# Overview of PandaX-4T experiment

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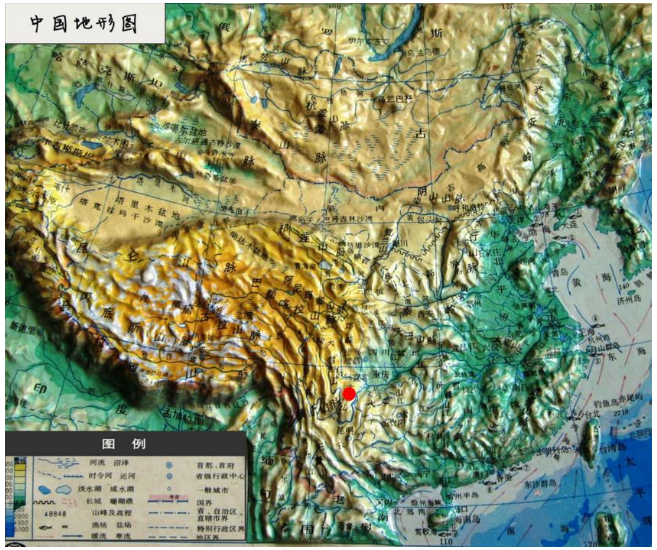
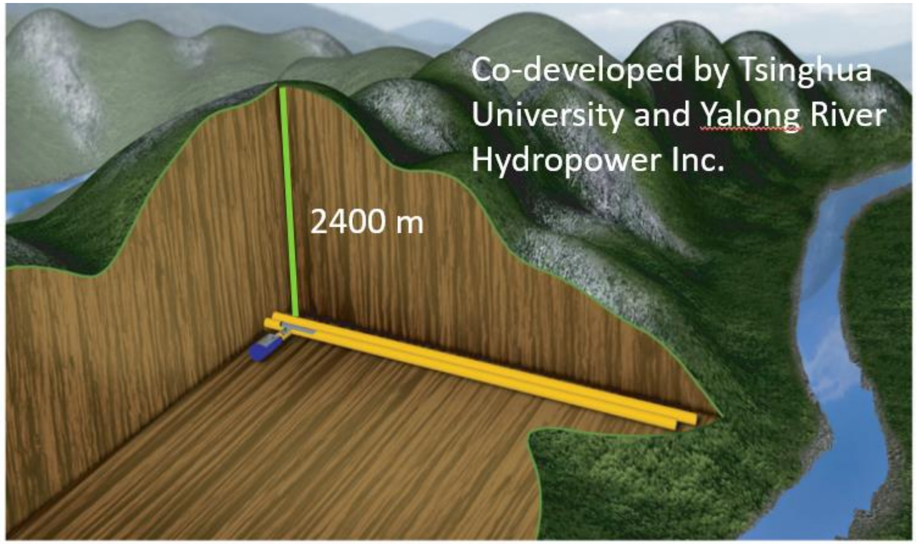
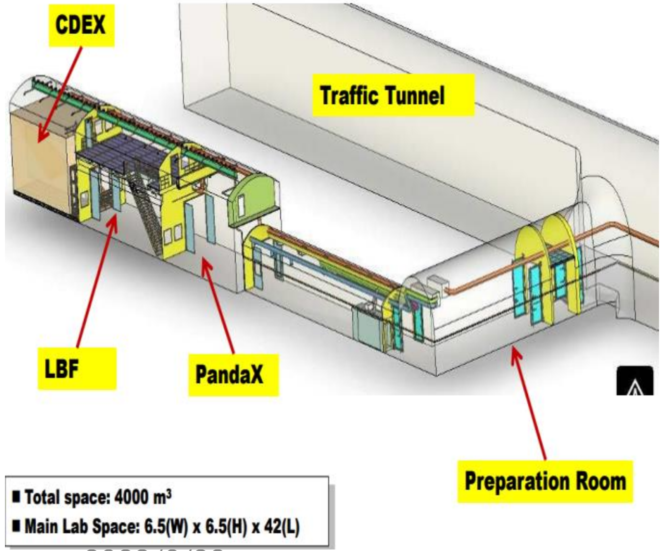
PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

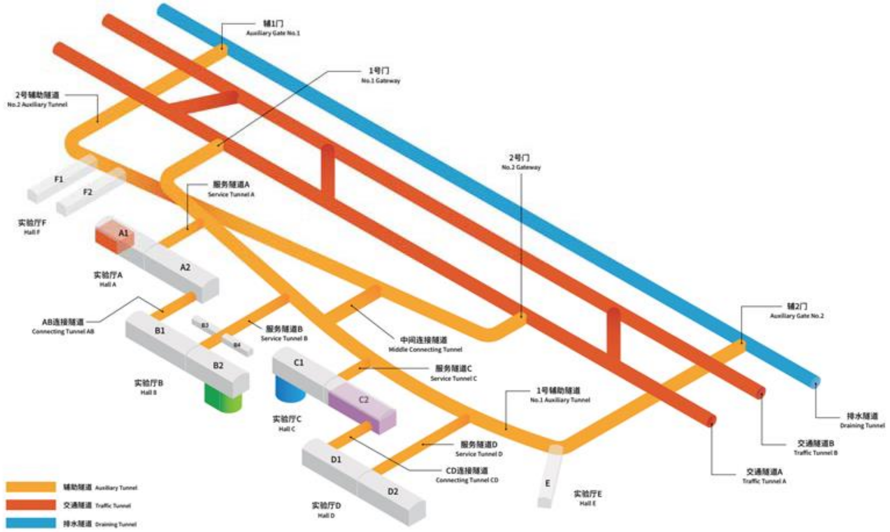
# PandaX Collaboration

# China JinPing Underground Laboratory – CJPL



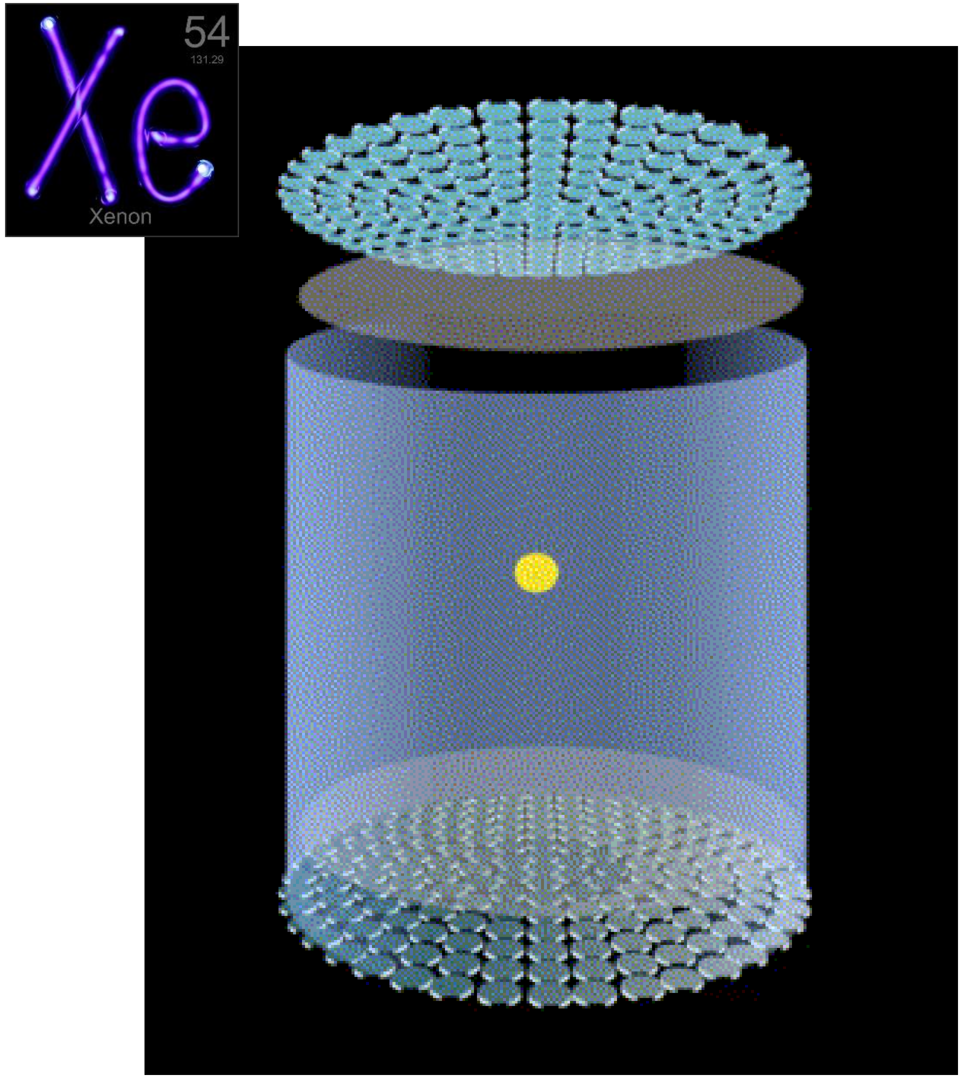



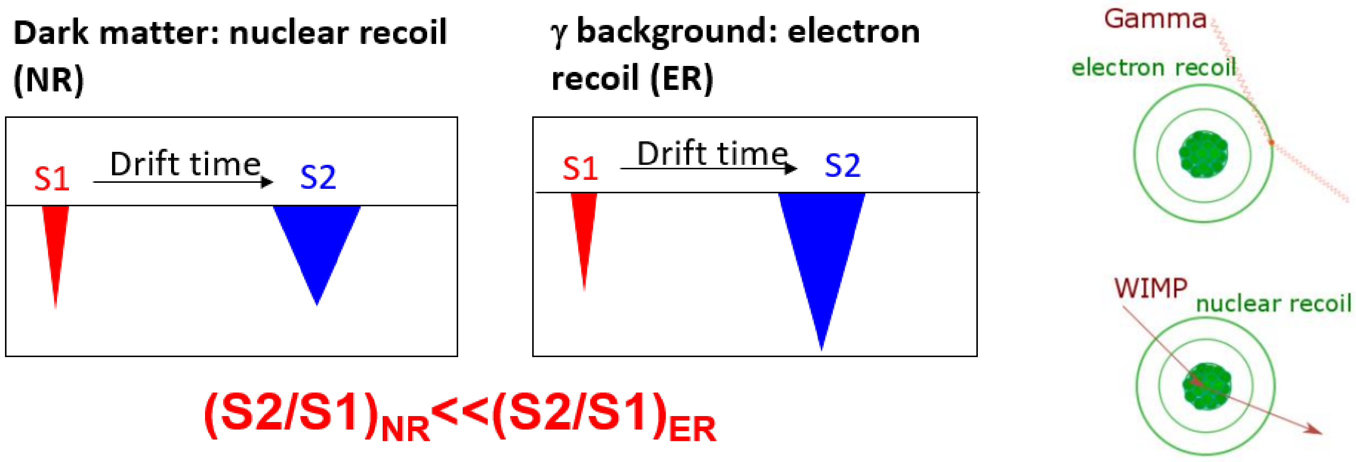



- Deepest (6800 m.w.e )
- Horizontal access
- Muon rate: 1 count/week/m$^2$
- From CJPL-I to CJPL-II

# Dual Phase Liquid Xenon TPC




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

- Purity liquid xenon target, high light & charge yield;
- Good ER/NR discrimination by S2/S1 ratio;
- 3D reconstruction rejects external background;

