Extending Dark Matter Search down to Sub-GeV Mass Range

Shao-Feng Ge, **Jie Sheng**

gesf@sjtu.edu.cn, shengjie04@sjtu.edu.cn

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]

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

李政道研究所 Tsung-Dao Lee Institute

Dark Interactions

November 14, 2022

Outline

1) Current status of dark matter search

2) **Cosmic ray boosted DM & diurnal modulation**

SFG, Jianglai Liu, Qiang Yuan, Ning Zhou [Phys.Rev.Lett. 126 (2021) 9, 091804]

PandaX-II + **SFG**, Qiang Yuan [Phys.Rev.Lett. 128 (2022) 17, 171801]

3) **Fermionic DM Absorption**

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]

Mass Span of DM

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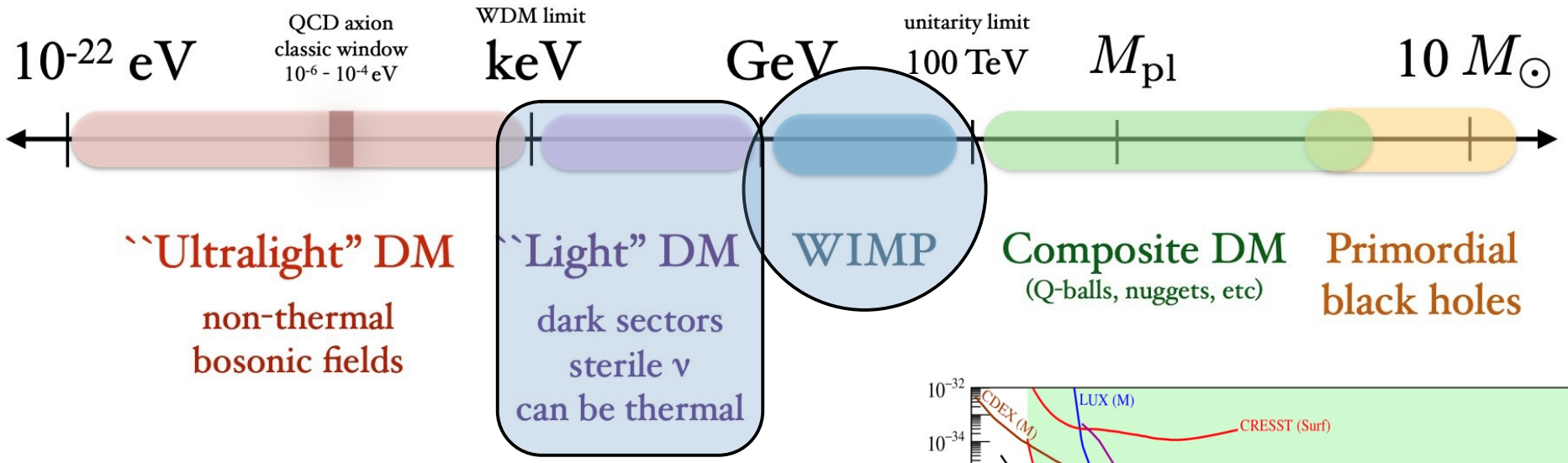
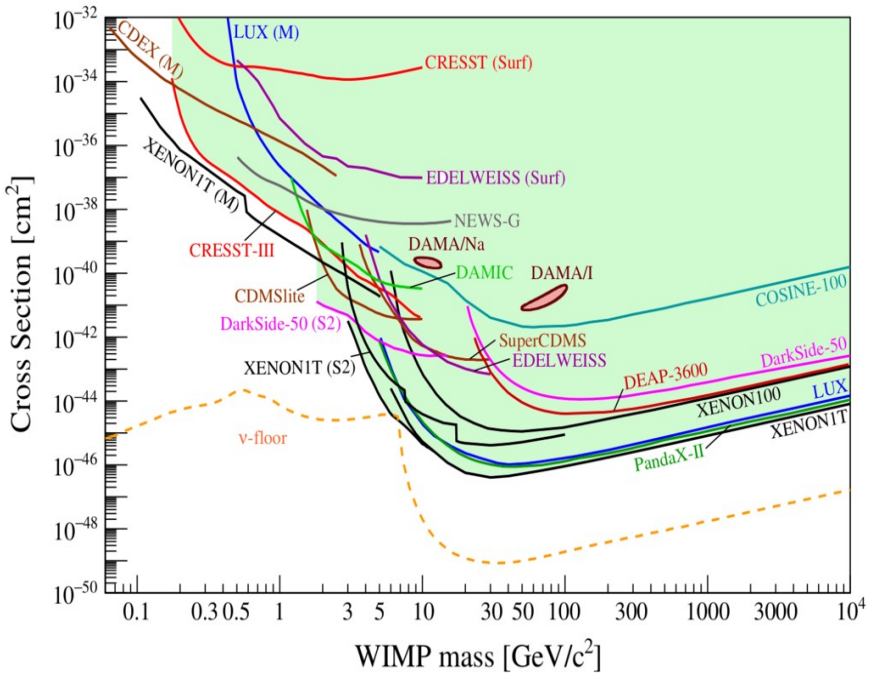


?

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

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



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**

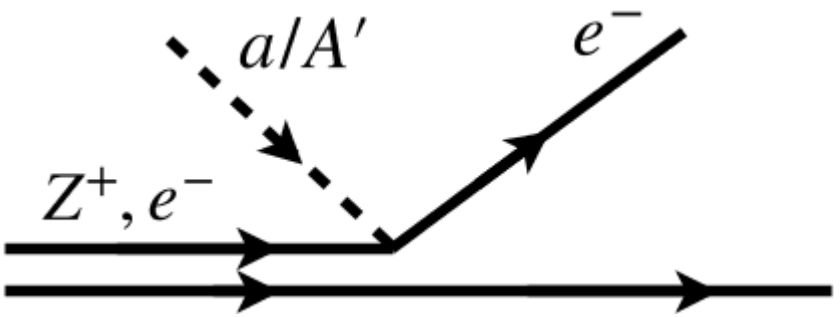
$$\chi + e \to \nu + e \qquad E_r \approx \frac{m_\chi^2}{2 m_e}$$

See also Dror, Elor & McGehee [1905.12635, 1908.10861], Li, Liao & Zhang [2201.11905]

Dror, Elor, McGehee & Yu [2011.01940]

Bosonic Absorption DM

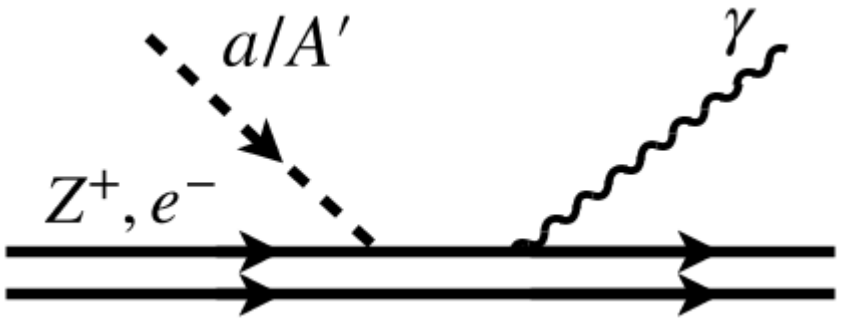
- **Dark absorption**



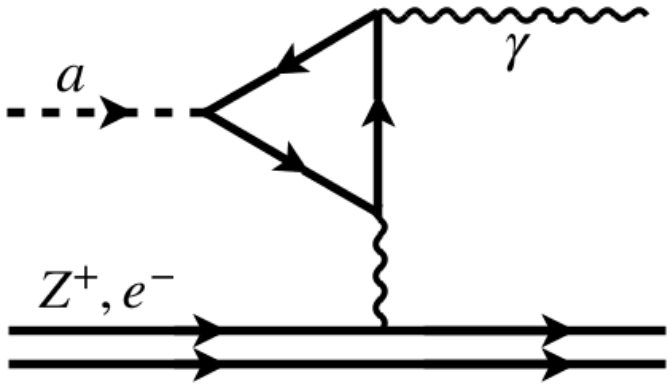
Pospelov, Ritz & Voloshin [0807.3279]

