RELICS: Measuring Coherent Neutrino-Nucleus Scattering Utilizing Dual-Phase Xenon TPC

Kaihang Li (Tsinghua University)

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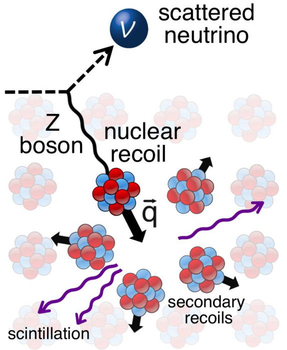
On behalf of the RELICS collaboration

Hong Kong, China, LIDINE 2025

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

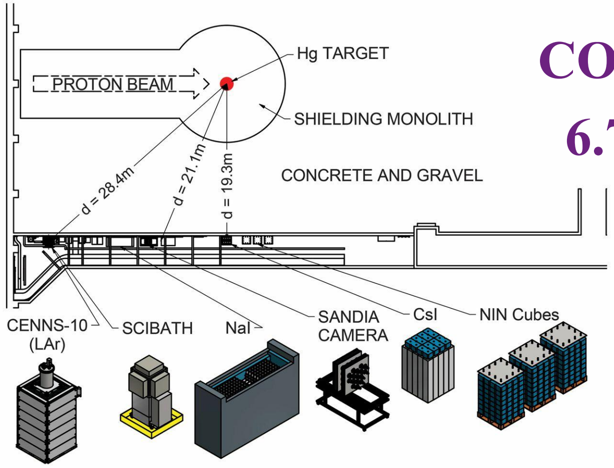
Opportunities:
- Cross section proportional to the square of the number of nucleons
- High neutrino flux



$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M\left(1 - \frac{MT}{2E_\nu^2}\right)F(Q^2)^2.$$

$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

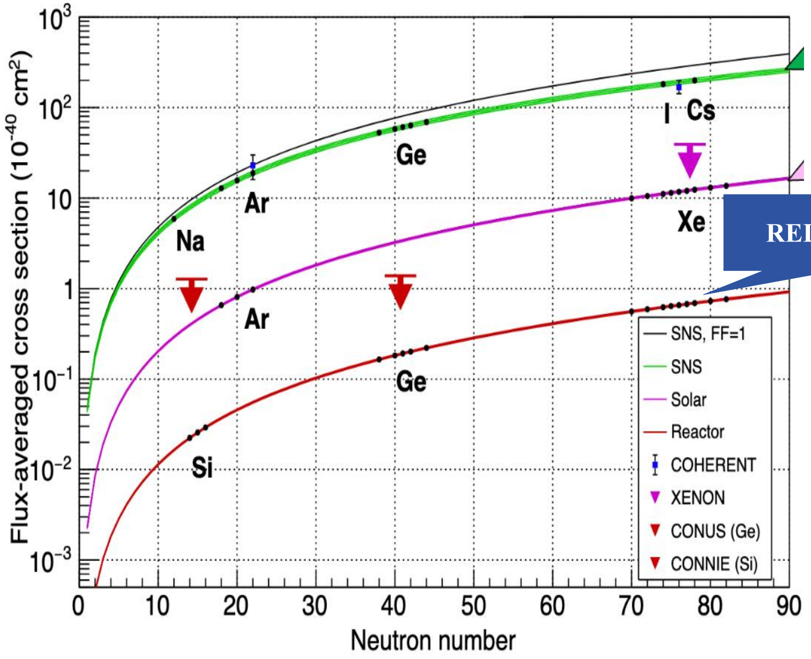
$$Q_W \propto N \implies \boxed{\frac{d\sigma}{dT} \propto N^2}$$



10.1126/science.aao0990

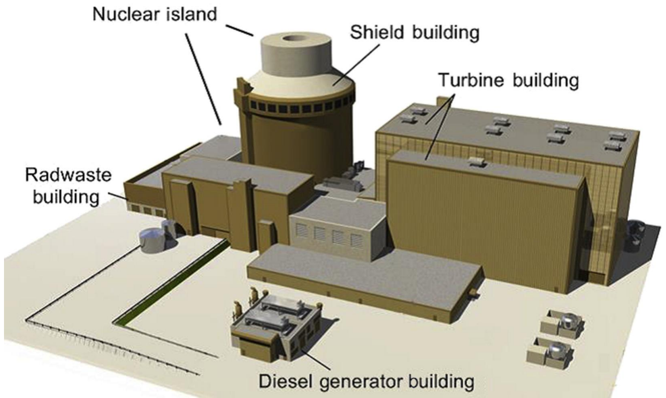
COHERENT
6.7σ (2017)

Challenges:
- Low nuclear recoil energy
- Energy ROI for RELICS: ~ keV$_{nr}$
- High detection efficiency



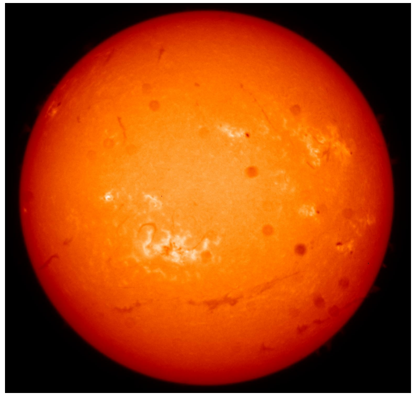
RELICS（Xe）

Reactor + Xenon



10.1038/s41586-025-09322-2

CONUS+
3.7σ (2025)



10.1103/PhysRevLett.133.191001
10.1103/PhysRevLett.133.191002

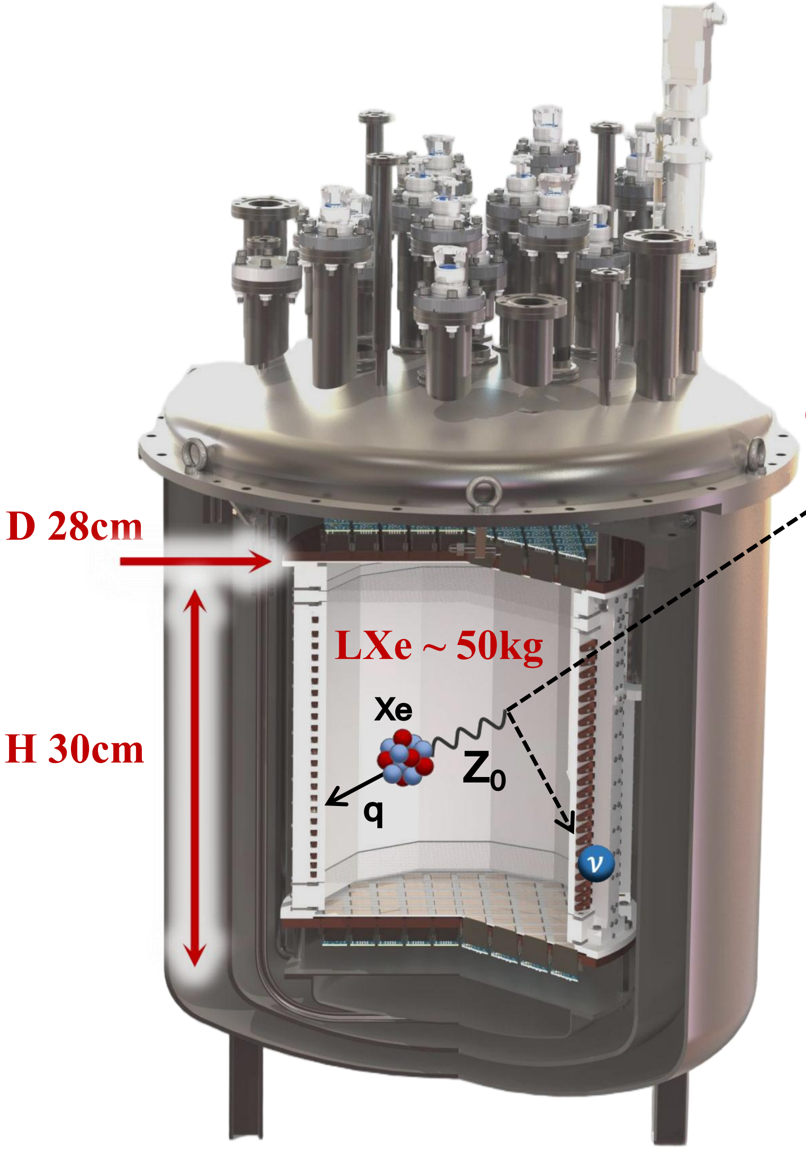
XENONnT, PandaX
2.6σ (2024)

