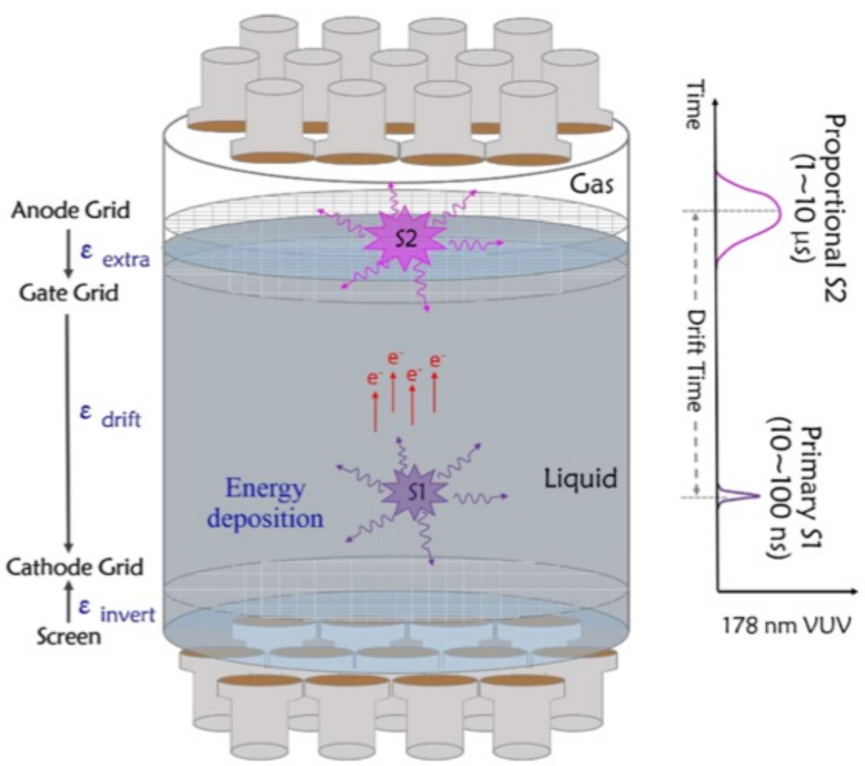
# Exploring Solar Axions with Electronic Recoil Data from PandaX-4T Detector

Xinning Zeng, SJTU
On behalf of the PandaX Collaboration

2024.05.10, COUSP2024@Xi Chang

PANDAX
PARTICLE AND ASTROPHYSICAL XENON TPC

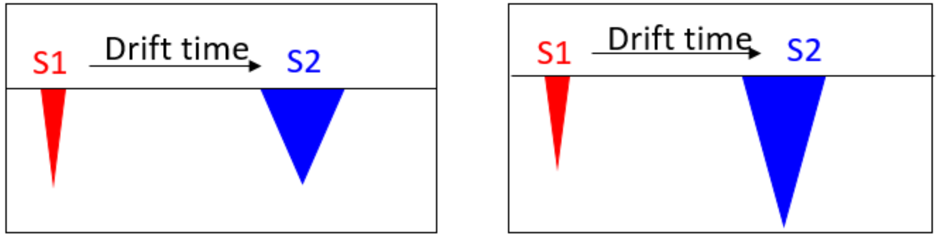
# Dual Phase Xenon TPC




**ZEPLIN · XENON · LUX · LZ · PandaX…**

1. Large A: large cross section & self-shielding;
2. 3D reconstruction and fiducialization;
3. Scalable;
4. Discrimination power
   - WIMPs, $\nu$, n → Nuclear Recoil (NR)
   - Axion, $\gamma$, $\beta$ → Electronic Recoil(ER)

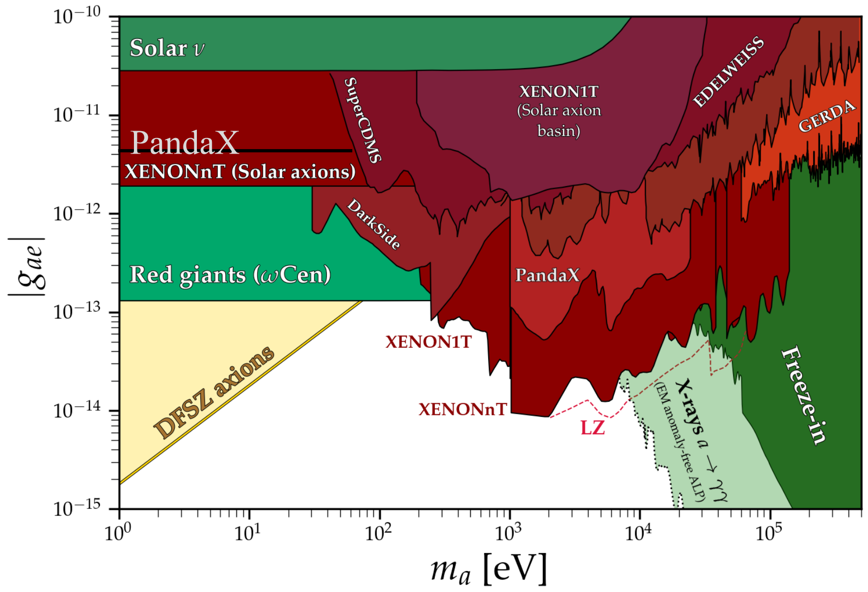
**Dark matter: nuclear recoil (NR)**  **γ background: electron recoil (ER)**

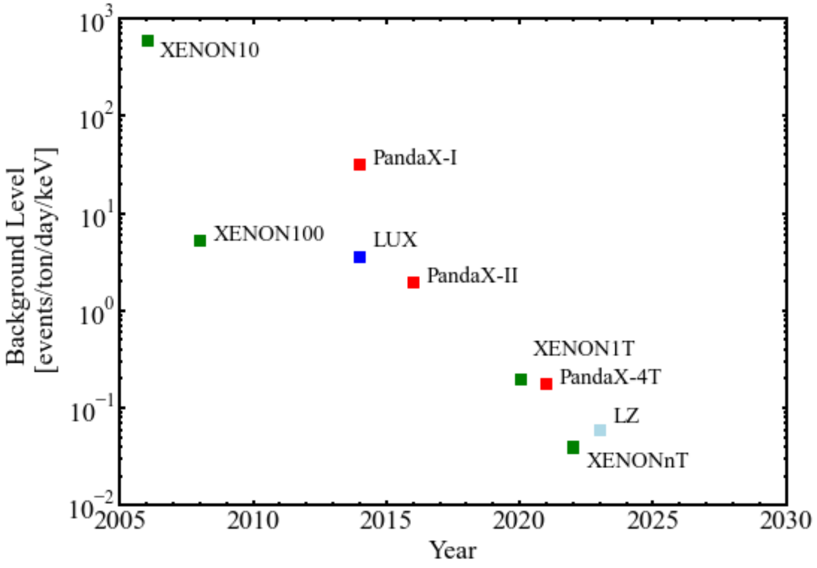



$(S2/S1)_{NR} << (S2/S1)_{ER}$

# Searching for Axions in Underground Experiments

https://cajohare.github.io/AxionLimits/

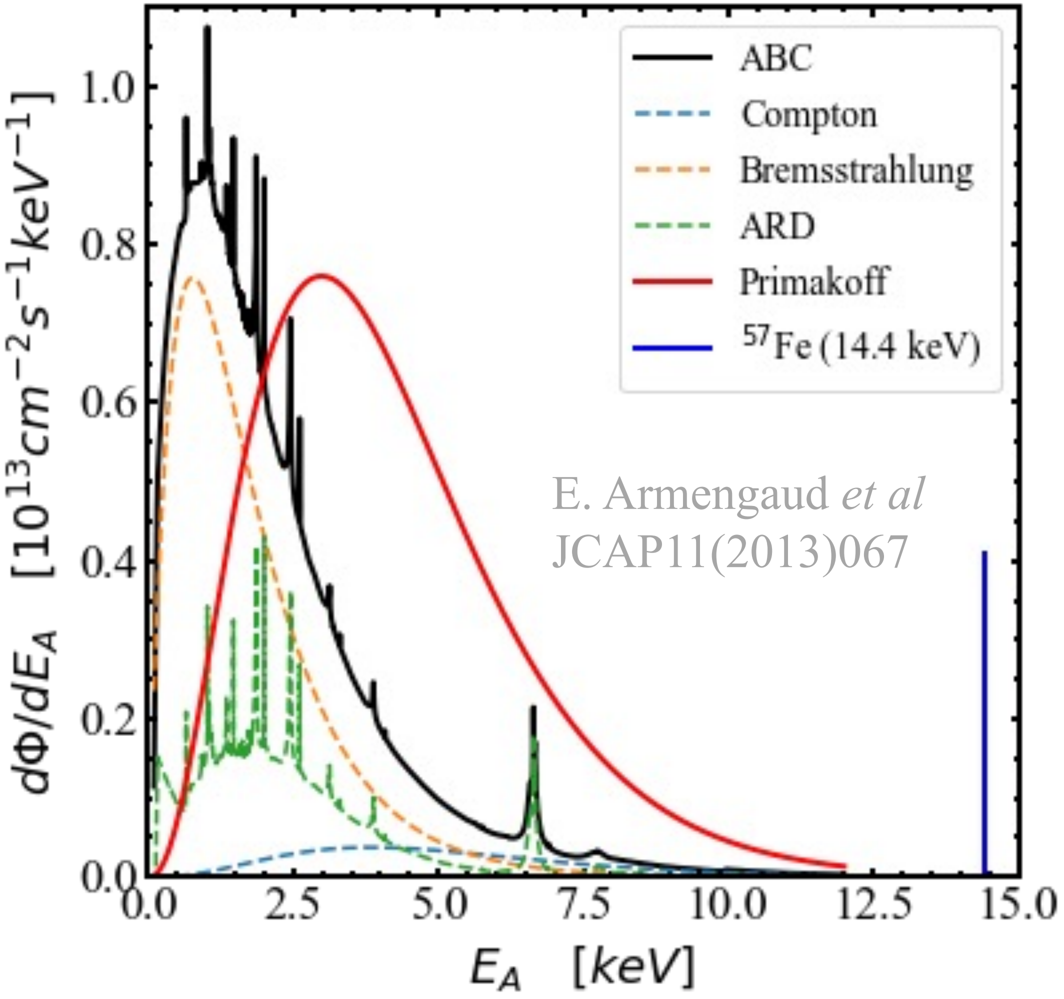



1. Axion is a leading particle candidate to provide the mysterious dark matter in the cosmos;
   - cover a large mass range: $10^{-24} - 10^{7} eV$

2. Detection of axions in underground experiments:
   - enegy deposition: ~ keV;
   - upgraded detectors: background budget and energy resolution are improved significantly.

