Search for Exotic Dark Matter with CDEX-10 Experiment at CJPL

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CJPL
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中国暗物质实验
China Dark matter EXperiment

Content

I. Introduction

I. Introduction

☐ Hunt for Dark Matter:

- ➢ Various astronomical observations favor the existence of Dark Matter (DM)

Since we may be surrounded by the dark matter, we may detect it via its interaction with ordinary matter

Collisions of the Bullet cluster

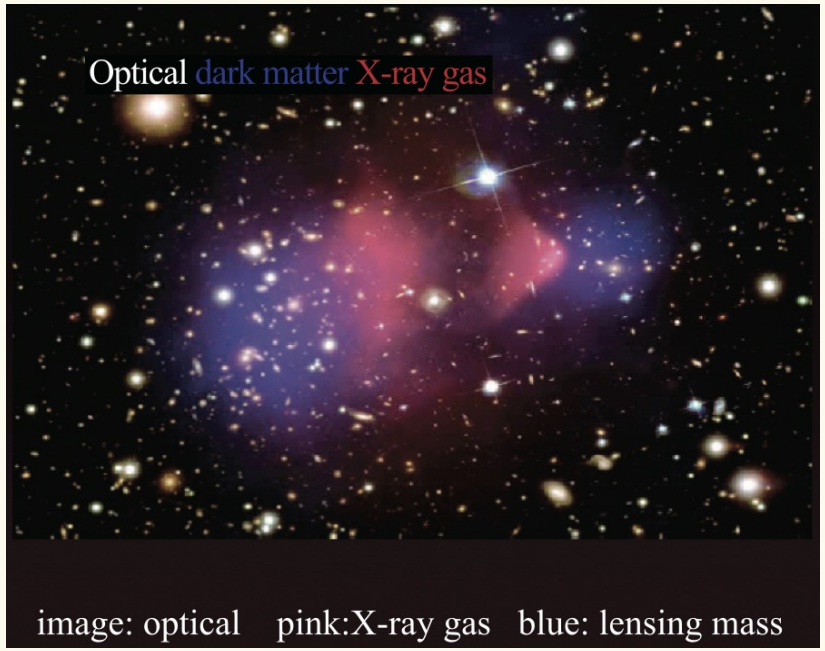
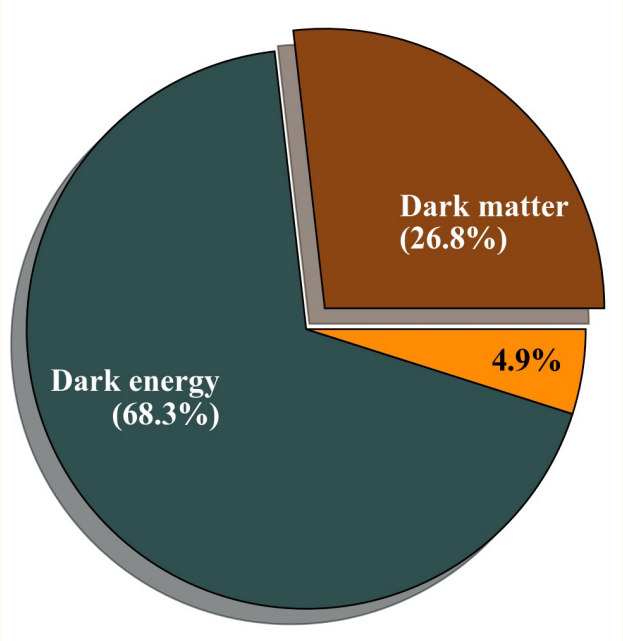


Fig from Young B. A survey of dark matter and related topics in cosmology. Front. Phys., 2017

The composition of the Universe



Data from: Zyla P, et al. Theor. Exp. Phys., 083C01, (2020).

Deep underground laboratories

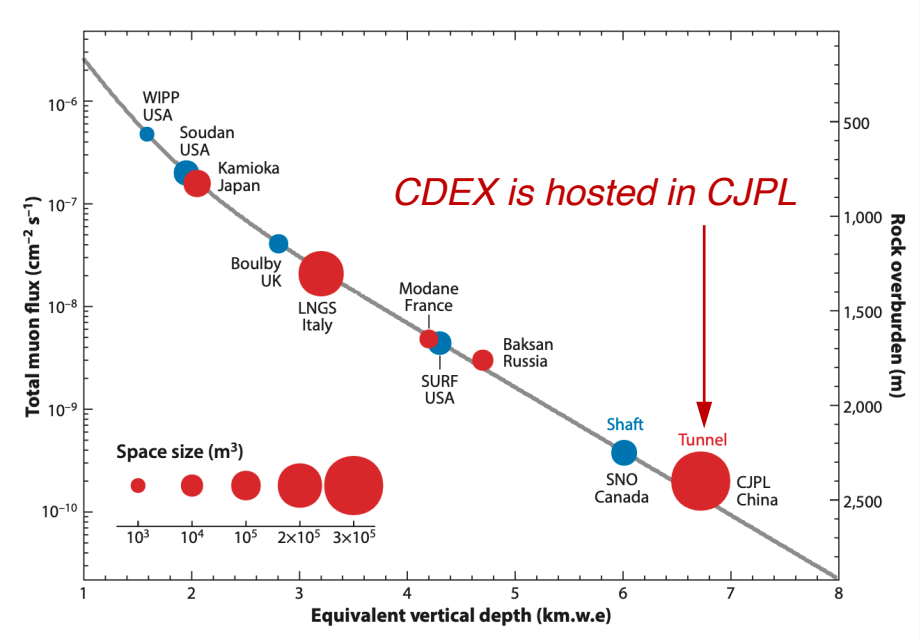


Fig from J.P. Cheng et al. Annu. Rev. Nucl. Part. Sci. 67:231–51, (2017)

I. Introduction

☐ Weakly interacting massive particles (WIMPs)

- ➢ WIMPs is one of the most popular dark matter candidates (mass in GeV – TeV scale)
- ➢ Direct search experiments have searched WIMPs via different detection technologies for several decades

However, no WIMPs has been discovered yet…

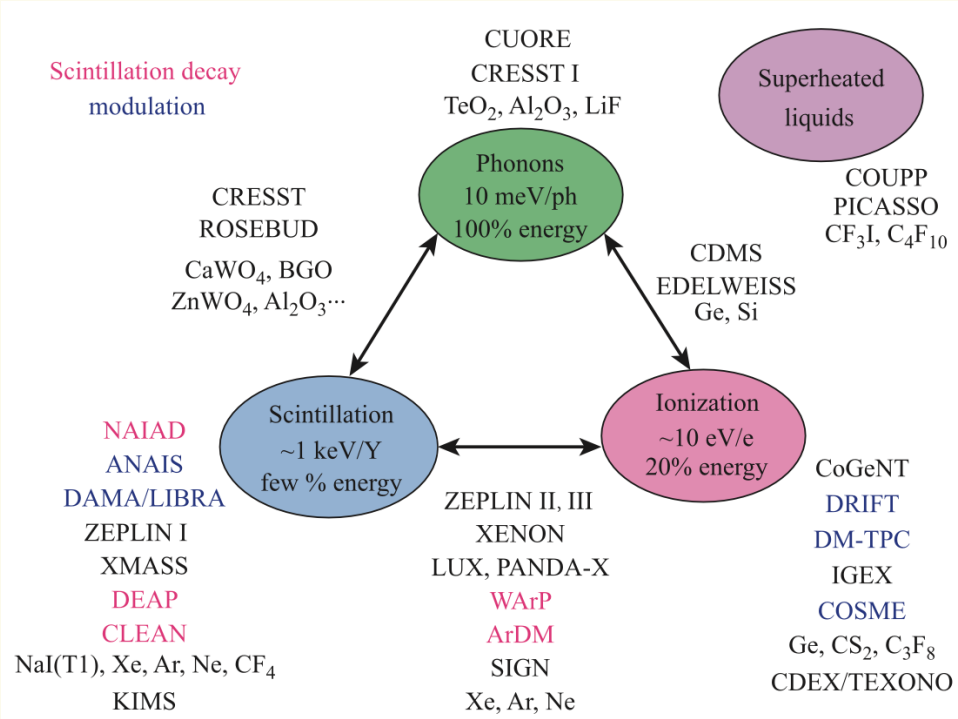
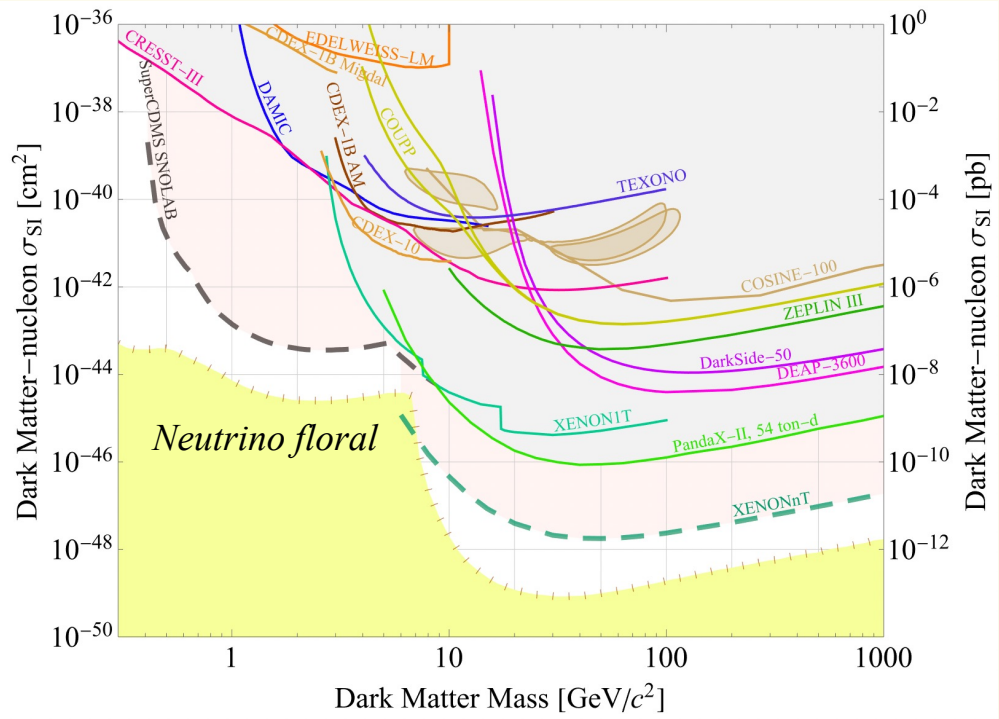


Fig from T. Saab, An introduction to dark matter direct detection searches & techniques, arXiv: 1203.2566



Draw by https://supercdms.slac.stanford.edu/dark-matter-limit-plotter

I. Introduction

☐ Other Dark Matter Candidates:

The null result from searches for WIMPs has motivated studies of other possible DM candidates

Light DM in keV-GeV scale contains many interesting DM candidates:

