Extending Dark Matter Search down to Sub-GeV Mass Range

葛韶锋

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]

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

PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [2206.02339]

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

第三届粒子物理前沿研讨会
July 23, 2022

李政道研究所
Tsung-Dao Lee Institute

Outline

Tsung-Dao Lee Institute

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]

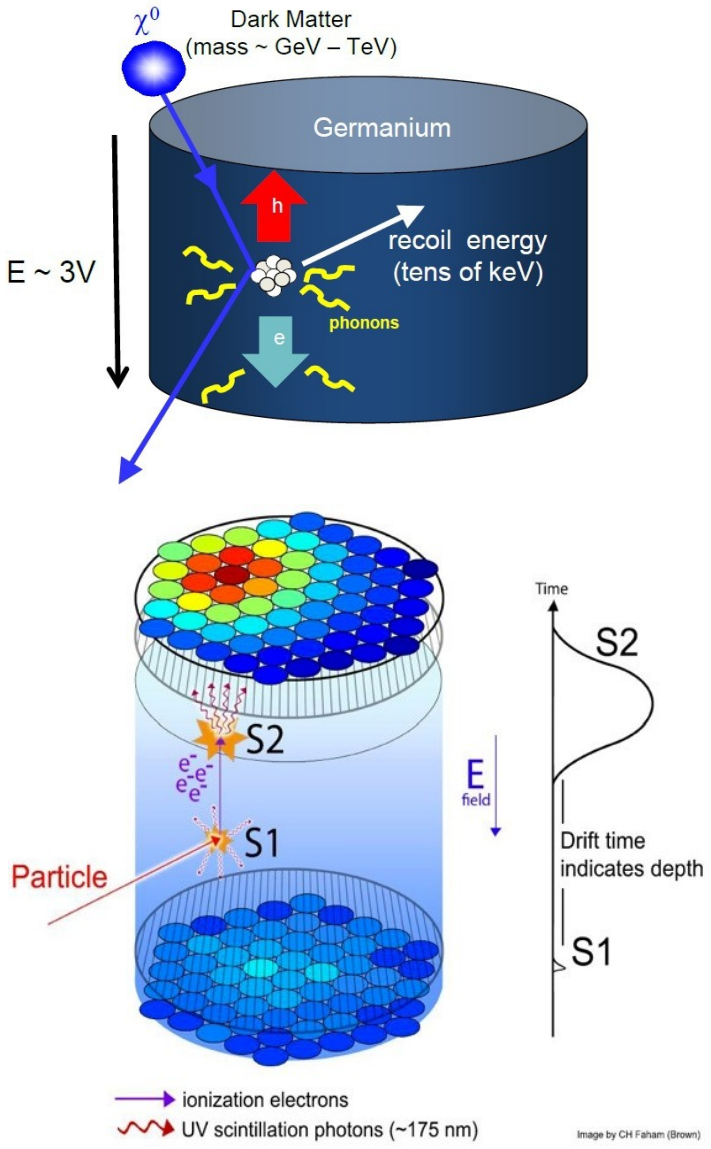
PandaX-II + **SFG**, Qiang Yuan [Phys.Rev.Lett. 128 (2022) 17, 171801]

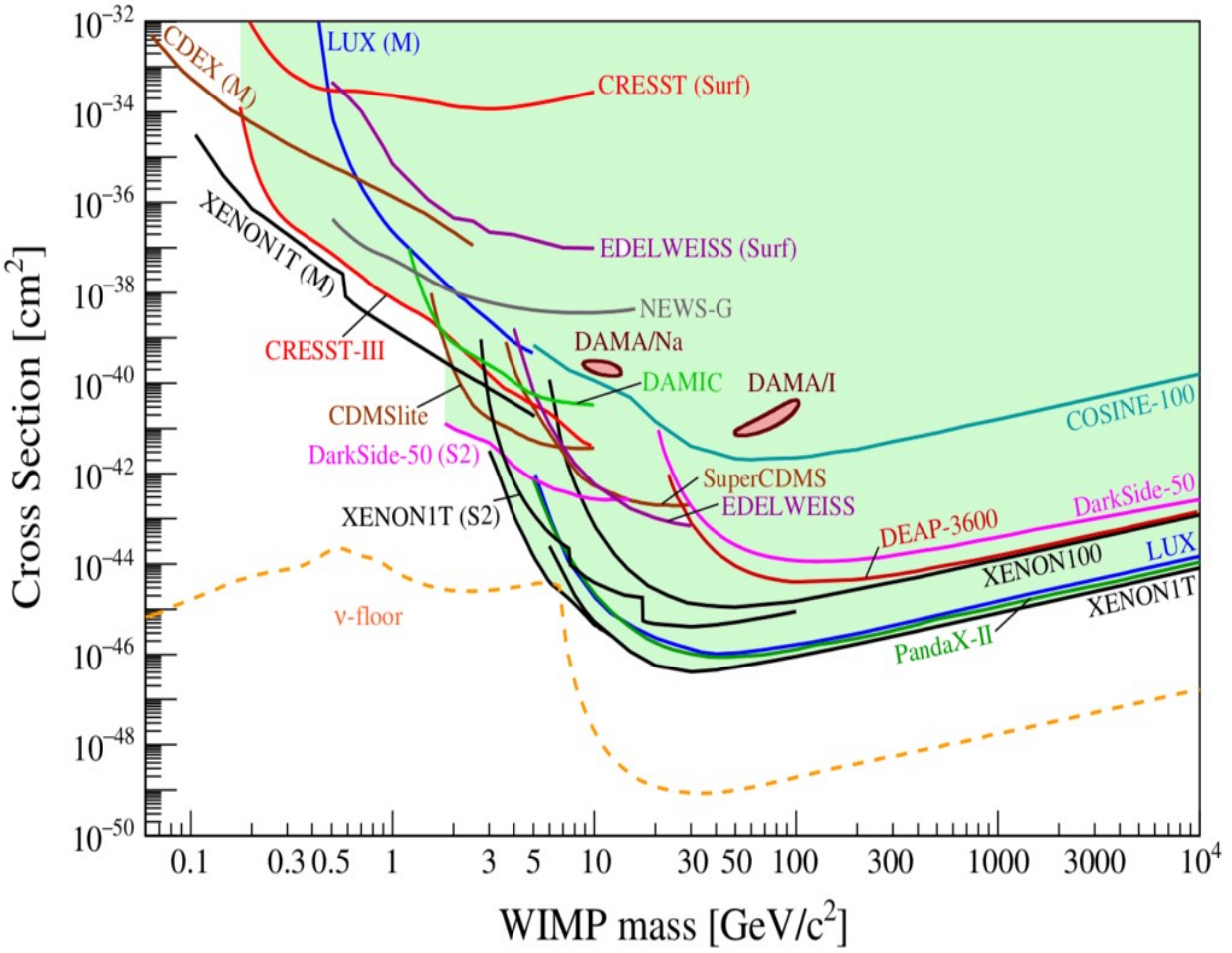
3) **Fermionic DM Absorption**

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

PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [2206.02339]

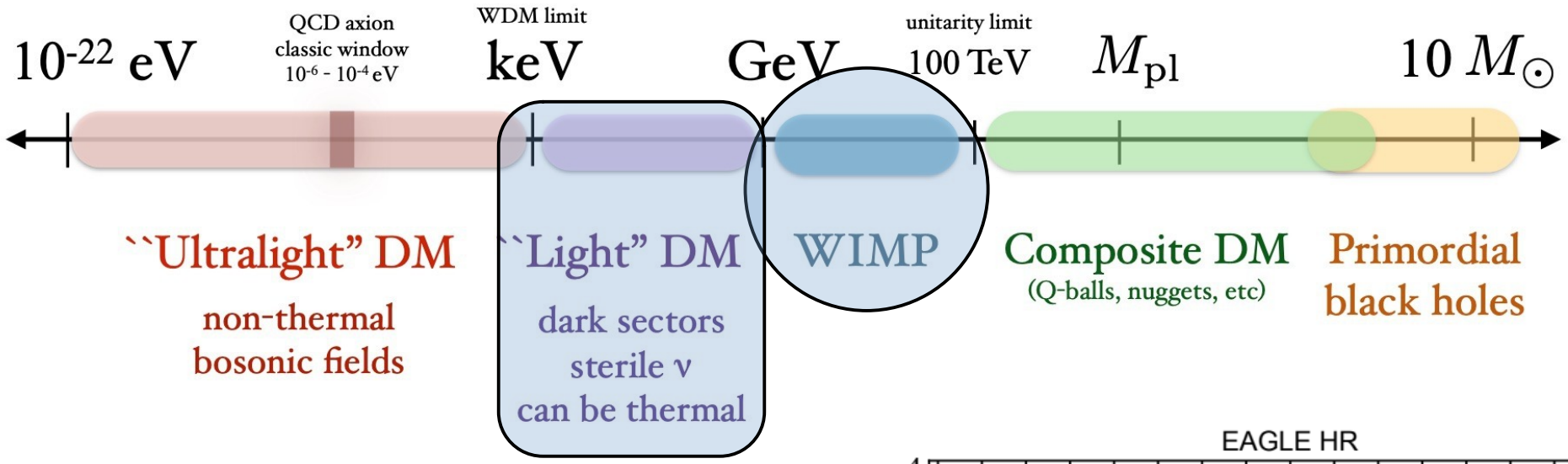
Direct Detection





APPEC Committee Report [2104.07634]

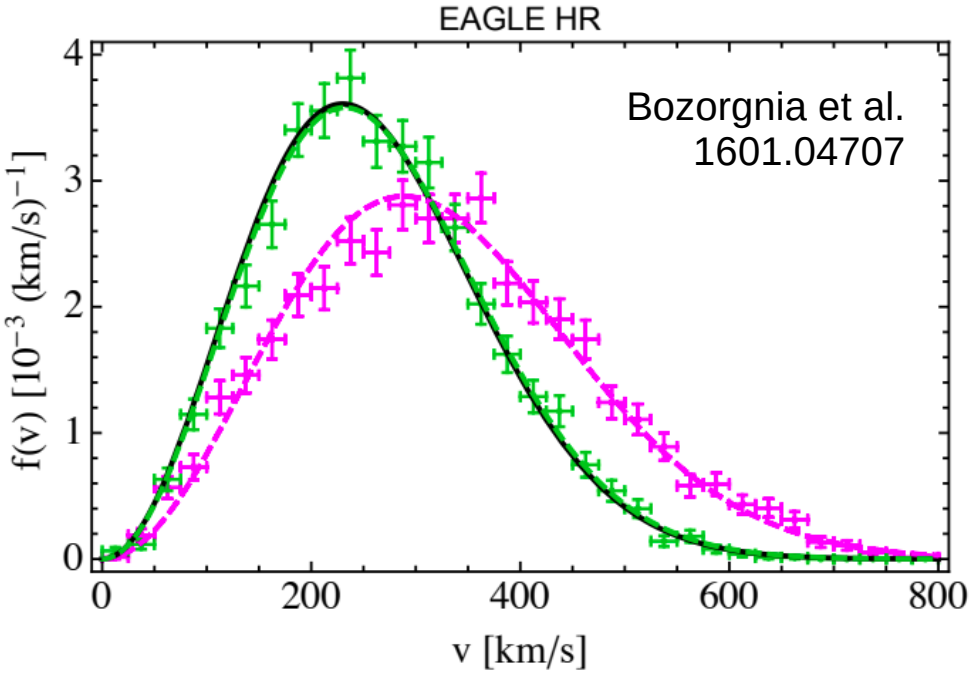
Mass Span of DM



?

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

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



Possible Improvements

1) Lowering the threshold

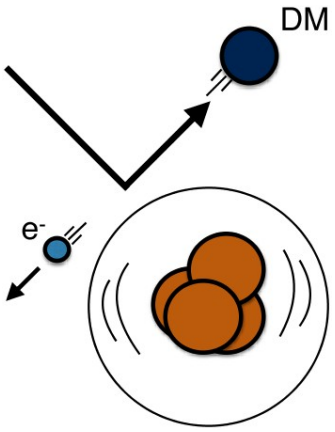
Bolometer [1904.00498, Ann.Rev.Nucl.Part.Sci. 67 (2017) 161-181]

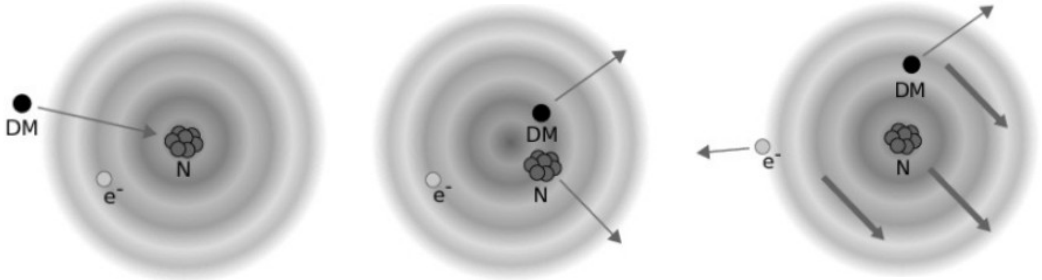
Bremsstrahlung [Kouvaris & Pradler, PRL 118, 031803 (2017)]

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

Migdal effect [Ibe et al [1707.07258]]

2) Electron target





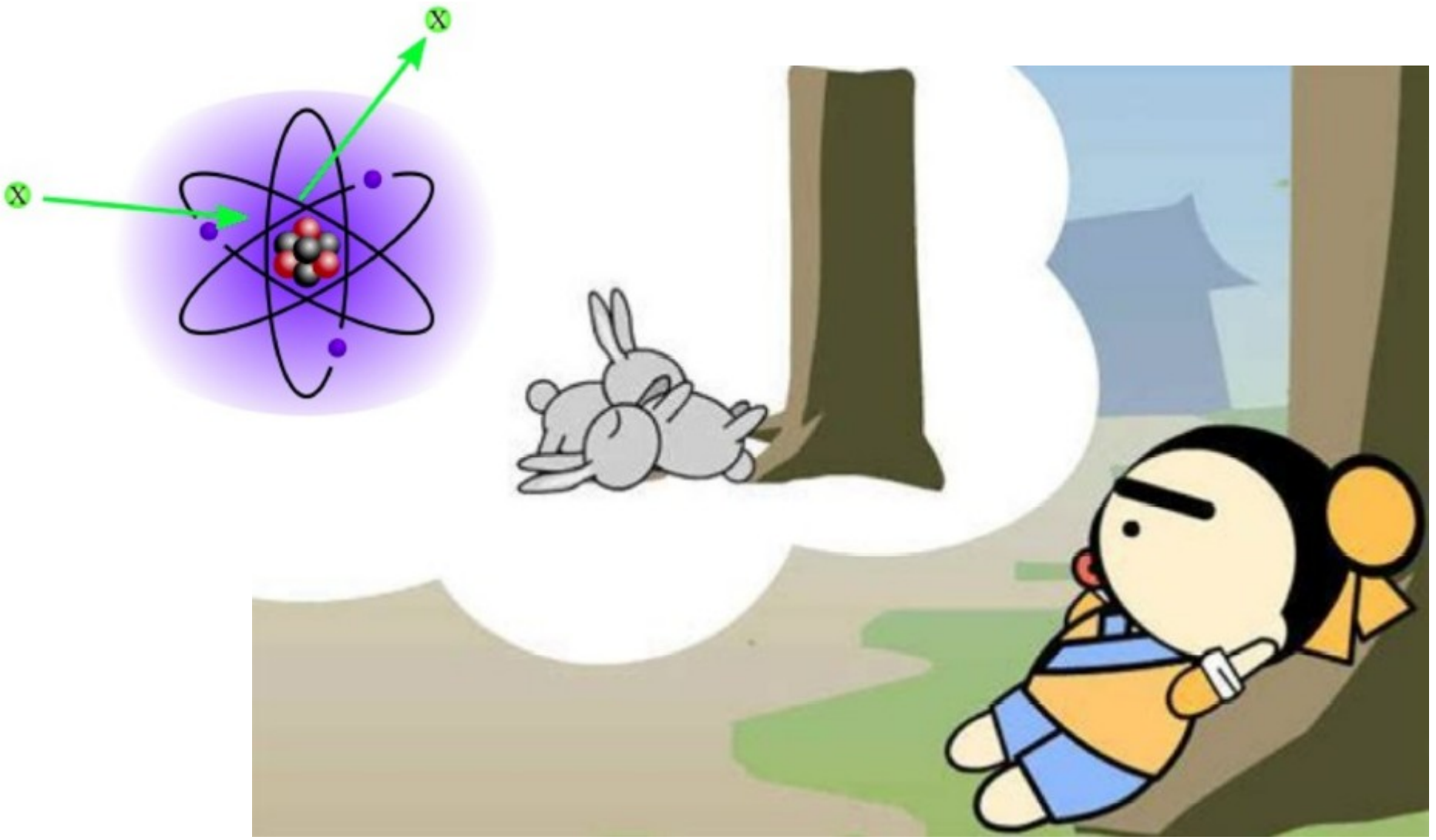
3) Boosting detector?

