Dark Matter Searches with PandaX Experiment

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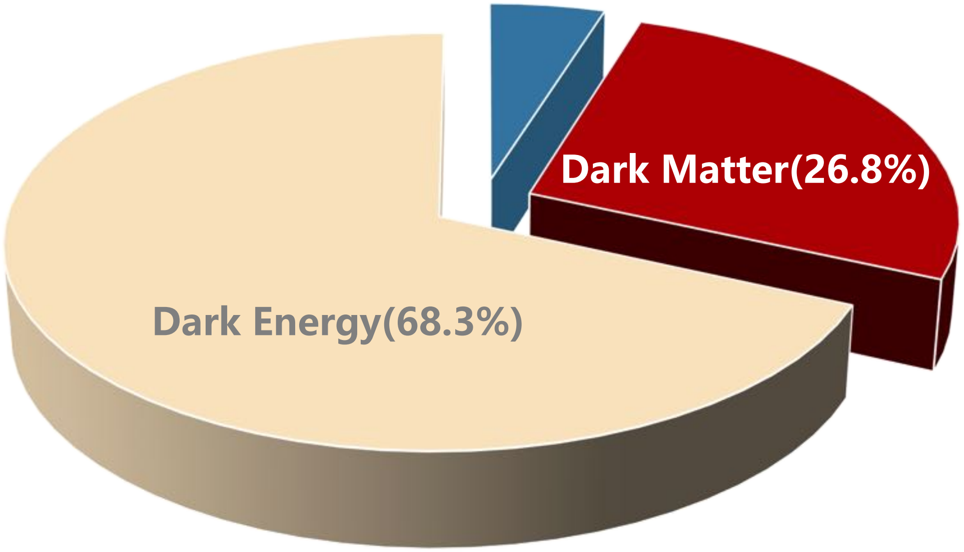
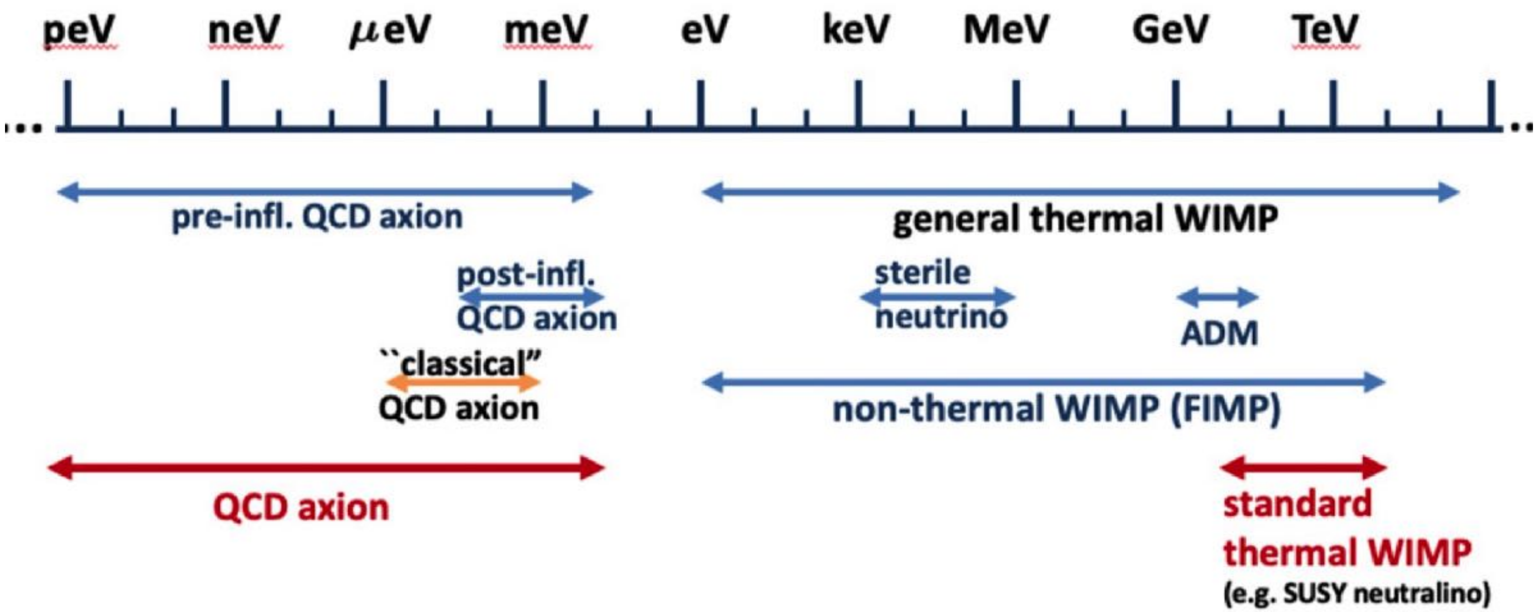
On behalf of PandaX Collaboration

17th Marcel Grossmann Meeting
2024/07/11, Pescara, Italy

Dark Matter

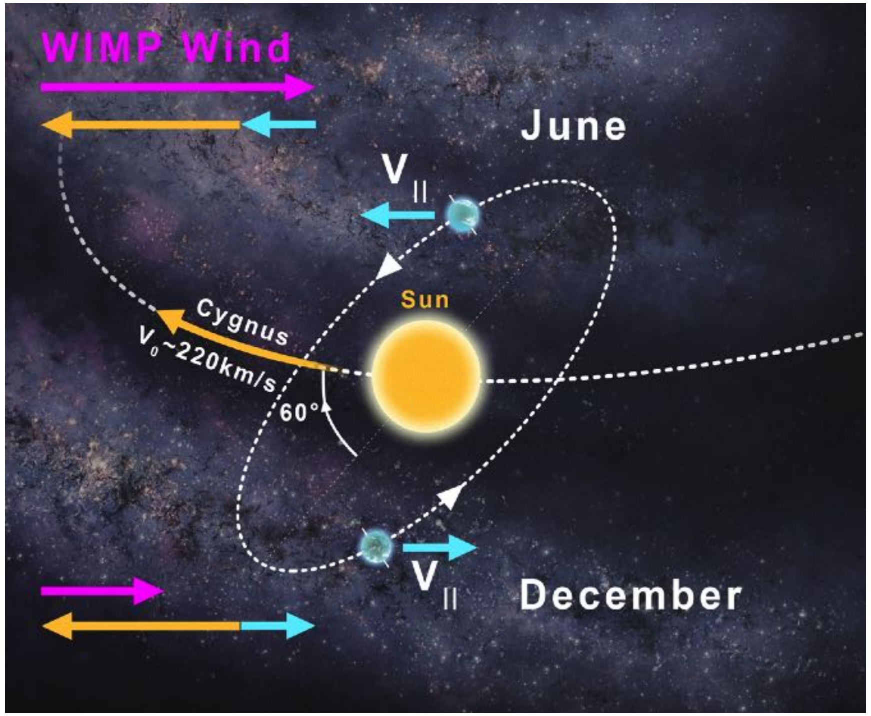
- **Strong evidences for the existence of dark matter**
- **Unknown physical nature**
  - Various types, covering extremely large mass range



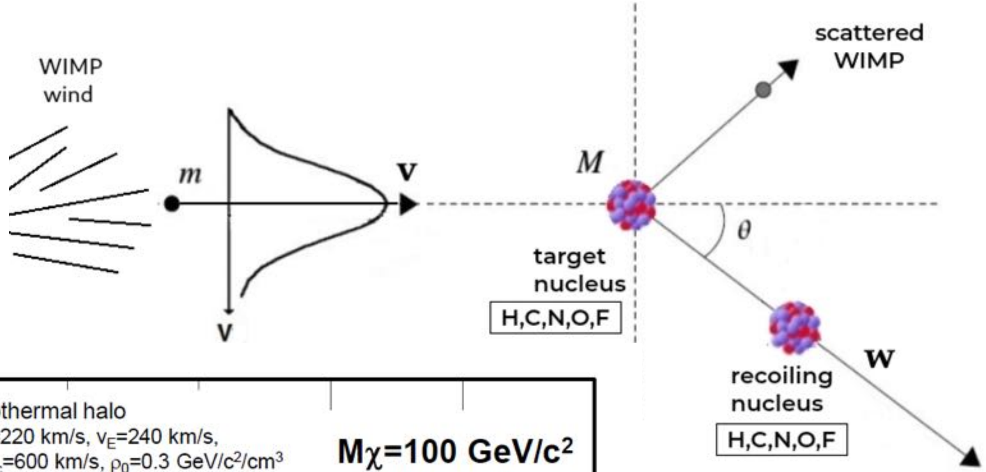


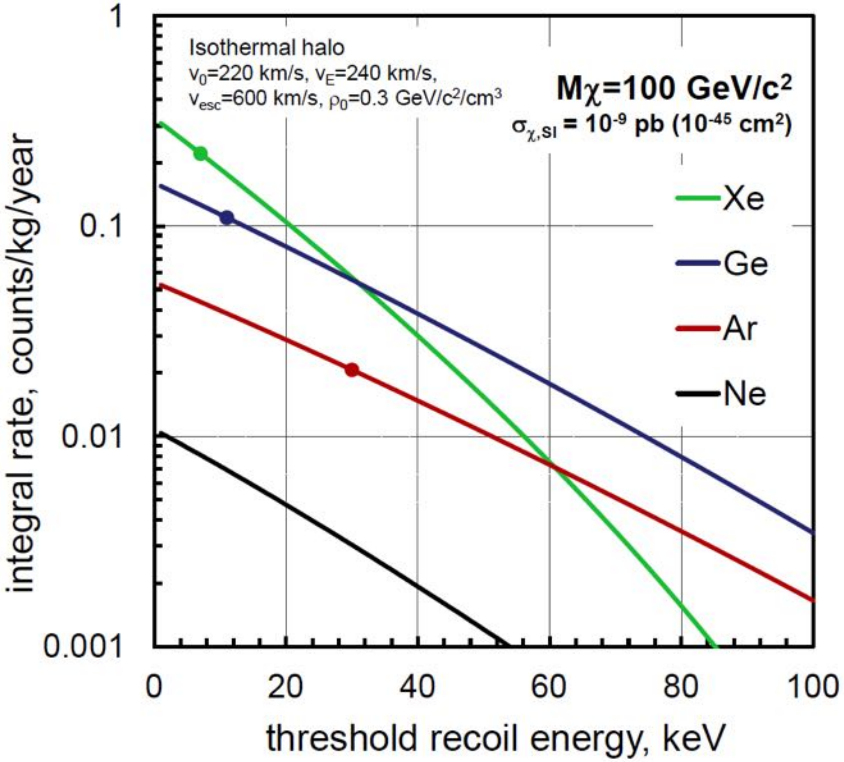
Dark Matter Direct Detection

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



Credit: James Josephides





Progress of Direct Detection

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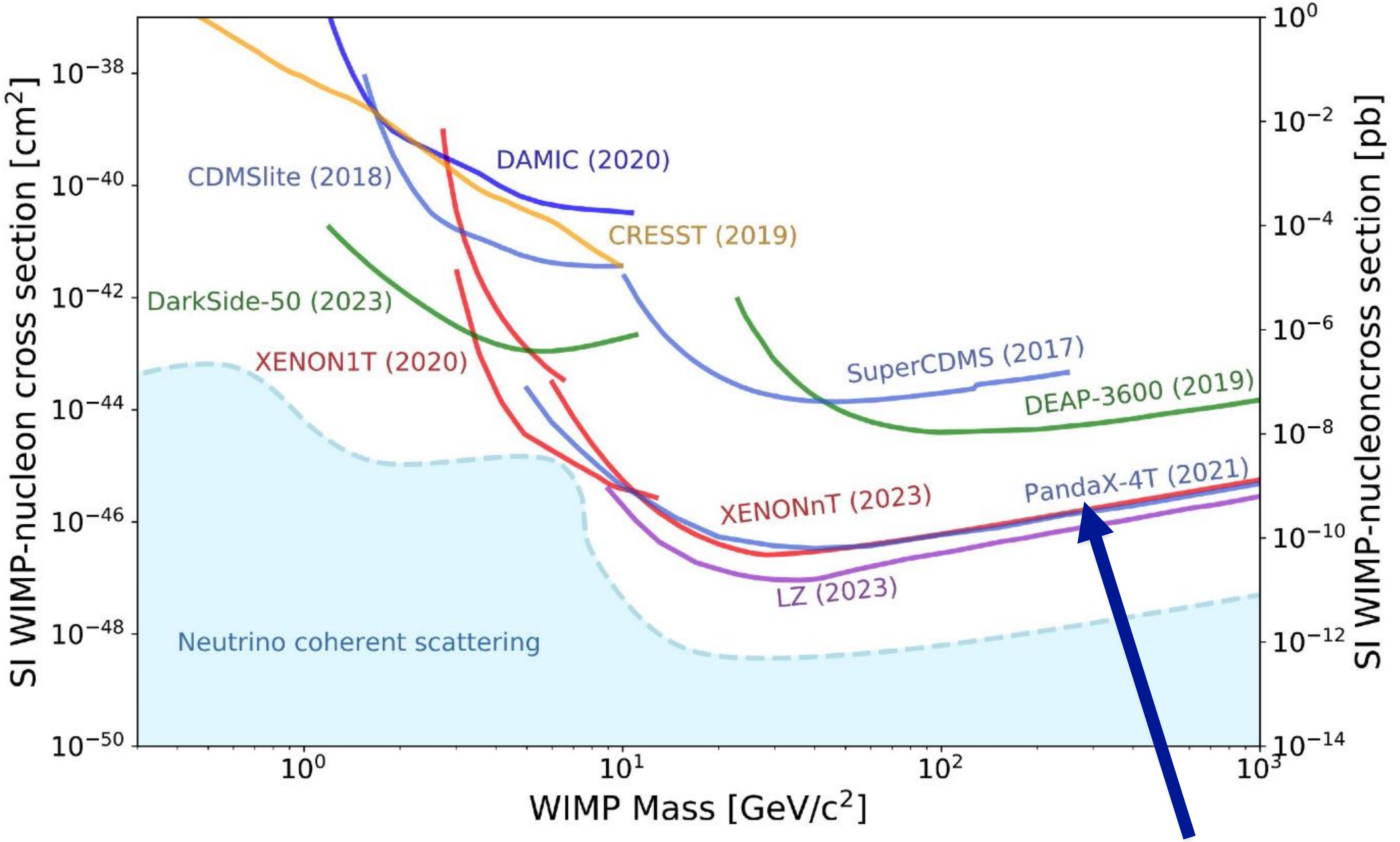


2021/07/08: PandaX-4T first result was released at MG16 conference

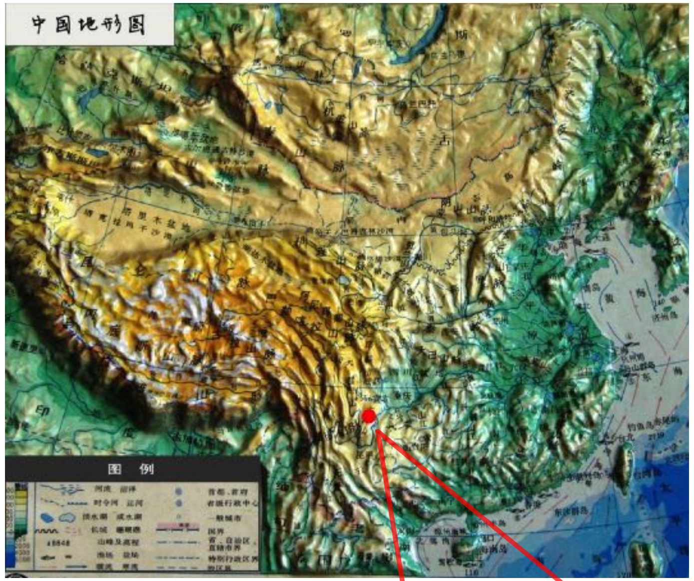
PRL 127, 261802 (2021), Editors' Suggestion

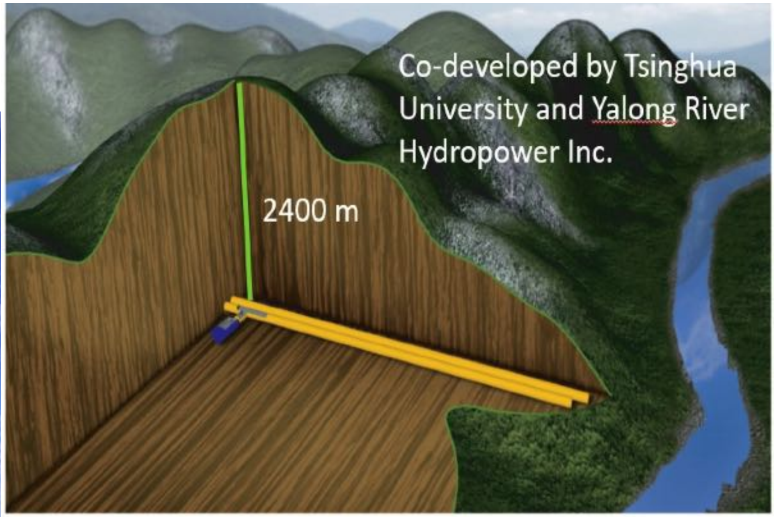
PandaX Collaboration

- **PandaX: Particle and Astrophysical Xenon Observatory**

China Jinping Underground Laboratory

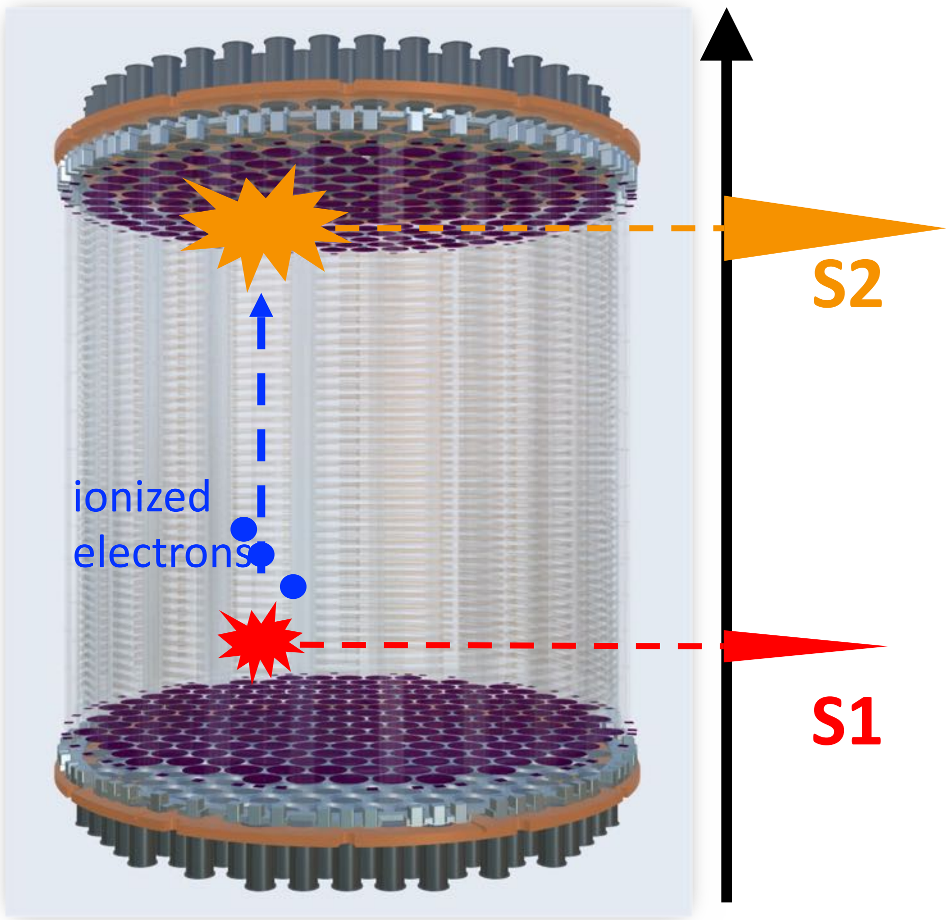
- **Deepest underground lab: 6700 m.w.e. and horizontal access**

