



# Fermionic Absorption DM

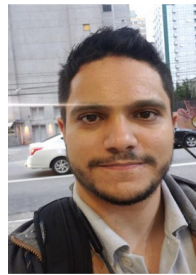
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Kai Ma



Xiao-Dong Ma



Pedro Pasquini



Jie Sheng

**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]



上海交通大学  
SHANGHAI JIAO TONG UNIVERSITY

December 5, 2023 @ Kashiwa DM

李改道研究所  
Tsung-Dao Lee Institute

## 1) Thresholds in DM search

## 2) Direct Detection & Atomic 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]

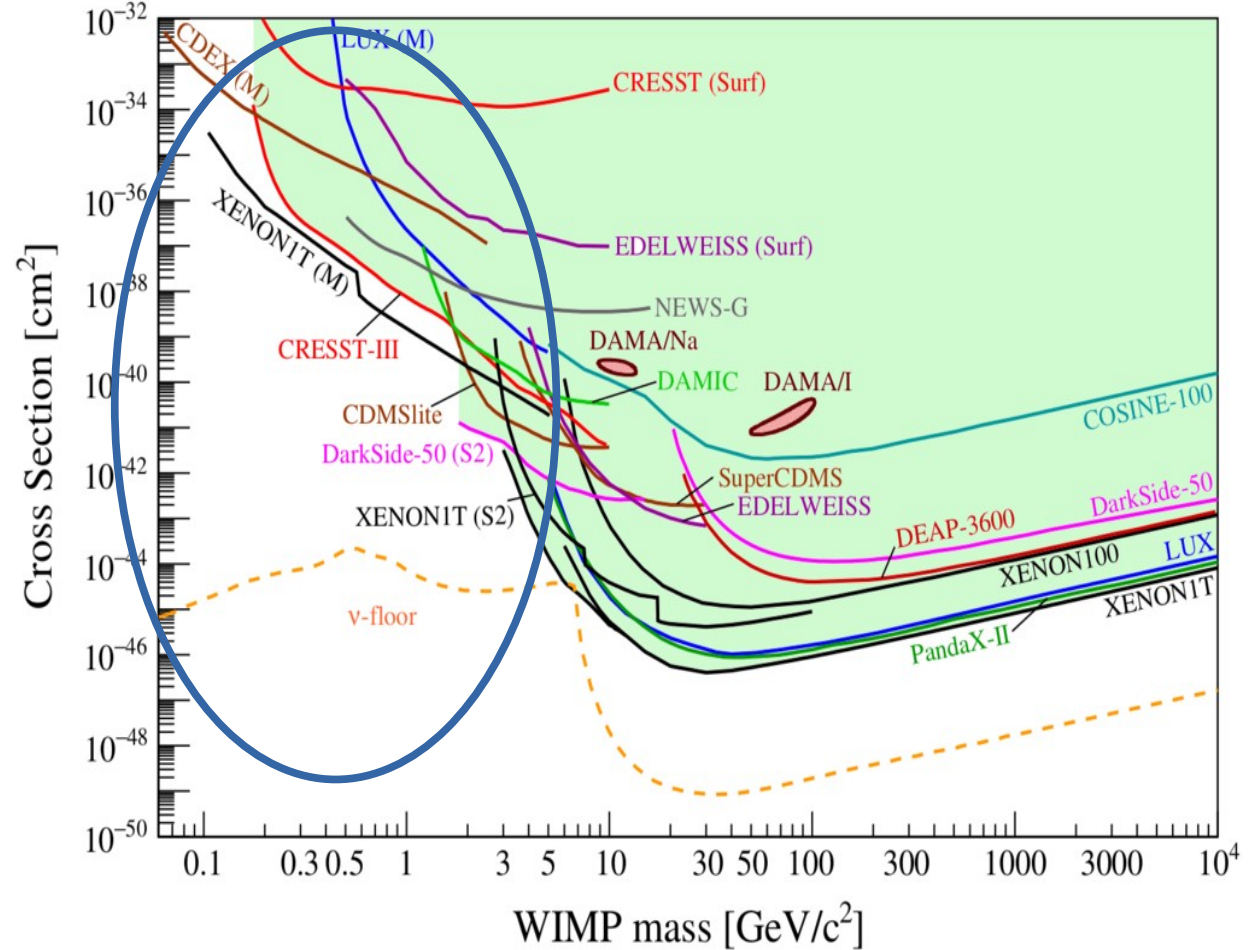
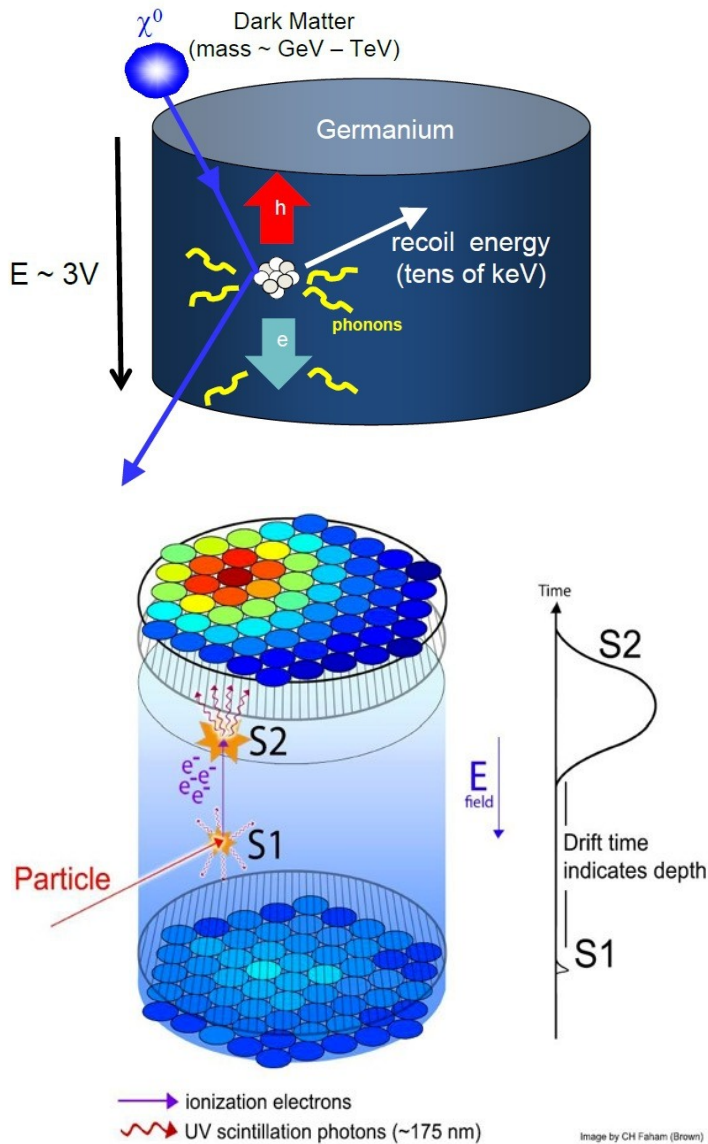
## 3) Astro & Cosmo Constraints

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

## 4) Complementary Searches @ Lepton Colliders

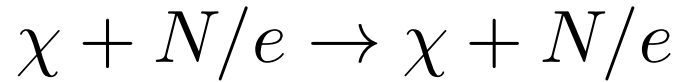
SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [JHEP 11 (2023) 190]

# Direct Detection



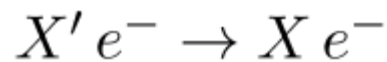
APPEC Committee Report [2104.07634]

- Elastic Scattering



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

- Exothermic

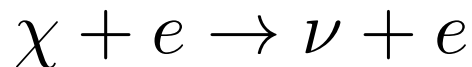


$$E_R \simeq \Delta m \left( 1 - \frac{v_{\text{DM}}}{v_e} \cos \theta_e \right)$$

He, Wang & Zheng [JCAP21, 2007.04963]

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

- Fermionic absorption

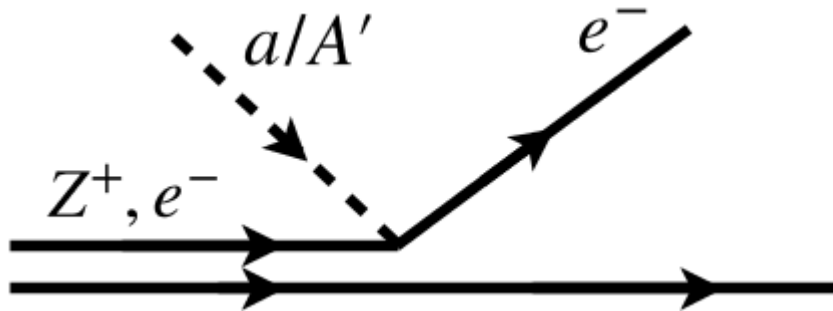


$$E_r \approx \frac{m_\chi^2}{2m_e} \quad m_\chi \sim \mathcal{O}(10) \text{ keV}$$

Dror, Elor, McGehee & Yu [2011.01940]

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

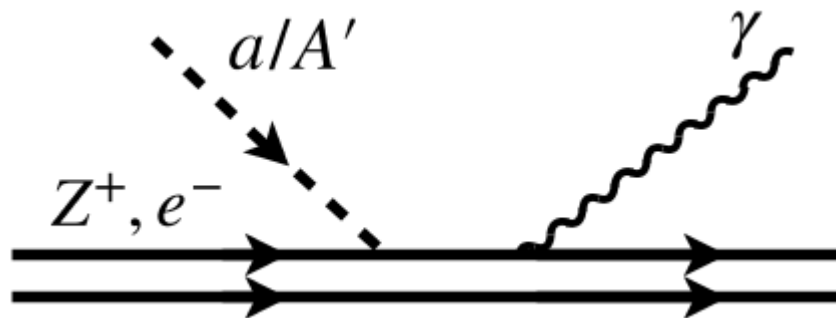
- Dark Photoelectric Effect



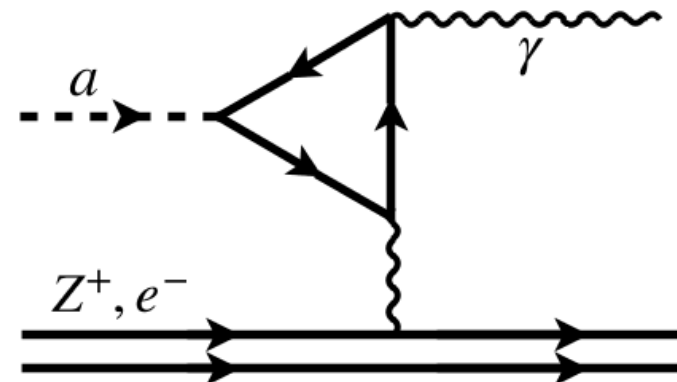
Pospelov, Ritz & Voloshin [0807.3279]

An, Pospelov, Pradler & Ritz [1412.8378]

- Dark Compton



- Inverse Primakoff



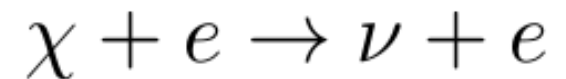
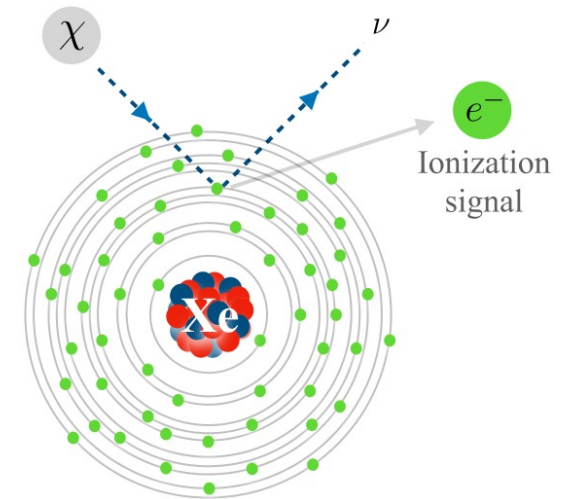
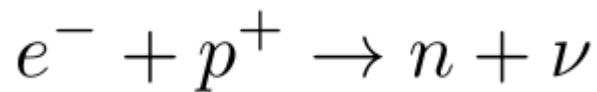
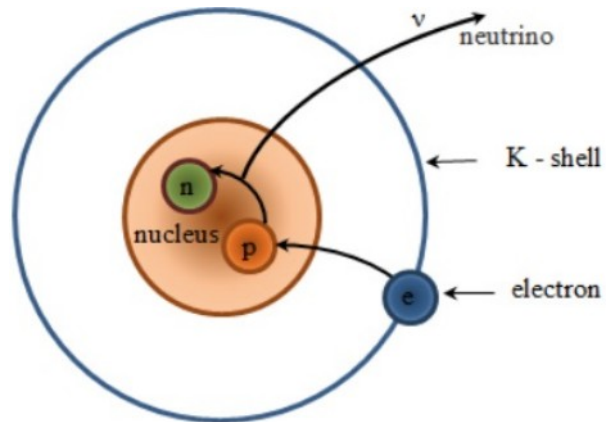
Hochberg, Krosigk, Kuflik & Yu [2109.08168]

# K-Shell Electron Capture for $\nu$



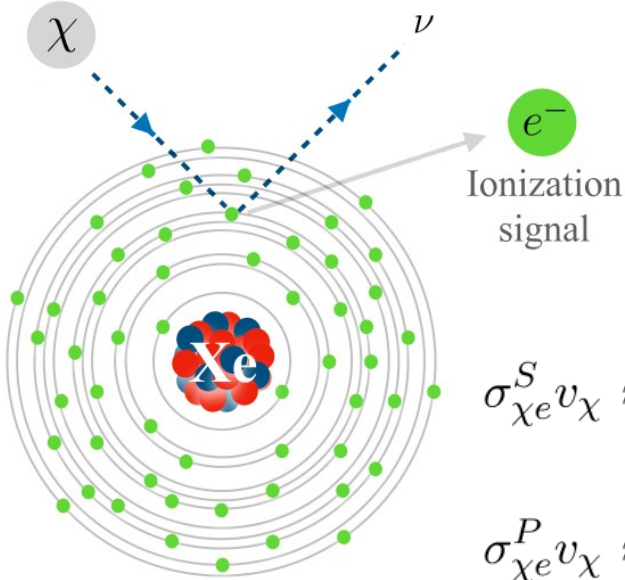
王淦昌

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



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

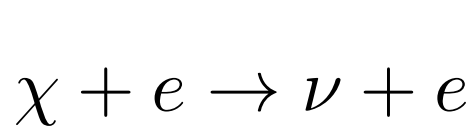
Kan Chang Wang, *Proposed Methods of Detecting the Neutrino*, Phys. Rev., 71, 645-646 (1947)