Boosting DM

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

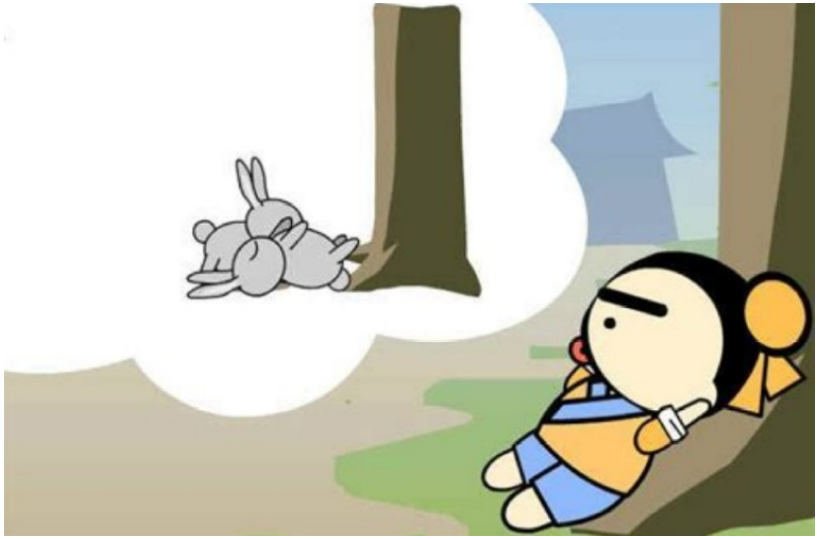
PandaX-II + **SFG**, Qiang Yuan [Phys.Rev.Lett. 128 (2022) 17, 171801]

DM Detection vs 守株待兔



If the sleepy rabbit is too small, the tree cannot feel it!

Hitting Rabbits



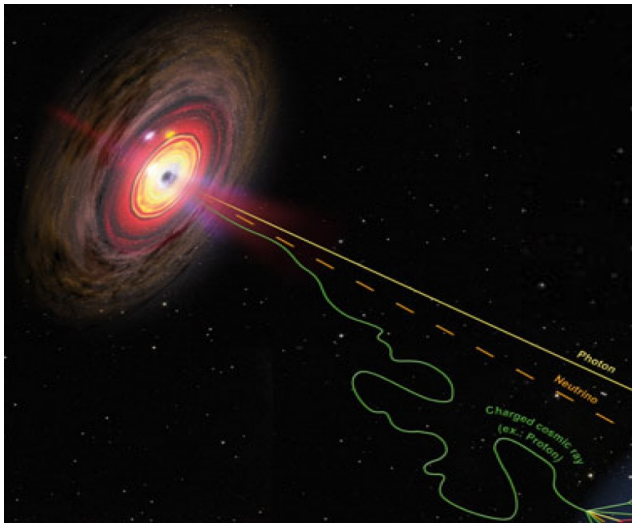
Stick has the same material as tree!

So long as direct detection is possible.

Cosmic Ray Boosted DM

Cappiello, Ng & Beacom, PRD 2019 [arXiv:1810.07705 [hep-ph]]
Bringmann & Pospelov, PRL 2019 [arXiv:1810.10543 [hep-ph]]
Ema, Sala & Sato [arXiv:1811.00520 [hep-ph]]

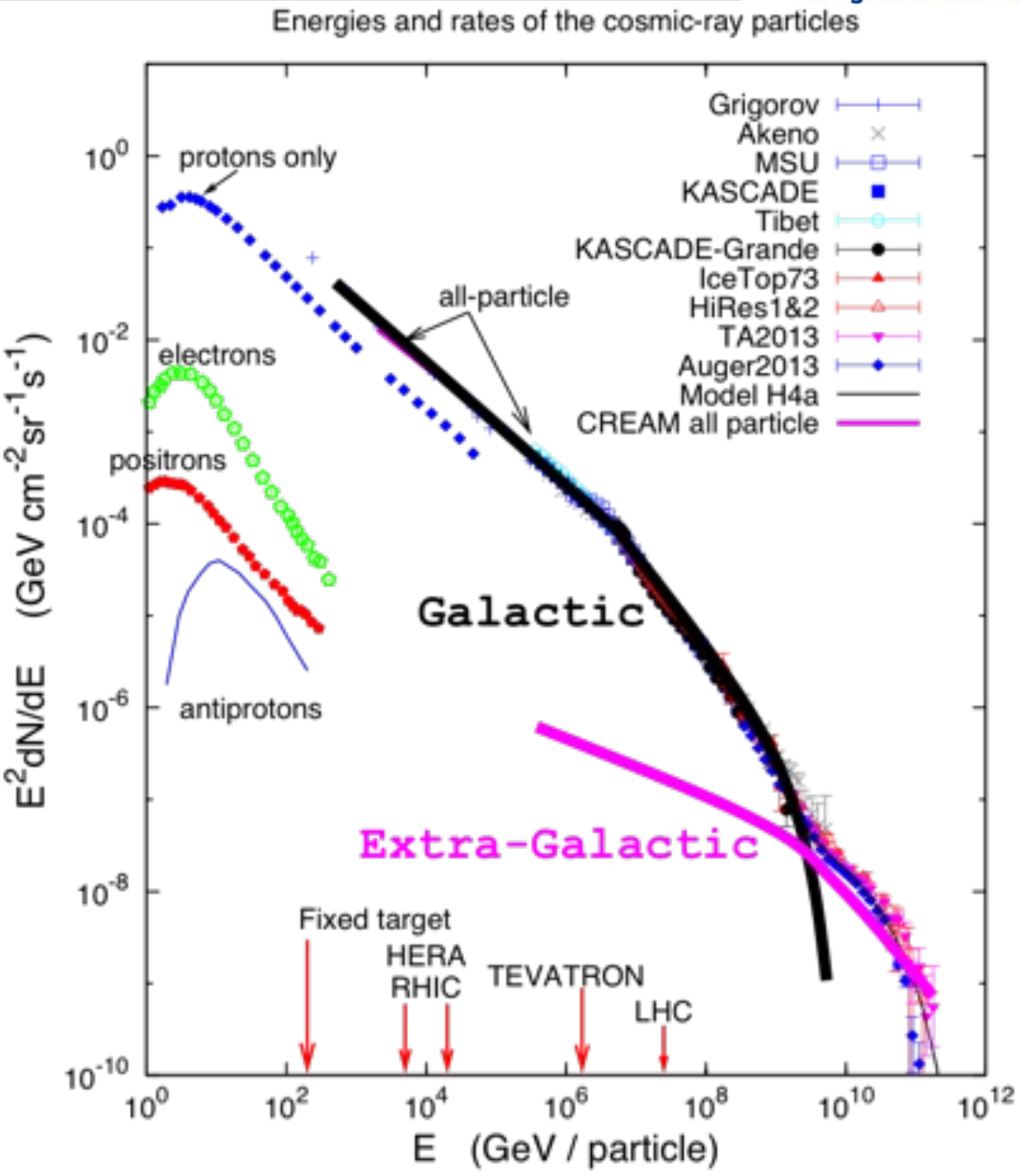
Cosmic Rays



1) Cosmic rays are almost everywhere in the galaxy

2) Cosmic rays are very energetic

3) Cosmic rays have several components (proton, electron, ...)



Galaxy DM Density Profile

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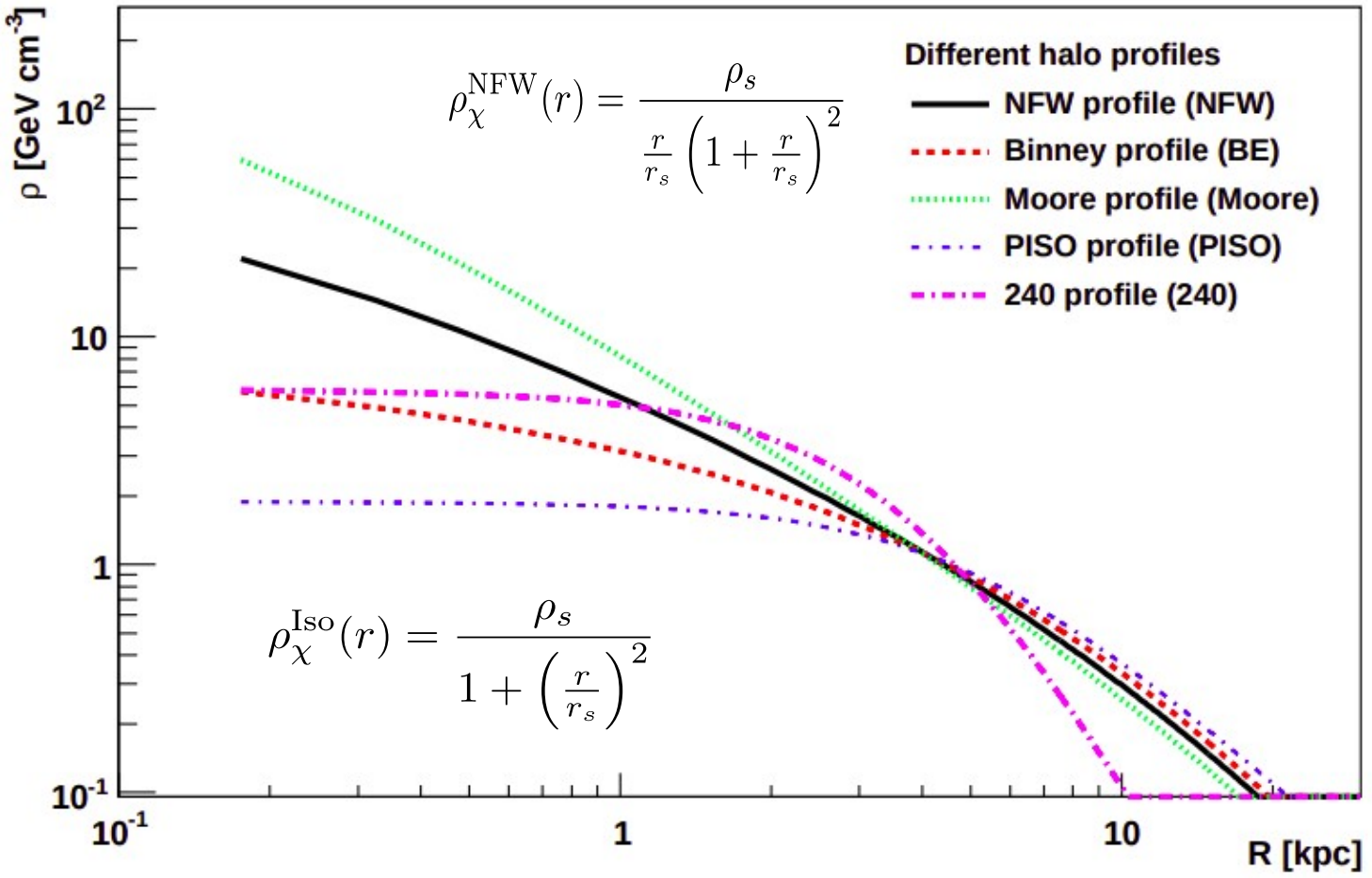
Weber & Boer [0910.4272]



DM particles are almost at rest in comparison to cosmic rays.

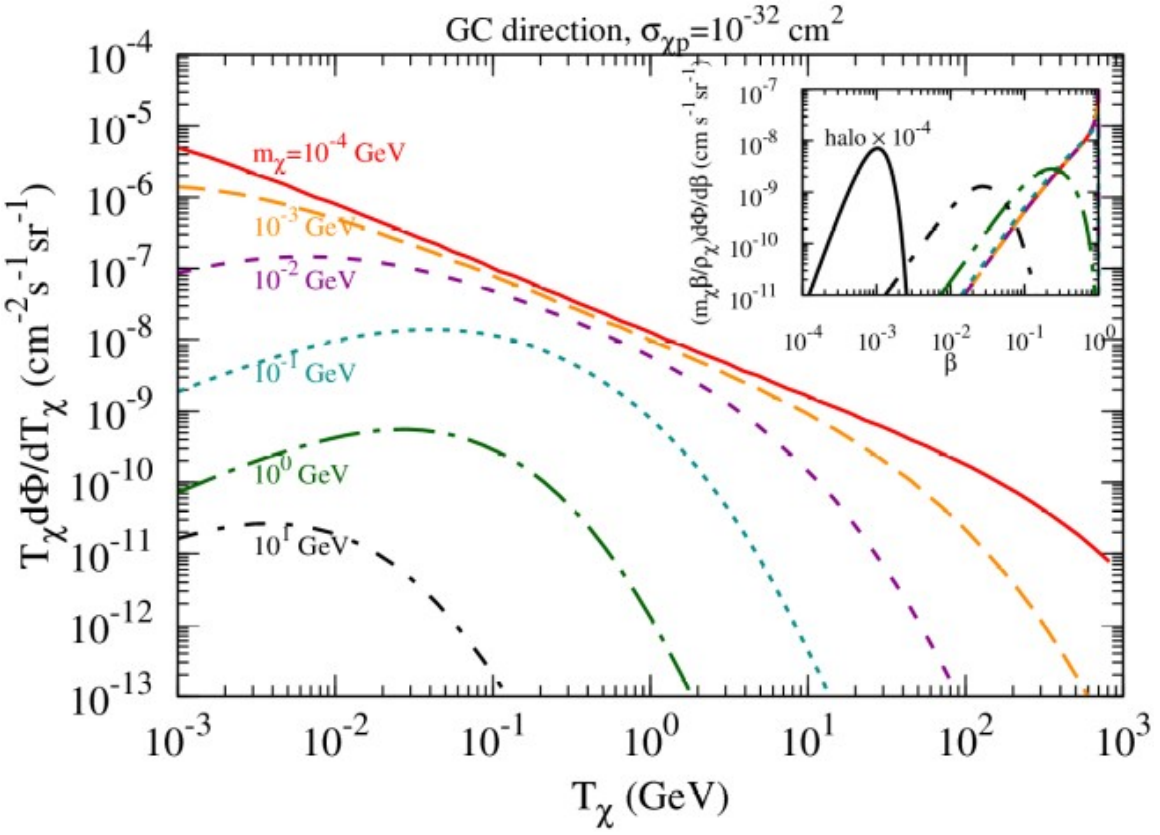
Cosmic Ray Boosted DM

Tsung-Dao Lee Institute

$$\zeta_\chi(\mathbf{r}, T_\chi) = \frac{\rho_\chi(|\mathbf{r}|)}{m_\chi} \sum_{i=p,\mathrm{He}} \int_{T_i^{\min}}^{\infty} \mathrm{d}T_i \frac{n_{\mathrm{CR},i}(\mathbf{r}, T_i)}{T_\chi^{\max}(T_i)} \times v_i \sigma_{\chi i} G_i^2(Q^2),$$

with constant $\sigma_{\chi p}$ & form factor $G_i(Q^2) \equiv 1/(1 + Q^2/\Lambda_i^2)^2$.

$$\frac{\mathrm{d}\Phi}{\mathrm{d}T_\chi}(\hat{\mathbf{n}}, T_\chi) = \frac{1}{4\pi} \int \zeta_\chi(\mathbf{r}, T_\chi)\, \mathrm{d}l$$



1. Heavier DM → smaller n_χ

$$n_\chi = \frac{\rho_\chi}{m_\chi} \propto \frac{1}{m_\chi}$$

2. lighter DM → softer spectrum

$$0 \le T_\chi \le \frac{T_i(T_i + 2m_i)}{T_i + m_\mu^i} \approx \frac{T_i^2}{T_i + m_i^2/2m_\chi}$$