An, Pospelov, Pradler & Ritz [1412.8378]

- **Dark Compton**



- **Inverse Primakoff**



Hochberg, Krosigk, Kuflik & Yu [2109.08168]

Effective Operators

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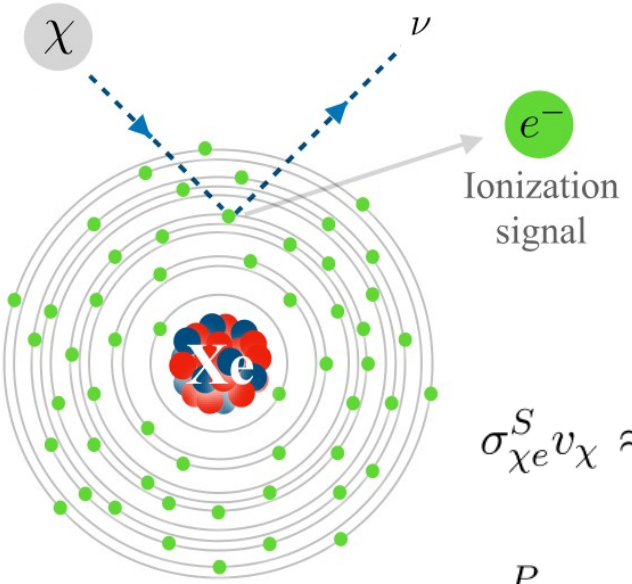


$$\mathcal{O}^S_{e\nu\chi} \equiv (\bar{e}e)(\bar{\nu}_L\chi_R),$$
$$\mathcal{O}^P_{e\nu\chi} \equiv (\bar{e}i\gamma_5 e)(\bar{\nu}_L\chi_R),$$
$$\mathcal{O}^V_{e\nu\chi} \equiv (\bar{e}\gamma_\mu e)(\bar{\nu}_L\gamma^\mu\chi_L),$$
$$\mathcal{O}^A_{e\nu\chi} \equiv (\bar{e}\gamma_\mu\gamma_5 e)(\bar{\nu}_L\gamma^\mu\chi_L),$$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

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

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

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

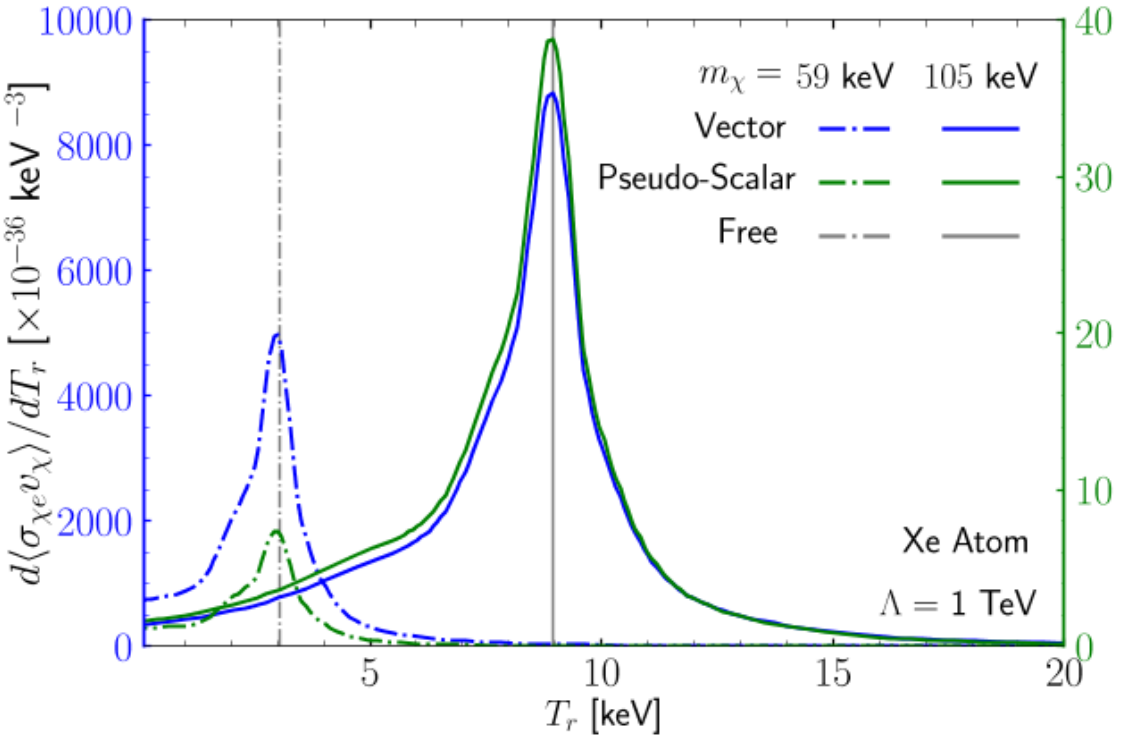
$$\sigma^A_{\chi e}v_\chi \approx \frac{1}{\Lambda^4}\frac{m_\chi^2(2m_e+m_\chi)^2(6m_e^2+8m_em_\chi+3m_\chi^2)}{32\pi(m_e+m_\chi)^4},$$

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

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

Kinematics of Absorption DM

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

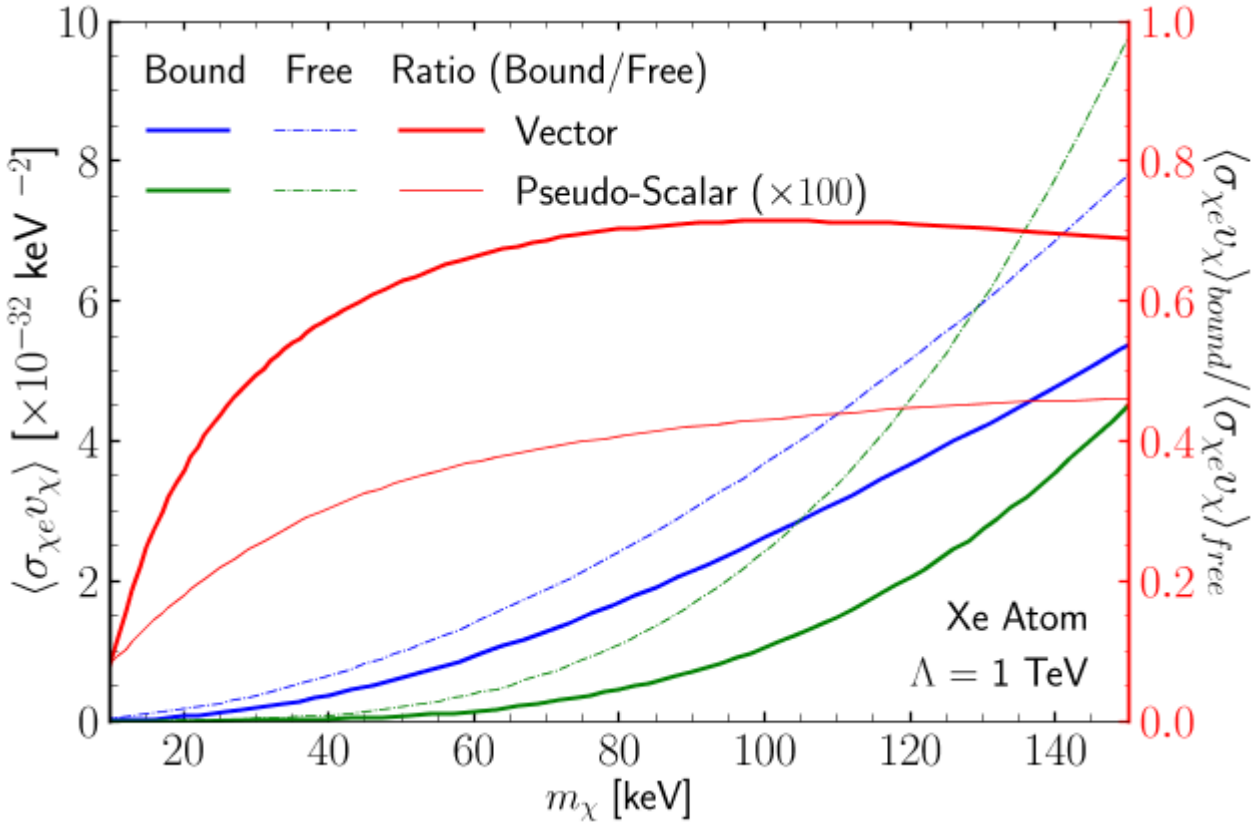


$$\frac{d\langle\sigma_{\chi e} v_\chi\rangle}{dT_r} = \sum_{nl}(4l+2)\frac{1}{T_r}\frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi}|\mathcal{M}|^2(\mathbf{q})K_{nl}(T_r, |\mathbf{q}|),$$

