Overcoming Thresholds for Dark Matter Search

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DM Landscape @ MITP
September 2, 2024

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Outline

1) Thresholds in DM search

2) **Fermionic DM Absorption & Nucleon Consumption**

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, Kai Ma, Xiao-Dong Ma, Jie Sheng [JHEP 11 (2023) 190]
Kai Ma, **SFG**, Lin-Yun He, Ning Zhou [arXiv:2405.16878]
SFG, Oleg Titov [arXiv:2405.05728]
SFG, Xiao-Dong Ma [arXiv:2406.00445]

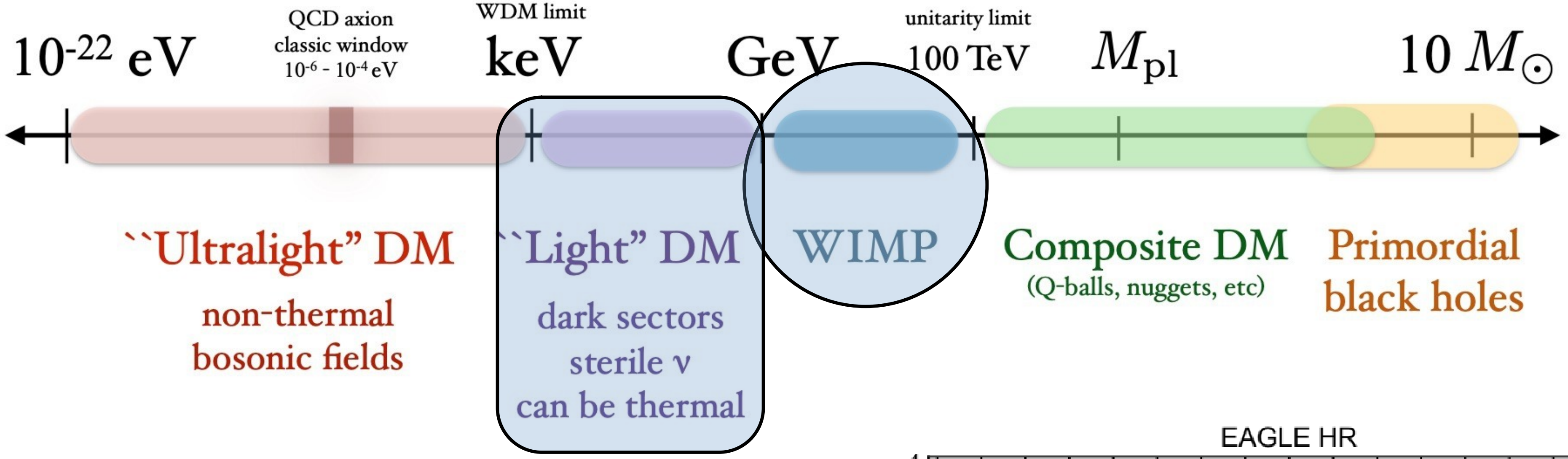
3) **Reactivate Forbidden DM @ Supermassive Black Hole**

Yu Cheng, **SFG**, Xiao-Gang He, Jie Sheng [Phys. Lett. B 847 (2023) 138294]
Yu Cheng, **SFG**, Jie Sheng, Tsutomu Yanagida [PhysRevD.107.123013]
Yu Cheng, **SFG**, Jie Sheng, Tsutomu Yanagida [arXiv:2309.12043]

4) **MeV Solar DM**

SFG, Jie Sheng, Chen Xia, Chuan-Yang Xing [arXiv:2408.12448]

Mass Span of DM



10^{-22} eV

QCD axion classic window 10^{-6} - 10^{-4} eV

WDM limit keV

GeV

unitarity limit 100 TeV

$M_{\rm pl}$

10 $M_\odot$

``Ultralight” DM

non-thermal bosonic fields

``Light” DM

dark sectors

sterile ν

can be thermal

WIMP

Composite DM

(Q-balls, nuggets, etc)

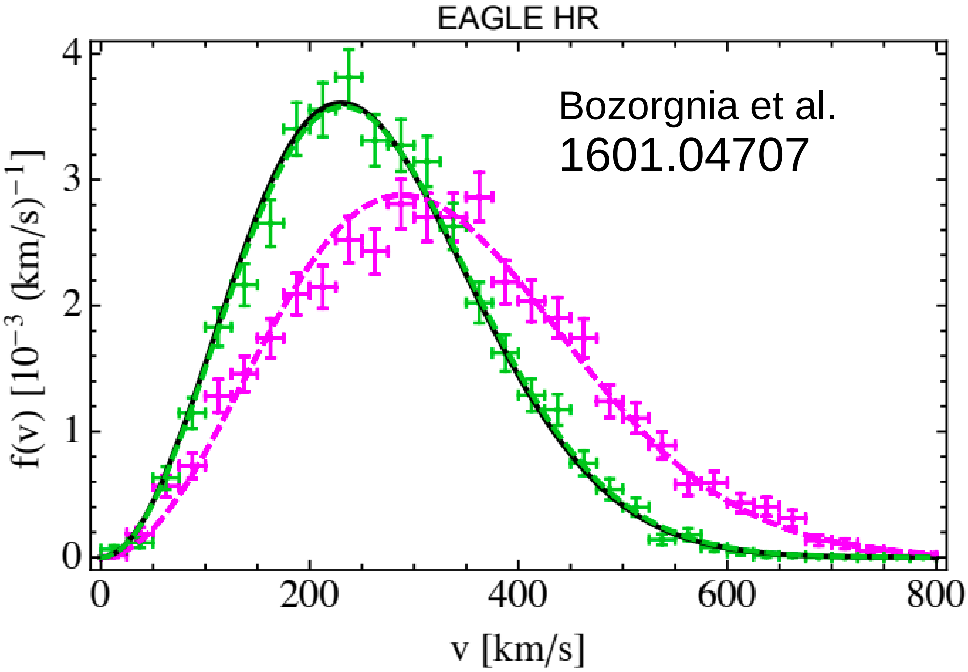
Primordial black holes

?

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

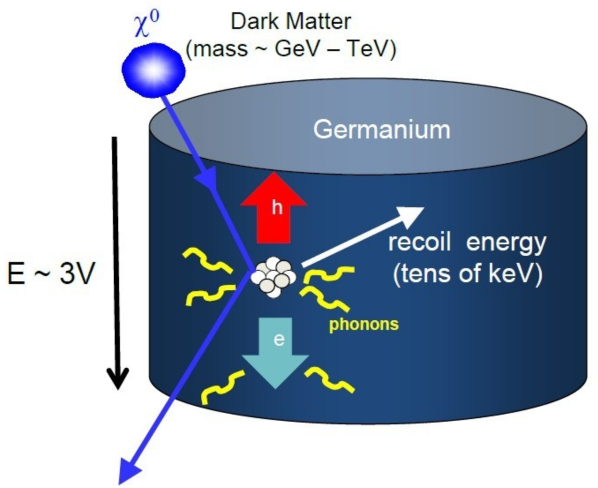
$$\approx \frac{4 m_\chi}{m_N} T_\chi \qquad T_\chi = \frac{1}{2} m_\chi v_\chi^2$$

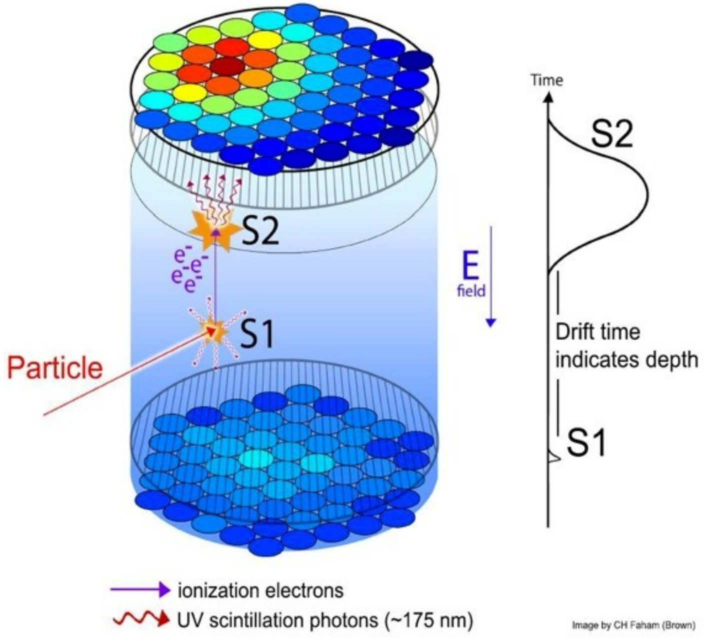
$$E_r \propto m_\chi^2$$

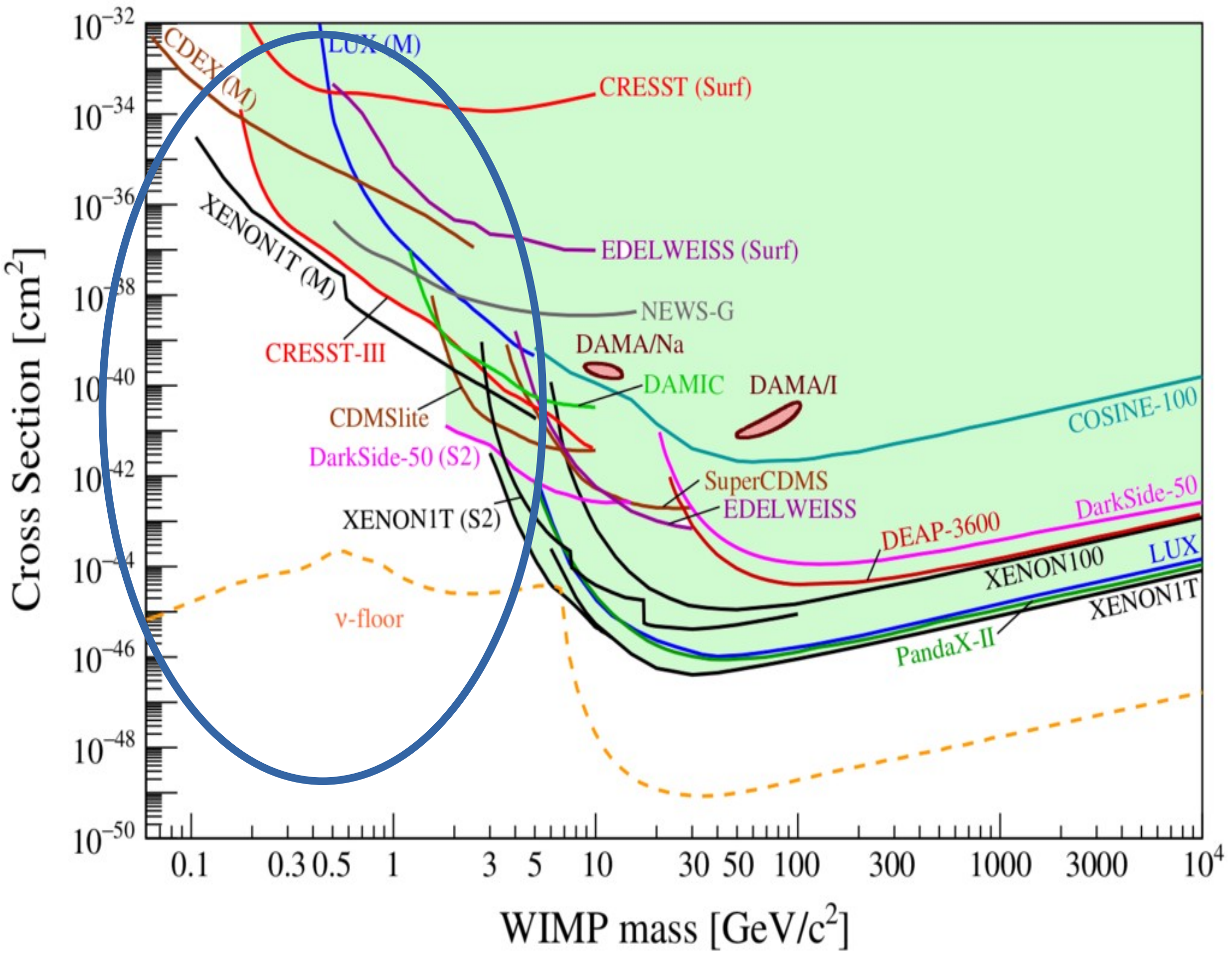


Bozorgnia et al. 1601.04707

Direct Detection







APPEC Committee Report [2104.07634]

Possible Improvements

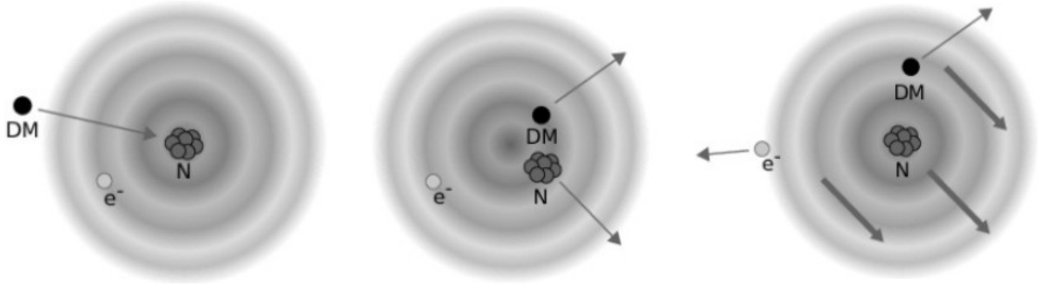
1) Lowering the threshold

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

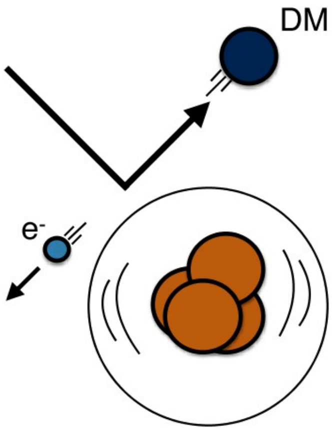
Bremsstrahlung [Kouvaris & Pradler, PRL 118, 031803 (2017)]

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

Migdal effect [Ibe et al [1707.07258]]



2) Electron target



3) Boost detector?

4) Boost 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]

1) Thresholds in DM search

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

3) **Fermionic DM Absorption**

4) **Reactivate Forbidden DM @ Supermassive Black Hole**

Fermionic Absorption

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

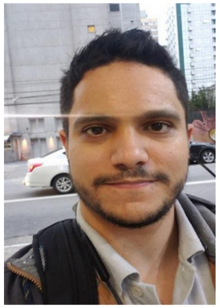
PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [Phys.Rev.Lett. 129 (2022) 16, 161804]

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

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

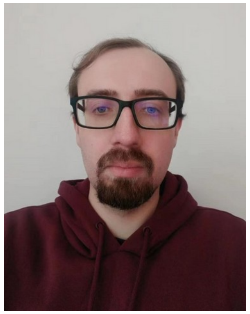
Kai Ma, **SFG**, Lin-Yun He, Ning Zhou [arXiv:2405.16878]

SFG, Oleg Titov [arXiv:2405.05728, to appear in PRD]



Pedro Pasquini

Jie Sheng



Oleg Titov

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**

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

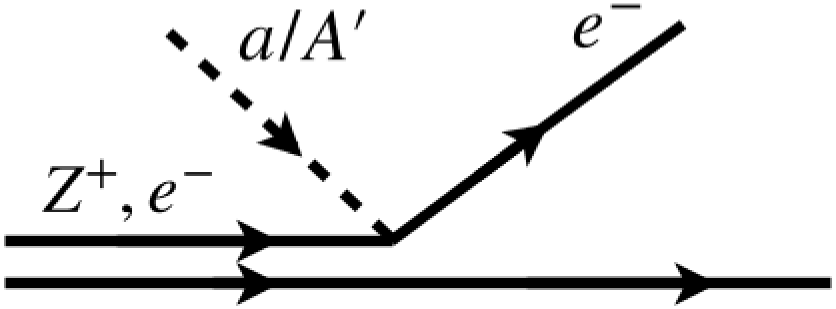
See also Dror, Elor & McGehee
[1905.12635, 1908.10861]

Li, Liao & Zhang [2201.11905]

Dror, Elor, McGehee & Yu [2011.01940]

Bosonic Absorption DM

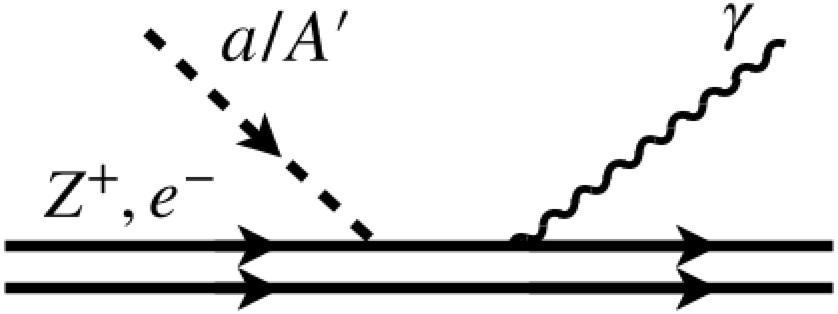
- **Dark absorption**



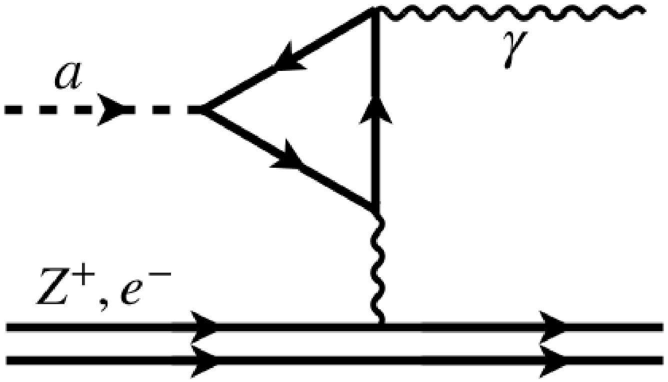
Pospelov, Ritz & Voloshin [0807.3279]

An, Pospelov, Pradler & Ritz [1412.8378]

- **Dark Compton**



- **Inverse Primakoff**

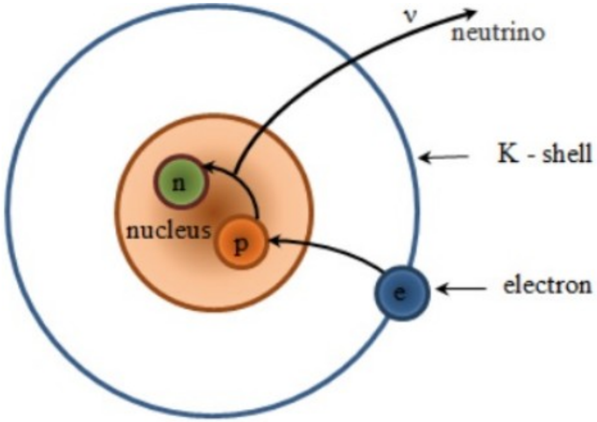


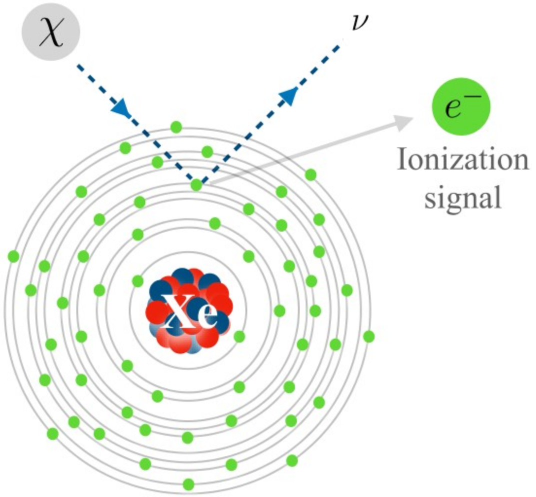
Hochberg, Krosigk, Kuflik & Yu [2109.08168]

K-Shell Electron Capture for ν

王淦昌

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





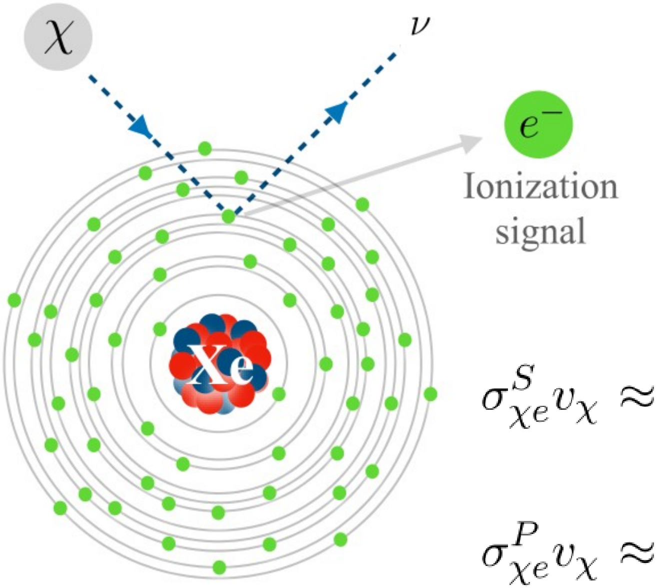
$$e^- + {}^{Z}_{A}N \to {}^{Z-1}_{A}N + \nu$$

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

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



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

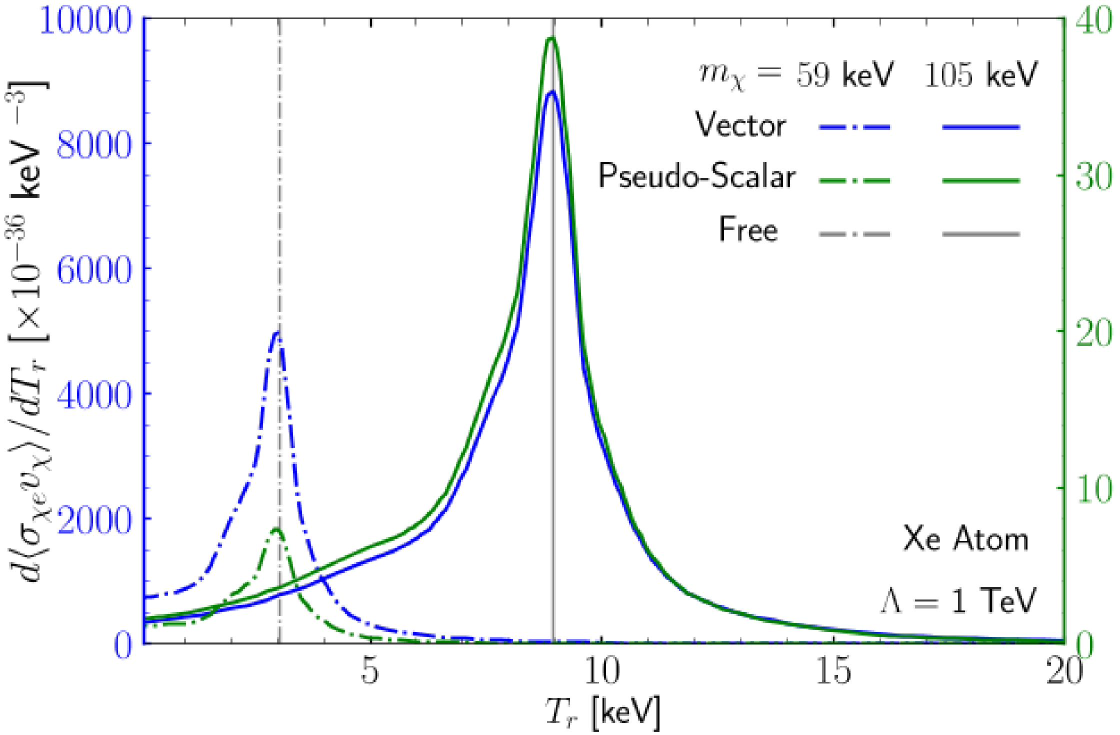
$$
\begin{aligned}
\sigma^S_{\chi e} v_\chi &\approx \frac{1}{\Lambda^4} \frac{m_\chi^2 (2m_e + m_\chi)^4}{64\pi (m_e + m_\chi)^4},\\
\sigma^P_{\chi e} v_\chi &\approx \frac{1}{\Lambda^4} \frac{m_\chi^4 (2m_e + m_\chi)^2}{64\pi (m_e + m_\chi)^4},\\
\sigma^V_{\chi e} v_\chi &\approx \frac{1}{\Lambda^4} \frac{m_\chi^2 (2m_e + m_\chi)^2 (2m_e^2 + 4m_e m_\chi + 3m_\chi^2)}{32\pi (m_e + m_\chi)^4},\\
\sigma^A_{\chi e} v_\chi &\approx \frac{1}{\Lambda^4} \frac{m_\chi^2 (2m_e + m_\chi)^2 (6m_e^2 + 8m_e m_\chi + 3m_\chi^2)}{32\pi (m_e + m_\chi)^4},\\
\sigma^T_{\chi e} v_\chi &\approx \frac{1}{\Lambda^4} \frac{m_\chi^2 (2m_e + m_\chi)^2 (6m_e^2 + 10m_e m_\chi + 5m_\chi^2)}{8\pi (m_e + m_\chi)^4}.
\end{aligned}
$$

Dror, Elor, McGehee & Yu [2011.01940]

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

Kinematics of Absorption DM

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



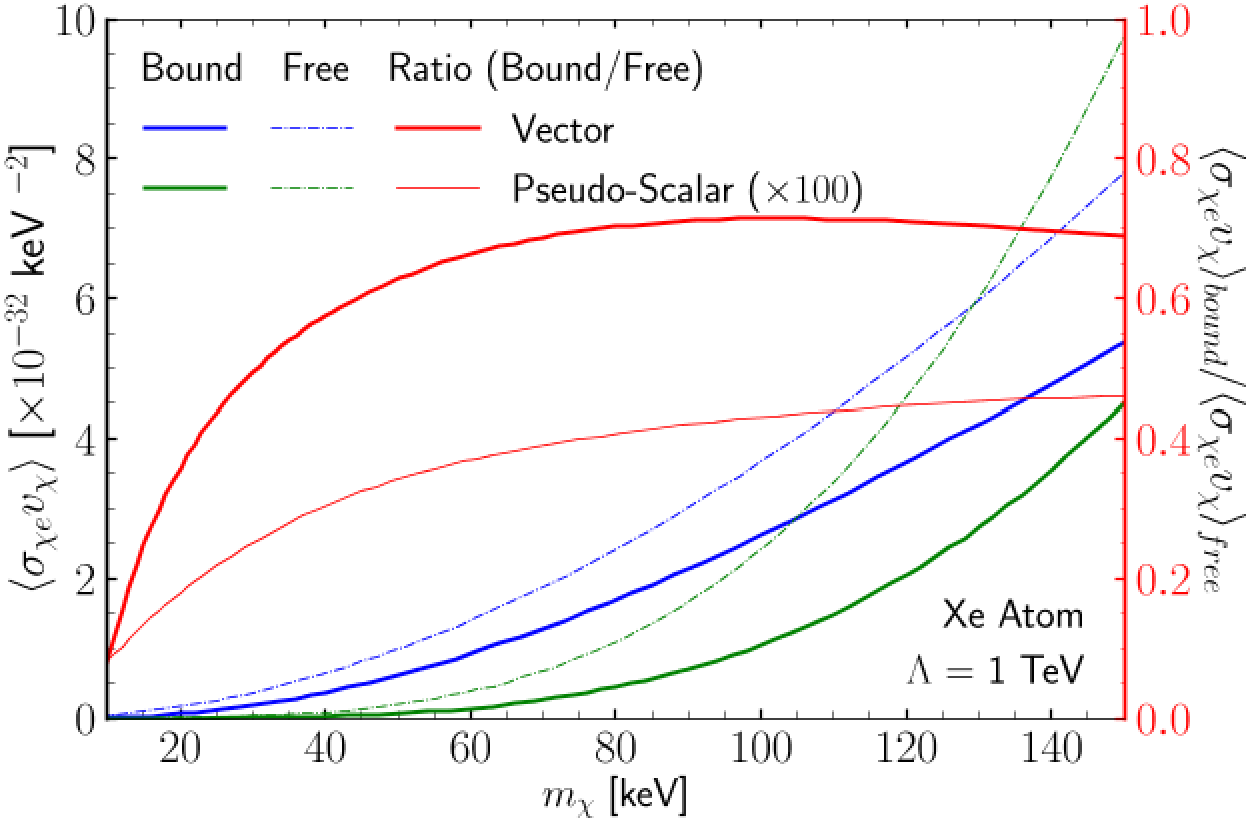
$$\frac{d\langle\sigma_{\chi e} v_\chi\rangle}{dT_r} = \sum_{nl} (4l+2) \frac{1}{T_r} \frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi} |\mathcal{M}|^2(\mathbf{q}) K_{nl}(T_r, |\mathbf{q}|),$$