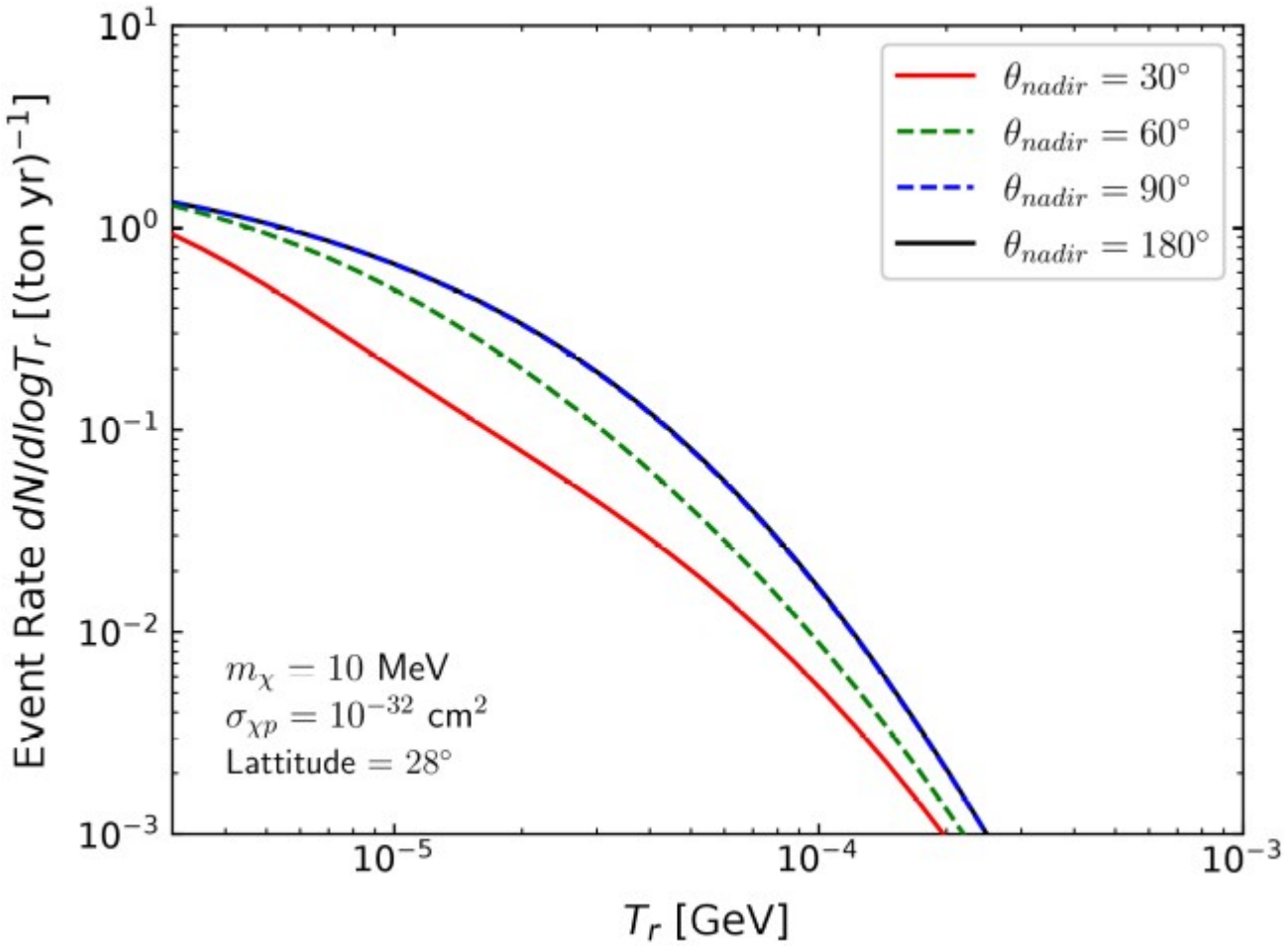
for $m_\chi \ll m_i$

SFG, Jianglai Liu, Ning Zhou, Qiang Yuan [arXiv:2005.09480 [hep-ph]]

See also Bringmann & Pospelov, PRL 2019 [arXiv:1810.10543 [hep-ph]]

Direct Detection

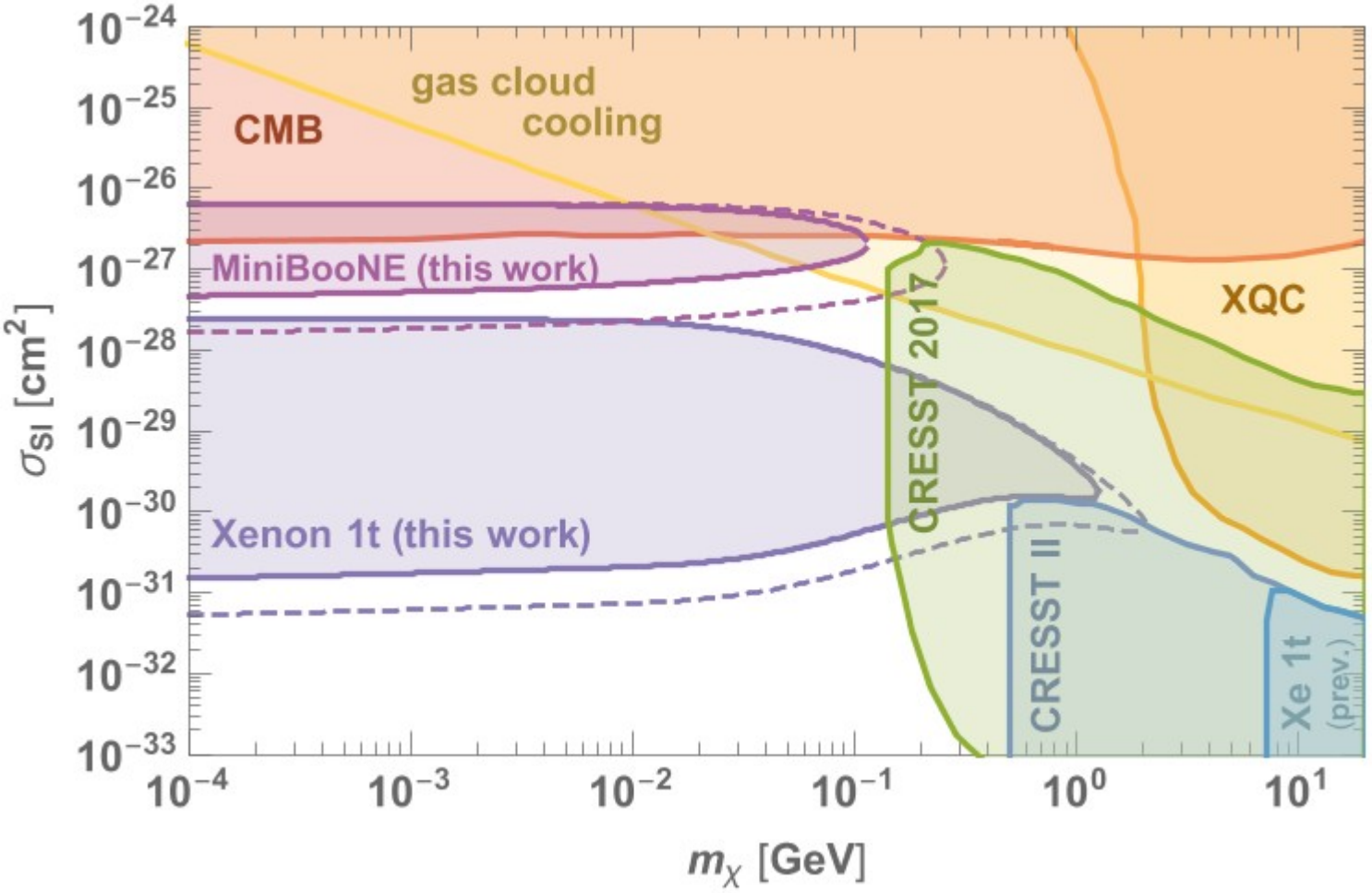
$$\sigma_{\chi A} = \sigma_{\chi p} A^2 \left[\frac{m_A(m_\chi + m_p)}{m_p(m_\chi + m_A)}\right]^2 \qquad G_i(Q^2) \equiv 1/(1 + Q^2/\Lambda_i^2)^2$$



The nuclear recoil from CRDM is much more energetic!

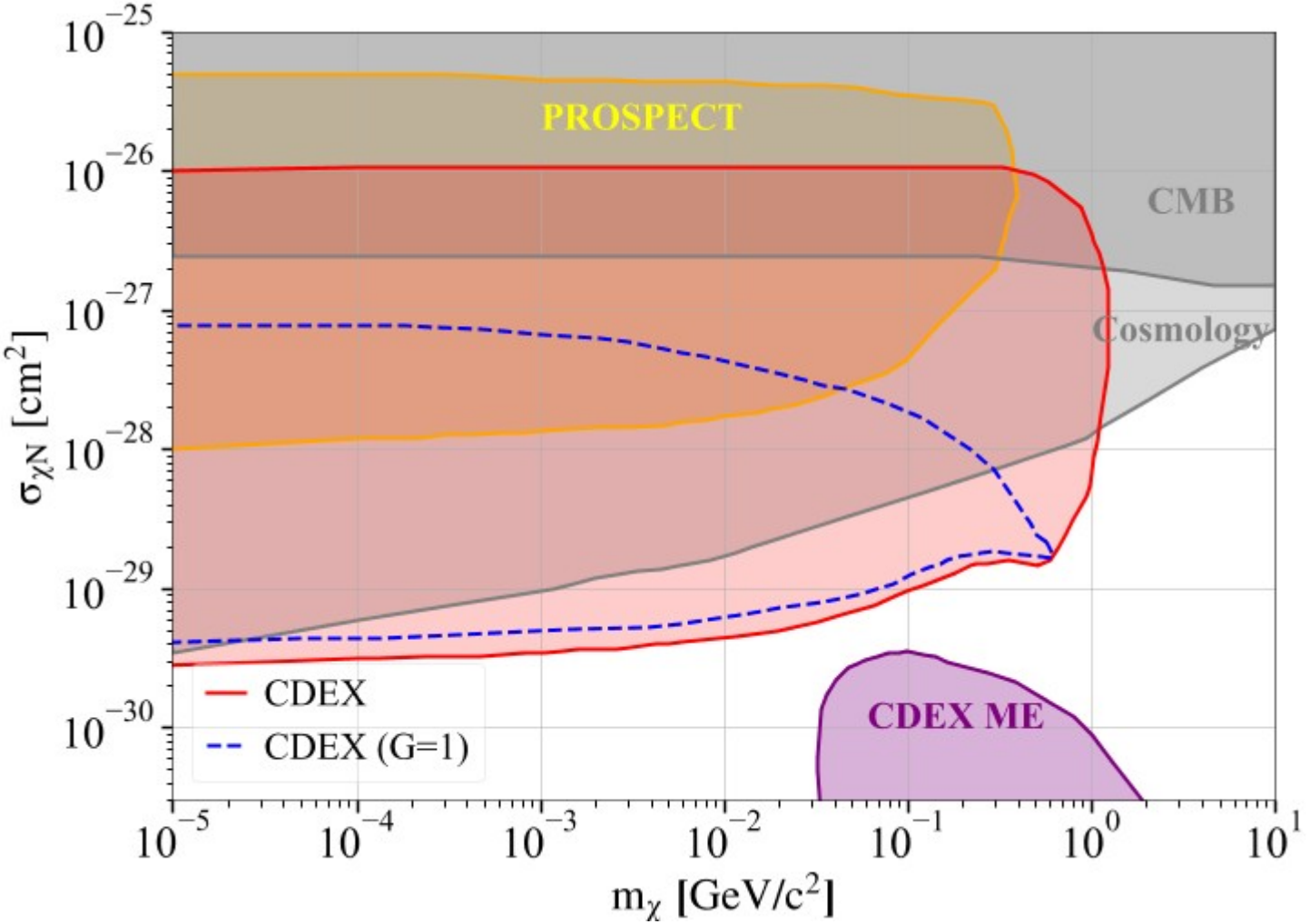
SFG, Jianglai Liu, Ning Zhou, Qiang Yuan [arXiv:2005.09480 [hep-ph]]

Projected Sensitivities



Bringmann & Pospelov, PRL 2019 [arXiv:1810.10543 [hep-ph]]

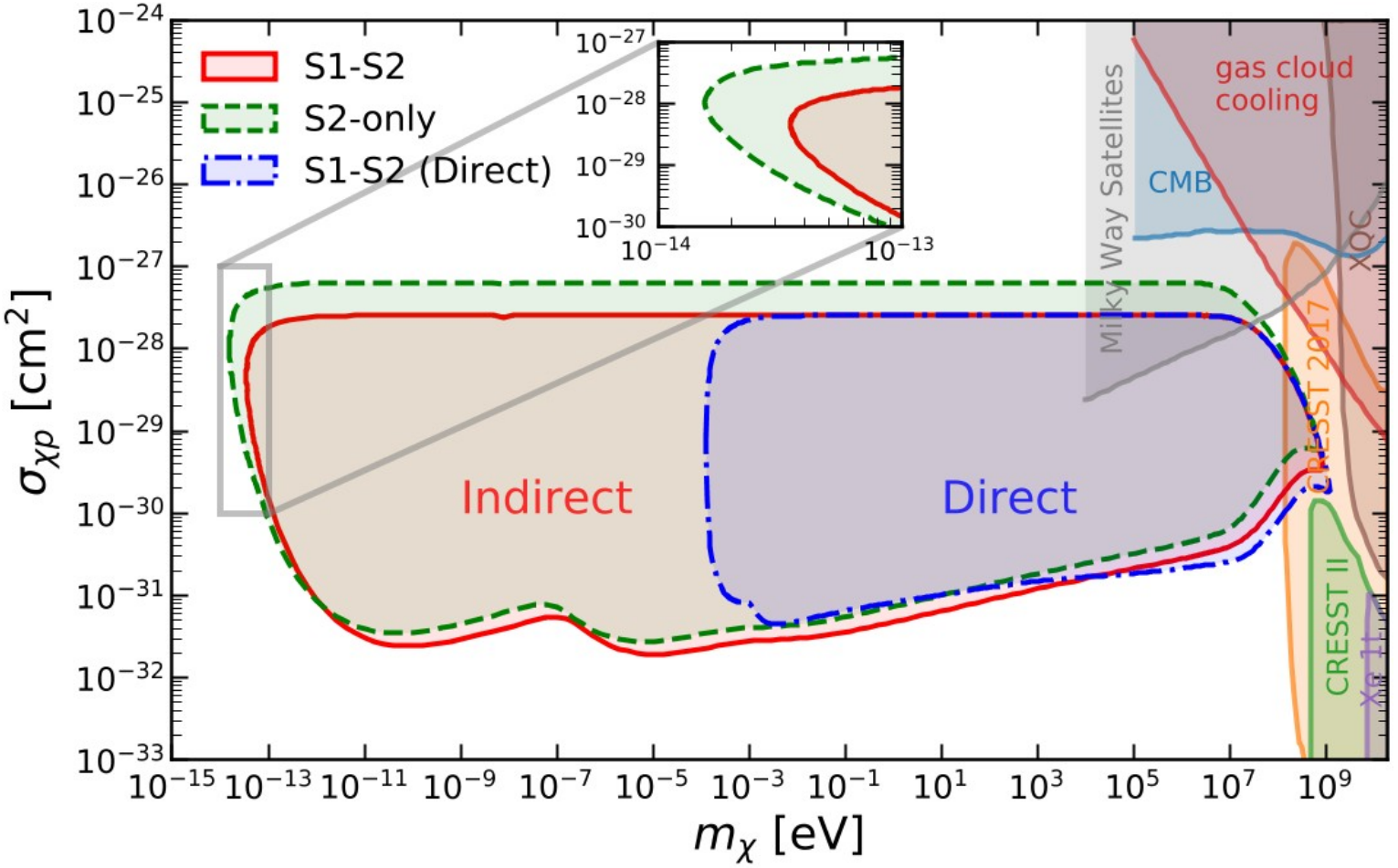
Sensitivity @ CDEX



Zhang, Lei & Tang [2008.07116]

CDEX [2201.01704]

Kinematic Limits



$$0 \leq T_\chi \leq \frac{T_i(T_i + 2m_i)}{T_i + m_\mu^i} \approx \frac{T_i^2}{T_i + m_i^2/2m_\chi} \quad \text{for} \quad m_\chi \ll m_i$$

Xia, Xu & Zhou [2009.00353]

