Dark Matter Indirect Detection with Astrophysical Signals

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Preparing Next-Generation Astrophysics in the MeV Window

Sep/16, 2025 @ IHEP, Beijing

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

李政道研究所 Tsung-Dao Lee Institute

Outline

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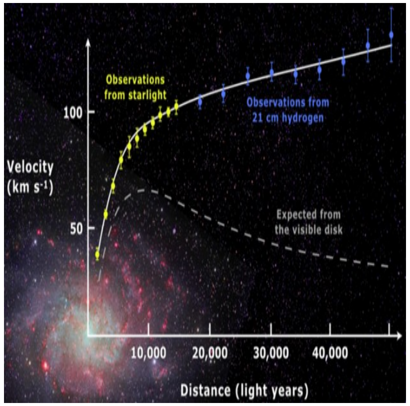
1) Overview

2) Fermionic Absorption DM

3) Reactivating Forbidden DM around SMBH

4) Summary

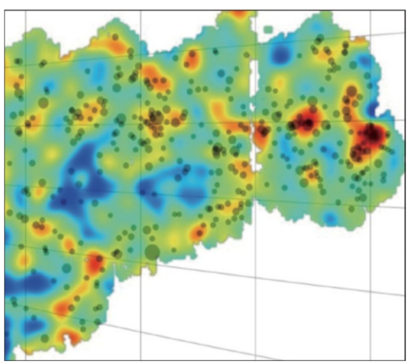
Evidences of Dark Matter



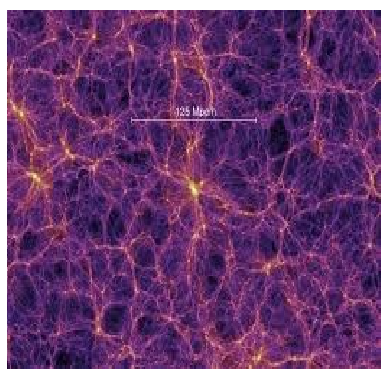
Rotation Curve

Bullet Cluster

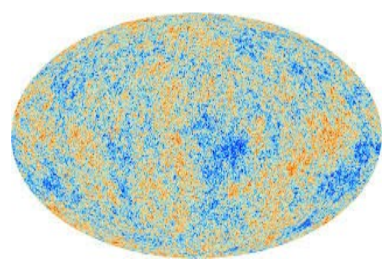
Grav Lensing



Galaxy Cluster



Large Scale Structure



Cosmic Microwave Background

Cosmic Energy Budget

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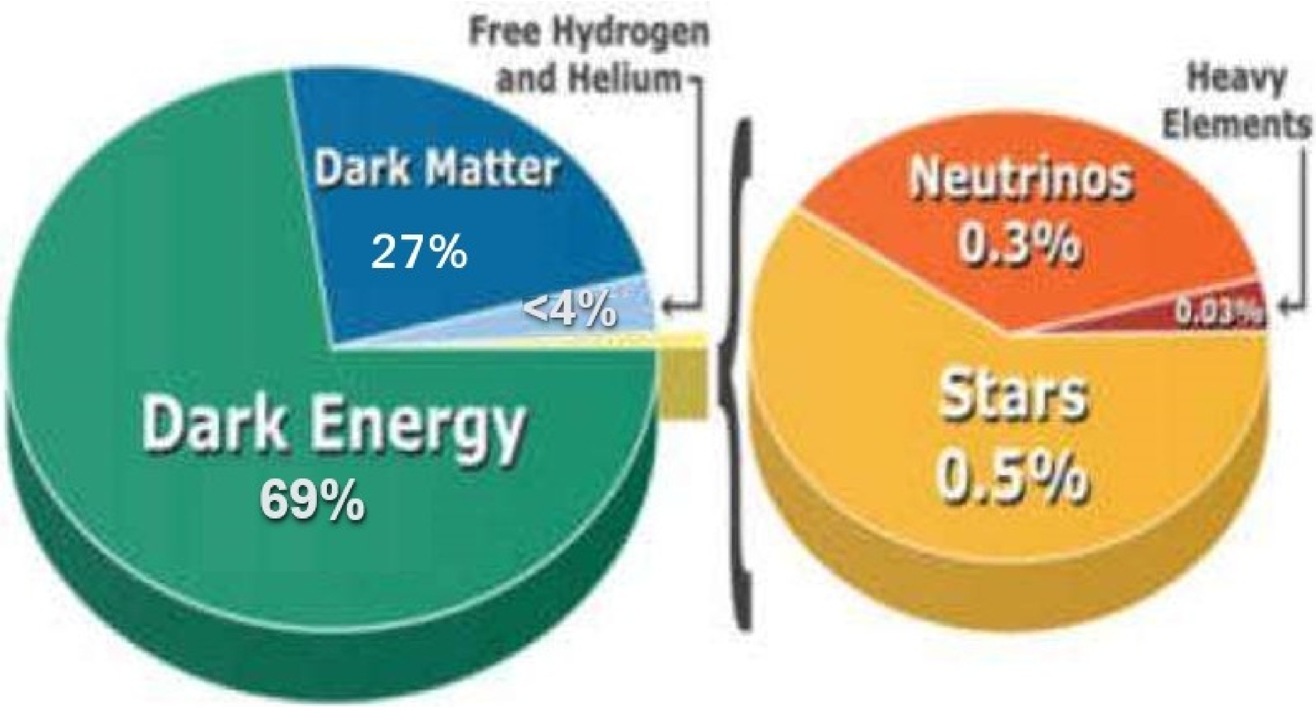
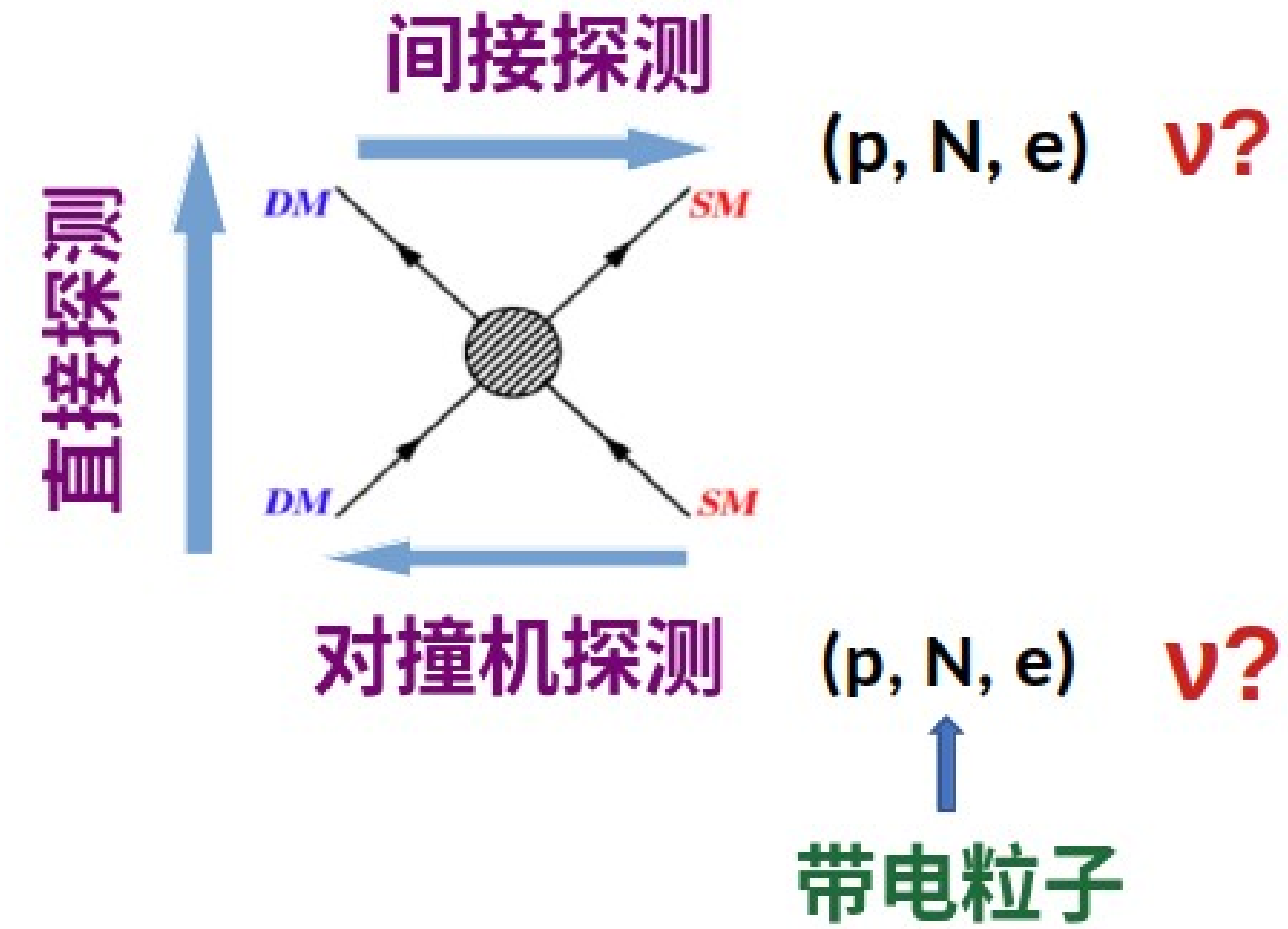


- Dark matter dominates the formation & evolution of our Universe.
- What's the nature of dark matter?

