Fermionic Dark Matter Absorption on Nucleus/Electron Targets with PandaX-4T Commissioning Data

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On behalf of PandaX collaboration

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arXiv: 2205.15771, 2206.02339

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

Outline

- Fermionic dark matter (FDM) absorption model
- Searching for neutral current nuclear recoil (NR) FDM-absorption signal
- Searching for electronic recoil (ER) FDM-absorption signal
- Summary and outlook

Motivation for Absorption FDM Model

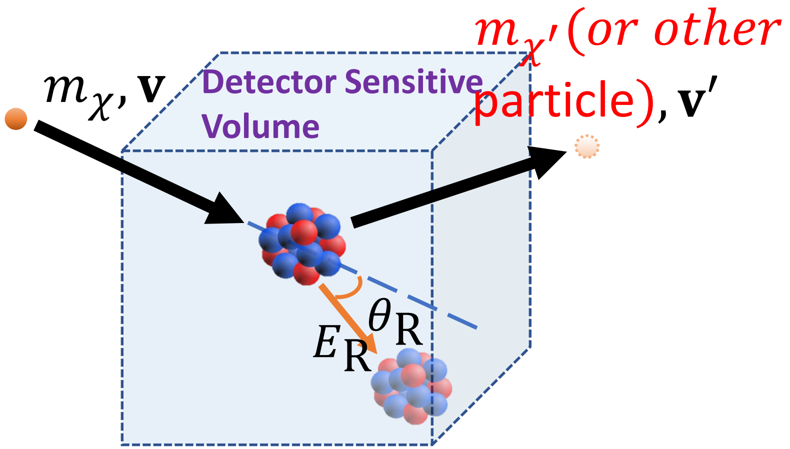
- Null results of WIMP search => lighter (< GeV) signal interests

DM detection (**signal**)

- **Scattering** —(nucleus, e^-)→ **Kinetic Energy (E_{kin})**
- **Absorption** → **Mass Energy (E_0)**, Mono-energetic

Interaction → **DM energy deposition**

Absorption:
- **Exothermic DM[2] (exoDM)**
- **Bosonic DM[1]**
- **Fermionic DM** — **This Topic**
- **Self-destructing DM[3] (SDDM)**



[1] *Y. Hochberg et al., PRD, 2017.*
[2] *P.W. Graham et al., PRD, 2010.*
[3] *Y. Grossman et al., JHEP, 2017.*

FDM: Fermionic Dark Matter

Introduction of Absorption FDM Model

Absorption FDM Model:

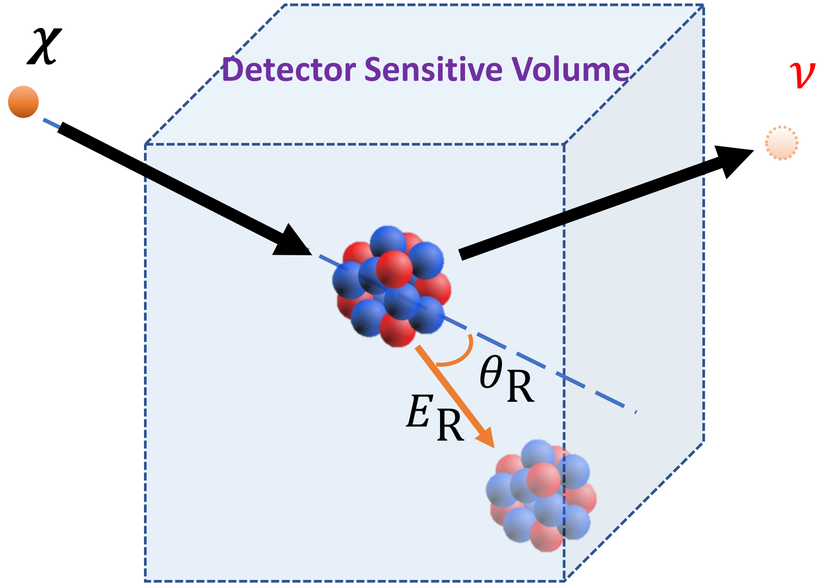
- Dark matter χ being absorbed, with an out-going neutrino ν
- Similar to WIMP scattering, detectable nuclear recoil (NR) and electronic recoil (ER) signals, respectively
- (Quasi-)Mono-energetic signal spectrum
- DM mass range
  - NR: sub-GeV
  - ER: sub-MeV

FDM: Fermionic Dark Matter

➢ NR-type:

$$\mathcal{O}_{\rm NC} = \frac{1}{\Lambda^2}\left(\bar{n}\gamma^\mu n + \bar{p}\gamma^\mu p\right)\bar{\chi}\gamma_\mu P_R \nu + {\rm h.c.}$$

$$\chi(\bar{\chi}) + {}^{A}Xe \rightarrow \nu(\bar{\nu}) + {}^{A}Xe$$

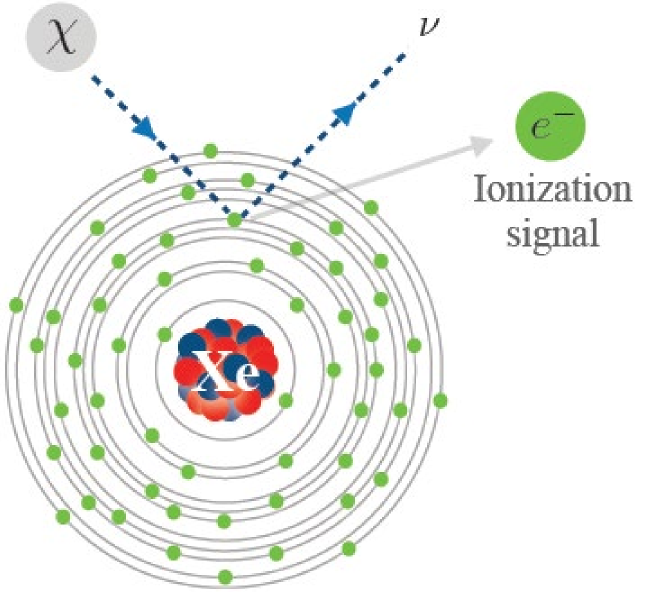


➢ ER-type:

$$\mathcal{O}^V_{e\nu\chi} = \frac{1}{\Lambda^2}(\bar{e}\gamma_\mu e)(\bar{\nu}_L\gamma^\mu\chi_L)$$

$$\mathcal{O}^A_{e\nu\chi} = \frac{1}{\Lambda^2}(\bar{e}\gamma_\mu\gamma_5 e)(\bar{\nu}_L\gamma^\mu\chi_L)$$