Anisotropies → Diurnal Effect

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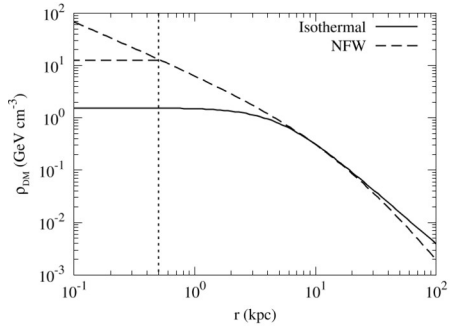
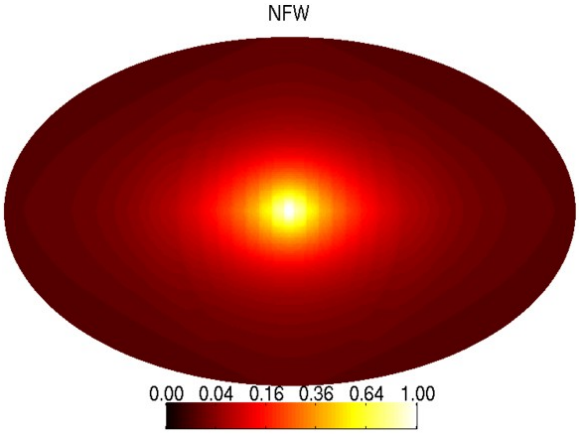
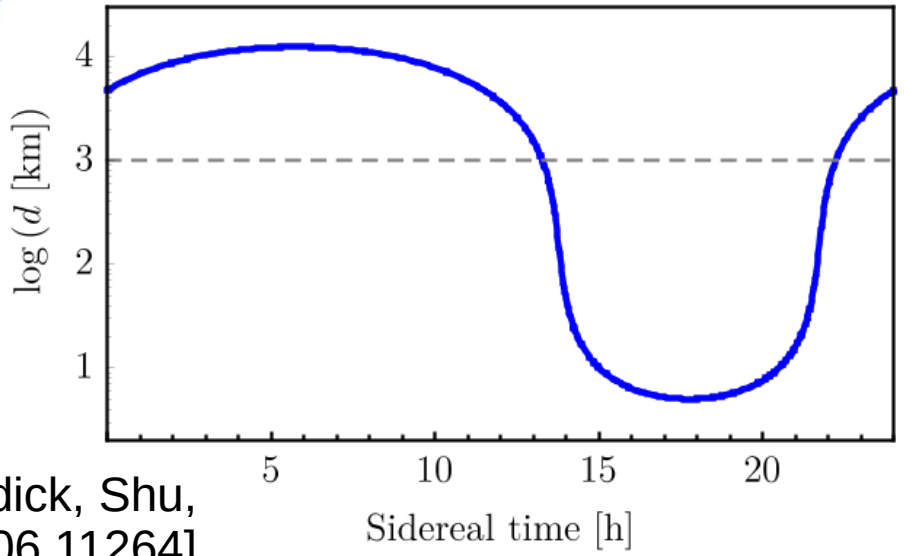


Cosmic Rays

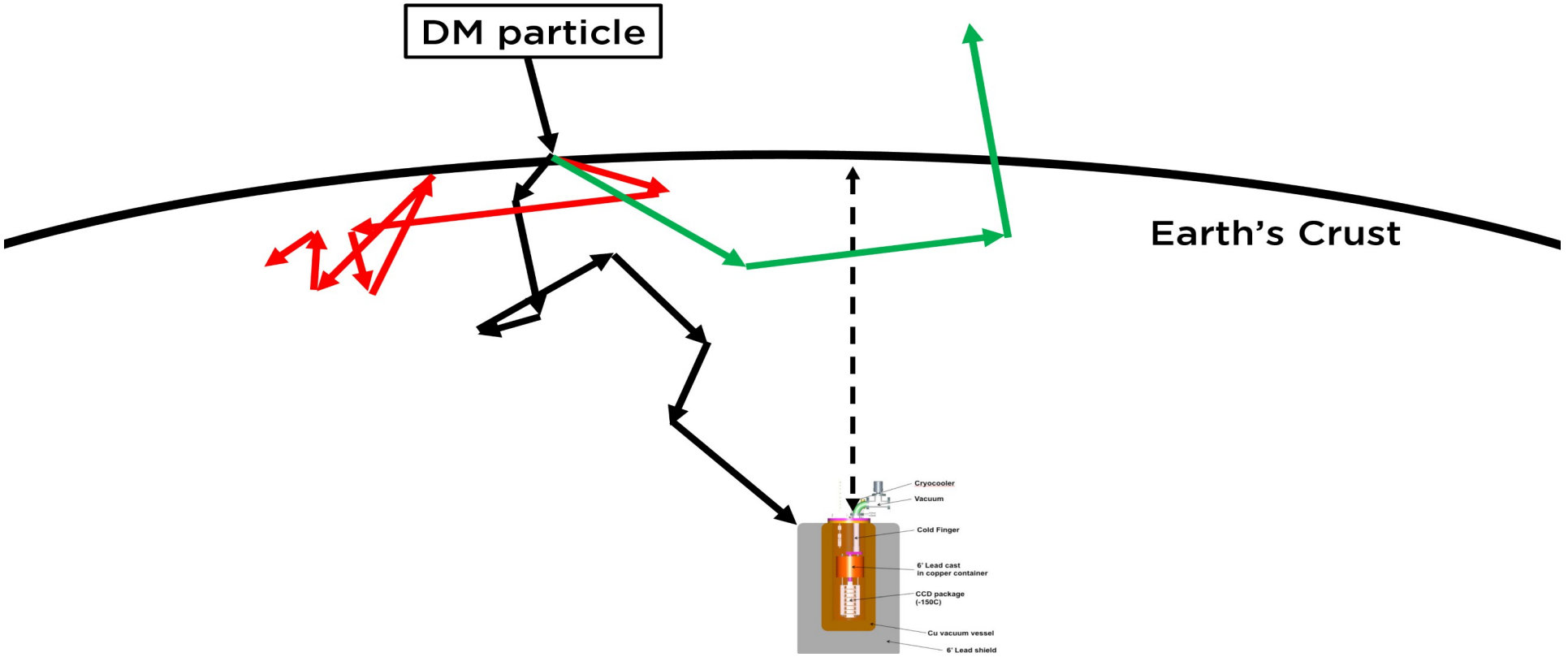
DM





Fornal, Sandick, Shu, Su & Zhao [2006.11264]

Earth Attenuation

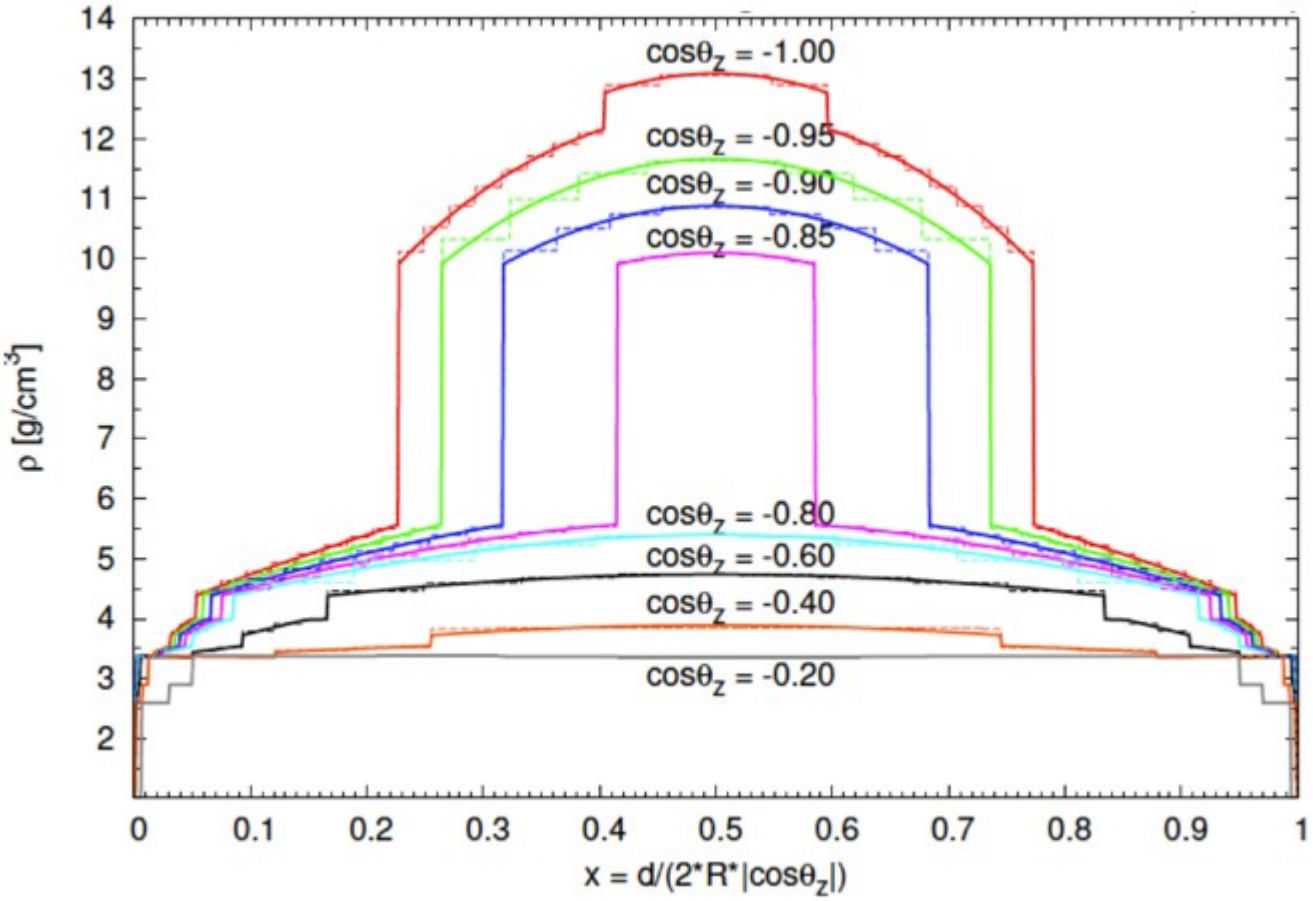


$$\frac{\partial}{\partial l}\frac{d\Phi(l,T_\chi)}{d\ln T_\chi} = \frac{\rho_N(l)}{m_N}\sigma_{\chi N}G_N^2(Q^2)\left[-\frac{d\Phi(l,T_\chi)}{d\ln T_\chi} + \int \frac{d\Phi\left(l,T'_\chi\right)}{d\ln T'_\chi}\frac{T_\chi(T'_\chi+m_\mu^N)}{T'_\chi(T'_\chi+2m_\chi)}d\ln T'_\chi\right]$$

Transfer to lower energy

Come from higher energy

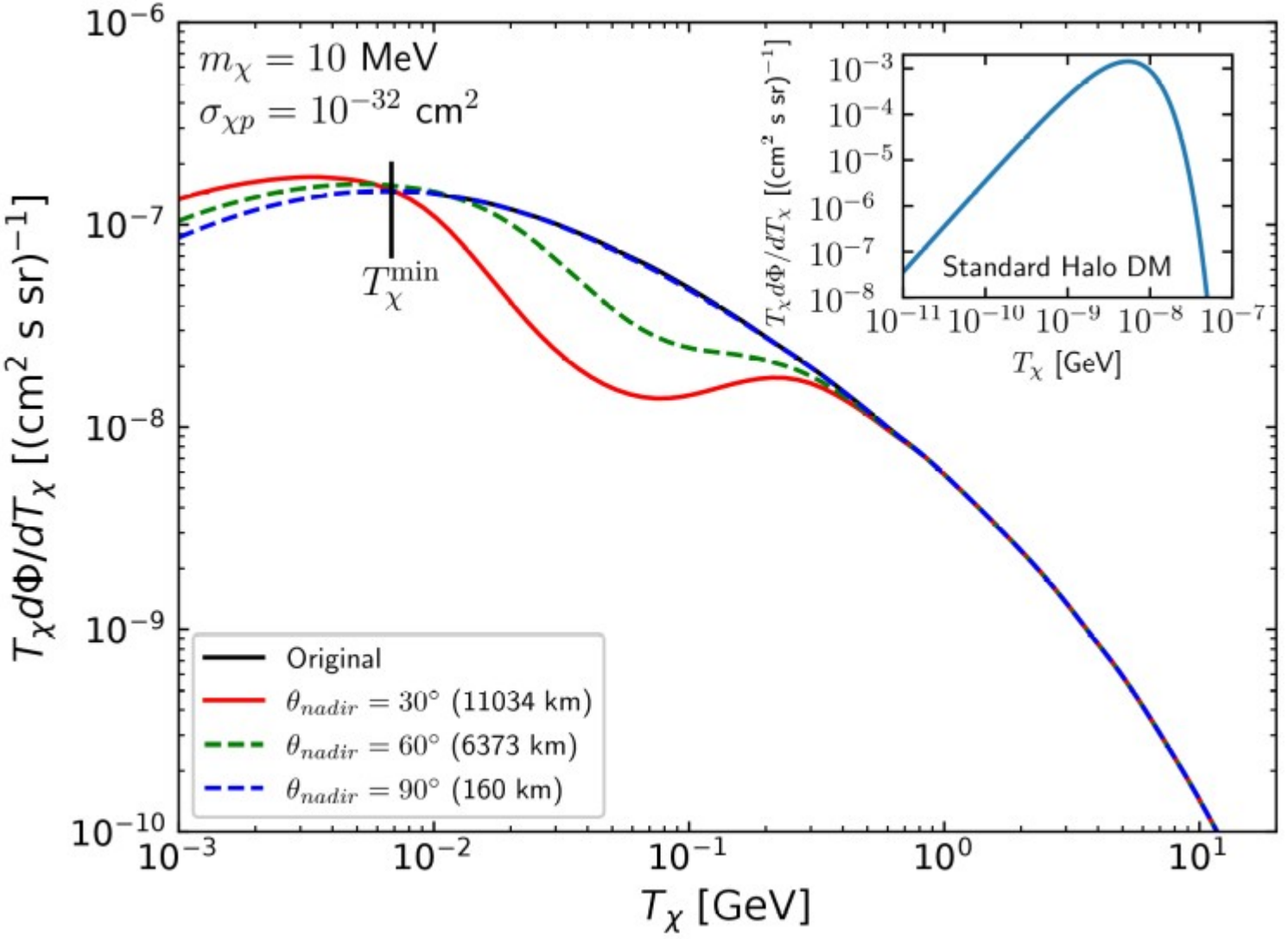
Earth Density Profile



SFG, Hagiwara, Rott [1309.3176]

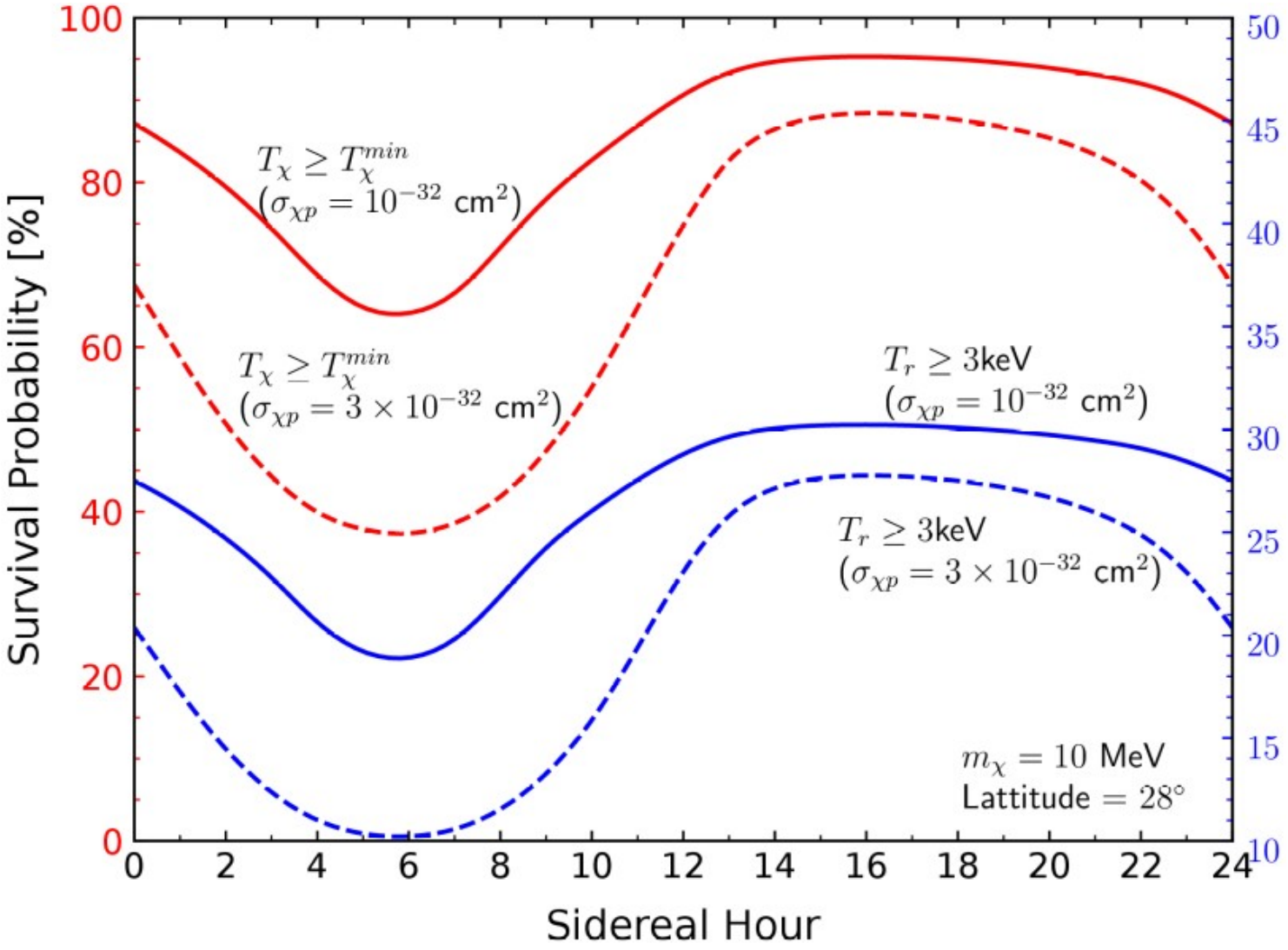
The earth matter can be approximated by 2-step profile.

