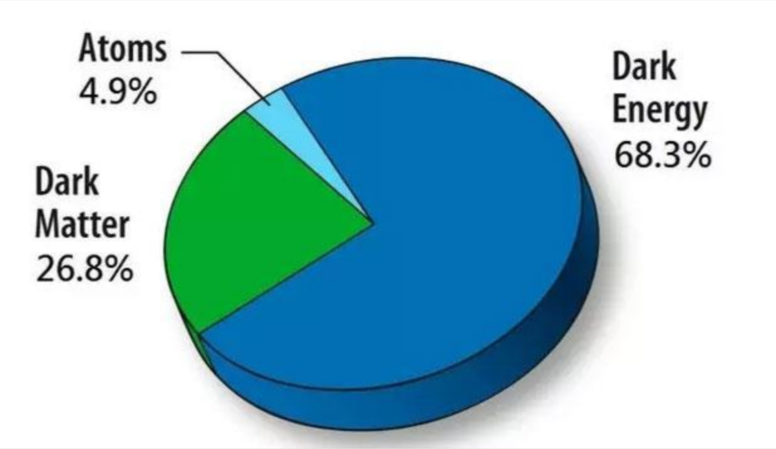
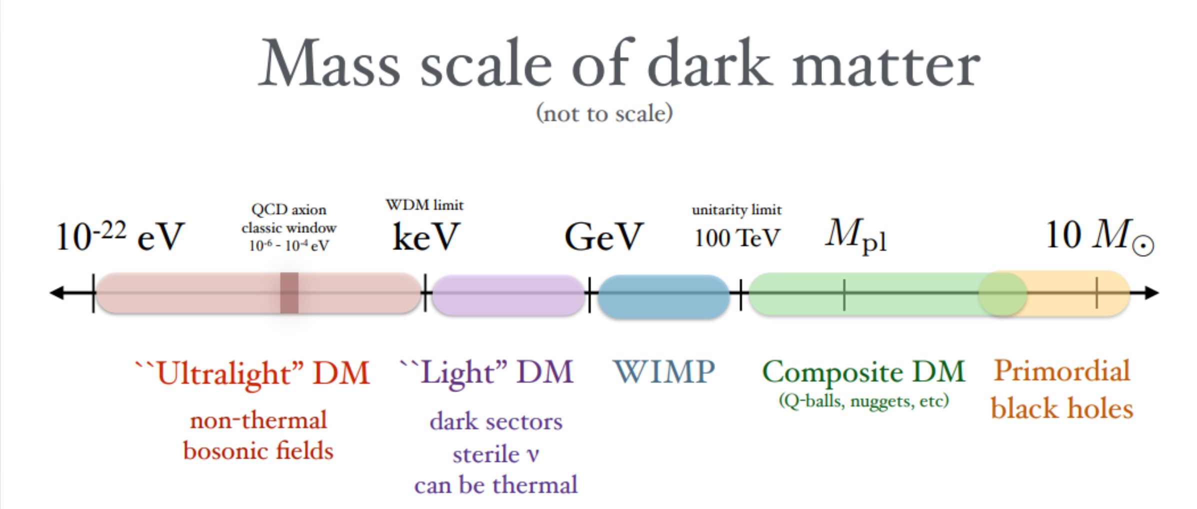
Recent results from PandaX-4T experiment

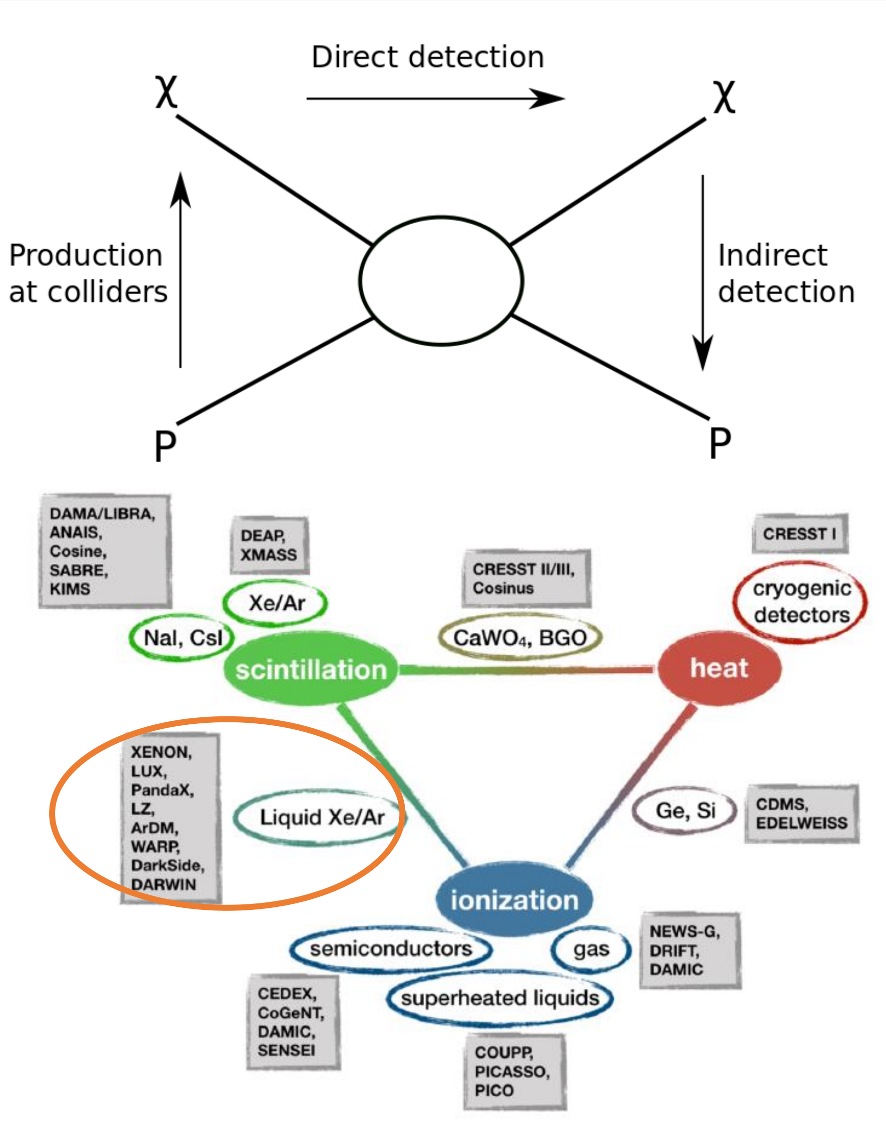
Xuyang Ning（宁旭阳）
Shanghai Jiao Tong University
On behalf of the PandaX Collaboration

Dark Matter direct detection





From arXiv:1904.07915

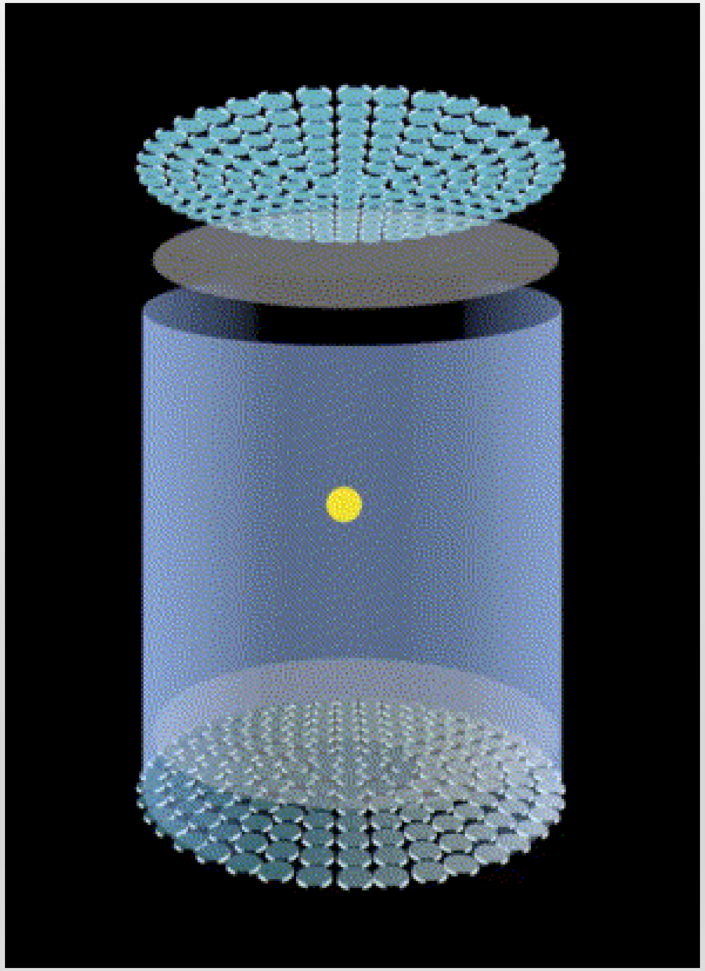


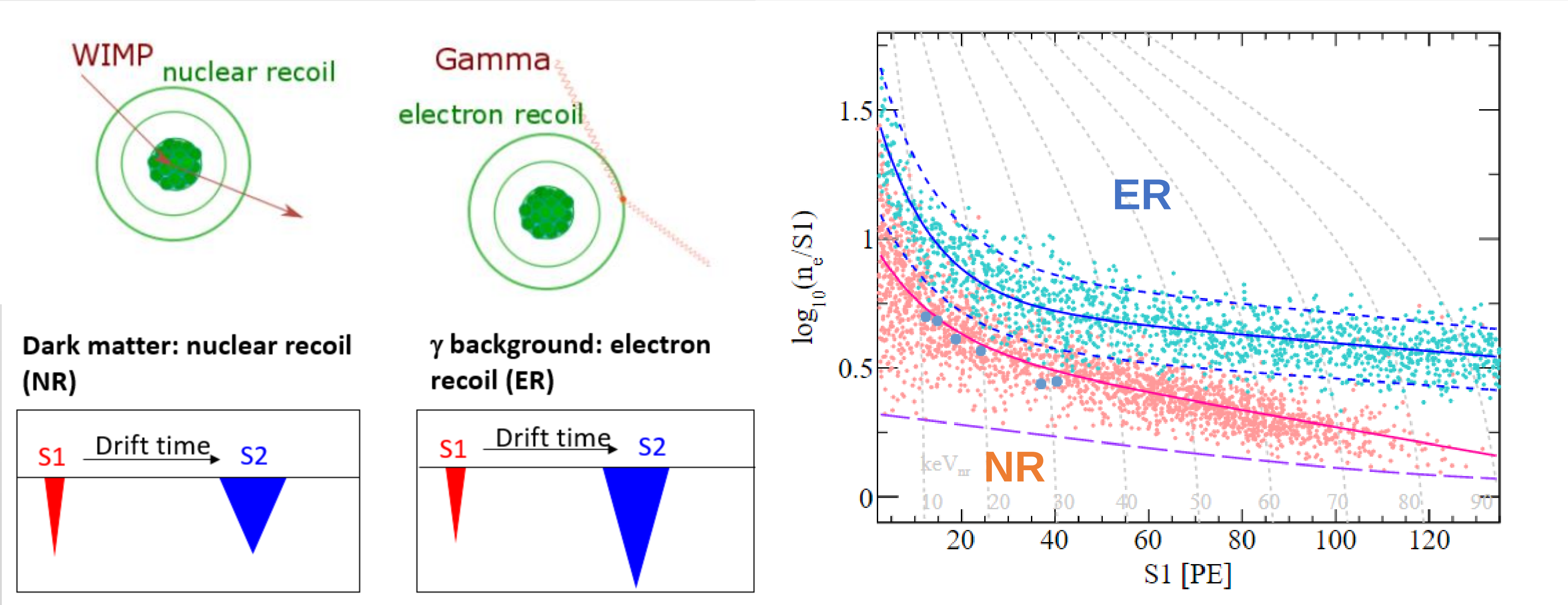
From Jure Zupan , Virtual Lectures on DM EFTs, Nankai, 2021

Dual-phase xenon detector

- S1: prompt scintillation signal
- S2: delayed ionization signal

- Time Projection Chamber
- Good ER/NR identification
- Precise Energy & 3D position reconstruction