Major ways of detecting DM



Indirect Detection of DM

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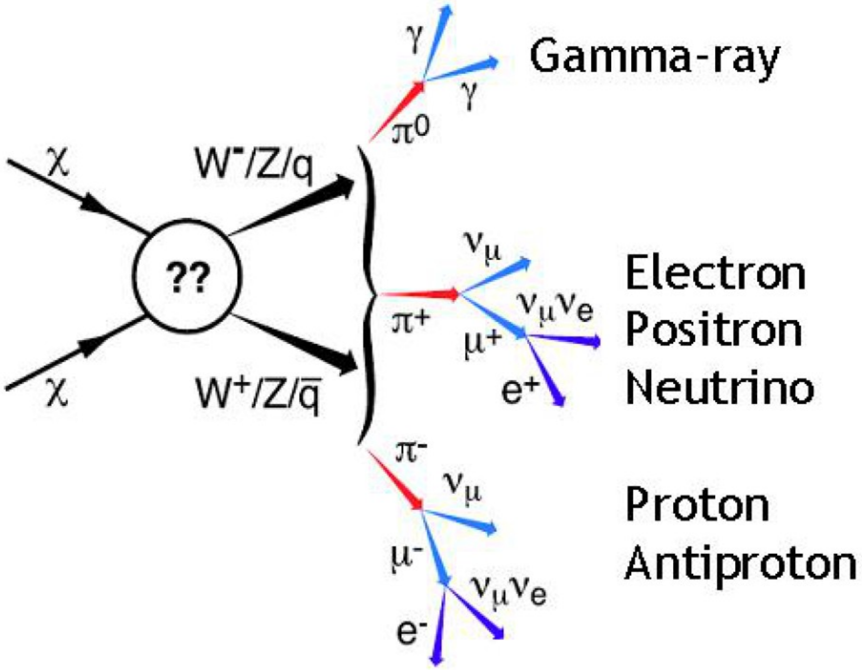
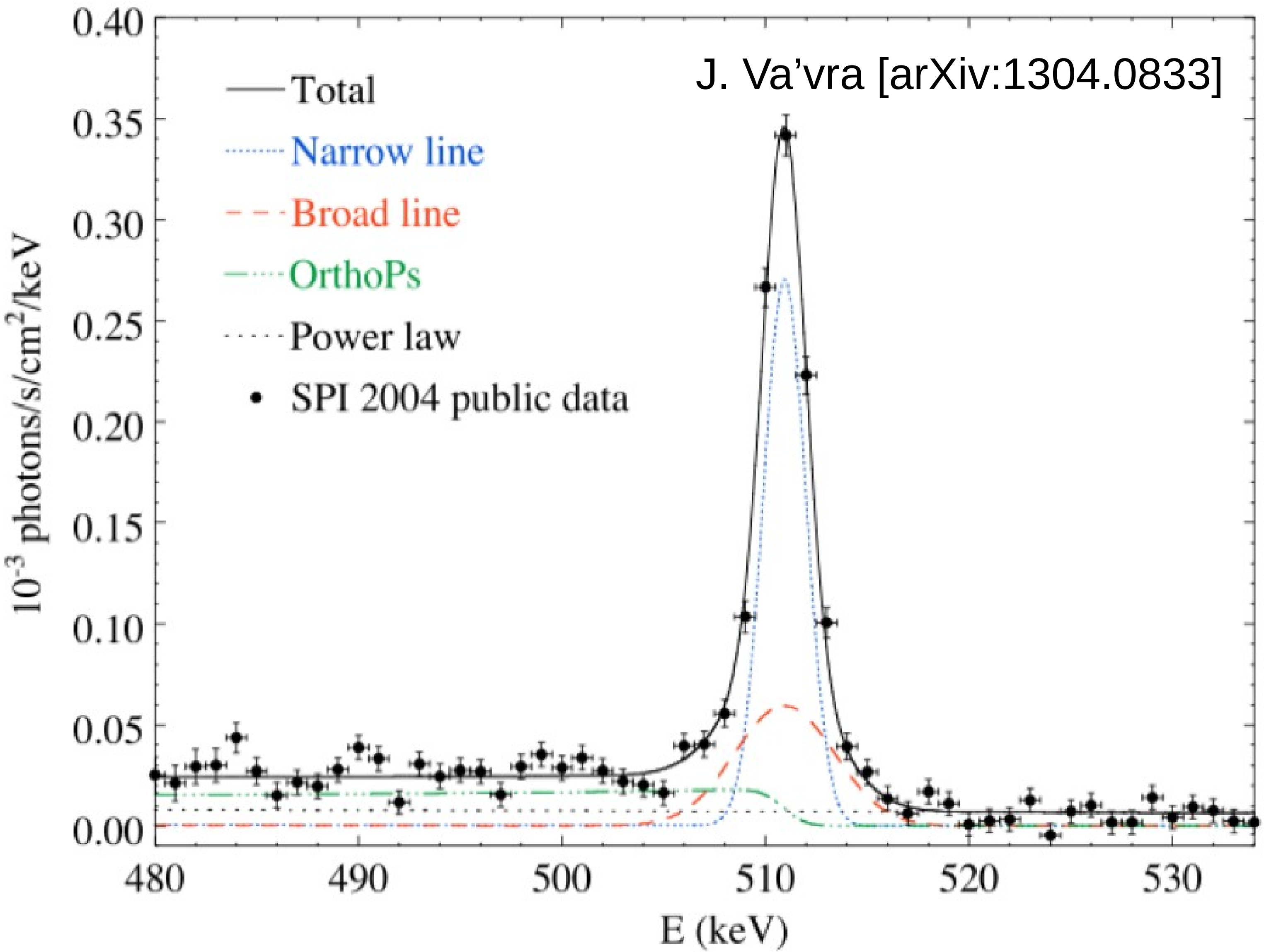


- **Large bulk of DM.**
- **Have various detectable signals.**
- **Can have unique peak structure.**
- **Can point back to the sources, especially gamma.**
- **Various observations & excesses.**

Persistent MeV Line



see also Prantzos et al [arXiv:1009.4620]

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Direct Detection

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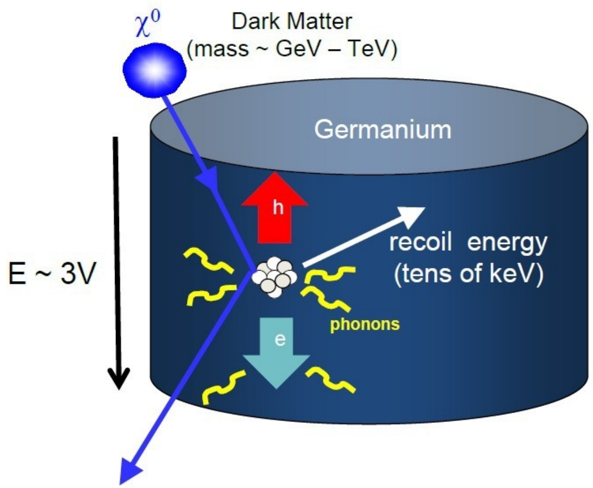

