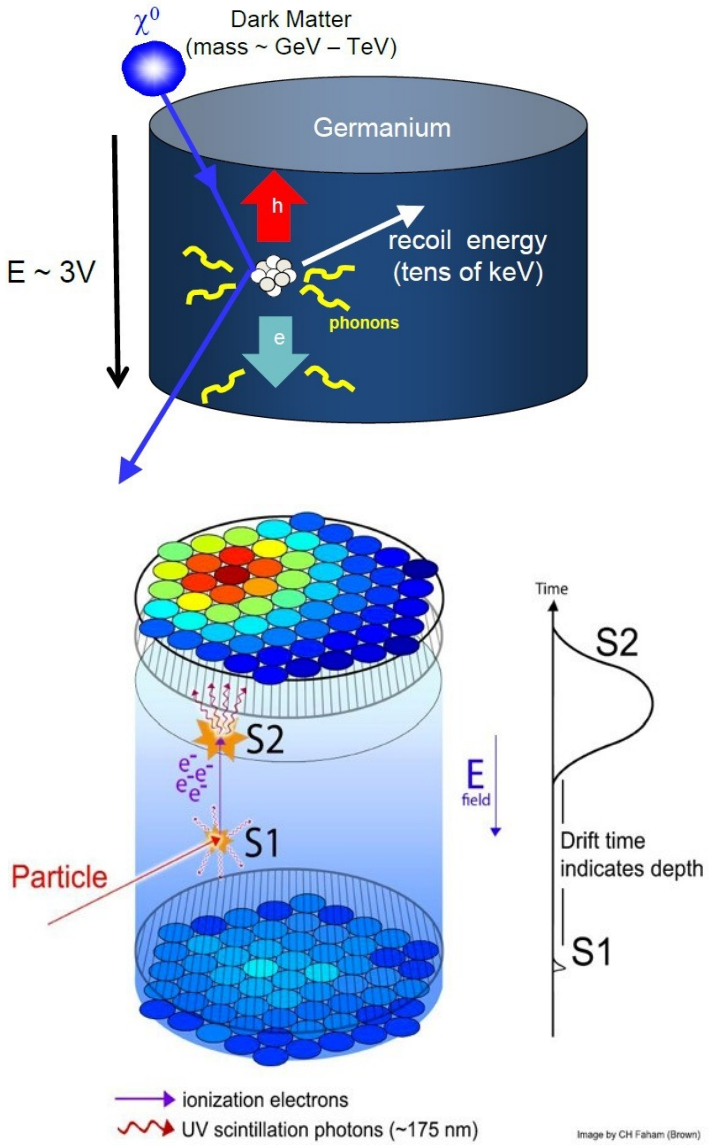
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

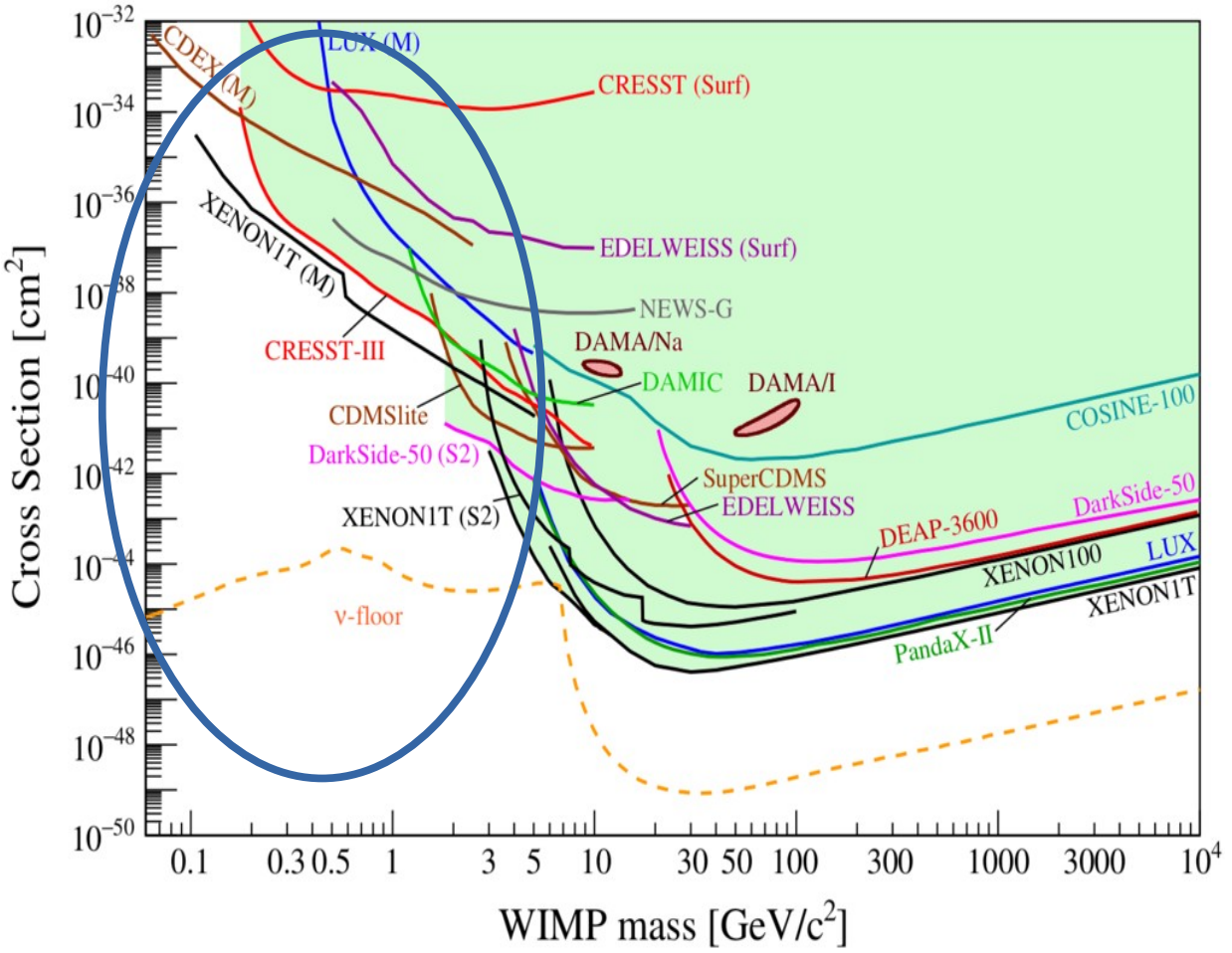
4) **Complementary Searches @ Colliders**

SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [JHEP 11 (2023) 190]

Kai Ma, **SFG**, Lin-Yun He, Ning Zhou [2405.16878 [hep-ph]]

Direct Detection





APPEC Committee Report [2104.07634]

Boosting recoil with mass

- **Elastic Scattering**

$$\chi + N/e \to \chi + N/e \qquad E_r \approx \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} T_\chi$$

- **Exothermic**

$$X' e^- \to X e^- \qquad E_R \simeq \Delta m \left(1 - \frac{v_{\rm DM}}{v_e} \cos\theta_e\right)$$

He, Wang & Zheng [JCAP21, 2007.04963]

Aboubrahim, Althueser, Klasen, Nath & Weinheimer [2207.08621]

- **Fermionic absorption**

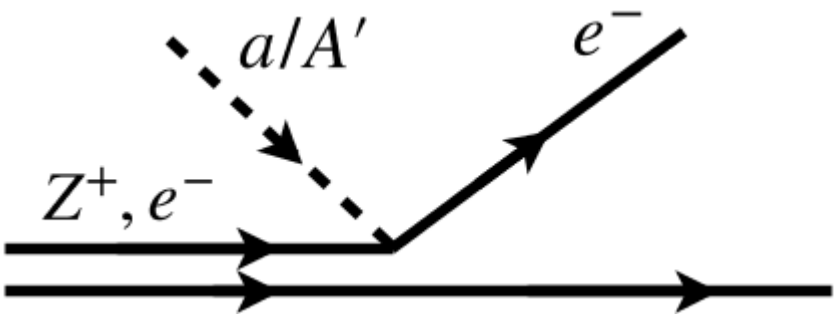
$$\chi + e \to \nu + e \qquad E_r \approx \frac{m_\chi^2}{2 m_e} \qquad m_\chi \sim \mathcal{O}(10)\,{\rm keV}$$

Dror, Elor, McGehee & Yu [2011.01940]

See also Dror, Elor & McGehee [1905.12635, 1908.10861]

Bosonic Absorption DM

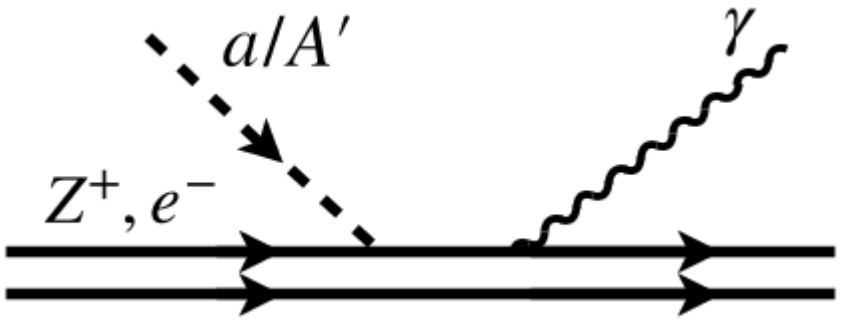
- **Dark Photoelectric Effect**



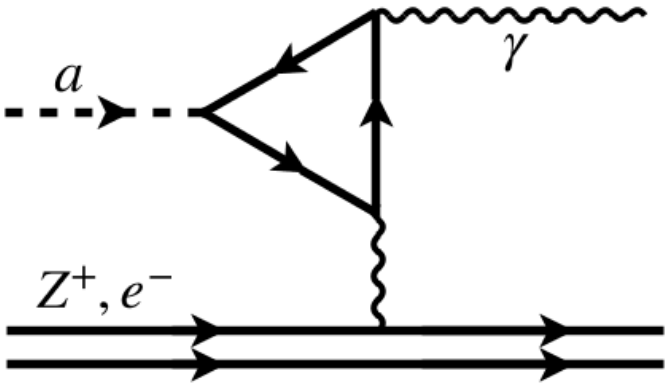
Pospelov, Ritz & Voloshin [0807.3279]

An, Pospelov, Pradler & Ritz [1412.8378]

- **Dark Compton**



- **Inverse Primakoff**

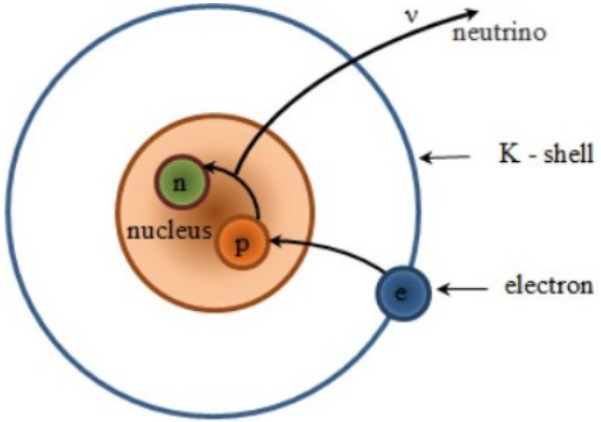


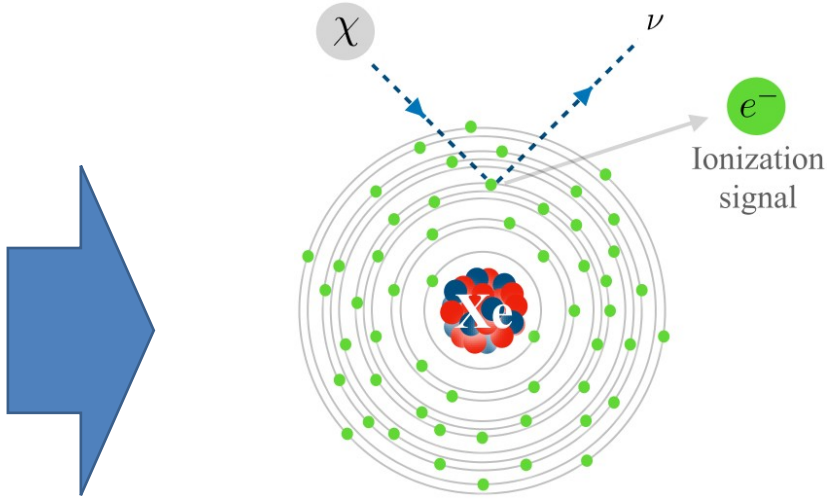
Hochberg, Krosigk, Kuflik & Yu [2109.08168]

K-Shell Electron Capture for ν


王淦昌

1942 – Kan Chang Wang proposed using K-shell electron capture for detecting neutrino





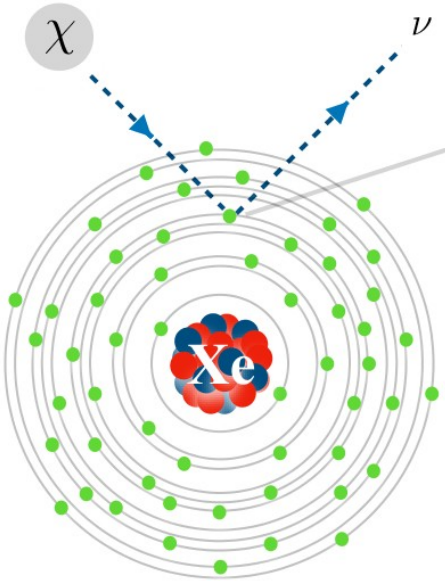
$$e^- + {}^{Z}_{A}N \rightarrow {}^{Z-1}_{A}N + \nu$$

$$\chi + e \rightarrow \nu + e$$

Kan Chang Wang, *A Suggestion on the Detection of the Neutrino*, Phys. Rev., 61, 97 (1942)

Kan Chang Wang, *Proposed Methods of Detecting the Neutrino* , Phys. Rev., 71, 645-646 (1947)

Effective Operators



$$\mathcal{O}^S_{e\nu\chi} \equiv (\bar{e}e)(\bar{\nu}_L\chi_R),$$
$$\mathcal{O}^P_{e\nu\chi} \equiv (\bar{e}i\gamma_5 e)(\bar{\nu}_L\chi_R),$$
$$\mathcal{O}^V_{e\nu\chi} \equiv (\bar{e}\gamma_\mu e)(\bar{\nu}_L\gamma^\mu\chi_L),$$
$$\mathcal{O}^A_{e\nu\chi} \equiv (\bar{e}\gamma_\mu\gamma_5 e)(\bar{\nu}_L\gamma^\mu\chi_L),$$
$$\mathcal{O}^T_{e\nu\chi} \equiv (\bar{e}\sigma_{\mu\nu}e)(\bar{\nu}_L\sigma^{\mu\nu}\chi_R),$$

$$\sigma^S_{\chi e}v_\chi \approx \frac{1}{\Lambda^4}\frac{m_\chi^2(2m_e+m_\chi)^4}{64\pi(m_e+m_\chi)^4},$$

$$\sigma^P_{\chi e}v_\chi \approx \frac{1}{\Lambda^4}\frac{m_\chi^4(2m_e+m_\chi)^2}{64\pi(m_e+m_\chi)^4},$$

$$\sigma^V_{\chi e}v_\chi \approx \frac{1}{\Lambda^4}\frac{m_\chi^2(2m_e+m_\chi)^2(2m_e^2+4m_em_\chi+3m_\chi^2)}{32\pi(m_e+m_\chi)^4},$$

$$\sigma^A_{\chi e}v_\chi \approx \frac{1}{\Lambda^4}\frac{m_\chi^2(2m_e+m_\chi)^2(6m_e^2+8m_em_\chi+3m_\chi^2)}{32\pi(m_e+m_\chi)^4},$$

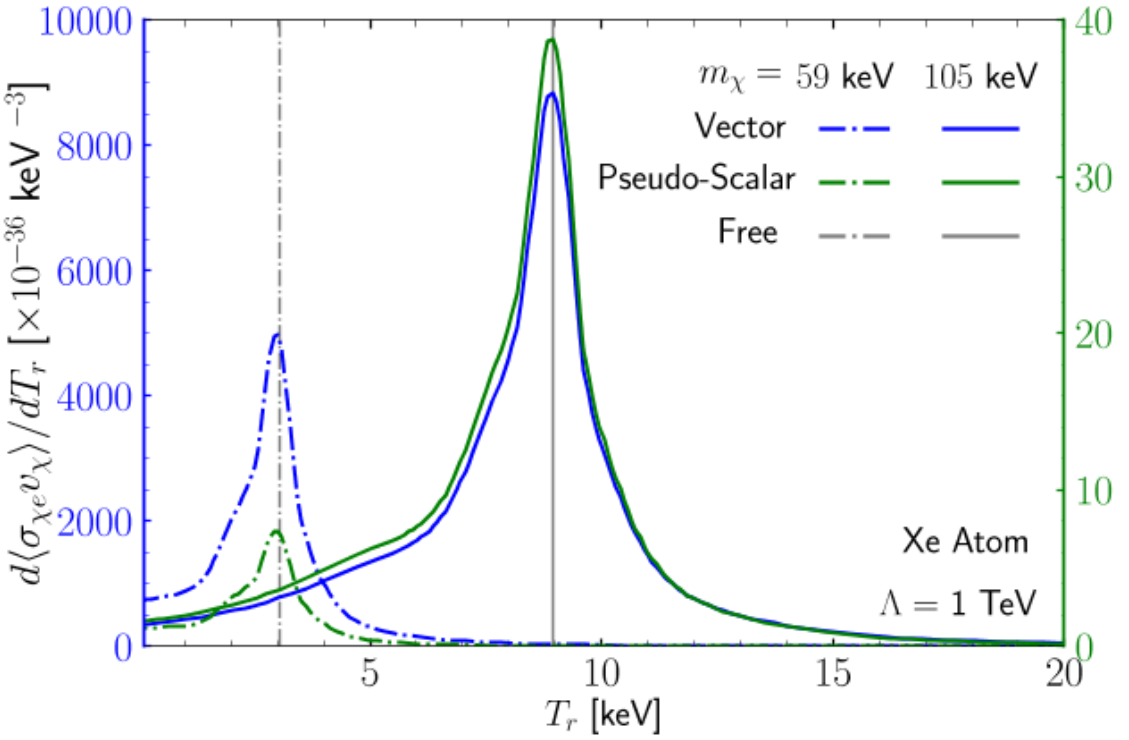
$$\sigma^T_{\chi e}v_\chi \approx \frac{1}{\Lambda^4}\frac{m_\chi^2(2m_e+m_\chi)^2(6m_e^2+10m_em_\chi+5m_\chi^2)}{8\pi(m_e+m_\chi)^4}.$$

SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

Kinematics of Absorption DM

Tsung-Dao Lee Institute

$$\chi + e \to \nu + e \qquad E_r = \frac{m_\chi^2}{2(m_e + m_\chi)} \approx \frac{m_\chi^2}{2m_e}$$



$$\frac{d\langle\sigma_{\chi e} v_\chi\rangle}{dT_r} = \sum_{nl}(4l+2)\frac{1}{T_r}\frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi}|\mathcal{M}|^2(\mathbf{q})K_{nl}(T_r, |\mathbf{q}|),$$