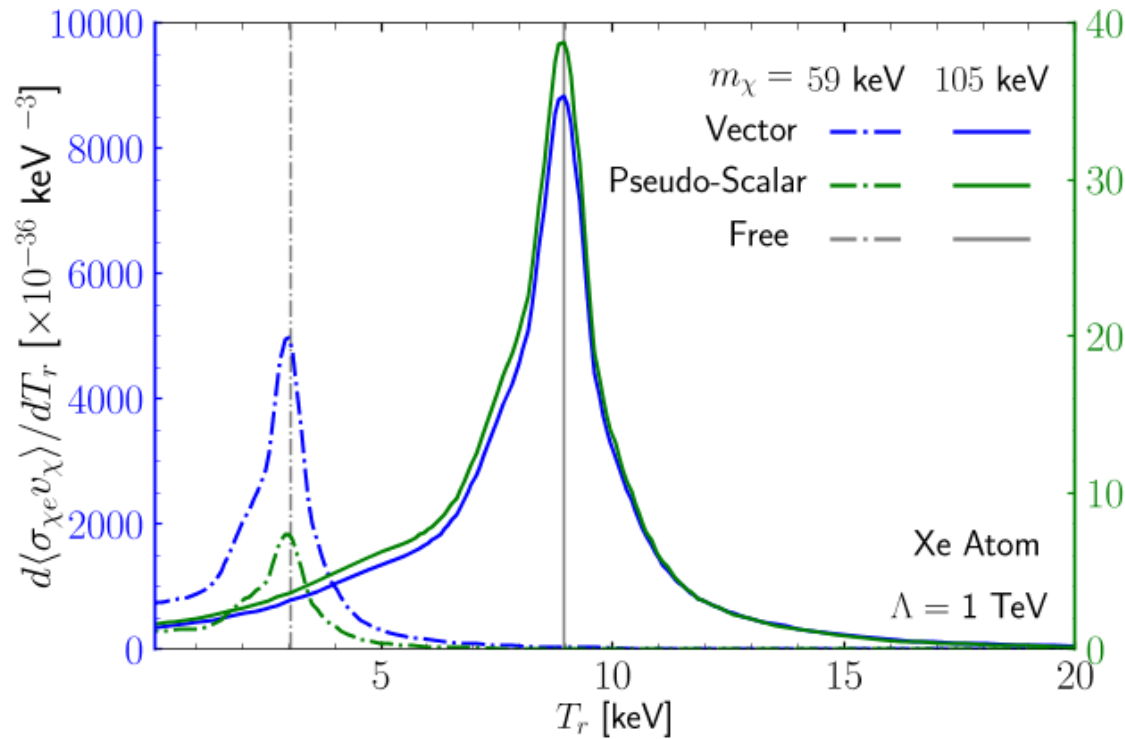
$$\begin{aligned} \mathcal{O}_{ev\chi}^S &\equiv (\bar{e}e)(\bar{\nu}_L\chi_R), \\ \mathcal{O}_{ev\chi}^P &\equiv (\bar{e}i\gamma_5e)(\bar{\nu}_L\chi_R), \\ \mathcal{O}_{ev\chi}^V &\equiv (\bar{e}\gamma_\mu e)(\bar{\nu}_L\gamma^\mu\chi_L), \\ \mathcal{O}_{ev\chi}^A &\equiv (\bar{e}\gamma_\mu\gamma_5e)(\bar{\nu}_L\gamma^\mu\chi_L), \\ \mathcal{O}_{ev\chi}^T &\equiv (\bar{e}\sigma_{\mu\nu}e)(\bar{\nu}_L\sigma^{\mu\nu}\chi_R), \\ \sigma_{\chi e}^S v_\chi &\approx \frac{1}{\Lambda^4} \frac{m_\chi^2(2m_e + m_\chi)^4}{64\pi(m_e + m_\chi)^4}, \\ \sigma_{\chi e}^P v_\chi &\approx \frac{1}{\Lambda^4} \frac{m_\chi^4(2m_e + m_\chi)^2}{64\pi(m_e + m_\chi)^4}, \\ \sigma_{\chi e}^V v_\chi &\approx \frac{1}{\Lambda^4} \frac{m_\chi^2(2m_e + m_\chi)^2(2m_e^2 + 4m_e m_\chi + 3m_\chi^2)}{32\pi(m_e + m_\chi)^4}, \\ \sigma_{\chi e}^A v_\chi &\approx \frac{1}{\Lambda^4} \frac{m_\chi^2(2m_e + m_\chi)^2(6m_e^2 + 8m_e m_\chi + 3m_\chi^2)}{32\pi(m_e + m_\chi)^4}, \\ \sigma_{\chi e}^T v_\chi &\approx \frac{1}{\Lambda^4} \frac{m_\chi^2(2m_e + m_\chi)^2(6m_e^2 + 10m_e m_\chi + 5m_\chi^2)}{8\pi(m_e + m_\chi)^4}. \end{aligned}$$

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

# Kinematics of Absorption DM



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



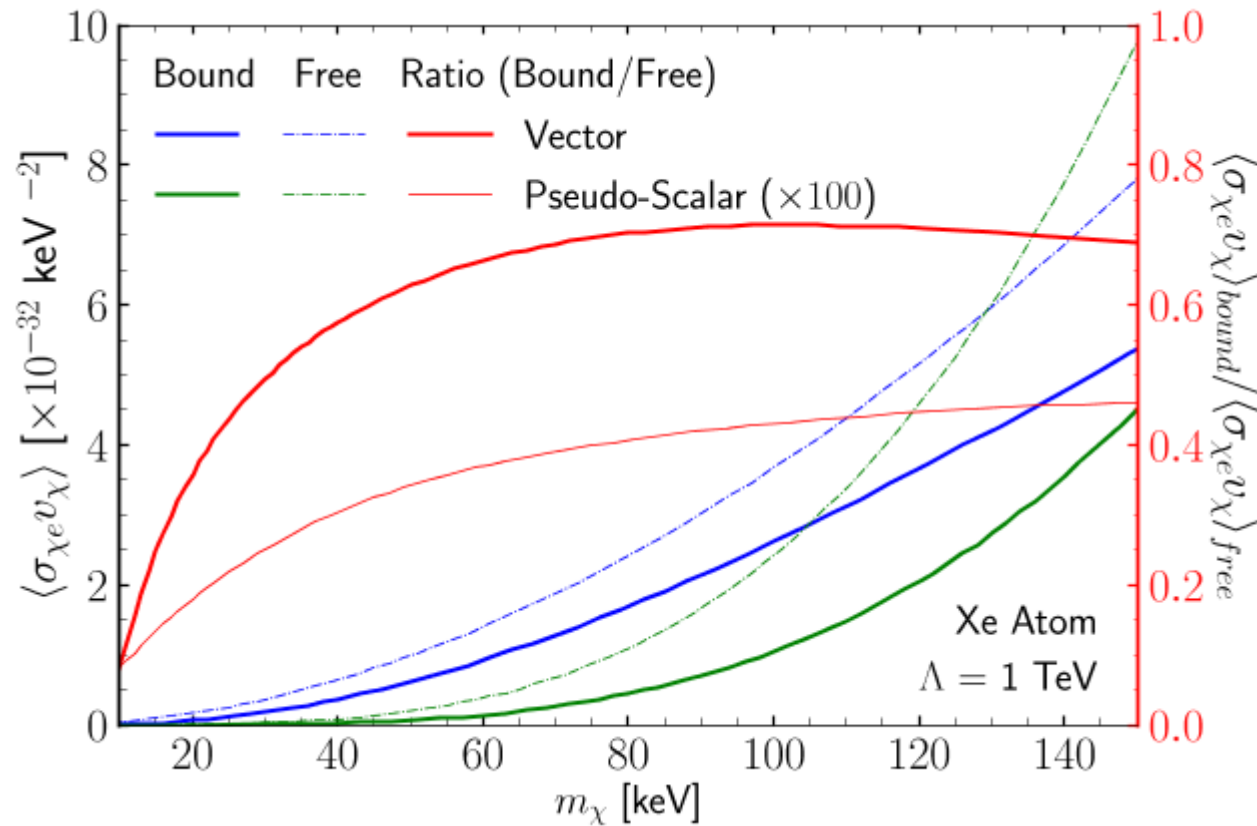
$$\frac{d\langle\sigma_{\chi e\nu\chi}\rangle}{dT_r} = \sum_{nl} (4l + 2) \frac{1}{T_r} \frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi} |\mathcal{M}|^2(\mathbf{q}) K_{nl}(T_r, |\mathbf{q}|),$$