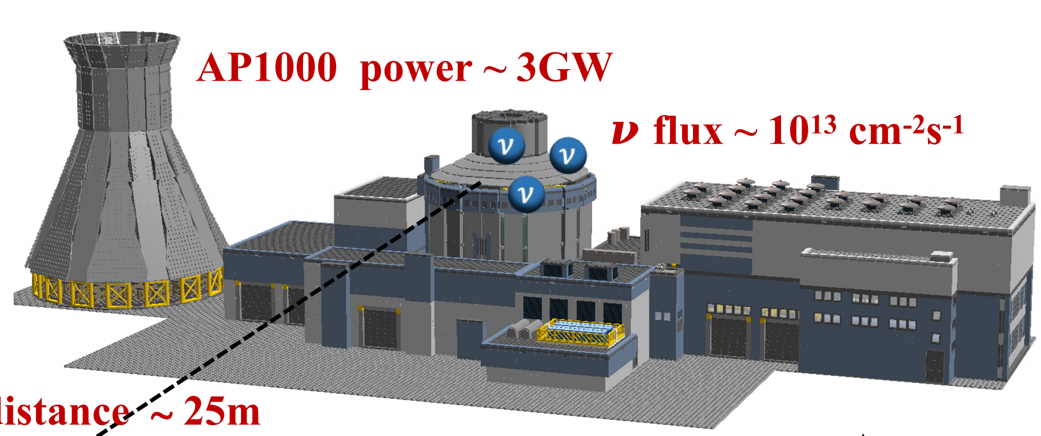
RELICS Collaboration

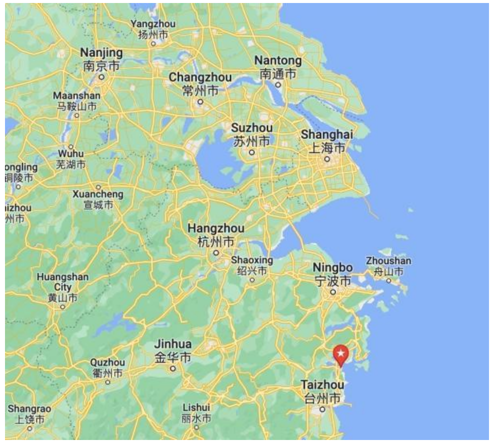
RELICS: REACTOR NEUTRINO LIQUID XENON COHERENT SCATTERING EXPERIMENT

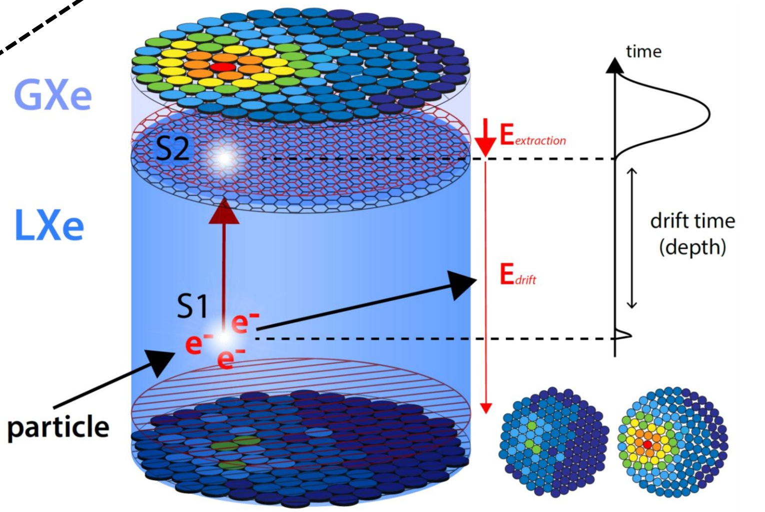
RELICS Experiment - LXe TPC

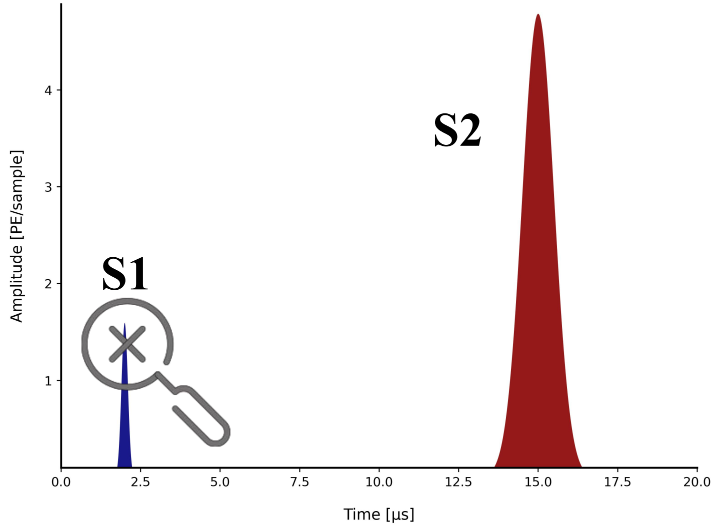
清華大學 Tsinghua University











- ☐ XY position reconstruction
- ☐ Low threshold
- ☐ Energy ROI : [0.63, 1.36] keV_{NR}
- ☐ S2 only analysis: S1 signal is too weak

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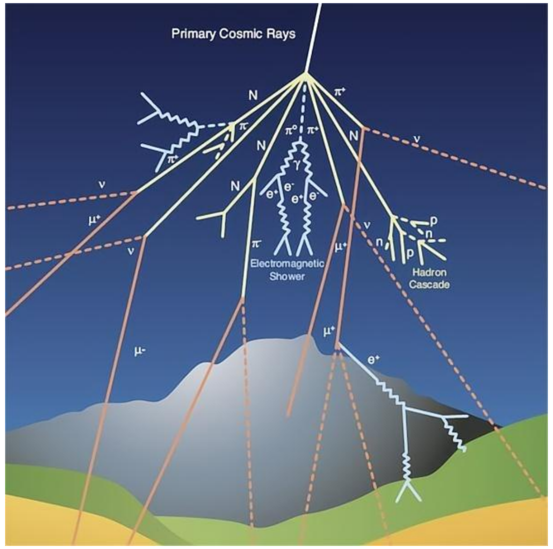
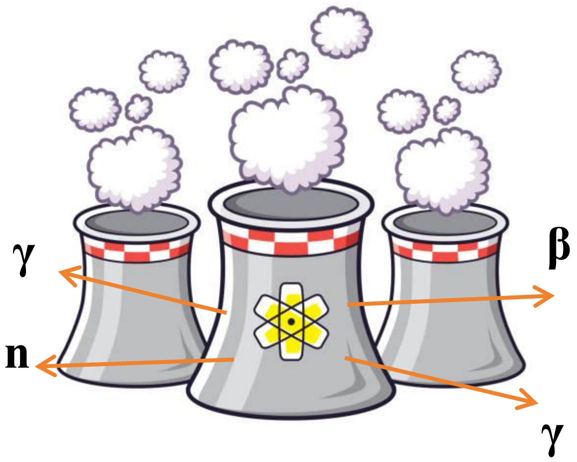
Challenges: Background Sources