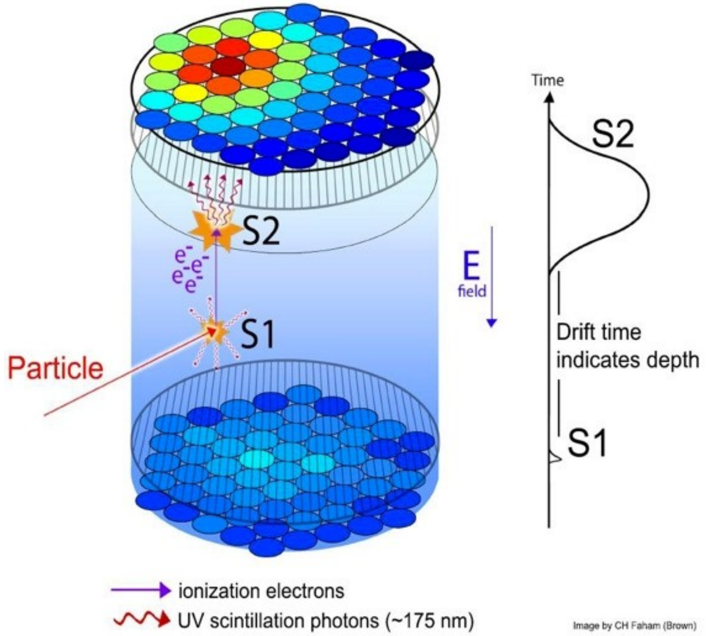

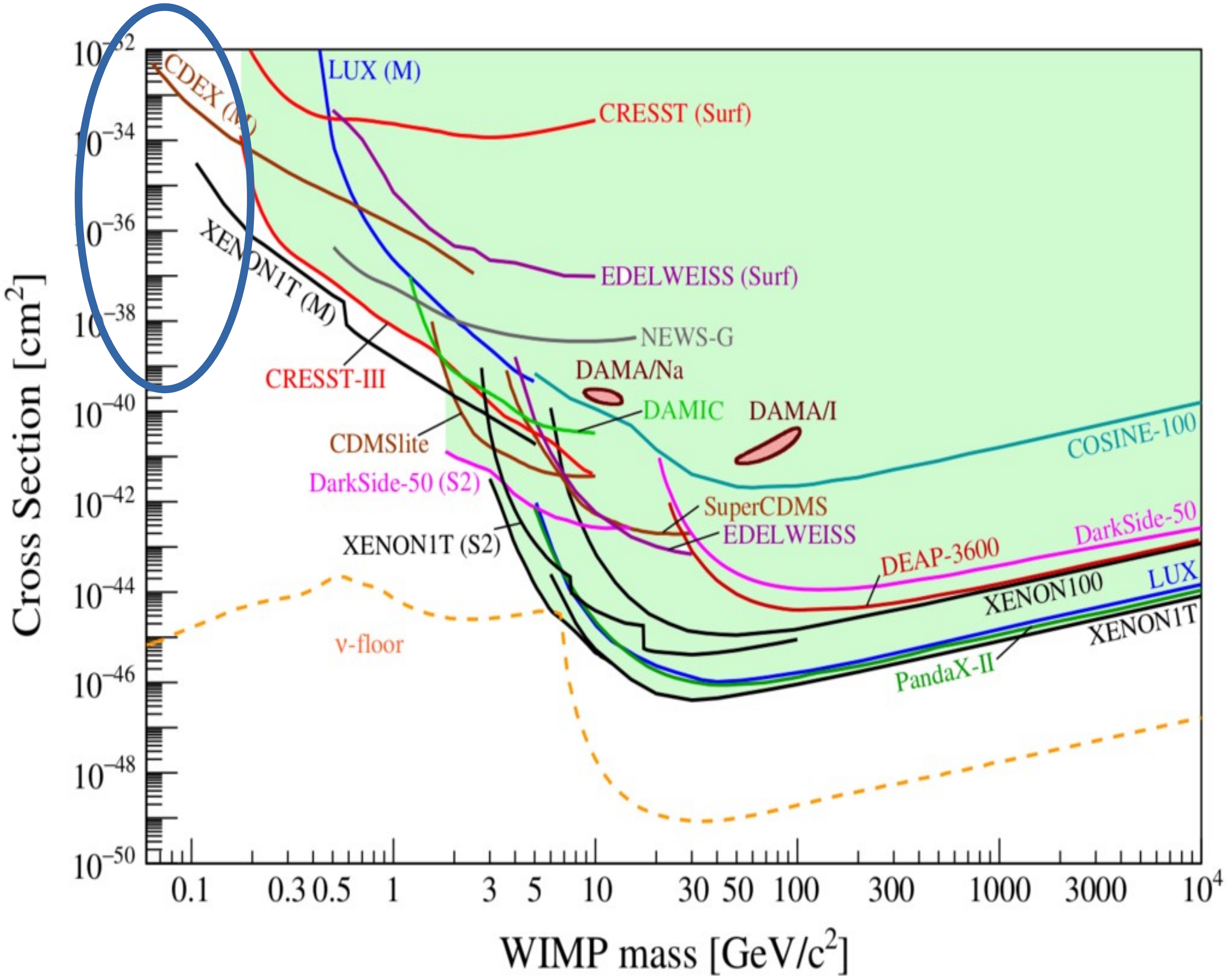

APPEC Committee Report [2104.07634]

Boosting recoil with mass

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- **Elastic Scattering**

$$\chi + N/e \to \chi + N/e$$

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

Suppressed!

- **Fermionic absorption**

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

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

Dror, Elor, McGehee & Yu [2011.01940]

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

Extend the sensitive mass window down to at least MeV range.

Kinematics of Absorption DM

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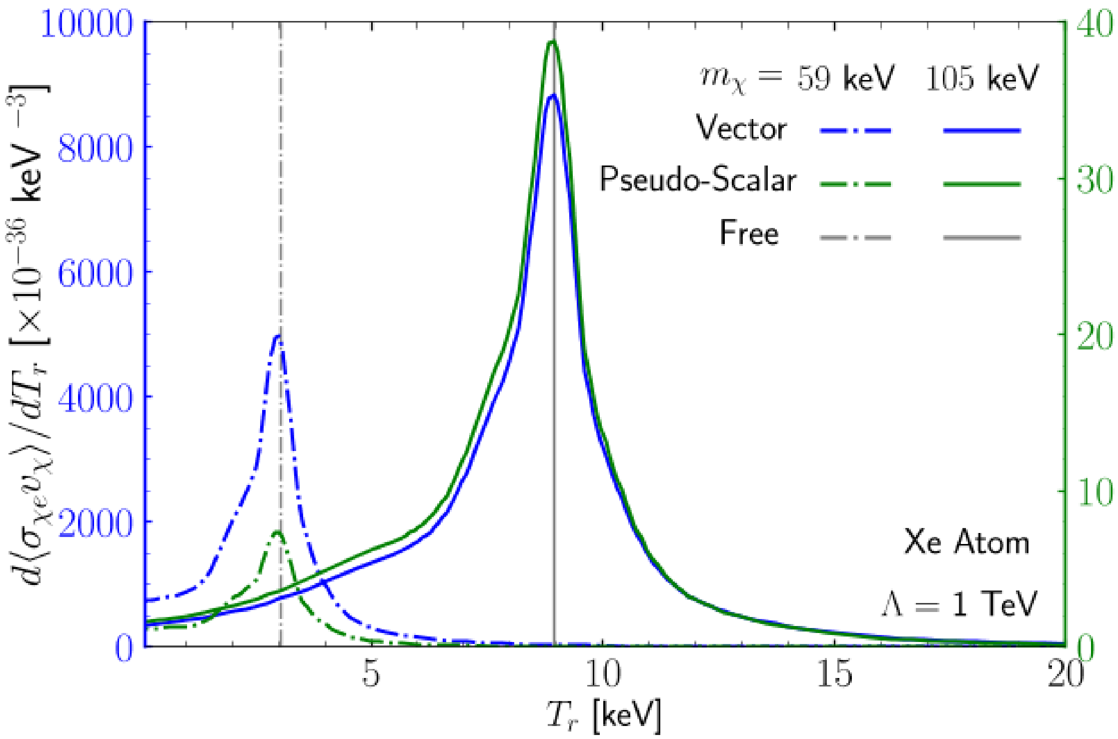
$$\chi + e \to \nu + e \qquad E_r = \frac{m_\chi^2}{2(m_e + m_\chi)} \approx \frac{m_\chi^2}{2m_e}$$

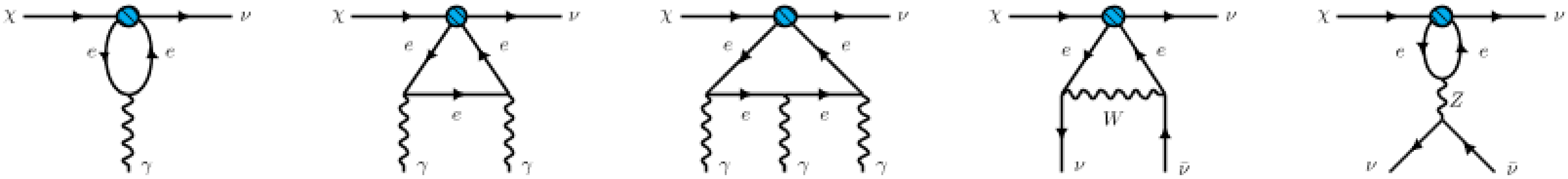


$$\frac{d\langle\sigma_{\chi e}v_\chi\rangle}{dT_r} = \sum_{nl}(4l+2)\frac{1}{T_r}\frac{m_\chi - \Delta E_{nl}}{16\pi m_e^2 m_\chi}|\mathcal{M}|^2(\mathbf{q})K_{nl}(T_r,|\mathbf{q}|),$$

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

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

Visible & Invisible Decays



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

Dror, Elor, McGehee & Yu [2011.01940]

