Dark Matter Searches with PandaX Experiment

Ning Zhou （周宁）

Shanghai Jiao Tong University

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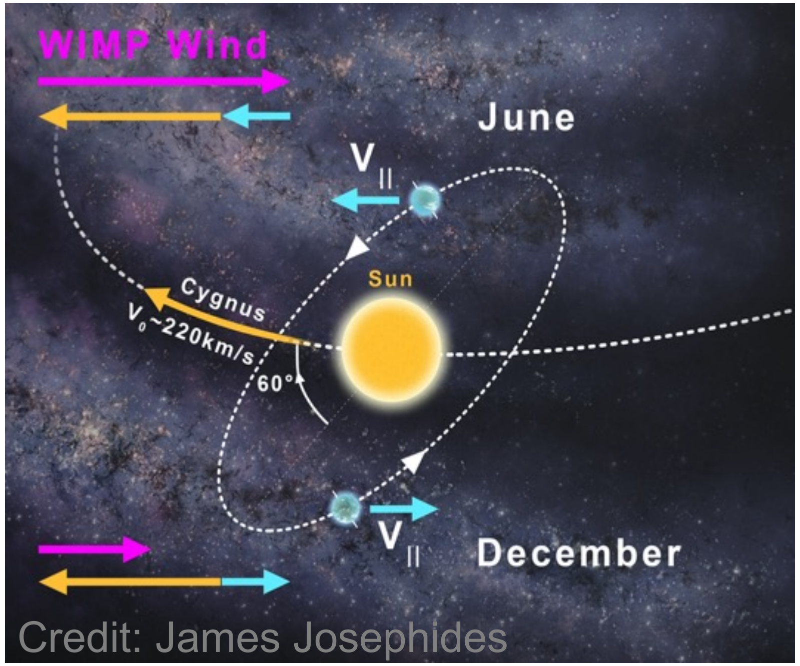
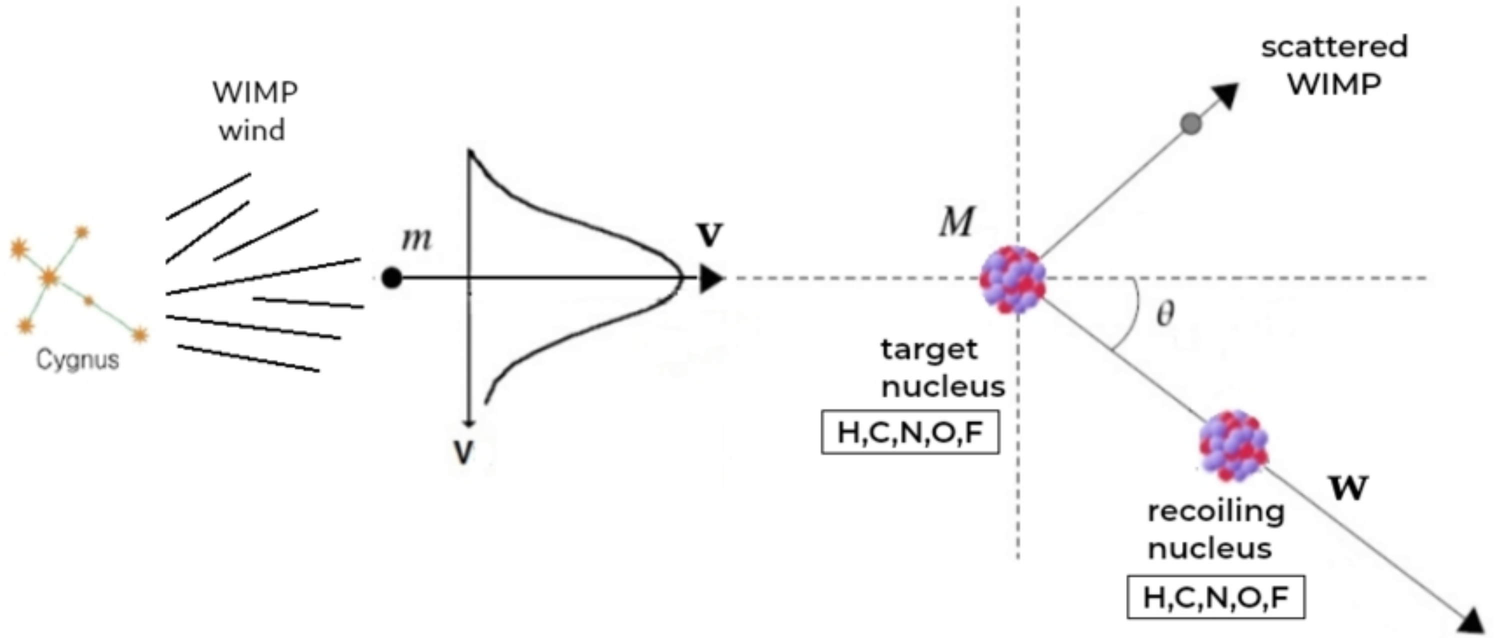
Dark Matter Direct Detection

- **Incoming dark matter from the universe**
- **Scattering with target atom (nucleus and electrons)**
  - Goodman and Witten (1985)
  - Energy deposit in the detector

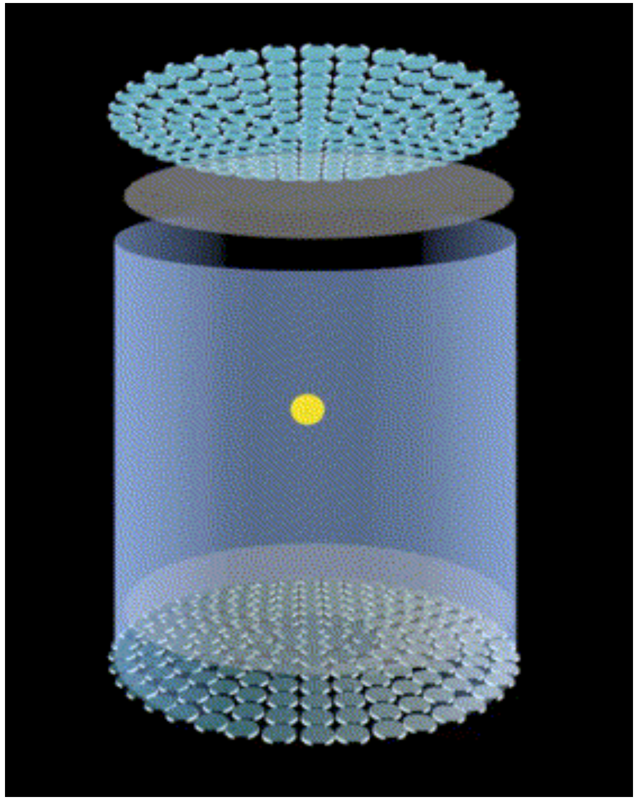


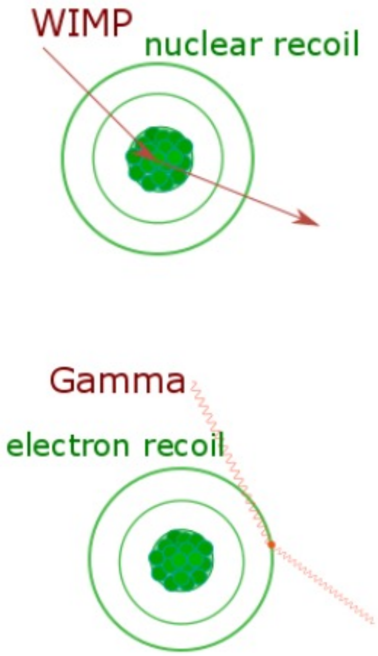
Credit: James Josephides

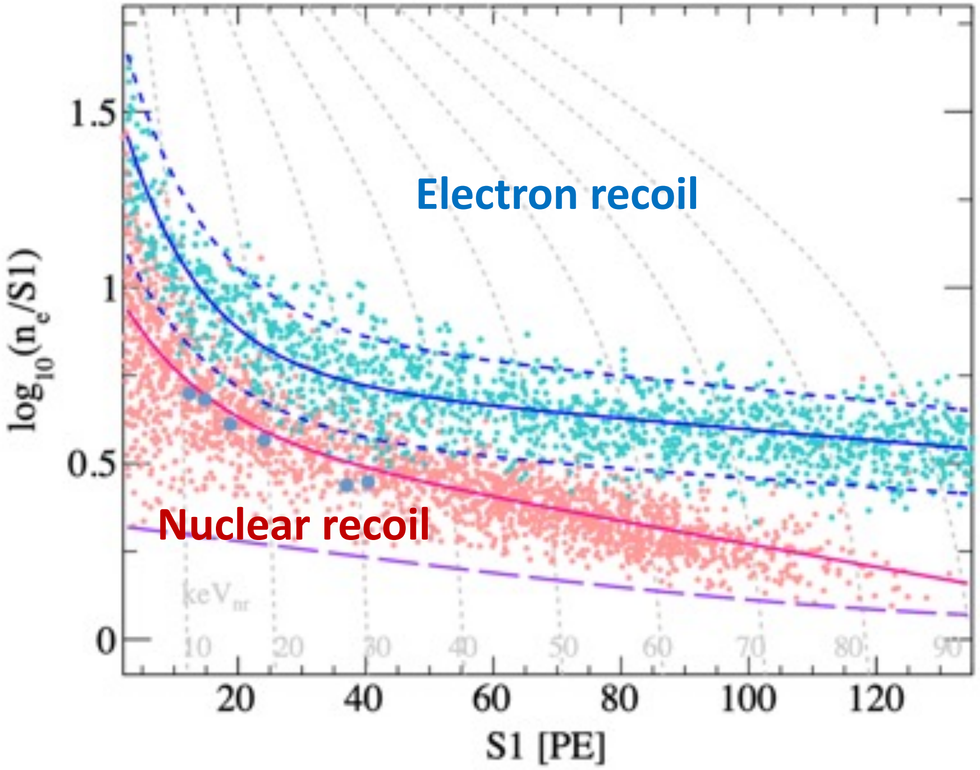


PandaX: dual-phase xenon TPC

- **Paired scintillation (S1) and ionization (S2) signals**
  - Precise energy measurement and 3-D position reconstruction
  - Discrimination of nuclear recoil and electron recoil signals







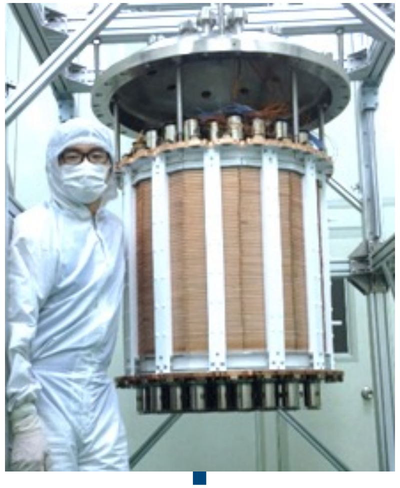
PandaX Detectors

- **Increasing the detector sensitive target volume**
- **Lowering radioactive background**