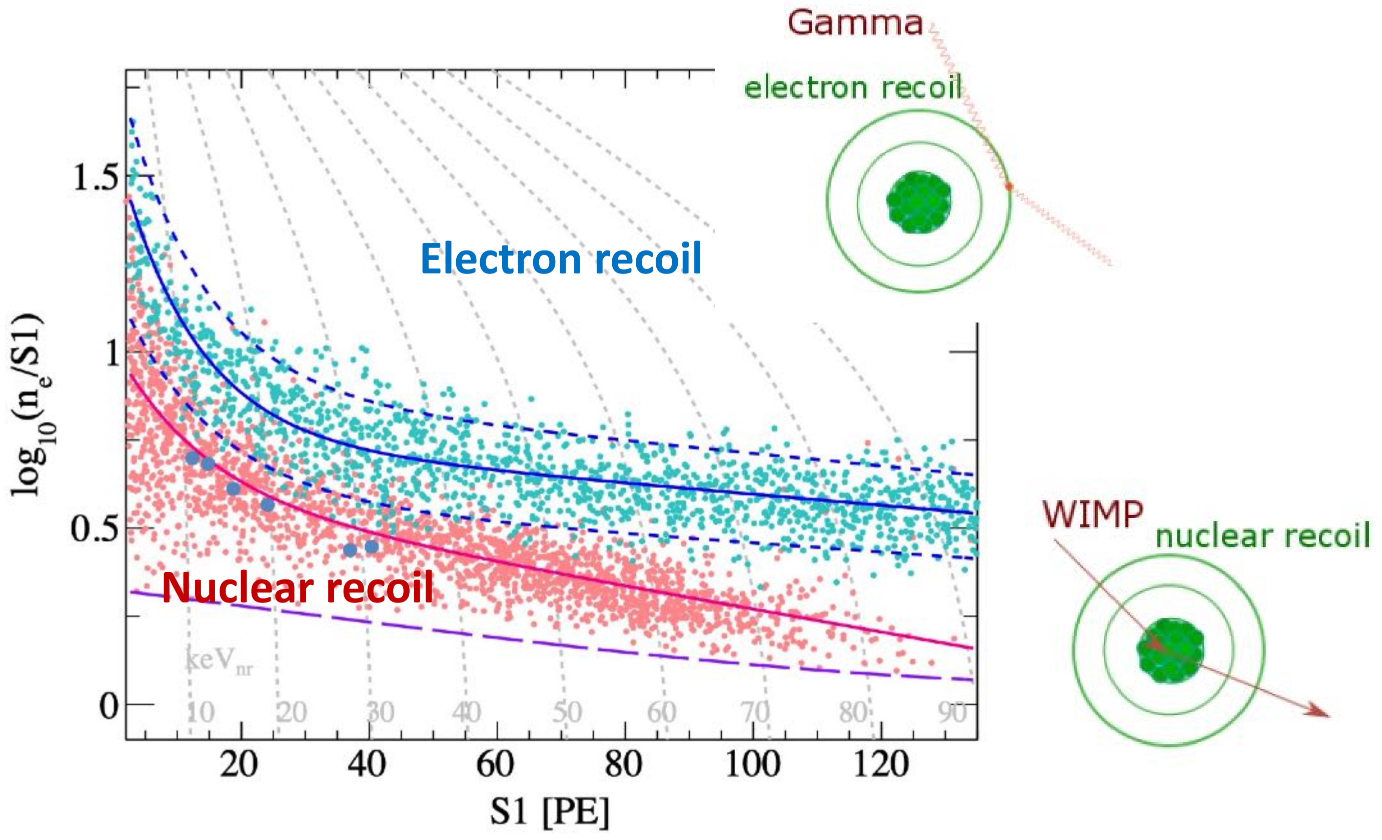




PandaX: Dual-phase xenon TPC

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





PandaX Development

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

PandaX start

PandaX-I
120kg

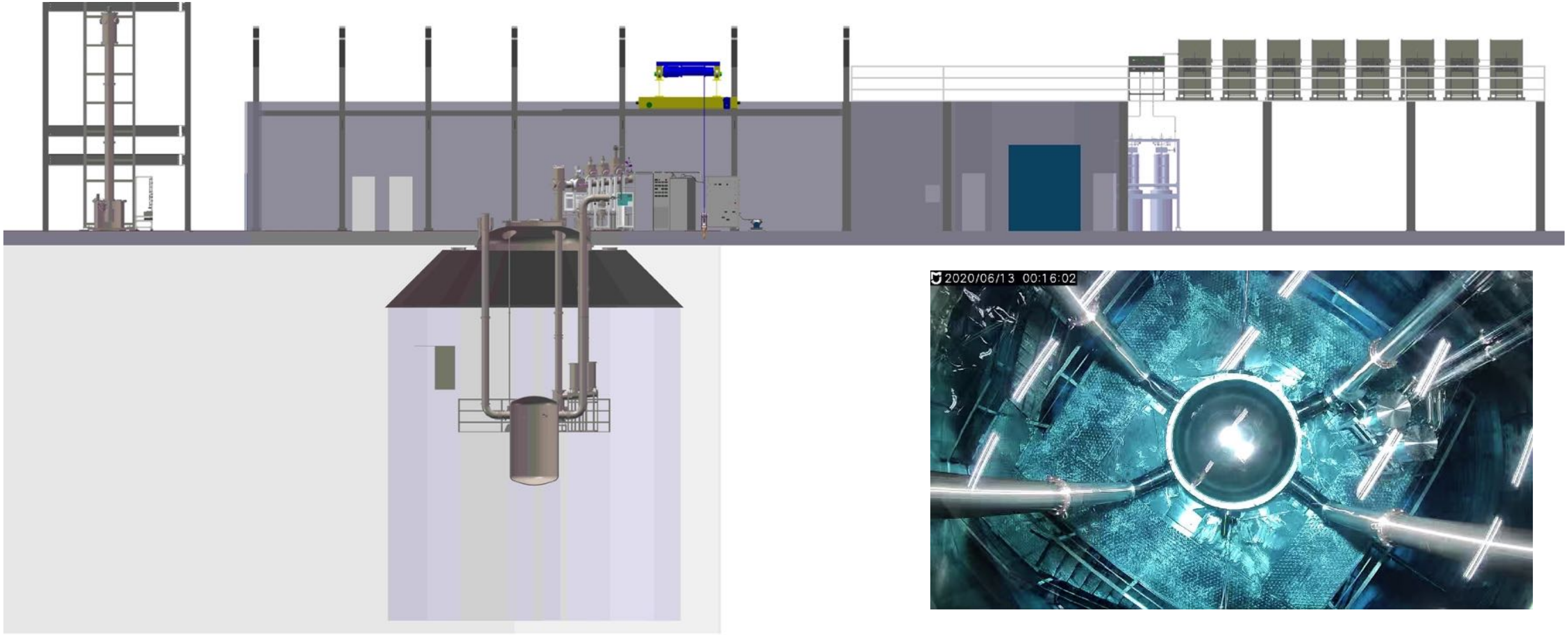
PandaX-II
580kg

PandaX-4T
(3.7 tonne)

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

PandaX-4T experiment @ CJPL-II

- **Sensitive target volume: 3.7 tonne liquid xenon**
- **Shielding tank: 900m^3 high-purity water**



PandaX-4T Physics Run

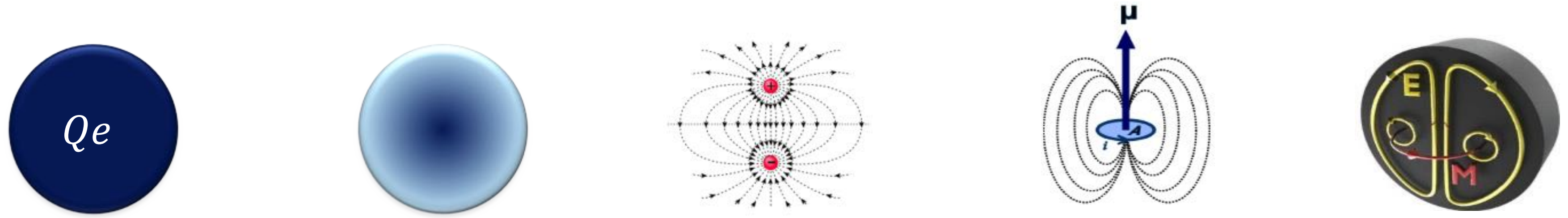
2020/11 – 2021/04	**Commissioning (Run0)** 95 days
2021/07 – 2021/10	**Tritium removal** xenon distillation, gas flushing, etc
2021/11 – 2022/05	**Physics run (Run1)** 164 days
2022/09 – 2023/12	**CJPL B2 hall construction** xenon recuperation, detector upgrade
Current Status	**Resuming physics data-taking**

How dark is dark matter?

Image Credit: Public Domain

Luminance of Dark Matter

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



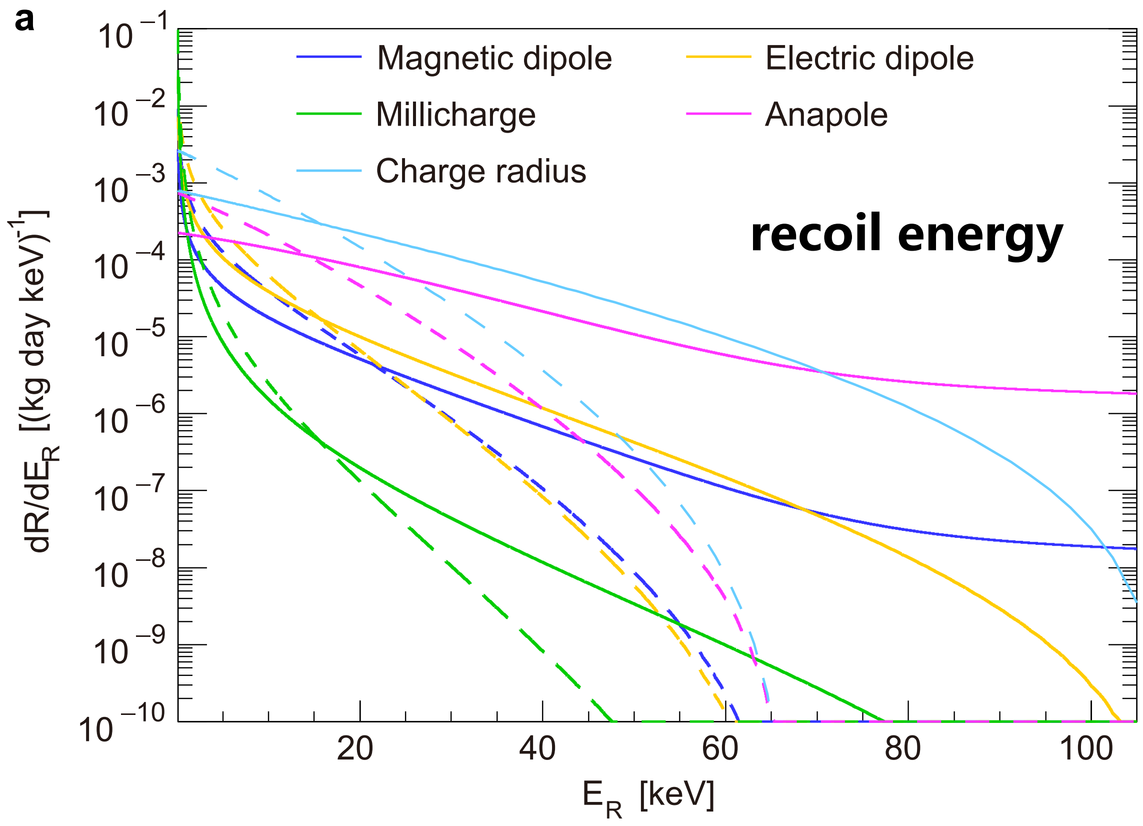
millicharge	charge radius	electric dipole	magnetic dipole	anapole

$$\mathcal{L} = \underbrace{Qe\bar{\chi}\gamma^{\mu}\chi A_{\mu}}_{\text{millicharge}} + \underbrace{\frac{\mu_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}}_{\text{magnetic dipole}} + \underbrace{i\frac{d_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu}}_{\text{electric dipole}} + \underbrace{b_{\chi}\bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu}}_{\text{charge radius}} + \underbrace{a_{\chi}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}}_{\text{anapole}}$$

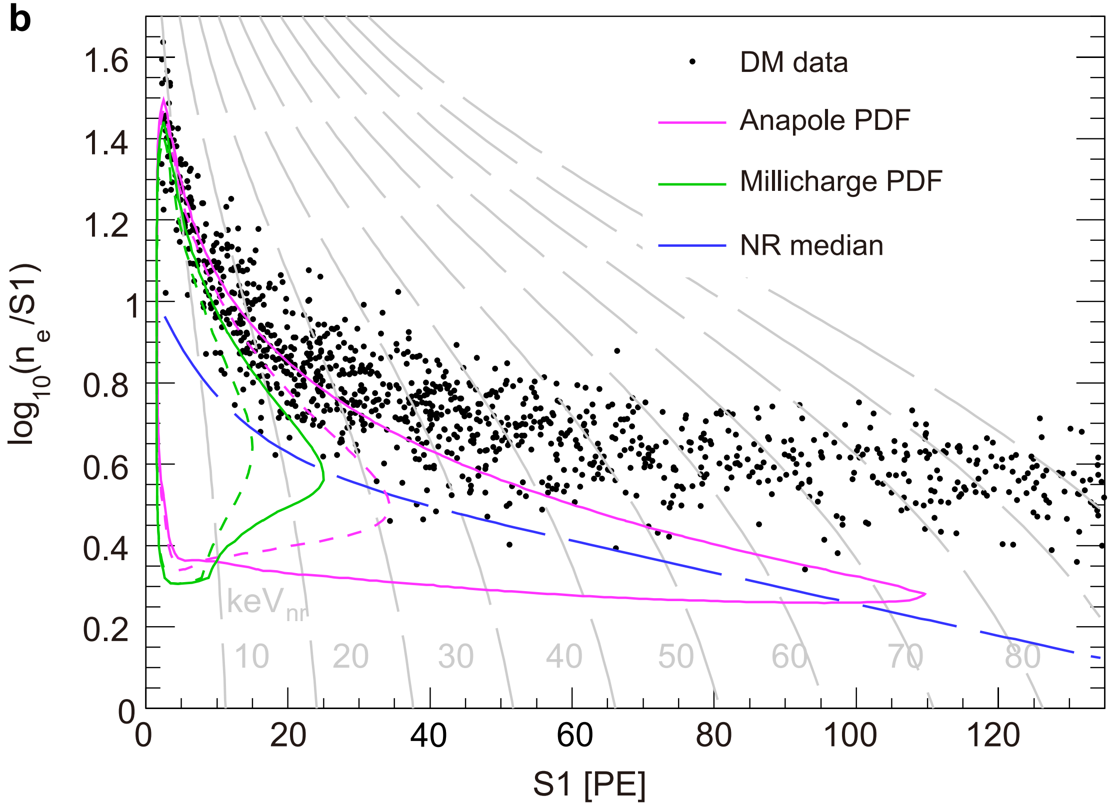
tree-level (millicharge) | **higher-order loop-level** (magnetic dipole, electric dipole, charge radius, anapole)

Photon-Mediated Interaction

- **Various nuclear recoil energy spectra**
- **Dedicated searches of these EM properties**



30 and 100 GeV/c² DM



Results from Run0 Data

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

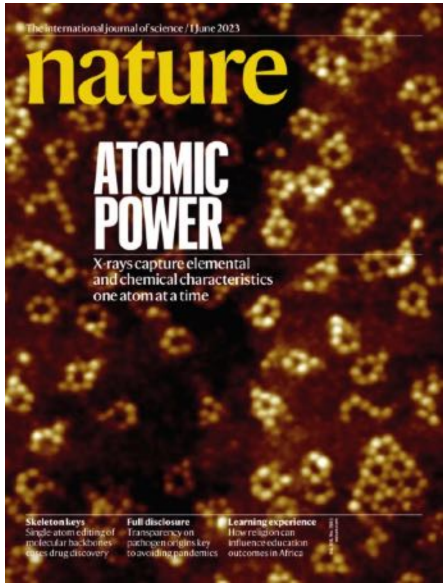
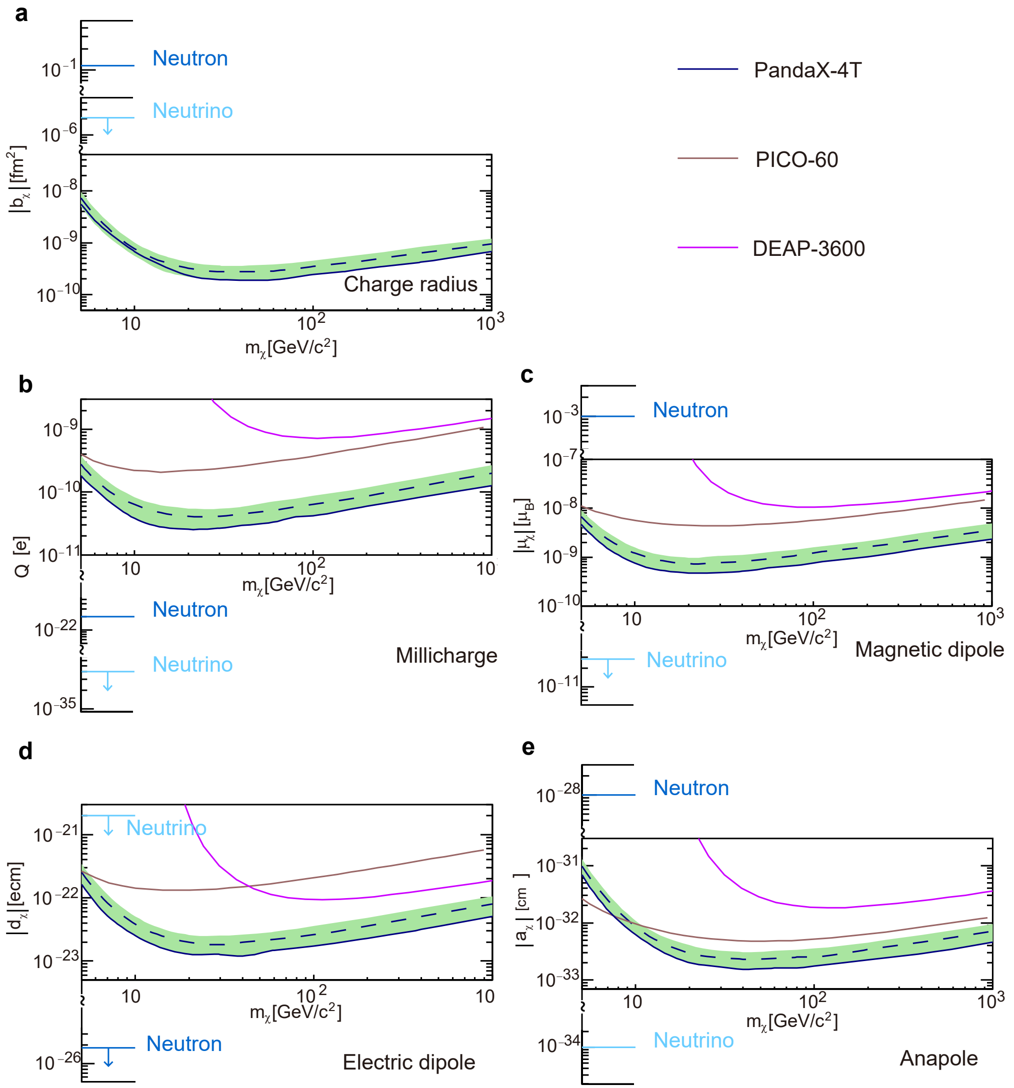