# PandaX Roadmap

**Particle and Astrophysical Xenon Experiments**

2009.3

**Collaboration formed**


2014.5-10

**PandaX-I, 120 kg operation**

2016.7-2019.7

**PandaX-II, 580 kg operation**

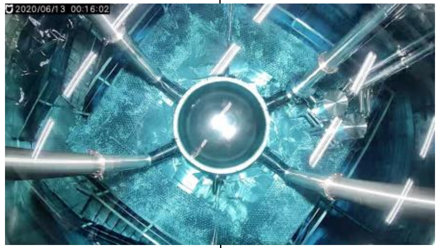
2019.8

**PandaX-4T moved to CJPL-II**

2020.11-2021.5

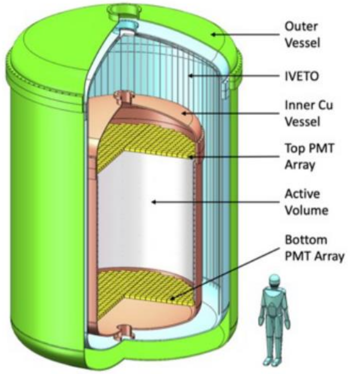
**PandaX-4T Commissioning**

2021.11




**PandaX-4T Run1**

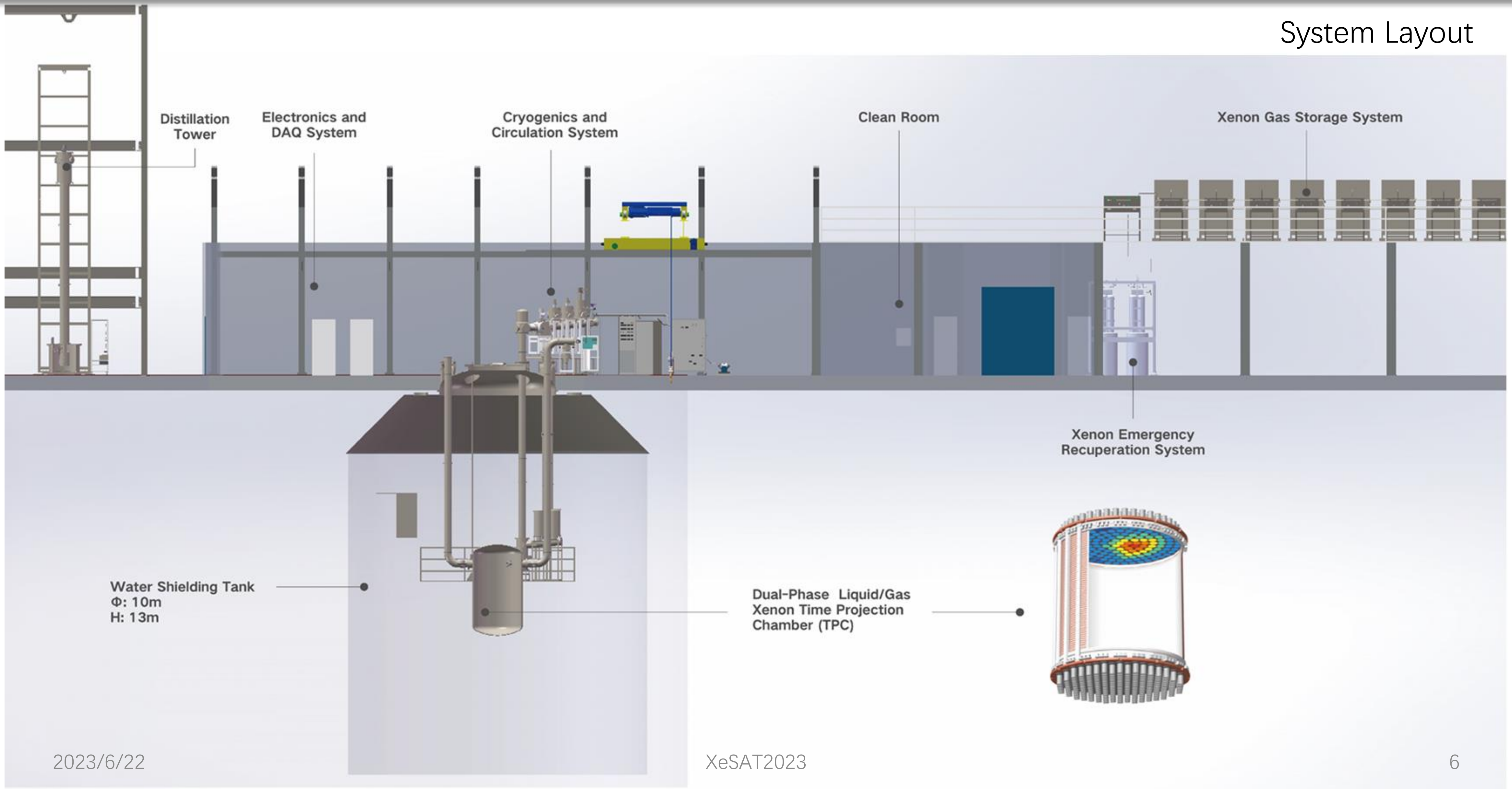
**Ongoing**




PandaX-xT

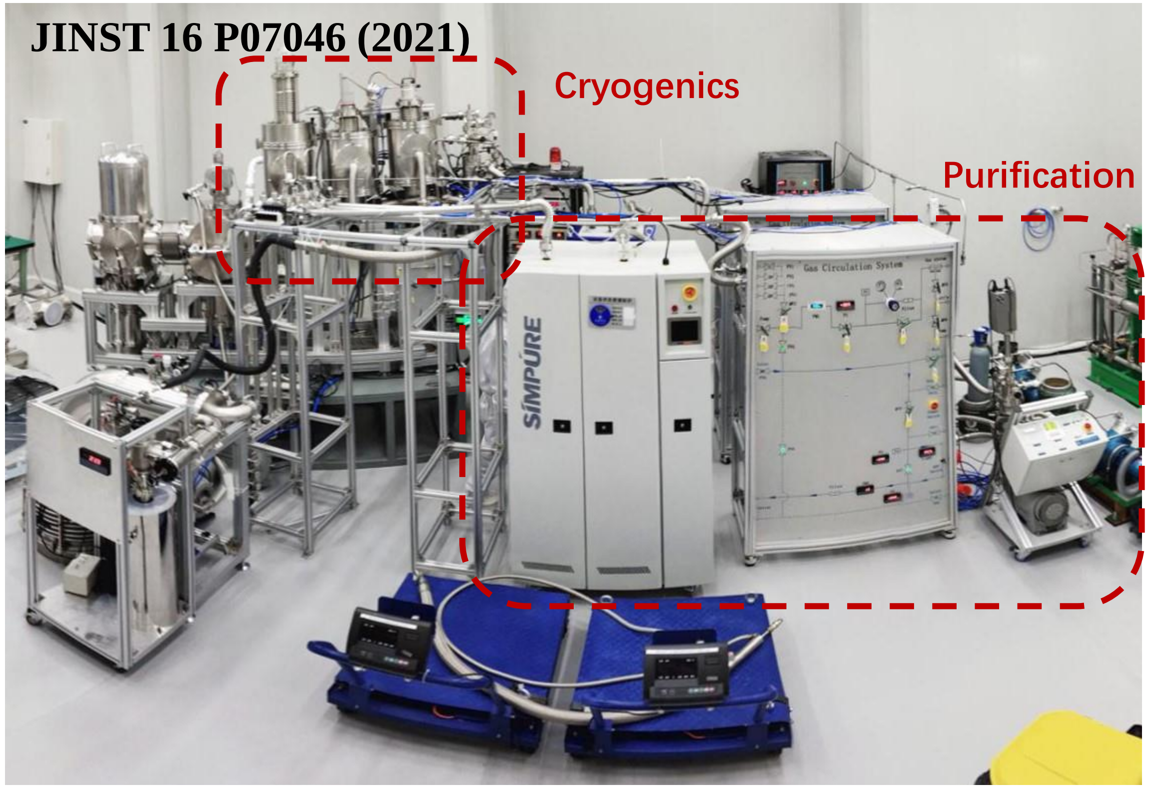
# PandaX-4T Overview

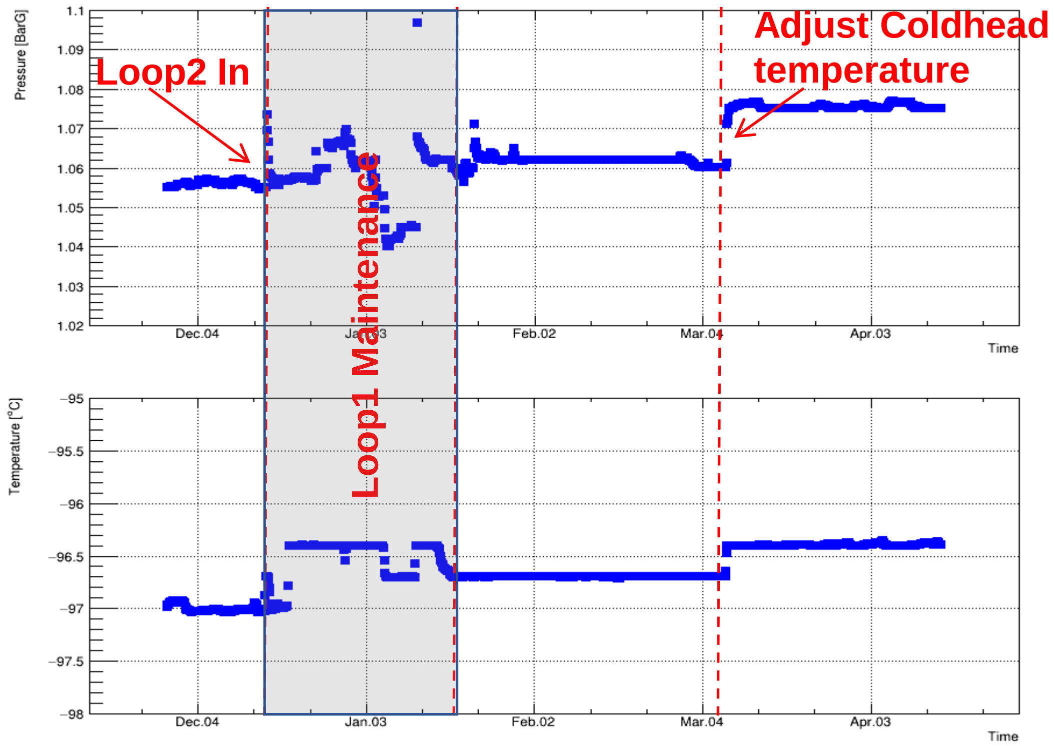
System Layout



# Cryogenics System

- Pressure and temperature stability within **0.5% and 0.1K .**



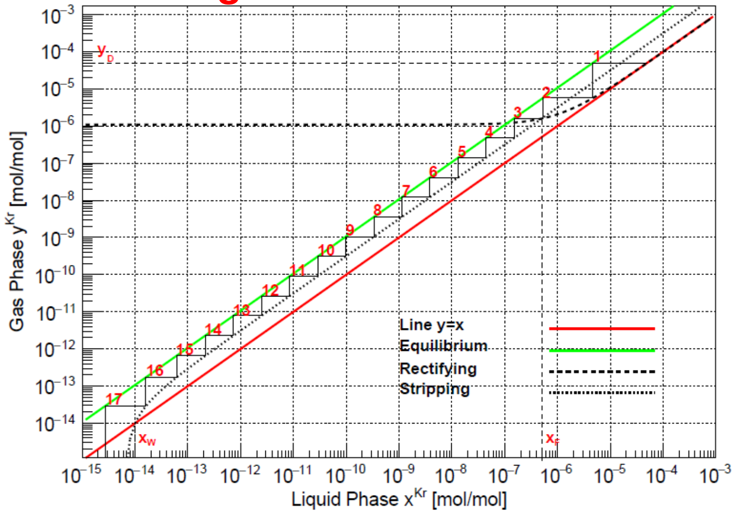




| Parameters | Heating load (No purification) | Maximum Cooling Power | Filling/Recuperation flow rate | Outer Vacuum |
|---|---|---|---|---|
| Value | ~50 W | ~580 W | ~1 ton/day | <2E-4 Pa |

# Distillation System

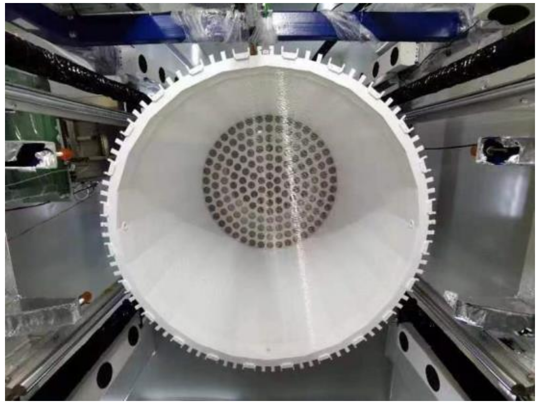

**Structured packing (inside)**

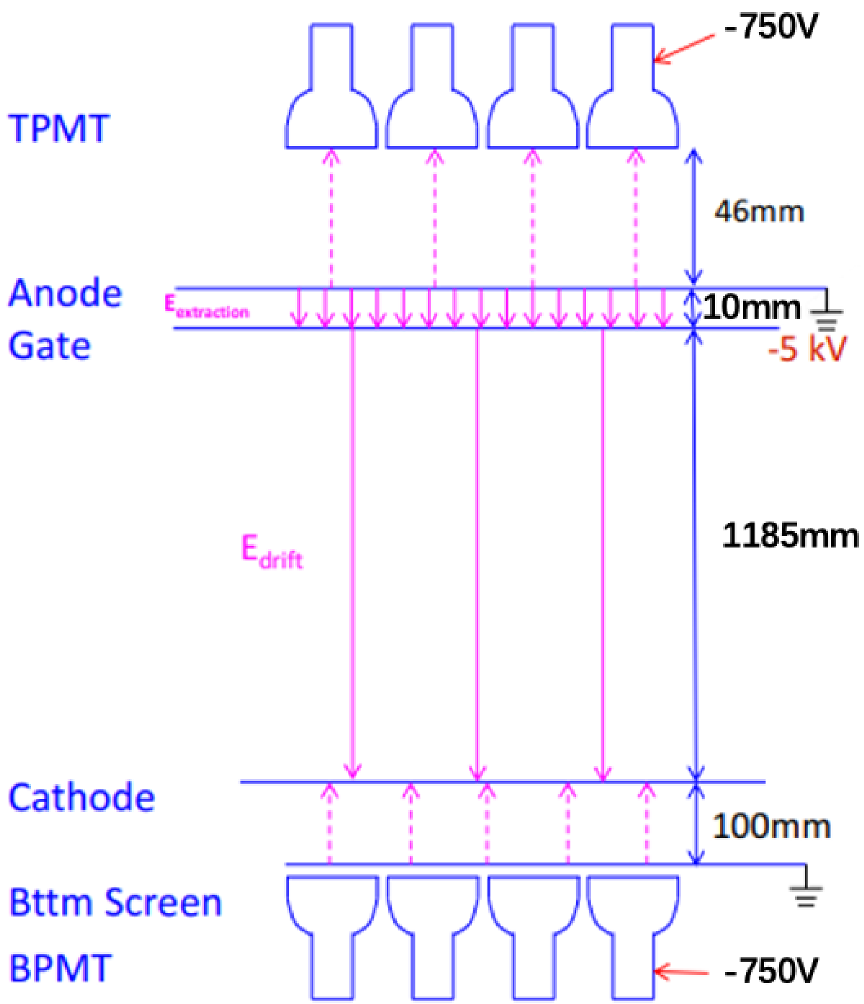
**M-T diagram for Kr removal**




- Distillation method for the LXe intrinsic background Kr & Rn removal;
- ~$10^6$ reduction factor for Kr removal with 10 kg/h;
- Reversed operation mode working for Rn removal;

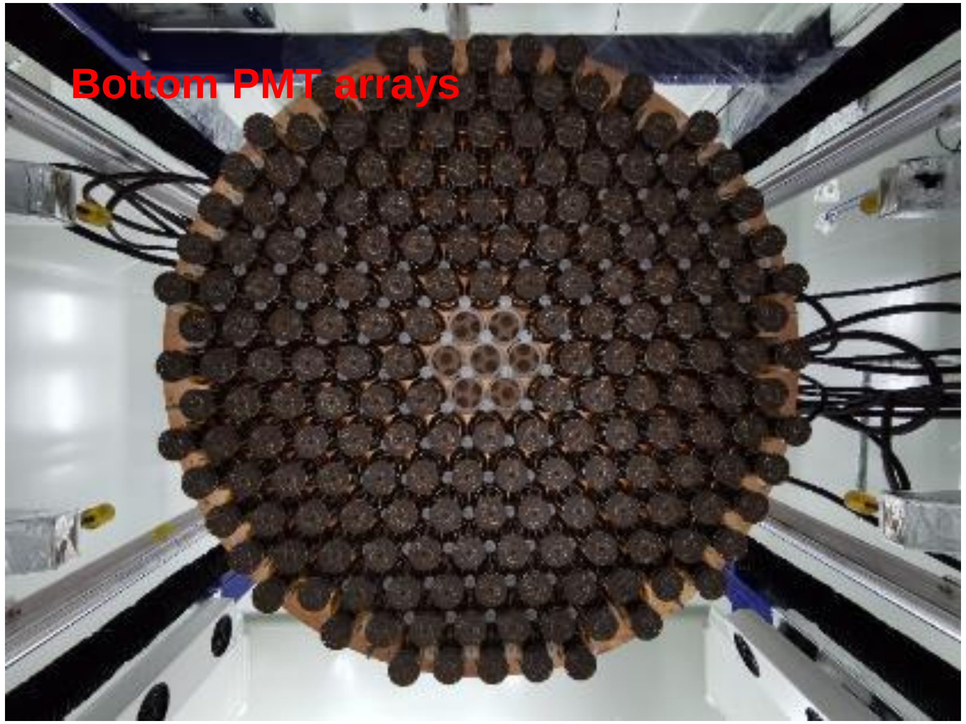
# TPC Conditions





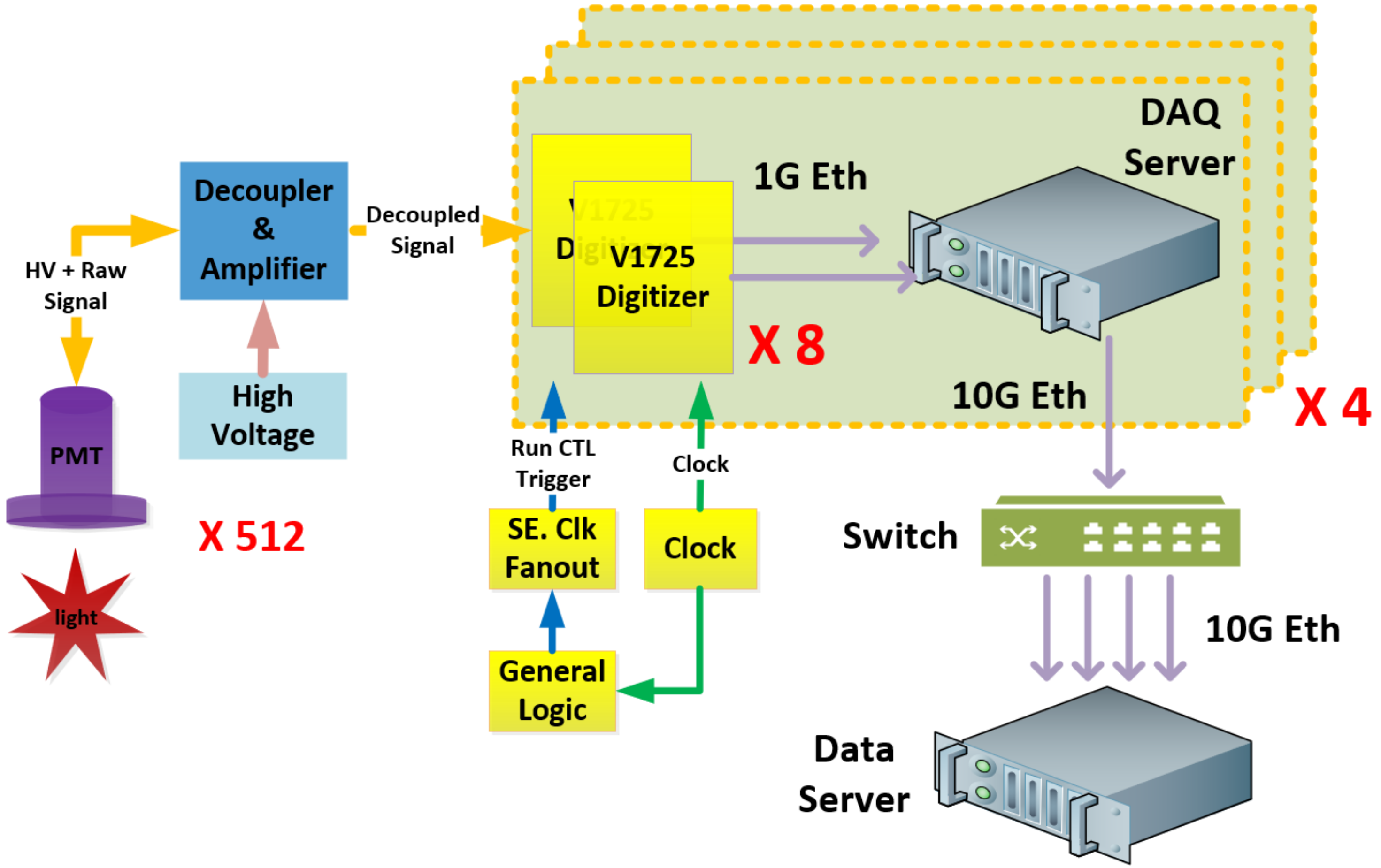

| | Set1 | Set2 | Set3 | Set4 | Set5 |
|---|---|---|---|---|---|
| Gate(kV) | -4.9 | | -5 | -5 | |
| Cathode (kV) | -20 | -18.6 | -18 | -16 | |

# PMT Arrays



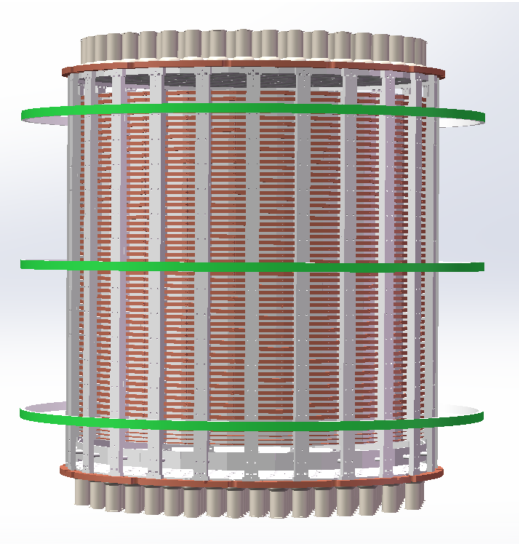

- 169 top + 199 bottom R11410-23 3-inch PMTs, with the average gain of $5.5\times10^6$;
- LED calibration every week, monitor gain stability;

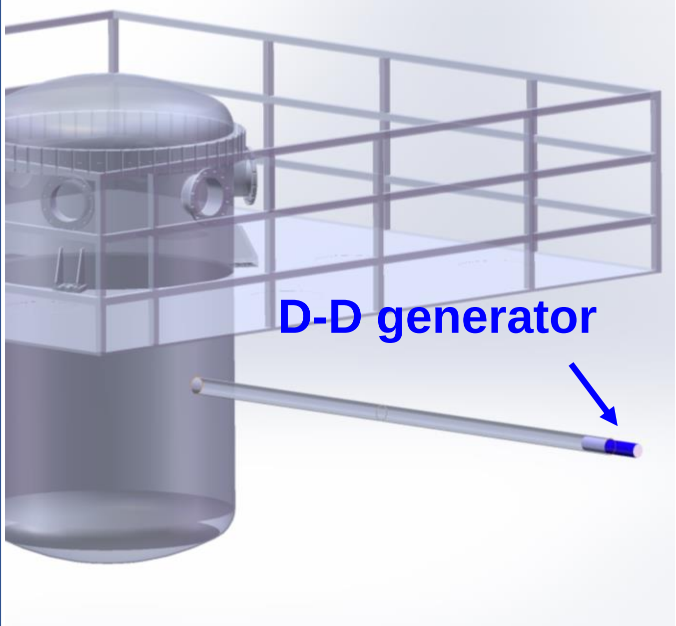
# Electronics




- From PMT to DAQ server;
- CERN V1725 Digitizer, 250 MS/s;
- Self-trigger mode: read out pulses above 20 ADC (~ 1/3 PE);