Cosmic Ray Particles



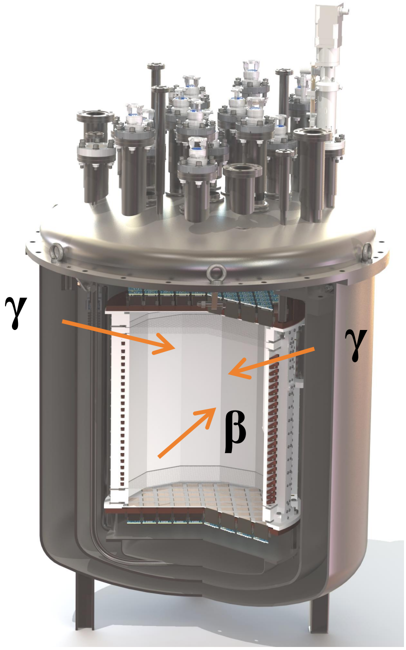
- ☐ Cosmic μ
- ☐ Cosmic neutron
- ☐ Others…

Reactor



- ☐ Reactor Neutron
- ☐ Reactor γ
- ☐ Others…

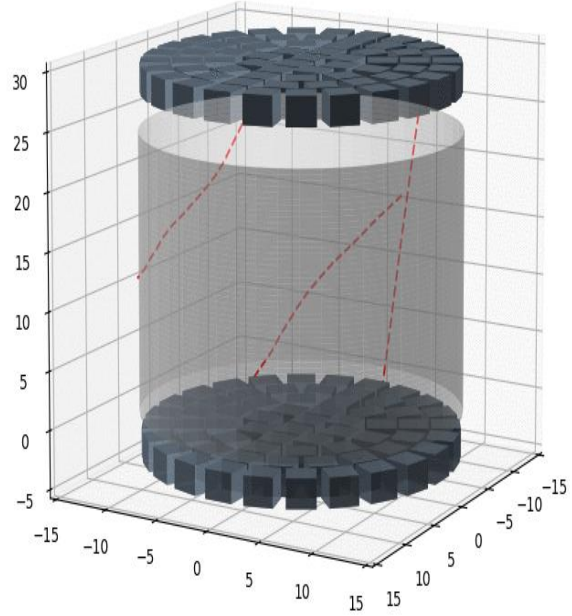
Detector Material



- ☐ Material γ, β
- ☐ Others…

Physics Background Simulation with Geant4

Spurious Signals



- ☐ Delayed Electrons
- ☐ Others…

Data-driven Modeling of Delayed Electron Backgrounds

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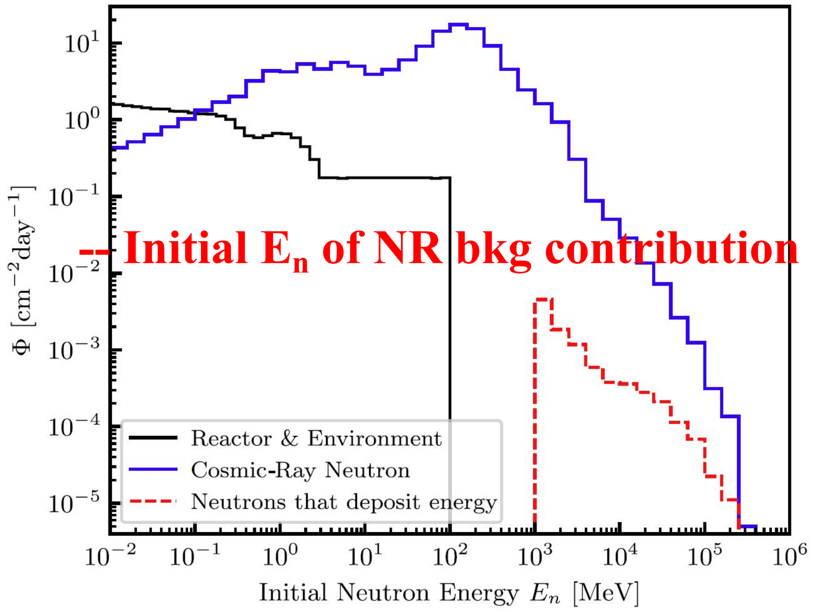
Nucleus Recoil (NR) Background

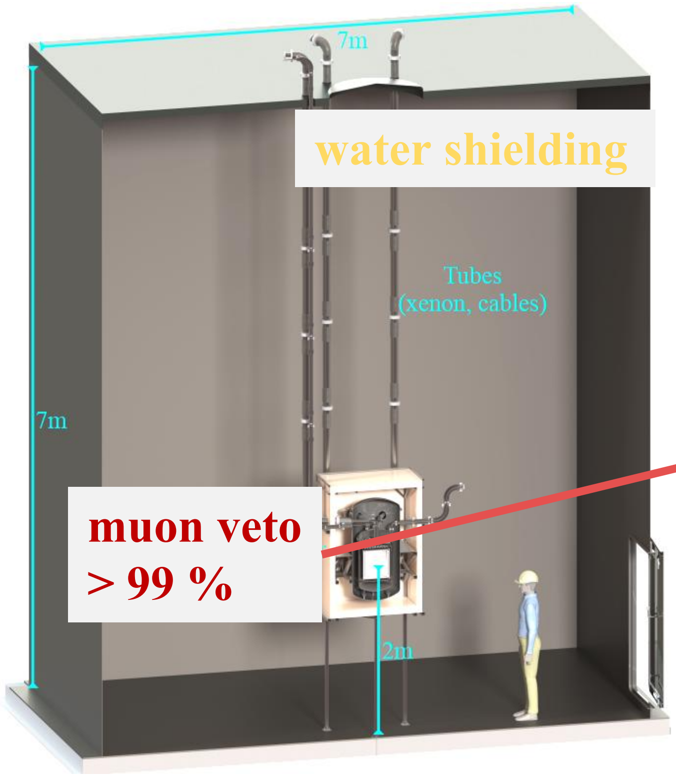
Neutron Sources：

- Reactor & Environment Neutron
- Cosmic Ray Neutron
- Muon induced Neutron

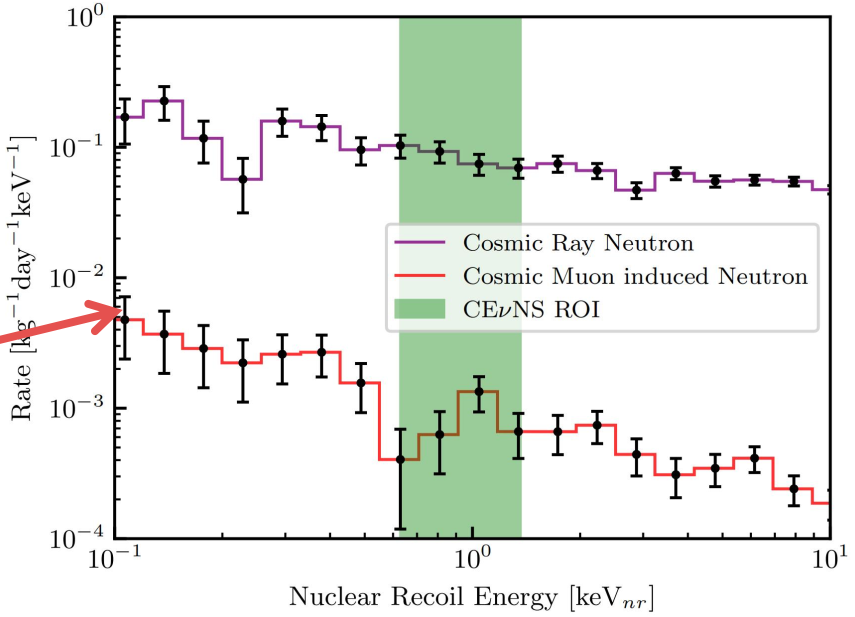


--- Cosmic-Ray neutron

---- Reactor & Environment neutron



With Water Shielding



NR Background：

- $(7.7 \pm 0.7) \times 10^{-2}$ kg$^{-1}\cdot$day^{-1} of [0.63 , 1.36] keV$_{NR}$
- Dominated by cosmic ray neutron