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

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

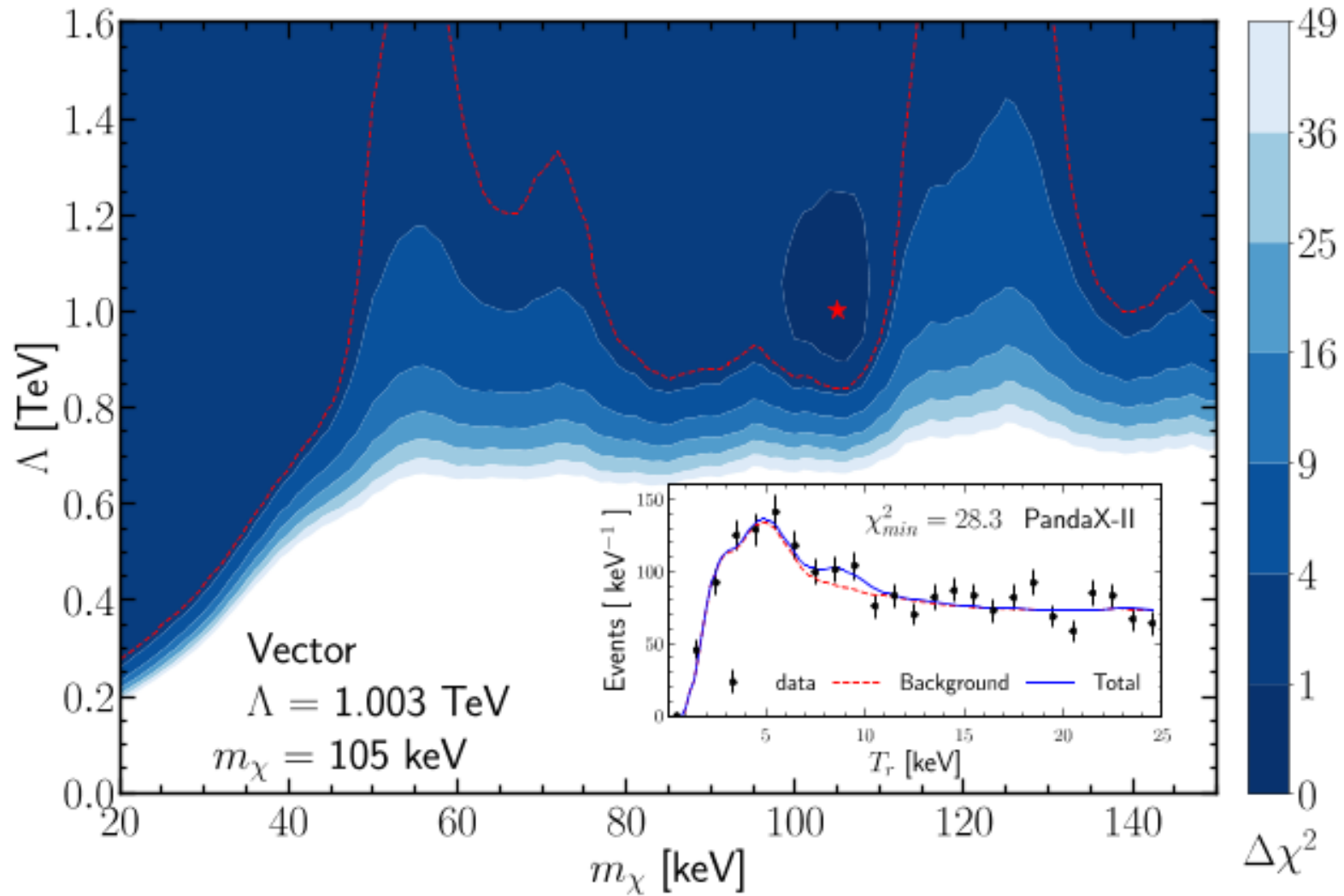


$$\chi + e \rightarrow \nu + e$$



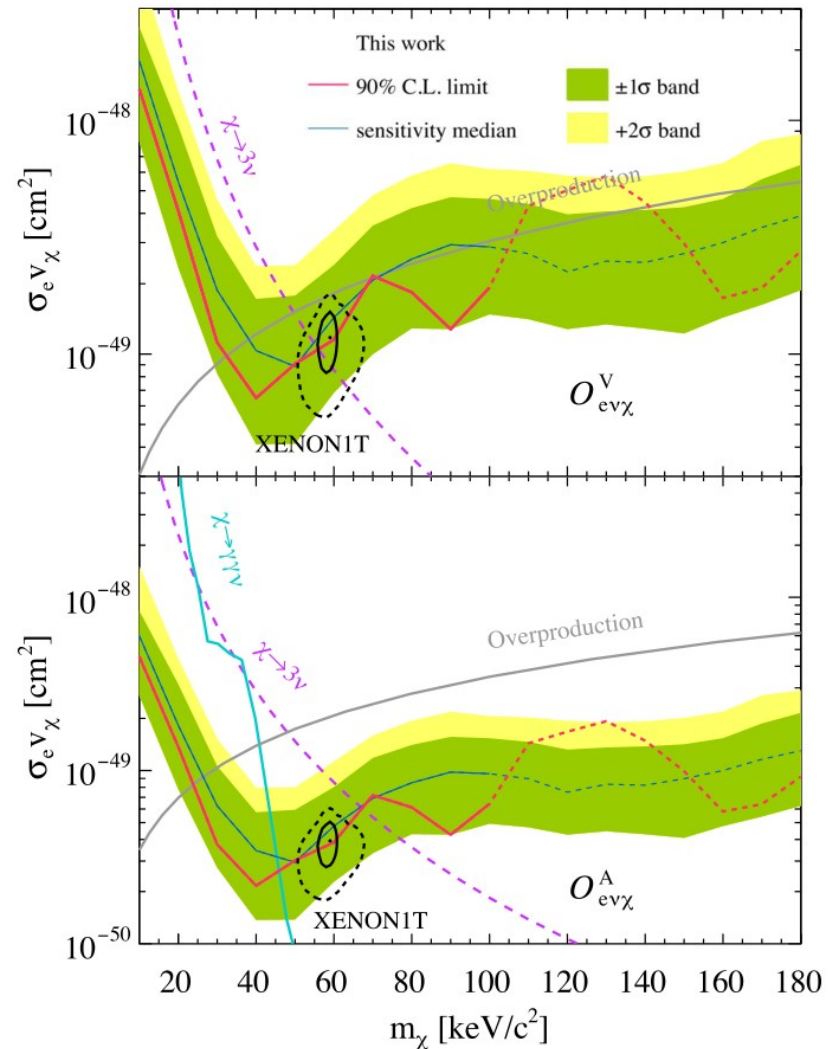
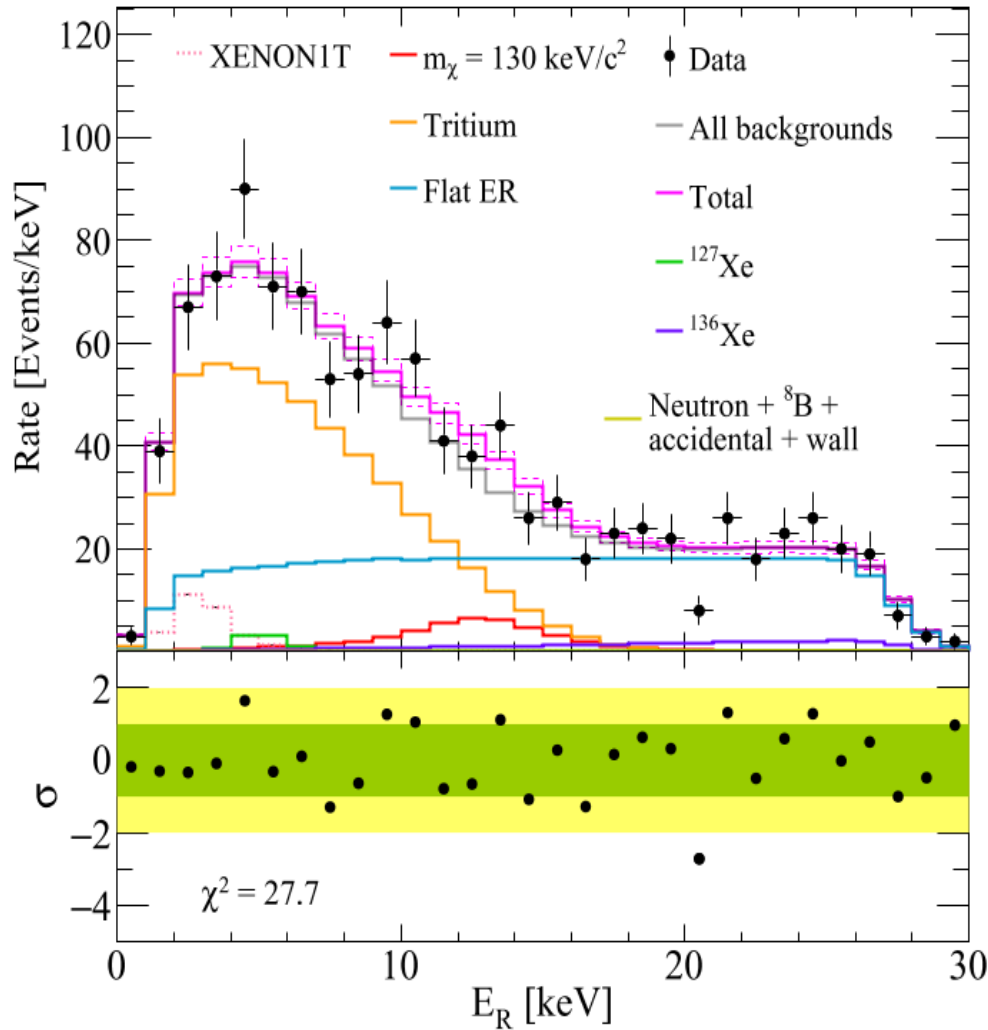
$$\frac{d\langle \sigma_{\chi e \nu \chi} \rangle}{dT_r} = \sum_{nl} (4l + 2) \frac{1}{T_r} \frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi} |\mathcal{M}|^2(\mathbf{q}) K_{nl}(T_r, |\mathbf{q}|),$$

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



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

# PandaX-4T Results



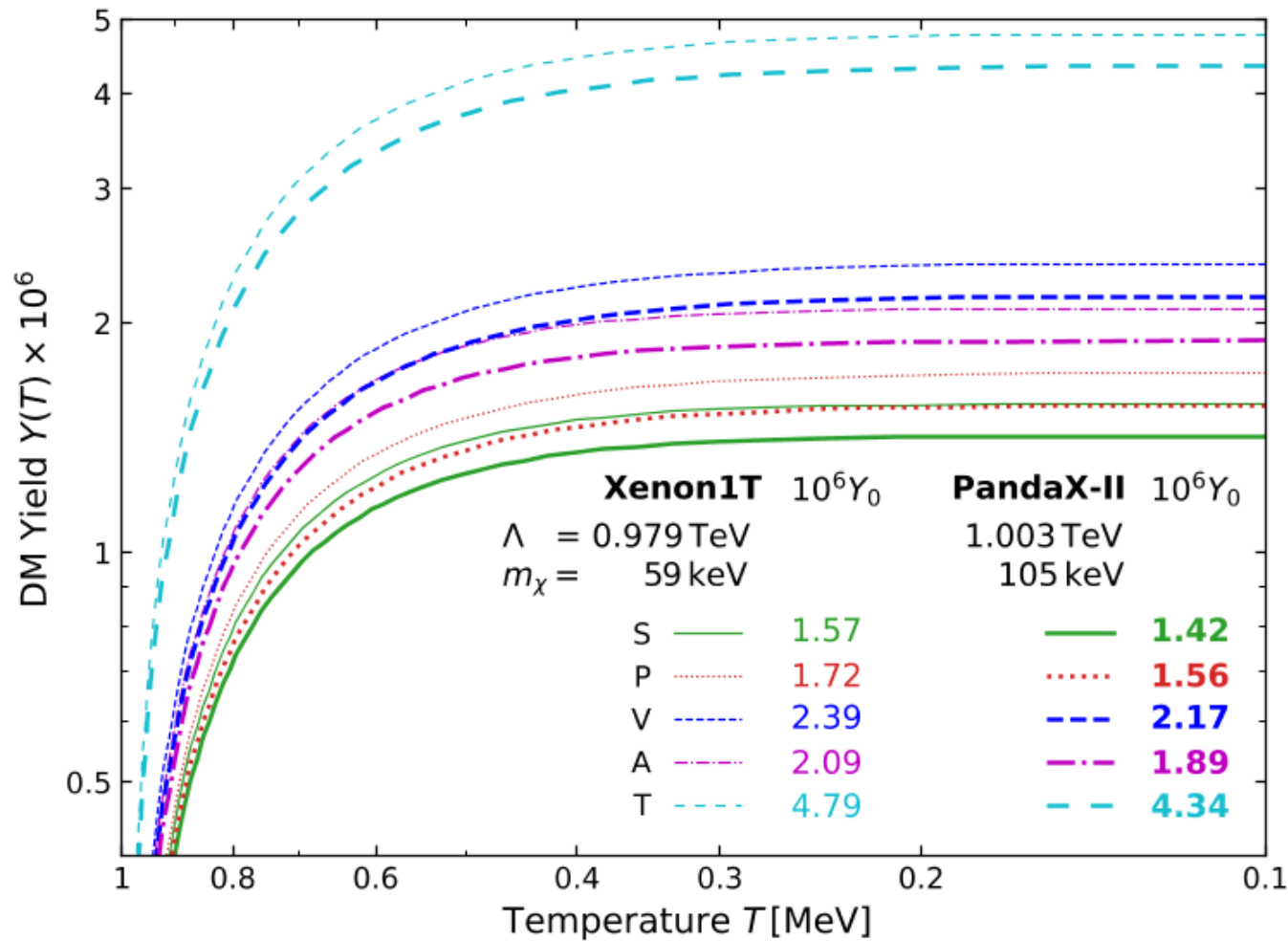
PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng, Phys.Rev.Lett. 129 (2022) 16, 161804 [2206.02339]

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

See Qiu-Hong's  
talk tomorrow

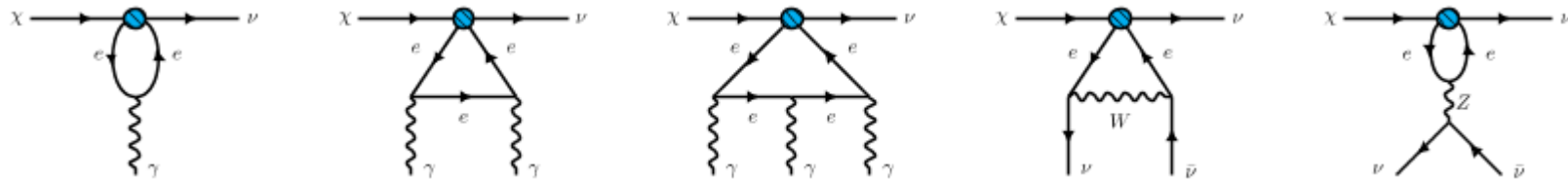
# Overproduction of Absorption DM

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



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

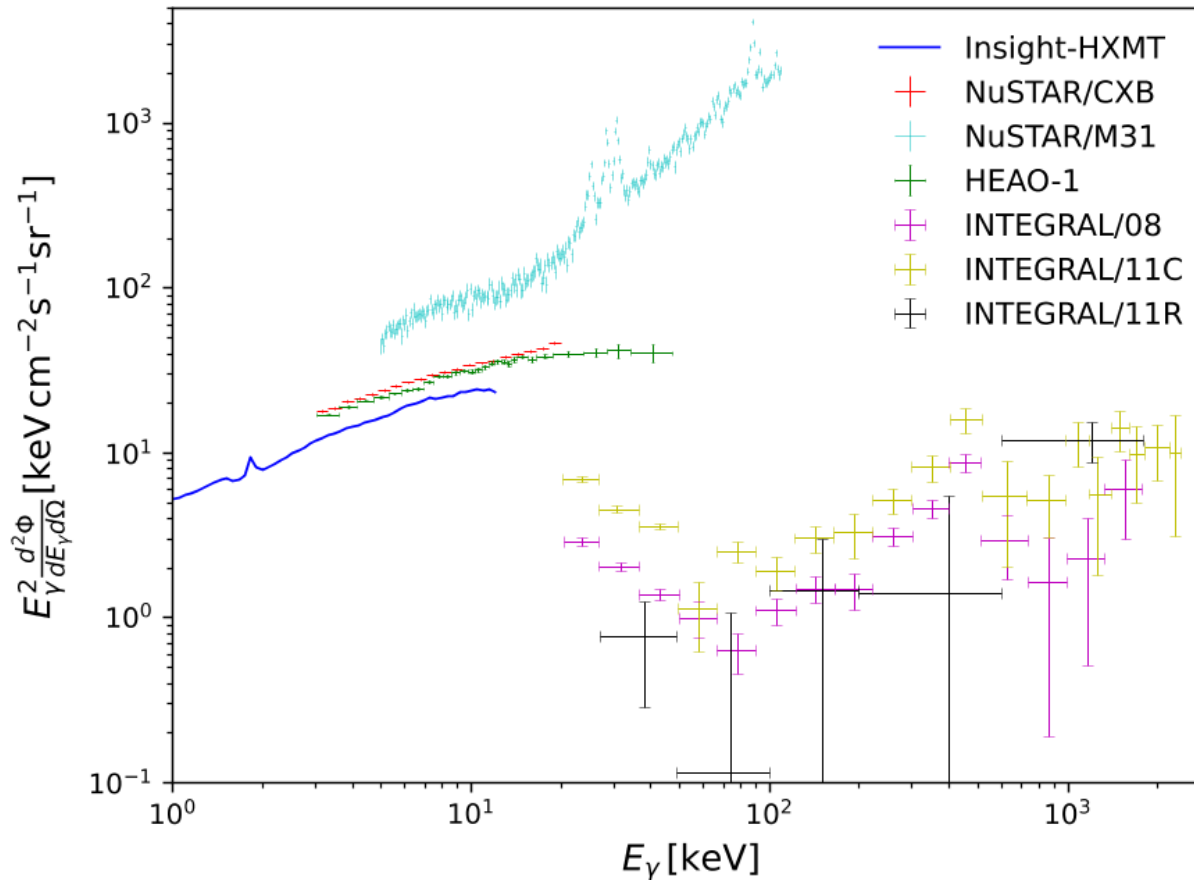
# Visible & Invisible Decays



Operator	Process	$\chi \rightarrow \nu\gamma$	$\chi \rightarrow \nu\gamma\gamma$	$\chi \rightarrow \nu\gamma\gamma\gamma$	$\chi \rightarrow 3\nu$
	S: $\mathcal{O}_{e\nu\chi}^S$		×	✓	×
P: $\mathcal{O}_{e\nu\chi}^P$		×	✓	×	×
V: $\mathcal{O}_{e\nu\chi}^V$		×	×	✓	✓
A: $\mathcal{O}_{e\nu\chi}^A$		×	✓	×	✓
T: $\mathcal{O}_{e\nu\chi}^T$		✓	×	×!	×!