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

Astro Observations

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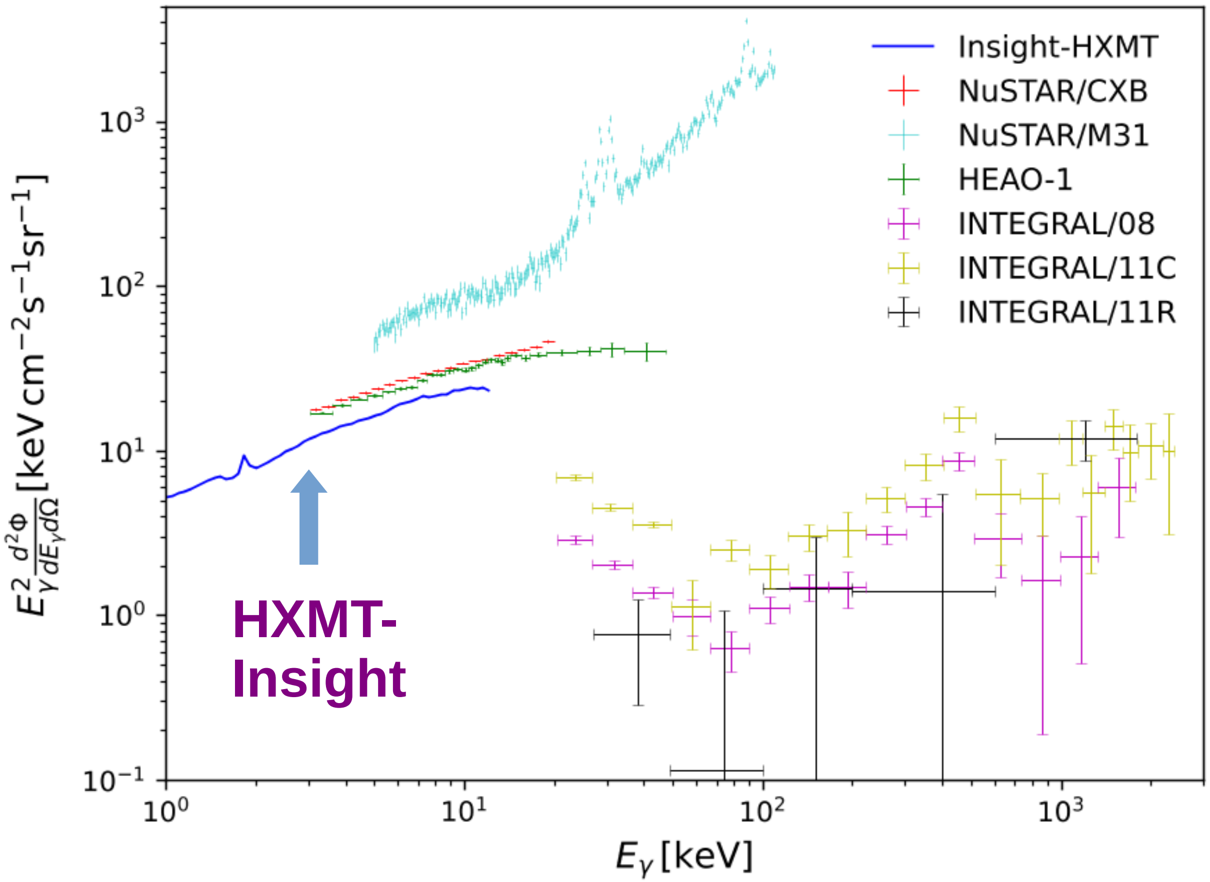

- **Galactic**

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

- **Extra-Galactic**

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

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

Astro Constraints

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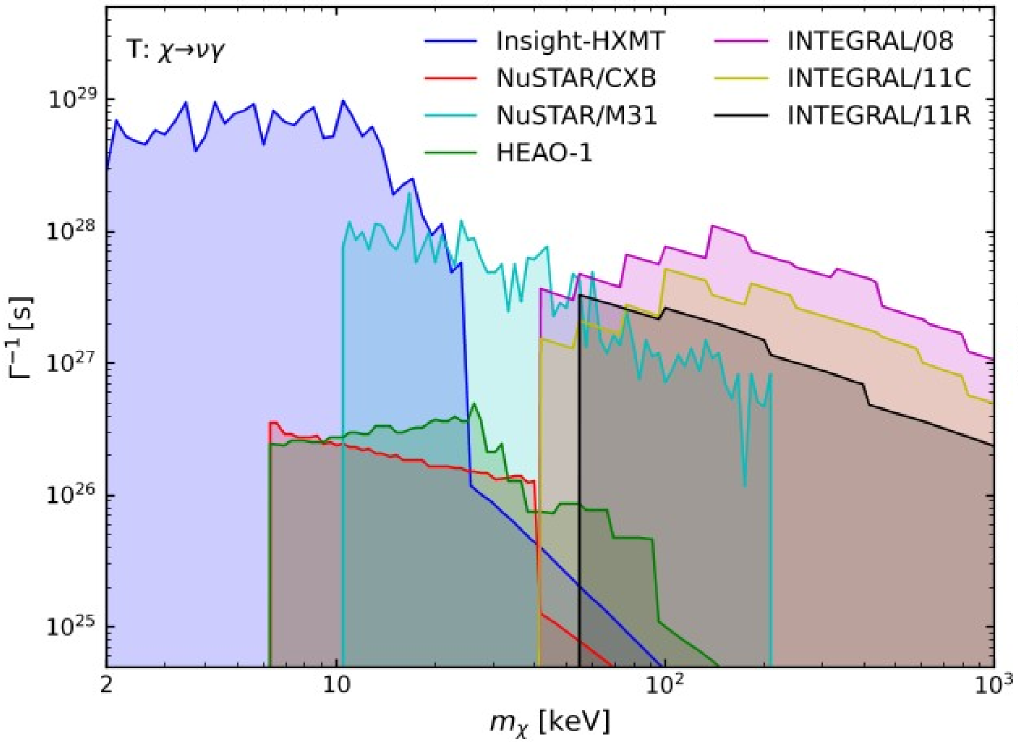
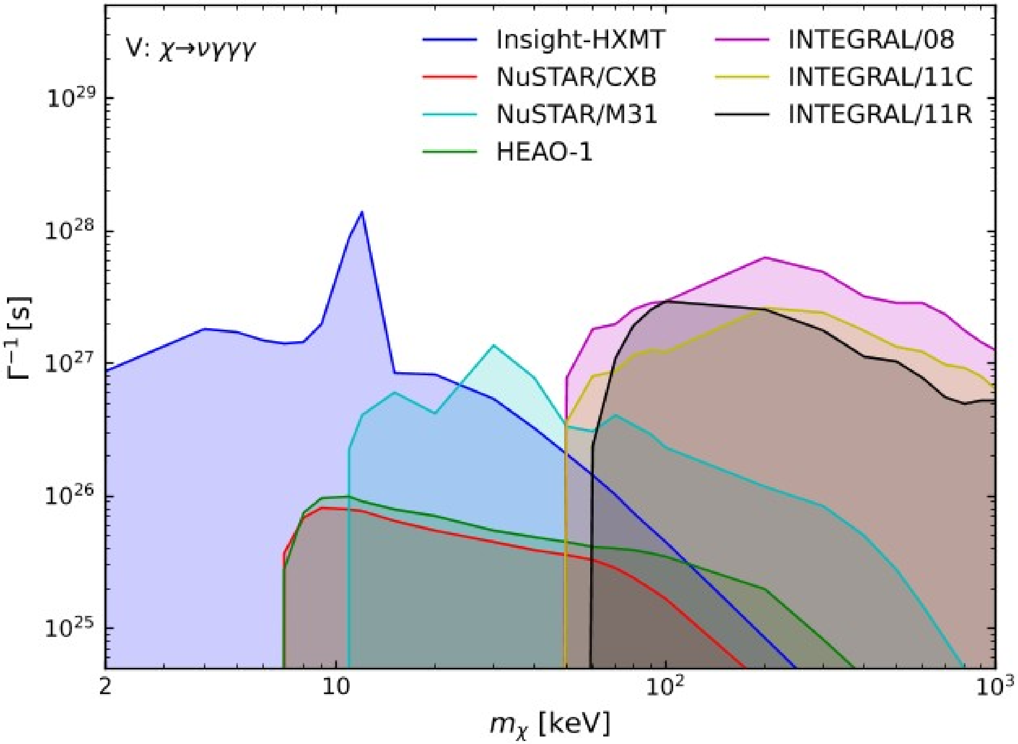
$$N_i^{\rm th} \le N_i^{\rm obs} \equiv A_{\rm eff} T_{\rm obs} \Delta\Omega \left(\frac{d^2\Phi_\gamma}{dE_\gamma d\Omega} \right)^i_{\rm exp@95\%} \Delta E_i$$