Table 1 | Comparison of electromagnetic properties

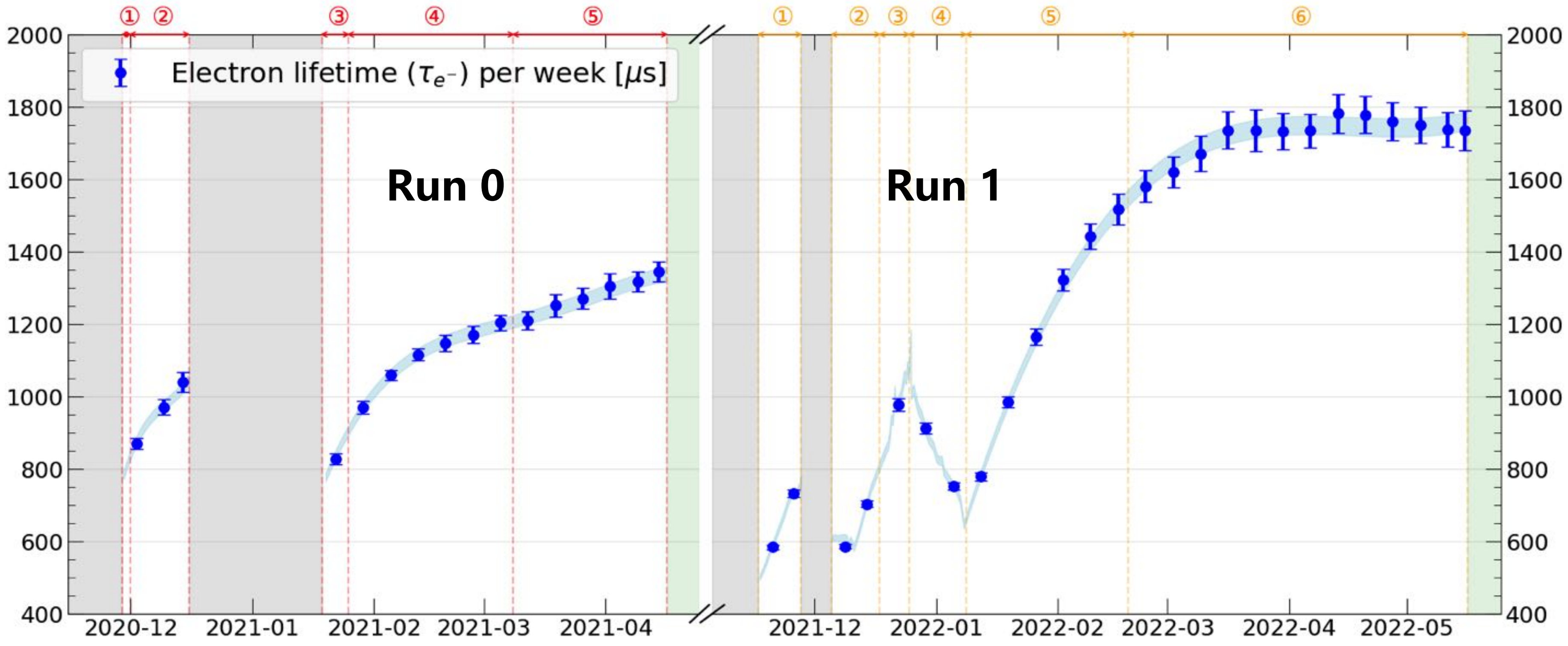
	dark matter	neutrino	neutron
Charge radius (fm^2)	$<1.9\times10^{-10}$	$[-2.1,3.3]\times10^{-6}$ *	-0.1155 *
Millicharge (e)	$<2.6\times10^{-11}$	$<4\times10^{-35}$ *	$(-2\pm8)\times10^{-22}$ *
Magnetic dipole (μ_B)	$<4.8\times10^{-10}$	$<2.8\times10^{-11}$ *	-1×10^{-3} *
Electric dipole (ecm)	$<1.2\times10^{-23}$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



Nature 618, 7963, 47-50 (2023)

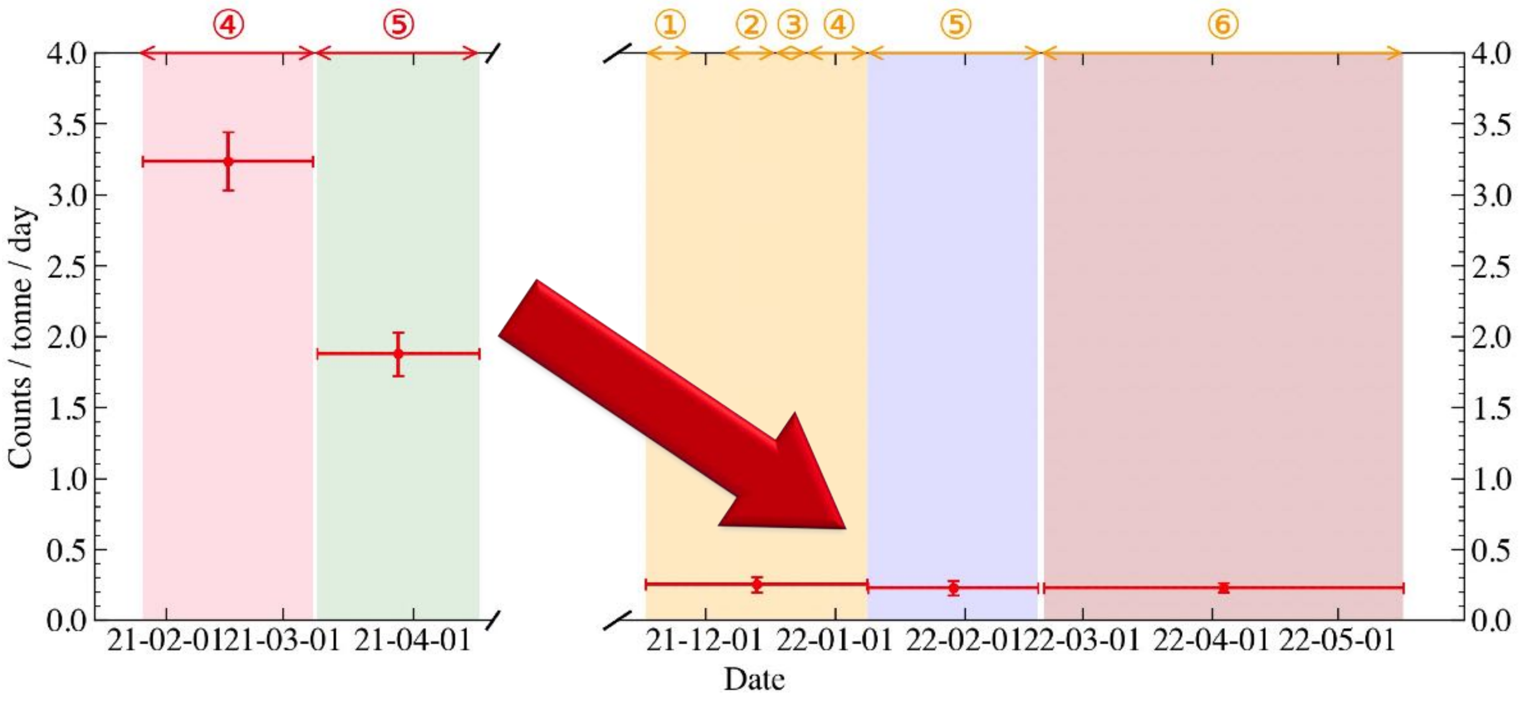
PandaX-4T New Data (Run1)

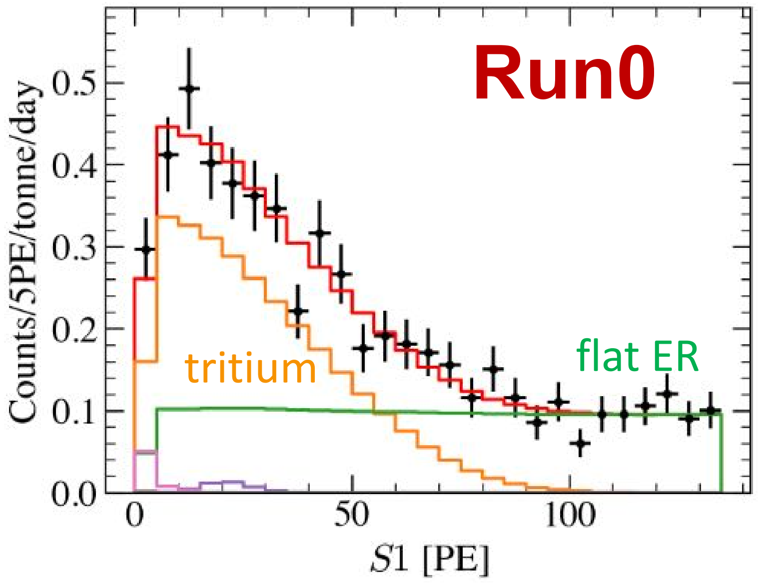
- **Combination of Run0 + Run1**
- **Total exposure: 1.54 tonne•year**

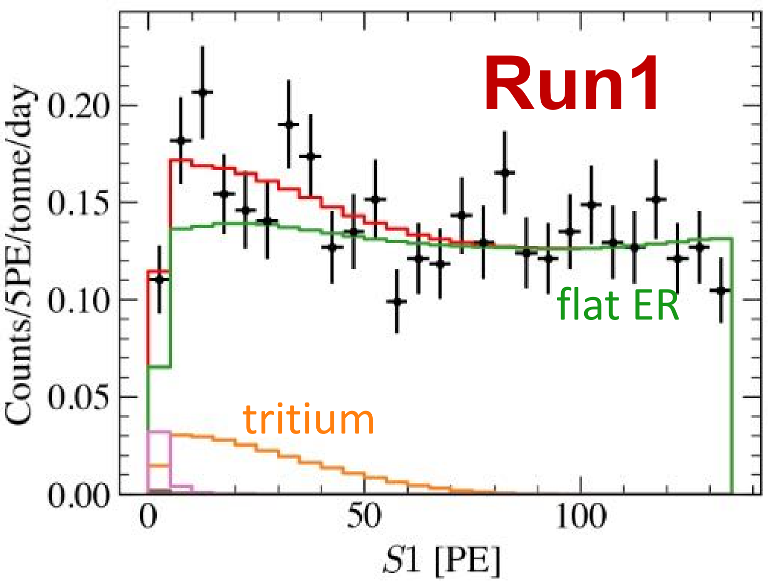


Major Improvement

- **Tritium background**
  - excess of low electron-recoil energy
- **Significant reduction from Run0 to Run1**





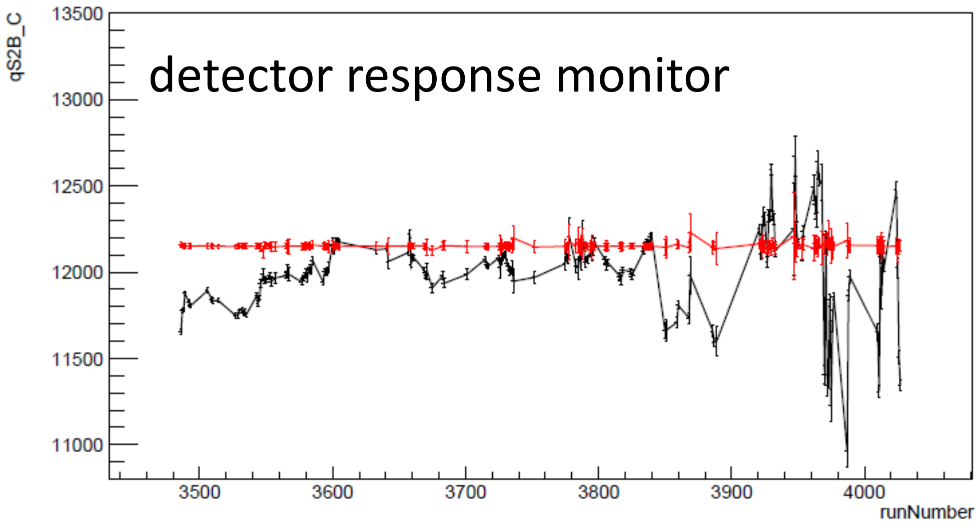


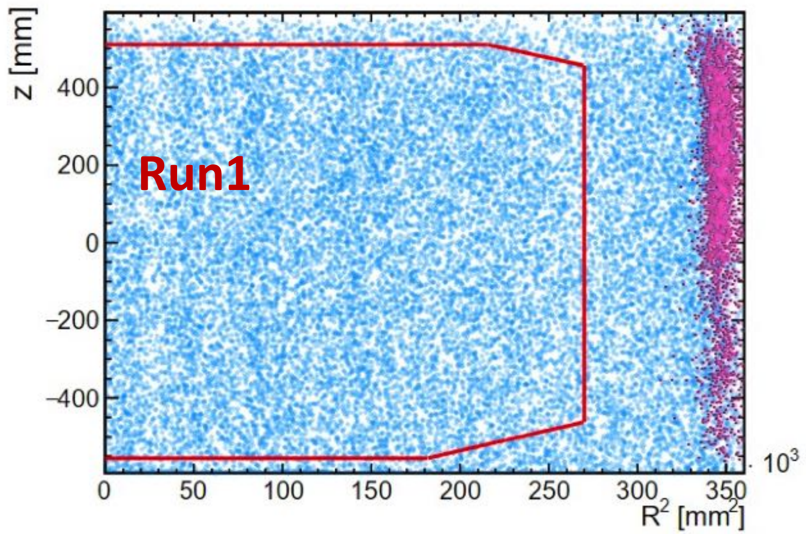
Run0: Set ①-⑤

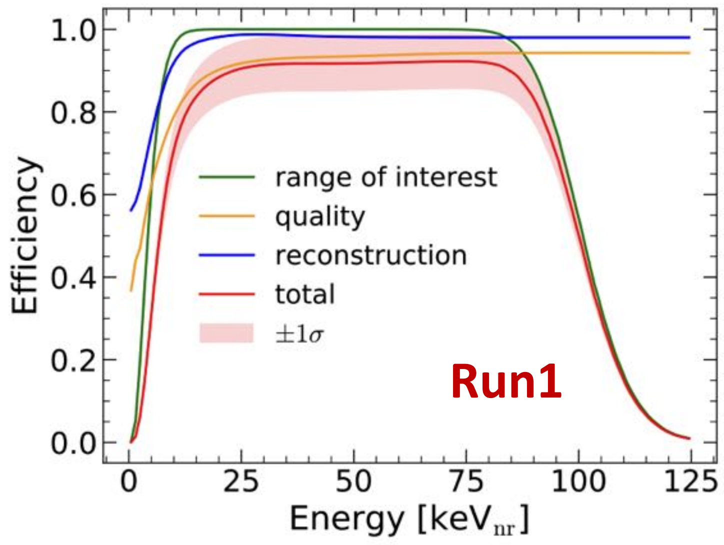
Run1: Set ①-⑥

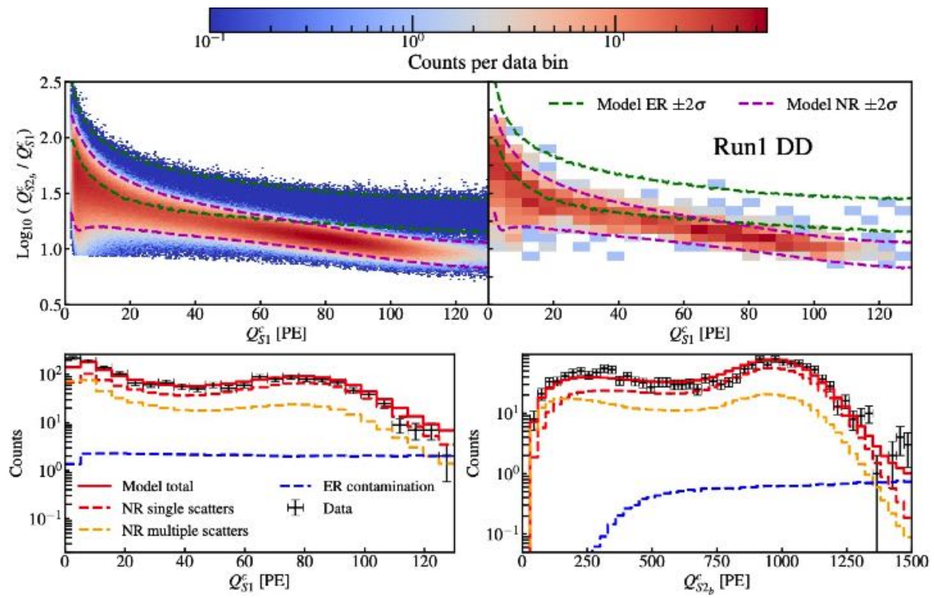
Major Improvement

- **More accurate detector response**
- **More accurate signal model**
- **Higher signal efficiency**



