Search for WIMP Dark Matter in PandaX-4T Experiment

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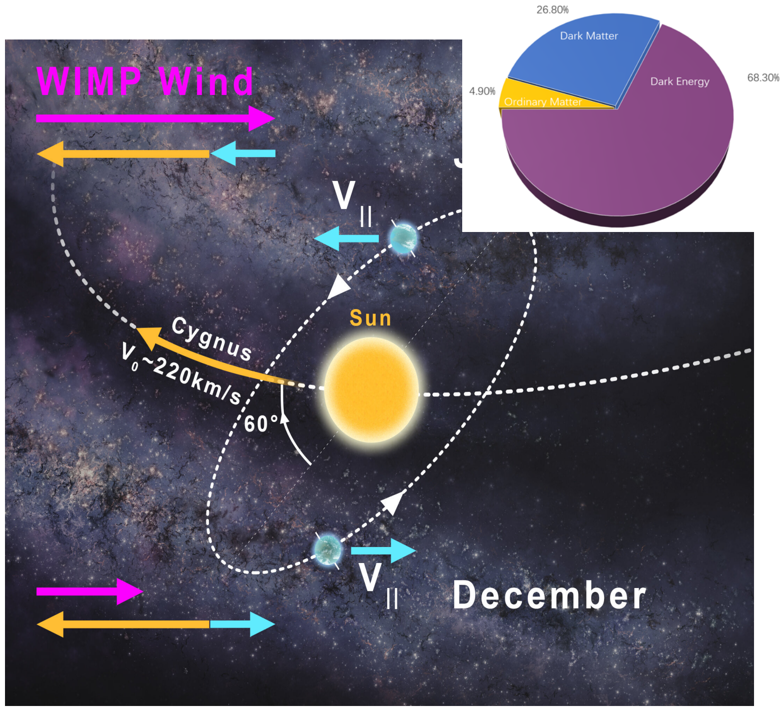
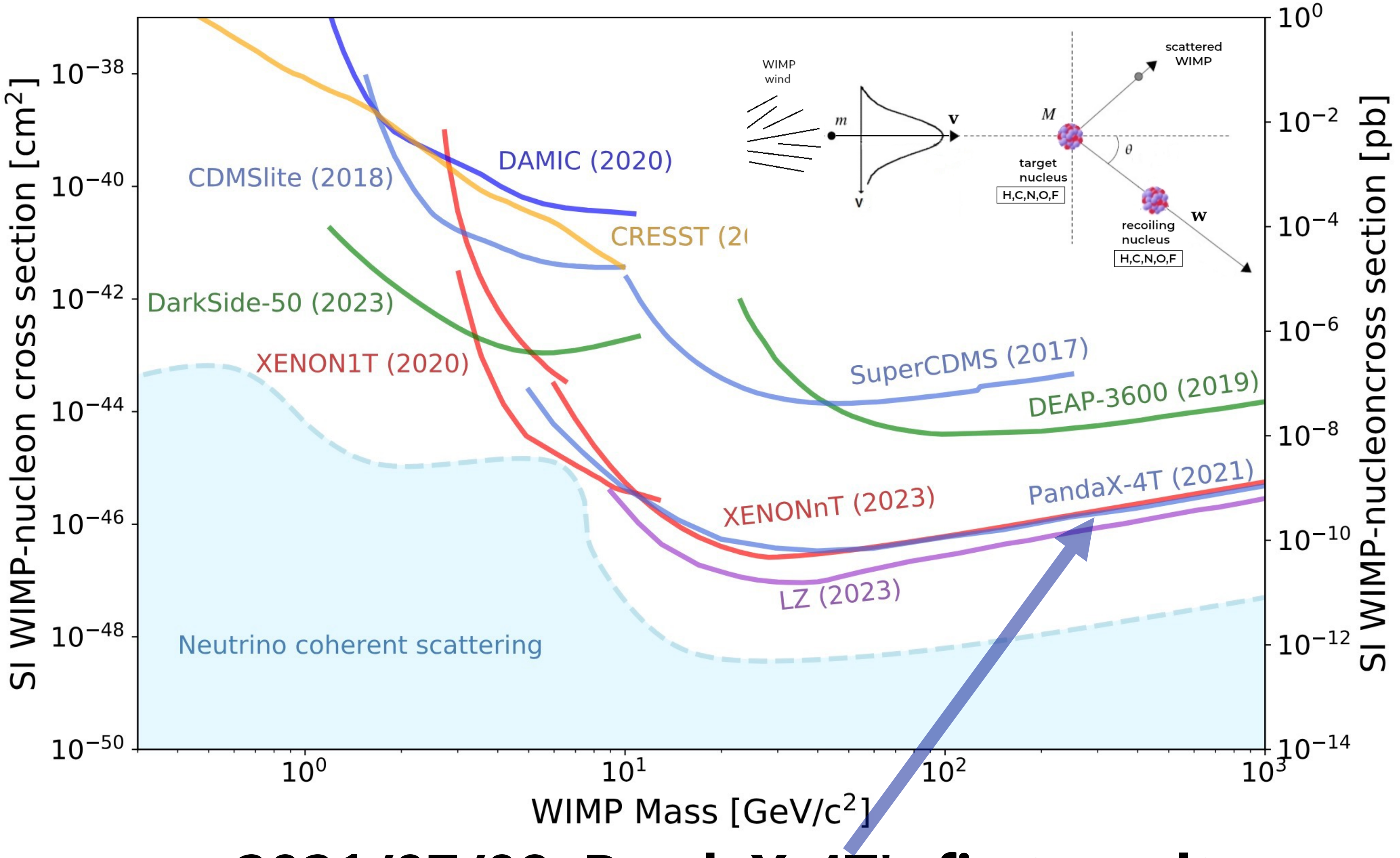
Progress of DM Direct Detection



Credit: James Josephides

- Incoming dark matter from the Universe
- Scattering with target atom



2021/07/08: PandaX-4T's first result

PRL 127, 261802 (2021), Editors' Suggestion

PandaX Collaboration

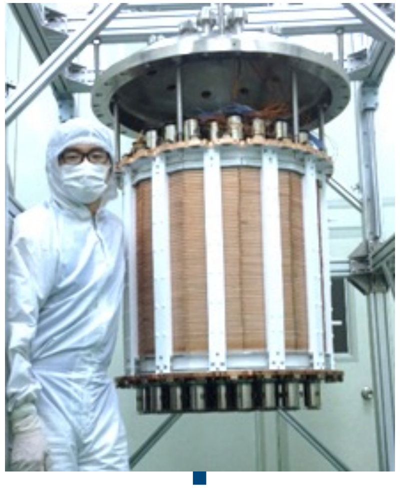
PandaX Detectors

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

PandaX start

PandaX-I
120kg

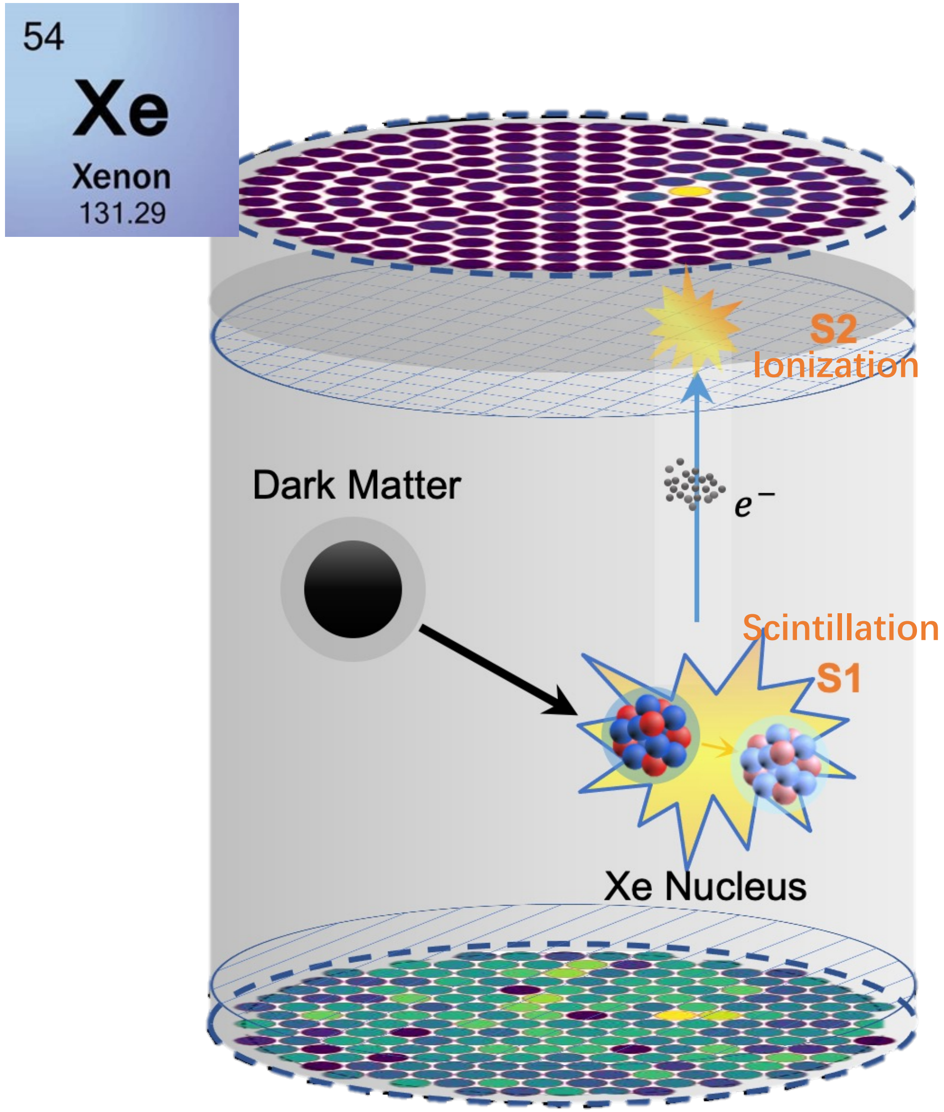
PandaX-II
580kg



PandaX-4T
(3.7 tonne)

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

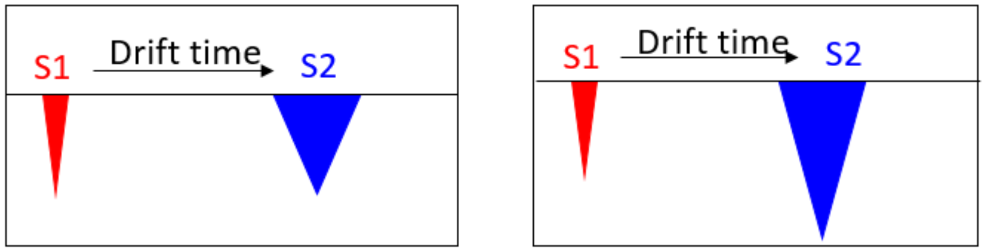
PandaX: A Dual-phase Xenon TPC

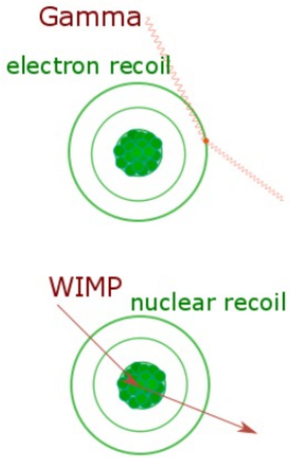


- **PandaX**: **P**article **and A**strophysical **X**enon Observatory
- Pure xenon target, enhanced DM signals, achievable liquefication temperature, high light & charge yield
- Good ER/NR discrimination by S2/S1 ratio

Dark matter: nuclear recoil (NR)

γ background: electron recoil (ER)





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

- 3D reconstruction rejects external background

Outline

- Run1 data taking and running conditions/challenges
- Low-energy calibration, reconstruction, selection & efficiency
- Signal response model
- Background evaluation
- Statistical inference results for WIMP search
- Summary and outlook

After Commissioning

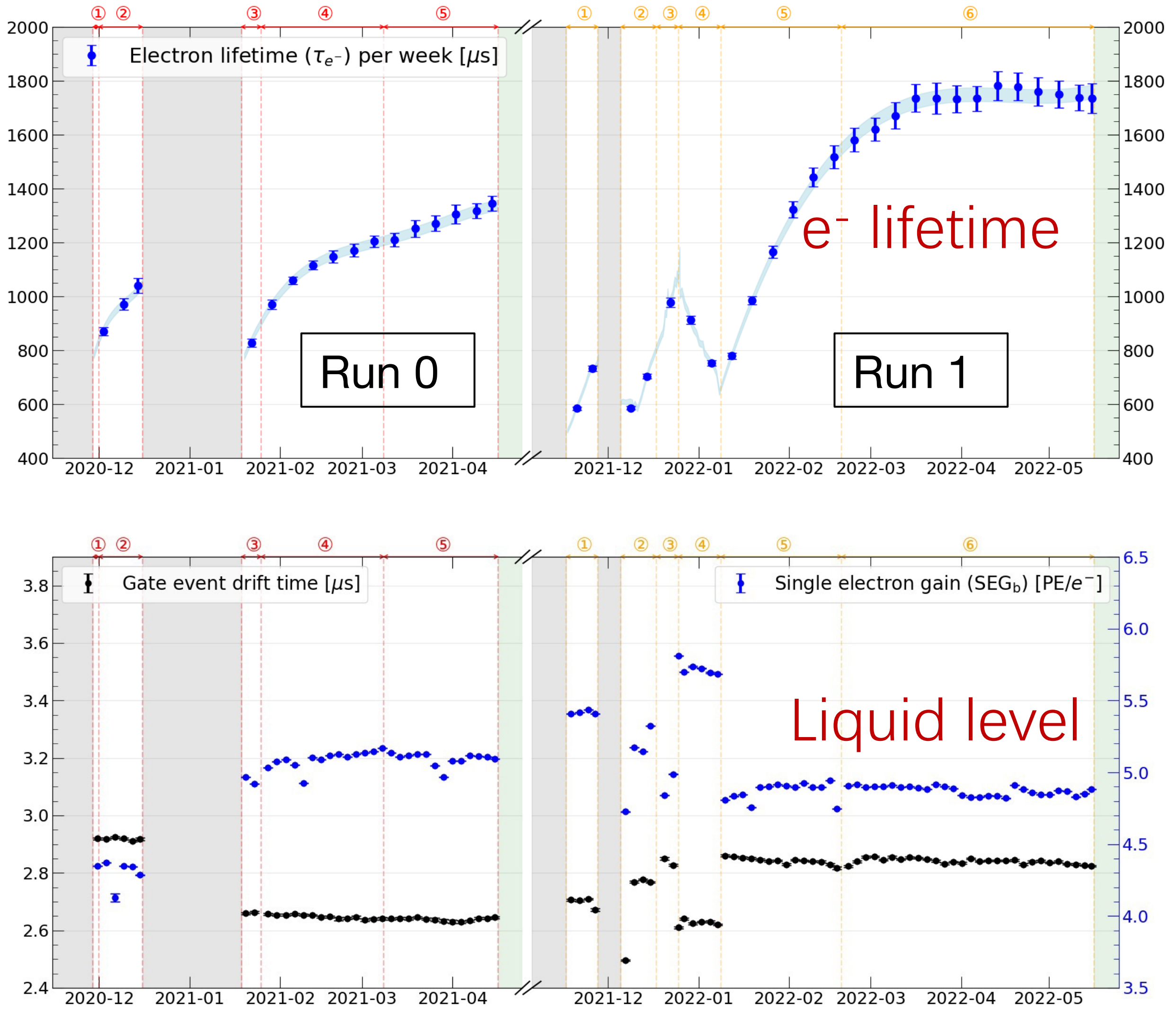
2020/11 – 2021/04	**Commissioning (Run 0)** 95 days
2021/07 – 2021/10	**Tritium removal** xenon distillation, gas flushing, etc
2021/11 – 2022/05	**Physics run (Run 1)** 164 days
2022/09 – 2023/12	**CJPL B2 hall construction** xenon recuperation, detector upgrade
Current Status	**Resuming physics data-taking**

re-blind

- WIMP search: Combined blind analysis of Run0 and Run1.
- Total exposure: 1.54 tonne·year

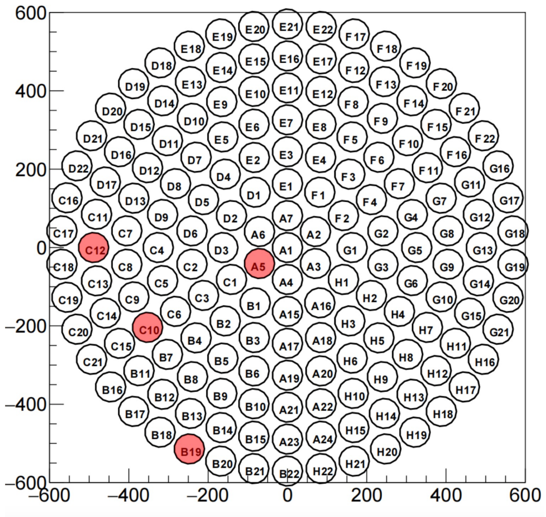
Run1 Data Taking & Challenges

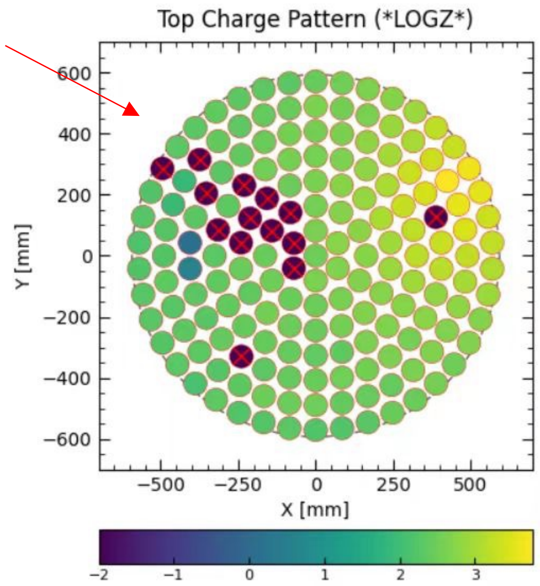
- **Gate -6kV, Cathode -16kV (Gate trip once)**
- **e⁻-lifetime monitoring through α events**
  - maximum reaches 1800 us
  - sensitive to operation condition
- **Failure of liquid level controlling**
  - liquid level sensitive to the circulation flow rate
  - monitoring through the drift time of gate events and single electron gain (SEG)
  - **dividing into 6 subsets accordingly**
- **Additional malfunctioned PMTs** (see next)
- **Improvements and updates**
  - Charge correction
  - Position correction