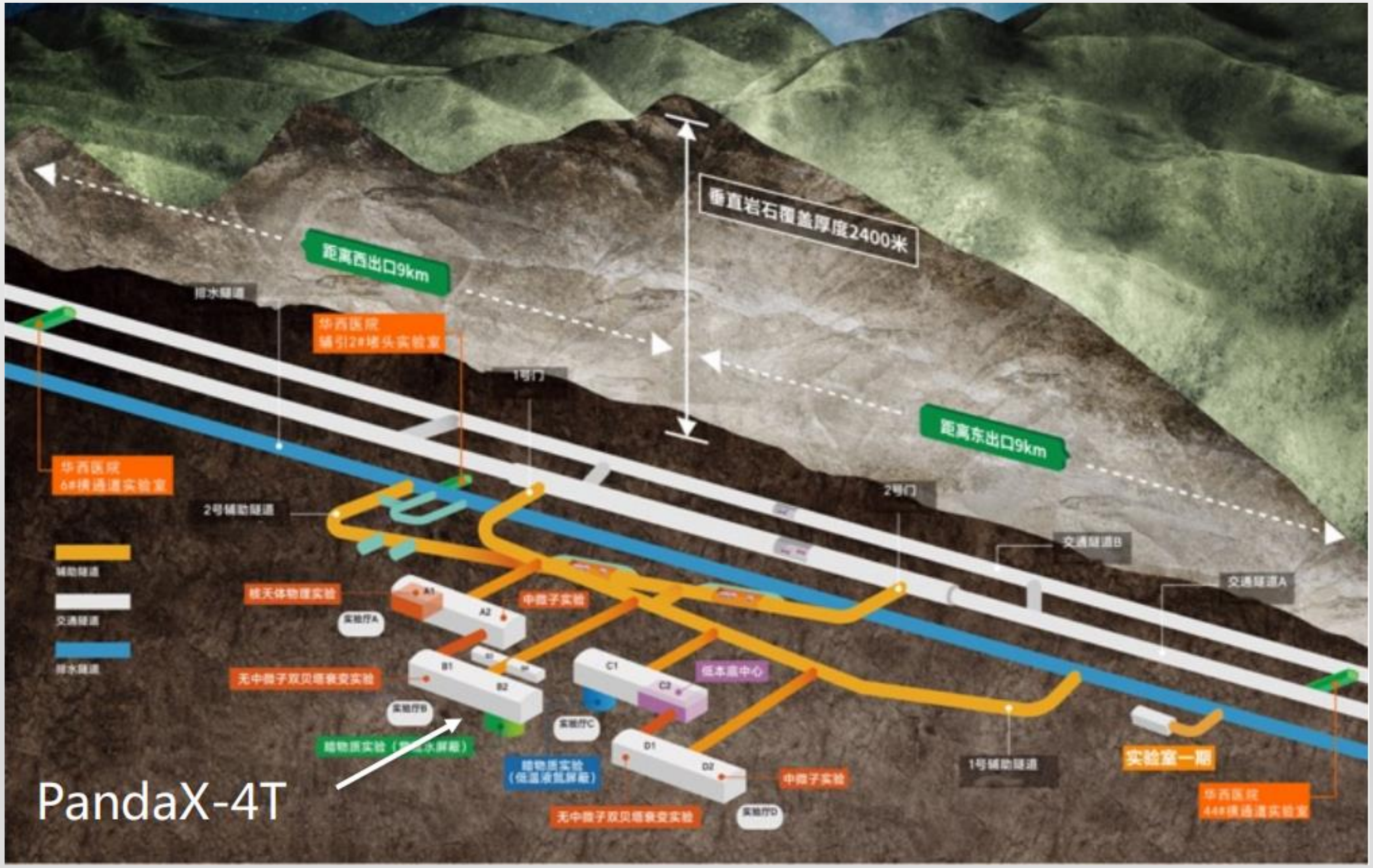
$(S2/S1)_{NR} << (S2/S1)_{ER}$

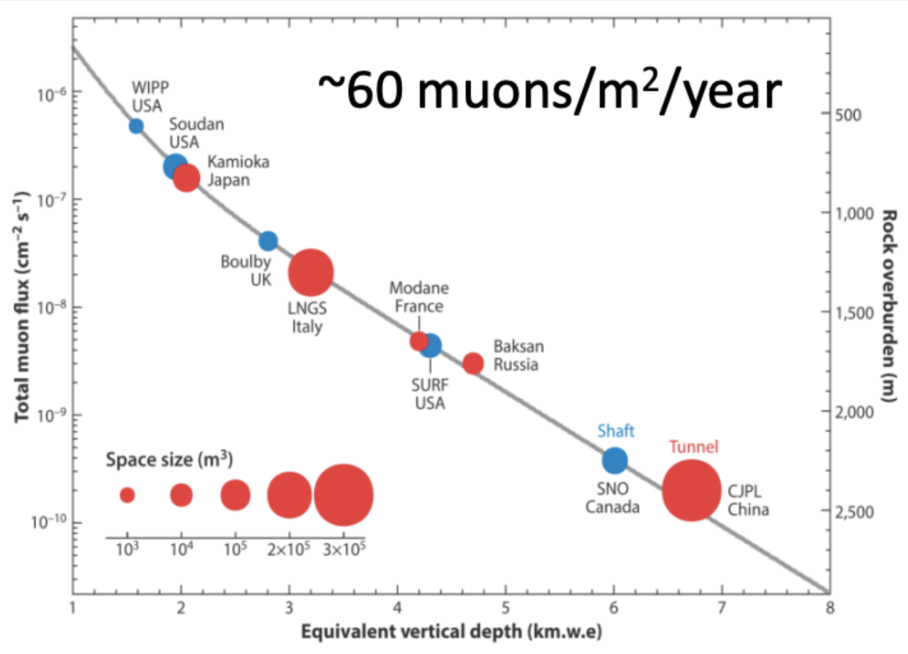
PandaX collaboration

Particle and Astrophysical Xenon Experiments

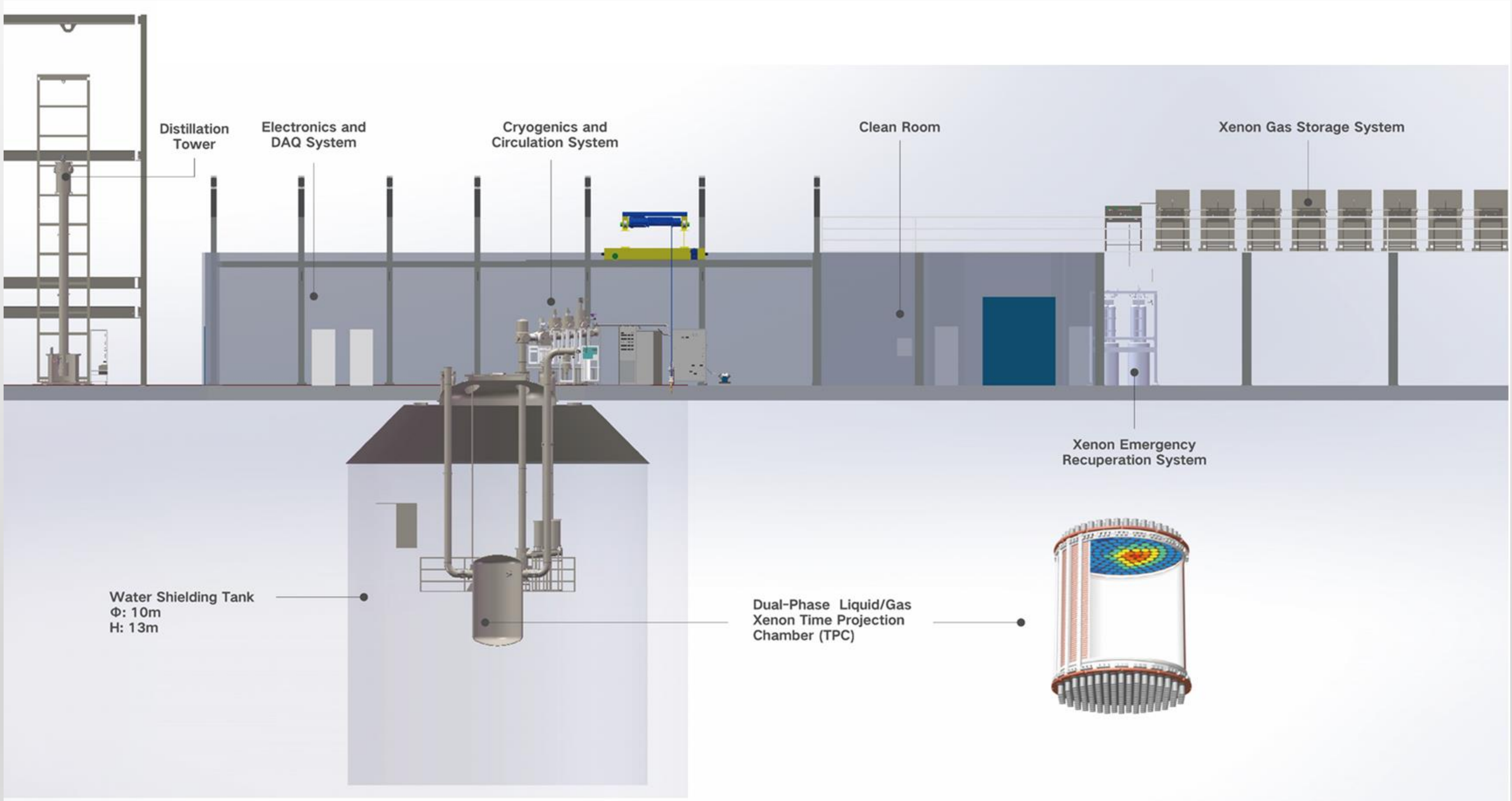
CJPL-II

- Deepest (equivalent vertical depth), 6700 m.w.e.
- Muon rate: 60 muon/m^2/year



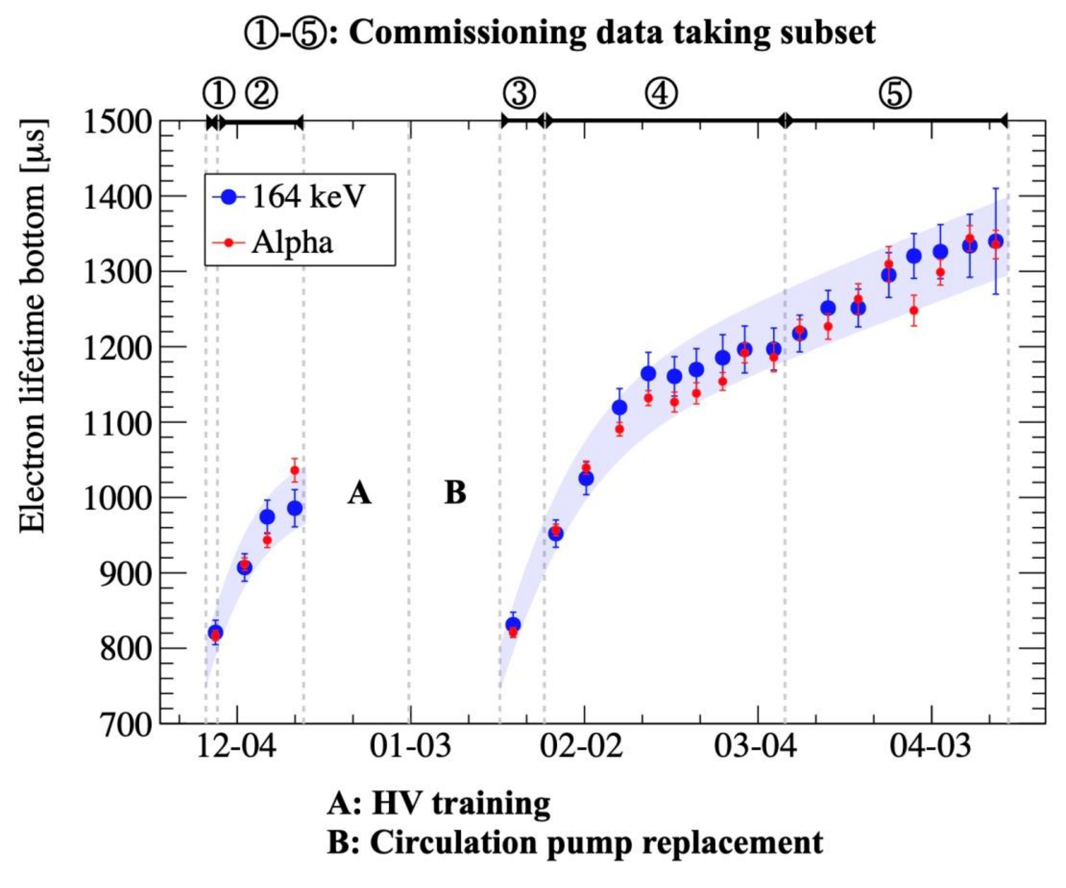


The PandaX-4T experiment



PandaX-4T commissioning run

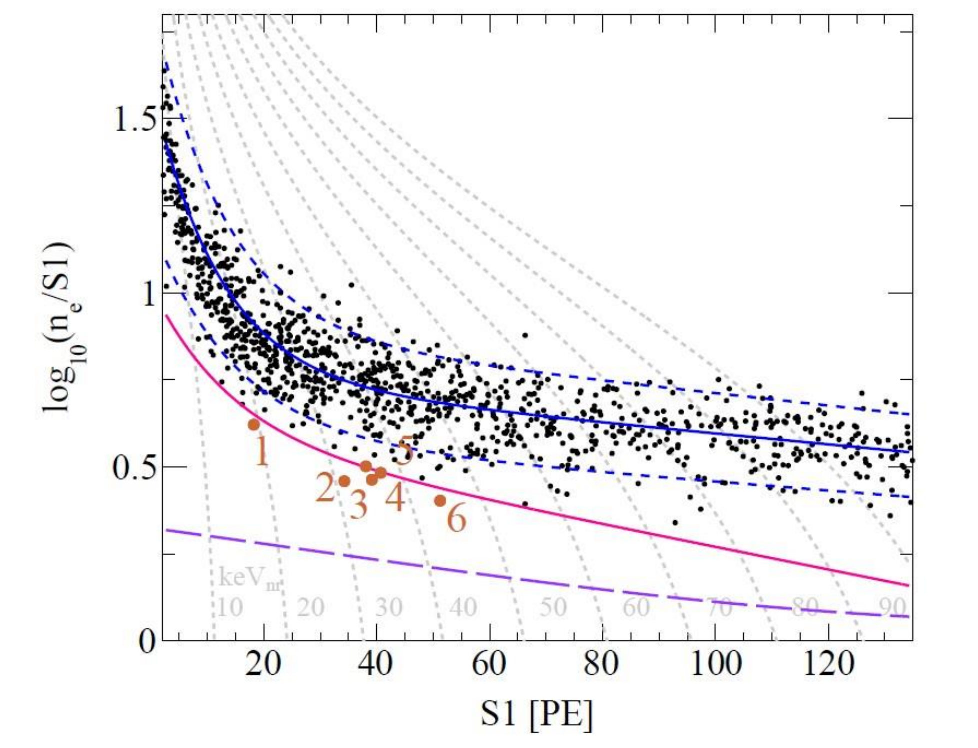
- Stable data running period: 95.0 calendar days (86 days after selection)



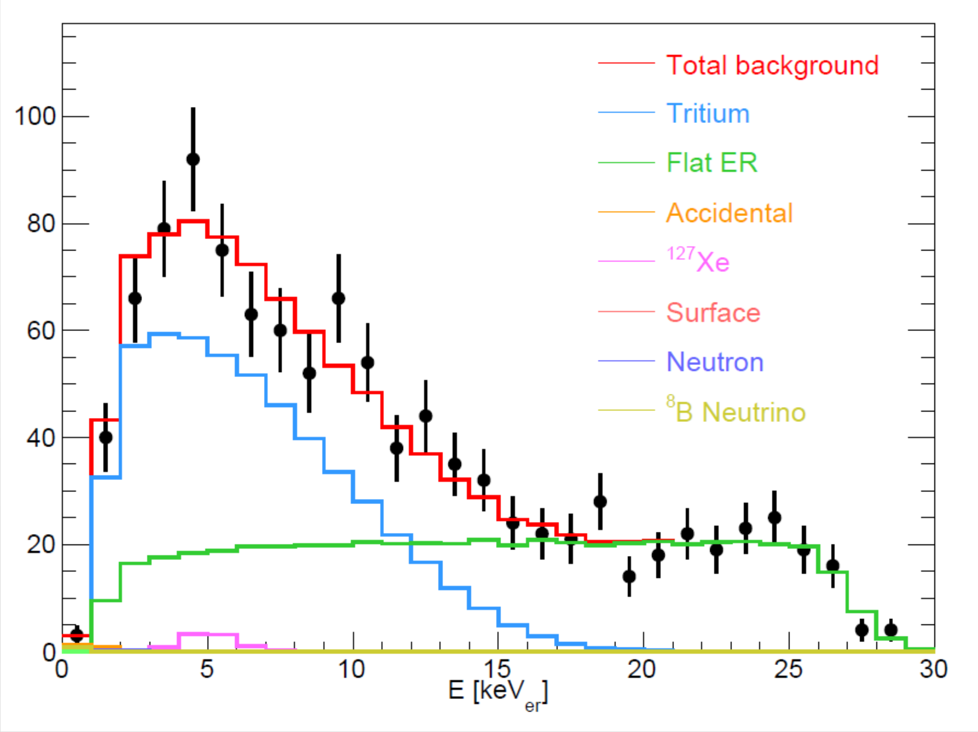
Set	1	2	3	4	5
Duration (days)	1.95	13.25	5.53	35.58	36.51
$\langle \tau_e \rangle$ (μs)	800.4	939.2	833.6	1121.5	1288.2
dt_{max} (μs)	800	810	817	841	841
$V_{cathode}$ (−kV)	20	18.6	18	16	16
V_{gate} (−kV)	4.9	4.9	5	5	5
PDE (%)	9.0 ± 0.2			9.0 ± 0.2	
EEE (%)	90.2 ± 5.4			92.6 ± 5.4	
SEG_b (PE/e)	3.8 ± 0.1			4.6 ± 0.1	

Data selection & Background

- 0.63 ton year exposure
- WIMP ROI: S1(2-135PE)
- 1058 candidates; 6 below NR median

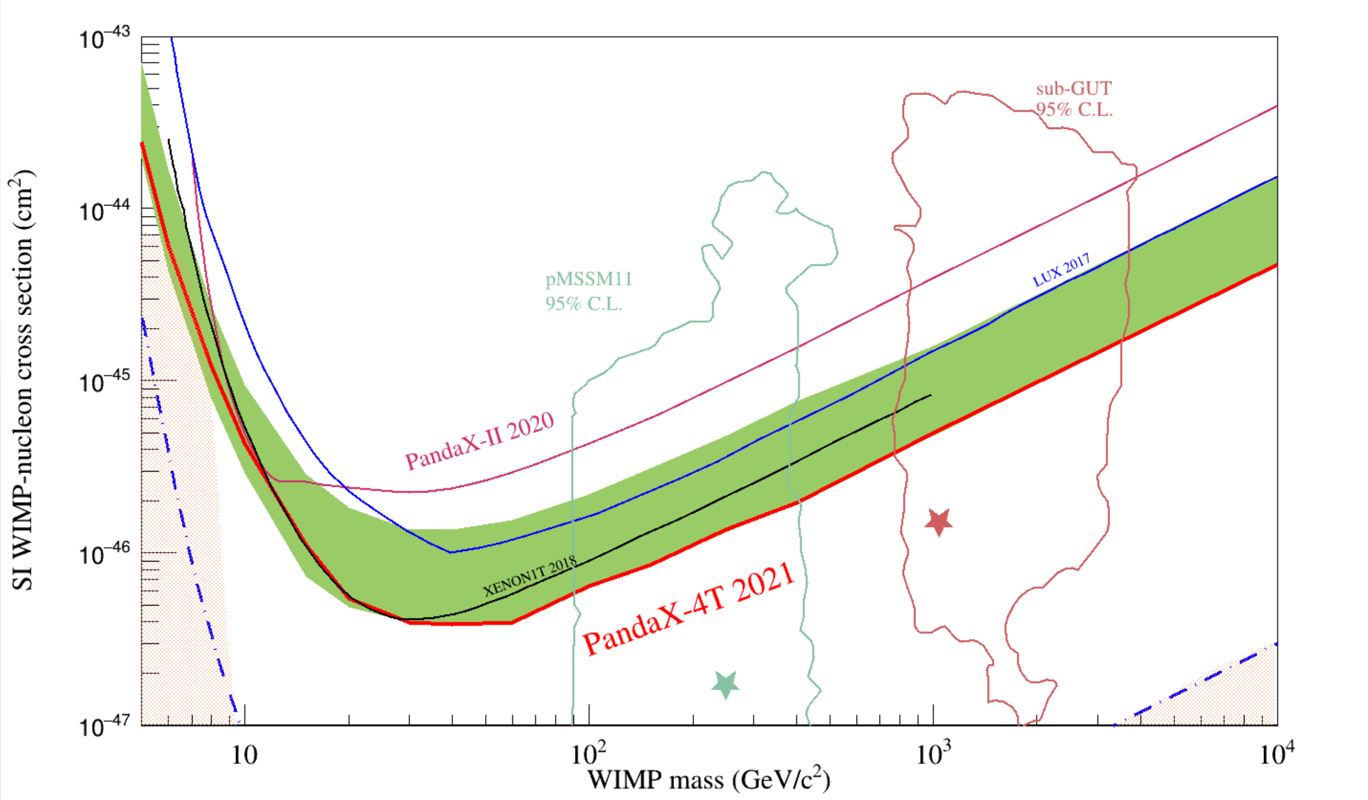