Attenuated Flux



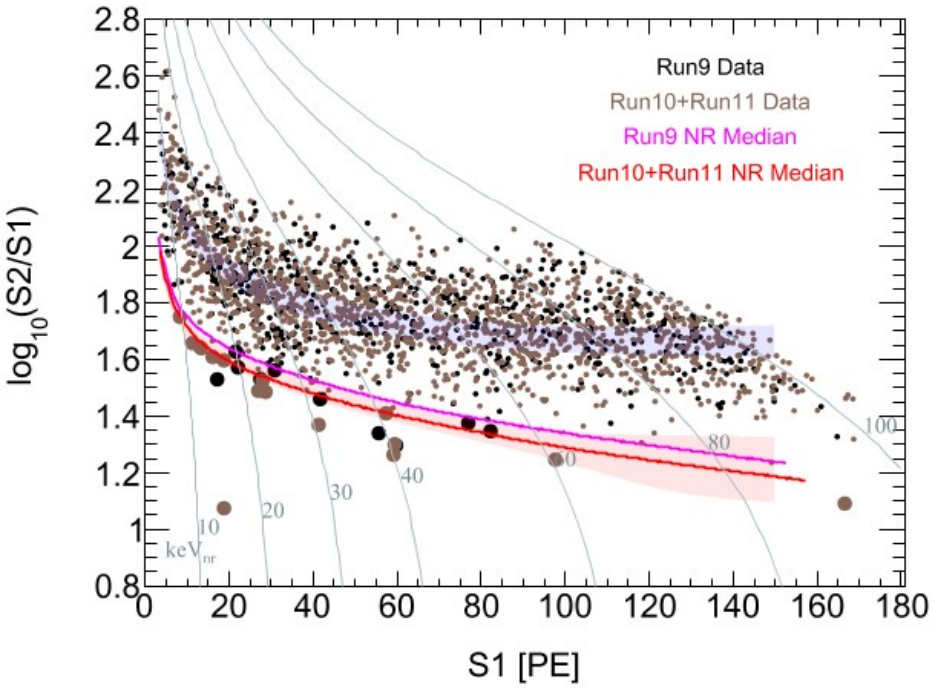
SFG, Jianglai Liu, Ning Zhou, Qiang Yuan [arXiv:2005.09480 [hep-ph]]

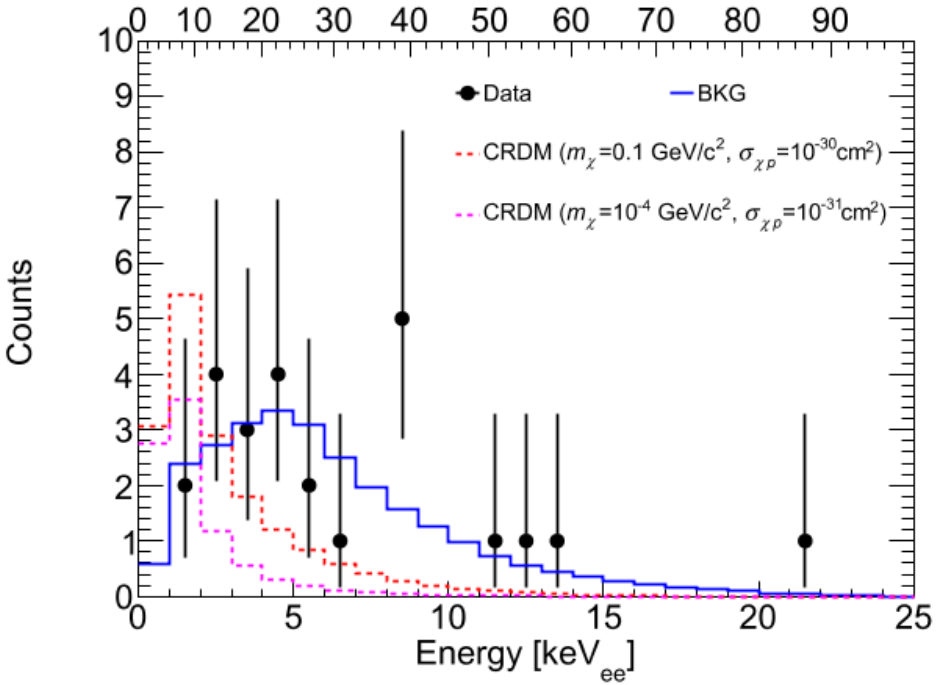
Diurnal Effect



SFG, Jianglai Liu, Ning Zhou, Qiang Yuan [arXiv:2005.09480 [hep-ph]]

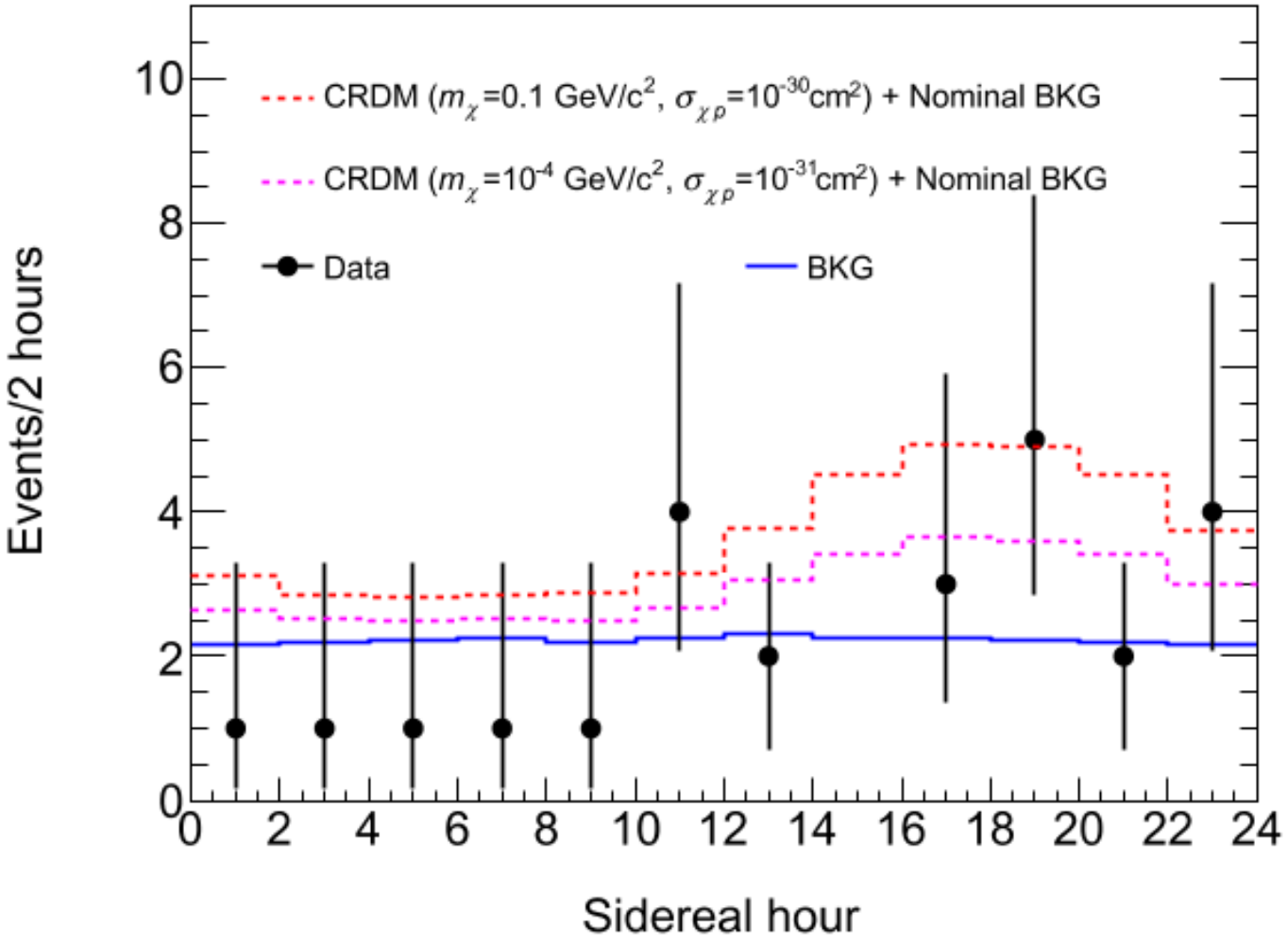
PandaX-II Data





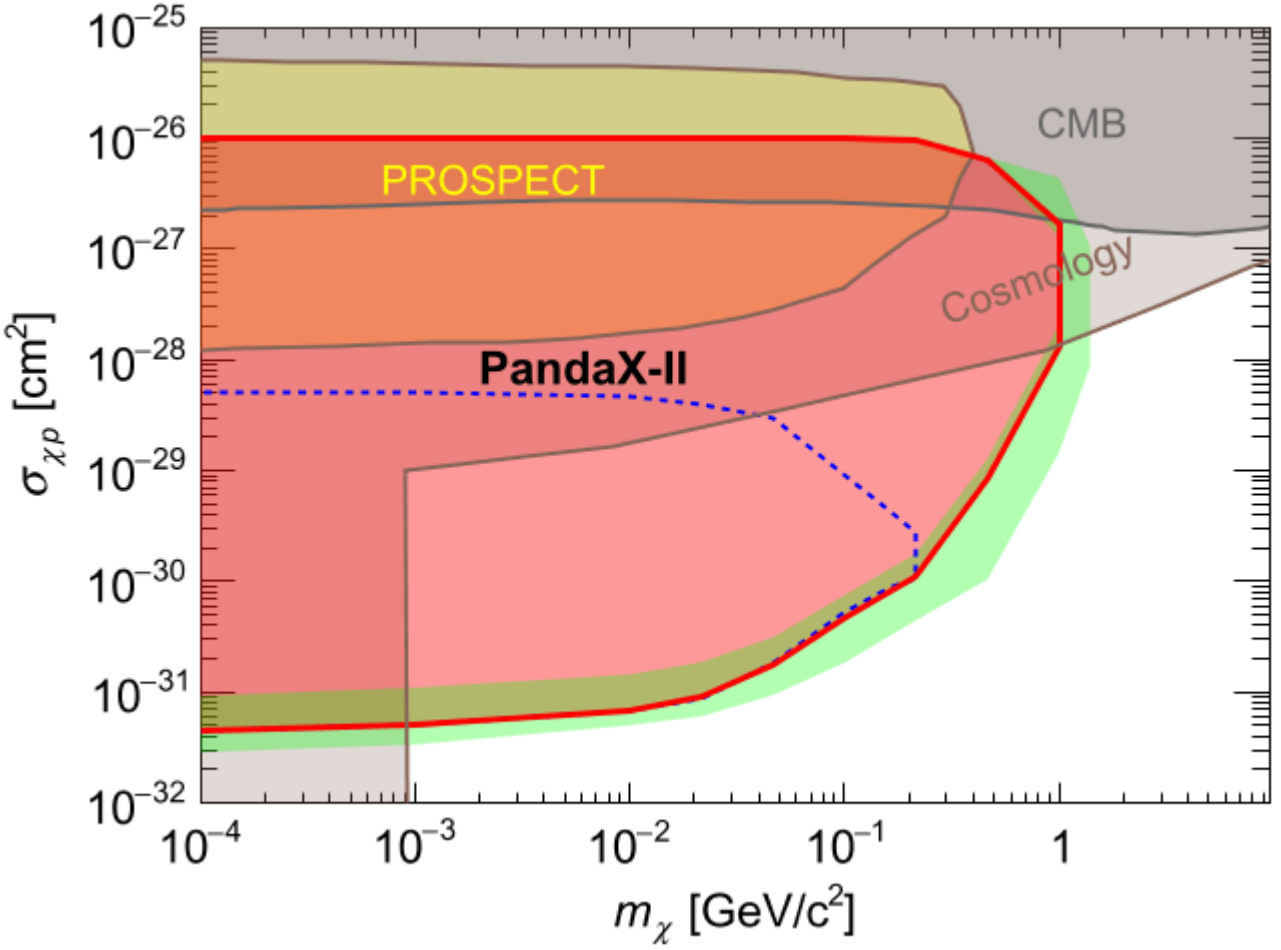
PandaX-II + **SFG** & Qiang Yuan [2112.08957]

Diurnal Modulation @ PandaX



PandaX-II + **SFG** & Qiang Yuan [2112.08957]

Sensitivity @ PandaX



PandaX-II + **SFG** & Qiang Yuan [2112.08957]

Fermionic Absorption

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

PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [2206.02339]

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**

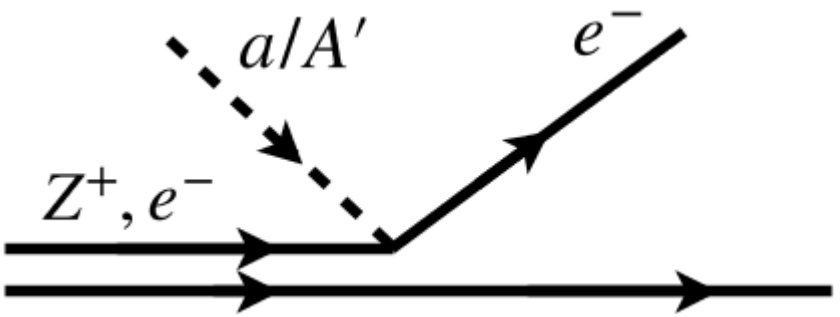
$$\chi + e \to \nu + e \qquad E_r \approx \frac{m_\chi^2}{2 m_e}$$

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

Dror, Elor, McGehee & Yu [2011.01940]

Bosonic Absorption DM

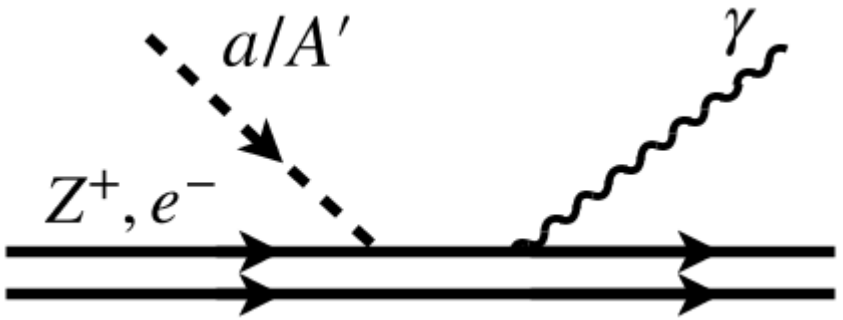
- **Dark absorption**



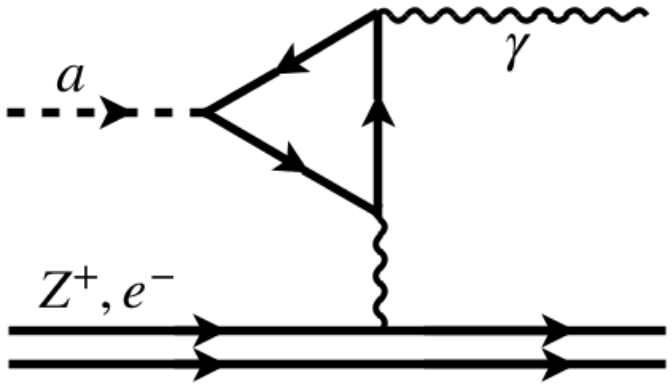
Pospelov, Ritz & Voloshin [0807.3279]