$$\chi(\bar{\chi}) + e^- \rightarrow \nu(\bar{\nu}) + e^-$$

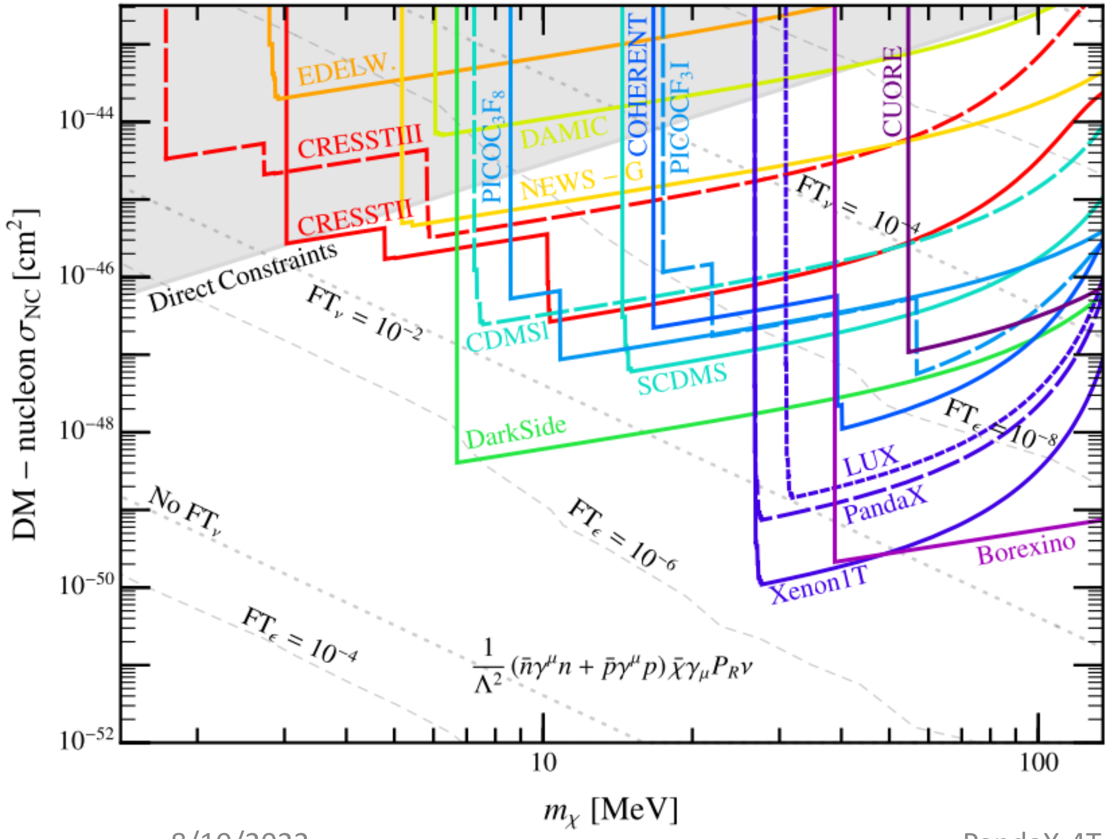


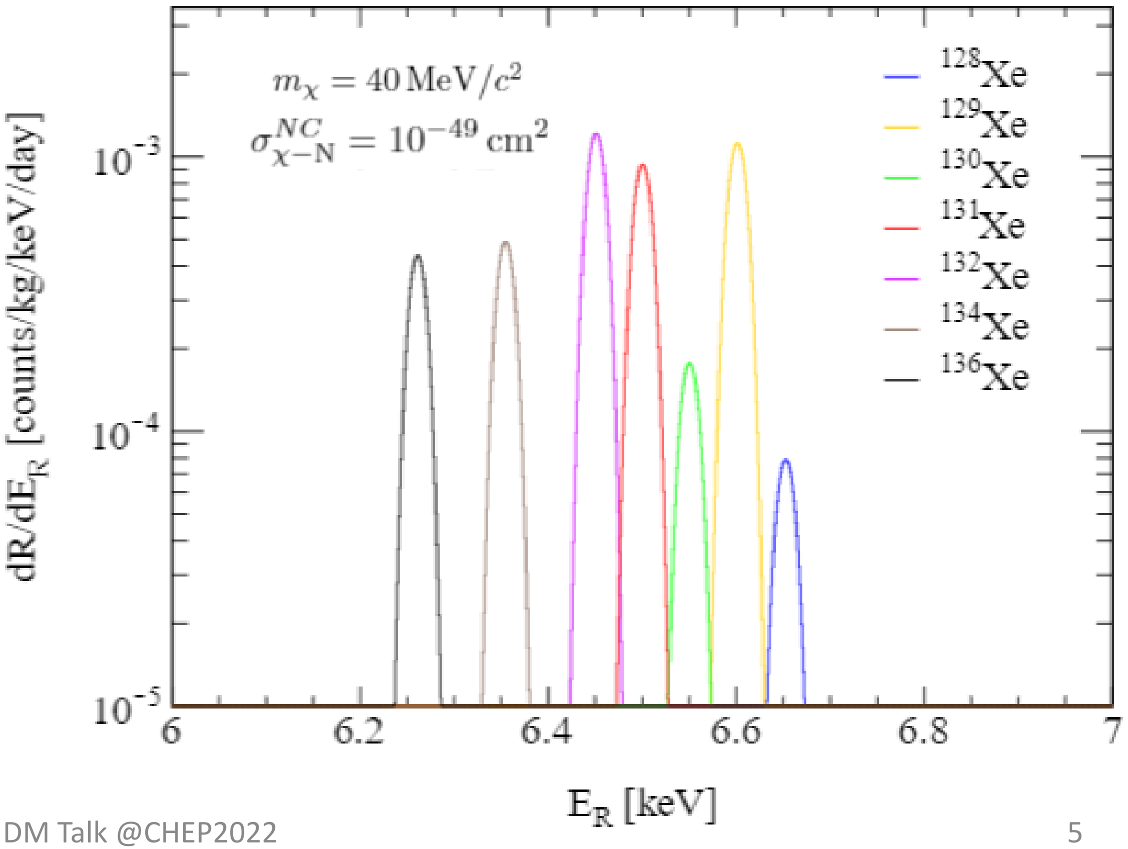
Nuclear Recoil (NR) Absorption Signal

- Mono-energetic: Isotope dependent energy spectrum
- Sensitivity: **energy threshold**, exposure

$$\frac{dR}{dE_R} = \frac{\rho_\chi \sigma_{\chi-N}^{NC}}{2m_\chi^3 M_T} \sum_j \frac{q_j}{p_{\nu,j}} N_j M_j A_j^2 F_j^2 \left\langle \frac{1}{v} \right\rangle_{v>v_{\min,j}}$$

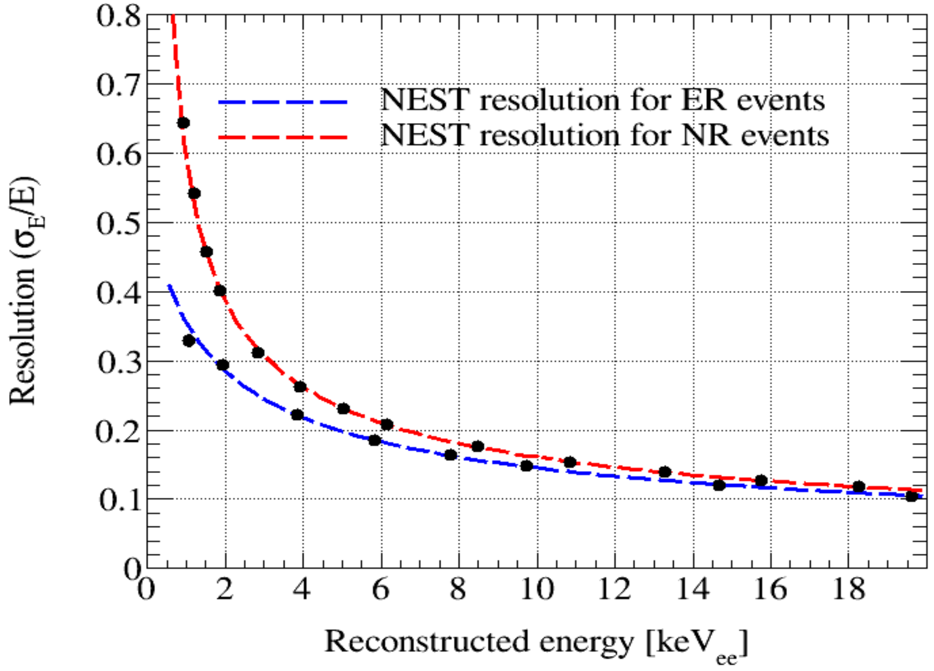
Jeff A. Dror et.al., PRL 124, 181301 (2020)
Jeff A. Dror et.al., JHEP 02 (2020) 134