Dror, Elor, McGehee & Yu [2011.01940]

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



## ● Galactic

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

## ● Extra-Galactic

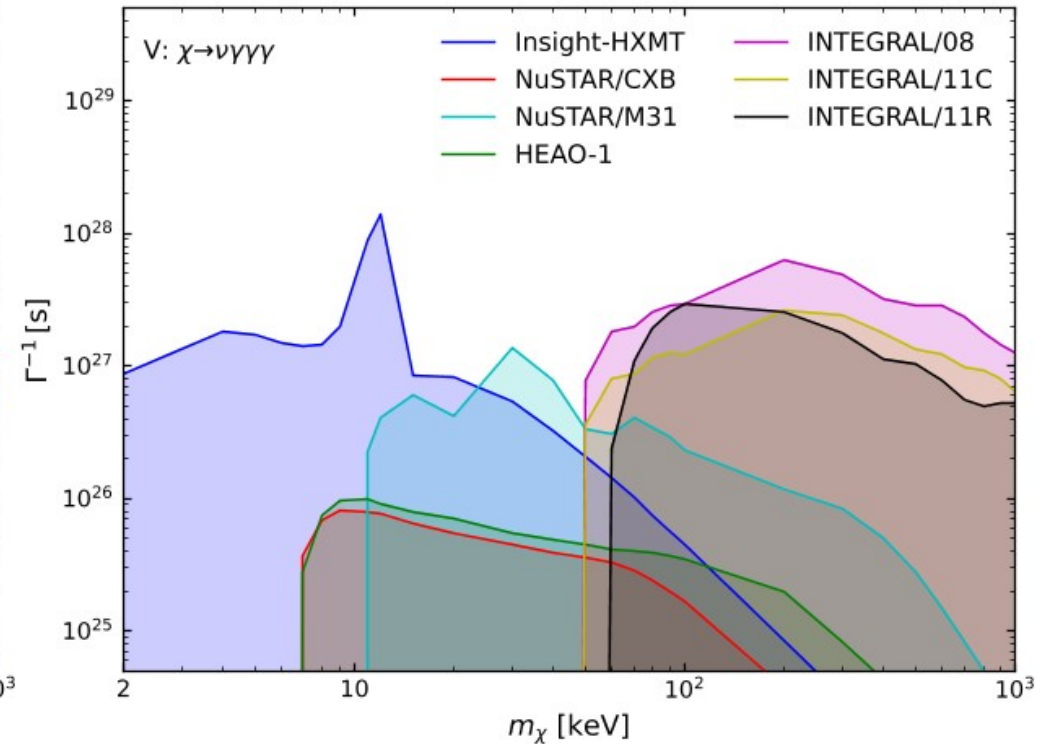
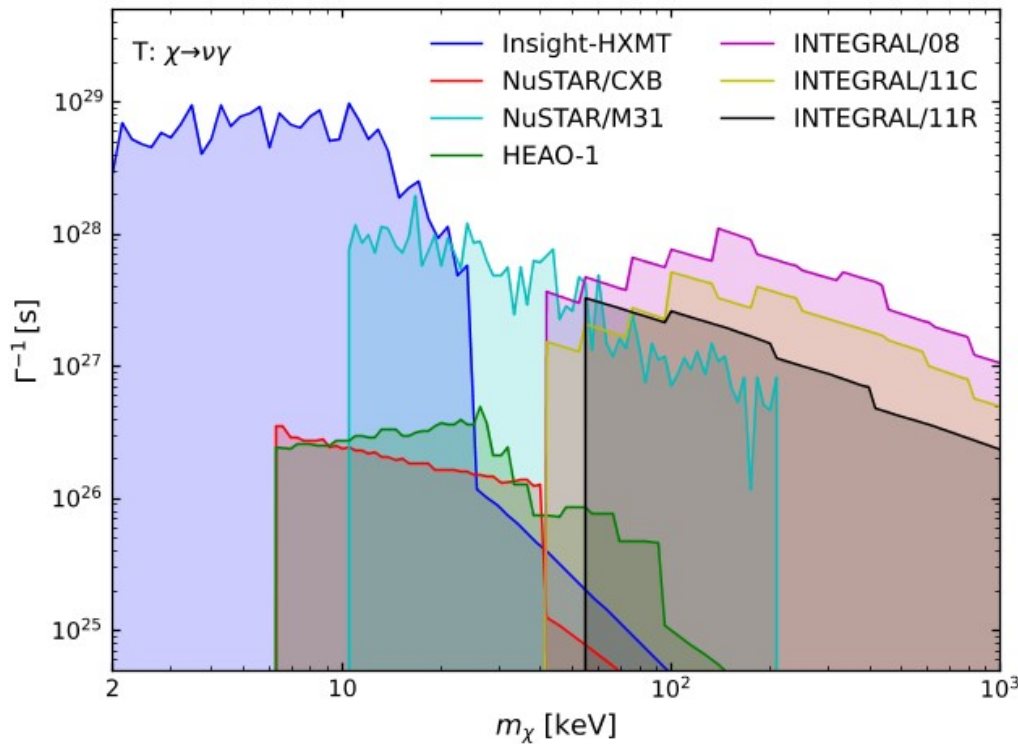
$$\frac{d^2\Phi_r^{\text{EG}}}{dE_\gamma d\Omega} = \frac{\Omega_{\text{DM}} \rho_c}{4\pi m_\chi H_0 \sqrt{\Omega_m}} \int_0^\infty \frac{d\Gamma_\chi}{dE_\gamma(z)} \frac{dz}{\sqrt{\kappa + (1+z)^3}}$$

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

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

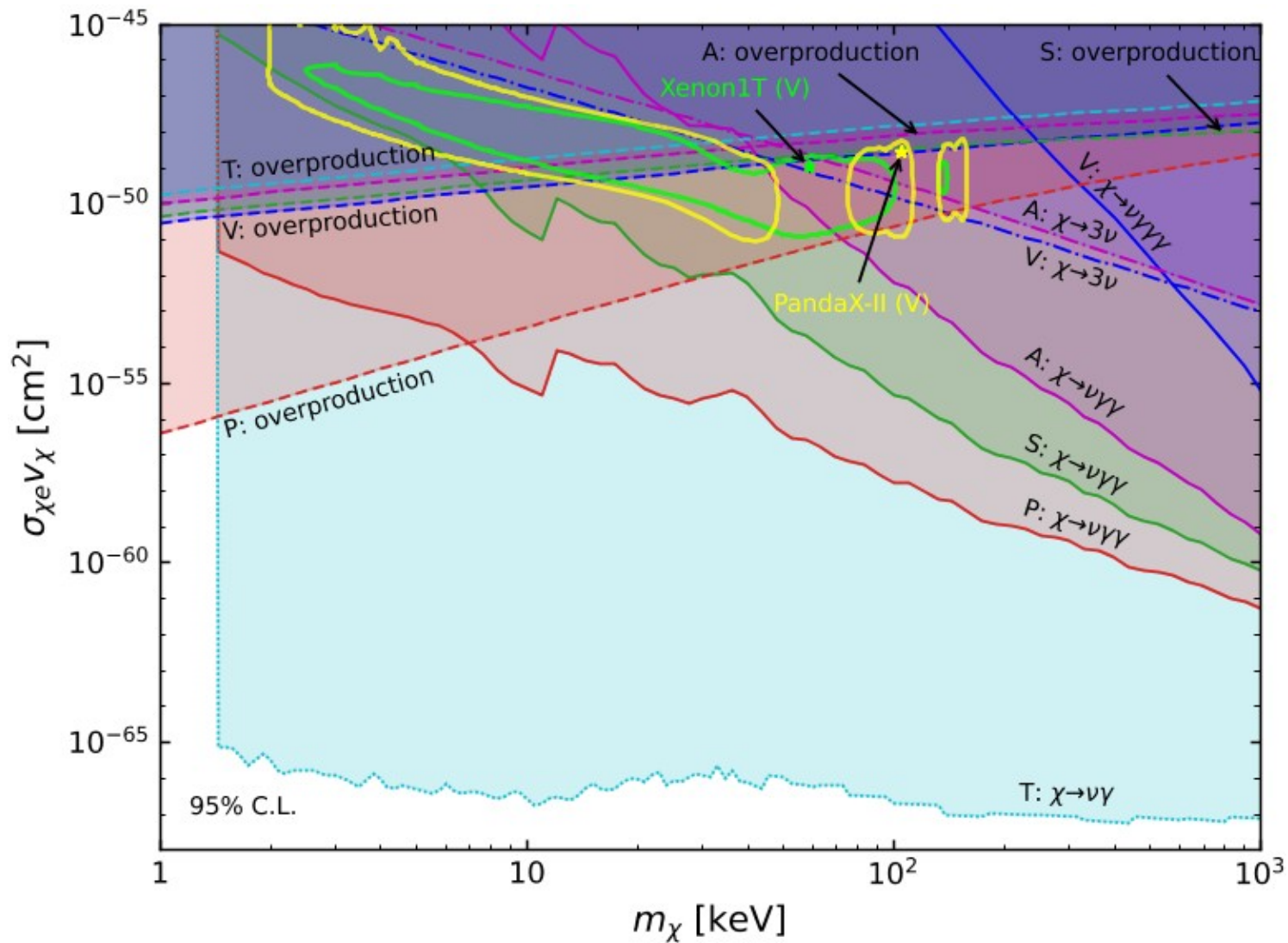
## • Mono-energetic $\gamma$

## • Continuous Spectrum



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

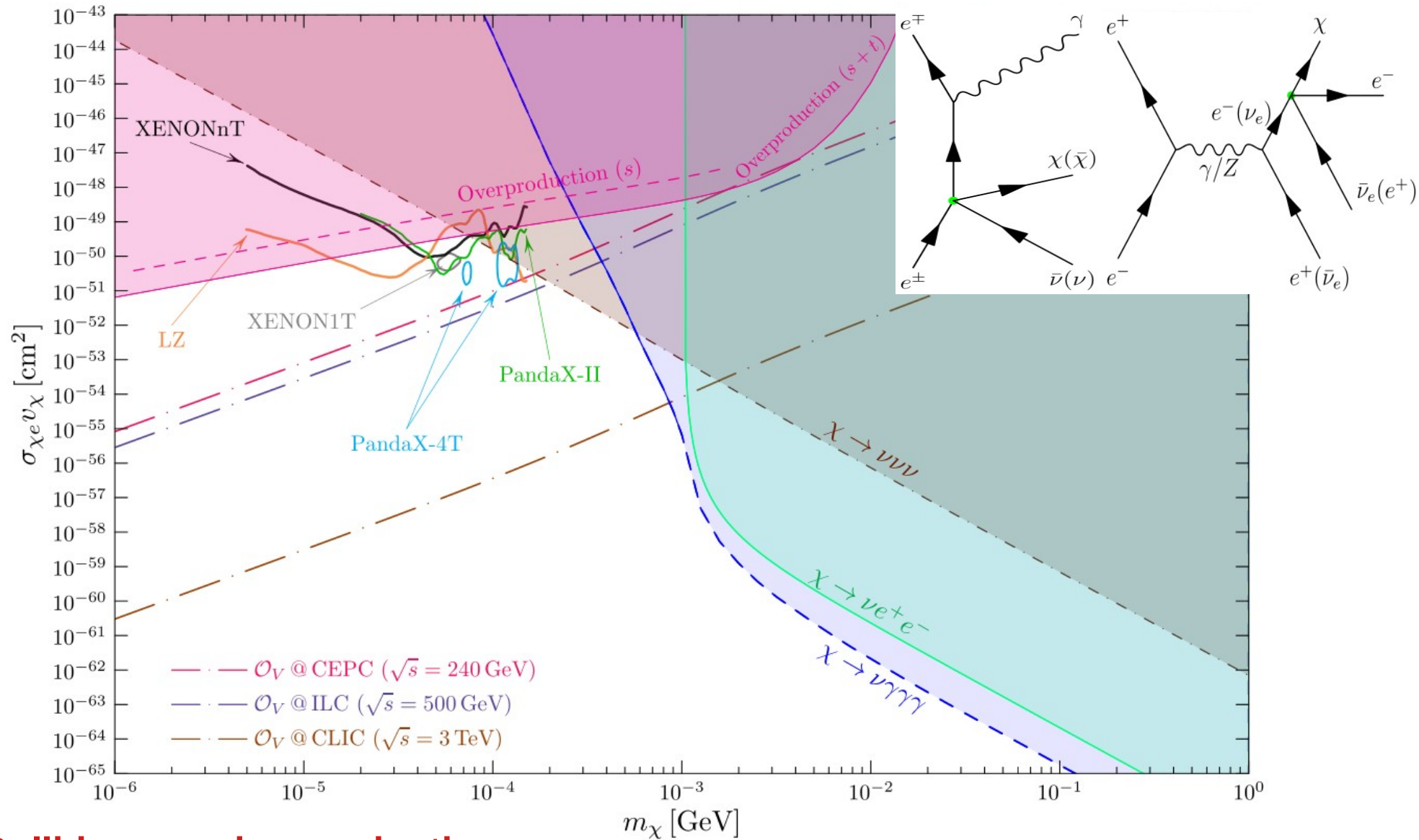
# Constraints from Astro & Cosmo



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



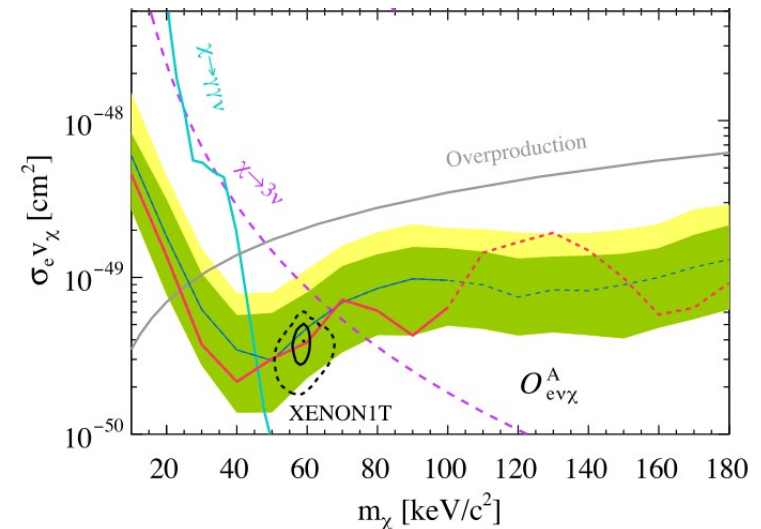
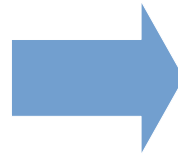
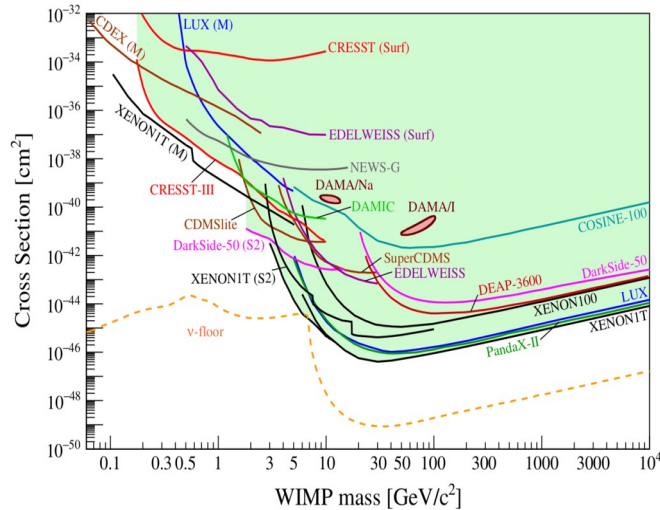
# PandaX-4T & Lepton Colliders