PandaX start

PandaX-I
120kg

PandaX-II
580kg

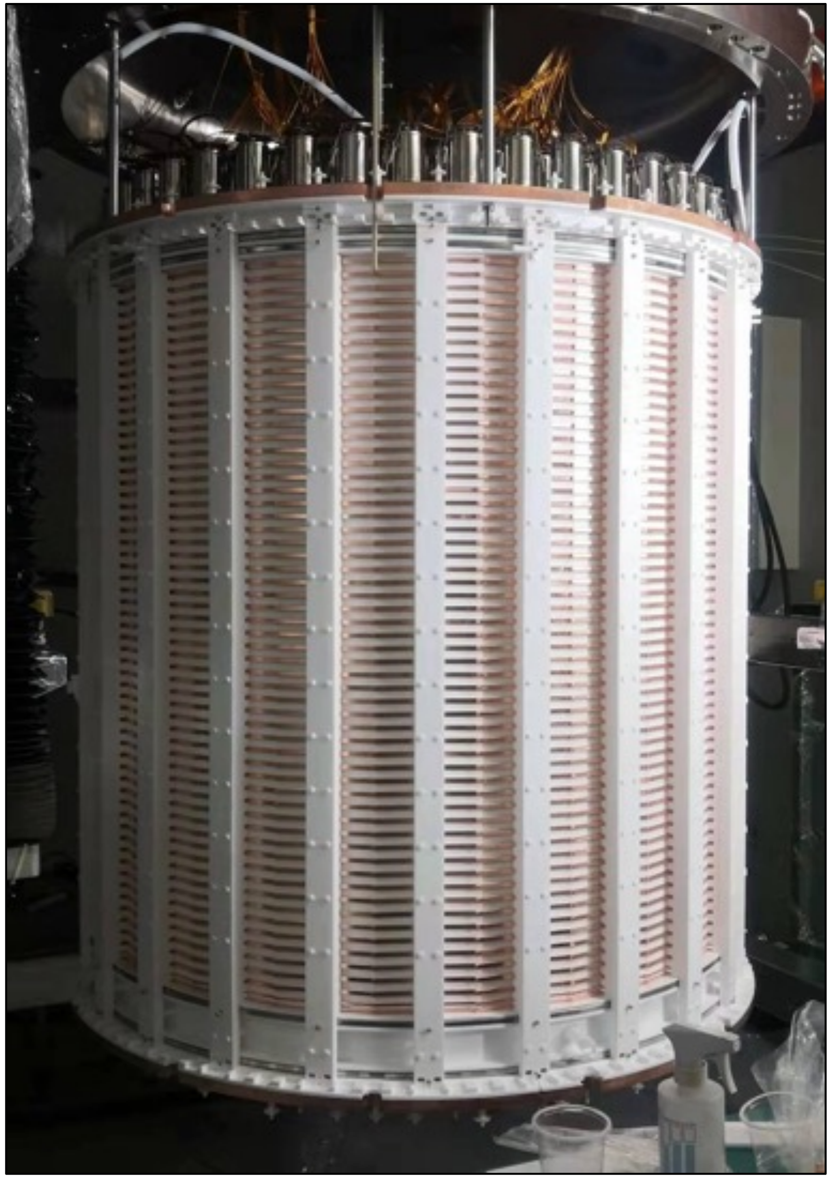


PandaX-4T
(3.7 tonne)

2009 | 2010-2014 | 2015-2019 | 2020-

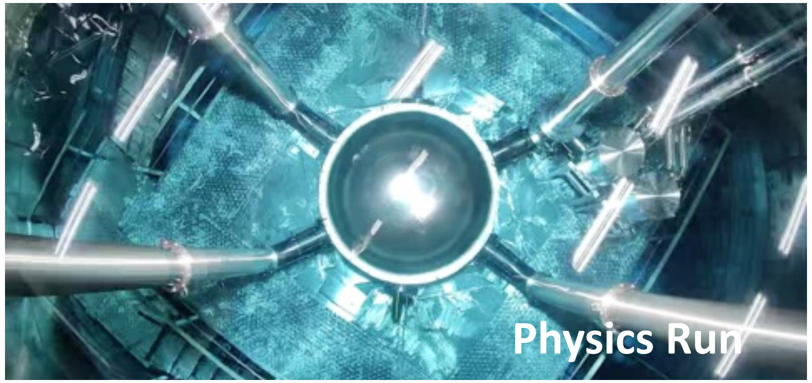
PandaX-4T Experiment

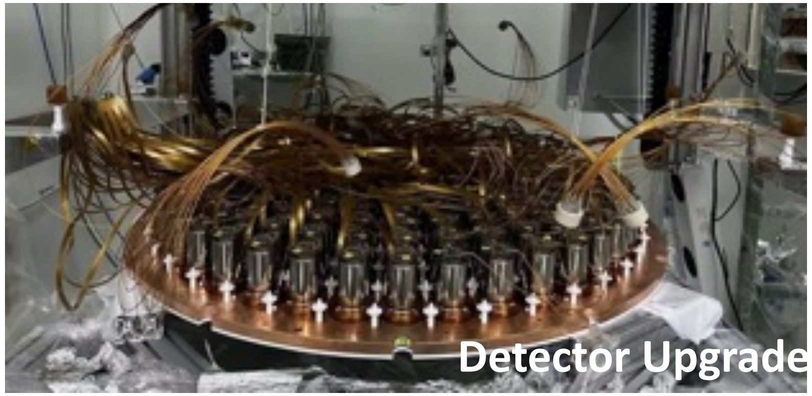
- **Sensitive volume: 3.7 tonne xenon**
- **800m^3 high-purity water shielding tank**
- **Commissioning started in 2020/11**



Physics Run

2020/11 – 2021/04	**Commissioning (Run 0)** 95 days: ~0.6 tonne-year
2021/07 – 2021/10	**Tritium removal** xenon distillation, gas flushing, etc
2021/11 – 2022/05	**Physics run (Run 1)** 164 days: ~1.0 tonne-year
2022/09 – 2023/09	**CJPL B2 hall construction** xenon recuperation, detector upgrade
Expect to resume by the end of 2023	

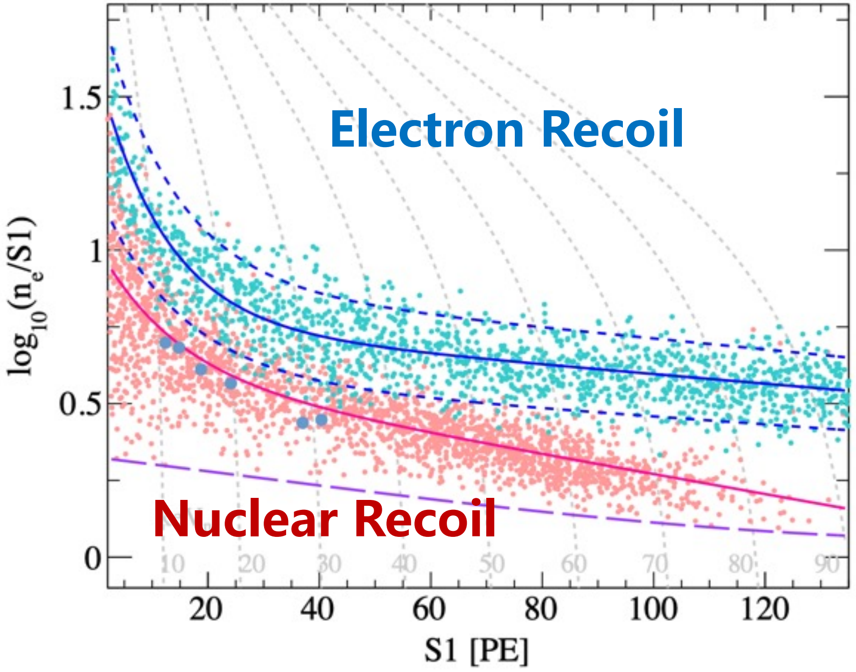




Detector Response Model

- **Detector response to DM signals**

Signal type	Response model parameters
DM-nucleon scattering **Nuclear Recoil Signal** **DM-electron scattering** **Electron Recoil Signal**	1. Energy reconstruction 2. Light yield 3. Charge yield 4. Re-combination & fluctuation



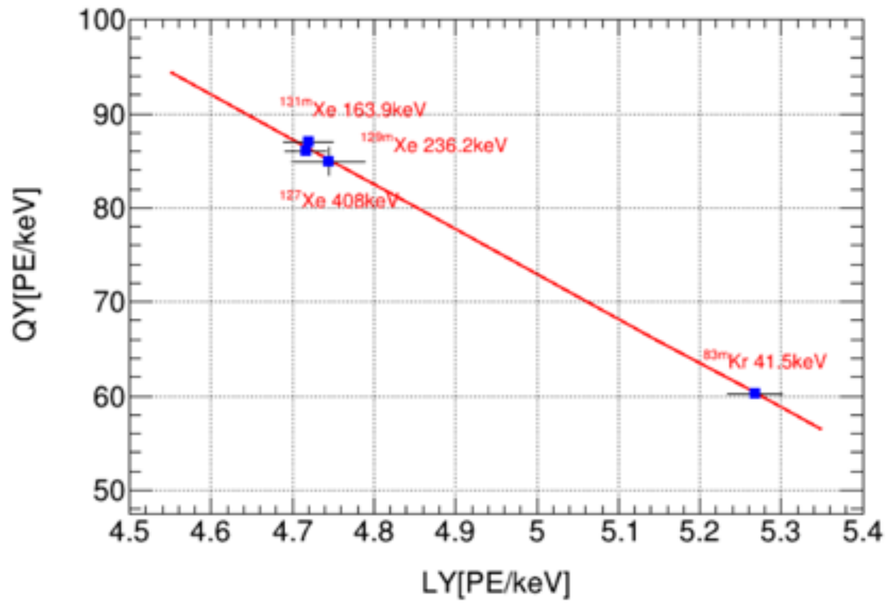
- **Various calibration approaches**

Type	Source	Method
Electron recoil	$^{83m}Kr/^{220}Rn$	injecting gas source
Nuclear recoil	^{241}Am-Be	external source
Nuclear recoil	D-D neutron	external source

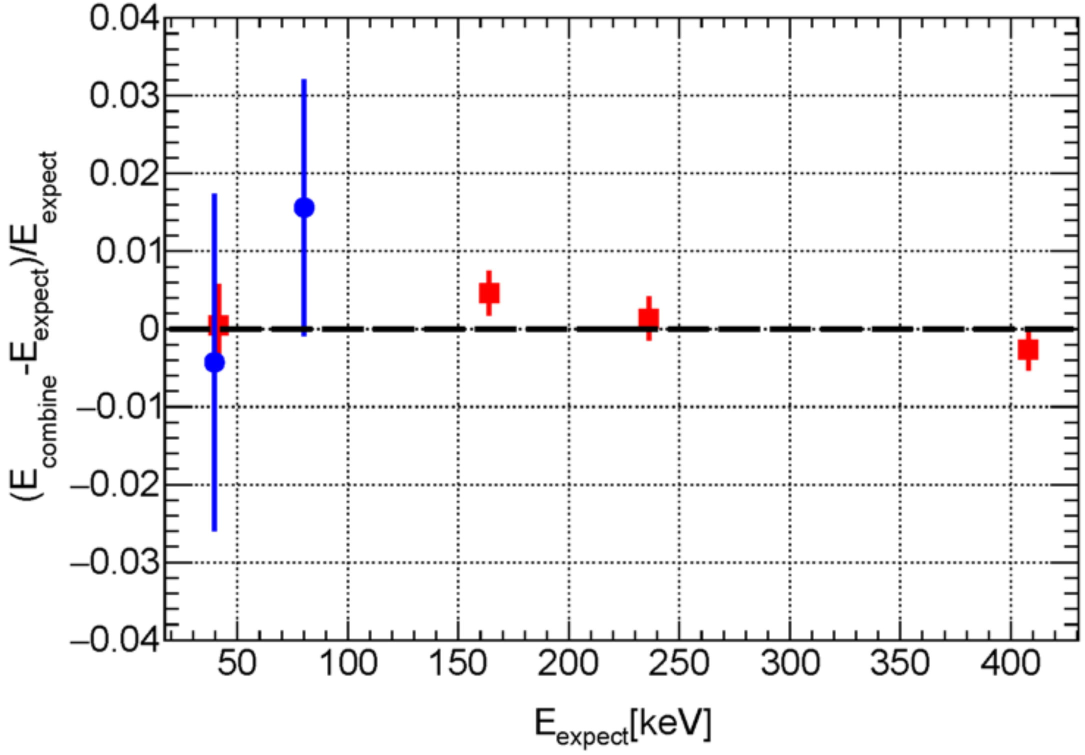
Energy Reconstruction

- **Light (S1) + Ionization (S2)**
- **Energy resolution @41.5keV: 6.8%**

$$E = 13.7\text{eV} \times \left(\frac{\text{S1}}{\text{PDE}} + \frac{\text{S2}_\text{b}}{\text{EEE} \times \text{SEG}}\right)$$