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

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

Atomic Effects

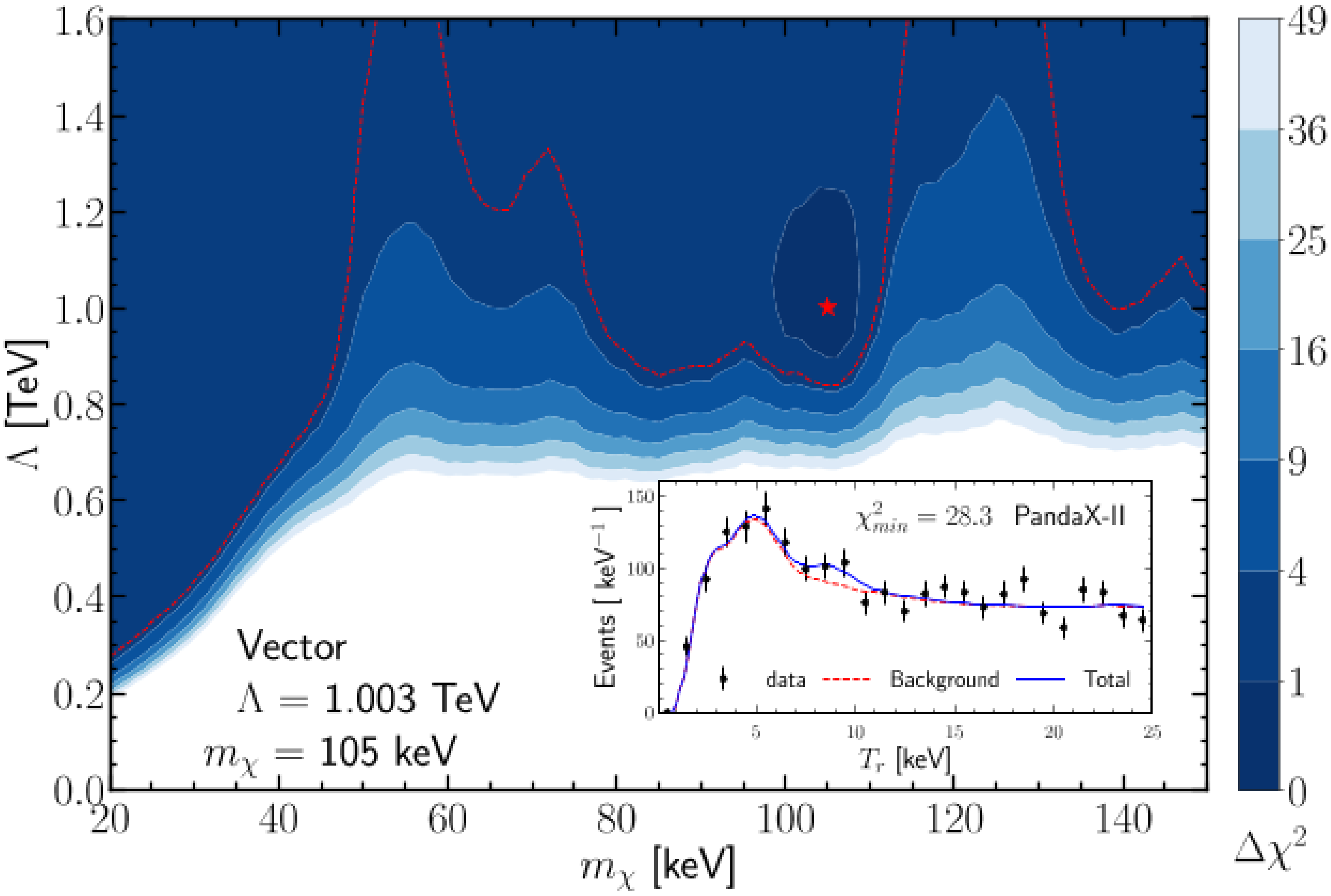
$$\chi + e \to \nu + e$$



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

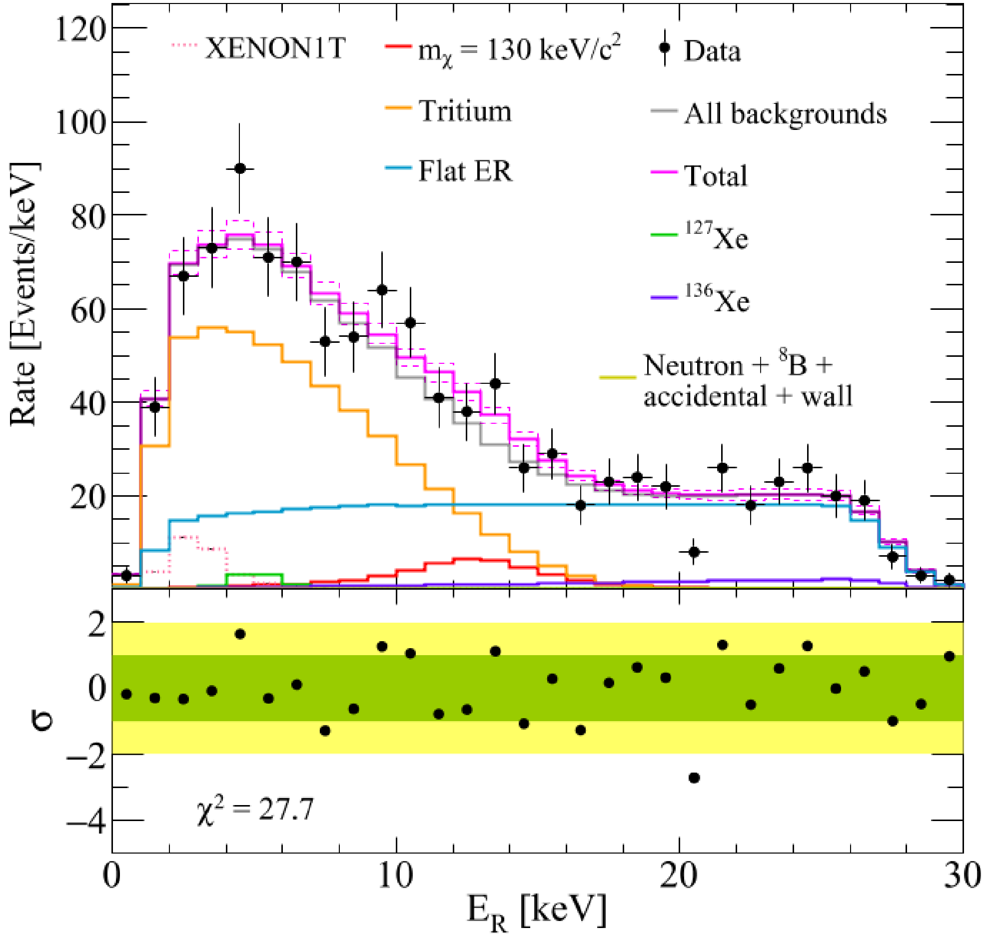
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

PandaX-II

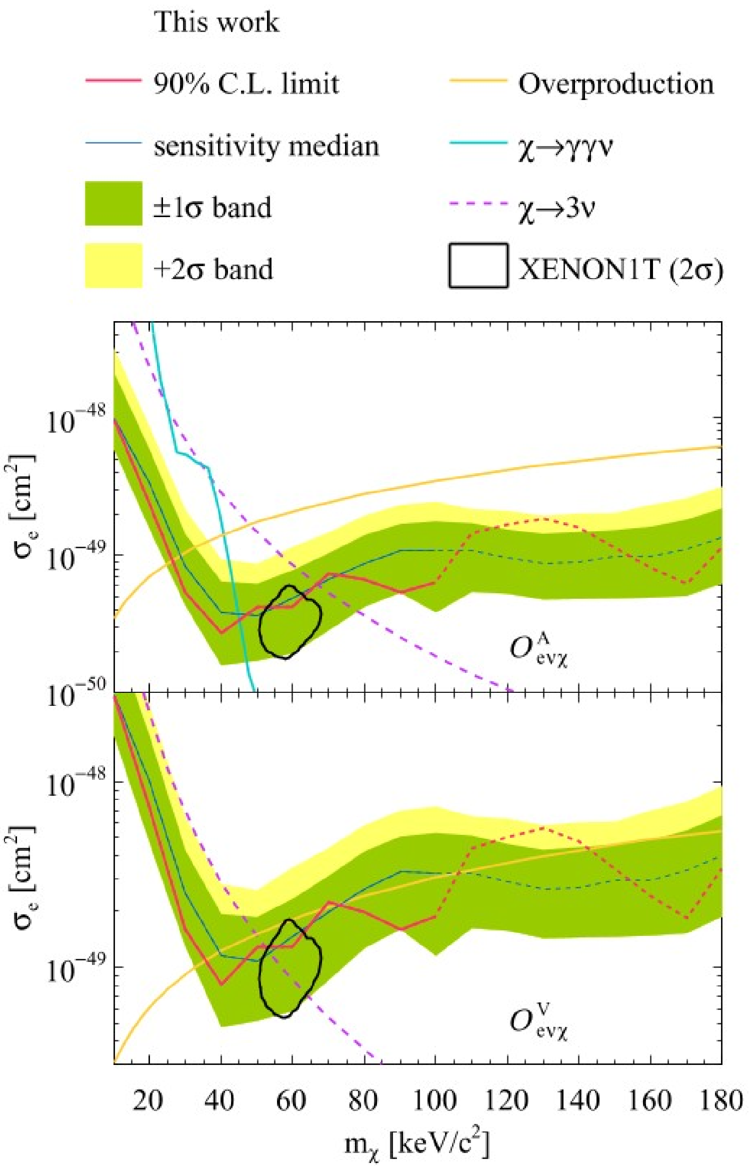


SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

PandaX-4T Results



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

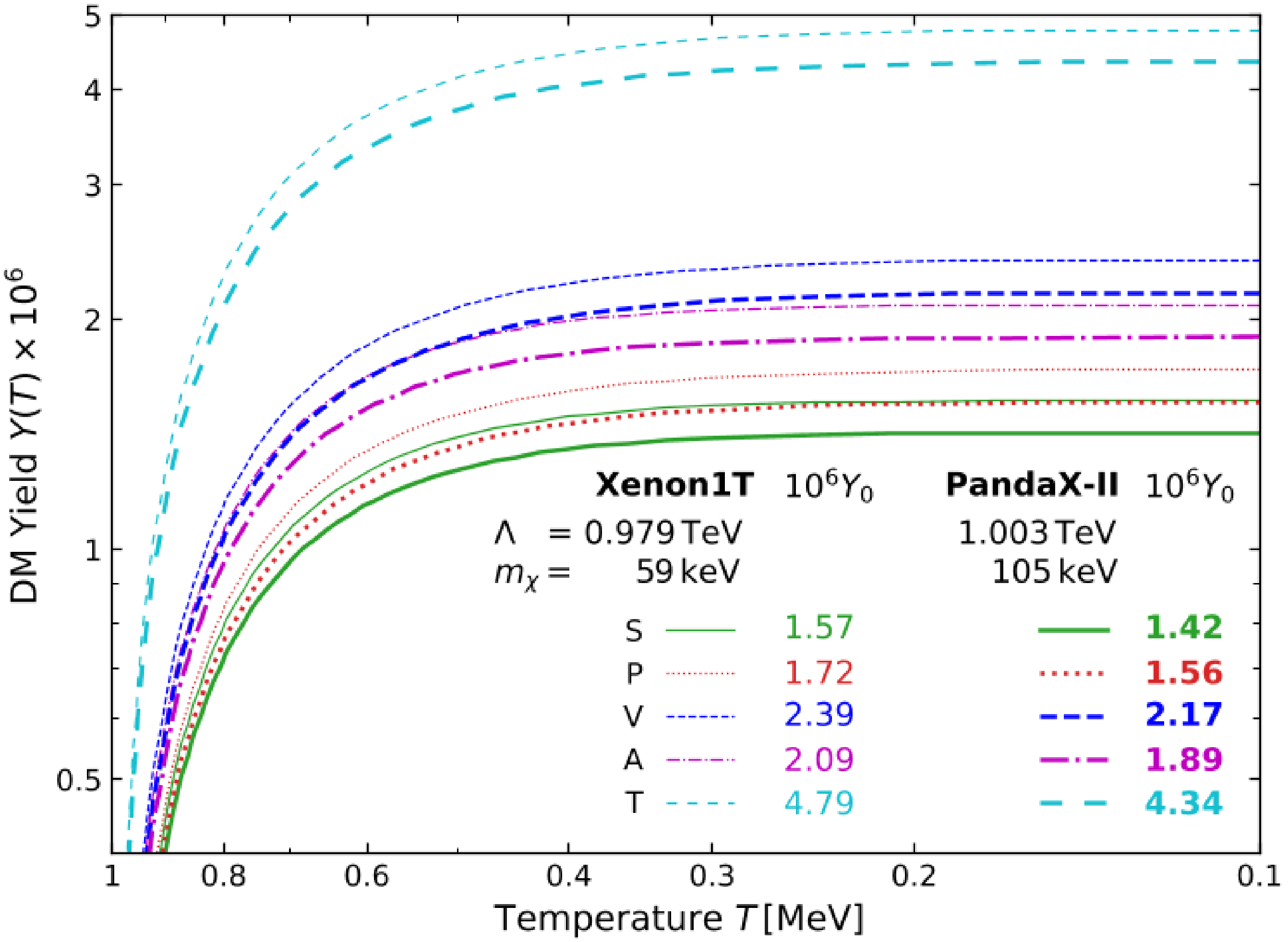


See also PandaX, Phys.Rev.Lett. 129 (2022) 16, 161803 [2205.15771]
CDEX, Phys.Rev.Lett. 129 (2022) 22, 221802 [2209.00861]

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

Overproduction (Freeze-In)

$$e^- e^+ \to \nu\bar{\chi}/\bar{\nu}\chi \qquad e^\pm \nu \to e^\pm \chi \qquad e^\pm \bar{\nu} \to e^\pm \bar{\chi}$$



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

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

Visible & Invisible Decays

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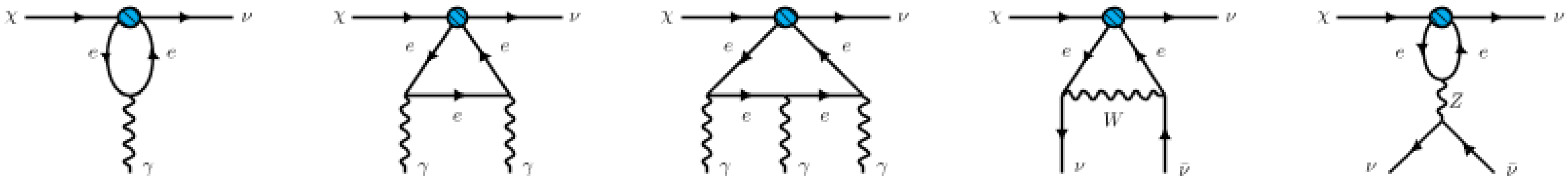

Operator \ Process	$\chi \to \nu\gamma$	$\chi \to \nu\gamma\gamma$	$\chi \to \nu\gamma\gamma\gamma$	$\chi \to 3\nu$
S: $\mathcal{O}^S_{e\nu\chi}$	×	✓	×	×
P: $\mathcal{O}^P_{e\nu\chi}$	×	✓	×	×
V: $\mathcal{O}^V_{e\nu\chi}$	×	×	✓	✓
A: $\mathcal{O}^A_{e\nu\chi}$	×	✓	×	✓
T: $\mathcal{O}^T_{e\nu\chi}$	✓	×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

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

Astro Observations

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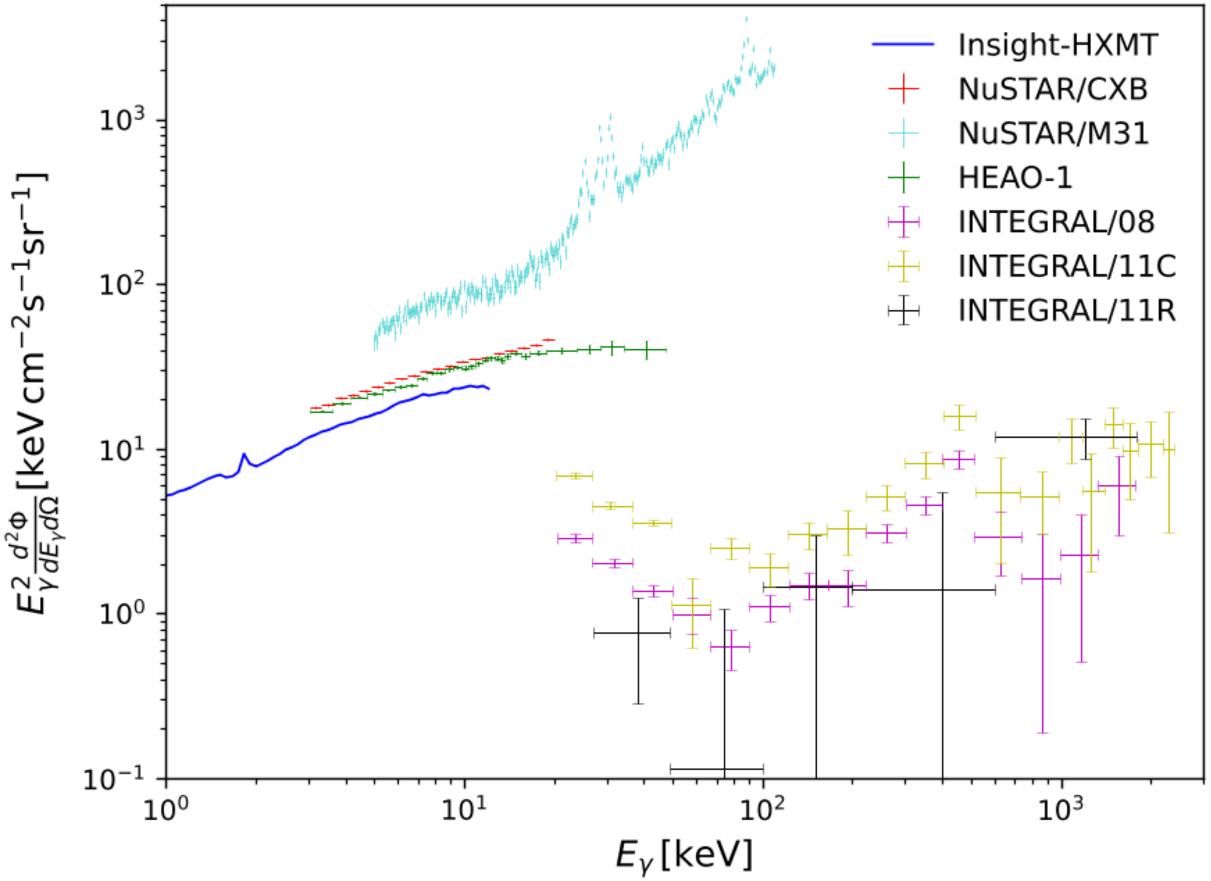


- **Galactic**

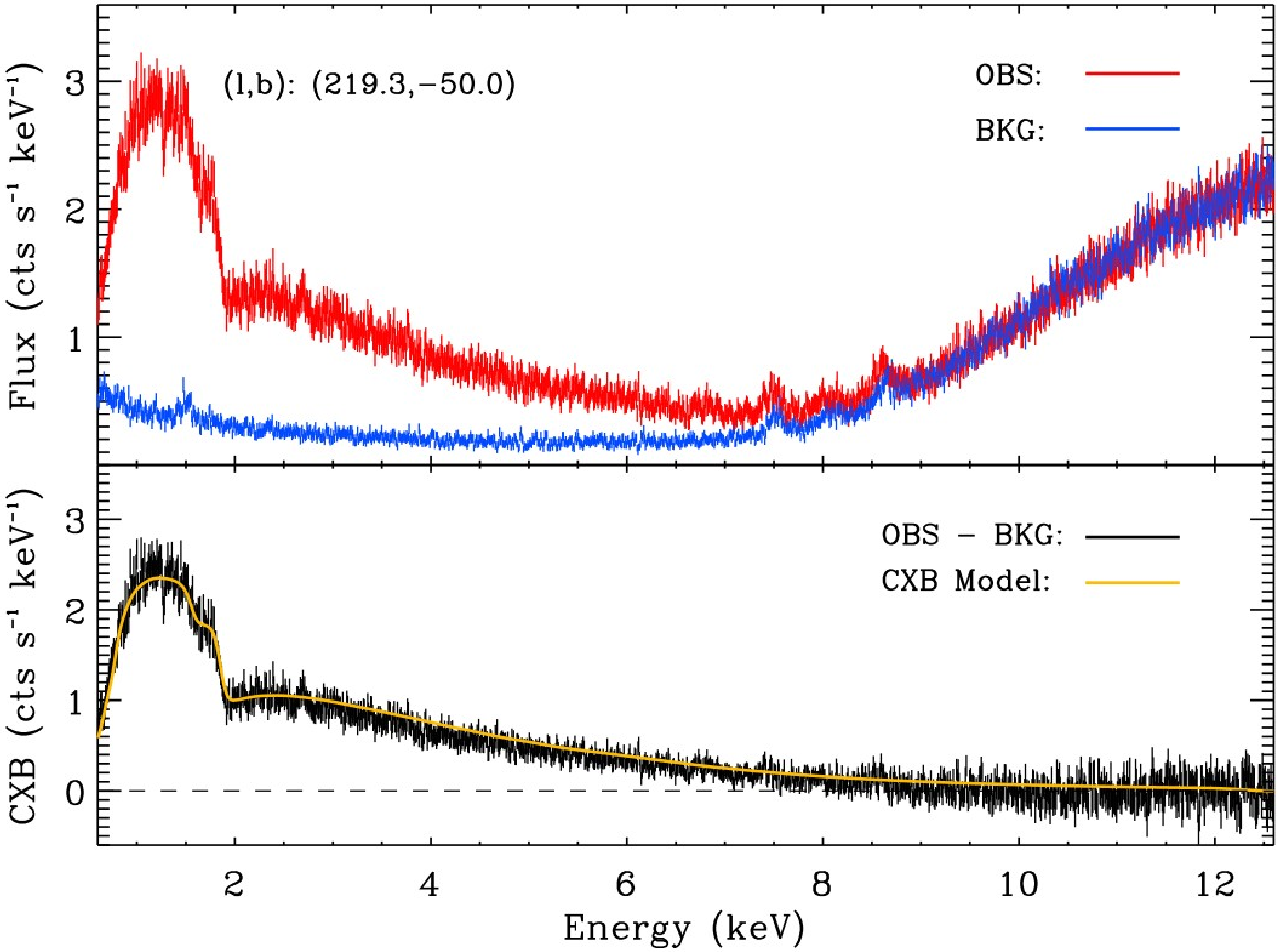
$$\frac{d^2\Phi_\gamma}{dE_\gamma d\Omega} = \frac{1}{4\pi}\frac{d\Gamma_\chi}{dE_\gamma}\int_{\rm l.o.s.}^{s_{\max}} \frac{\rho_\chi(r)}{m_\chi} ds$$

- **Extra-Galactic**

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

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

HXMT Data

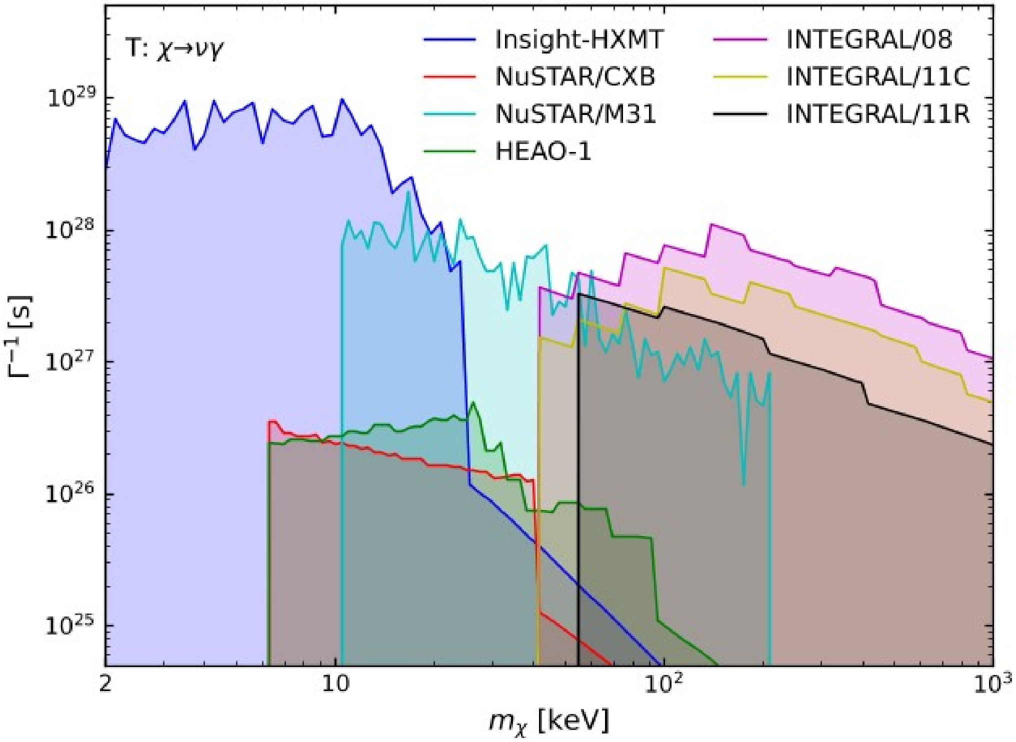


Jin-Yuan Liao et al [JHEAp 27 (2020) 24-32, arXiv:2004.01432]

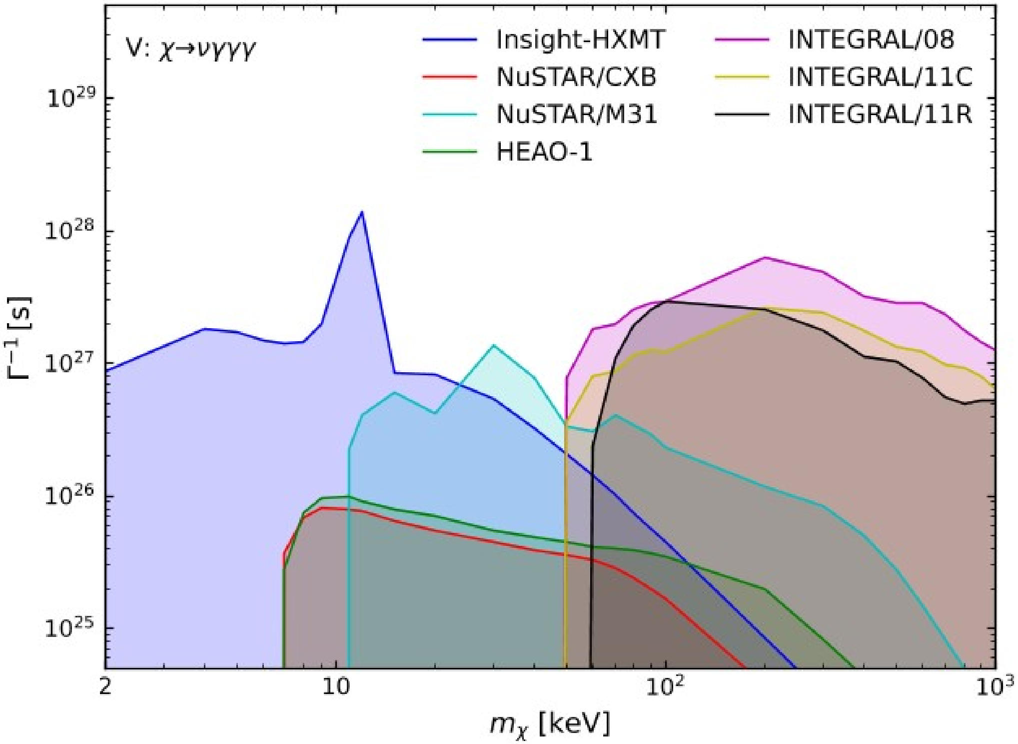
Astro Constraints

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

- Mono-energetic γ

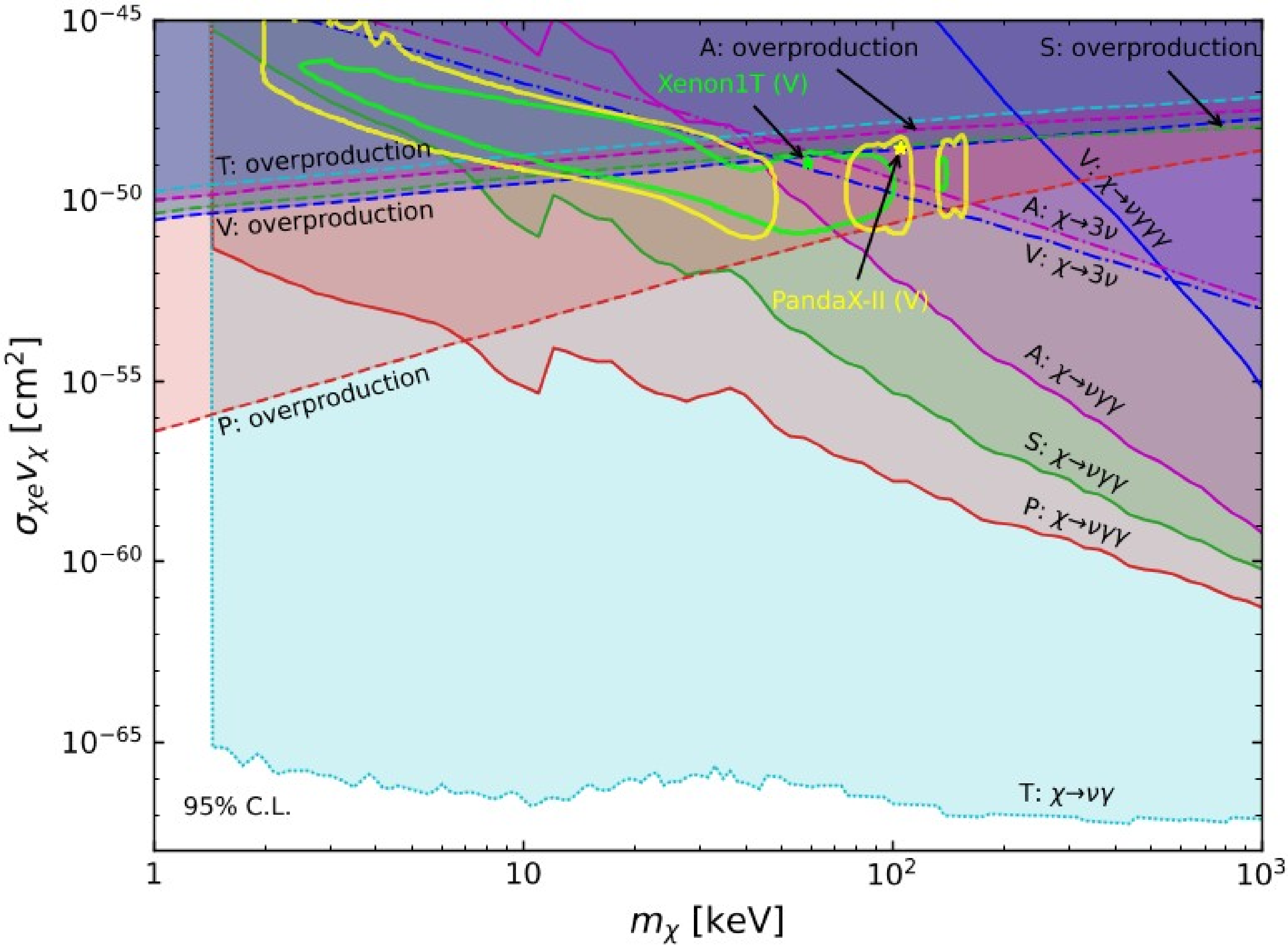


- Continuous Spectrum



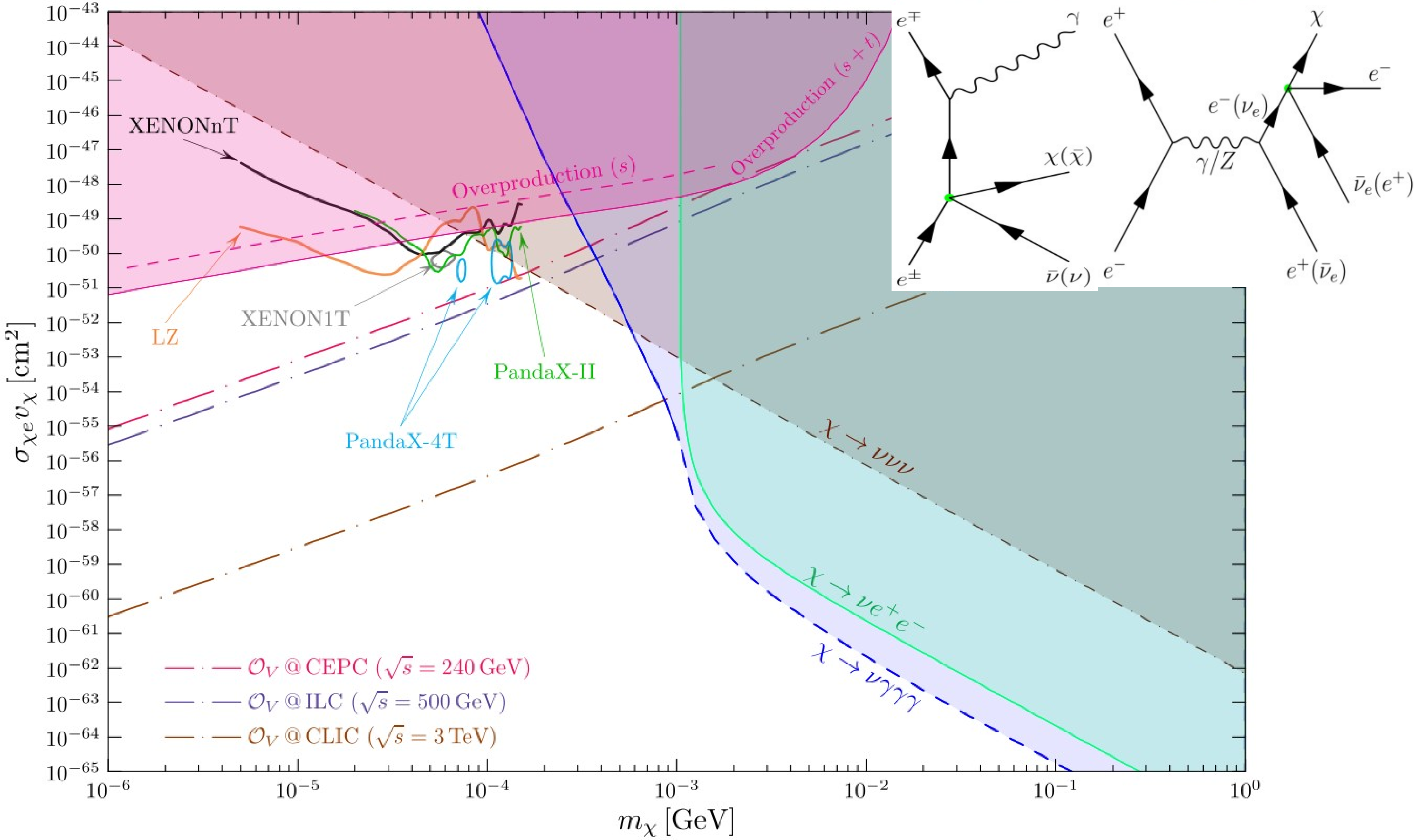
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