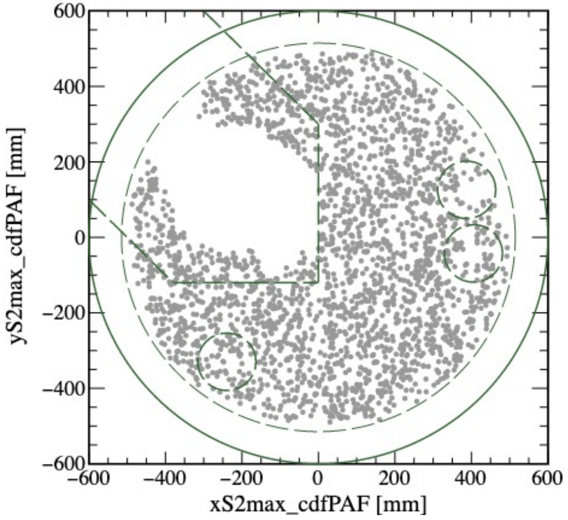
Additional “Off-PMT” Problem

- **Additional non-functioning PMT channels at top,** with 8 channels sharing the same negative HV due to the short of the photocathode.
- Concentrated in the same top area, **affecting event reconstruction and selection** (TBA, position reconstruction, etc.).
- **Solution in Run2:** During the detector upgrade, repair the non-functioning PMTs and **distribute them** as **evenly as possible to reduce the coupling of adjacent channels.**

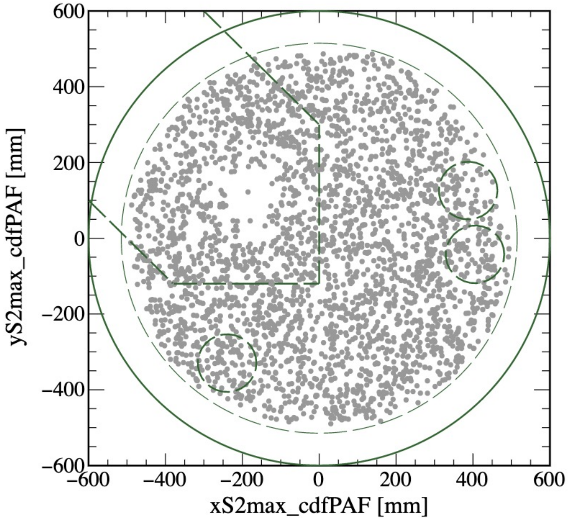




Impact（eg. ER calibration）

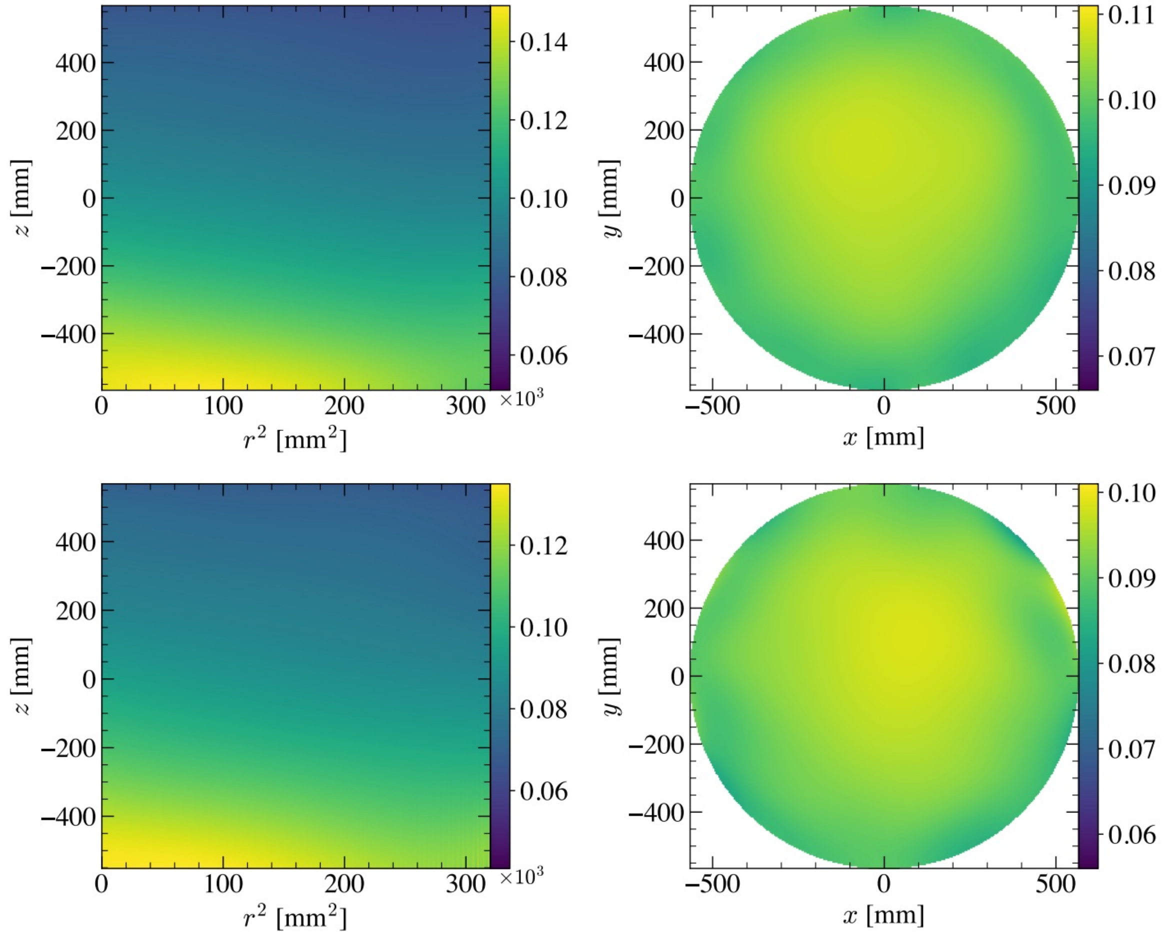


Update selection



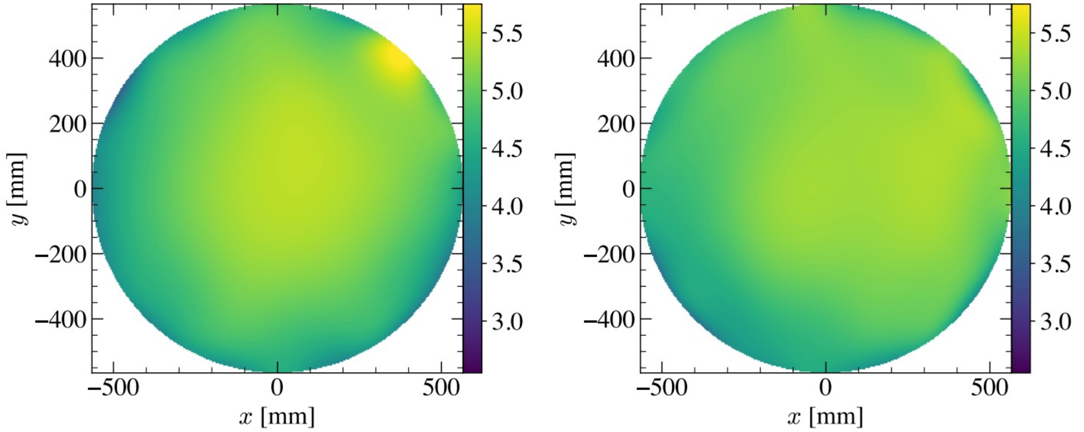
Charge Spatial Uniformity Correction

S1 gain maps



- ^{83m}Kr (41.5 keV): internal conversion e$^-$
- Binned map → Unbinned map
  - Perform a 9th-degree polynomial function fit
    $\sum_{ijk} c_{ijk} x^i y^j z^k$ where $i, j, k = 0, \ldots 9$

S2 gain maps

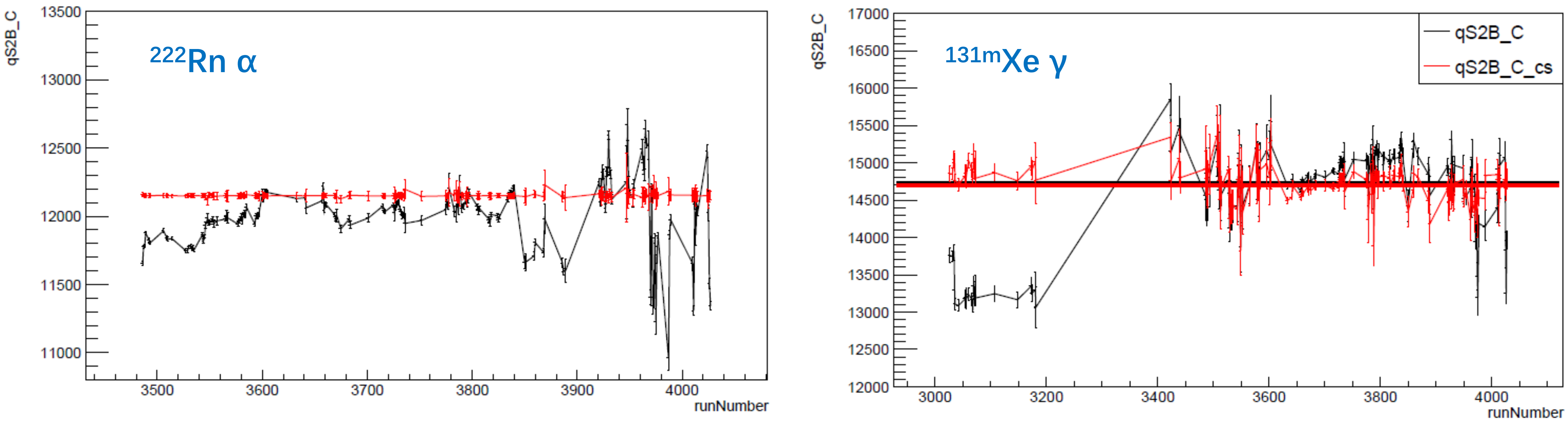


- S2 also adopts z-dependent charge correction according to its e$^-$ lifetime

Charge Temporal Variation Correction

- Due to the change in liquid level over time, both the light signals and ionization signals fluctuate over time.
- Method：Run-by-run correction utilizing ^{222}Rn 5.6MeV α event (mono-energy, existing over time)

Ionization charge before/after correction

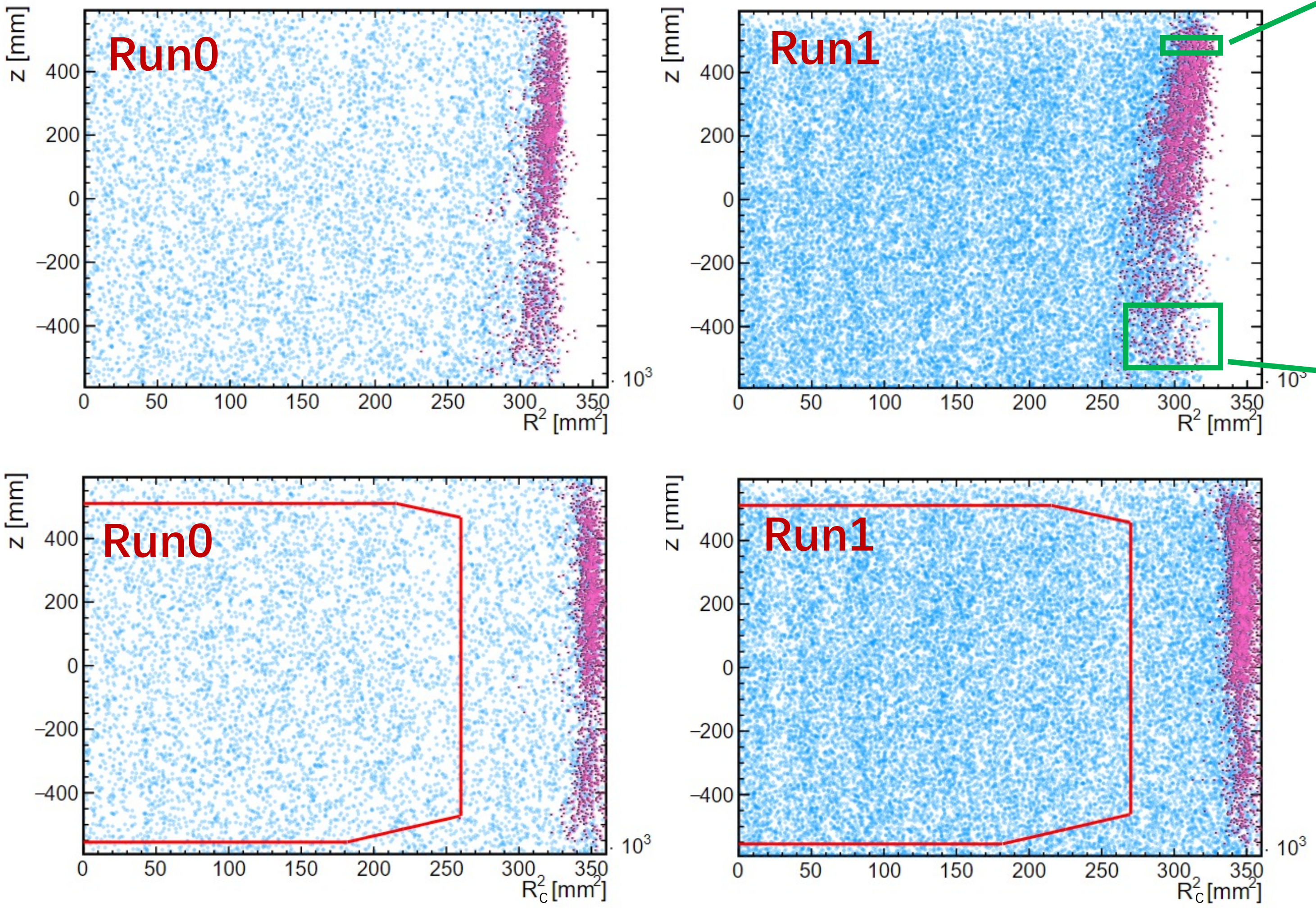


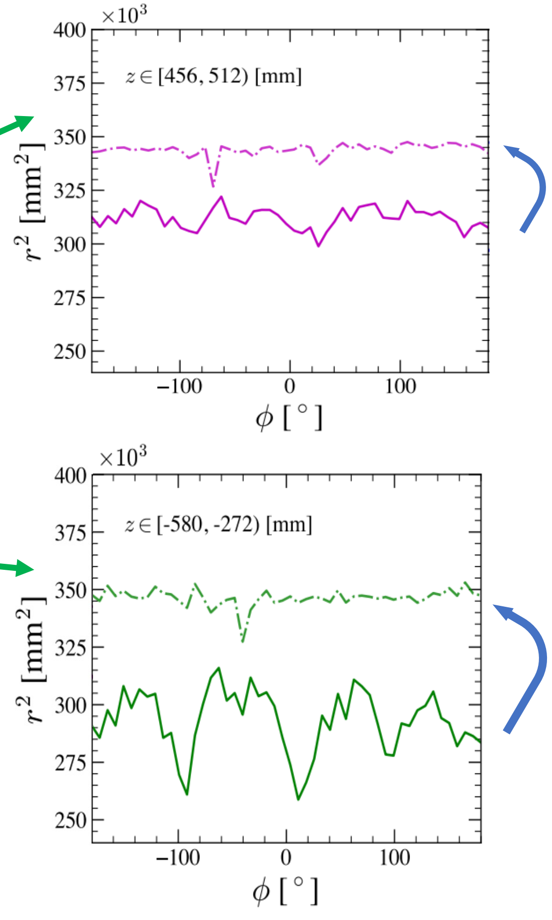
Position Correction

- An azimuth-angle-dependent & z-dependent horizontal radial position affine scaling, based on ^{83m}Kr → Direct comparison with MC simulation

Before radial scaling

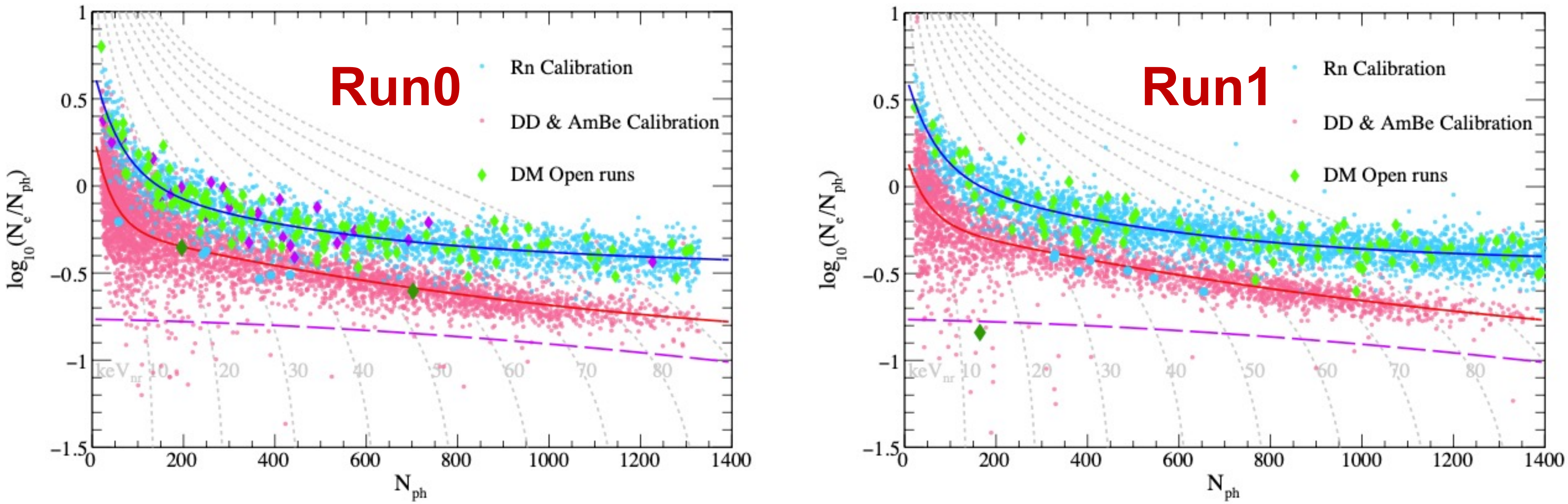
After radial scaling





● ^{83m}Kr
● ^{210}Po
— FV boundary

Low-energy ER/NR Calibration



- End-of-run low-E ER/NR calibration (ER: $^{220/222}$Rn, NR: DD + ^{241}AmBe)
- Determine all selection criteria, efficiencies and charge biases (together with waveform simulation)
- 0.3% ER leak ratio in Rn calibration → good ER/NR separation