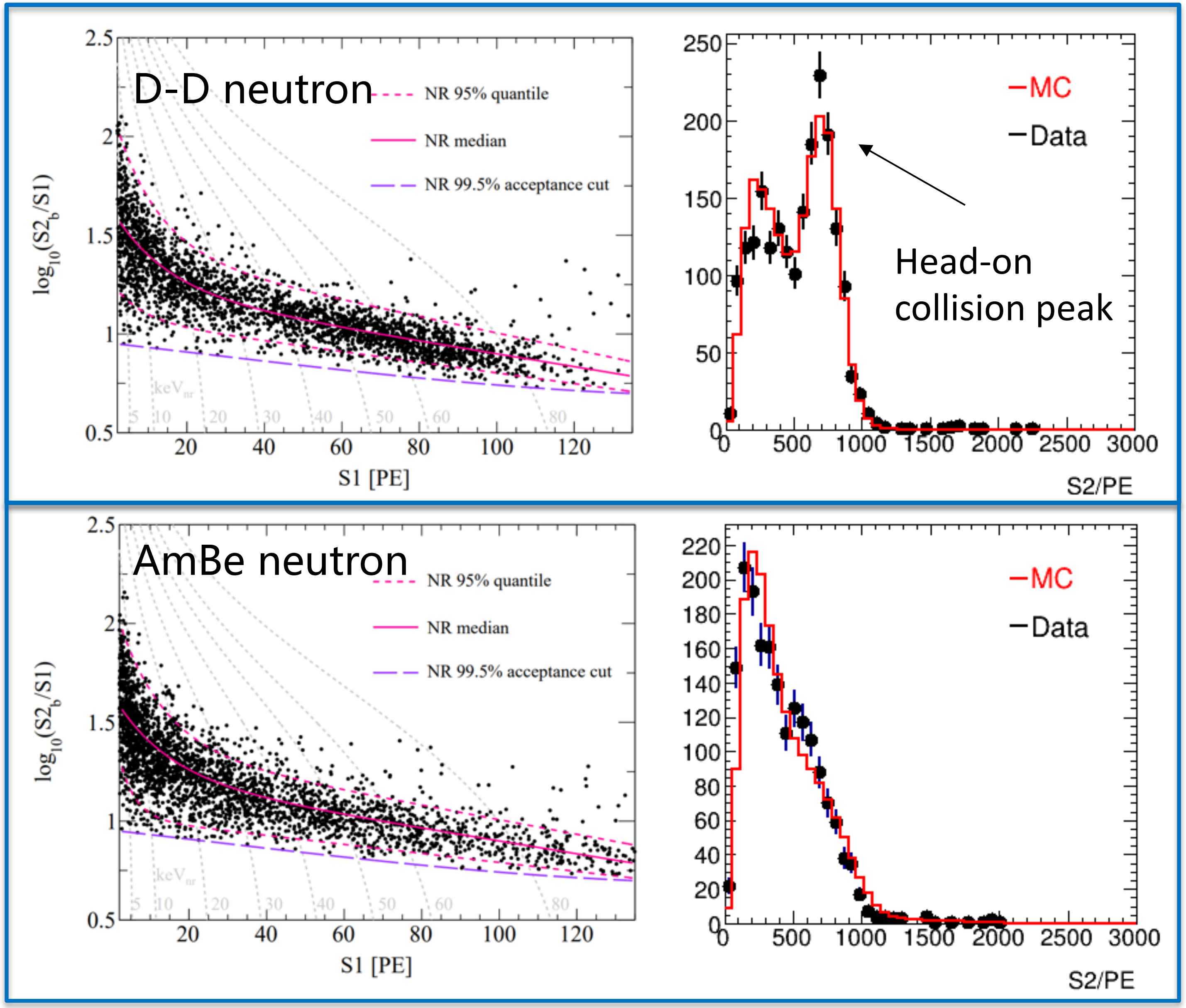


#Set	PDE [%]	EEE [%]	SEG [PE/e]
1-2	9.0±0.2	90.2±5.4	3.8±0.1
3-5	9.0±0.2	92.6±5.4	4.6±0.1



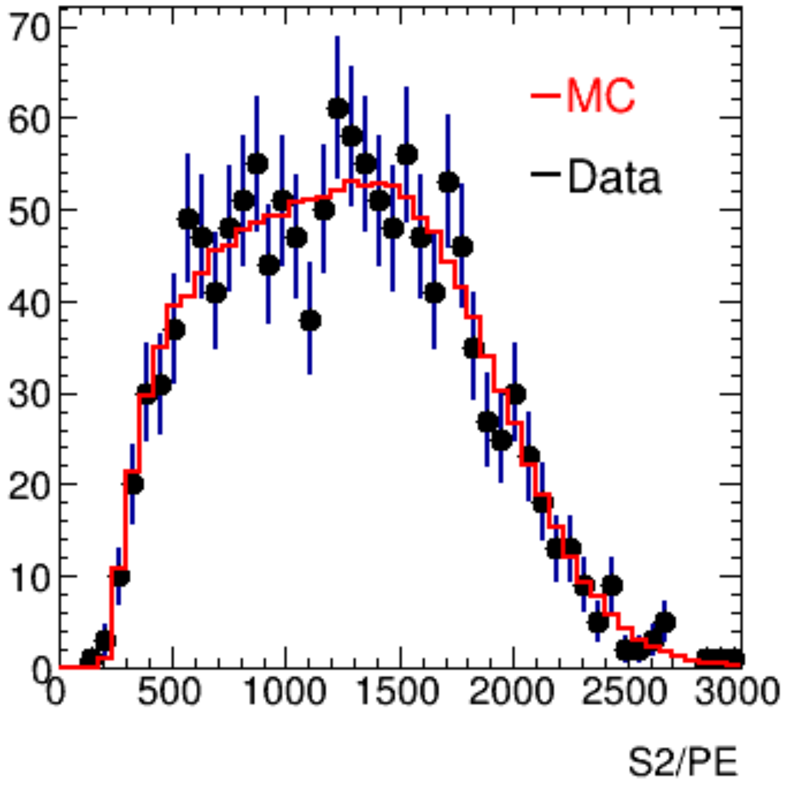
Nuclear Recoil Calibration

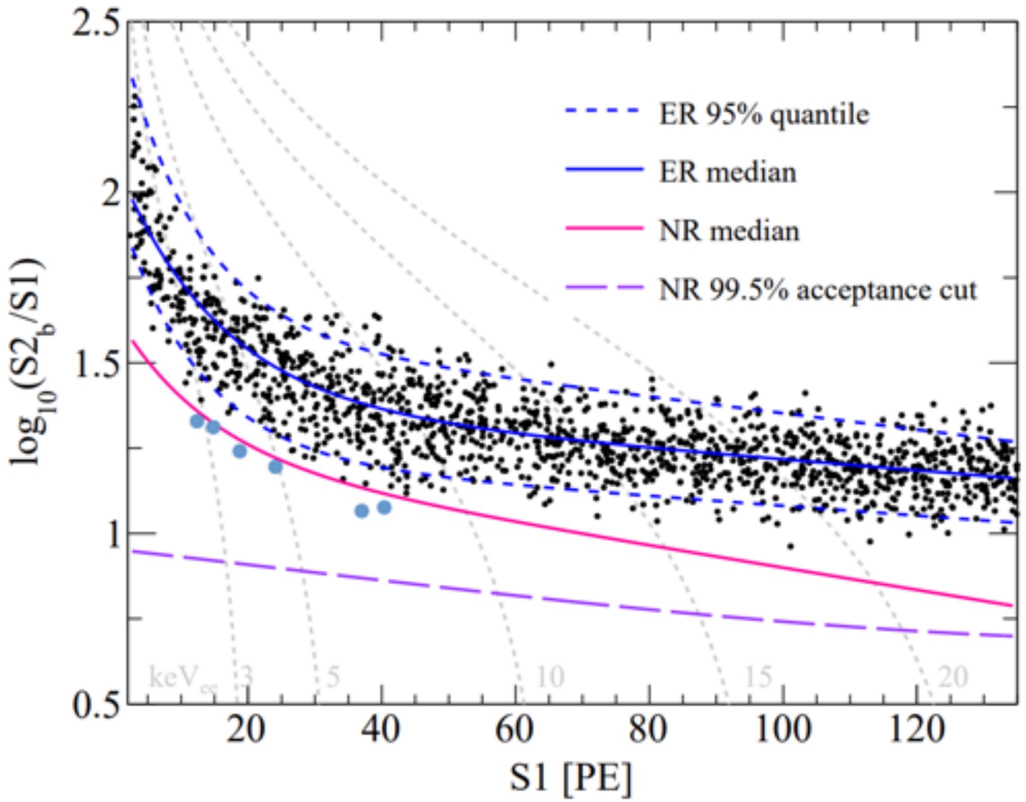
- **Neutron sources**
  - Deuteron-deuteron and AmBe neutrons
- **Combined fitting to get the parameters**
  - Light yield
  - Charge yield
  - Fluctuations



Electron Recoil Calibration

- **Inject ^{220}Rn into the detector, uniformly distributed**
- **Leakage of electron recoil events below NR median**
  - 6/1393 = 0.44±0.18%, response model agrees with data

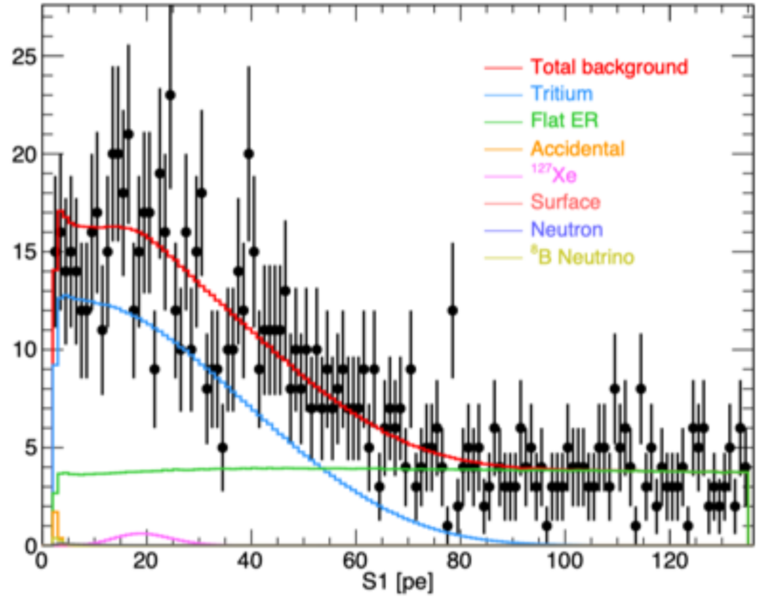




Background composition

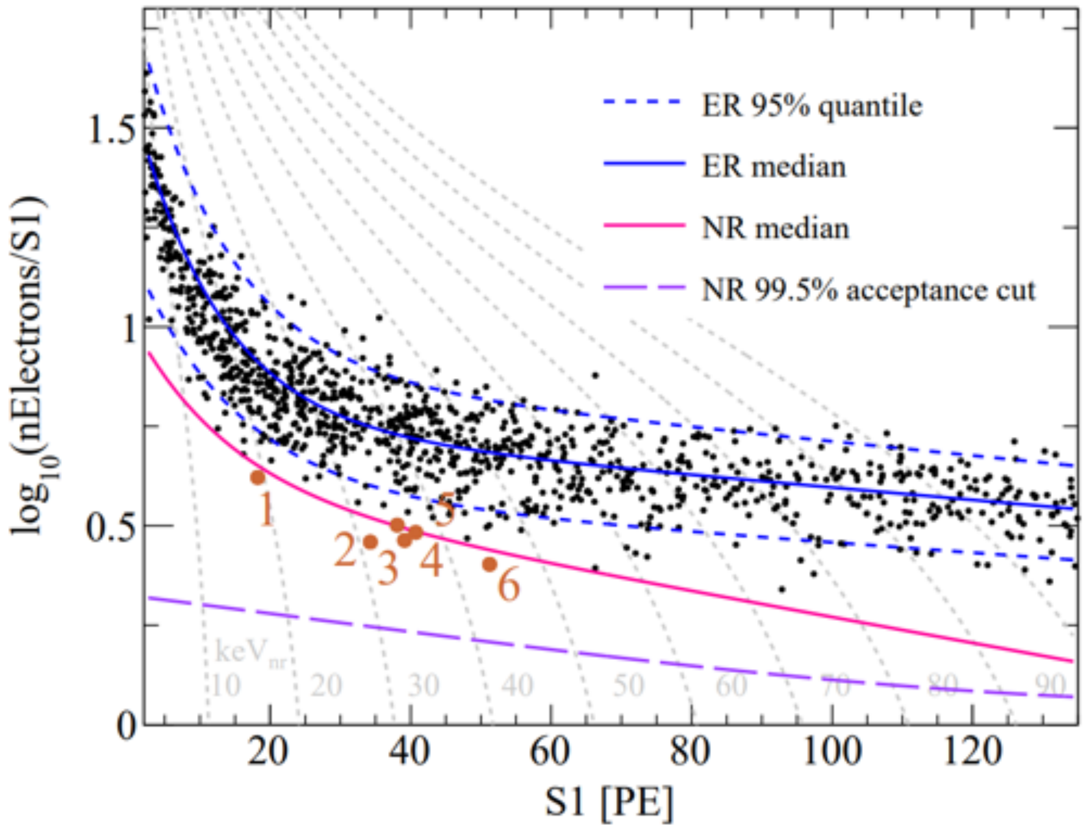
Component	Nominal (evts)
^{3}T (from fit to data)	**532 (32)**
Flat ER* (18-30keV side band)	**492 (31)**
Rn	347 (190)
Kr	53 (34)
Material	40 (5)
pp neutrino	37 (8)
Xe-136	31 (6)
Xe-127	8 (1)
Neutron	0.9 (0.5)
Neutron-X	0.2 (0.1)
Surface	0.5 (0.1)
Accidental	2.4 (0.5)
B8	0.6 (0.3)
Sum	**1037 (45)**