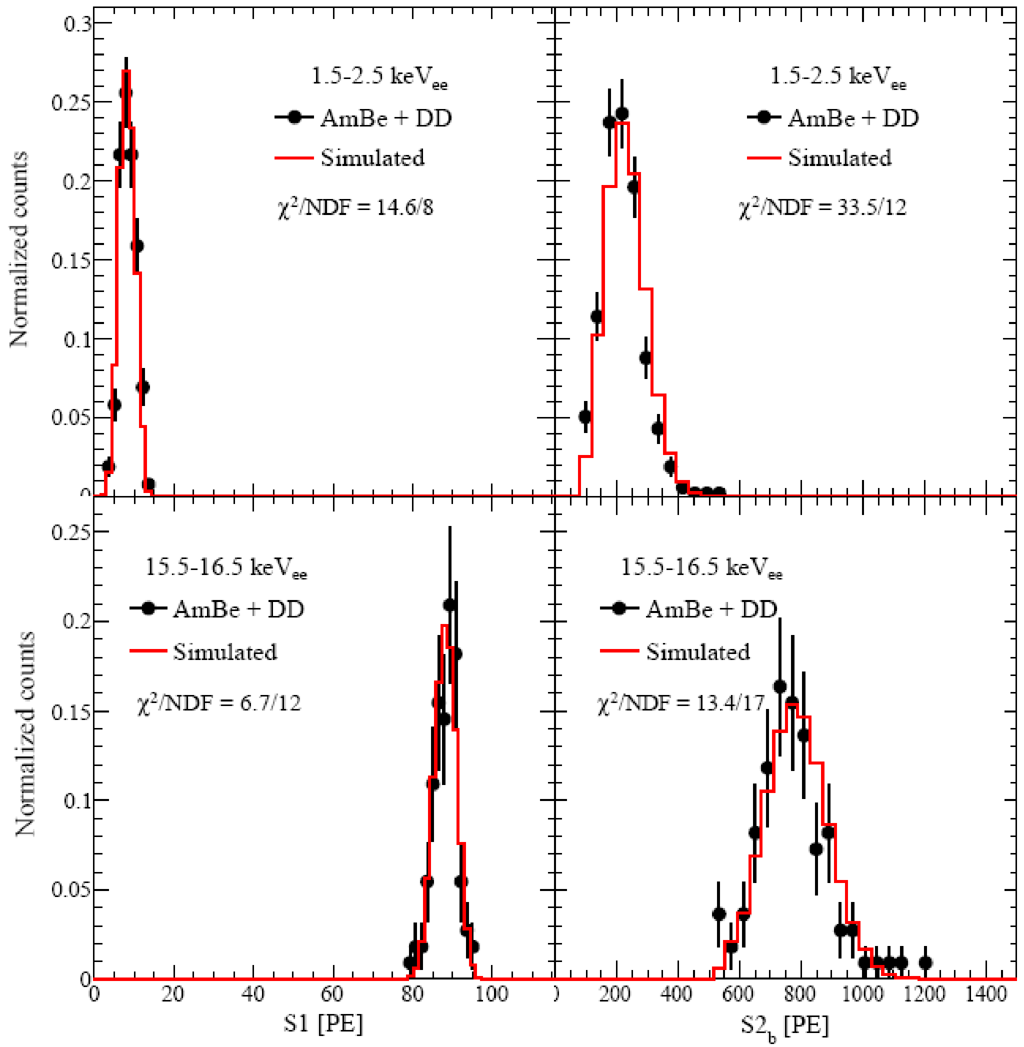




Energy resolution: Simulation vs. Data (NR)

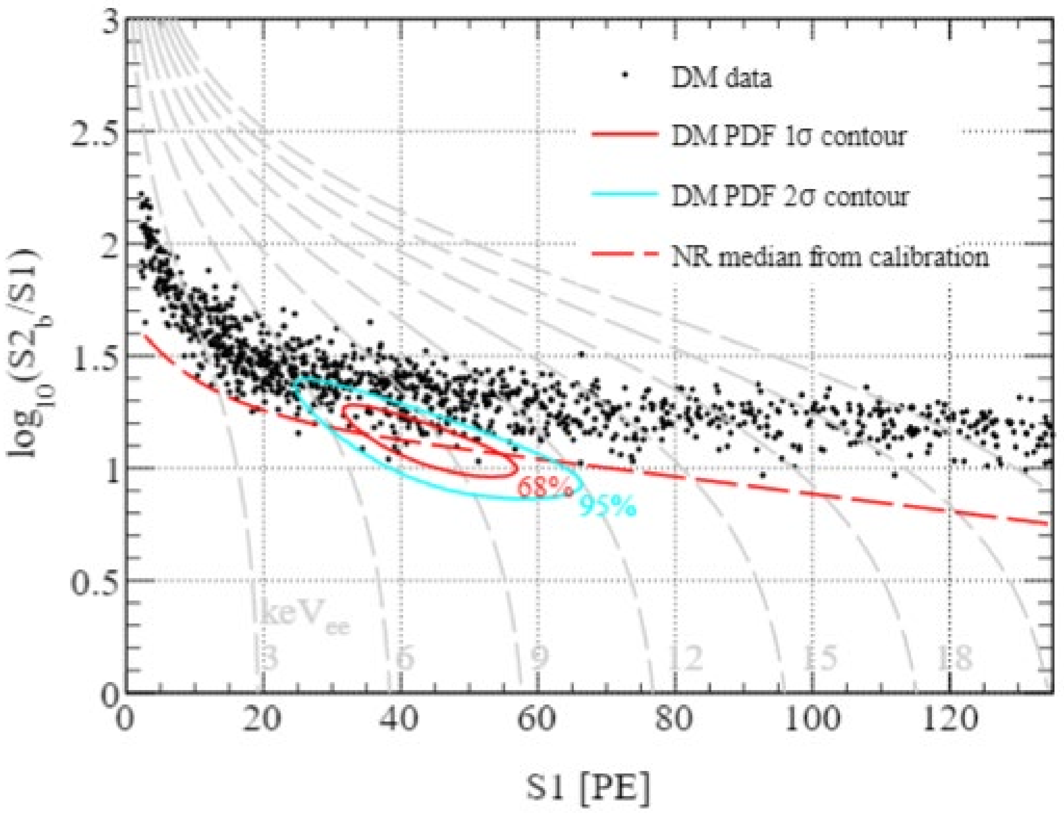
- Scanning 1-16 keVee ^{241}Am-Be + D-D calibration data, compared with NEST simulated distribution
- Reconstructed energy resolution within ROI given by the simulation can be well depicted by $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E}$
- The NR energy resolution @1 keVee(16 keVee) is 59%(13%).





Low Energy Candidate Events

- PandaX-4T 95-day commission run data
- Follows the WIMP search analysis
  - ROI:
    - S1 2-135 PE
    - Raw S2 80-20,000 PE
  - Backgrounds: tritium, flat ER (Rn, Kr, Material), surface, accidental, neutron, etc.
  - Total 1058 candidates



Profile Likelihood Ratio (PLR) Analysis

arXiv:2105.0059 (white paper)

- Unbinned likelihood with nuisance parameters with (S1, $S2_b$) observables
- $n_{set} = 5$

penalty term

$$\mathcal{L}_{\rm tot}(\mu) = [\prod_{n=1}^{n_{set}} \mathcal{L}_n] \times [\prod_{p_i} {\rm Gaus}(\delta_{p_*}, \sigma_{p_*})] \times [\prod_b {\rm Gaus}(\delta_b, \sigma_b)],$$

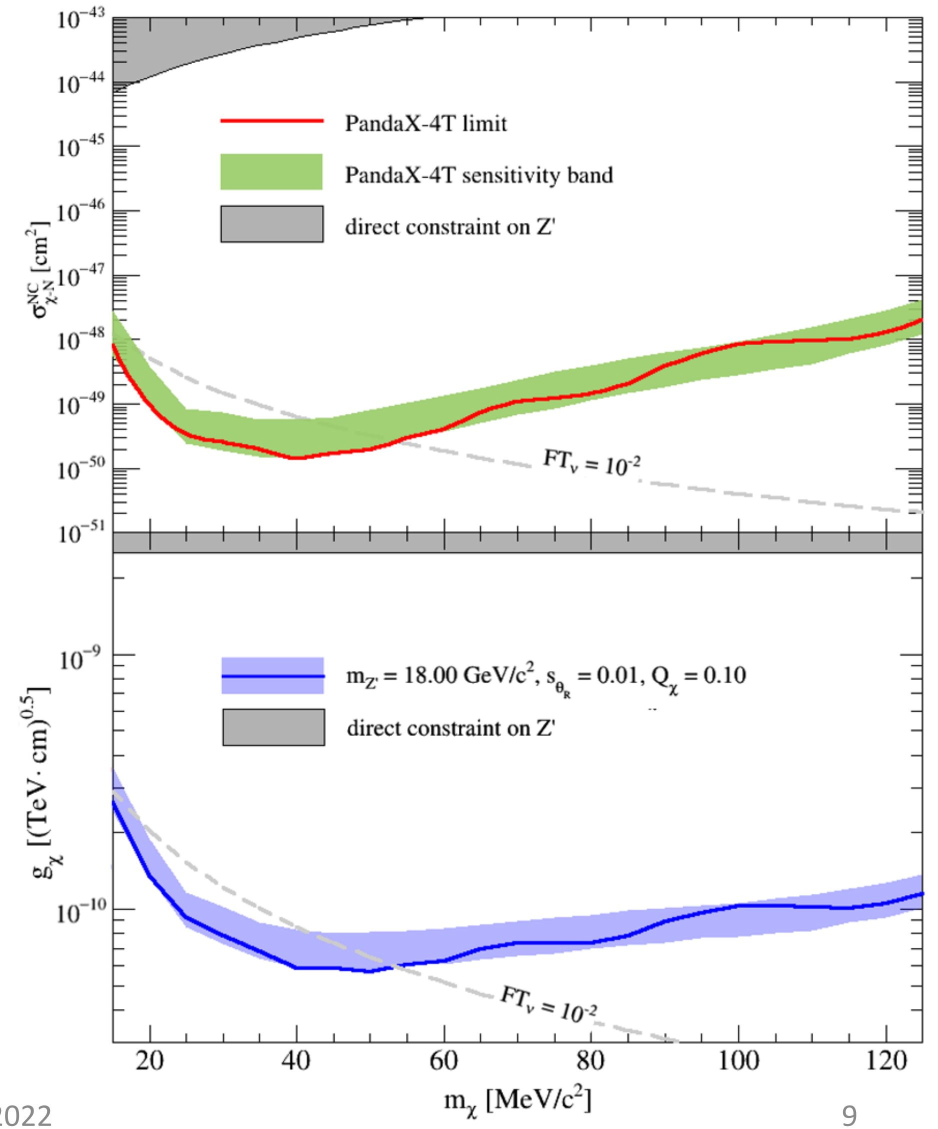
$$\mathcal{L}_n = {\rm Poiss}(N^n_{\rm meas}|N^n_{\rm fit}) \times [\prod_{i=1}^{N^n_{\rm meas}} (\frac{N^n_\mu \epsilon^n_\mu P^n_\mu(S1^i, S2^i_b|\{p_*\})}{N^n_{\rm fit}}$$