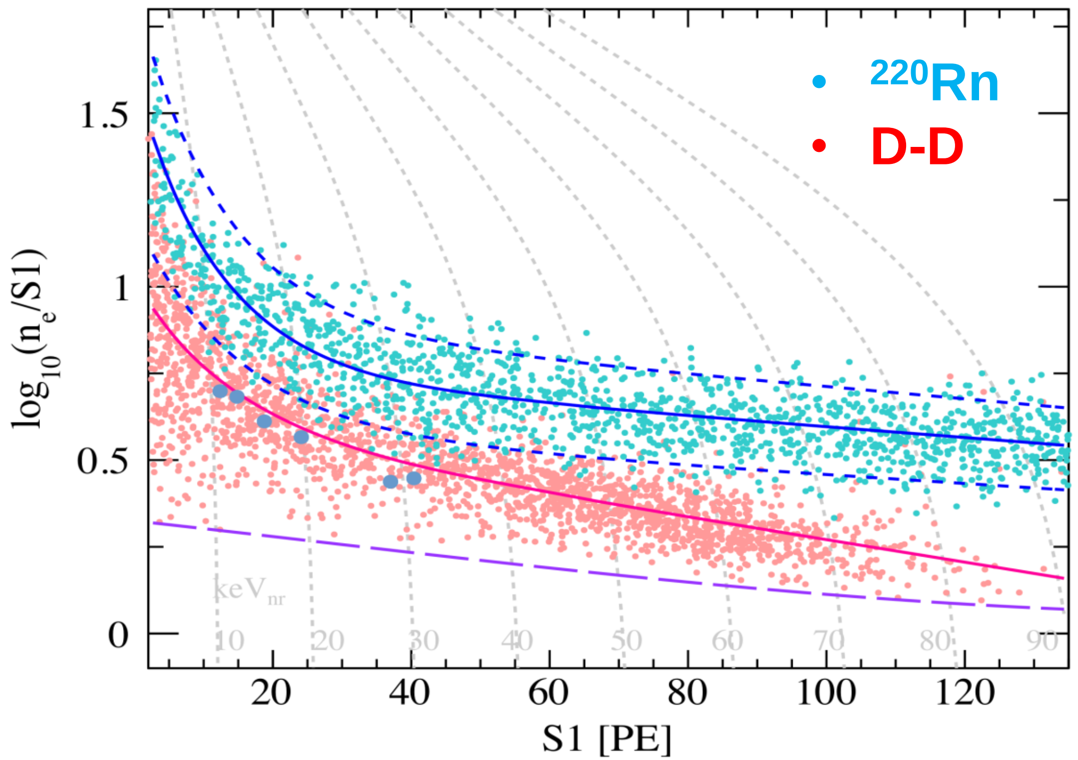
# Calibration System

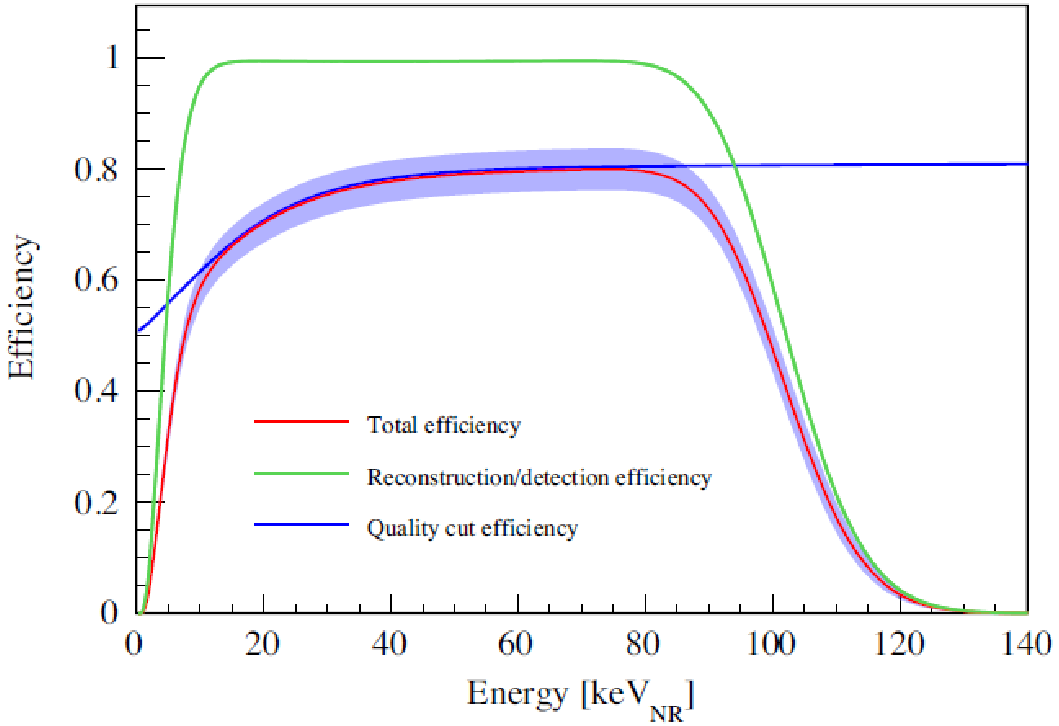




| Calibration source | Position |
|---|---|
| $^{83m}Kr/^{220}Rn$ | Injected from gas panel |
| $^{241}Am$-Be | Calibration tubes |
| D-D neutron | Beam pipe |

# Detector Response

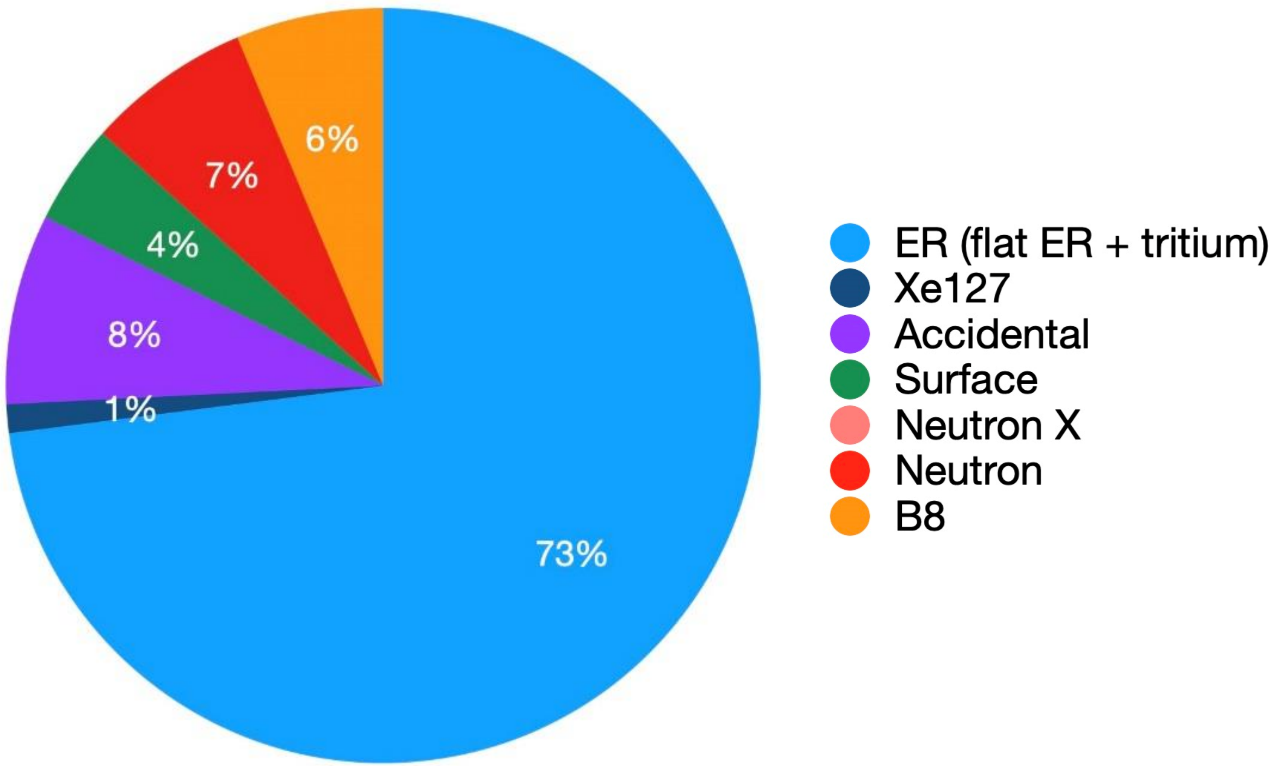



- ER leak ratio (below NR median curve) is 0.43%±0.18%;
- Efficiencies separately determined from ER or NR calibration data are all consistent;

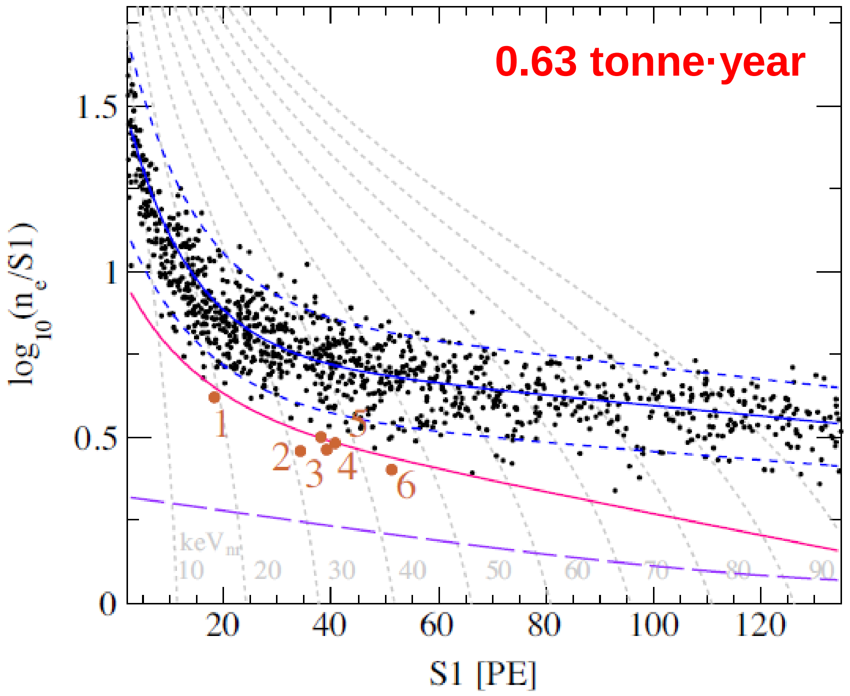
# Backgrounds

**Expected below-NR-median events: 9.8 (0.6) evts**

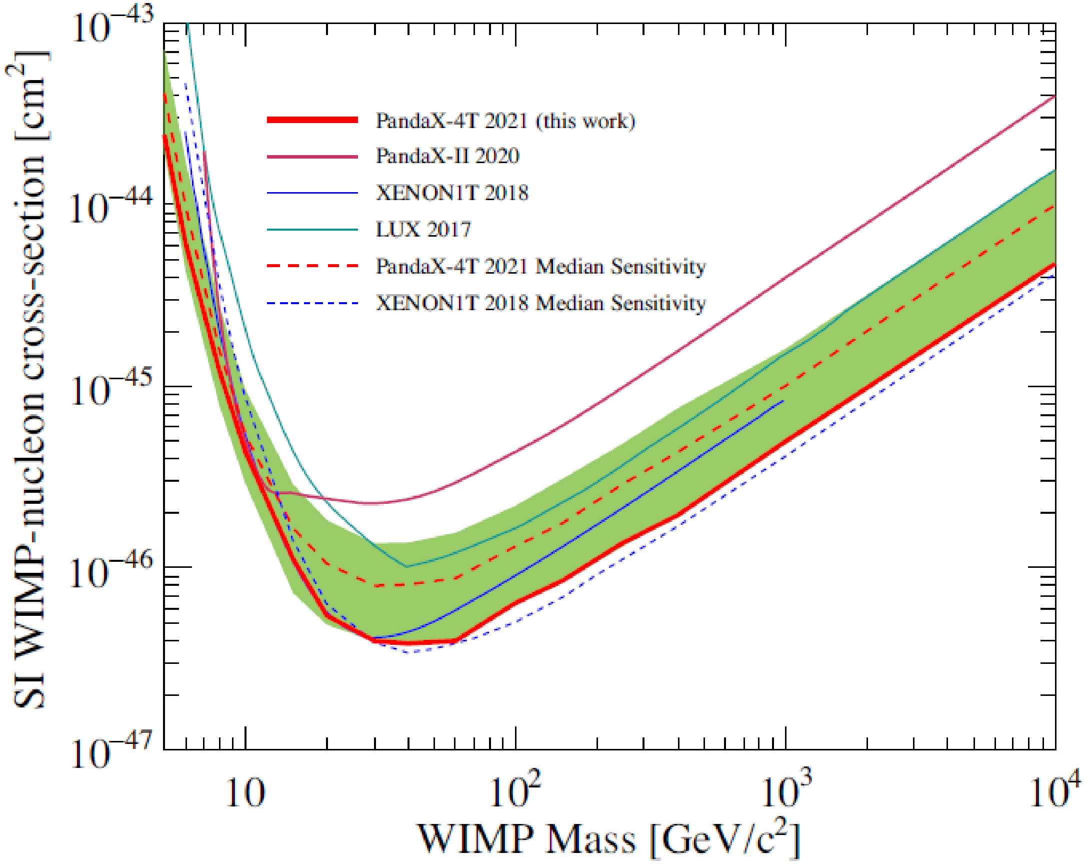



- ER (Rn+Kr+Material+Tritium) background dominated in the selection region;
- Background per unit target is improved from PandaX-II by 4 times (<10 keV);

# PandaX-4T first commissioning Result - WIMPs

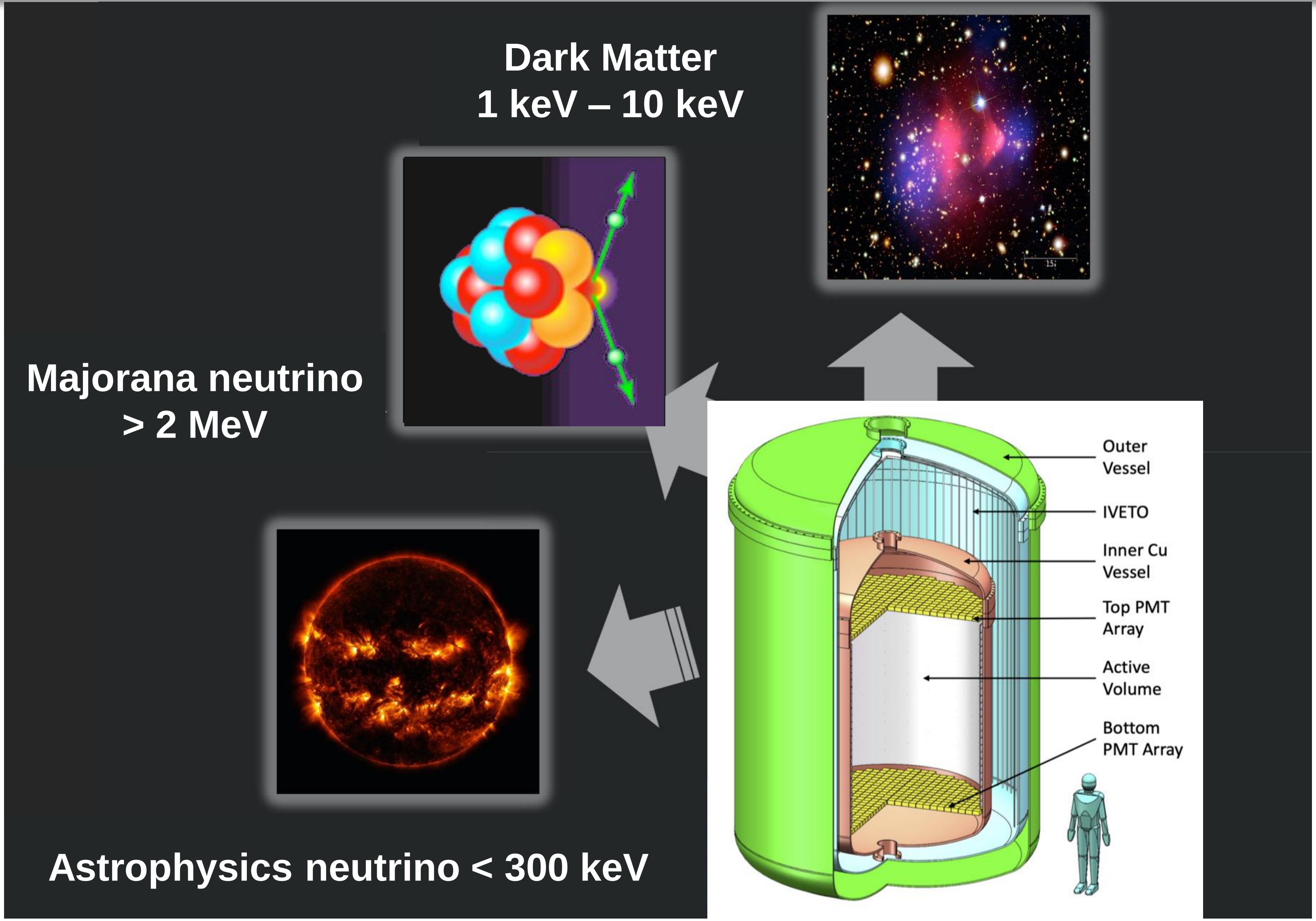



Y. Meng et al. PRL 127, 261802 (2021)



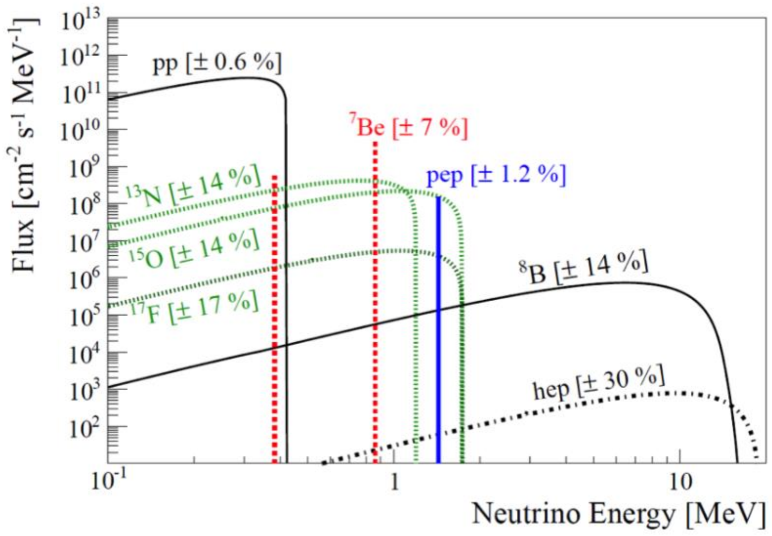

- 1058 candidates (expected 1054±39), 6 below NR median curve (expected 9.8±0.6);
- Sensitivity improved from PandaX-II final analysis by 2.9 times (30 GeV/c$^2$);