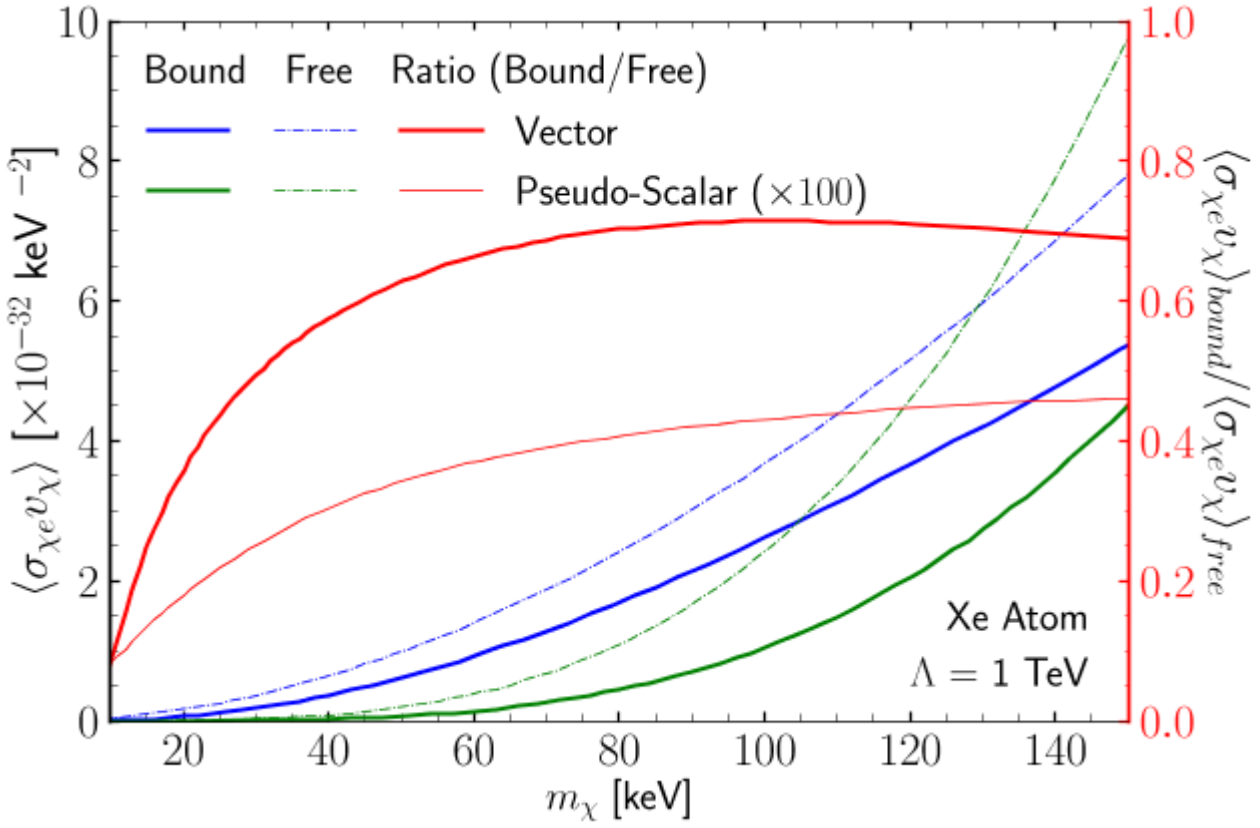
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

SFG, Pedro Pasquini, Jie Sheng [JHEP 05 (2022) 088]

Atomic Effects

Tsung-Dao Lee Institute

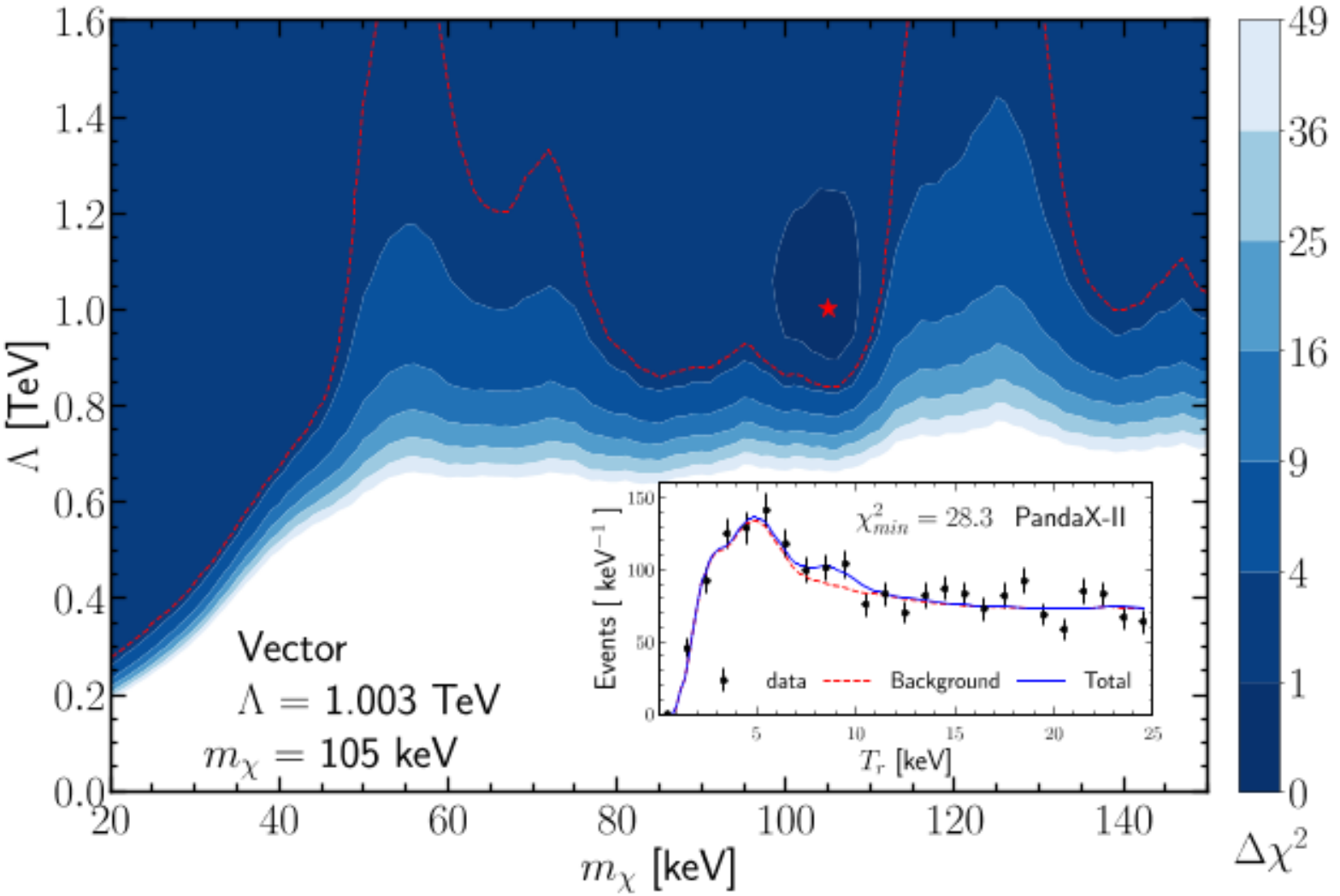
$$\chi + e \to \nu + e$$



$$\frac{d\langle\sigma_{\chi e} v_\chi\rangle}{dT_r} = \sum_{nl}(4l+2)\frac{1}{T_r}\frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi}|\mathcal{M}|^2(\mathbf{q})K_{nl}(T_r, |\mathbf{q}|),$$

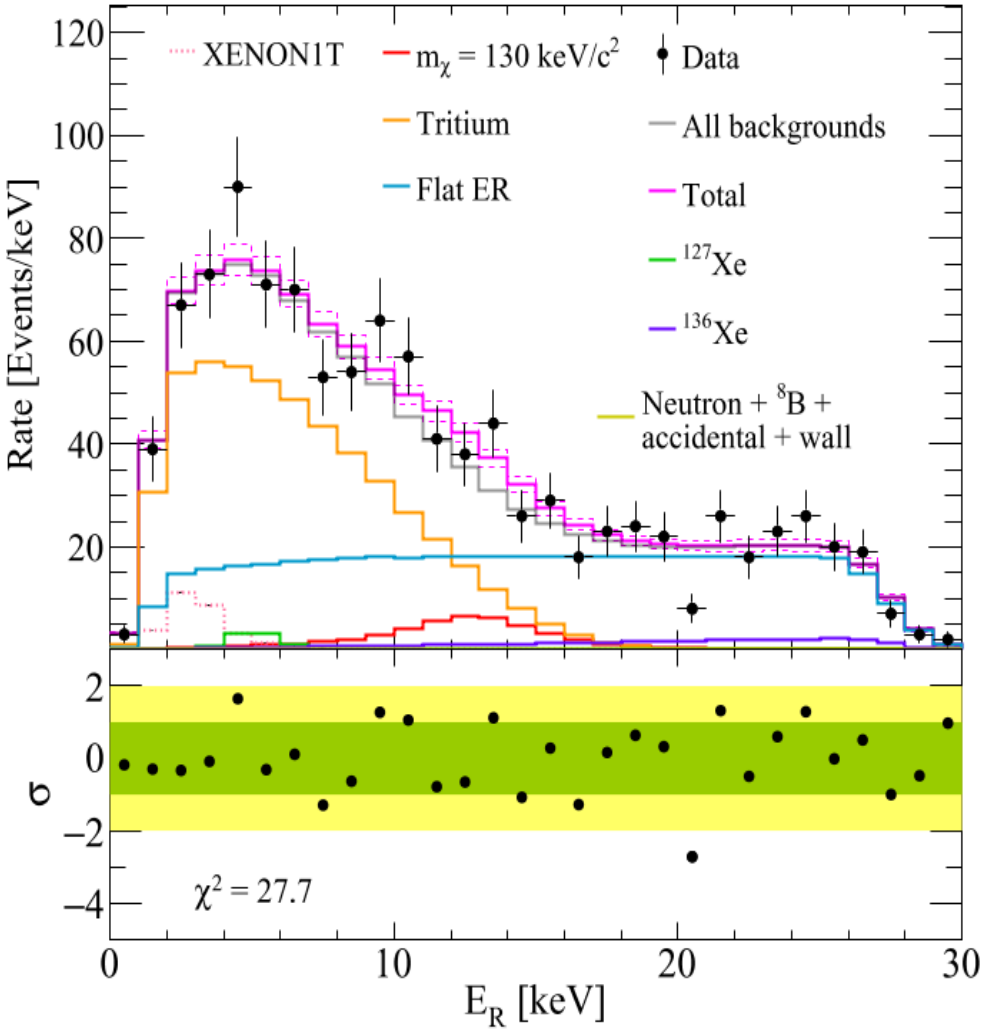
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

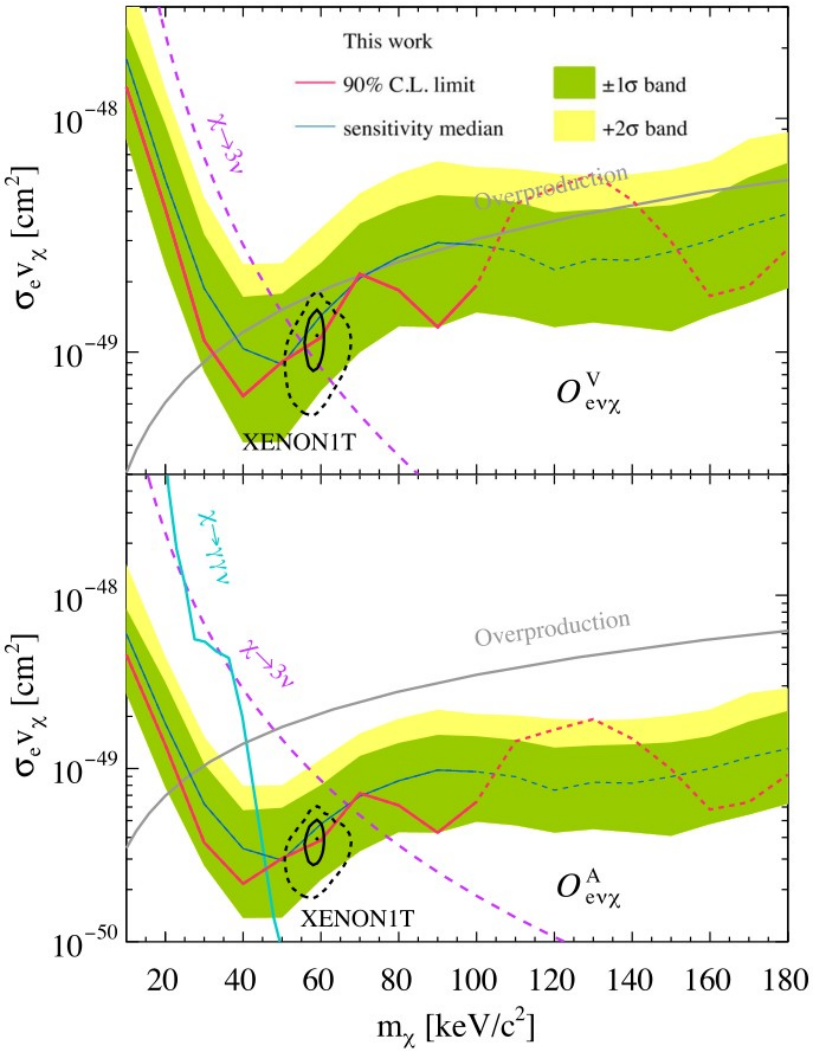
PandaX-II



SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

PandaX-4T Results





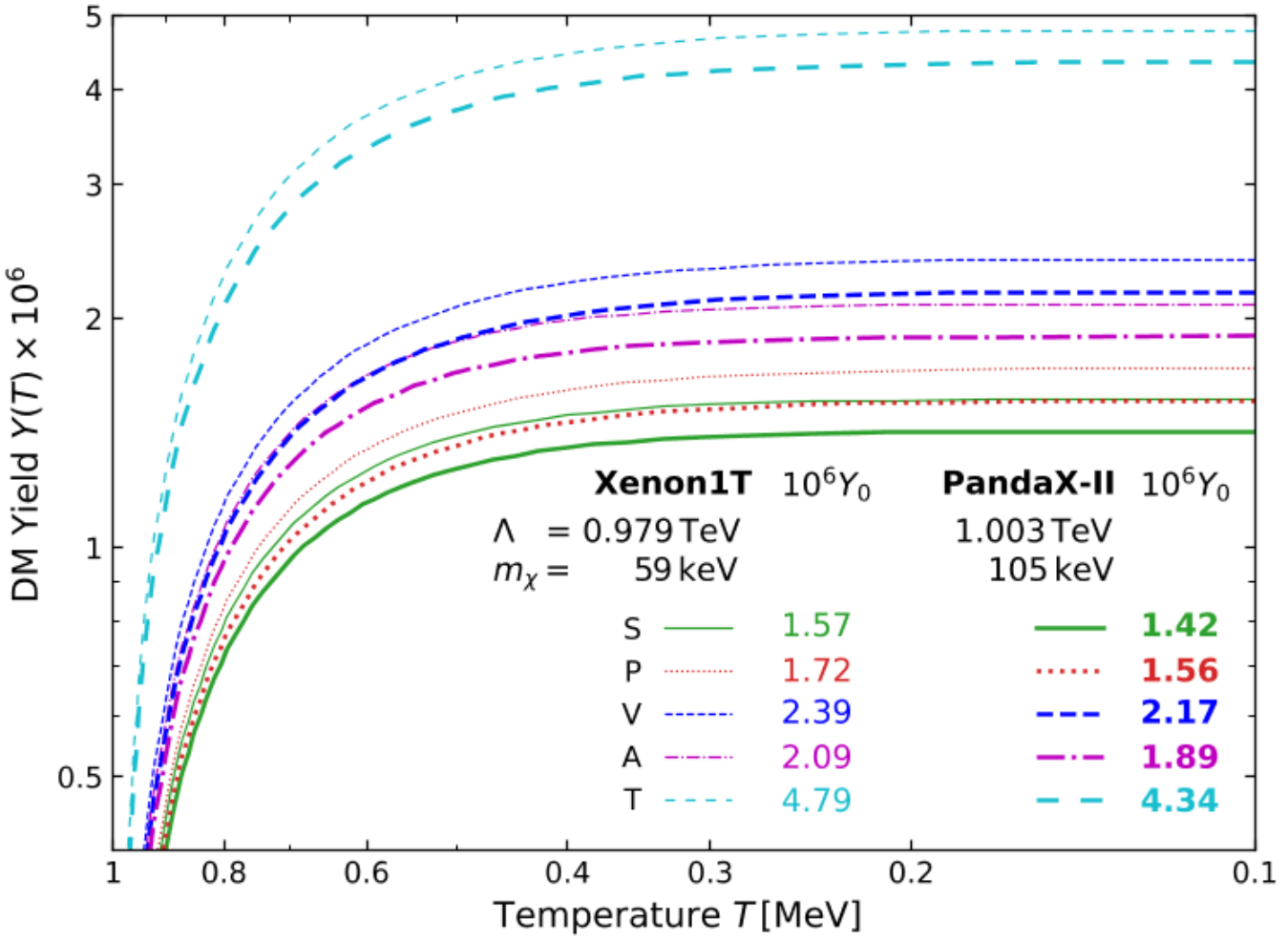
PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng, Phys.Rev.Lett. 129 (2022) 16, 161804 [2206.02339]

$\chi + N \to \nu N$ PandaX, Phys.Rev.Lett. 129 (2022) 16, 161803 [2205.15771]

Overproduction of Absorption DM

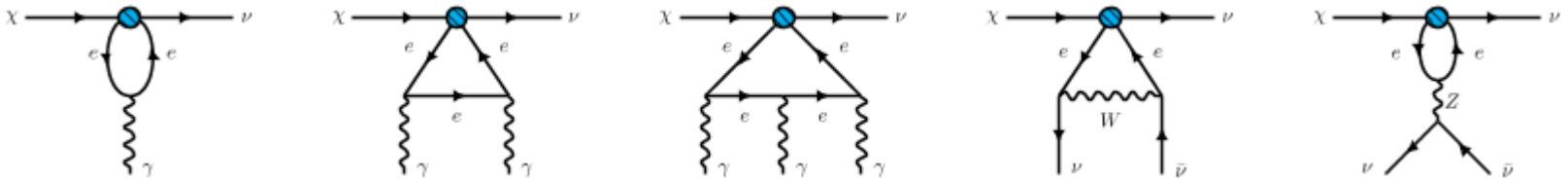
Tsung-Dao Lee Institute

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle v_{\text{Møl}}\sigma_{e^+e^-}\rangle n_{e^+}^{\text{eq}} n_{e^-}^{\text{eq}}$$



SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

Visible & Invisible Decays

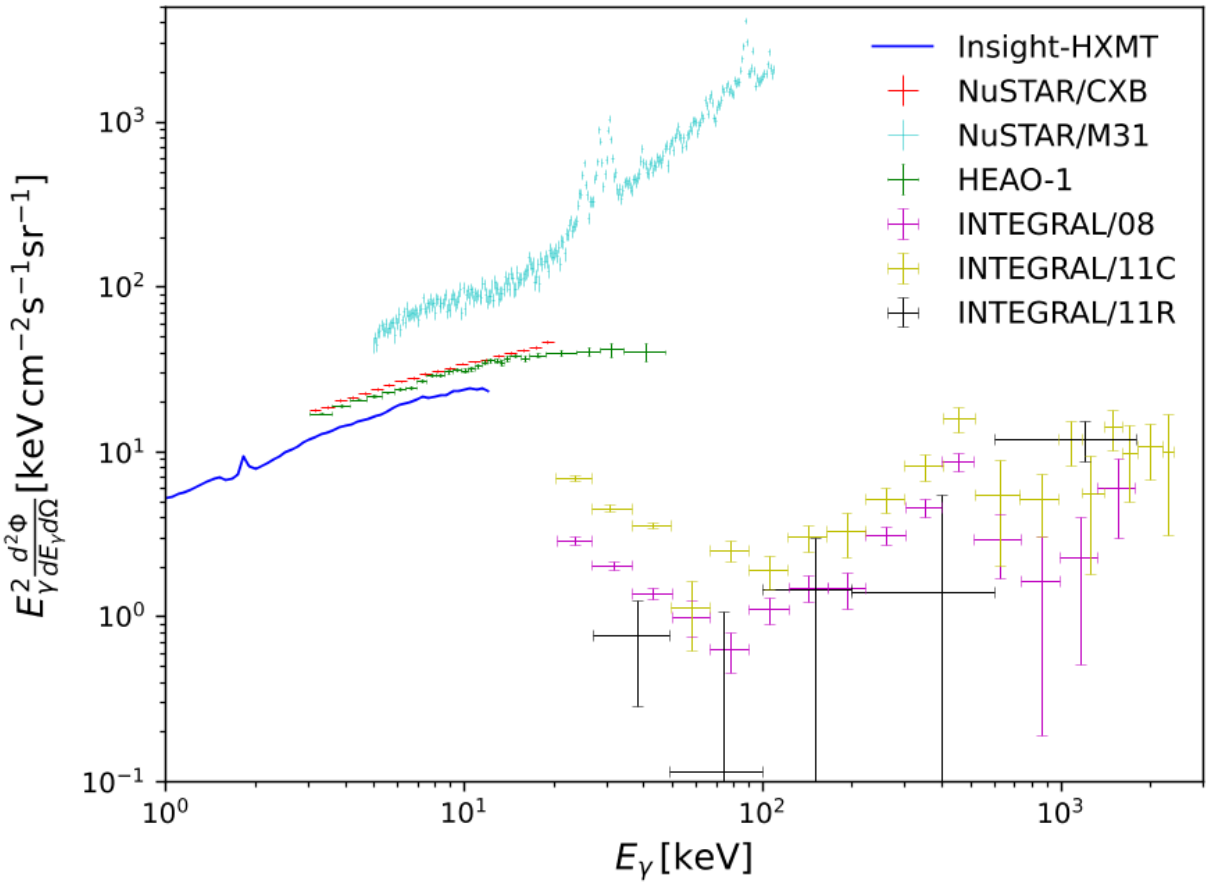


Process / Operator	$\chi \to \nu\gamma$	$\chi \to \nu\gamma\gamma$	$\chi \to \nu\gamma\gamma\gamma$	$\chi \to 3\nu$
S: $\mathcal{O}^S_{e\nu\chi}$	×	✓	×	×
P: $\mathcal{O}^P_{e\nu\chi}$	×	✓	×	×
V: $\mathcal{O}^V_{e\nu\chi}$	×	×	✓	✓
A: $\mathcal{O}^A_{e\nu\chi}$	×	✓	×	✓
T: $\mathcal{O}^T_{e\nu\chi}$	✓	×	×!	×!

Dror, Elor, McGehee & Yu [2011.01940]

SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

Astro Observations



- **Galactic**

$$\frac{d^2\Phi_\gamma}{dE_\gamma d\Omega} = \frac{1}{4\pi}\frac{d\Gamma_\chi}{dE_\gamma}\int_{\text{l.o.s.}}^{s_{\max}} \frac{\rho_\chi(r)}{m_\chi} ds$$

- **Extra-Galactic**

$$\frac{d^2\Phi_r^{\text{EG}}}{dE_\gamma d\Omega} = \frac{\Omega_{\text{DM}}\rho_c}{4\pi m_\chi H_0\sqrt{\Omega_m}}\int_0^\infty \frac{d\Gamma_\chi}{dE_\gamma(z)}\frac{dz}{\sqrt{\kappa+(1+z)^3}}$$

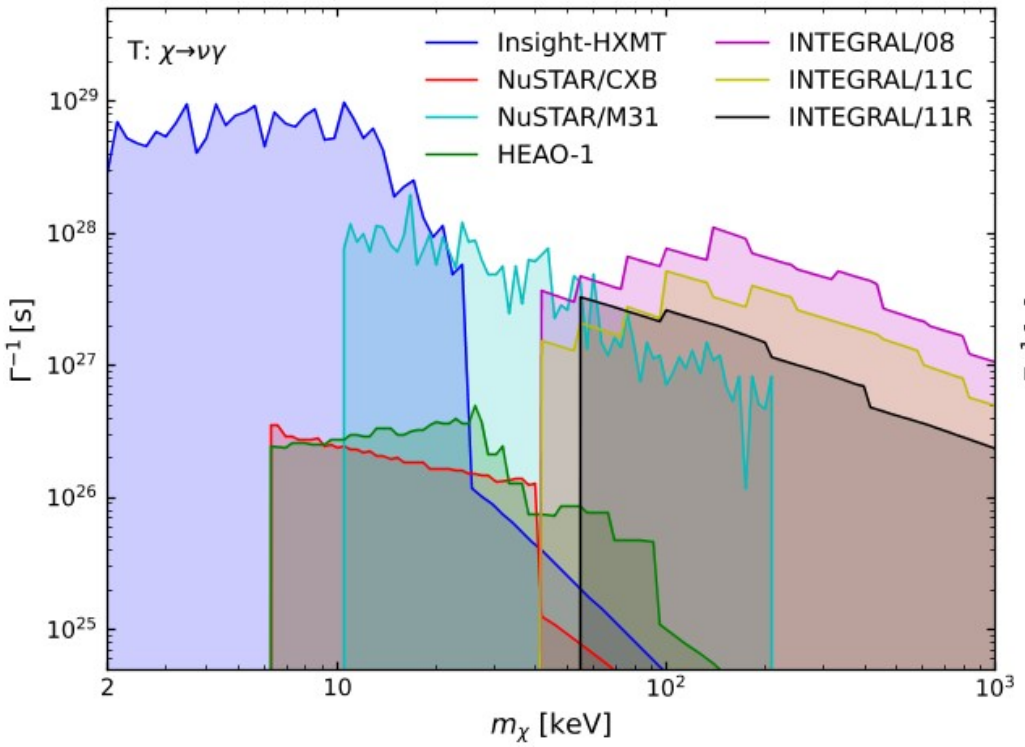
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

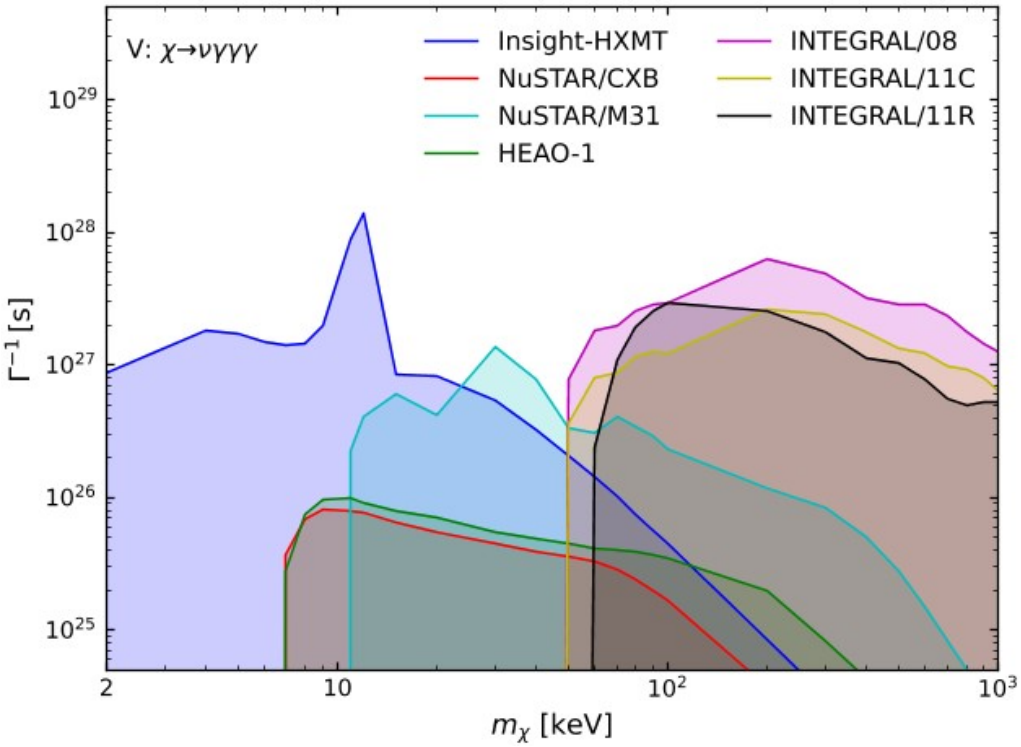
Astro Constraints

Tsung-Dao Lee Institute

$$N_i^{\rm th} \leq N_i^{\rm obs} \equiv A_{\rm eff} T_{\rm obs} \Delta\Omega \left(\frac{d^2\Phi_\gamma}{dE_\gamma d\Omega} \right)^i_{\rm exp@95\%} \Delta E_i$$

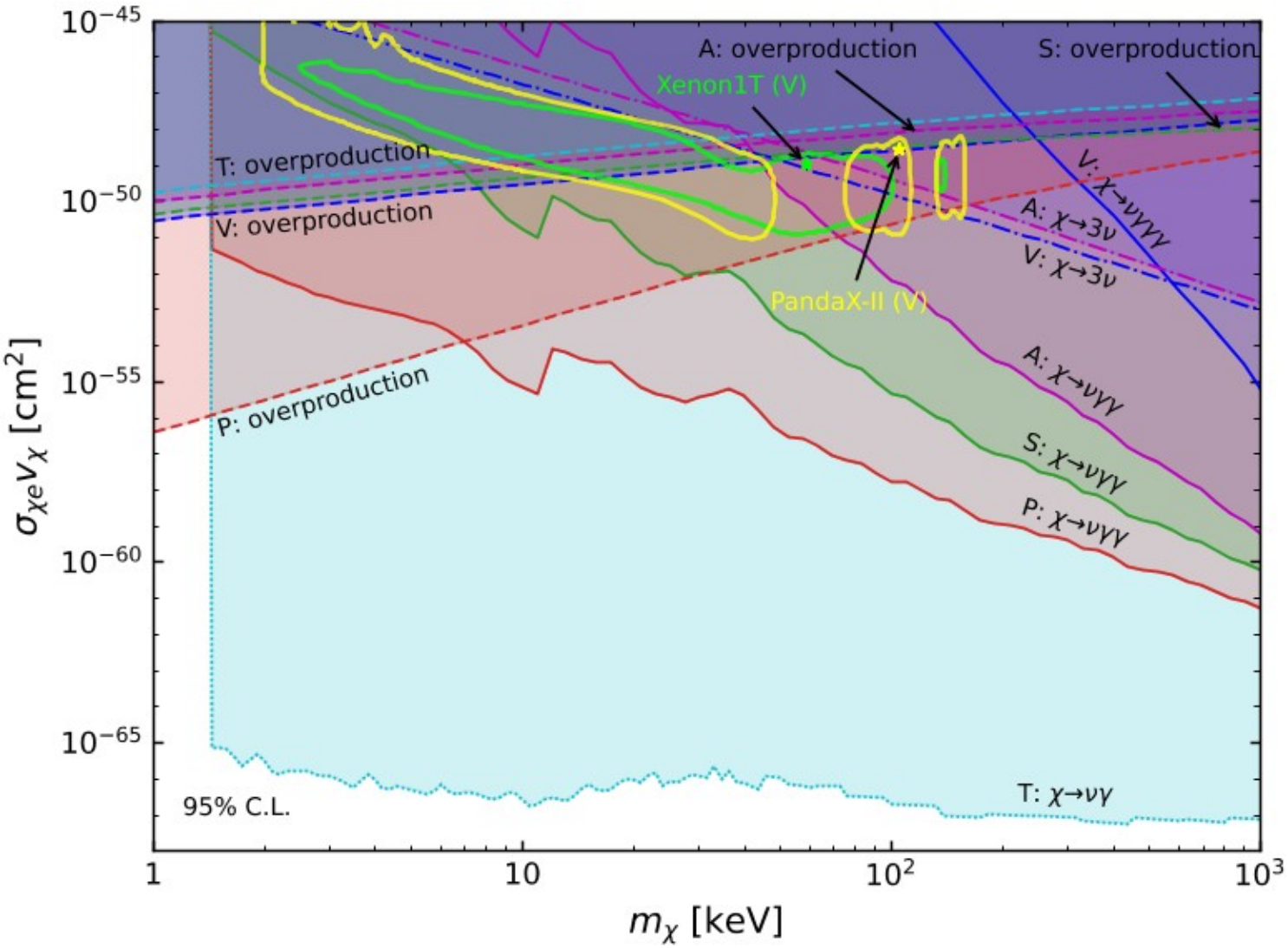
- **Mono-energetic γ**
- **Continuous Spectrum**





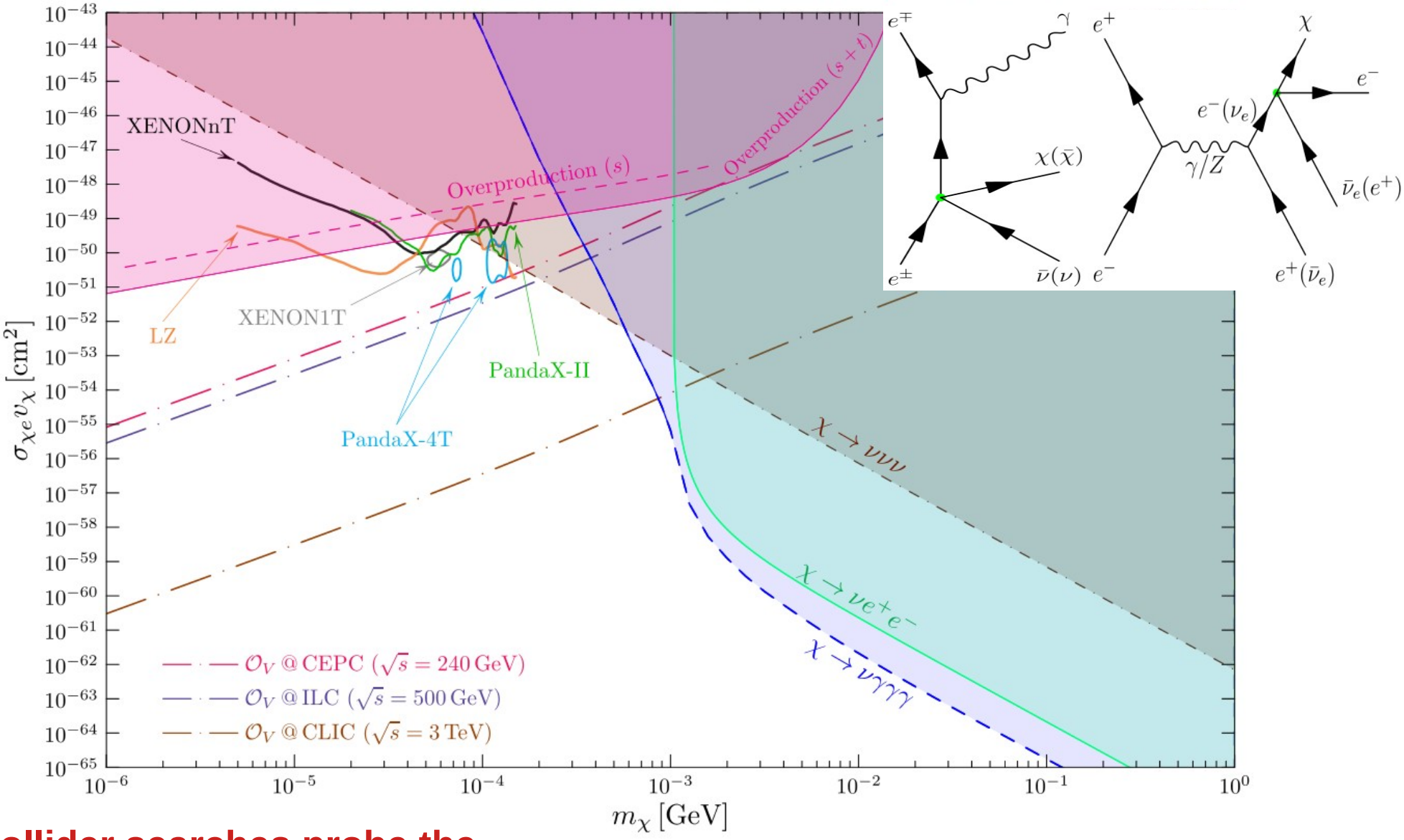
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

Constraints from Astro & Cosmo



SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

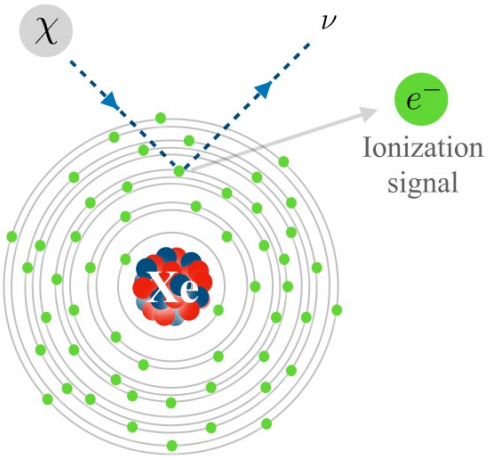
PandaX-4T & Lepton Colliders



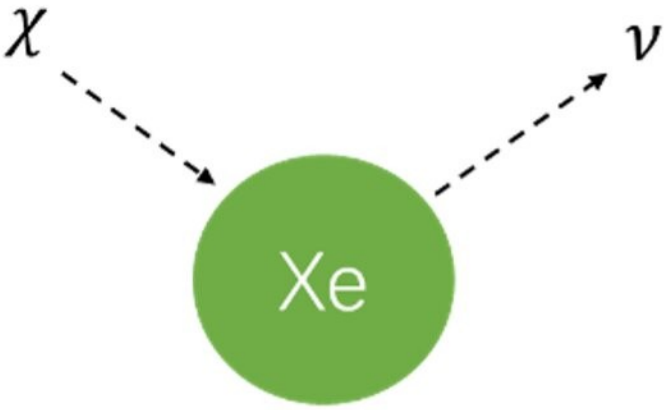
Collider searches probe the dark sector, not just DM

SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [arXiv:2306.00657]

Absorption @ Nuclear Targets



$$\chi + e \to \nu + e$$



$$\chi + {}^{A}Xe \to \nu + {}^{A}Xe$$

$$T_r = \frac{m_\chi^2}{2(m_A + m_\chi)} \gtrsim 1\,\mathrm{keV} \quad \Rightarrow \quad m_\chi \gtrsim \mathcal{O}(10)\,\mathrm{MeV}$$

See also Dror, Elor & McGehee [1905.12635, 1908.10861]

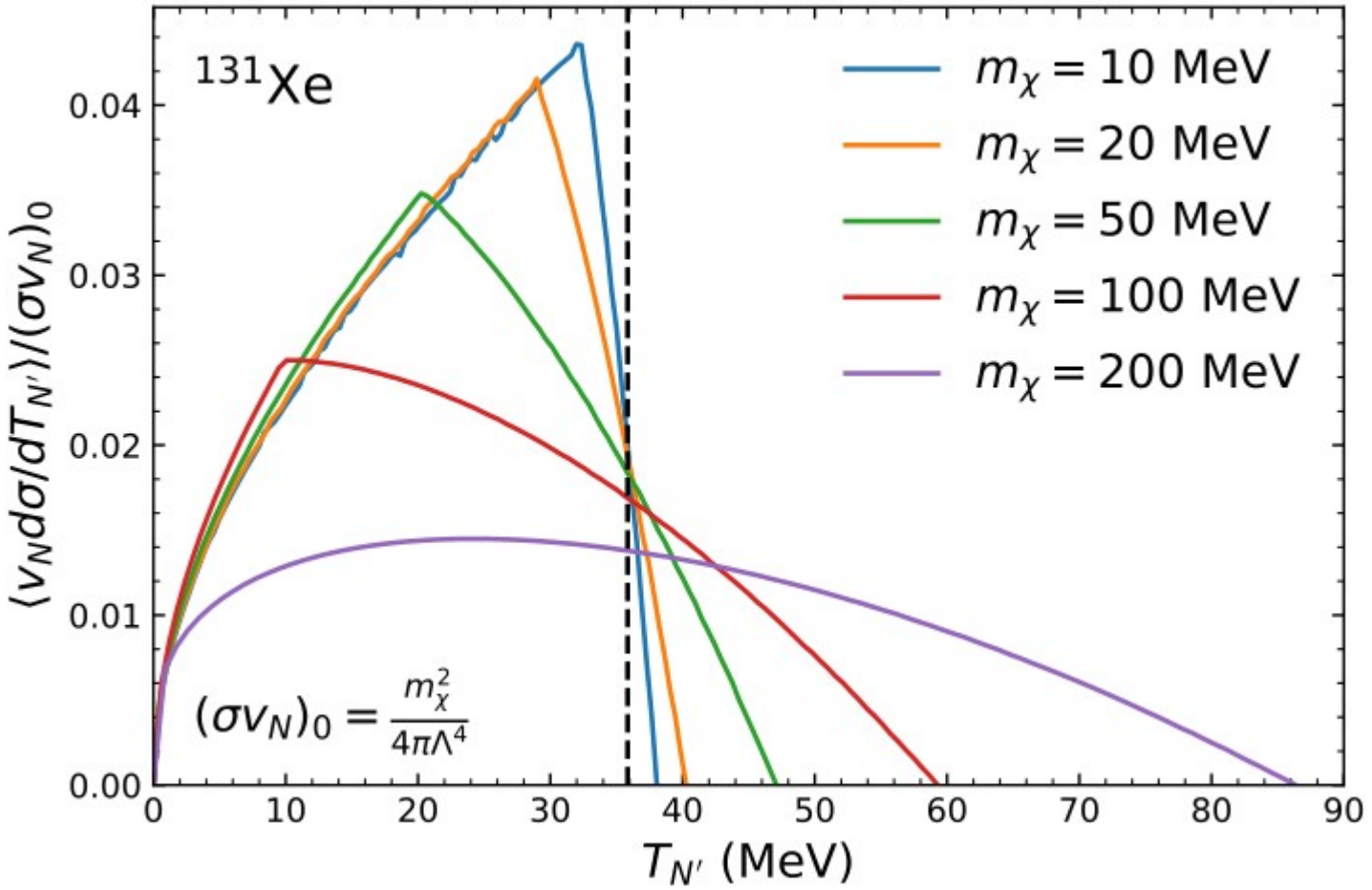
SFG, Oleg Titov [Phys.Rev.D 110 (2024) 055003]

Fermi Motion & Pauli Blocking

Tsung-Dao Lee Institute

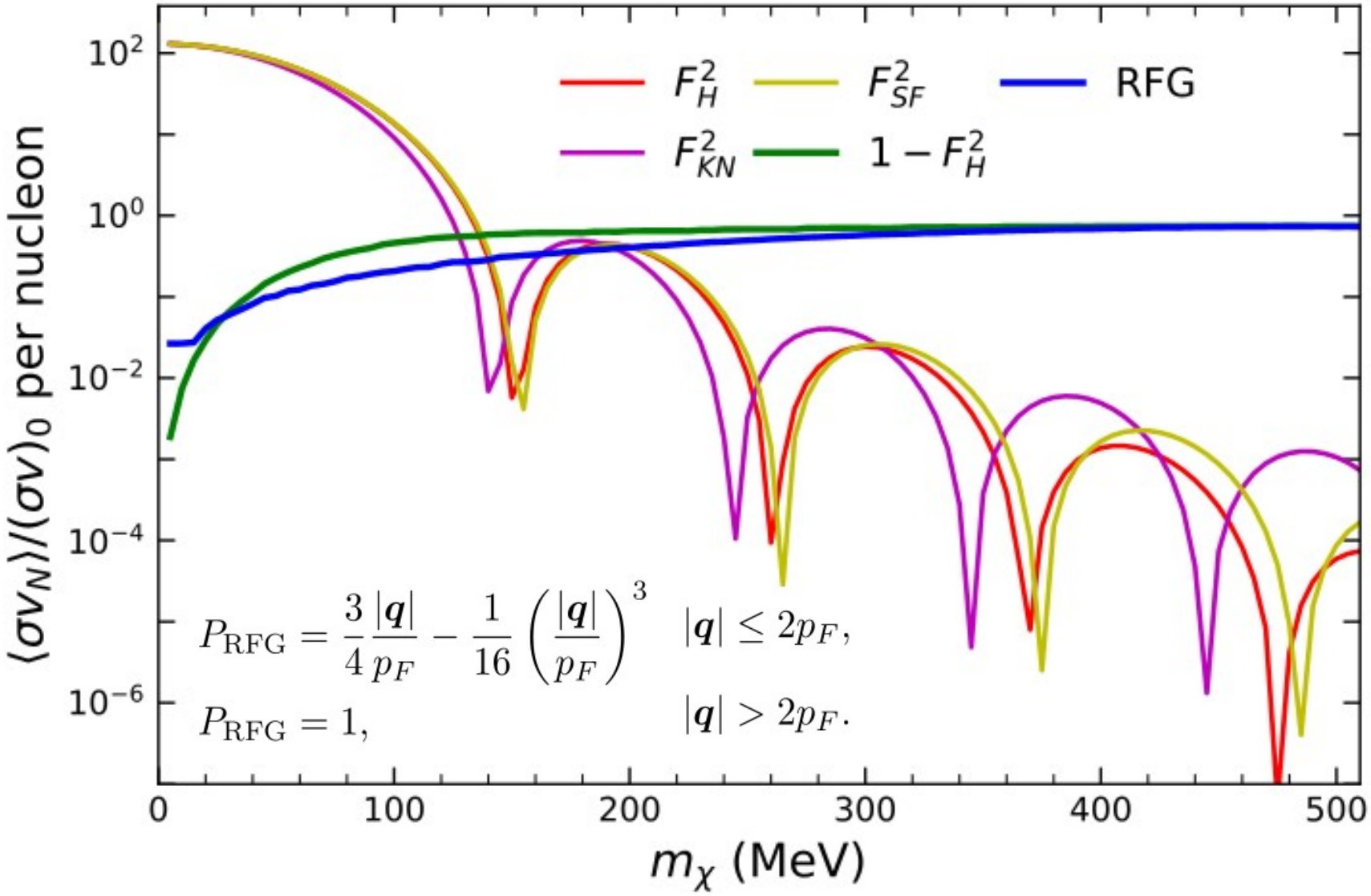
$$|\boldsymbol{q}| = |\boldsymbol{p}_\nu| = m_\chi - \frac{m_\chi^2}{2(m_N + m_\chi)} \approx m_\chi$$

$$T_{N'}^{\pm} \approx \frac{m_\chi \pm |\mathbf{p}_N|)^2}{2m_N}$$



SFG, Oleg Titov [Phys.Rev.D 110 (2024) 055003]

Incoherent vs Coherent

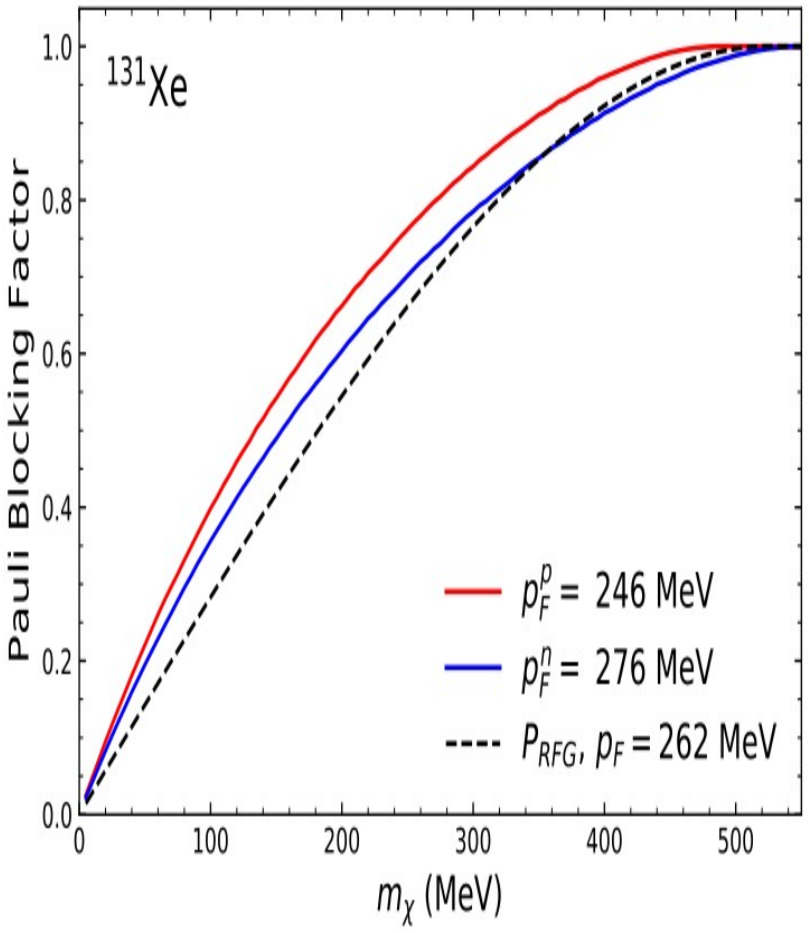


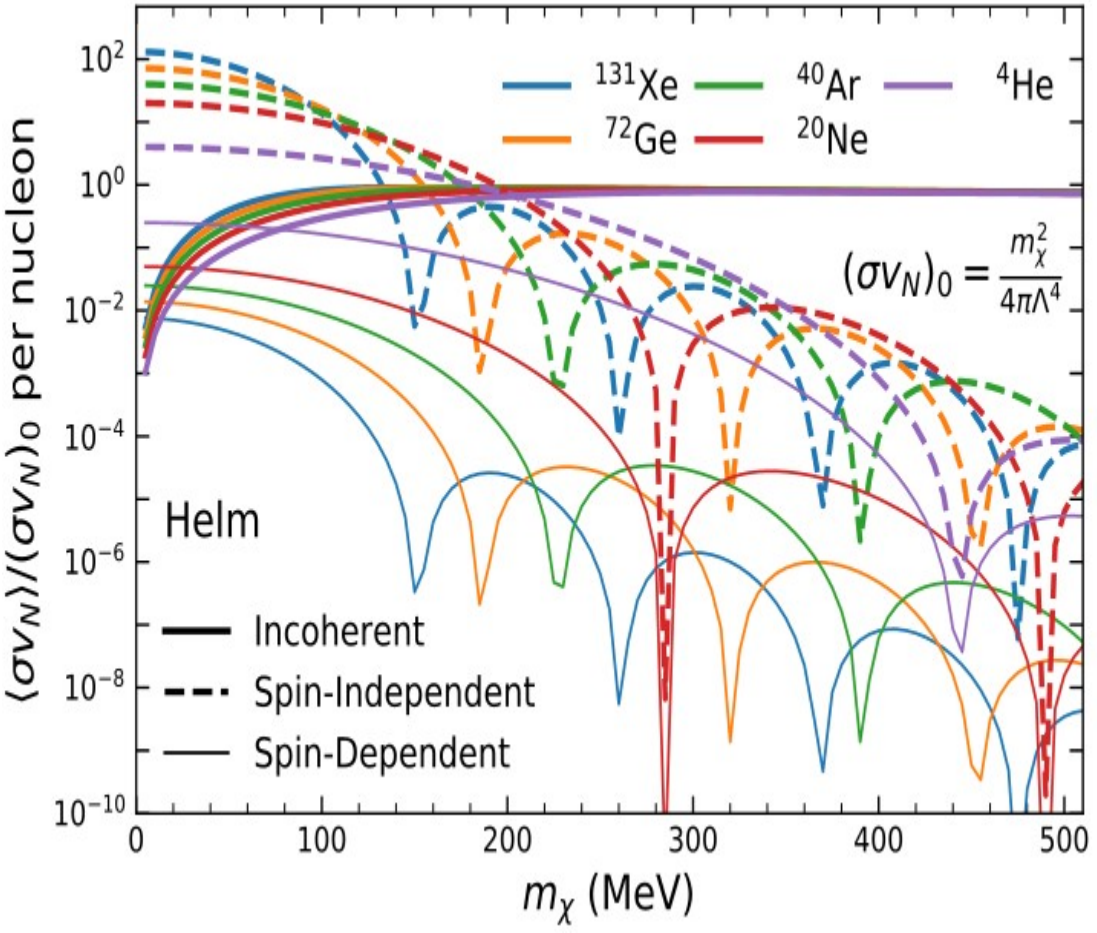
SFG, Oleg Titov [Phys.Rev.D 110 (2024) 055003]

Incoherent vs Coherent

Tsung-Dao Lee Institute

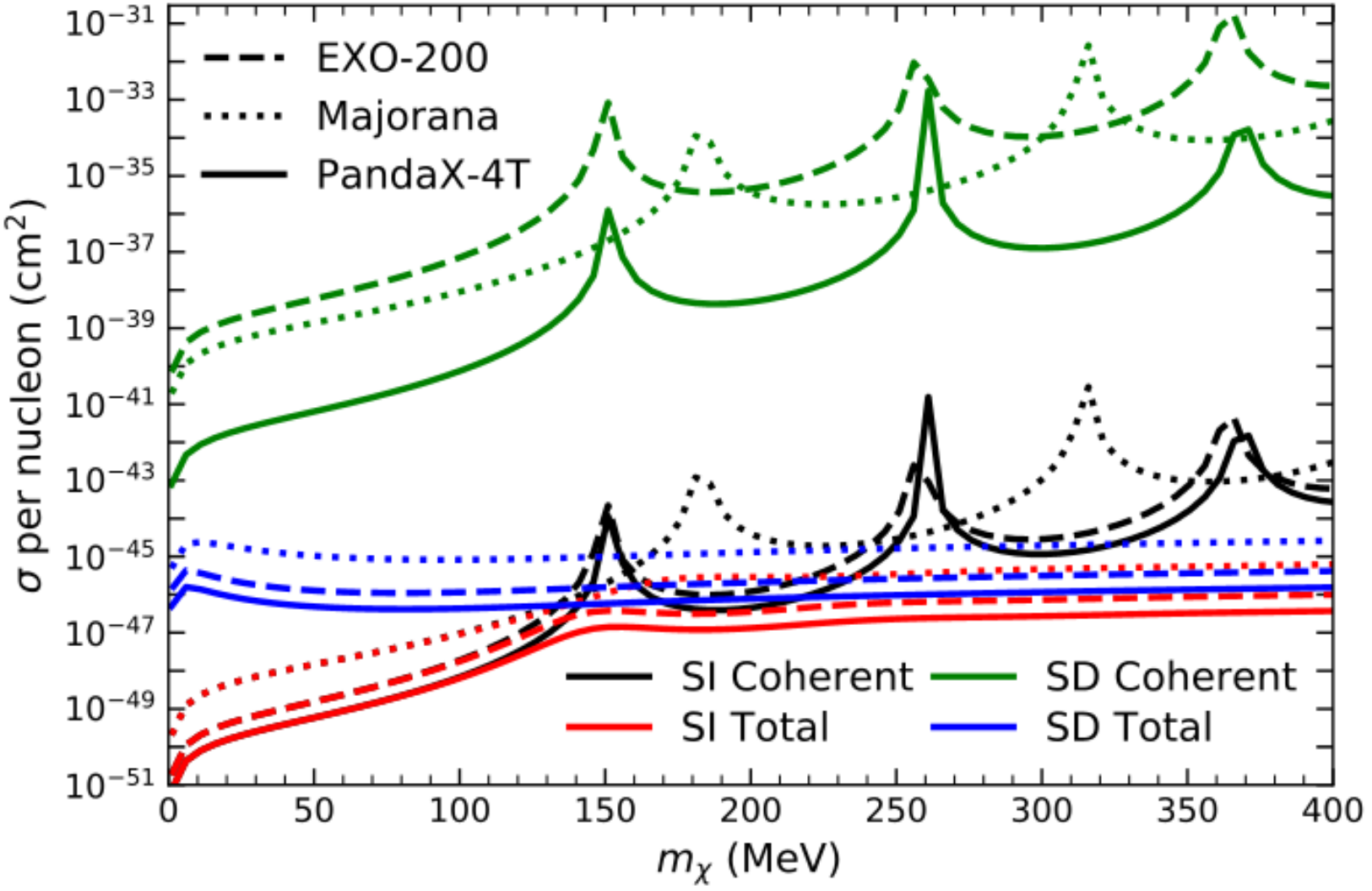
$$|\boldsymbol{q}| = |\boldsymbol{p}_\nu| = m_\chi - \frac{m_\chi^2}{2(m_N + m_\chi)} \approx m_\chi$$





SFG, Oleg Titov [Phys.Rev.D 110 (2024) 055003]