# Solar Axion




**Axion Formalism:**

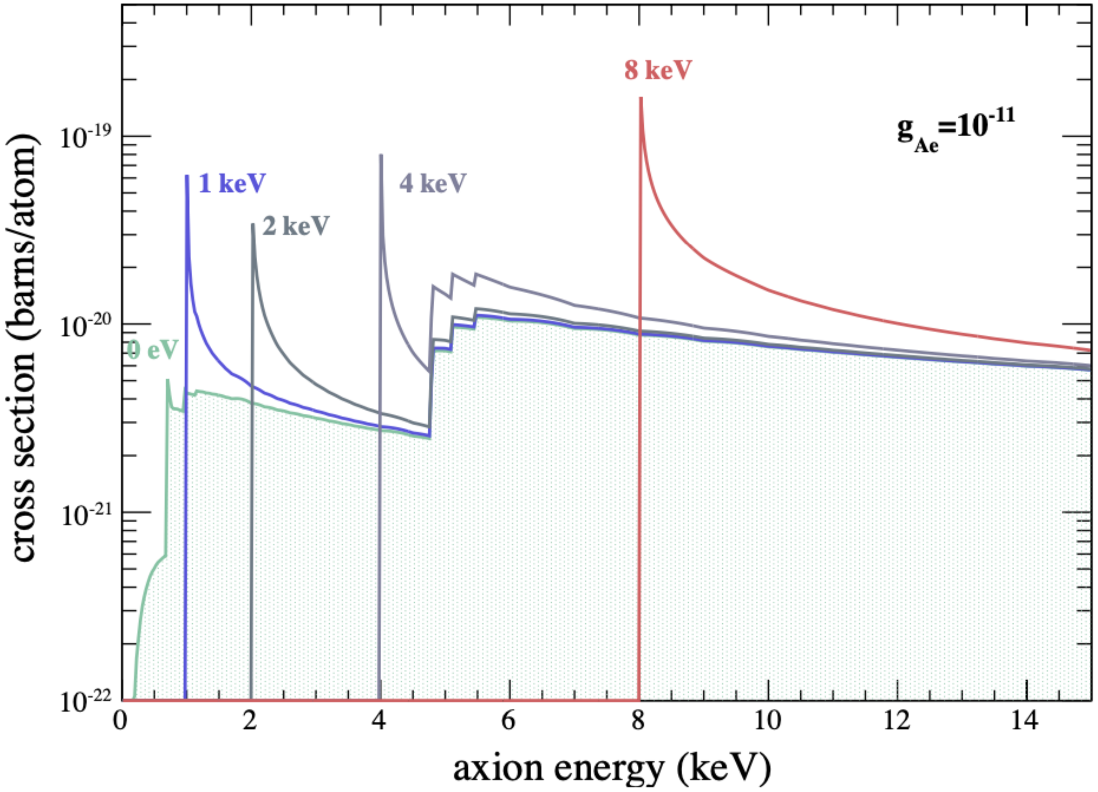
$$L \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \sum_f i g_{af} a \bar{f} \gamma_5 f - i a \bar{N} \gamma_5 (g_{aN}^0 + g_{aN}^3 \tau^3) N$$

**Production in the sun:**

- ❑ABC Process: Atomic recombination and deexcitation (ARD), Bremsstrahlung, and Compton;
- ❑Primakoff effect;
- ❑M1 nuclear transition of $^{57}Fe$ (14.4 keV).

Corresponding axion couplings in flux: $g_{ae} = 1 \times 10^{-11}$, $g_{a\gamma\gamma} = 1 \times 10^{-9} GeV^{-1}$, $g_{aN}^{eff} = 3 \times 10^{-6}$.

# ER Signals from Axio-electric Effect



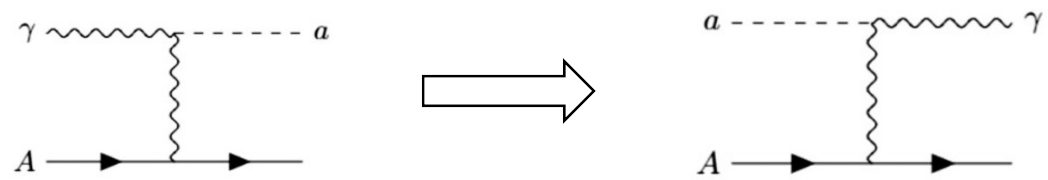

Astroparticle Physics Volume 44, April 2013, Pages 59-67

The approximate cross section of axio-electric effect is:

$$\sigma_{Ae}(E) = \sigma_{\rm pe}(E)\frac{g_{Ae}^2}{\beta}\frac{3E^2}{16\pi\alpha m_e^2}\left(1-\frac{\beta^{\frac{2}{3}}}{3}\right)$$

where $g_{Ae} = C_{ae} m_a / f_a$, $C_{ae}$ is model dependent.

# ER Signals from Inverse Primakoff Effect




production in sun          detection on earth

$$\frac{d\sigma}{d\Omega} = \frac{\alpha g_{a\gamma\gamma}^2 E_a^3 p_a \sin^2\theta}{4\pi(E_a^2 + p_a^2 - 2E_a p_a \cos\theta)^2} \times \left| \int d^3\boldsymbol{x} e^{-i\boldsymbol{q}\cdot\boldsymbol{x}} \langle A_0|\rho(\boldsymbol{x})|A_0\rangle \right|^2$$
$$= \frac{\alpha g_{a\gamma\gamma}^2 E_a^3 p_a \sin^2\theta}{4\pi(E_a^2 + p_a^2 - 2E_a p_a \cos\theta)^2} \times |Z - F(\boldsymbol{q})|^2$$

**Two kind of form factors:**

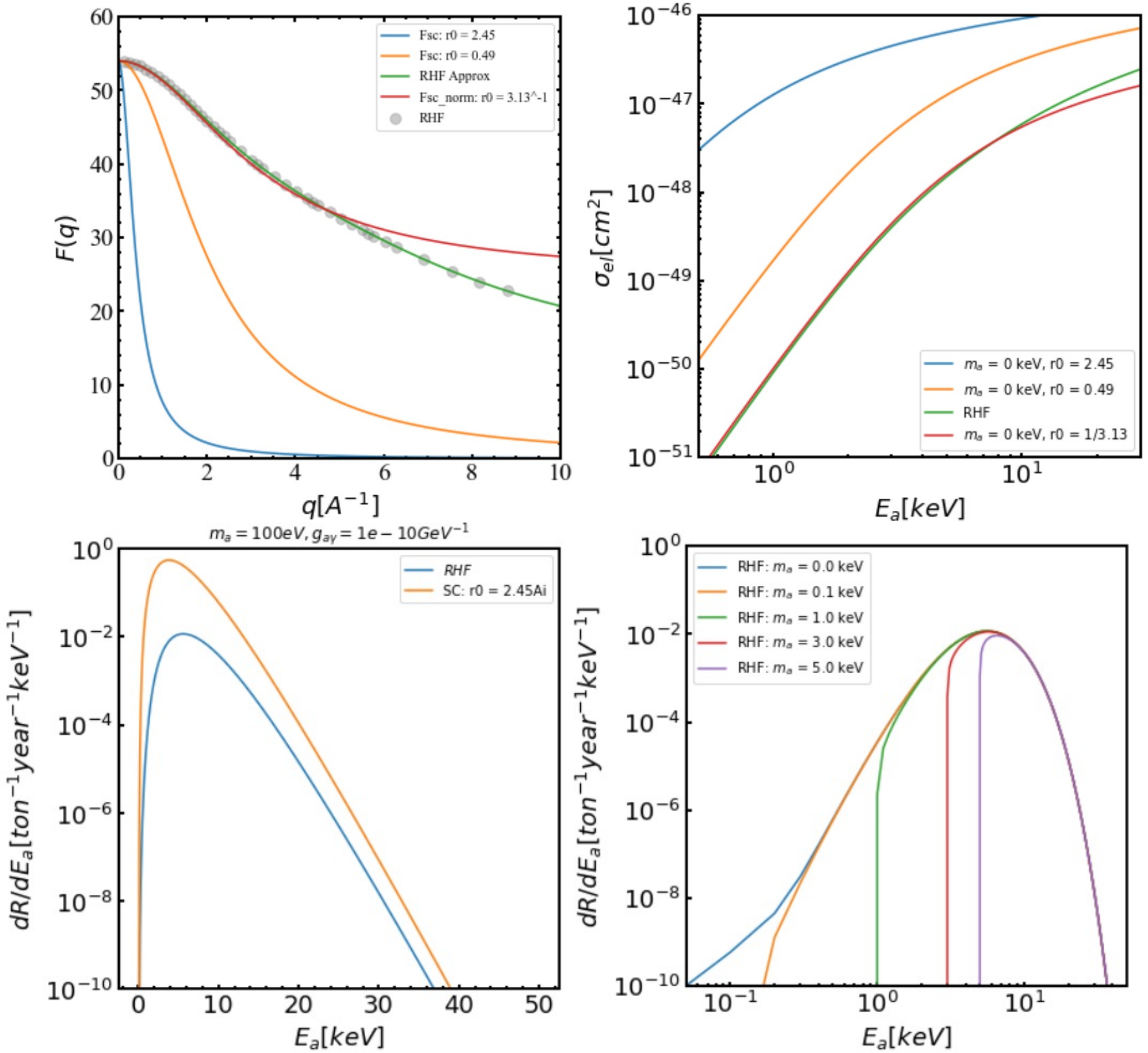
(1) Screened Coulomb potential (SC):

$$F_{SC}(q; r_0) = \frac{Z}{1 + q^2 r_0^2}$$

(2) Relative Hartree-Fock wavefunction (RHF):