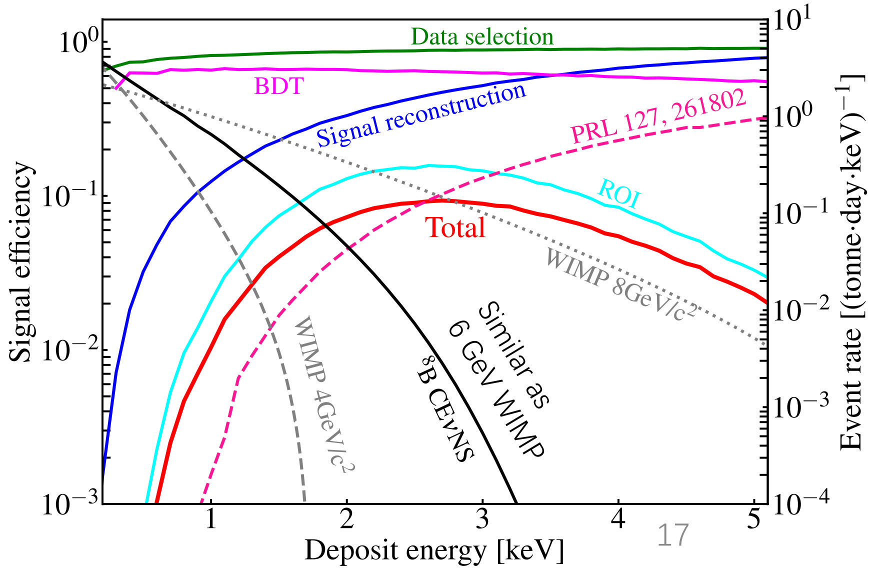
# PandaX: Multi-physics Goals



# PandaX-4T Search for $^{8}B$ CEvNS

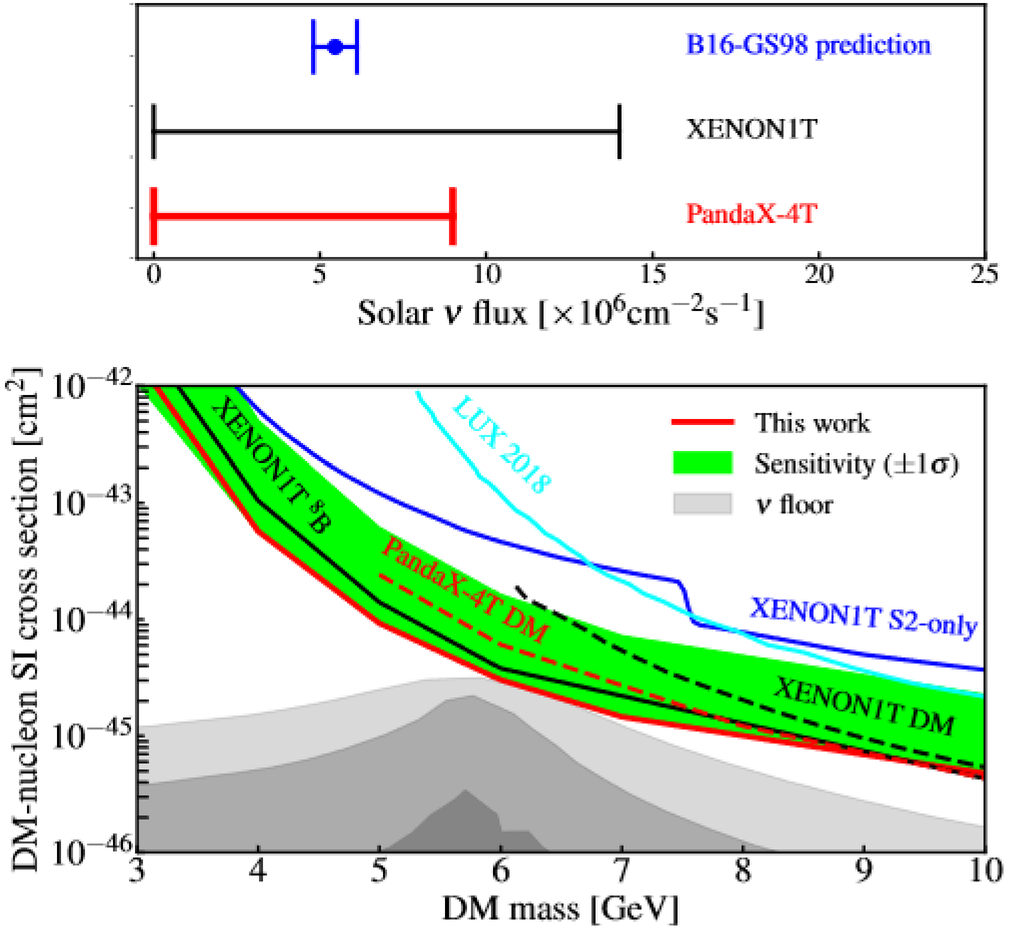
- **To enhance** sensitivity on $^{8}B$ (like a 6 GeV WIMP), need to lower selection threshold (S1 ↓, S2 ↓)
- Major challenge: Accidental background (AC, non-physical S1 and S2 randomly paired)
- Blind analysis: 0.48 ton-year data, excluding data with increase of noises rate (micro-discharge)



# Constraints on $^8$B neutrino

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




- A multi-variate (BDT) algorithm trained to suppress AC background
  - Some downward fluctuation

ROI (BDT applied)

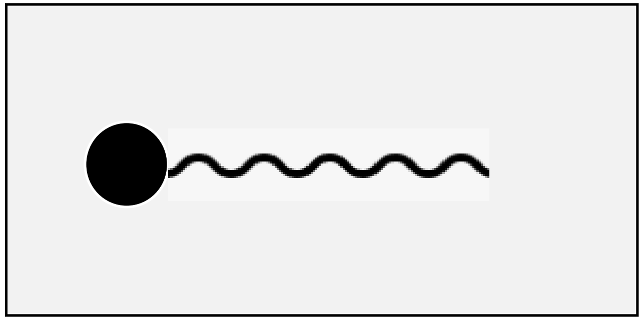
| ER+NR+AC | 8B | Total prediction | Unblind data |
|---|---|---|---|
| 1.46 | 1.42 | 2.88 | 1 |
| 0.04 | 0.29 | 0.33 | 0 |

- Leading constraint on $^8$B neutrino flux through CEvNS

- Assuming nominal $^8$B background, set strongest constraints on light WIMP of 3 -10 GeV

# Luminance of Dark Matter

- Residual weak EM properties
- Coupling with photons



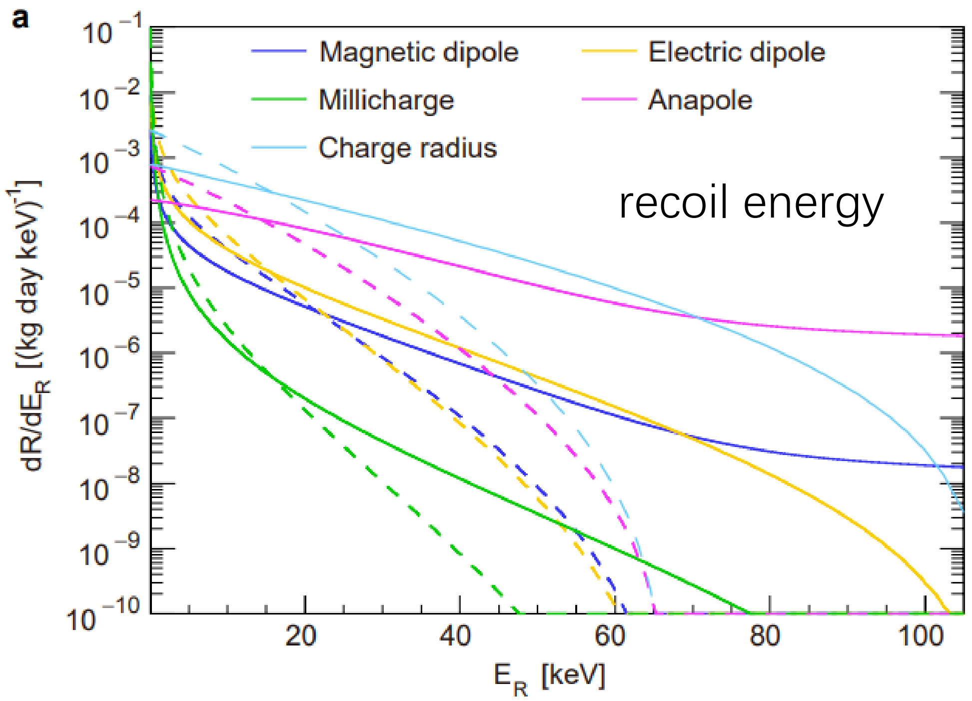
$$\mathcal{L} = Qe\bar{\chi}\gamma^{\mu}\chi A_{\mu} + \frac{\mu_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + i\frac{d_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu} + b_{\chi}\bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu} + a_{\chi}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$$

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

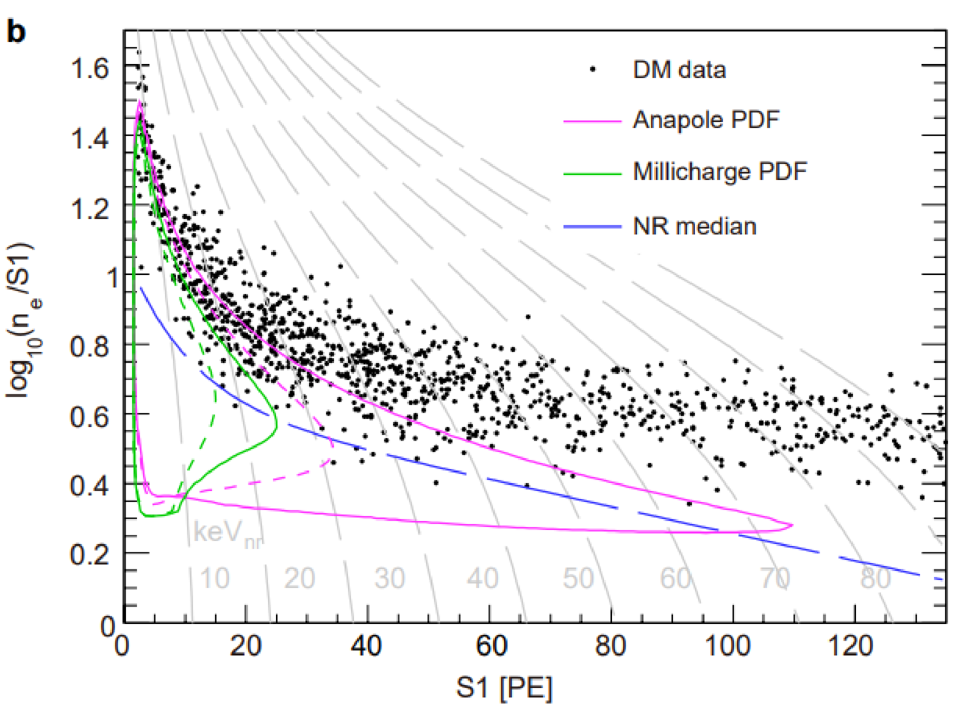
**tree-level** | **higher-order loop-level**

# Photon-mediated Interaction

- Nuclear recoil signature
  - Charge radius: similar to SI
  - Millicharge: $1/E_R^2$
  - MD and ED: $1/E_R$




**30 and 100 GeV/c² DM**



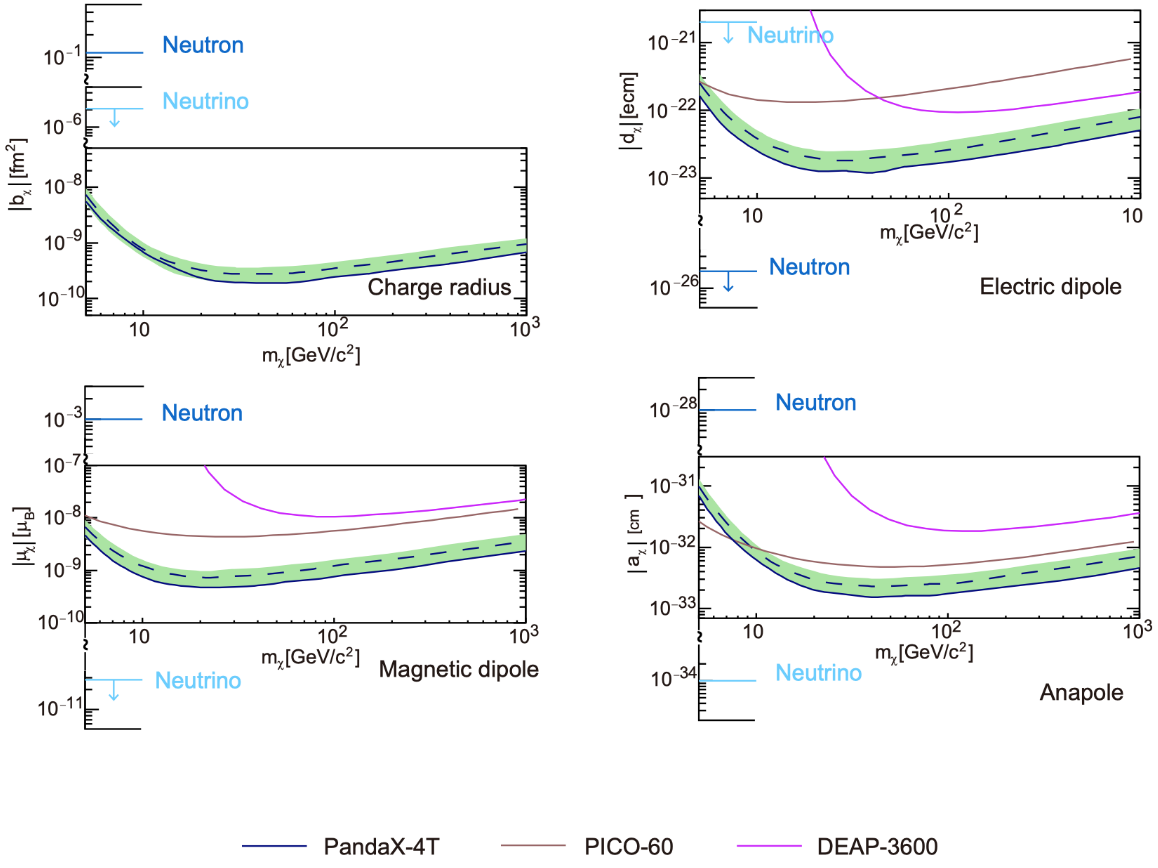
# Results from Xenon Recoil Data

- First experimental constraints on DM charge radius
  - 4 orders of magnitude smaller than neutrino
- 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 ($\mu_B$) | $<4.8\times10^{-10}$ | $<2.8\times10^{-11}$ * | $-1\times10^{-3}$ * |
| Electric dipole (ecm) | $<1.2\times10^{-23}$ | $<2\times10^{-21}$ † | $<1.8\times10^{-26}$ * |
| Anapole ($cm^2$) | $<1.6\times10^{-33}$ | $\sim10^{-34}$ ‡ | $\sim10^{-28}$ § |

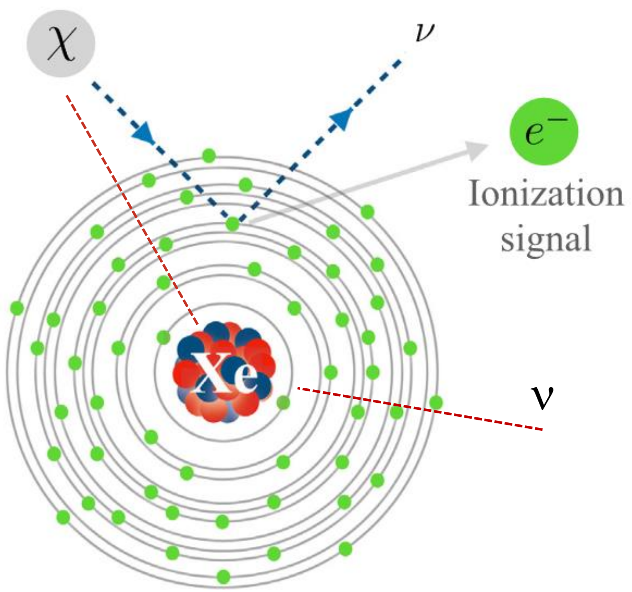
* Datas are taken from PDG [33]
† Taken from [32]
‡ Taken from [34]
§ Taken from [35]