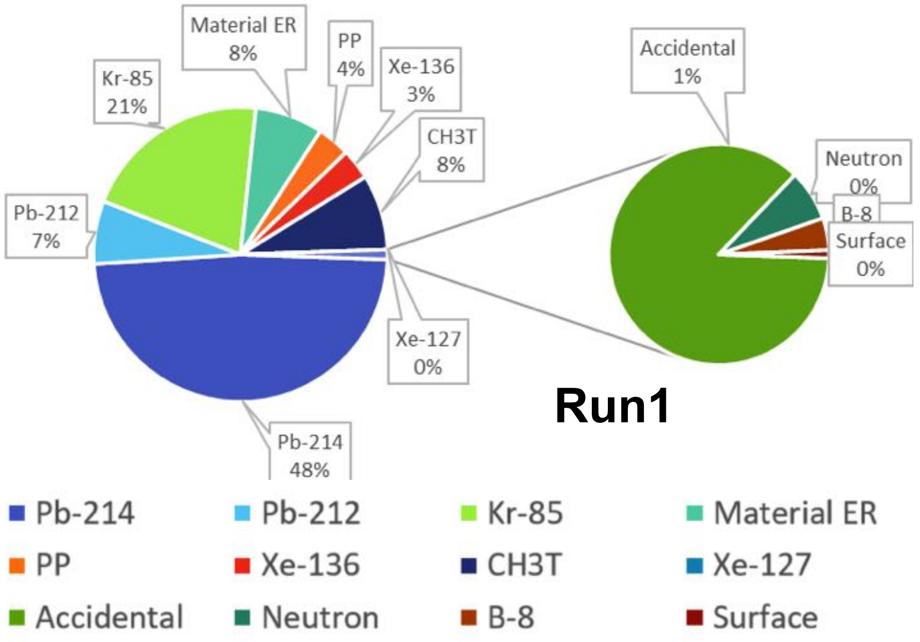






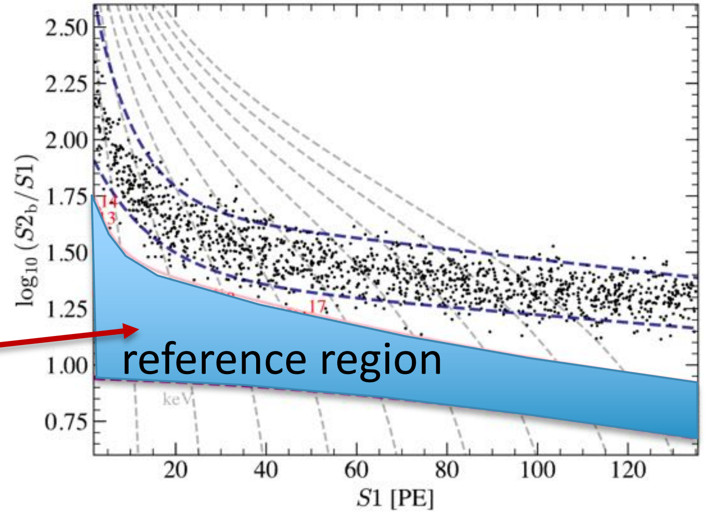
Background Composition

	Run0	Run1	Total	Below NR median	Best fit
^{214}Pb	281 ± 13	675 ± 35	956 ± 38	$3.6^{+0.9}_{-0.7}$	-
^{212}Pb	49 ± 13	97 ± 25	146 ± 30	$0.6^{+0.2}_{-0.2}$	-
^{85}Kr	80 ± 40	289 ± 88	369 ± 96	$1.4^{+0.5}_{-0.5}$	-
Material ER	42 ± 5	105 ± 11	147 ± 12	$0.6^{+0.2}_{-0.1}$	-
Solar ν	37.5 ± 3.8	73.7 ± 7.4	111.2 ± 8.3	$0.42^{+0.10}_{-0.08}$	-
^{136}Xe	27.8 ± 1.4	59.3 ± 3.1	87.0 ± 3.4	$0.16^{+0.05}_{-0.03}$	-
Other ER (data)	504 ± 16	1226 ± 28	1730 ± 32	$6.4^{+1.7}_{-1.2}$	1767 ± 39
CH_3T	556 ± 33	114 ± 33	670 ± 47	$5.2^{+1.2}_{-1.1}$	677 ± 47
^{127}Xe	7.65 ± 0.77	0.02 ± 0.00	7.67 ± 0.77	$0.10^{+0.02}_{-0.02}$	7.69 ± 0.17
^{124}Xe	2.26 ± 0.61	4.05 ± 1.09	6.31 ± 1.70	$0.03^{+0.01}_{-0.01}$	6.25 ± 1.68
Neutron	0.63 ± 0.18	1.10 ± 0.24	1.73 ± 0.30	$1.04^{+0.13}_{-0.13}$	1.75 ± 0.28
^{8}B CEνNS	0.31 ± 0.03	0.69 ± 0.07	0.99 ± 0.08	$0.98^{+0.30}_{-0.30}$	1.10 ± 0.33
Surface	0.09 ± 0.06	0.17 ± 0.11	0.26 ± 0.12	$0.26^{+0.12}_{-0.12}$	0.25 ± 0.11
Accidental	11.3 ± 3.4	12.7 ± 3.8	24.0 ± 5.1	$6.42^{+1.36}_{-1.36}$	25.7 ± 5.2
Sum	1079 ± 37	1355 ± 43	2434 ± 43	$20.5^{+2.5}_{-2.2}$	2487 ± 56
Observed	1117	1373	2490	24	-



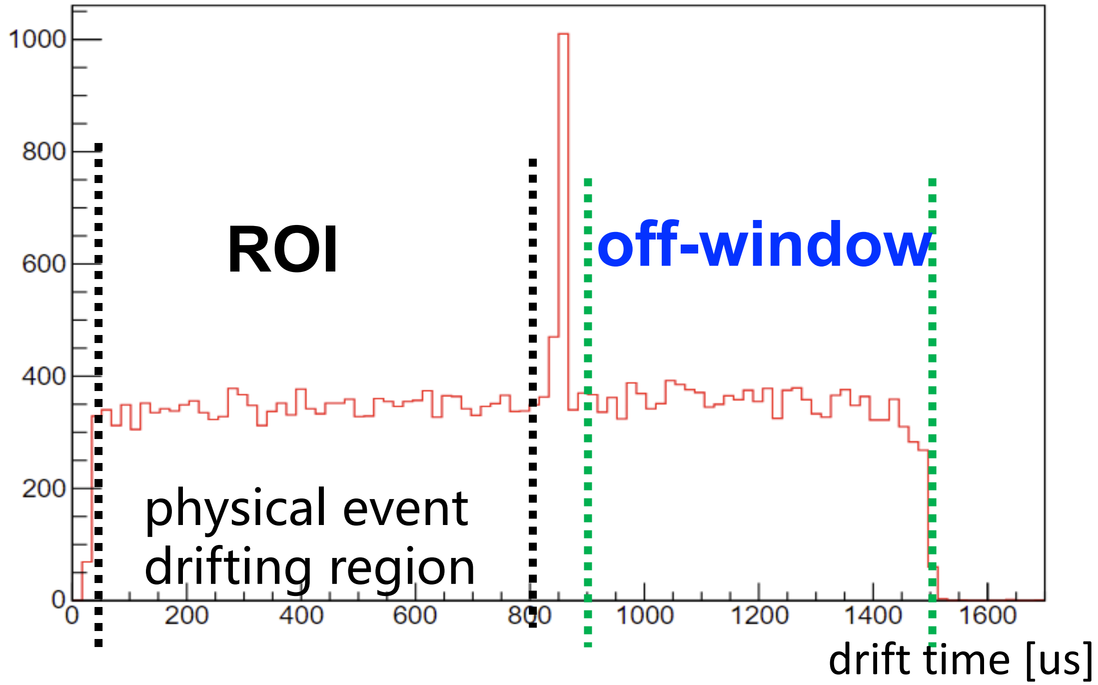
- **WIMP reference region (below NR median)**
  - Tritium: significant reduction
  - ^{214}Pb from radon decay
  - Accidental background

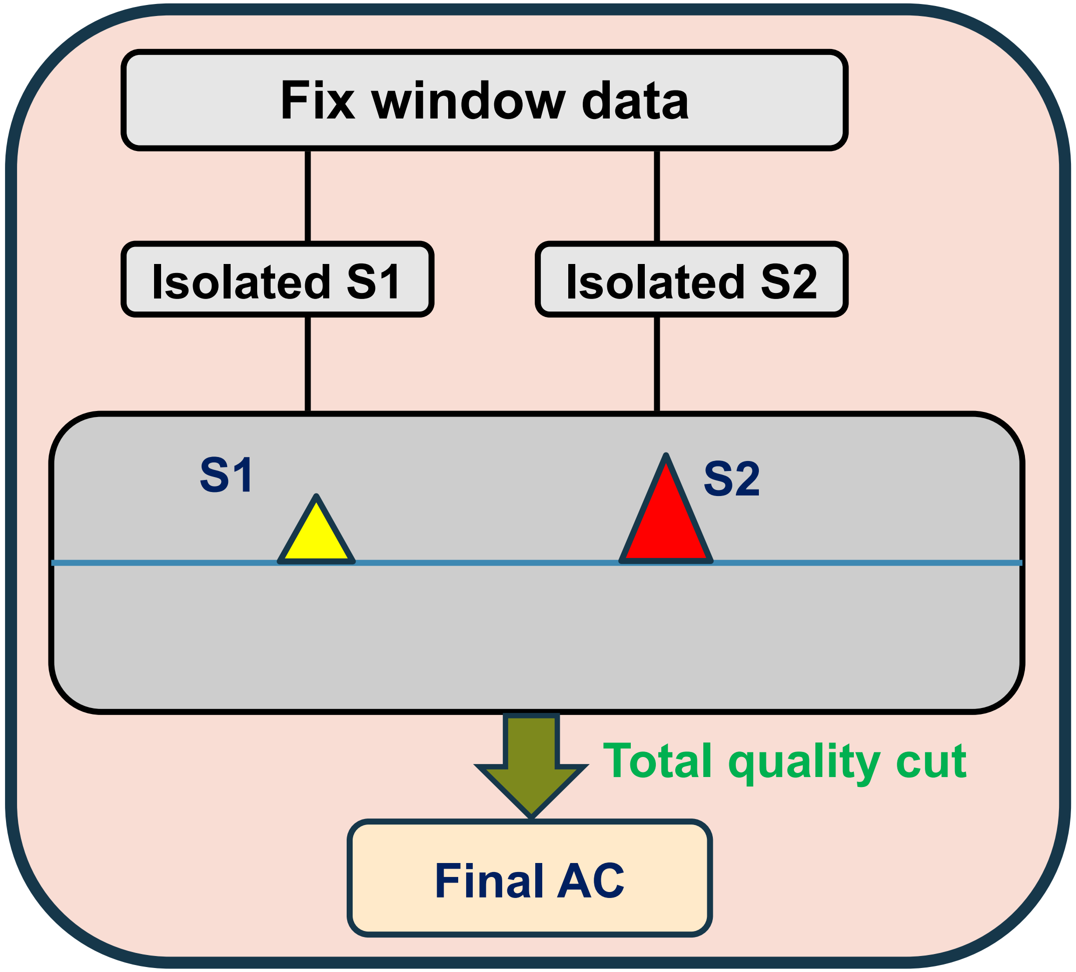
Blinded Analysis



Accidental Background

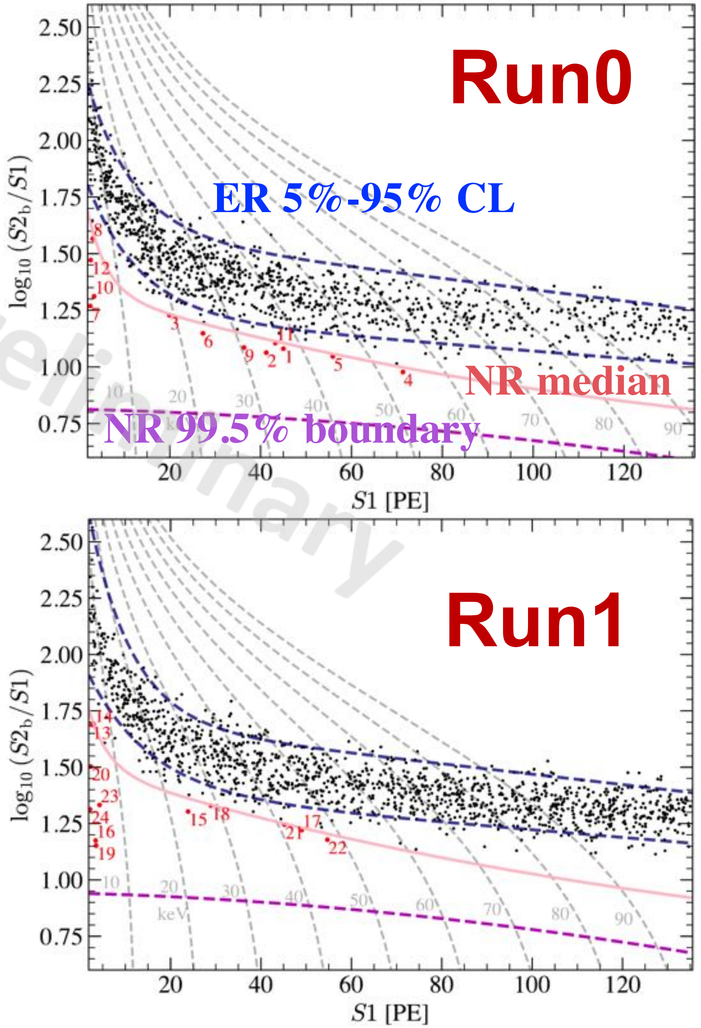
- **Origin: Isolated S1 and S2 accidentally in a signal window**
- **Strategy**
  - PDF: randomly paring isolated S1, S2
  - Normalization: related to S1, S2 rates
  - Validation through off-window region

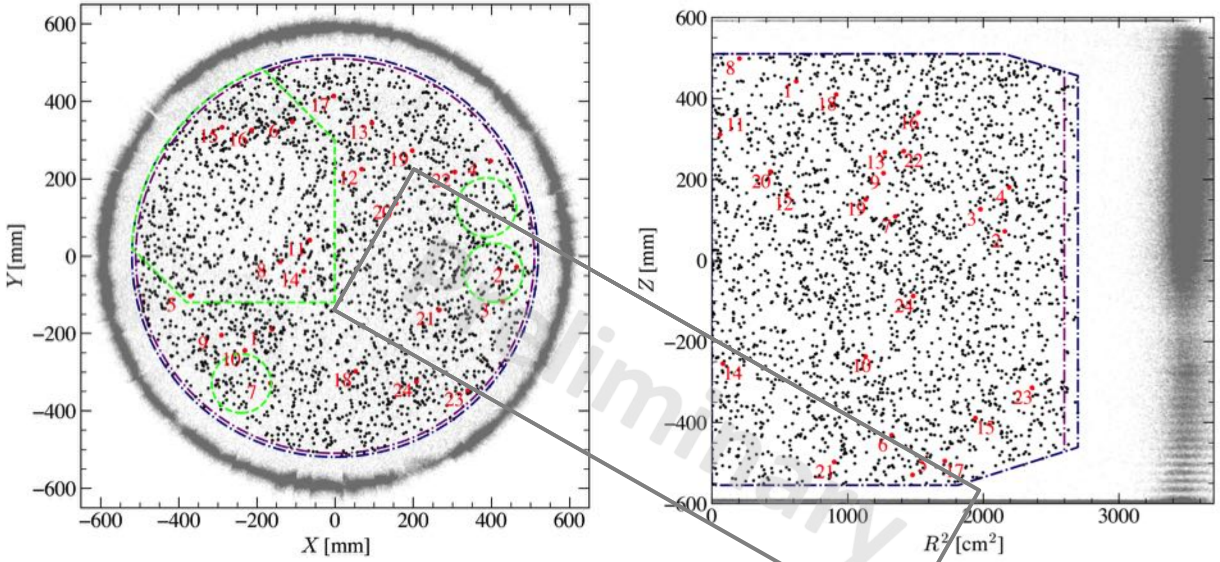


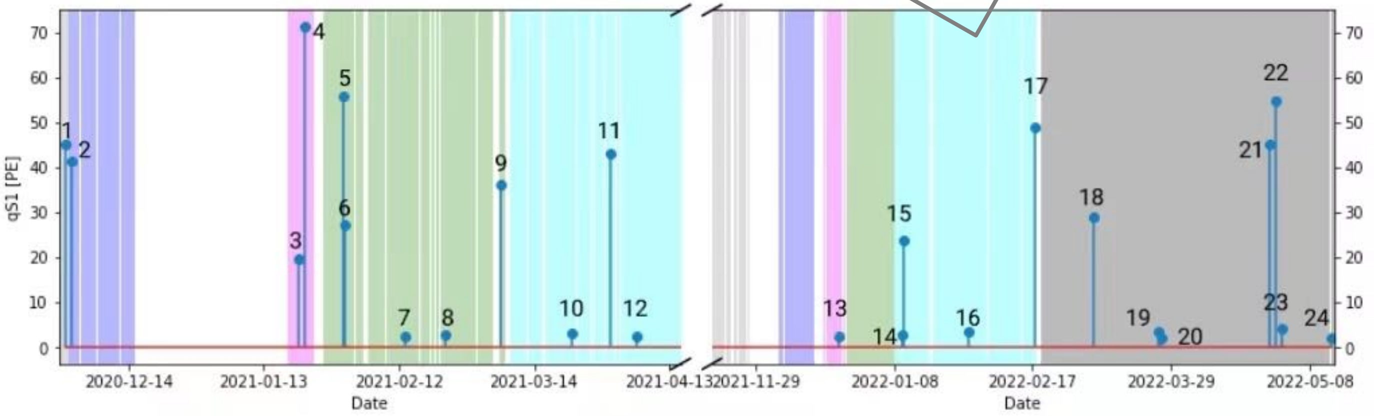


Unblinded Data

- **WIMP reference region (below NR median)**
  - Data: 24 vs Expectation 20.5 ± 2.5