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

Atomic Effects

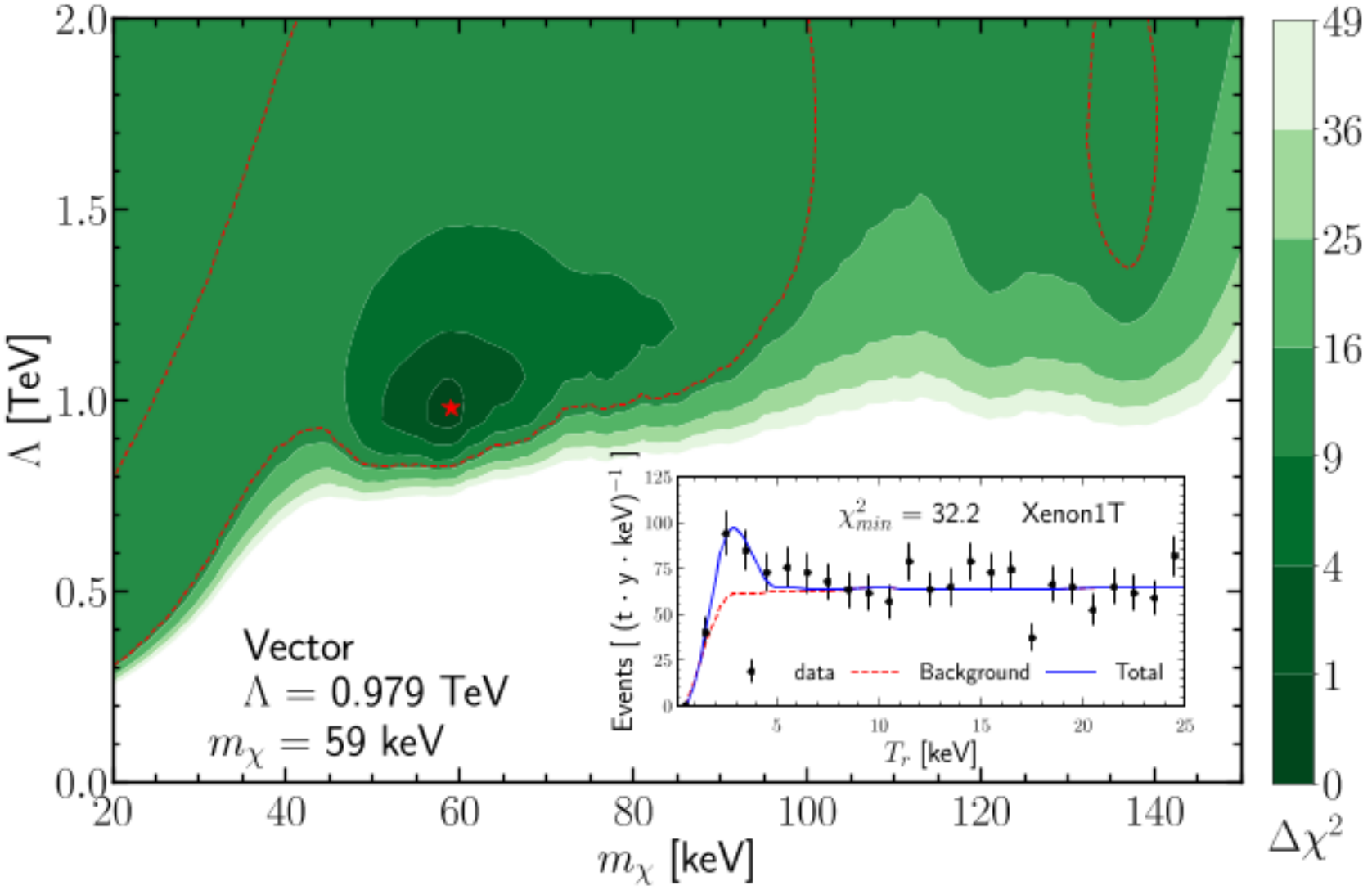
$$\chi + e \to \nu + e$$



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

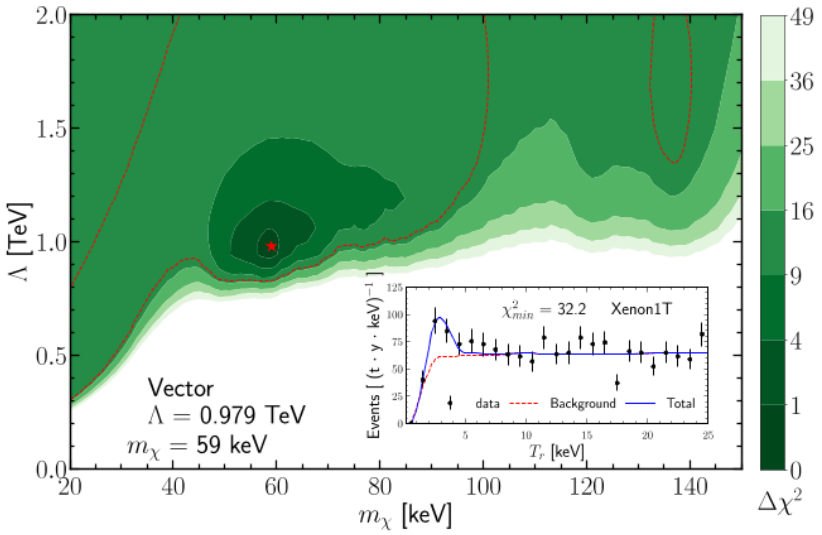
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