- Flat ER for $^{85}\mathrm{Kr}$, $^{222}\mathrm{Rn}$, $^{136}\mathrm{Xe}$, solar neutrino and material ER
- Spectrum agrees with expected background



PandaX-4T SI interaction

- Limits on WIMP-nucleon spin-independent cross section down to $3.8 \times 10^{-47}\,\mathrm{cm}^2$
- Approaching the “solar neutrino floor”

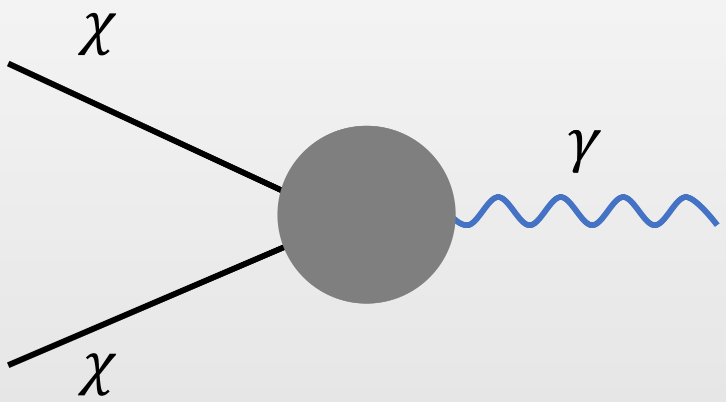


Y. Meng et al. PRL 127, 261802 (2021)
Editors’ suggestion;Featured in Physics

How Dark is Dark Matter

Credit: public domain

Luminance of dark matter



- **DM could couple with photons**
- **Individual dark matter-photon interactions are taken into the analysis**
- **Matched to non-relativistic EFT operators**
  - DMFormFactor. N. Anand, A. Fitzpatrick, W. Haxton PRC 89, 065501 (2014)

$$\mathcal{L} = \boxed{Q\bar{\chi}\gamma^\mu\chi A_\mu} + \boxed{\frac{\mu_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + i\frac{d_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu} + b_\chi\bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu} + a_\chi\bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu}},$$