$$+\sum_b \frac{N^n_b \epsilon^n_b (1+\delta_b) P^n_b(S1^i, S2^i_b|\{p_*\})}{N^n_{\rm fit}})]$$

$$N^n_{\rm fit} = N^n_\mu \epsilon^n_\mu + \sum_b N^n_b \epsilon^n_b (1+\delta_b)$$

Exclusion Limits of Neutral Current FDM Absorption (NR)

- **No significant excess above 1σ**. 90% C.L. upper limit within the ±1σ sensitivity band (slight downward fluctuation in the DM mass range [40,55] MeV/c^2, power-constrained to −1σ)
- The strongest limit achieved is **1.7×10^{-50} cm^2** at a fermionic dark matter mass of **35 MeV/c^2**
- Constraints on the coupling g_χ to the order of $\mathbf{10^{-10}(TeV\cdot cm)^{0.5}}$



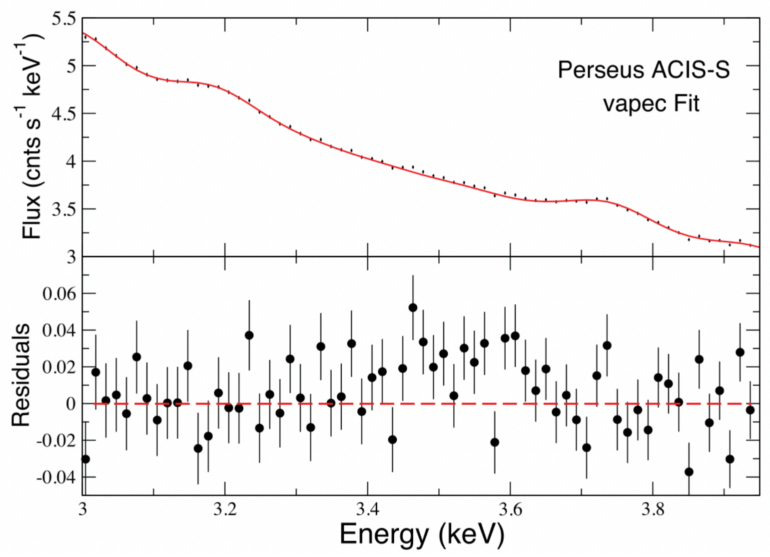
Motivation for ER Absorption FDM Model

- Controversial 3.55 keV excess from Astro. X-ray observations

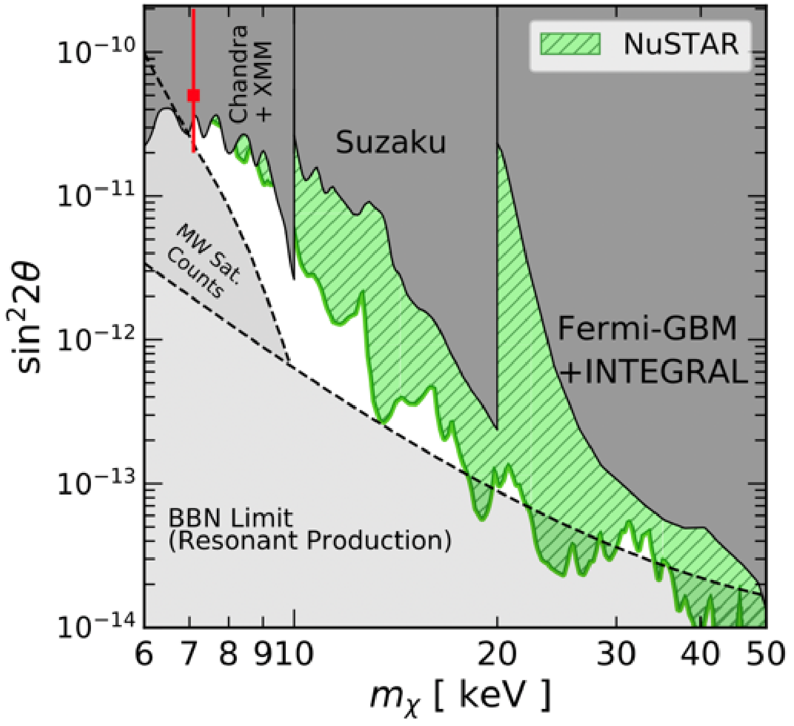
Allowed decay channel: $\chi \rightarrow \nu\gamma$

- ☑ Observed in Perseus cluster and stacked X-ray spectra
- ☐ Not following the DM profile for Perseus cluster and the Galactic center
- ☐ Not in another stacked X-ray spectrum which expected to have lower backgrounds

XMM-Newton and Chandra (Esra Bulbul et. al. 2014 ApJ 789 13)



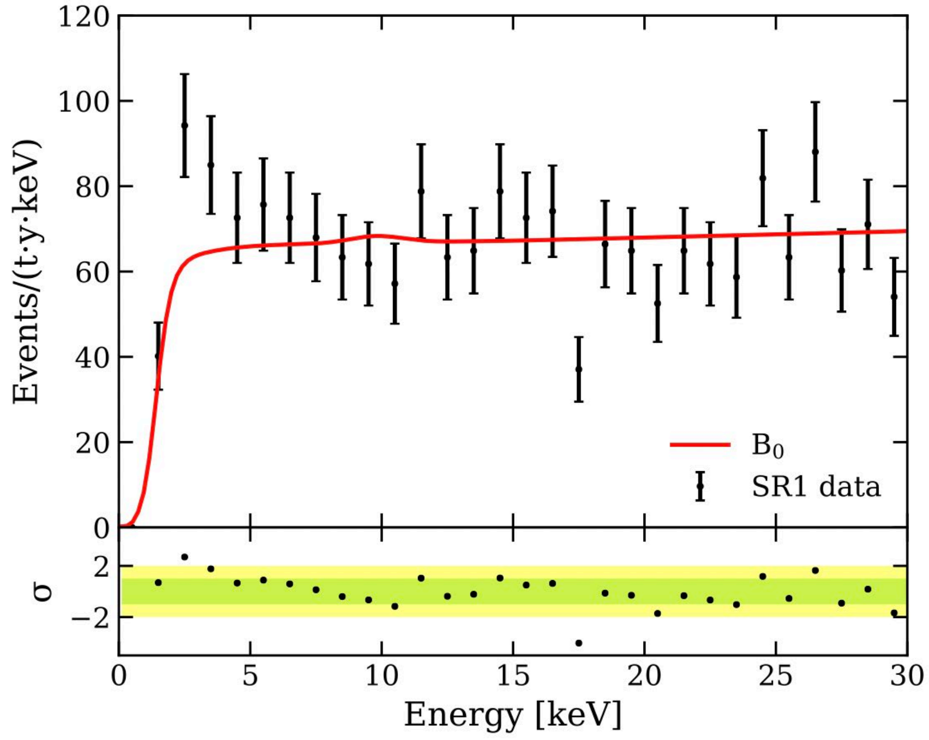
NuSTAR, PhysRevD.101.103011 (2020)