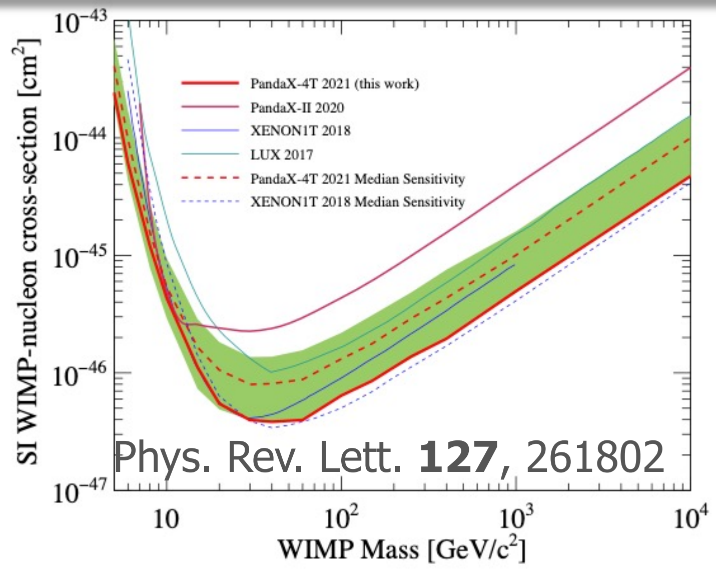
$$F(q) \simeq \sum_{i=1}^{4} a_i \exp\left[ -b_i \left(\frac{|\boldsymbol{q}|}{4\pi}\right)^2 \right] + c$$

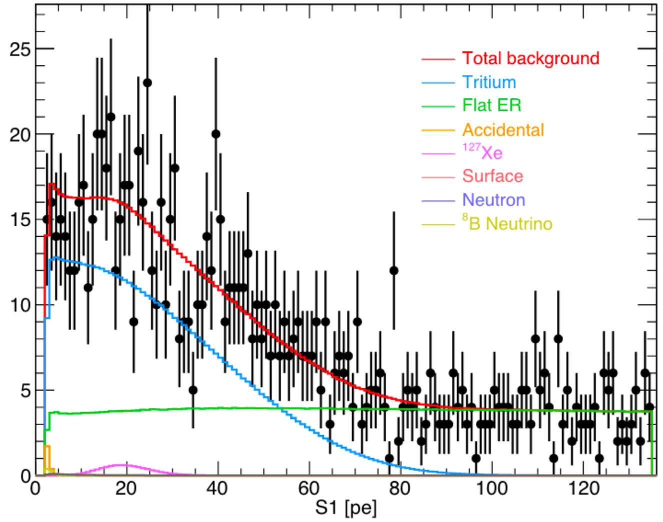
Physics Letters B Volume 815, 10 April 2021, 136174



# PandaX-4T Commissioning Run (Run 0)

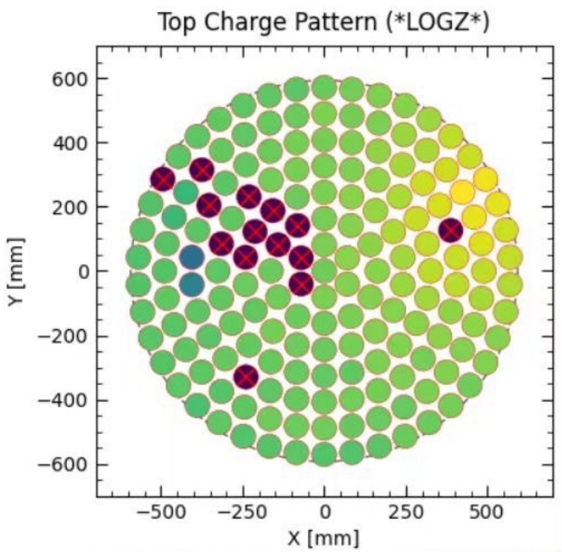
- ❑**Sensitive volume: 3.7 tonne xenon**
- ❑**Commissioning started from Nov/2020 (95 days)**
  - 0.63 tonne-year exposure, 1058 candidates
  - Sensitivity improved from PandaX-II final analysis by 2.9 times (30 GeV/c2);
- ❑**Tritium removal after Run 0**
  - xenon distillation, gas flushing, etc

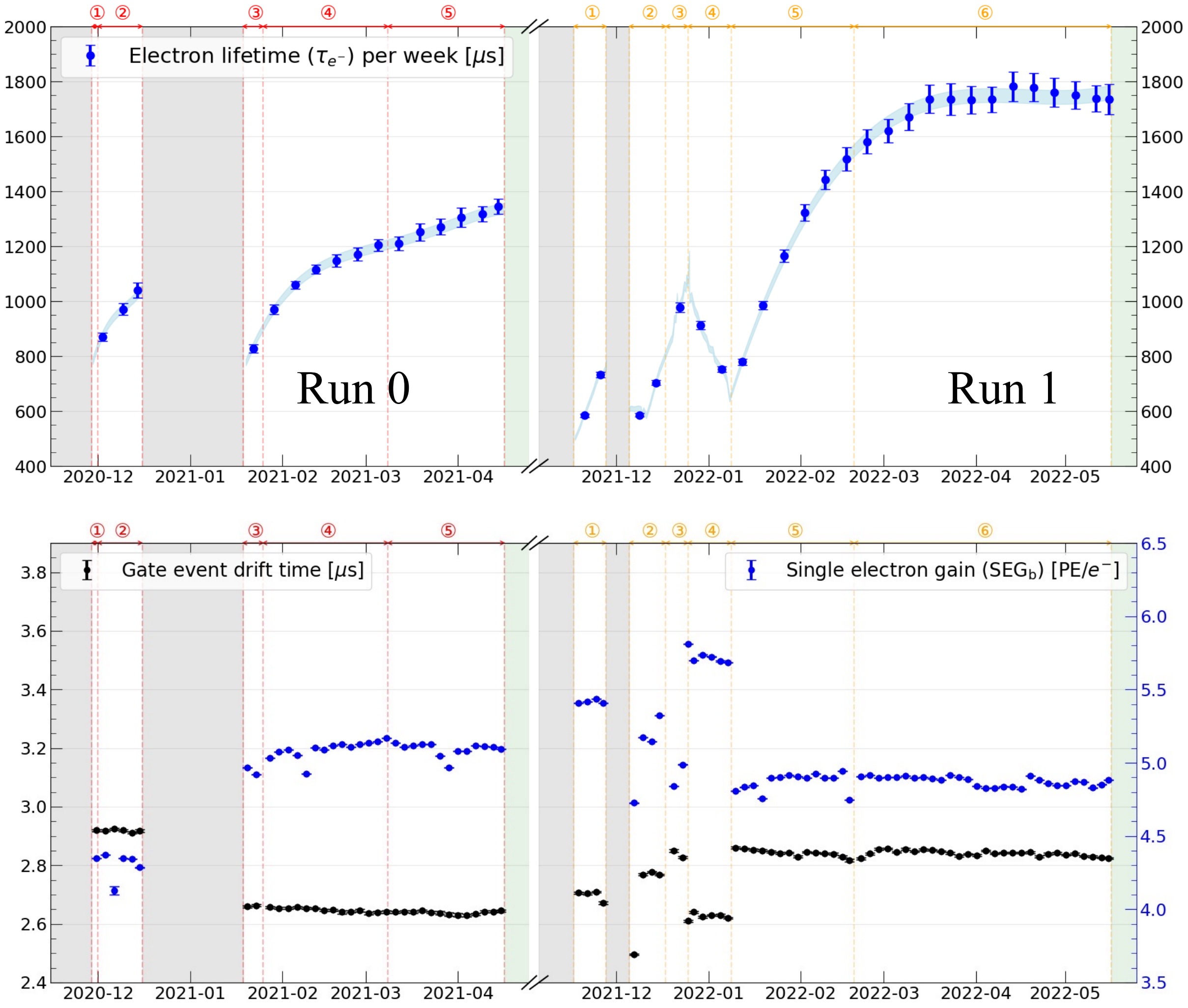


# Data Taking Condition of Run 1

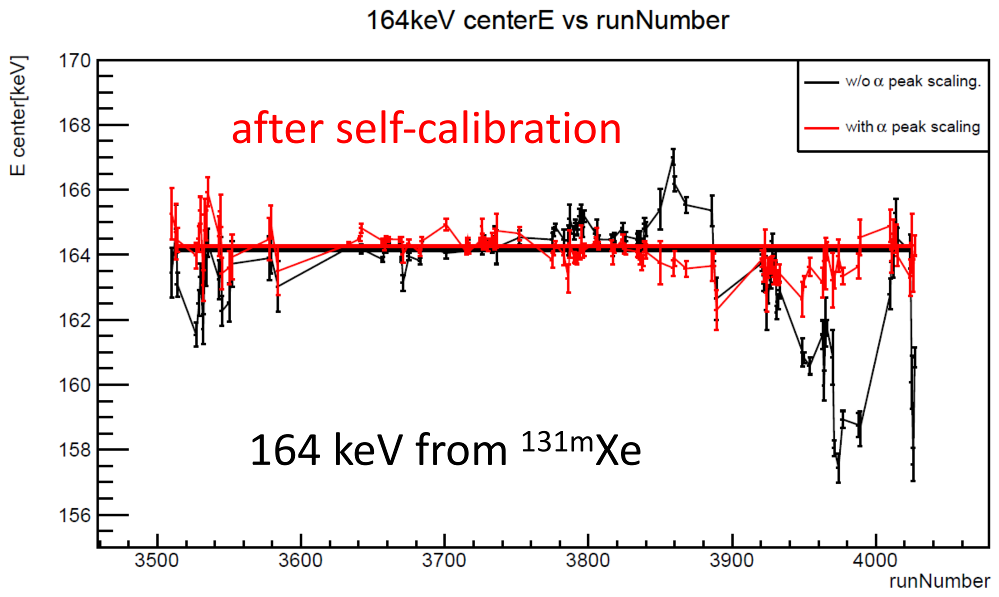
- **2021/11 – 2022/05: ~1 ton-year (164 d)：**
- **Xenon purity monitor: Maximum electron lifetime reaches 1800 us;**
- **Liquid level is monitored through the drift time of gate events and single electron gain (SEG);**
- **Add[illegible]-off.**