Millicharge | Magnetic dipole | Electric dipole | Charge radius | Anapole

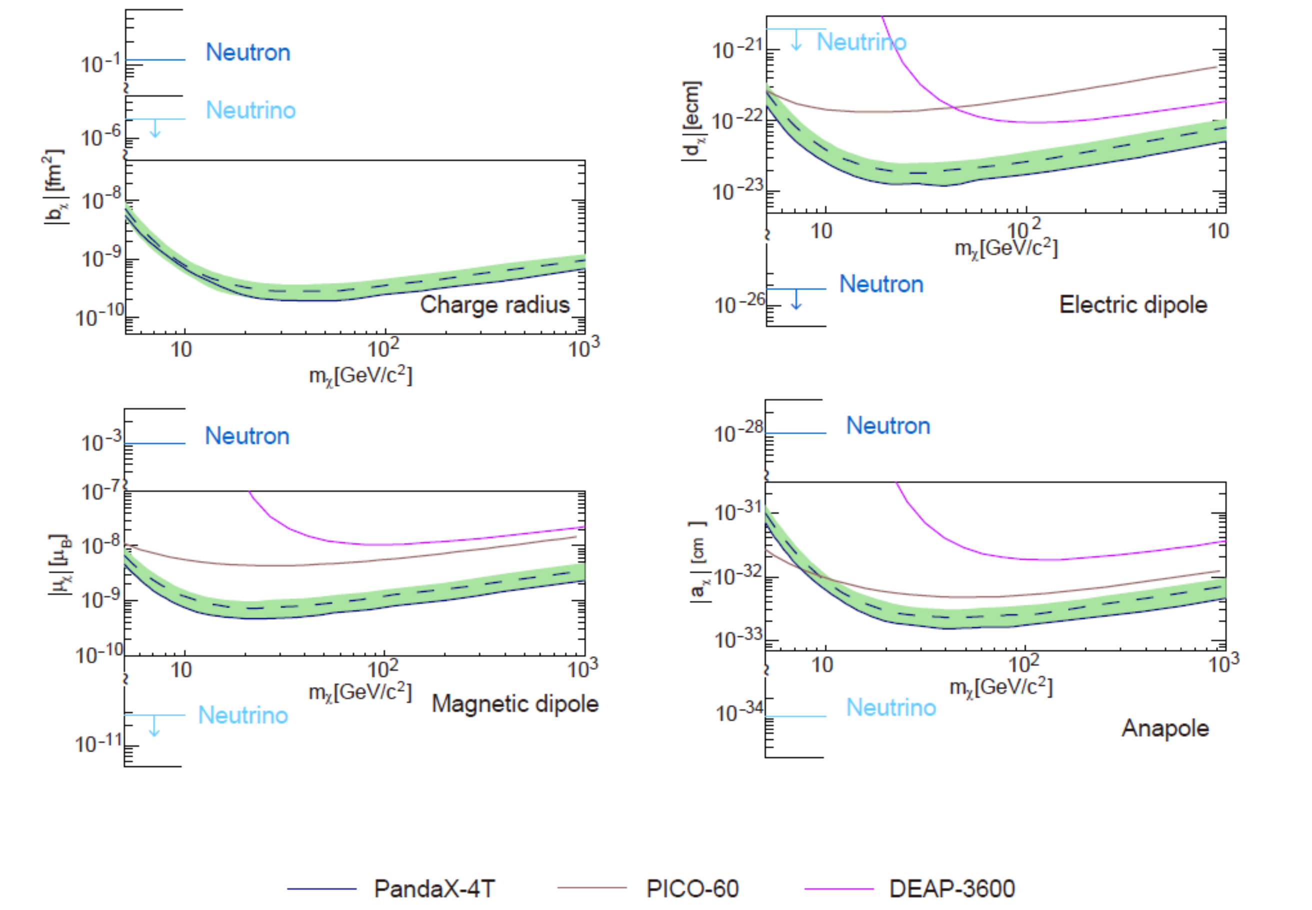
Tree-level | Loop-level

Result from xenon recoil data

- **The first constraint on the charge radius of dark matter.**
  - Lowest excluded value of $1.9 \times 10^{-10}\text{fm}^2$ @ $m_\chi = 40\text{GeV}$
  - More stringent than that for neutrinos by four orders of magnitude.
- **Other EM properties**
  - up to 3 – 10 times improvement

Table 1 | Comparison of electromagnetic properties

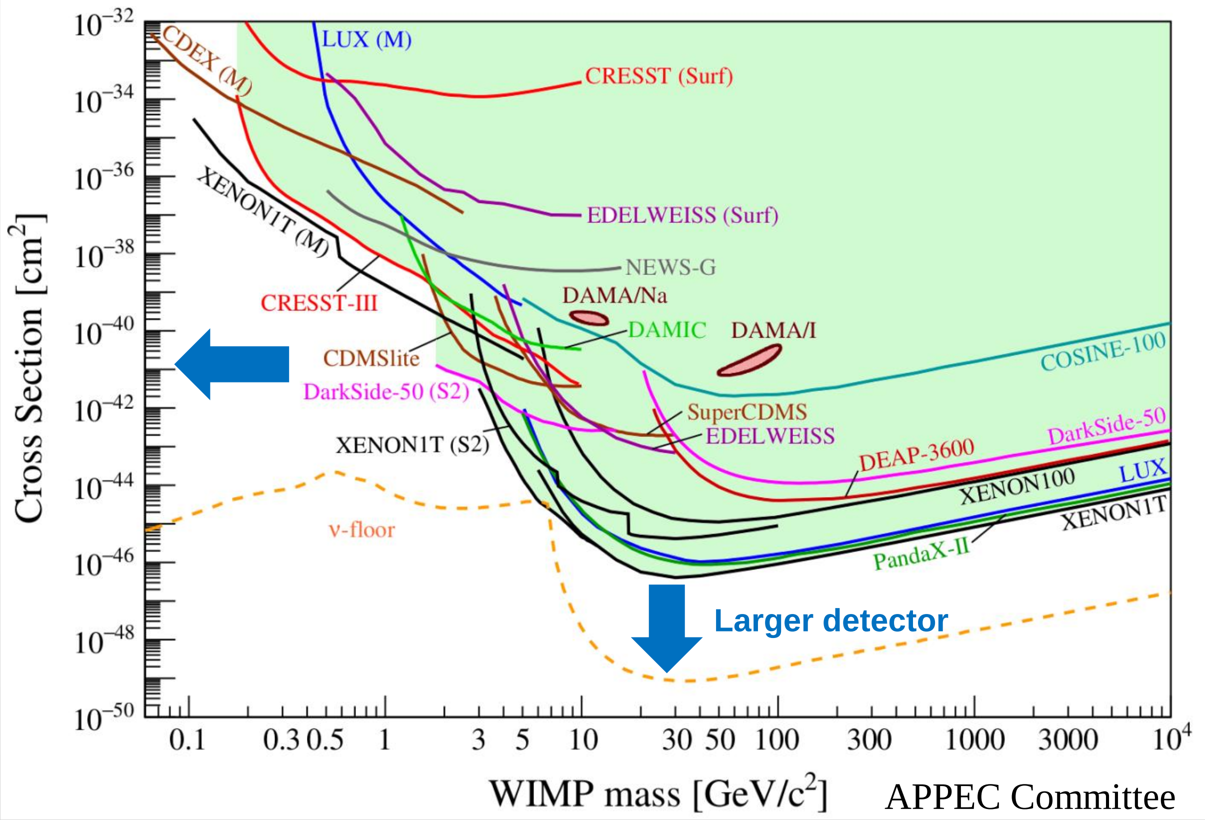
	dark matter	neutrino	neutron
Charge radius (fm^2)	$<1.9\times10^{-10}$	$[-2.1,3.3]\times10^{-6}$ *	-0.1155 *
Millicharge (e)	$<2.6\times10^{-11}$	$<4\times10^{-35}$ *	$(-2\pm8)\times10^{-22}$ *
Magnetic dipole (μ_B)	$<4.8\times10^{-10}$	$<2.8\times10^{-11}$ *	-1×10^{-3} *
Electric dipole (ecm)	$<1.2\times10^{-23}$	$<2\times10^{-21}$ †	$<1.8\times10^{-26}$ *
Anapole (cm^2)	$<1.6\times10^{-33}$	$\sim10^{-34}$ ‡	$\sim10^{-28}$ §



X.Ning et al. Nature 618, 47-50(2023)

To Light DM

- **2 directions: larger detector; lower threshold**
- **Ways to search light DM in PandaX:**
  - Kinetic boosting
    - ➢ Boosted DM
  - DM mass->deposit energy
    - ➢ Absorption DM
  - Lower the threshold
    - ➢ e-WIMP

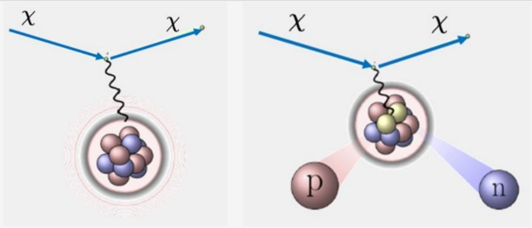


APPEC Committee Report (arXiv:2104.07634)

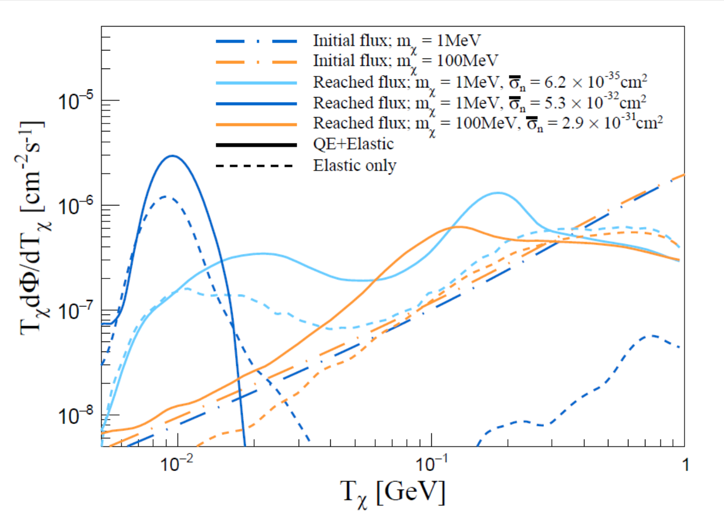
Boosted DM from atmosphere

- **Large kinetic energy to overcome threshold**
- **Boosted mechanism**
  - Mesons from cosmic-ray dump in atmosphere may decay into light DM
- **Benchmark model**
  - Hadrophilic scalar mediator $\mathcal{L} \supset -g_\chi S \bar{\chi}_L \chi_R - g_u S \bar{u}_L u_R + \text{ h.c.}$
  - DM is generated via $\eta \to \pi^0 S \to \pi^0 \chi\bar{\chi}$

- **A dedicated MC attenuation simulation**
  - For T_χ> 0.2 GeV, QE becomes significant
  - Elastic & **Quasi-elastic** process is included.



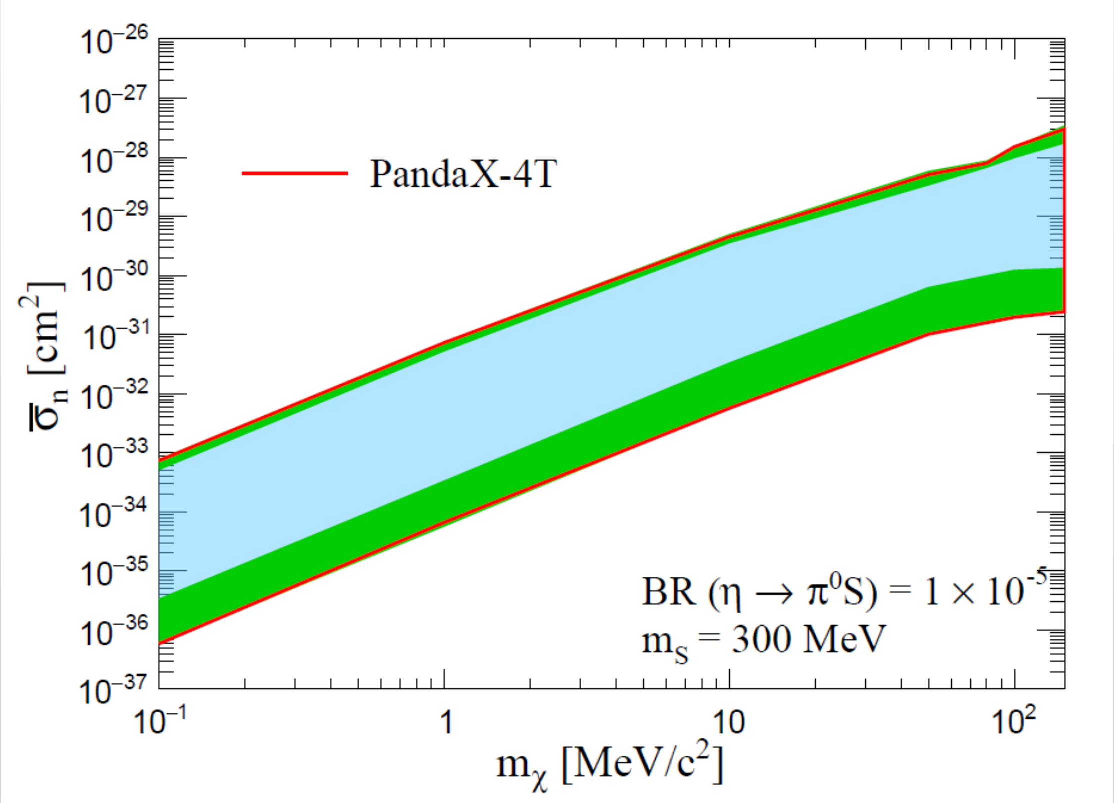
L. Su, L. Wu, NZ, B. Zhu arXiv:2212.02286