An, Pospelov, Pradler & Ritz [1412.8378]

- **Dark Compton**

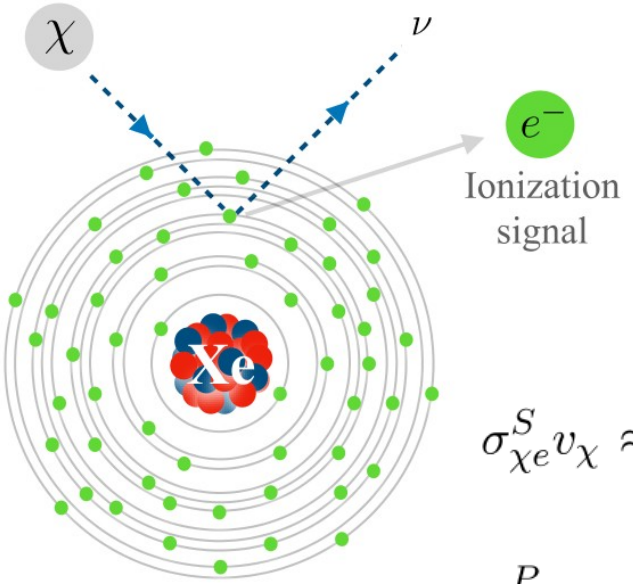


- **Inverse Primakoff**



Hochberg, Krosigk, Kuflik & Yu [2109.08168]

Effective Operators



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

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

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

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

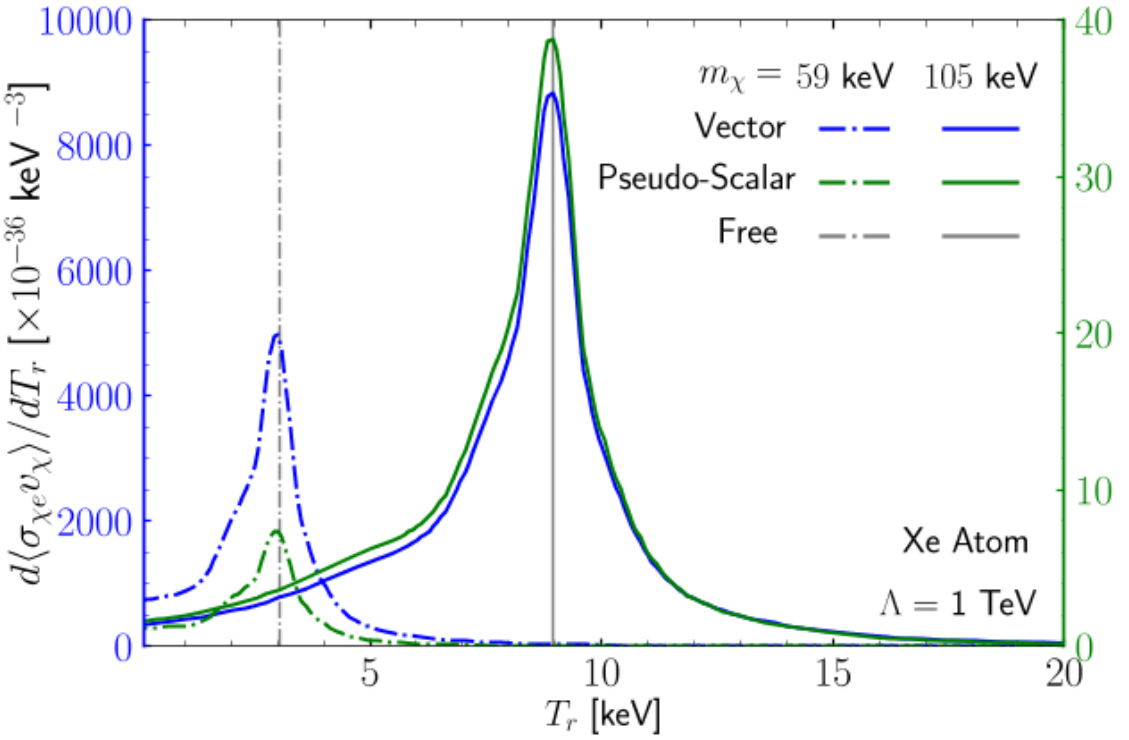
$$\sigma^A_{\chi e}v_\chi \approx \frac{1}{\Lambda^4}\frac{m_\chi^2(2m_e+m_\chi)^2(6m_e^2+8m_em_\chi+3m_\chi^2)}{32\pi(m_e+m_\chi)^4},$$

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

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

Kinematics of Absorption DM

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

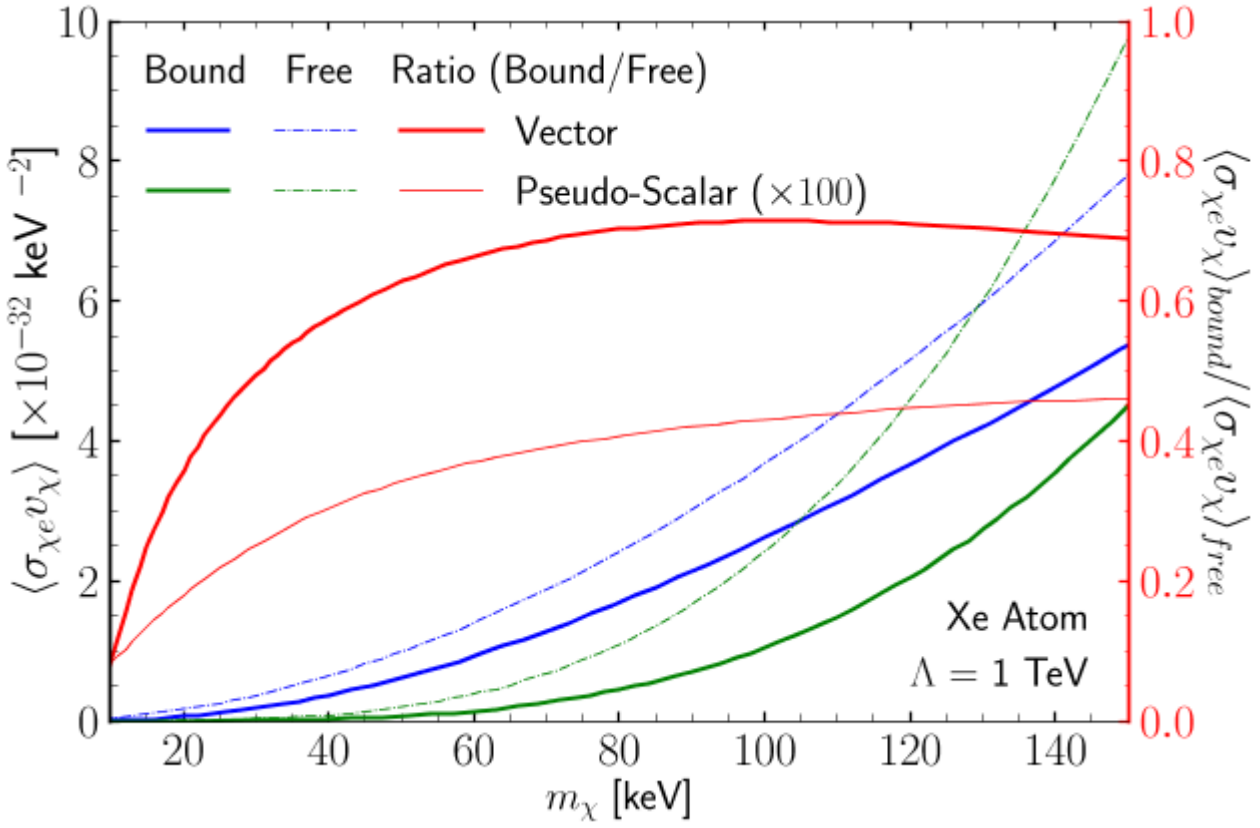


$$\frac{d\langle\sigma_{\chi e} v_\chi\rangle}{dT_r} = \sum_{nl}(4l+2)\frac{1}{T_r}\frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi}|\mathcal{M}|^2(\mathbf{q})K_{nl}(T_r, |\mathbf{q}|),$$

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

Atomic Effects

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



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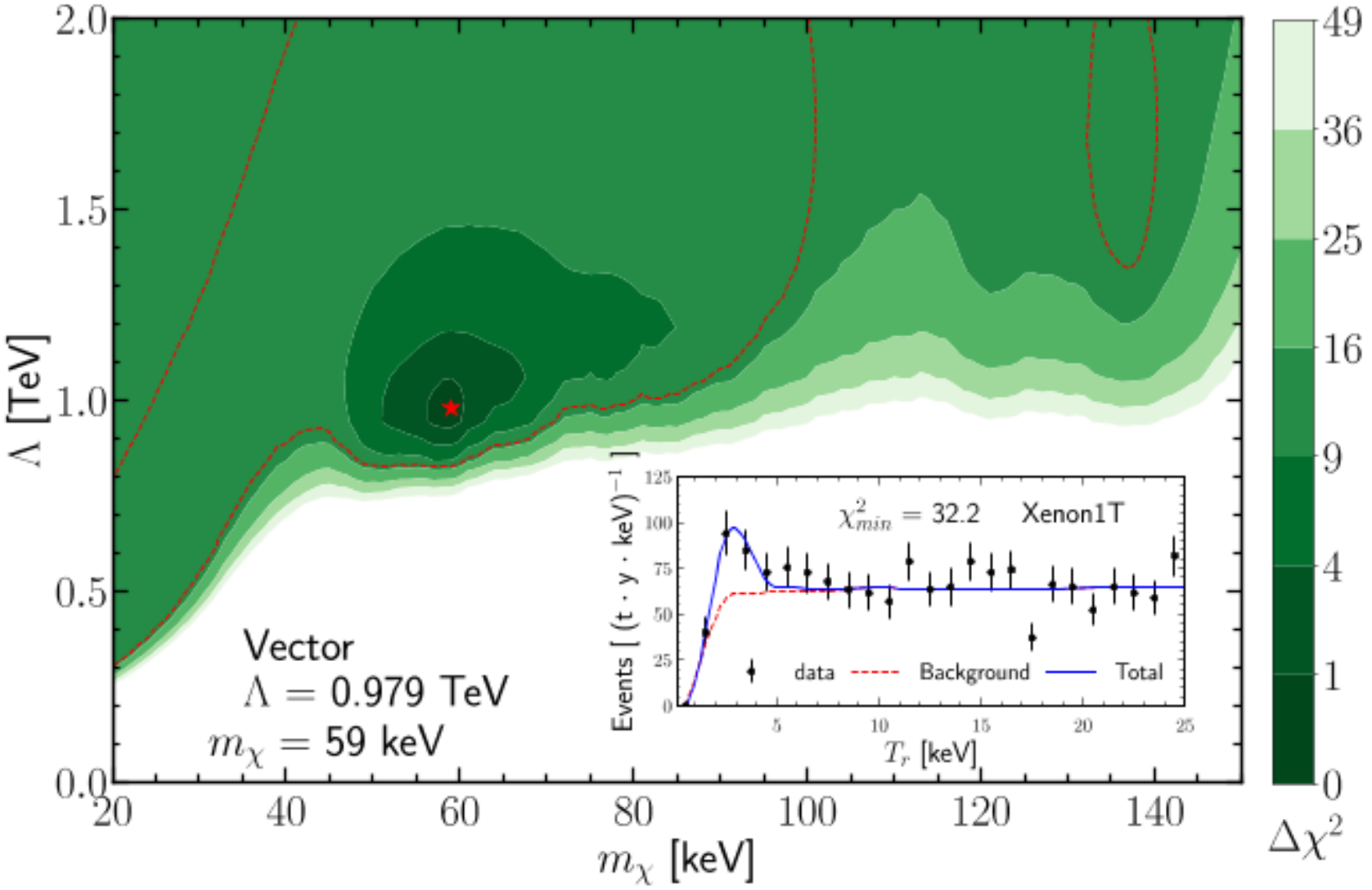
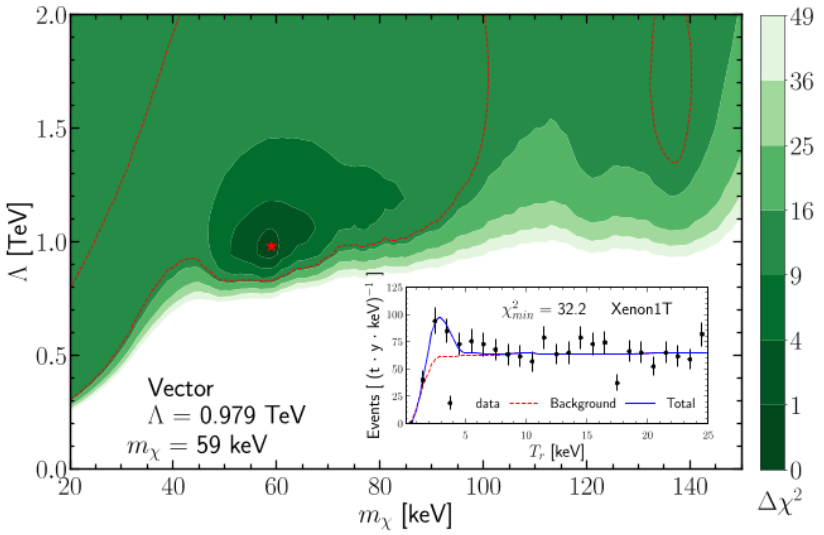
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