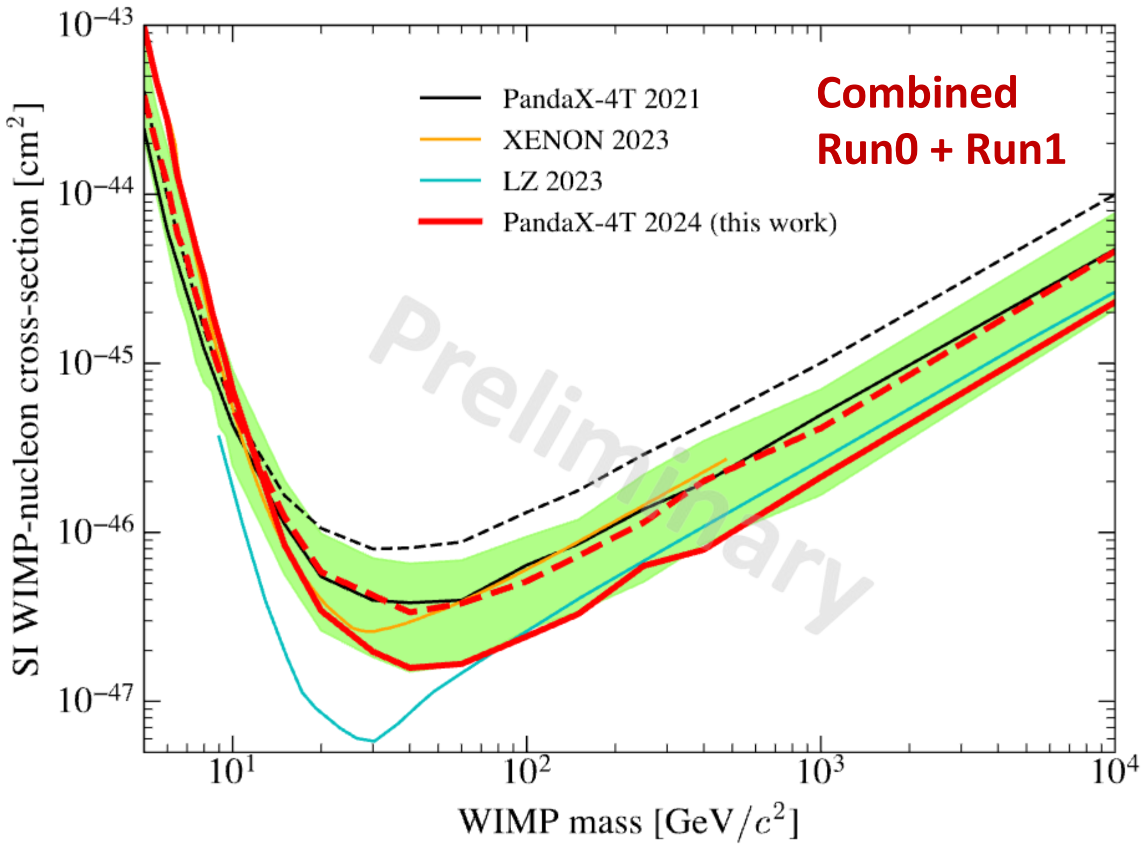






Constraints on spin-independent xsec

- **Improved by a factor of ~2 (1.6E-47cm² @ 40GeV)**
  - some upward fluctuation for DM mass < 8GeV, and some downward fluctuation for high mass DM



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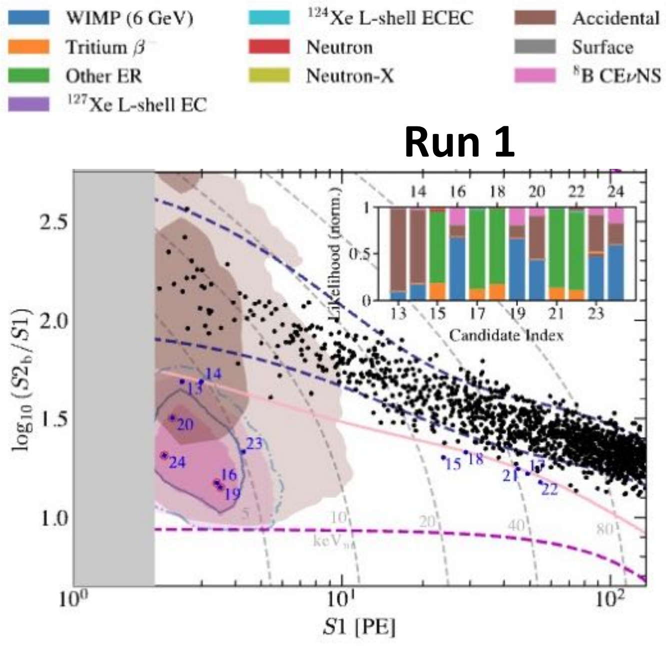

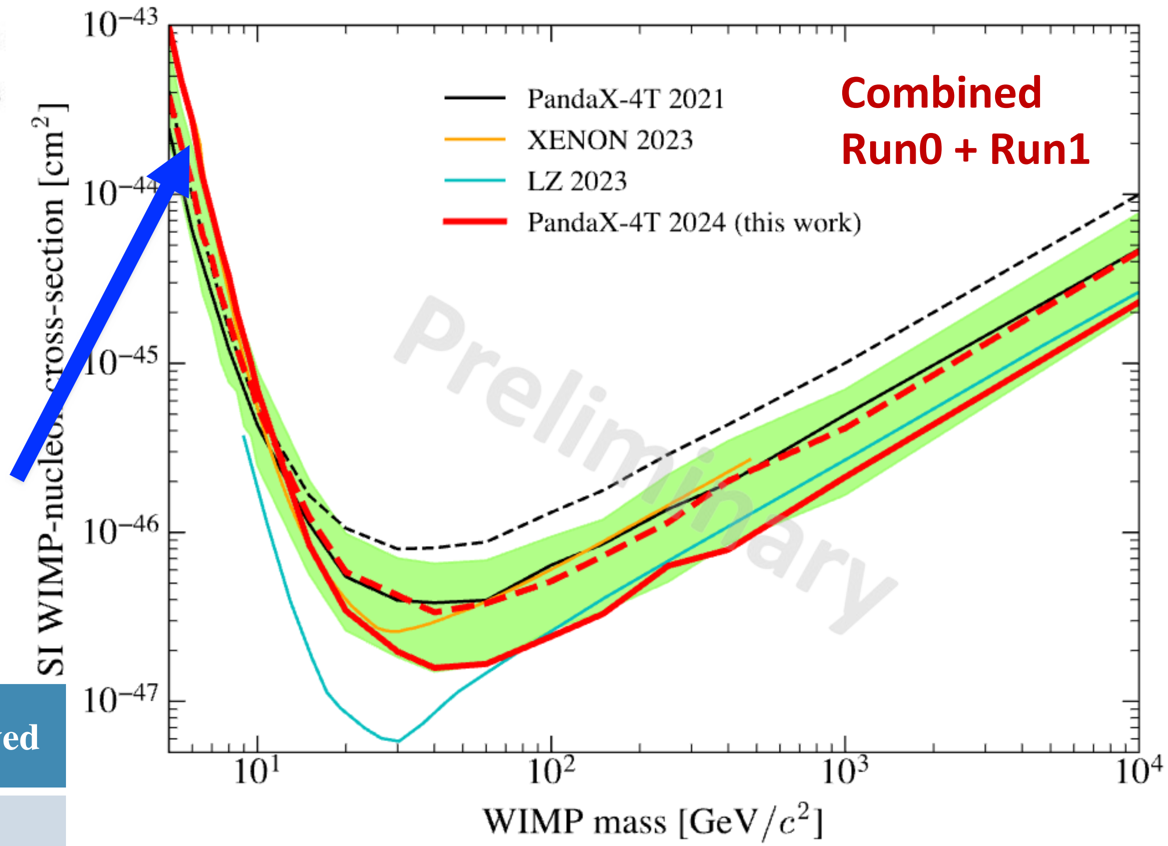

S1<5PE below NR median	Expected	Observed
Run0	2.7±0.4	4
Run1	3.6±0.5	7

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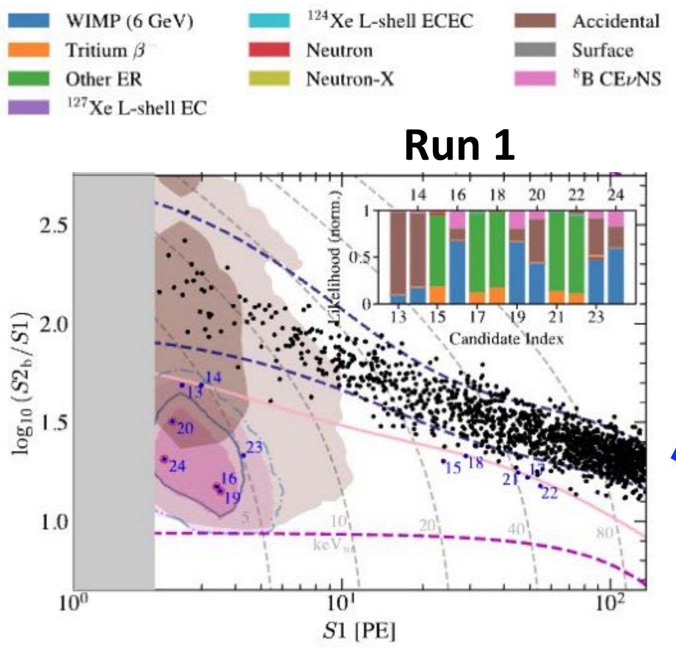

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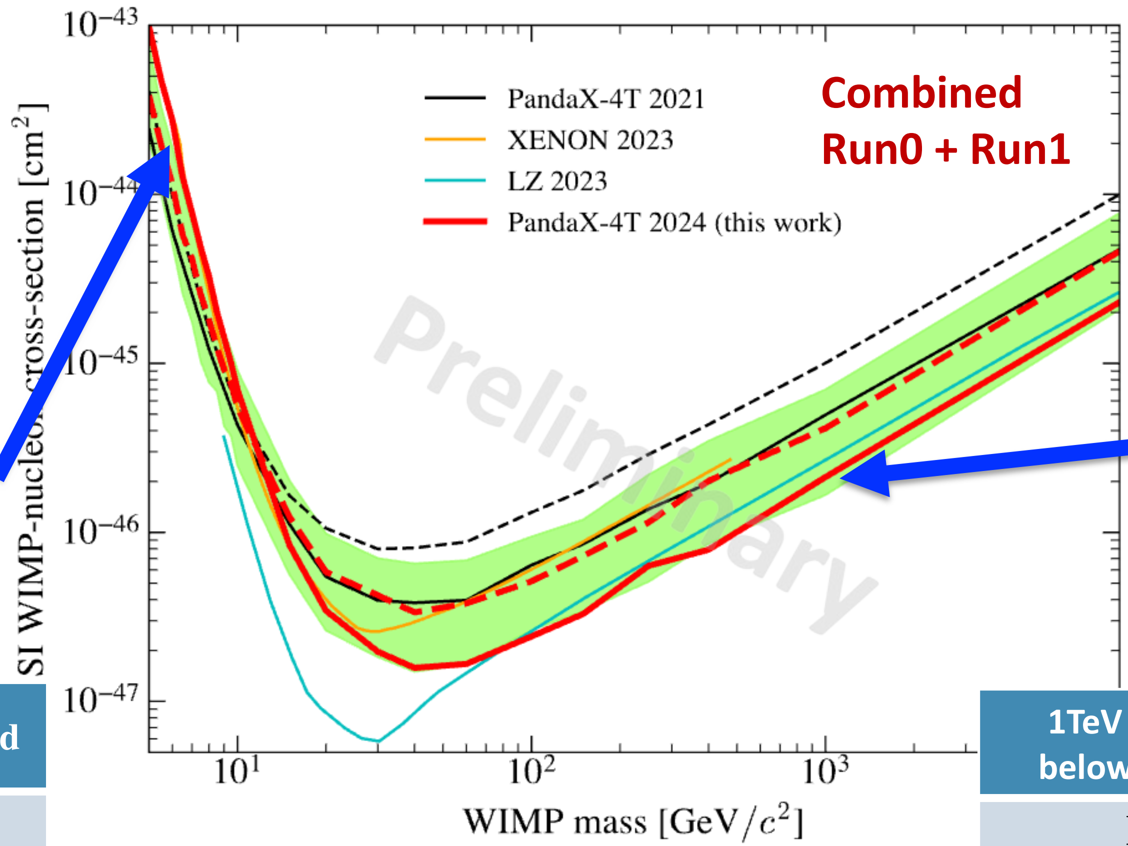
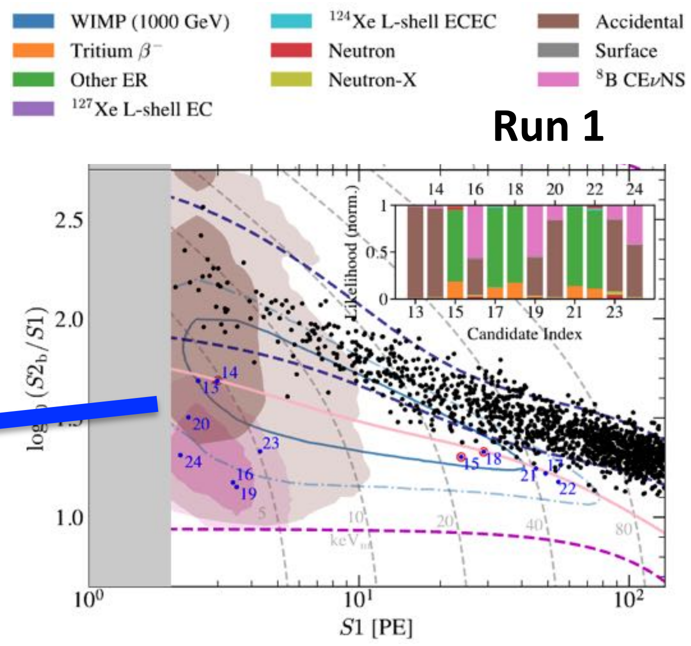
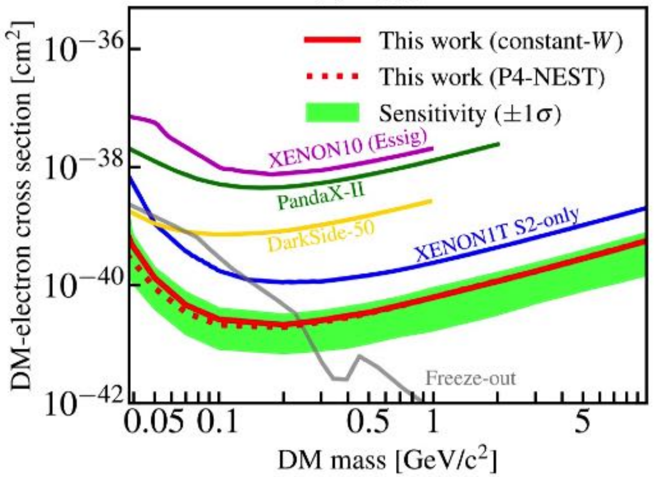




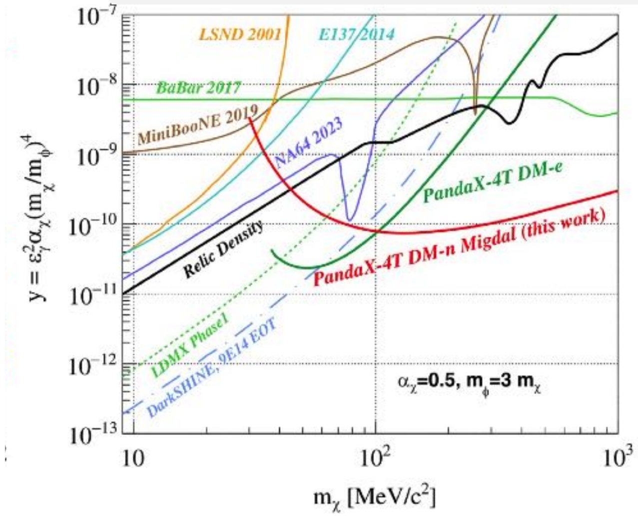
1TeV 1σ contour below NR median	Expected	Observed
Run0	4.5	5
Run1	4.7	3

More DM Results from PandaX-4T

DM-electron interaction

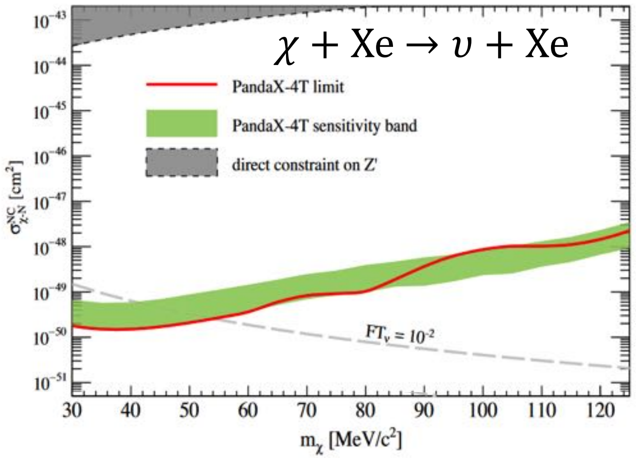


PRL 130, 261001 (2023)
Editors' Suggestion

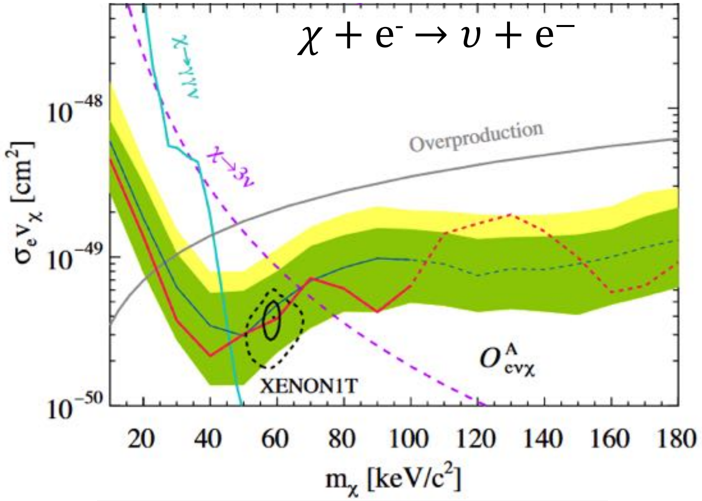


PRL 131, 191002 (2023)