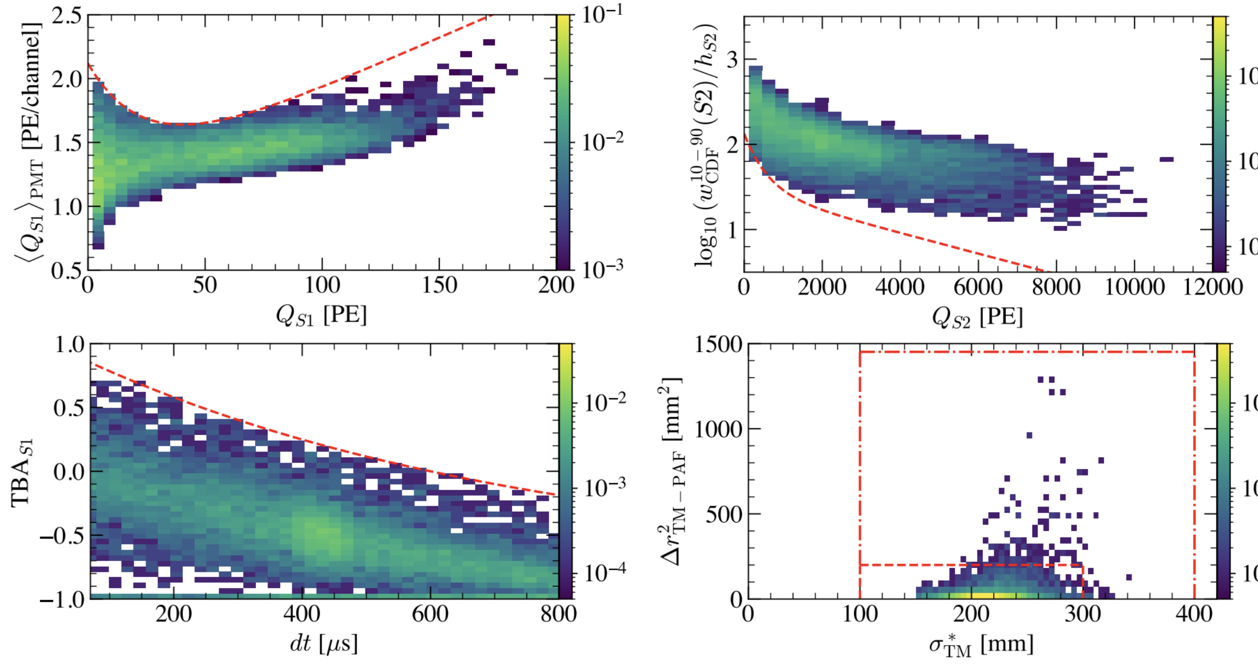
Quality Cuts & Efficiencies

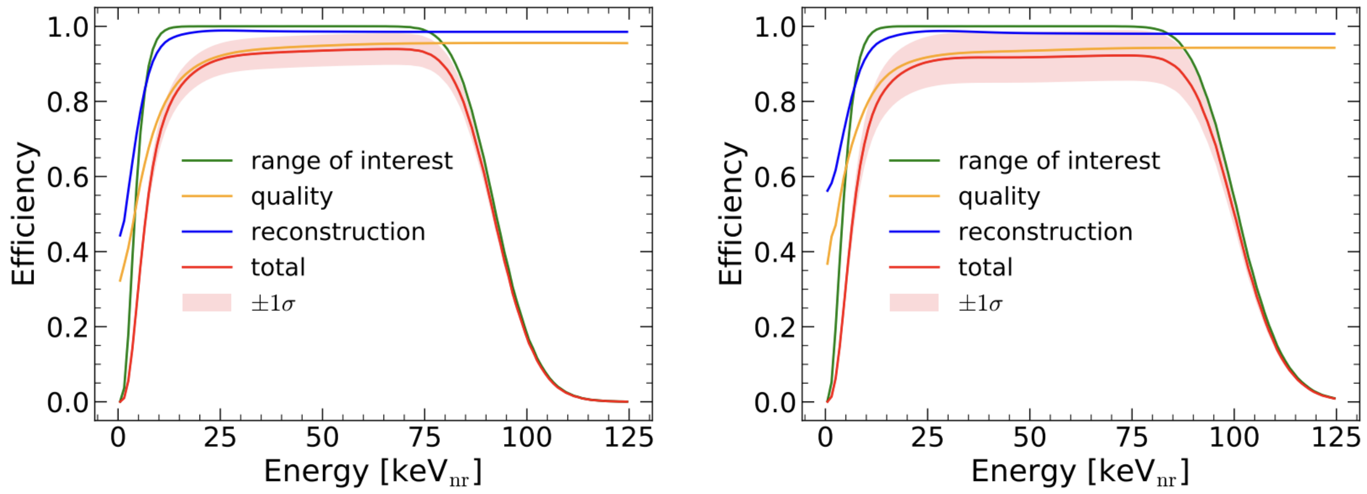
Quality selection cuts:

- S1- and S2-related, waveform cleanness
- Relaxed version for "off-PMT" region

Total efficiencies as a function of energy: plateau ~90%

- **Quality**
- **ROI**
  - $S1^c$: 2-135 PE, ≥2-hit coincidence
  - $S2^{raw}$: 120-20,000 PE
- **Reconstruction**
  - Signal classification (tagging)
  - S1-S2 pairing



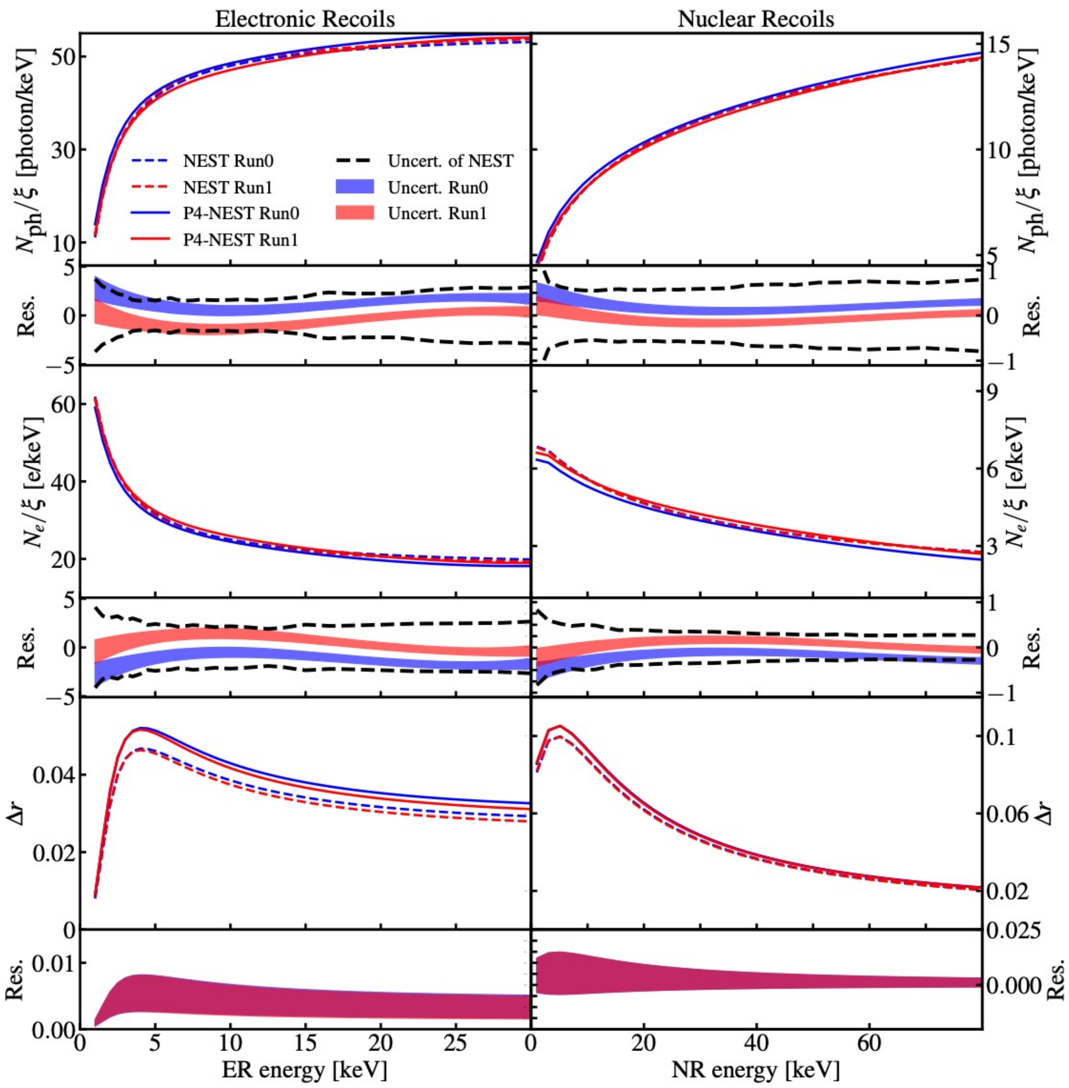


PandaX-4T Signal Response Model

- **Signal Response of the PandaX-4T detector (Run0 & Run1)：How deposited energy converts to detectable signals**
  - Light yield & Charge yield
  - Recombination fluctuation
- **Compare w/ nominal NEST**
  - the mean recombination fraction ⟨r⟩ is adjusted by adding a 3rd-order Legendre polynomial multiplied by an exponential function P
  - the recombination fluctuation Δr is scaled by a factor λ

$$\langle r\rangle(\xi) = \langle r\rangle_0(\xi) + P_3(\xi/\xi_{\text{norm}}; p_0, p_1, p_2, p_3) \cdot e^{-\xi/\xi_{\text{norm}}}$$
$$\Delta r(\xi) = \Delta r_0(\xi) \cdot \lambda,$$

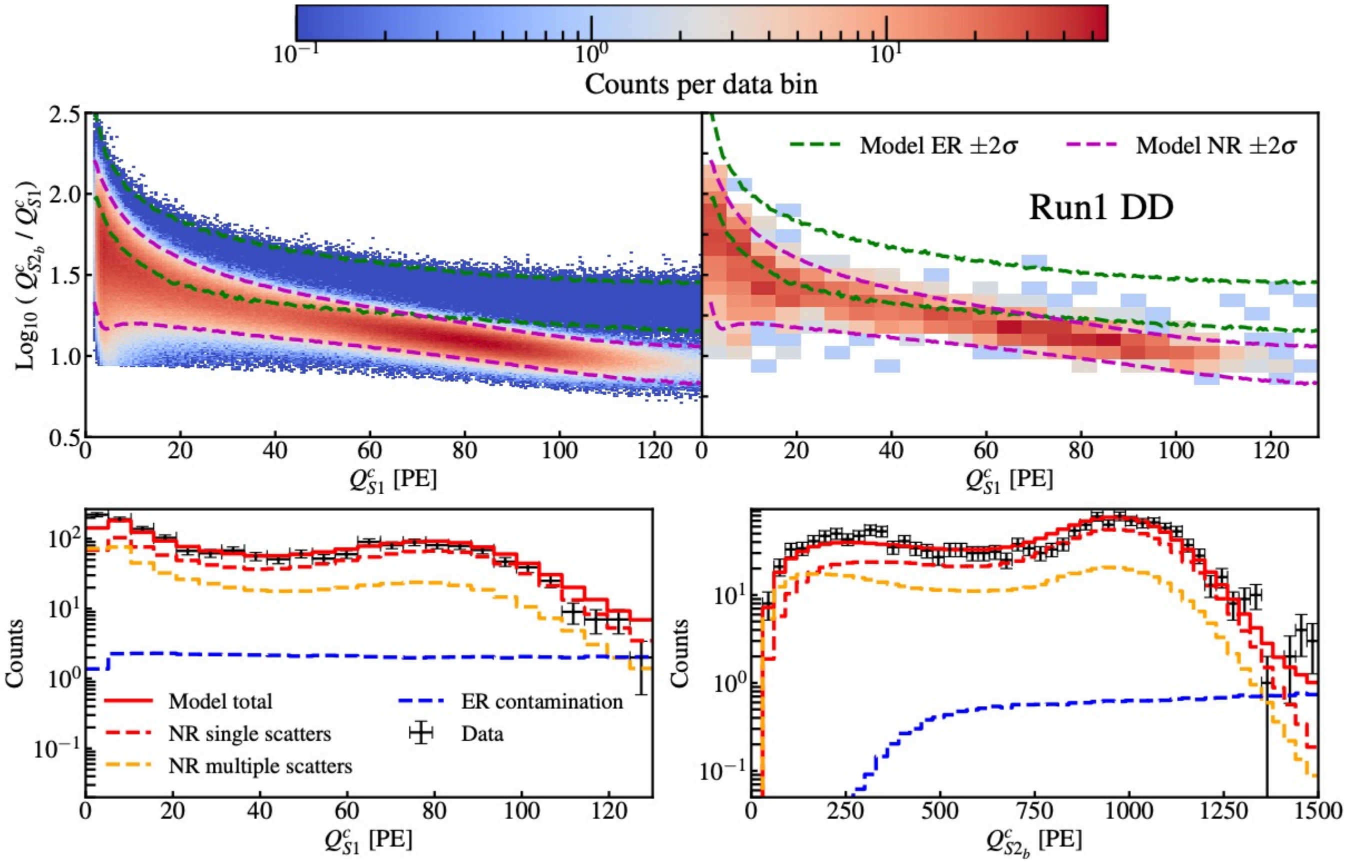
- **Run0+Run1 simultaneous fit to all ER/NR calibration data (DD + AmBe + Rn)**
- **Data-driven determined detector effects, corrections, etc.**



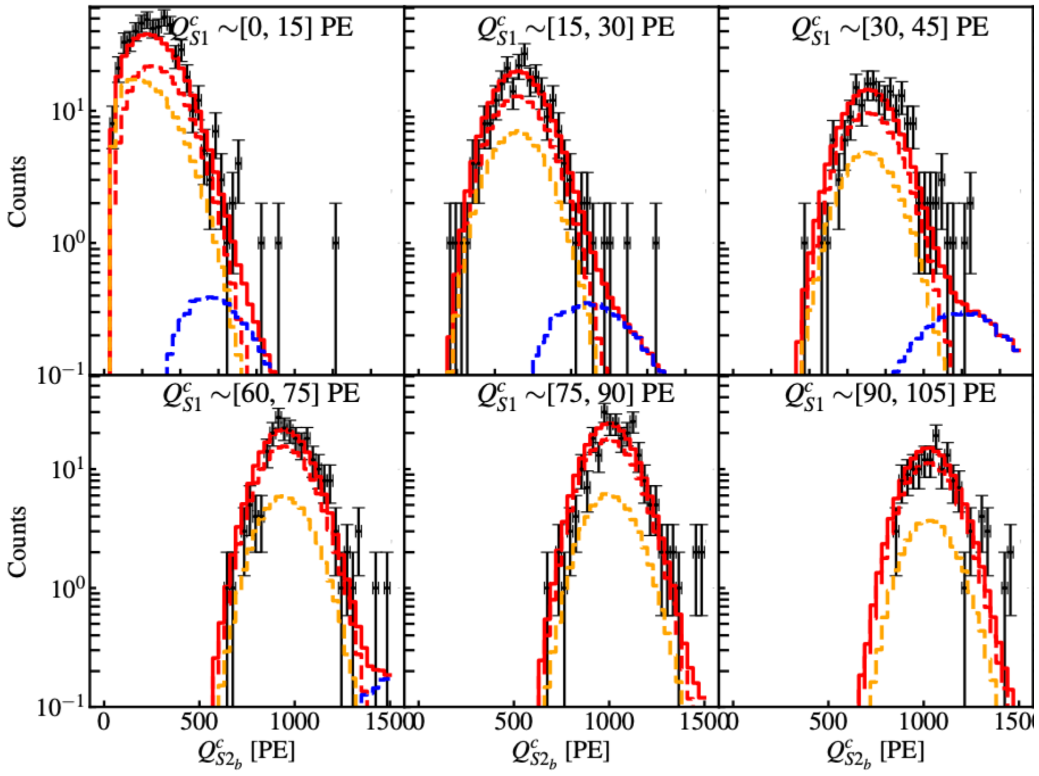
PRD 110, 023029 (2024)

P4-NEST vs. Data: Run1 DD

- Comparing the observed calibration data with the signal response model, a good agreement has been achieved.