**X. Ning et al. Nature (2023)**

# DM-$\upsilon$ Conversion

$$E_R = \frac{m_\chi^2}{2(m_T + m_\chi)}$$

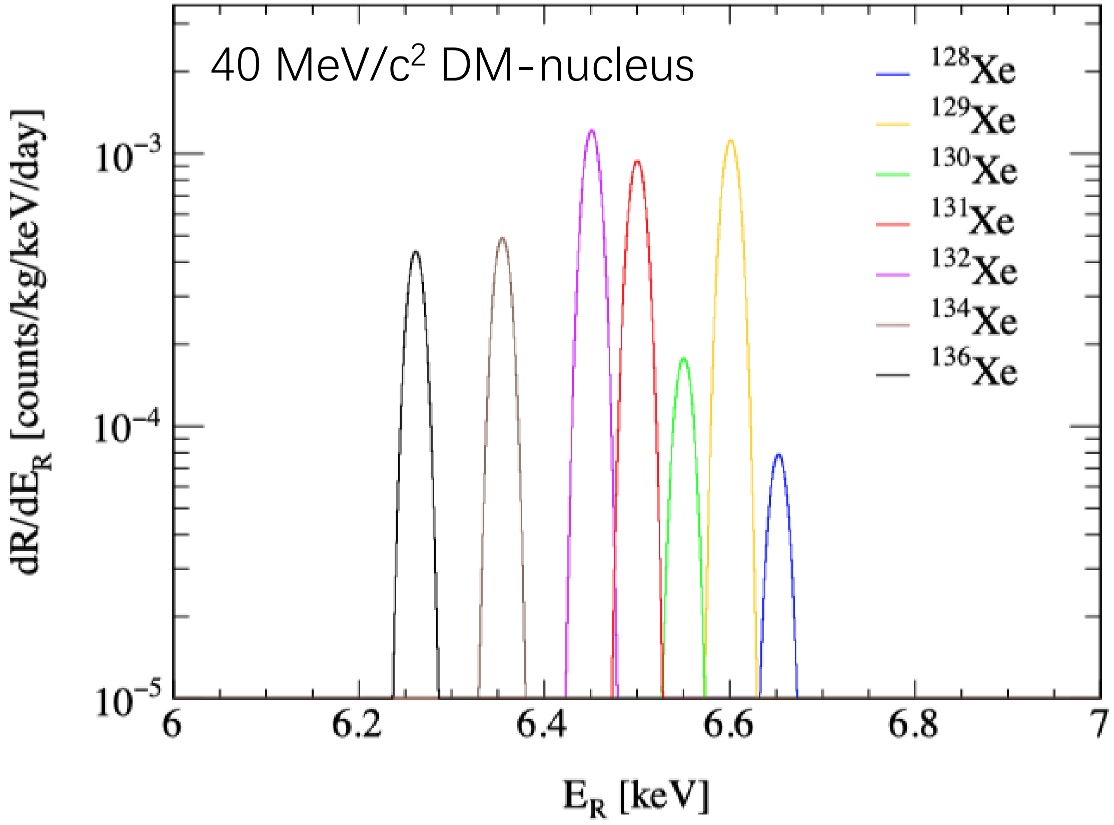



J. Dror et al, PRL 124, 181301 (2020)

**Characteristic mono-energetic signal:**

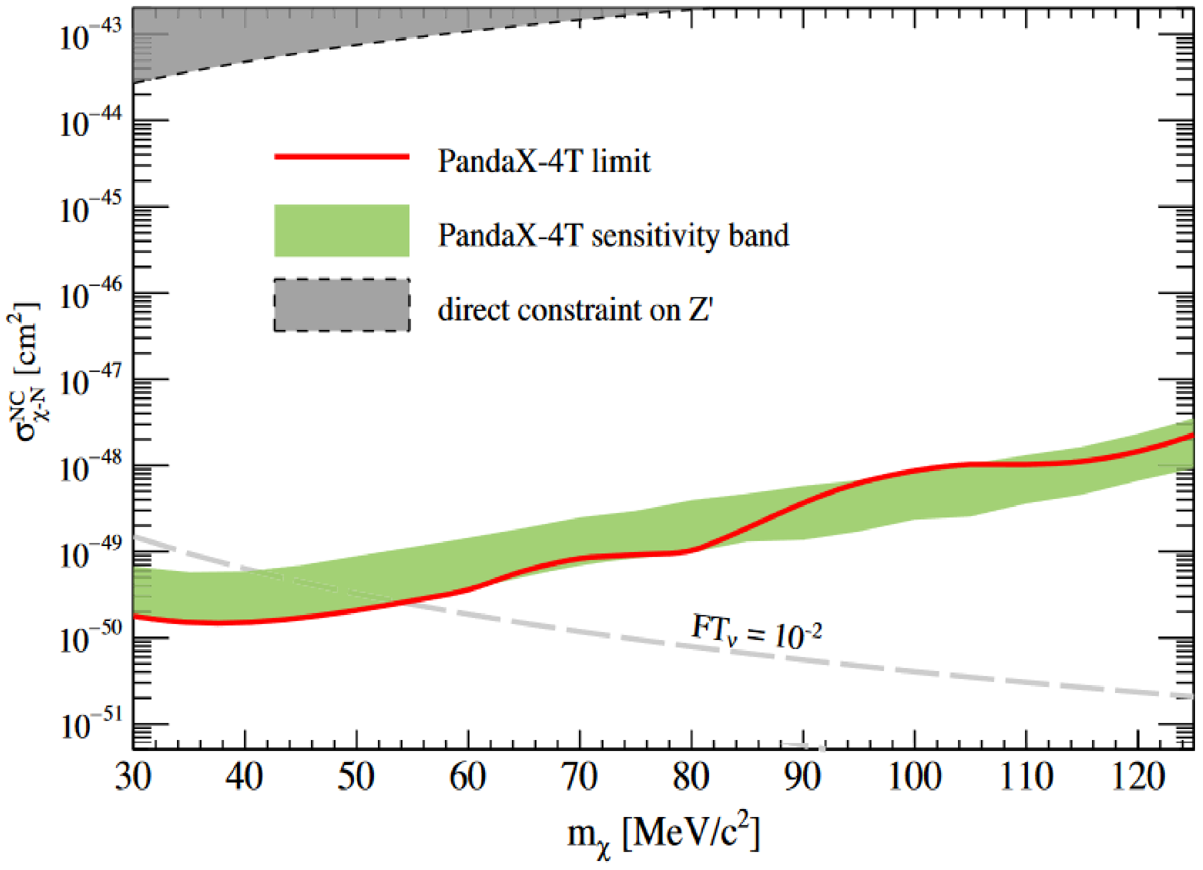
(a) Xe-nucleus targets, $m_x$ = 40 MeV, $E_R$ ~ 6.5 keV

(b) Electrons targets, $m_x$ = 40 keV, $E_R$ ~ 1.5 keV



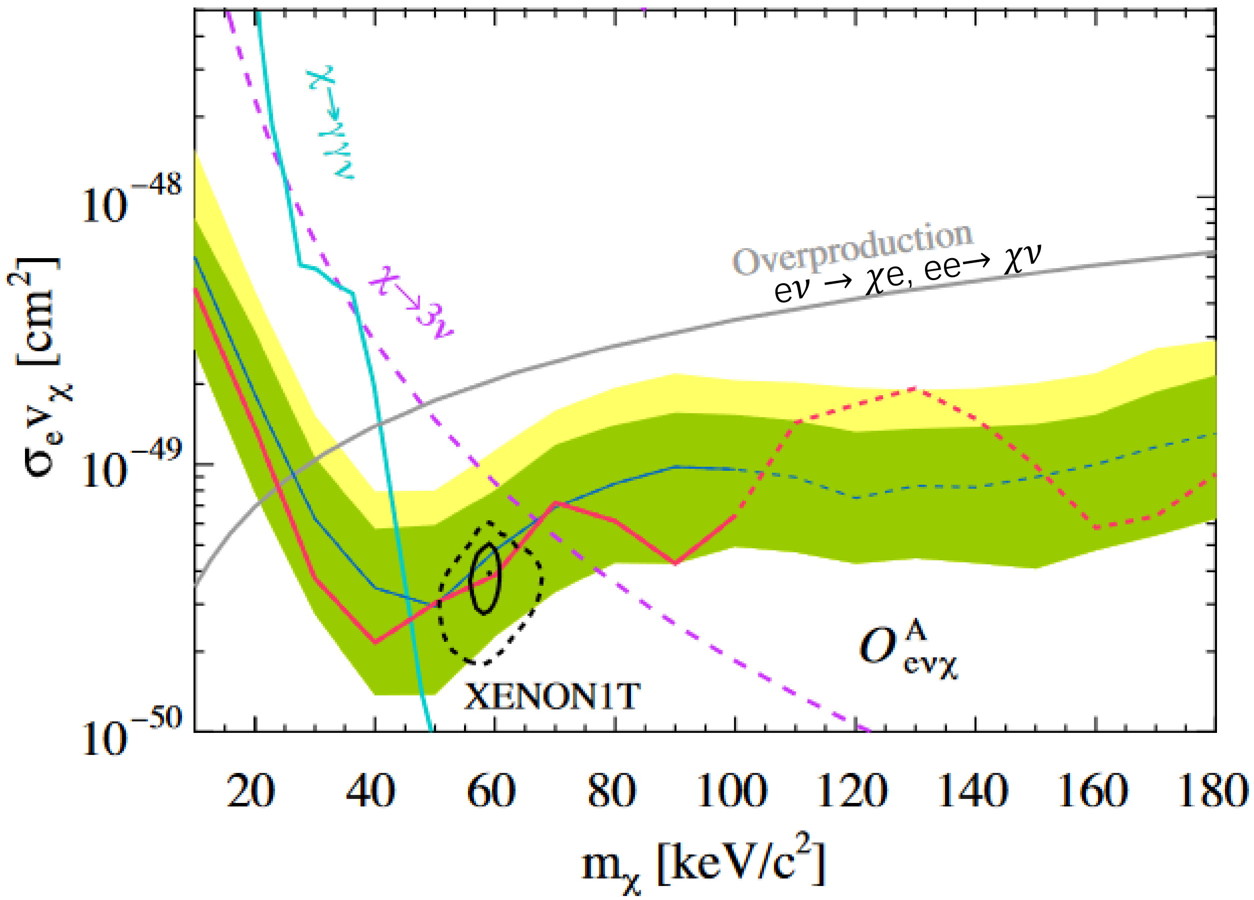
# Mono-energetic Signal Search

$\chi + Xe \rightarrow \upsilon + Xe$



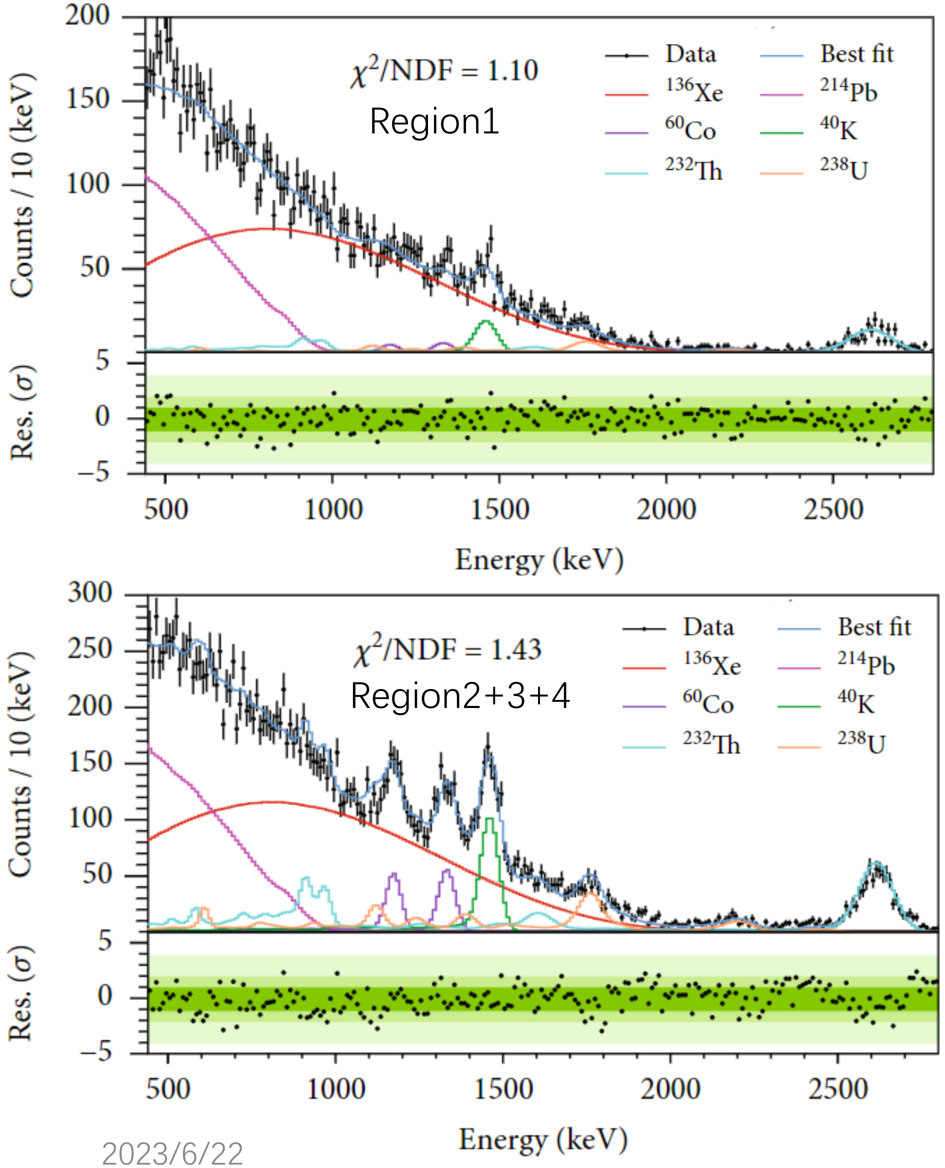

**L. Gu et al. PRL 129, 161803 (2022) , Editors' Suggestion**

$\chi + e \rightarrow \upsilon + e$




**D. Zhang et al. PRL 129, 161804 (2022) , Editors' Suggestion**

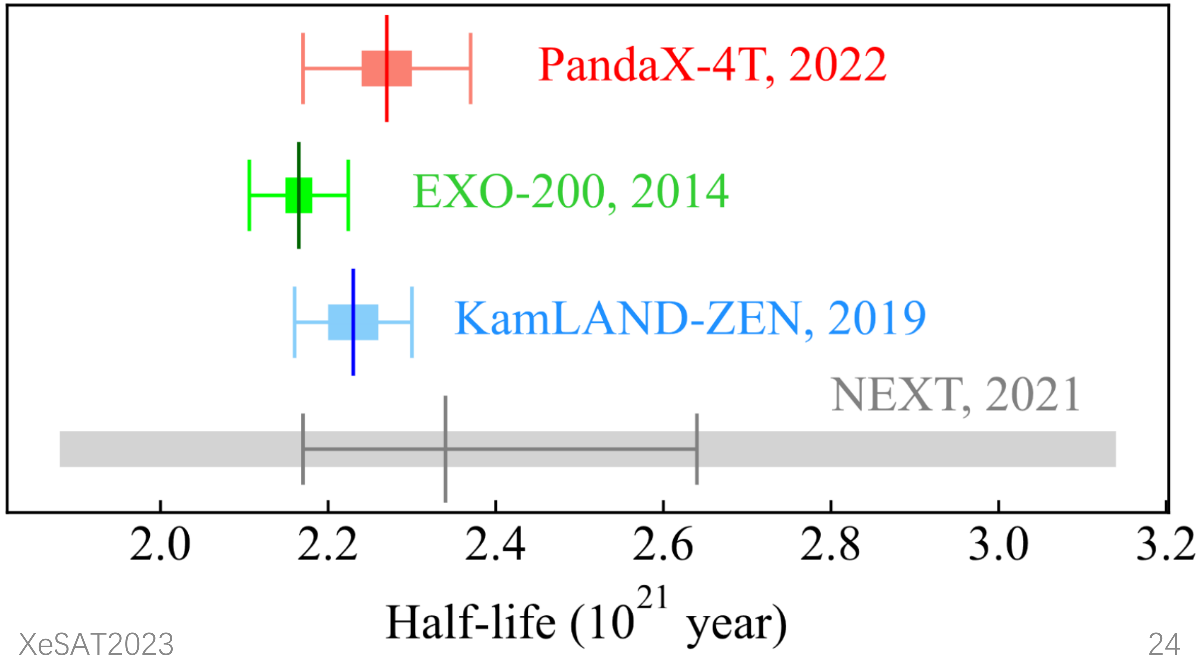
# $^{136}$Xe 2$\upsilon$DBD Half-life Measurement




- PandaX-4T: $^{136}$Xe/Xe 8.86%, 59.6kg in FV, up to 2.8MeV
- First natural xenon measurement with a dark matter detector

  2.27 ± 0.03 (stat) ± 0.10 (syst) x $10^{21}$ years
- Consistent with $^{136}$Xe-enrich experiments.