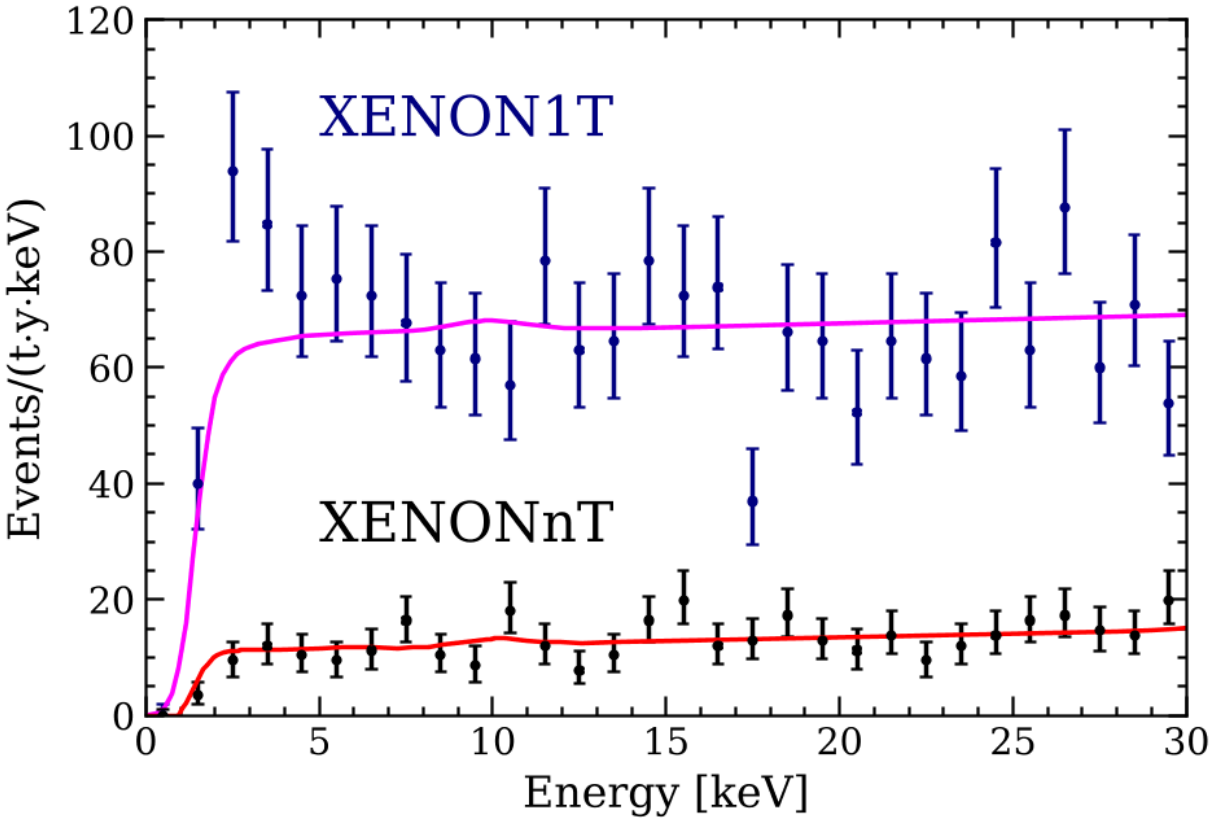
Xenon1T excess



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

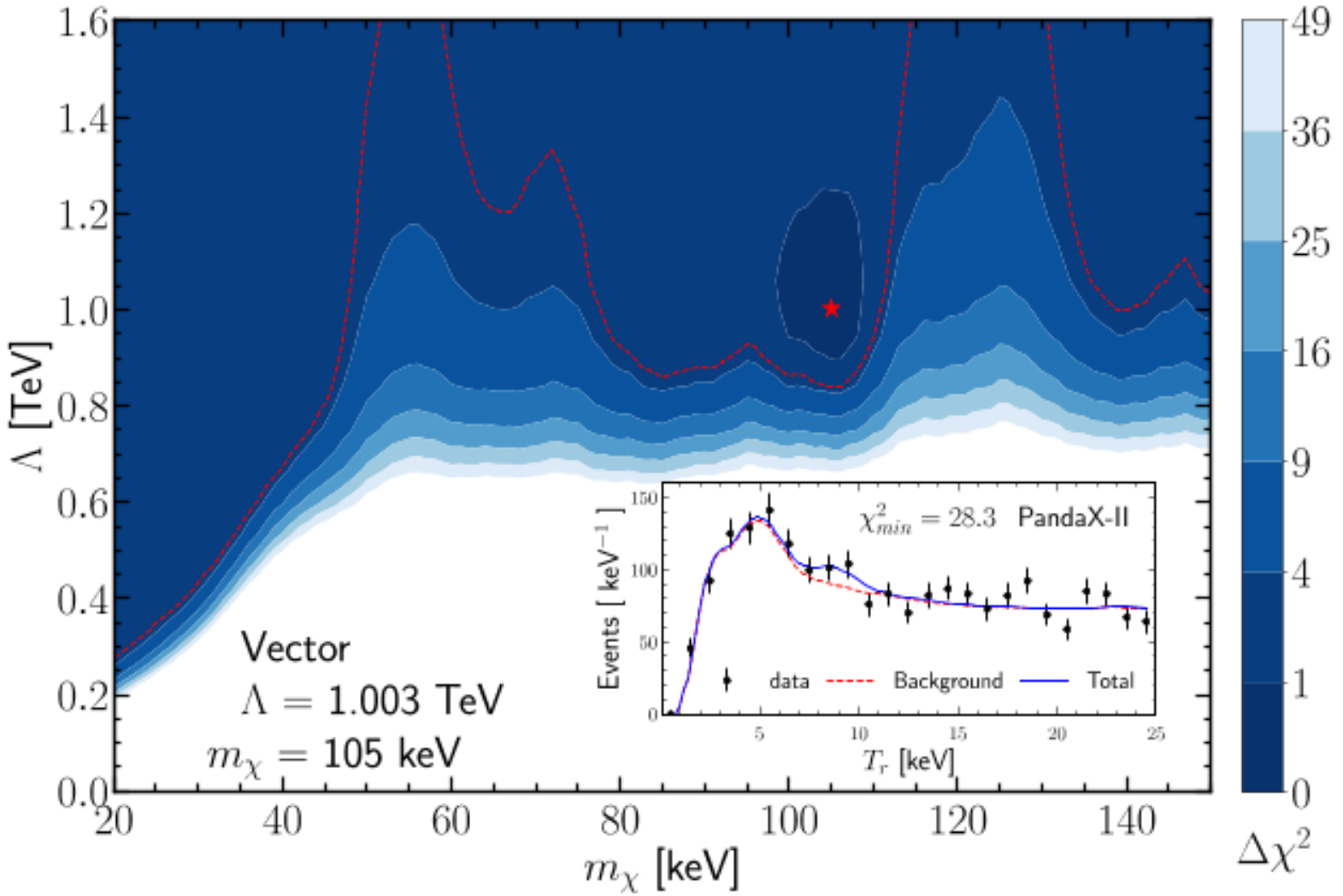
Xenon1T excess





Knut Dundas Morå @ IDM2022

PandaX-II



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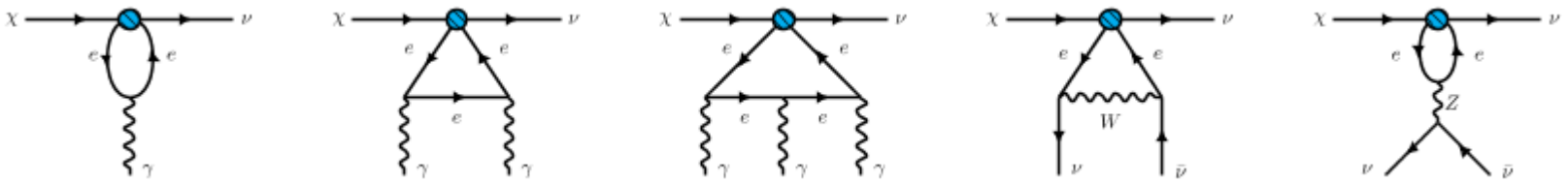
Visible & Invisible Decays



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: $\mathcal{O}^T_{e\nu\chi}$	✓	×	×!	×!