Constraints from Astro & Cosmo



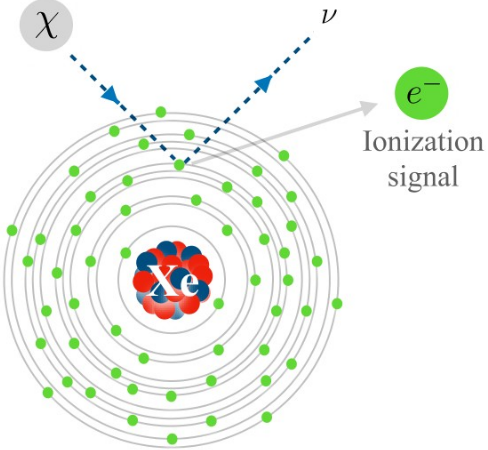
SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

PandaX-4T & Lepton Colliders

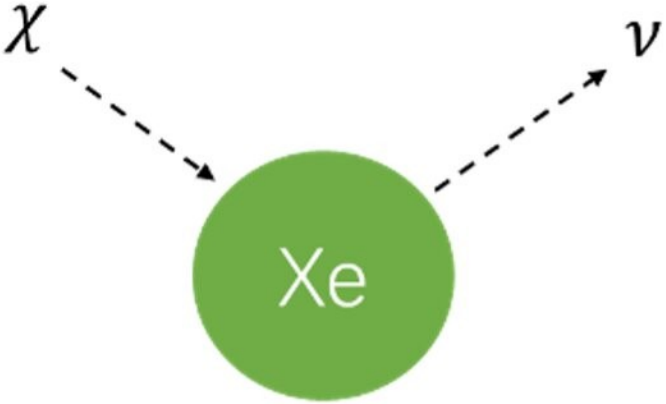


SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [JHEP 11 (2023) 190]

Absorption @ Nuclear Targets



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



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

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

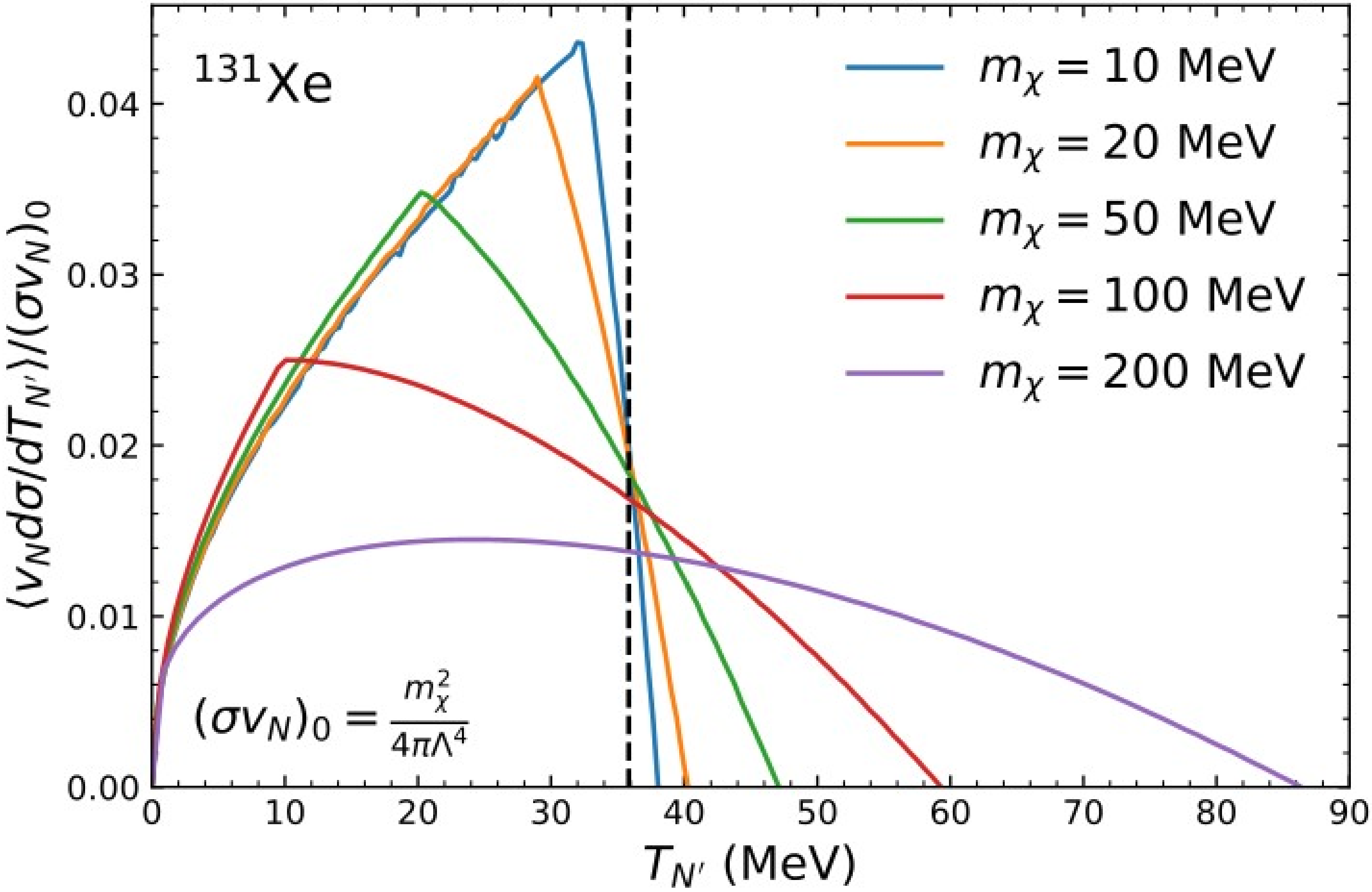
See also Dror, Elor & McGehee
[1905.12635, 1908.10861]

SFG, Oleg Titov [arXiv:2405.05728, to appear in PRD]

Fermi Motion & Pauli Blocking

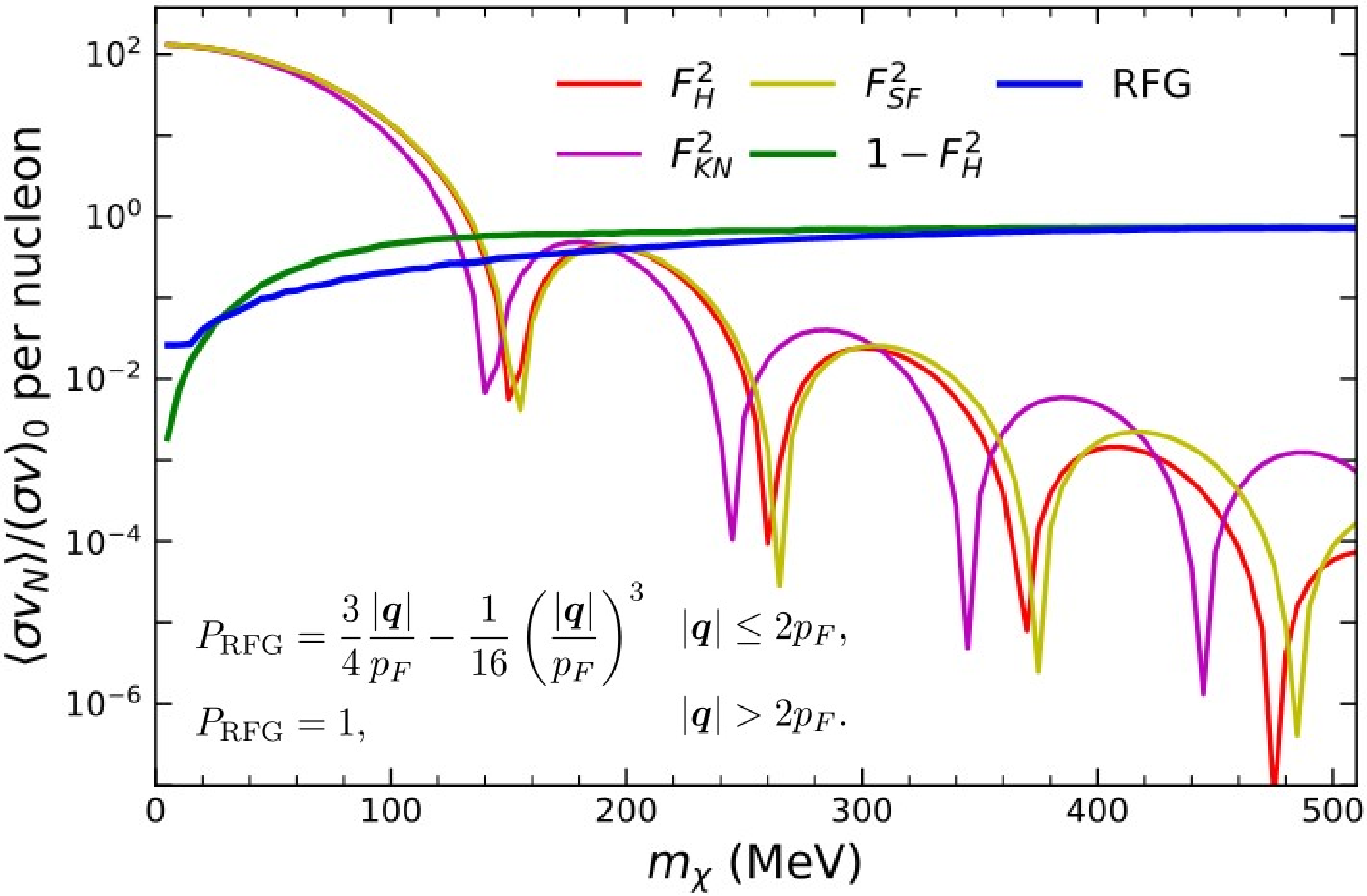
$$|\boldsymbol{q}| = |\boldsymbol{p}_\nu| = m_\chi - \frac{m_\chi^2}{2(m_N + m_\chi)} \approx m_\chi$$

$$T^{\pm}_{N'} \approx \frac{m_\chi \pm |\mathbf{p}_N|)^2}{2m_N}$$



SFG, Oleg Titov [arXiv:2405.05728, to appear in PRD]

Incoherent vs Coherent



$$P_{\rm RFG} = \frac{3}{4}\frac{|\boldsymbol{q}|}{p_F} - \frac{1}{16}\left(\frac{|\boldsymbol{q}|}{p_F}\right)^3 \qquad |\boldsymbol{q}| \leq 2p_F,$$

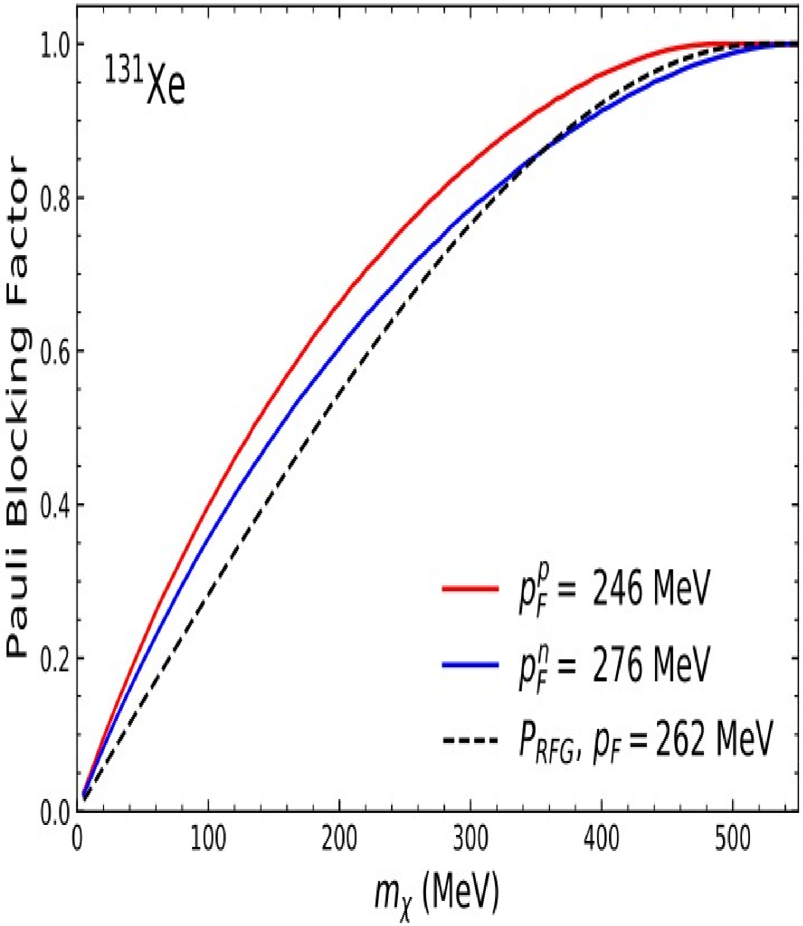
$$P_{\rm RFG} = 1, \qquad |\boldsymbol{q}| > 2p_F.$$

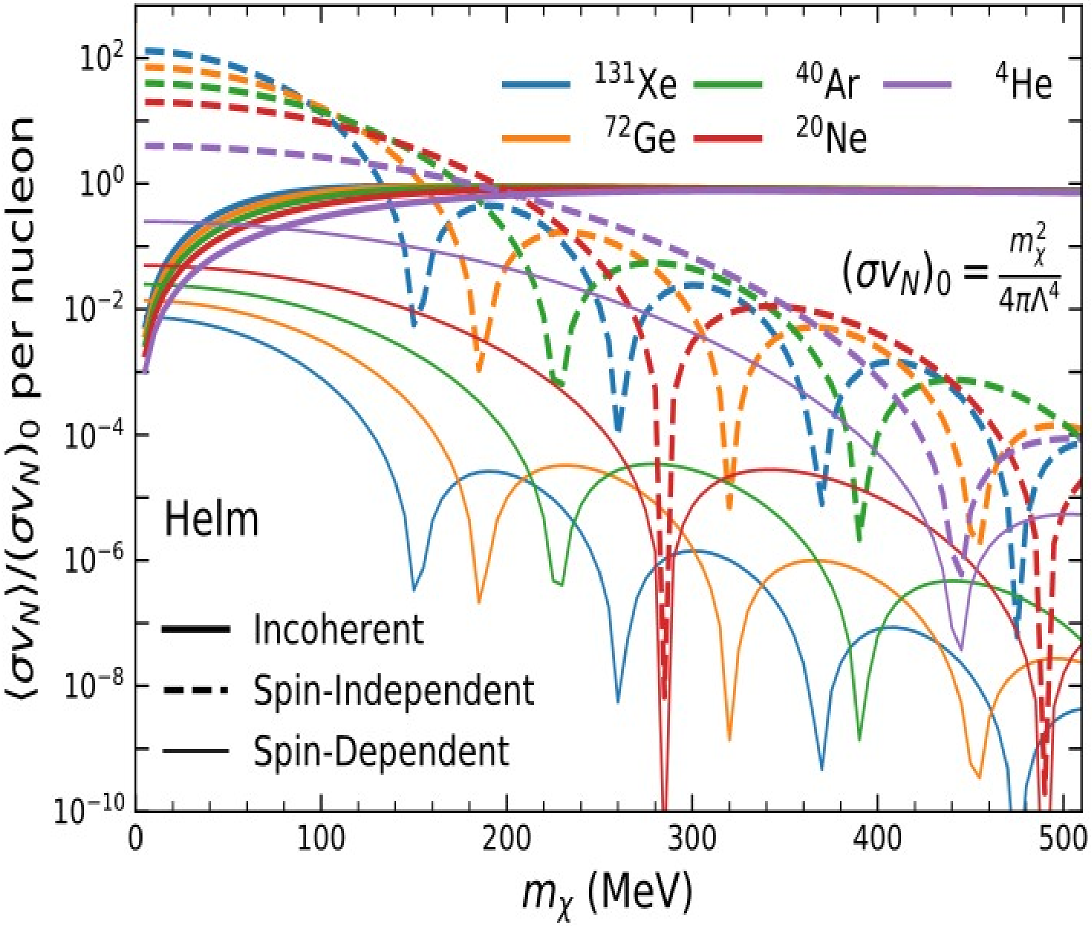
SFG, Oleg Titov [arXiv:2405.05728, to appear in PRD]

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 [arXiv:2405.05728, to appear in PRD]

Incoherent Domination @ large m

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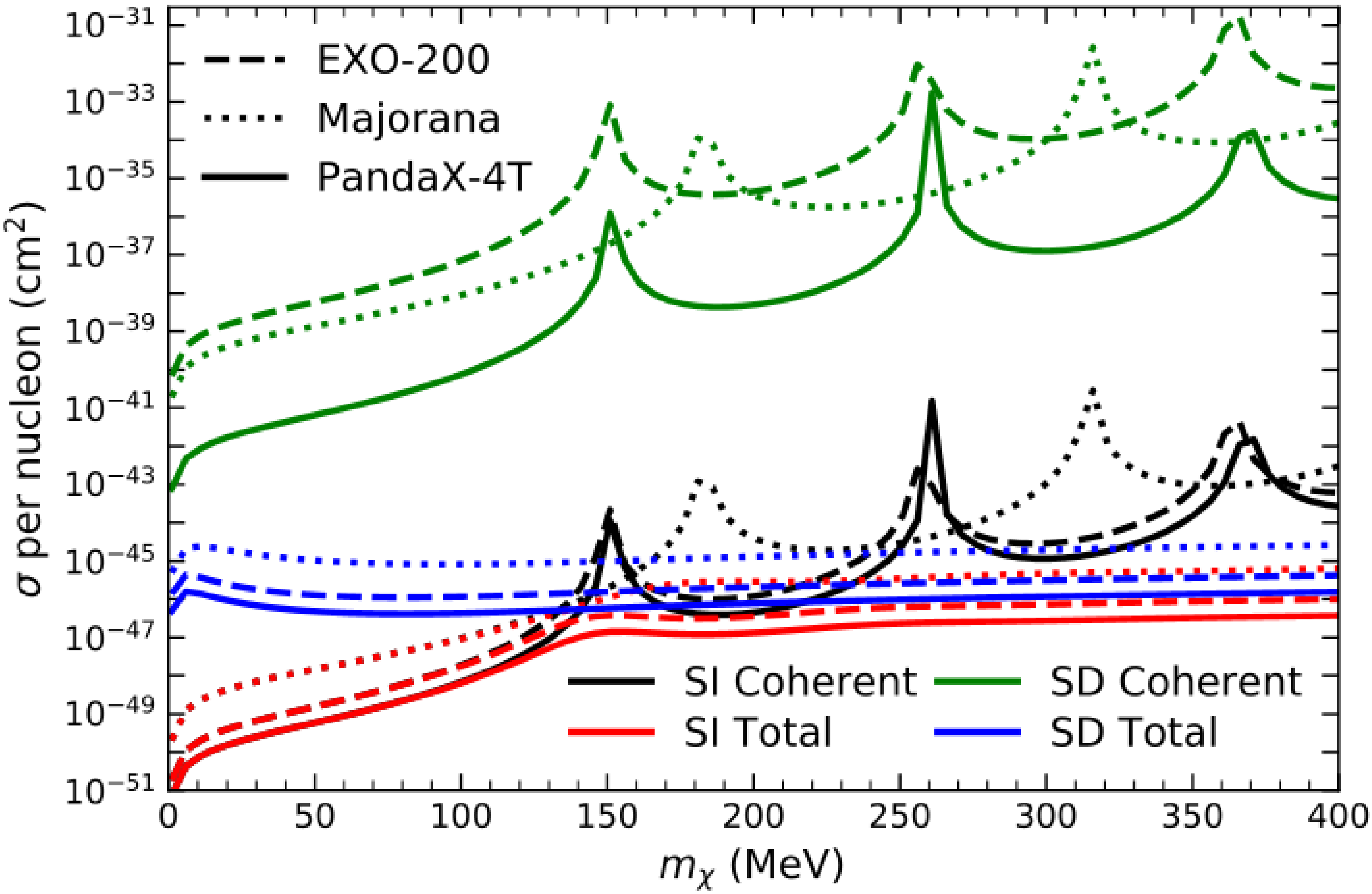
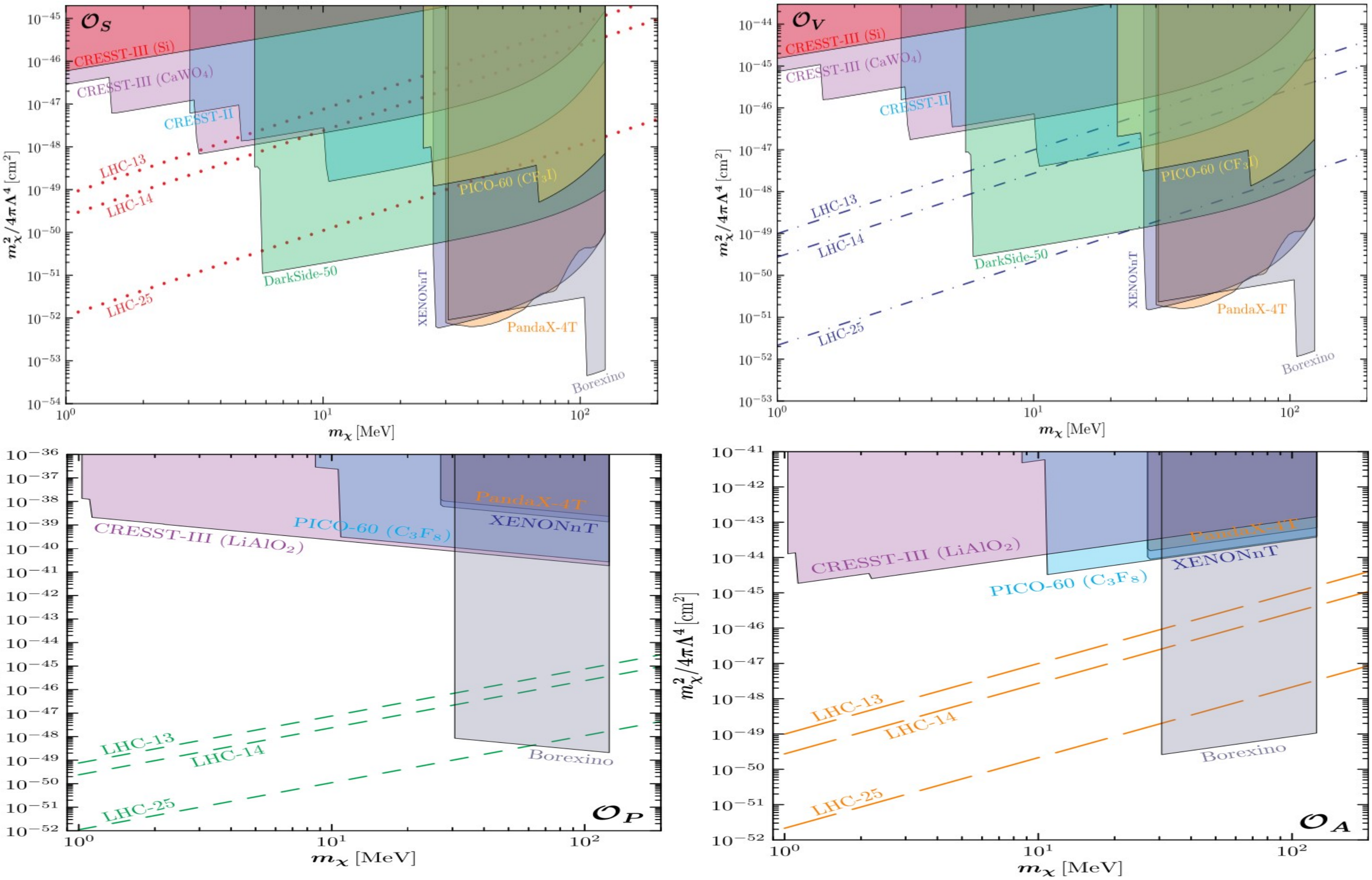


SFG, Oleg Titov [arXiv:2405.05728, to appear in PRD]

Nuclear Absorption @ Collider

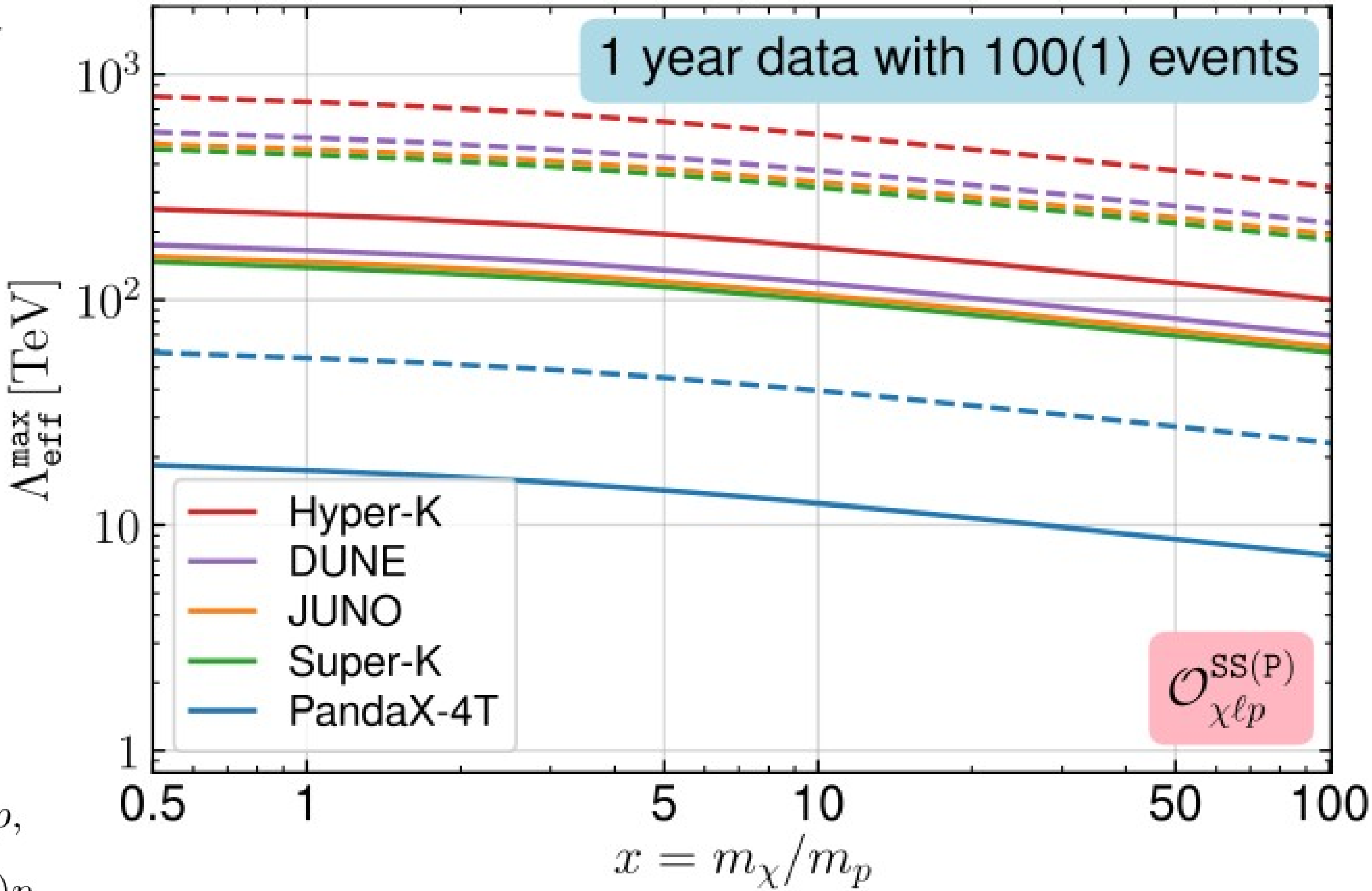
Kai Ma, **SFG**, Lin-Yun He, Ning Zhou [arXiv:2405.16878]



Nucleon Consumption

$$\chi + p \rightarrow \chi + \ell^+$$

$$\chi + n \rightarrow \chi + \nu$$



$$\mathcal{O}_{\chi\ell p}^{\text{SS(P)}} = \overline{\chi}\chi\,\overline{\ell^c}(i\gamma_5)p,$$
$$\mathcal{O}_{\chi\ell p}^{\text{PS(P)}} = \overline{\chi}i\gamma_5\chi\,\overline{\ell^c}(i\gamma_5)p,$$
$$\mathcal{O}_{\chi\ell p}^{\text{VV(A)}} = \overline{\chi}\gamma_\mu\chi\,\overline{\ell^c}\gamma^\mu(\gamma_5)p,$$
$$\mathcal{O}_{\chi\ell p}^{\text{AV(A)}} = \overline{\chi}\gamma_\mu\gamma_5\chi\,\overline{\ell^c}\gamma^\mu(\gamma_5)p,$$
$$\mathcal{O}_{\chi\ell p}^{\text{TT}(\tilde{\text{T}})} = \overline{\chi}\sigma_{\mu\nu}\chi\,\overline{\ell^c}\sigma^{\mu\nu}(i\gamma_5)p,$$

SFG, Xiao-Dong Ma [arXiv:2406.00445]

1) Thresholds in DM search

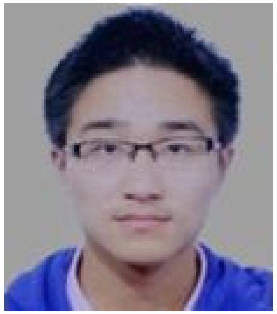
2) Cosmic ray boosted DM & diurnal modulation

3) Fermionic DM Absorption

4) Reactivate Forbidden DM @ Supermassive Black Hole

Forbidden DM

Yu Cheng, **SFG**, Xiao-Gang He, Jie Sheng [Phys. Lett. B 847 (2023) 138294, arXiv:2211.05643]
Yu Cheng, **SFG**, Jie Sheng, Tsutomu Yanagida [PhysRevD.107.123013; arXiv:2309.12043]