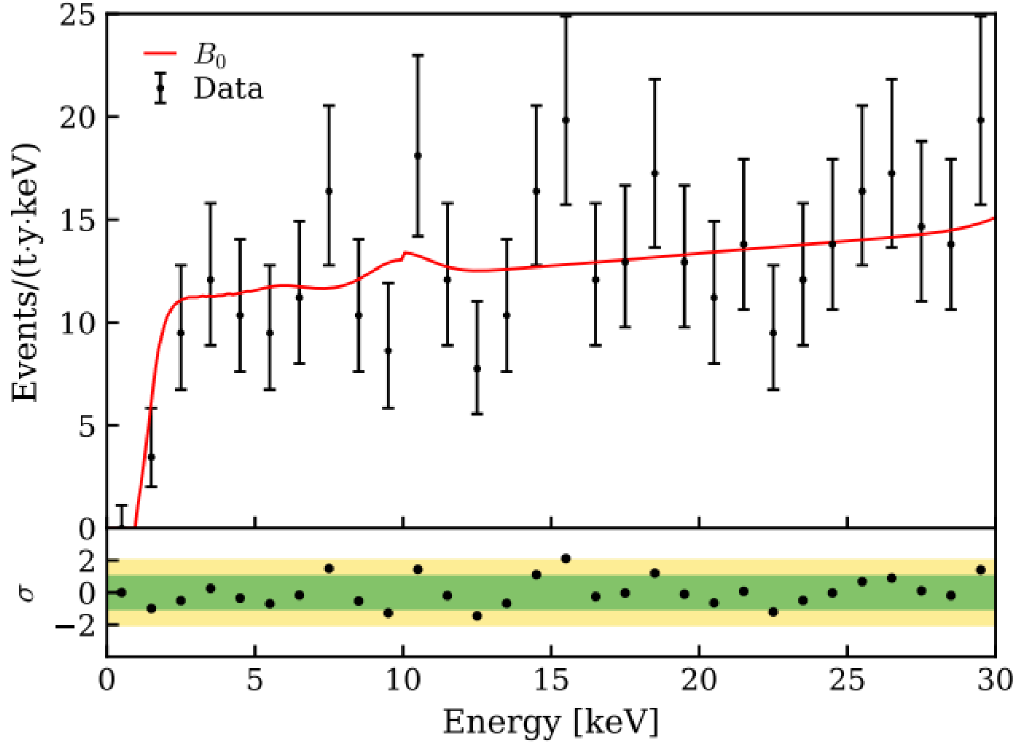
Motivation for ER Absorption FDM Model

- XENON1T ER excess at low energy

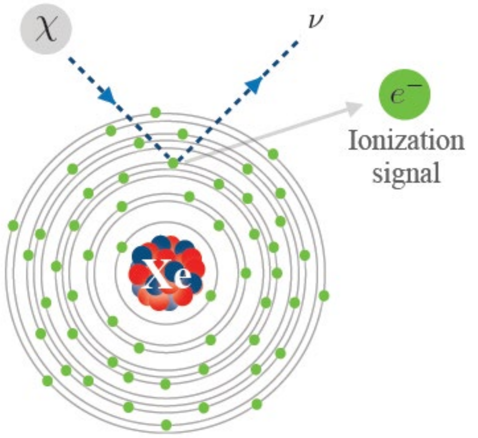
XENON1T, PhysRevD.102.072004 (2020)



XENONnT, arXiv: 2207.11330



Electronic Recoil (ER) Absorption Model

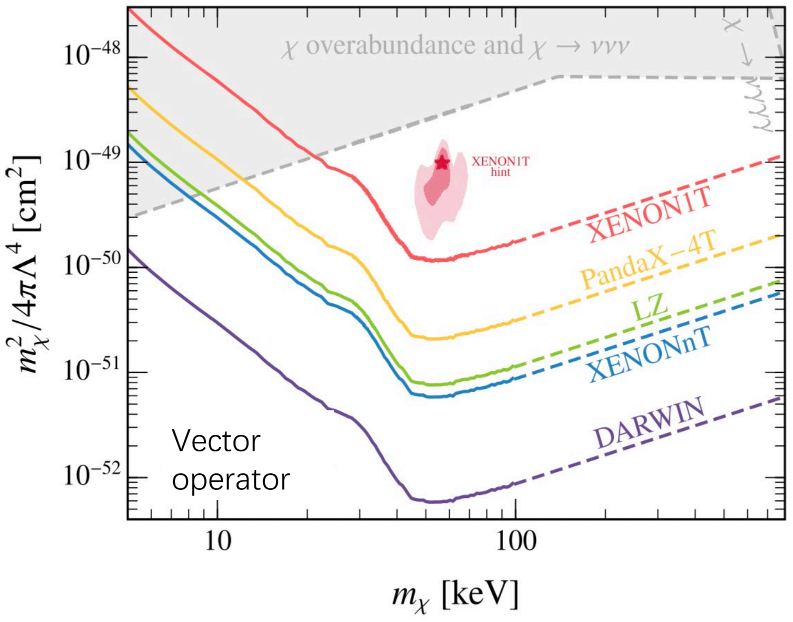


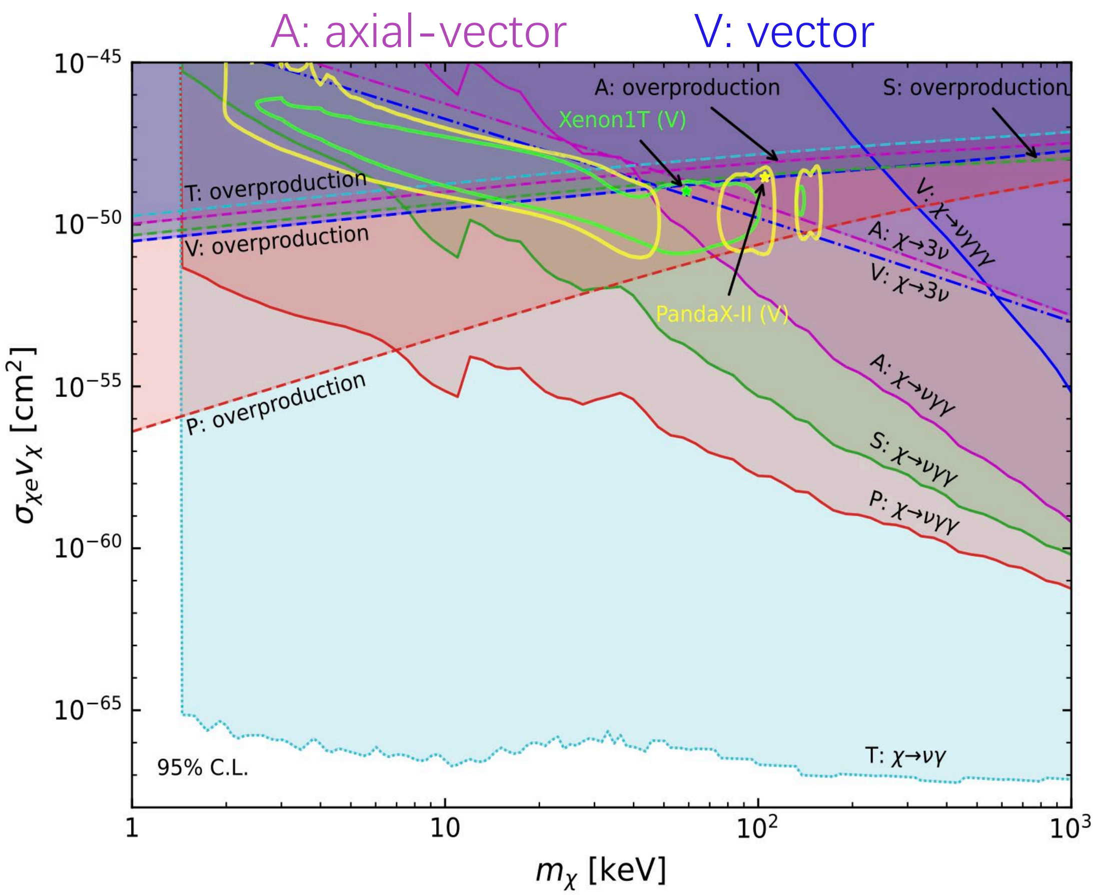
$$\mathcal{O}^V_{e\nu\chi} = \frac{1}{\Lambda^2}(\bar{e}\gamma_\mu e)(\bar{\nu}_L\gamma^\mu\chi_L)$$

$$\mathcal{O}^A_{e\nu\chi} = \frac{1}{\Lambda^2}(\bar{e}\gamma_\mu\gamma_5 e)(\bar{\nu}_L\gamma^\mu\chi_L)$$

$$\chi(\bar{\chi}) + e^- \rightarrow \nu(\bar{\nu}) + e^-$$

Jeff A. Dror et.al., PRD.103.035001 (2020)





SF Ge et.al. arXiv: 2201.11497 (accepted by JHEP)