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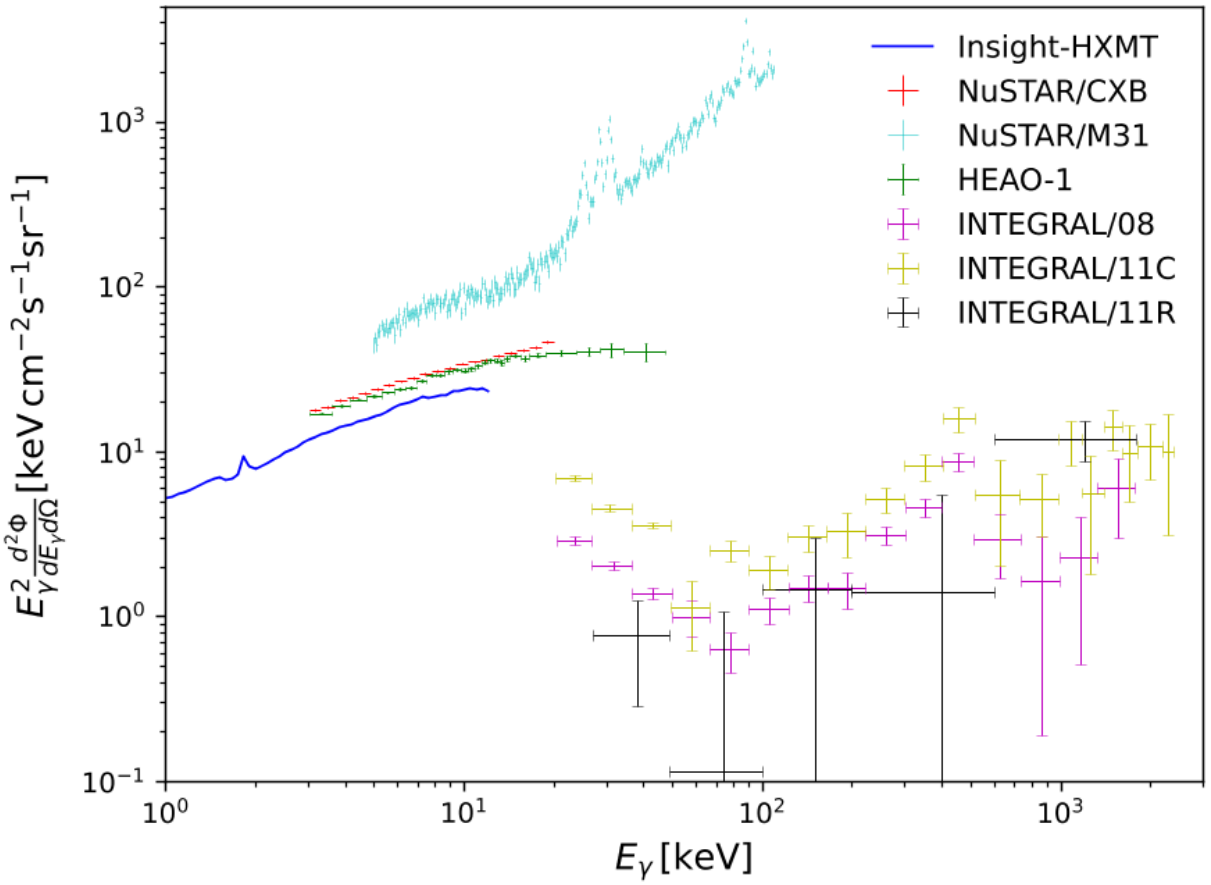
Astro Observations



- **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**

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

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Astro Constraints

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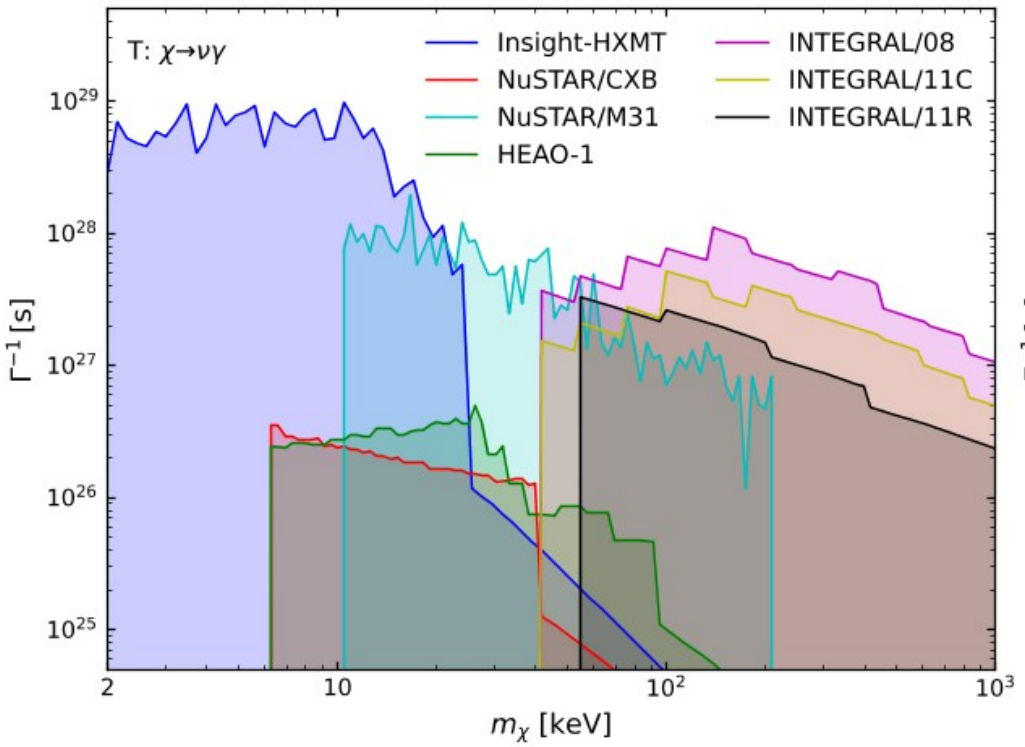
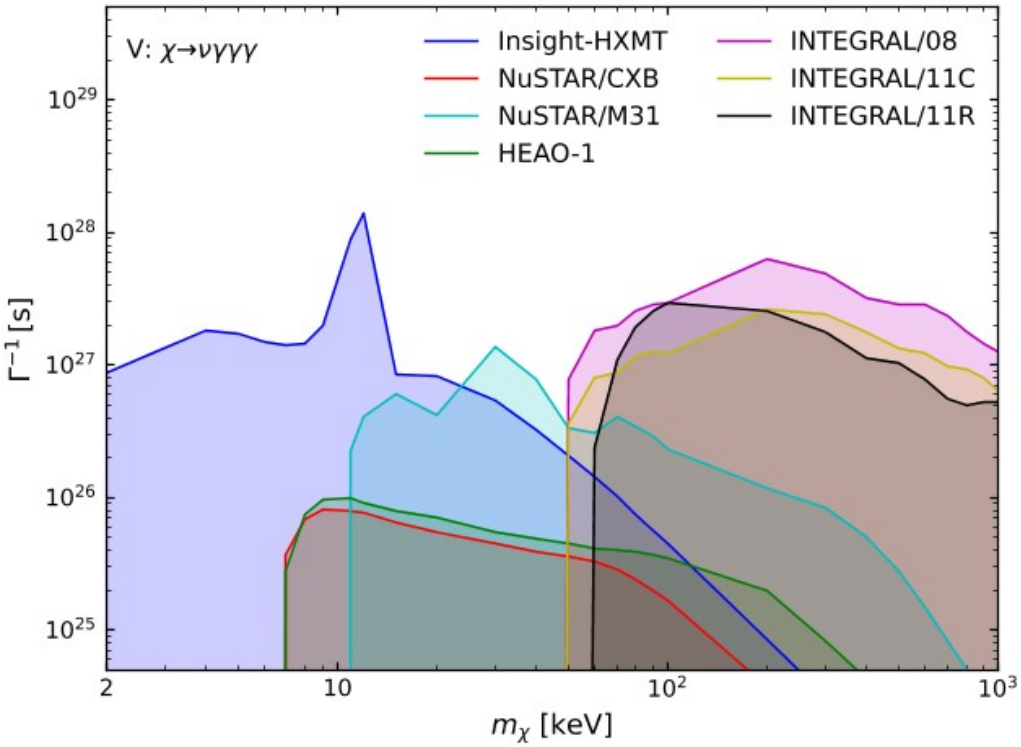
$$N_i^{\rm th} \leq N_i^{\rm obs} \equiv A_{\rm eff} T_{\rm obs} \Delta\Omega \left(\frac{d^2\Phi_\gamma}{dE_\gamma d\Omega} \right)^i_{\rm exp@95\%} \Delta E_i$$