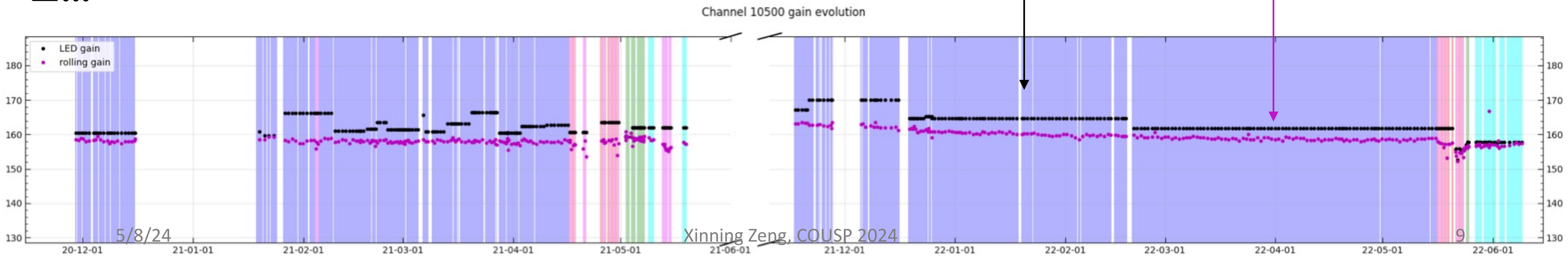



# Updates on signal reconstruction

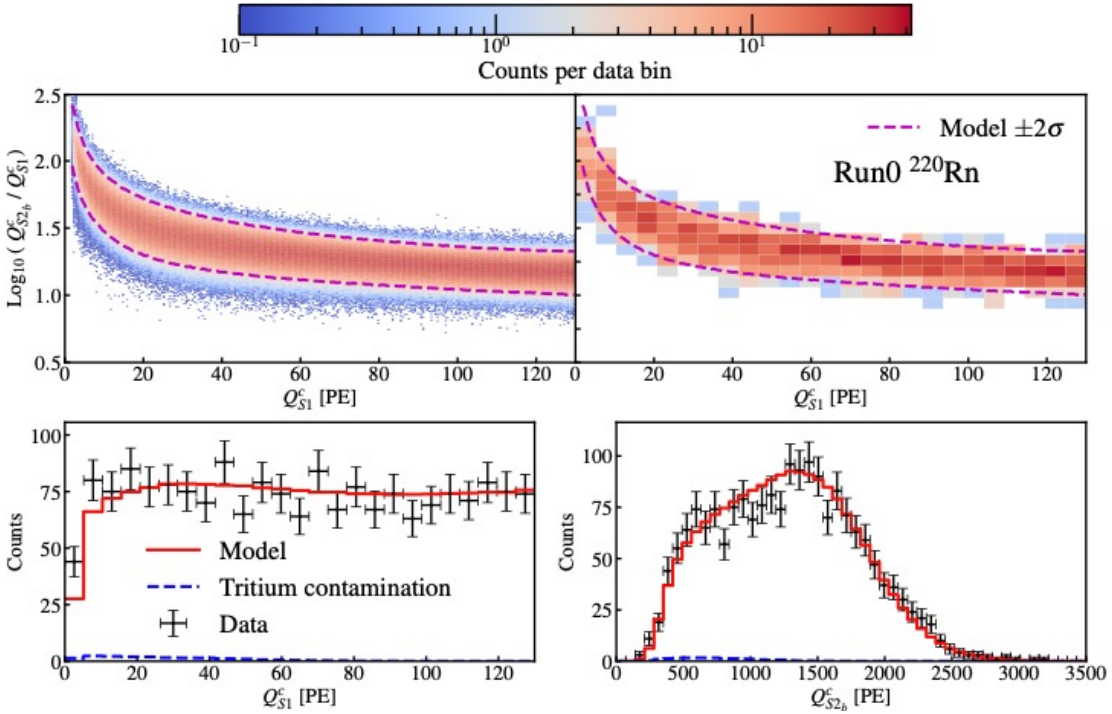
- **Instant monitoring of PMTs:**
  - correction factor derived from single hit distribution.
- **Instability of signal yield: S1 & S2 of monoenergetic peak evolve by time:**
  - correction factor derived from S1 and S2 with 5.5MeV alpha events from $^{222}$Rn decay;
- **New event window based on S2**
  - fix window: 1ms before and after
- **...**

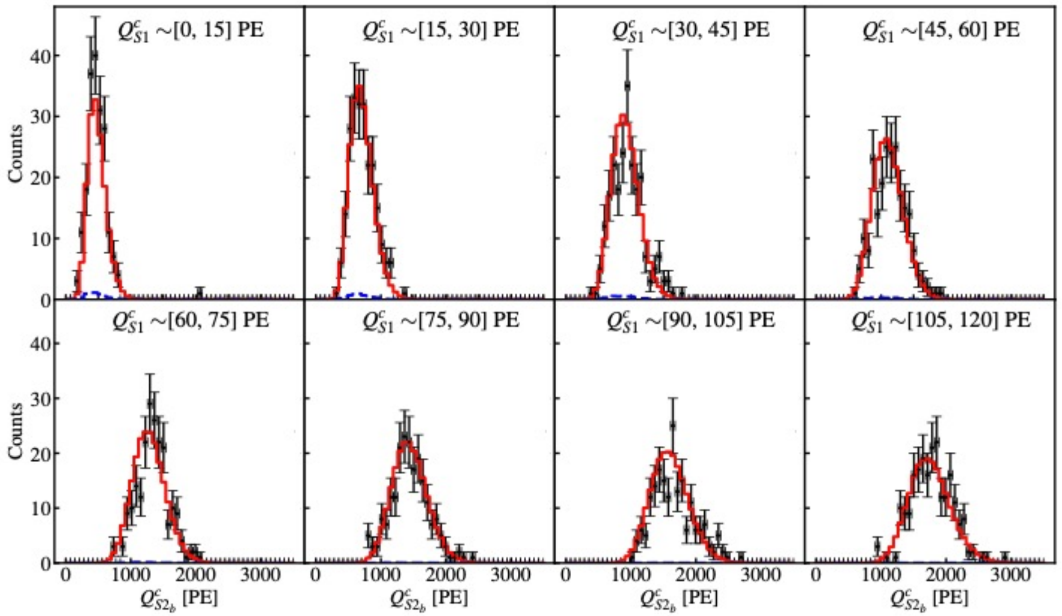



LED calibration vs Self-calibration



# Rn Calibration & ER Response

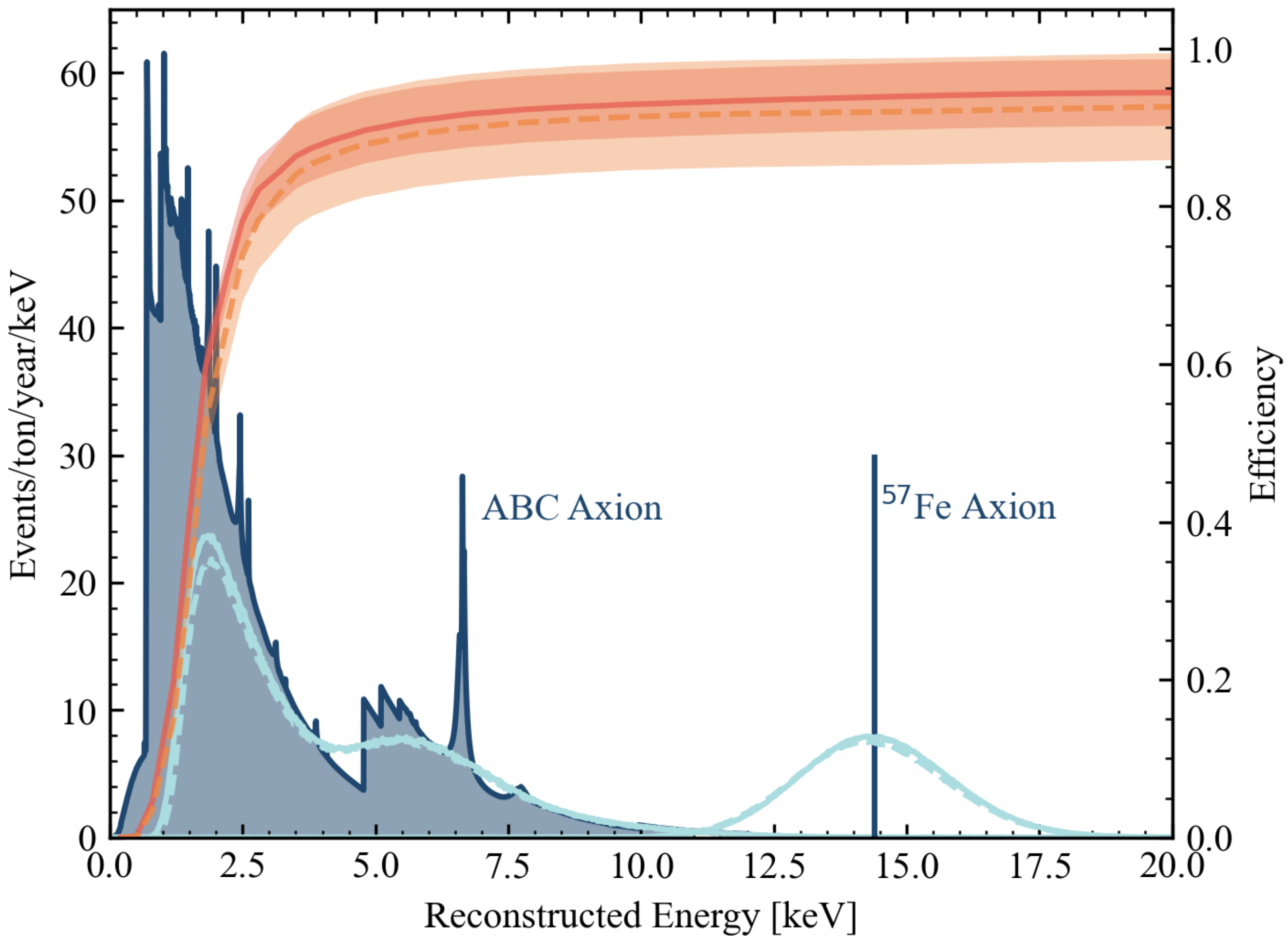



- ❑ The detector response is modelled by NEST ( Noble Element Simulation Technique).
- ❑ Detector parameters are fit to Rn calibration data using unbinned likelihood fitting with emcee;
- ❑ Calibrated NEST also fits well with sliced calibration data.