Axion-like particles, sterile neutrino, and other exotic DM …

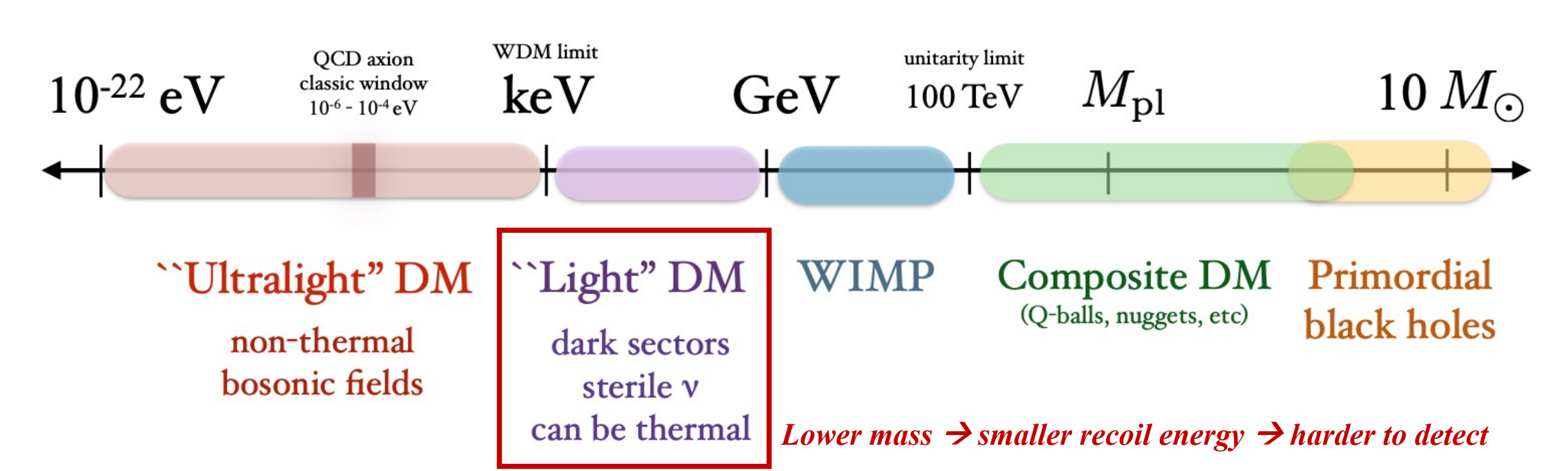
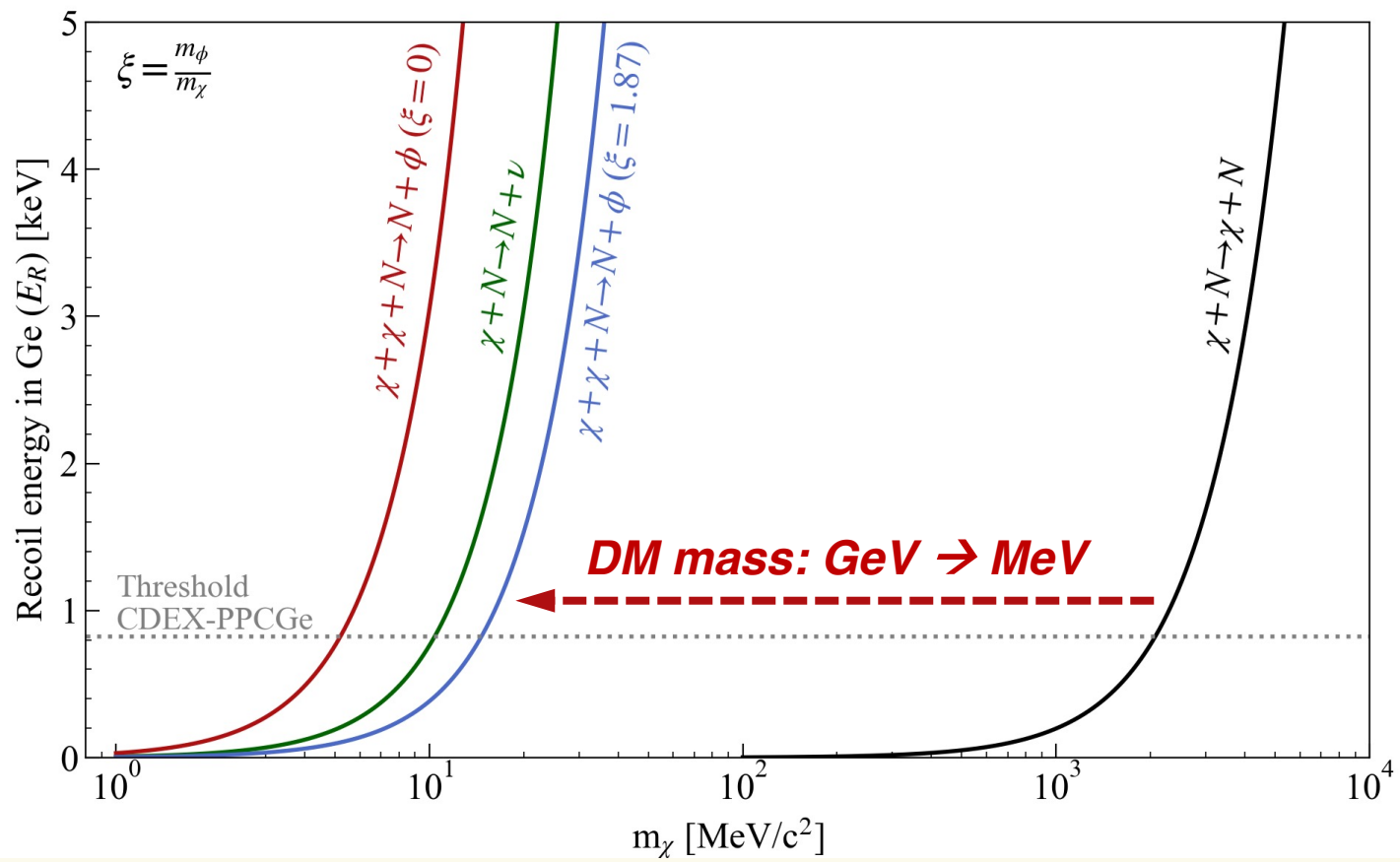


Fig from: Tongyan Lin, TASI lectures on dark matter models and direct detection, arXiv:1904.07915

I. Introduction

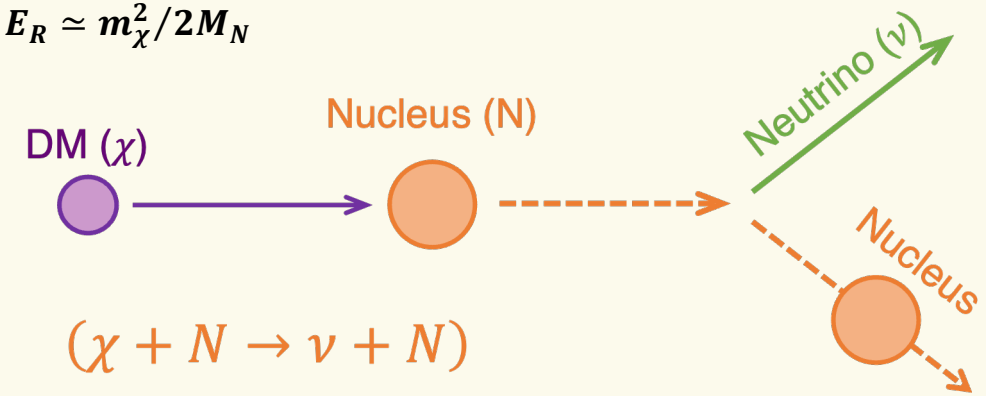
☐ Search for Light Dark Matter:

- **Lower detection threshold:** HPGe detector
- **Larger recoil energy:** absorption or Inelastic scattering



Neutral current fermionic DM absorption

$E_R \simeq m_\chi^2/2M_N$

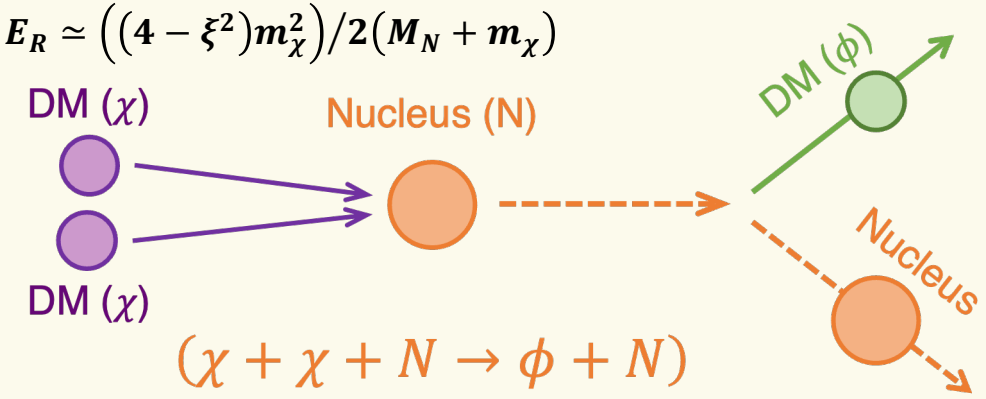


$(\chi + N \to \nu + N)$

J. A. Dror, G. Elor, and R. McGehee, Phys. Rev. Lett. 124, 181301 (2020).
T. Li, J. Liao, and R.J. Zhang. High Energy Phys. 05, 071 (2022).

DM-nucleus 3-2 scattering

$E_R \simeq \left((4-\xi^2)m_\chi^2\right)/2(M_N + m_\chi)$



$(\chi + \chi + N \to \phi + N)$

W. Chao et al, arXiv:2109 14944.

II. CDEX-10 Experiment

☐ CDEX-10 Experiment:

CDEX-10 experiment is hosted in a polyethylene room at CJPL-I

- A 10 kg PPCGe detector array directly cooled by liquid nitrogen and surrounded by multi-layer shieldings
- The C10-B1 detector accumulates 205.4 kg·day data and achieves the lowest analysis threshold of 160 eVee

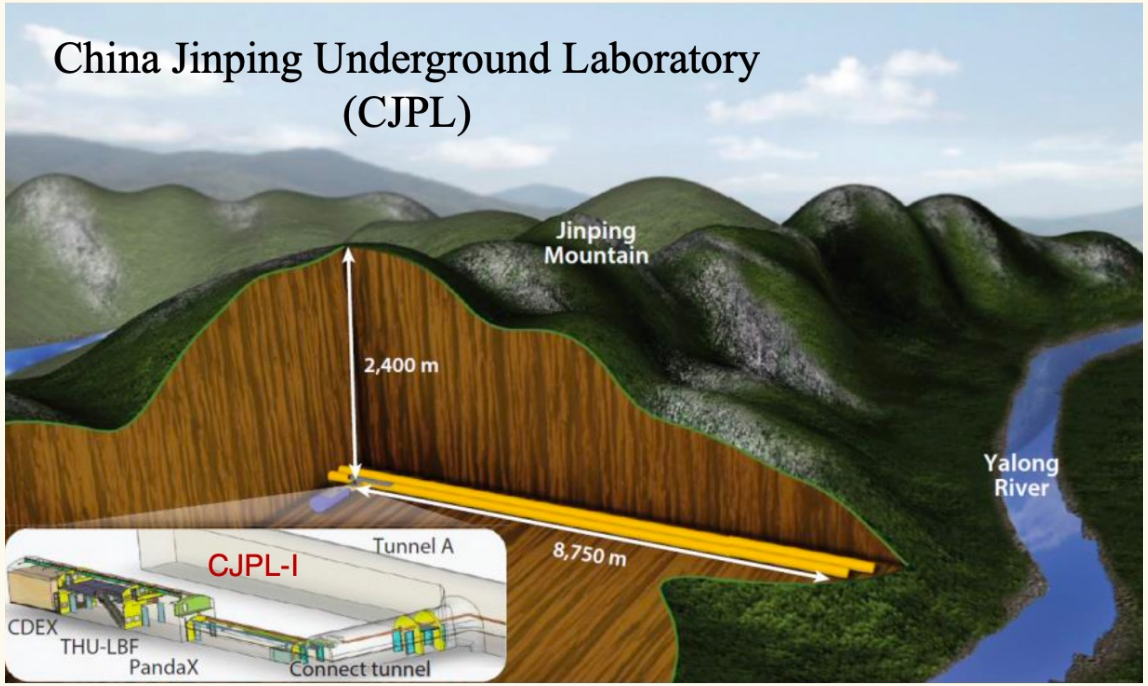


Fig from J.P. Cheng et al. Annu. Rev. Nucl. Part. Sci. 67:231–51, (2017)