DM-neutrino interaction

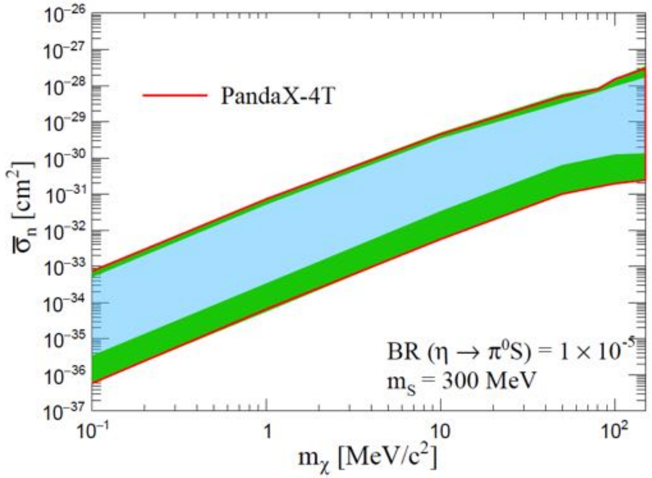


PRL 129, 161803 (2022)
Editors' Suggestion

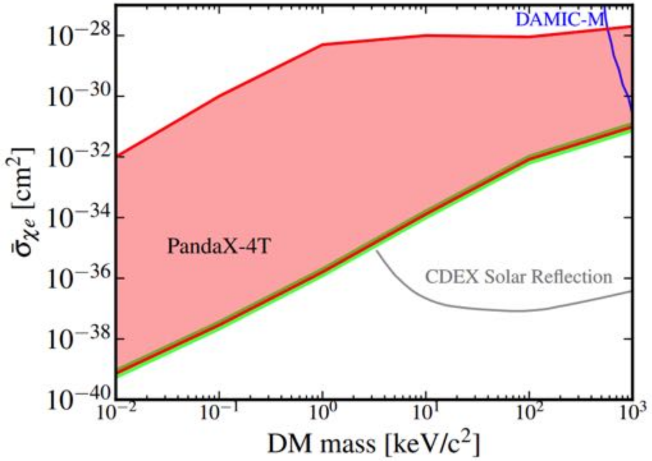


PRL 129, 161804 (2022)
Editors' Suggestion

Boosted DM



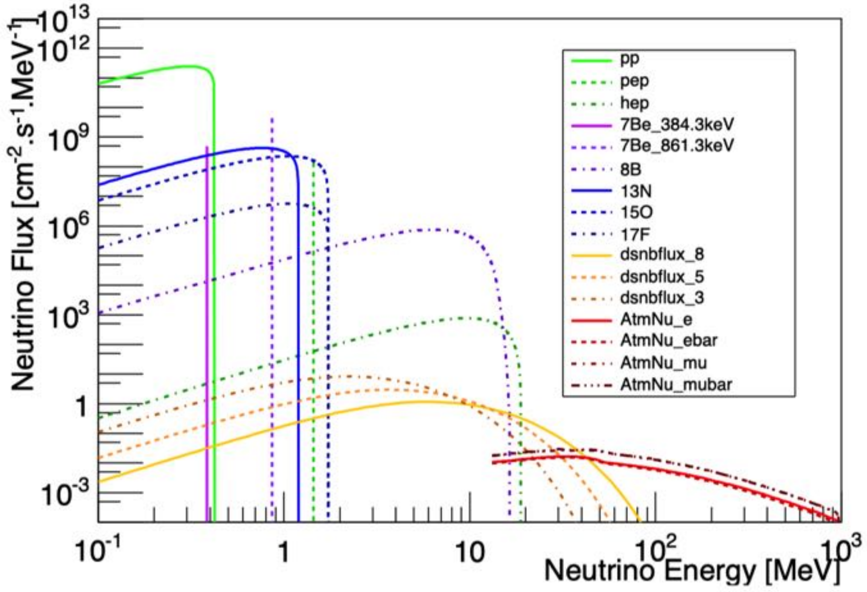
PRL 131, 041001 (2023)

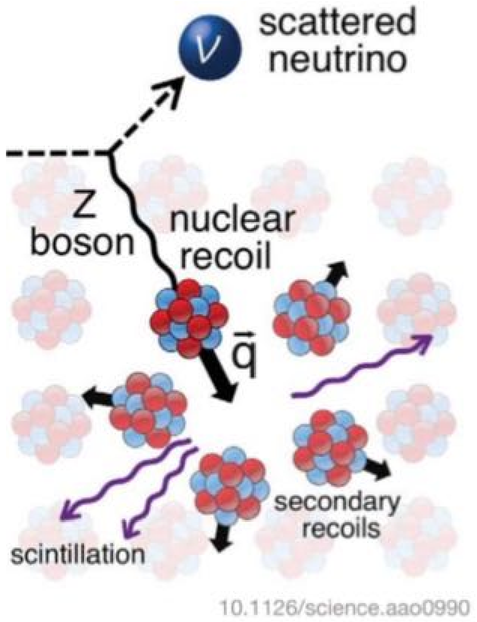


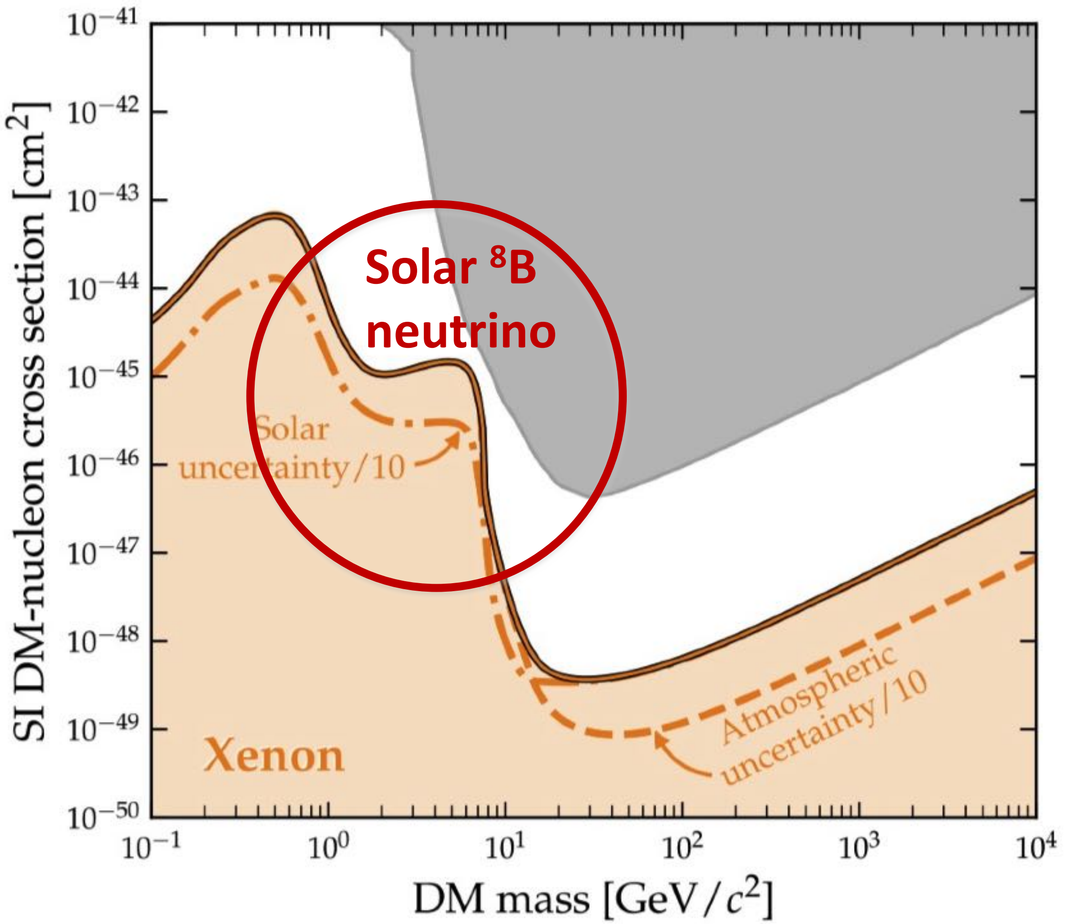
arXiv: 2403.08361

Neutrino Floor

- **Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)**



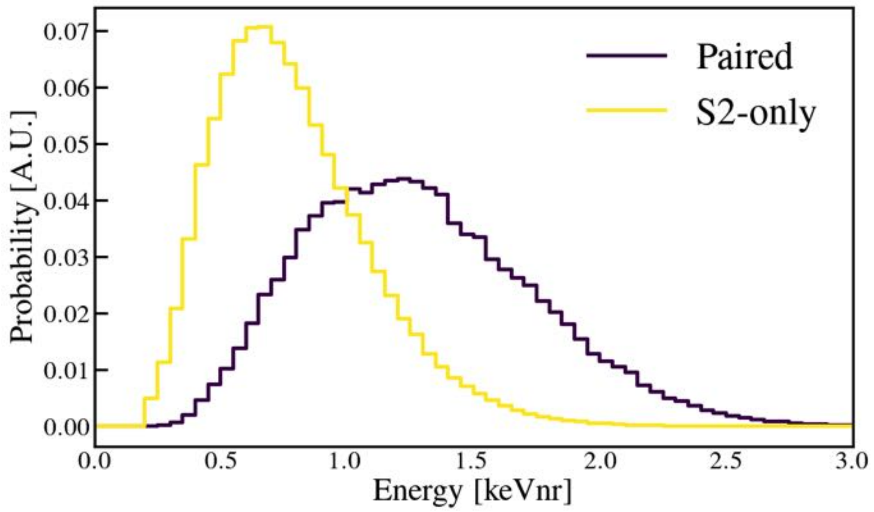




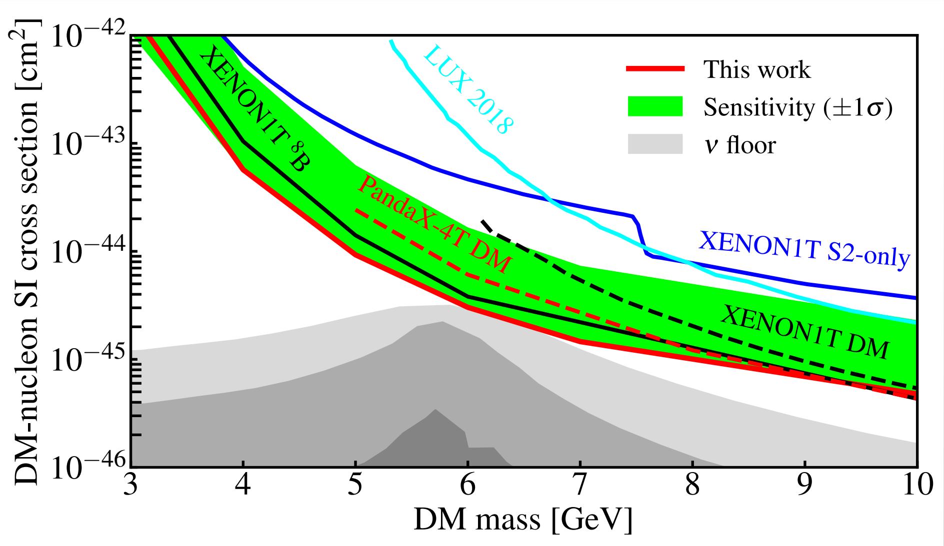
C. O'Hare PRL 127, 251802 (2021)

Solar ^{8}B neutrino

- **Low threshold detection mode**
  - low threshold paired ROI
  - Ionization S2-only ROI

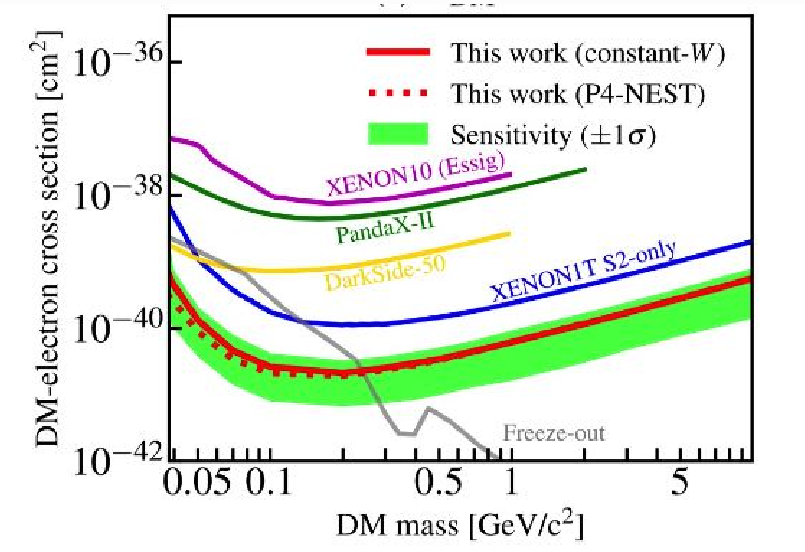


Low threshold paired ROI



PRL 130, 021802 (2023)

Ionization S2-only ROI

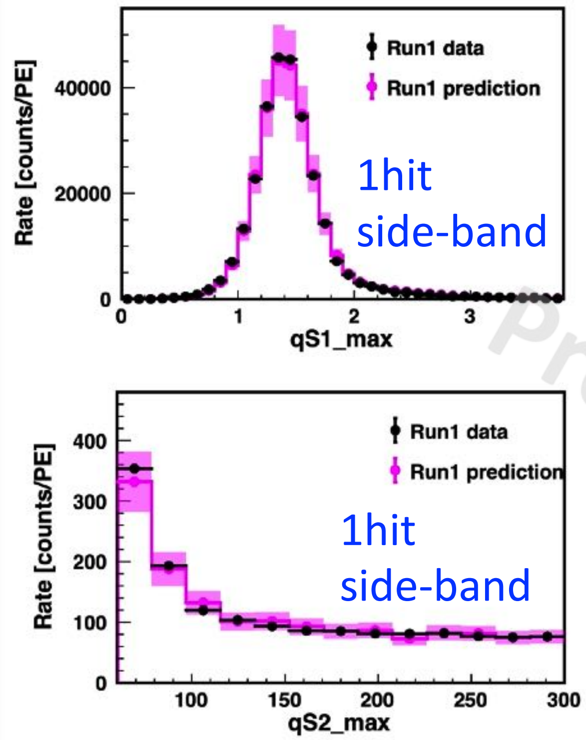


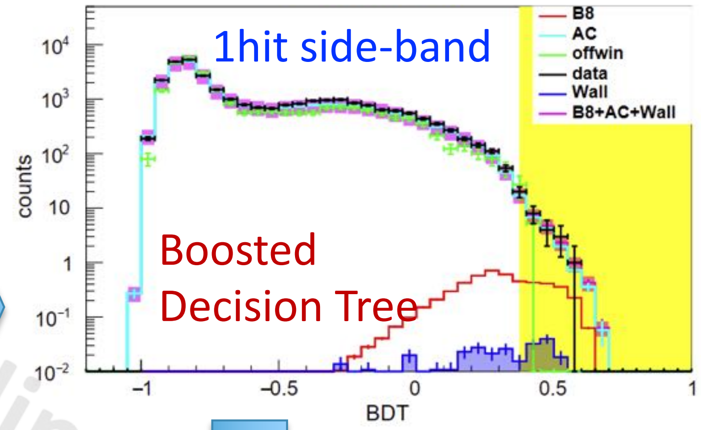
PRL 130, 261001 (2023), Editors' Suggestion

Low threshold paired ROI

1.25 tonne-year

- **Lowering selection threshold for solar B8**
  - Cut on the scintillation signal (S1) from 2 PE to 0.3 PE
- **Accidental paired (AC) background modeling and rejection**



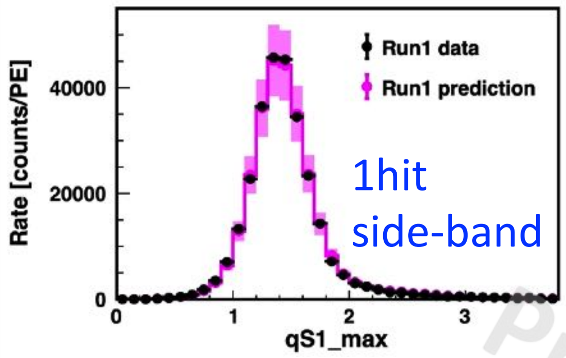


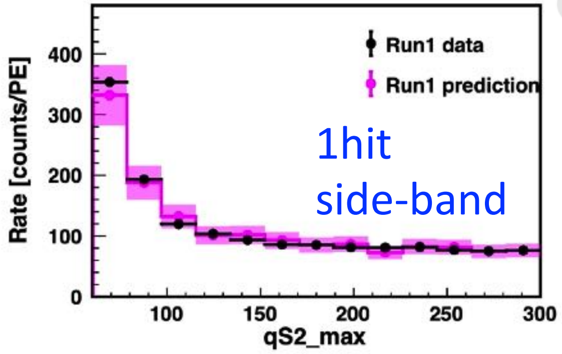
		Run0 WO BDT	Run0 W. BDT	Run1 WO BDT	Run1 W. BDT
Off-window	Model	209±25	1.2±0.4	485±43	0
	Data	209	1	495	2
OD	Model	26±6	0.12±0.04	34±7	0.06±0.02
	Data	18	0	29	0
1-hit side-band	Model	17095±2564	14±4	27567±4135	15±5
	Data	17374 →	9	29359 →	17

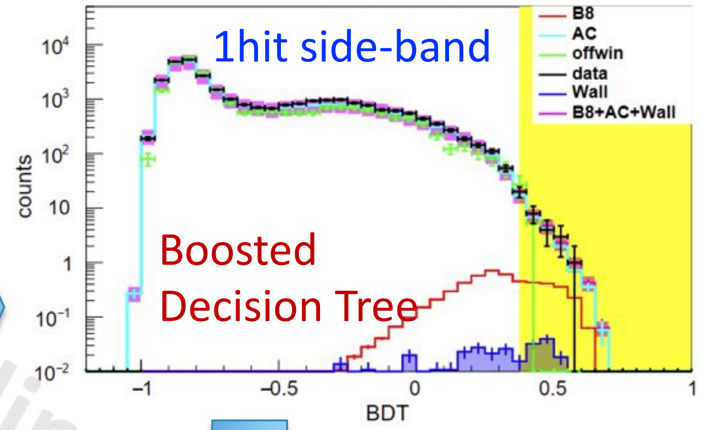
Low threshold paired ROI

- **Lowering selection threshold for solar B8**
  - Cut on the scintillation signal (S1) from 2 PE to 0.3 PE
- **Accidental paired (AC) background modeling and rejection**