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





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

Constraints from Astro & Cosmo

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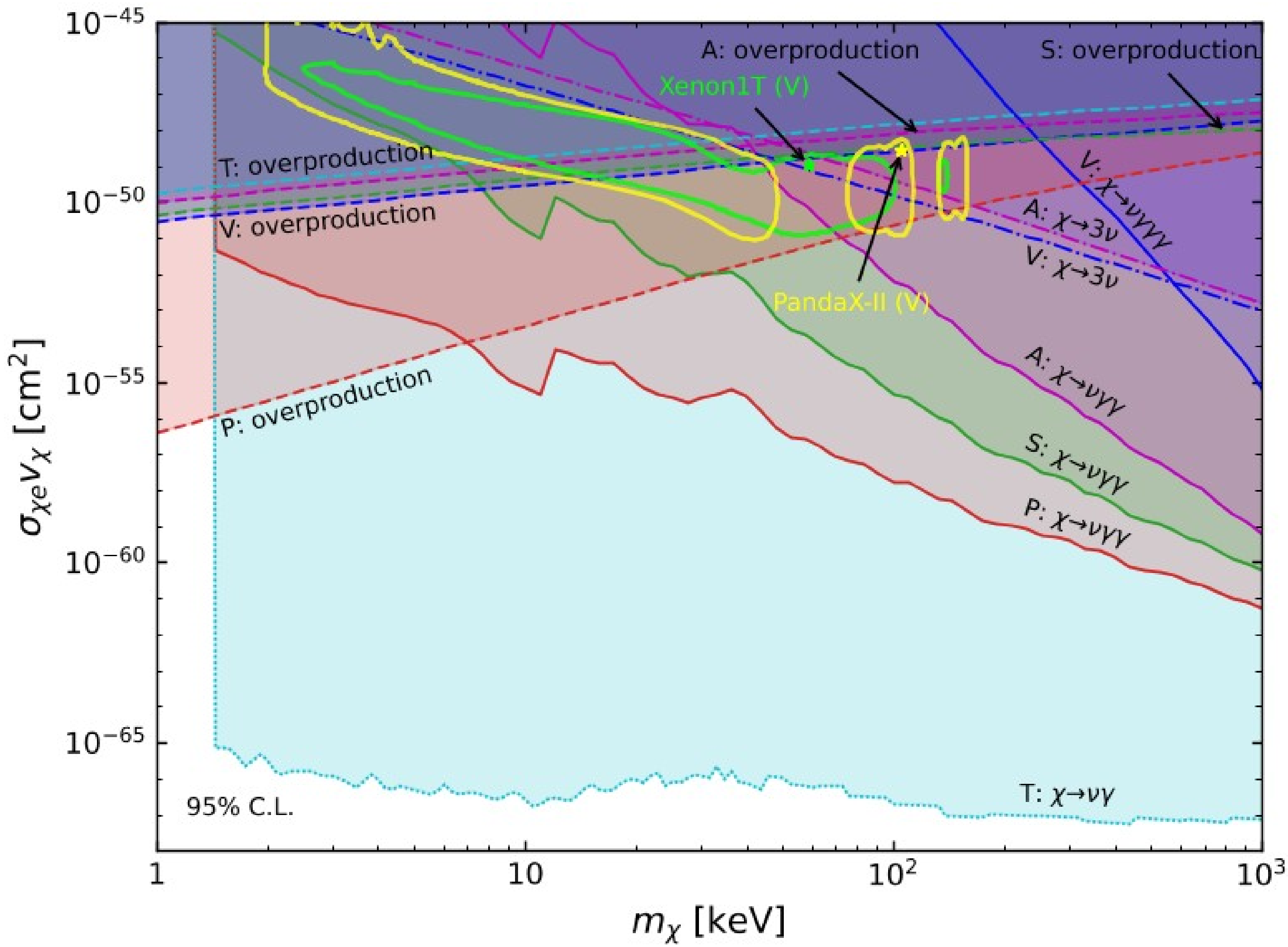

SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

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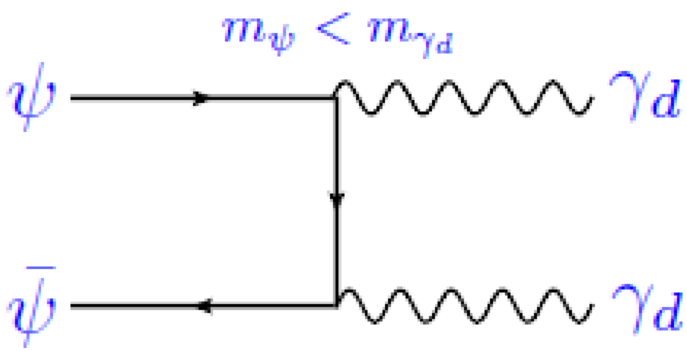
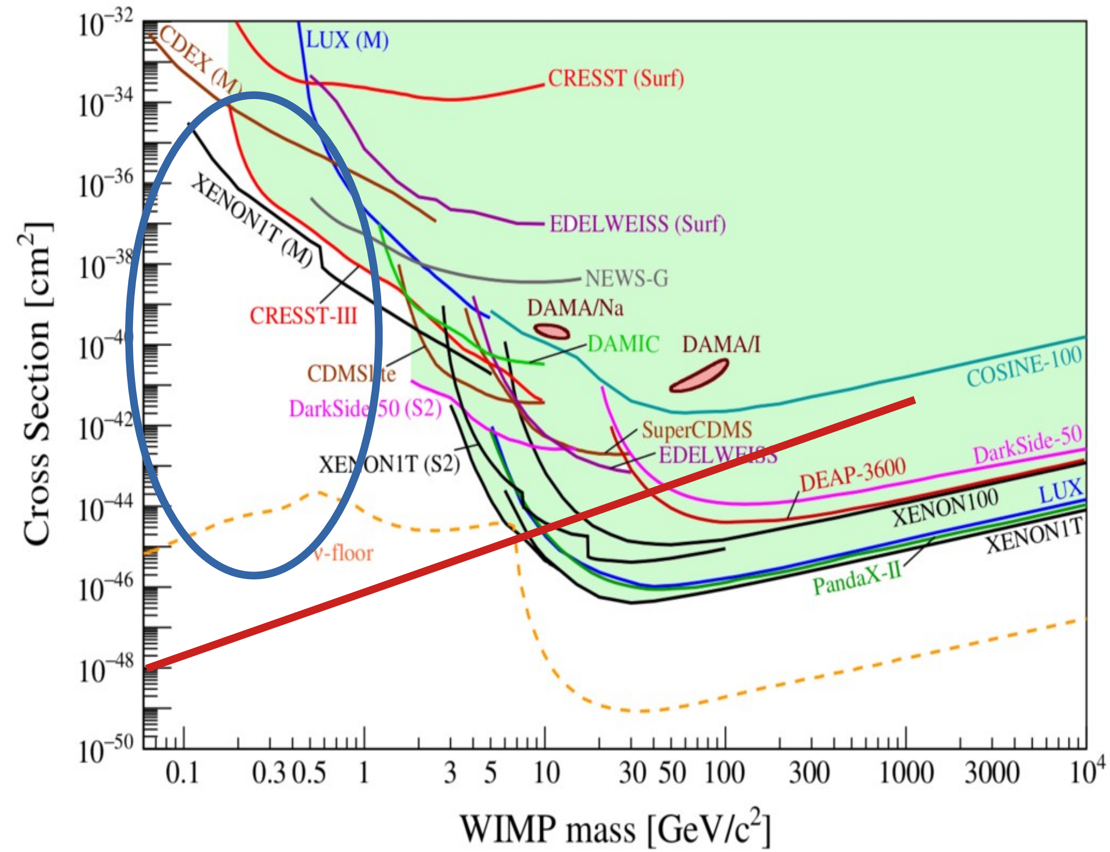
Forbidden DM

1) forbidden annihilations:



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

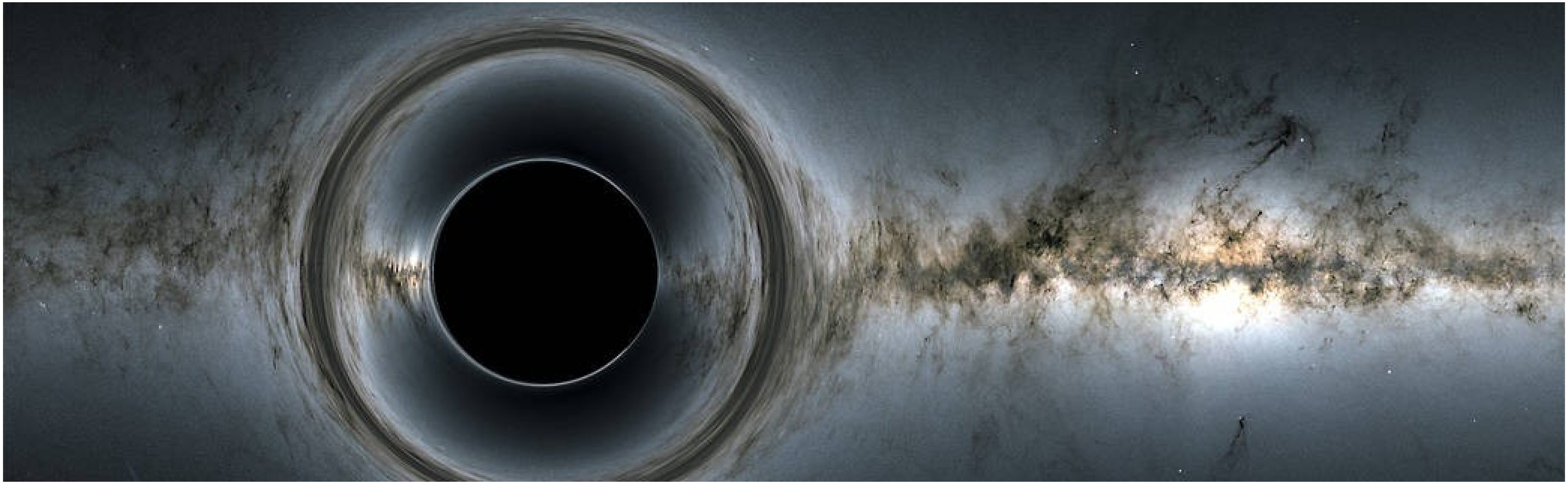
$$\langle \sigma_{\chi\bar{\chi}} v \rangle = \frac{\left(n_{\gamma_d}^{eq}\right)^2}{\left(n_{\psi}^{eq}\right)^2} \langle \sigma_{\gamma_d \gamma_d} v \rangle \approx 8\pi f_\Delta \frac{\alpha_d^2}{m_\psi^2} e^{-2\Delta x}$$