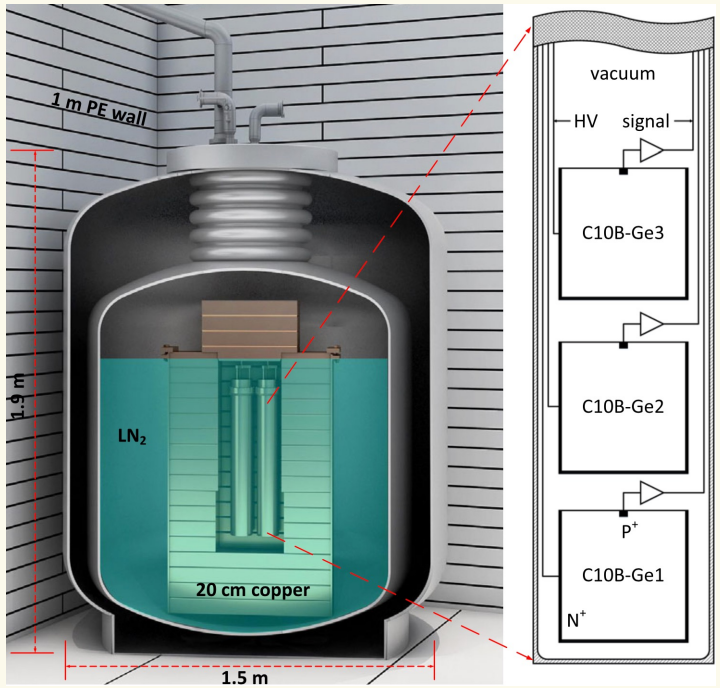
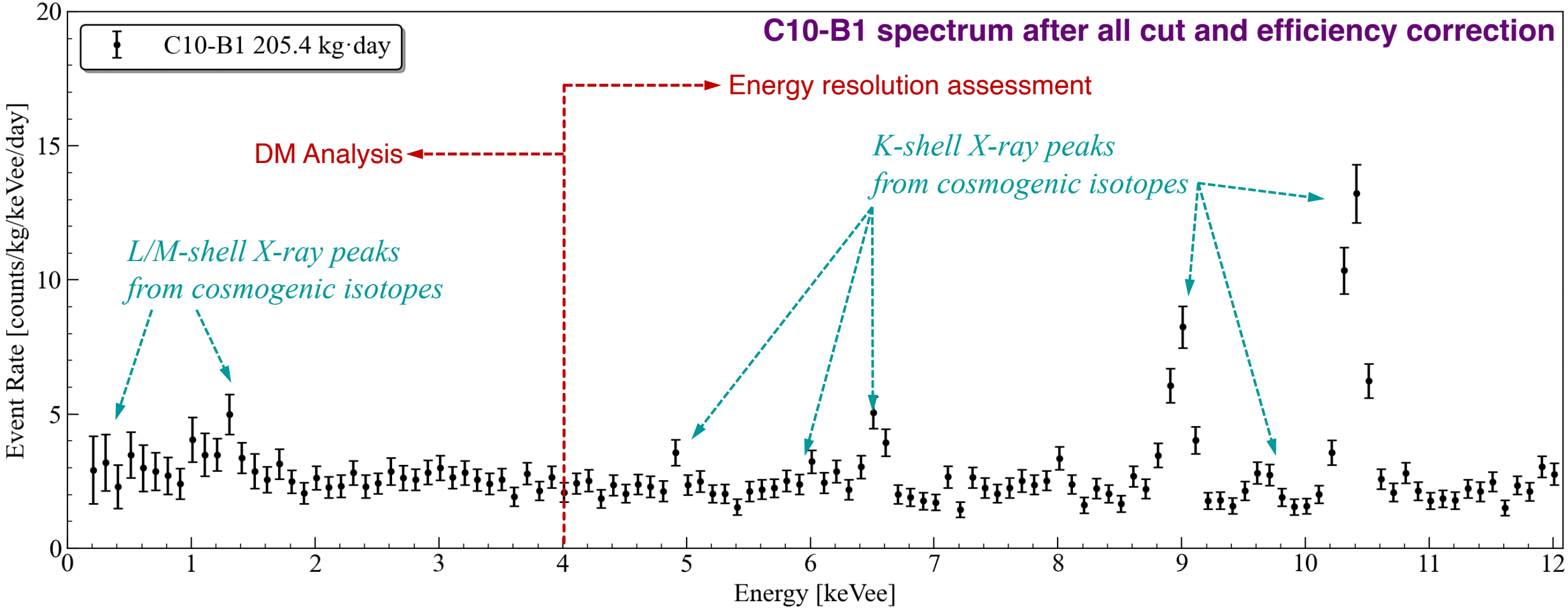


Fig from H. Jiang et al. (CDEX Collaboration) Phys. Rev. Lett. 120, 241301 (2018).

C10-B1 Spectrum:

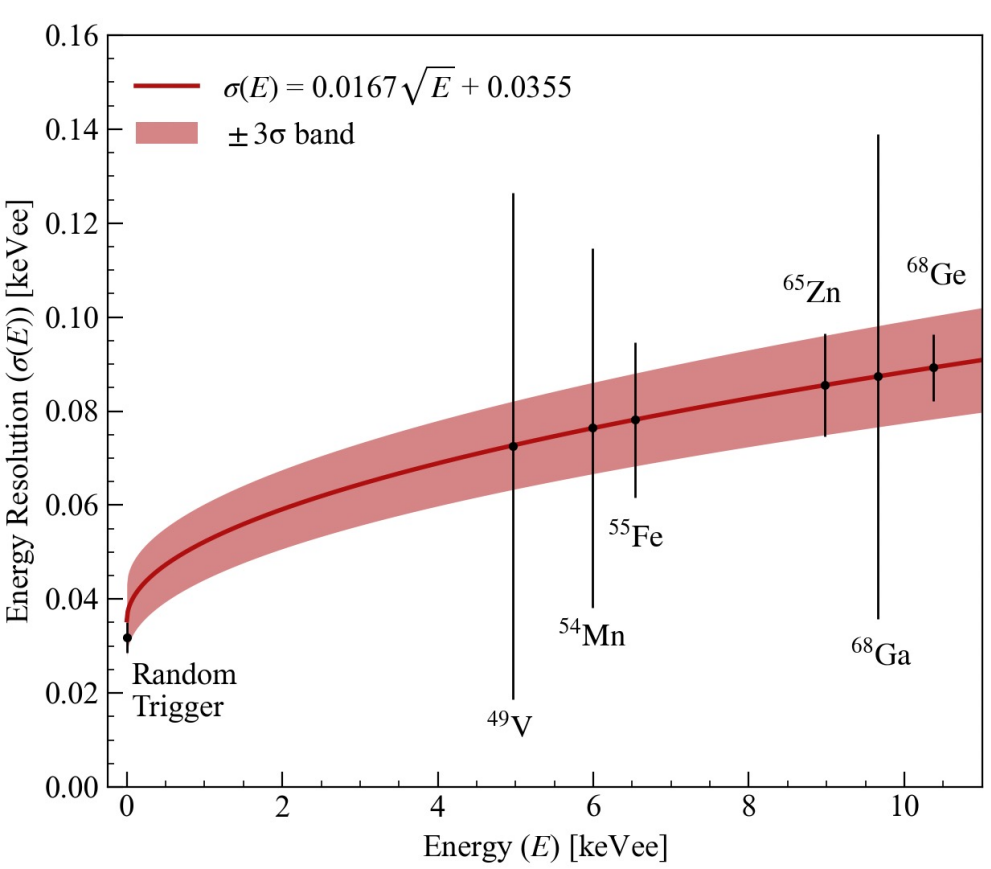
Spectrum after all data selection and efficiency correction

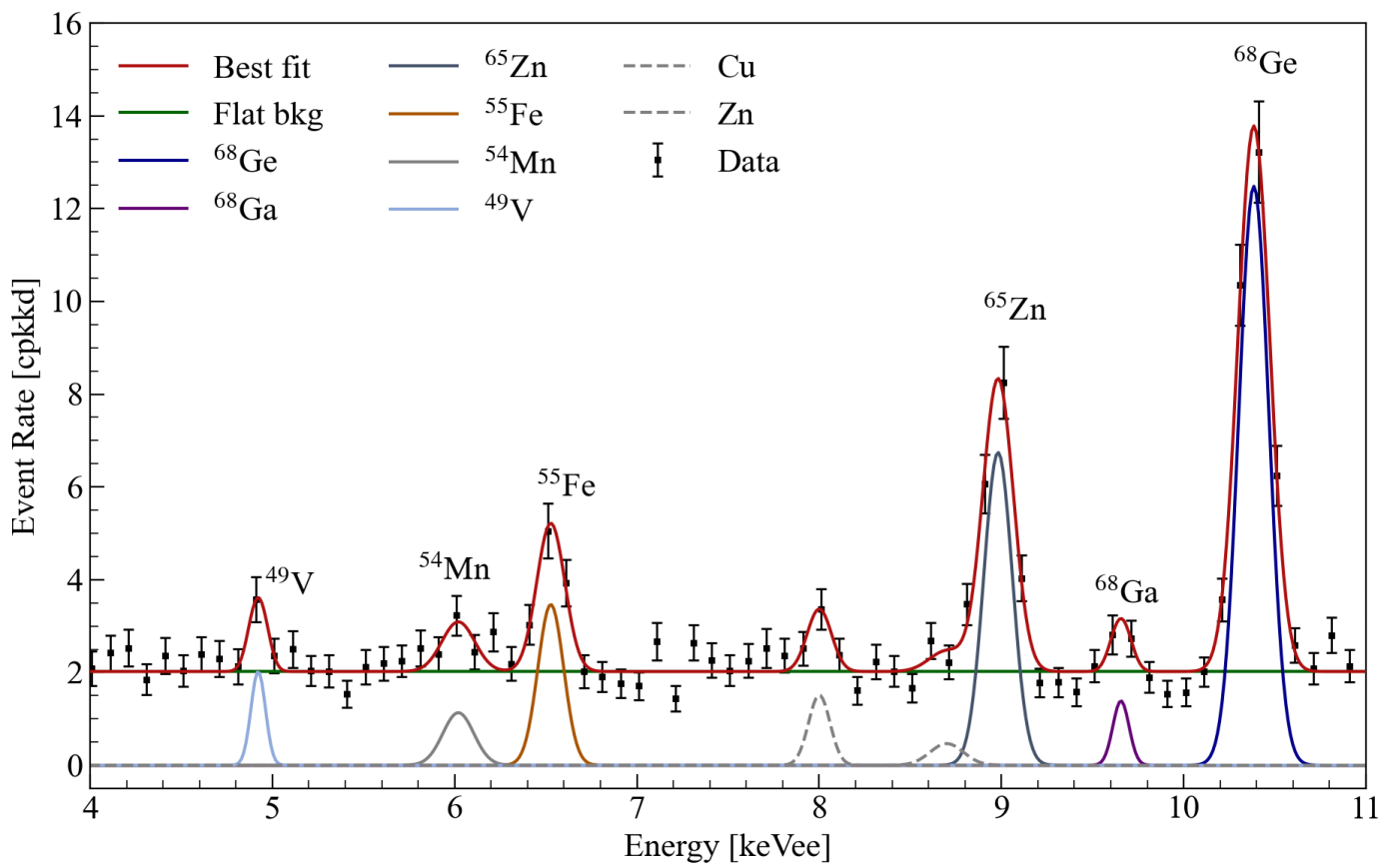


II. CDEX-10 Experiment

☐ Energy resolution of C10-B1 detector:

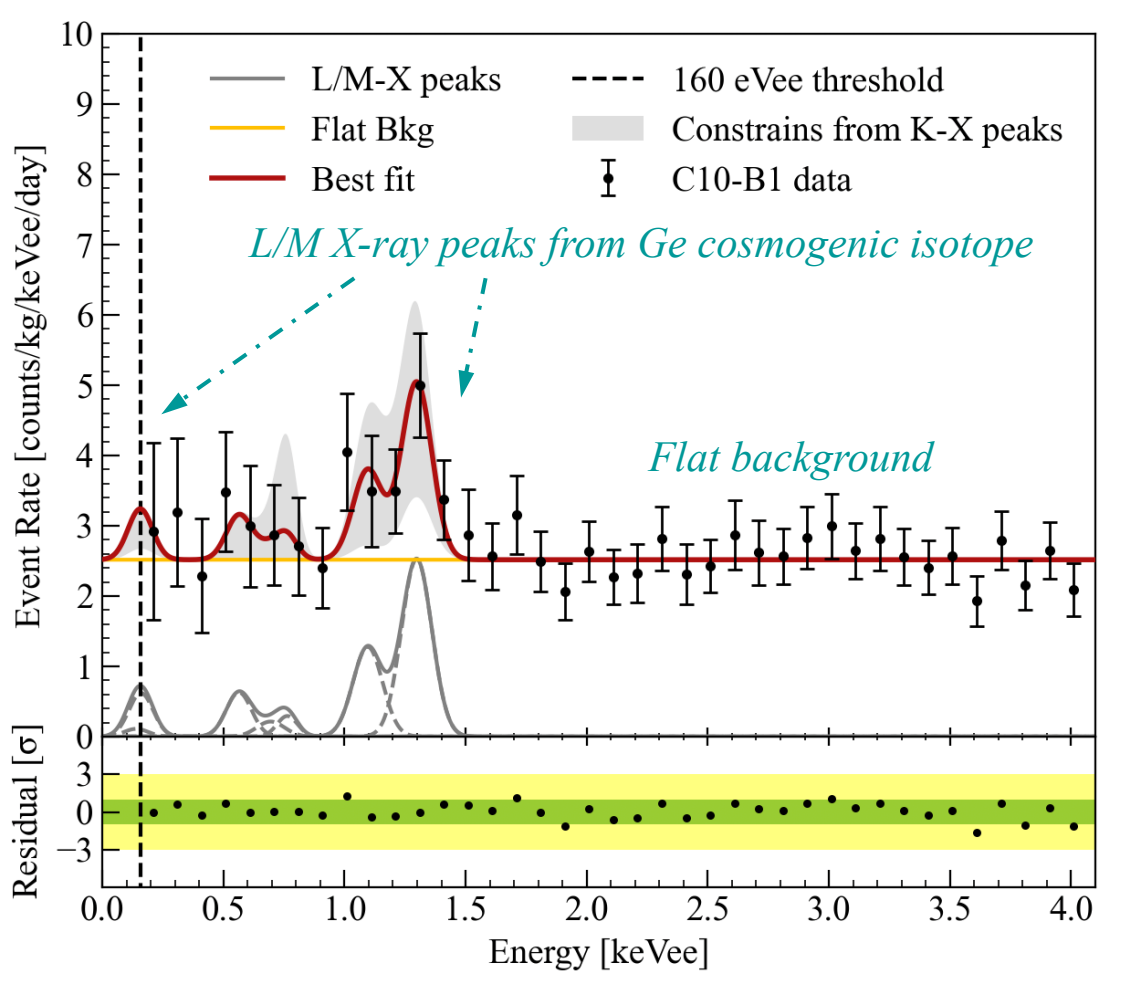
- Resolution fitted by random trigger signals and KX-ray peaks
- Resolution near analysis threshold ~ 50 eVee @ 1 keVee





☐ Background Model in 0.16-4.0 keVee spectrum:

Background in 0.16-4 keVee spectrum consists of a flat component and L/M X-ray peaks



$$B(E) = Flat + \underbrace{\sum \frac{A_L}{\sqrt{2\pi}\sigma_L} e^{\left(\frac{-(E-E_L)^2}{2\sigma_L^2}\right)}}_{\text{L-X peaks}} + \underbrace{\sum \frac{A_M}{\sqrt{2\pi}\sigma_M} e^{\left(\frac{-(E-E_M)^2}{2\sigma_M^2}\right)}}_{\text{M-X peaks}}$$

➢ **Constrain L/M-X peaks by K-X peaks:**

$$A_{L,M} \in \left(A_K \pm 3\sigma_{A_K}\right) \cdot R_{L,M/K}$$

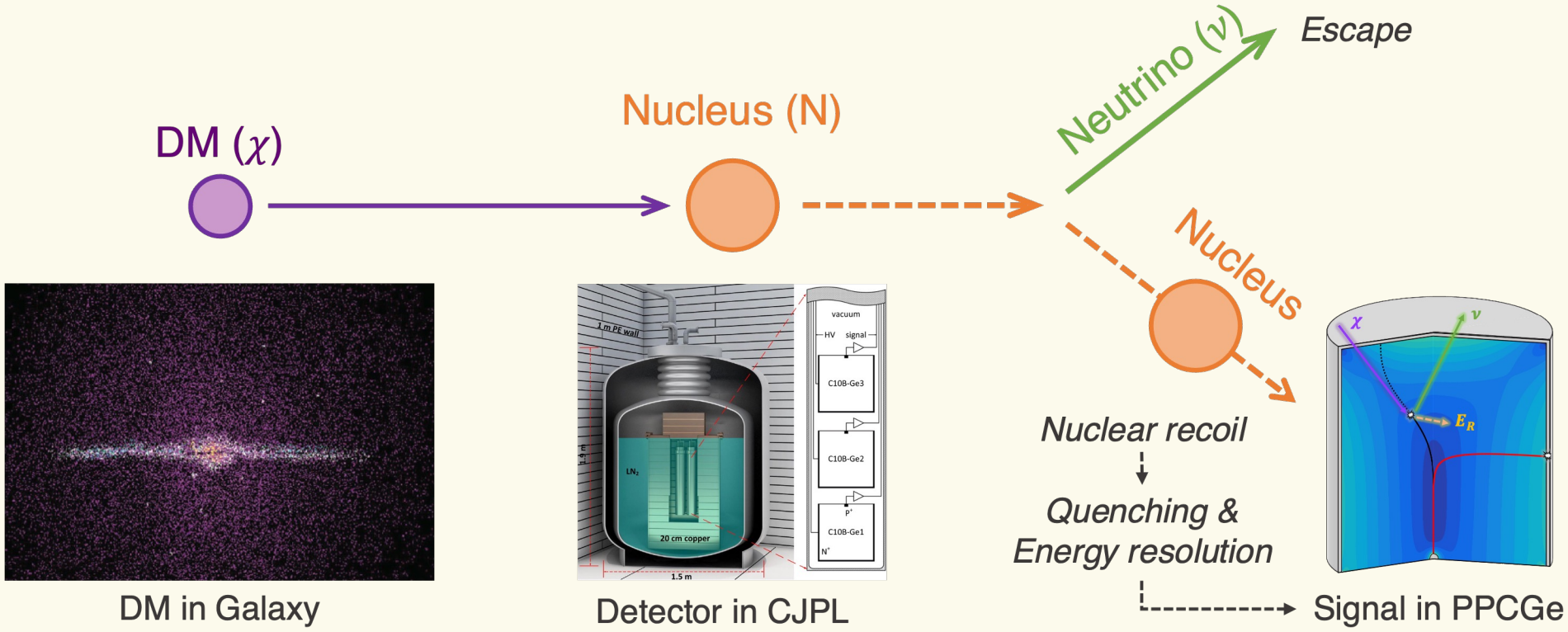
Isotope	E_K	E_L	$R_{L/K}$	E_M	$R_{M/K}$
Ge-68	10.37 keV	1.298 keV	0.133	0.16 keV	0.0189
Ga-68	9.66 keV	1.194 keV	0.111	0.14 keV	0.0185
Zn-65	8.98 keV	1.096 keV	0.119		
Fe-55	6.54 keV	0.764 keV	0.117		
Mn-54	5.99 keV	0.695 keV	0.106		
V-49	4.97 keV	0.564 keV	0.106		

III. Fermionic dark matter neutral current absorption

III. Fermionic DM neutral current absorption

☐ Direct detection of Neutral current fermionic DM absorption:

- ➢ DM (χ) mixes with massless Dirac neutrino (ν) through a Yukawa interaction of a scalar field
- ➢ Absorption of DM gives a monoenergetic nuclear recoil energy, $E_R \simeq m_\chi^2/(2M_N)$



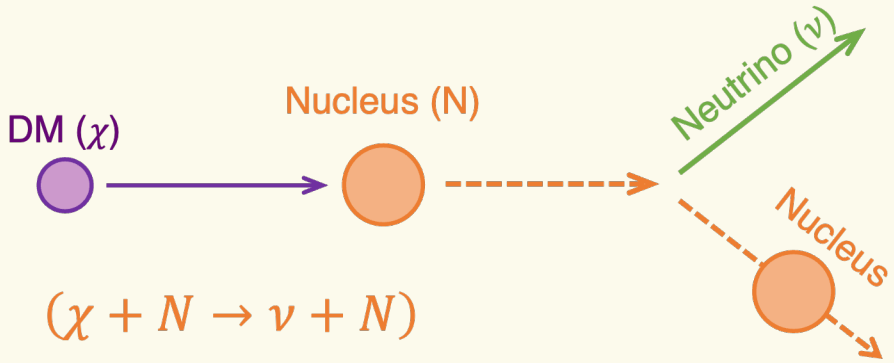
Theory: J. A. Dror, G. Elor, and R. McGehee, Phys. Rev. Lett. 124, 181301 (2020).

III. Fermionic DM neutral current absorption

☐ Differential event rate:

$$\frac{dR_j}{dE_R} = \frac{\rho_\chi}{m_\chi} \cdot \sigma_{NC} N_j M_j A_j^2 F_j^2 \cdot \frac{\sqrt{2E_R M_j}}{2p_\nu m_\chi^2} \left\langle \frac{1}{v_\chi} \right\rangle$$

DM density — *Cross Section* — *Spectra shape*



σ_{NC}:	cross section per nucleon
m_χ:	DM mass
ρ_χ:	DM local density $\simeq$ 0.3 GeV/cm^3
A_j:	mass number of isotope j
$N_j \cdot M_j$:	mass of isotope j
E_R:	nuclear recoil energy
v_χ:	DM velocity in Lab
F_j:	Helm nuclear form factor

$$p_\nu = \sqrt{q_j(2m_\chi - q_j - 2E_R)}, \qquad q_j = \sqrt{2E_R M_j}$$

III. Fermionic DM neutral current absorption

☐ Differential event rate:

- ➢ Spectra shape term relates to E_R and DM velocity
- ➢ Capped Maxwell distribution for DM velocity

$$\left\langle \frac{1}{v_\chi} \right\rangle = \int_{v_{min}}^{\infty} d^3v \frac{f(\vec{v})}{v}$$

$$v_{min} = \frac{\left|E_R + \sqrt{2M_j E_R} - m_\chi\right|}{m_\chi}$$

$$f(\vec{v}) = \frac{1}{f_N} \exp\left[-\frac{\vec{v}+\vec{v}_e}{v_0^2}\right] \Theta(v_{esc} - |\vec{v}+\vec{v}_e|)$$

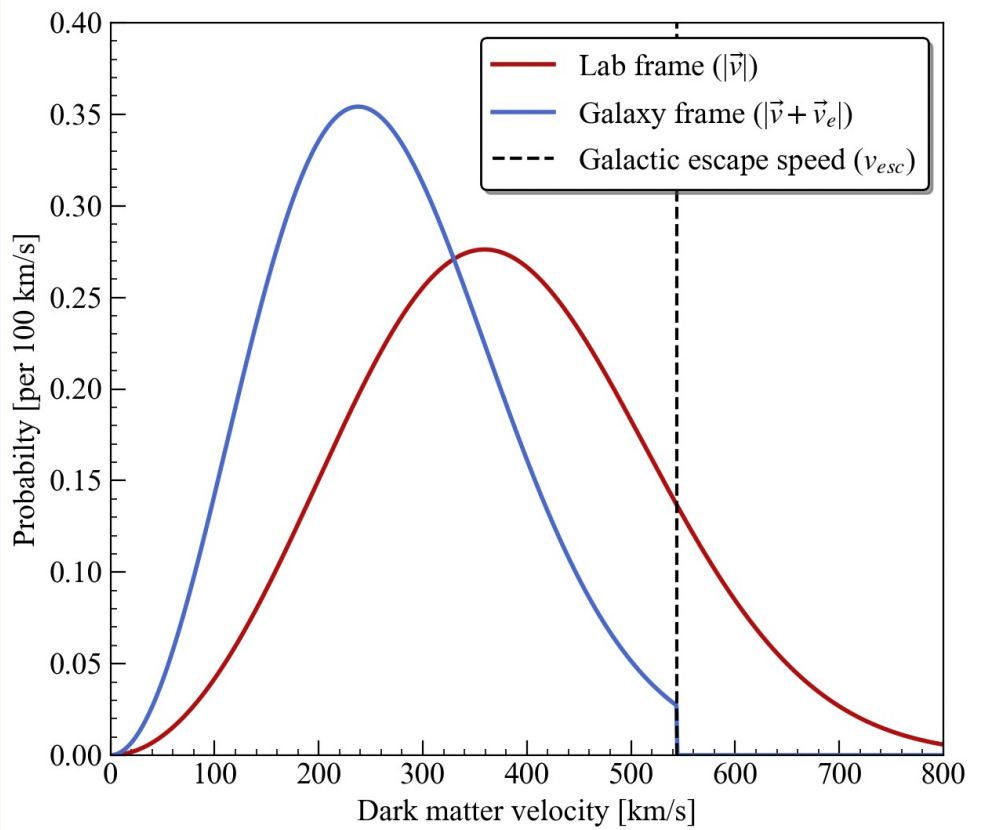
$\vec{v}$:	DM velocity at Lab frame	$\vec{v}_e$:	Earth speed at Galaxy
v_{min}:	Minimum v for E_R	v_{esc}:	Galactic escape speed
f_N:	Normalize factor	v_0:	Local standard rest speed
Θ:	Step function		