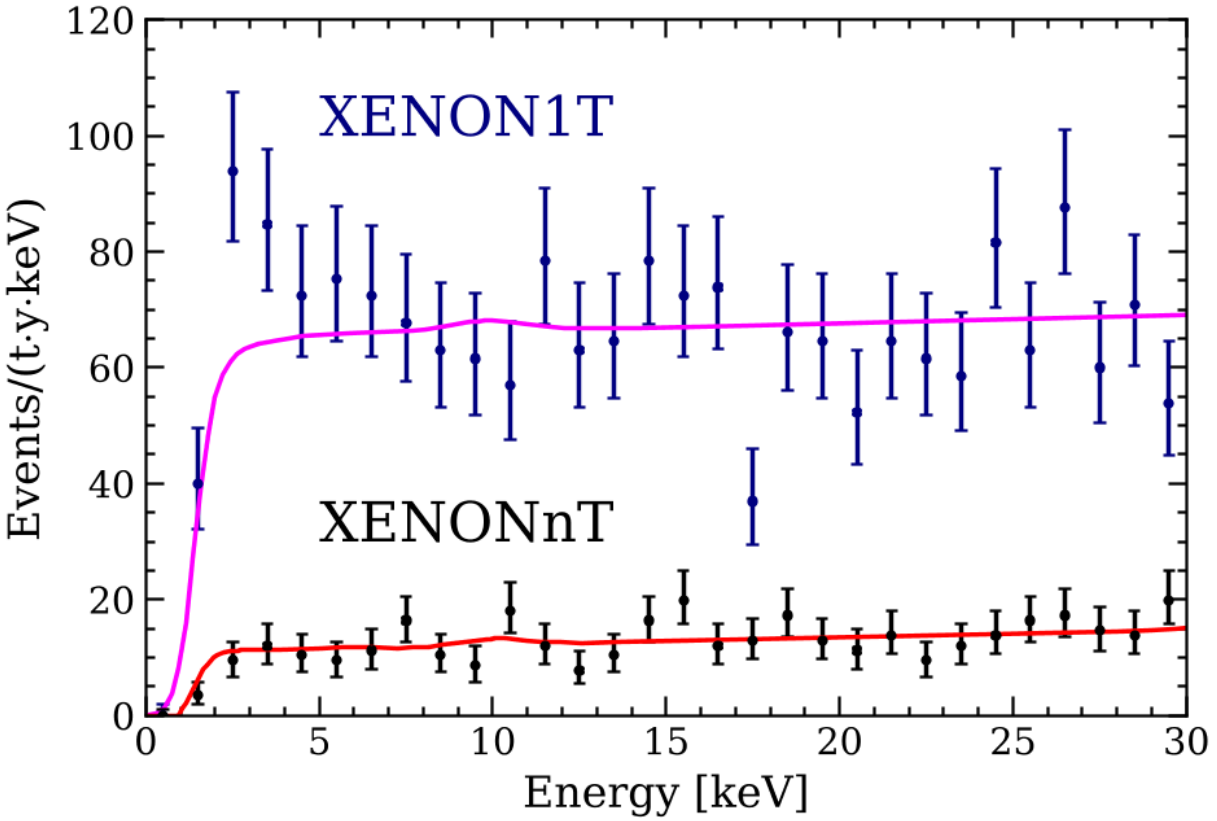
Xenon1T excess



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

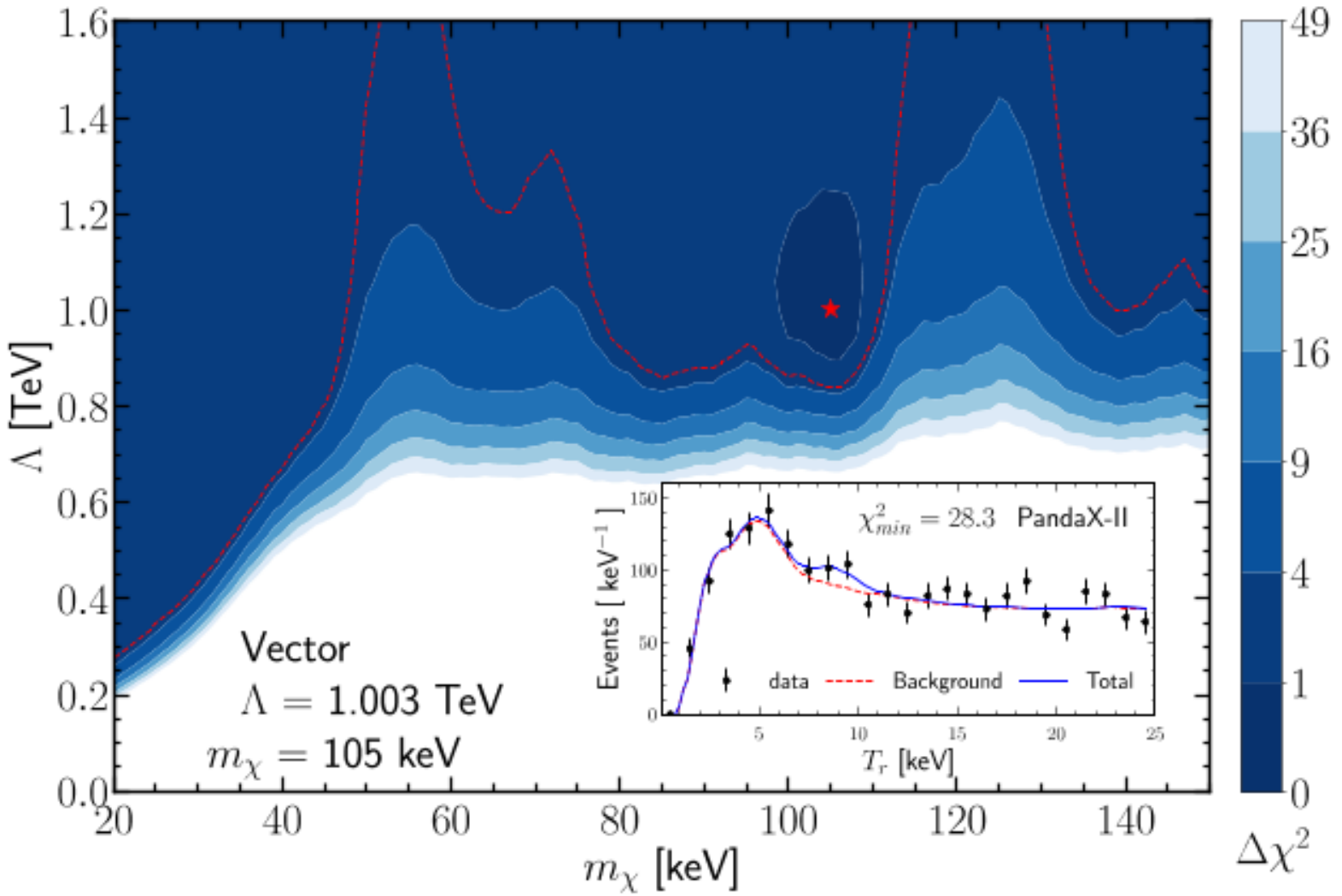
Xenon1T excess





Knut Dundas Morå @ IDM2022

PandaX-II



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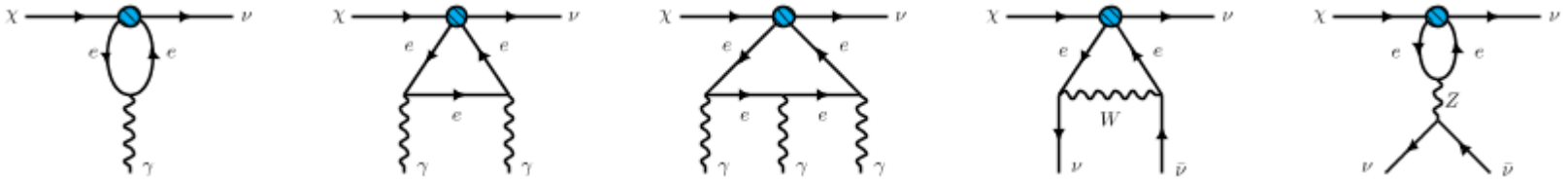
Visible & Invisible Decays



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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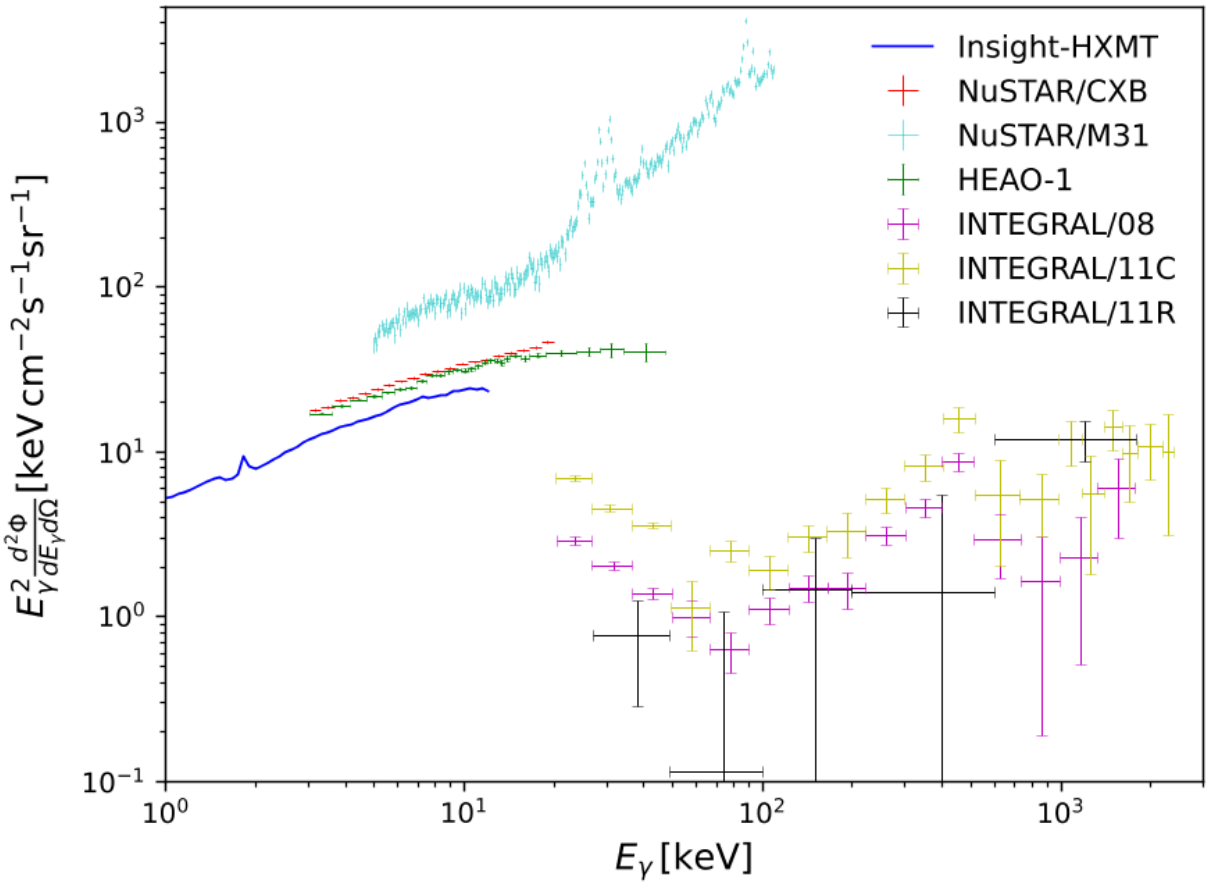
Astro Observations



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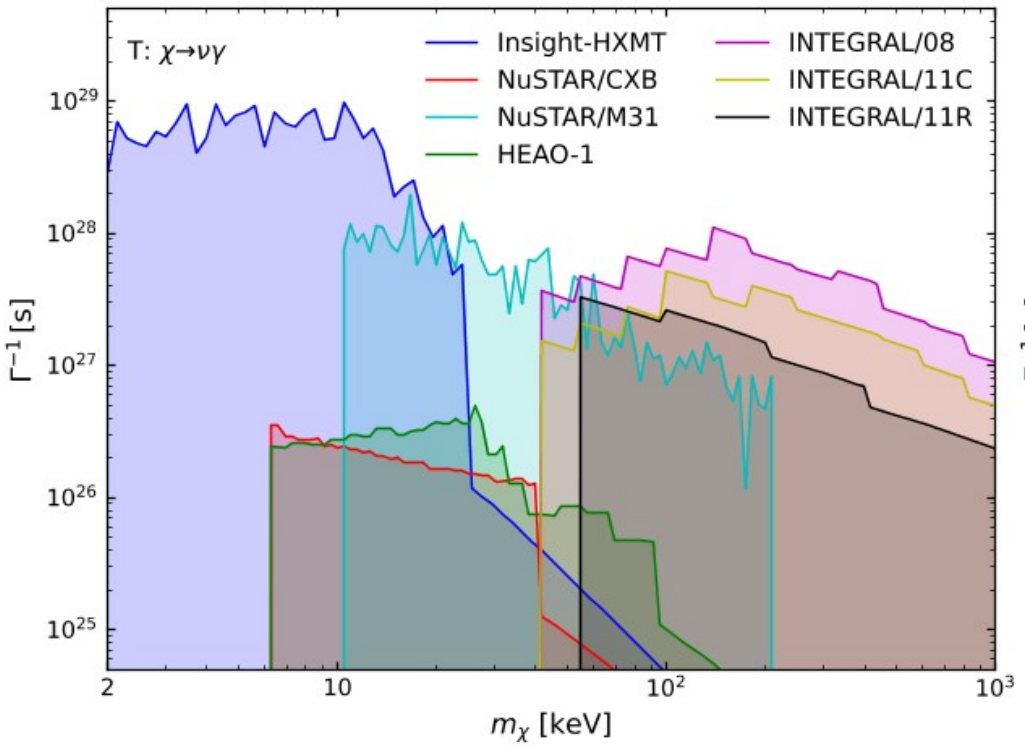
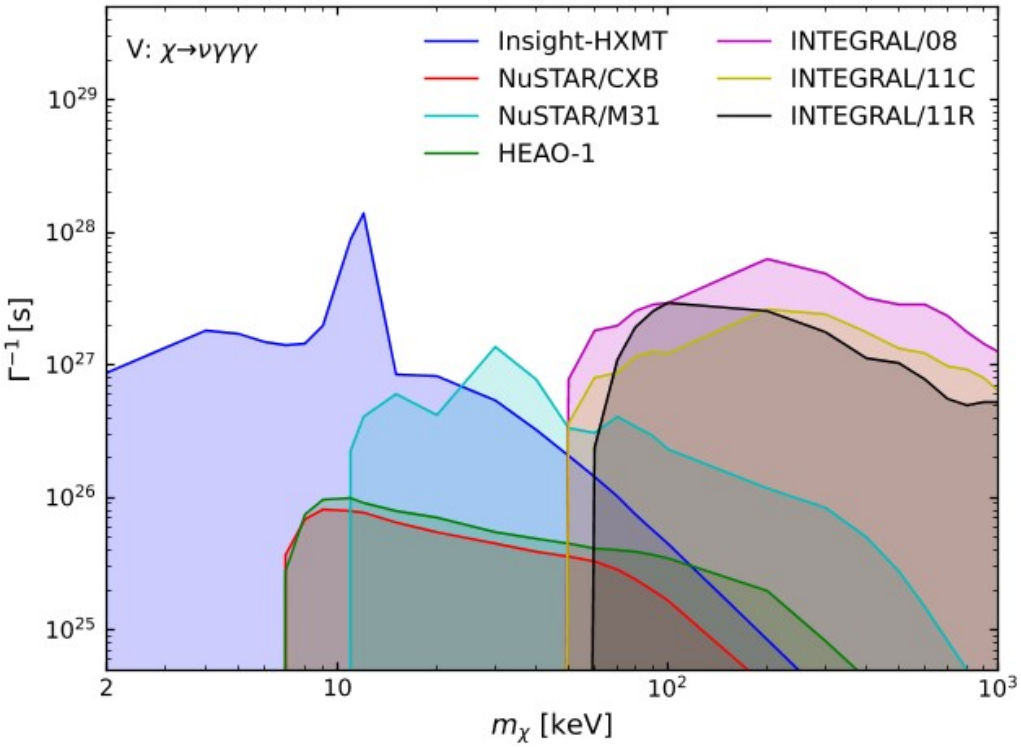
$$N_i^{\rm th} \leq N_i^{\rm obs} \equiv A_{\rm eff} T_{\rm obs} \Delta\Omega \left(\frac{d^2\Phi_\gamma}{dE_\gamma d\Omega} \right)^i_{\rm exp@95\%} \Delta E_i$$

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





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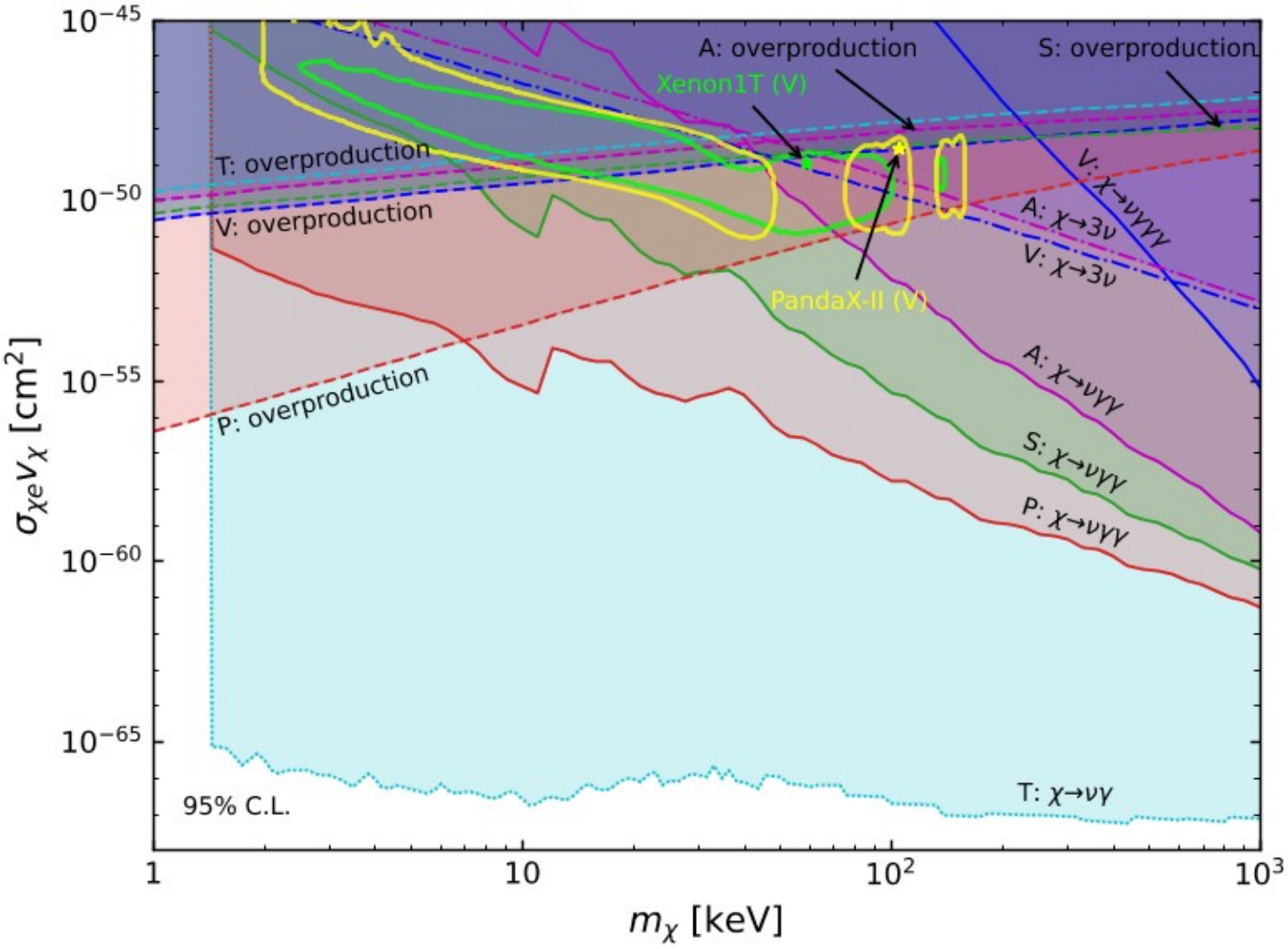
Constraints from Astro & Cosmo