**Collider searches probe the dark sector, not just DM**

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

## 1) Extension to O(10)keV mass range

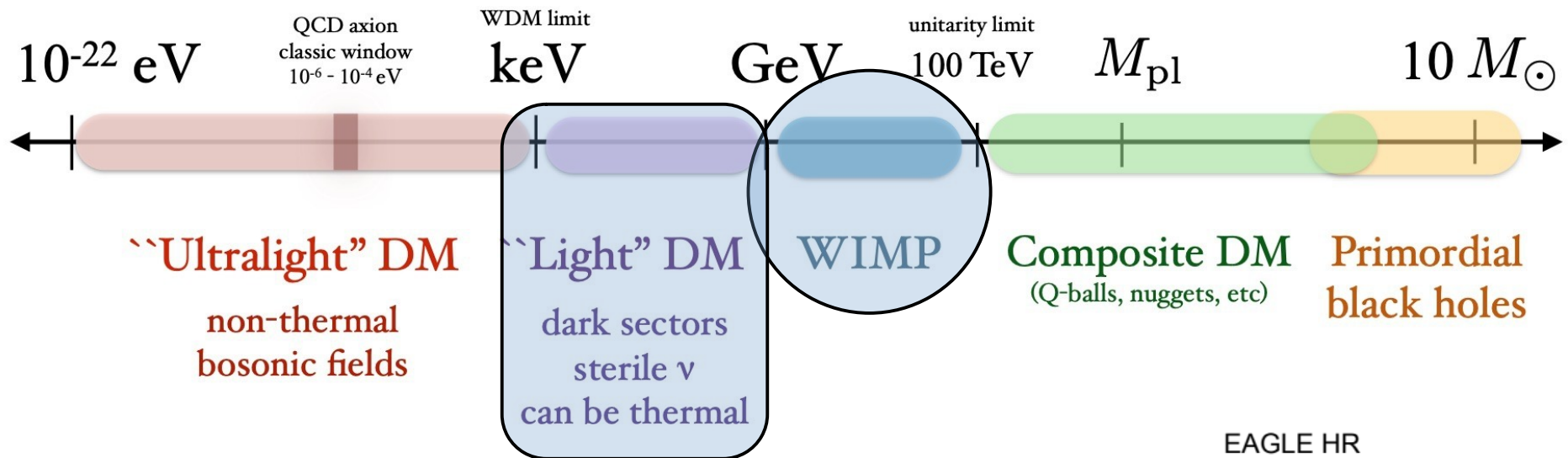


- 2) Atomic effects should be treated more exactly
- 3) Decaying DM with astro/cosmo constraints
- 4) Complementary searches @ collider
- 5) Active-Sterile conversion

# Thank You

# Backup Slides

# Mass Span of DM

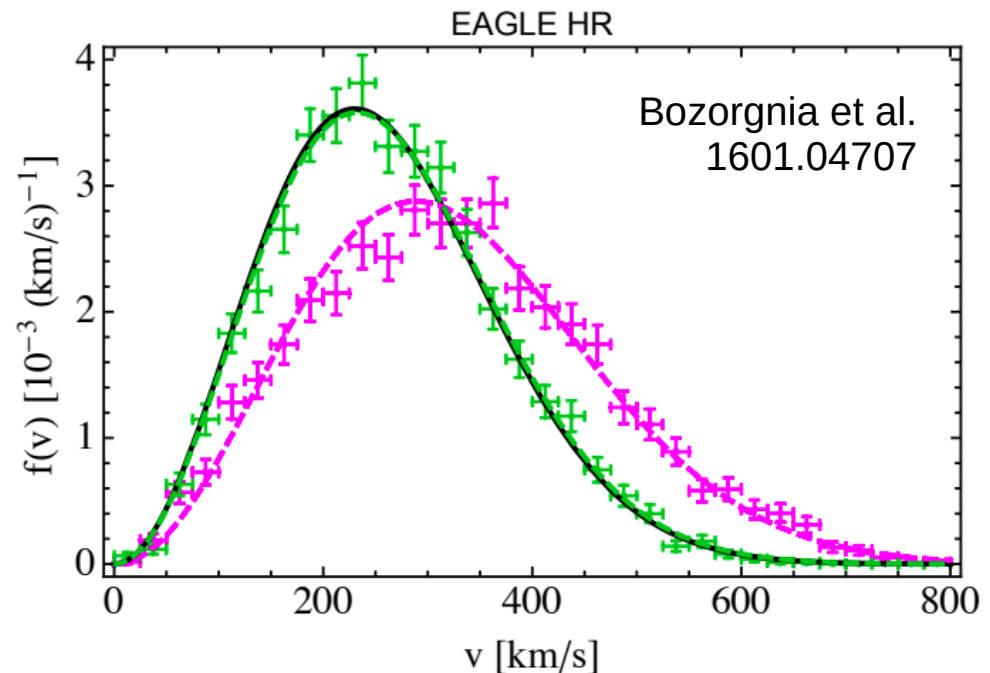


?

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

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

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



## 1) Lowering the threshold

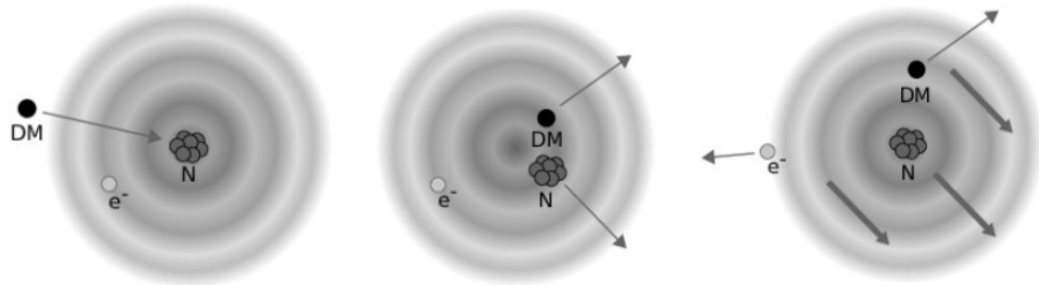
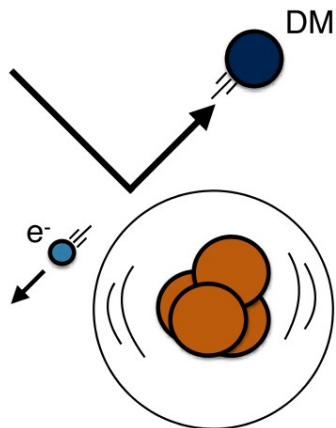
**Bolometer** [1904.00498, Ann.Rev.Nucl.Part.Sci. 67 (2017) 161-181]

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



**Migdal effect** [Ibe et al [1707.07258]]

## 2) Electron target



## 3) Boosting detector?

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

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

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

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

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

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

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

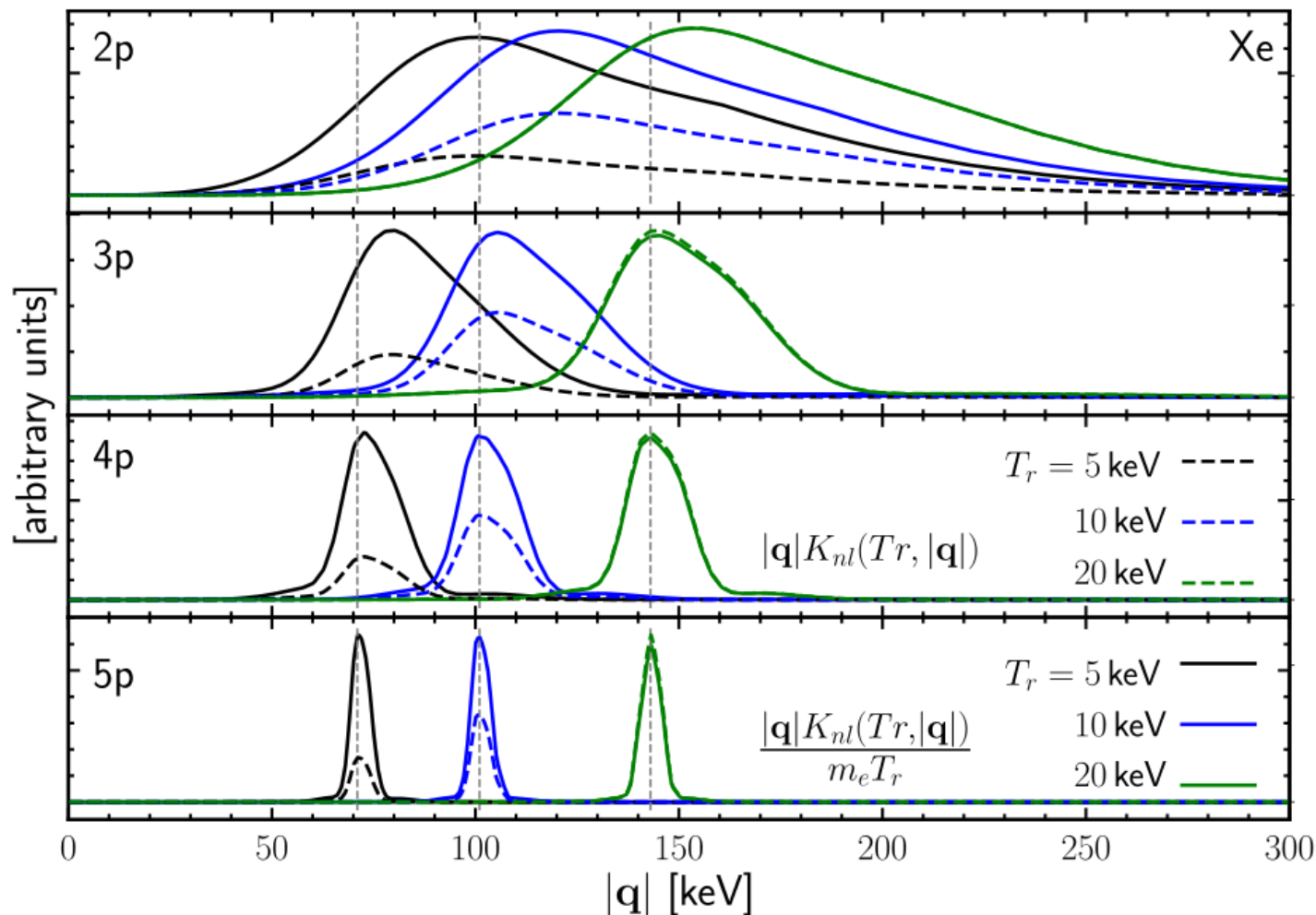
$$A_e^S \equiv \frac{\bar{u}(m_e) u(m_e)}{2m_e} \int d^3 \mathbf{y} e^{i\mathbf{q} \cdot \mathbf{y}} \phi_{T_r l' m'}^*(\mathbf{y}) \phi_{nlm}(\mathbf{y})$$

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

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

# Atomic Effect with 2<sup>nd</sup> Quantization

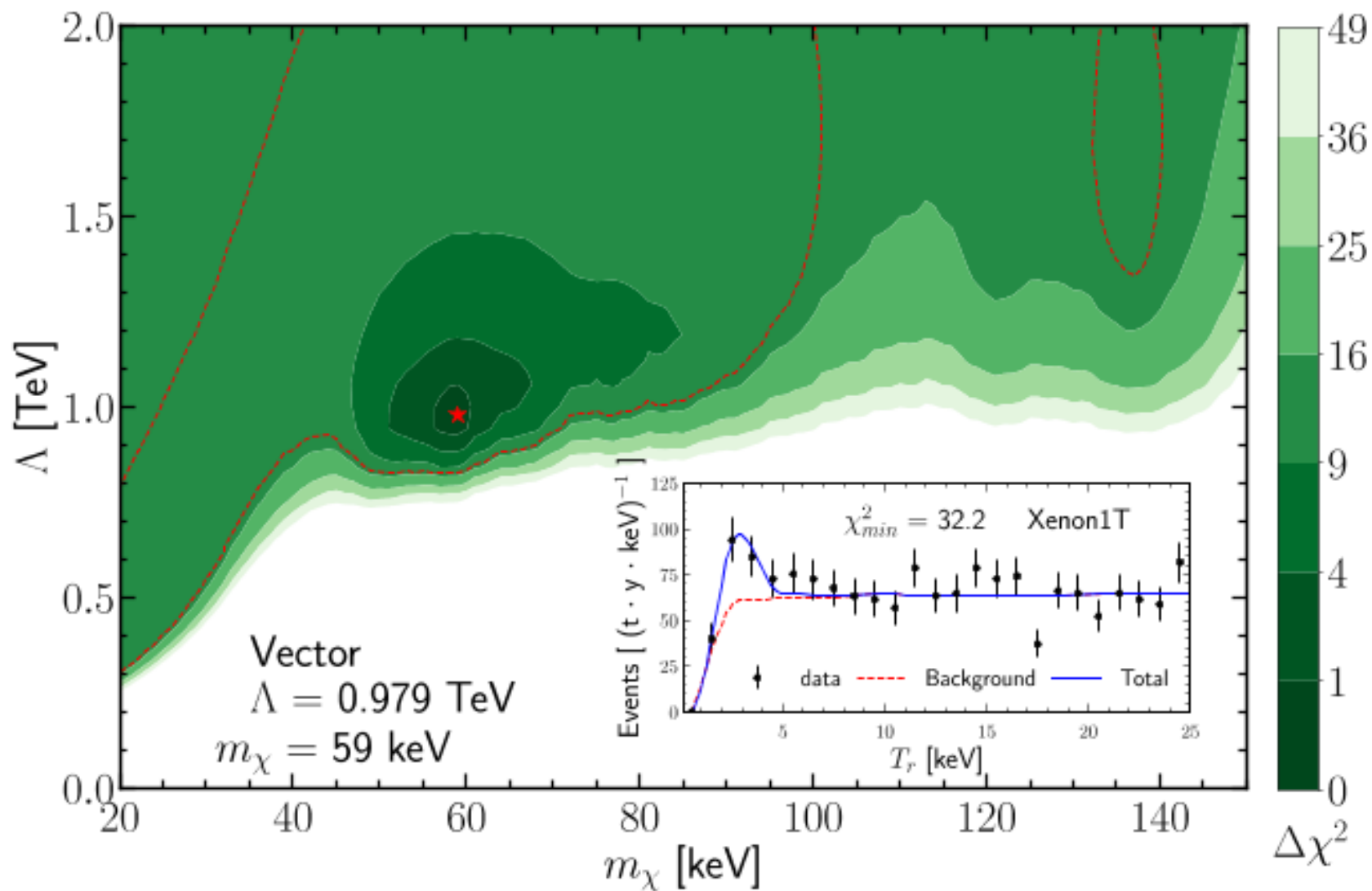
$$\frac{d\langle\sigma_{Xe}v_{\chi}\rangle}{dT_r} = \sum_{nl} (4l + 2) \frac{1}{T_r} \frac{m_{\chi} - \Delta E_{nl}}{16\pi m_e^2 m_{\chi}} |\mathcal{M}|^2(\mathbf{q}) K_{nl}(T_r, |\mathbf{q}|),$$