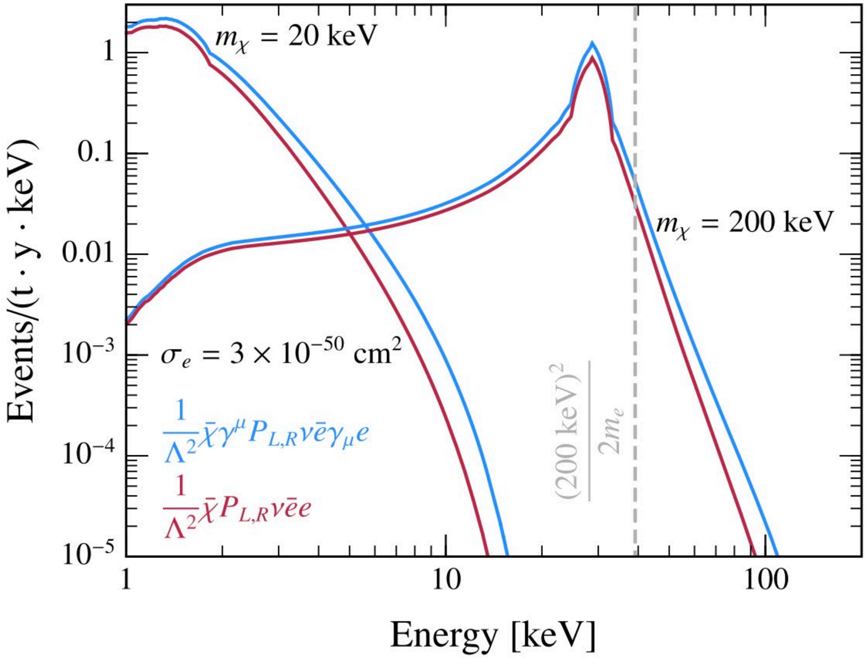
ER Absorption Signal Spectrum

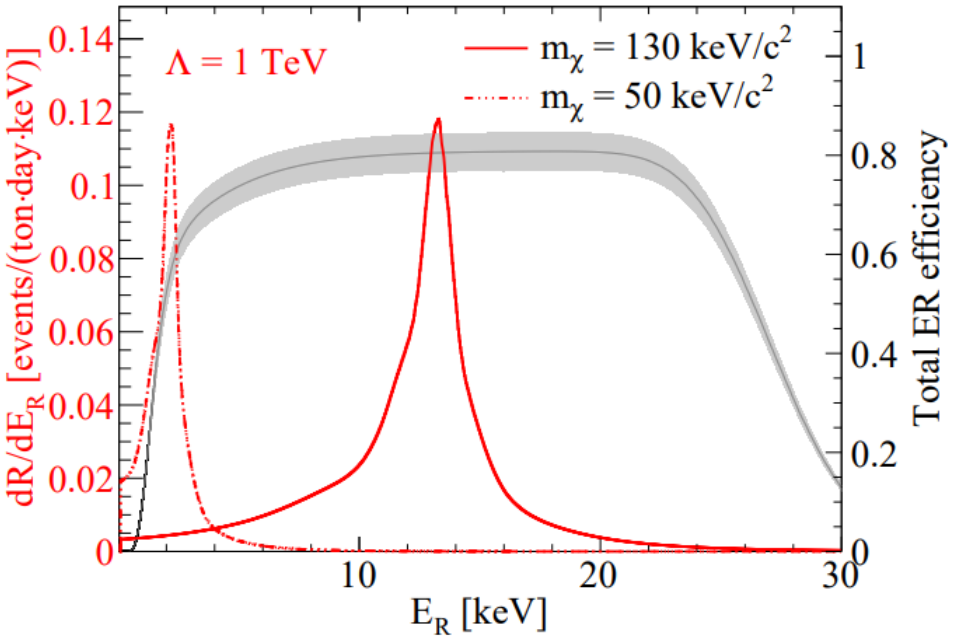
Absorption of FDM: characteristic mono-energetic signal ($E_R = m_\chi^2/2m_T$, T=e$^-$)

- Quasi-mono-energetic structure
- Intrinsic smearing with atomic effect: $m_\chi = E_\nu + |E_B^{nl}| + E_R$

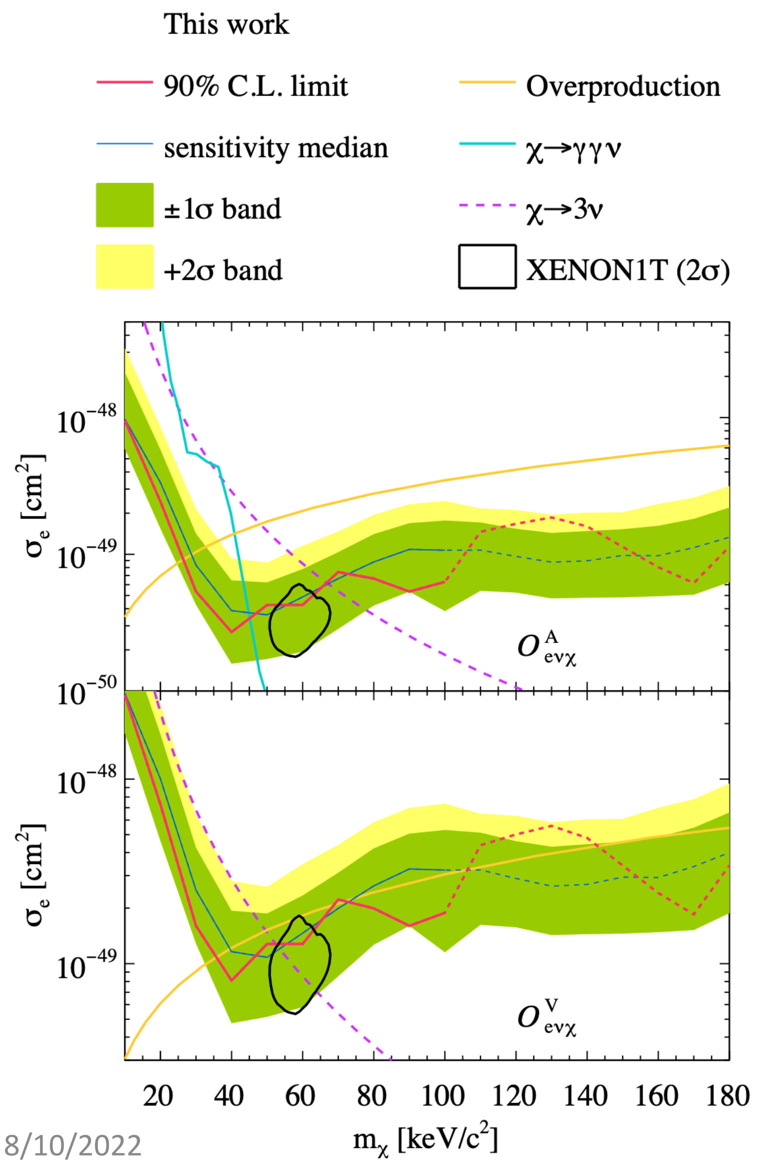
$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \sum_{nl} (4l+2) \frac{|\mathbf{q}|}{16\pi m_e^2 m_\chi E_R} |M(|\mathbf{q}|)|^2 K_{nl}(E_R, |\mathbf{q}|)$$

Jeff A. Dror et.al., PRD.103.035001 (2020)





Exclusion Limits of FDM Absorption on Electron



$\sigma^A_{e\chi\nu} \approx 3\sigma^V_{e\chi\nu}$ w.r.t. the same Λ

- A general fermionic (sterile neutrino-like) dark matter absorption on electron.
- In soft tension with XENON1T's ER excess, consistent with XENONnT latest result.
- Strong sensitivity to vector and axial-vector mediators, complementary to astrophysical constraints, but much less theoretical uncertainties.
- Competitive constraint in 20-55 keV/c^2 .

Summary and Outlook

- Explored fermionic DM absorption signals in the PandaX-4T 0.63 tonne-year exposure data.
- First search for a mono-energetic NR signature in DM direct detection.
- No significant excess is observed for both absorption mechanisms (<1σ(NR) and <1.7σ(ER)).
- Competitive constraints on the interaction key parameters, compared to the astronomical and cosmological observations.
- Consistent with the latest global experimental results.
- Continue taking physics data. Stay tuned!

Thank you for listening!