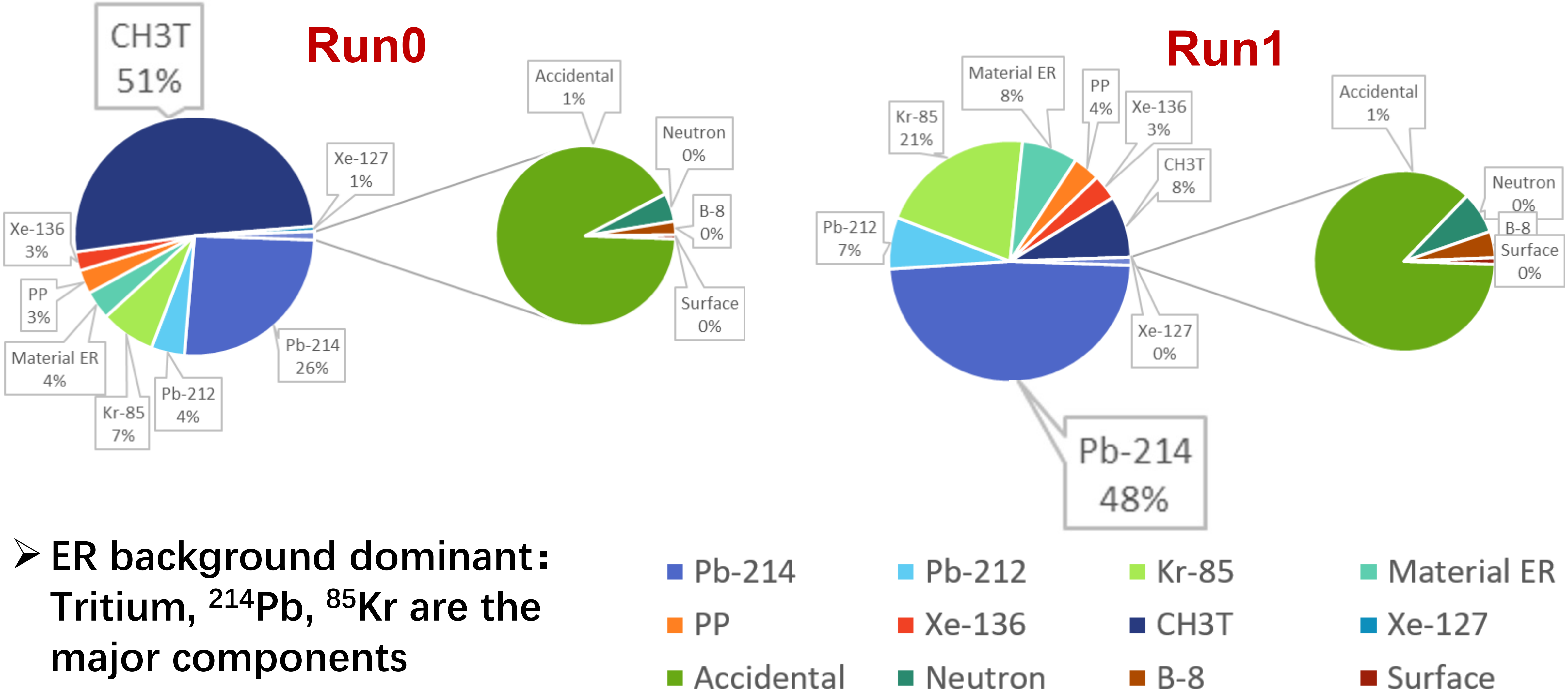


- S2 spectra in different S1 ranges



More details also see Yunyang's poster

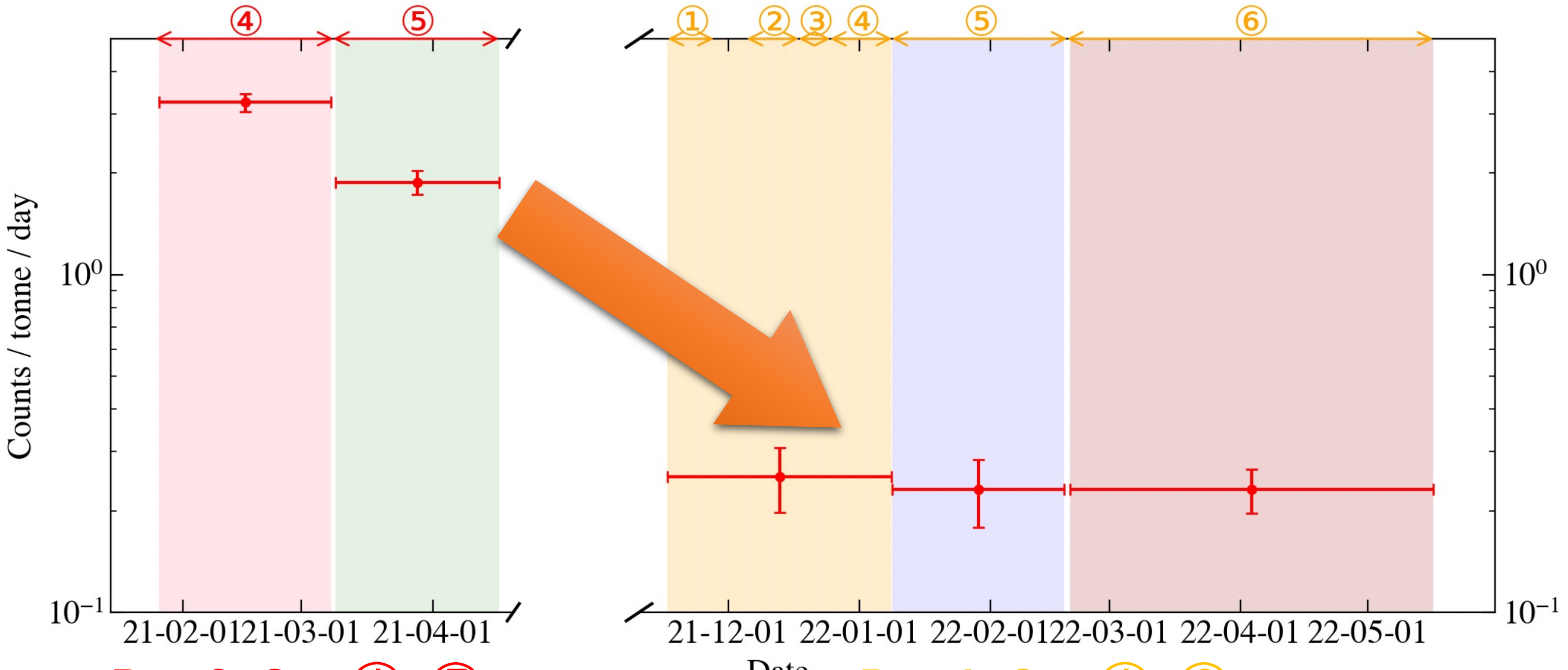
Background Budget



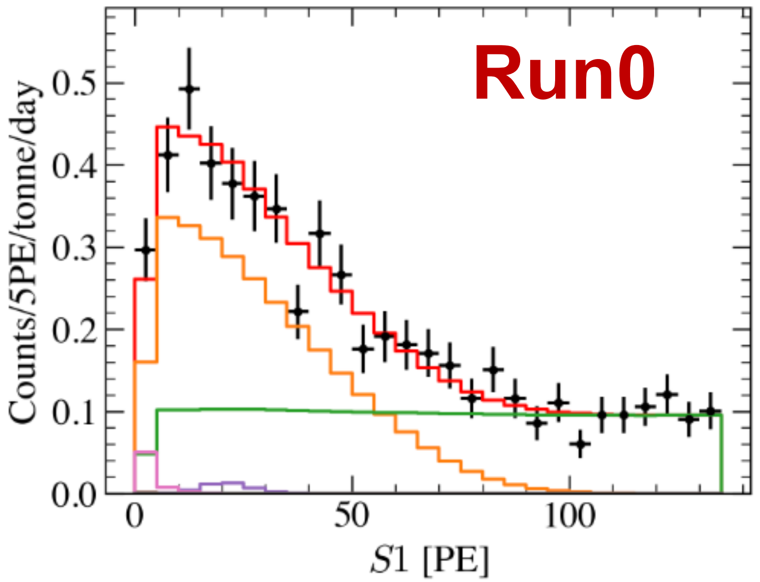
- ER background dominant: Tritium, ^{214}Pb, ^{85}Kr are the major components

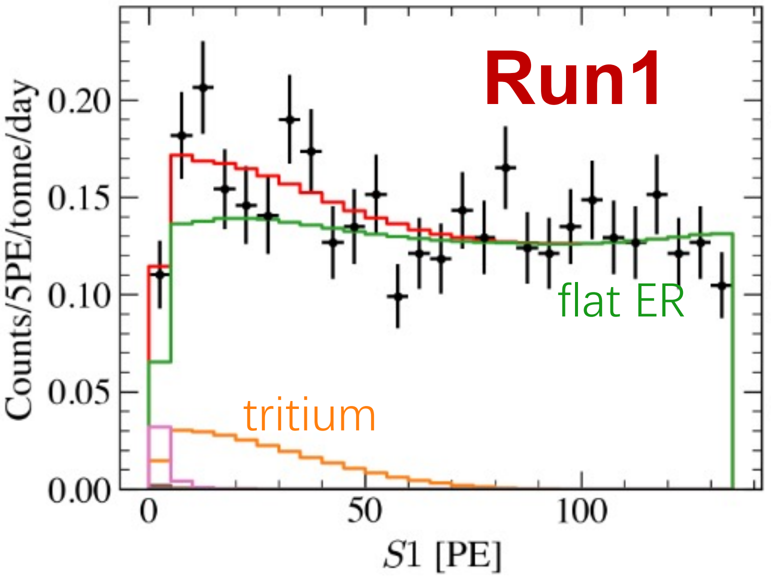
Tritium Level (after unblinding)

- Significant reduction from Run0 to Run1 (~8 times)
- Consistent with S1-only estimation used before unblinding
- Floating in the final PLR fit



Run0: Set ①-⑤ Run1: Set ①-⑥

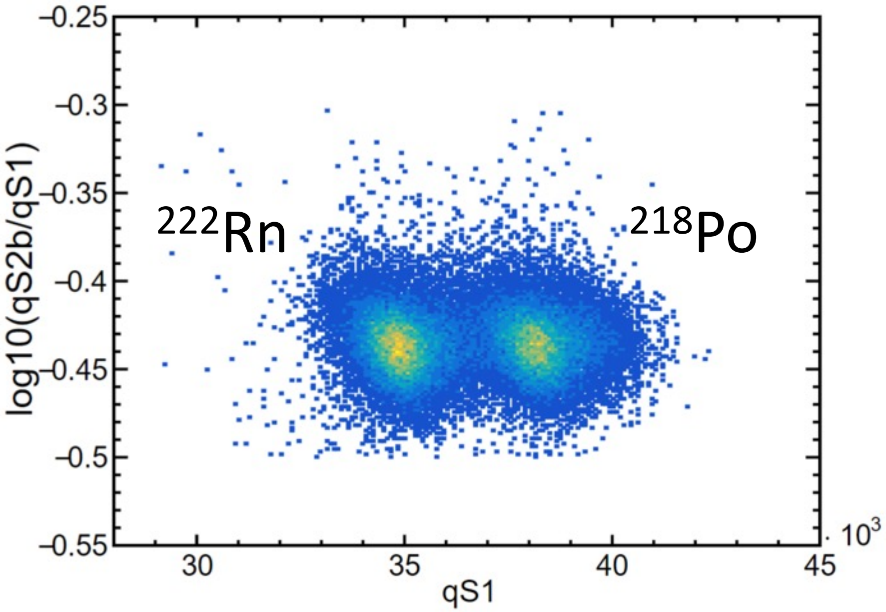




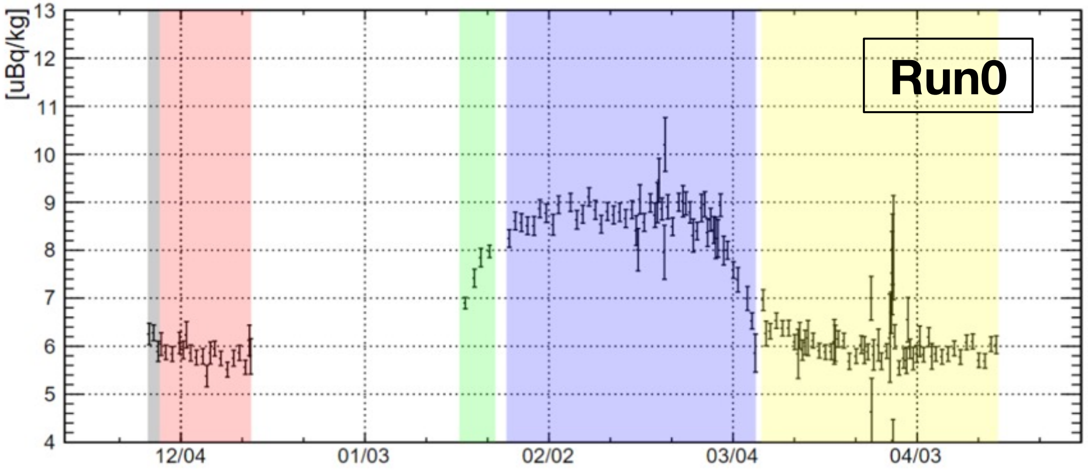
^{214}Pb Background

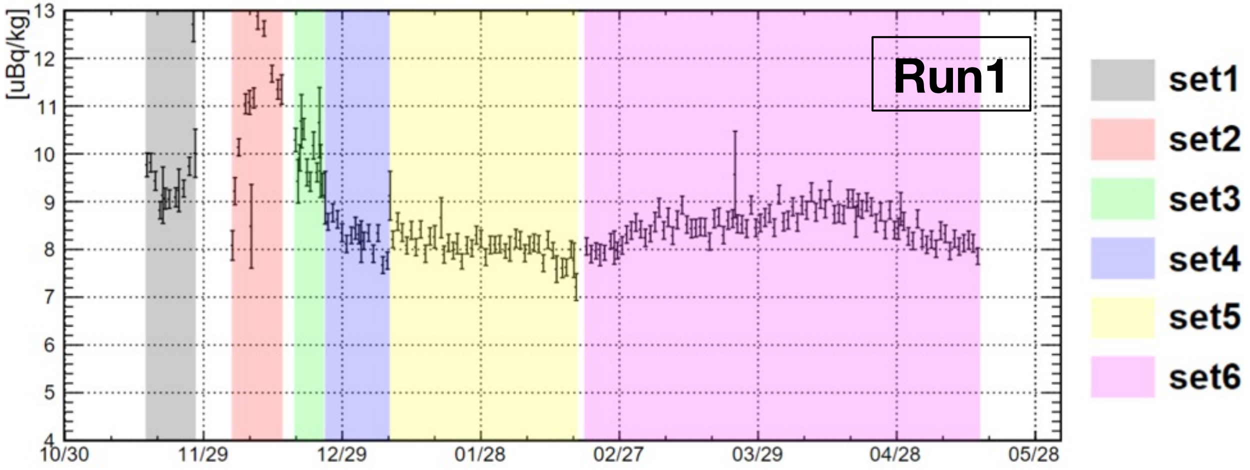
- ^{214}Pb: daughter nuclei of ^{222}Rn
- Select ^{222}Rn alpha events as a monitor
- ^{222}Rn level varies with running condition

Rn-222 level	[μBq/kg]
Run 0	7.07 ± 0.02(stat.) ± 0.23(sys.)
Run 1	8.67 ± 0.01(stat.) ± 0.27(sys.)



- ^{214}Pb is derived from spectrum fitting (0.2-1MeV)

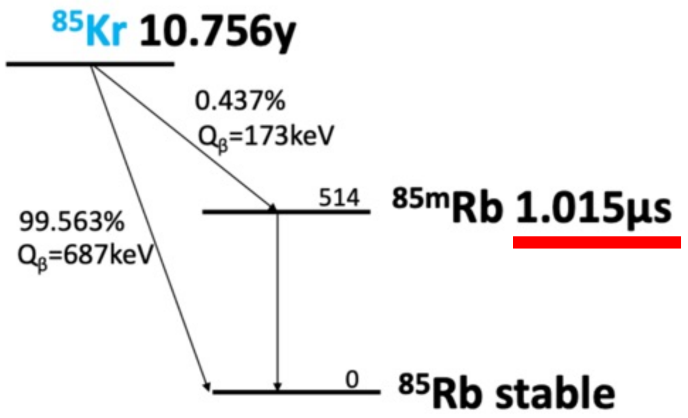


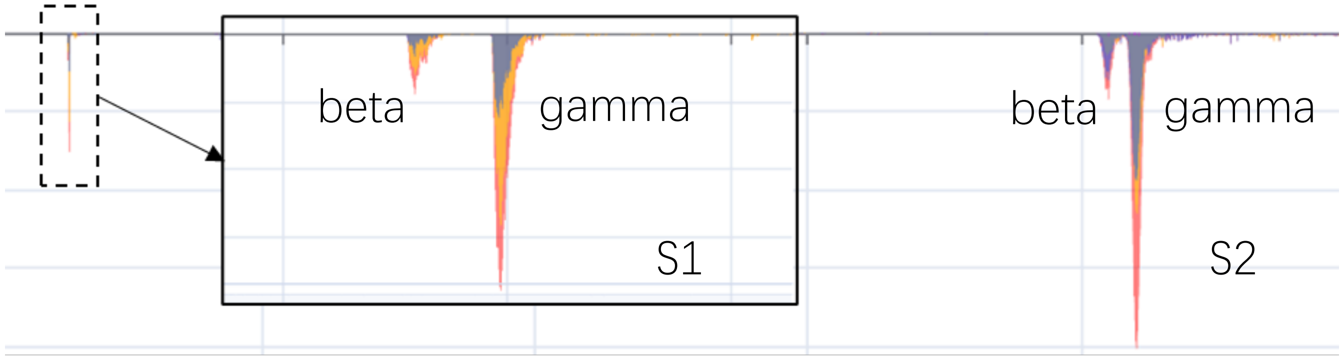


^{85}Kr Background

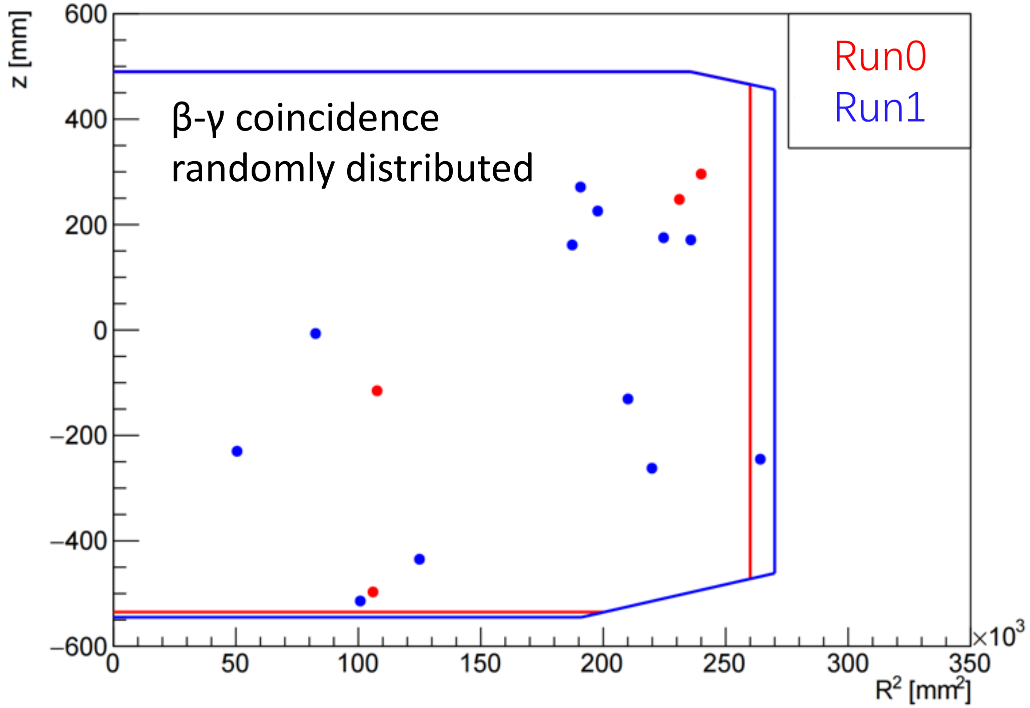
- Residual impurity in product xenon
- Identified through β-γ coincidence selection