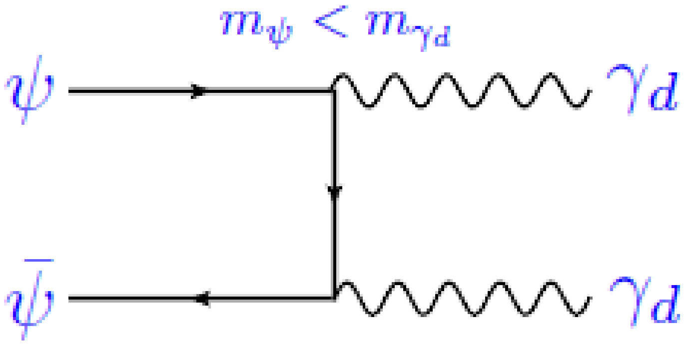


Yu Cheng

Jie Sheng

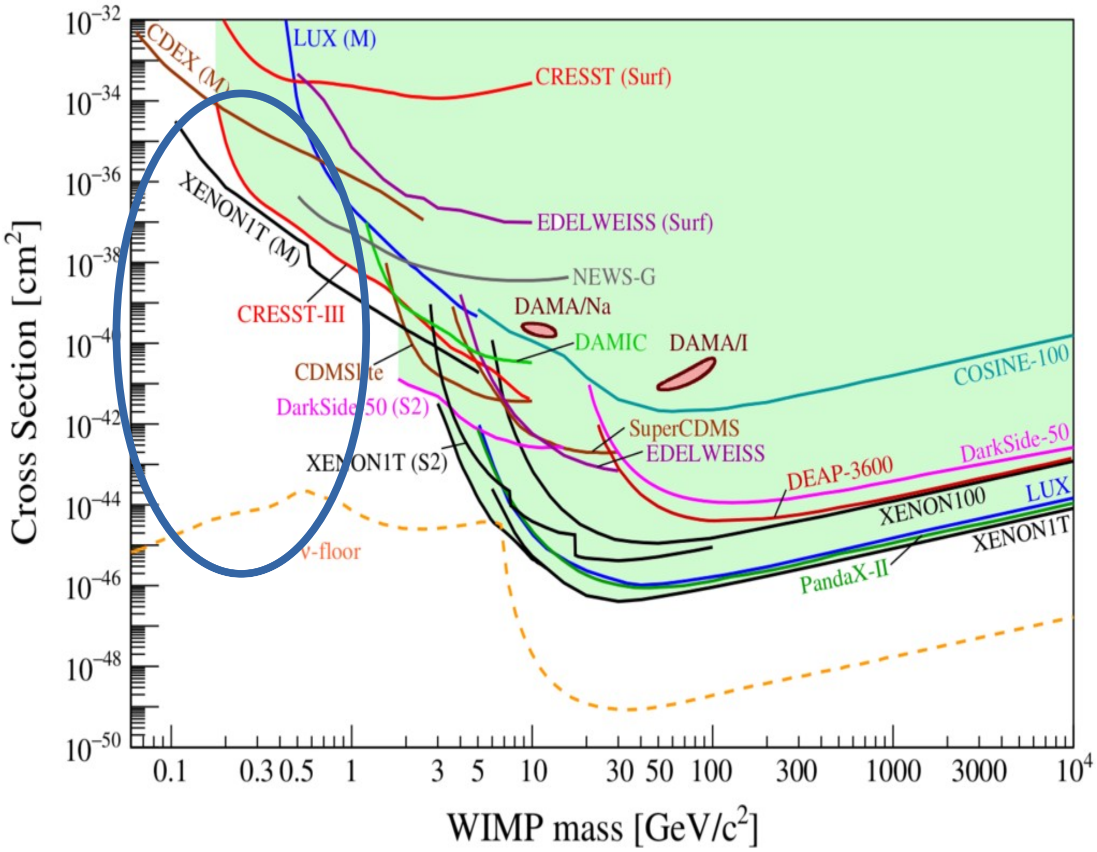
Forbidden DM

1) forbidden annihilations:



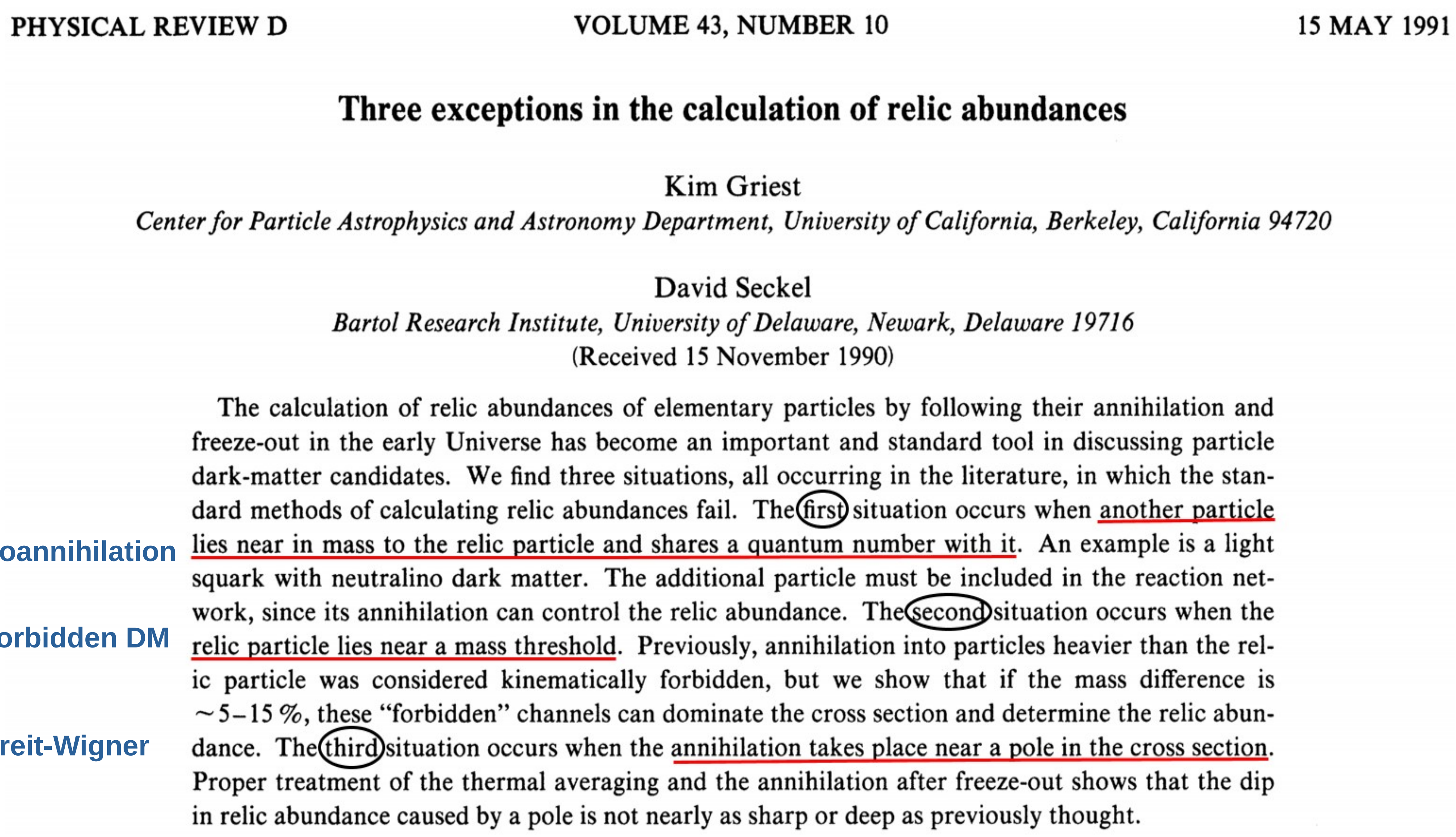
$$\langle \sigma_{\gamma_d\gamma_d} v\rangle \sim \alpha_d^2/m_{\gamma_d}^2$$

$$\langle\sigma_{\chi\bar\chi}v\rangle = \frac{\left(n_{\gamma_d}^{eq}\right)^2}{\left(n_\psi^{eq}\right)^2}\langle\sigma_{\gamma_d\gamma_d}v\rangle \approx 8\pi f_\Delta \frac{\alpha_d^2}{m_\psi^2}e^{-2\Delta x}$$



D'Agnolo & Ruderman, Phys.Rev.Lett. 115 (2015) 6, 061301 [1505.07107]

How to test Forbidden DM?



PHYSICAL REVIEW D VOLUME 43, NUMBER 10 15 MAY 1991

Three exceptions in the calculation of relic abundances

Kim Griest
Center for Particle Astrophysics and Astronomy Department, University of California, Berkeley, California 94720

David Seckel
Bartol Research Institute, University of Delaware, Newark, Delaware 19716
(Received 15 November 1990)

The calculation of relic abundances of elementary particles by following their annihilation and freeze-out in the early Universe has become an important and standard tool in discussing particle dark-matter candidates. We find three situations, all occurring in the literature, in which the standard methods of calculating relic abundances fail. The first situation occurs when another particle lies near in mass to the relic particle and shares a quantum number with it. An example is a light squark with neutralino dark matter. The additional particle must be included in the reaction network, since its annihilation can control the relic abundance. The second situation occurs when the relic particle lies near a mass threshold. Previously, annihilation into particles heavier than the relic particle was considered kinematically forbidden, but we show that if the mass difference is ~5–15%, these "forbidden" channels can dominate the cross section and determine the relic abundance. The third situation occurs when the annihilation takes place near a pole in the cross section. Proper treatment of the thermal averaging and the annihilation after freeze-out shows that the dip in relic abundance caused by a pole is not nearly as sharp or deep as previously thought.

Coannihilation

Forbidden DM

Breit-Wigner

How to test Forbidden DM?

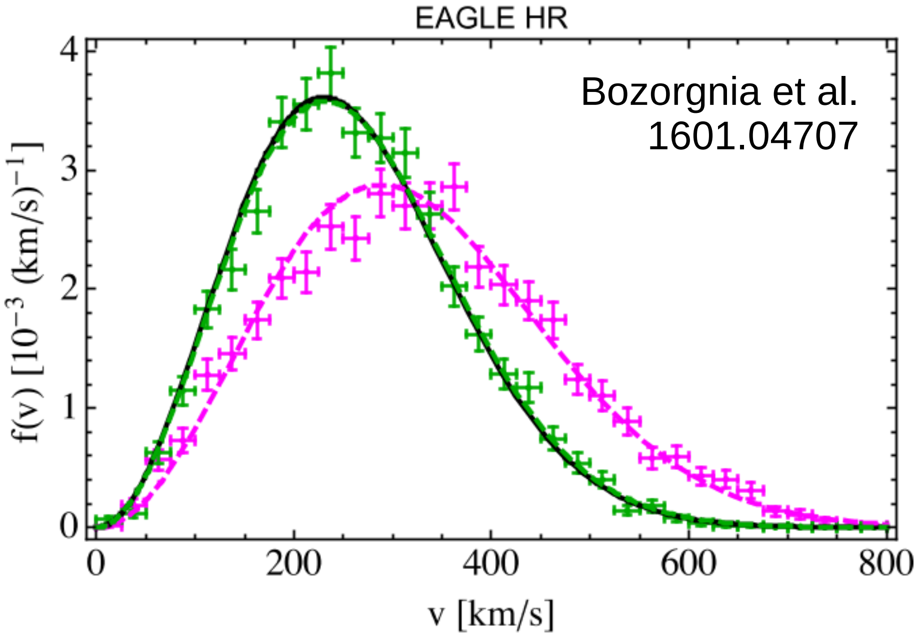
- **Boltzmann Distribution**

$$f_0(v) = \frac{\rho_\chi}{m_\chi}\frac{4}{\sqrt{\pi}}\frac{v^2}{(\sqrt{2/3}v_d)^3}e^{-\frac{v^2}{(\sqrt{2/3}v_d)^2}}$$

$$\Delta_{F\chi} \equiv \frac{m_F - m_\chi}{m_\chi}$$

$$\sim 1\%$$

$$v_d \sim 10\%$$

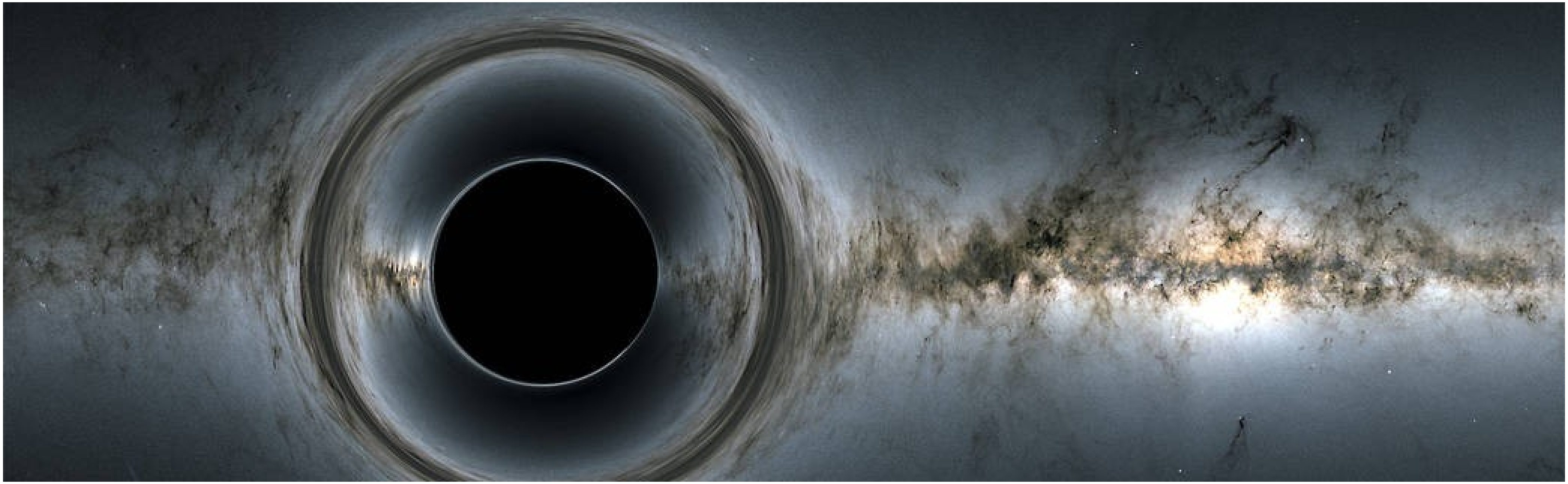


Bozorgnia et al.
1601.04707

- **Juttner Distribution**

$$f_J(\mathbf{p}) = \frac{1}{4\pi T m_\chi^2 K_2(x)} e^{-\frac{\sqrt{|\mathbf{p}|^2 + m_\chi^2}}{T}} \qquad x \equiv m_\chi/T$$

Velocity Scaling @ Black Holes



$$v^2 \sim \frac{GM}{r} \quad \Rightarrow \quad v(r) \sim \frac{1}{\sqrt{r}}$$

$$\rho \propto r^?$$

Core: Isothermal Gas

- **NFW Profile**

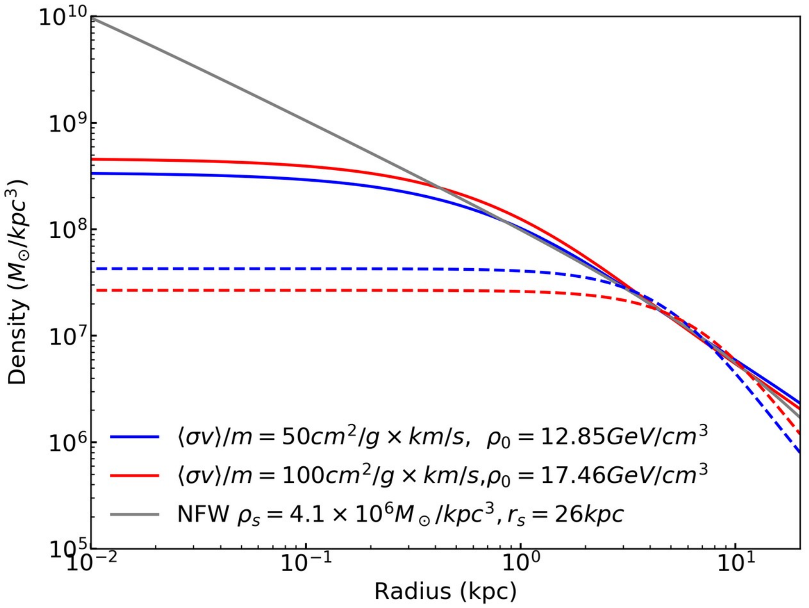
$$\rho(r) = \begin{cases} \rho_{\text{iso}}(r), & r < r_1 \\ \rho_{\text{NFW}}(r), & r > r_1 \end{cases}$$

$$\rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

- **Jeans equation**

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2 \frac{\mathrm{d}\ln\rho}{\mathrm{d}r}\right) = -\frac{4\pi G r^2(\rho+\rho_b)}{\sigma_0^2}$$

1. Isothermal gas: constant velocity dispersion σ_0
2. Mass contained inside core the same
3. Continuity



Kaplinghat, Keeley, Linden & H. B. Yu, Phys. Rev. Lett. 113, 021302 (2014) [arXiv:1311.6524]
Kaplinghat, Tulin & H. B. Yu, Phys. Rev. Lett. 116, no.4, 041302 (2016) [arXiv:1508.03339]

Spike: Conductive Fluid

- **Inner region more influenced by BH potential**

$$\rho(r) = \begin{cases} \rho_{\rm NFW}(r), & r > r_1, \\ \rho_{\rm iso}(r), & r_0 < r < r_1 \\ \rho_{\rm spike}(r), & r < r_0. \end{cases}$$

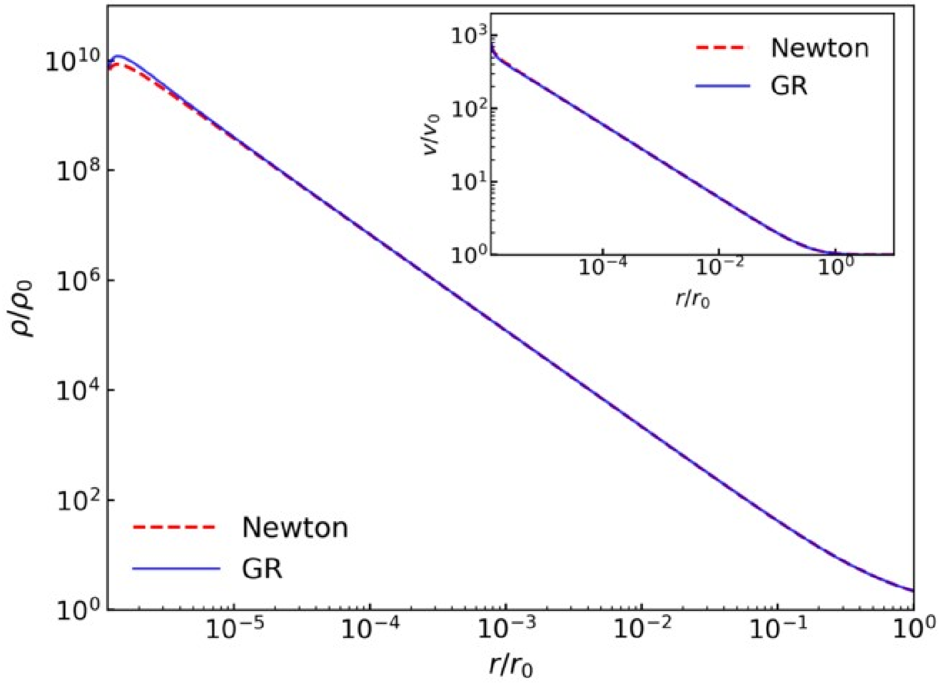
$$r_0 \equiv GM/v_0^2$$

- **Conductive fluid**

$$\frac{dv}{dr} = \frac{D}{v^{2-a}\rho^2 r^4}$$

$$\frac{d\rho}{dr} = -\frac{\rho}{v^2 r^2} - \frac{2D}{v^{3-a}\rho r^4}$$

$$\rho = 0, \quad r = r_{in} \equiv 4GM$$



$$v_d \propto r^{-1/2} \qquad \rho \propto r^{-(3+a)/4}$$

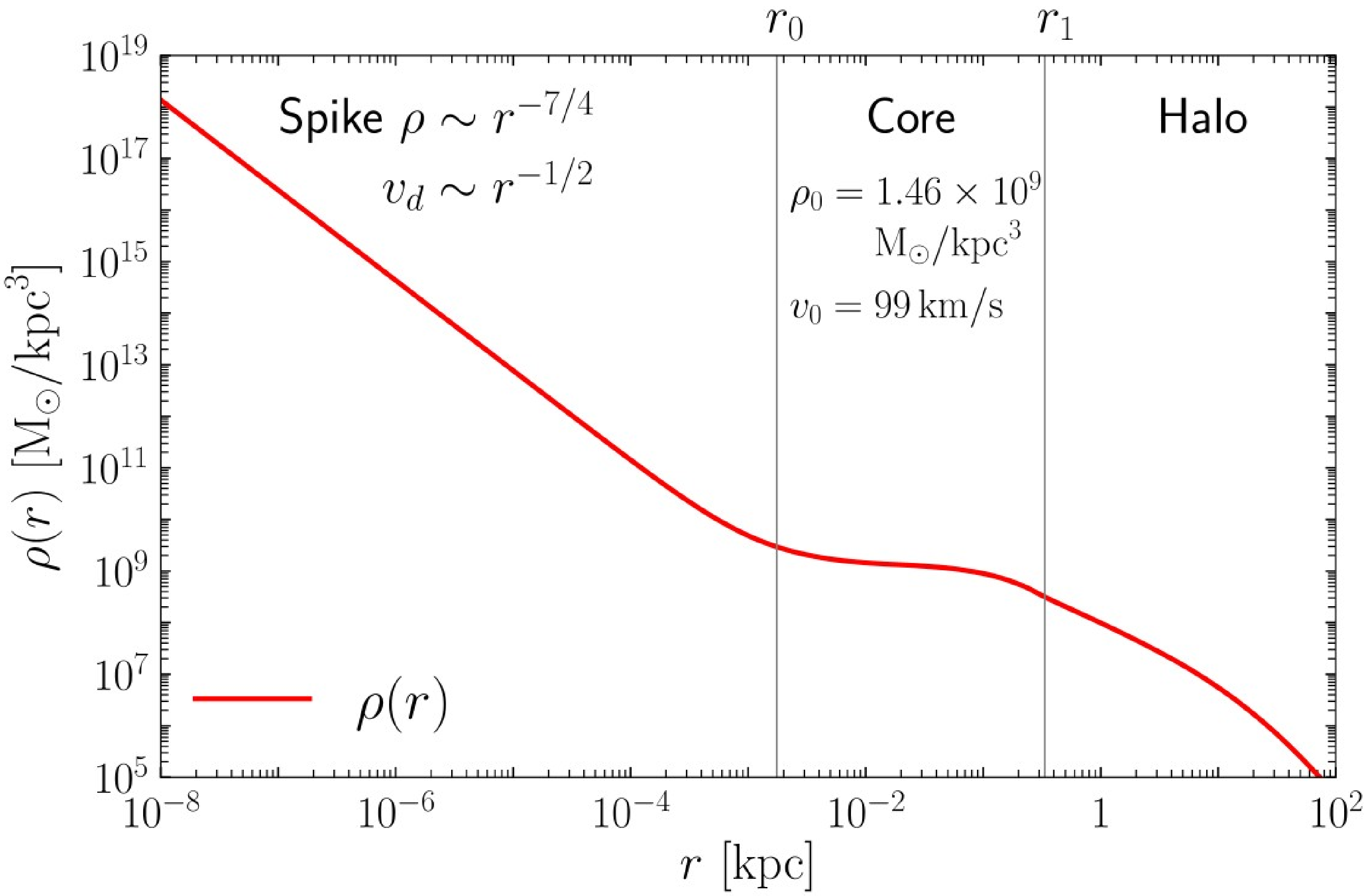
$$\sigma = \sigma_0 (v_d/v_0)^a$$

Shapiro & Paschalidis, Phys. Rev. D 89, no.2, 023506 (2014) [arXiv:1402.0005]

DM Profiles

Tsung-Dao Lee Institute

$$\rho(r) = \begin{cases} \rho_{\rm NFW}(r), & r > r_1, \\ \rho_{\rm iso}(r), & r_0 < r < r_1 \\ \rho_{\rm spike}(r), & r < r_0. \end{cases}$$



Gamma Fluxes

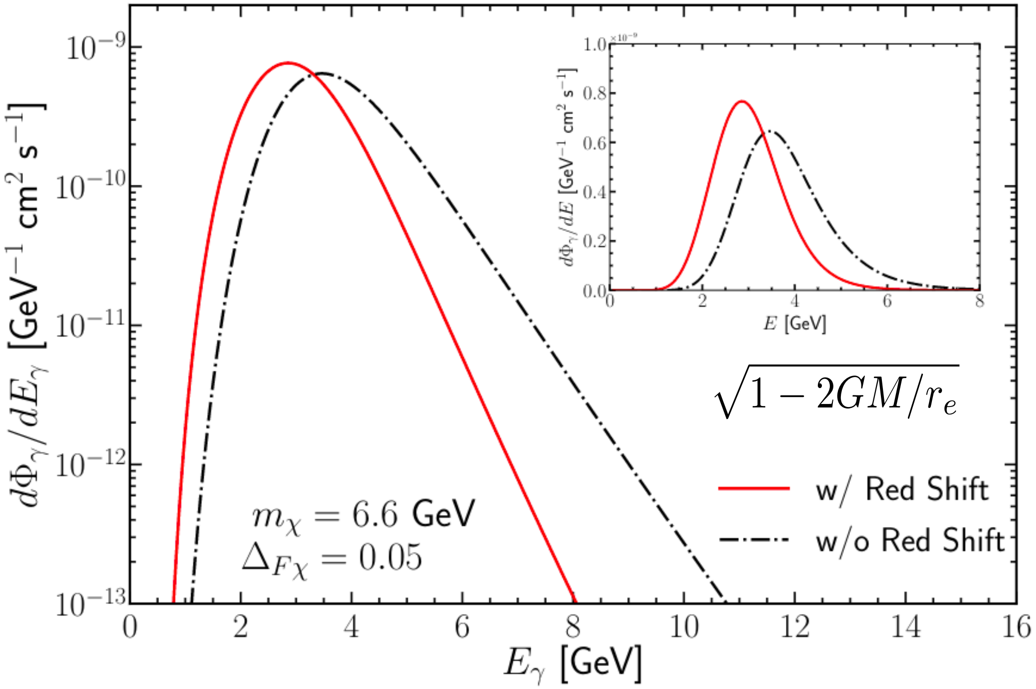
$$\mathcal{L}_{\rm DM} = g_\chi \bar\chi \gamma^\mu \chi \phi_\mu + g_{F\chi} \bar F \gamma^\mu F \phi_\mu$$

- **Forbidden channel**

$$\chi\bar\chi \to F\bar F \qquad m_\chi \lesssim m_F$$

$$\frac{d\sigma}{d\Omega} \approx \sqrt{\frac{s-4m_F^2}{s-4m_\chi^2}} \frac{4m_F^2 + 4m_\chi^2 + s}{64\pi^2 (s-m_\phi^2)^2}$$

Isotropic in the C.O.M. frame



- **Signal channel**

$$F \to \nu\gamma$$

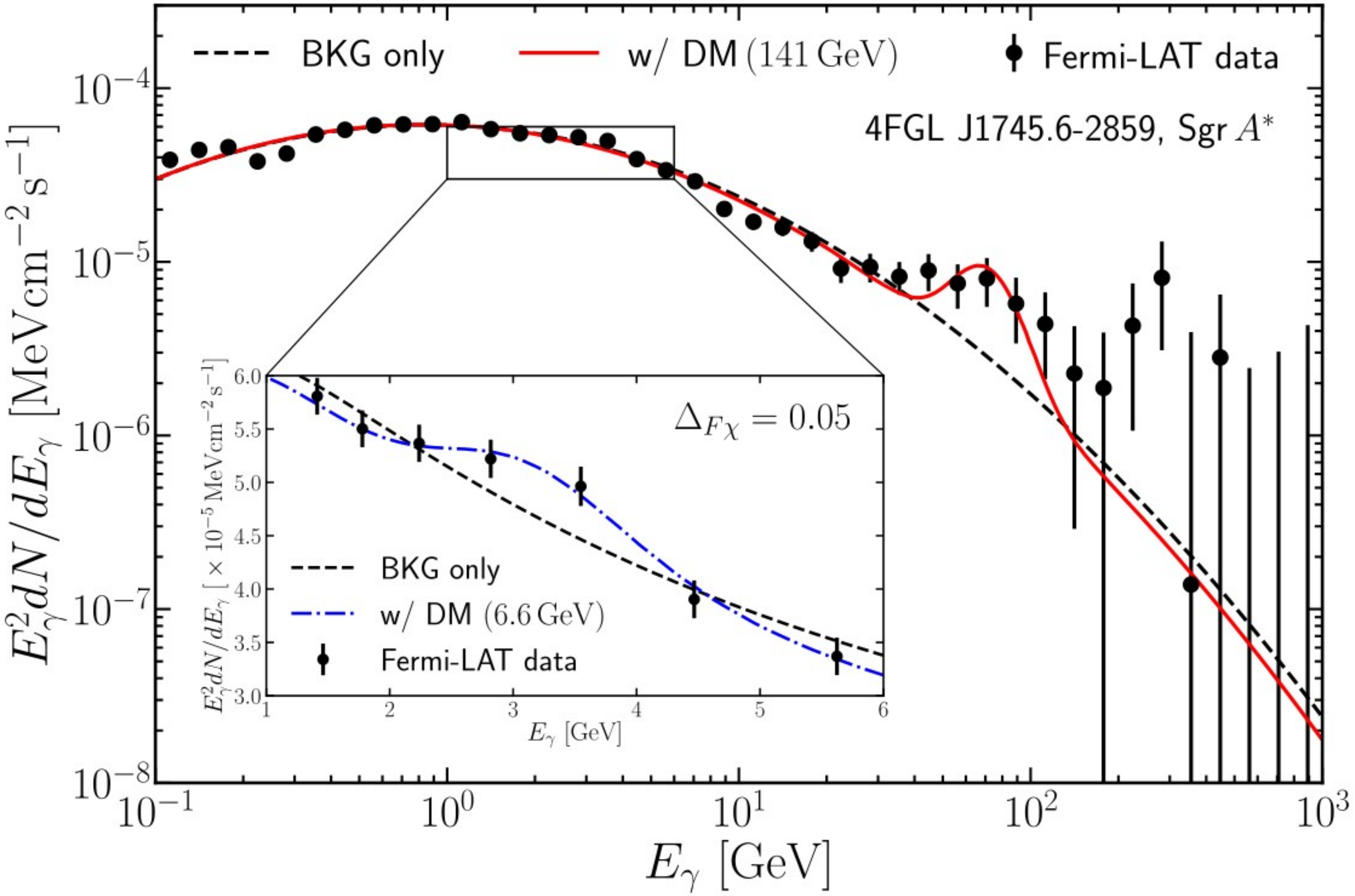
Box-shaped spectrum in C.O.M.

$$\frac{dF_\gamma}{dE_\gamma}(r) = \int_0^1 dV_r dV_c \mathcal{P}_r\left(V_r, V_c\right) \sigma V_r \frac{dN_\gamma}{dE_\gamma}(V_r, V_c)$$

$$\mathcal{P}_{\rm r}\left(V_r, V_c\right) \equiv \frac{x^2}{K_2^2(x)} \frac{\gamma_r^3(\gamma_r^2-1)V_c^2}{(1-V_c^2)^2} e^{-x\sqrt{(2+2\gamma_r)/(1-V_c^2)}}$$