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

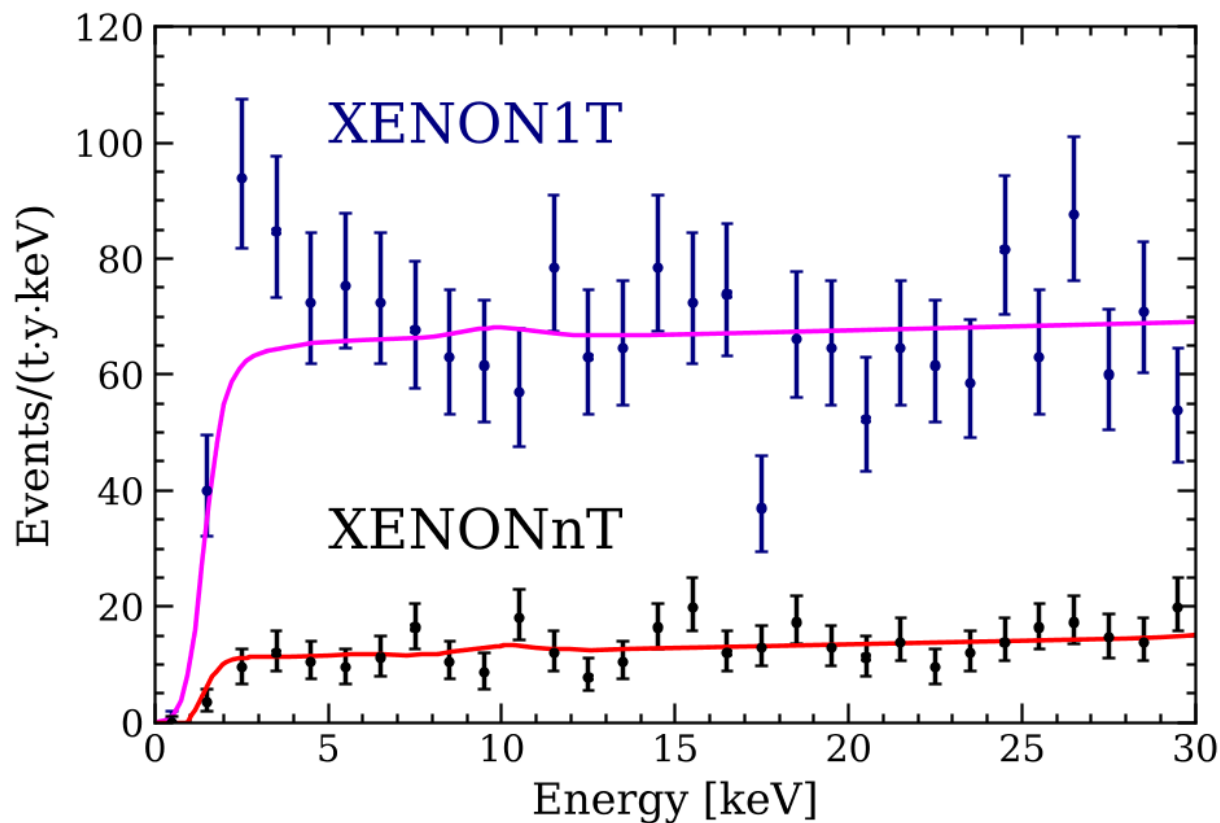
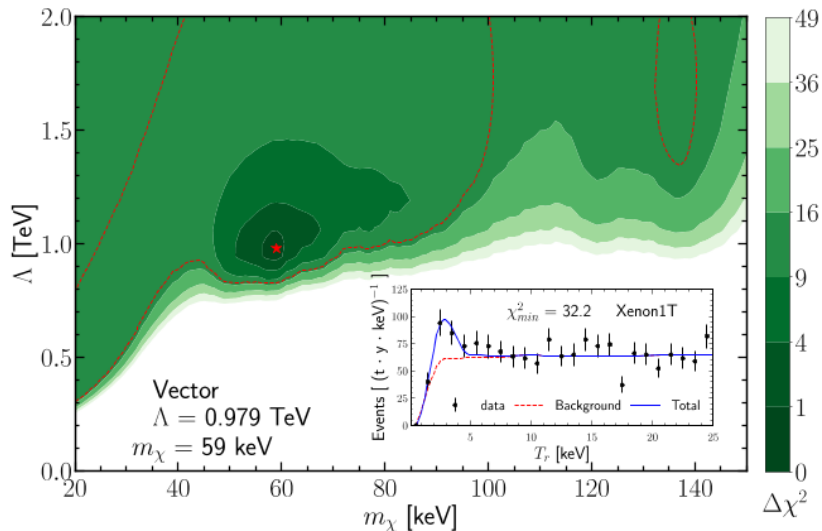


# Xenon1T Excess



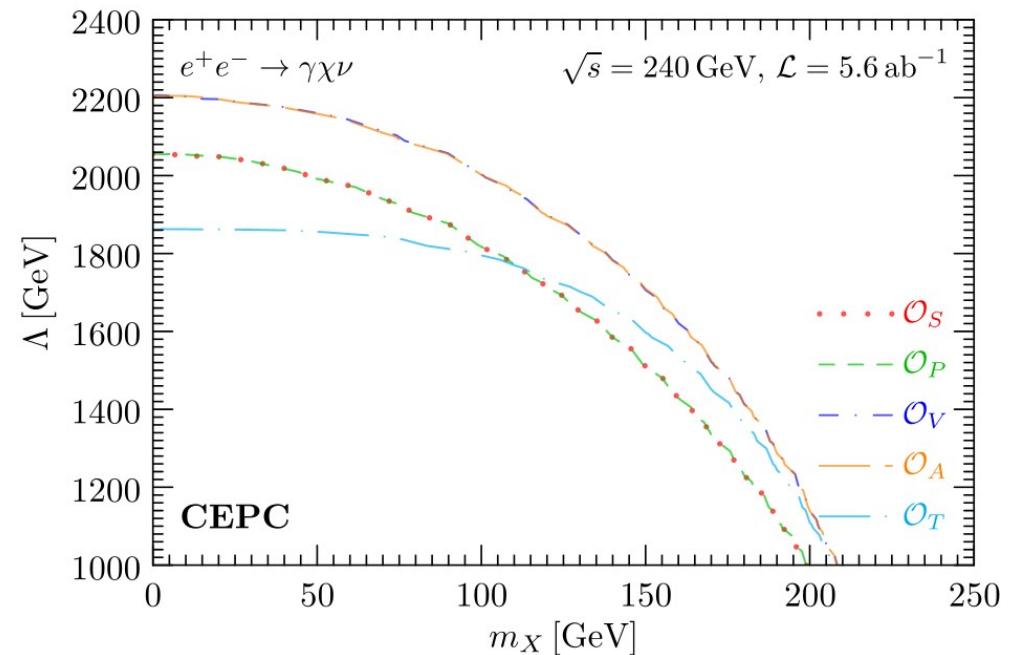
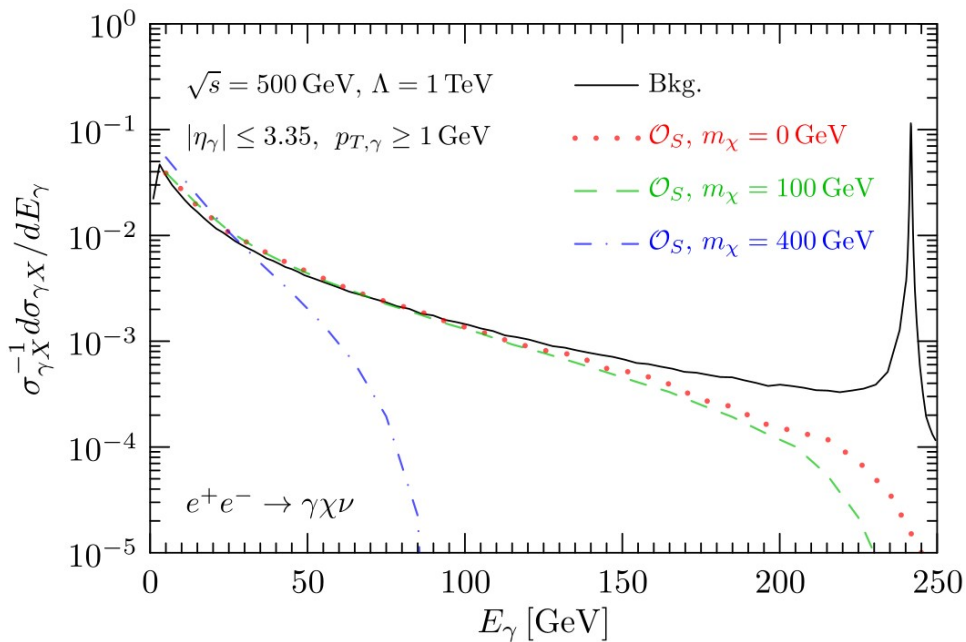
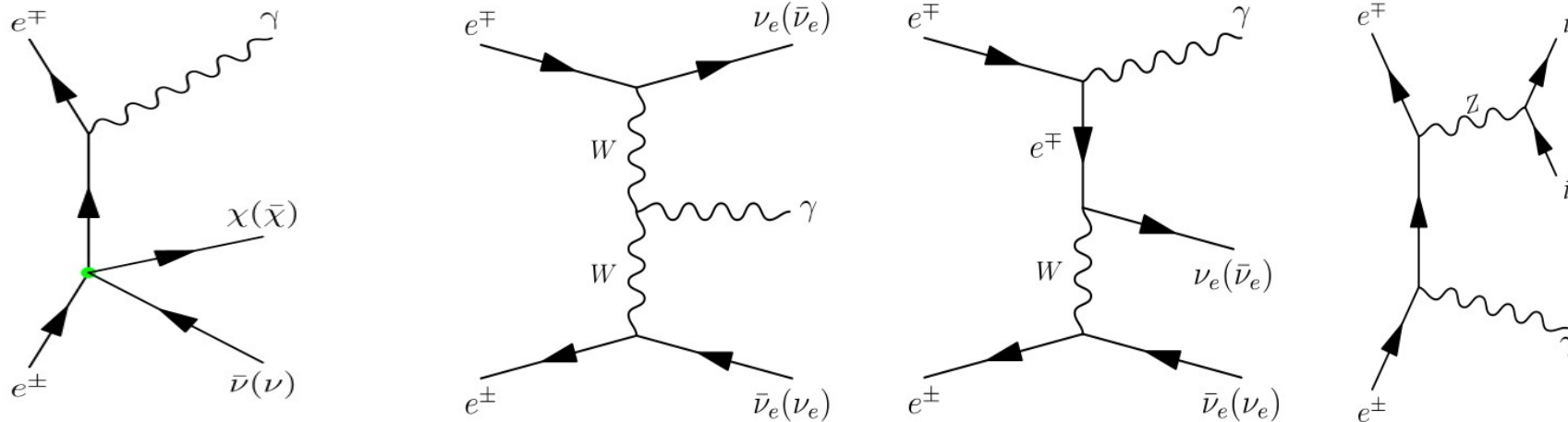
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

# Xenon1T Excess



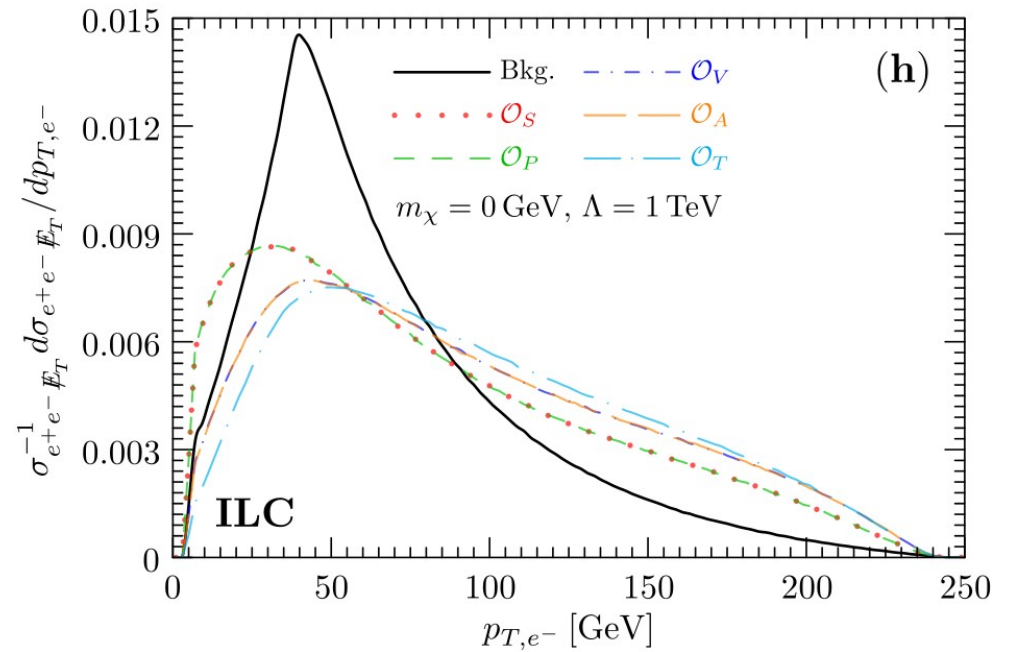
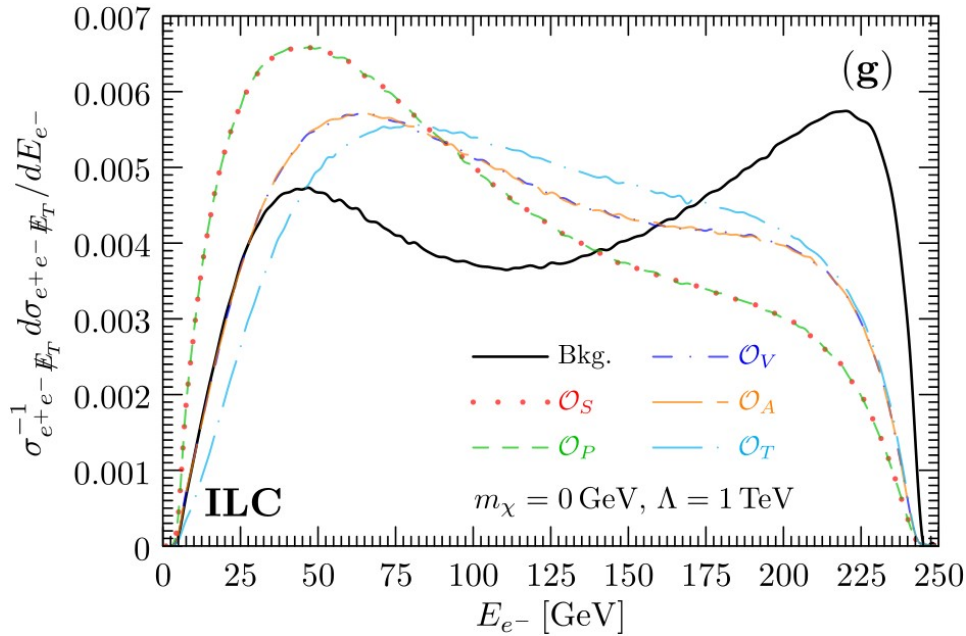
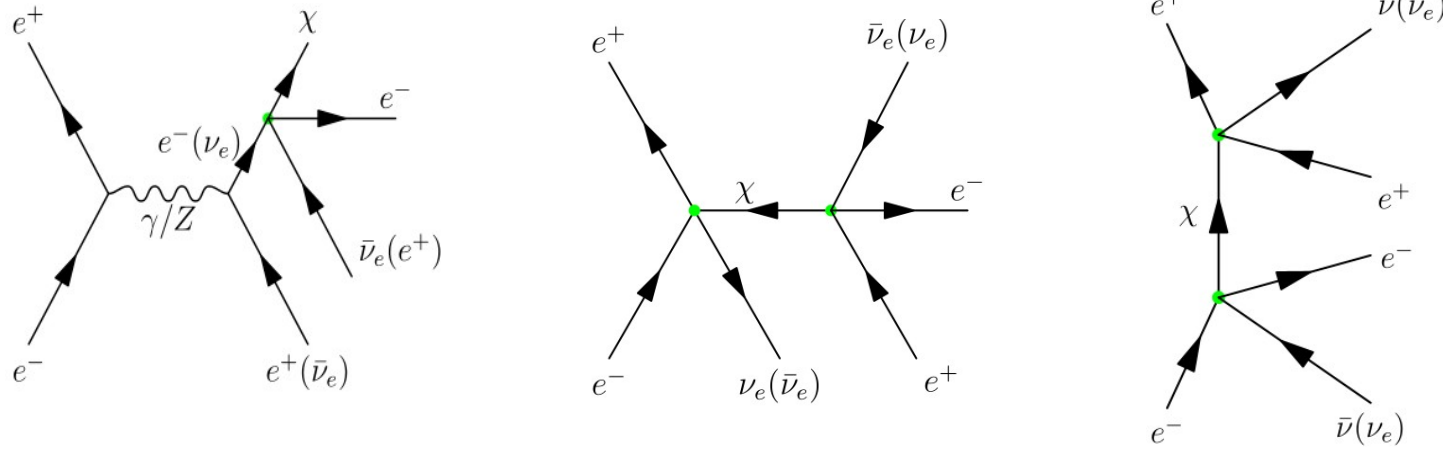
Knut Dundas Morå @ IDM2022  
XENONnT, Phys.Rev.Lett. 129 (2022) 16, 161805 [2207.11330]