- **Background level at low energy region is 1/4 of PandaX-II**
  - Radon is reduced to 1/6
  - Kr is reduced to 1/20
  - Residual tritium is observed



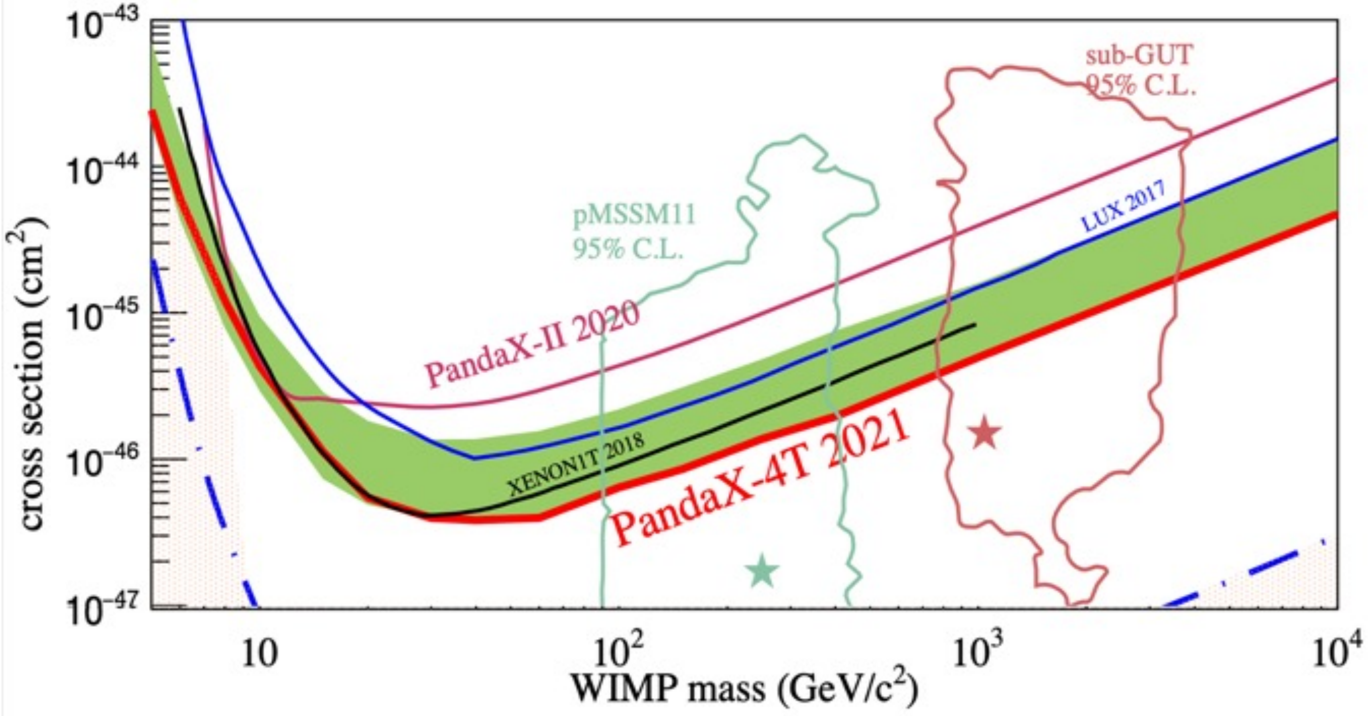
Signal ROI

- **Fiducial volume: 2.67 tonne xenon**
- **Exposure: 0.63 tonne-year**
- **Signal selection criteria**
  - S1: 2 – 135 PE
  - S2raw: > 80 PE
  - S2 < 20000 PE
- **Data: 1058 events observed**
  - 6 events below NR median, consistent with expectation of 9.8±0.6 events



DM-nucleon Spin-independent Scattering

- **Sensitivity improved from PandaX-II final analysis by 2.6 times at 40 GeV/c²**
- **Dived into previously unexplored territory!**



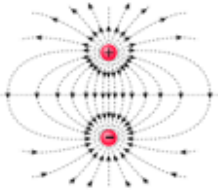
PRL 127, 261802 (2021), **Editors' suggestion**

Luminance of Dark Matter

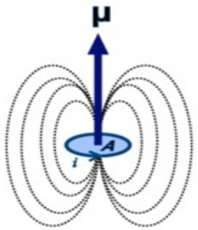
- **Residual weak EM properties: coupling with photons**

微弱电荷
millicharge

电荷半径
charge radius



电偶极矩
electric dipole



磁偶极矩
magnetic dipole

零极矩
anapole

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

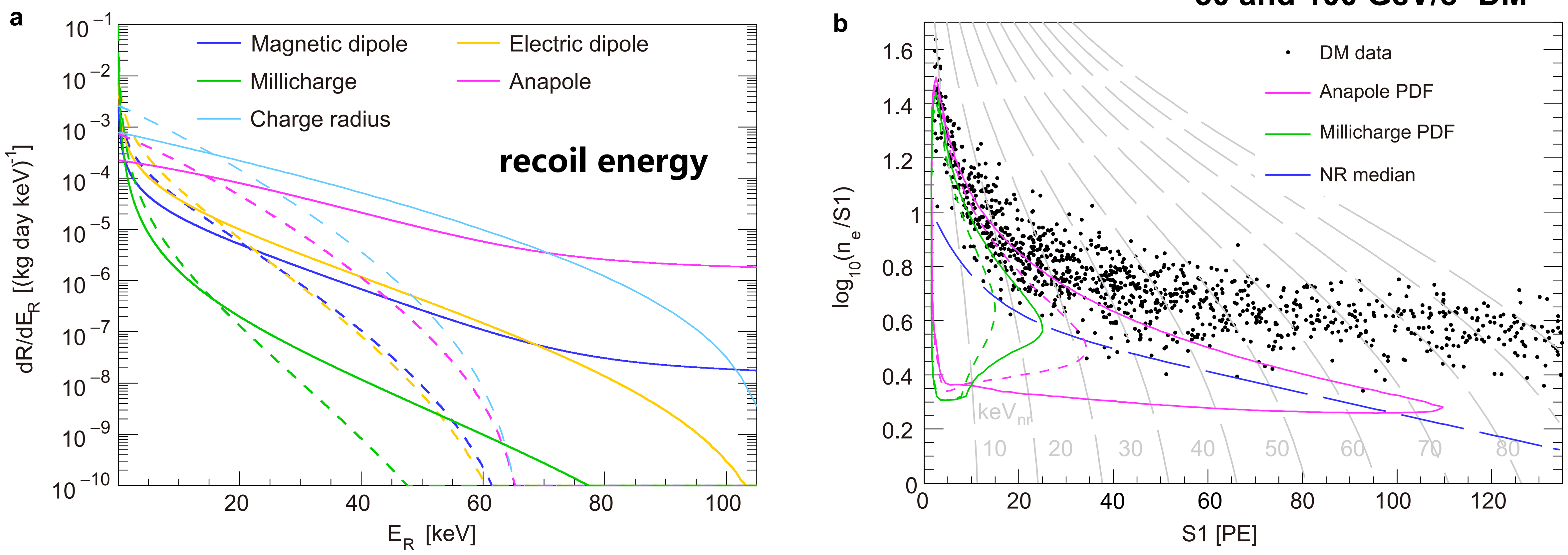
millicharge | magnetic dipole | electric dipole | charge radius | anapole

tree-level | **higher-order loop-level**

Photon-Mediated Interaction

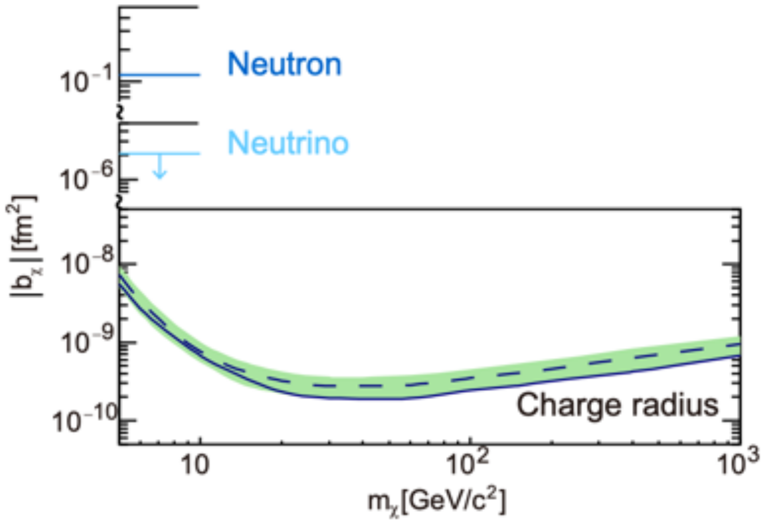
- **Various nuclear recoil signatures**
- **Dedicated searches of these EM properties**

30 and 100 GeV/c² DM



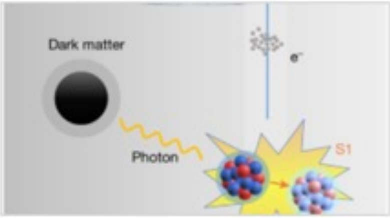
Results from Xenon Recoil Data

- **First experimental constraints on DM charge radius**
  - 4 orders of magnitude smaller than neutrino
- **Strong constraints on other EM properties**
  - – up to 3 – 10 times improvement



Limits on the luminance of dark matter from xenon recoil data

A direct search for effective electromagnetic interactions between dark matter and xenon nuclei that produce a recoil of the latter is carried out and the first constraint on charge radius of dark matter is derived.



Xuyang Ning, Abdusalam Abdukerim ... Yubo Zhou

Article | 17 May 2023

Table 1 | Comparison of electromagnetic properties

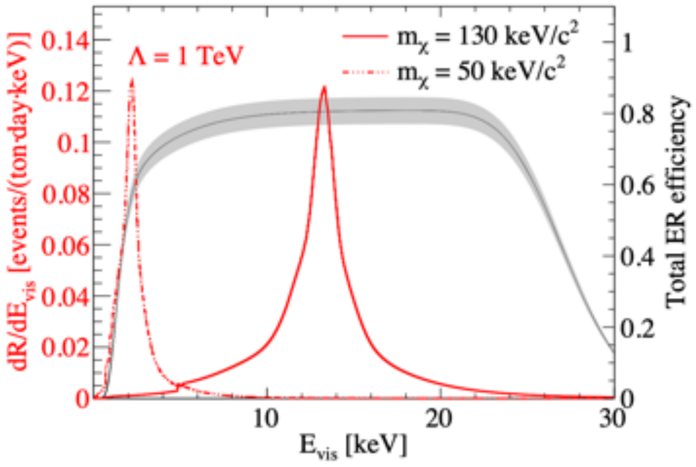
	dark matter	neutrino	neutron
Charge radius (fm^2)	$<1.9\times10^{-10}$	$[-2.1,3.3]\times10^{-6}$ *	-0.1155 *
Millicharge (e)	$<2.6\times10^{-11}$	$<4\times10^{-35}$ *	$(-2\pm8)\times10^{-22}$ *
Magnetic dipole (μ_B)	$<4.8\times10^{-10}$	$<2.8\times10^{-11}$ *	-1×10^{-3} *
Electric dipole (ecm)	$<1.2\times10^{-23}$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

* Datas are taken from PDG [32]
† Taken from [31]
‡ Taken from [33]
§ Taken from [34]

Nature Vol. 618, Issue 7963, 47-50 (2023)