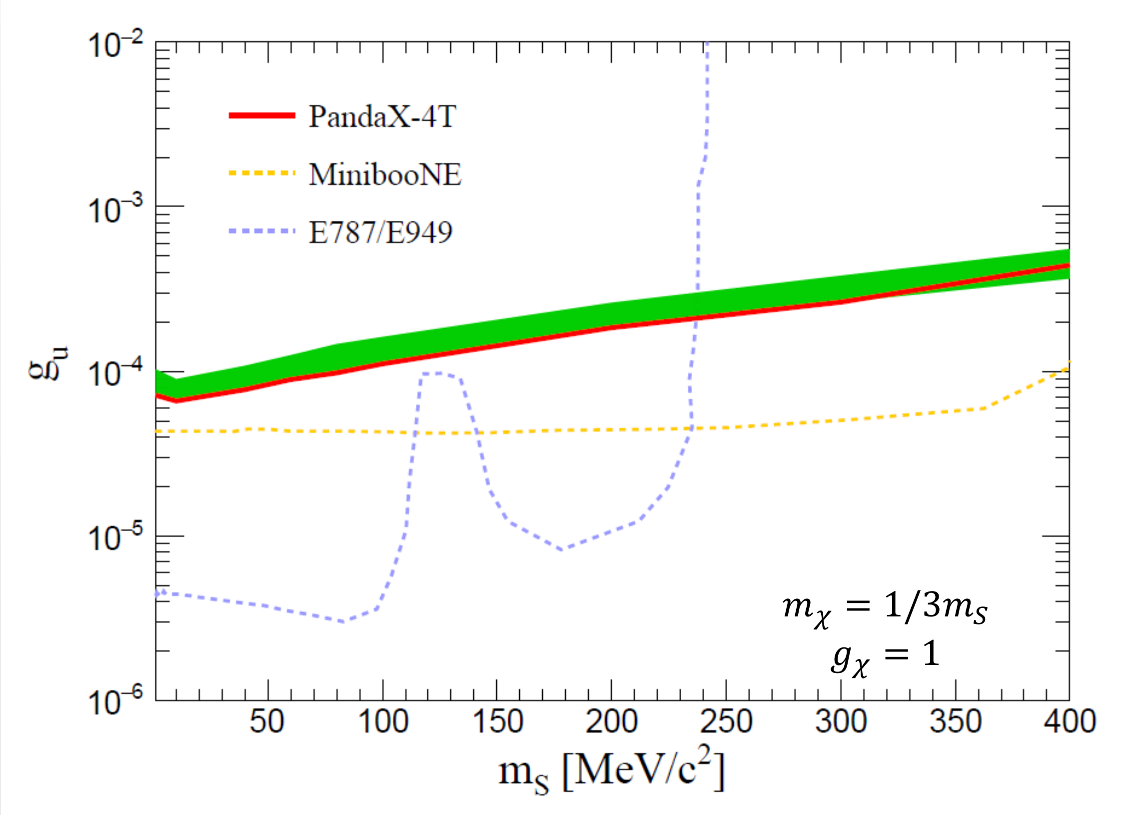


J. Alvey, M. Campos, M. Fairbairn, T. You, PRL 123, 261802 (2019)

Constraints on boosted DM

- Cosmic-ray beam dump gives a unique window to search this scalar mediated DM-nucleon interaction
- Same model could be searched in MinibooNE and E787/E949



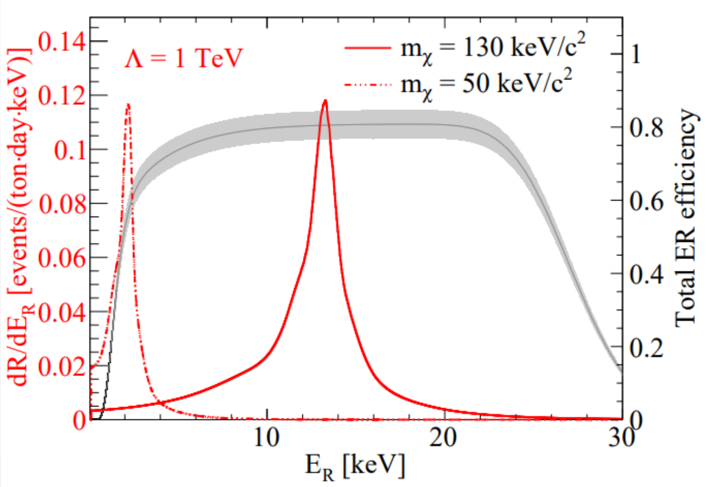


X. Ning et al. arXiv:2301.03010

DM - ν conversion

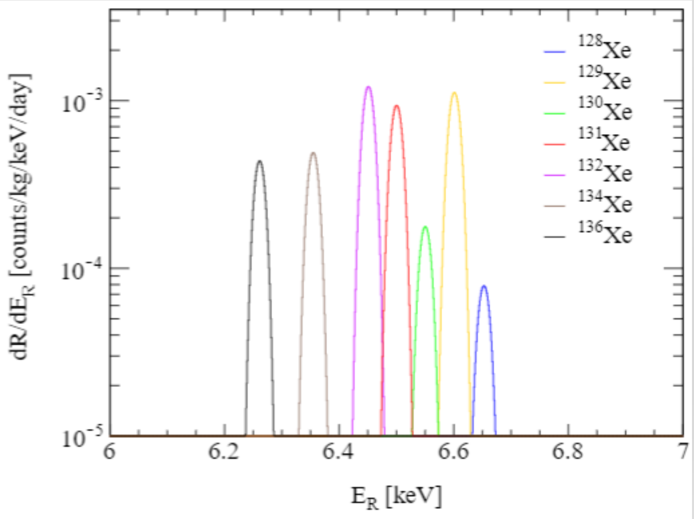
- **DM mass convert to deposit energy**
  - Dark matter χ being absorbed, with an out-going neutrino ν
- **Mono-energetic spectrum**
  - $\boldsymbol{E_R = m_\chi^2/2m_T}$
- **Lower mass range**
  - NR: sub-GeV
  - ER: sub-MeV

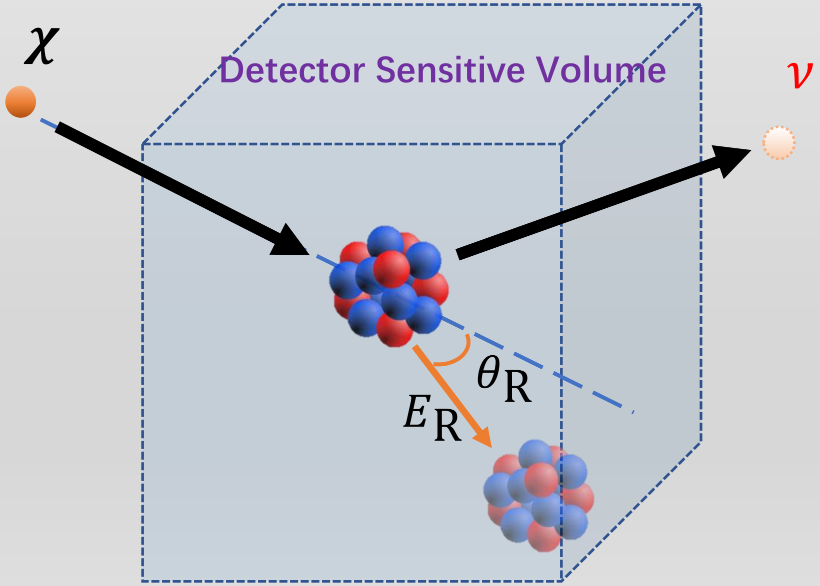
J. Dror, G. Elor, R. McGehee, PRL (2020)

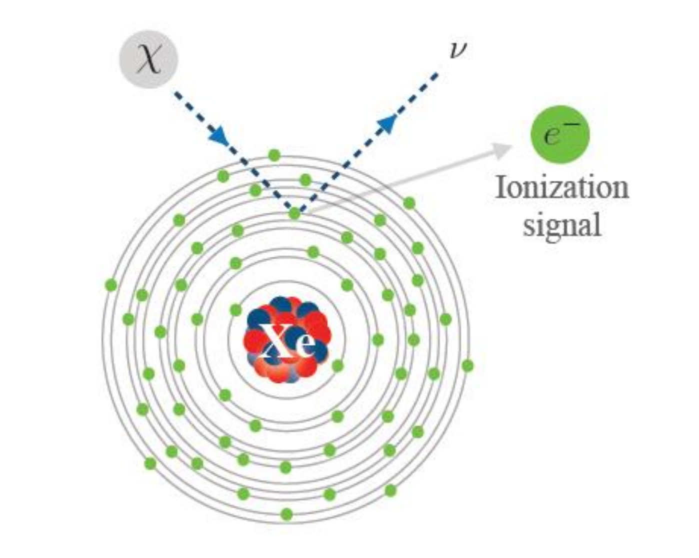


$$\chi(\bar{\chi}) + {}^{A}Xe \to \nu(\bar{\nu}) + {}^{A}Xe$$

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

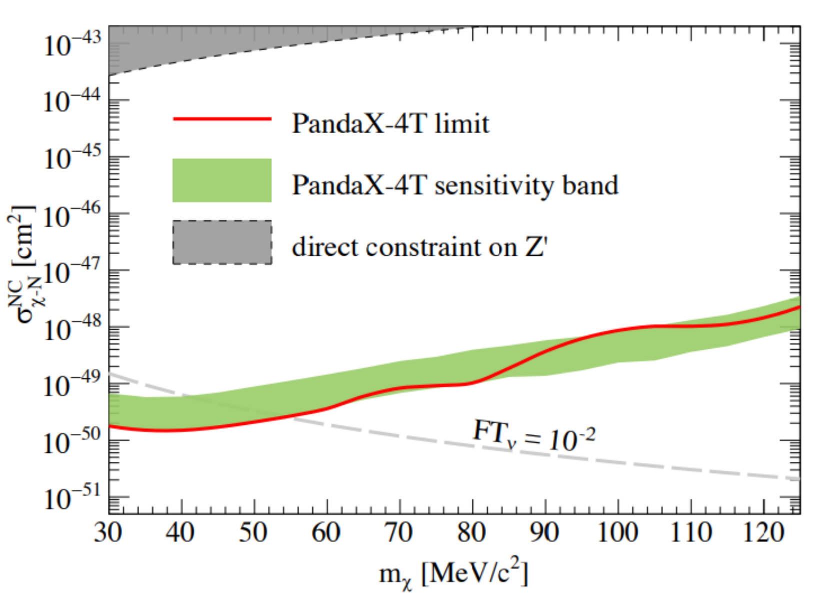




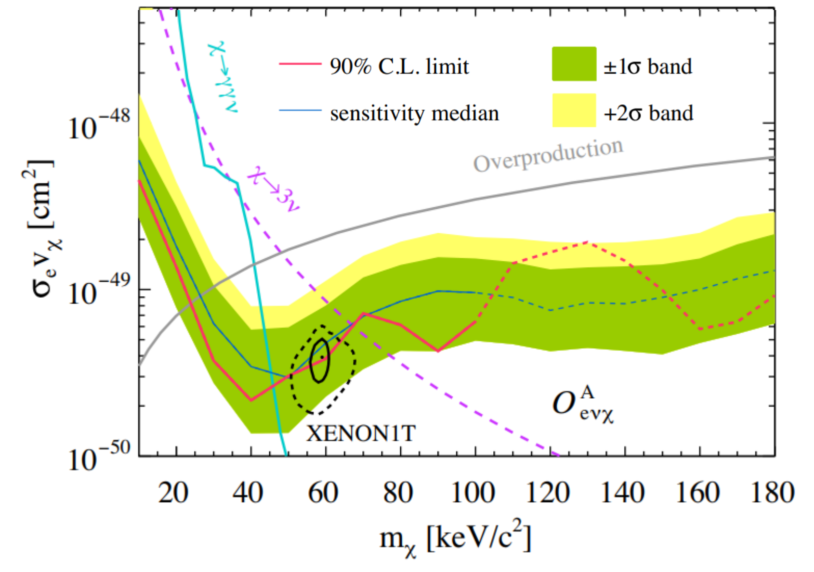


Mono-energetic signal search

- **NR channels** L. Gu et al. PRL 129, 161803 (2022)
  - First search for fermionic dark matter absorption signal in direct detection experiments
  - Strongest limit,1.5 x 10^{-50} cm^2@40 MeV/c^2 fermionic DM mass