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





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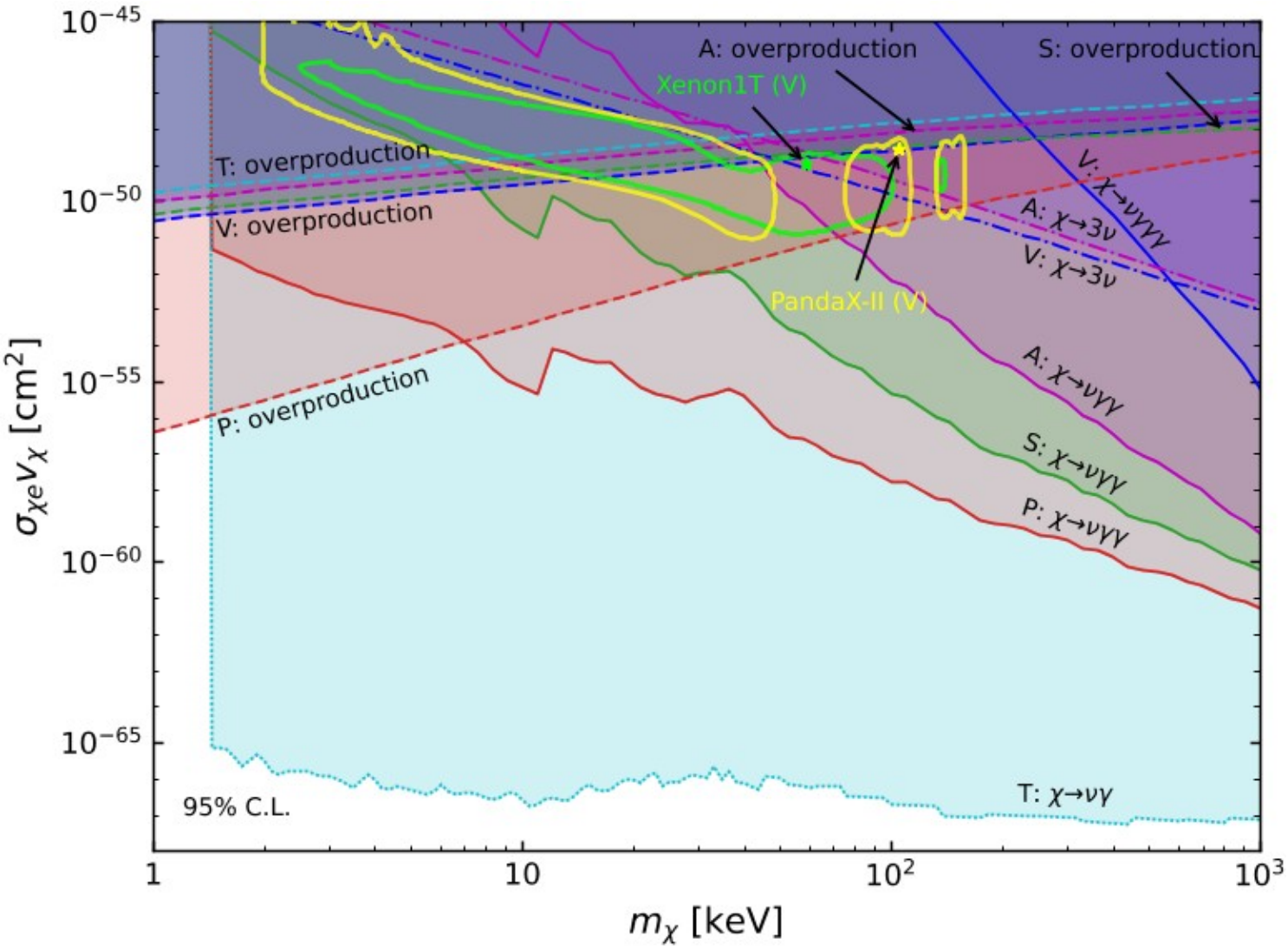
Constraints from Astro & Cosmo



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PandaX-4T Results

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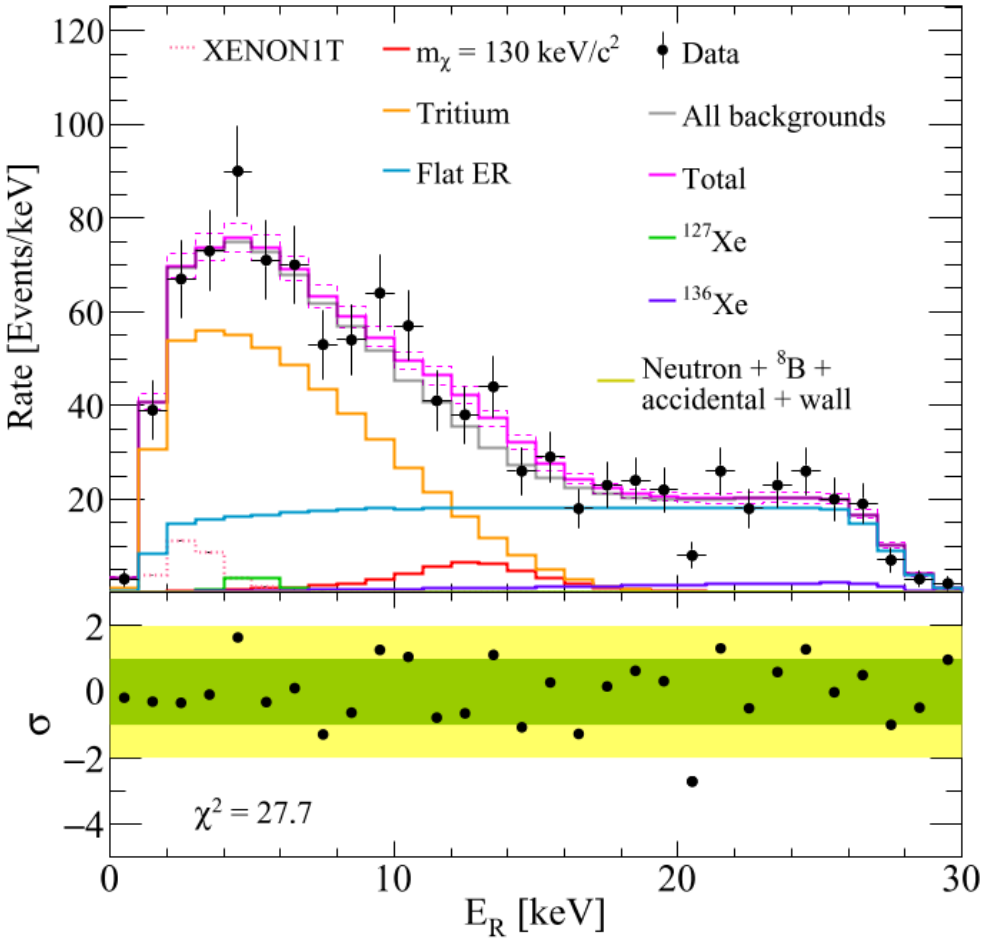

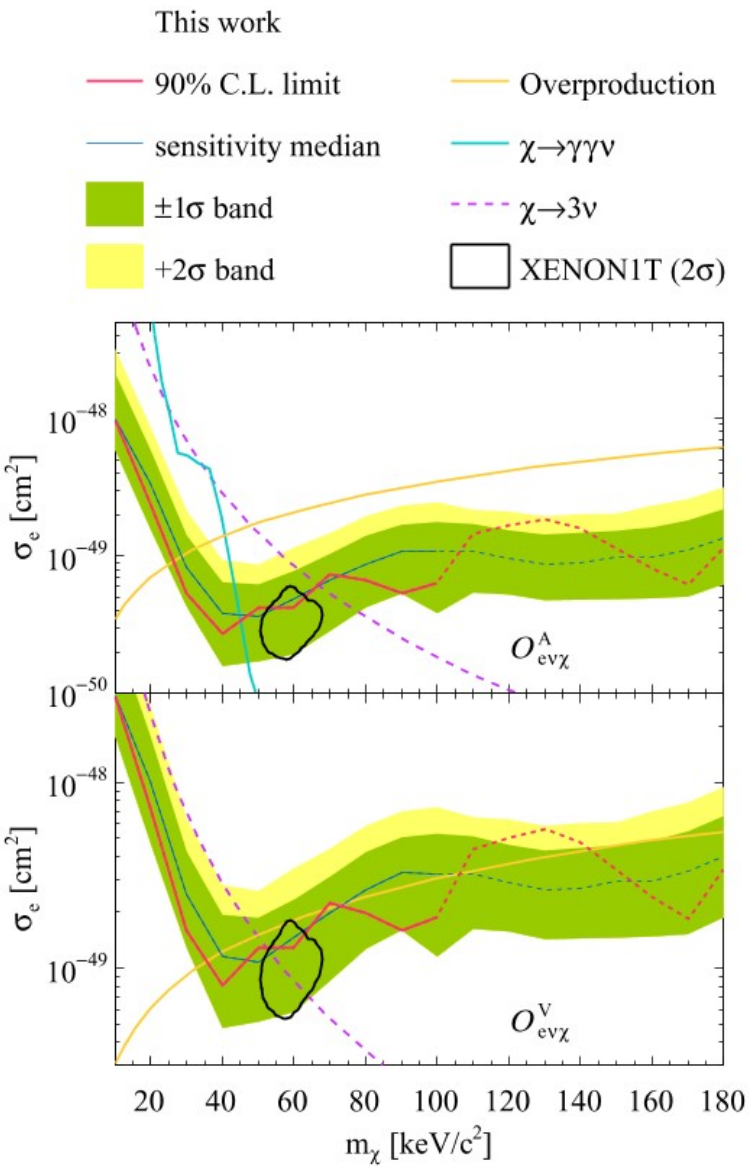

PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [Phys.Rev.Lett. 129 (2022) 16, 161804]

Summary

1) How to exhaust the sub-GeV range?