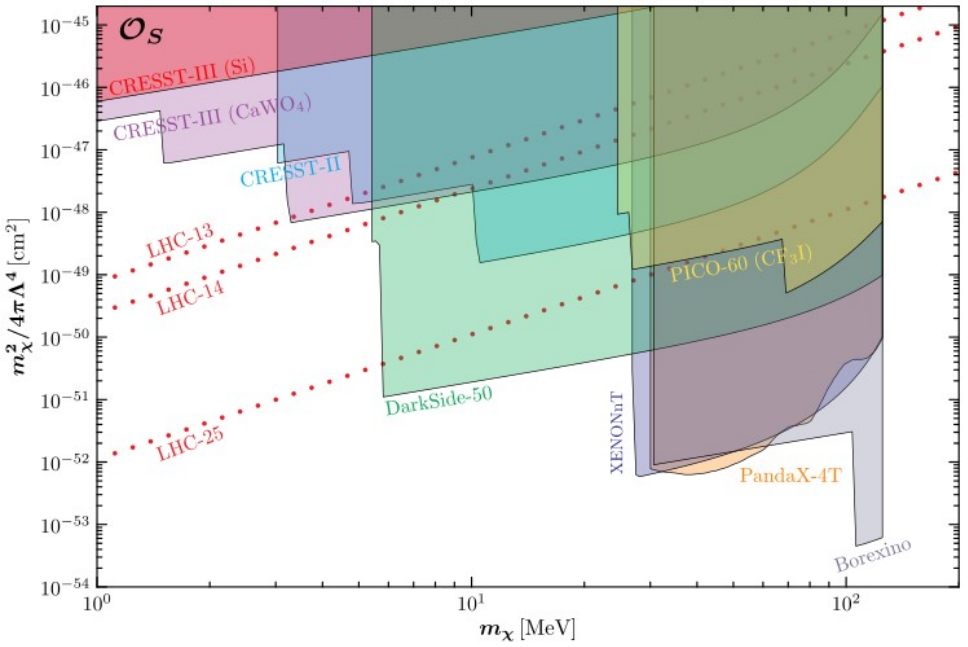
Incoherent Domination @ large m

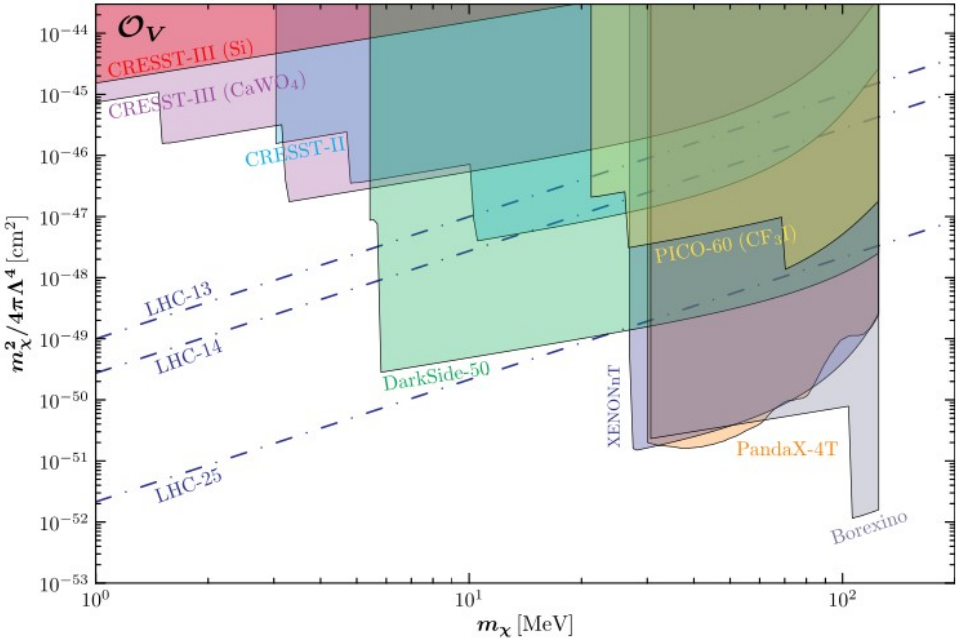


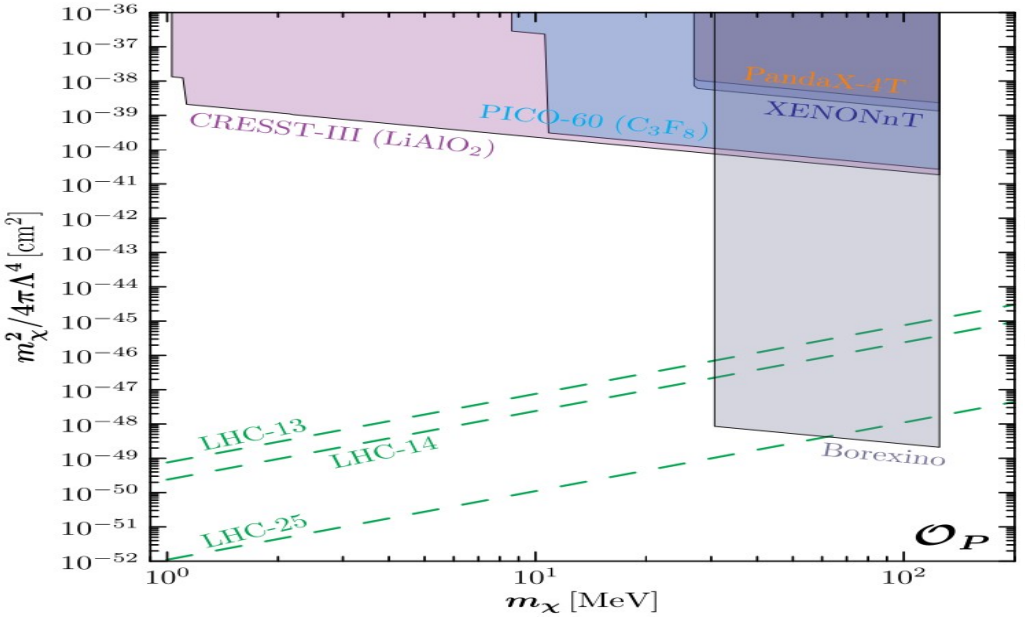
SFG, Oleg Titov [Phys.Rev.D 110 (2024) 055003]

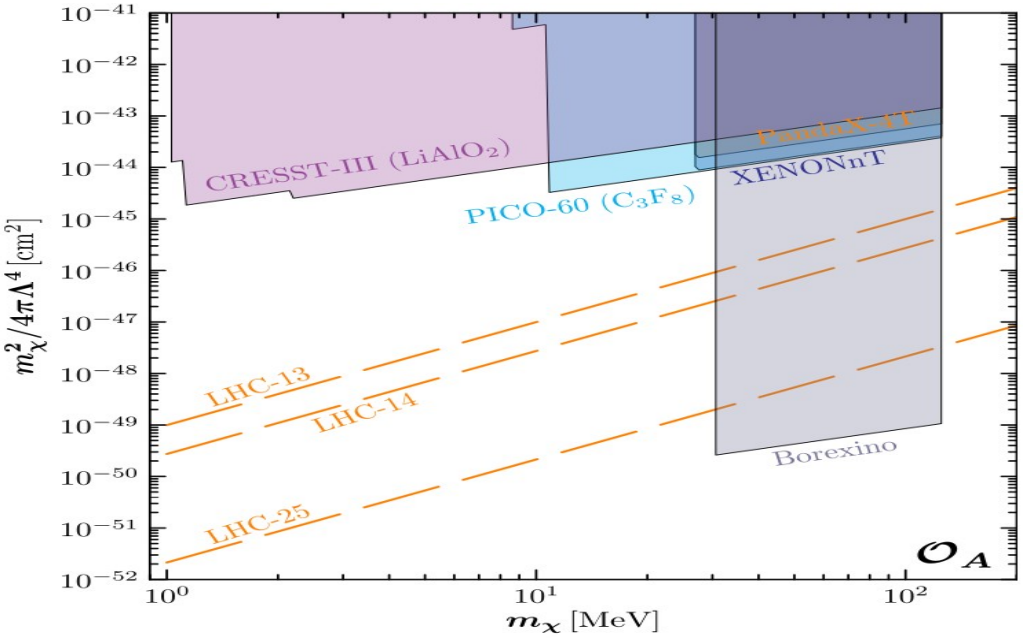
Nuclear Absorption @ Collider

Kai Ma, **SFG**, Lin-Yun He, Ning Zhou [arXiv:2405.16878]





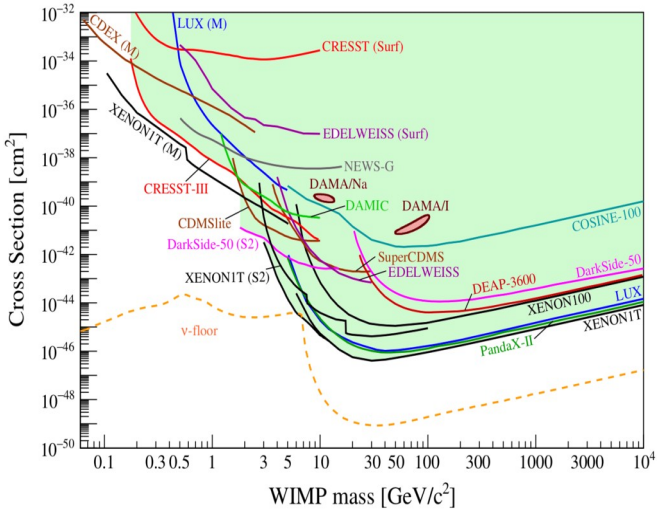


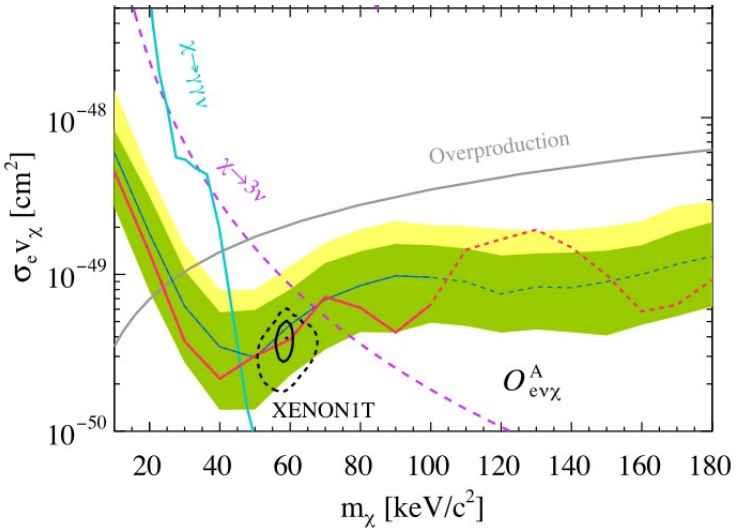


Summary

Tsung-Dao Lee Institute

1) Extension to O(10)keV mass range





2) Atomic effects should be treated more exactly

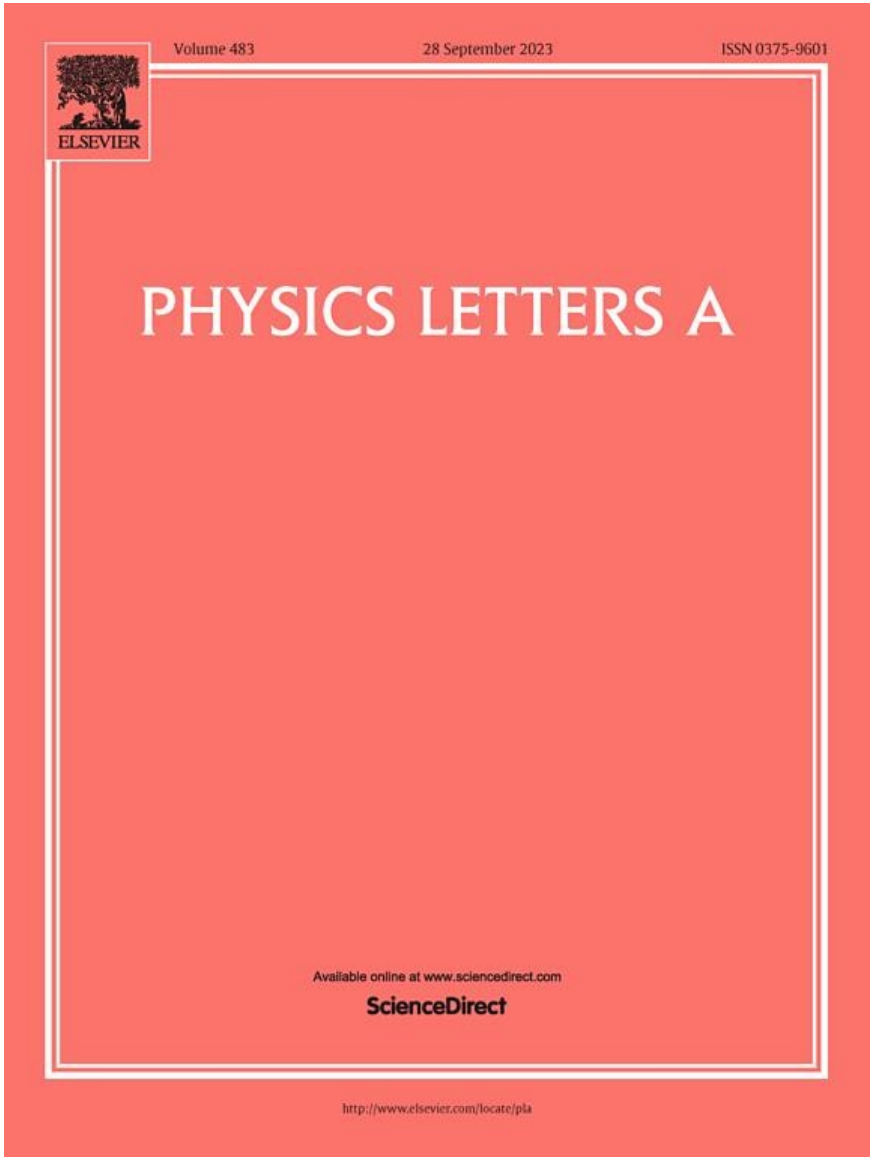
3) Decaying DM with astro/cosmo constraints

4) Complementary searches @ collider

5) Active-Sterile conversion

Thank You

《 Physics Letters A 》

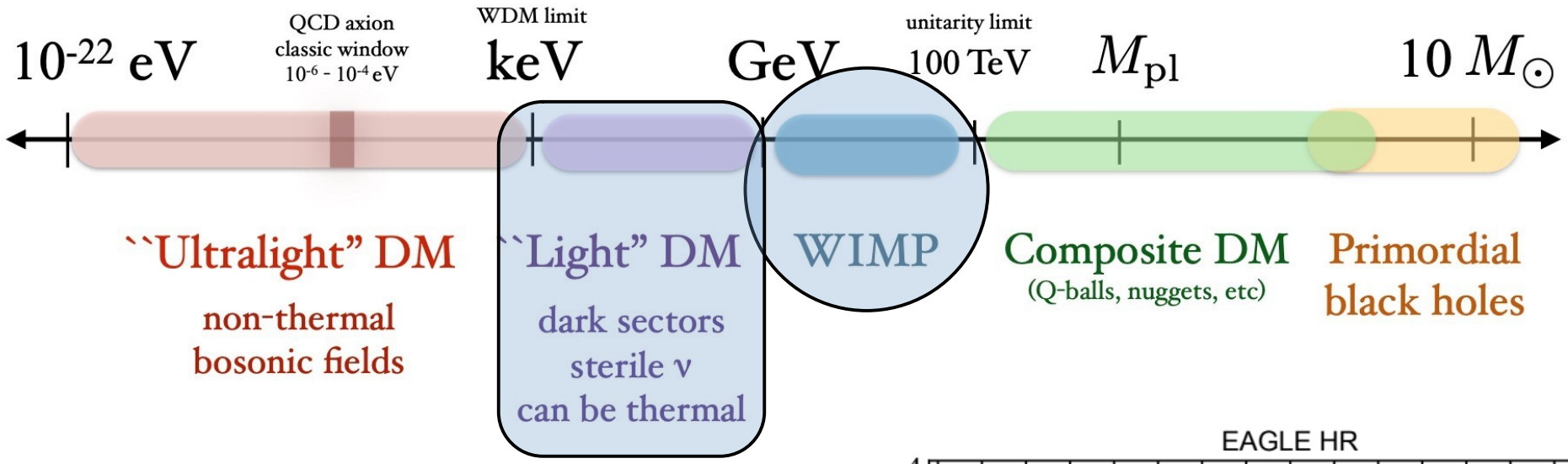


Aims & Scope

- Nonlinear science,
- Statistical physics,
- Mathematical and computational physics,
- AMO and physics of complex systems,
- Plasma and fluid physics,
- Optical physics,
- General and cross-disciplinary physics,
- Biological physics and nanoscience,
- Astrophysics, Particle physics and Cosmology.

Backup Slides

Mass Span of DM

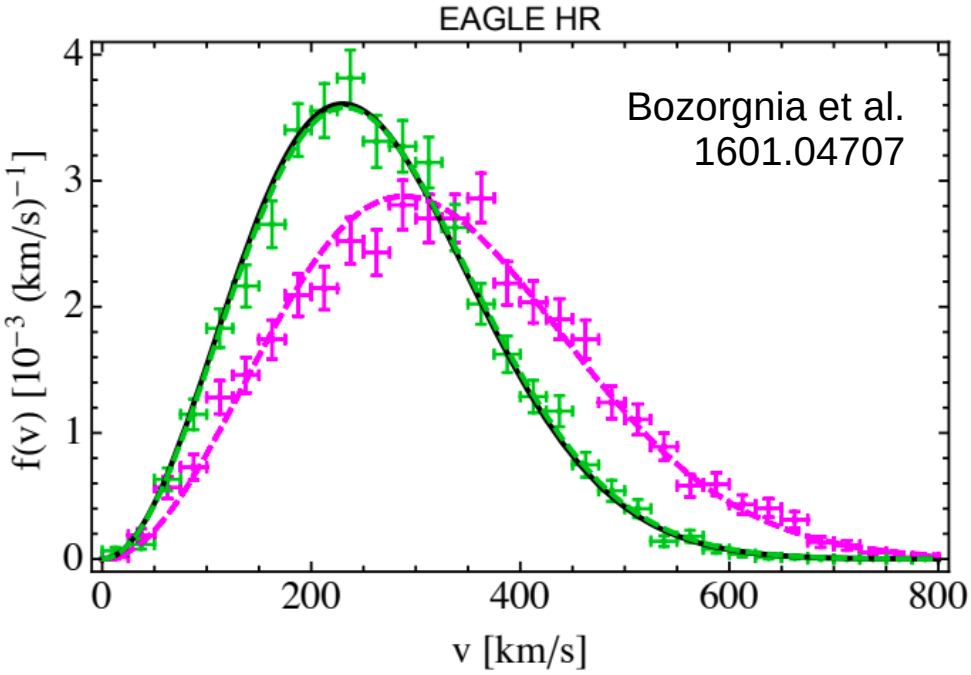


?

$$E_r \approx \frac{4m_\chi m_N}{(m_\chi + m_N)^2} T_\chi$$

$$\approx \frac{4m_\chi}{m_N} T_\chi \qquad T_\chi = \frac{1}{2} m_\chi v_\chi^2$$

$$E_r \propto m_\chi^2$$



Possible Improvements

1) Lowering the threshold

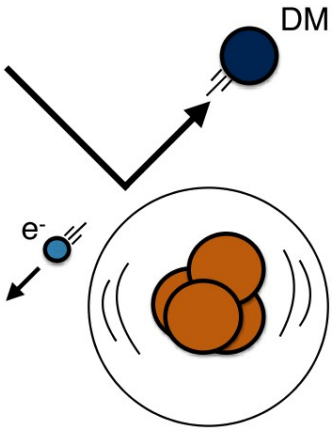
Bolometer [1904.00498, Ann.Rev.Nucl.Part.Sci. 67 (2017) 161-181]

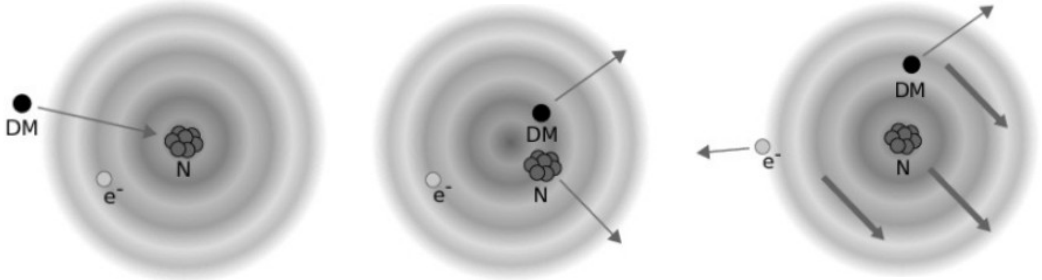
Bremsstrahlung [Kouvaris & Pradler, PRL 118, 031803 (2017)]

$$\chi + N \to \chi + N(E_R) \quad \Rightarrow \quad \chi + N \to \chi + N(E'_R) + \gamma(\omega)$$

Migdal effect [Ibe et al [1707.07258]]

2) Electron target





3) Boosting detector?