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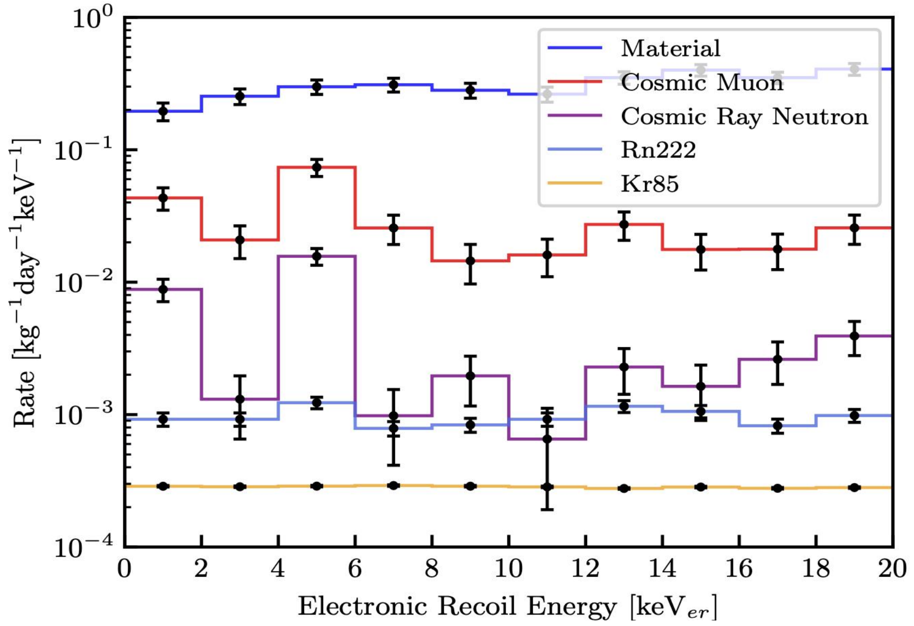
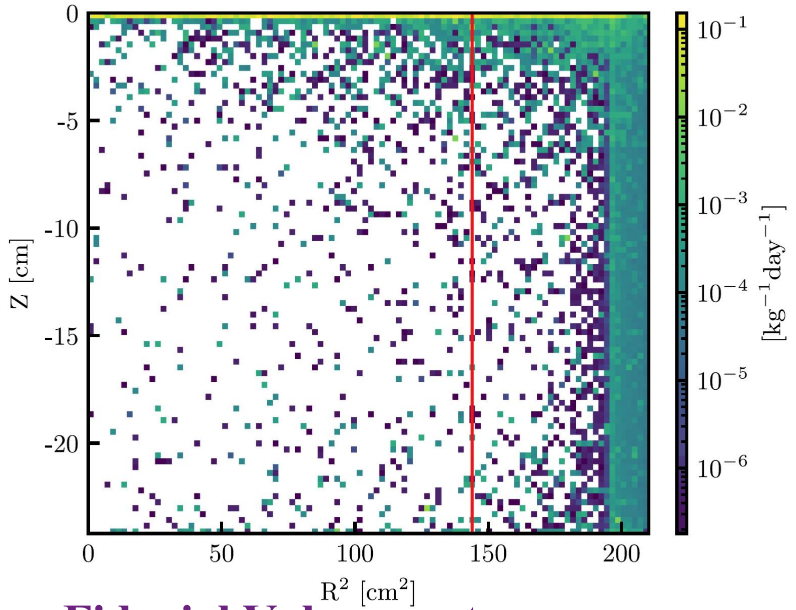
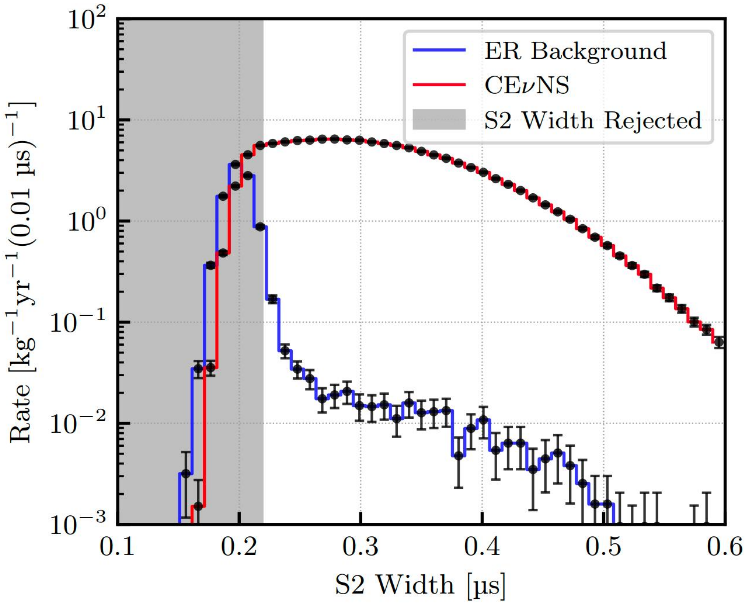
Electron Recoil (ER) Background

γ / β Sources：

- ☐ Material
- ☐ Muon
- ☐ Cosmic Ray Neutron
- ☐ LXe intrinsic







Fiducial Volume cut：

- ✔ R < 12 cm
- ✘ No Z Position

S2 Width selection：

- ✔ S2 Width > 0.22us
- ✔ Signal Acceptance ~ 86%
- ✔ Rejection Power ~ 94%

ER Background：

- ☐ $(3.10 \pm 0.10) \times 10^{-1}$ kg^{-1}·day^{-1}·keV^{-1} average of [0,20] keV$_{ER}$ before S2 width cut

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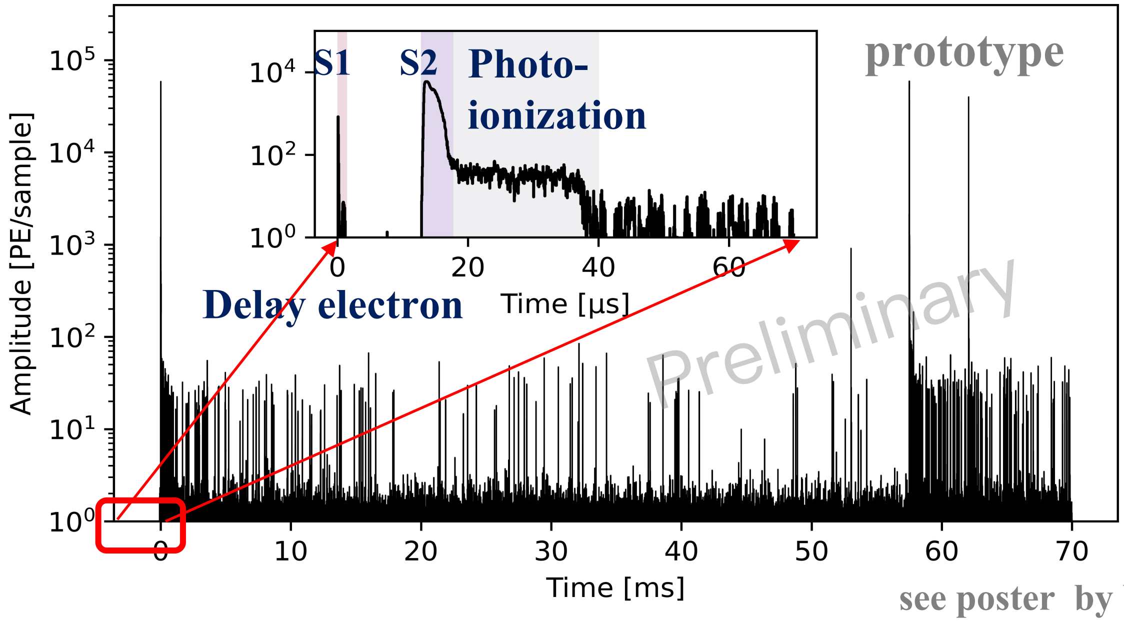
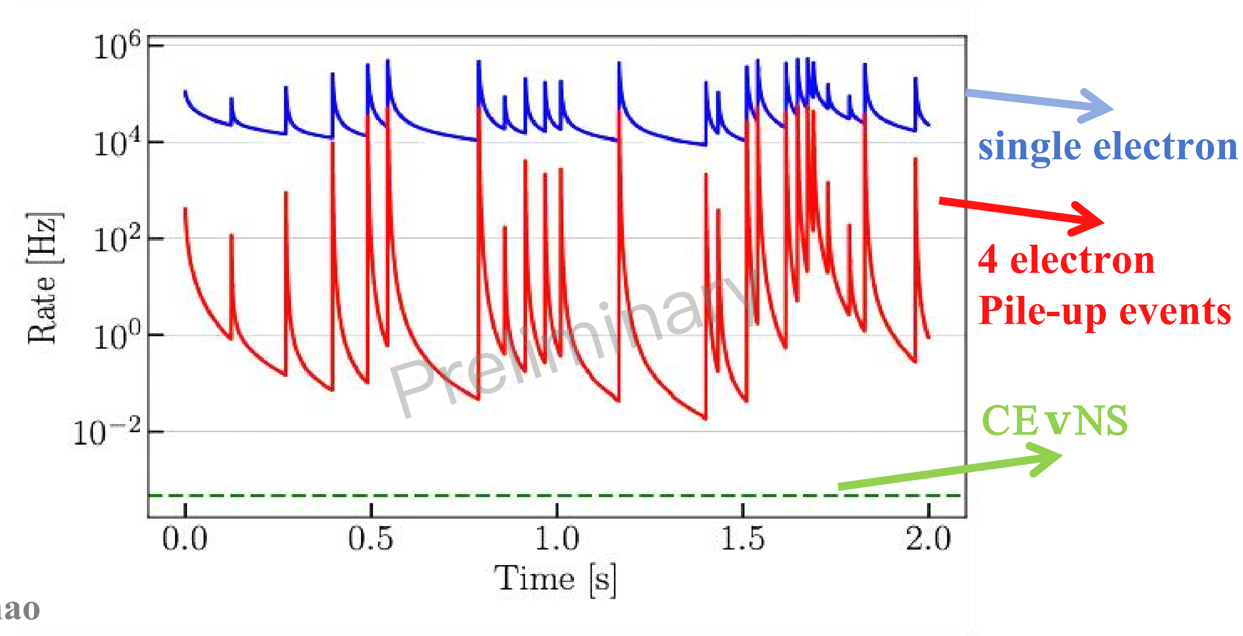
Delayed Electrons (DE) Background