Fitting the Fermi-LAT data

Tsung-Dao Lee Institute



Aug/4, 2008

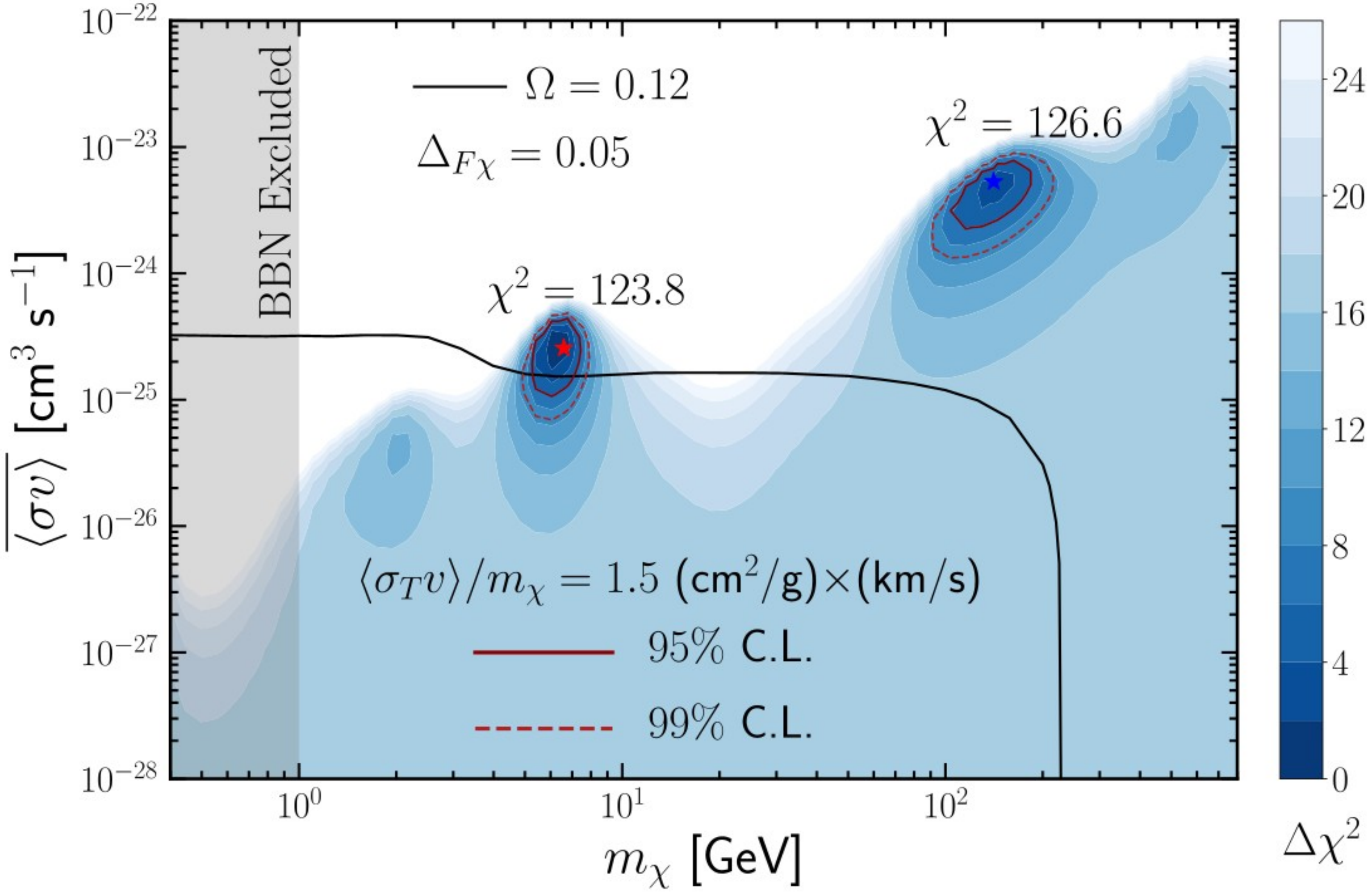
~

Oct/26, 2022

Background Model:

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\log(E/E_0)}$$

Sensitivity Plots



- **Bkg-only hypothesis**

$$\chi^2_{\rm BKG} = 140.8$$

- **1st Peak @ 6.6GeV** $\langle\sigma v\rangle = 1.99 \times 10^{-22}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$
- **2nd Peak @ 141GeV** $\overline{\langle\sigma v\rangle} = 4.12 \times 10^{-21}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$

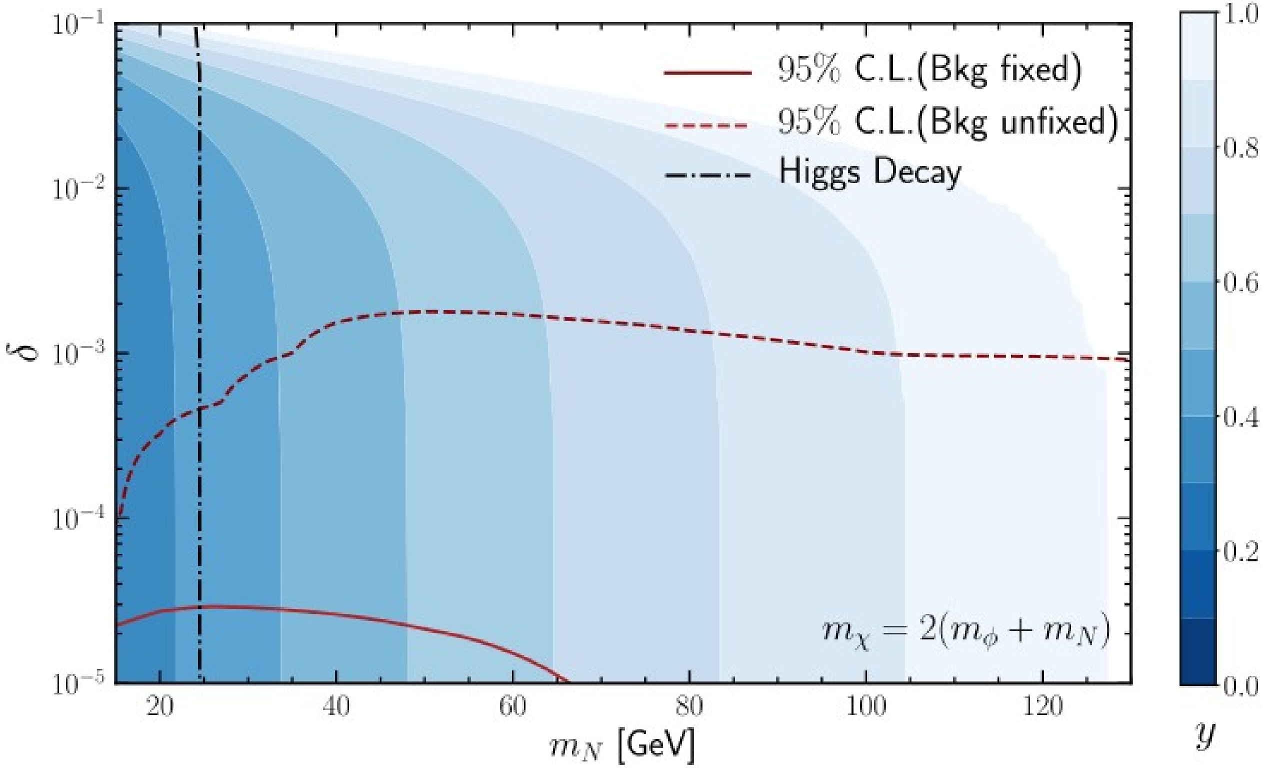
Forbidden with Right-Handed ν

Tsung-Dao Lee Institute

$$\mathcal{L}_{\rm int} = (y \phi N \chi + h.c.) + \lambda m_\phi \phi H^\dagger H$$

DM freezes out through the forbidden channel $N + N \leftrightarrow \phi + \phi$

$$\langle \sigma_{NN} v \rangle \equiv \left(\frac{n_\phi^{\rm eq}}{n_N^{\rm eq}} \right)^2 \langle \sigma_{\phi\phi} v \rangle = \frac{(1+\delta)^3}{4} e^{-2x\delta} \langle \sigma_{\phi\phi} v \rangle$$



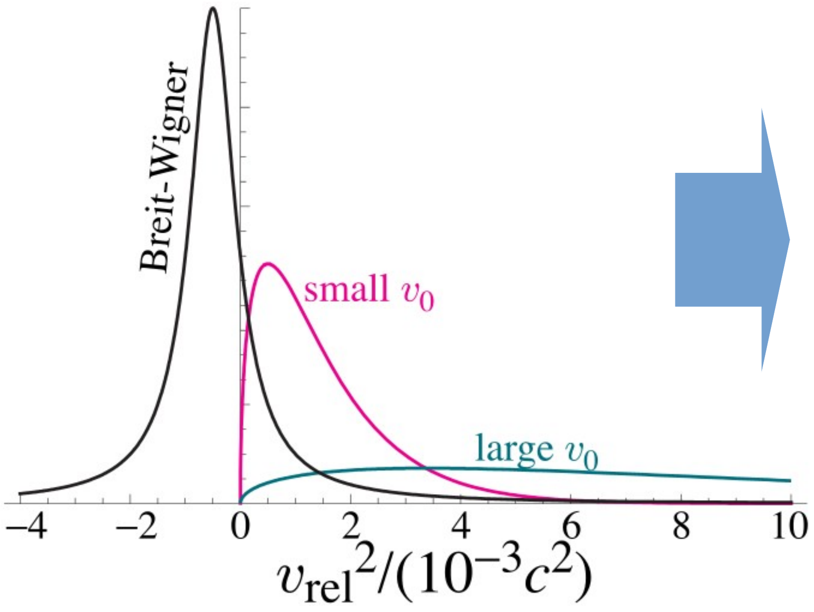
$$\delta \equiv \frac{m_\phi - m_N}{m_N}$$

Yu Cheng, **SFG**, Jie Sheng, Tsutomu Yanagida [PhysRevD.107.123013]

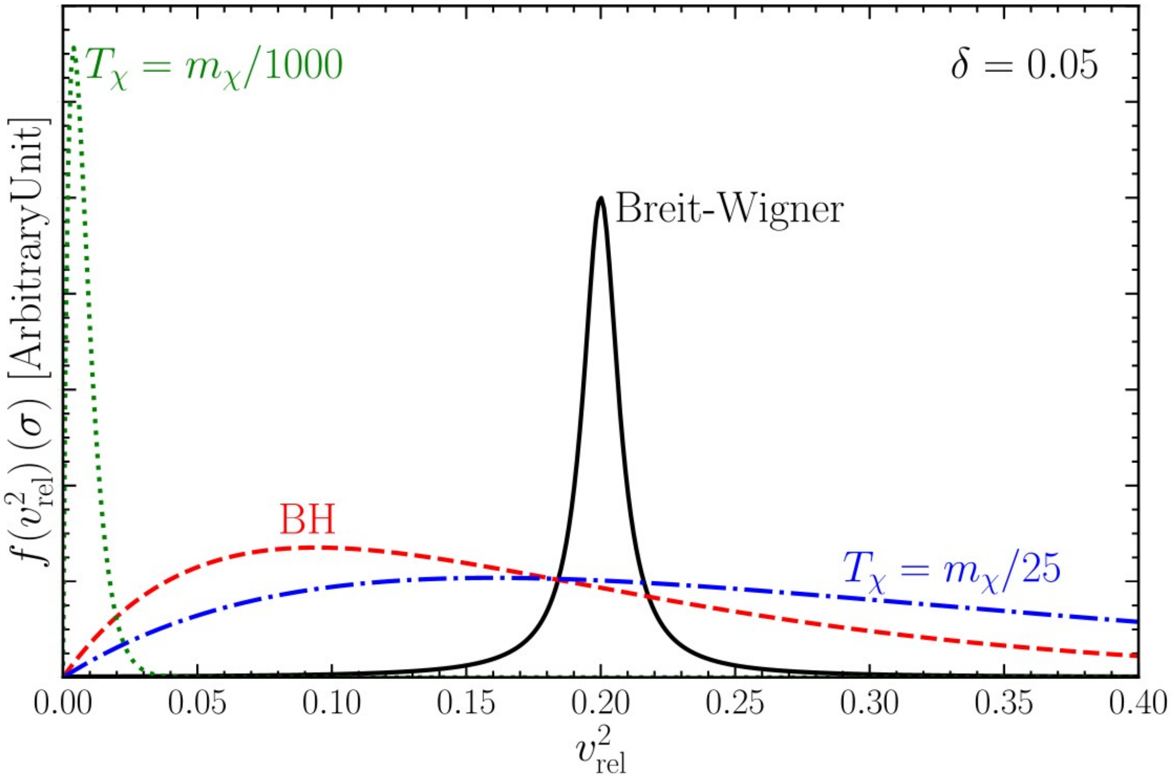
BW Resonance with Heavy Mediator

$$\sigma = \frac{16\pi\beta_f}{s\bar{\beta}_i\bar{\beta}_f\beta_i}\frac{\gamma^2}{\left(\frac{\vec{v}_{\rm rel}^2/4-\delta}{1+\delta}\right)^2+\gamma^2}B_iB_f$$

$$\mathcal{L}_{\rm int} = (y\phi N_\chi^T\epsilon N_\chi + h.c.) + \lambda m_\phi \phi H^\dagger H$$



Ibe, Murayama, Yanagida [Phys.Rev.D 79 (2009) 095009]



Yu Cheng, **SFG**, Jie Sheng, Tsutomu Yanagida [PhysRevD.107.123013; arXiv:2309.12043]

1) Thresholds in DM search

2) Cosmic ray boosted DM & diurnal modulation

3) Fermionic DM Absorption

4) **Reactivate Forbidden DM @ Supermassive Black Hole**

5) **Energetic MeV Solar DM from pp-chaim**

MeV Solar DM

SFG, Jie Sheng, Chen Xia, Chuan-Yang Xing [arXiv:2408.12448]

Jie Sheng

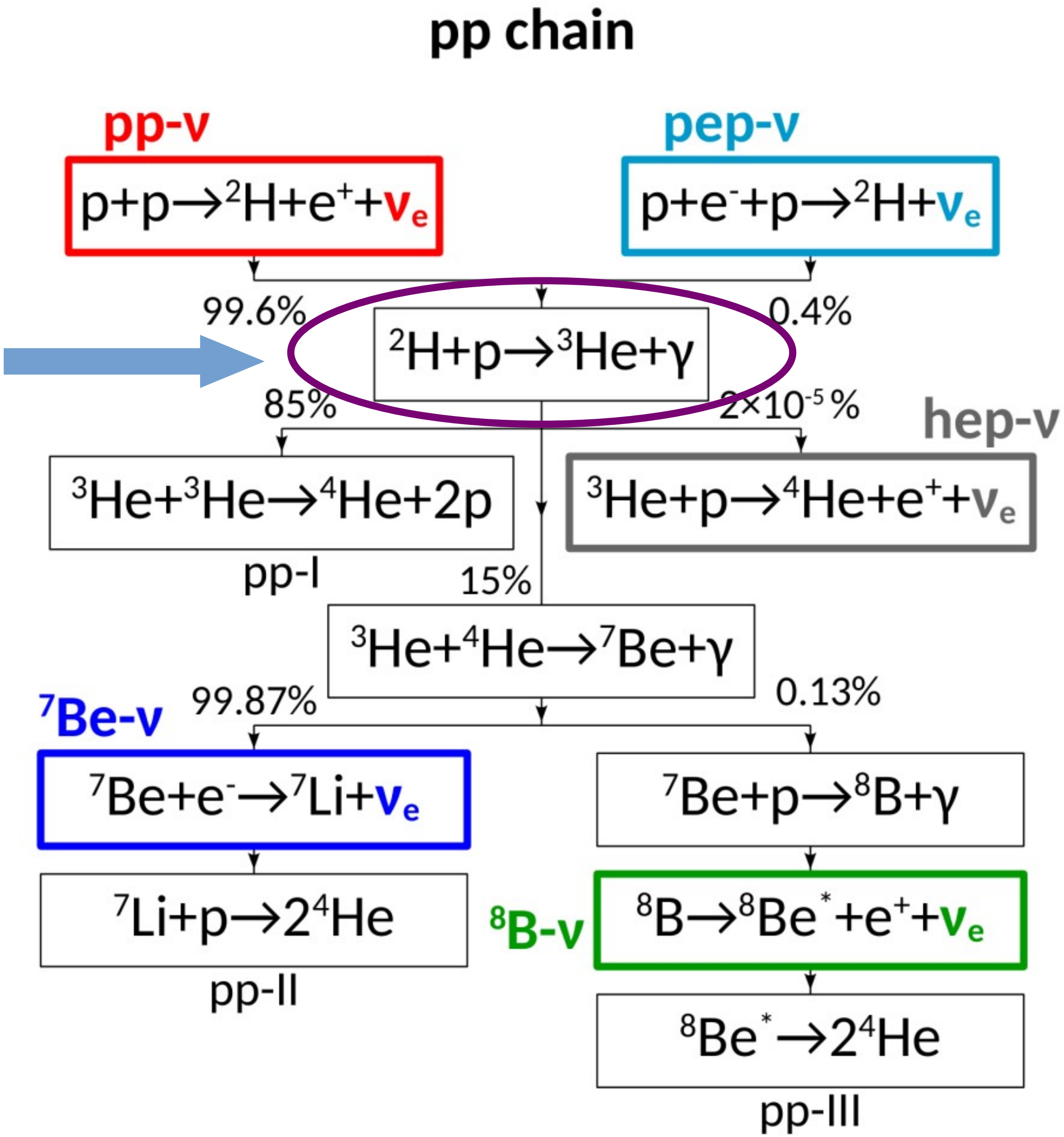
Chen Xia

Chuan-Yang Xing

MeV Energy in Sun

$$4p \to {}^4He + 2e^+ + 2\nu_e$$

5.5MeV



pp chain

pp-ν

$p+p \to {}^2H+e^+ + \nu_e$

pep-ν

$p+e^- +p \to {}^2H+\nu_e$

99.6%

0.4%

${}^2H+p \to {}^3He+\gamma$

85%

2×10^{-5} %

hep-ν

${}^3He+{}^3He \to {}^4He+2p$

pp-I

${}^3He+p \to {}^4He+e^+ + \nu_e$

15%

${}^3He+{}^4He \to {}^7Be+\gamma$

^{7}Be-ν

99.87%

0.13%

${}^7Be+e^- \to {}^7Li+\nu_e$

${}^7Be+p \to {}^8B+\gamma$

${}^7Li+p \to 2{}^4He$

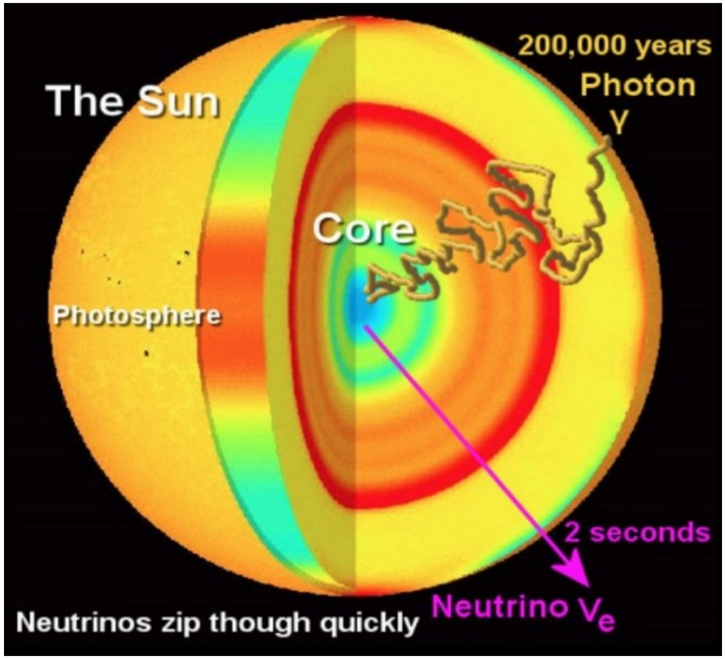
pp-II

^{8}B-ν

${}^8B \to {}^8Be^* + e^+ + \nu_e$

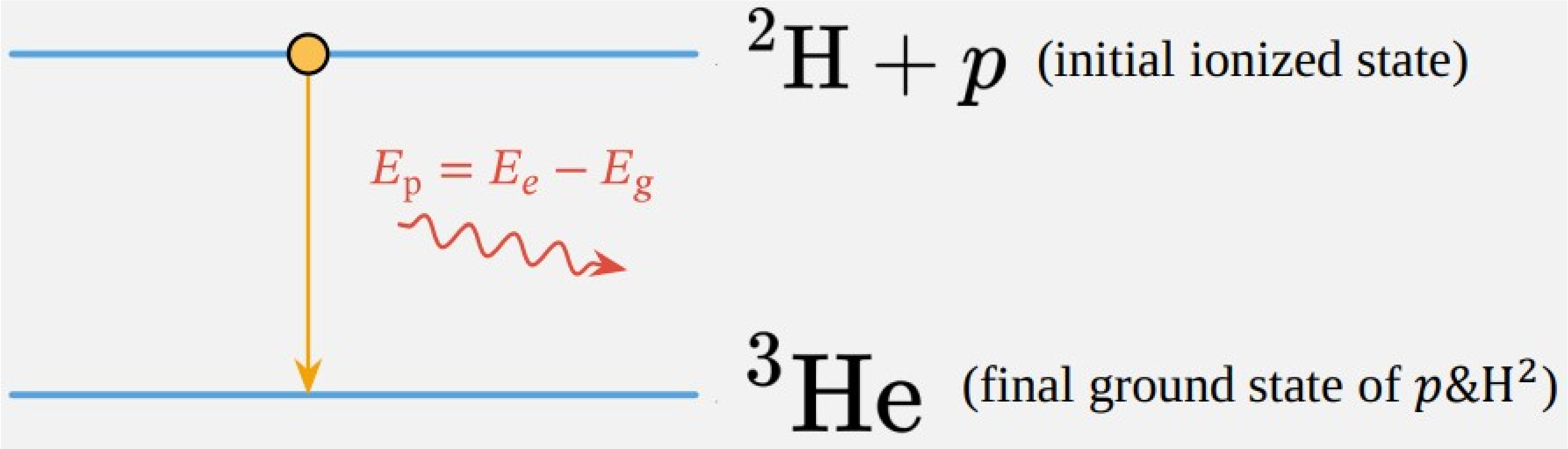
${}^8Be^* \to 2{}^4He$

pp-III



MeV DM Production in Sun

$$p + d \to {}^3\mathrm{He} + \gamma$$

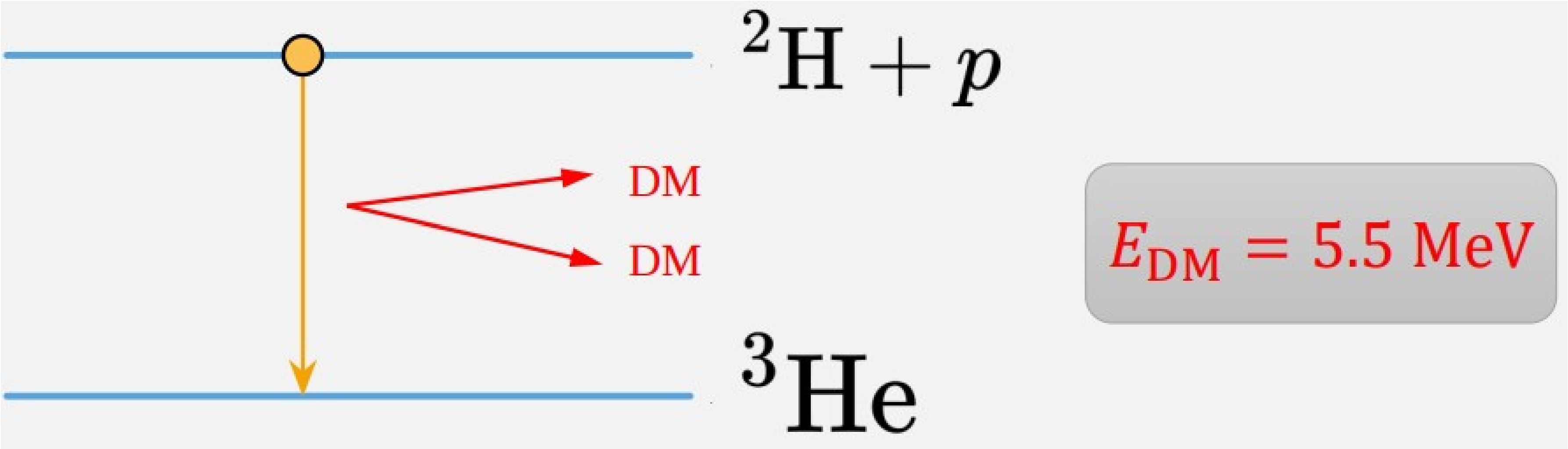


$^2\mathrm{H} + p$ (initial ionized state)

$E_\mathrm{p} = E_e - E_g$

$^3\mathrm{He}$ (final ground state of p&H^2)

$$p + d \to {}^3\mathrm{He} + DMDM$$



$^2\mathrm{H} + p$

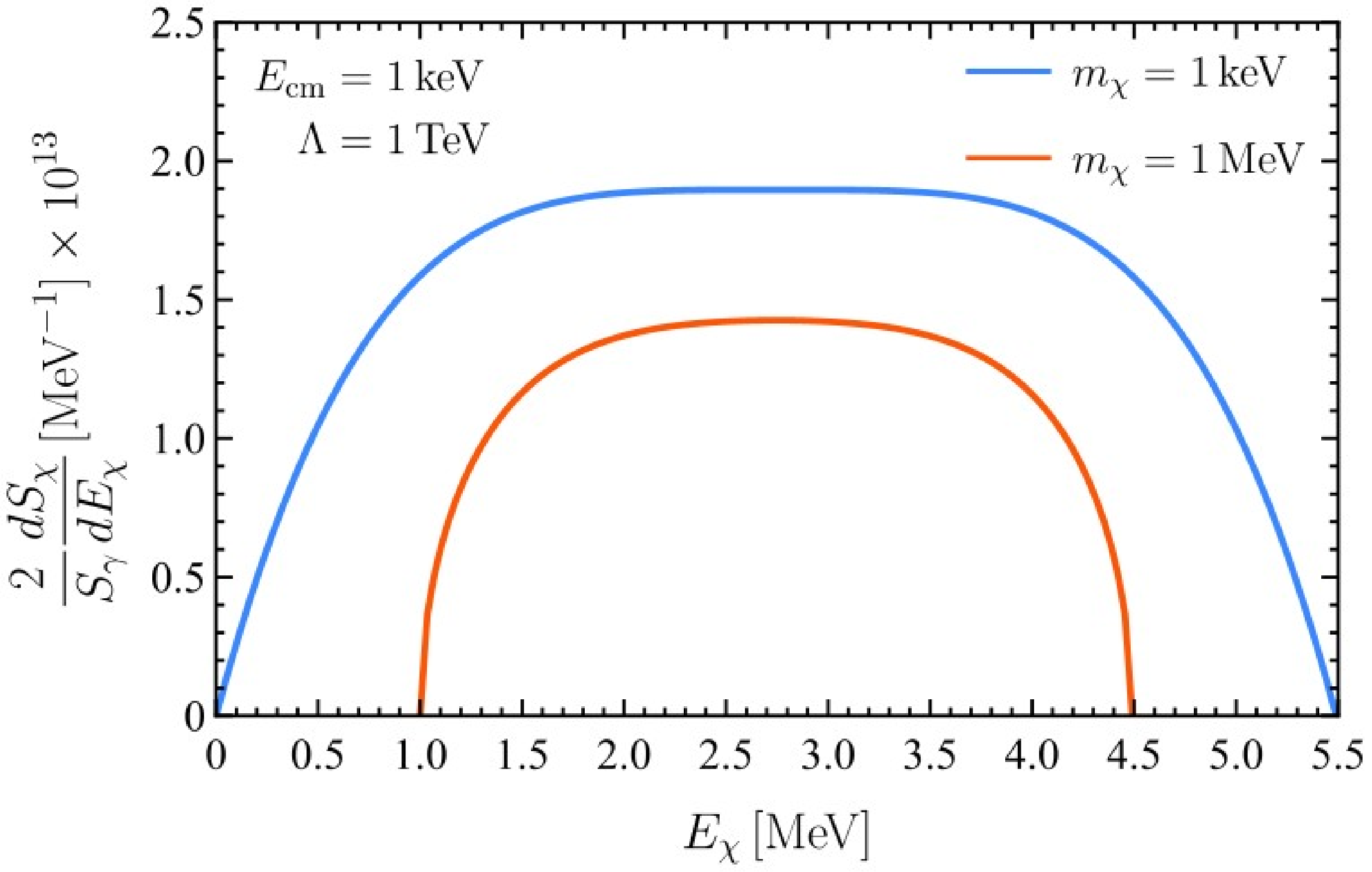
DM

DM

$^3\mathrm{He}$

$E_\mathrm{DM} = 5.5$ MeV

Nuclear S-Factor

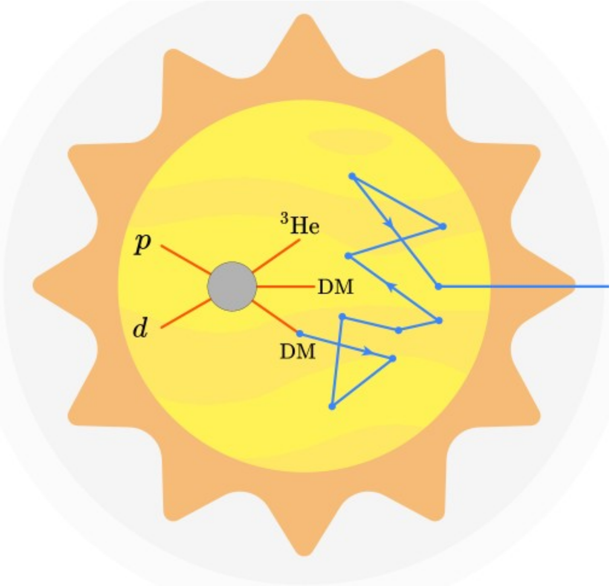


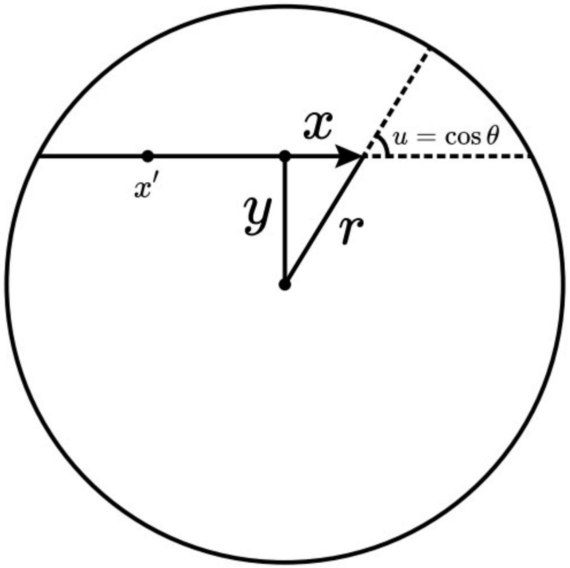
$$V_0 + V_S(\mathbf{L}\cdot\mathbf{S}) + V_C$$

$$\frac{d^3 N_\chi}{dt\,dE_\chi\,dV_\odot} \simeq \frac{2}{S_\gamma}\frac{dS_\chi}{dE_\chi}\frac{d^2 N_\gamma}{dt\,dV_\odot}$$

$$S(E_{\rm cm}) \equiv \sigma(E_{\rm cm}) E_{\rm cm} e^{2\pi\eta}$$

Analytical Attenuation in Sun

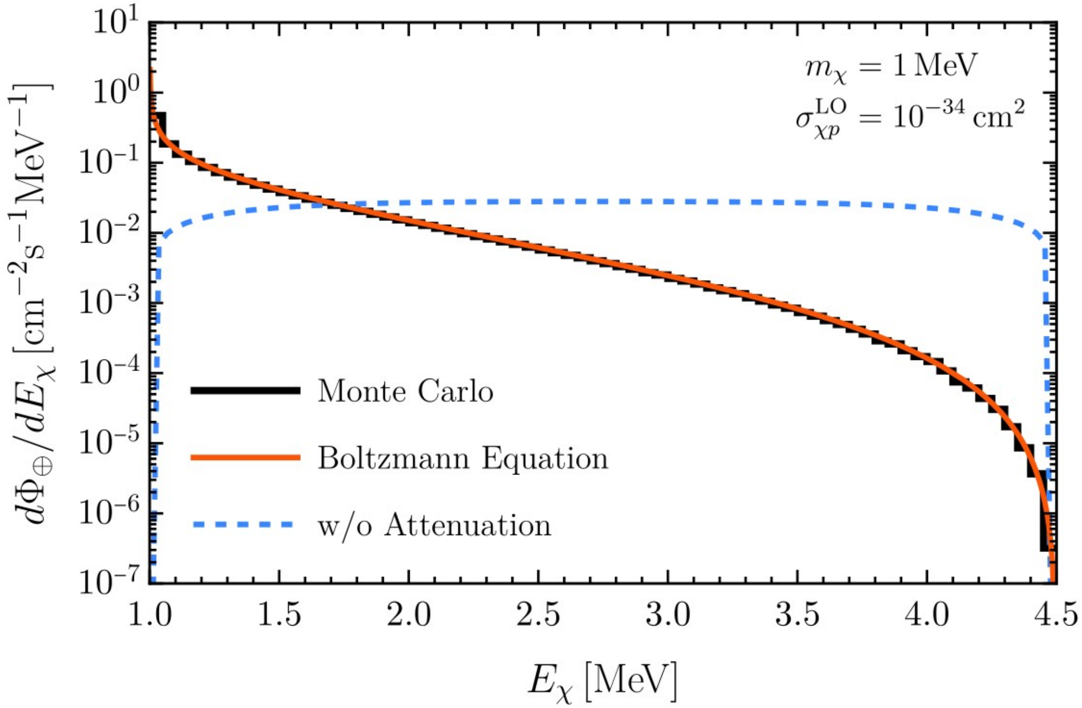




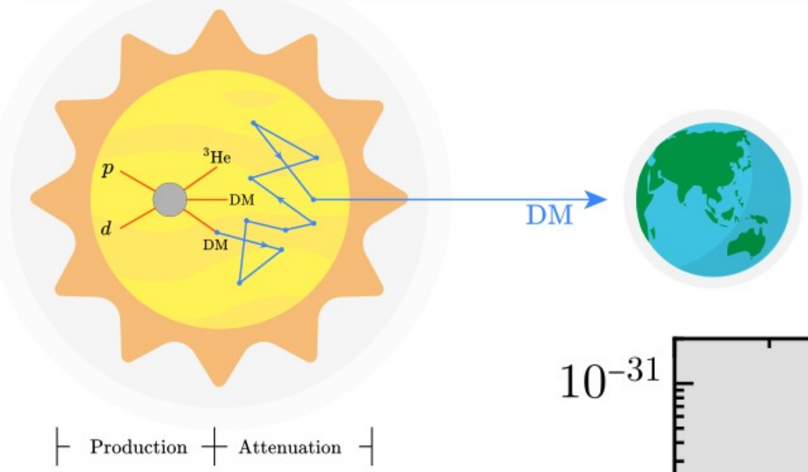
$$\hat{\mathbf{L}}[f_\chi] = |\mathbf{p}_\chi| \left(u \frac{\partial f_\chi}{\partial r} + \frac{1-u^2}{r} \frac{\partial f_\chi}{\partial u} \right)$$