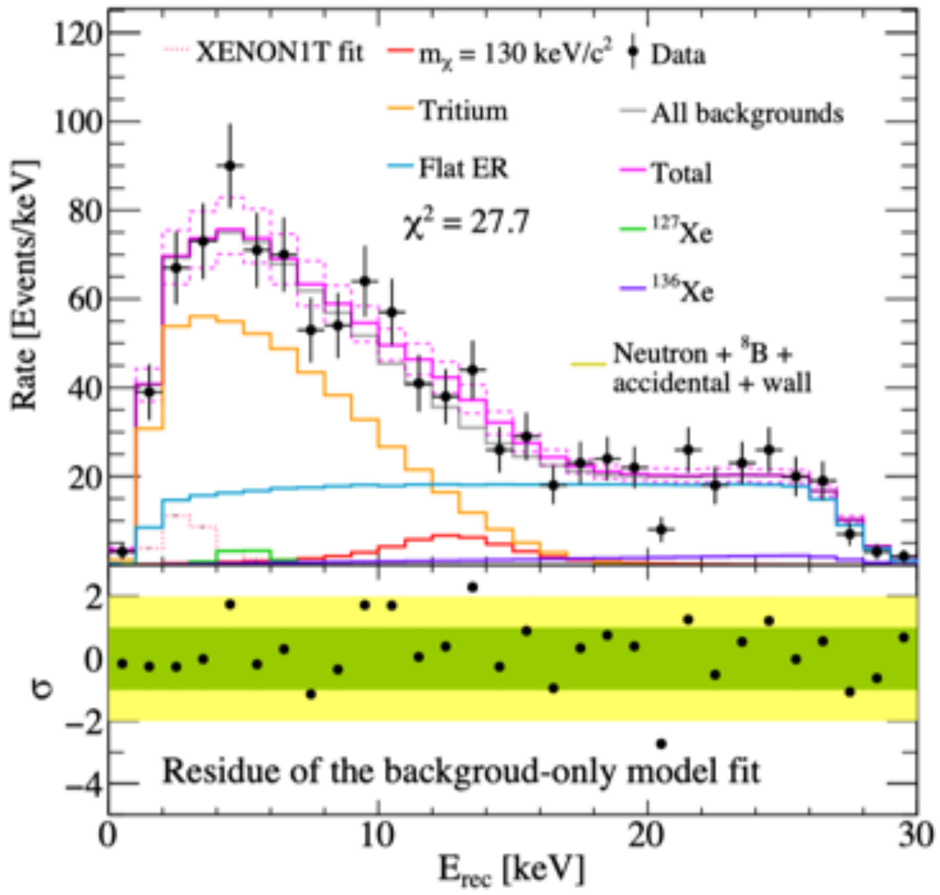
DM-electron Scattering

- **DM and neutrino may have a connection**
  - Behave similarly as a heavy neutrino
  - **Mono-energetic recoil energy**



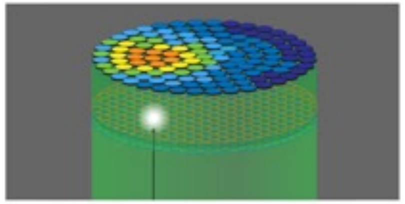
- **Bump-hunting on the electron recoil spectrum**

$\chi e \to e\nu$



Cross-check XENON1T Excess

- **Effective field models**
  - vector, axial-vector
- **Result doesn’t support the excess**



Physics NEWS AND COMMENTARY

Potential Dark Matter Signal Gives Way to New Limits

October 13, 2022

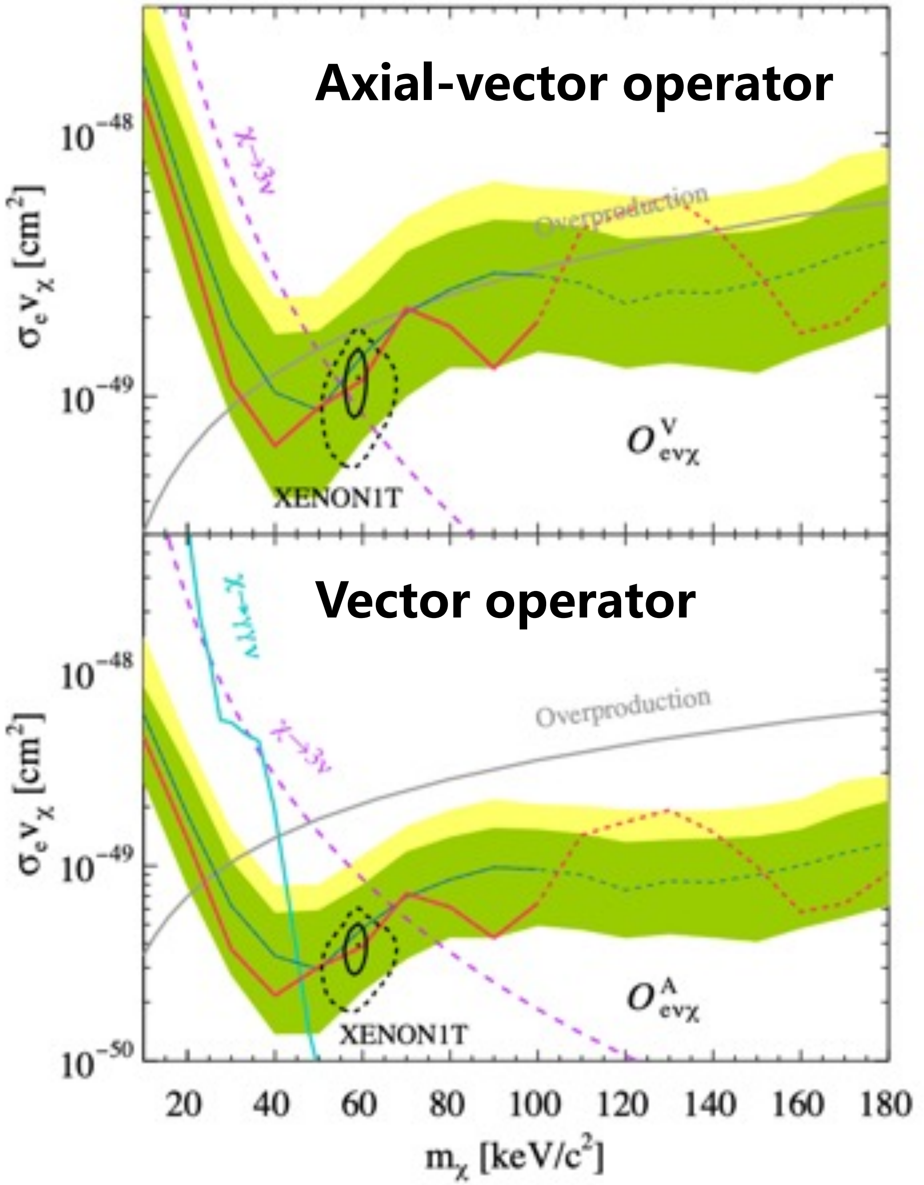
Results from two leading dark matter experiments—XENONnT and PandaX-4T—rule out an enigmatic signal detected in 2020 and set new constraints on dark matter particle candidates consisting of light fermions, respectively.

Feature on:

E. Aprile *et al.* (XENON Collaboration)
Phys. Rev. Lett. **129**, 161805 (2022)

Dan Zhang *et al.* (PandaX Collaboration)
Phys. Rev. Lett. **129**, 161804 (2022)

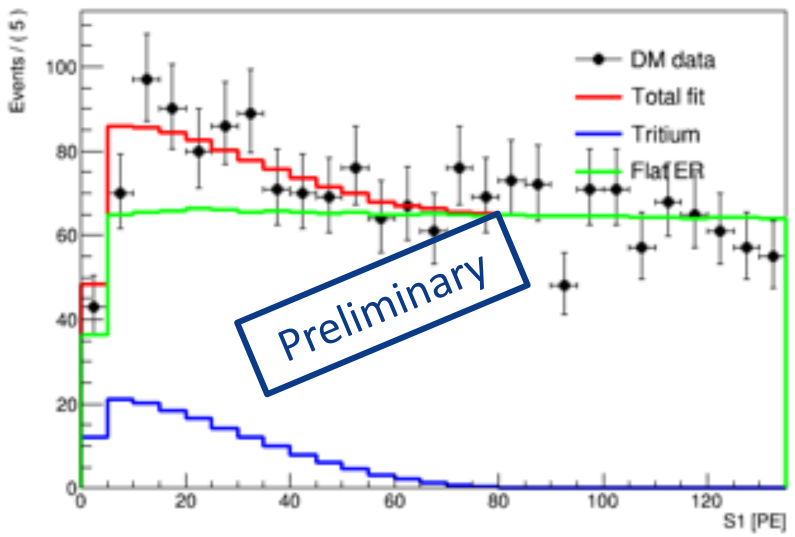
PRL 129, 161804 (2022) **Editors’ Suggestion**

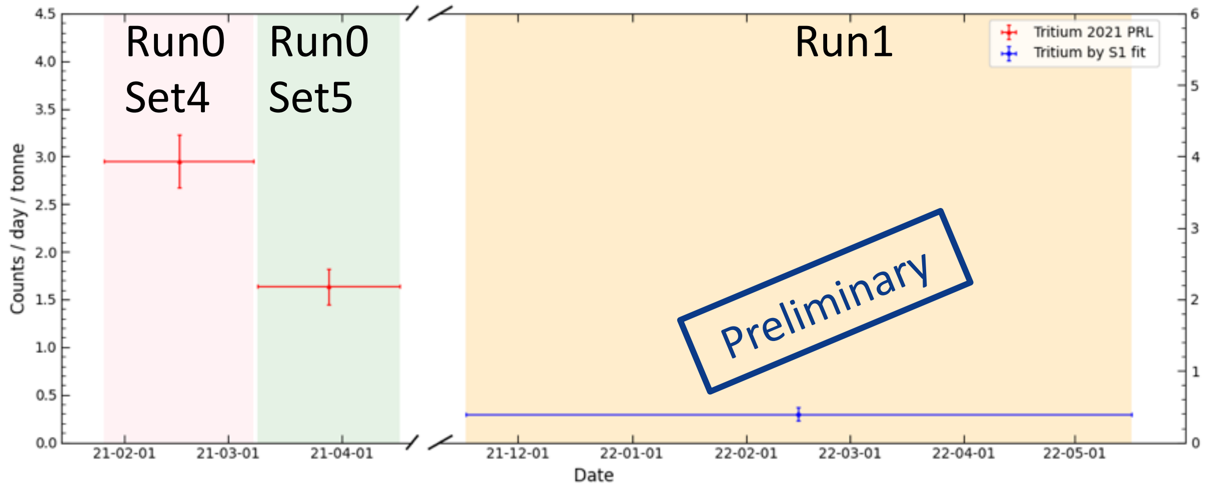


Tritium Removal

- **Preliminary estimation of tritium level for Run 1**
  - Fitting S1 spectrum, **keeping S2 blinded**
- **Extensive tritium measures planned for next run (Run 2)**