Large Energy deposition



see poster by Yifei Zhao



Delayed Electrons phenomenon:

- Observed by large LXeTPC experiments and prototype
- Emission of electron following large energy deposition
- Pile-up of single electrons distorts the physical signal

Delayed Electrons background:

- Related to muon rate ~ 10 Hz
- Pile-up DE events rate higher than CEvNS events

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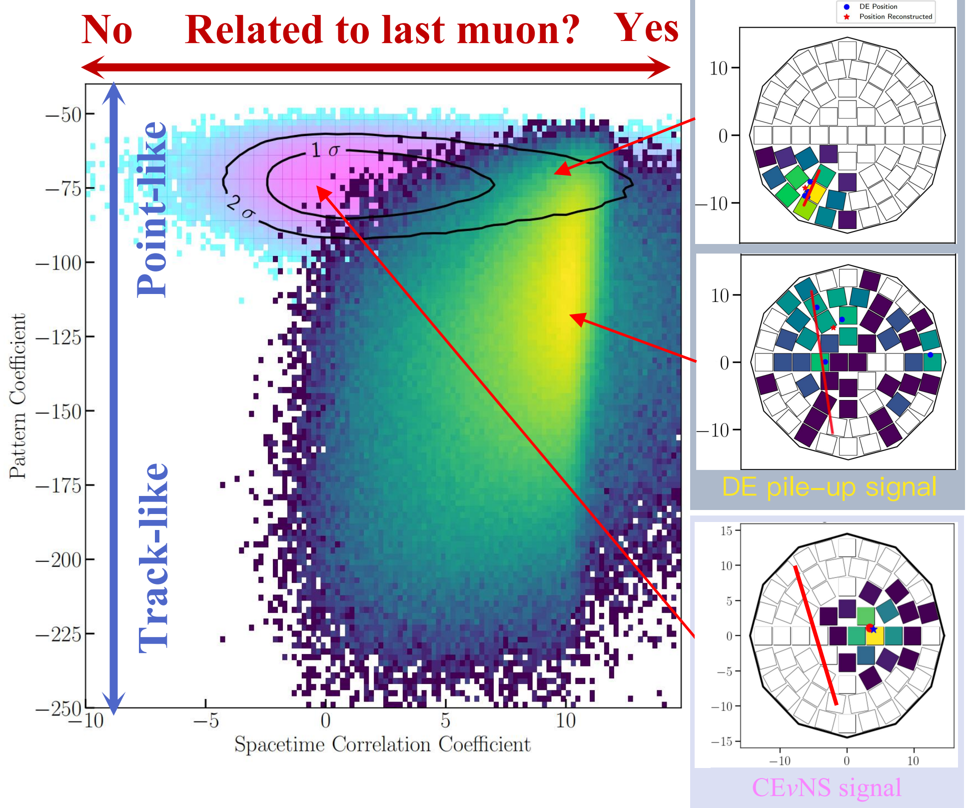
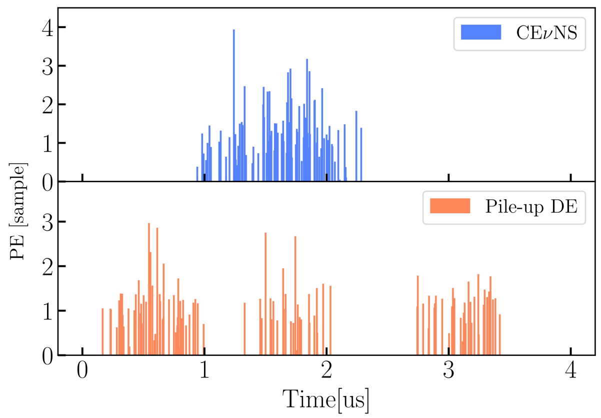
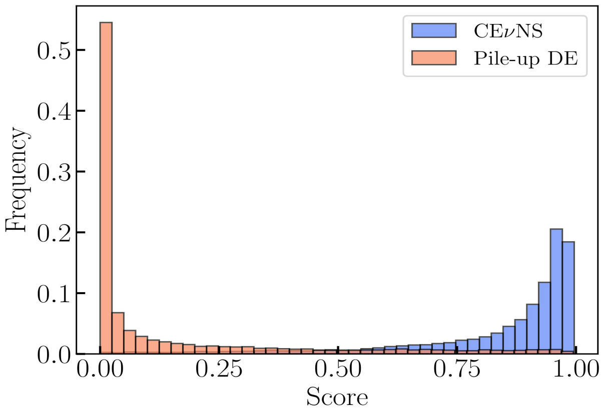
Background Rejection







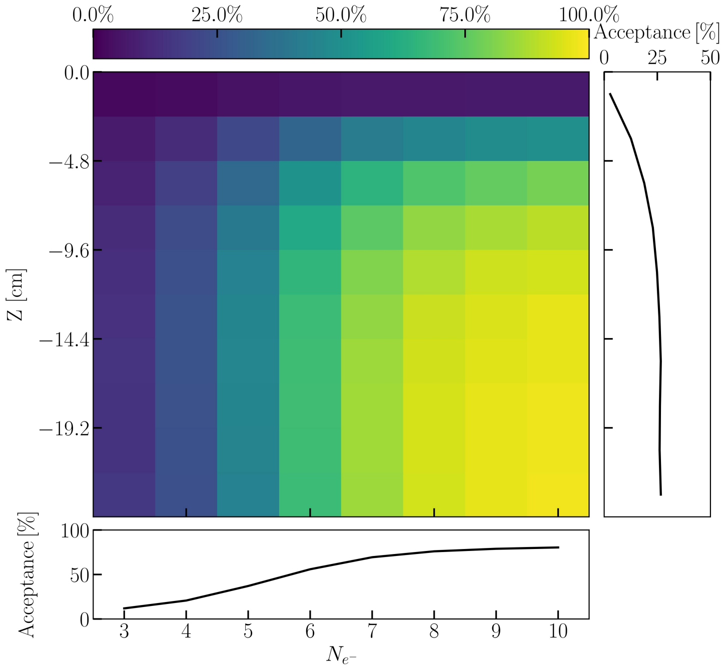
Pattern + Correlation selection:

- CEvNS: Closer to single-point events
- DE: Linked to the preceding muon track

Waveform selection:

- CEvNS: Gaussian
- DE: More dispersed

Summary of Signal Acceptance



Selection Name	Signal Acceptance	Rejection Power
S2 Width	~ 86%	~ 94%
Pattern + Correlation	~ 52%	~99.99%
Waveform	~ 80%	~90%

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Physical Potential for CEvNS

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CEvNS ROI: [120, 240] PE

Name	Events / (32kg·year)
CEvNS	4639.7
Cosmic Ray Neutron	339.9
Muon Induced Neutron	1.7
ER	21.1
DE Pile-ups	1325.1

OPEN ACCESS

Reactor neutrino liquid xenon coherent elastic scattering experiment

Chang Cai[1], Guocai Chen[2], Jiangyu Chen[3], Rundong Fang[4], Fei Gao[1,*], Xiaoran Guo[5,6], Jiheng Guo[4], Tingyi He[7,//], Chengjie Jia[1,‡] *et al.* (RELICS Collaboration)

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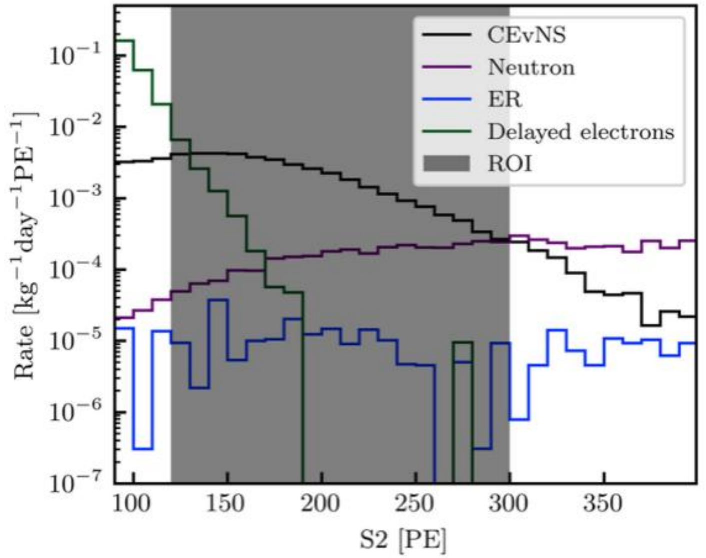
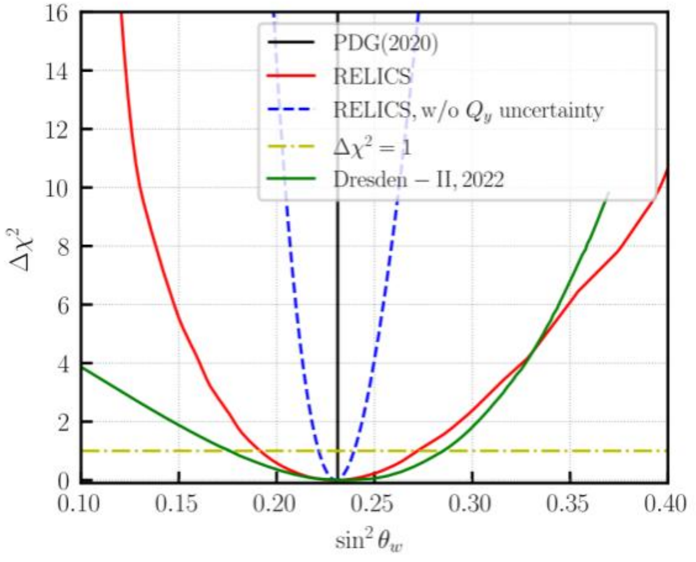
Phys. Rev. D **110**, 072011 – **Published 18 October, 2024**