Forbidden by kinematics:
DM is lighter than final SM particles

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

Velocity Scaling @ Black Holes



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

$$\rho \propto r^?$$

Gamma Fluxes

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

- **Forbidden channel**

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

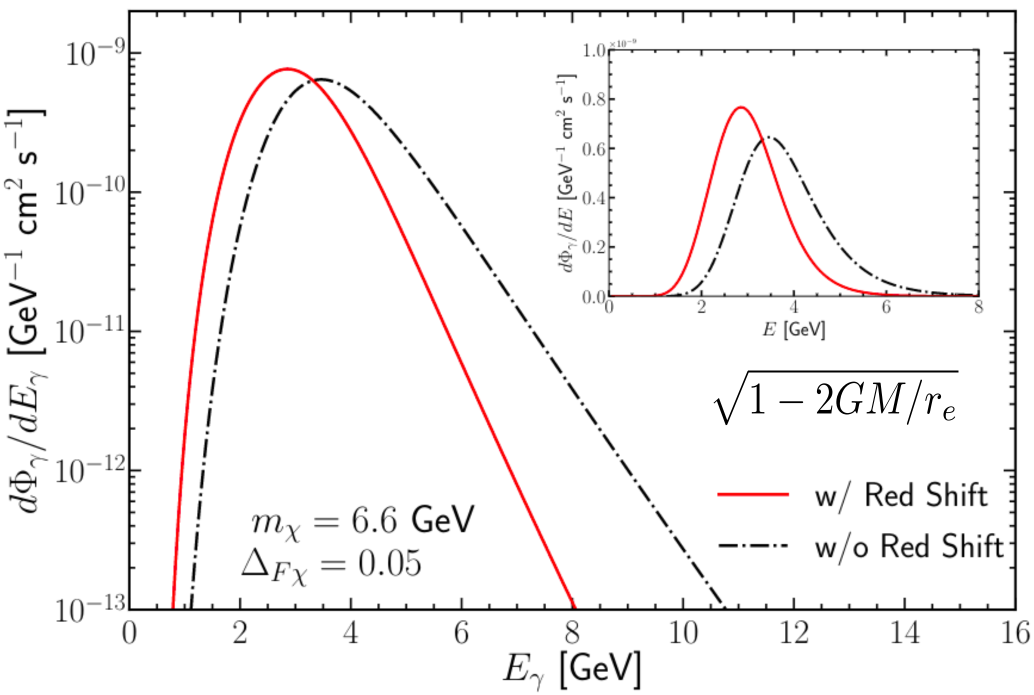
$$\frac{d\sigma}{d\Omega} \approx \sqrt{\frac{s-4m_F^2}{s-4m_\chi^2}}\frac{4m_F^2+4m_\chi^2+s}{64\pi^2(s-m_\phi^2)^2}$$

Isotropic in the C.O.M. frame

- **Signal channel**

$$F \to \nu\gamma$$

Box-shaped spectrum in C.O.M.



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

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

Fitting the Fermi-LAT data

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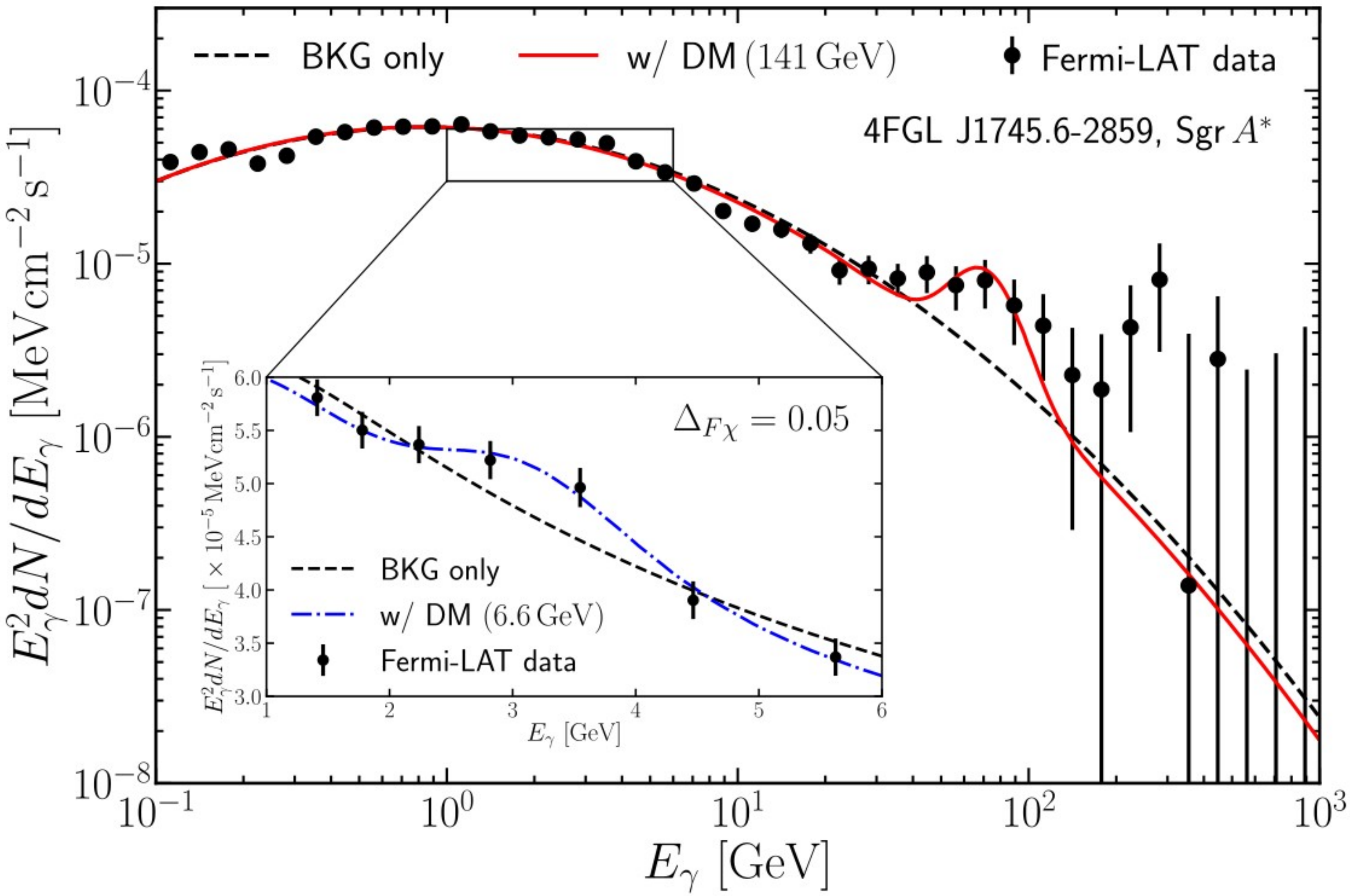