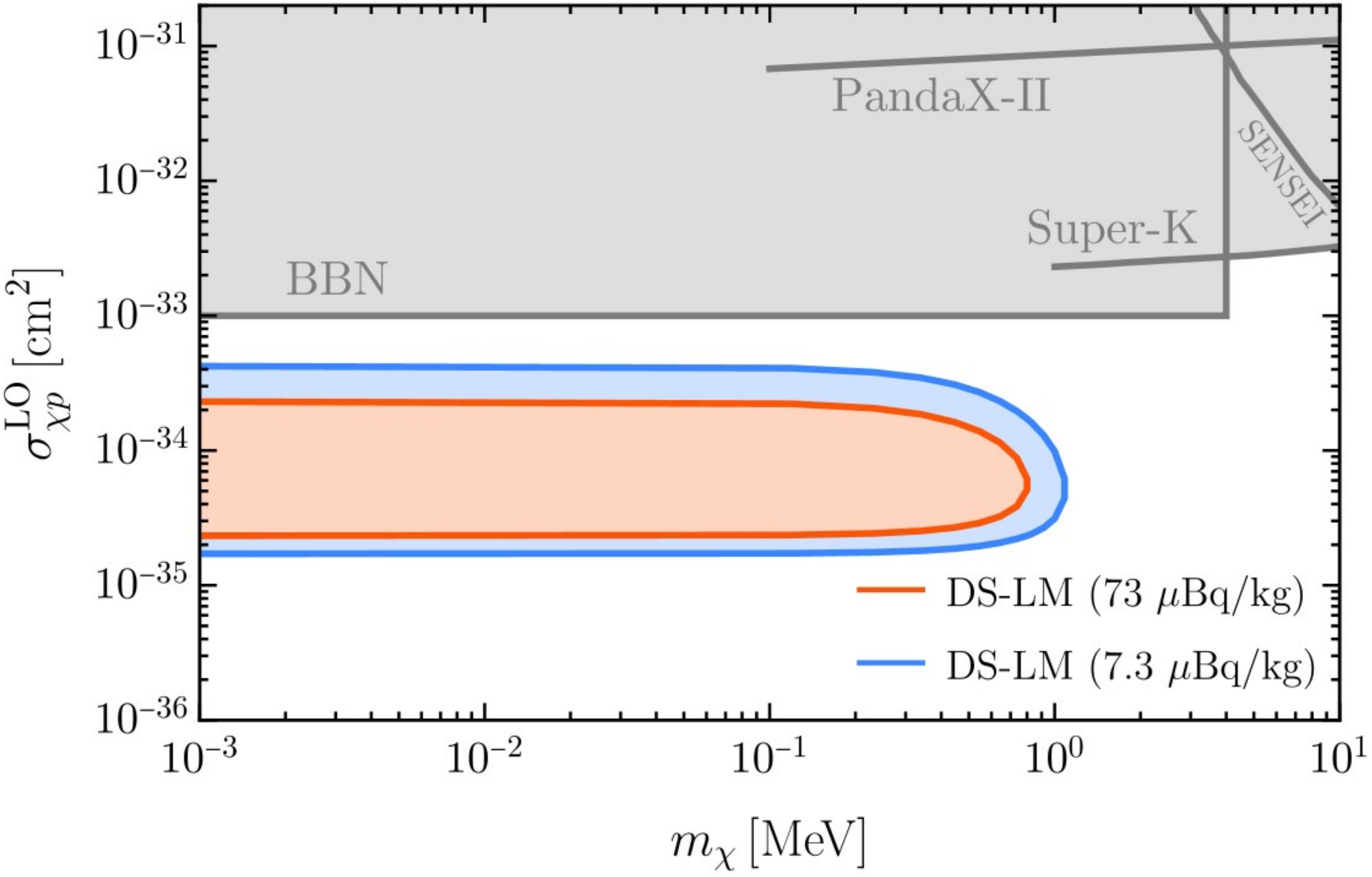
$$x \equiv r u \qquad y \equiv r\sqrt{1-u^2}$$

$$\hat{\mathbf{L}}[f_\chi] = |\mathbf{p}_\chi| \partial_x f_\chi$$



Detection at DarkSide-Low





Summary

Threshold exists in not just direct detection but also indirect detection!

0) **Cosmic Ray Boosted DM & Diurnal Modulation**

1) **Fermionic DM Absorption & Nucleon Consumption**
   - **Efficient energy release**
   - **Peak shape by atomic effects**

2) **Forbidden DM @ SMBH**
   - **How to uniquely test forbidden DM?**
   - **Point source around supermassive BH**

3) **MeV Solar DM**
   - **5.5MeV energy release from pp-chain**
   - **Analytic attenuation**

《 Physics Letters A 》

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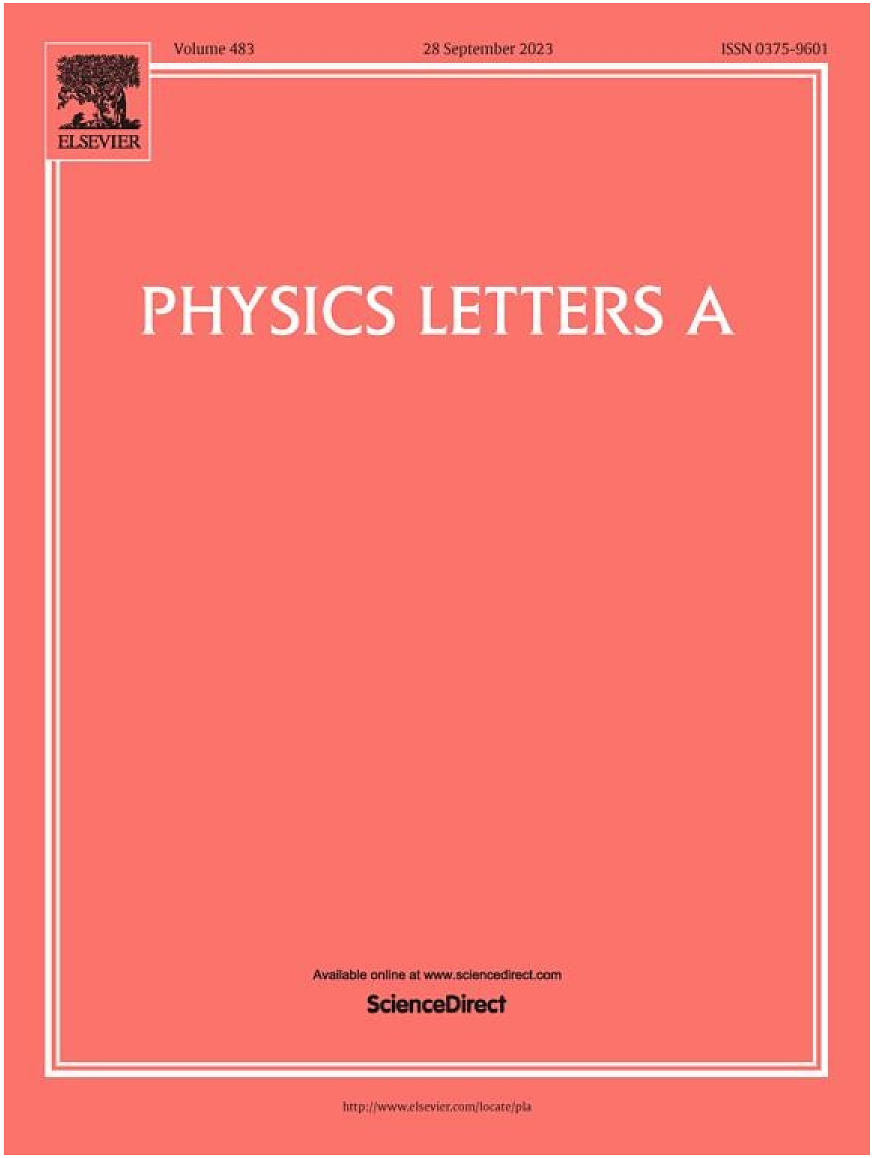

Volume 483 28 September 2023 ISSN 0375-9601

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PHYSICS LETTERS A

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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.

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Thank You

1) Thresholds in DM search

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

3) **Fermionic DM Absorption**

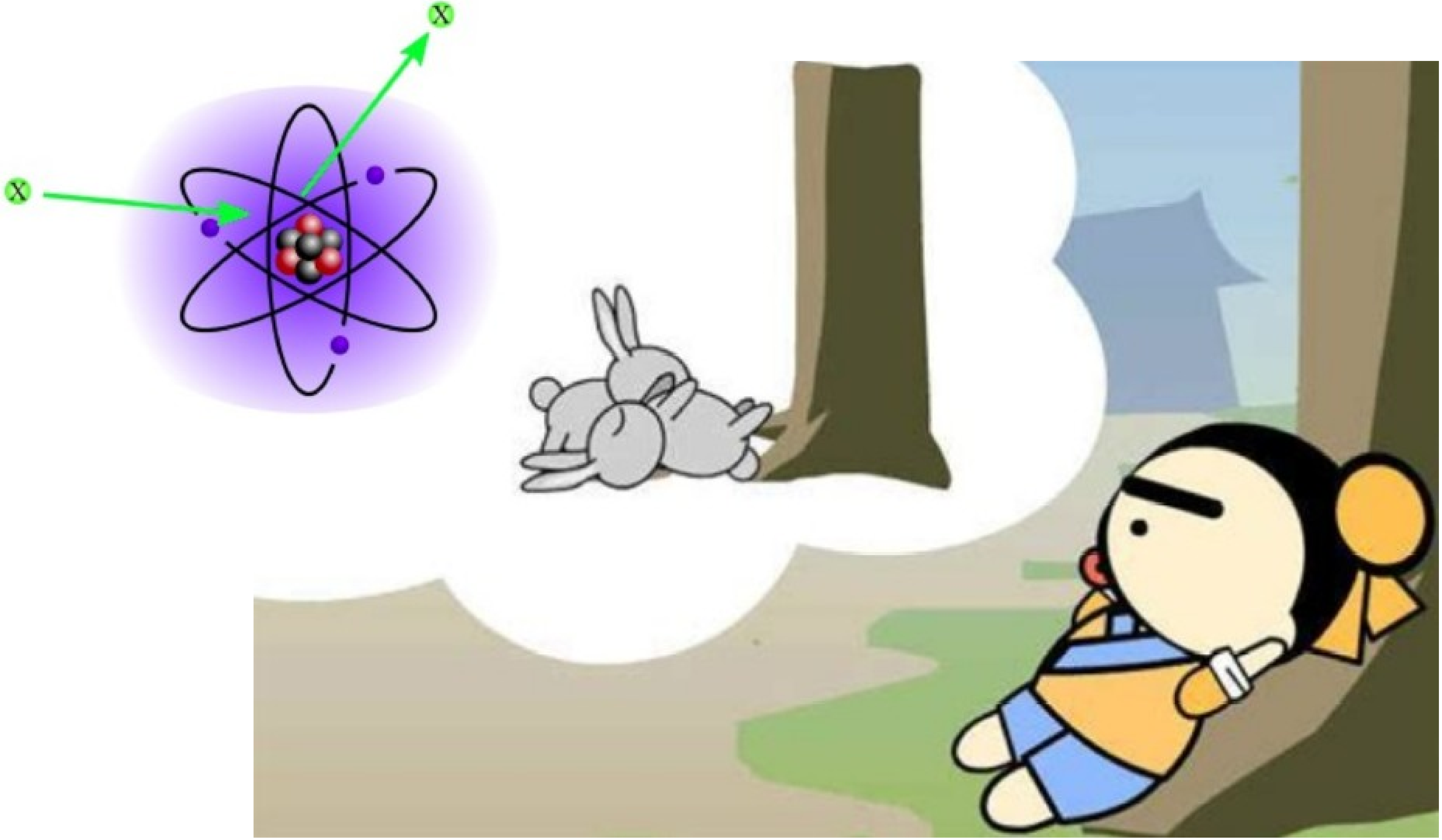
4) **Reactivate Forbidden DM @ Supermassive Black Hole**

CR Boosted DM

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

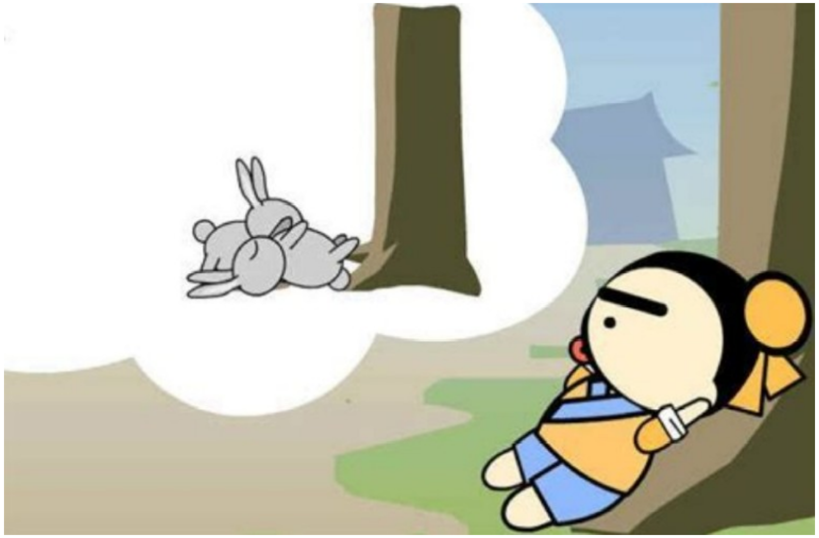
PandaX-II + **SFG**, Qiang Yuan [Phys.Rev.Lett. 128 (2022) 17, 171801]

DM Detection vs 守株待兔



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

Beatting Rabbits



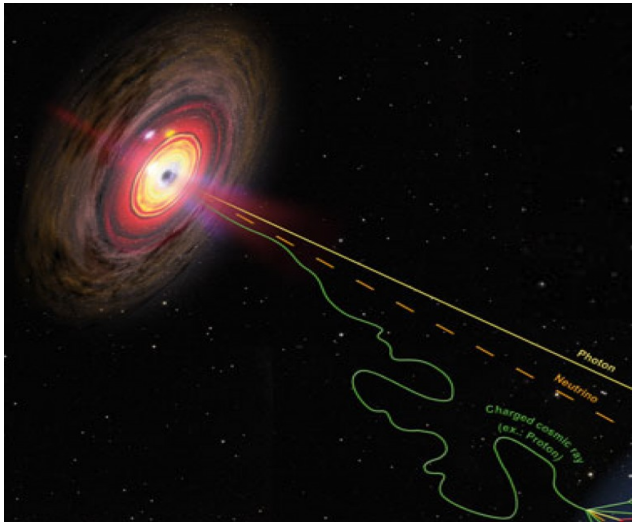
Stick has the same material as tree!

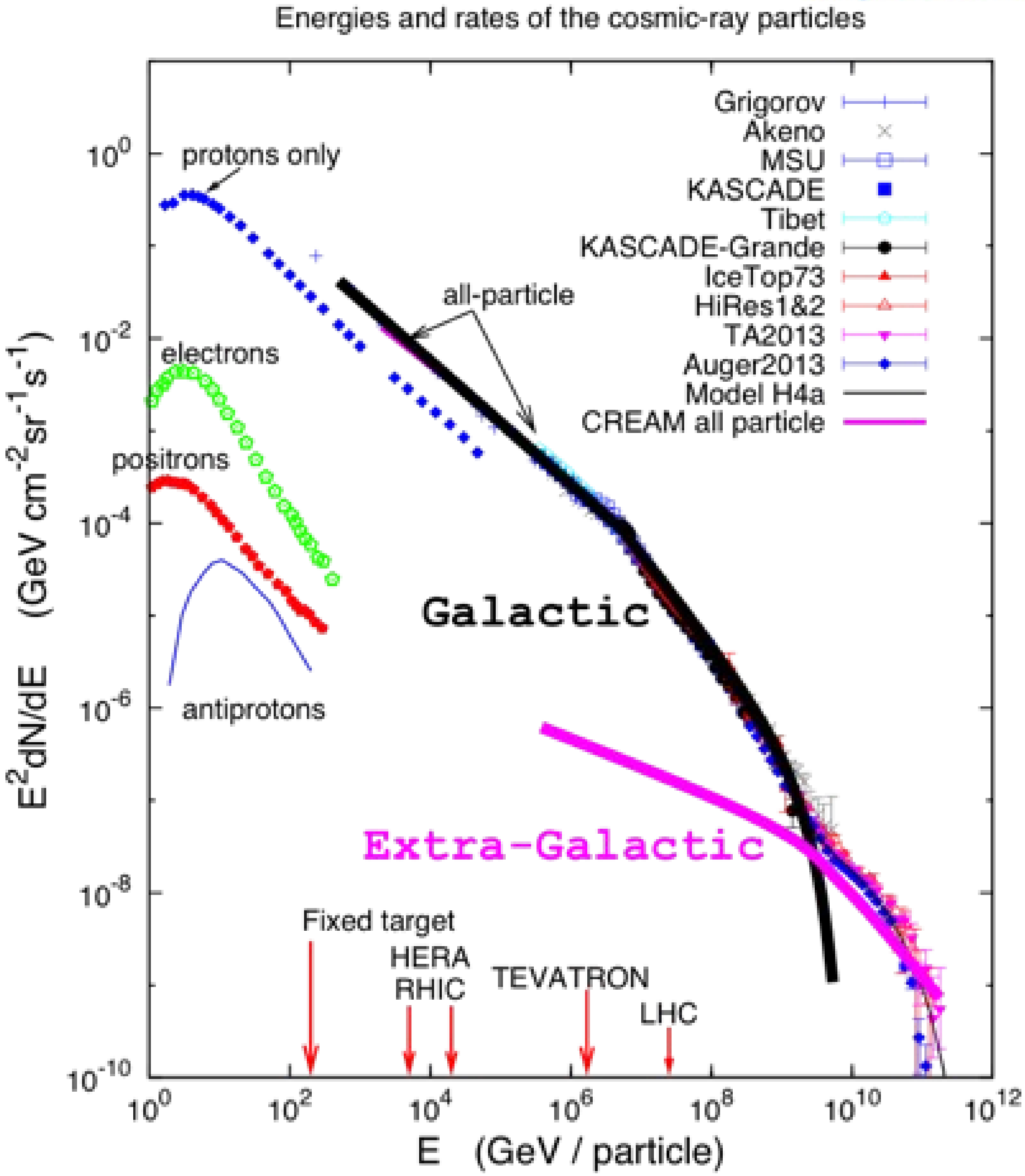
So long as direct detection is possible.

Cosmic Ray Boosted DM

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

Cosmic Rays





1) Cosmic rays are almost everywhere in the galaxy

2) Cosmic rays are very energetic

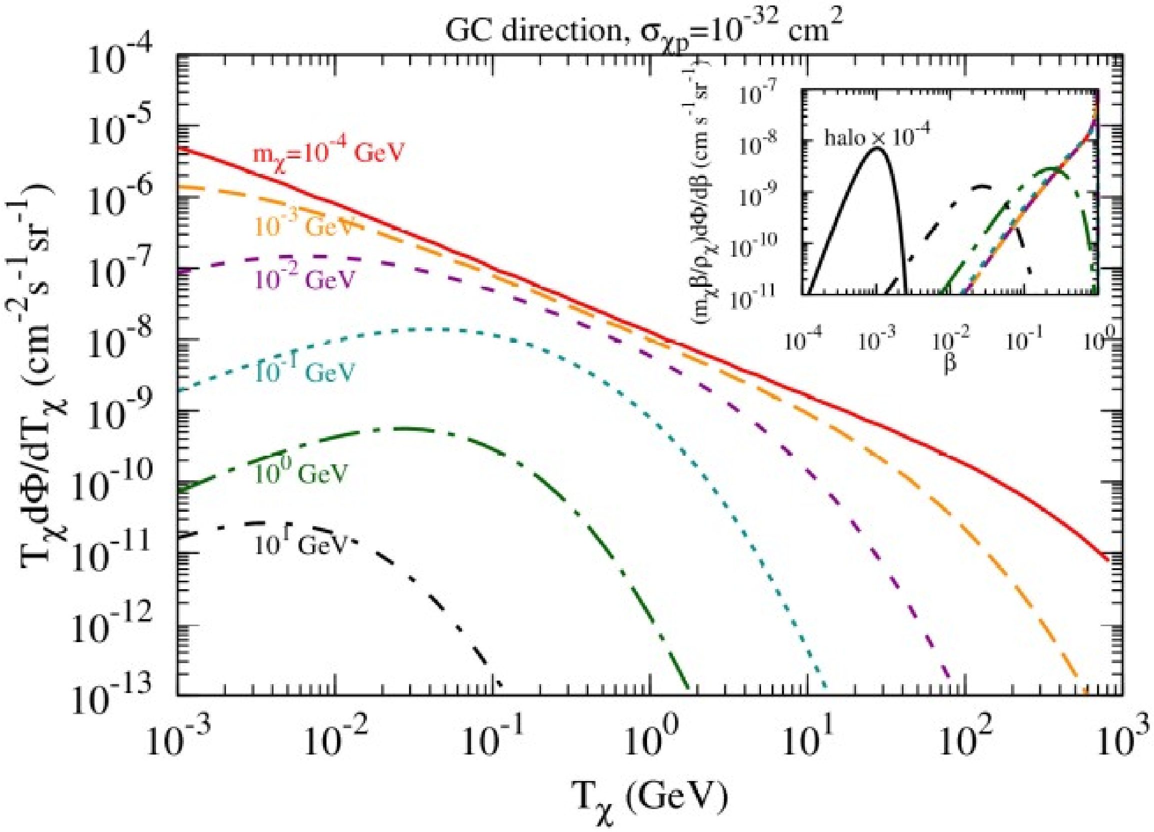
3) Cosmic rays have several components (proton, electron, ...)

Cosmic Ray Boosted DM

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

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

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

$$\approx \frac{T_i^2}{T_i + m_i^2/2m_\chi}$$

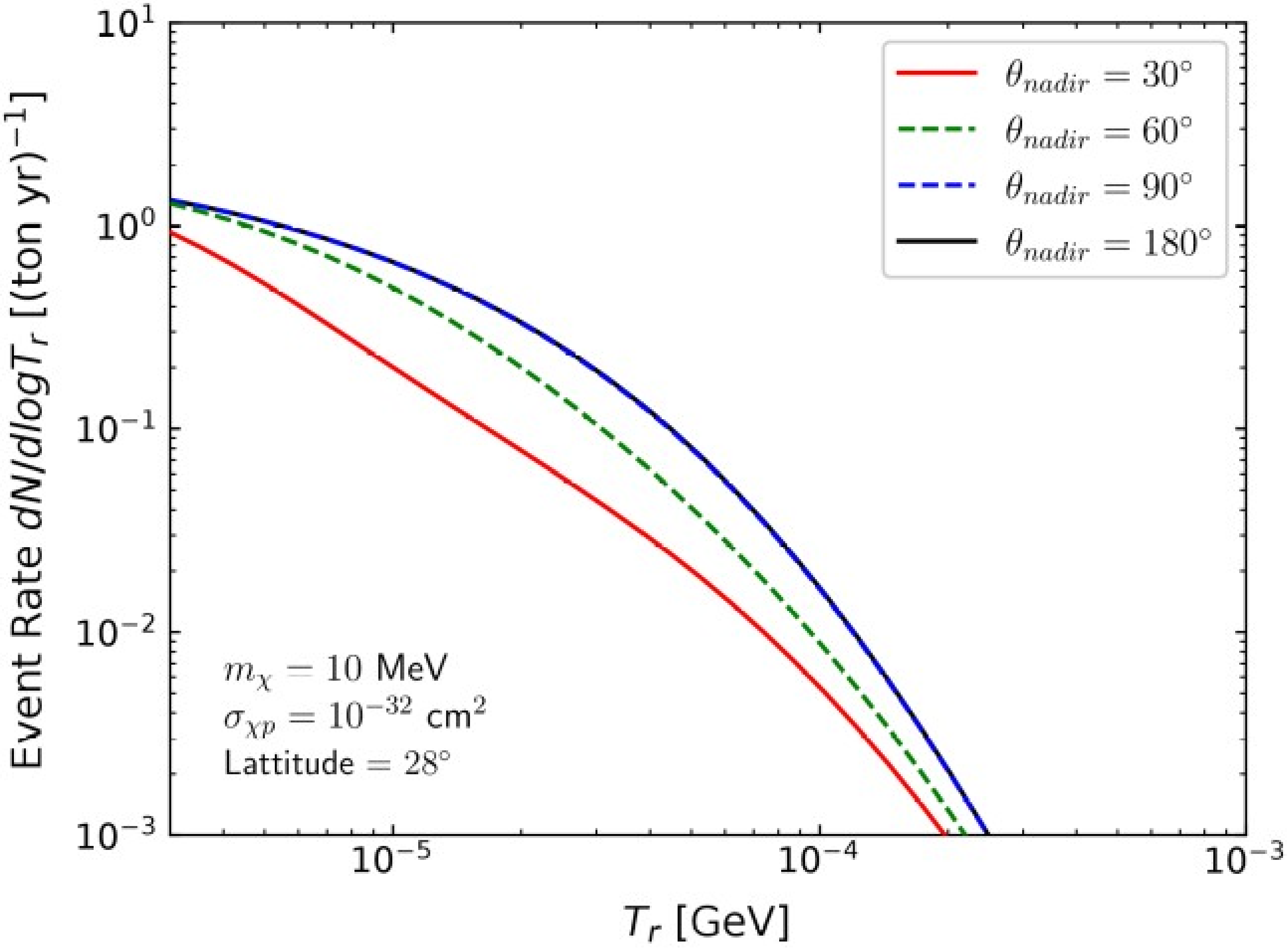
$$\text{for} \quad m_\chi \ll m_i$$

SFG, Jianglai Liu, Ning Zhou, Qiang Yuan, PRL 2021 [arXiv:2005.09480]

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

Direct Detection

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

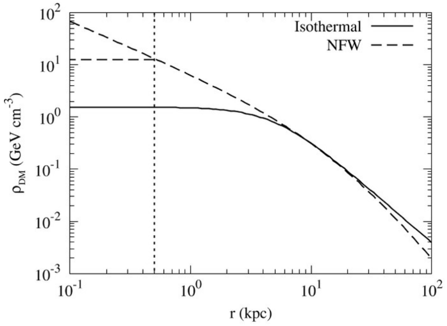


The nuclear recoil from CRDM is much more energetic!