DOI: https://doi.org/10.1103/PhysRevD.110.072011



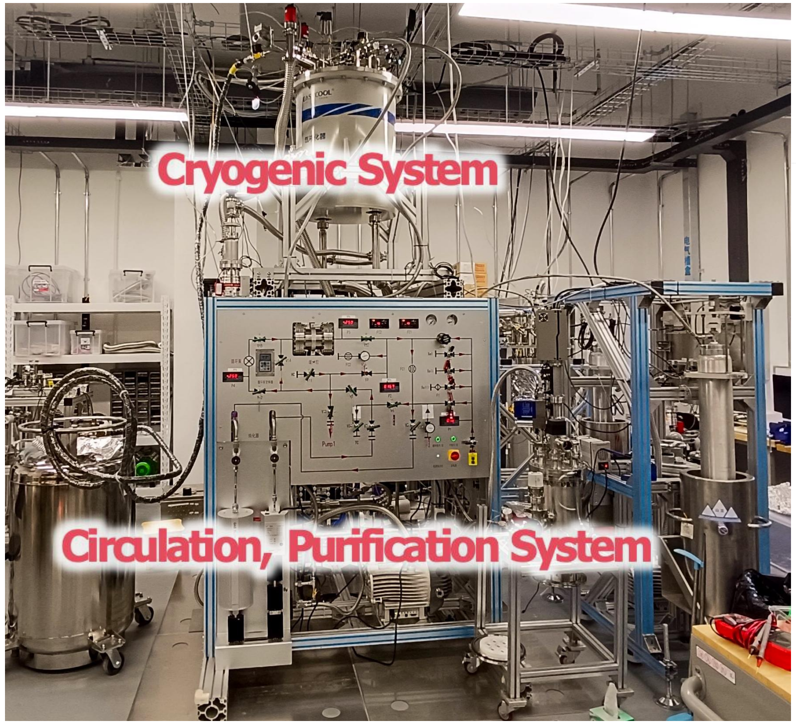


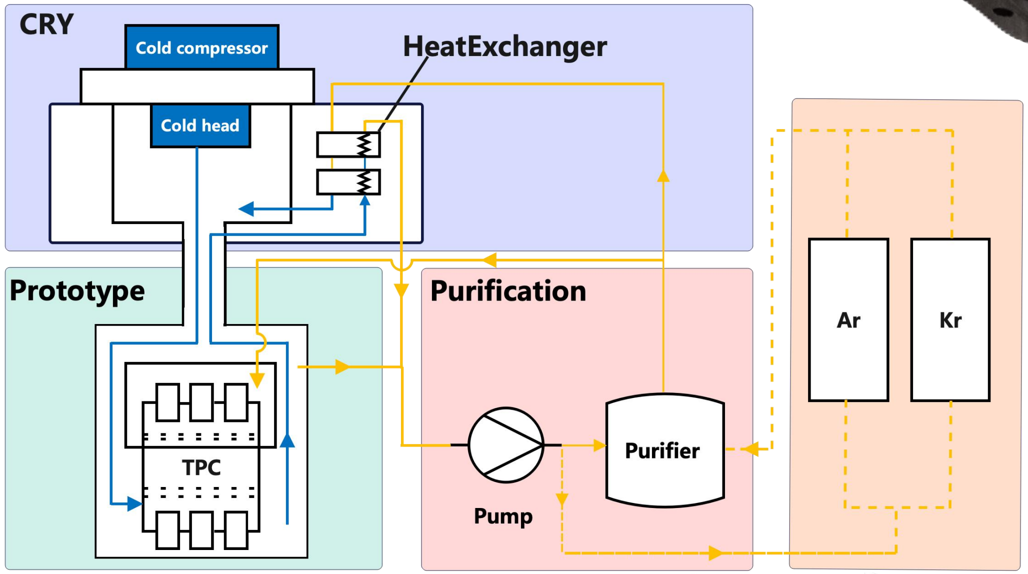
Progress and Future Outlook - Prototype

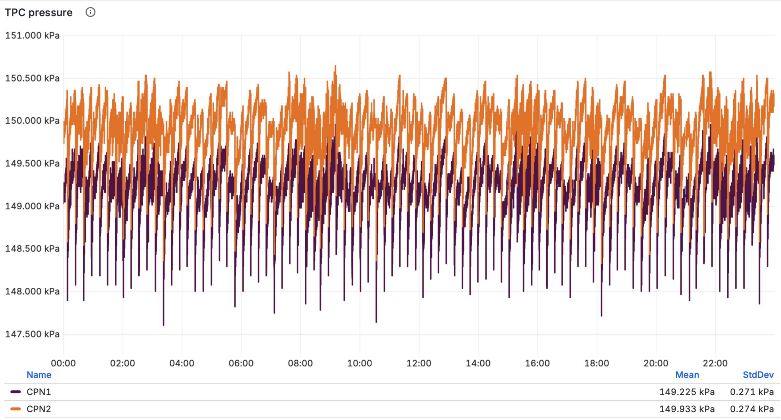
2024 ✅

RELICS Prototype：

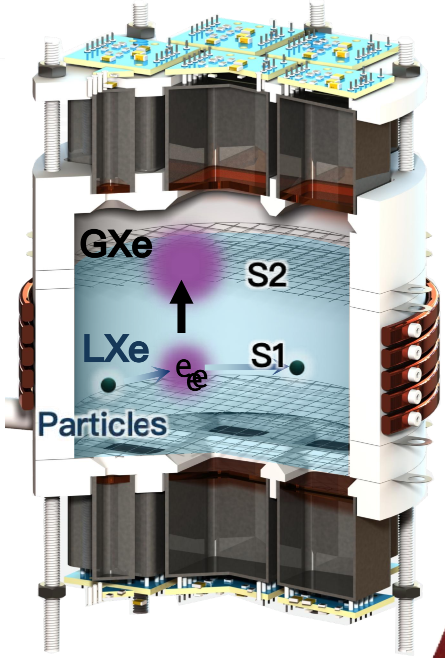
- ✓ Detector Design and Installation
- ✓ System Commissioning
- Low-Threshold Measurement
- DE background Analysis

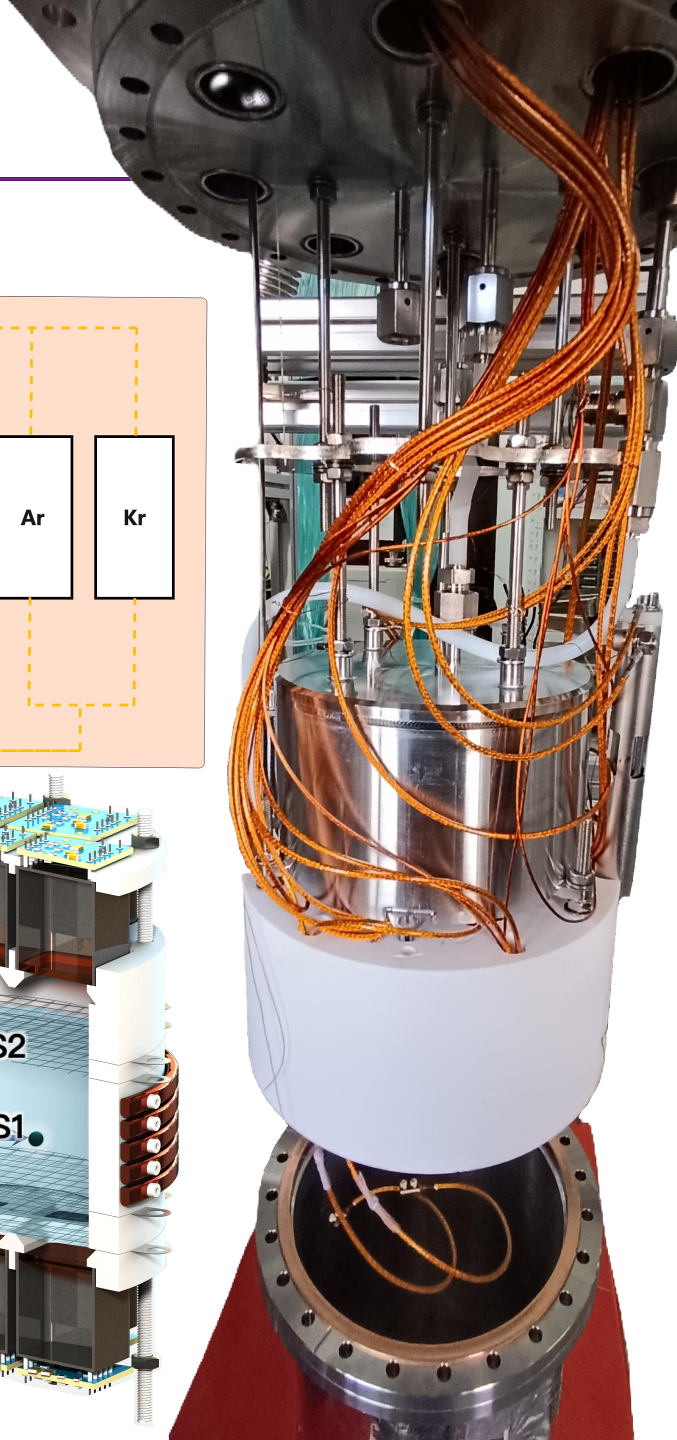






Stable TPC Pressure ～ 150kPa



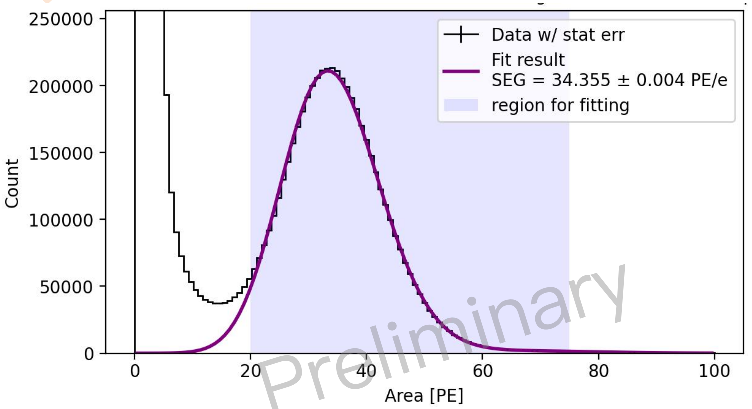


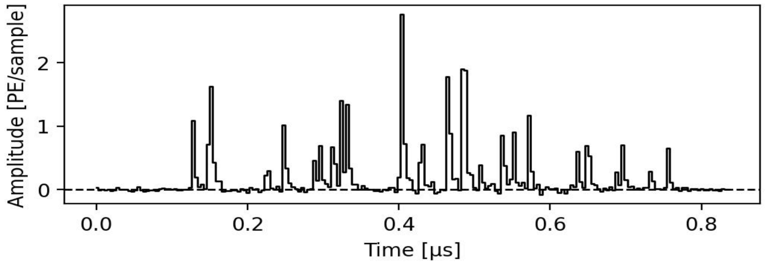
Progress and Future Outlook - Prototype

2024 ✅

RELICS Prototype：

- ✓ Detector Design and Installation
- ✓ System Commissioning
- ✓ Low-Threshold Measurement
- ✓ DE background Analysis