Data from: D. Baxter et al., Eur. Phys. J. C 81, 907 (2021).

$$\boldsymbol{f(\vec{v}) = \frac{1}{f_N} \exp\left[-\frac{\vec{v}+\vec{v}_e}{v_0^2}\right] \Theta(v_{esc} - |\vec{v}+\vec{v}_e|)}$$

$\vec{v}_e$ = 278.9 km/s $\quad$ v_{esc} = 544 km/s

v_0 = 238 km/s $\quad$ f_N: $\int f(\vec{v}) dv^3 = 1$



III. Fermionic DM neutral current absorption

☐ Expect spectra (nuclear recoil):

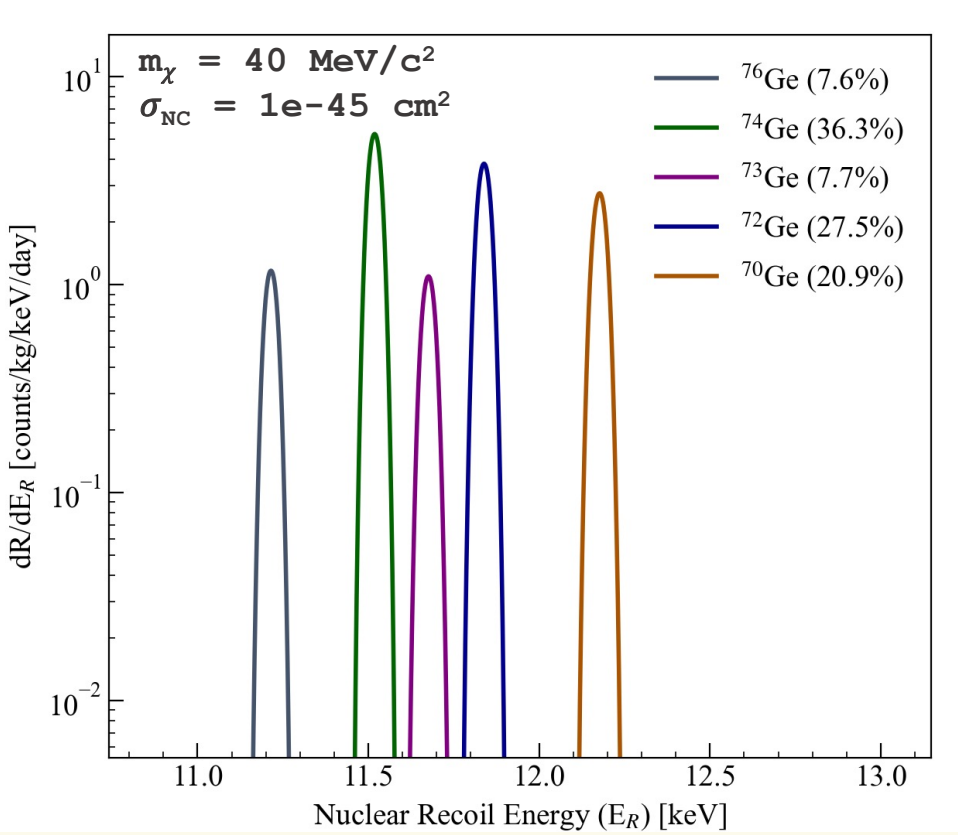
- ➢ Compute Helm form factor for Ge
- ➢ Nuclear recoil spectra for different Ge isotopes

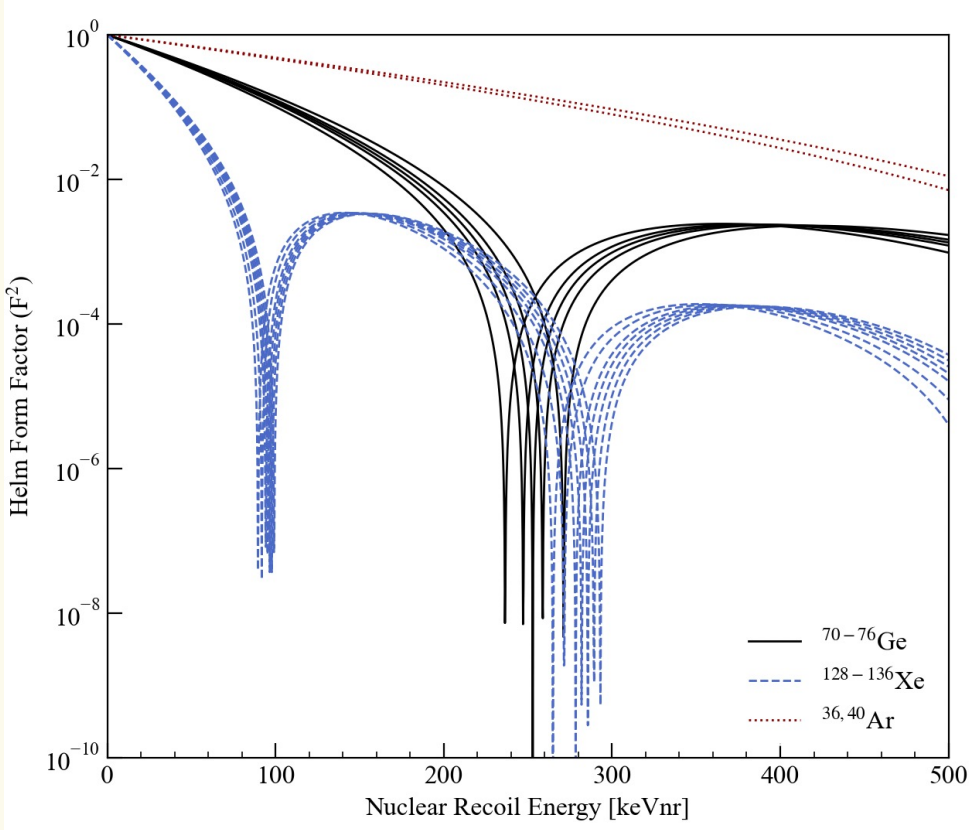
J. D. Lewin and P. F. Smith, Astropart. Phys. 6, 87 (1996).

$$F(q) = 3\frac{j_1(qr_n)}{qr_n} \times e^{-(qs)^2/2}$$

q: transform momentum — r_n: effective nuclear radius

s: nuclear skin thickness — $j_1(x)$: Bessel function





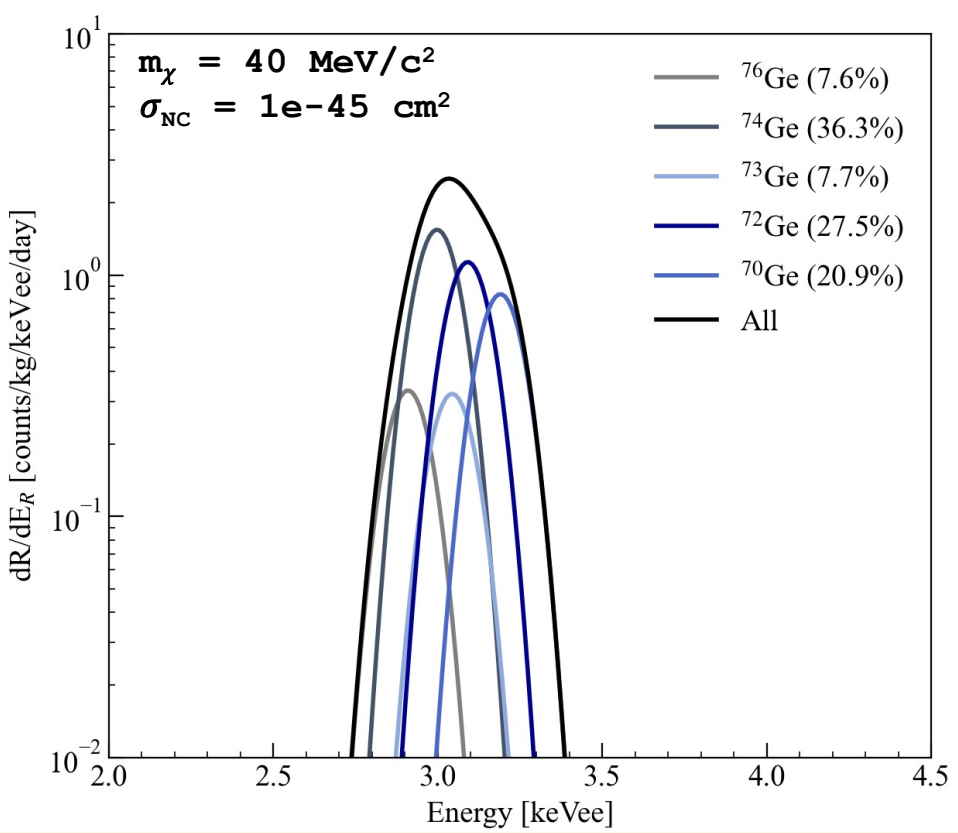
III. Fermionic DM neutral current absorption

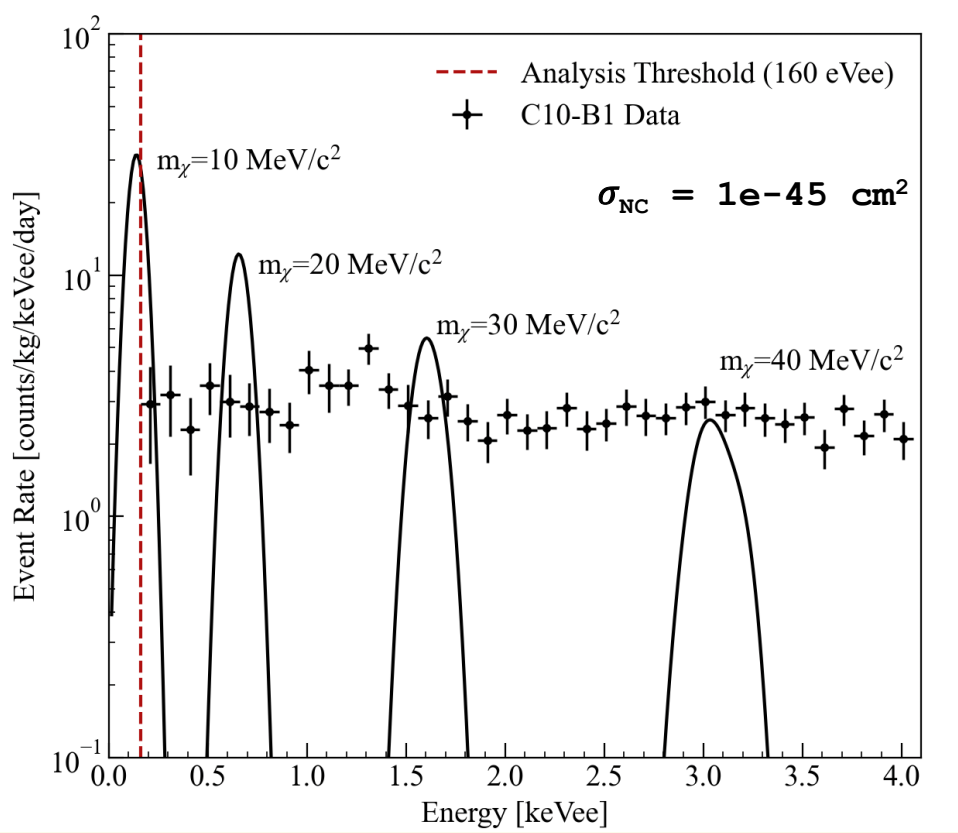
☐ Expect spectra (visible energy):

- ➢ Consider quenching and energy resolution in DM signal
- ➢ Quenching factor for Ge is compute via TIRM software

Calculation of Quenching factor for Ge follows our previous works:
Q. Yue et al. (CDEX Collaboration), Phys. Rev. D 90, 091701 (2014).
H. Jiang et al. (CDEX Collaboration) Phys. Rev. Lett. 120, 241301 (2018).