Atomic Effect

$$\sigma v_{1\to 2} = \frac{\overline{\sigma}_e}{\mu_{\chi e}^2} \int \frac{d^3q}{4\pi}\, \delta\left(\Delta E_{1\to 2} + \frac{q^2}{2m_\chi} - \vec{q}\cdot\vec{v}\right) \times |F_{\rm DM}(q)|^2 |f_{1\to 2}(\vec{q})|^2$$

$$\overline{\sigma}_e \equiv \frac{\mu_{\chi e}^2 \overline{|\mathcal{M}_{\rm free}(\alpha m_e)|^2}}{16\pi m_\chi^2 m_e^2}$$

DM Form Factor: $$F_{\rm DM}(q) = \frac{m_{A'}^2 + \alpha^2 m_e^2}{m_{A'}^2 + q^2} \simeq \begin{cases} 1\,, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e^2}{q^2}\,, & m_{A'} \ll \alpha m_e \end{cases}$$

Atomic Form Factor: $$f_{1\to 2}(\vec{q}) = \int d^3x\, \psi_2^*(\vec{x})\psi_1(\vec{x}) e^{i\vec{q}\cdot\vec{x}}$$

Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu [JHEP 05 (2016) 046]

Atomic Effect with 2nd Quantization

Tsung-Dao Lee Institute

$$\mathcal{T} = \bar{u}_\chi(p_\chi)\Gamma_\nu u_\nu(p_\nu)\frac{i}{q^2 - M^2}\int d^4y e^{-iq\cdot y}\overline{\psi}_{T_r l'm'}(\mathbf{y})\Gamma_e\psi_{nlm}(\mathbf{y})e^{i\Delta E_{nl}t}$$

$$\psi_{N,s}(\mathbf{x}) \approx \frac{1}{\sqrt{2}}\begin{pmatrix}(1 + i\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}/2m_e)f_{N,s}(\mathbf{x})\\(1 - i\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}/2m_e)f_{N,s}(\mathbf{x})\end{pmatrix}, \qquad f_{N,s}(\mathbf{x}) \equiv \phi_N(\mathbf{x})\xi_s,$$

$$A_e^S \equiv \frac{\bar{u}(m_e)u(m_e)}{2m_e}\int d^3\mathbf{y} e^{i\mathbf{q}\cdot\mathbf{y}}\phi^*_{T_r l'm'}(\mathbf{y})\phi_{nlm}(\mathbf{y})$$

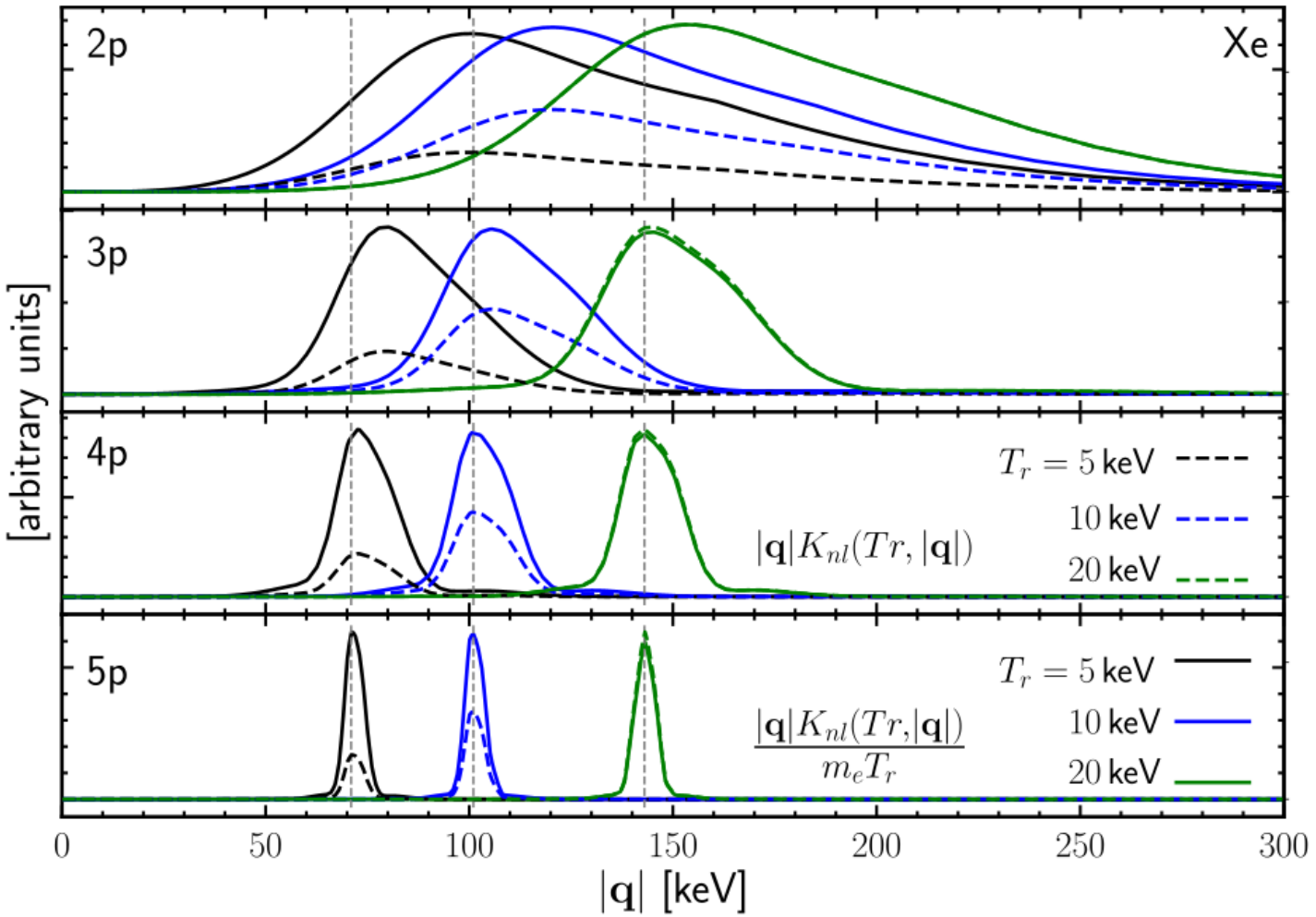
$$\frac{d\langle\sigma_{\chi e}v_\chi\rangle}{dT_r} = \sum_{nl}(4l+2)\frac{1}{T_r}\frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi}|\mathcal{M}|^2(\mathbf{q})K_{nl}(T_r, |\mathbf{q}|),$$

SFG, Pedro Pasquini, Jie Sheng [JHEP 05 (2022) 088]

Atomic Effect with 2nd Quantization

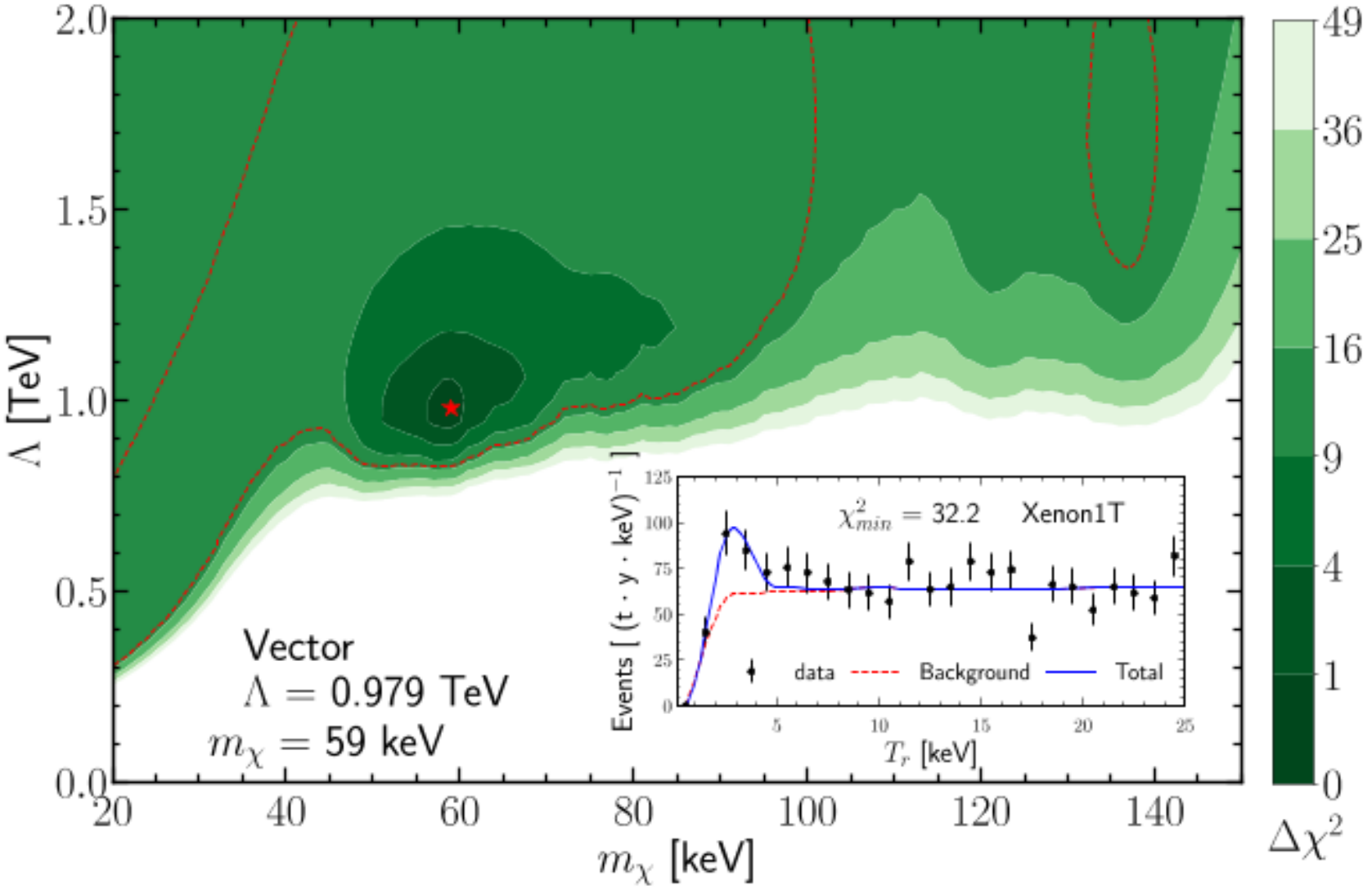
Tsung-Dao Lee Institute

$$\frac{d\langle\sigma_{\chi e} v_\chi\rangle}{dT_r} = \sum_{nl}(4l+2)\frac{1}{T_r}\frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi}|\mathcal{M}|^2(\mathbf{q})K_{nl}(T_r,|\mathbf{q}|),$$



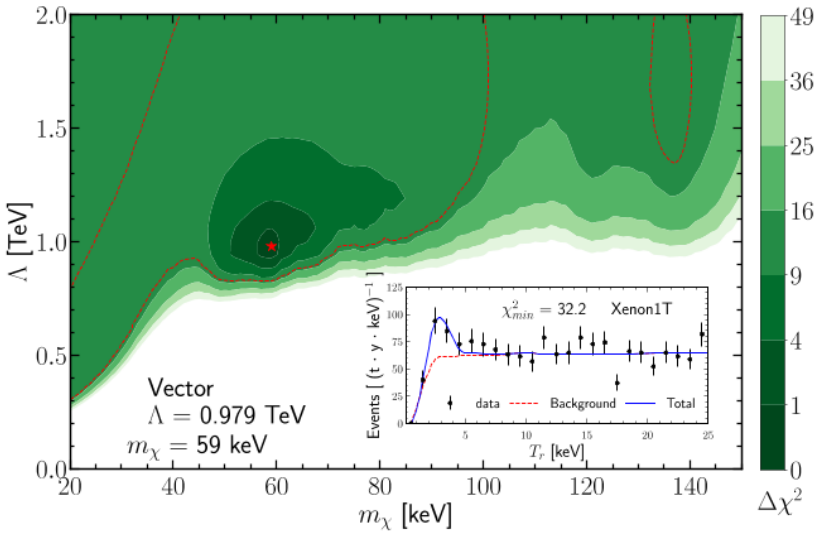
SFG, Pedro Pasquini, Jie Sheng [JHEP 05 (2022) 088]