Kr/Xe	[ppt]
Run 0	**0.5 ± 0.3**
Run 1	**0.9 ± 0.3**





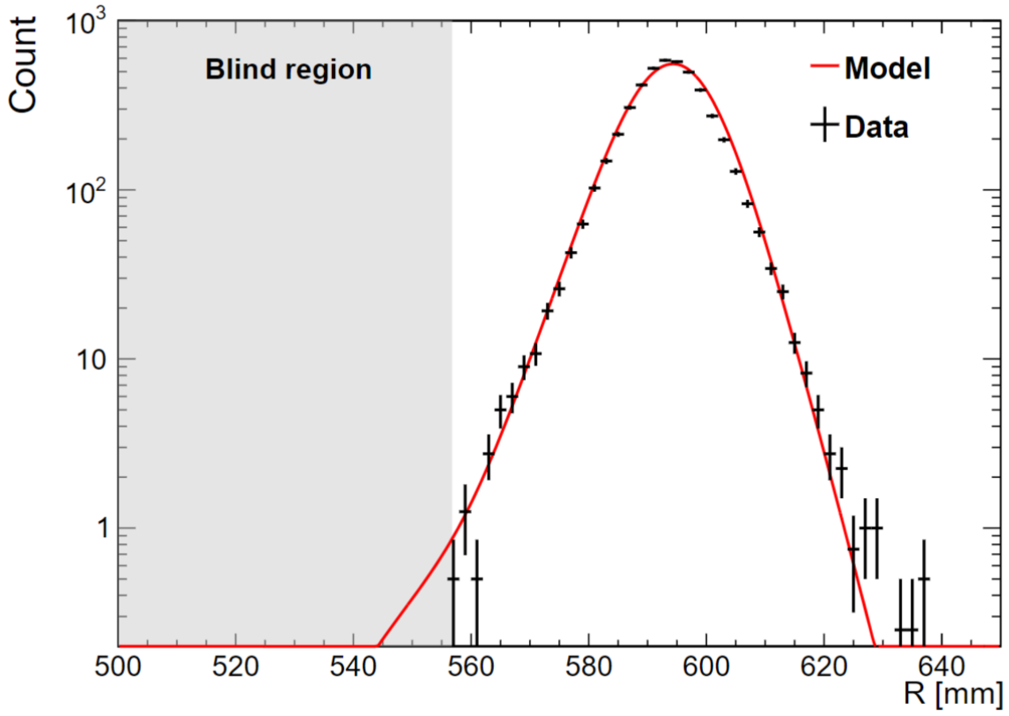
Waveform of ^{85}Kr's β-γ coincidence

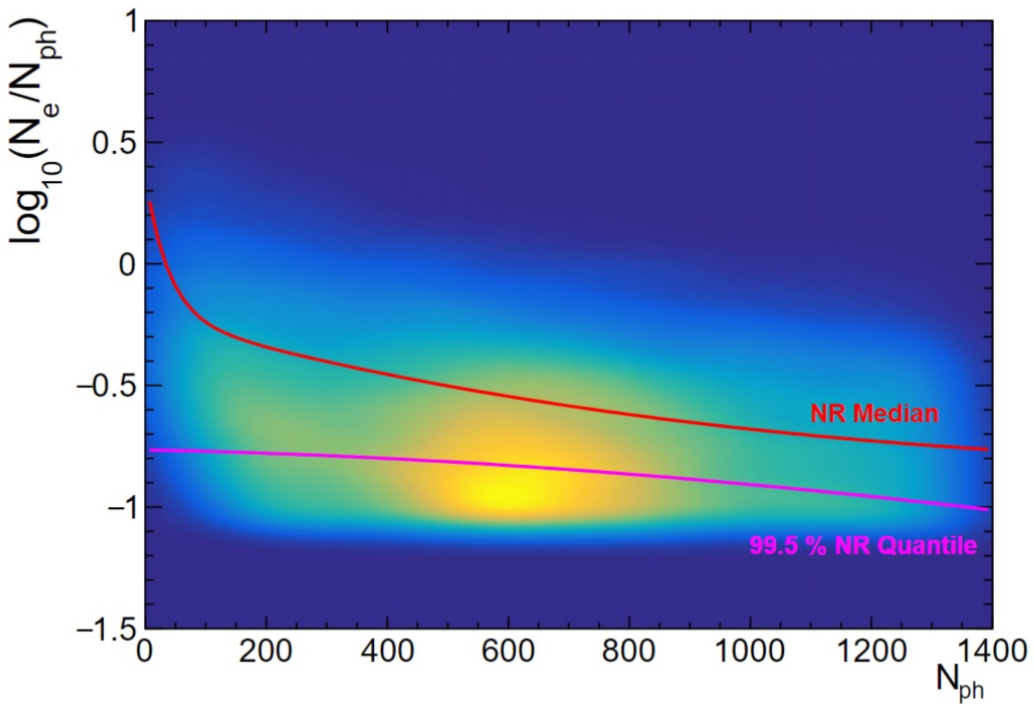


Surface Background

- ER events, whose S2 suppressed by the TPC surface
- Estimate the radial distribution by ^{210}Po alpha events
- Good consistency with data outside blind region

Surface events in fiducial volume	
Run0	0.09 ± 0.06
Run1	0.17 ± 0.11

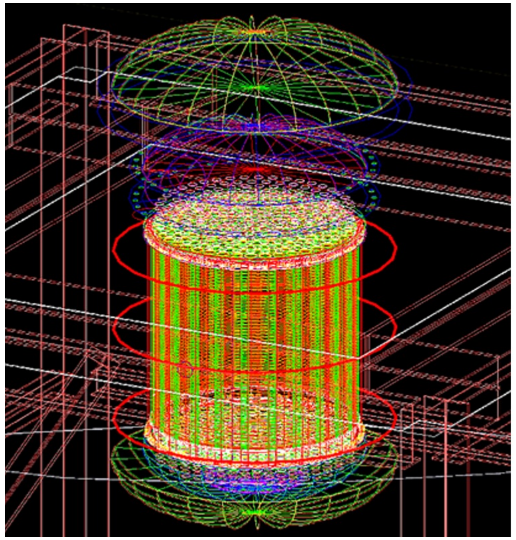




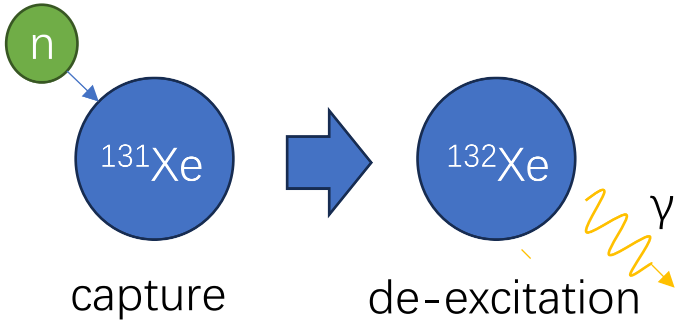
Neutron Background

➢ **Combine 3 approaches to estimate (weighted average):**

GEANT4 + signal model

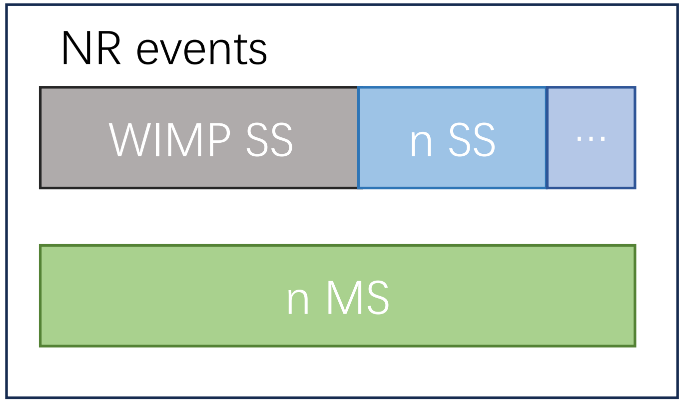


High energy γ / neutron ratio



$$N_{\text{neutron}} = N_{\gamma} * r_{\text{n}/\gamma}$$

Multi-scatter / single-scatter ratio

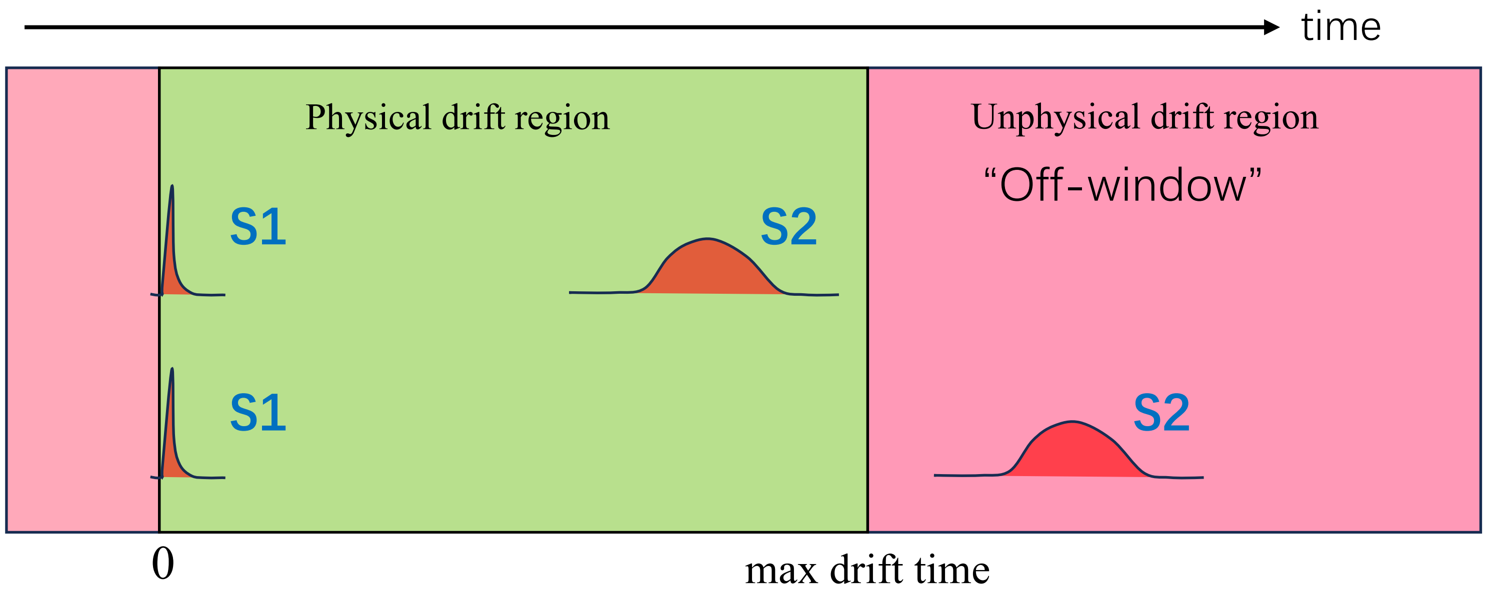


$$N_{\text{neutron}} = N_{MS} * r_{SS/MS}$$

Unit: counts	Run0	Run1
Pure Neutron	0.44 ± 0.13	0.81 ± 0.17
Neutron X	0.19 ± 0.06	0.29 ± 0.06
Total Neutron	**0.63 ± 0.18**	**1.10 ± 0.24**

Accidental Background

- **Accidental coincidence (AC):** The pairing of random isolated S1s and S2s that can mimic real physical single-scatters
- Use random pair MC and “off-window” events to determine unphysical AC background

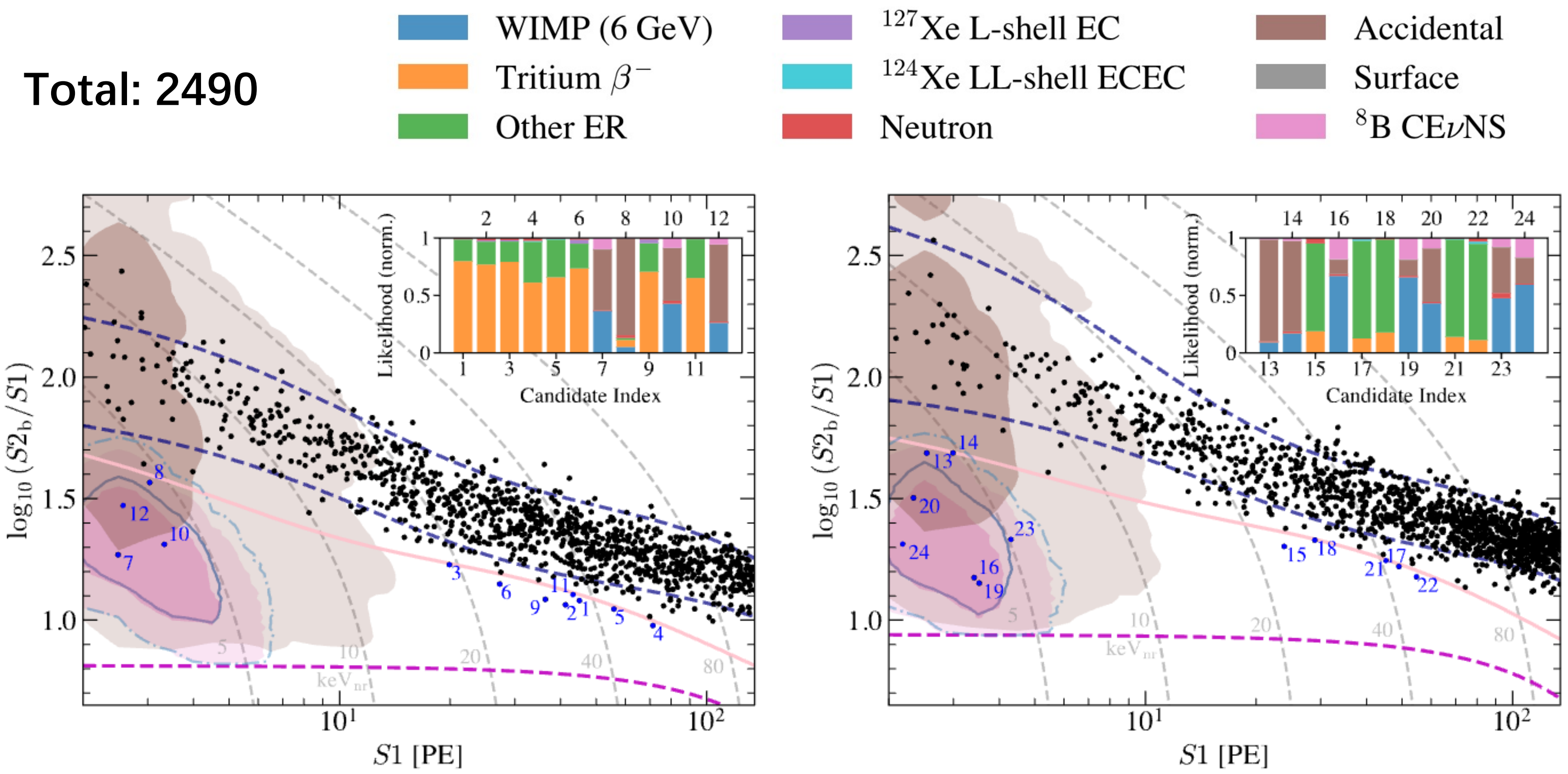


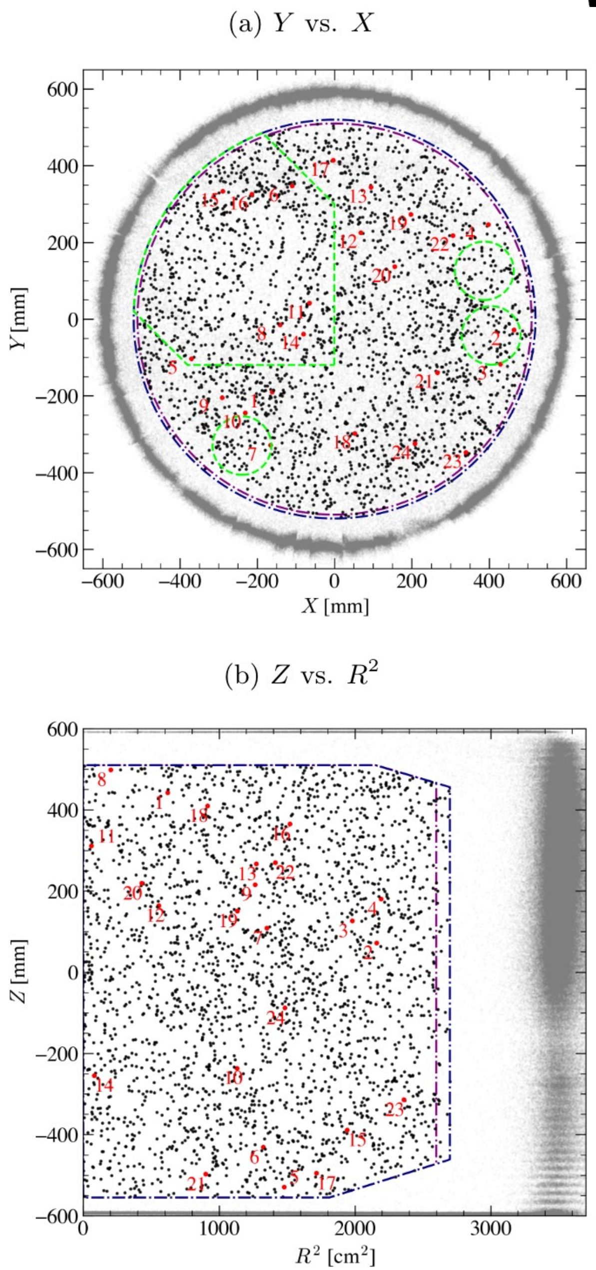
- The AC background is underestimated (~2 times) due to **an inconsistent acceptance cut** on the scrambled data (found after unblinding, yet no further selection cuts are added/tuned).

Unit: counts	Run0	Run1
Accidental (updated)	11.3 ± 3.4	12.7 ± 3.8

Distribution of DM Candidates

Total: 2490





- 24 (12+12) **below NR median events**
- Uniformly distributed in the FV.