**Research Vol 2022, 9798721 (2022)**



# After Commissioning

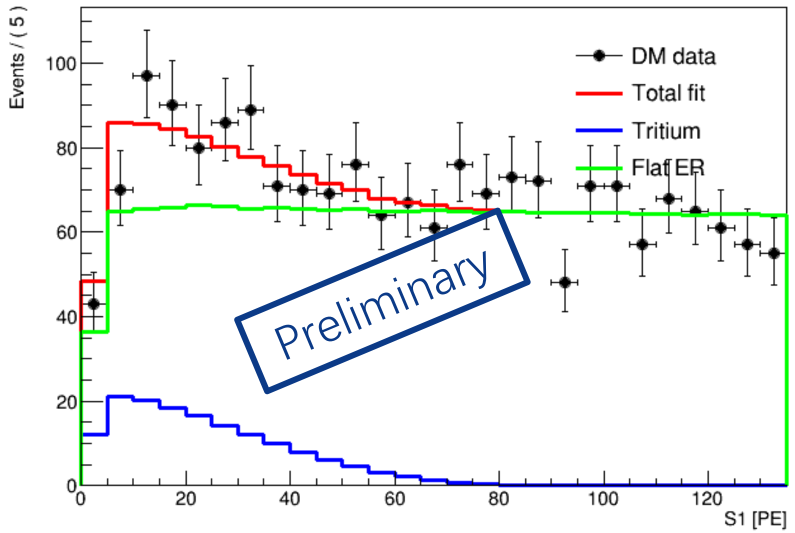
- Tritium identified in commissioning data
- Offline xenon distillation
- 1st physics run (Run1)
    - – Data still under blind analysis
- CJPL-II B2 hall construction
- Detector upgrade

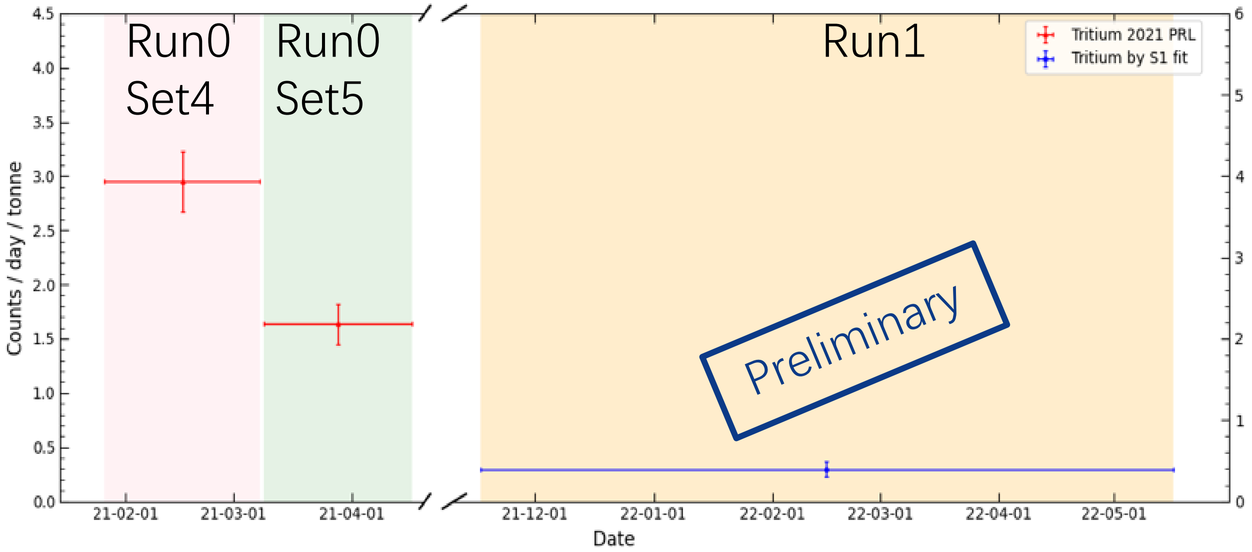

| Commissioning (Run 0) | Calibration | Distillation | Physics Run (Run 1) | Calibration | Detector Upgrade |
|---|---|---|---|---|---|
| 2020/11/28 – 2021/04/16 | 2021/04/17 – 2021/06/09 | | 2021/11/15 – 2022/05/15 | 2022/05/16 – 2022/07/08 | |

# Tritium Removal

- Preliminary estimation of tritium level (keep S2 blinded)
- Extensive tritium measures planned for the next run (Run 2)

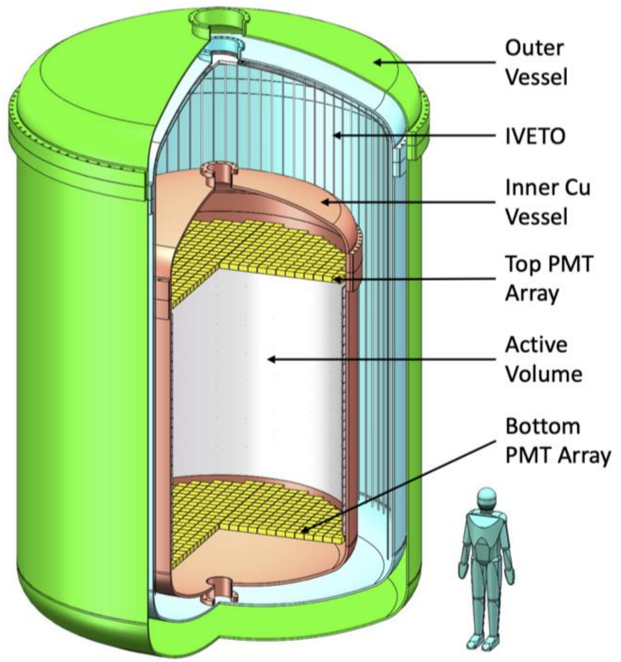
| Period | Run0 Set 4 | Run0 Set 5 | Run1 |
|---|---|---|---|
| Tritium Counts/day/tonne | 3.0 ± 0.3 | 1.6 ± 0.2 | 0.4 ± 0.1 |

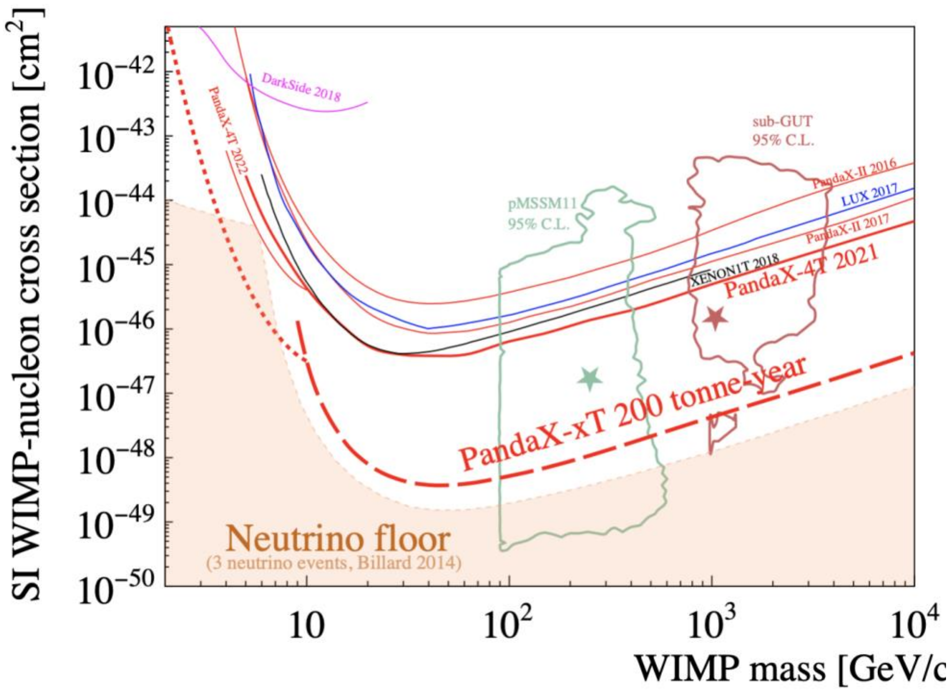


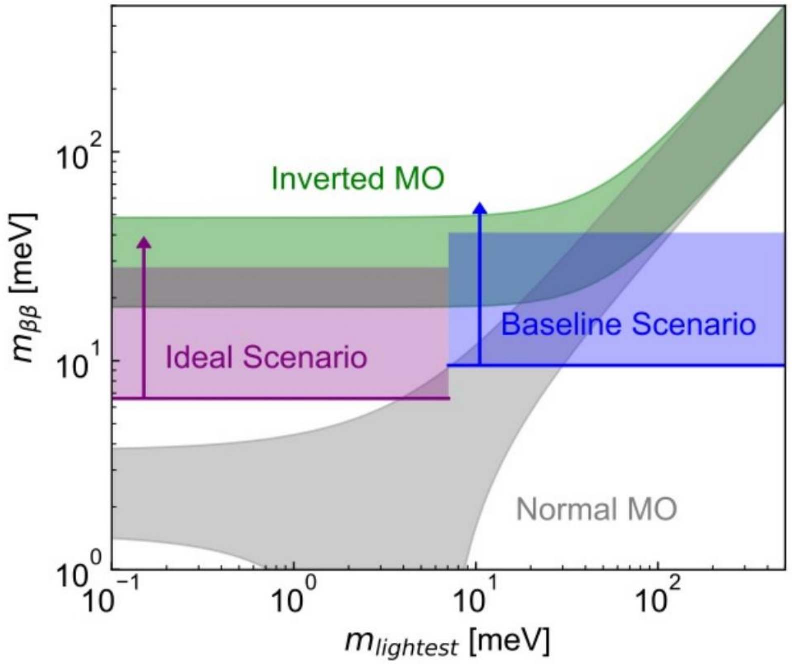



# Future plan: PandaX-xT

- **“Ultimate”liquid xenon experiment**
  - With >30 tonne sensitive volume
  - Letter-of-interest sent to Chinese funding agency
  - Decisive test on WIMP and key test on Dirac/Majorana neutrino



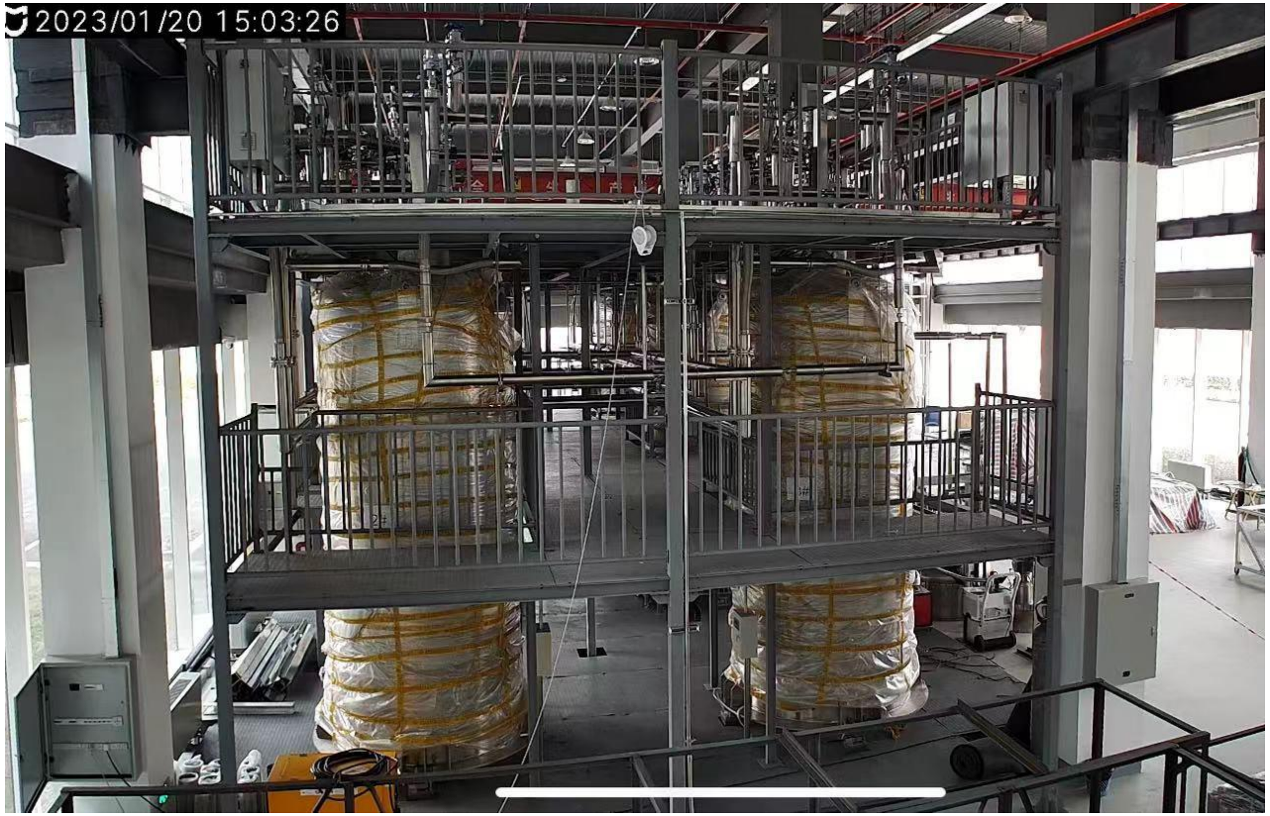



# PandaX-xT R&D: Electrode and Xenon Storage

TPC: Large size high light transmission electrode


Large xenon storage system



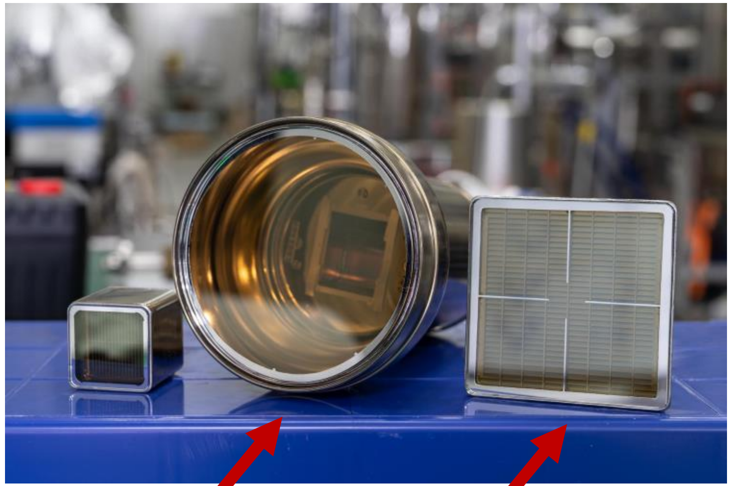
# PandaX-xT R&D: 2-inch PMTs and New Electronics

PMT:

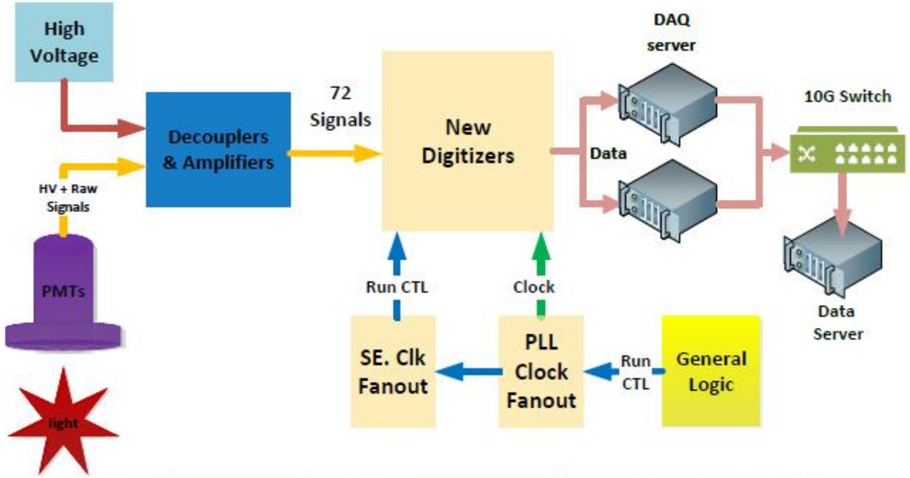
- R12699 2-inch PMTs with 4 independent anode readout;
- Better time response for better waveform building;
- Lower radioactivity;

Electronics:

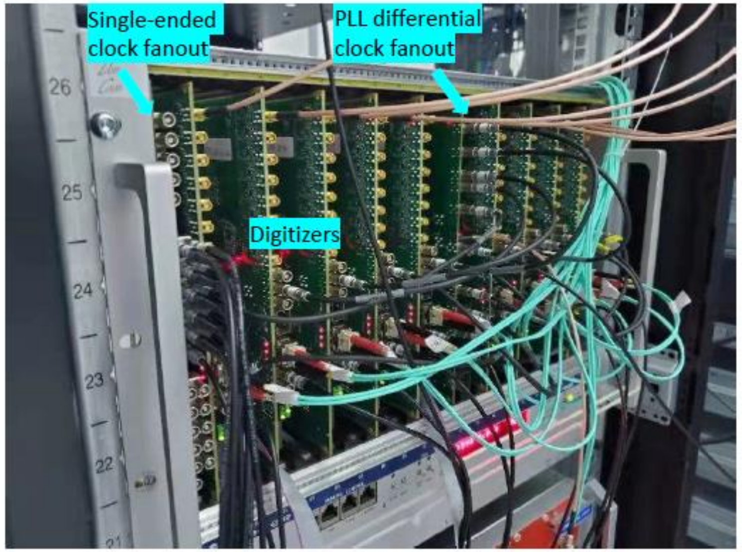
- Higher sampling rate;
- Accept out-trigger mode;



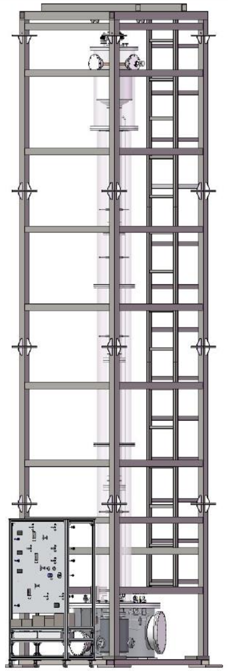
Custom-developed: 14-bit, 500MS/s

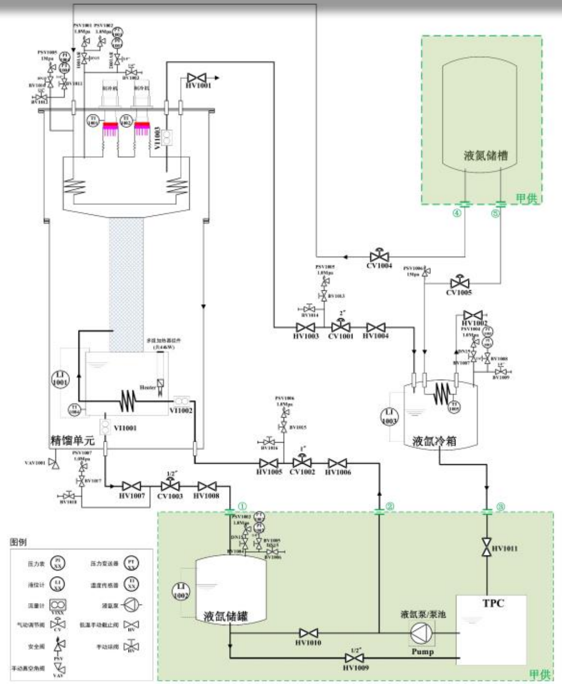



| | | R11410 | R12699 (4ch/piece) |
|---|---|---|---|
| Time Response [ns] | Rise Time | 5.5 | 1.2 |
| | Transit Time | 46 | 5.9 |
| Radioactivity [mBq/pc] | Co-60 | < 2.34 | < 0.07 |
| | Th-232 | < 7.82 | < 0.40 |
| | U-238 | < 56.48 | 0.47 ± 0.11 |



# PandaX-xT R&D: Distillation and Purification






| | | PandaX-4T | Upgraded |
|---|---|---|---|
| Flow rate [kg/h] | Kr | 10 | 30 |
| | Rn | 56.5 | 856 |
| Reduction factor | Kr | $10^6$ | $10^8$ |
| | Rn | 2.2 | 4.4 |