Reference for TRIM software:
J. F. Ziegler, NIM-Phys. Res. Sect. B. 1027, 219220 (2004).





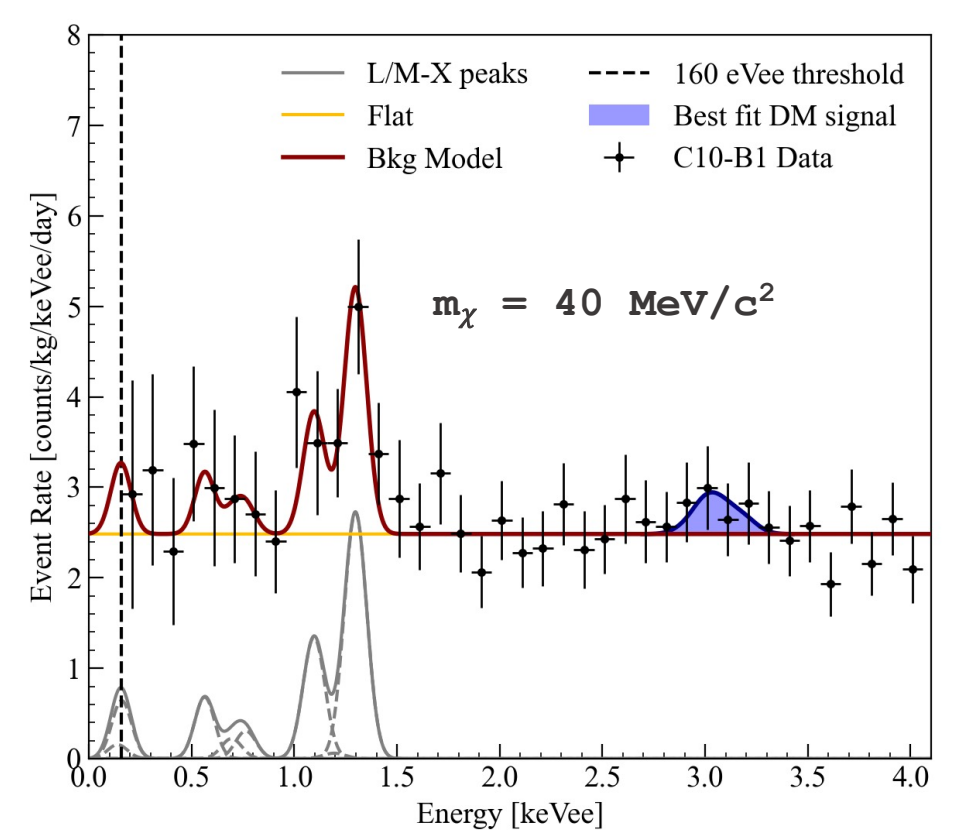
III. Fermionic DM neutral current absorption

☐ Search for DM signal in C10-B1 spectrum:

- ➢ No significant DM signal is found via minimum χ^2 method
- ➢ Upper limit on σ_{NC} set by the Feldman-Cousins method

$$\chi^2 = \sum_i \frac{\left[n_i - S_i(m_\chi, \sigma_{NC}) - B_i\right]^2}{\sigma_i^2}$$

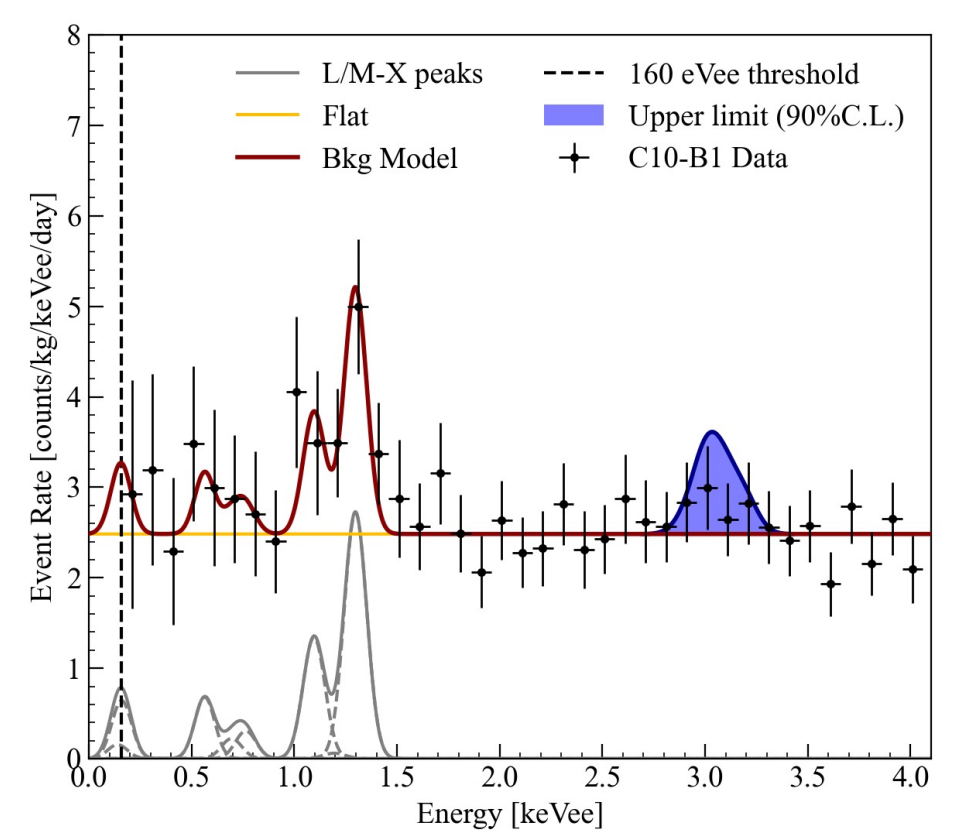
n_i: event rate in i-th bin
S_i: expected DM signal
B_i: background model
σ_i: uncertainty of event rate



Not significant

90% Upper limit using FC-method

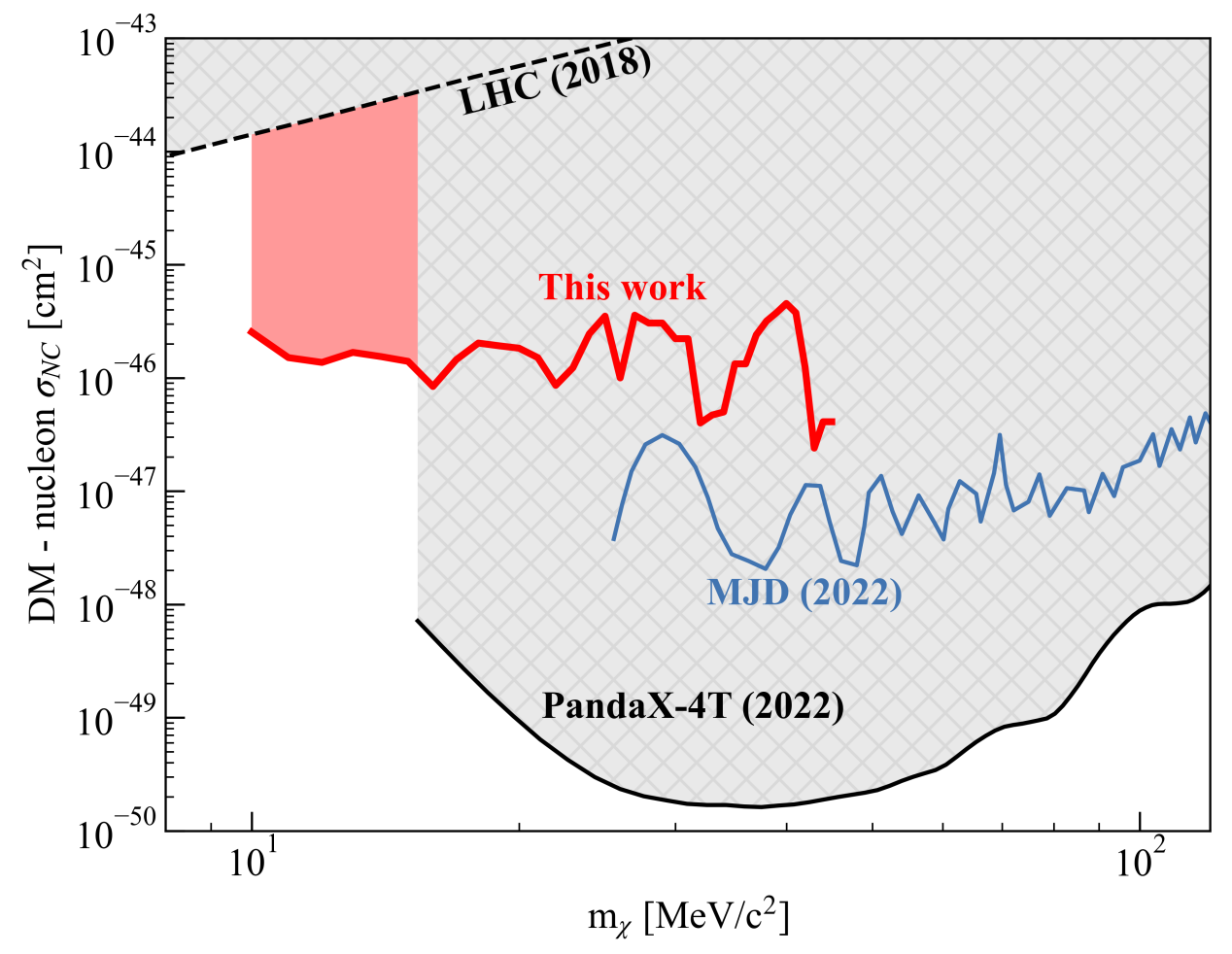
FC-method: G. J. Feldman and R. D. Cousins, Phys. Rev. D 57, 3873, (1998).



III. Fermionic DM neutral current absorption

☐ Upper limit of σ_{NC}:

- This work achieves lowest DM mass reach (~10 MeV/c^2) among direct detection experiments to date



This work:

- **C10-B1 PPCGe: 160 eVee threshold**
- **Lowest DM mass: ~ 10 MeV/c^2**

Other experiments:

- **MAJORANA DEMONSTRATOR (MJD): HPGe**
- **PandaX-4T: LXe-TPC**
- **LHC: Collider experiment**

MJD: I. J. Arnquist et al. (Majorana Collaboration), arXiv:2206 10638.
PandaX-4T: L. Gu et al. (PandaX Collaboration), Phys. Rev. Lett. 129, 161803 (2022).