ER 5%-95% quantiles

NR median

NR 99.5% acceptance

SI Upper Limit & Sensitivity Band

arXiv: 2408.00664

Fully blind analysis Run0+Run1:

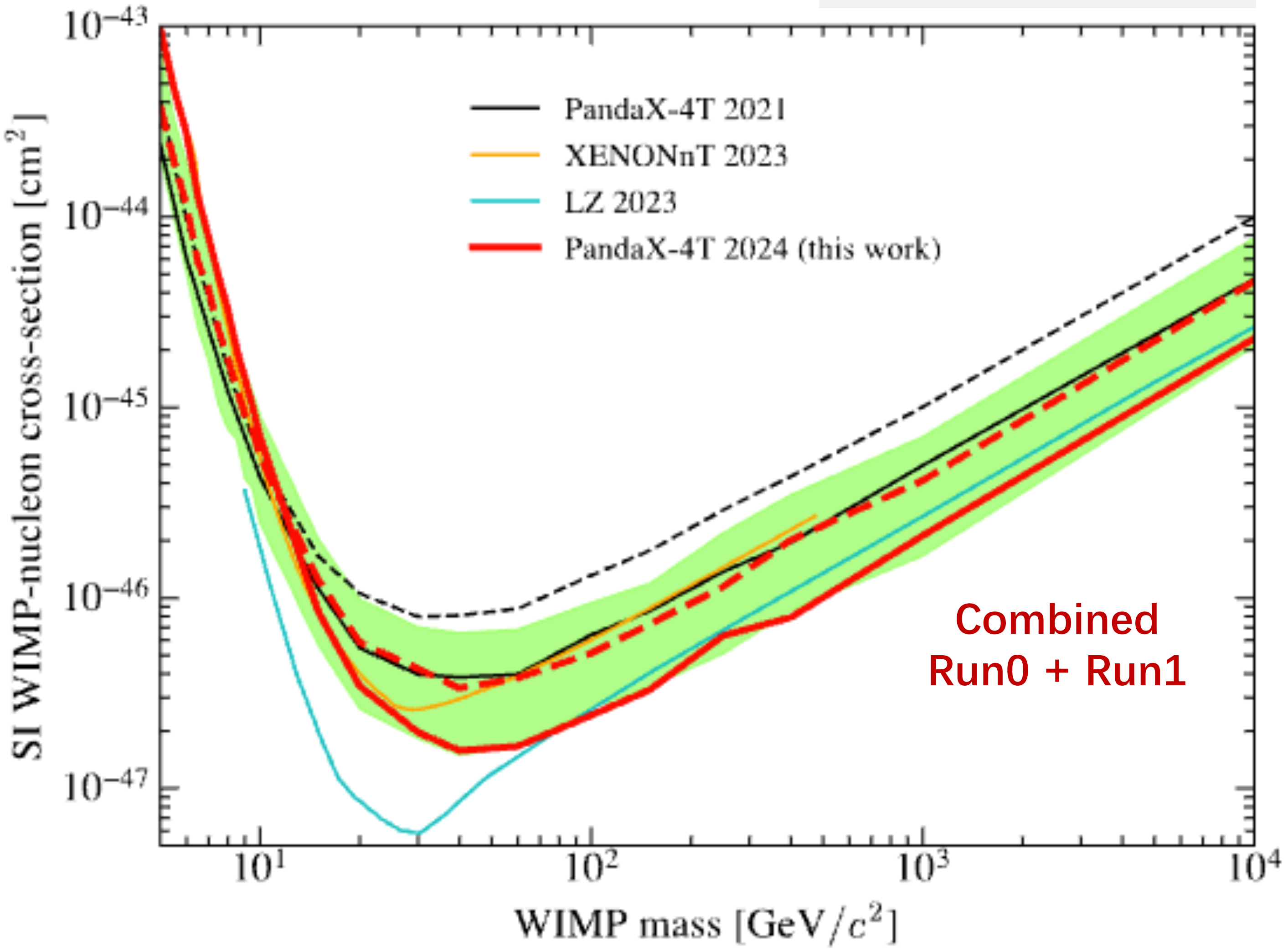
- ➢ **Scanning WIMP mass from 5 to 10000 GeV/c^2**
- ➢ **→ No significant excess!**

- **+1σ upward fluctuation: < 8GeV/c^2**

Global significance (after LEE correction):

$$Z^{\text{global}} = 1.2$$

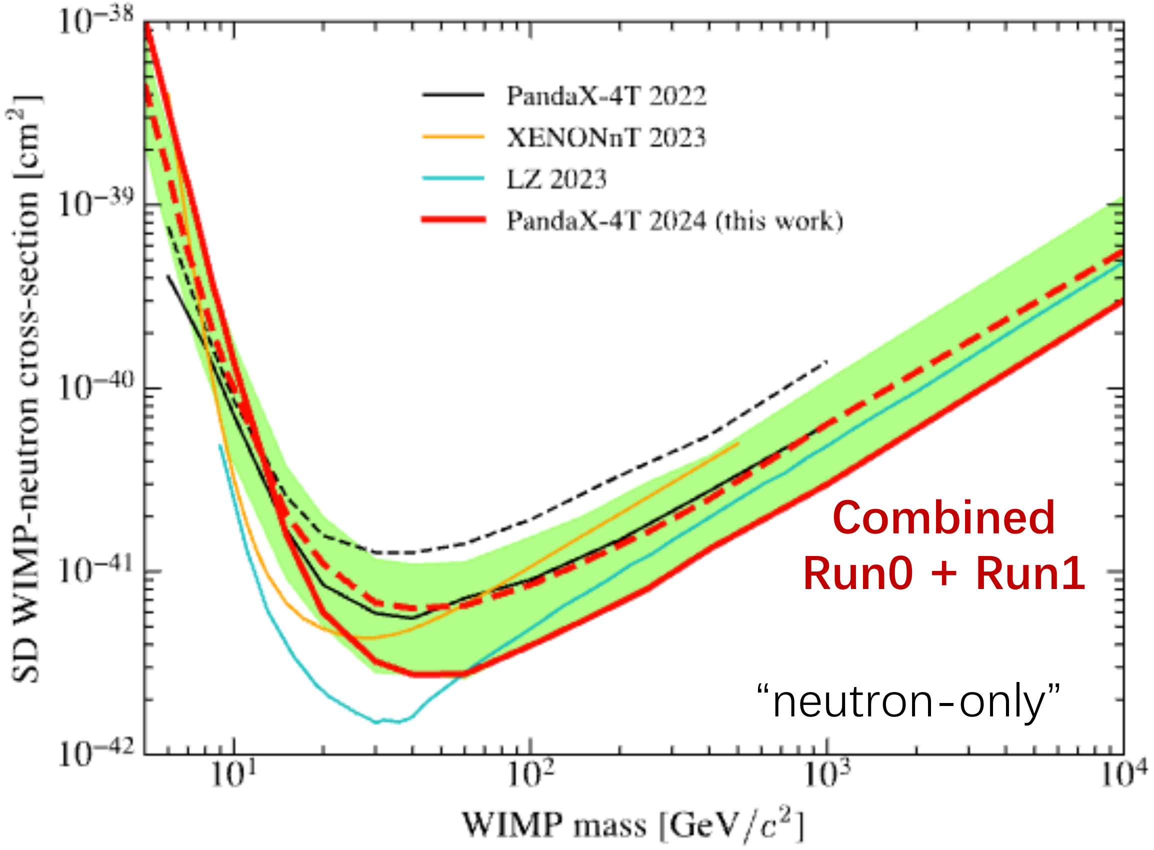
- **State-of-the-art: >100 GeV/c^2**
- **Lowest upper limit: 1.6×10^{-47} cm^2** at **40 GeV/c^2** after -1σ power-constraint

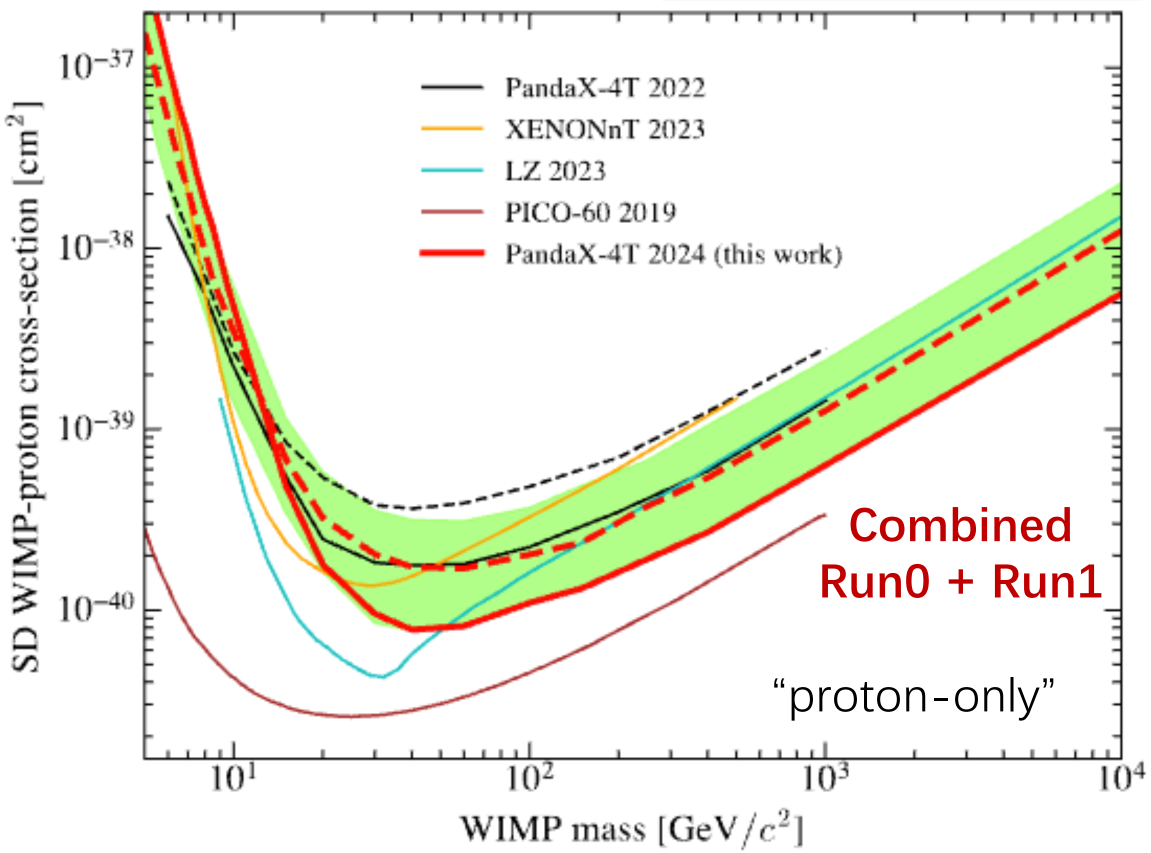


SD Upper Limit & Sensitivity Band

- Refresh spin-dependent constraints for Xe-based experiment

arXiv: 2408.00664





Summary and Outlook

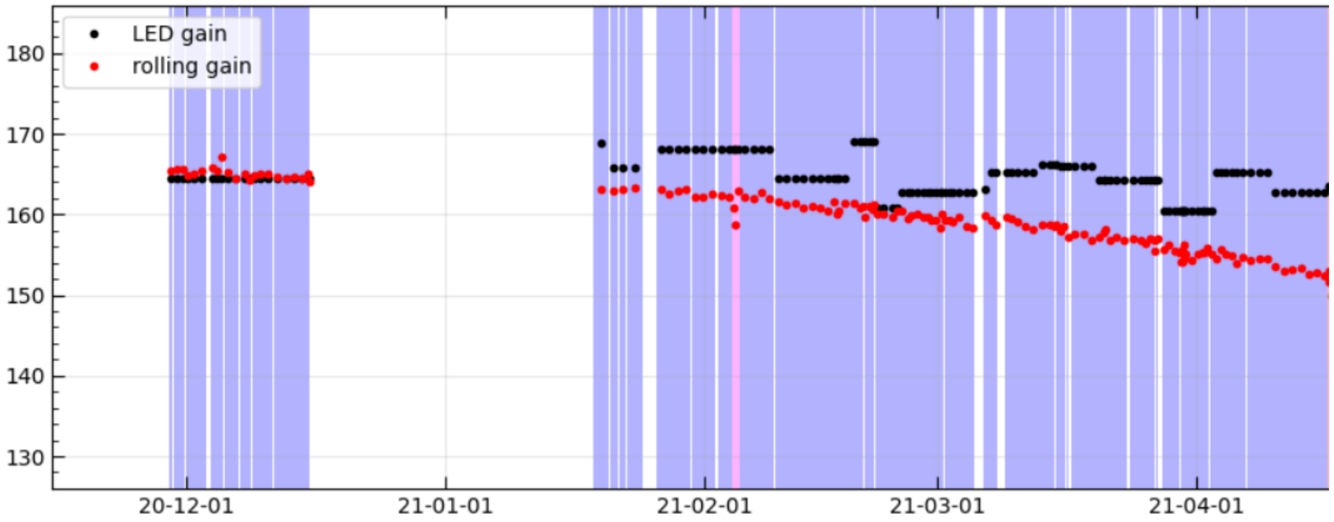
- A combined blind analysis of PandaX-4T Run0+Run1 for WIMP search comes out
- No significant excess and we present the latest stringent upper limit for DM mass above 100 GeV/c^2
- Studies of more physical topics are ongoing, and we keep accumulating more data & Stay tuned!

Thank you for your attention！

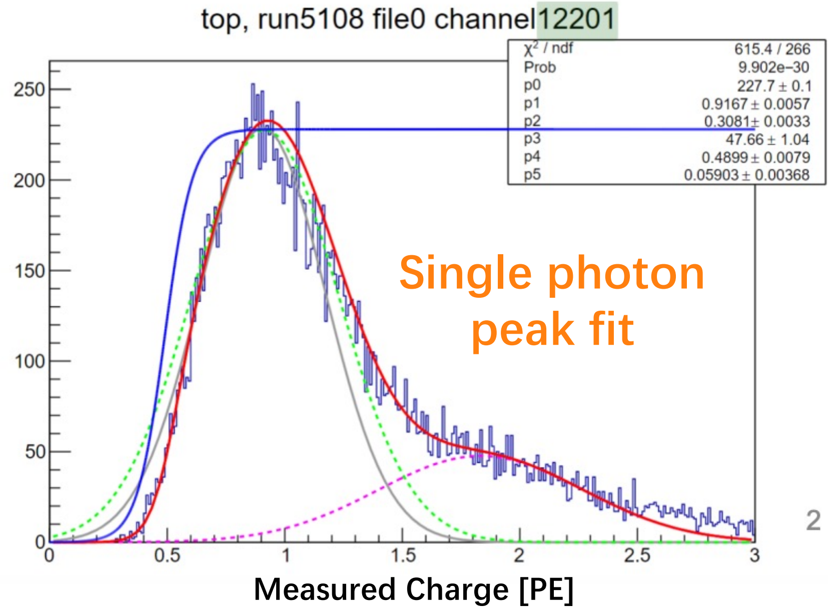
Backups

PMT Gain Self-calibration

- **Previous**
  - Approach: Weekly gain calibration with LED light.
  - Problem: The response to changes in gain （due to aging, etc.） is not timely enough.
- **New:**
  - Approach: Self-calibration via the fitted single photon peak from its own run.



LED gain calibration PMT self-calibration



PandaX-4T Signal Response Model

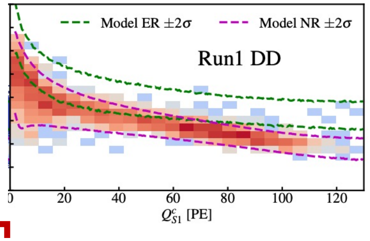
- To study how deposited energy converts to the detectable signals
- Run0+Run1 simultaneous fit to ER/NR data (DD+AmBe+Rn)
- Tune light & charge yields

$$E_{\rm ee} = W_q \left(\frac{Q^c_{S1}}{g_1} + \frac{Q^c_{S2_b}}{g_{2_b}} \right)$$

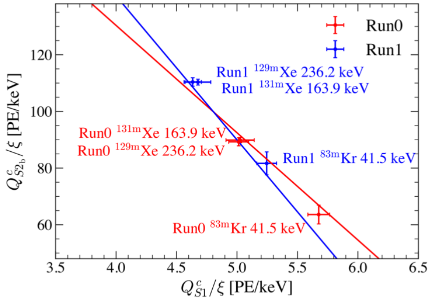
Binned likelihood

α: indices of dataset

β: indices of 2D-distribution



$$\mathcal{L} = \prod_{\alpha,\beta} \frac{\lambda_{\alpha\beta}^{N_{\alpha\beta}}}{N_{\alpha\beta}!} e^{-\lambda_{\alpha\beta}} \cdot e^{\Lambda}$$



Penalty from energy calibration

$$\Lambda = \sum_i \left(E_{{\rm rec},i} - E_{{\rm tr},i}\right)^2 / \left(2\sigma^2_{E_{{\rm rec},i}}\right)$$

i: Kr83m, Xe129m, and Xe131m

Maximum likelihood fitting in GPUs through MCMC

$$p_{accept} = \min\left(\frac{L(\theta_{n+1})}{L(\theta_n)}, 1\right)$$

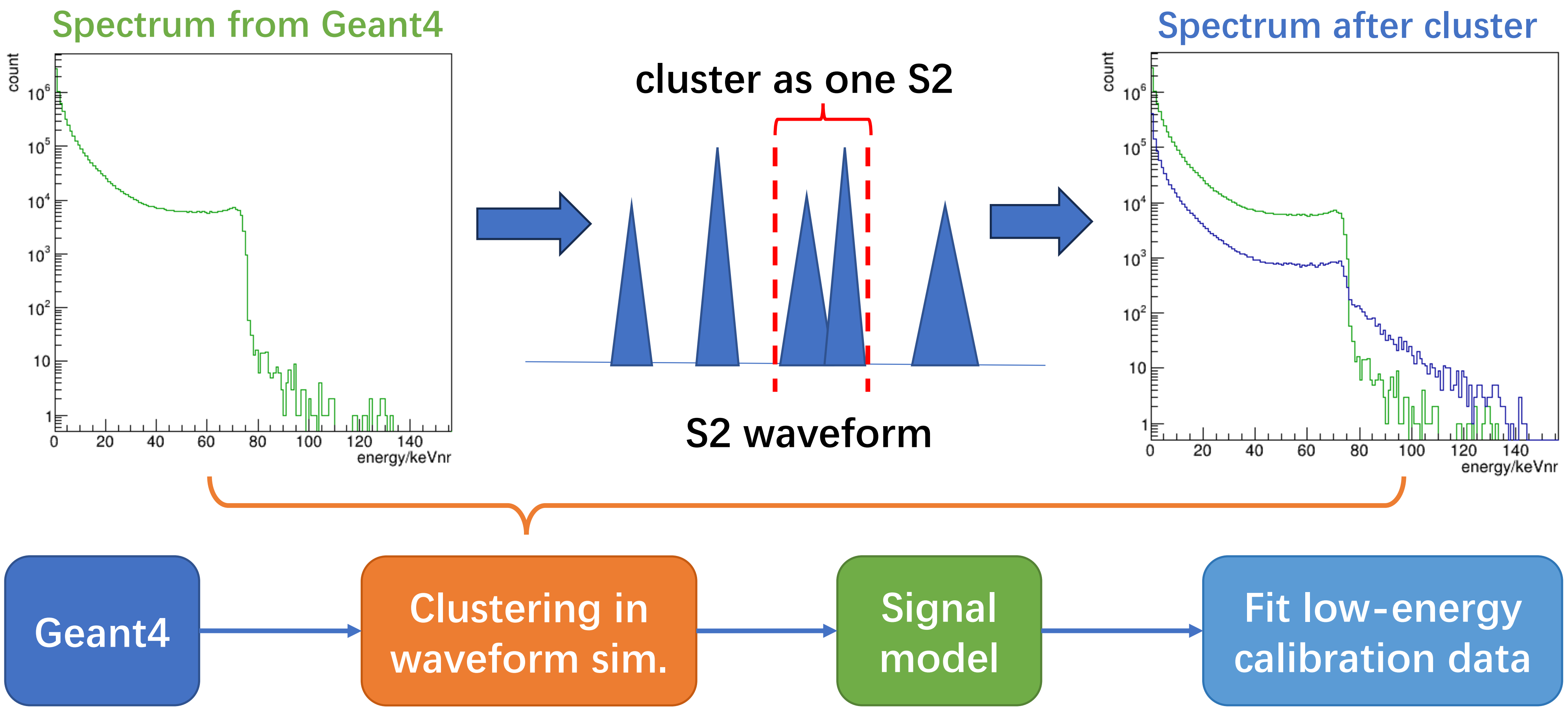
Step 1 … → Step n → Step n+1 { accept: p / refuse: 1-p