arxiv: 2403.04239

# Solar Axion Signals in PandaX-4T

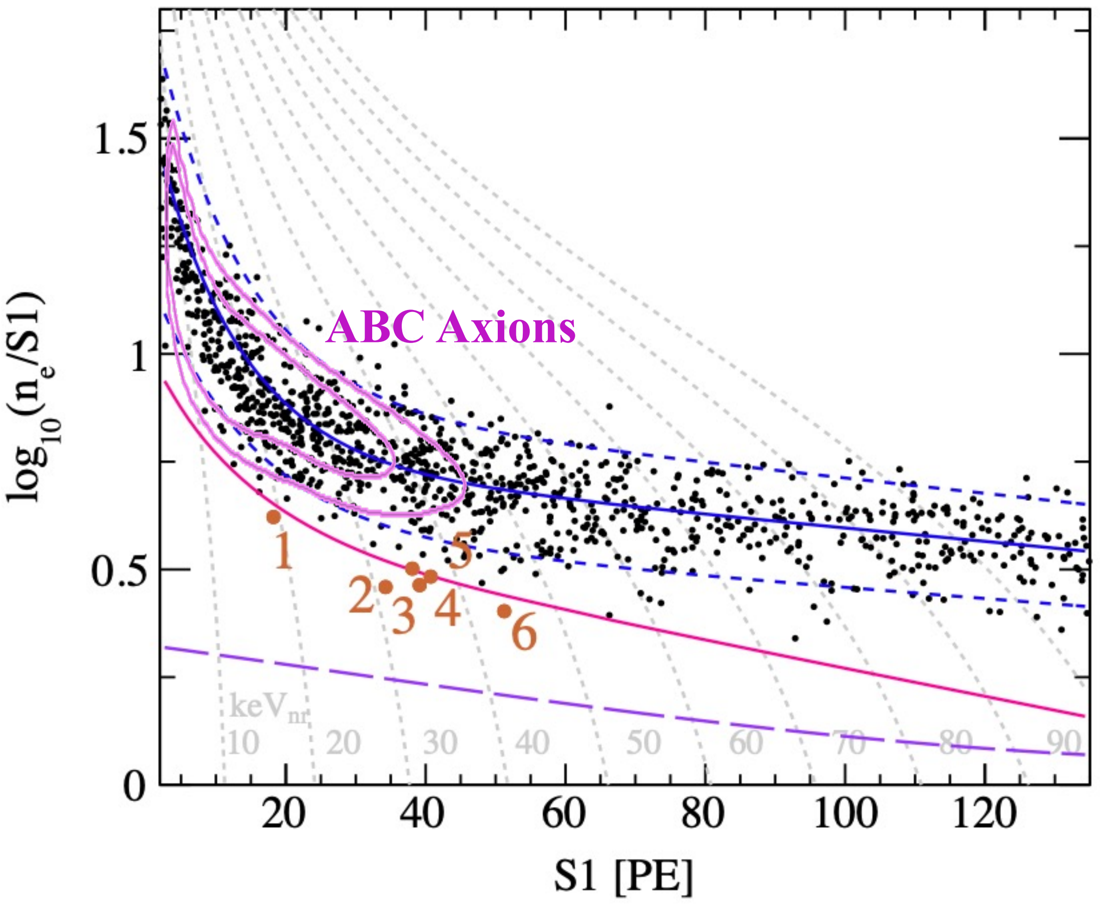



With the calibrated signal model, we can simulate the spectrum of signals from solar axion:

1. couplings used in figure: $g_{ae} = 3.1\times10^{-12}, g_{aN}^{eff} = 8.3\times10^{-7}$;

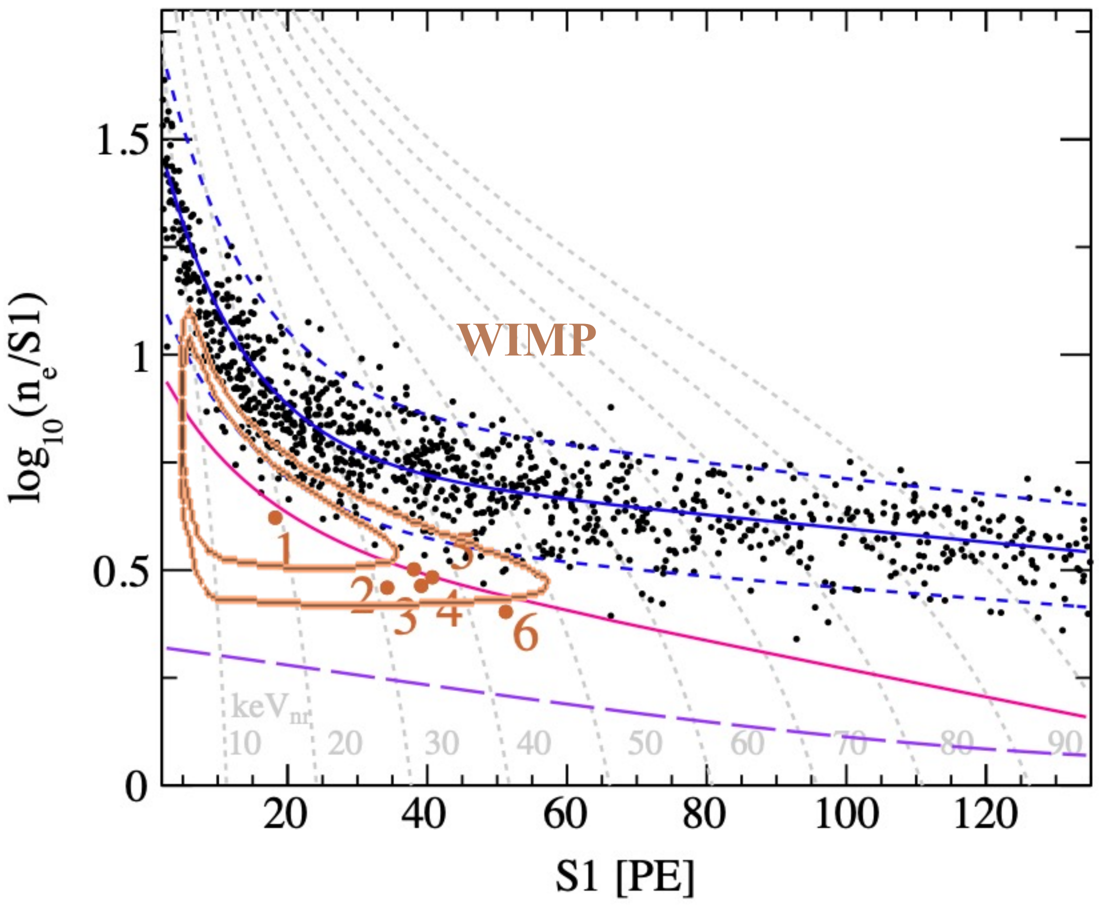
2. Filled region for theoretical spectrum; solid and dashed line for Run 0 and Run 1;

# NR Searches V.S. ER Searches




**Excess** over known ER backgrouds!

Phys. Rev. Lett. 127, 261802

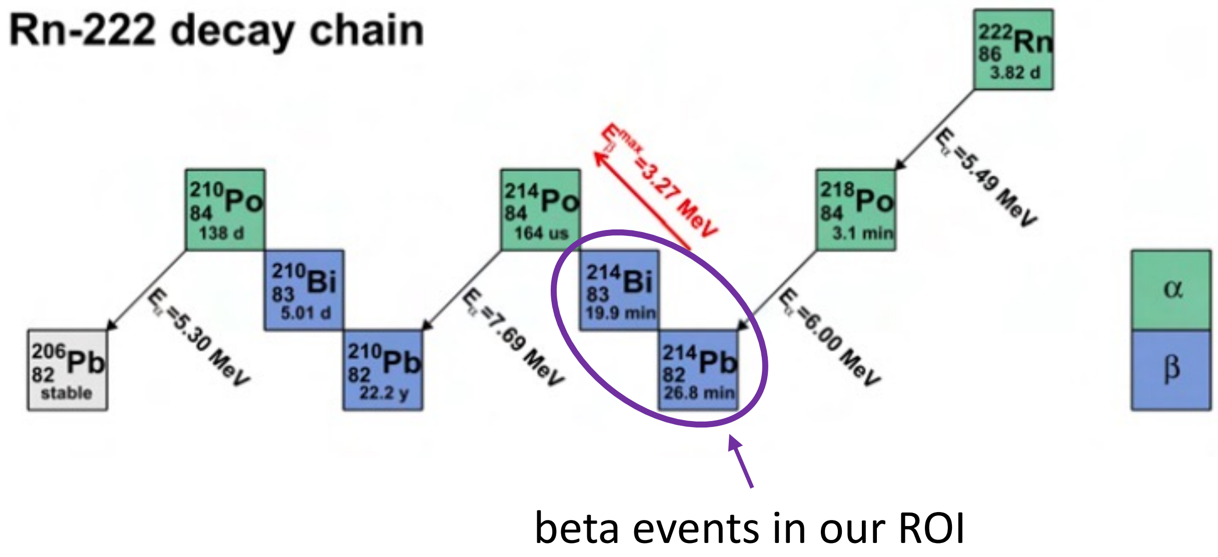


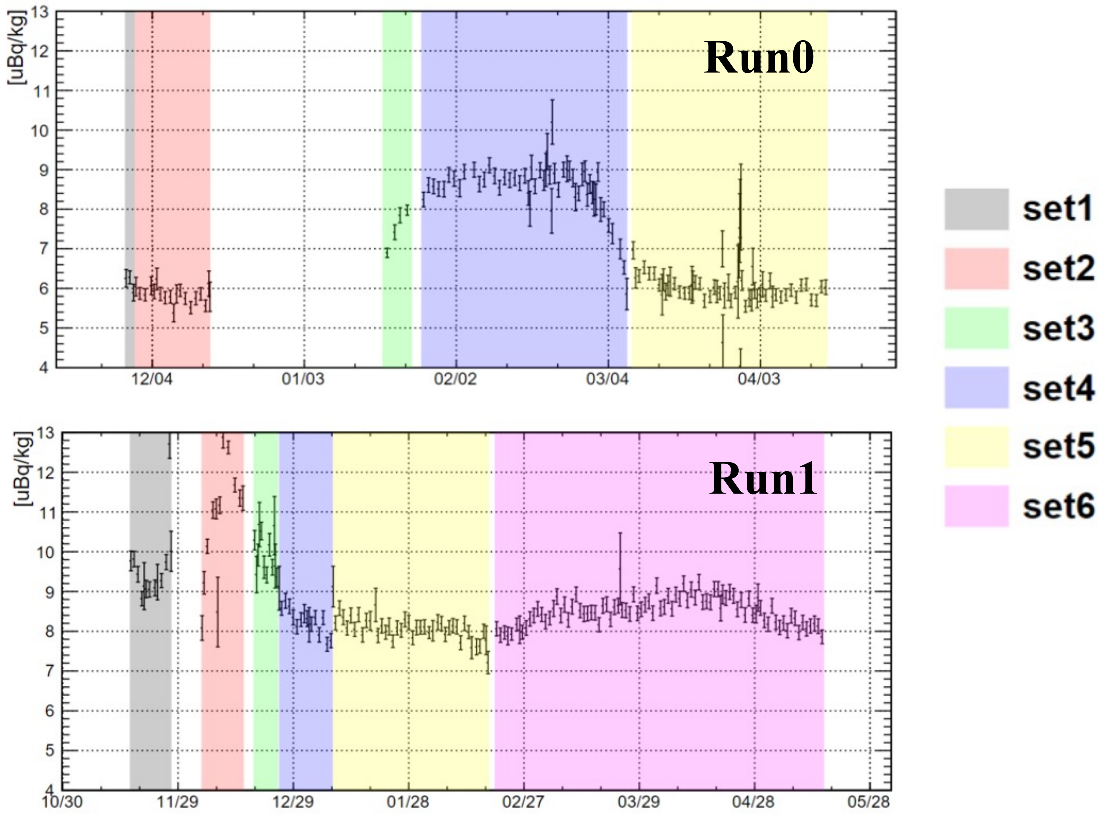

Below NR median **candidates**.