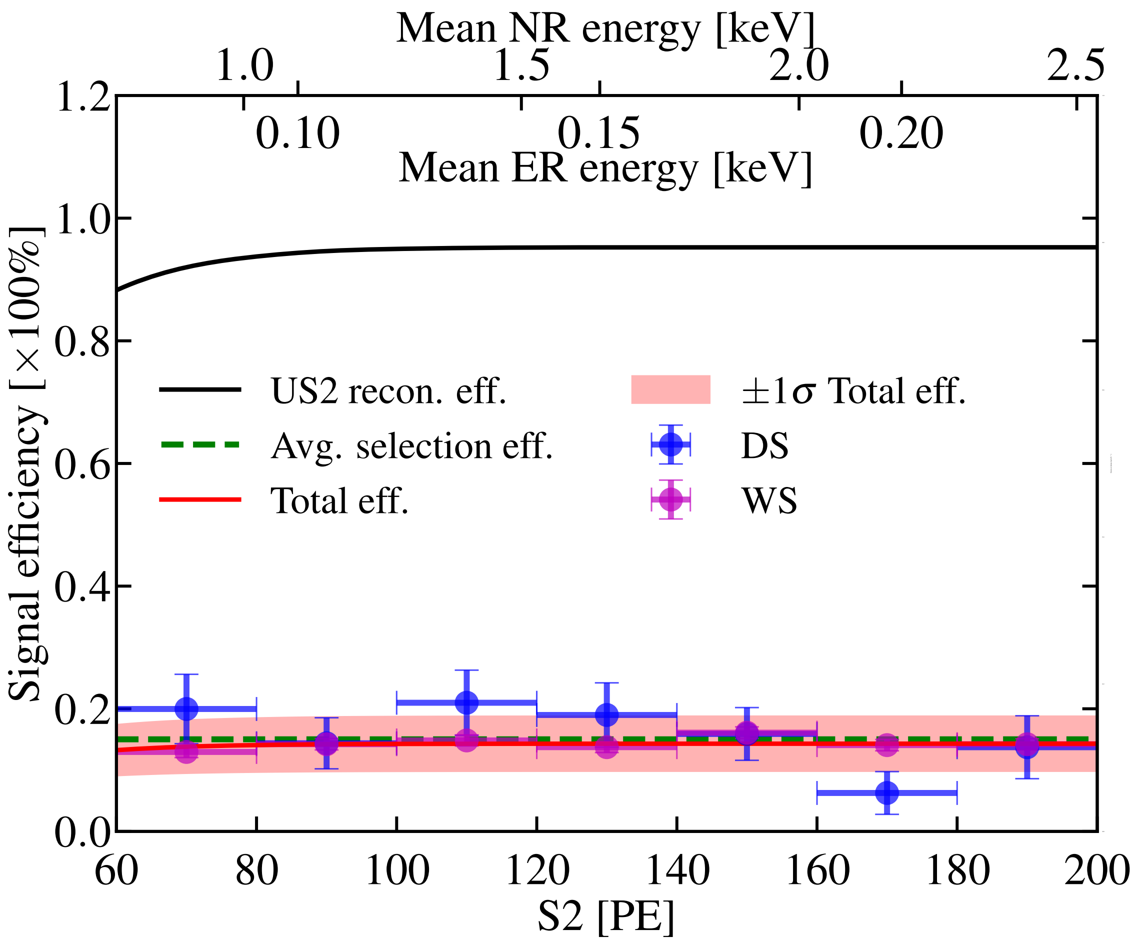
Period	Run0 Set 4	Run0 Set 5	Run1
Tritium Counts/day/tonne	3.0 ± 0.3	1.6 ± 0.2	0.4 ± 0.1





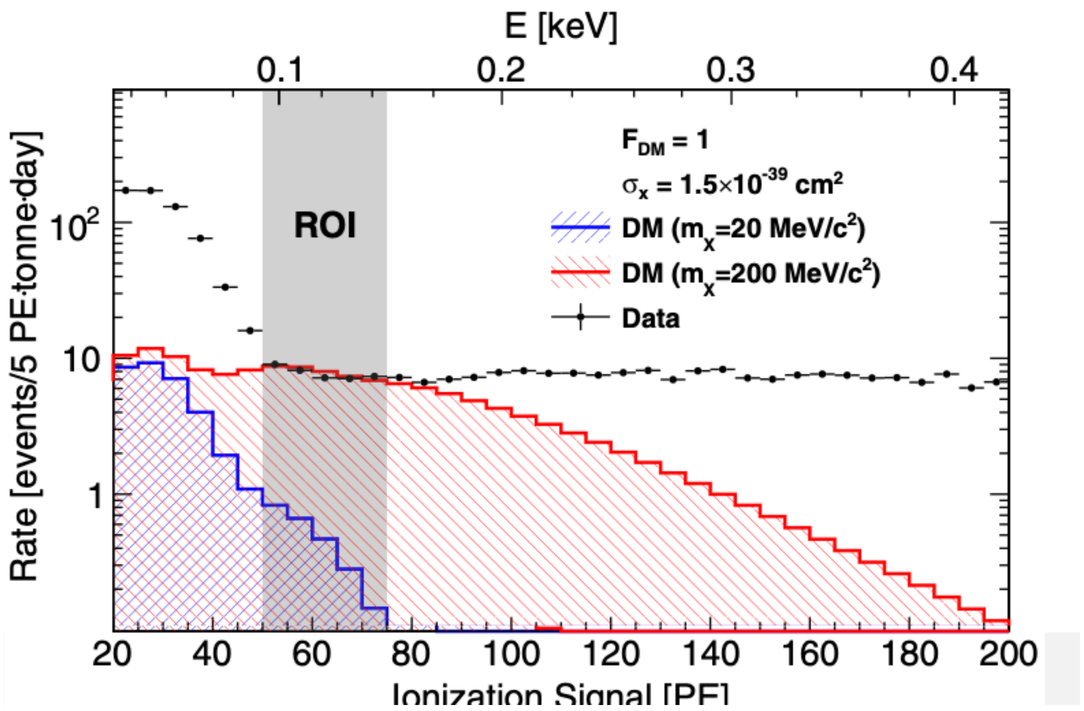
Reducing Detection Threshold

- **Ionization-only (S2-only): no scintillation signal (S1) requirement**
  - ROI S2 [60, 200]PE: threshold down to ~100 eV (from ~1 keV)

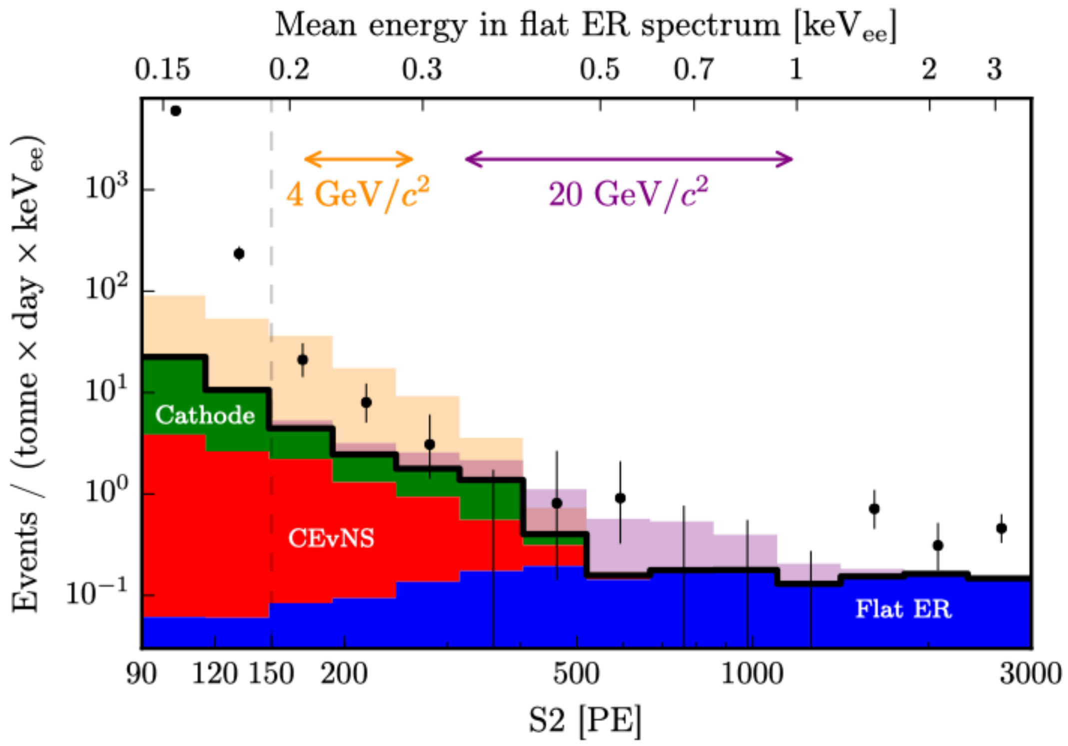


Ionization-only ROI

- **Key challenge: background components**
  - No full picture in previous xenon-based experiments
  - Conservative results only



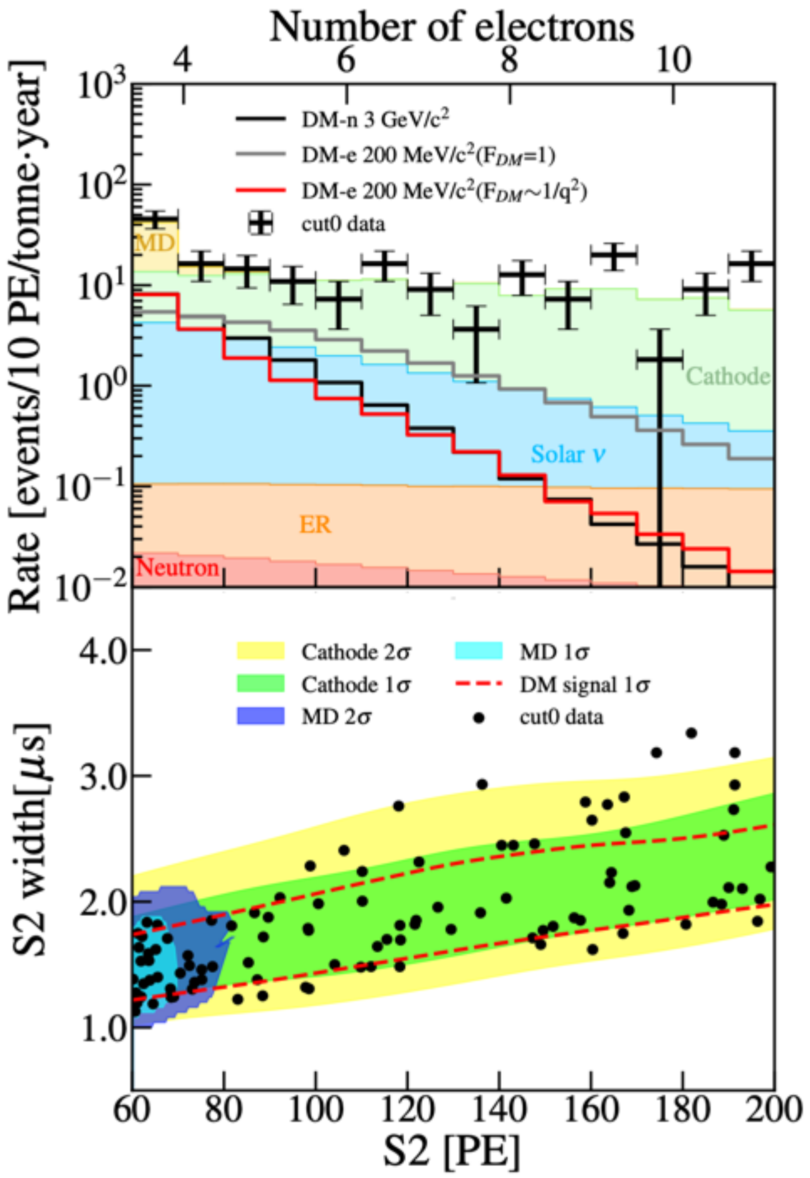
PandaX-II PRL



XENON1T PRL

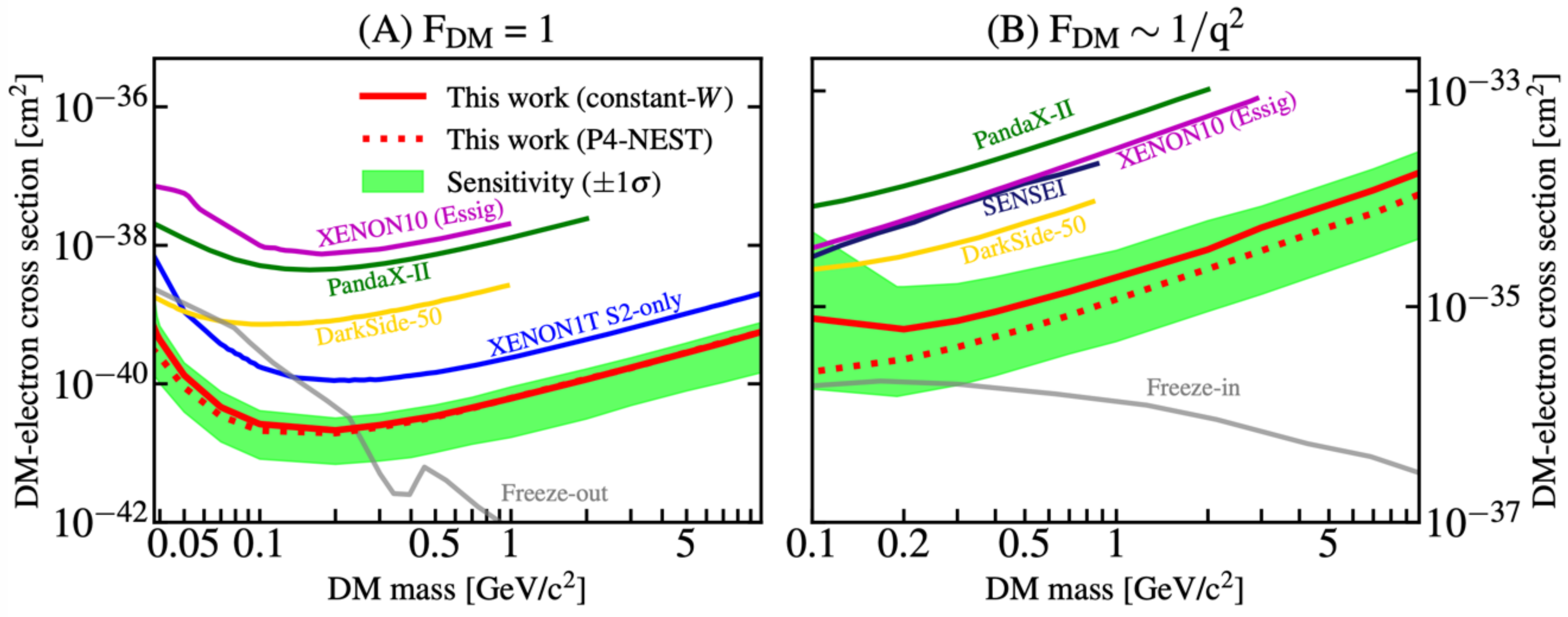
Ionization-only Data

- **First complete understanding of all the main backgrounds**
  - Micro-discharging (MD)
    - ➢ Small charge, strong run-condition dependence
  - Cathode activity
    - ➢ Large charge, large pulse-shape width
- **Blind analysis of 0.55 tonne-year exposure**
  - 105 events
  - Best-fit background: 95.8 ± 11.3