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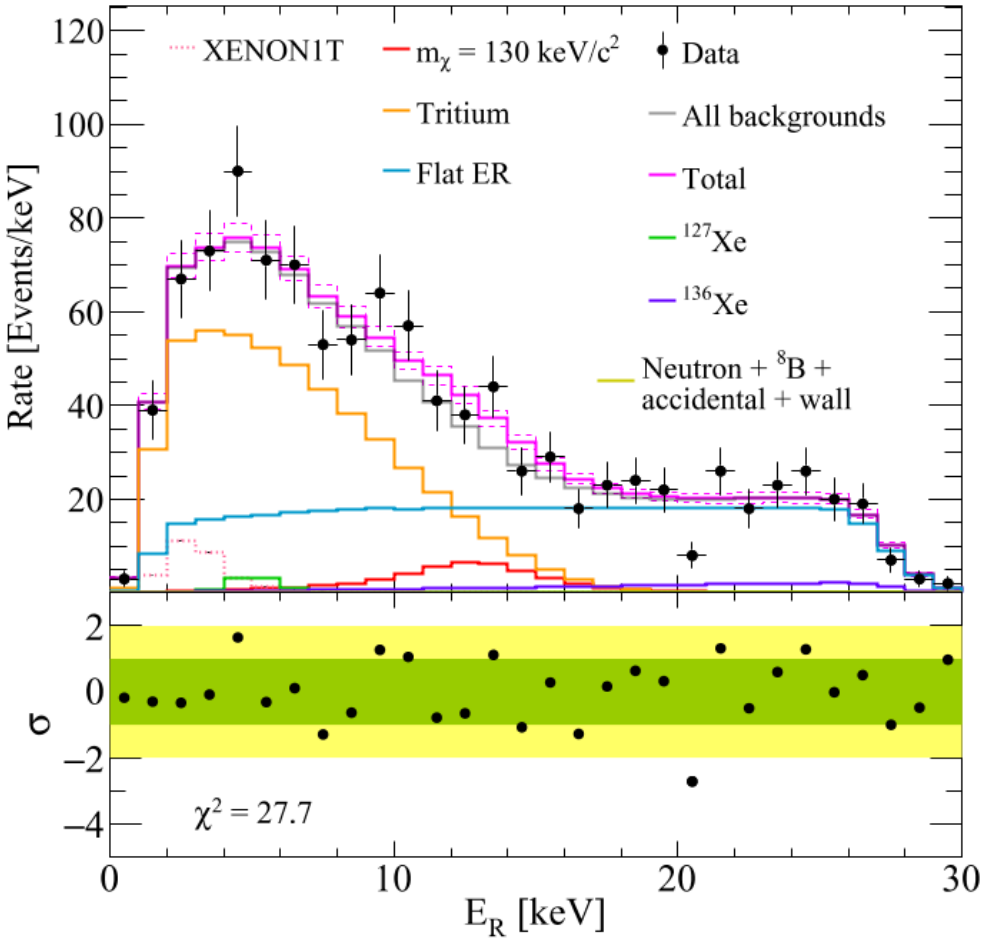
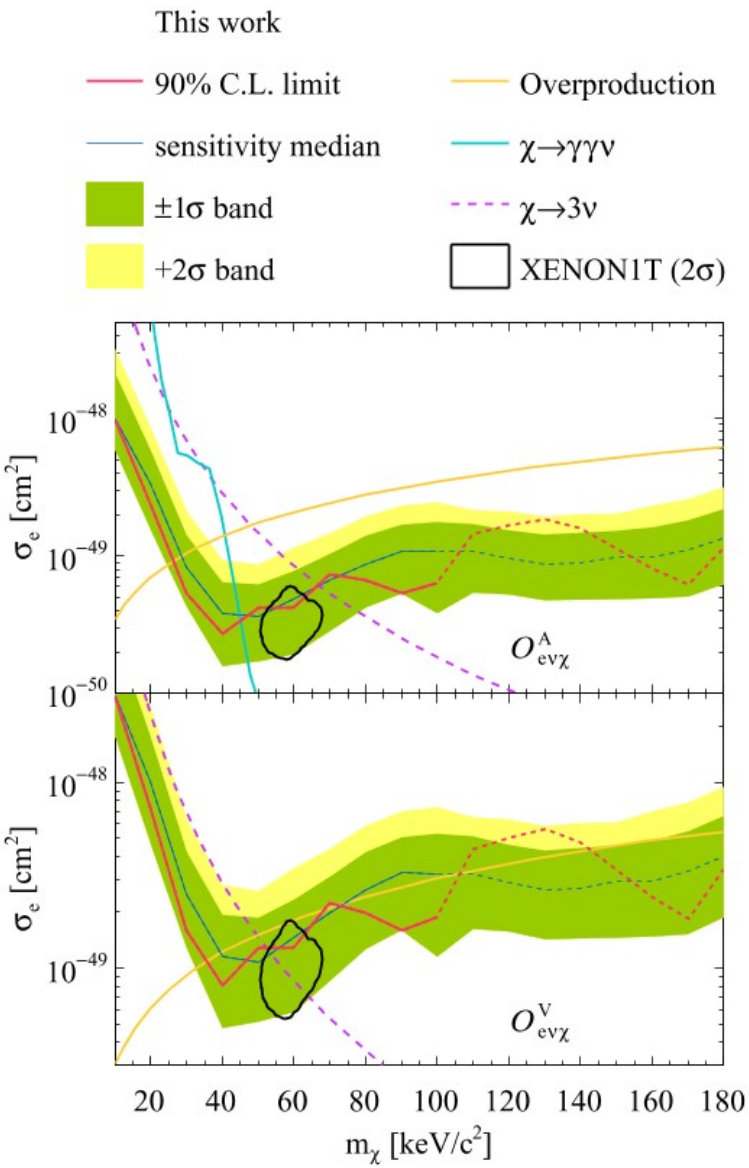
PandaX-4T Results





PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [2206.02339]

Summary

1) How to exhaust the sub-GeV range?

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

- **Can happen as long as DM scatters with nuclei**
- **Large recoil**
- **Diurnal modulate as prominent feature**

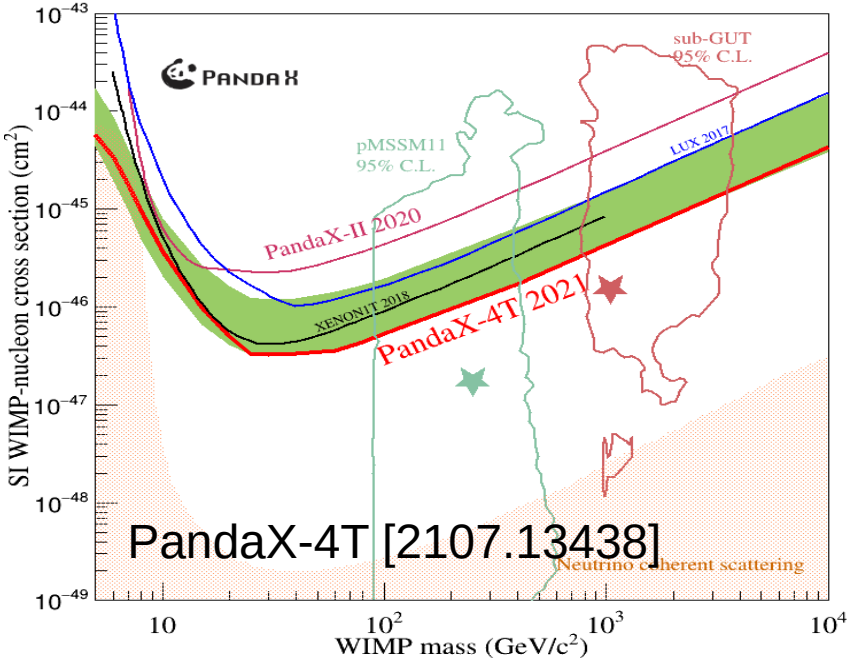
3) **Fermionic DM absorption**

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

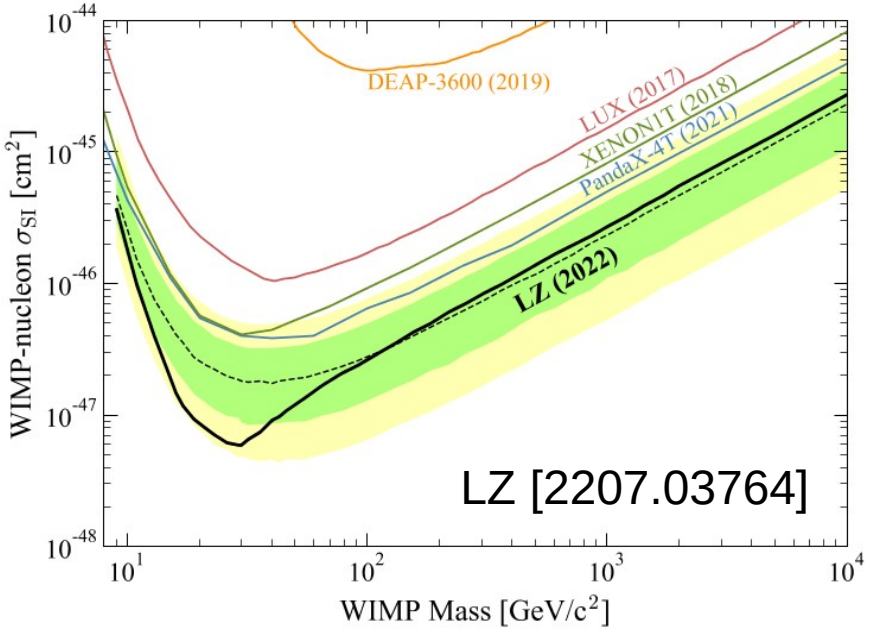
李政道研究所
Tsung-Dao Lee Institute

Thank You

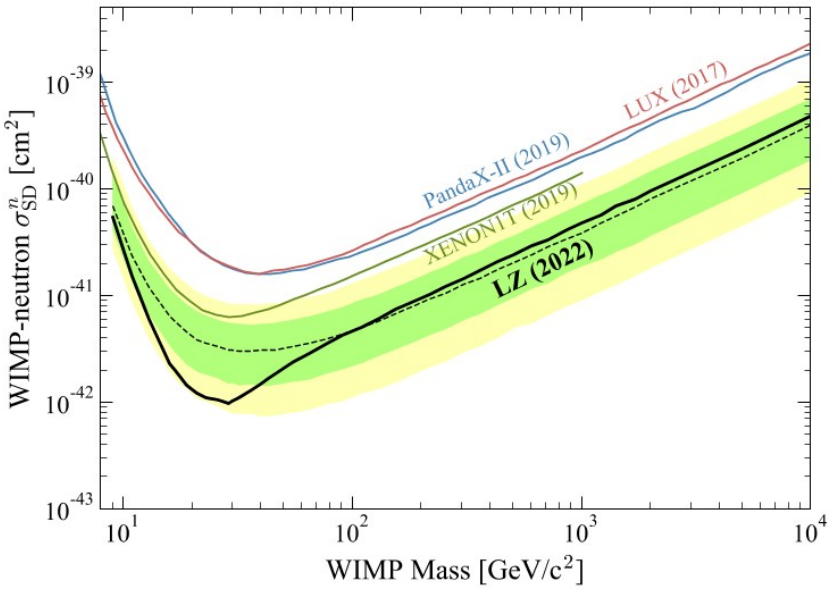
Current Sensitivity



PandaX-4T [2107.13438]



LZ [2207.03764]



Overproduction

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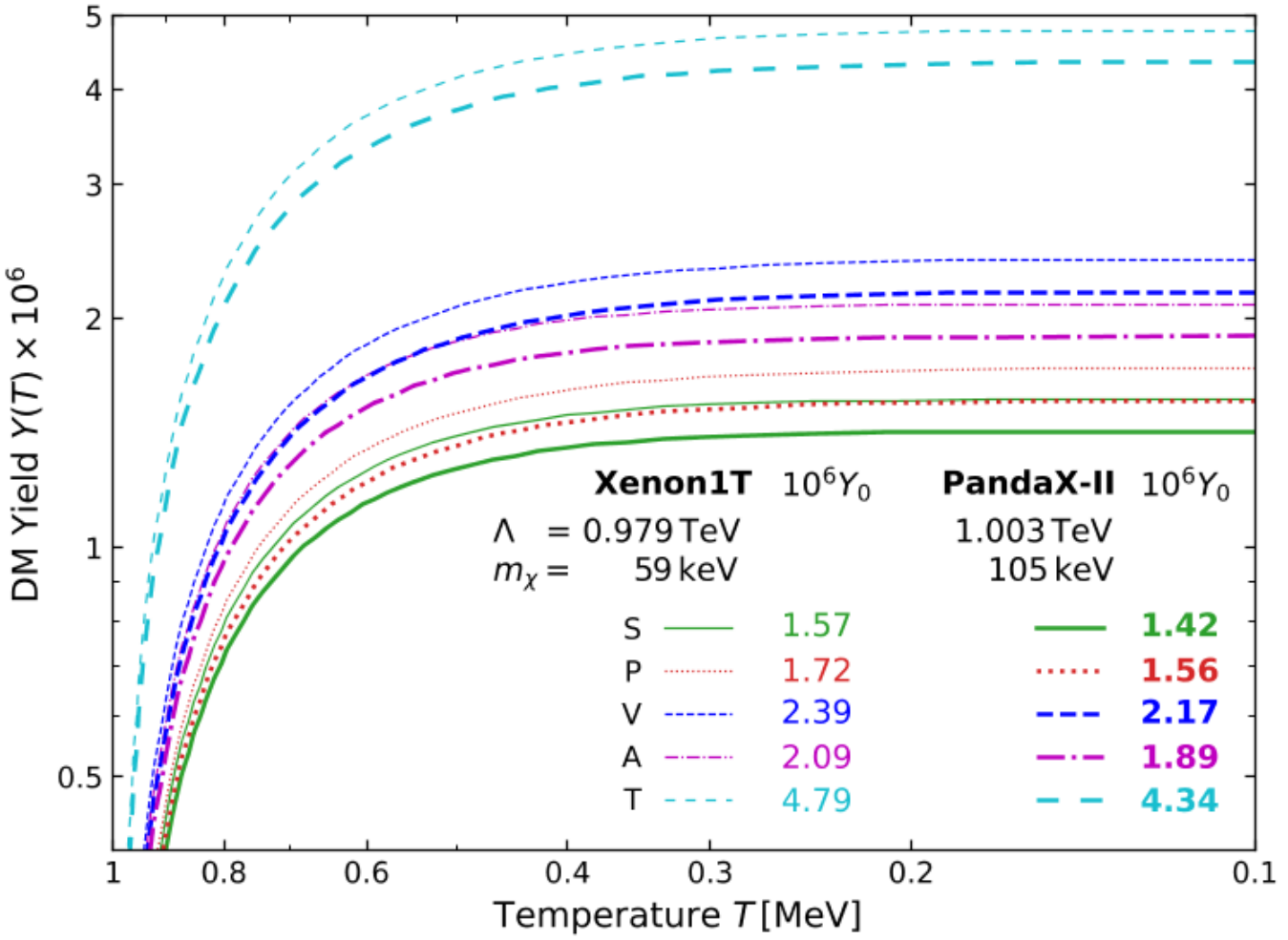
$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle v_{\text{Møl}}\sigma_{e^+e^-}\rangle n_{e^+}^{\text{eq}} n_{e^-}^{\text{eq}}$$



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