2) Cosmic ray boosted DM & diurnal modulation

3) **Fermionic DM absorption**

- **Efficient energy release**
- **Peak shape by atomic effects**

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Thank You

Possible Improvements

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1) Lowering the threshold

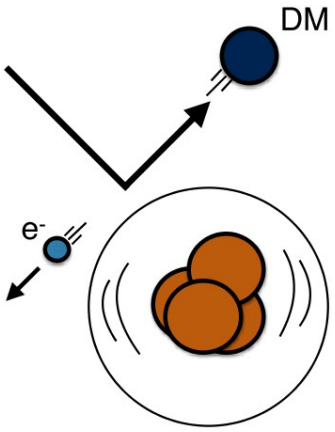
Bolometer [1904.00498, Ann.Rev.Nucl.Part.Sci. 67 (2017) 161-181]

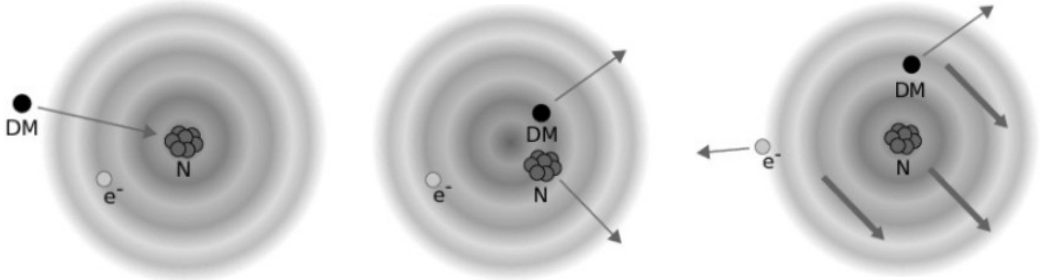
Bremsstrahlung [Kouvaris & Pradler, PRL 118, 031803 (2017)]

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

Migdal effect [Ibe et al [1707.07258]]

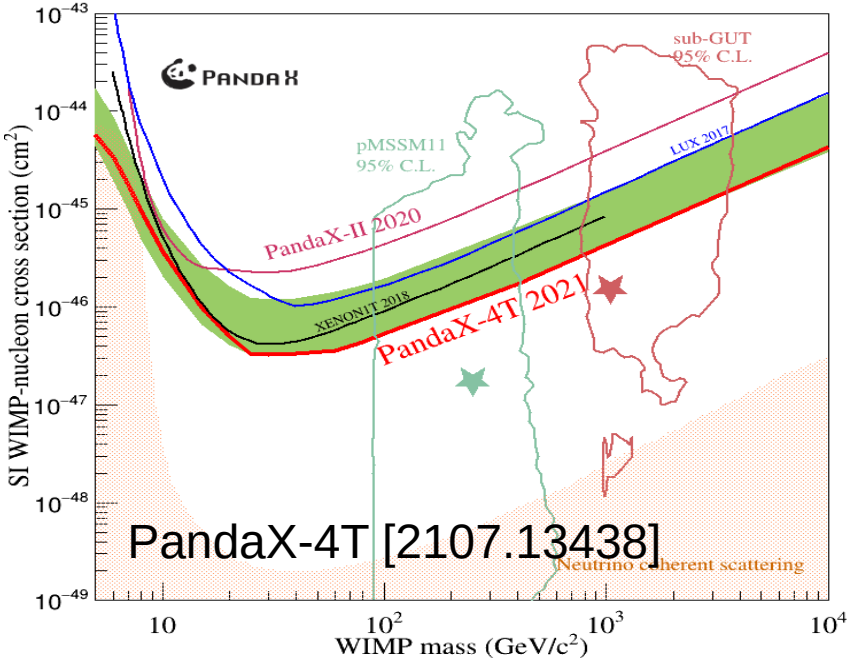
2) Electron target



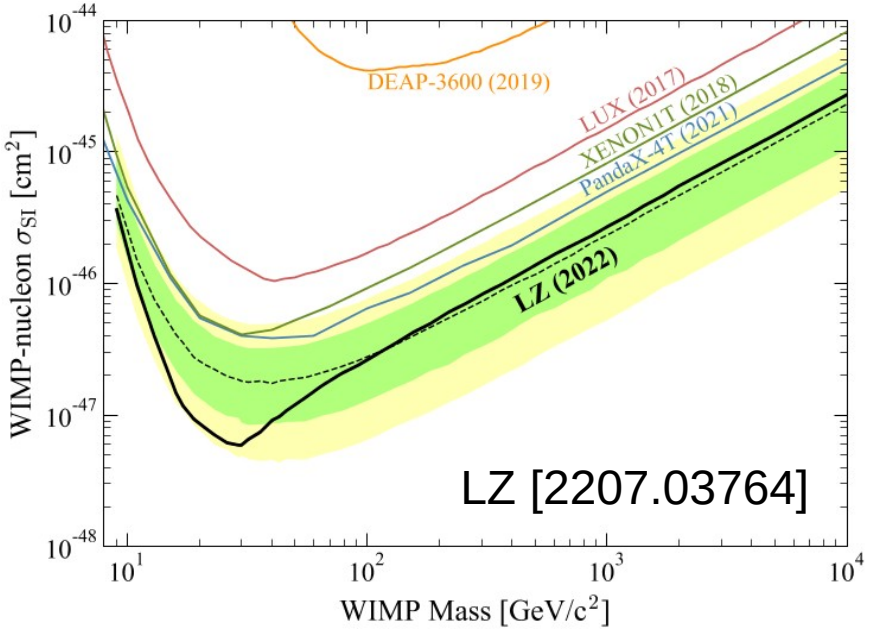


3) Boosting detector?