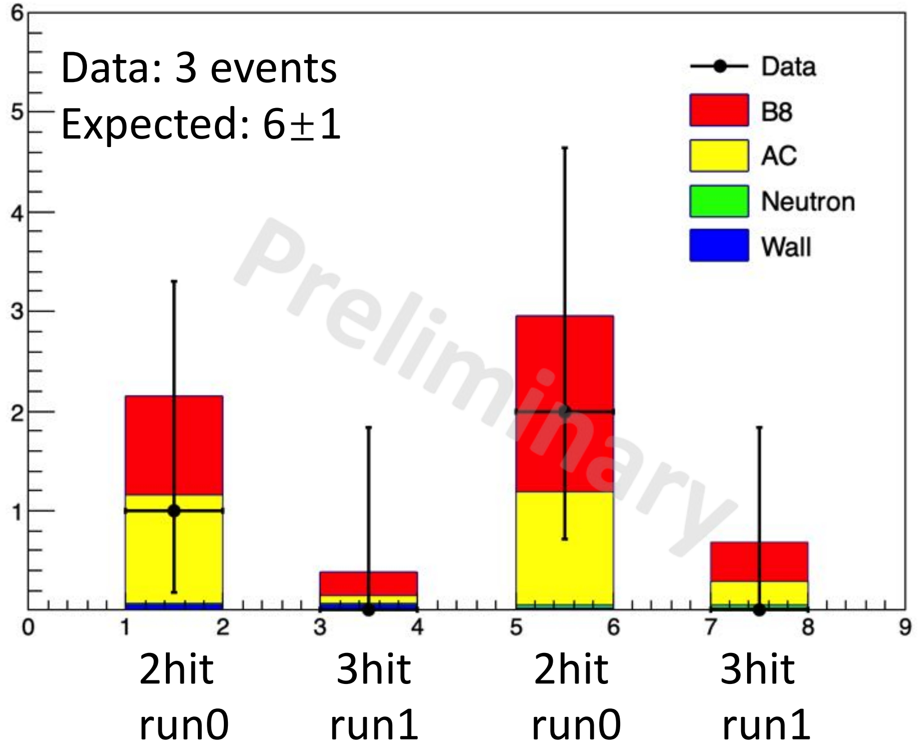
1.25 tonne-year







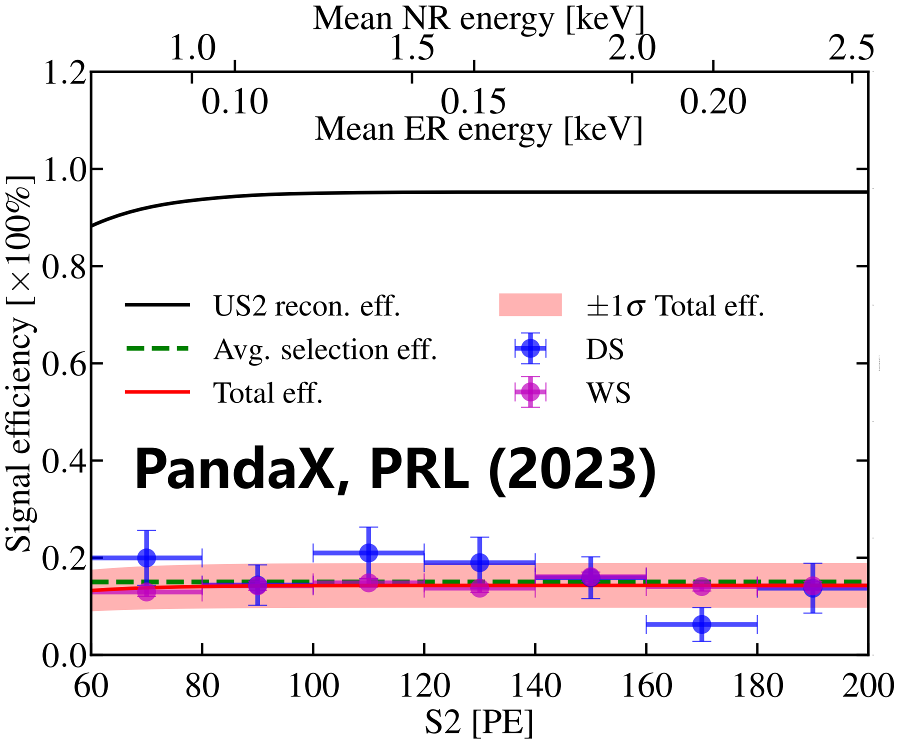
		Run0		Run1	
		WO BDT	W. BDT	WO BDT	W. BDT
Off-window	Model	209±25	1.2±0.4	485±43	0
	Data	209	1	495	2
OD	Model	26±6	0.12±0.04	34±7	0.06±0.02
	Data	18	0	29	0
1-hit side-band	Model	17095±2564	14±4	27567±4135	15±5
	Data	17374 →	9	29359 →	17



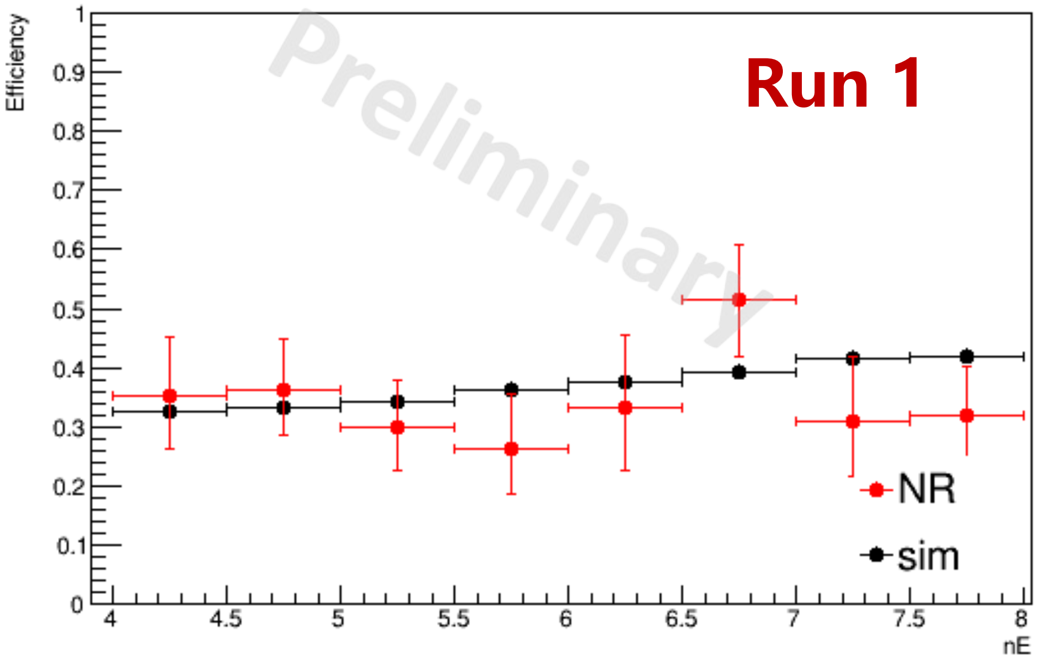
Unblinded Data

Ionization S2-only ROI

- **Ionization-only: no scintillation signal requirement**
  - ROI S2 [60, 200]PE: threshold down to ~100 eV_{ee} (from ~1 keV_{ee})
- **Key Challenge: signal efficiency and background control**

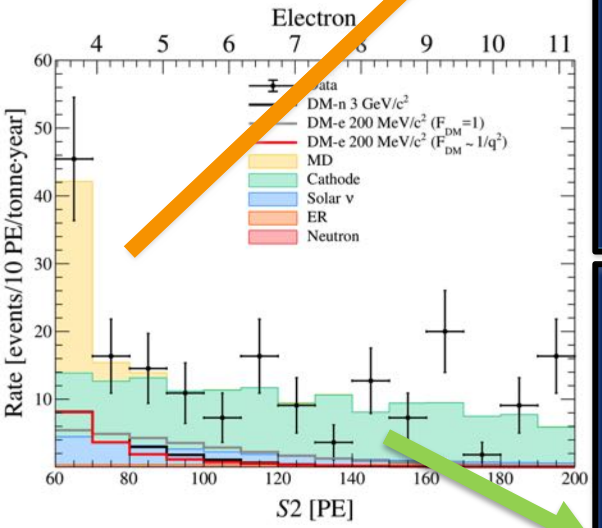


Signal efficiency



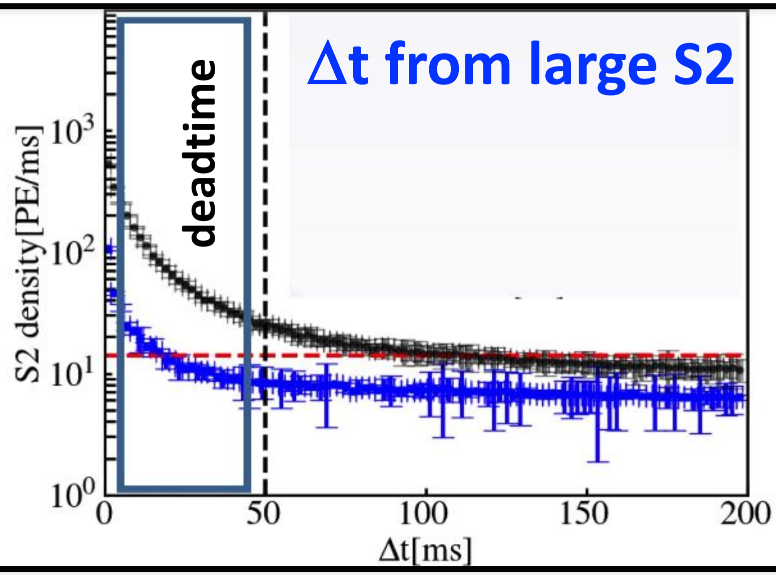
S2-only Background Modelling

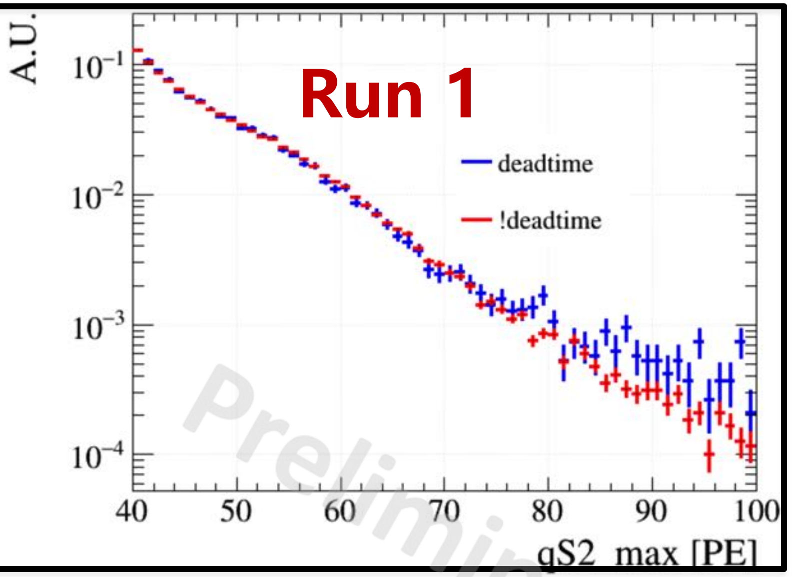
- **Low threshold region: two instrumental background sources**



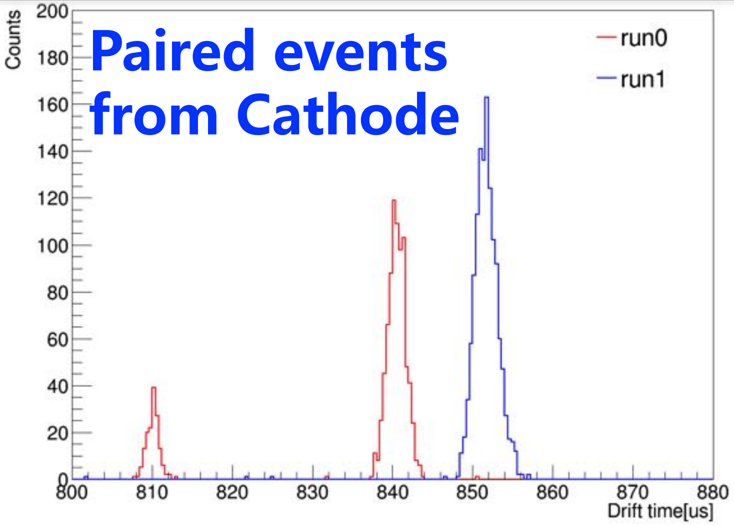
PandaX, PRL (2023)

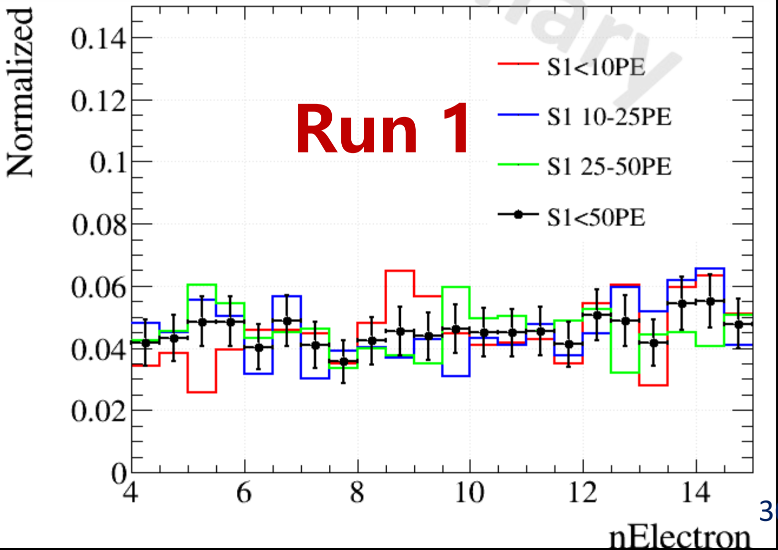
Delayed electron emission after large S2





Electron emission from Cathode

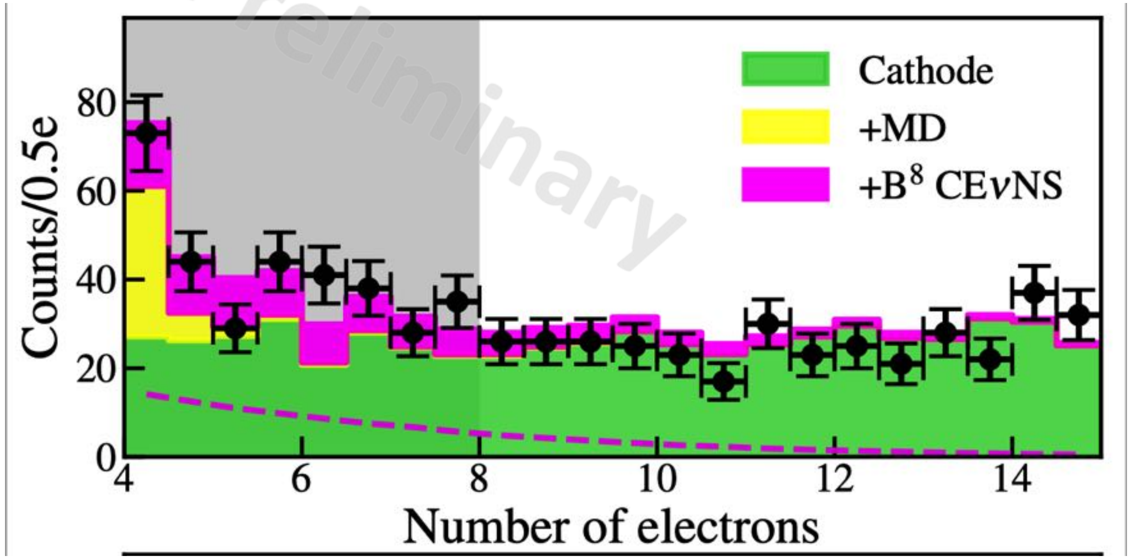


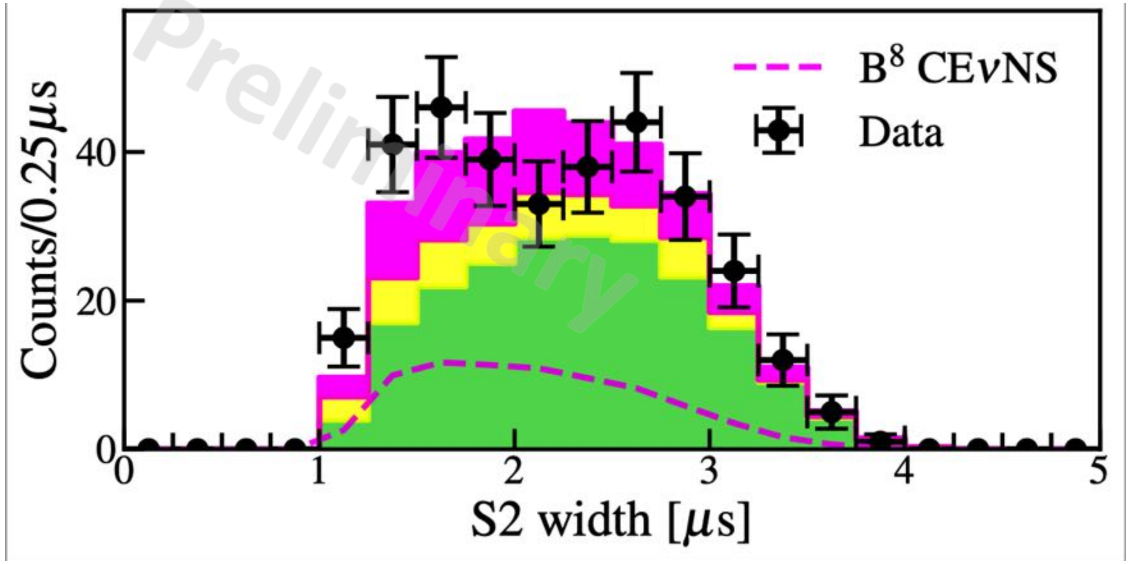


Unblinded S2-only Data

- **Preliminary result from 1D fitting on S2 charge spectrum**
  - Excess in run0+run1 data, best-fit B8 rate: μ = 1.8±0.8
- **Further 2D fitting on charge vs width work-in-progress**
- **First measurement of solar neutrino CEvNS process with Xe**