SFG, Jianglai Liu, Ning Zhou, Qiang Yuan, PRL 2021 [arXiv:2005.09480]

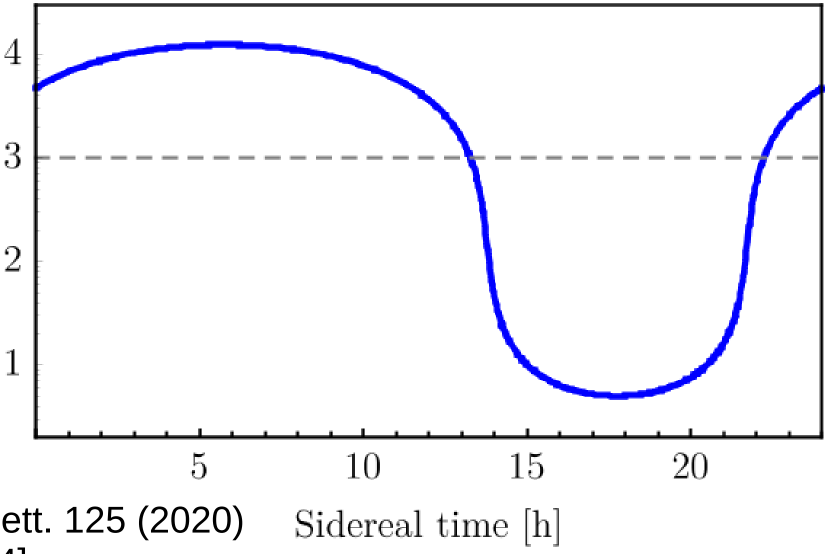
Anisotropies → Diurnal Effect

SFG, Jianglai Liu, Ning Zhou, Qiang Yuan,
PRL 2021 [arXiv:2005.09480]

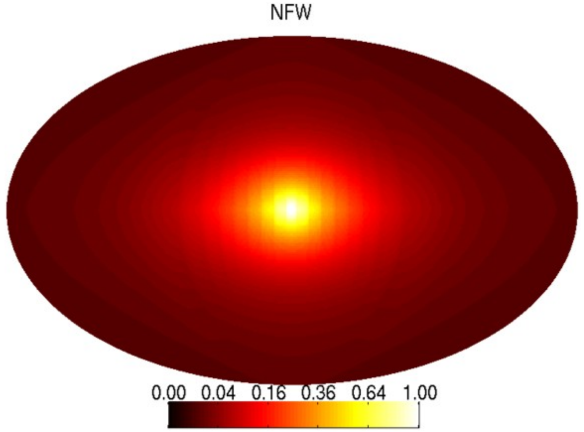


Cosmic Rays

DM



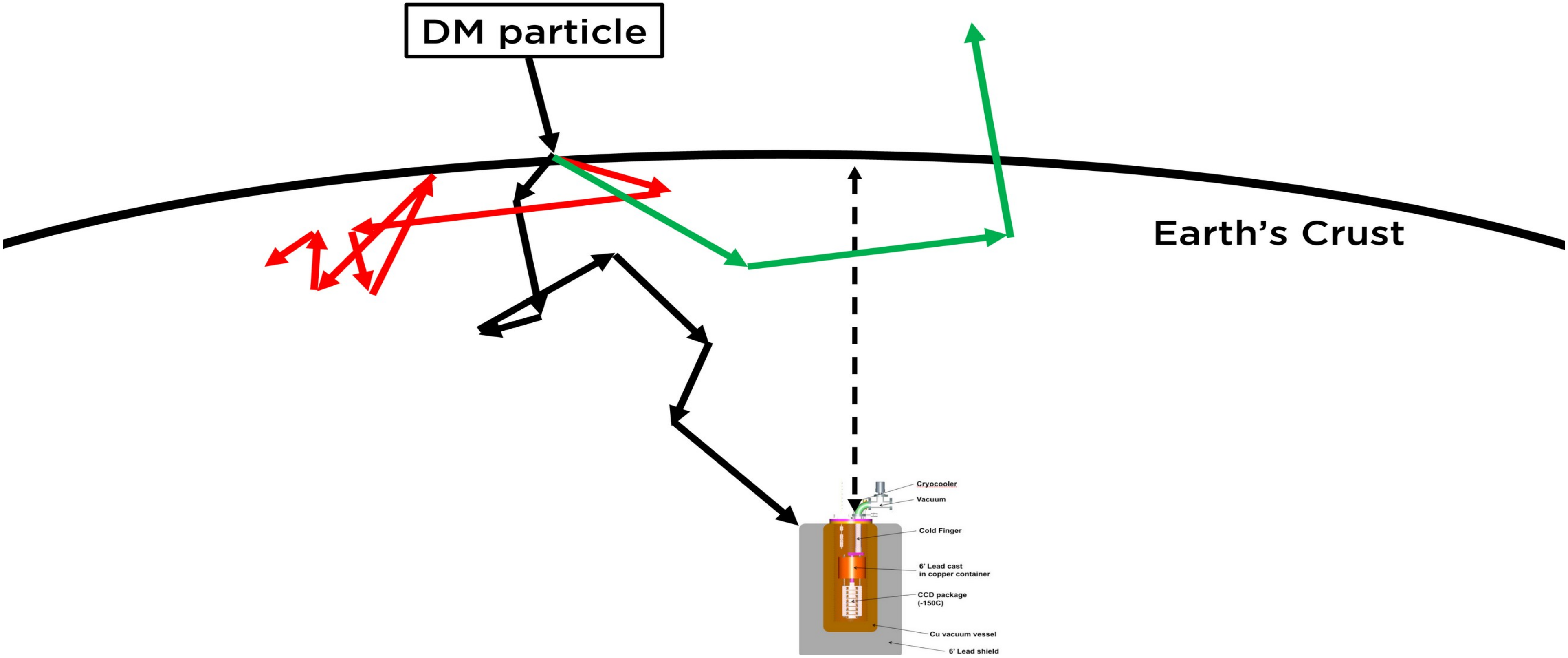
Fornal, Sandick, Shu,
Su & Zhao, Phys.Rev.Lett. 125 (2020)
16, 161804 [2006.11264]



See also Xia, Xu & Zhou [2206.11454]

Earth Attenuation

Tsung-Dao Lee Institute



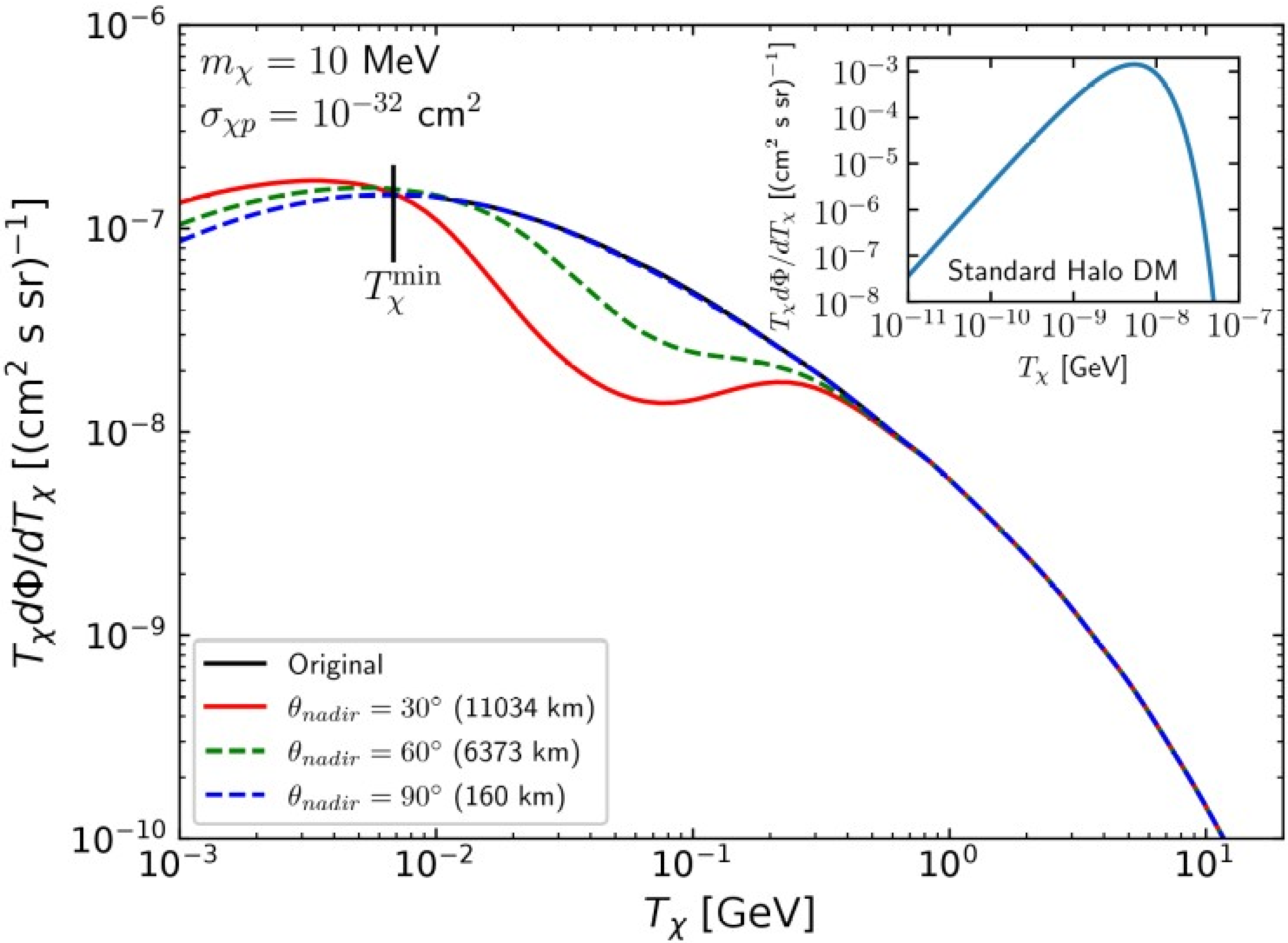
$$\frac{\partial}{\partial l}\frac{d\Phi(l,T_\chi)}{d\ln T_\chi} = \frac{\rho_N(l)}{m_N}\sigma_{\chi N} G_N^2(Q^2)\left[-\frac{d\Phi(l,T_\chi)}{d\ln T_\chi} + \int \frac{d\Phi\left(l,T'_\chi\right)}{d\ln T'_\chi}\frac{T_\chi(T'_\chi+m_\mu^N)}{T'_\chi(T'_\chi+2m_\chi)}\,d\ln T'_\chi\right]$$

Transfer to lower energy

Come from higher energy

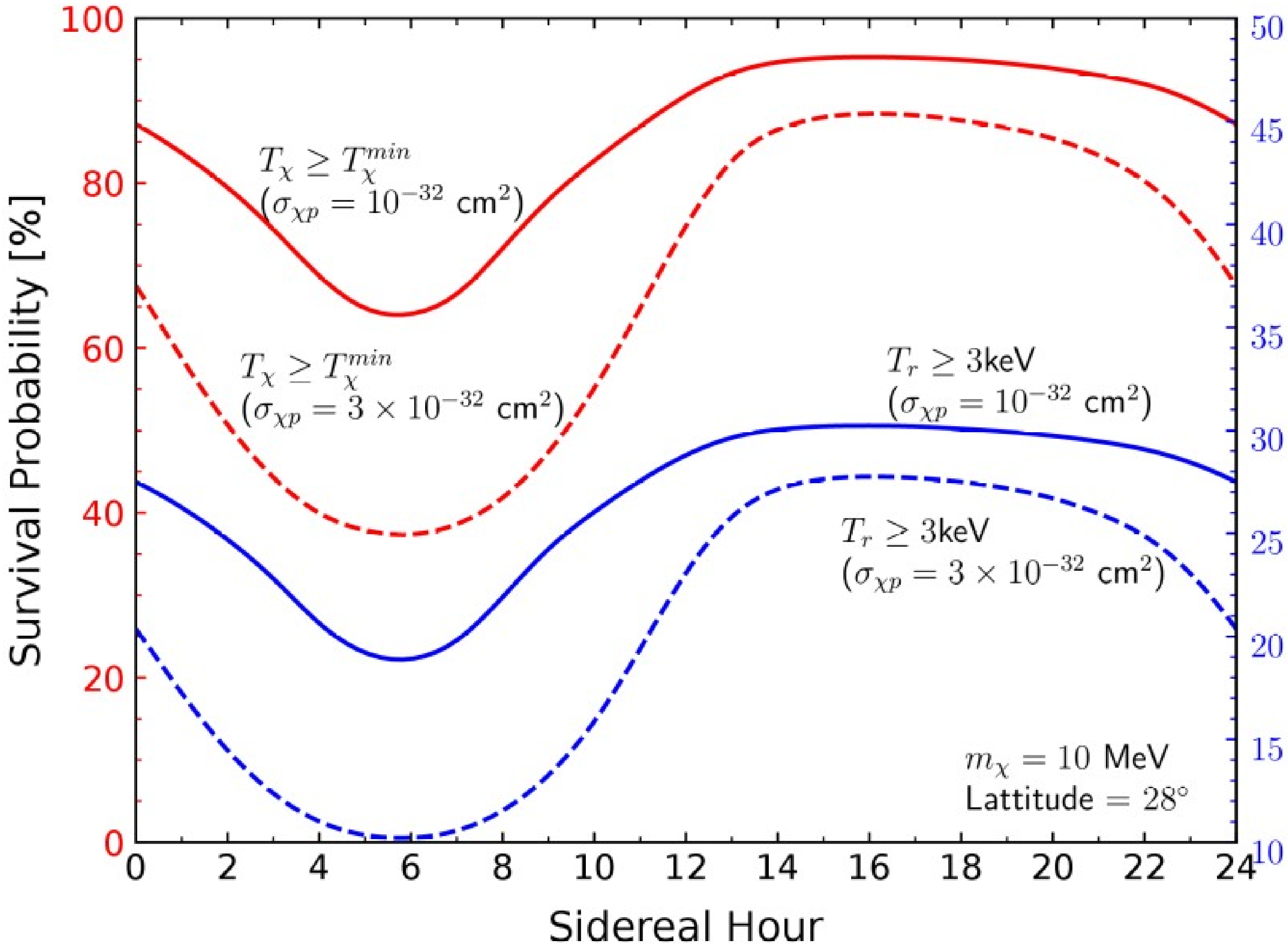
Xia, Xu & Zhou, JCAP 02 (2022) 02, 028 [2111.05559]

Attenuated Flux



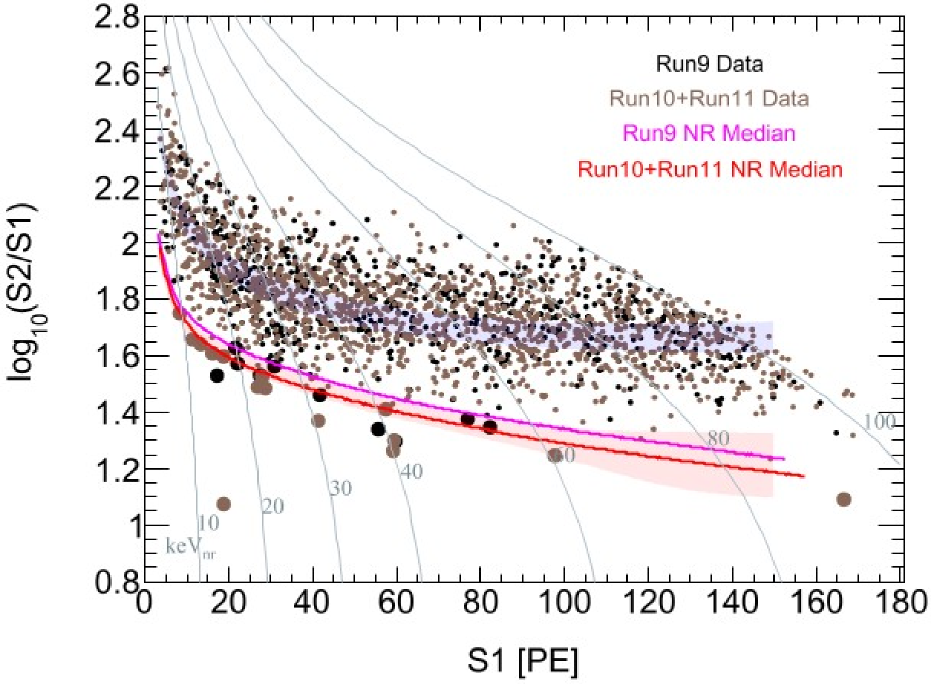
SFG, Jianglai Liu, Ning Zhou, Qiang Yuan, PRL 2021 [arXiv:2005.09480]

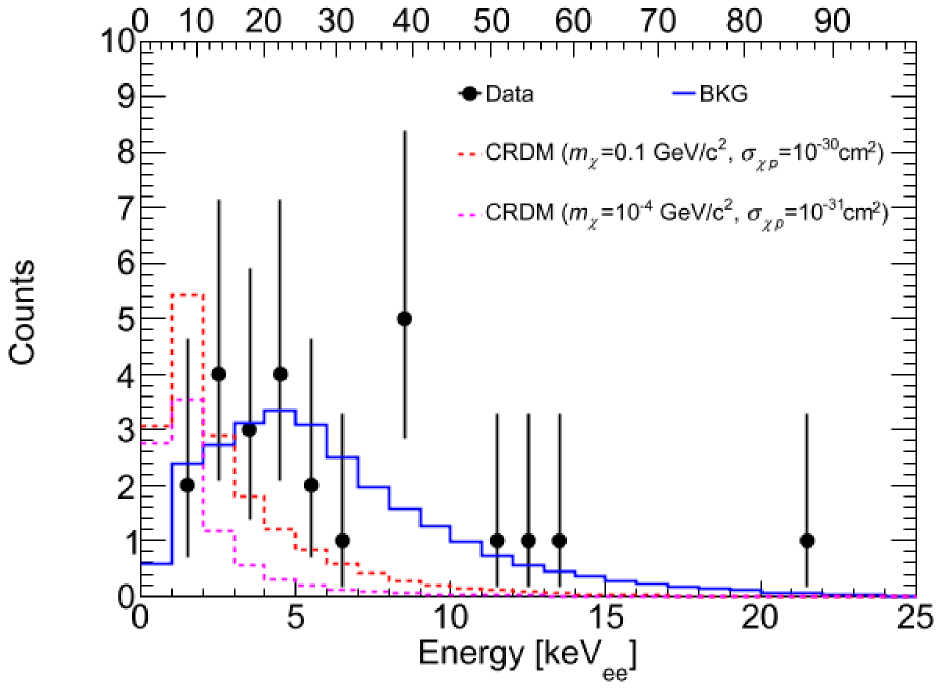
Diurnal Effect



SFG, Jianglai Liu, Ning Zhou, Qiang Yuan, PRL 2021 [arXiv:2005.09480]

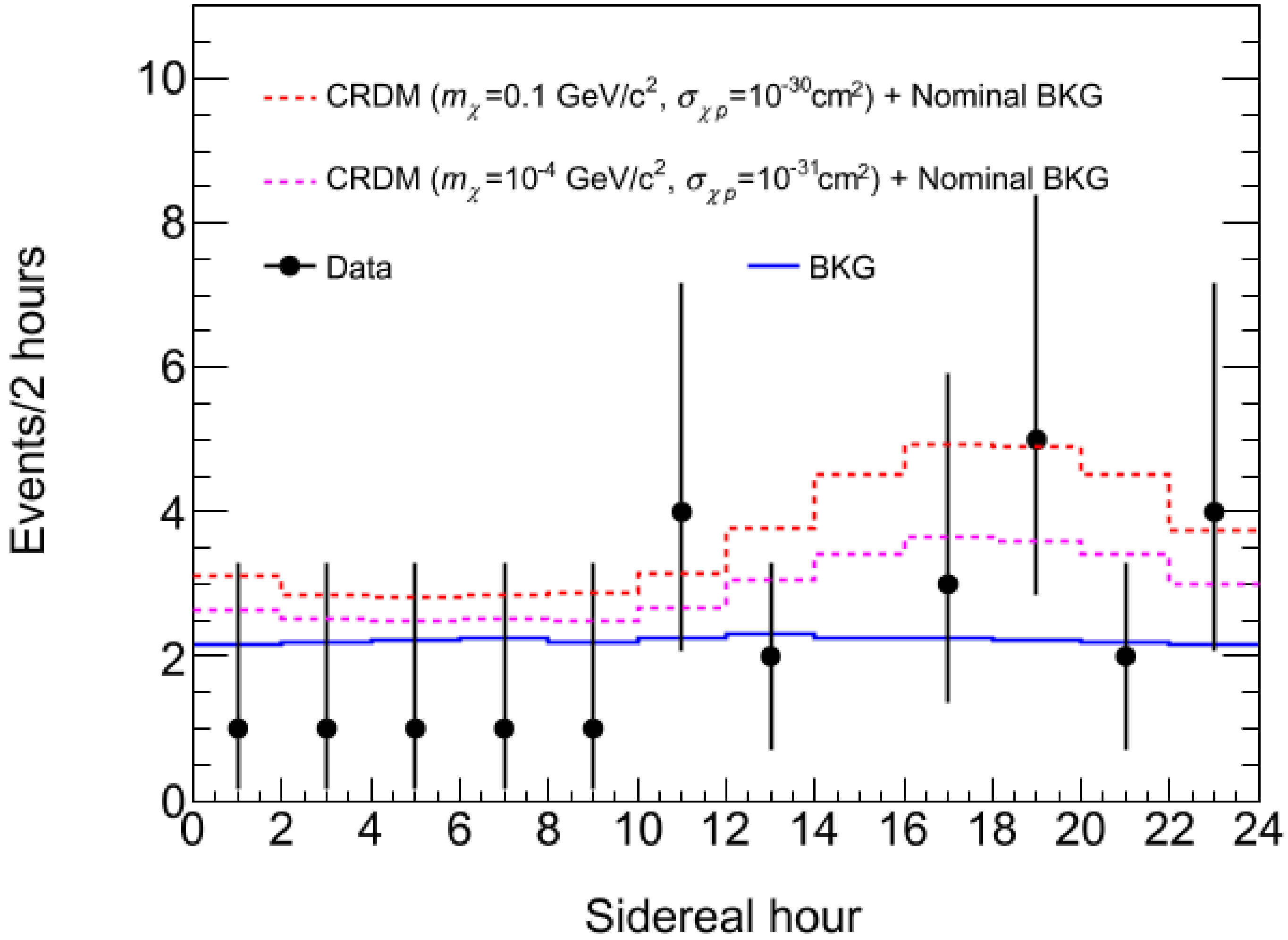
PandaX-II Data





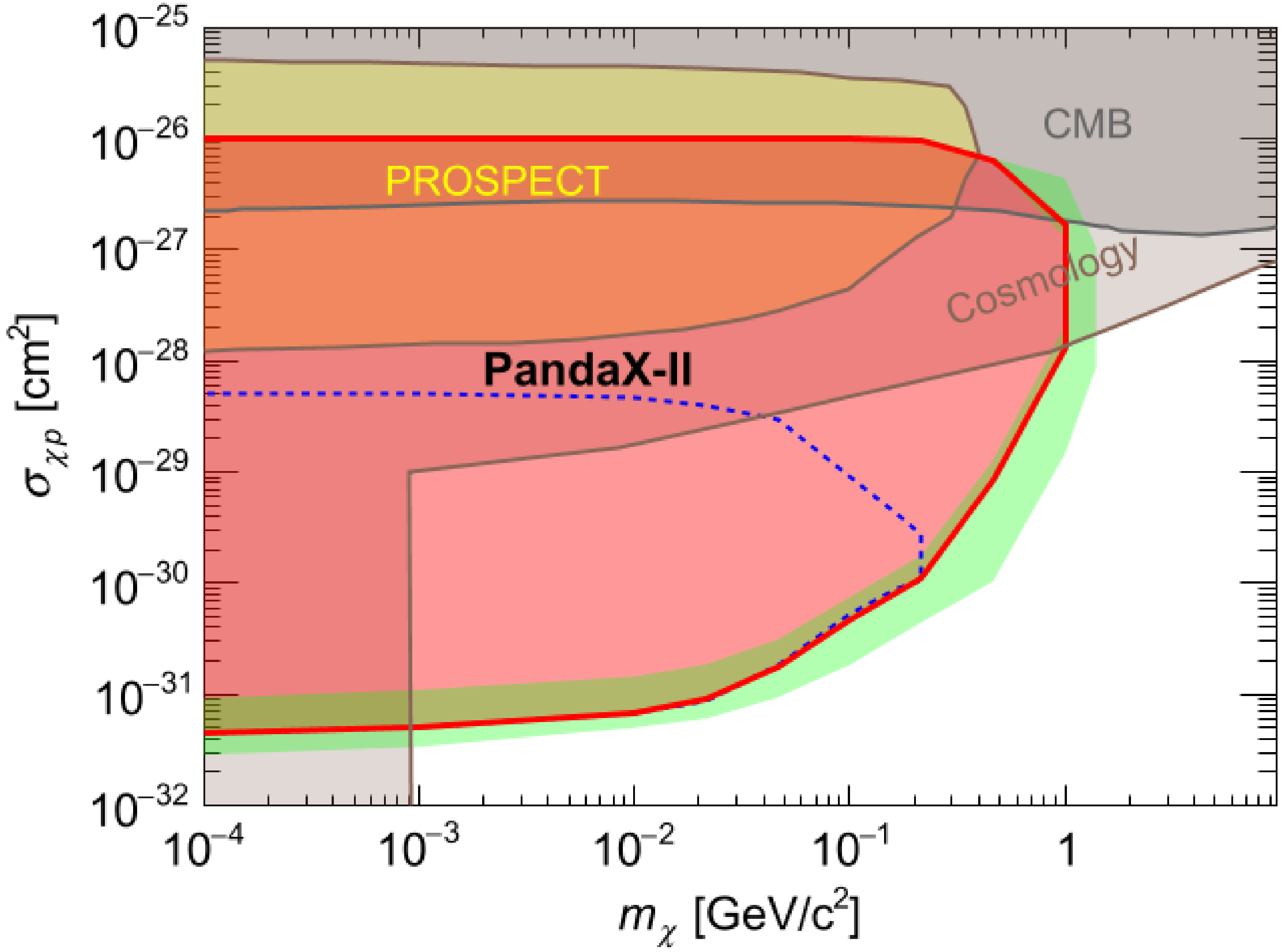
PandaX-II + **SFG** & Qiang Yuan, Phys.Rev.Lett. 128 (2022) 17, 171801 [2112.08957]

Diurnal Modulation @ PandaX



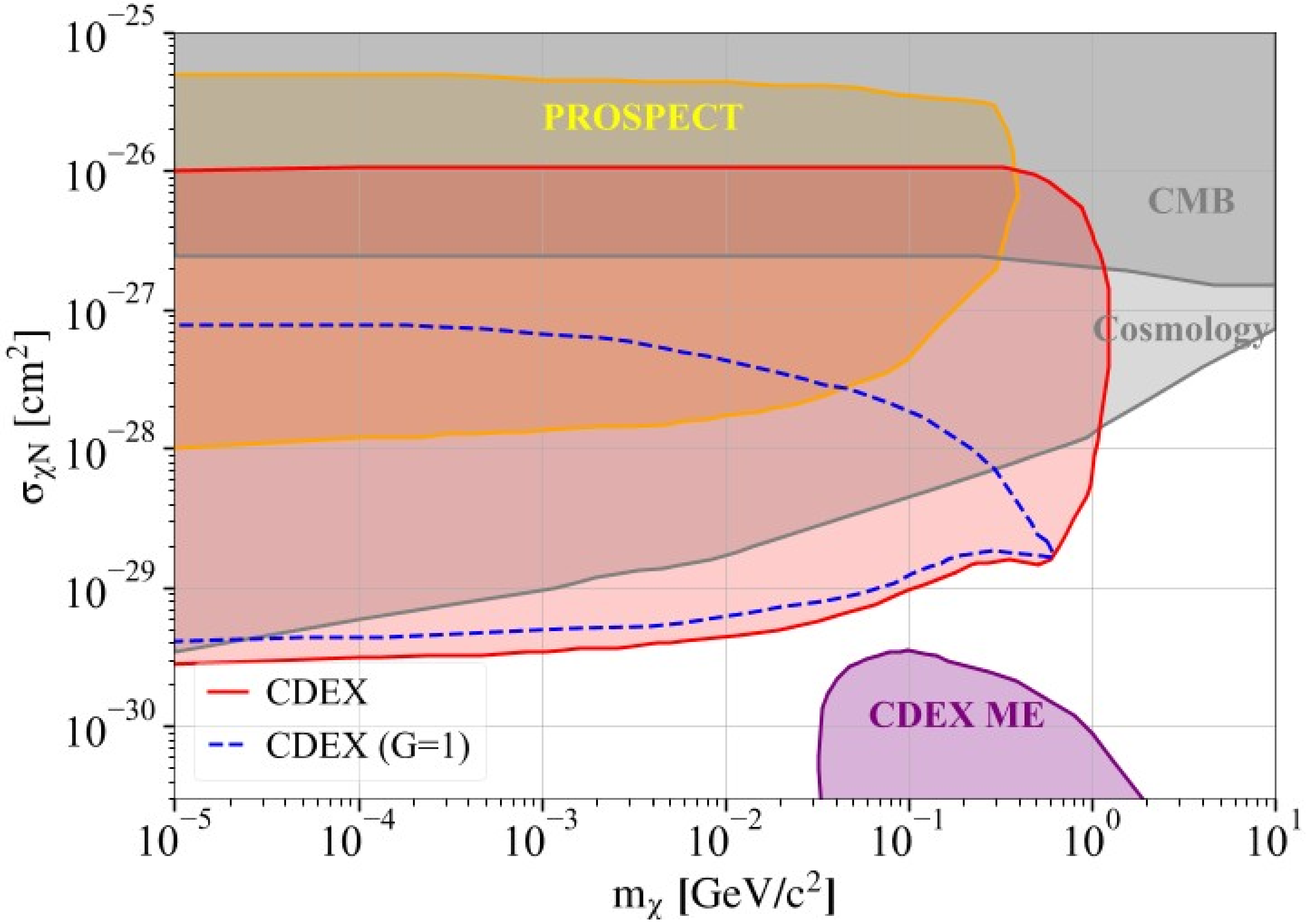
PandaX-II + **SFG** & Qiang Yuan, Phys.Rev.Lett. 128 (2022) 17, 171801 [2112.08957]

Sensitivity @ PandaX



PandaX-II + **SFG** & Qiang Yuan, Phys.Rev.Lett. 128 (2022) 17, 171801 [2112.08957]