Backups

NR Absorption: Neutral Current Model

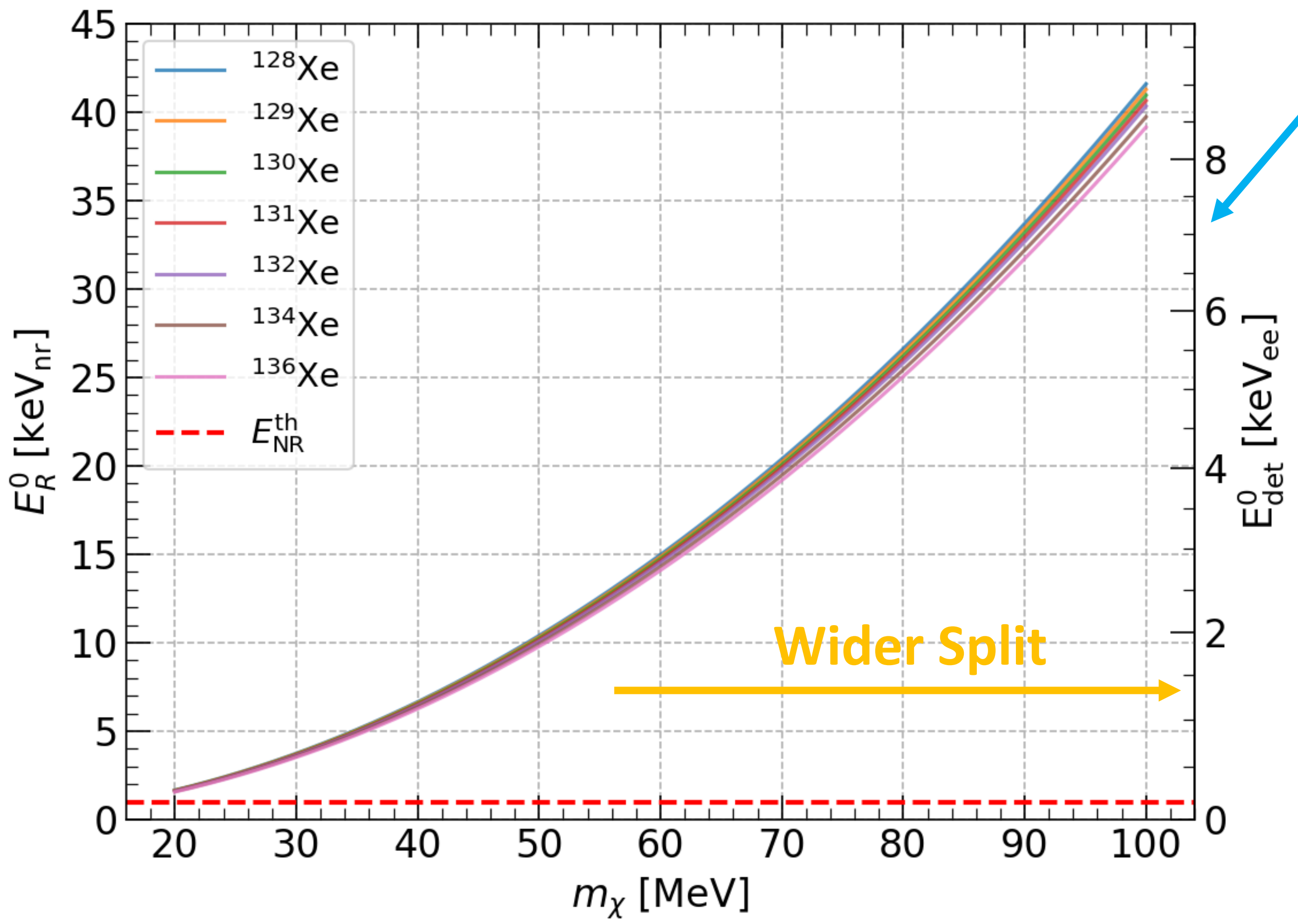
- Suppose that DM mixes with the SM neutrinos through a Yukawa interaction of a scalar ϕ
- Consider a model with lepton number charged DM and approximately massless Dirac neutrinos such that the U(1)' invariant mass term is given by:

$$\mathcal{L}_{\text{mass}} \supset m_\chi \bar{\chi}\chi + (y\phi\bar{\chi}P_R\nu + \text{h.c.}) = (\bar{\nu}\ \bar{\chi}) \begin{pmatrix} 0 & 0 \\ y\langle\phi\rangle & m_\chi \end{pmatrix} P_R \begin{pmatrix} \nu \\ \chi \end{pmatrix} + \text{h.c.} + \ldots$$

- After diagonalization, there is one massless state (identified with the SM neutrino) and one massive state with mass $\sqrt{m_\chi^2 + y^2\langle\phi\rangle^2}$. Furthermore, a mixing is induced with a mixing angle, θ_R given by: $s\theta_R = \frac{y\langle\phi\rangle}{\sqrt{m_\chi^2+y^2\langle\phi\rangle^2}}$
- Effective operator at the nucleon scale is

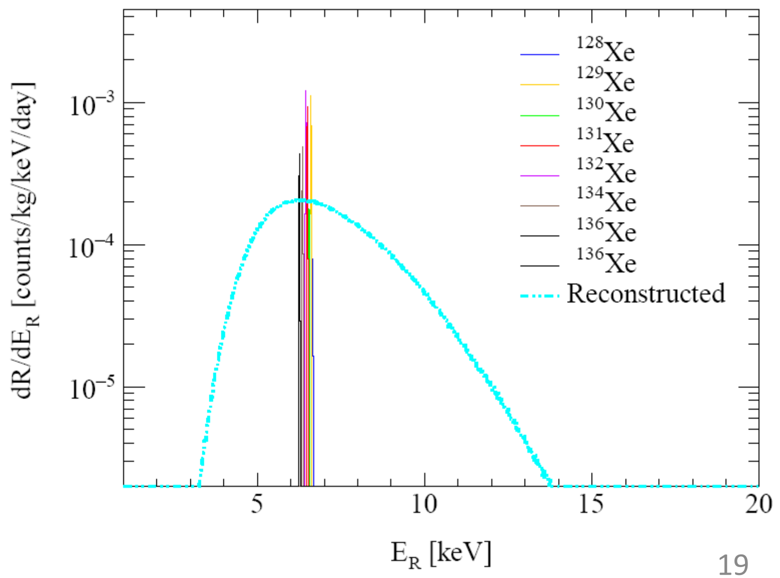
$$\mathcal{L} \supset \frac{Q_\chi g_\chi^2 s\theta_R \boldsymbol{c}\theta_R}{m_{z'}^2}(\bar{n}\gamma_\mu n + \bar{\boldsymbol{p}}\gamma_\mu \boldsymbol{p})\bar{\chi}\gamma_\mu P_R \nu + \boldsymbol{h.c.}$$