Markov Chain

Monte Carlo

PandaX-4T Signal Response Model

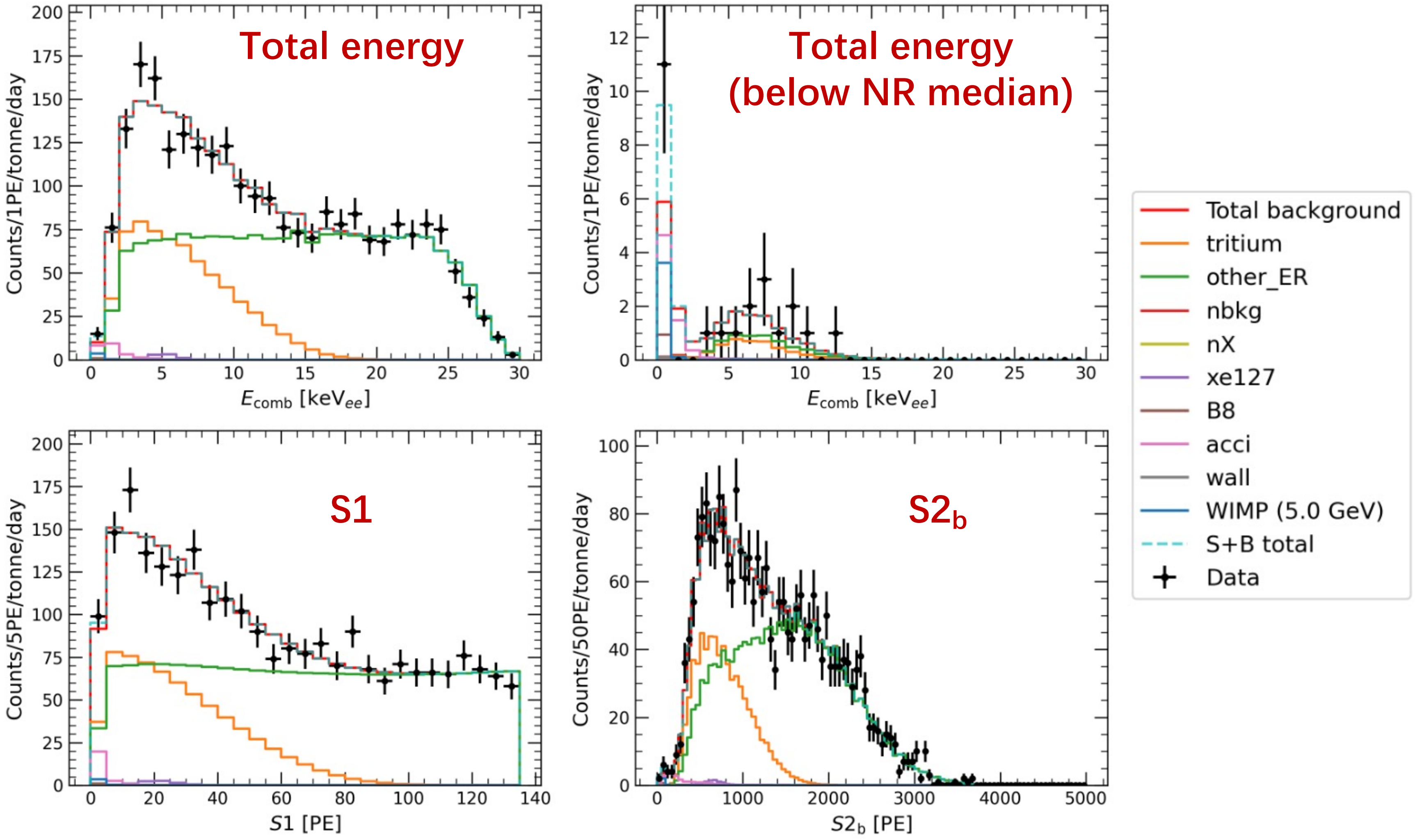
➢ Consider multiple-scatter (MS) process



Best Fit Result (Run0+Run1)

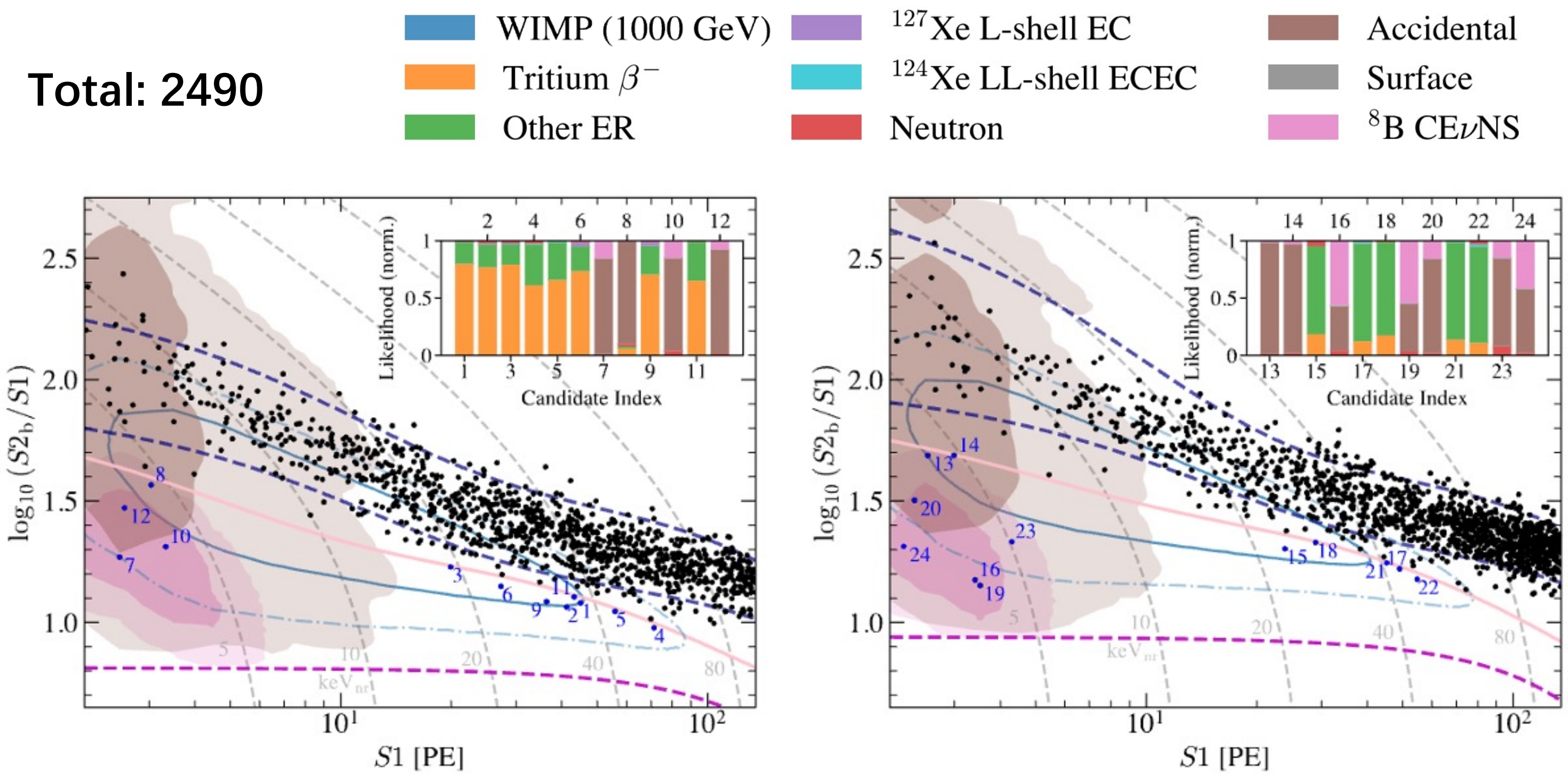
- **PLR fit:** with unbinned likelihood with all signal/background PDFs in (S1, $S2_b$)

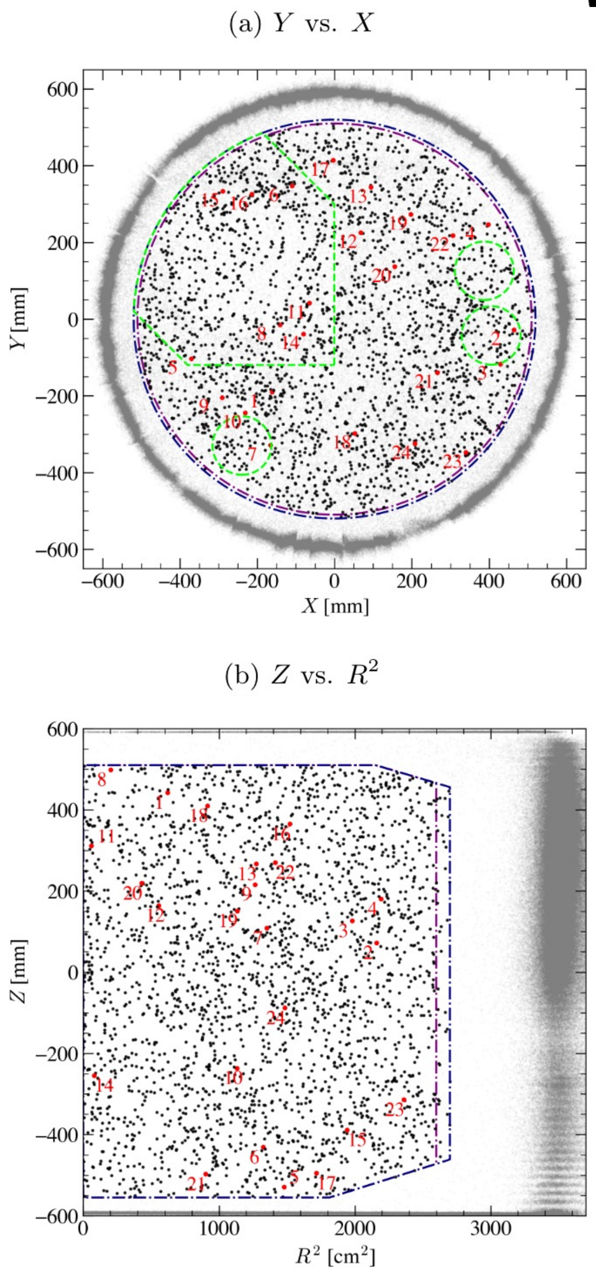
- **Best fit DM counts**:
  - 3.7 w/ 5 GeV WIMP
  - 0 w/ 40 GeV WIMP



Distribution of DM Candidates

Total: 2490





- 24 (12+12) below NR median events
- Uniformly distributed in the FV.

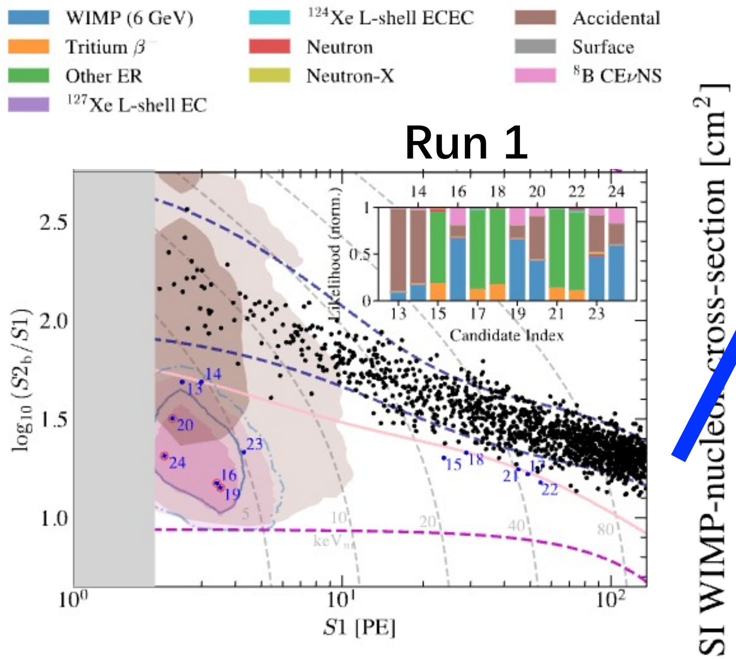
ER 5%-95% quantiles

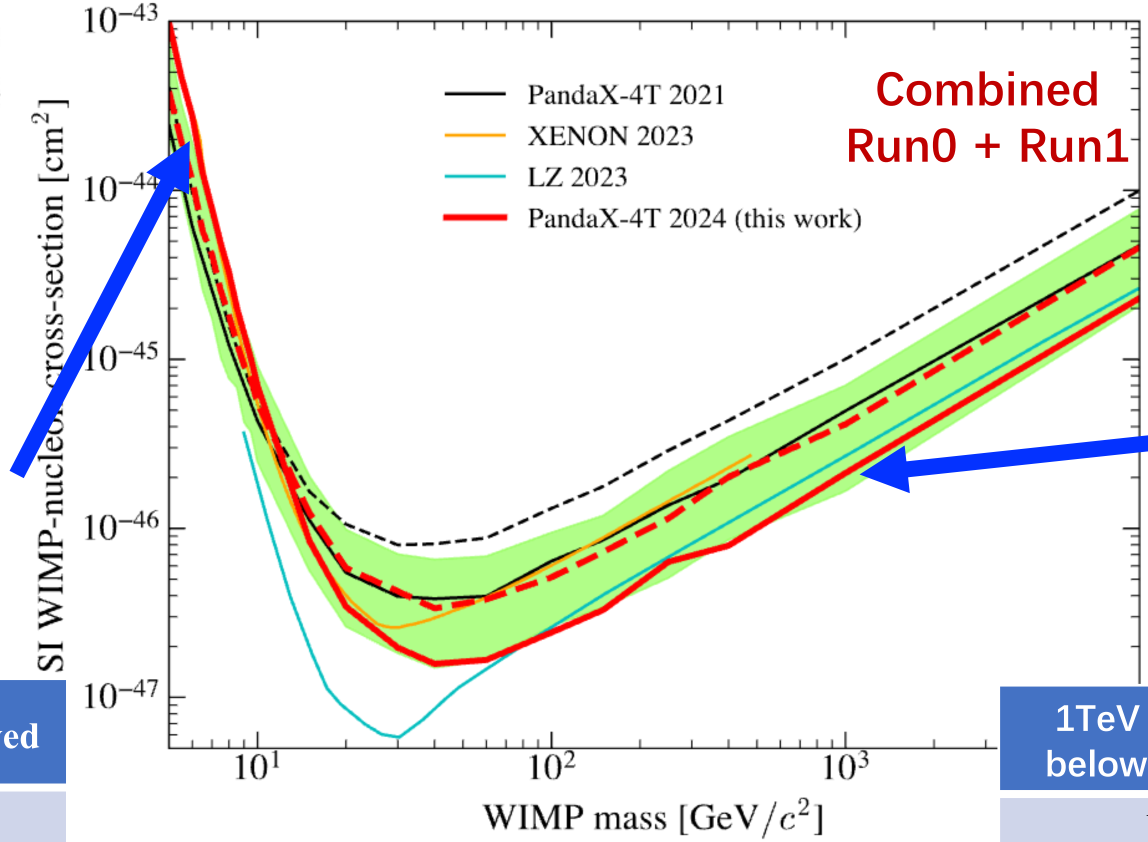
NR median

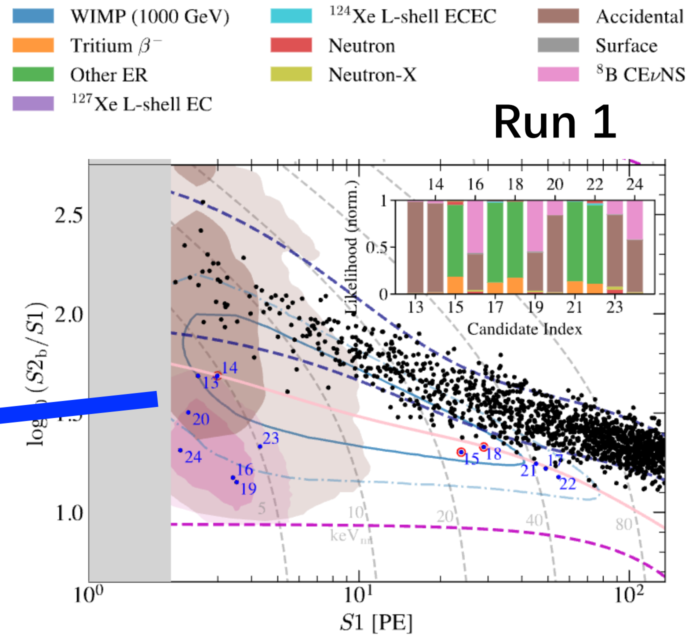
NR 99.5% acceptance

Constraints on SI Cross Section

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







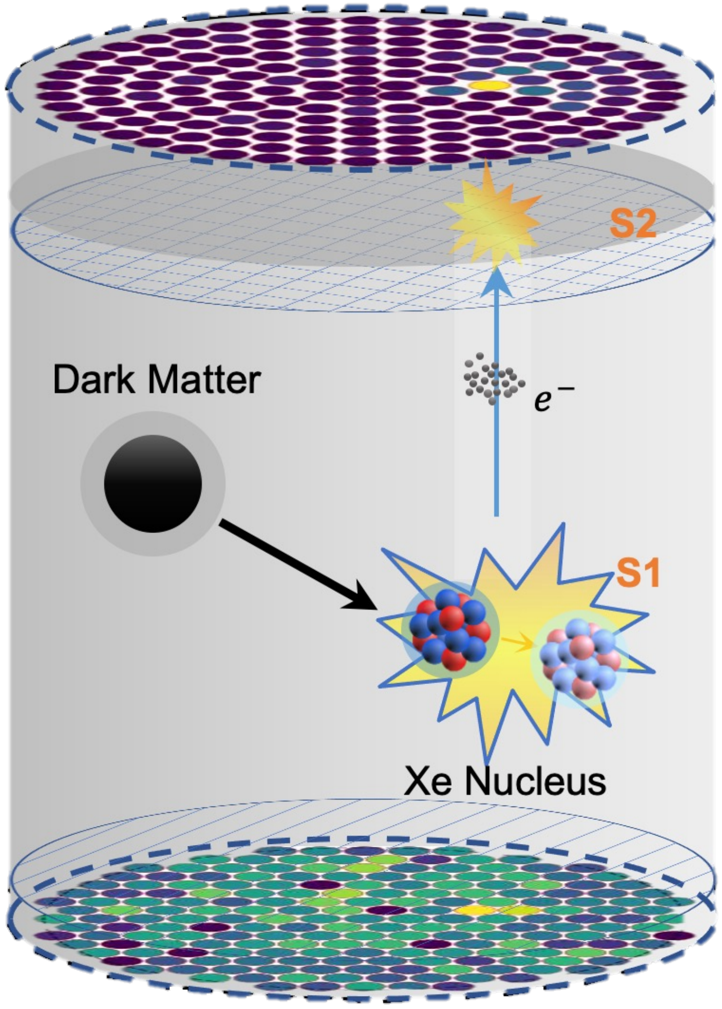
S1<5PE below NR median	Expected	Observed
Run0	2.7±0.4	4
Run1	3.6±0.5	7