# Main ER Backgrounds: $^{222}$Rn

- **Rn level is monitored and varies with running conditions;**
- **Circulation system will be upgraded after Run 1.**

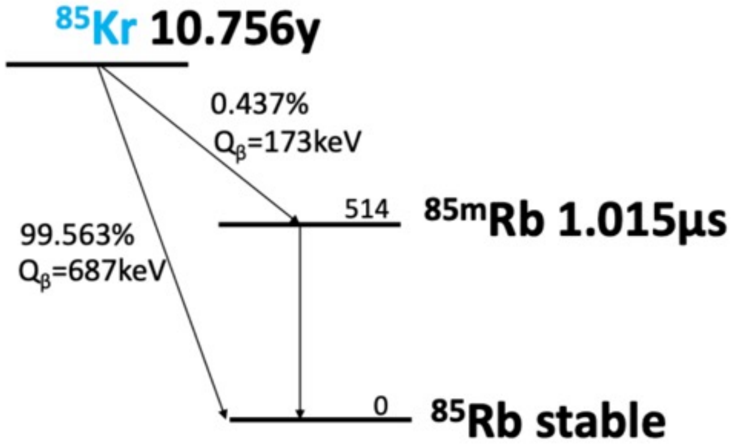
| Rn level | μBq/kg |
|---|---|
| Run 0 | **7.07 ± 0.02(stat.) ± 0.23(sys.)** |
| Run 1 | **8.67 ± 0.01(stat.) ± 0.27(sys.)** |

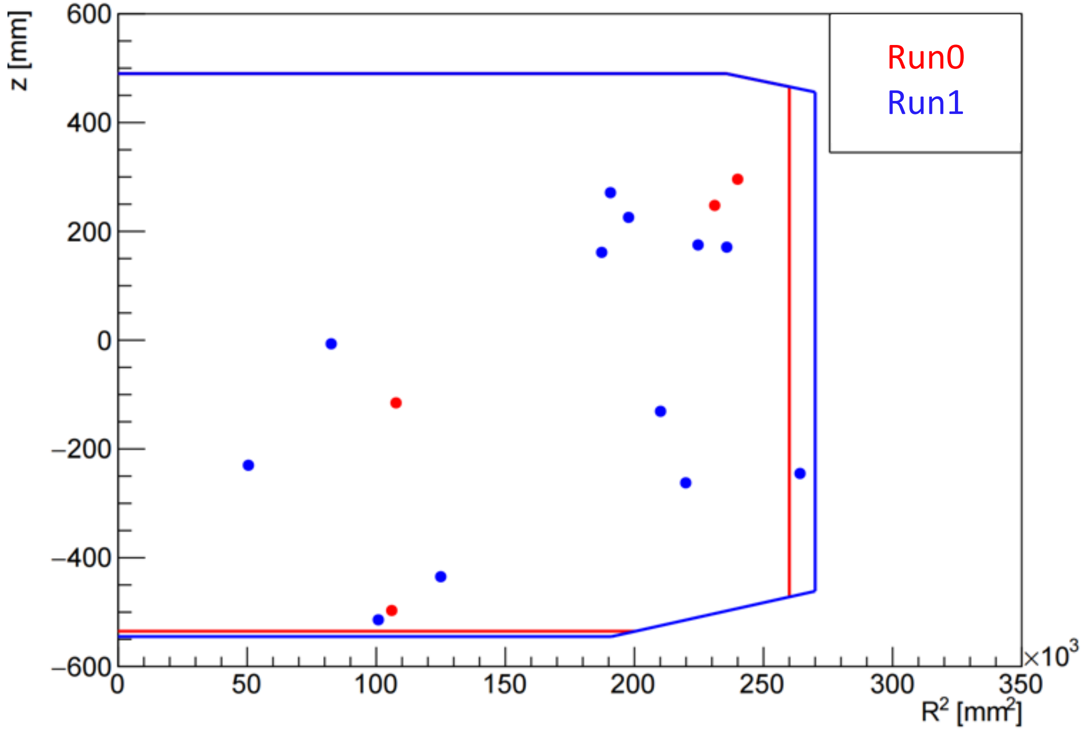


# Main ER Backgrounds: $^{85}Kr$

- **Compare to Commissioning run**
  - tightening beta-gamma coincidence selection
  - less contributions from accidental events

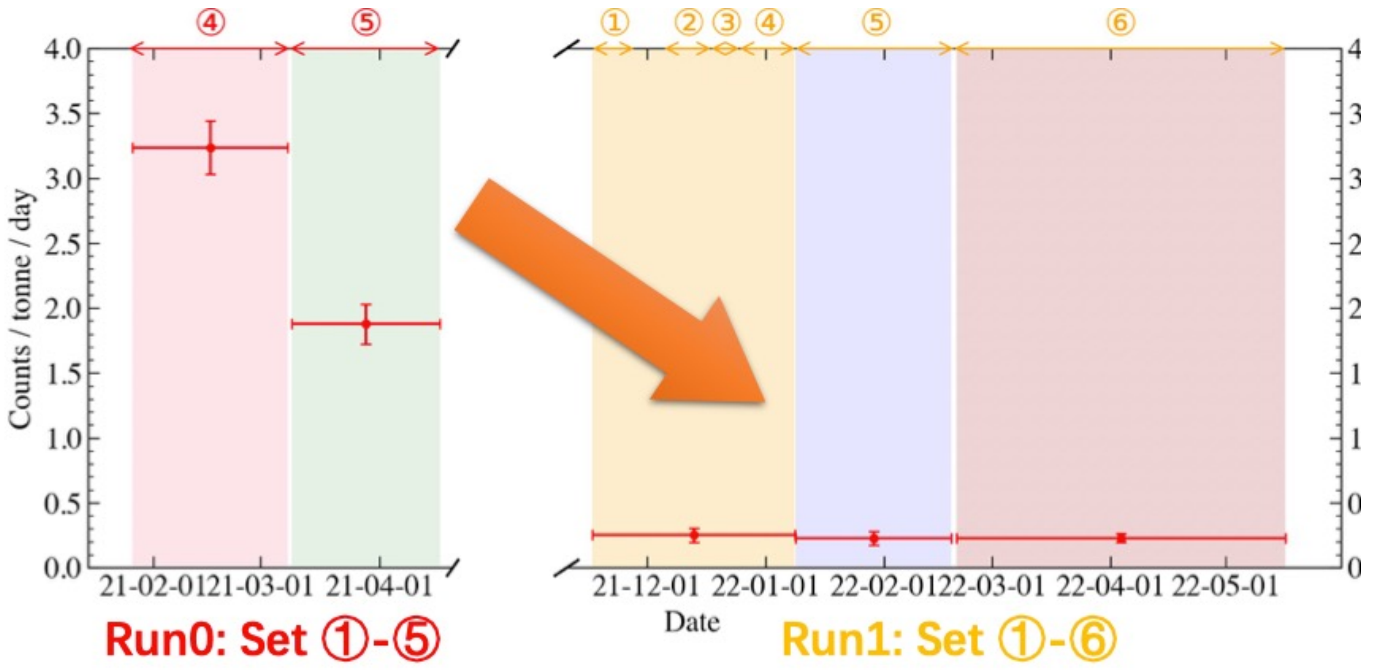



| | $\beta-\gamma$ events | accidental events | Kr/Xe [ppt ($10^{-12}$)] |
|---|---|---|---|
| Run0 | 4 | 0.14 ± 0.04 | **0.5 ± 0.3** |
| Run1 | 12 | 0.25 ± 0.05 | **0.9 ± 0.3** |

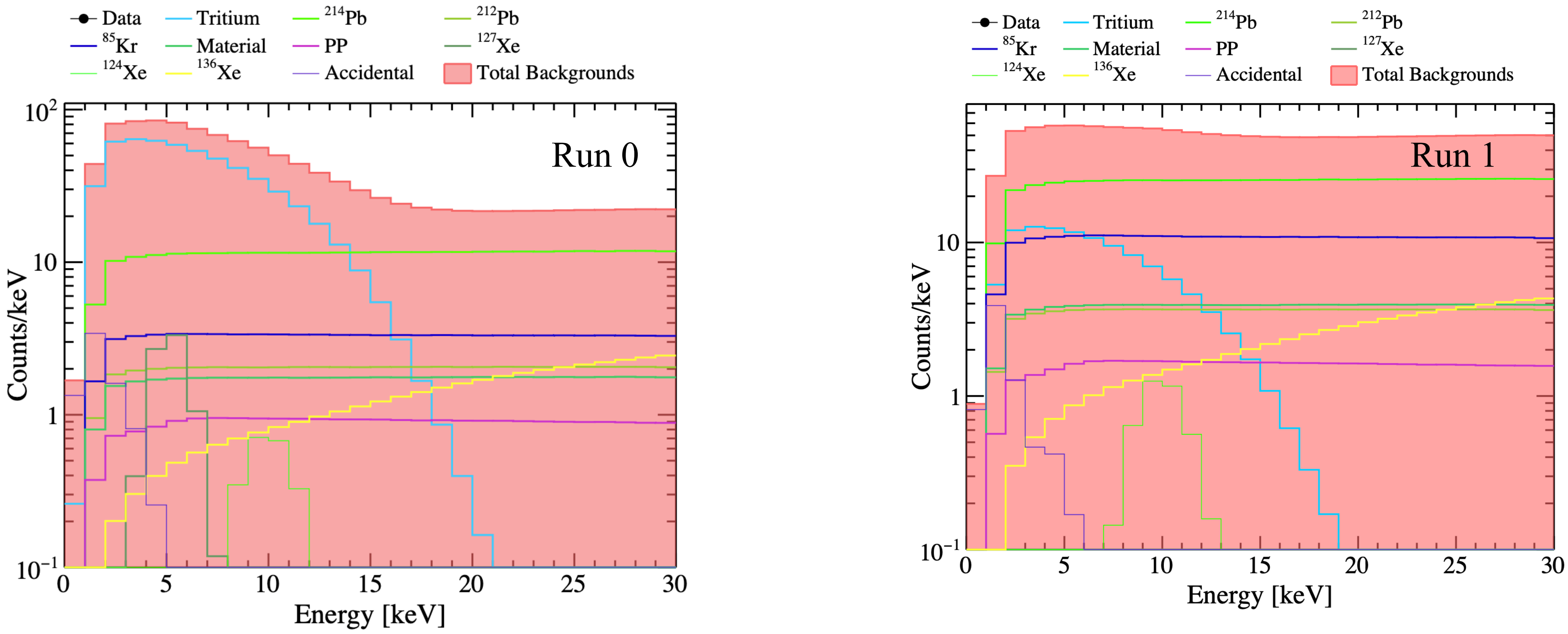
# Main ER Backgrounds: Tritium

- **Tritium spectrum identified in the data**
- **Likely originated from a tritium calibration at the end of PandaX-II；**
- **Preliminary estimation of tritium level in Run 1**




| Dataset | Run0 Set4 | Run0 Set5 | Run1 Set1-4 | Run1 Set5 | Run1 Set6 |
|---|---|---|---|---|---|
| Rate [/tonne/day] | 3.24±0.20 | 1.88±0.15 | 0.25±0.05 | 0.23±0.05 | 0.23±0.03 |