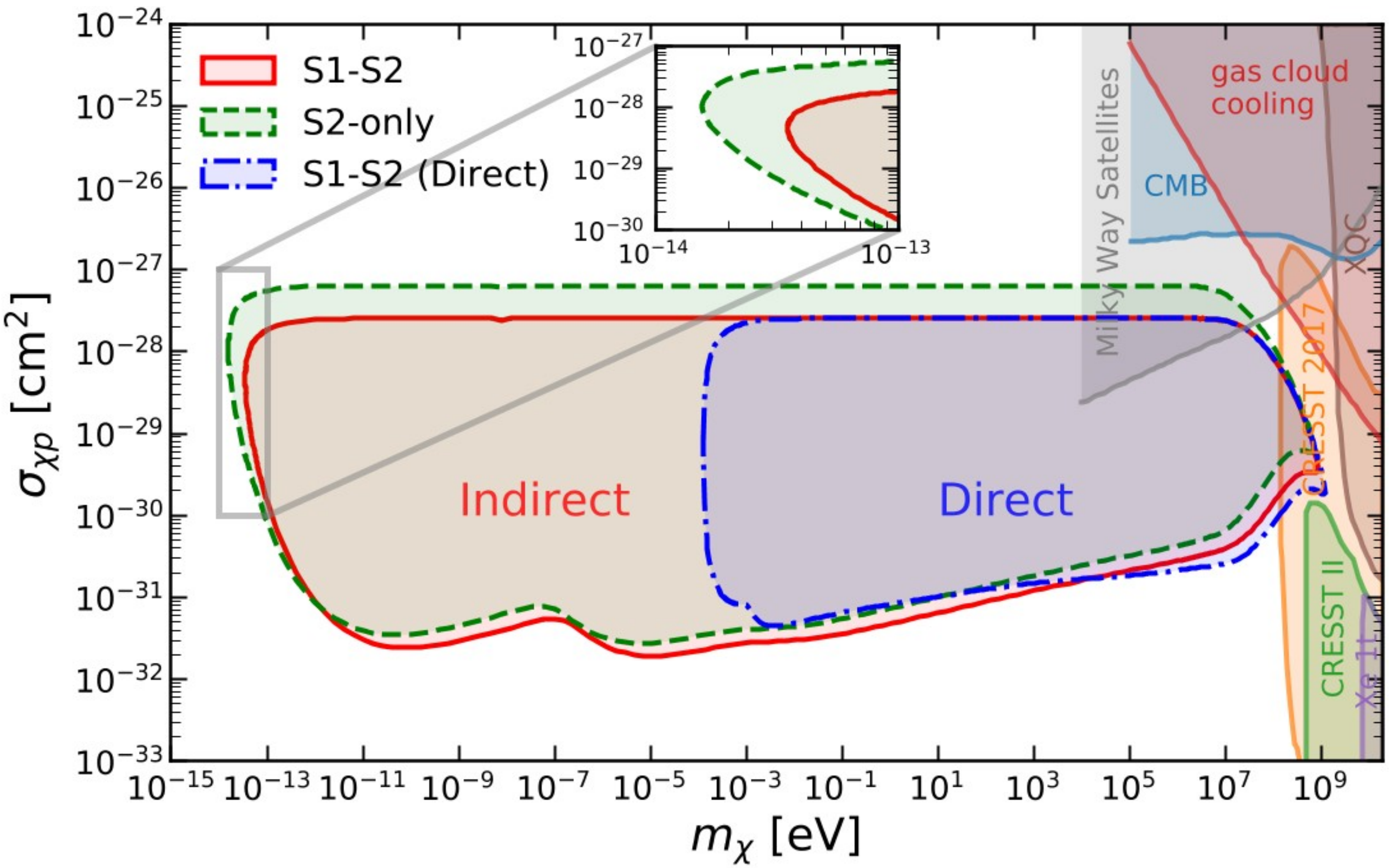
Sensitivity @ CDEX



Zhang, Lei & Tang, Chin.Phys.C 46 (2022) 8, 085103 [2008.07116]

CDEX, Phys.Rev.D 106 (2022) 5, 052008 [2201.01704]

Kinematic Limits

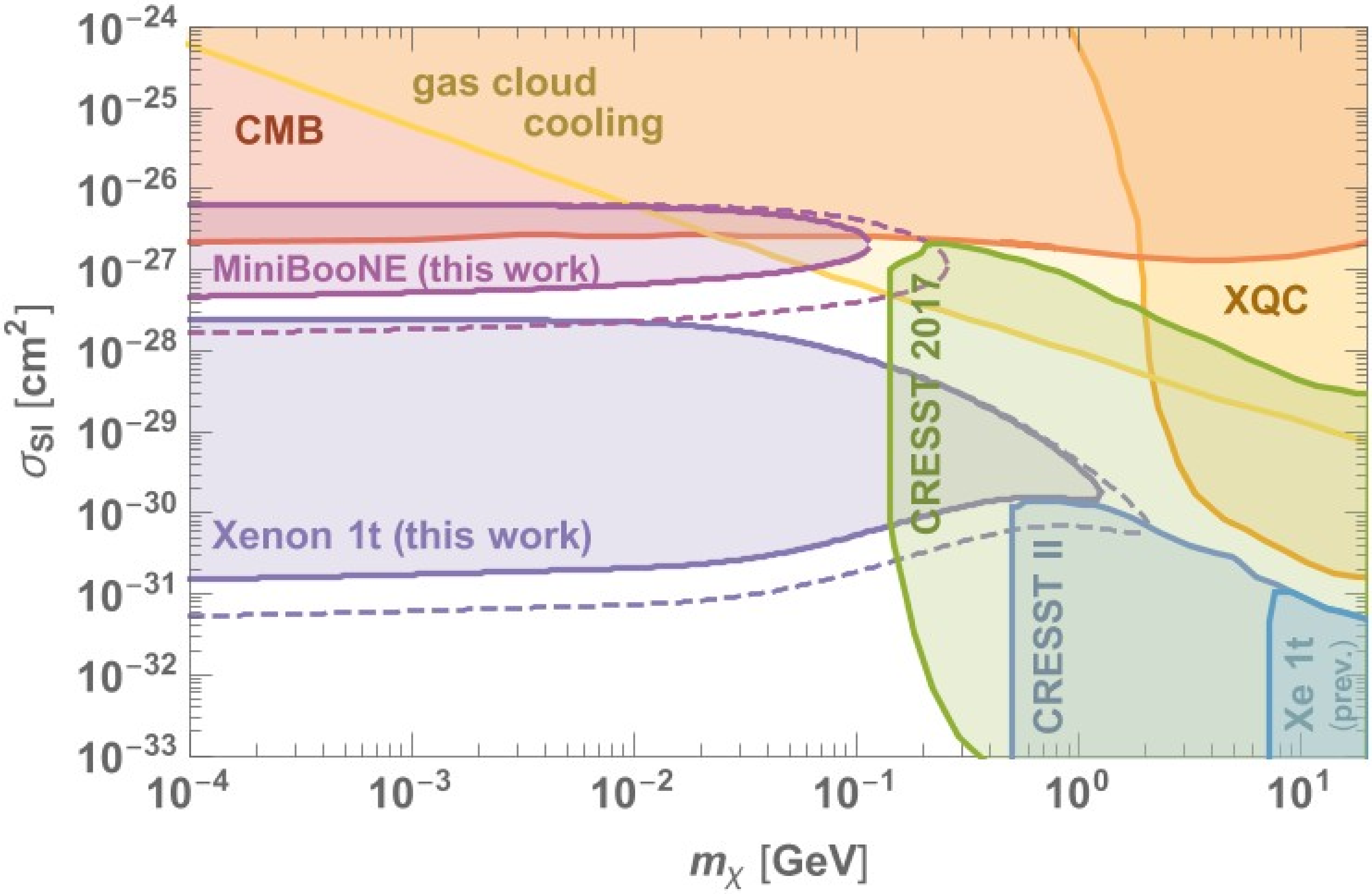


$$0 \le T_\chi \le \frac{T_i(T_i + 2m_i)}{T_i + m_\mu^i} \approx \frac{T_i^2}{T_i + m_i^2/2m_\chi} \quad \text{for} \quad m_\chi \ll m_i$$

Xia, Xu & Zhou, Nucl.Phys.B 969 (2021) 115470 [2009.00353]

Backup Slides

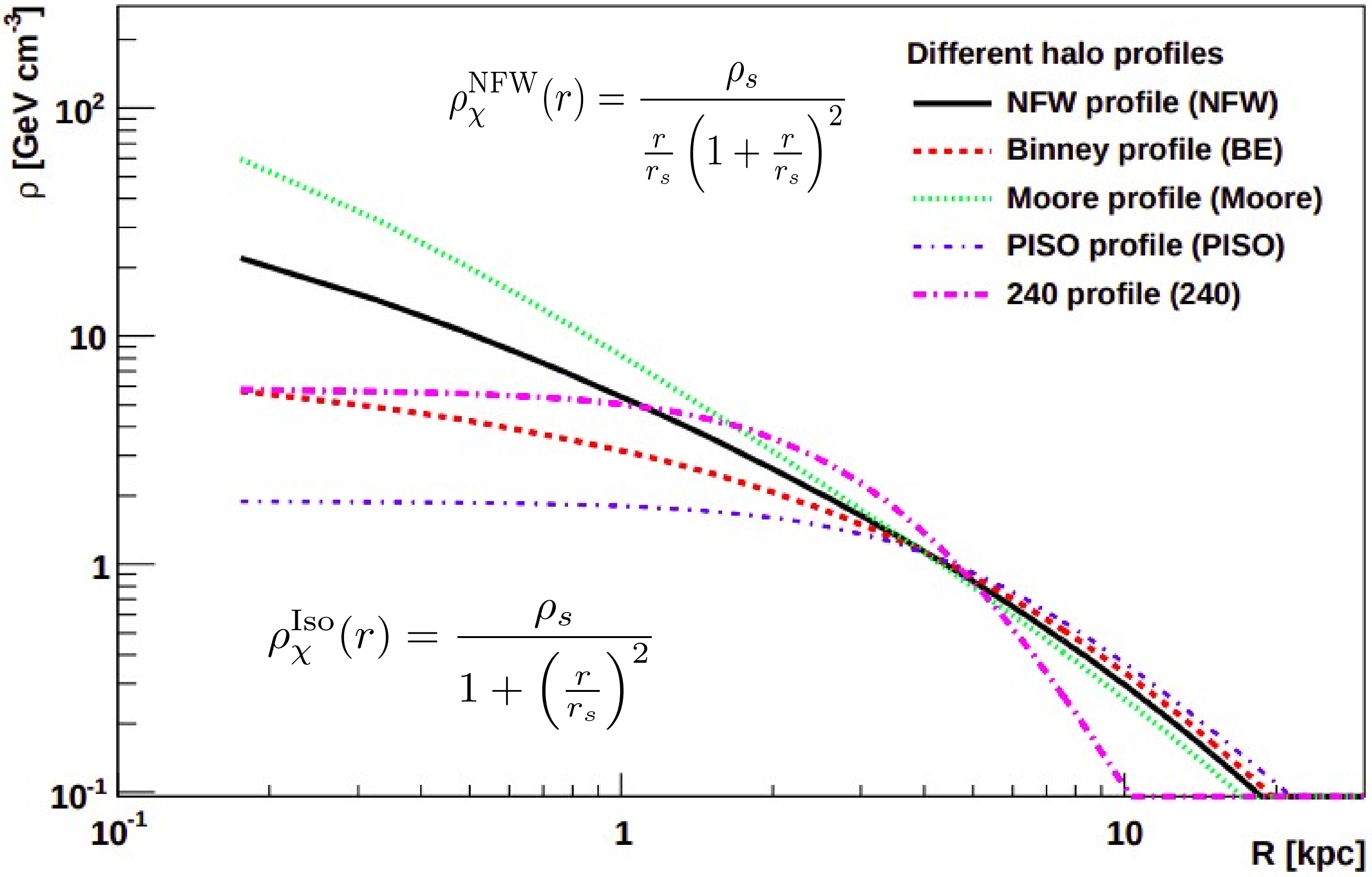
Projected Sensitivities



Bringmann & Pospelov, PRL 2019 [arXiv:1810.10543]

Galaxy DM Density Profile

Weber & Boer [0910.4272]

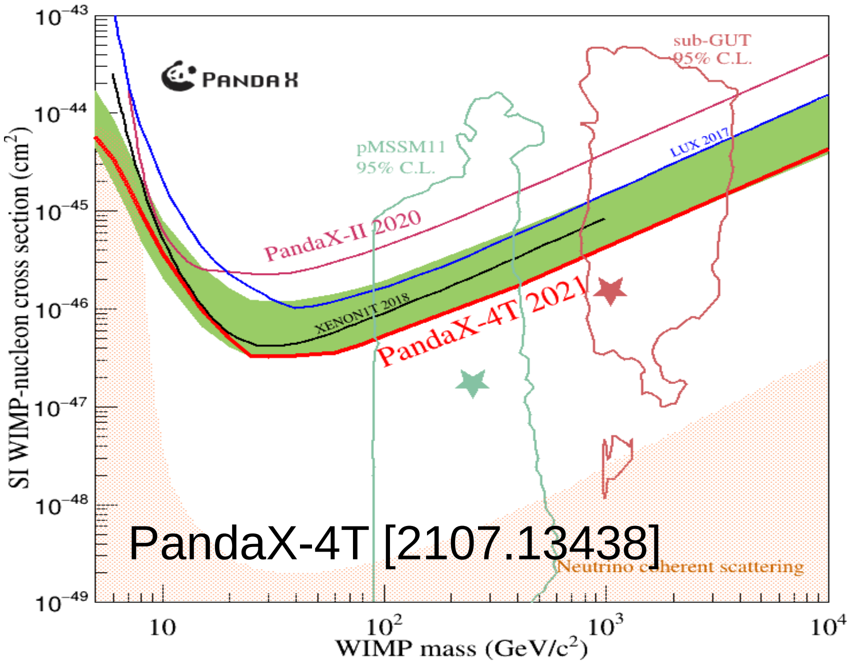


$$\rho_\chi^{\rm NFW}(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

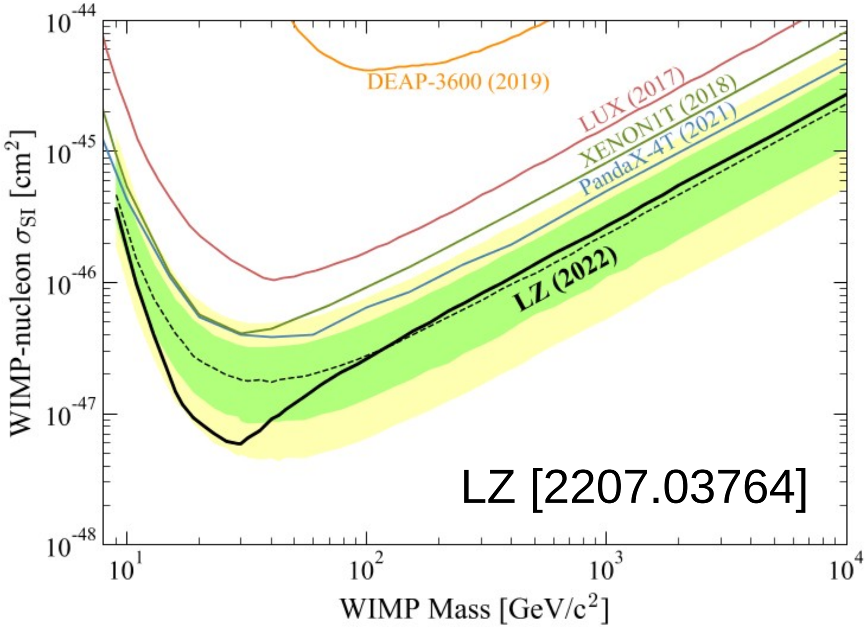
$$\rho_\chi^{\rm Iso}(r) = \frac{\rho_s}{1+\left(\frac{r}{r_s}\right)^2}$$

DM particles are almost at rest.

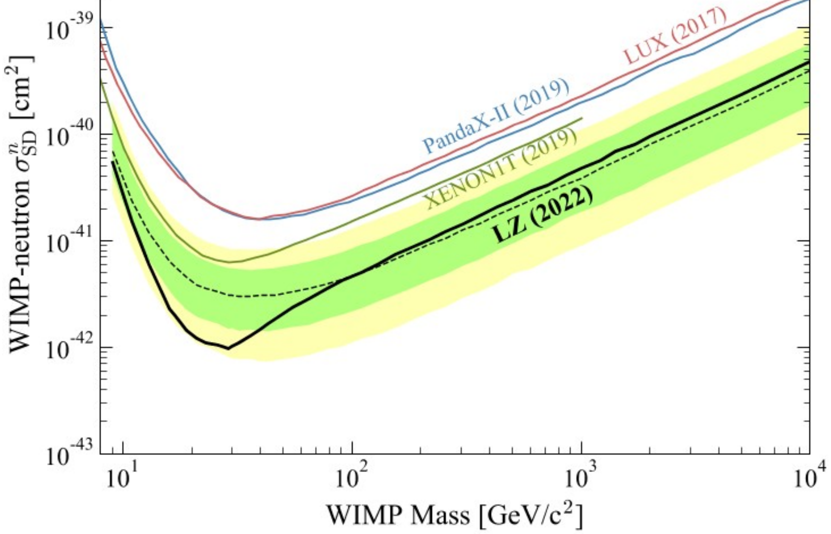
Current Sensitivity



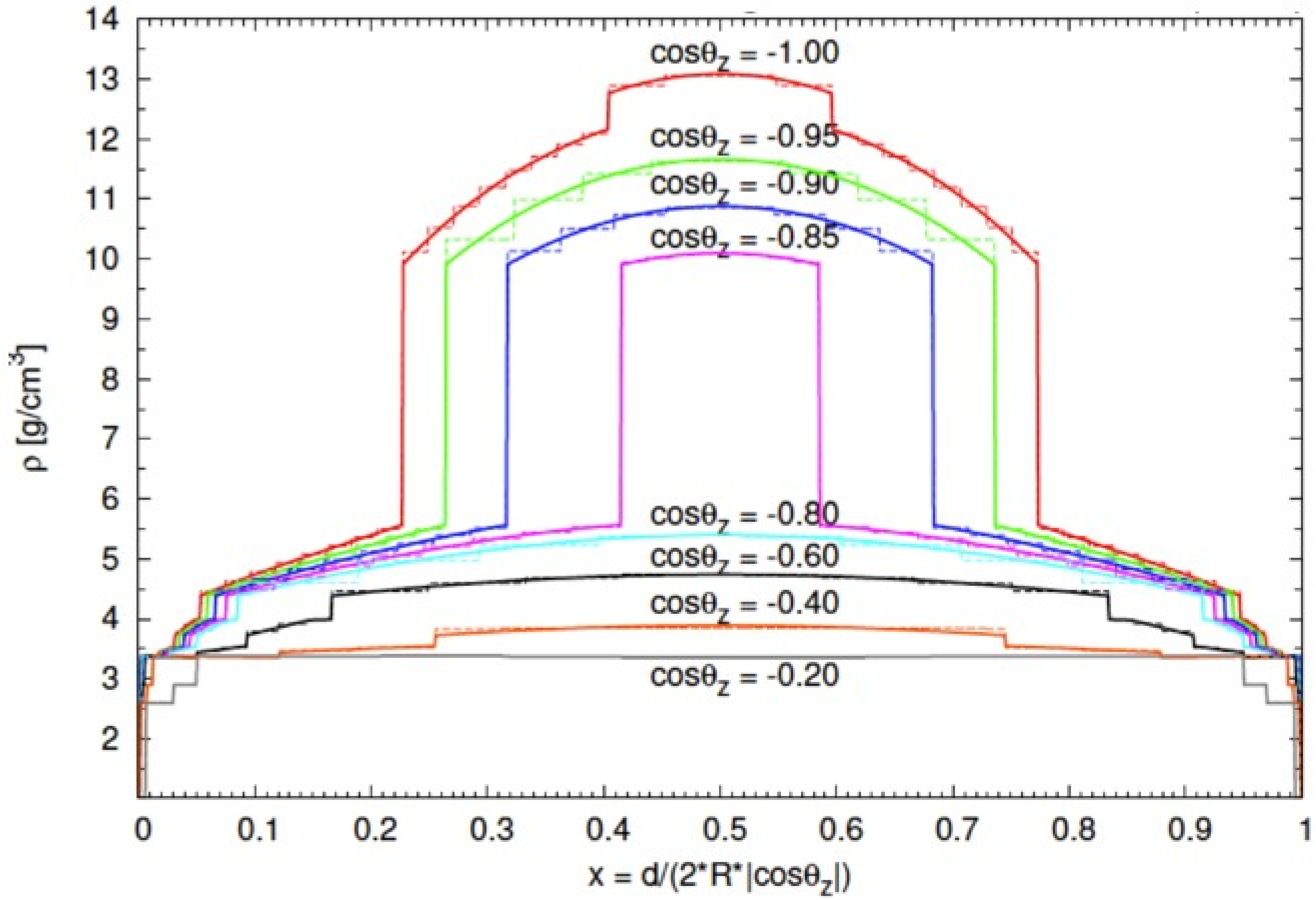
PandaX-4T [2107.13438]



LZ [2207.03764]



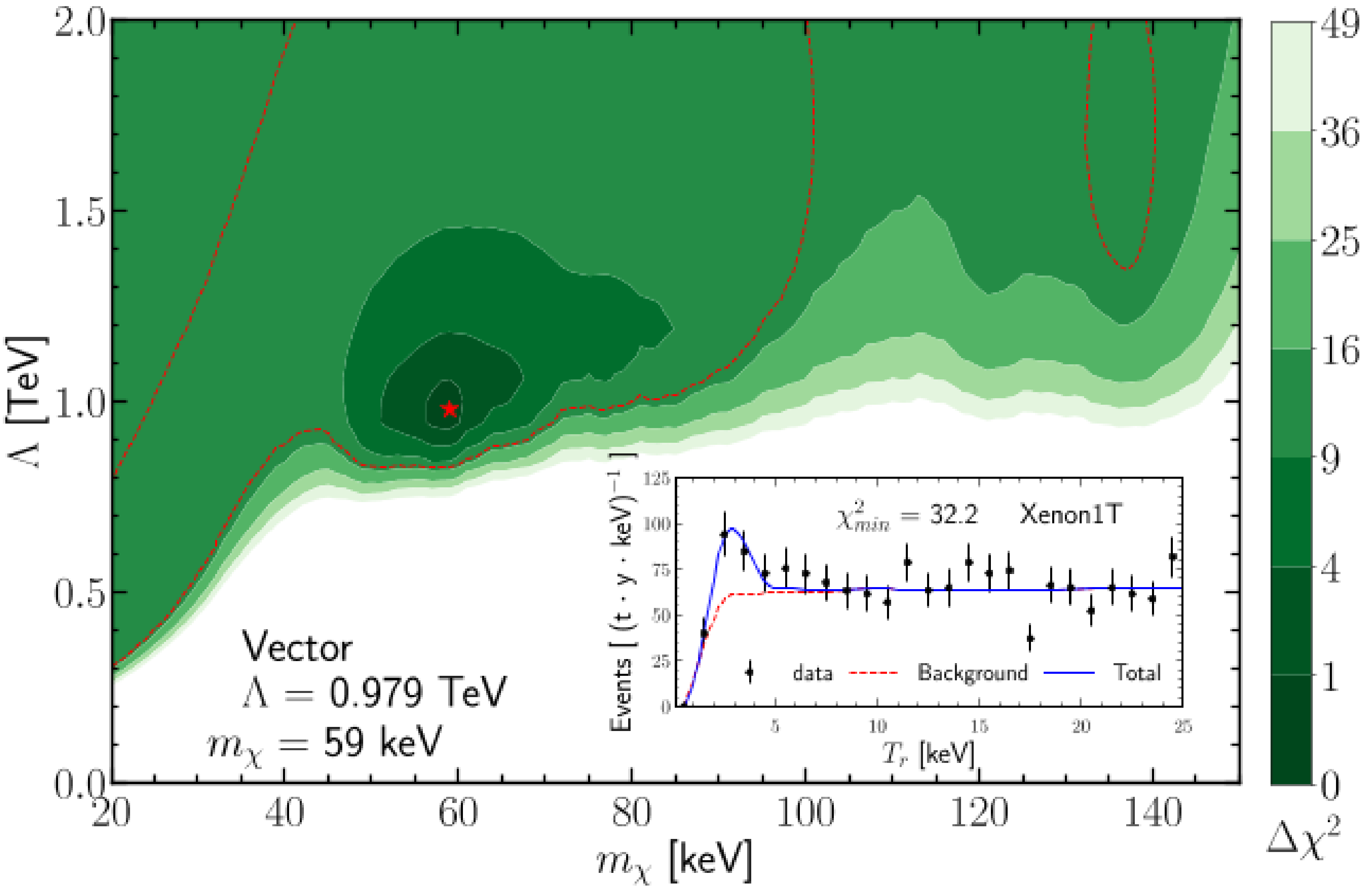
Earth Density Profile



SFG, Hagiwara, Rott [1309.3176]

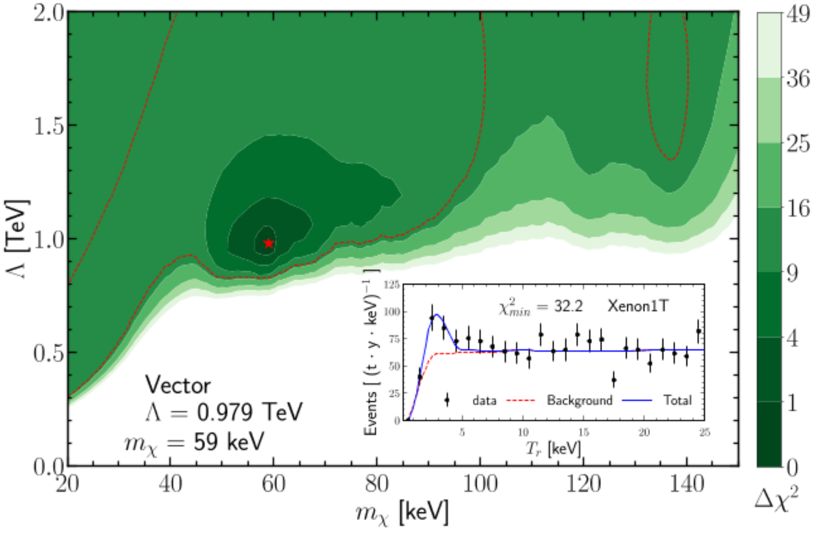
The earth matter can be approximated by 2-step profile.

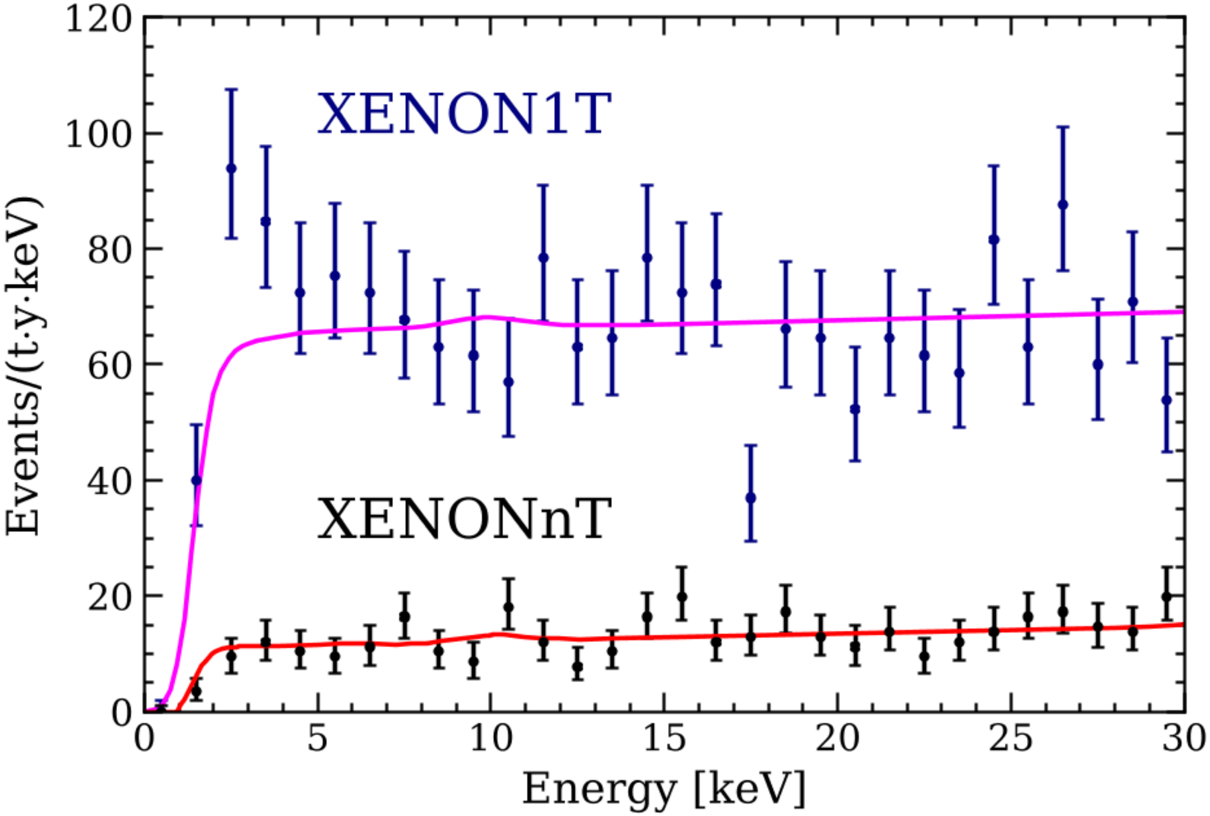
Xenon1T excess



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

Xenon1T excess

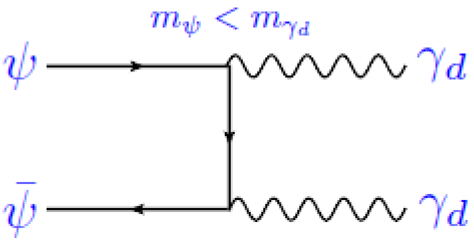




Knut Dundas Morå @ IDM2022
XENONnT, Phys.Rev.Lett. 129 (2022) 16, 161805 [2207.11330]

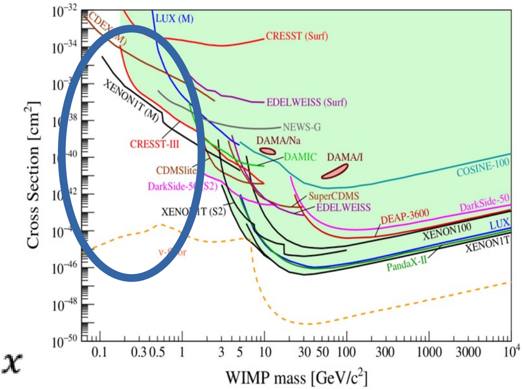
Forbidden DM

1) forbidden annihilations:

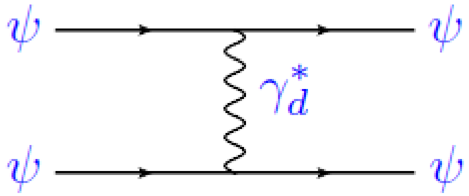


$$\langle \sigma_{\gamma_d \gamma_d} v \rangle \sim \alpha_d^2 / m_{\gamma_d}^2$$

$$\langle \sigma_{\chi\bar{\chi}} v \rangle = \frac{\left(n_{\gamma_d}^{eq}\right)^2}{\left(n_{\psi}^{eq}\right)^2} \langle \sigma_{\gamma_d \gamma_d} v \rangle \approx 8\pi f_\Delta \frac{\alpha_d^2}{m_\psi^2} e^{-2\Delta x}$$

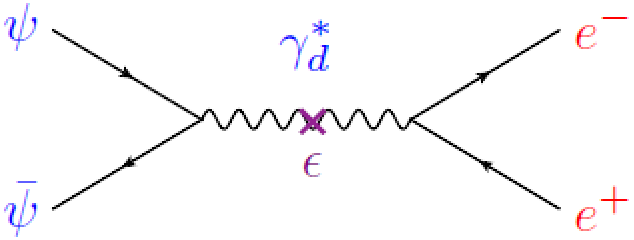


2) self-interactions:

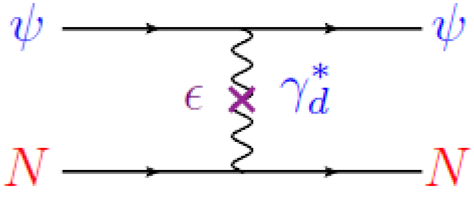


- Naturally includes large self-interactions.
- An exponentially larger cross section than the forbidden annihilation rate.

3) indirect detection:



4) direct detection:



- Signal suppressed by

D'Agnolo & Ruderman, Phys.Rev.Lett. 115 (2015) 6, 061301 [1505.07107]