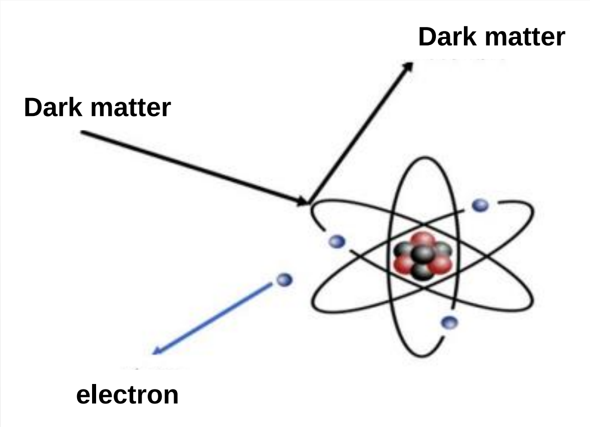


- **ER channels** D. Zhang et al. PRL 129, 161804 (2022)
  - Competitive constraint in 25-45 keV/c^2
  - Complementary to astrophysical constraints.

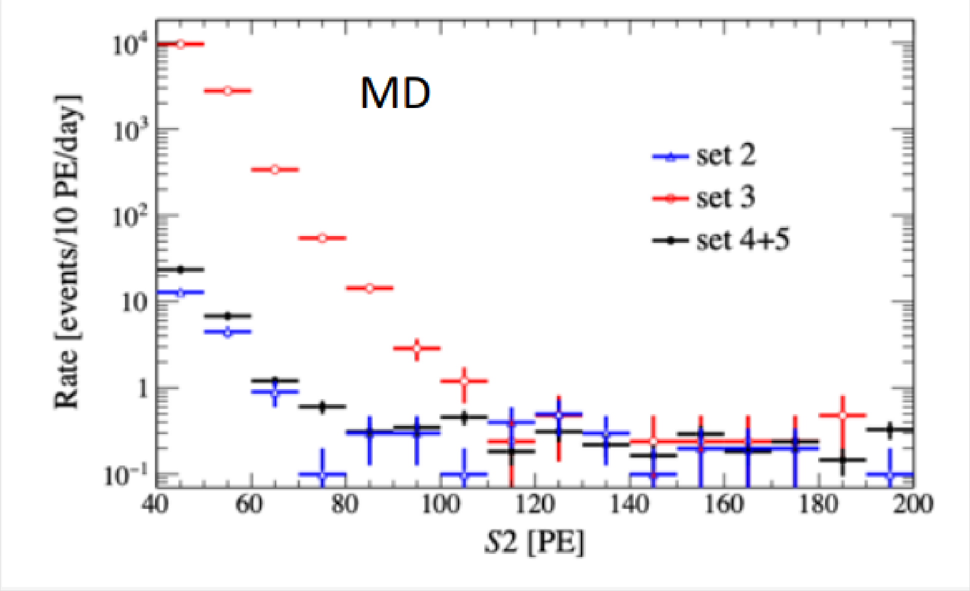


Constraints WIMP-e

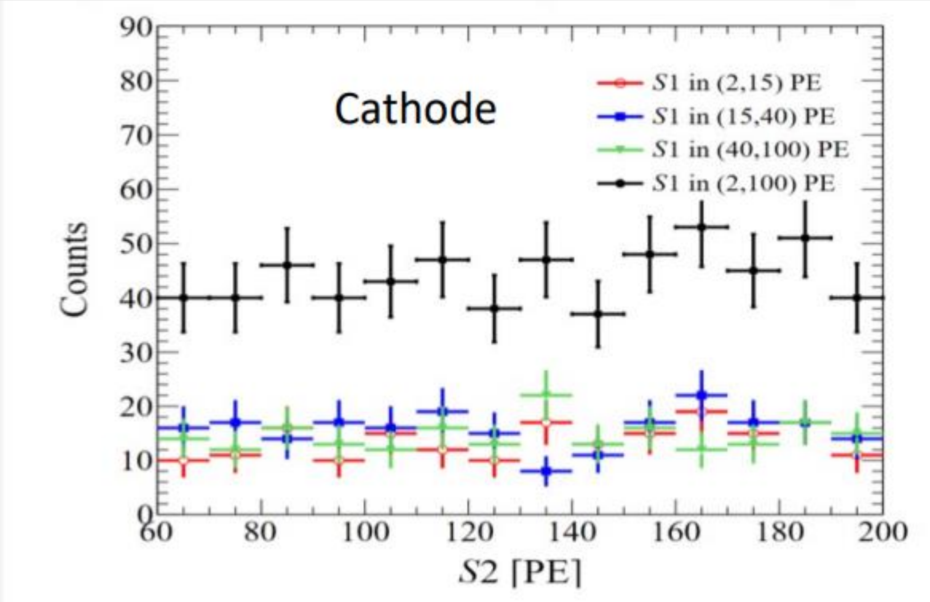
- **Lowering selection threshold: S2 only**
  - ROI: S2[60,200]PE
  - Threshold down to ~100 eV
- **Key challenge: background components**
  - First complete estimation of all the main background



- Micro-discharge (DM)

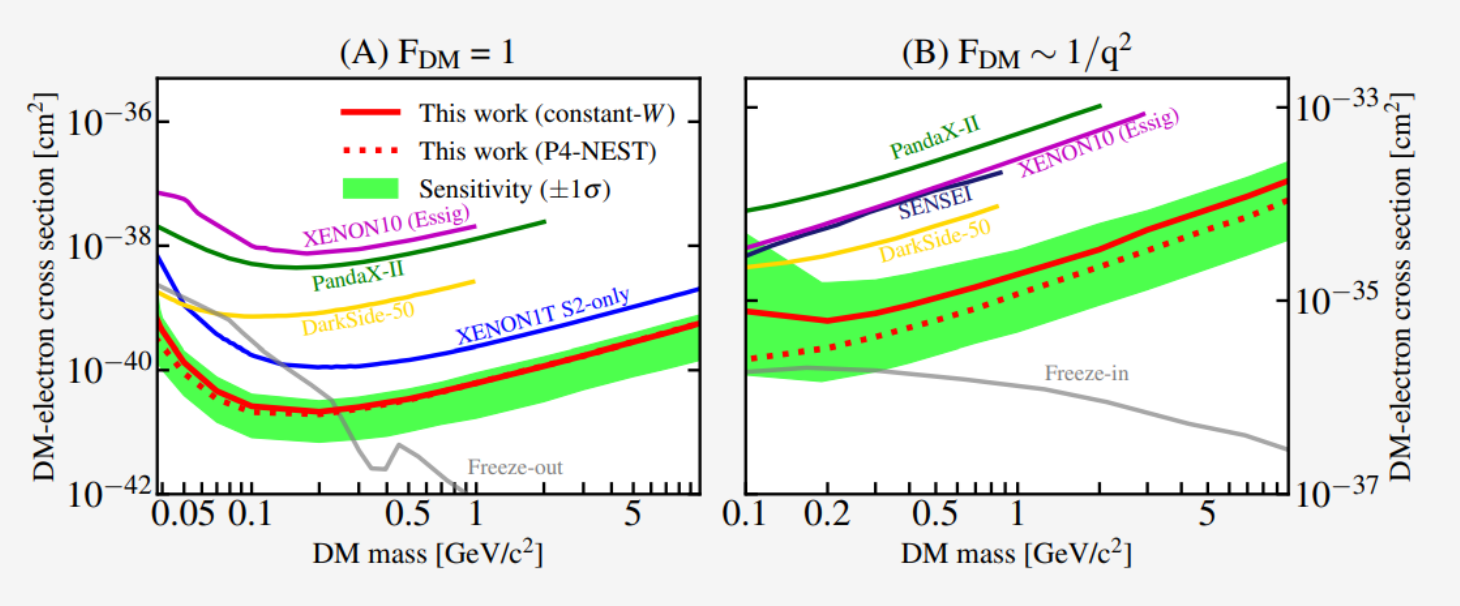


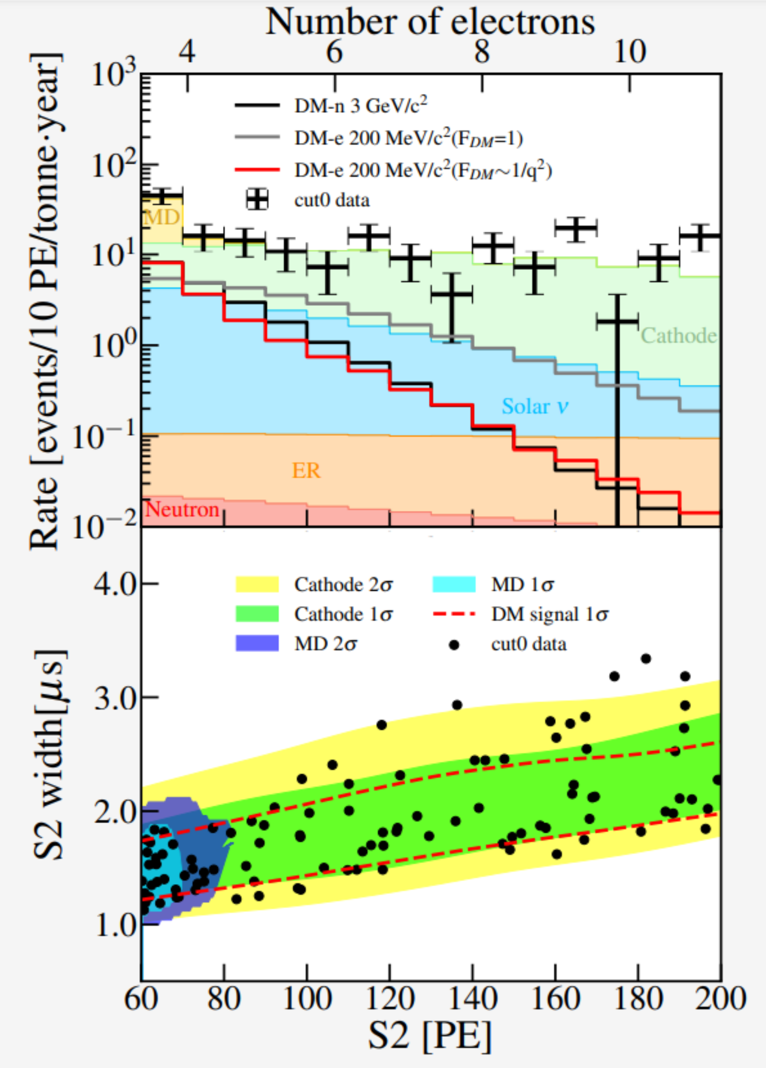
- Cathode activity



Constraints WIMP-e

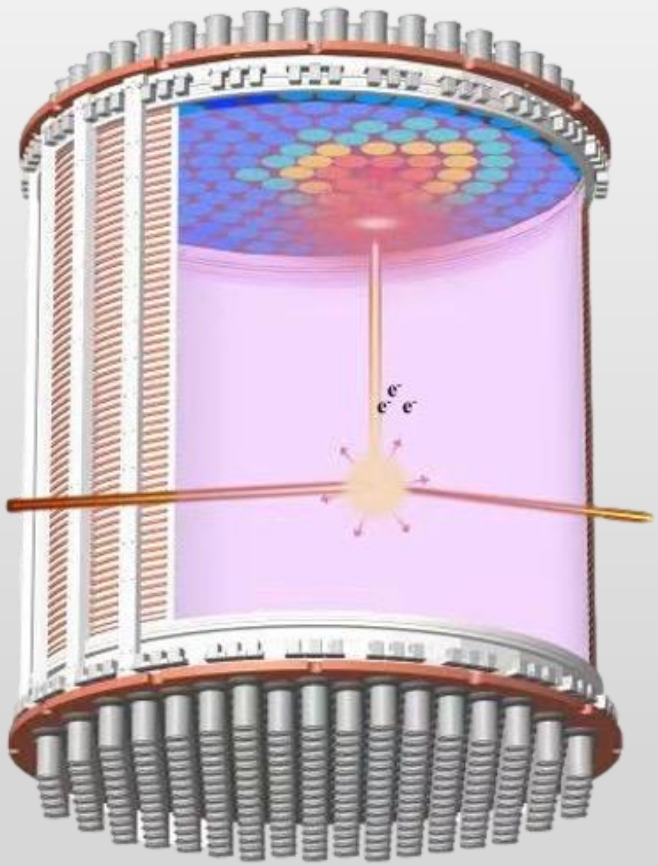
- **Blind analysis of 0.55 ton-year exposure**
- **Most stringent constraints are derived**
  - DM-electron interaction, $2 \times 10^{-41}\mathrm{cm}^2$