Aug/4, 2008

Oct/26, 2022

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

Sensitivity Plots

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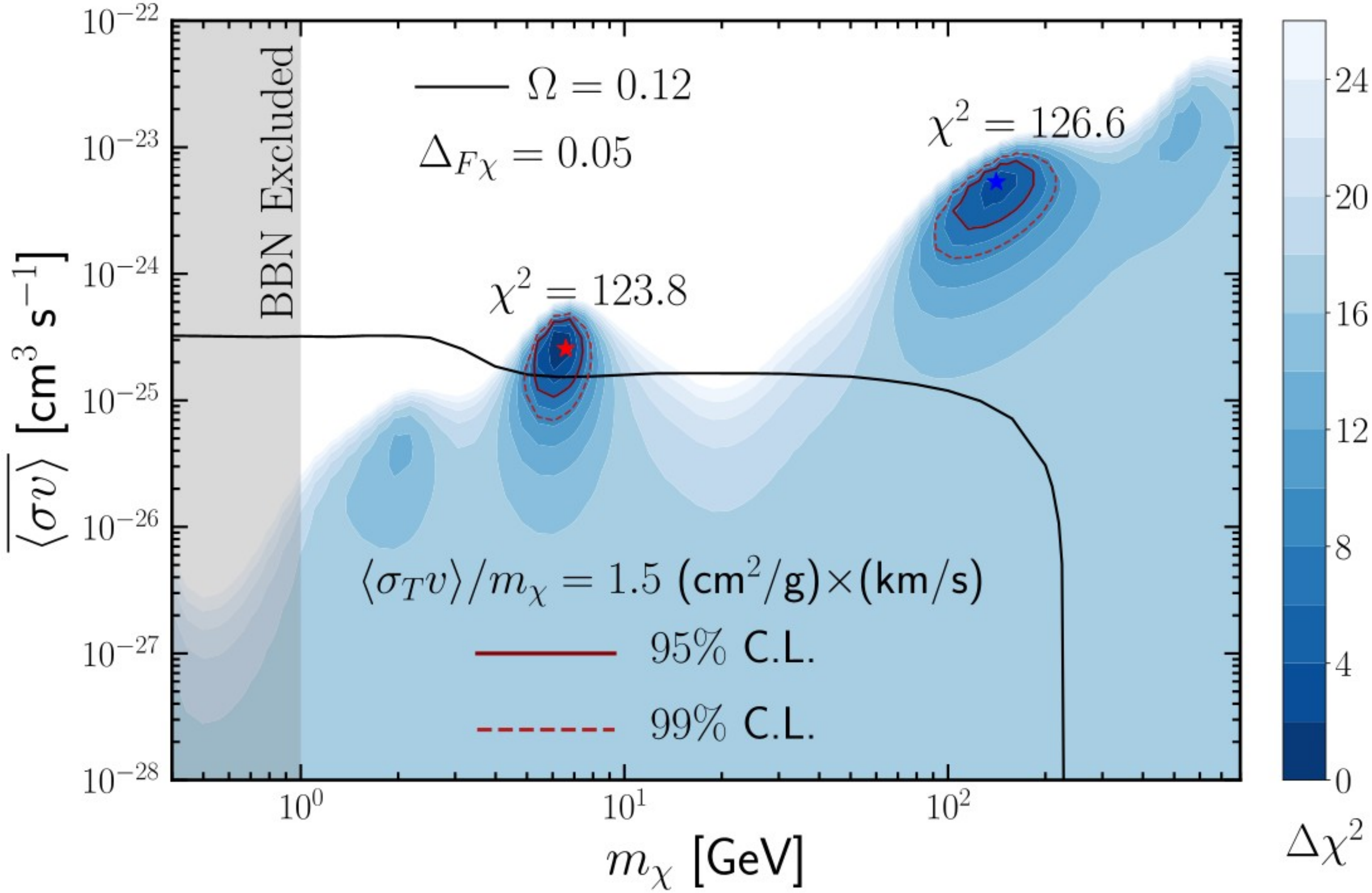

- **Bkg-only hypothesis**

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

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

Summary

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1) Advantages of indirect detection

- Large bulk of DM.
- Have various detectable signals.
- Can have unique peak structure.
- Can point back to the sources, especially gamma.
- Various observations & excesses.

2) Fermionic absorption DM

- Mono-energetic & continuous spectrum.

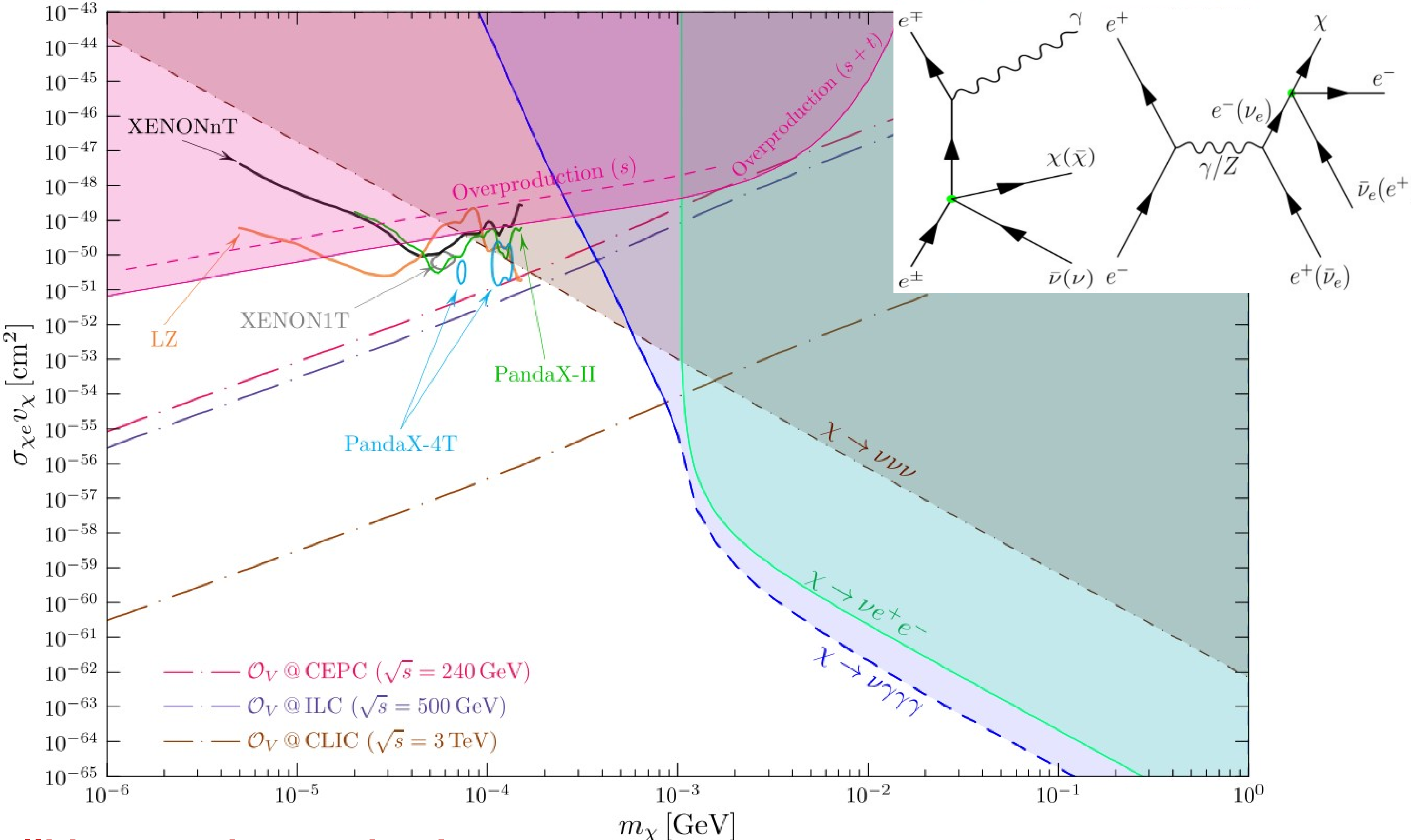
3) Reactivate forbidden DM

- Point source.
- Characteristic peak.

Thank You

Backup Slides

PandaX-4T & Lepton Colliders



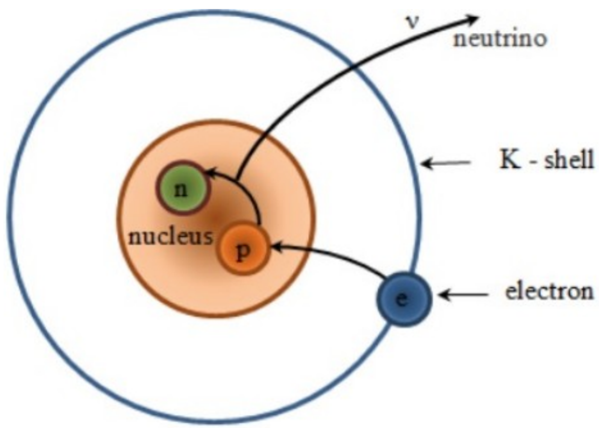
Collider searches probe the dark sector, not just DM

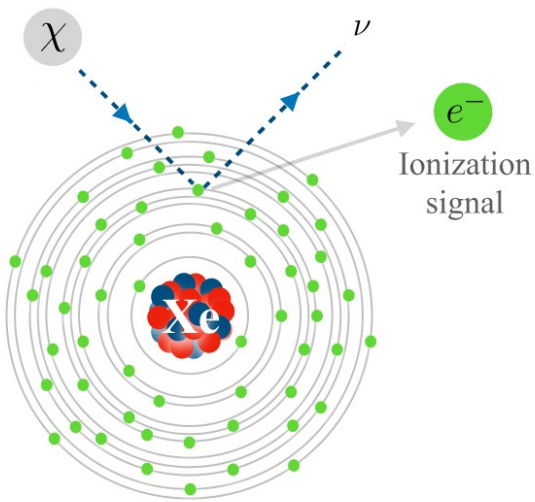
SFG, Kai Ma, Xiao-Dong Ma, Jie Sheng [arXiv:2306.00657]

K-Shell Electron Capture for ν

王淦昌

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





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

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

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

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

How to test Forbidden DM?