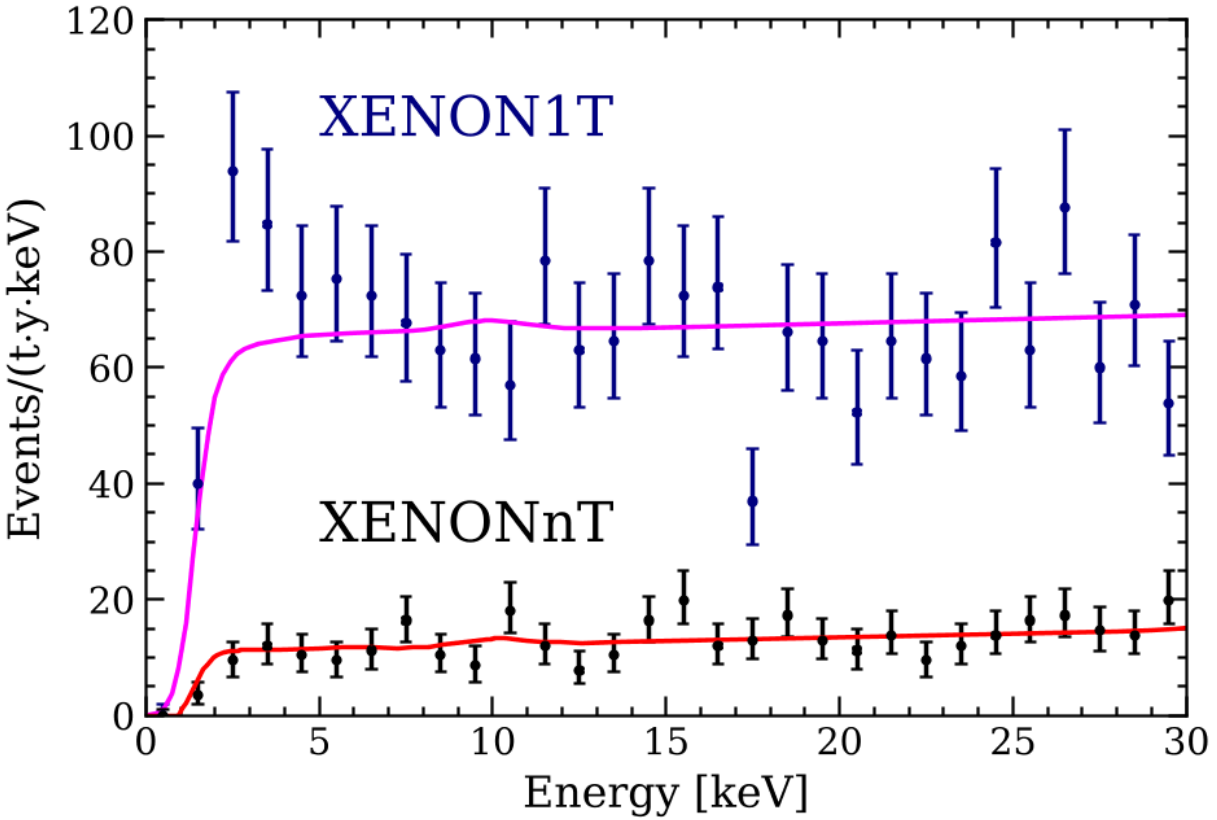
Xenon1T Excess



SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

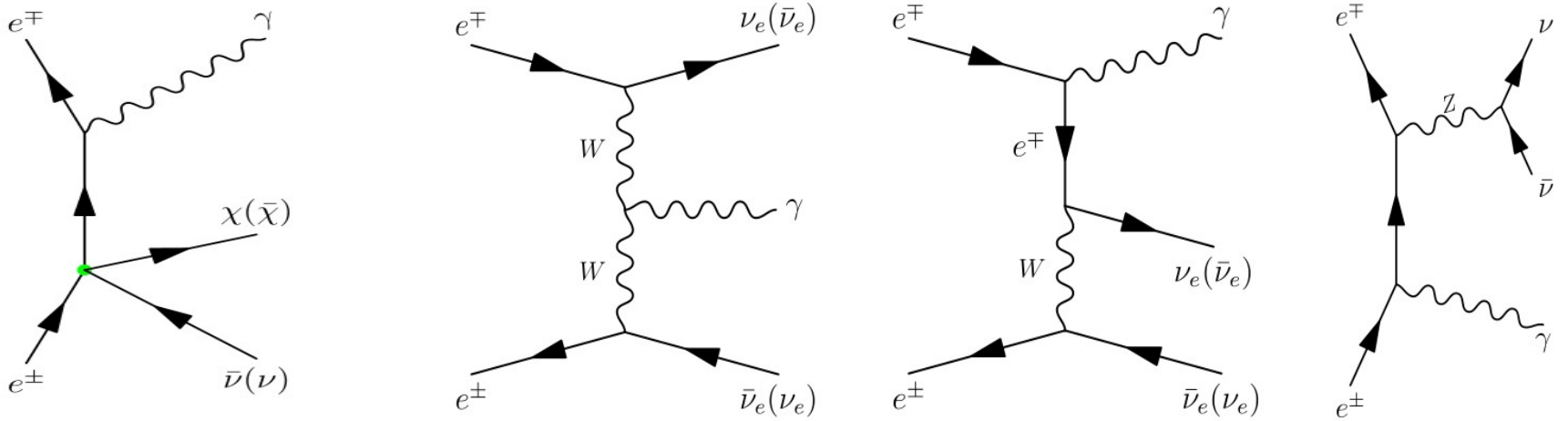
Xenon1T Excess

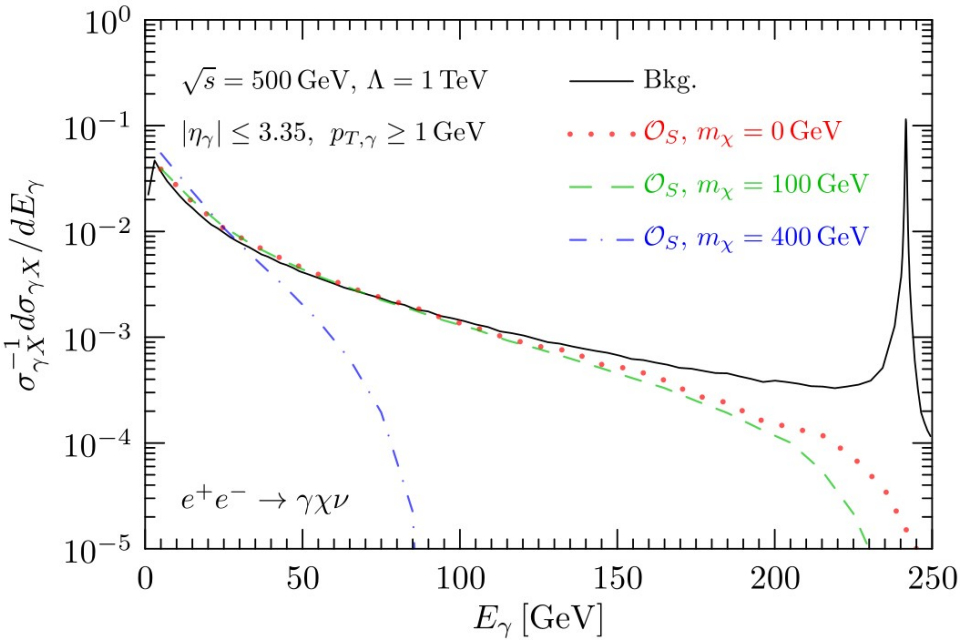


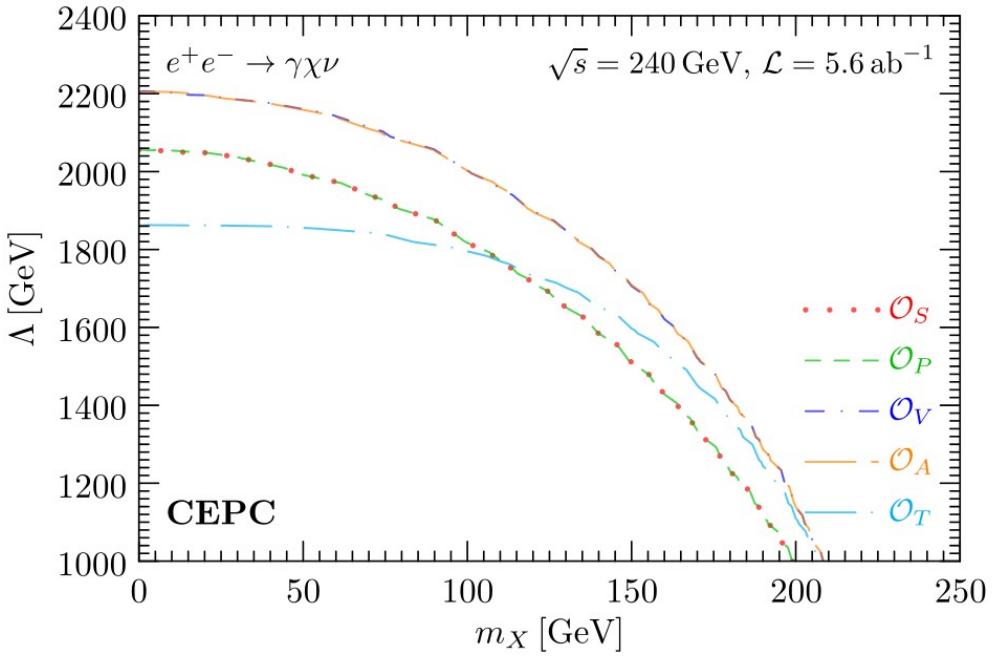


Knut Dundas Morå @ IDM2022
XENONnT, Phys.Rev.Lett. 129 (2022) 16, 161805 [2207.11330]

Mono-Photon @ Lepton Collider

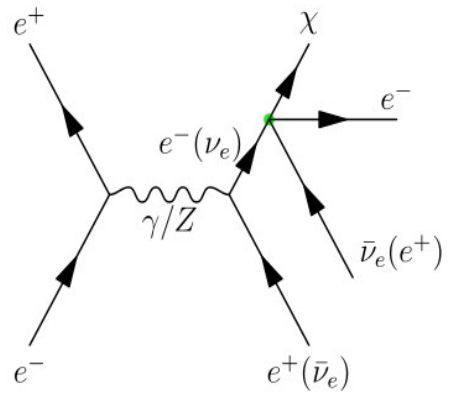


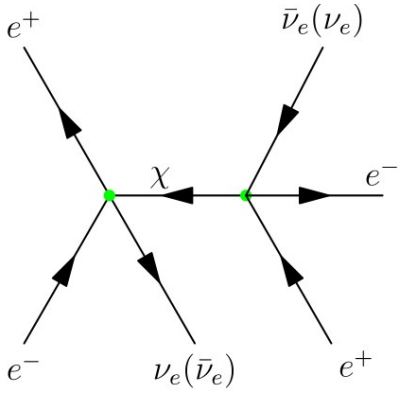


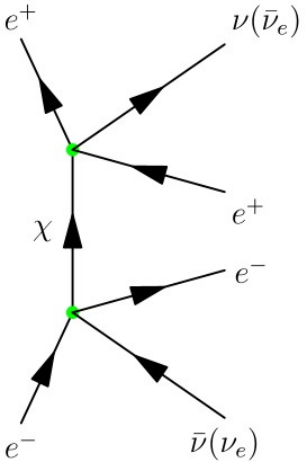


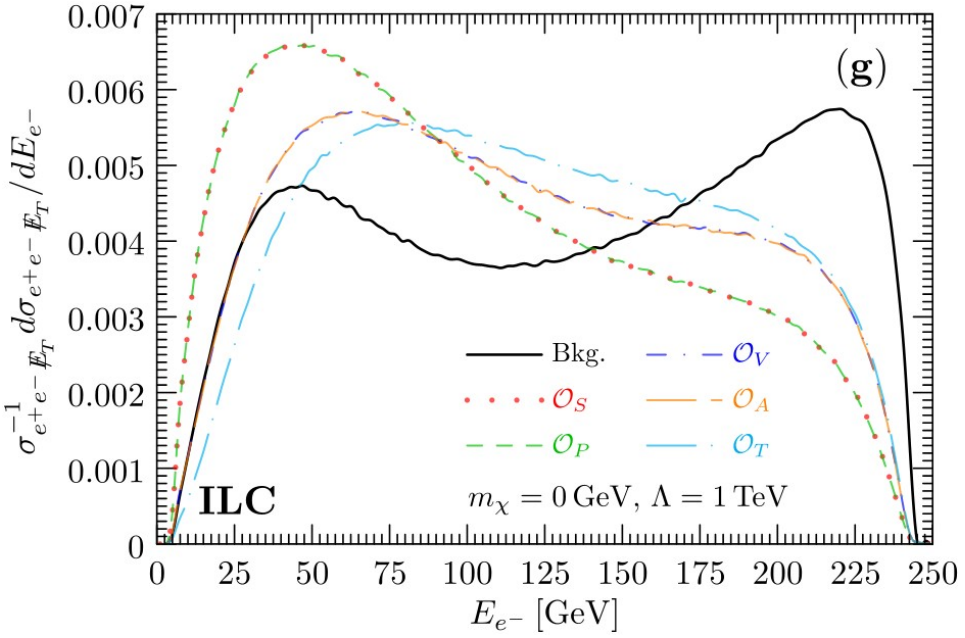
SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [JHEP 11 (2023) 190]

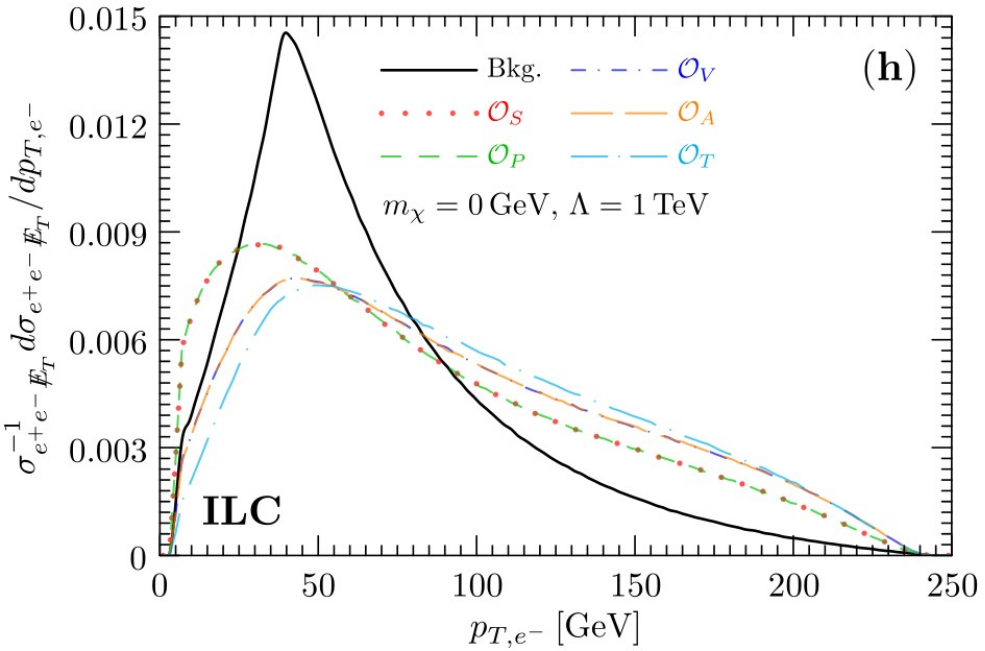
e^+e^- Pair + Missing Energy











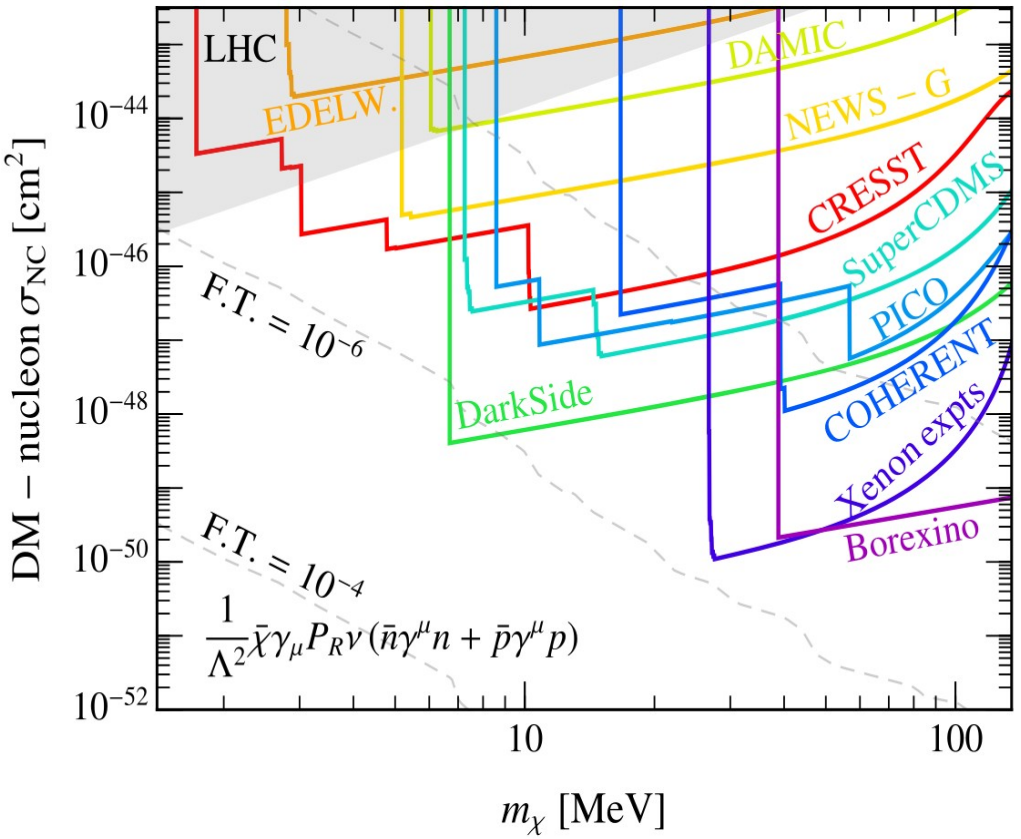
SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [JHEP 11 (2023) 190]

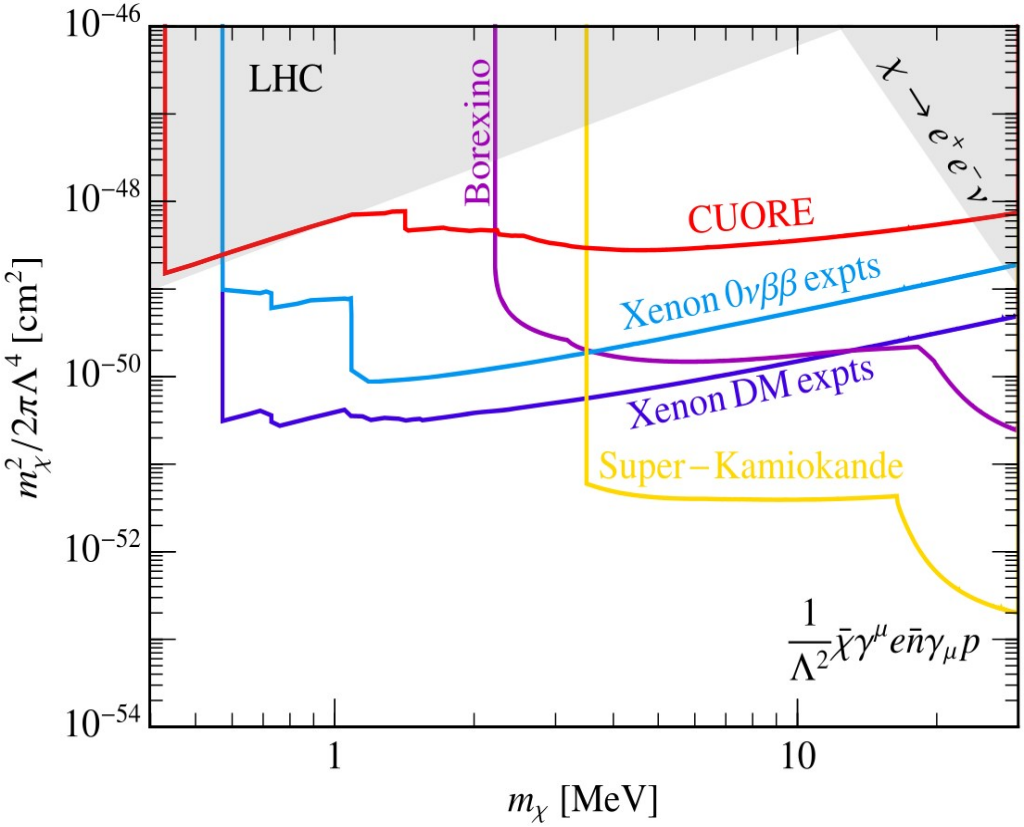
DM Absorption by Nuclei

Tsung-Dao Lee Institute

$$\chi + N \to \nu + N$$

$$\chi + N \to e + N'$$





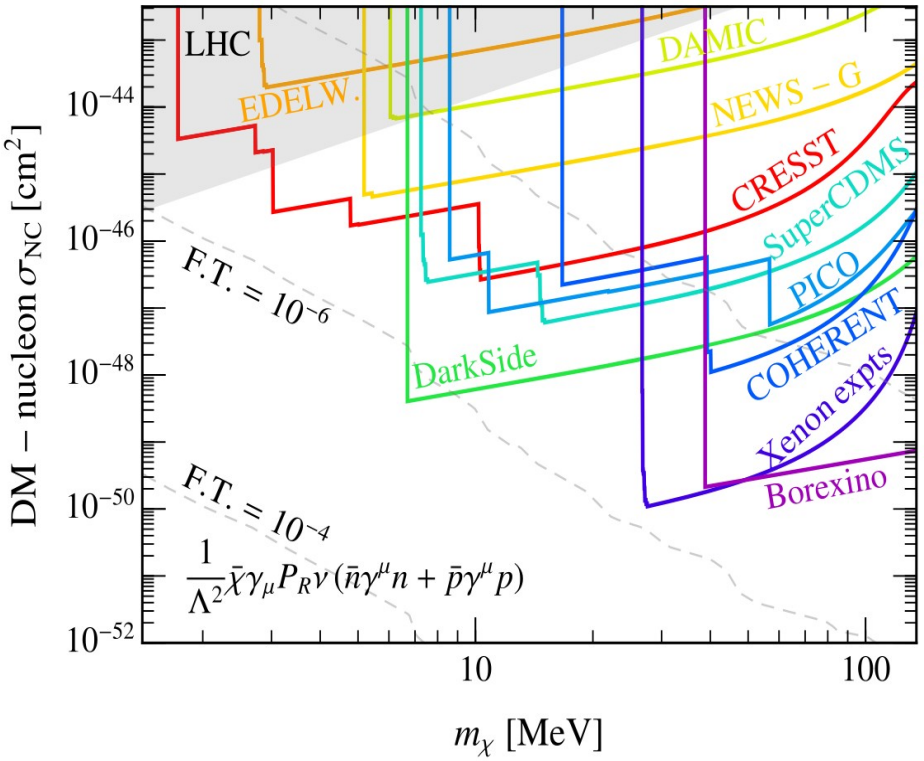
Jeff A. Dror, Gilly Elor, and Robert McGehee [Phys.Rev.Lett. 124 (2020) 18, 18]