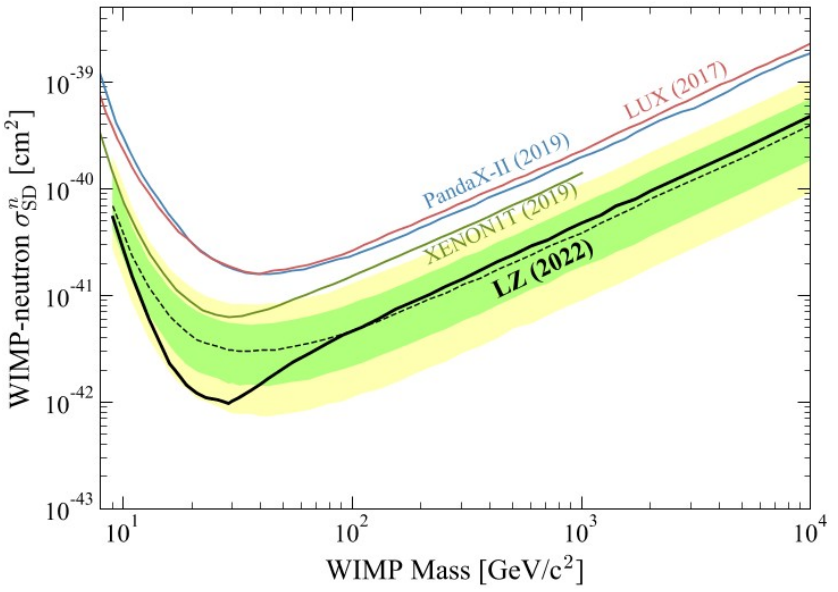
Current Sensitivity



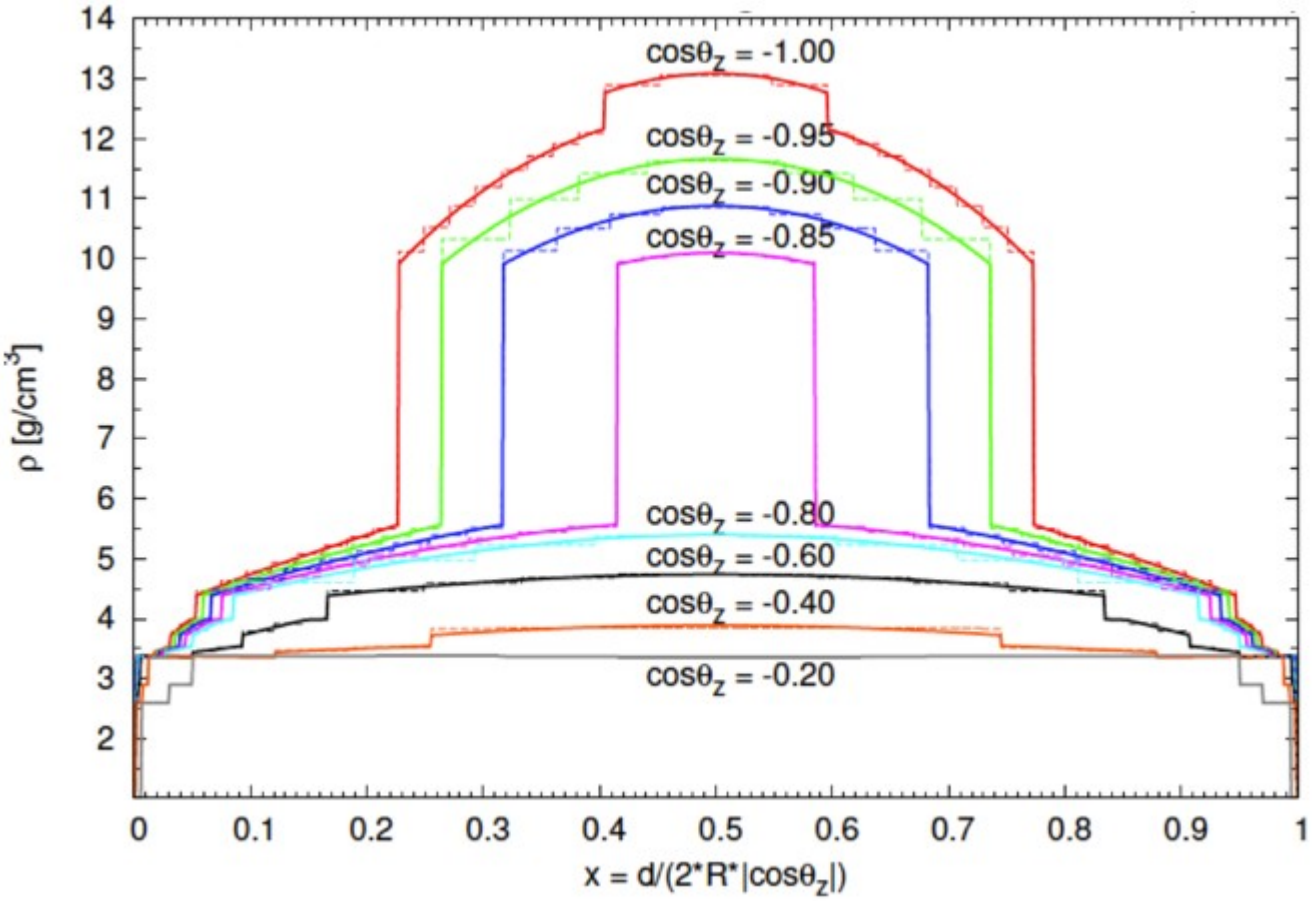
PandaX-4T [2107.13438]



LZ [2207.03764]



Earth Density Profile



SFG, Hagiwara, Rott [1309.3176]

The earth matter can be approximated by 2-step profile.

Overproduction

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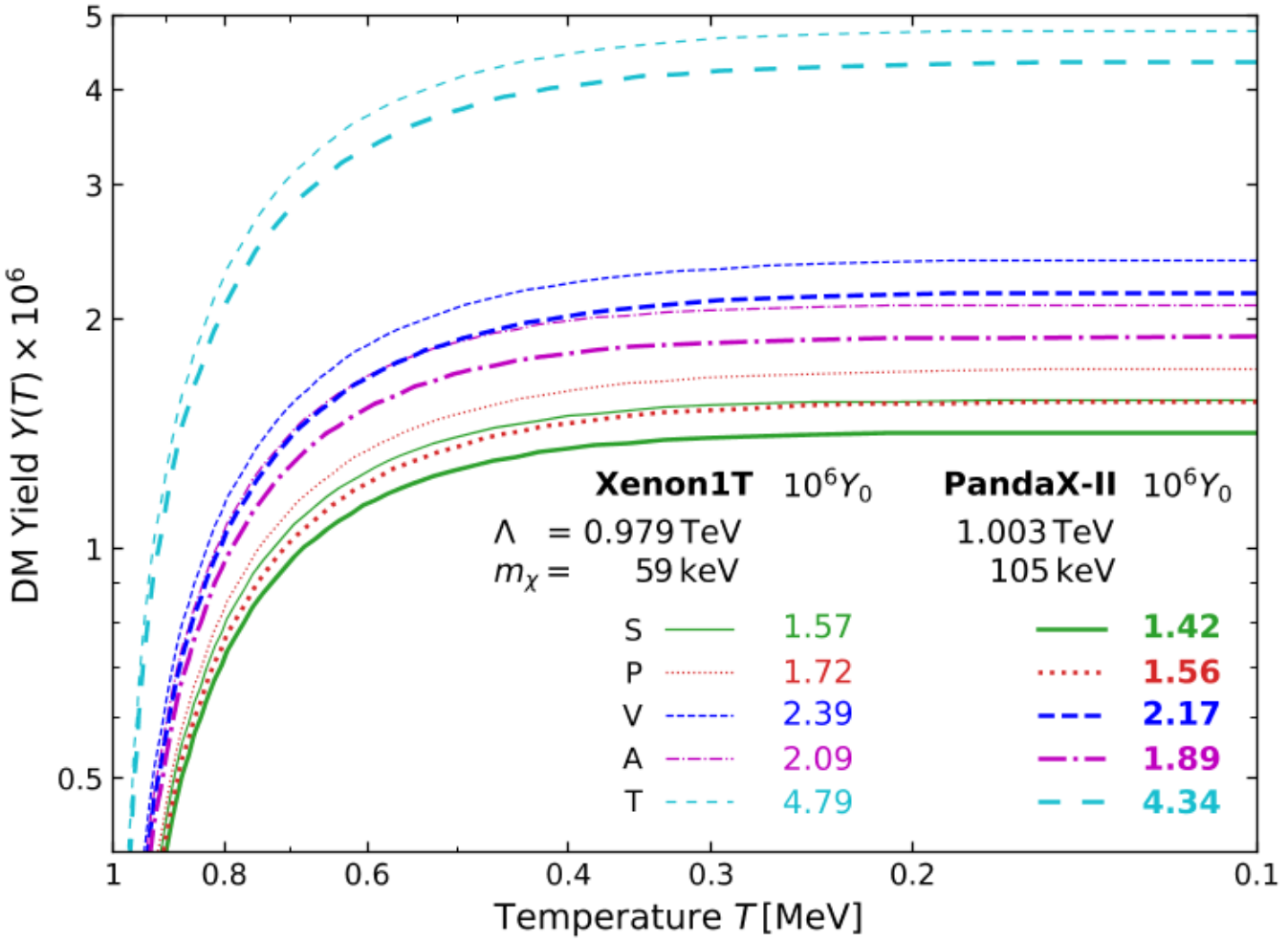
$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle v_{\text{Møl}}\sigma_{e^+e^-}\rangle n_{e^+}^{\text{eq}} n_{e^-}^{\text{eq}}$$



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