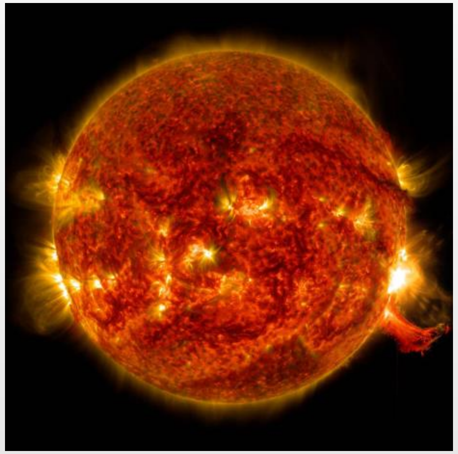




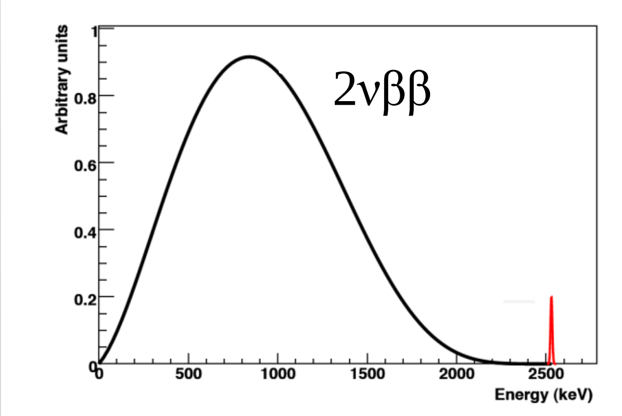
S. Li et al. arXiv:2212.10067 Accepted by PRL, Editors' Suggestion

Neutrino in PandaX-4T





- Touch the neutrino floor: ^{8}B solar neutrino
- Energy region: sub-keV

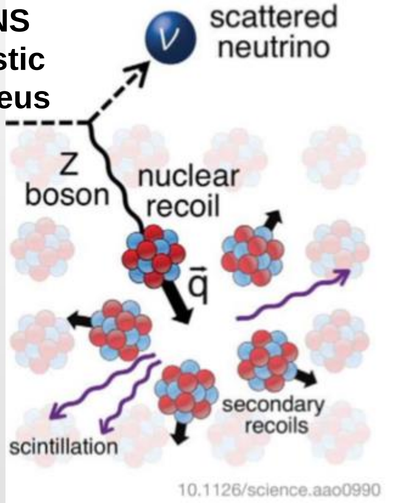


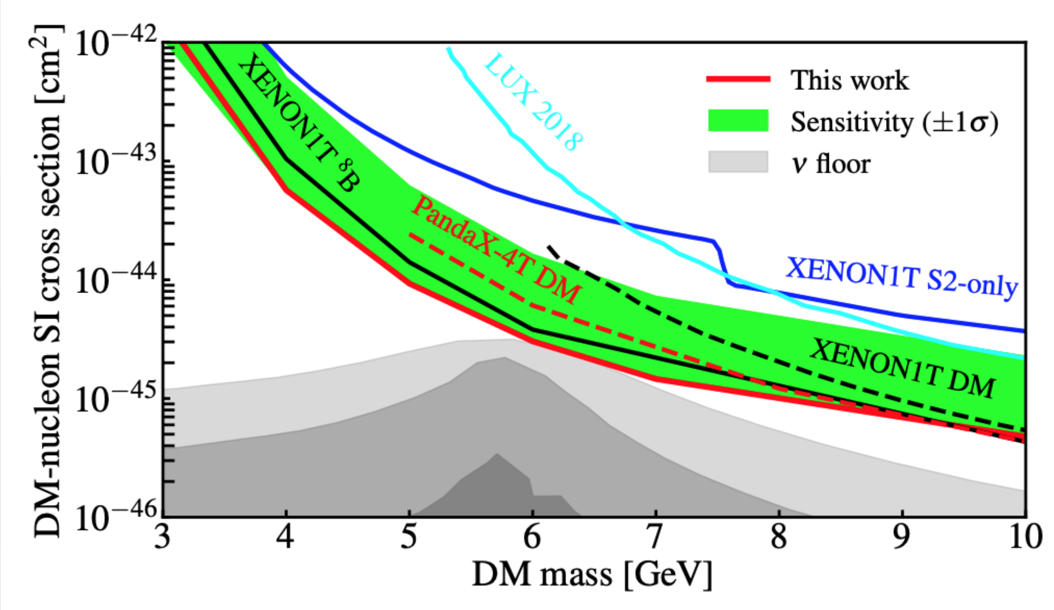
- Neutrinoless/neutrino double beta decay (NL)DBD
- Energy region: ~MeV

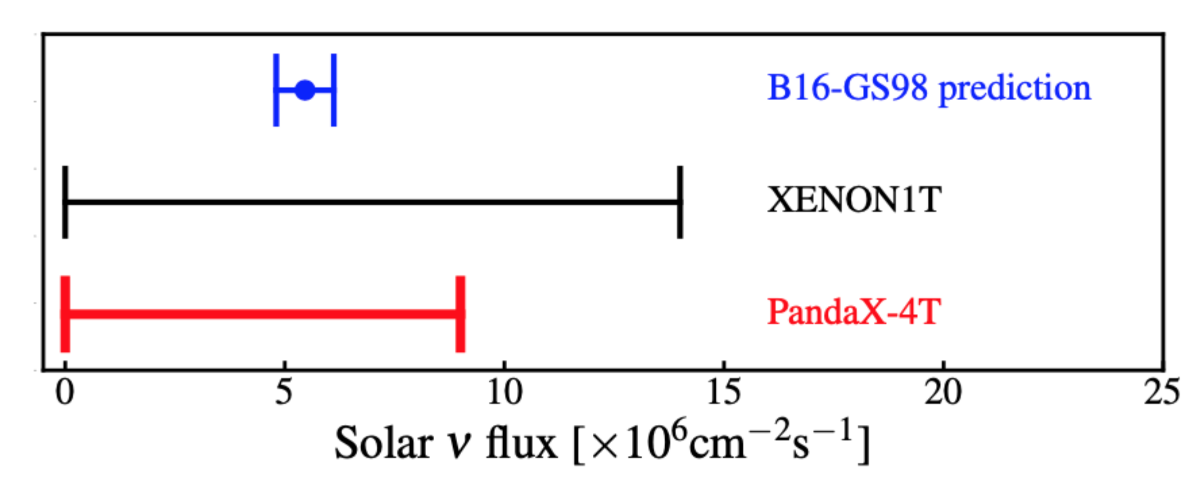
^{8}B ν and WIMP

- **ROI:**
  - S1 down to 0.3 PE
  - S2 down to 65 PE
- **Leading constraints on ^{8}B neutrino flux through CEνNS**
  - Touching neutrino floor
  - New insight on neutrino-nucleus interactions
- **Stronger constraints on WIMP in 3-10 GeV region**

Solar ^{8}B CEνNS (coherent elastic neutrino-nucleus scattering)



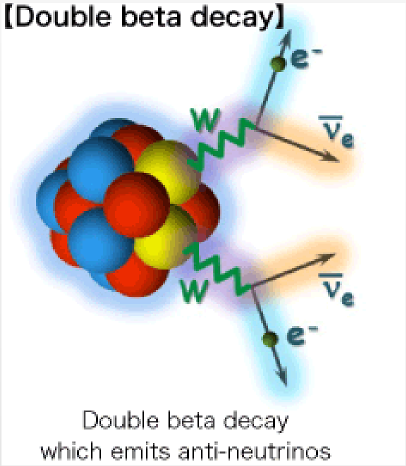


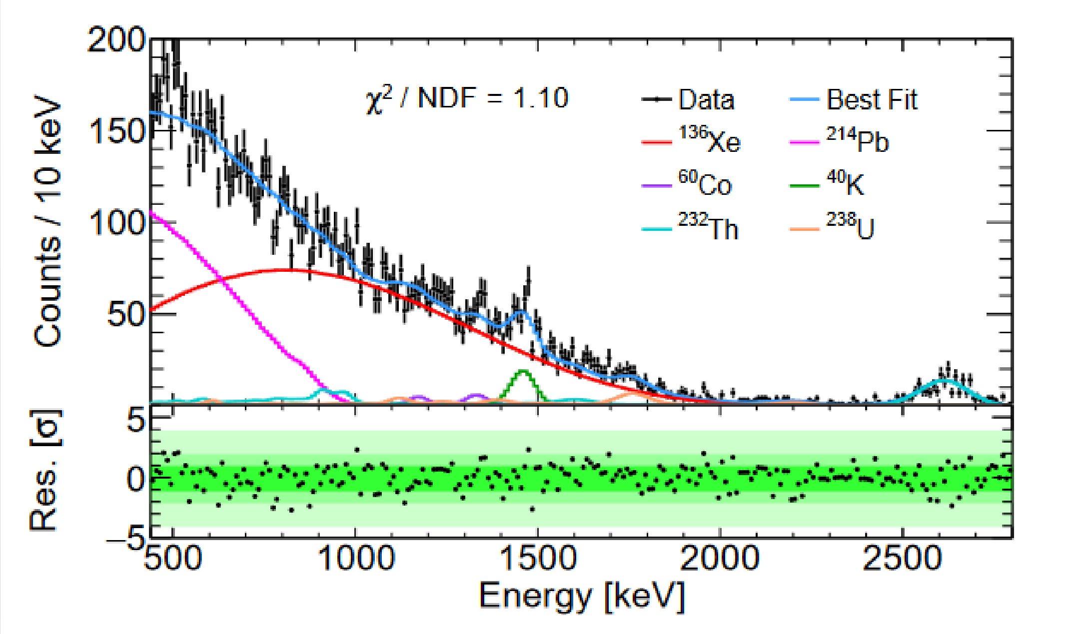


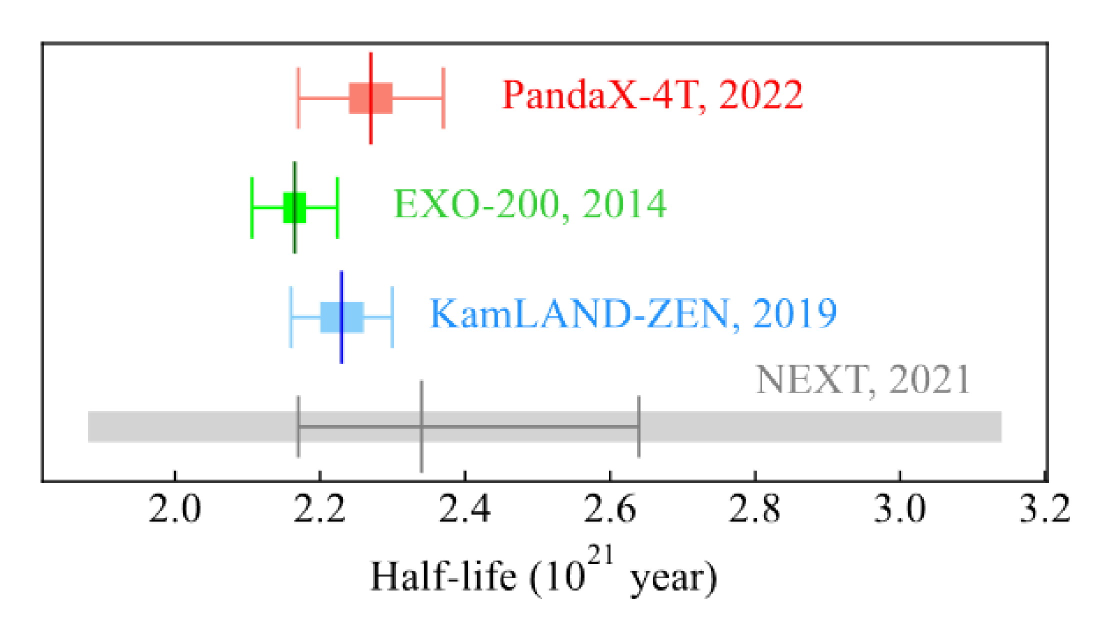
W. Ma et al. PRL 130, 021802 (2023)