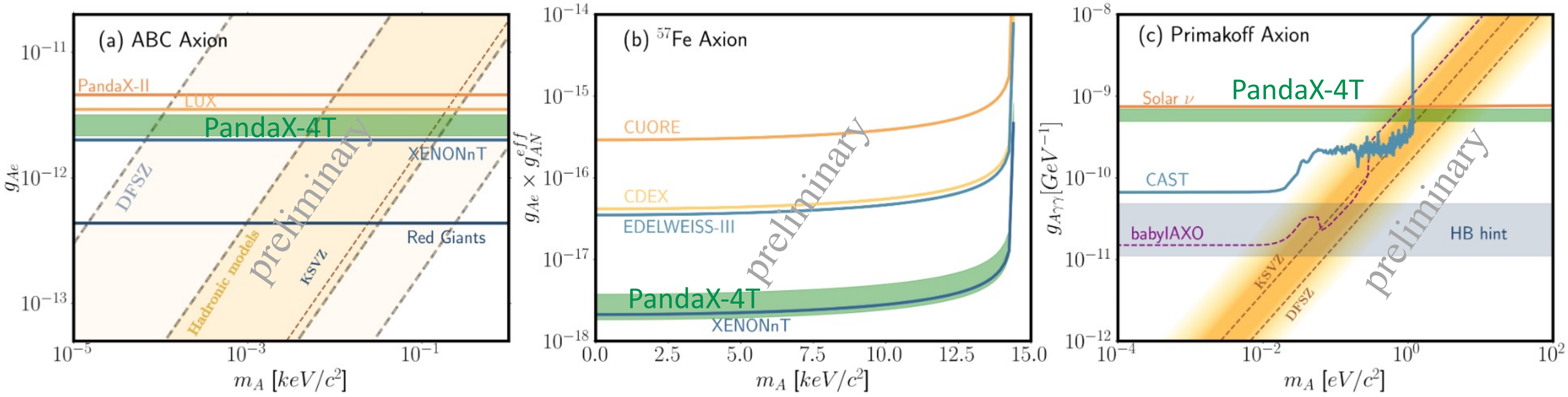
# Background Summary




**Compare to WIMP analysis:**

1. extended the ROI to 30 keV: better constraints on ER backgrounds;
2. reject events below ER 99.5%: remove neutron and surface backgrounds

# Sensitivity Estimation




1. **Binned Likelihood fitting based on HistFitter: $CL_{s+b}$ technique, 90% C.L..**
2. **Independent estimation of different couplings:**
   (a) **ABC axion: ABC Flux * $\sigma_{Ae}$**
   (b) **$^{57}$Fe axion: $^{57}$Fe Flux * $\sigma_{Ae}$**
   (c) **Primakoff axion: Primakoff Flux * $\sigma_{invPri}$ (RHF is used.)**
3. **Sensitivity of $g_{Ae}$ is improved by ~ 2 times compare to PandaX-II.**
4. **Final result is under consistency check.**

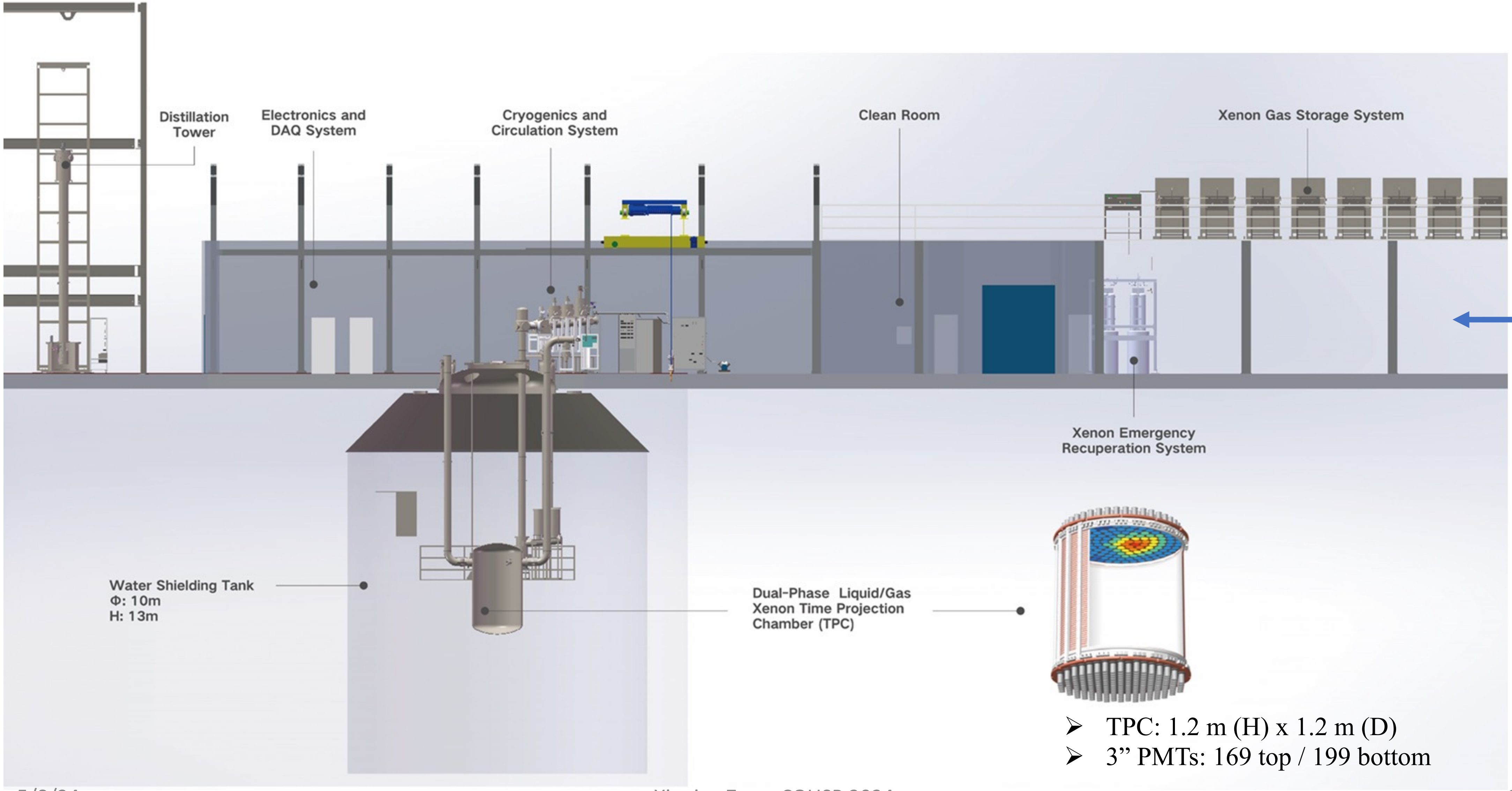
# Summary and Outlook

- **Combined analysis of Run0 and Run1 are updated;**
- **Low energy ER responses are calibrated with Rn calibration;**
- **Expected background contributions are estimated respectively; tritium level has significantly reduced in Run1;**
- **Sensitivity of solar axion detection is estimated and final results are under consistency check.**