IV. DM-nucleus 3-2 scattering

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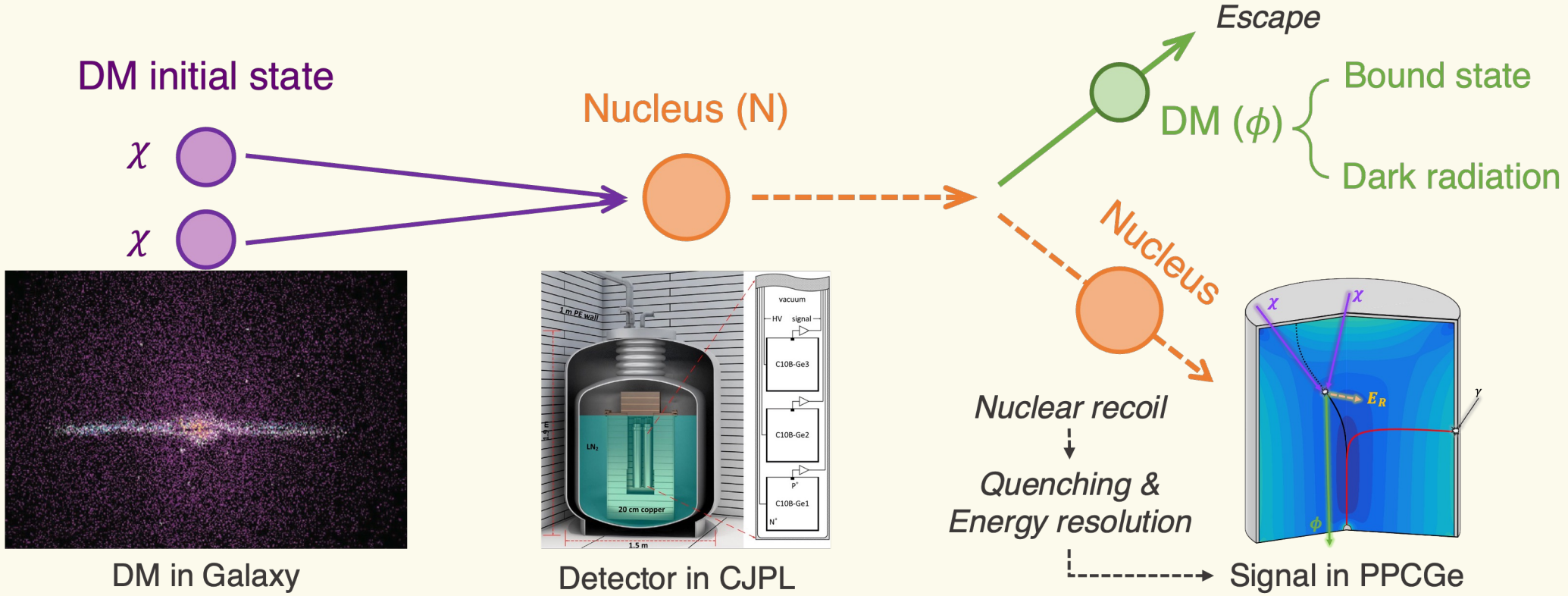
☐ Direct detection of DM-nucleus 3-2 scattering signal:

- Two DM particles (χ) interact with nucleus (N) and transform into a DM final state (ϕ)
- This inelastic scattering process of DM gives a monoenergetic nuclear recoil energy



Theory: W. Chao et al, arXiv:2109 14944.

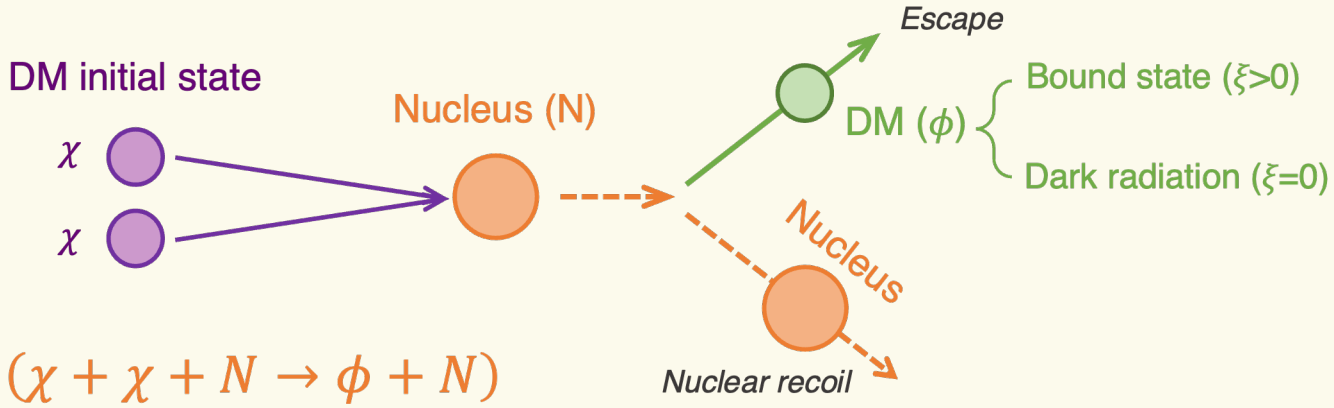
IV. DM-nucleus 3-2 scattering

☐ Total event rate:

$$R_{3\to2} = \frac{\rho_\chi}{m_\chi} \cdot n_\chi \langle \sigma_{3\to2} \cdot v_\chi^2 \rangle \frac{1}{M_T} \sum_j N_j M_j A_j^2 F_j^2$$

$$E_R \simeq \frac{(4-\xi^2) m_\chi^2}{2(M_j + m_\chi)}, \qquad \xi = \frac{m_\phi}{m_\chi}$$

- ϕ = Bound State ($\xi = 1.87$)
- ϕ = Dark photon ($\xi = 0$)



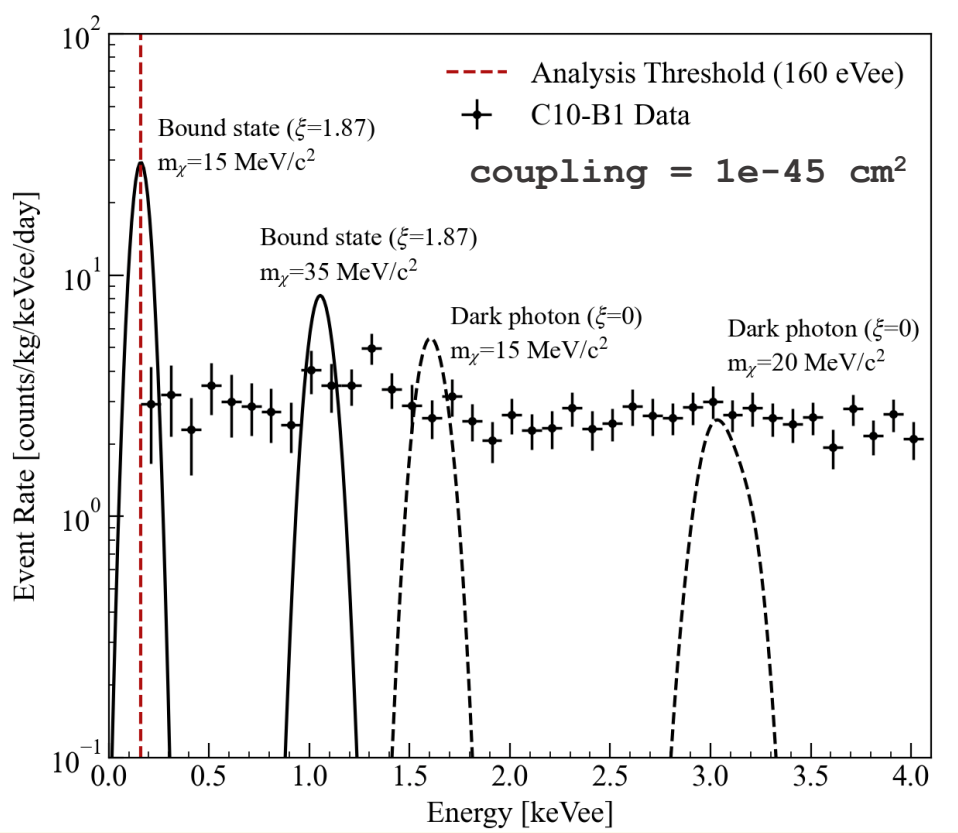
$n_\chi \langle \sigma_{3\to2} \cdot v_\chi^2 \rangle$:	DM-nucleus coupling, cm^2, $n_\chi = \frac{\rho_\chi}{m_\chi}$
m_χ:	DM mass
ρ_χ:	DM local density $\simeq$ 0.3 GeV/cm^3
A_j:	mass number of isotope j
$N_j \cdot M_j$:	mass of isotope j
E_R:	nuclear recoil energy
v_χ:	DM velocity in Lab
F_j:	Helm nuclear form factor
M_T:	Total target mass
$m_{\chi/\phi}$:	Mass of DM initial/final state

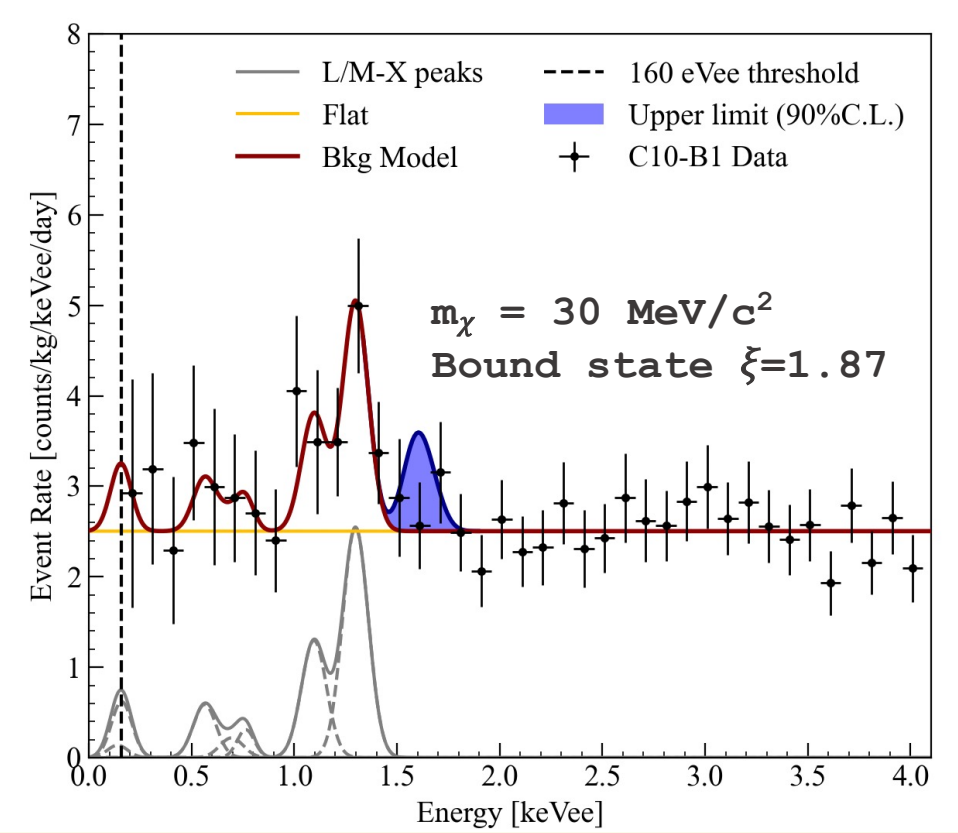
IV. DM-nucleus 3-2 scattering

☐ Expect spectra (visible energy):

- ➢ Set (ξ=1.87) for bound DM final state as recommended
- ➢ Set limit on coupling $n_\chi \langle \sigma_{3\to2} \cdot v_\chi^2 \rangle$

References for set ξ=1.87:
W. Chao et al., arXiv:2109.14944.
I. J. Arnquist et al. (Majorana Collaboration), arXiv:2206 10638.