# Mono-Photon @ Lepton Collider



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

# $e^+e^-$ Pair + Missing Energy

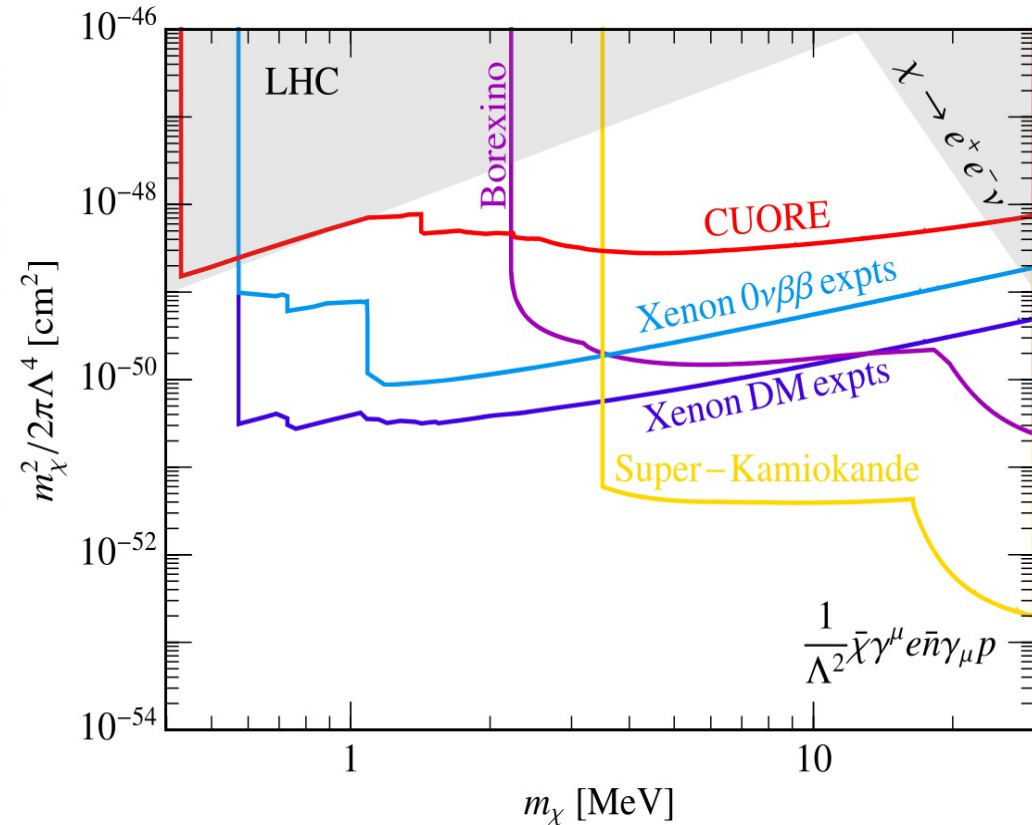
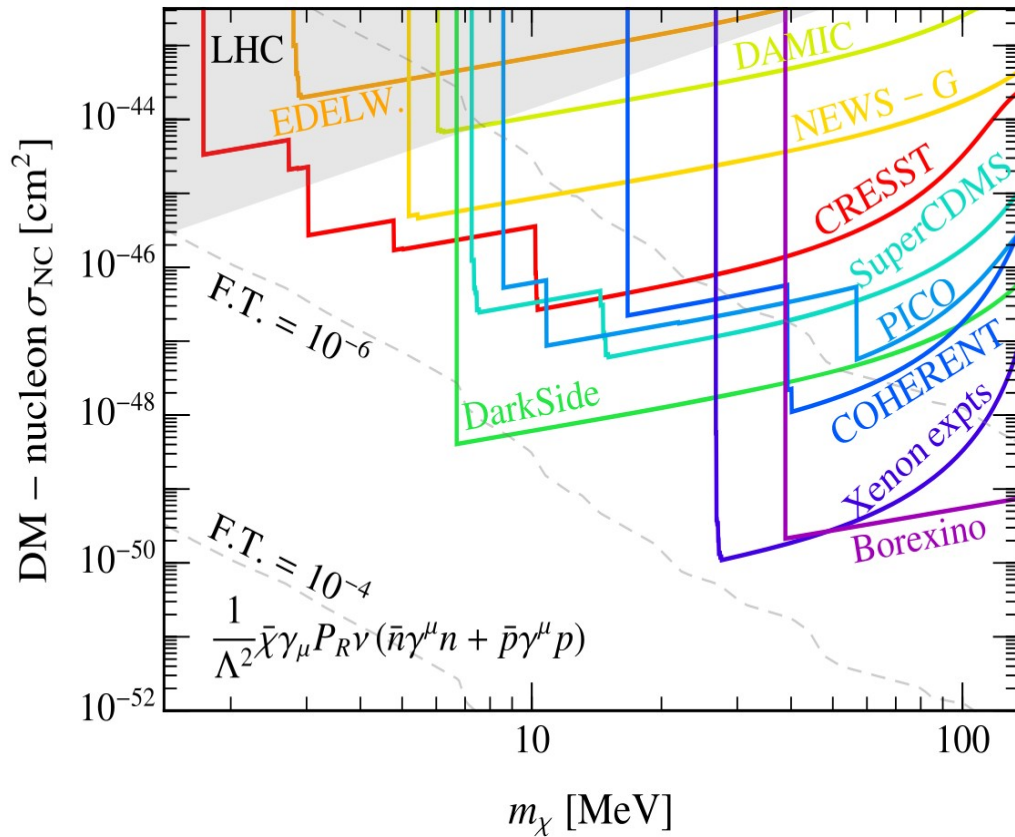


SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [JHEP 11 (2023) 190]

# DM Absorption by Nuclei

$$\chi + N \rightarrow \nu + N$$

$$\chi + N \rightarrow e + N'$$

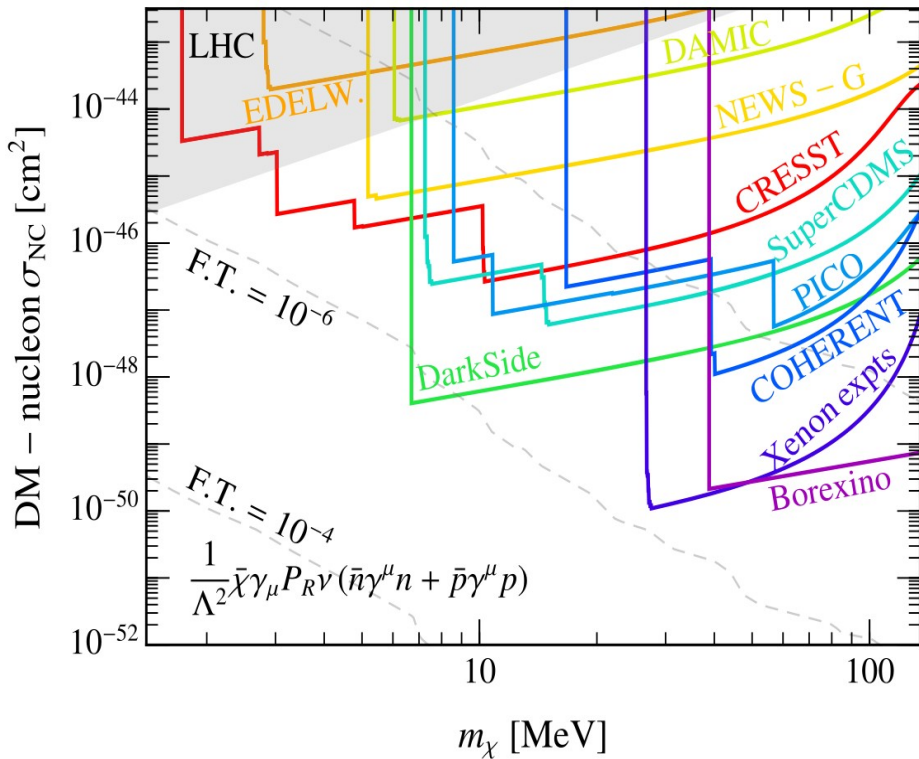


Jeff A. Dror, Gilly Elor, and Robert McGehee [Phys.Rev.Lett. 124 (2020) 18, 18]

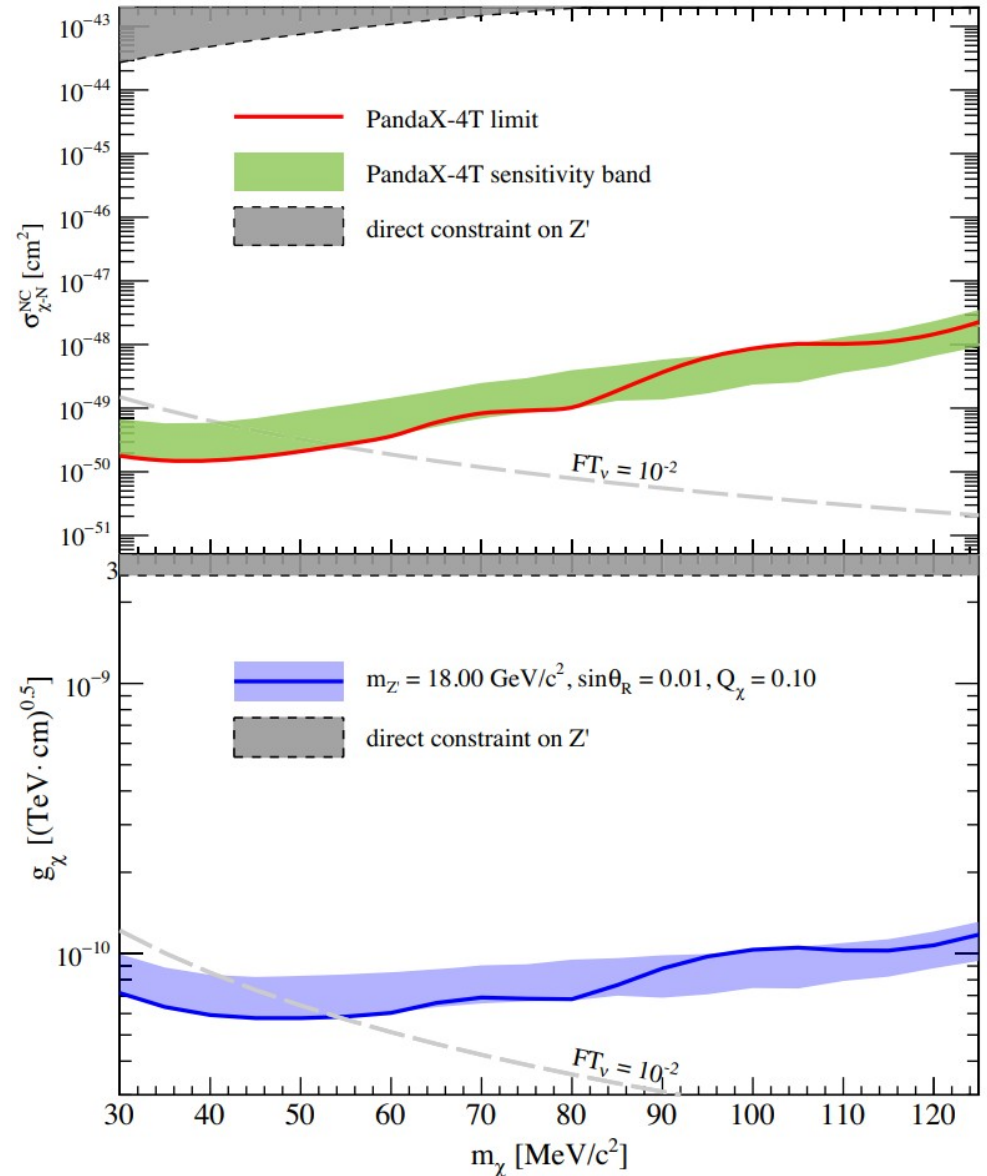
Jeff A. Dror, Gilly Elor, and Robert McGehee [JHEP 02 (2020) 134]