Magnetic driven pump

- Low Outgassing


Oxygen-free copper

- High flow rate

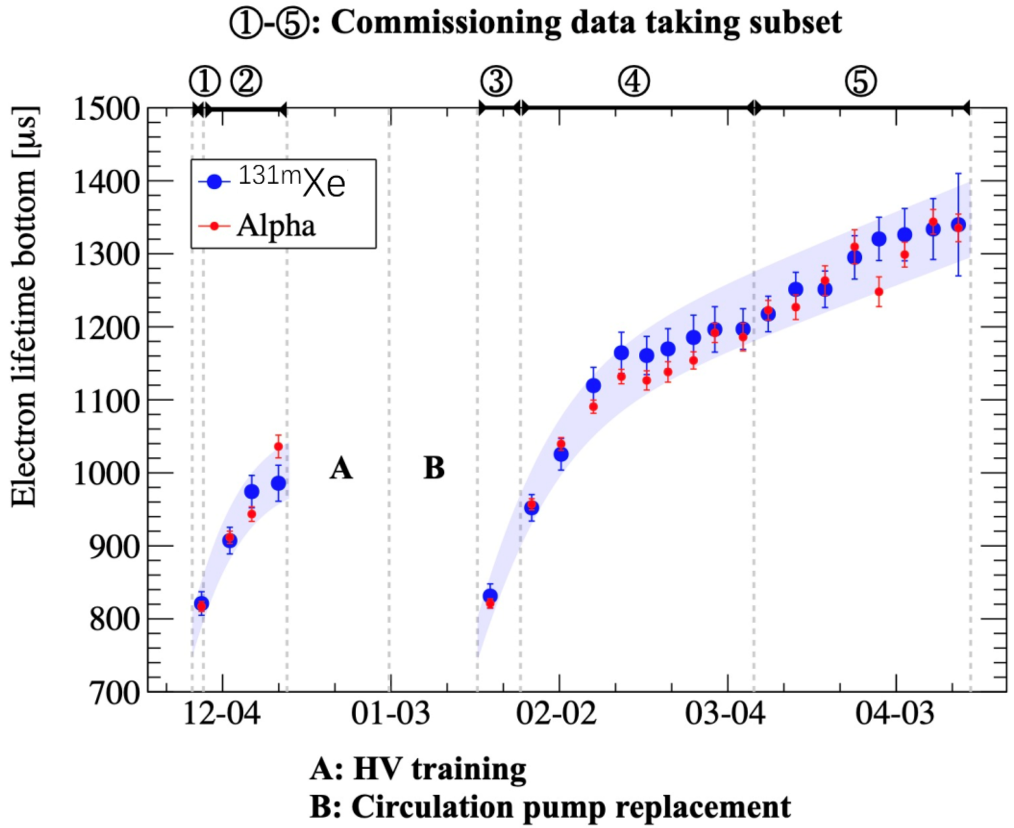
# Summary

- PandaX-4T is one of the new generation multi-tonne xenon experiments
- Intense searches for various types of physics, including DMs and neutrinos
- Expecting more interesting results from PandaX
- Highly welcome new collaborators!

**Thank You！**

# Backups

# Purification System




Ref. the maximum drift time ~ 840 μs

NEXT

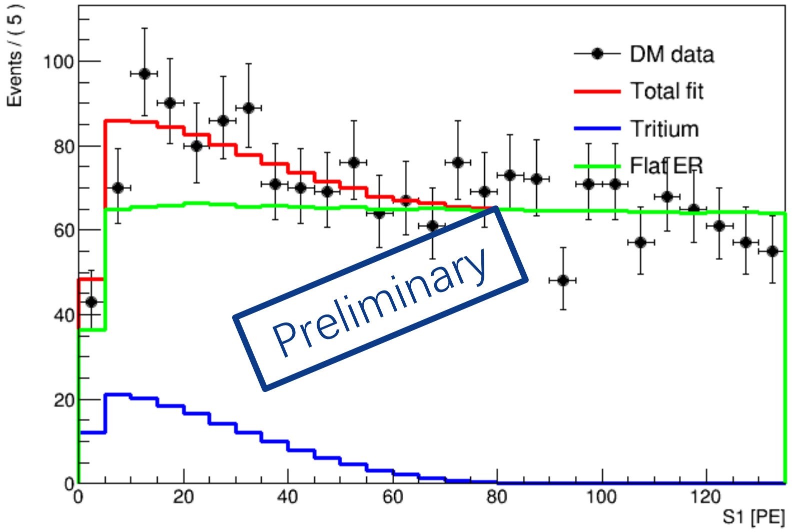
Magnetic driven pump

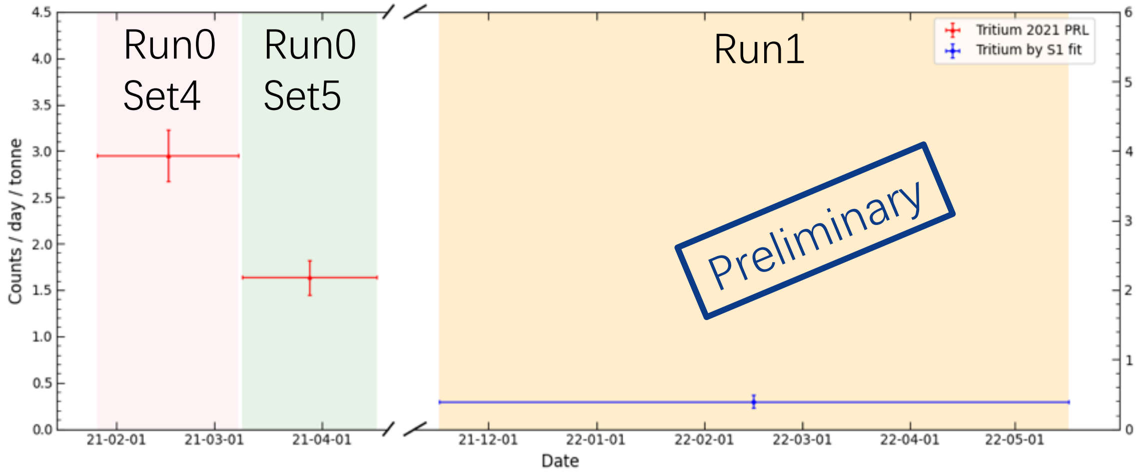
- Low Outgassing

Oxygen-free copper

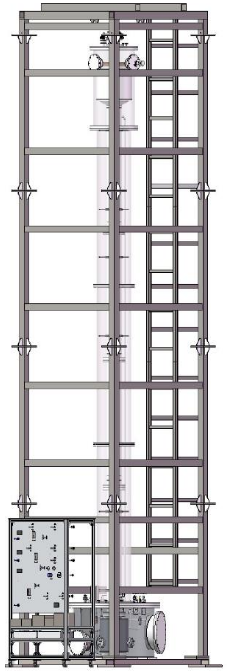
- High flow rate

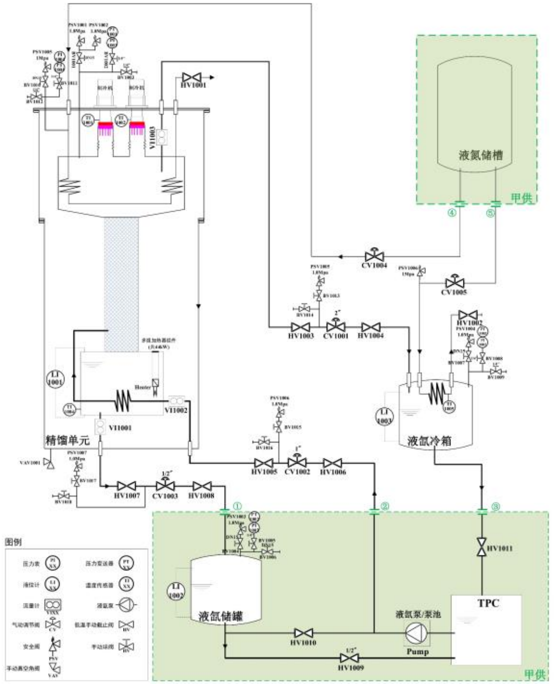
# Distillation System




NEXT

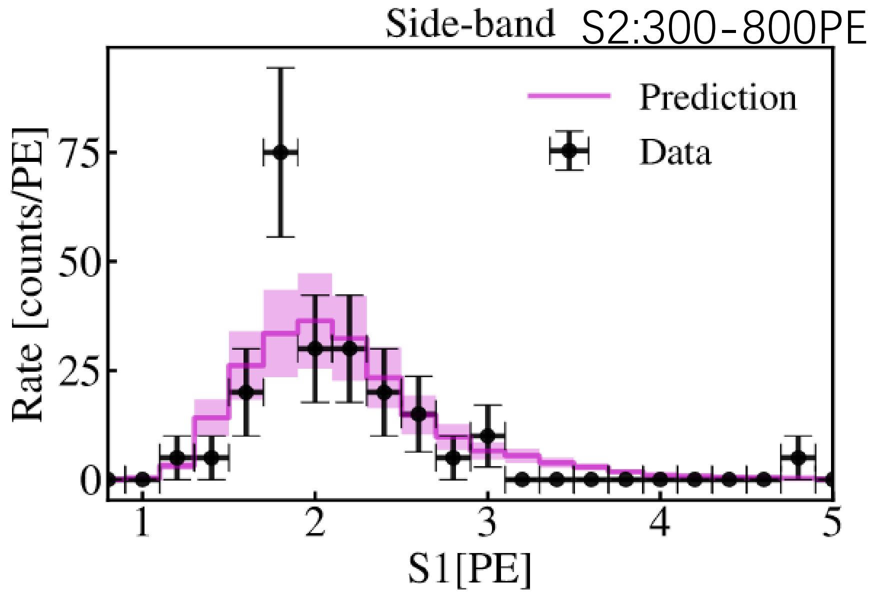


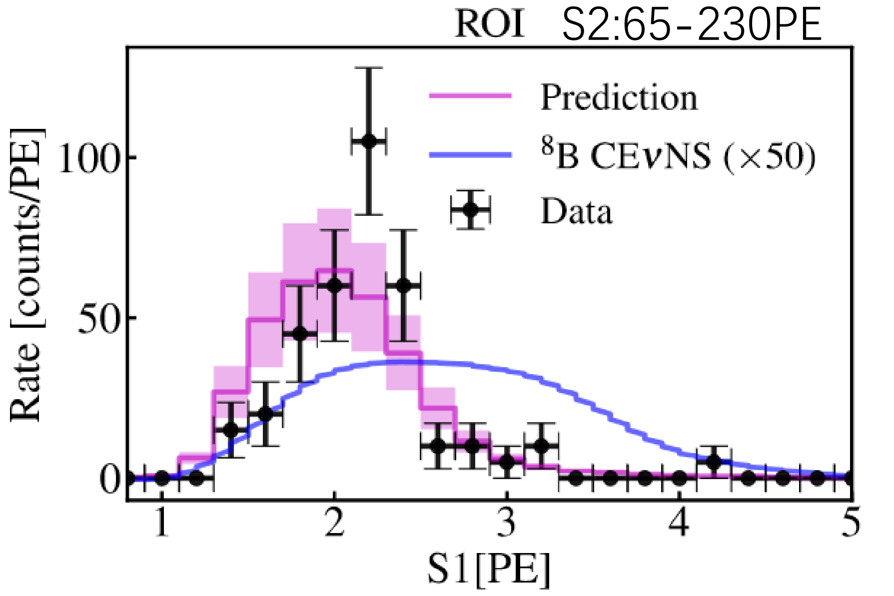



| | | PandaX-4T | Upgraded |
|---|---|---|---|
| Flow rate [kg/h] | Kr | 10 | 30 |
| | Rn | 56.5 | 856 |
| Reduction factor | Kr | $10^6$ | $10^8$ |
| | Rn | 2.2 | 4.4 |

# Control of Accidental Background in $^8B$ Search

- Use "scrambled" real data to model accidental background
- A multi-variate (BDT) algorithm trained to suppress AC background
- Training/selection is blinded
- postBDT: $N_{obs}=1$, $N_{bkg}=1.6$, $N_{sig}=1.7$




| $N_{hit}$ | $S2$ range [PE] | BDT | ER | NR | Surf | AC | Total BKG | $^8B$ | **Obs** |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 65-230 | pre | 0.04 | 0.10 | 0.14 | 62.43 | 62.71 | 2.32 | **59** |
| | | post | 0.02 | 0.04 | 0.03 | 1.41 | 1.50 | 1.42 | **1** |
| 3 | 65-190 | pre | 0.01 | 0.05 | 0.08 | 0.79 | 0.93 | 0.42 | **2** |
| | | post | 0.00 | 0.02 | 0.03 | 0.02 | 0.07 | 0.29 | **0** |

# How dark is dark matter?

Image Credit: Public Domain

# Photon-mediated Interaction

- Matched to non-relativistic EFT
  - Nuclear response function N. Anand, A. Fitzpatrick, W. Haxton PRC 89, 065501 (2014)

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

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

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

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

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

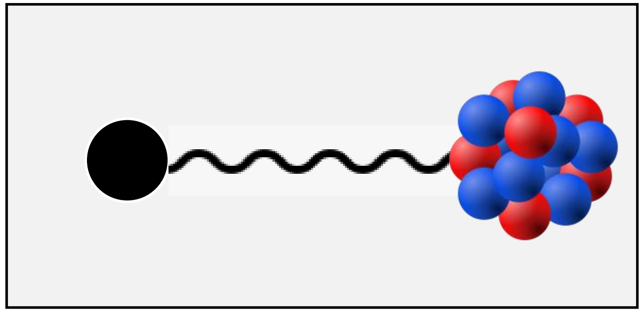
$$\mathcal{L}_{\rm A} = a_\chi\bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} \to \mathcal{O}_{\rm A} = ea_\chi\left(2Q_{p,n}\mathcal{O}_8 - g_{p,n}\mathcal{O}_9\right),$$

$$\mathcal{O}_1 = 1$$
$$\mathcal{O}_4 = \mathbf{S}_\chi\cdot\mathbf{S}_N$$
$$\mathcal{O}_5 = i\mathbf{S}_\chi\cdot\left(\frac{\mathbf{q}}{m_N}\times\mathbf{v}^\perp\right)$$
$$\mathcal{O}_6 = \left(\mathbf{S}_\chi\cdot\frac{\mathbf{q}}{m_N}\right)\left(\mathbf{S}_N\cdot\frac{\mathbf{q}}{m_N}\right)$$
$$\mathcal{O}_8 = \mathbf{S}_\chi\cdot\mathbf{v}^\perp$$
$$\mathcal{O}_9 = i\mathbf{S}_\chi\cdot\left(\mathbf{S}_N\times\frac{\mathbf{q}}{m_N}\right)$$
$$\mathcal{O}_{11} = i\mathbf{S}_\chi\cdot\frac{\mathbf{q}}{m_N}$$

**Nuclear response function:**

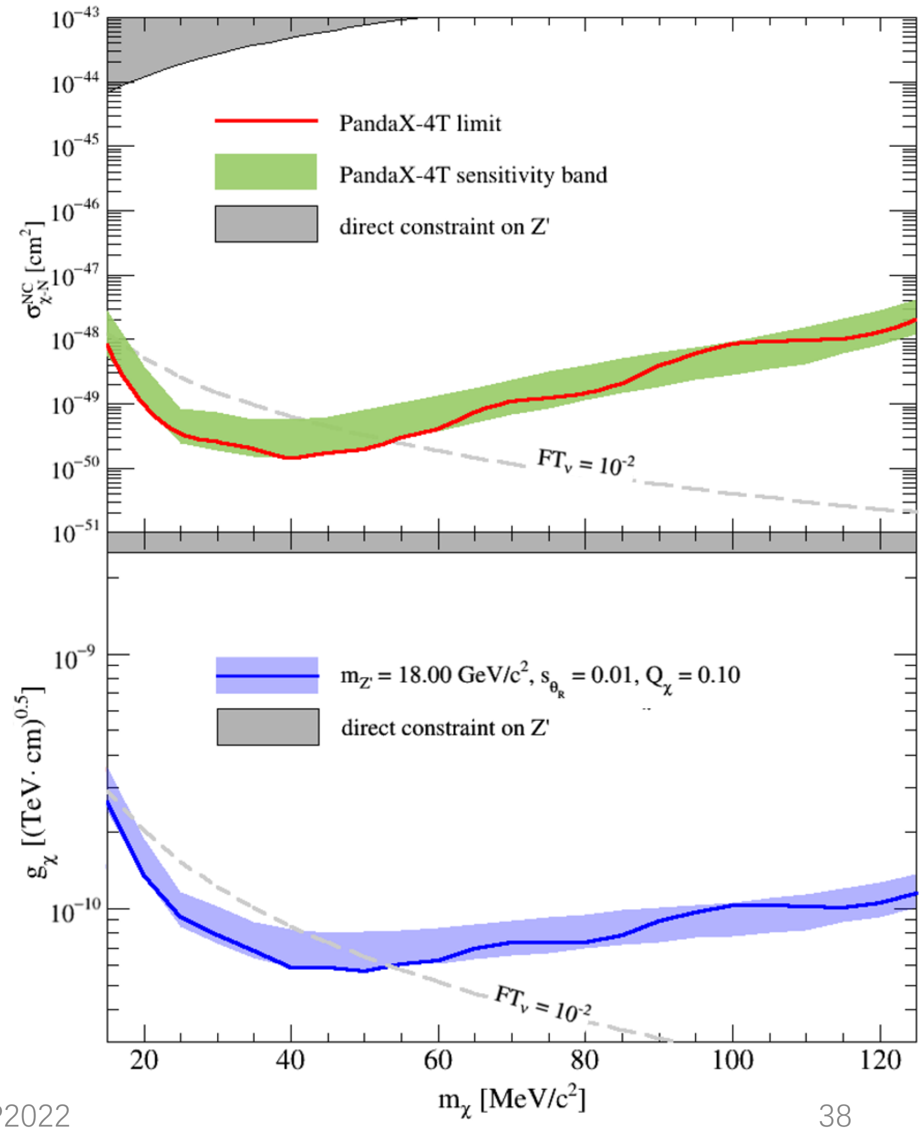
- full-basis shell-model calculations (GCN5082 interaction).
- No truncation (9 billion Slater determinants)!