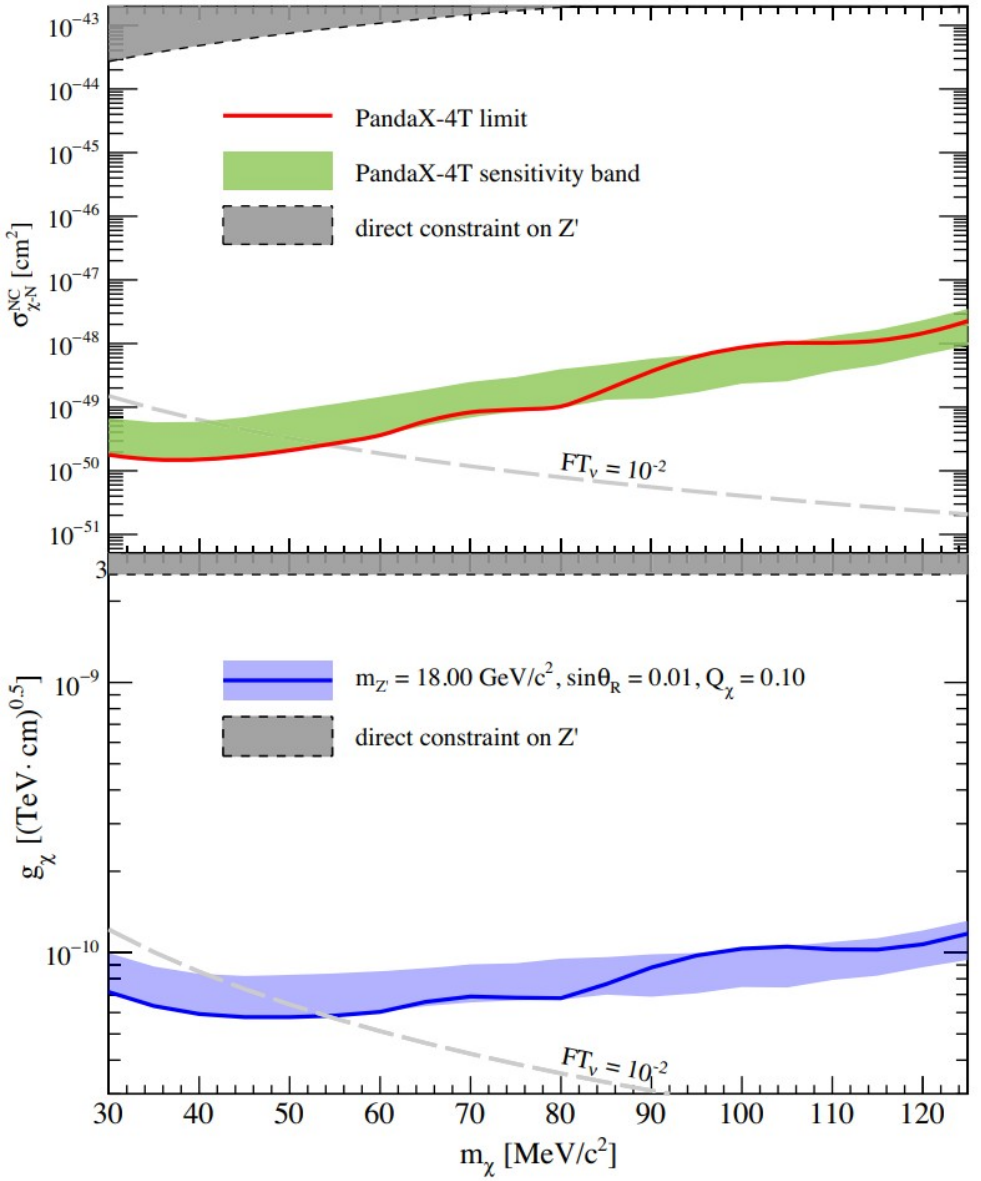
Jeff A. Dror, Gilly Elor, and Robert McGehee [JHEP 02 (2020) 134]

DM Absorption @ PandaX

李政道研究所
Tsung-Dao Lee Institute

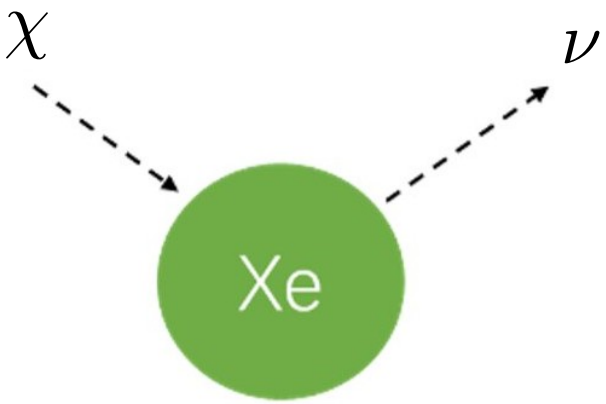
$$\chi + N \to \nu + N$$



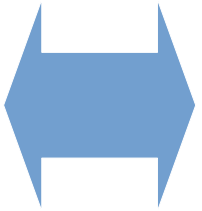


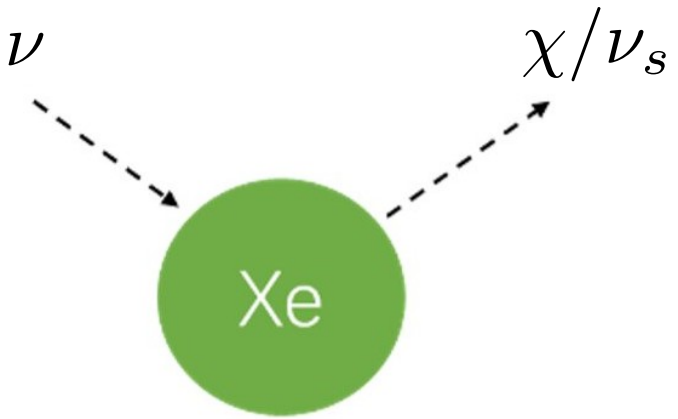
PandaX, Phys.Rev.Lett. 129 (2022) 16, 161803 [2205.15771]

Active-Sterile Neutrino Conversion



$$\chi + e \to \nu + e$$





$$\nu + e \to \nu_s + e$$

SFG, Pedro Pasquini, Jie Sheng [Phys.Lett.B 810 (2020) 135787]

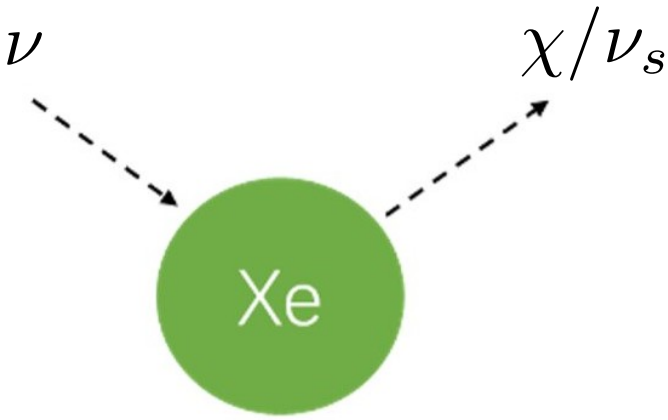
SFG, Pedro Pasquini, Jie Sheng [JHEP 05 (2022) 088]

Active-Sterile Neutrino Conversion

Tsung-Dao Lee Institute

Recoil matrix element $|M|^2$ with a light mediator

$$(2m_e T_r + m_s^2)\frac{(y_S^\nu y_S^e)^2(2m_e + T_r) + (y_P^\nu y_P^e)^2 T_r}{8\pi E_\nu^2 (2m_e T_r + m_\phi^2)^2}$$



$$\nu + e \to \nu_s + e$$

- **Active ν final state**

$$m_s \to 0 \quad m_\phi \to 0$$

$$|\mathcal{M}|^2 \sim \begin{cases} \frac{1}{T_r^2} & \text{Scalar (S)} \\ \text{const} & \text{Pseudo-scalar (P)} \end{cases}$$

- **Active-Sterile conversion**

$$m_s \gtrsim \sqrt{2m_e T_r}$$

$$|\mathcal{M}|^2 \sim \frac{1}{T_r}$$

Pseudo-scalar mediator is also enhanced at low energy.

SFG, Pedro Pasquini, Jie Sheng [Phys.Lett.B 810 (2020) 135787]

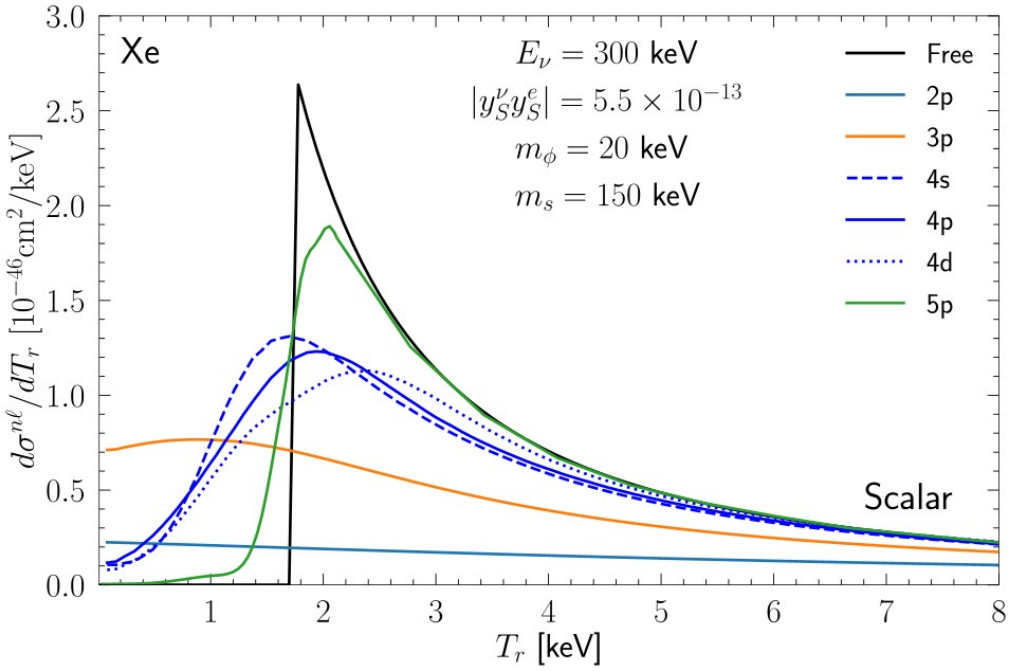
SFG, Pedro Pasquini, Jie Sheng [JHEP 05 (2022) 088]

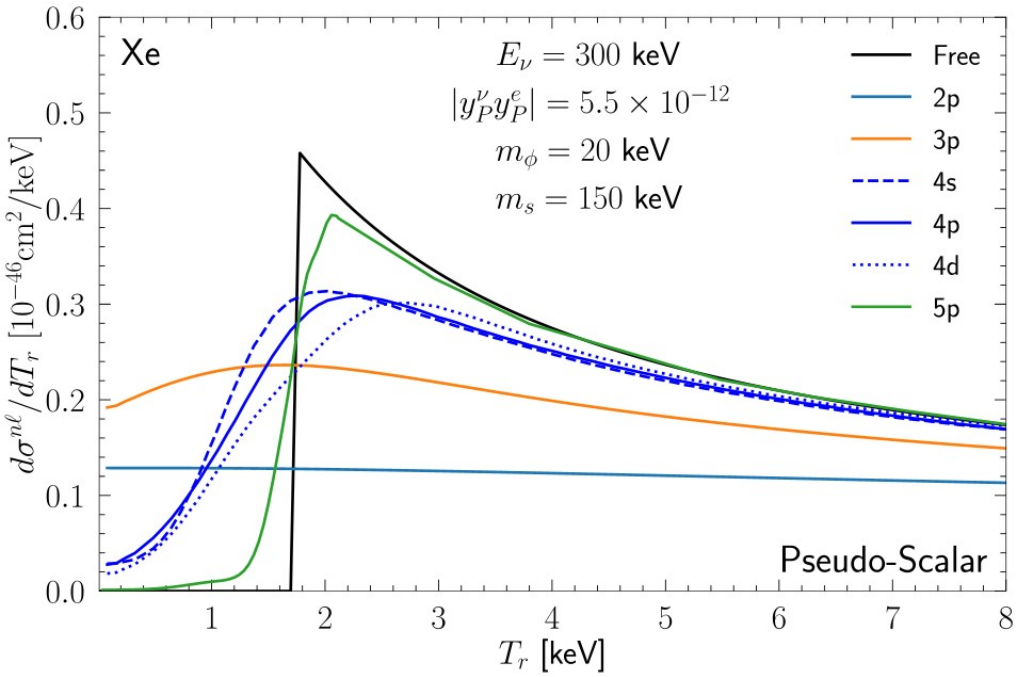
Active-Sterile Neutrino Conversion

Tsung-Dao Lee Institute

$$|\mathcal{M}|^2 \sim \frac{1}{T_r^2}$$

$$|\mathcal{M}|^2 \sim \frac{1}{T_r}$$

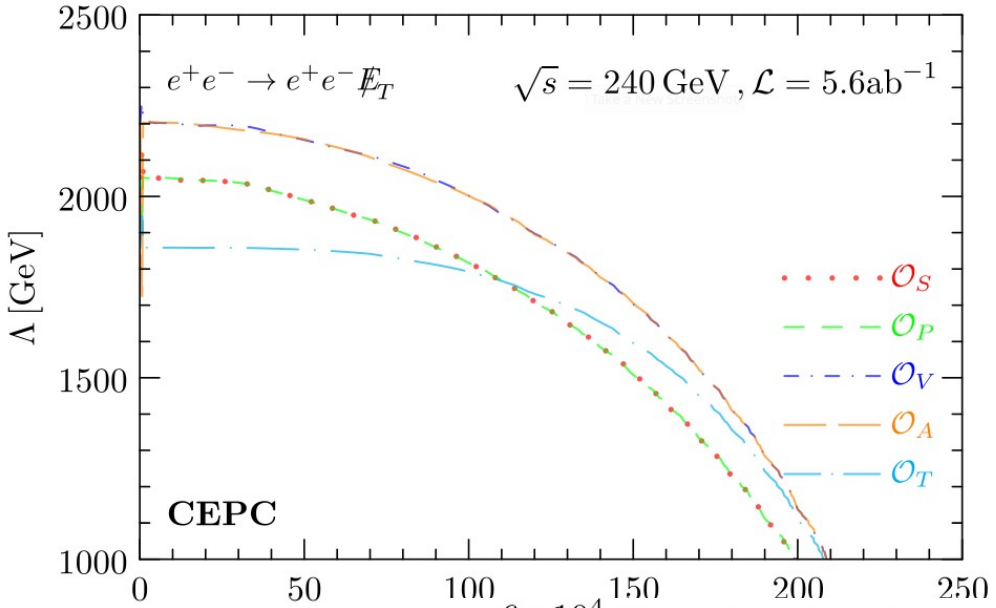


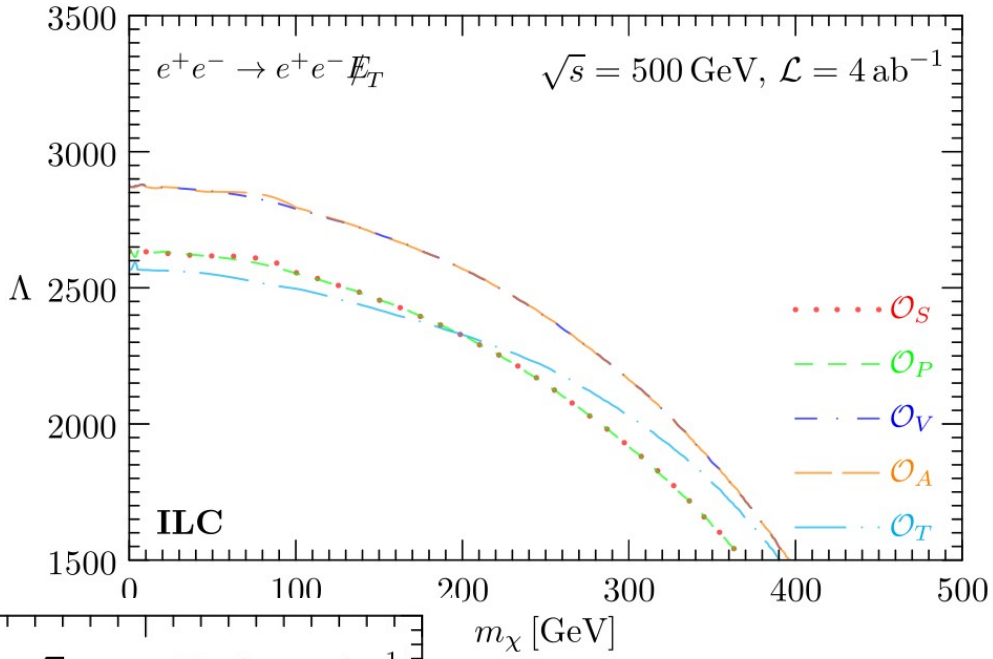


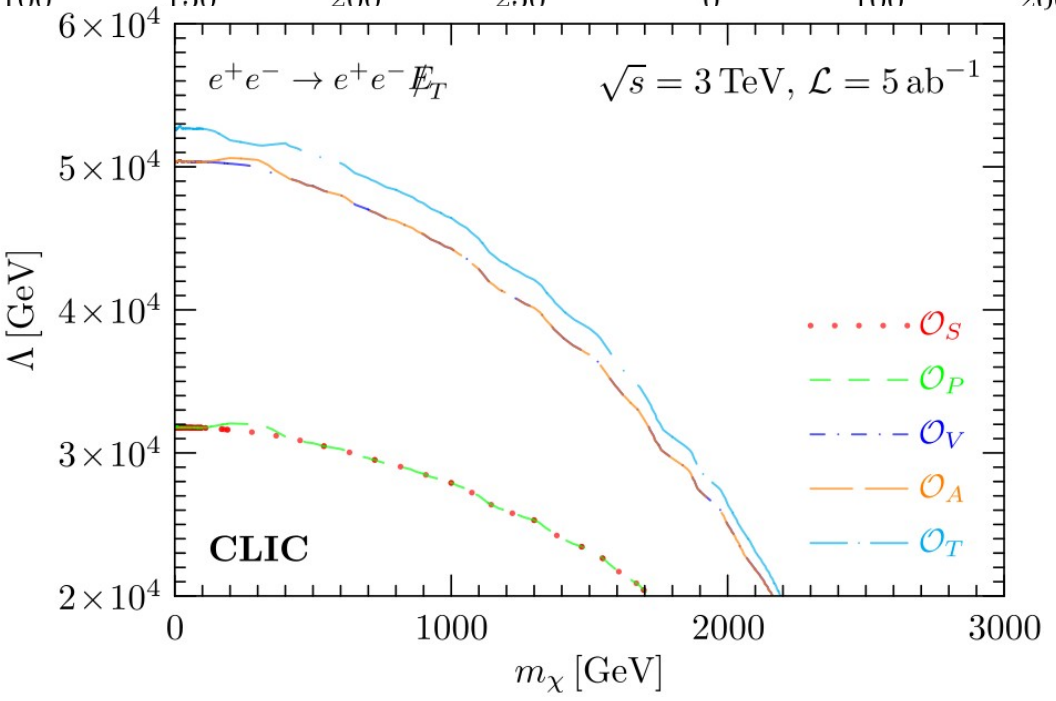
SFG, Pedro Pasquini, Jie Sheng [Phys.Lett.B 810 (2020) 135787]

SFG, Pedro Pasquini, Jie Sheng [JHEP 05 (2022) 088]

Fermionic Absorption @ Collider







SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [arXiv:2306.00657]