1.04 tonne-year

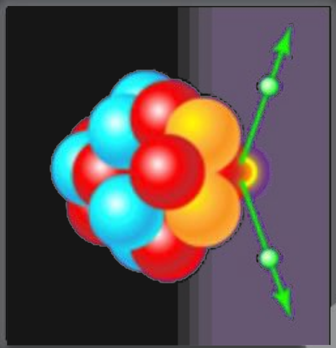




Multi-physics Targets

Large energy range: keV ~ MeV

Dark Matter
1 keV – 10 keV

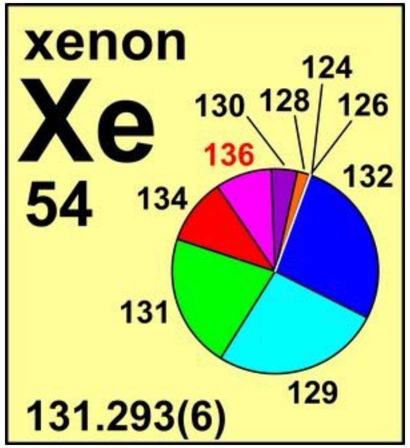


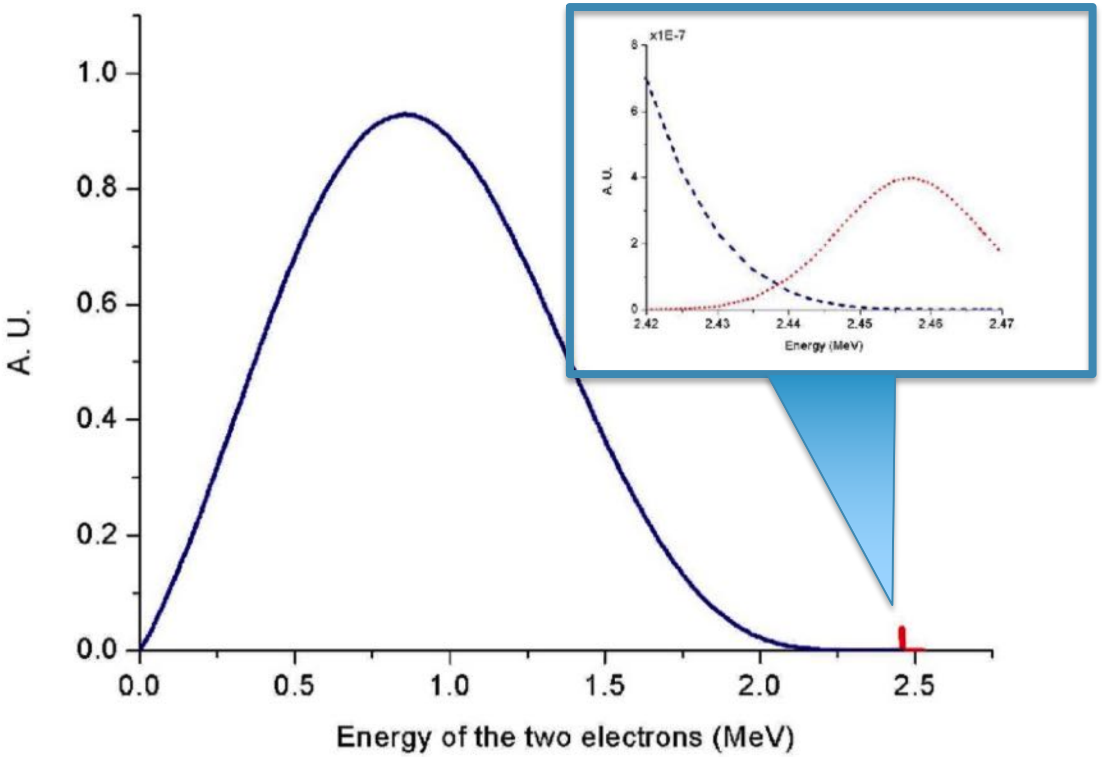
Majorana Neutrino
> 2 MeV

Astrophysical Neutrino
< 300 keV

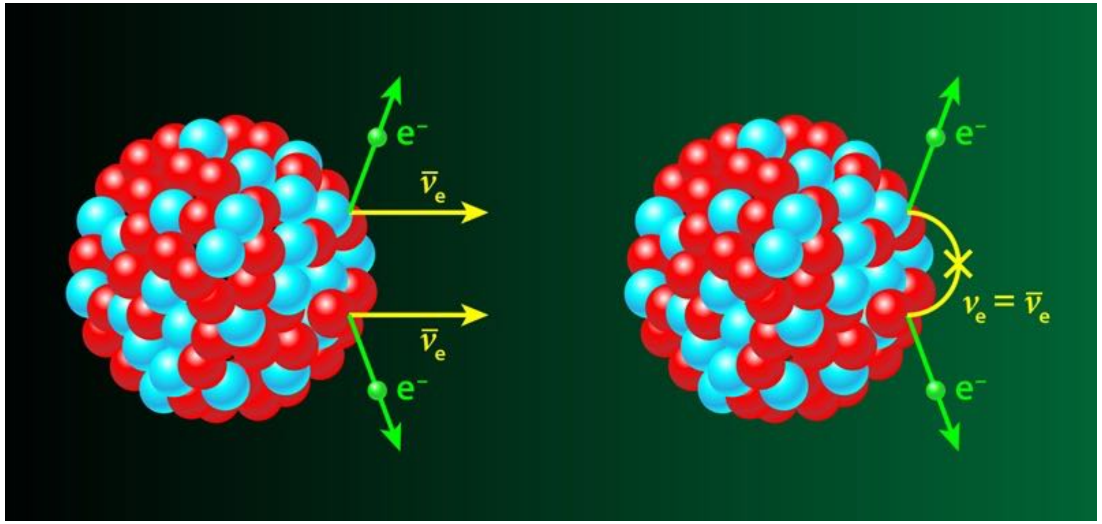
Majorana Neutrino

- **Neutrinoless double-beta decay**
  - Golden channel for Majorana neutrino searches
- **Xe-136: natural abundance 8.9%**
  - $2\nu\beta\beta$ $T_{1/2}$ $2.2\text{x}10^{21}$ years, $Q_{\beta\beta}$ 2.46 MeV



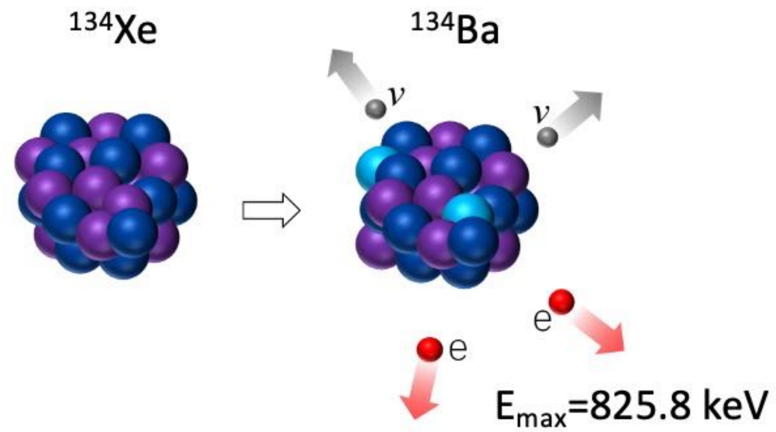


$$^{136}\text{Xe} \rightarrow {}^{136}\text{Ba} + 2e^{-} + ?\,\nu$$

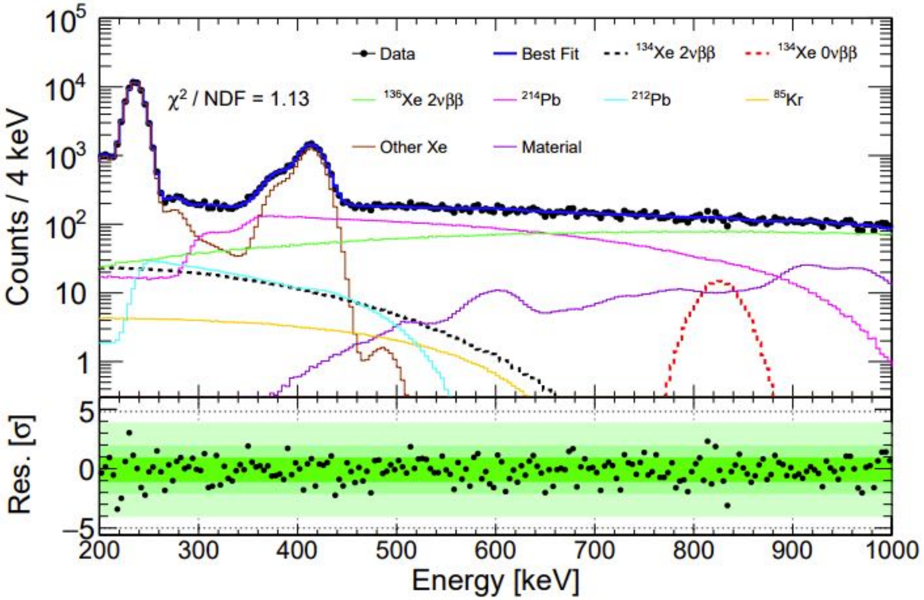


Xe-134 @ PandaX-4T

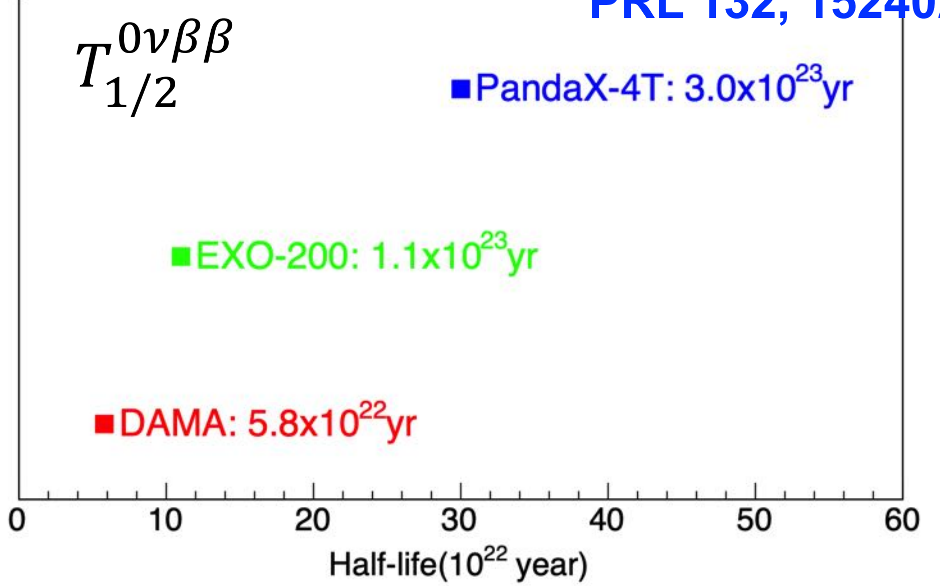
- **Next promising discovery of 2νββ decay**
  - natural abundance 10.4%
  - 2νββ $T_{1/2}$ ~10^{24} years, $Q_{\beta\beta}$ 0.83 MeV



- **95 live-days with 656 kg natural xenon**
  - 90%CL limits on half-life $T_{1/2}^{2\nu\beta\beta} > 2.8 \cdot 10^{22}$ yr and $T_{1/2}^{0\nu\beta\beta} > 3.0 \cdot 10^{23}$ yr

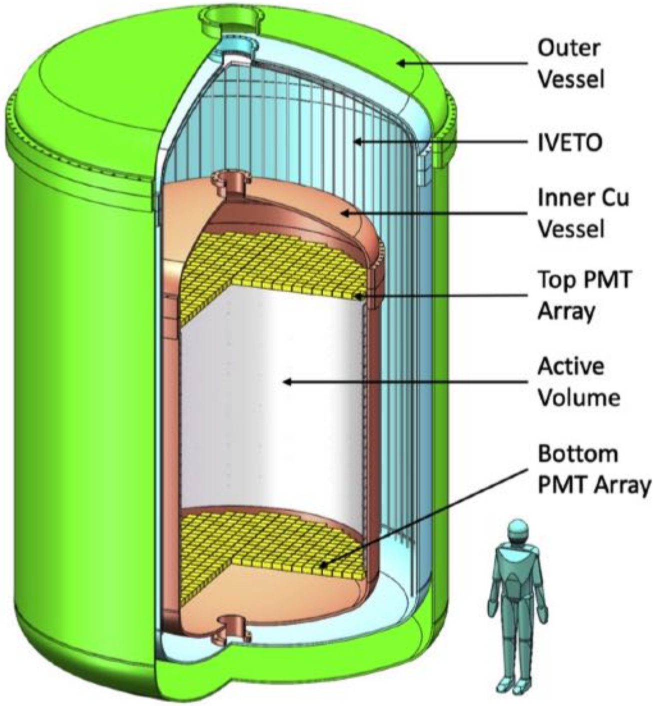


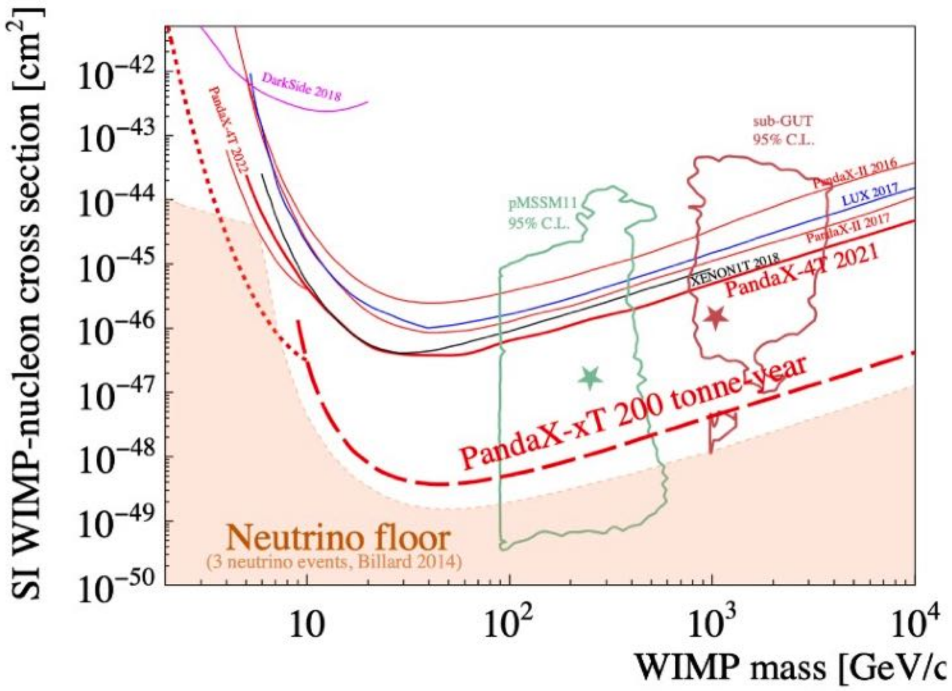
PRL 132, 152402 (2024)

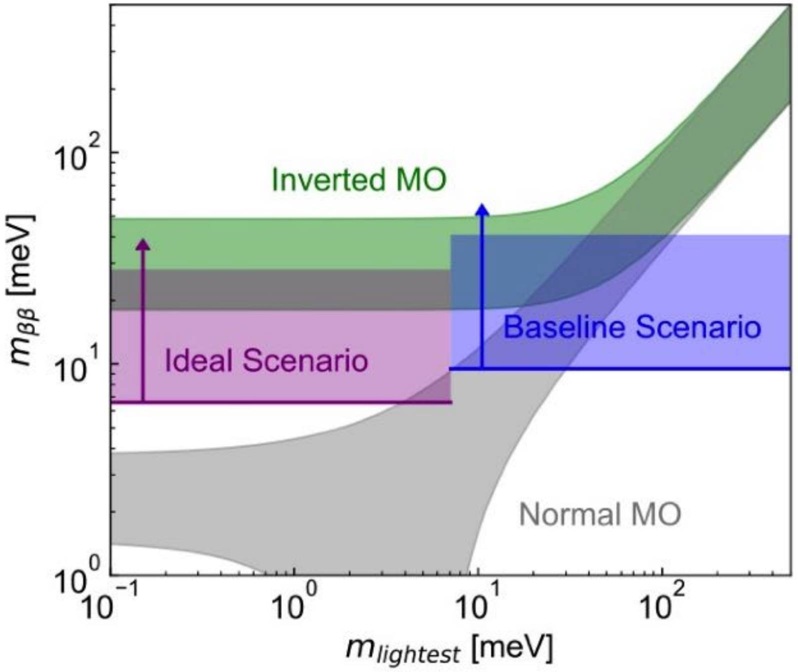


Future plan: PandaX-xT

- **Ultimate liquid xenon experiment**
  - With >30 tonne sensitive volume
  - Letter-of-interest sent to Chinese funding agency
  - Key tests on WIMP and Dirac/Majorana neutrino







arXiv:2402.03596

20T Experiment R&D

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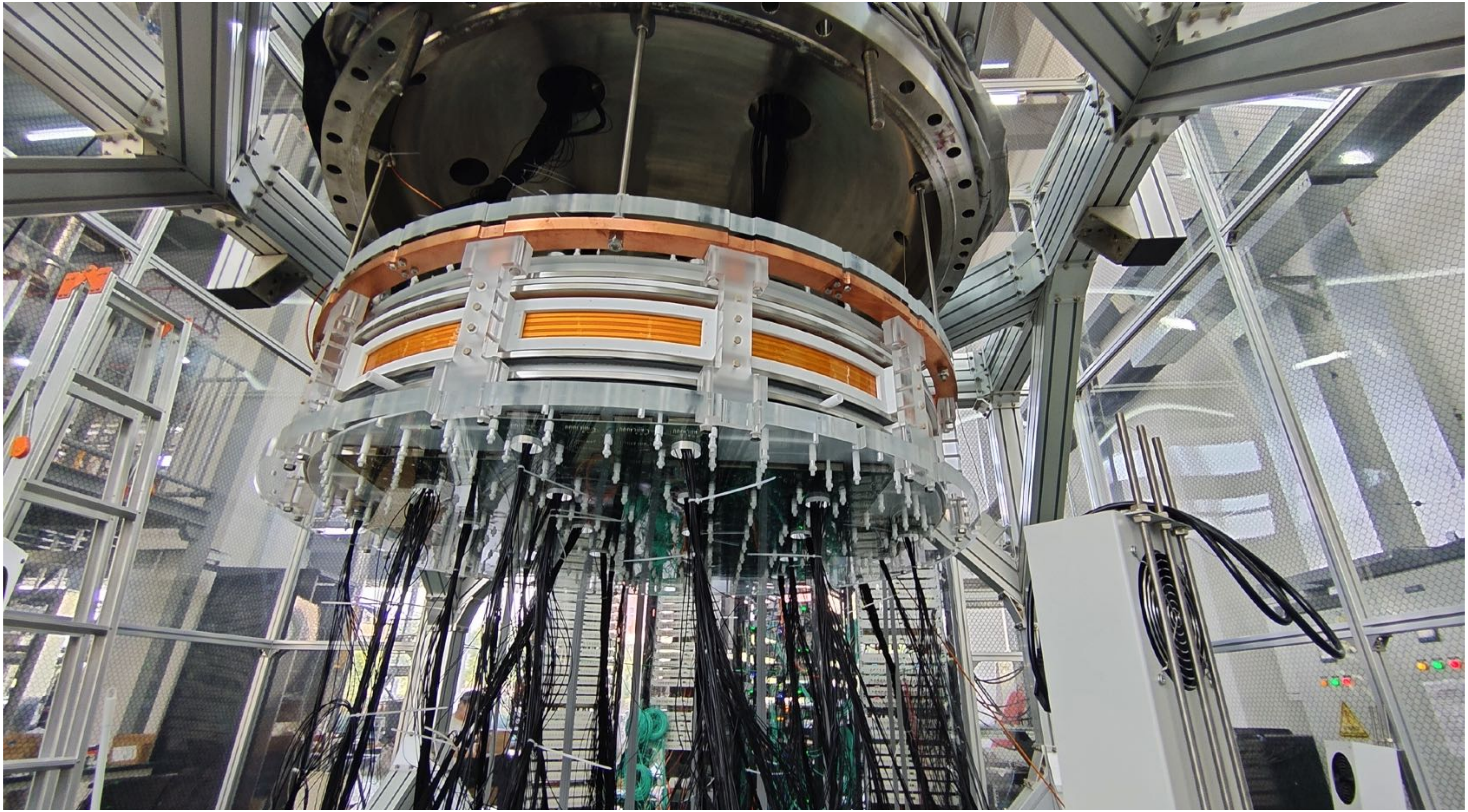

20T Experiment R&D

- 

Expected to be online in 2027

Summary

- **PandaX-4T is one of the new generation multi-tonne xenon experiments**
  - Intense searches for various types of physics, including WIMPs, axions, neutrinos, etc.
  - Expecting more interesting results
- **Next stage: 20T is expected to be online in 2027**
- **Highly welcome new collaborators!**

THANK YOU

Night view @ CJPL (Image credit S. Zhang)