陶奕 中国物理学会高能物理分会(2024)

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

PandaX-4T DM Results in Run0

- **Standard WIMP searches**
  - Spin-independent (SI)
  - Spin-dependent (SD)
- **Luminance of DM**
- **Several novel approaches**
  - Lower threshold (S2-only)
  - Migdal effect
  - χ-ν conversion
  - Boosted mechanism



PandaX-4T DM Results in Run0

- **Standard WIMP searches**
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- Luminance of DM
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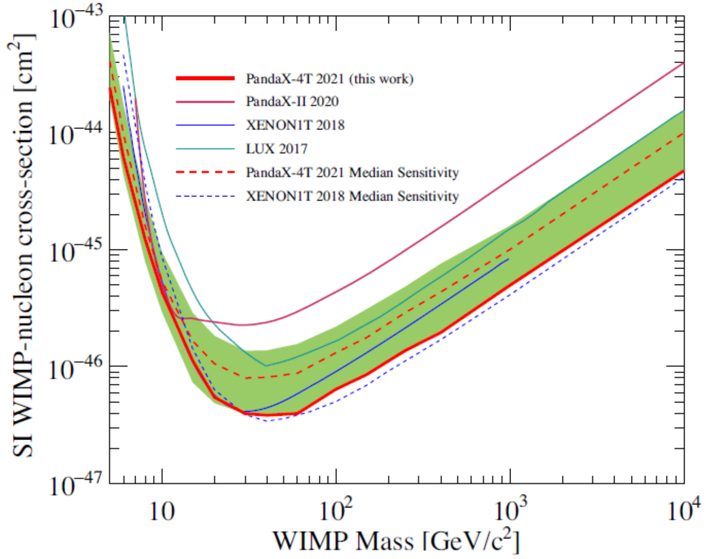
  - Migdal effect
  - χ-ν conversion
  - Boosted mechanism

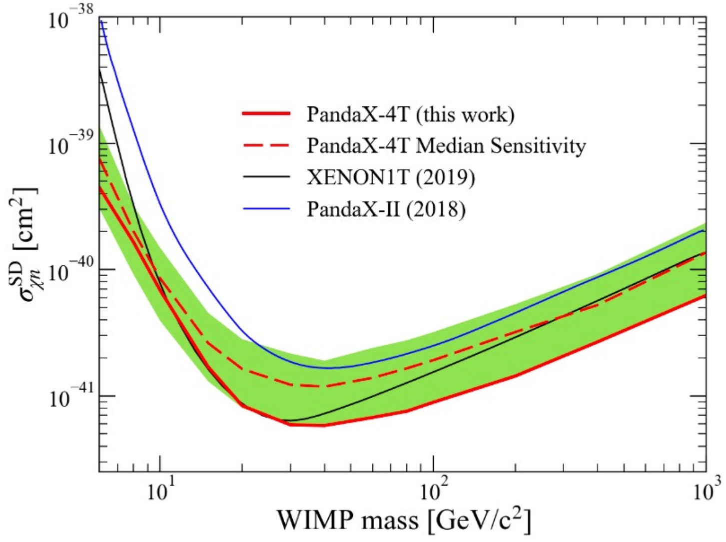
➢ Sensitivity improved from PandaX-II final analysis by 2.9 times

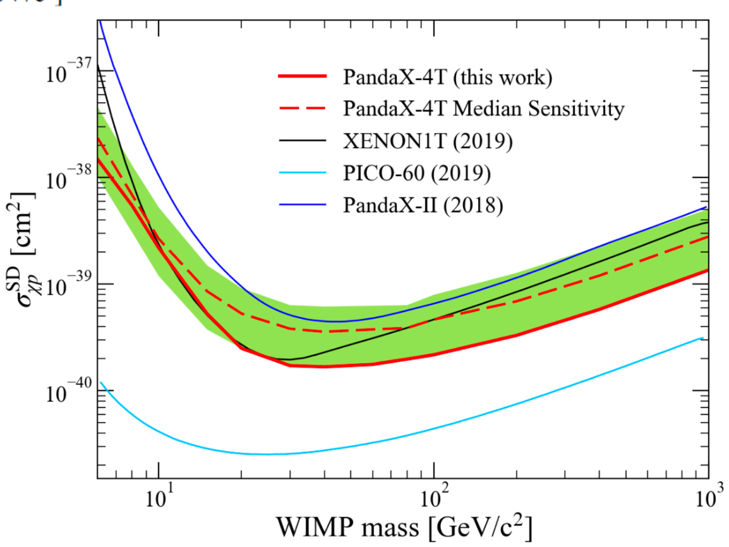


Y. Meng et al. **PRL** 127, 261802 (2021), **Editors' Suggestion**

0.63 tonne·year

Z. Huang et al. PLB 834, 137487 (2022)





PandaX-4T DM Results in Run0

- Standard WIMP searches
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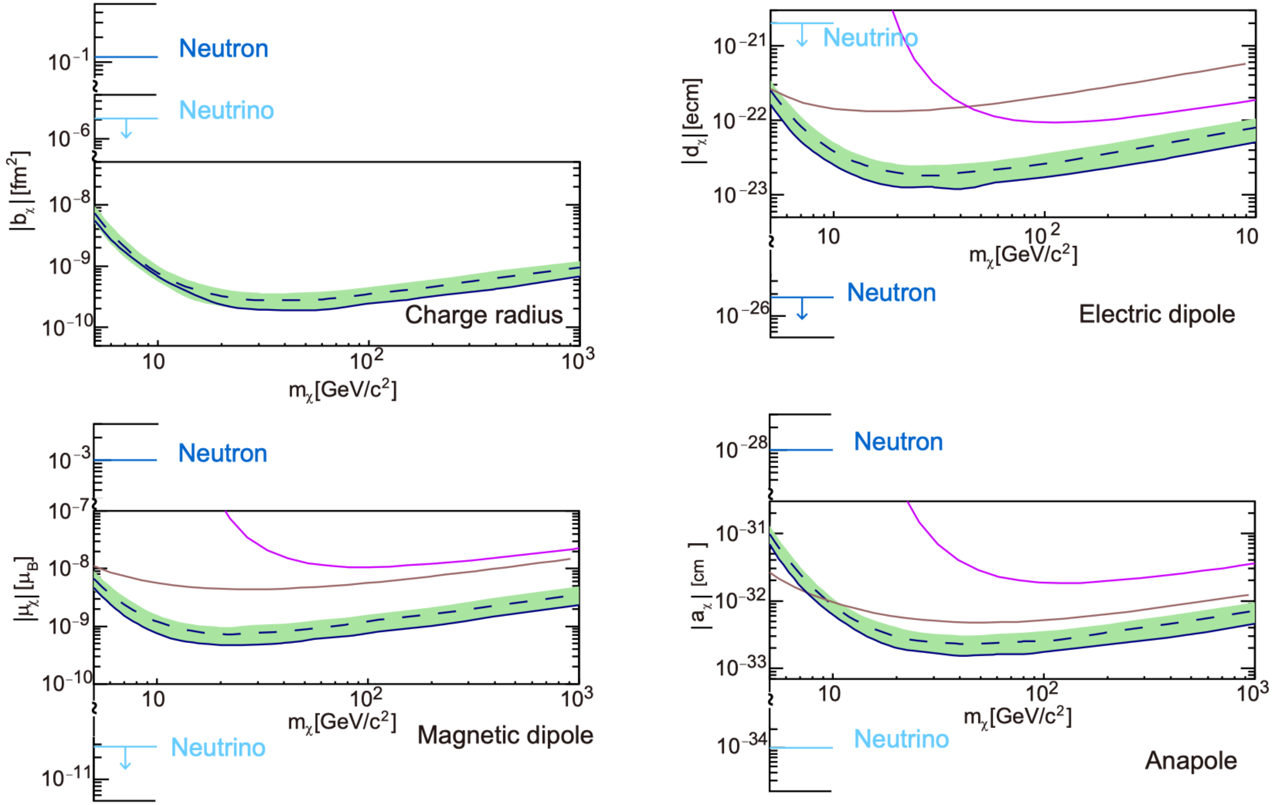
  - Spin-dependent (SD)
- **Luminance of DM**
- Several novel approaches
  - Lower threshold (S2-only)
  - Migdal effect
  - *χ-ν* conversion
  - Boosted mechanism

- **First experimental constraints on DM charge radius: 4 orders of magnitude than the neutrino**
- **Up to 3 – 10 times improvement for other electro-magnetic properties**



X. Ning et al. **Nature** 618 (2023)

PandaX-4T　PICO-60　DEAP-3600

PandaX-4T DM Results in Run0

- **Standard WIMP searches**
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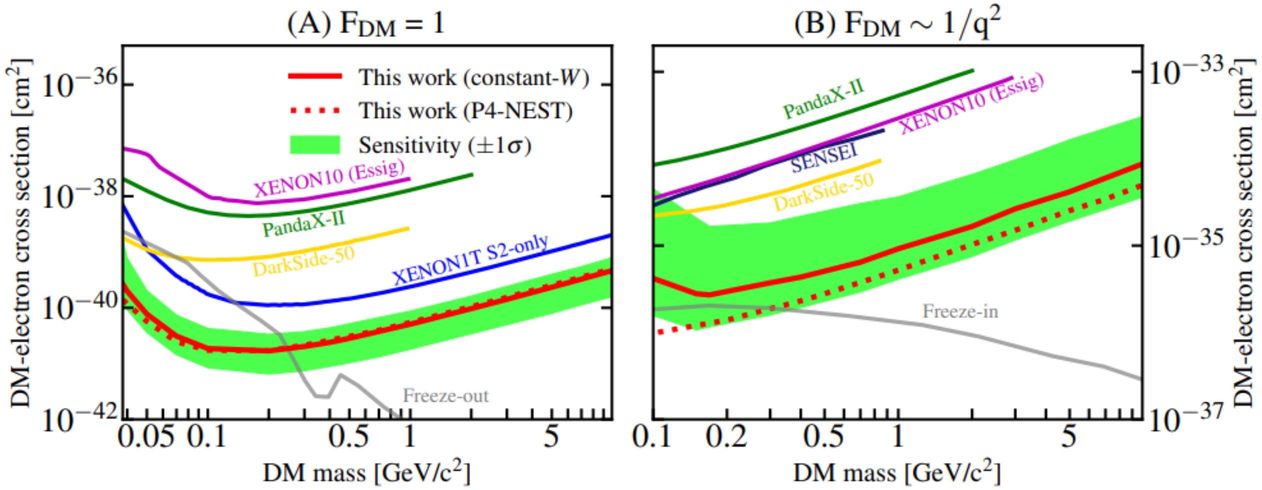
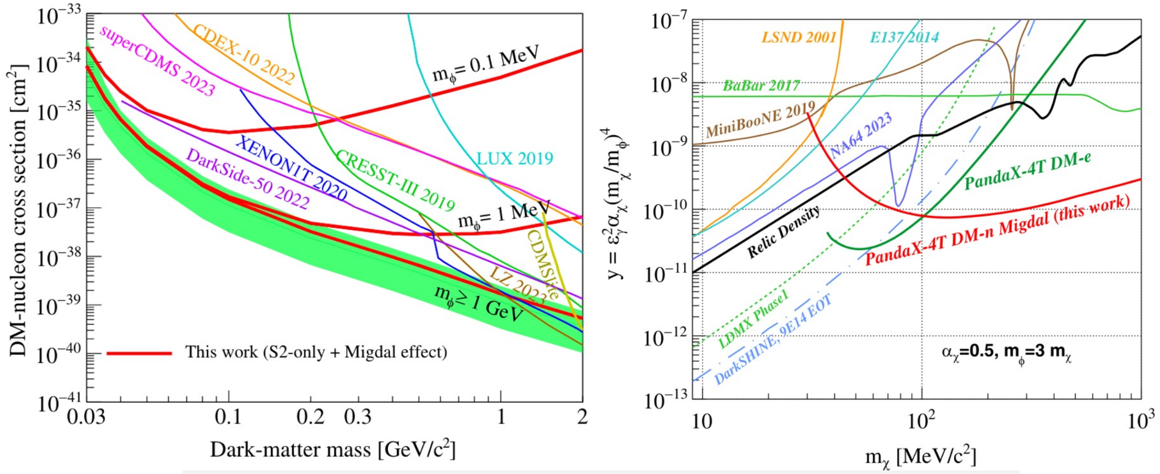
- **Luminance of DM**
- **Several novel approaches**
  - Lower threshold (S2-only)
  - Migdal effect
  - *χ*-*ν* conversion
  - Boosted mechanism

➢ Most stringent constraints are derived



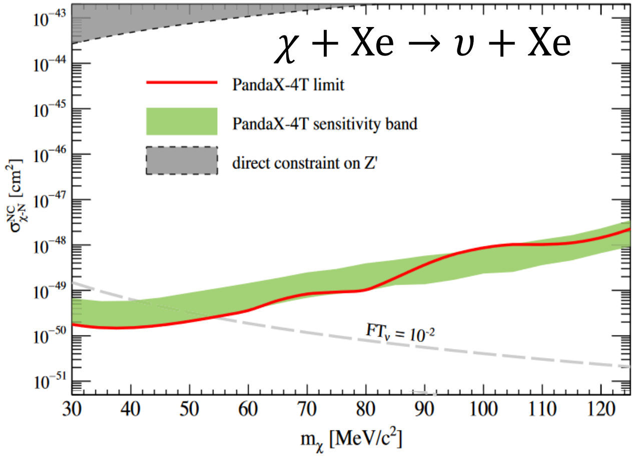
S. Li et al. **PRL** 130, 261001 (2022), **Editors' Suggestion**



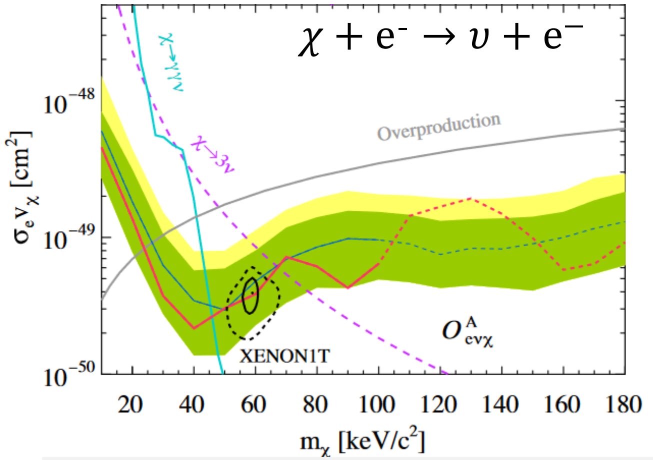
D. Huang et al. **PRL** 131, 191002 (2023)

PandaX-4T DM Results in Run0

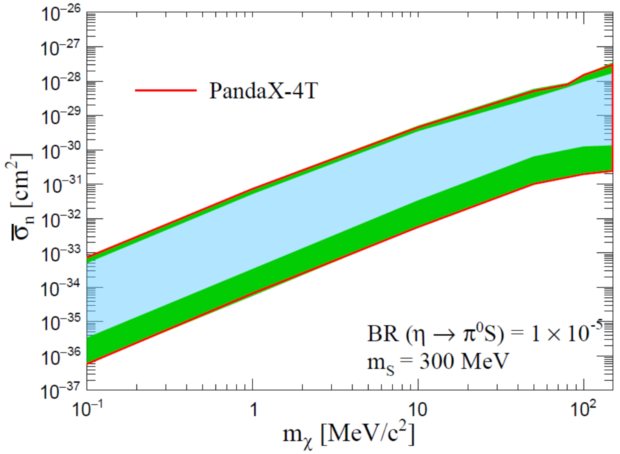
- **Standard WIMP searches**
  - Spin-independent (SI)
  - Spin-dependent (SD)
- **Luminance of DM**
- **Several novel approaches**
  - Lower threshold (S2-only)
  - Migdal effect
  - χ-ν conversion
  - Boosted mechanism
    - ➢ **Overcome detection threshold**



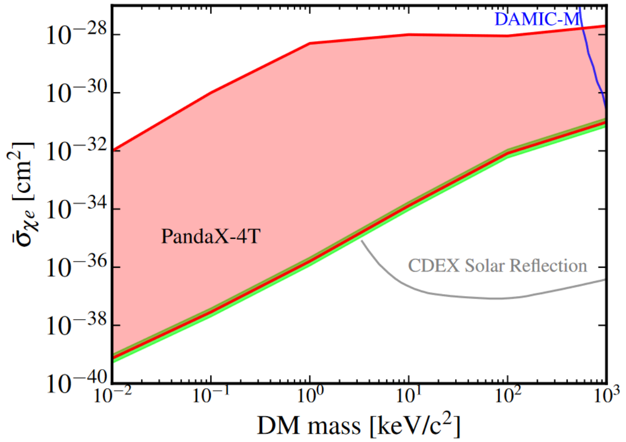
L. Gu et al. **PRL** 129, 161803 (2022), **Editors' Suggestion**



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



X. Ning et al. **PRL** 131, 041001 (2023)



arXiv: 2403.08361