Constraints on DM-electron Scattering

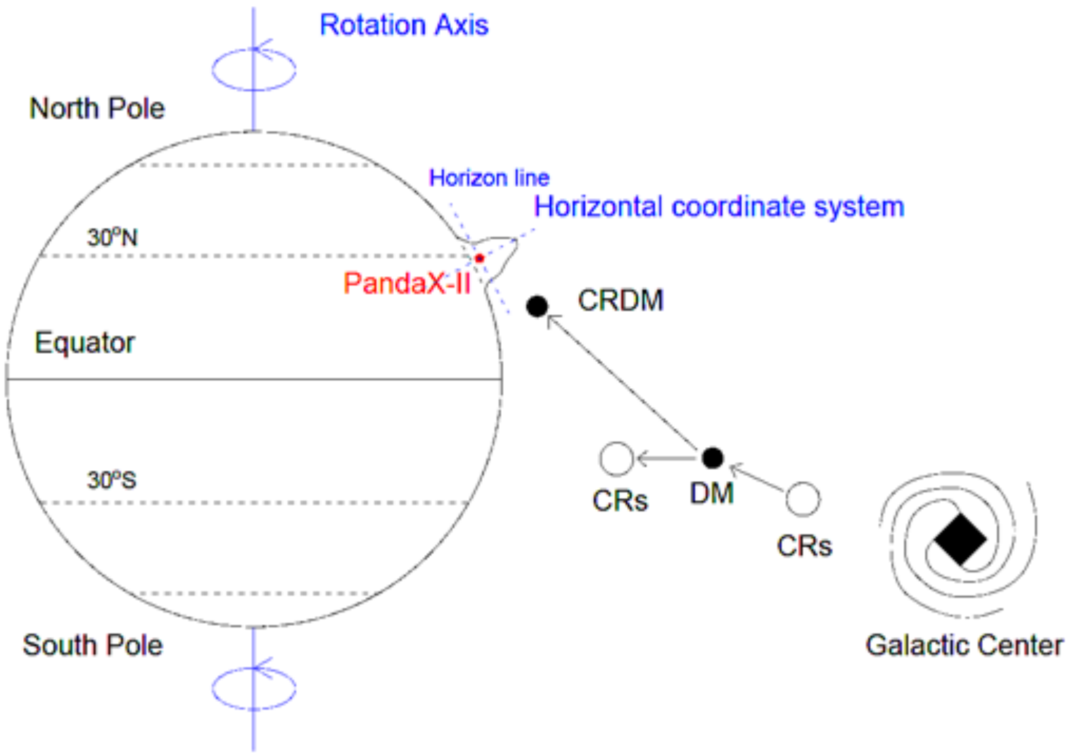
- **Most stringent constraints are derived**
  - DM-electron interaction with heavy mediator, 2×10^{-41} cm^2
  - Freeze-out and Freeze-in

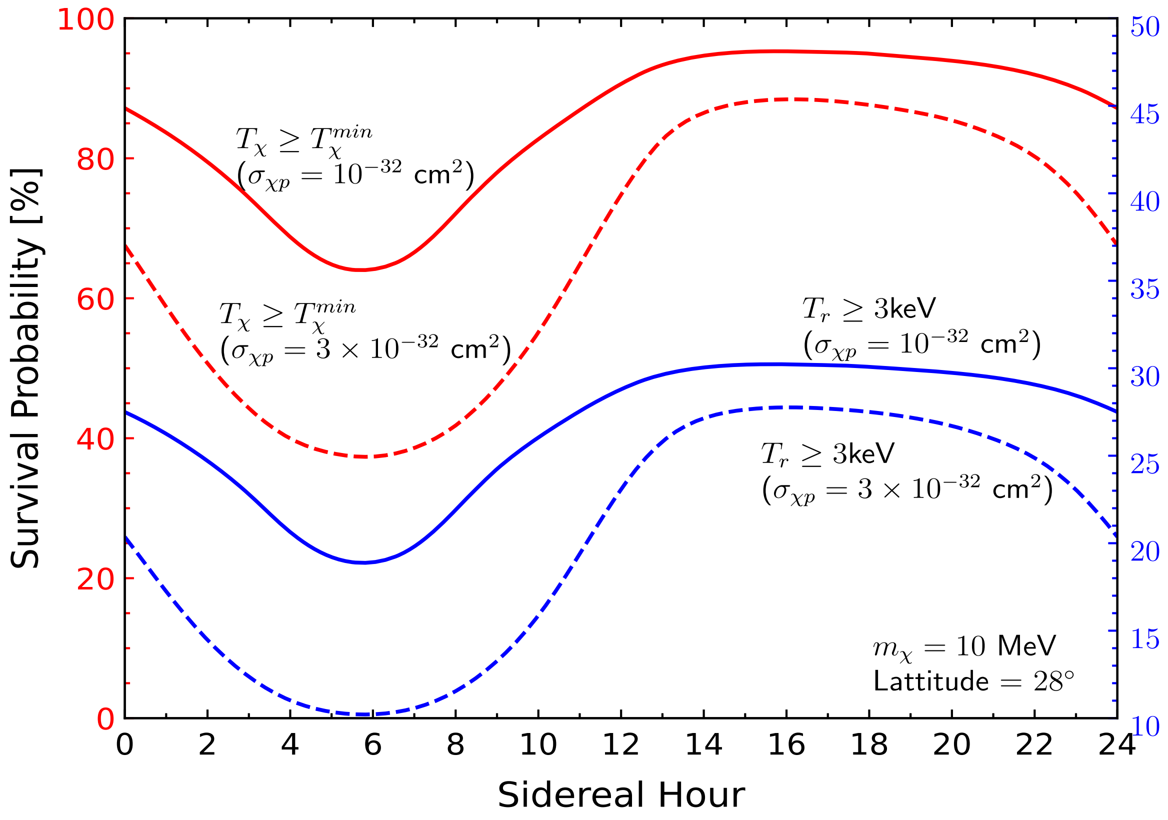


PRL 130, 261001 (2023), **Editors' Suggestion**

Cosmic-ray Boosted Dark Matter

- **Light DM with cosmic ray boosting**
- **New signature: diurnal modulation due to earth shielding**

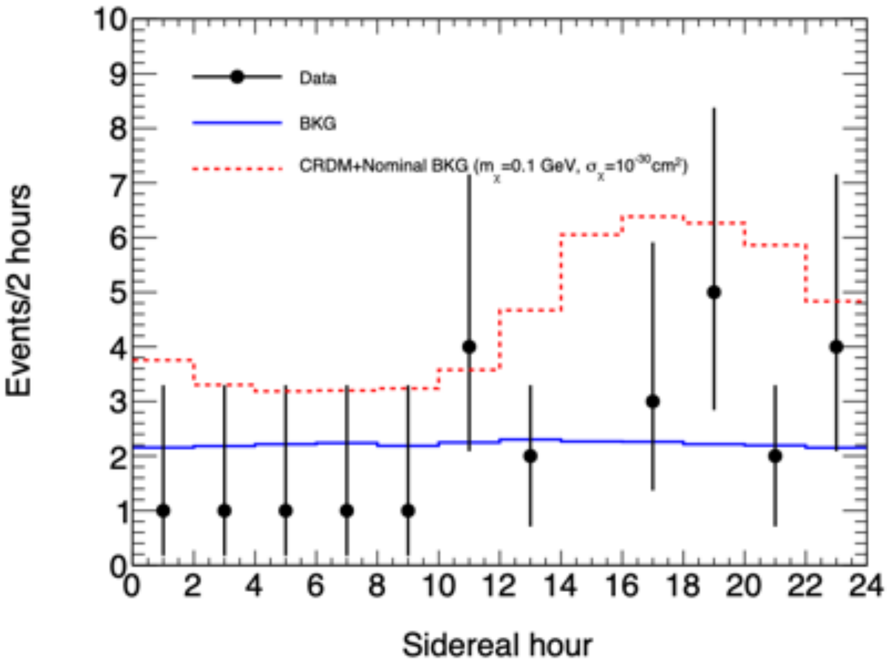


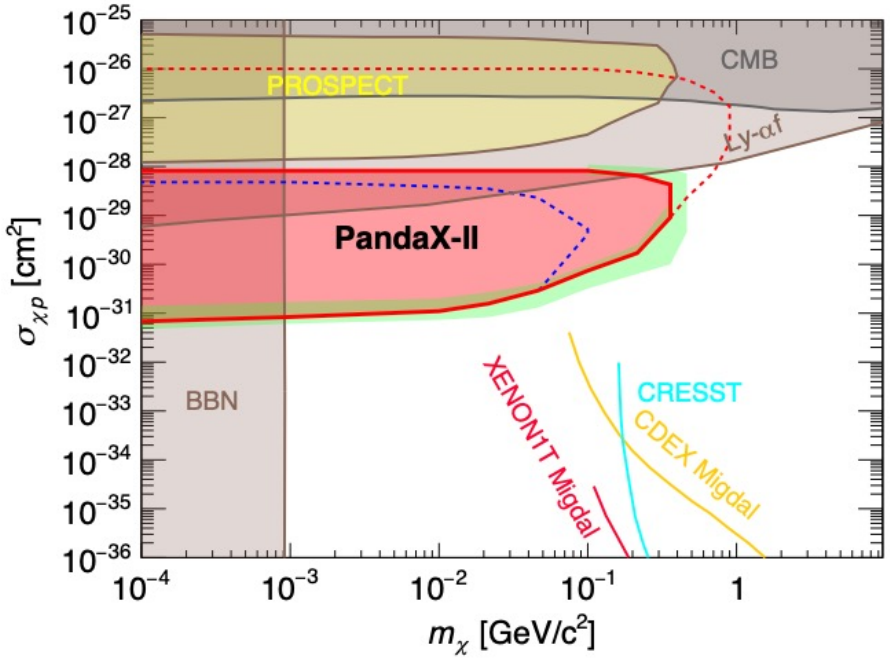


S.-F. Ge, J. Liu, Q. Yuan, NZ, **PRL** 126, 091804 (2021)

Diurnal Modulation Search

- **PandaX-II data**
  - Using events below NR median: 25 events (expected 26.6 background)
- **Extend the DM search window to sub-GeV**
  - Expand to the region beyond the astrophysical and cosmological probes