# PandaX Collaboration

# Backups

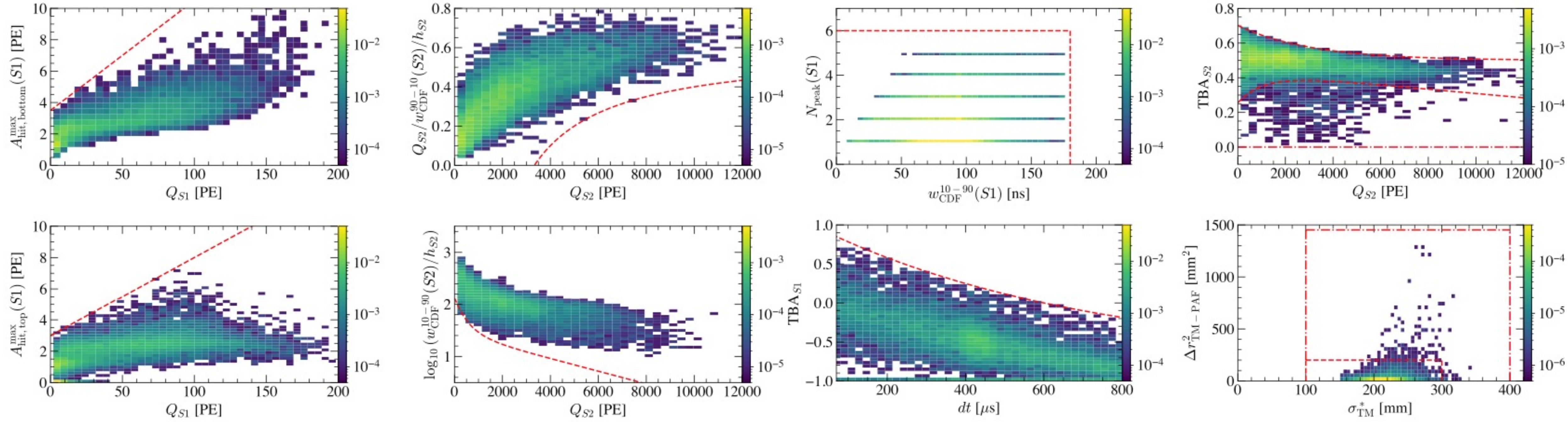
# PandaX-4T Detector System Layout

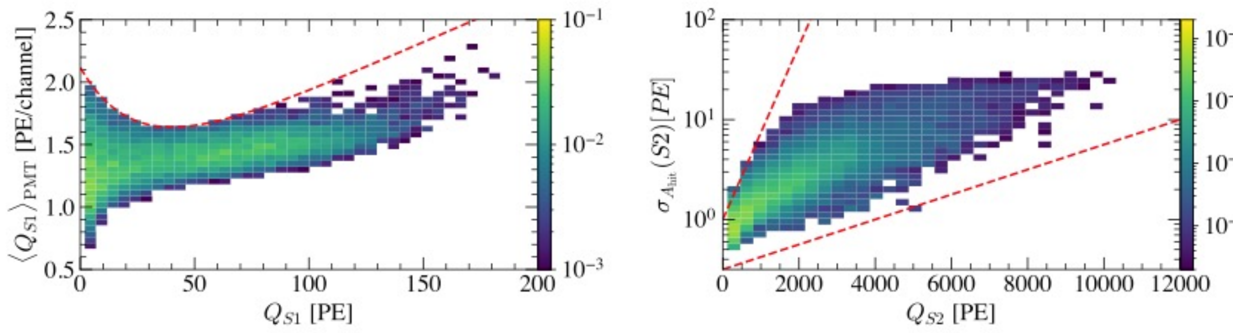



Entry

- TPC: 1.2 m (H) x 1.2 m (D)
- 3” PMTs: 169 top / 199 bottom

# Data Selection



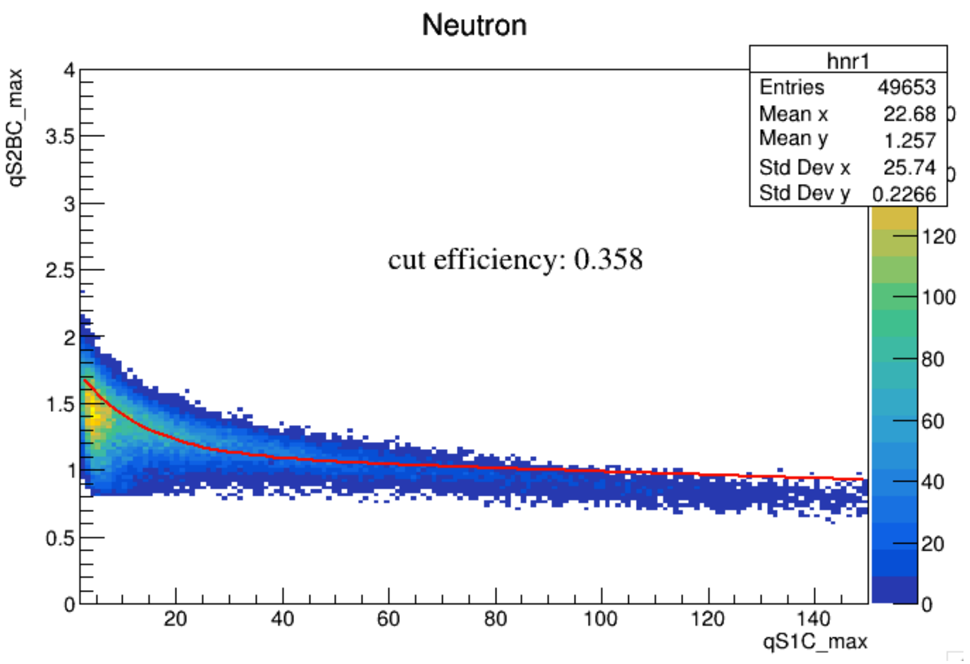



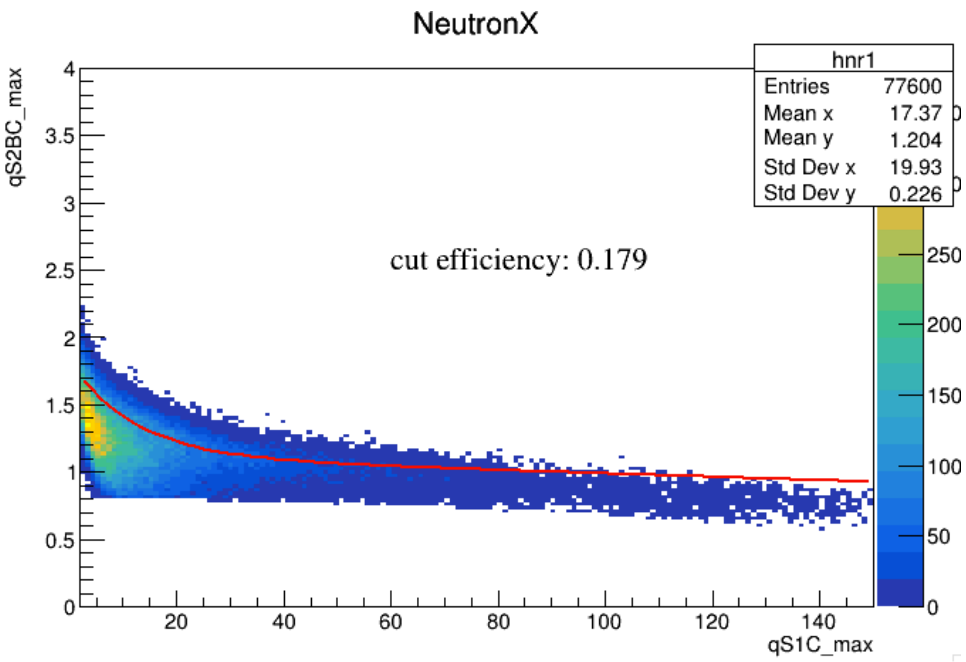

Three Categories of selcection rules:

1. Data quality: remove high noise data, e.g. delayed S2 signals;
2. Quality selection: Individual signal quality & S1-S2 correlation;
3. Others: single scatter & ROI

arxiv: 2403.04239

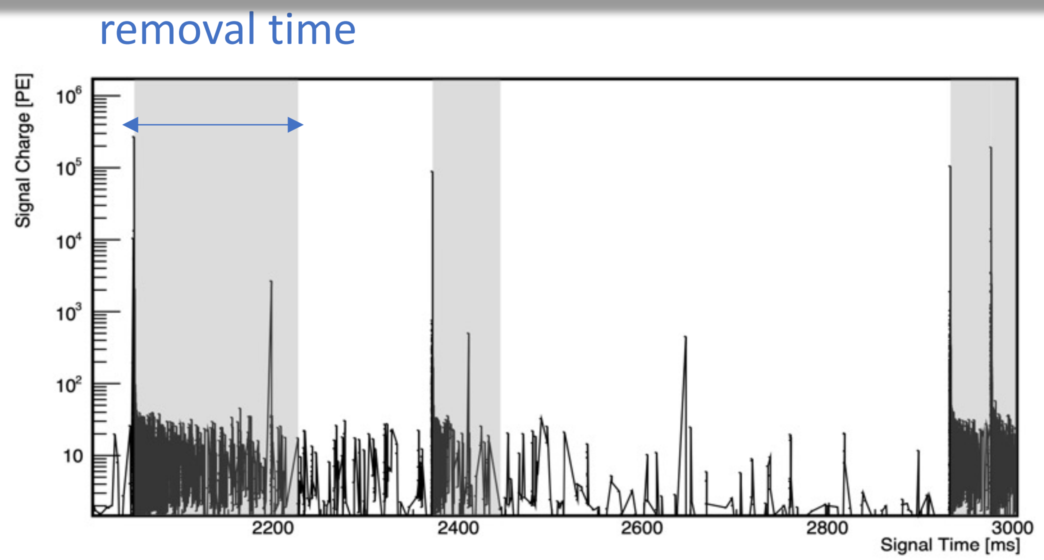
# Data Selection

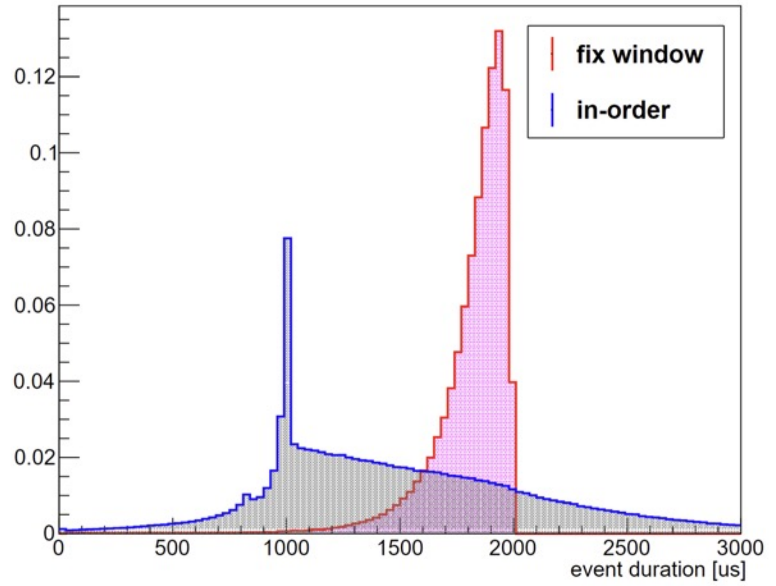


# Combined Analysis of Run0 + Run1

- **New active time determination**
  - window-size of removal time depending on the charge of large signal in front
- **New event window based on S2**
  - fix window: 1ms before and after
- **New event builder**
  - S1-S2 pairing requires quality of S1 in prior
- **New selection criteria**
  - charge-dependent cut threshold



# Normalised Form Factor of SC model

$$F_{SC}(q; r_0) = \frac{Z[1 + (1 - \mathcal{N})q^2 r_0^2]}{1 + q^2 r_0^2} \tag{19}$$

$\mathcal{N}$ and $r_0$ are fitted to be: $\mathcal{N} = 0.54$, $r_0 = 3.13$ Å$^{-1}$ (This notation is from paper, but it actually means $3.13^{-1}$Å. The result is also plotted on Figure 3). This form factor is found to be in good agreement with RHF for $|\boldsymbol{q}| \lesssim 5$ Å$^{-1}$ ($E_a \lesssim 8$ keV).

# After Run 0

- **Tritium removal**
  - xenon distillation, gas flushing, etc
- **2021/11 – 2022/05: physics run (Run1)**
  - 164 days: ~ 1 tonne-year
- **2022/09 - 2023/10: hall construction**
  - xenon recuperation
  - detector upgraded
- **Started at the end of 2023**

| 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 | |