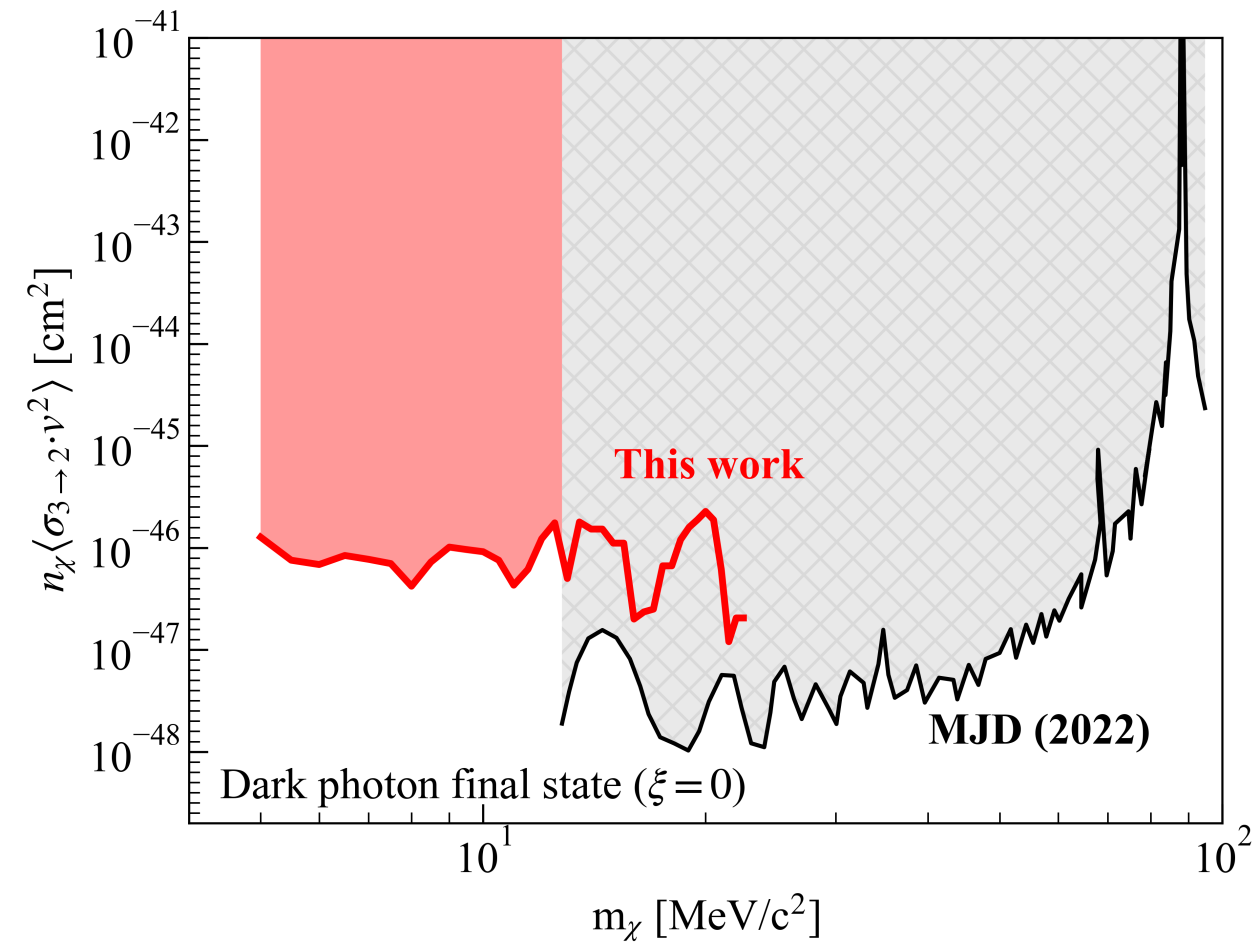


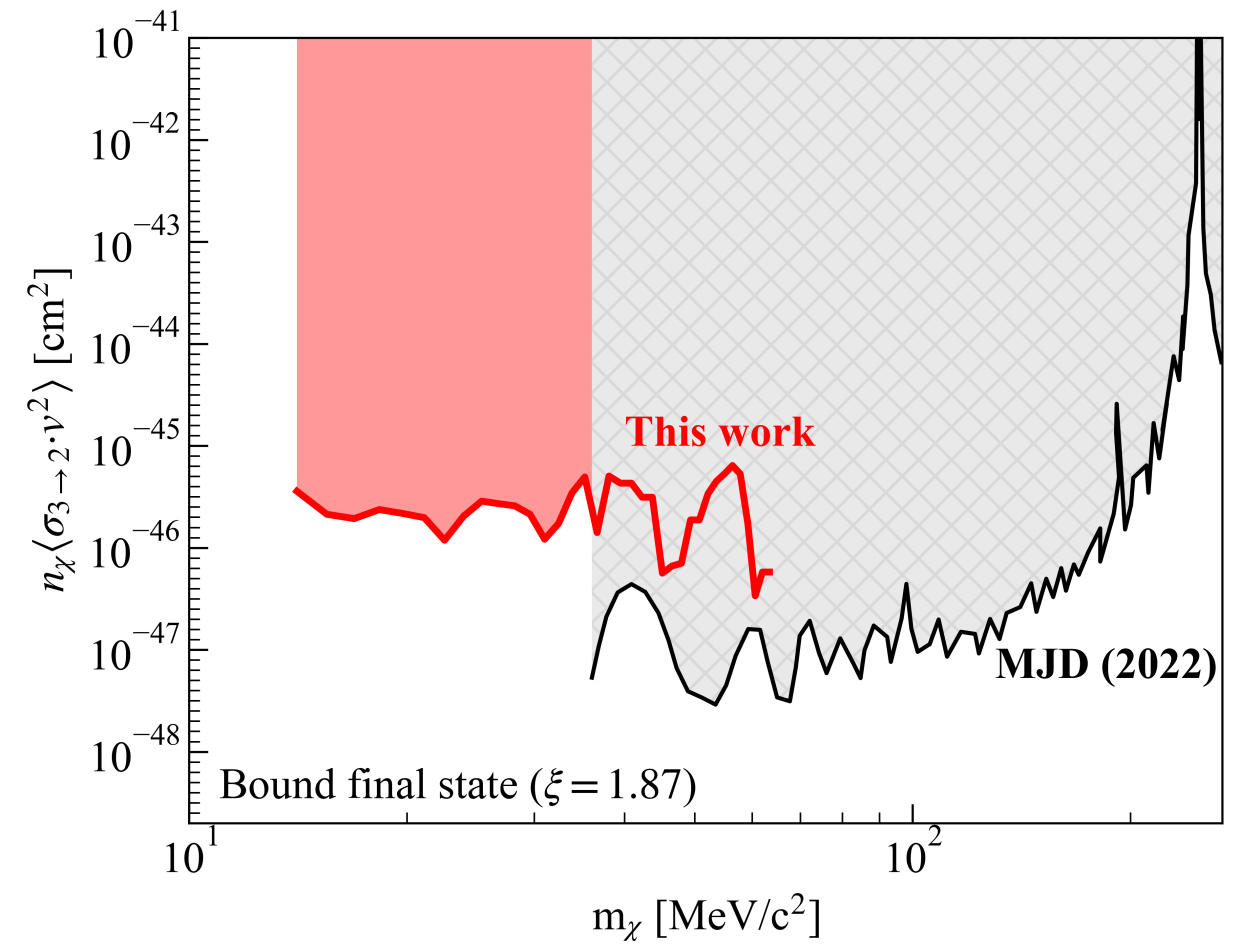


IV. DM-nucleus 3-2 scattering

☐ Upper limit of coupling $n_\chi\langle\sigma_{3\to2}\cdot v_\chi^2\rangle$:

- This work achieves lowest DM mass reach among searches in direct detection experiments to date





MJD: I. J. Arnquist et al. (Majorana Collaboration), arXiv:2206 10638.

V. Conclusion

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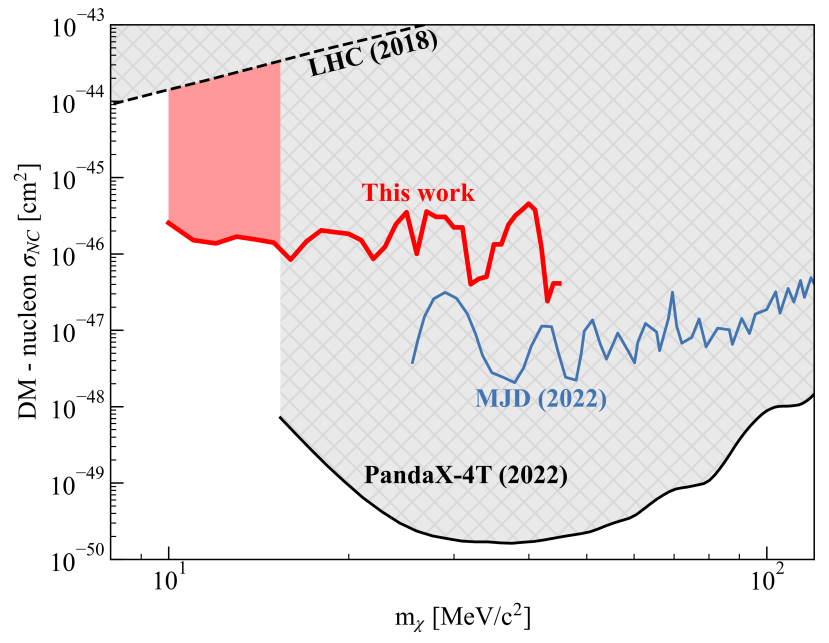
☐ Search for sub-GeV exotic DM with CDEX-10 experiment:

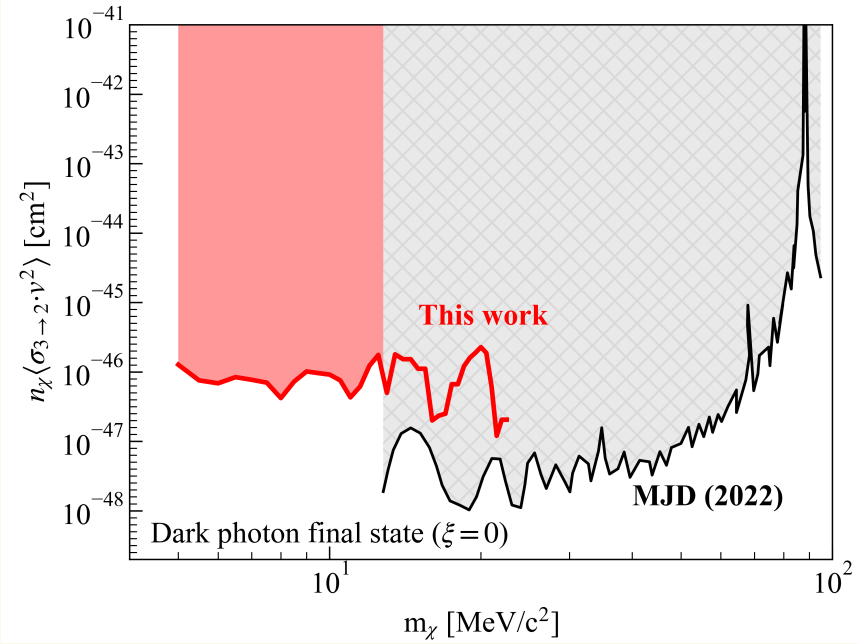
- ➢ C10-B1 PPCGe detector: 205.4 kg·day exposure @ 160 eVee analysis threshold
- ➢ Two physical channels: <Neutral current fermionic DM absorption> and <DM-nucleus 3-2 scattering>

Achieves lowest DM mass reach among searches in direct detection experiments to date

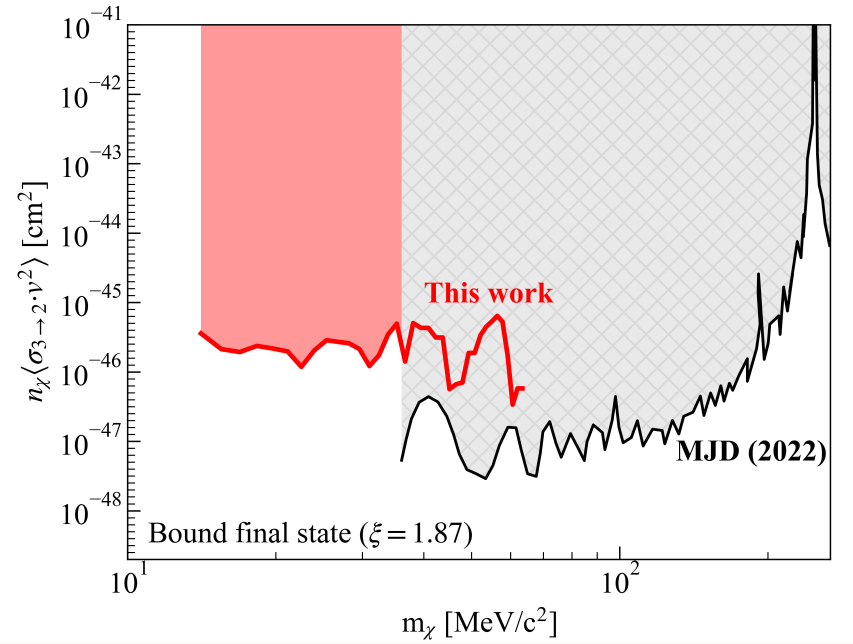
$\chi + N \rightarrow N + \nu$



$\chi + \chi + N \rightarrow N + \phi\ (\xi = 0)$



$\chi + \chi + N \rightarrow N + \phi\ (\xi = 1.87)$



W.H. Dai et al. (CDEX Collaboration), Phys. Rev. Lett. 129, 221802, 2022

Thanks