Xe Target Absorption Peak vs. m_χ at $\mathcal{O}(v^0)$



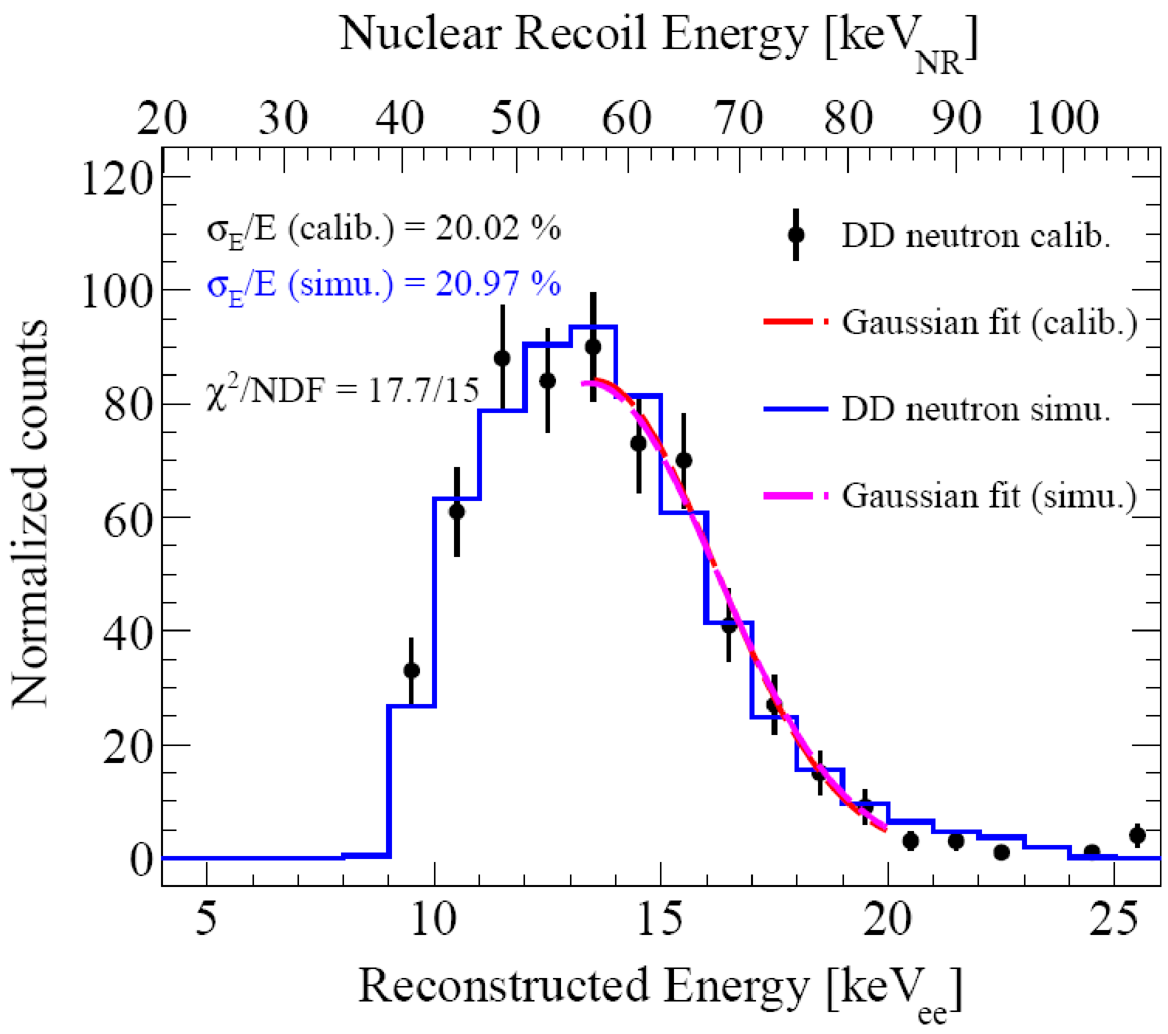
Non-linear Lindhard factor applied

Isotope	Mass	Abundance	Spin
^{128}Xe	127.903531	1.91%	0
^{129}Xe	128.904780	26.4%	1/2
^{130}Xe	129.903509	4.1%	0
^{131}Xe	130.905072	21.2%	3/2
^{132}Xe	131.904144	26.9%	0
^{134}Xe	133.905395	10.4%	0
^{136}Xe	135.907214	8.9%	0



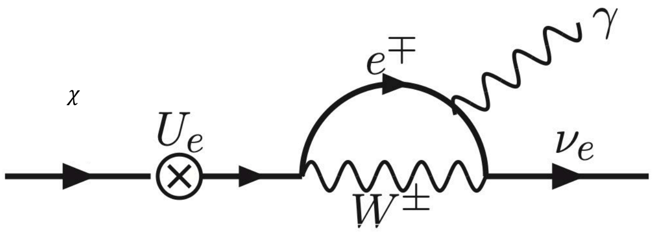
Energy resolution: Simulation vs. Data (NR)

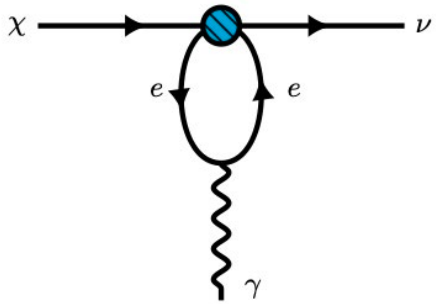
- Fit 2.2MeV D-D back-scatter peak, right half peak by gaussian
- Resolution Consistency validation between simulation and data
- **Uncertainty** determination of energy resolution



Generalization of $\chi e \to e\nu$

A new four-fermion interaction among χ (Dirac particle assumed), ν and e treated with the effective field theory





Dimension-six operators (neutral)

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

Leading decay channel(s)

- Charge conjugation
- Gauge symmetry in renormalization

Operator \ Process	$\chi \to \nu\gamma$	$\chi \to \nu\gamma\gamma$	$\chi \to \nu\gamma\gamma\gamma$
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: $\mathcal{O}^T_{e\nu\chi}$	✓	×	×!

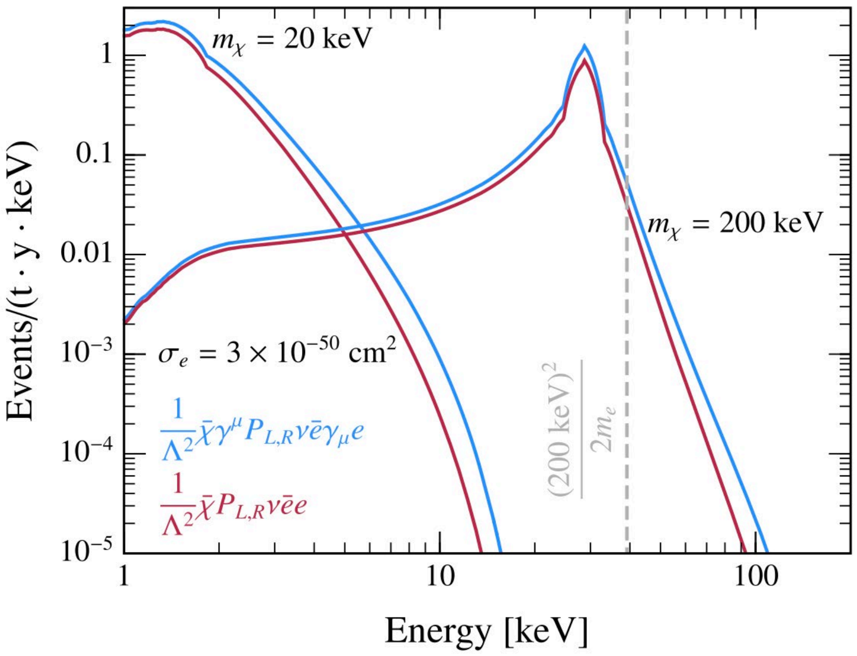
Ref: PhysRevD.103.035001 (2021) and arXiv:2201.11497 (accepted to JHEP)

ER Absorption Signal

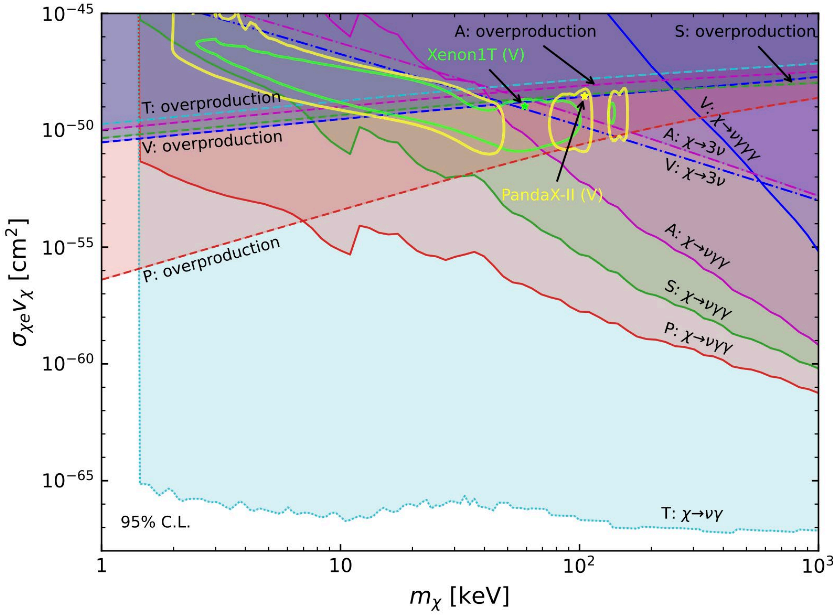
- Absorption signal of a sub-MeV fermionic dark matter on electron targets
  - Energy conservation + atomic effects: $m_\chi = E_\nu + |E_B^{nl}| + E_R$
  - Vector operator: $\mathcal{O}^V_{e\nu\chi} = \frac{1}{\Lambda^2}(\bar{e}\gamma_\mu e)(\bar{\nu}_L\gamma^\mu\chi_L)$
  - Λ [mass] reflects the mediator mass level scaled with a dimensionless coupling constant

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

Jeff A. Dror et.al., PhysRevD.103.035001 (2020)



A: axial-vector V: vector



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Best fit with (S1, $S2_b$) projected onto E_R

- Represent global best fit ($m_\chi = 130\text{keV}/c^2$,$\Lambda = 1.1\text{TeV}$). 1.7σ excess is reduced to 0.6σ with the look elsewhere effect
- $\pm 1\sigma$ uncertainty band (dashed lines) includes detector parameters
- $\chi^2 = 27.7$ counts the statistical fluctuation in each bin