^{136}Xe 2νDBD

- **ROI: [440, 2800] keV**
  - Identifying MS(MeV gamma) and SS(signals)
  - PMT desaturation algorithm
- **Accurate background model**
- **First result from a dark matter detector with natural xenon**
  - 2.27 +/- 0.03 (stat) +/- 0.10 (syst) x 10^{21} years
  - Comparable with enriched ^{136}Xe experiments



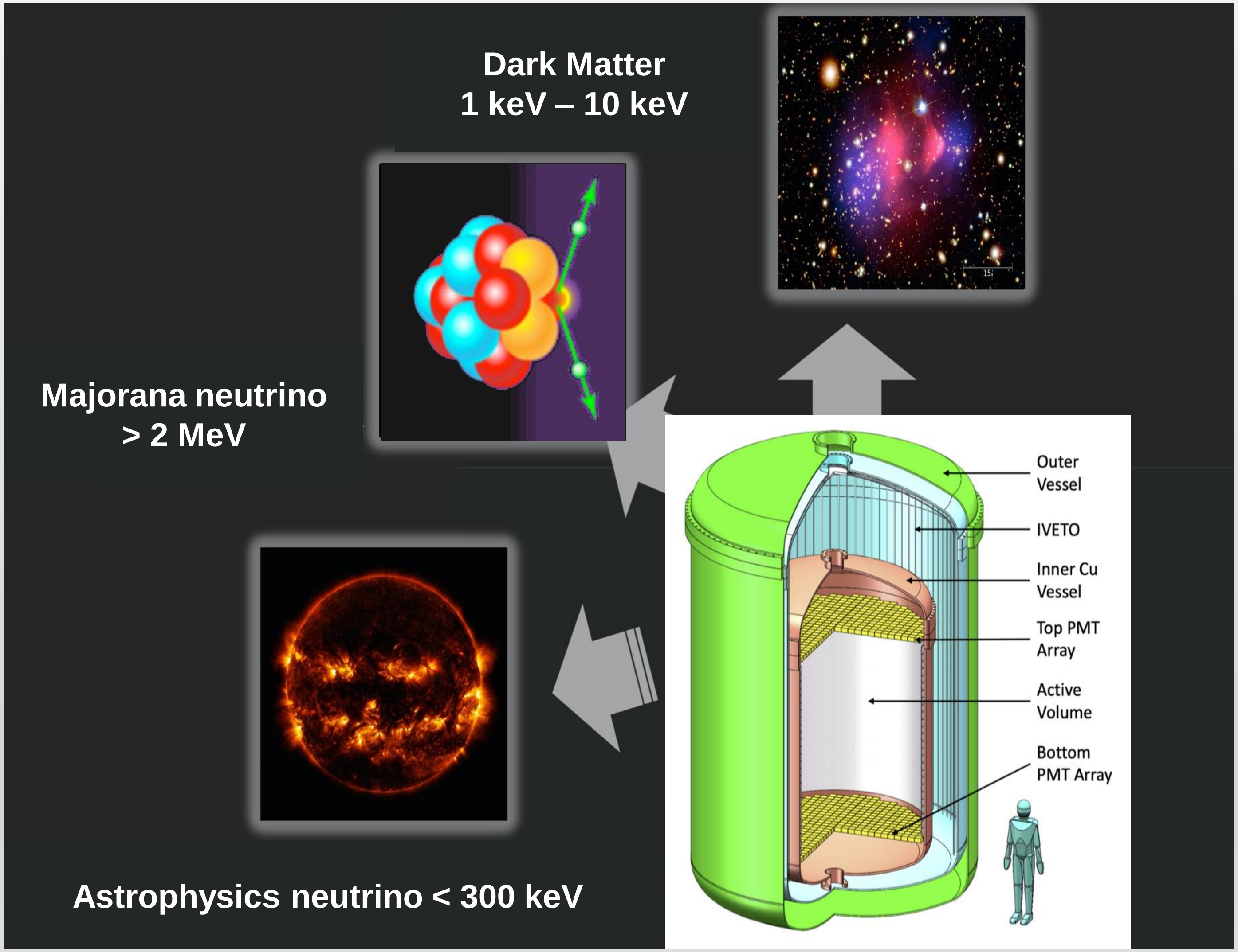




Research 2022, 9798721 (2022)

Future

- **PandaX-xT**
  - With >30 tonne liquid xenon in the sensitive volume;
  - Decisive test on WIMP and key test on Dirac/Majorana neutrino;



Summary

- PandaX-4T has completed its commissioning run
- PandaX-4T provides leading results on **Luminance of DM**
- PandaX-4T provides leading results on **multiple topics**

Light dark matter	Neutrino physics
− Boosted DM − DM absorption − e-WIMP	− ^{8}B CEνNS − ^{136}Xe (0ν/2ν) $\beta\beta$ decay

- The next generation of PandaX-xT is on-going.

Backup

- **Matched to non-relativistic EFT operators**
  - DMFormFactor. N. Anand, A. Fitzpatrick, W. Haxton PRC 89, 065501 (2014)
- **Individual dark matter-photon interactions are taken into the analysis**

$$\mathcal{L}_{\mathrm{MC}} = Q\overline{\chi}\gamma^{\mu}\chi A_{\mu} \to \mathcal{O}_{\mathrm{MC}} = eQQ_{p,n}\frac{\mathcal{O}_1}{q^2},$$

$$\mathcal{L}_{\mathrm{MD}} = \frac{\mu_\chi}{2}\overline{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$$

$$\to \mathcal{O}_{\mathrm{MD}} = e\mu_\chi\left[-Q_{p,n}\left(\frac{\mathcal{O}_1}{2m_\chi} + \frac{2m_{p,n}}{q^2}\mathcal{O}_5\right) - \frac{g_{p,n}}{m_{p,n}}\left(\mathcal{O}_4 - \frac{m_{p,n}^2}{q^2}\mathcal{O}_6\right)\right],$$

$$\mathcal{L}_{\mathrm{ED}} = i\frac{d_\chi}{2}\overline{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu} \to \mathcal{O}_{\mathrm{ED}} = ed_\chi Q_{p,n}\frac{2m_{p,n}}{q^2}\mathcal{O}_{11},$$

$$\mathcal{L}_{\mathrm{CR}} = b_\chi\overline{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu} \to \mathcal{O}_{\mathrm{CR}} = eb_\chi Q_{p,n}\mathcal{O}_1,$$

$$\mathcal{L}_{\mathrm{A}} = a_\chi\overline{\chi}\gamma^{\mu}\gamma^5\chi\partial^{\nu}F_{\mu\nu} \to \mathcal{O}_{\mathrm{A}} = ea_\chi\left(2Q_{p,n}\mathcal{O}_8 - g_{p,n}\mathcal{O}_9\right),$$

$$\mathcal{O}_1 = 1$$

$$\mathcal{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_N$$

$$\mathcal{O}_5 = i\mathbf{S}_\chi \cdot \left(\frac{\mathbf{q}}{m_N} \times \mathbf{v}^{\perp}\right)$$

$$\mathcal{O}_6 = \left(\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_N}\right)\left(\mathbf{S}_N \cdot \frac{\mathbf{q}}{m_N}\right)$$

$$\mathcal{O}_8 = \mathbf{S}_\chi \cdot \mathbf{v}^{\perp}$$

$$\mathcal{O}_9 = i\mathbf{S}_\chi \cdot \left(\mathbf{S}_N \times \frac{\mathbf{q}}{m_N}\right)$$

$$\mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_N}$$

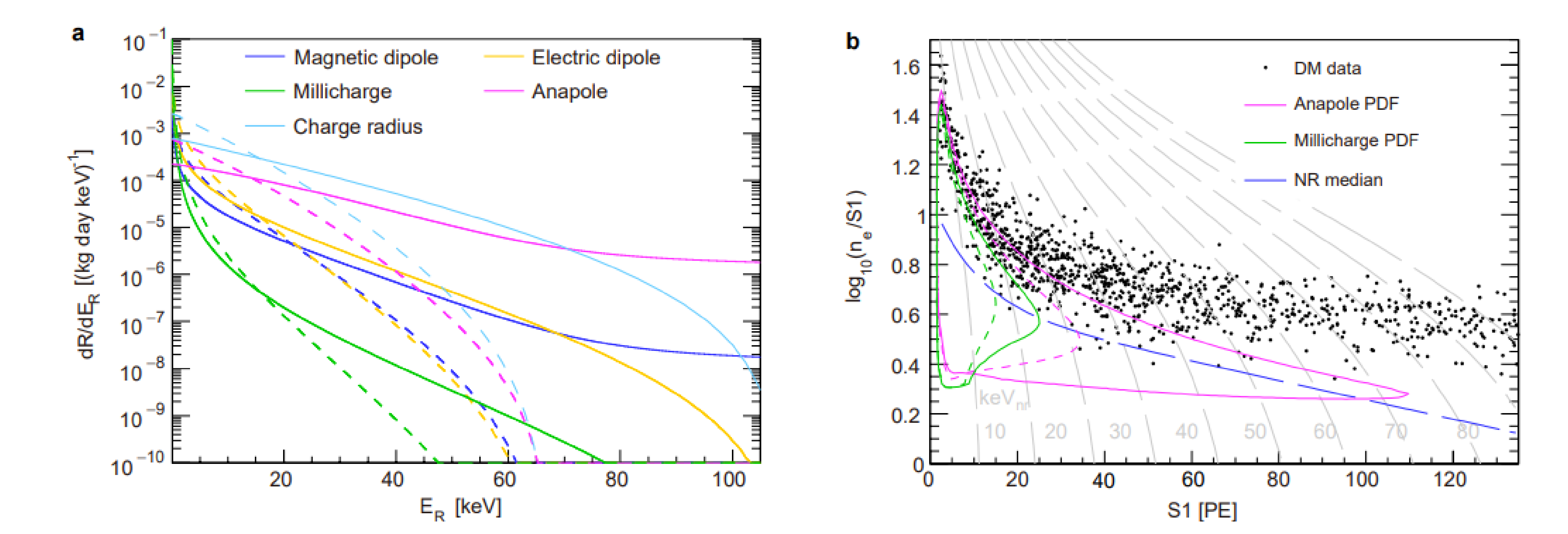
Nuclear response function:

- full-basis shell-model calculations (GCN5082 interaction).
- No truncation (9 billion Slater determinants)!

Eugenio Del Nobile Phys. Rev. D, 98(12), Dec 2018
A.Liam Fitzpatric et al. JCAP, 2013(02):004004, Feb 2013
Bradley J. et al. JHEP 2019(4), Apr 2019
Chiara Arina et al. Eur. Phys. J. C, 81(3):223, 2021
A.Liam Fitzpatric et al. arXiv: 1211.2818
Fady Bishara et al. JHEP 11:059, 2017

Backup

- **Matched to non-relativistic EFT operators**
  - DMFormFactor. N. Anand, A. Fitzpatrick, W. Haxton PRC 89, 065501 (2014)
- **ROI:** same as WIMP
- **Xenon recoil spectra @ 30 and 100 GeV DM**



Backup

- **A dedicated MC attenuation simulation for PandaX experiment**
  - For T_χ> 0.2 GeV, QE becomes significant
  - Elastic & Quasi-elastic process is included.

L. Su, L. Wu, NZ, B. Zhu arXiv:2212.02286

- **ROI:** same as WIMP