# DM Absorption @ PandaX

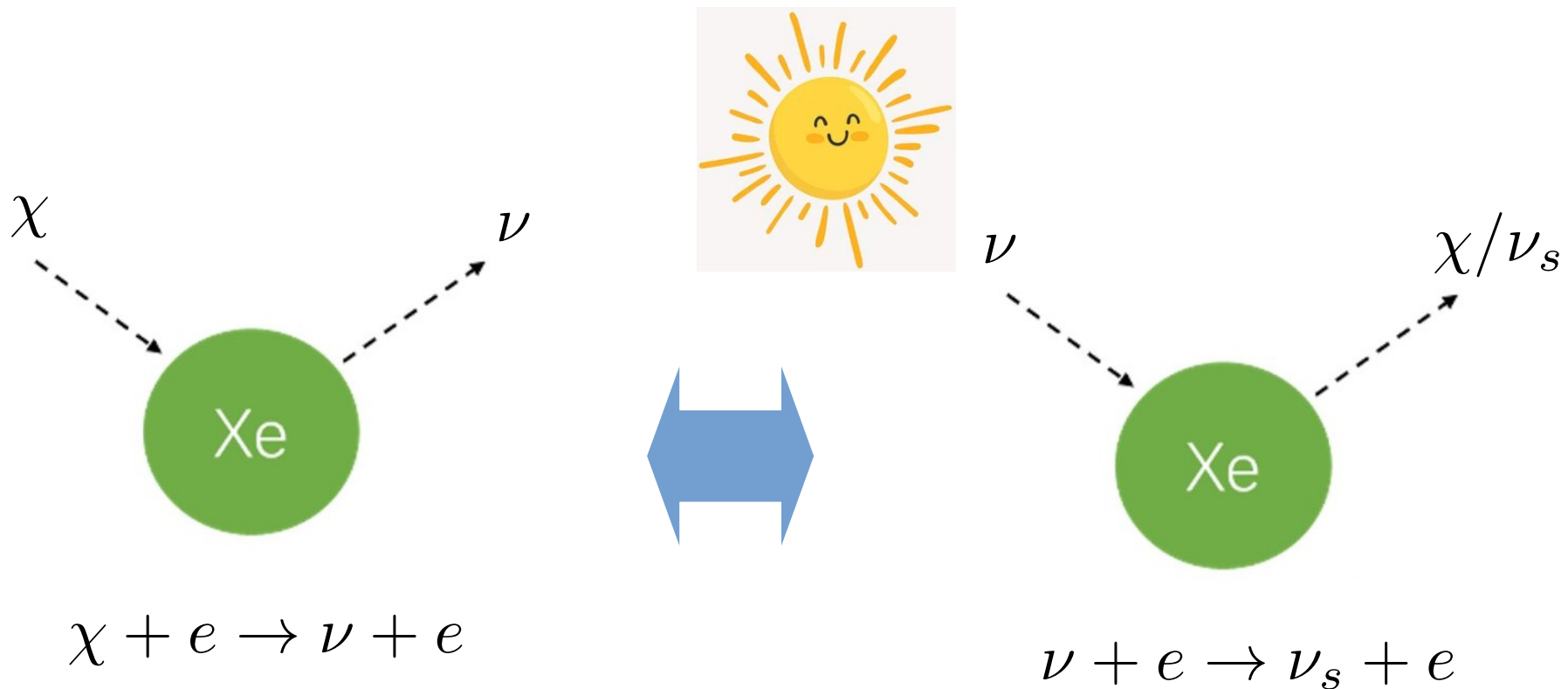
$$\chi + N \rightarrow \nu + N$$



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



# Active-Sterile Neutrino Conversion

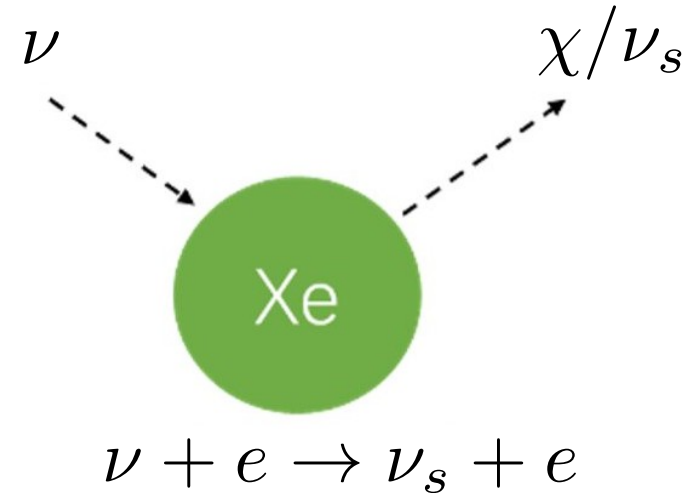


SFG, Pedro Pasquini, Jie Sheng [Phys.Lett.B 810 (2020) 135787]

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

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

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



- Active  $\nu$  final state

$$m_s \rightarrow 0 \quad m_\phi \rightarrow 0$$

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

- 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.**

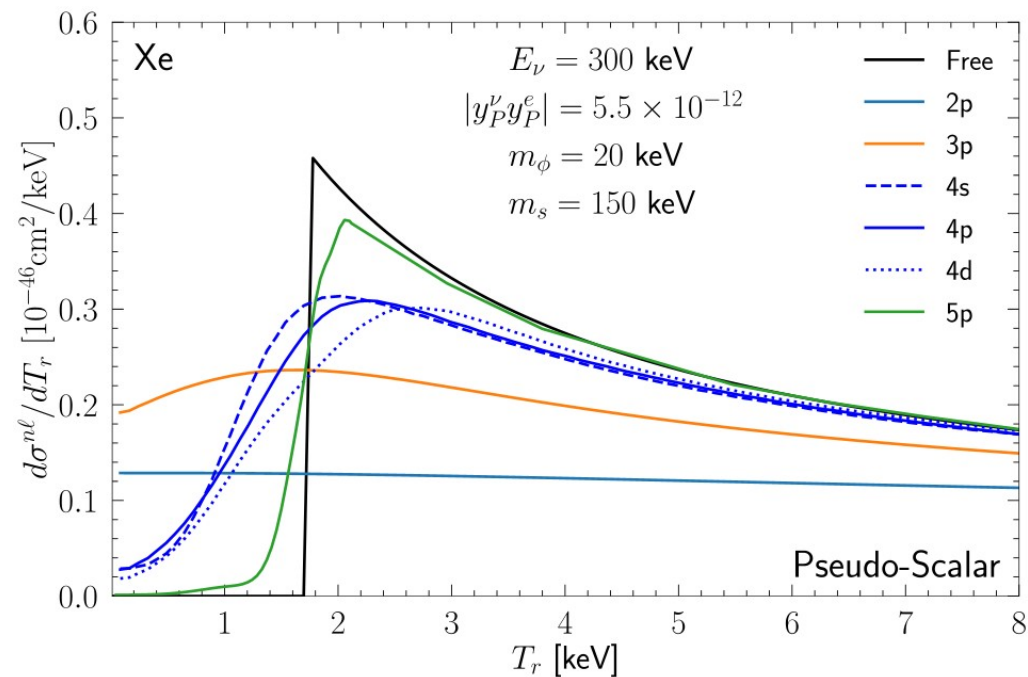
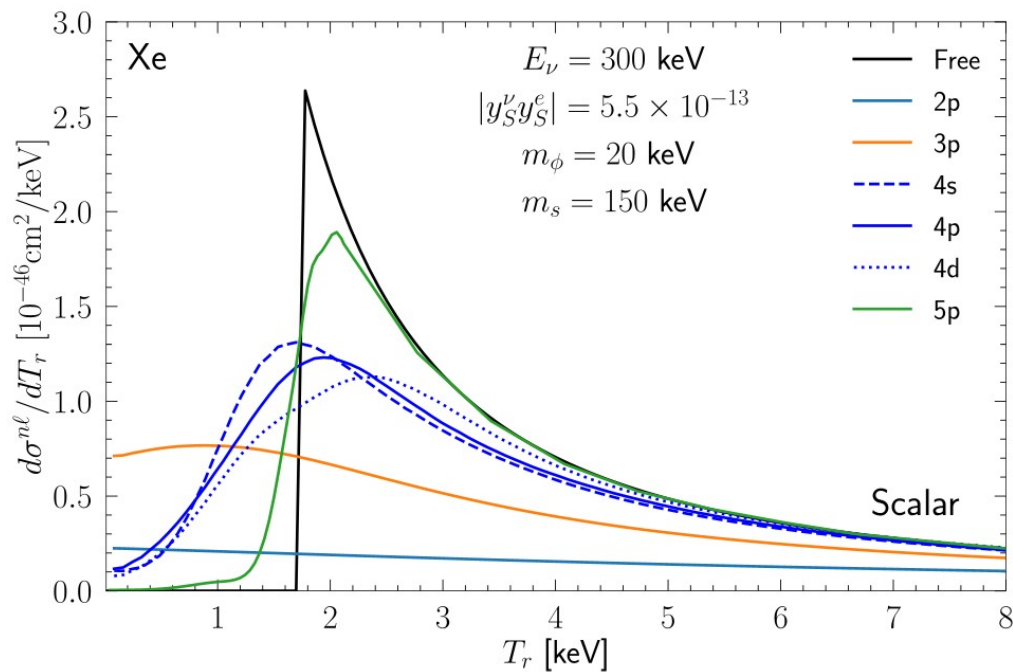
SFG, Pedro Pasquini, Jie Sheng [Phys.Lett.B 810 (2020) 135787]

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



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

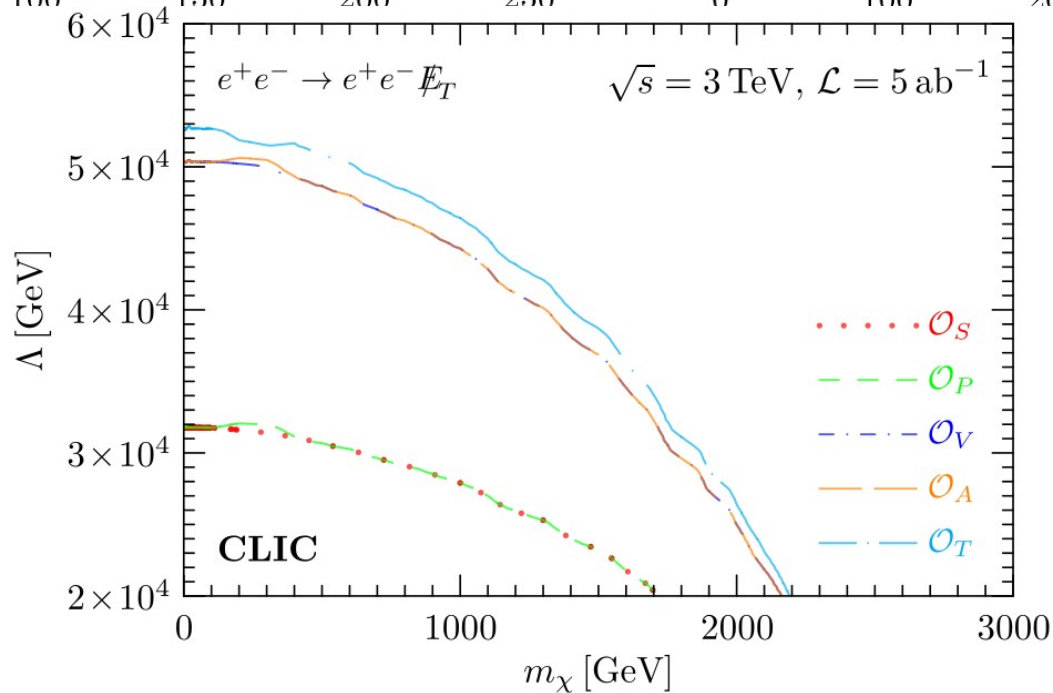
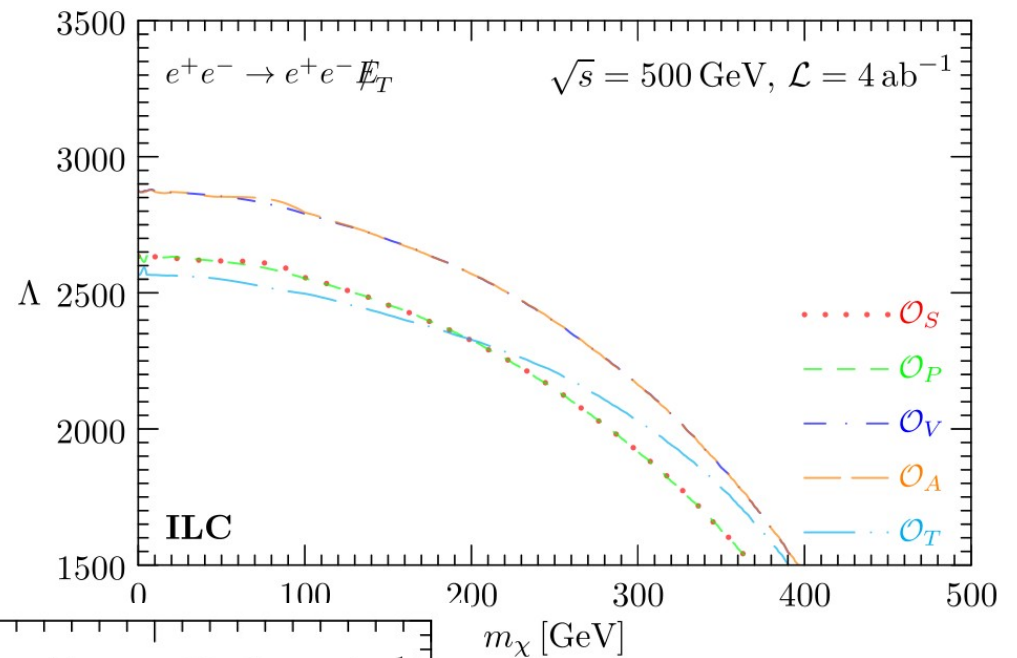
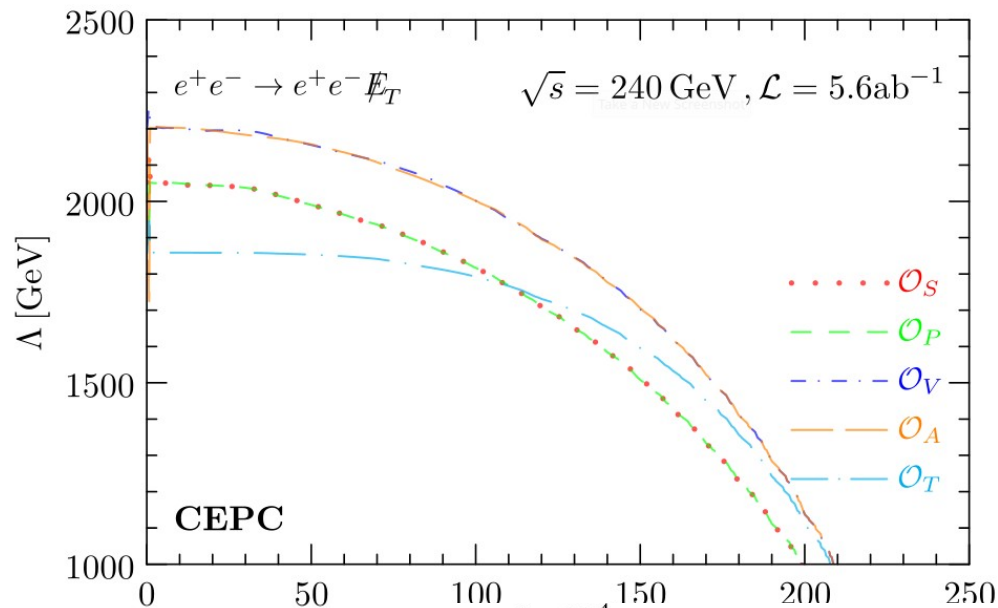
$$|\mathcal{M}|^2 \sim \frac{1}{T_r}$$



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]