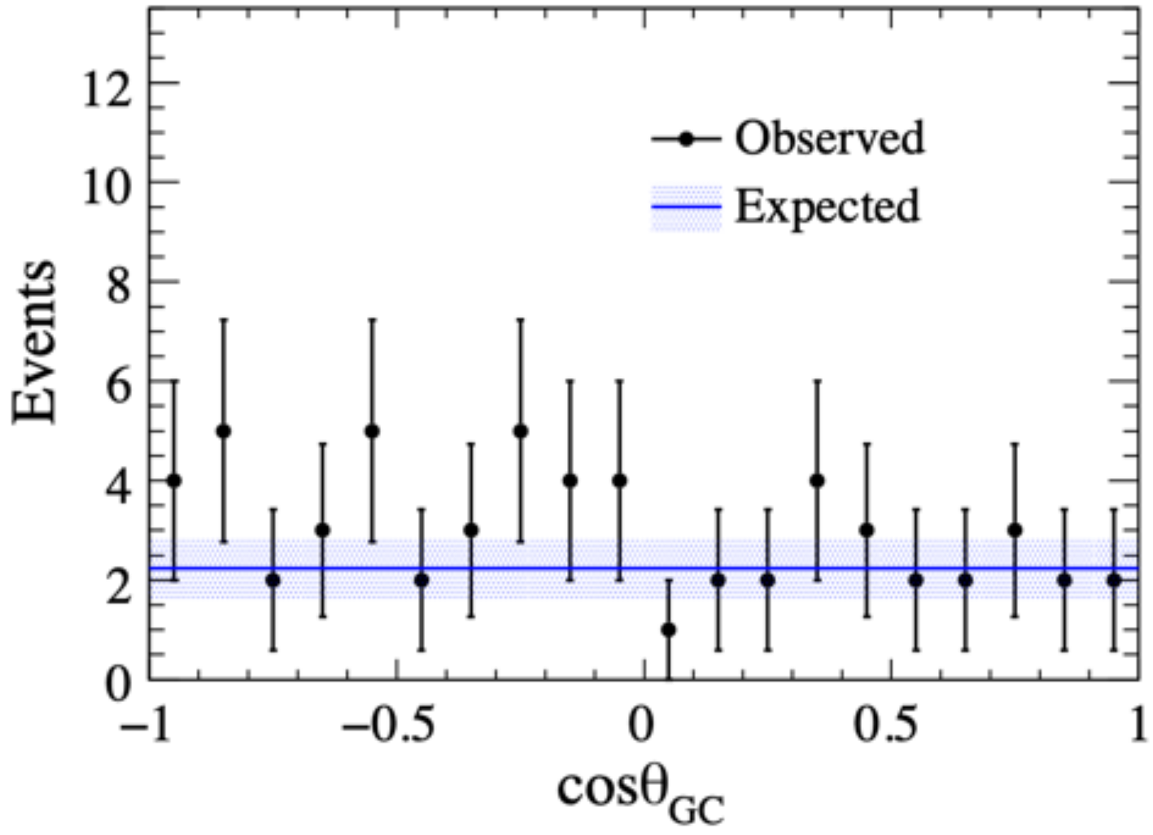


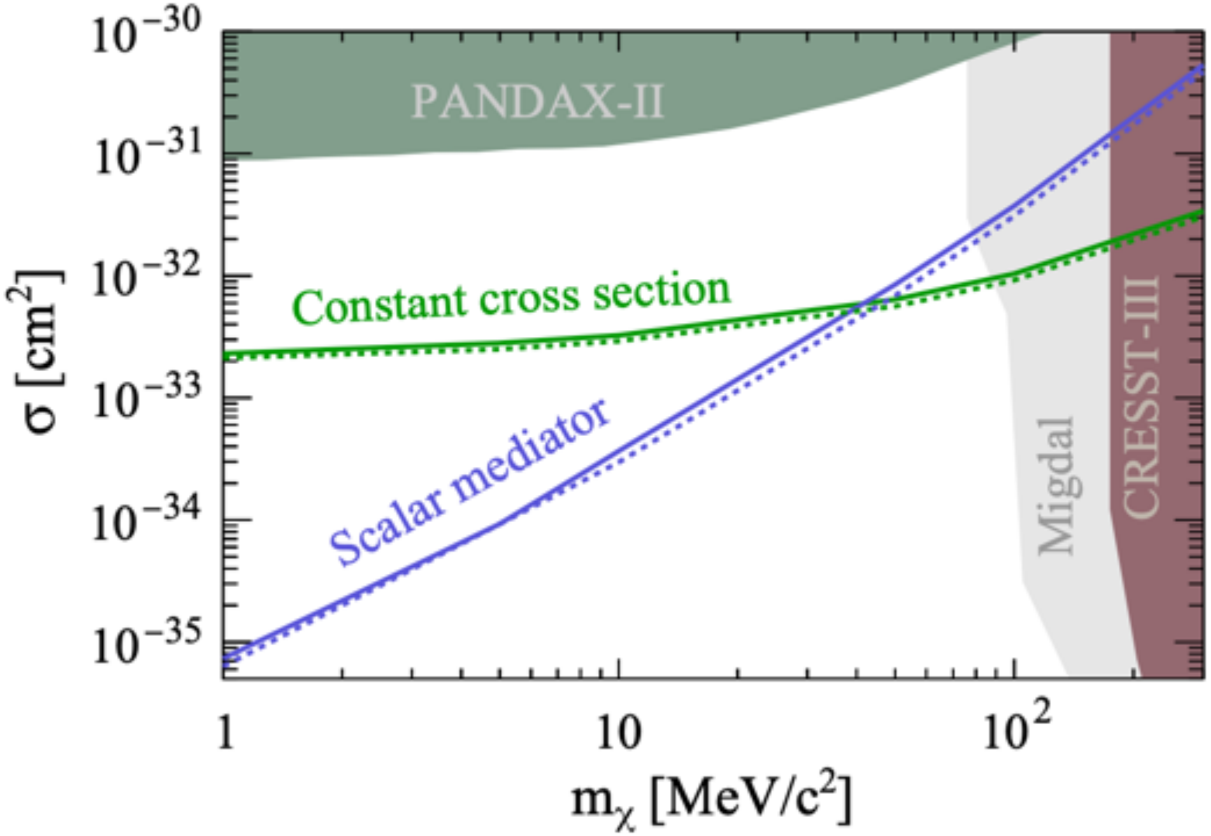


PRL 128, 171801 (2022) **Editors' Suggestion**

New results from Super-K

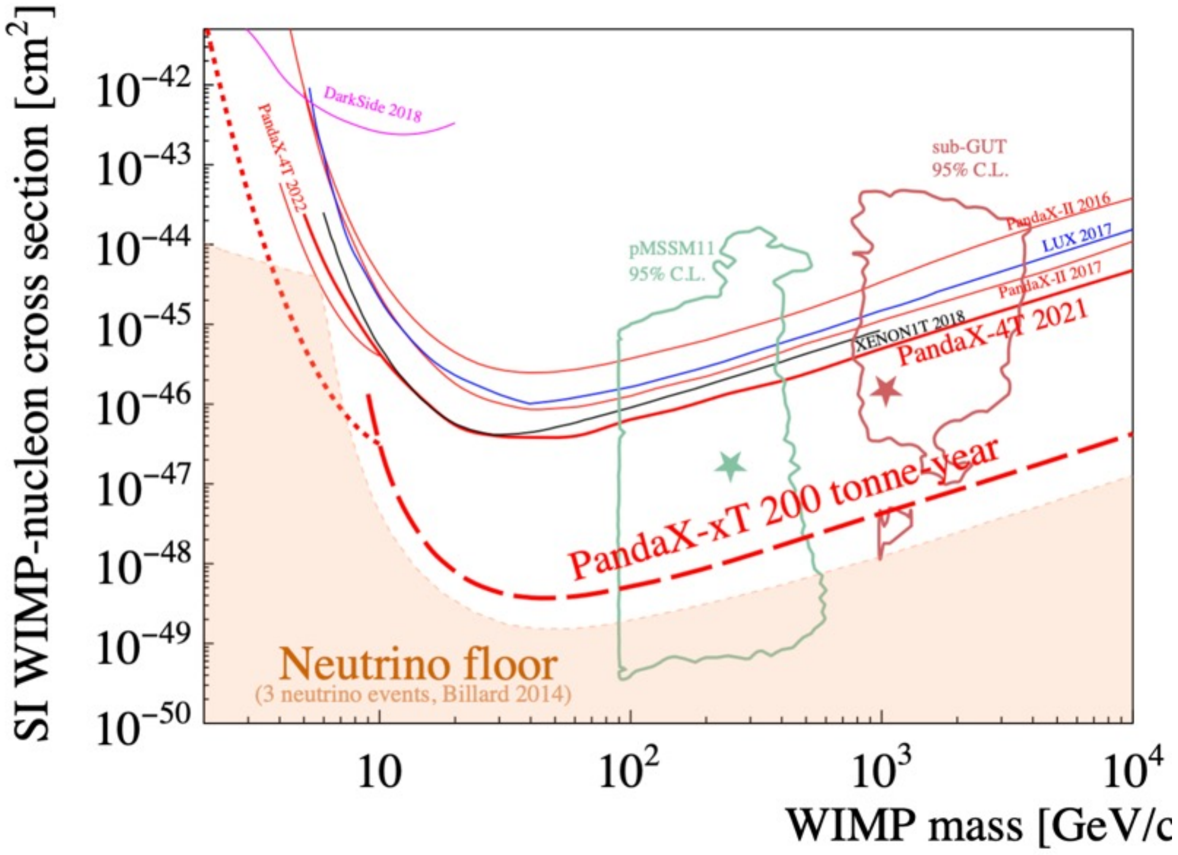
- **20 years' data from Super-Kamiokande** PRL 130, 031802 (2023)
- **Directional detection of cosmic-ray boosted DM**

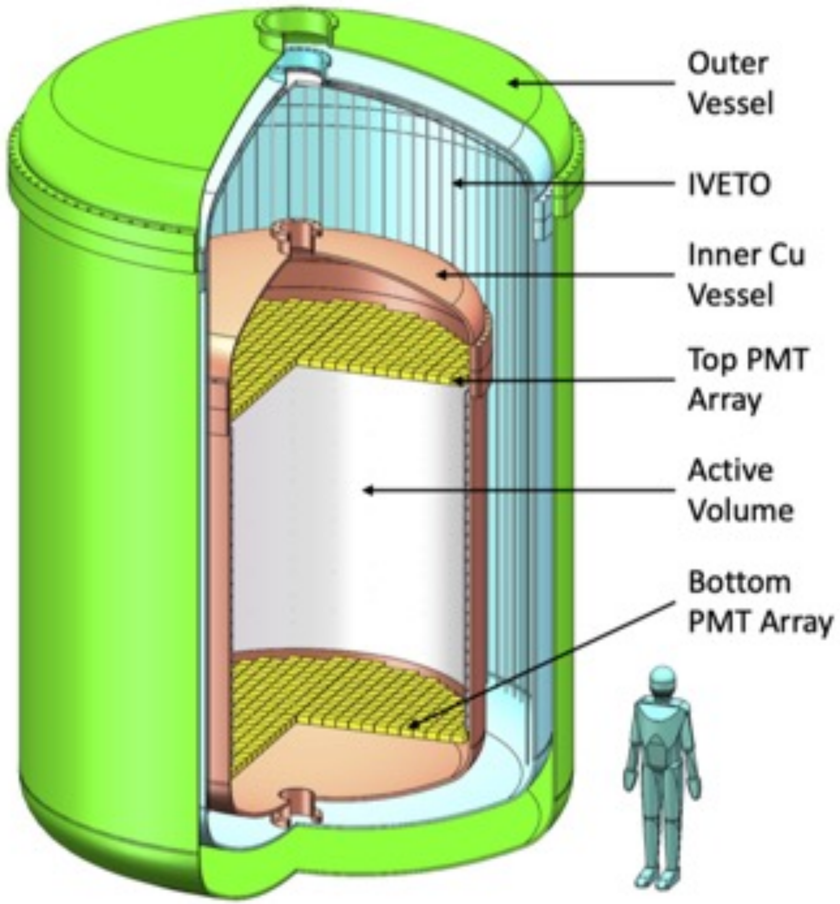




Future plan: PandaX-xT

- **Next generation liquid xenon experiment**
  - with >30 tonne sensitive volume
  - decisive test on WIMP with 200 tonne-year





Summary

- PandaX-4T is exploring various types of DM
- Novel probes are tested to expand the physics reach
- Run 2 data-taking will start soon
- Planning future PandaX-xT project

Thank You！

PandaX

- **PandaX: particle and astrophysical xenon detector**
  - dark matter, Majorana neutrino, astrophysical neutrino

54
Xe
Xenon
131.29