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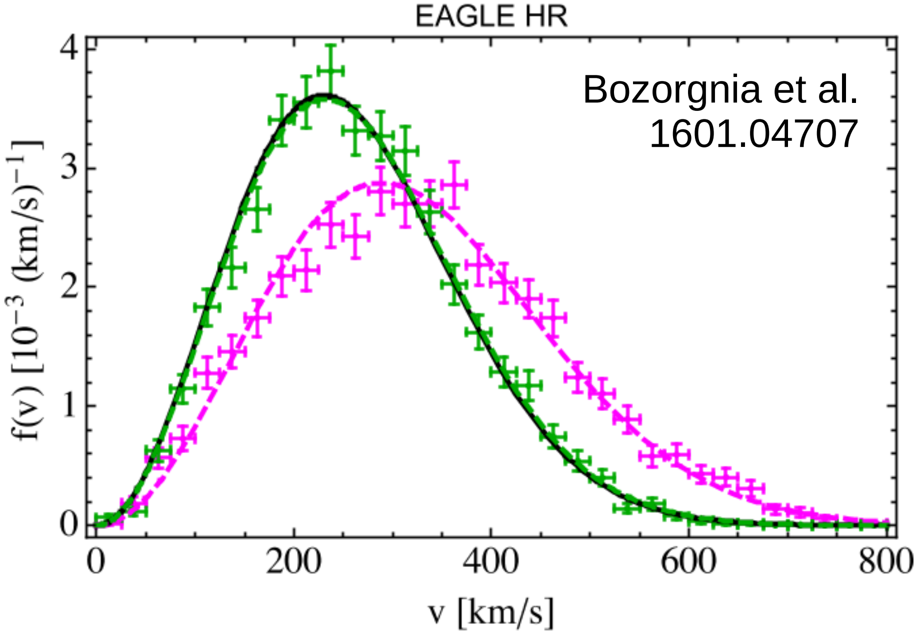
- **Boltzmann Distribution**

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

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

$$\sim 1\%$$

$$v_d \sim 10\%$$



- **Juttner Distribution**

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

DM Profiles

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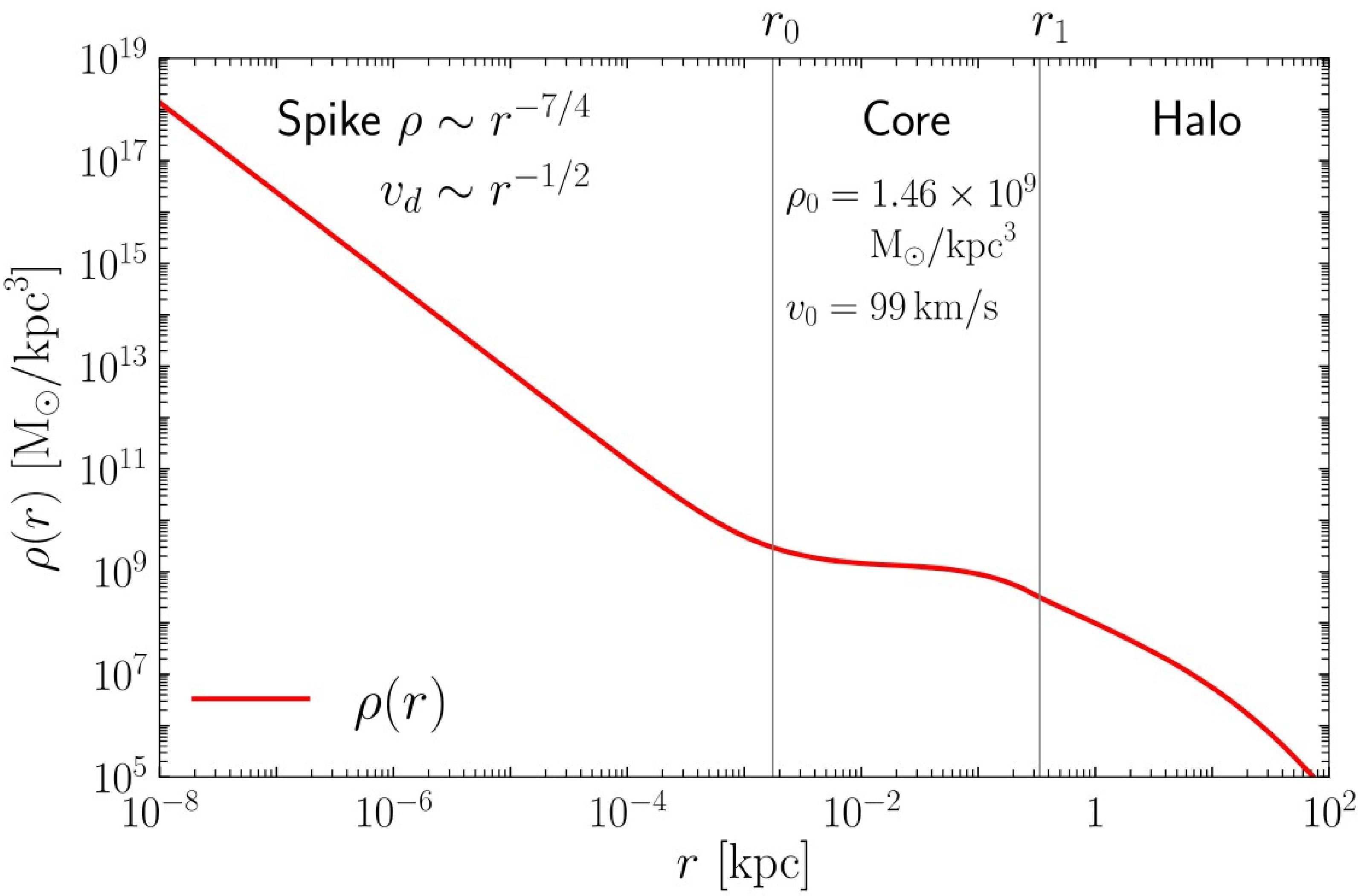
$$\rho(r) = \begin{cases} \rho_{\rm NFW}(r), & r > r_1, \\ \rho_{\rm iso}(r), & r_0 < r < r_1 \\ \rho_{\rm spike}(r), & r < r_0. \end{cases}$$



《 Physics Letters A 》

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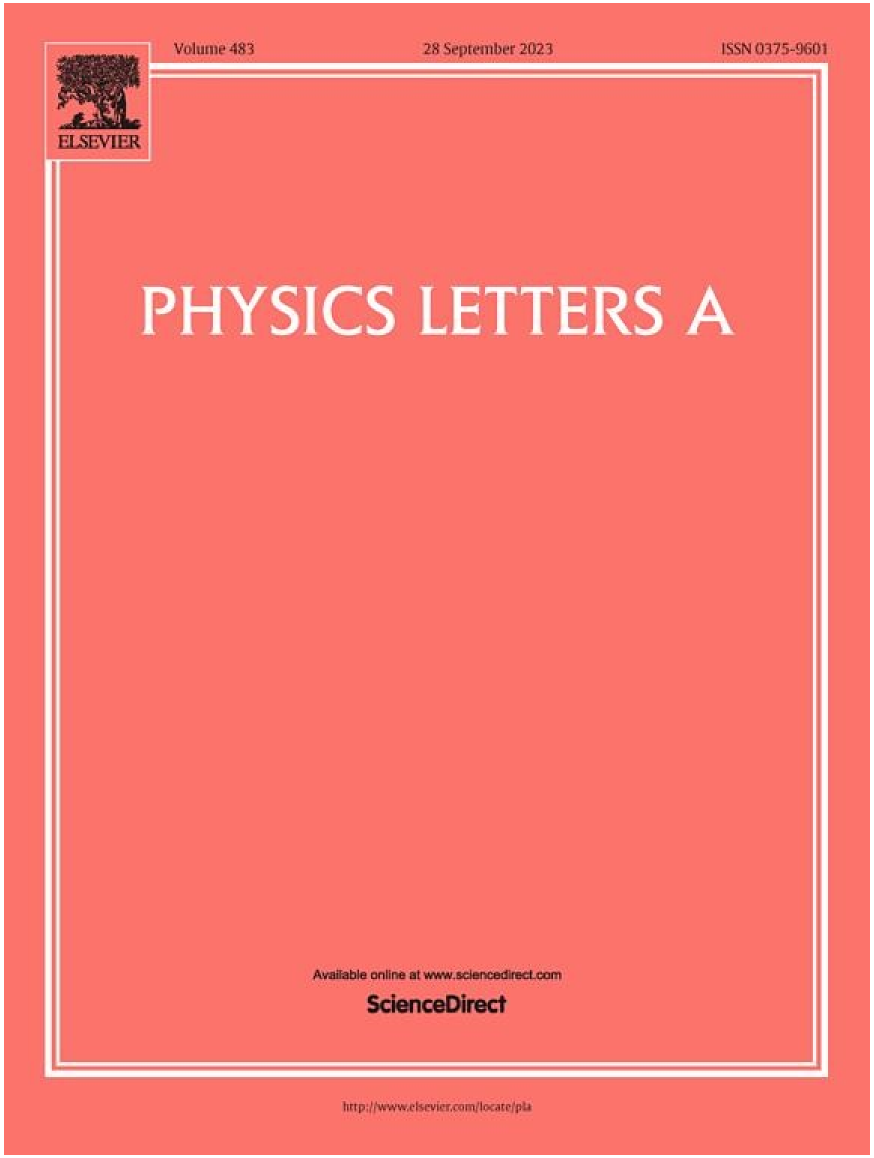

Aims & Scope

- 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.