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

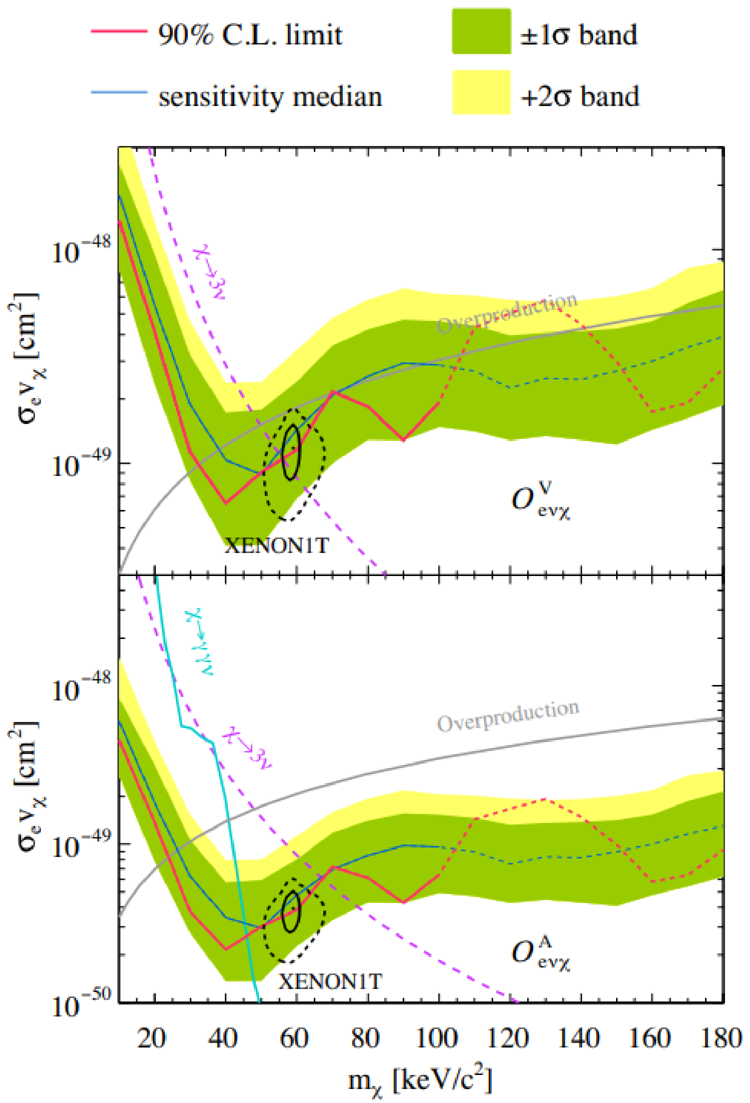


# Exclusion Limits of Neutral current FDM Absorption (NR)

- **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 **$1.4\times10^{-50}$ cm$^2$** at a fermionic dark matter mass of **35 MeV/$c^2$**
- Constraints on the coupling $g_\chi$ to the order of $\mathbf{10^{-10}(TeV\cdot cm)^{0.5}}$



# Exclusion Limits of FDM Absorption on Electron

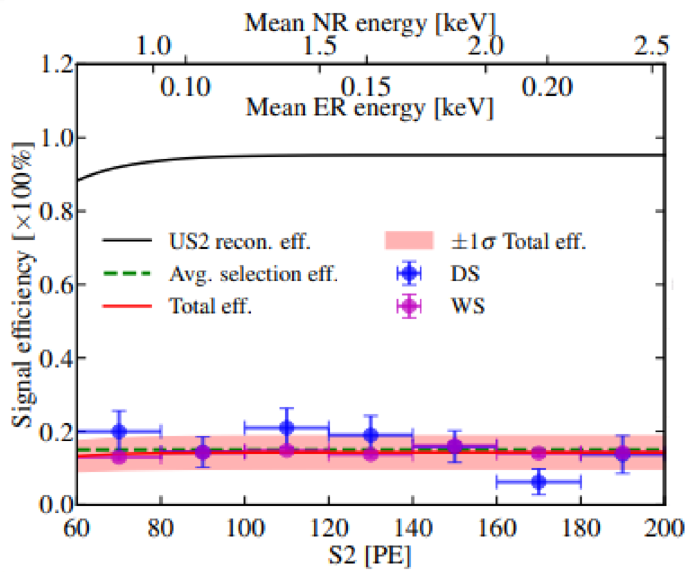


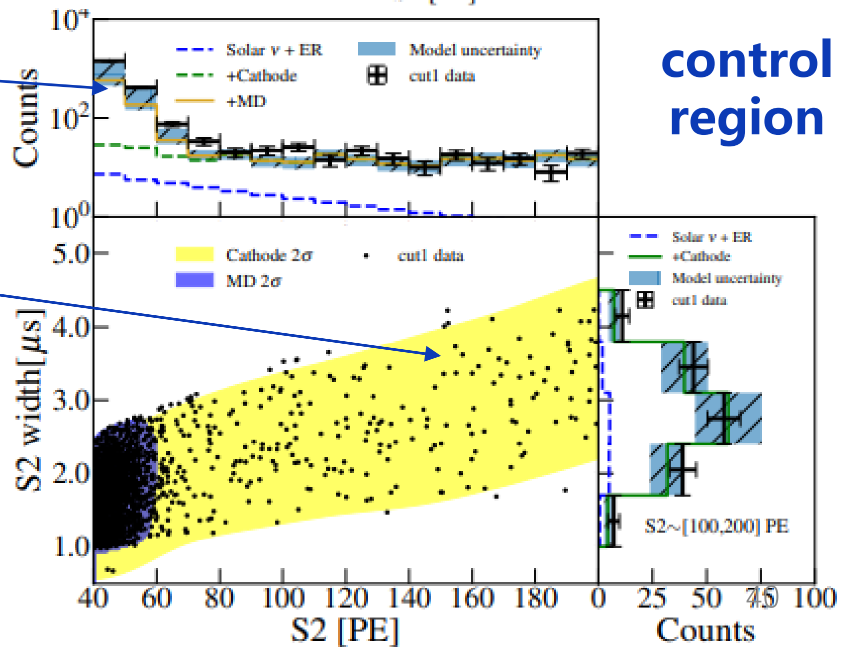

$\sigma^A_{e\chi\nu} \approx 3\sigma^V_{e\chi\nu}$ w.r.t. the same $\Lambda$

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

# Ionization-only Search

- **Abandon the scintillation signal cut**
  - ROI: S2 [60, 200] PE
  - Threshold down to ~100 eV (from ~1 keV)
  - Tight quality cuts on the ionization signal
- **Background components**
  - **Micro-discharging (MD)**
    - Small charge, strong run-condition dependence
  - **Cathode activity**
    - Large charge, large pulse-shape width
  - **Data-driven estimation**
    - Validated in control region

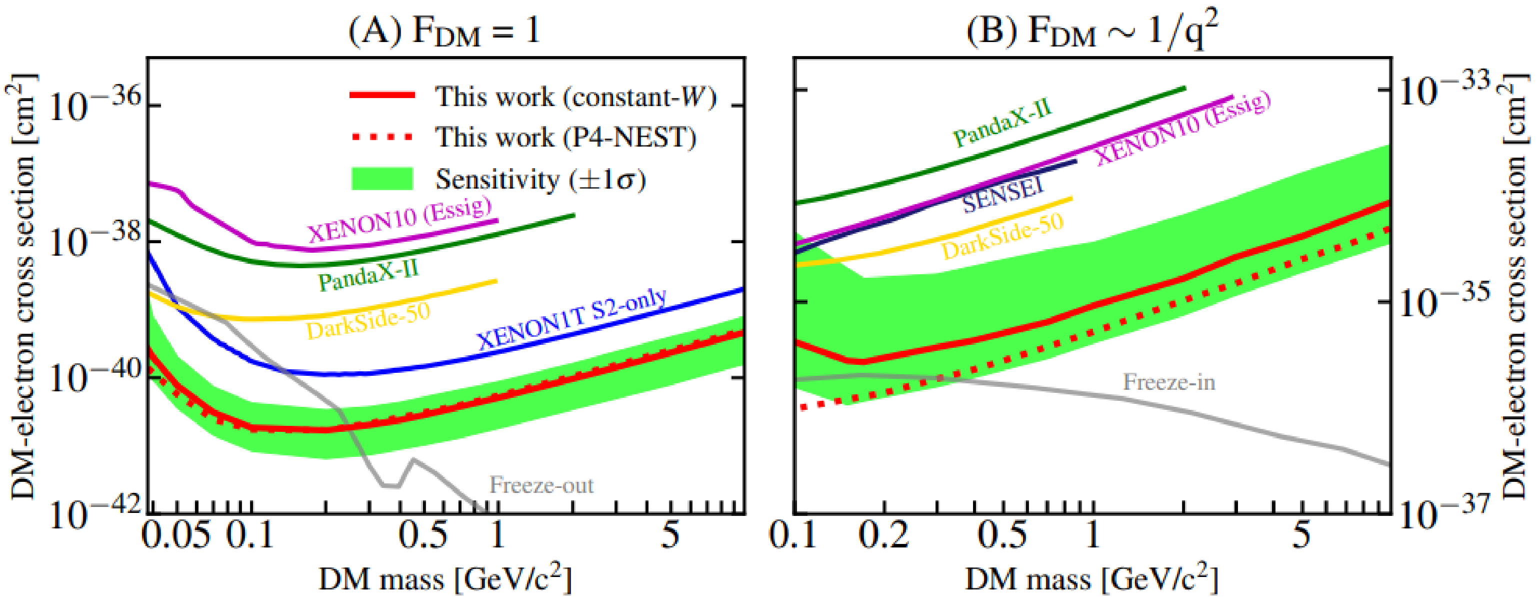


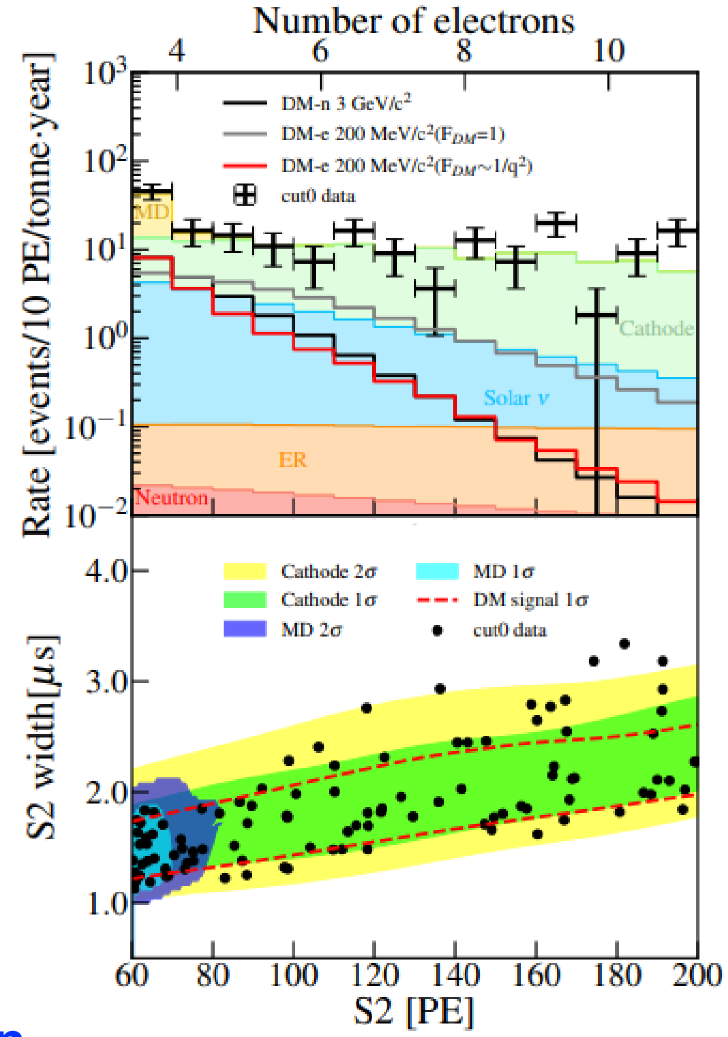




control region

# Constraints on light dark matter

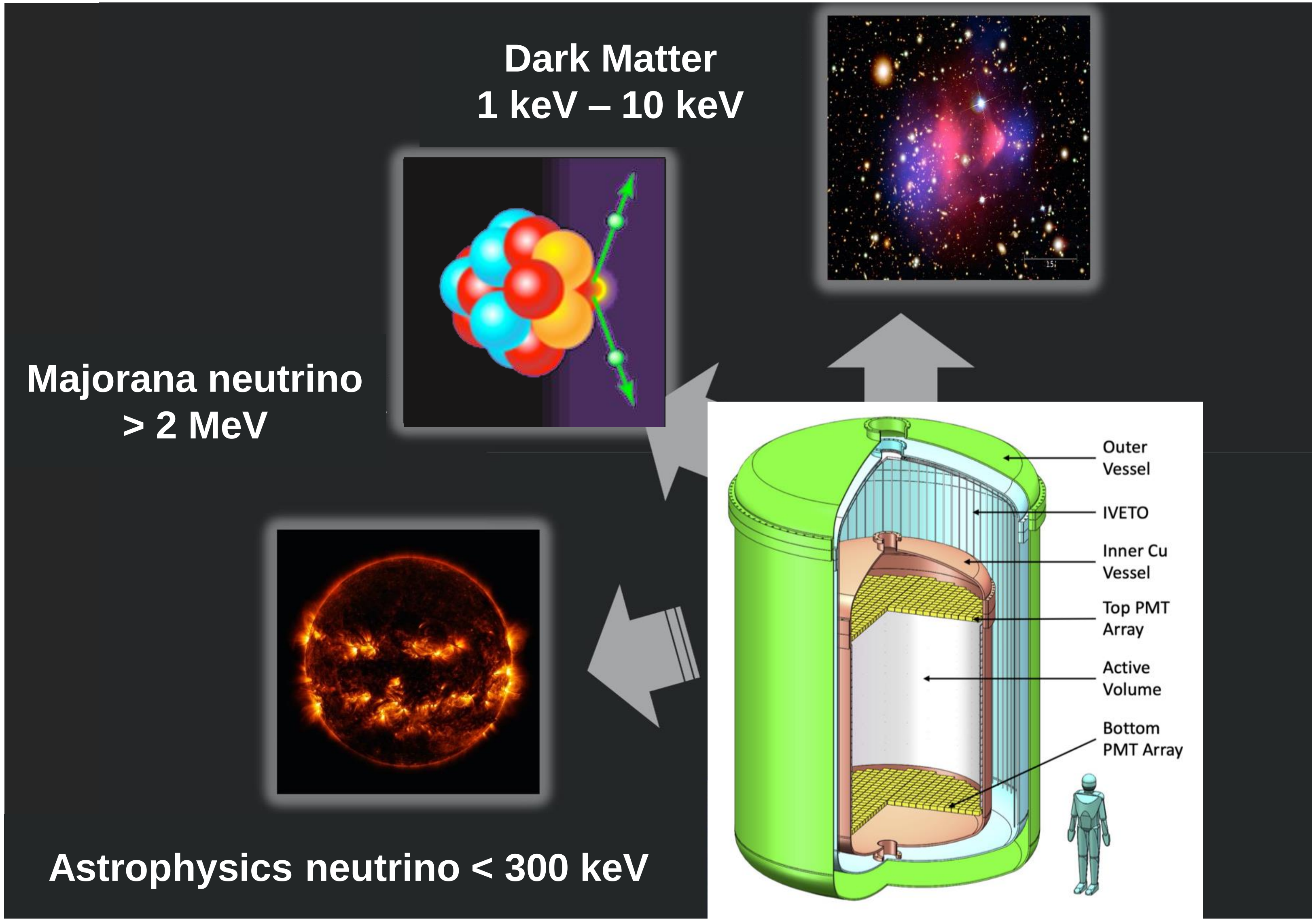
- **Blind analysis of 0.55 tonne-year exposure**
- **Most stringent constraints are derived**
  - DM-electron interaction, $2 \times 10^{-41}$ cm$^2$

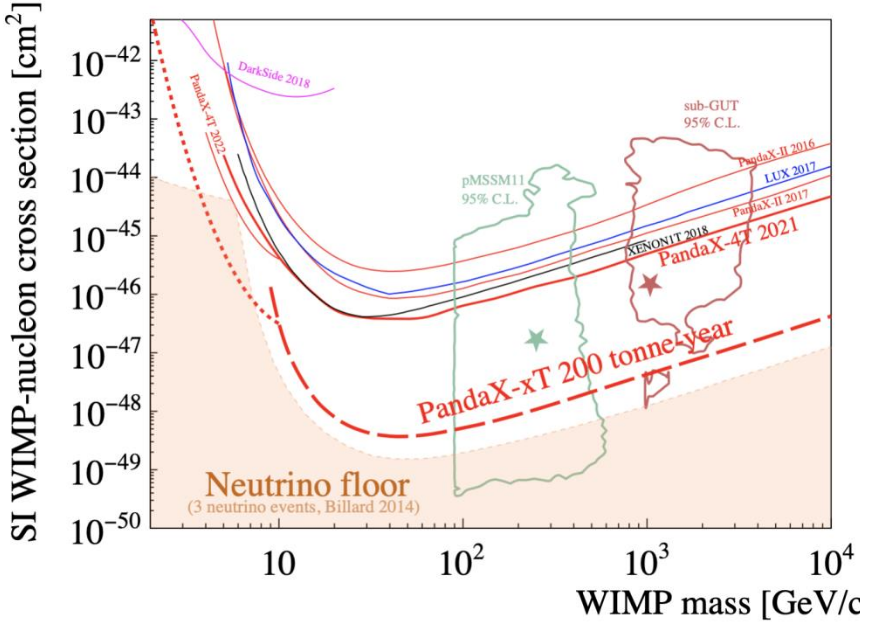



**S. Li et al. [arXiv:2212.10067](arXiv:2212.10067) Accepted by PRL, Editors' Suggestion**

# Future




- Multi-physics goals;
- With > 30 tonne liquid xenon in the sensitive volume;
- Decisive test on WIMP and key test on Dirac/Majorana neutrino;
- Stay tuned!