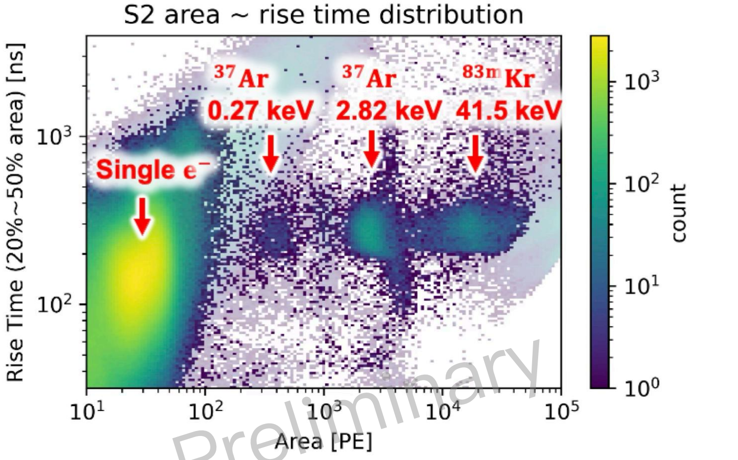


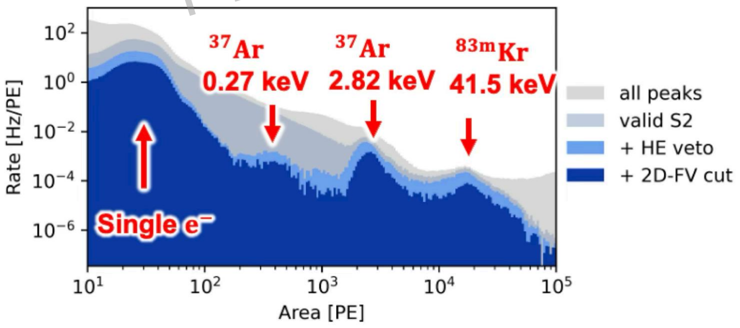


Single-electron gain ~ 35 PE/e

S2-only analysis

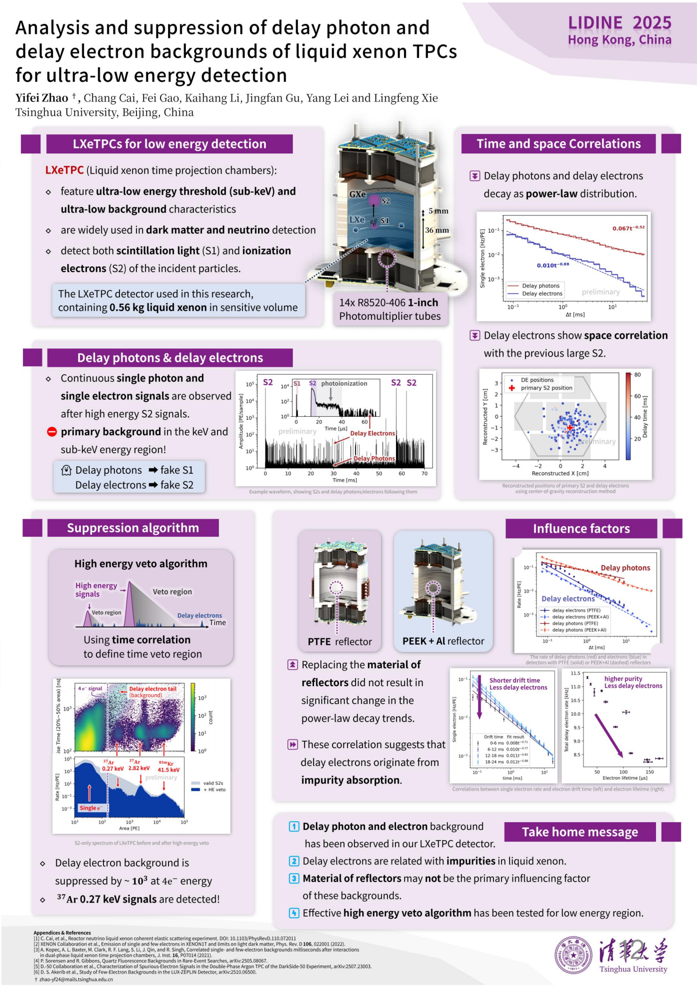
- ☐ Achieved Sub-keV Detection
- ☐ Validated CEvNS-Ready Threshold
- ☐ Validated Background Selections





Delayed Electron - Poster

Yifei Zhao



Progress and Future Outlook - RELICS 5

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2024 ✅

RELICS Prototype:

- ☐ No Shielding
- ☐ Ar and Kr Sources
- ☐ LXe Mass ~ 0.55kg
- ☐ PMT Number ~ 14

2026 ⚒

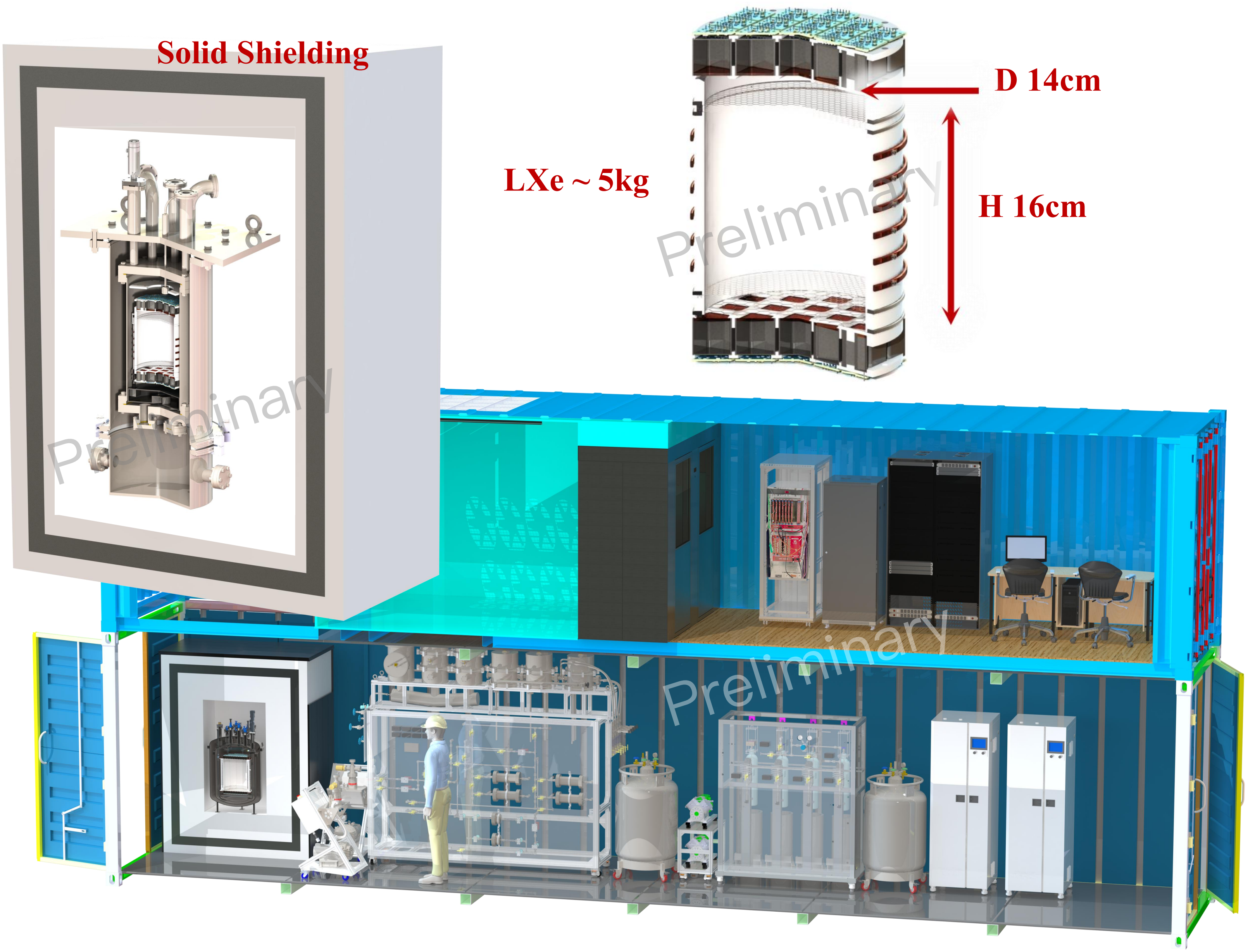
RELICS 5:

- ☐ Solid Shielding
- ☐ Reactor Neutrino
- ☐ 99% Muon Veto
- ☐ LXe Mass ~ 5kg
- ☐ PMT Number ~ 38

2028 ⚒

RELICS 50:

- ☐ Water Shielding
- ☐ Reactor Neutrino
- ☐ 99% Muon Veto
- ☐ LXe Mass ~ 50kg
- ☐ PMT Number ~ 128



Summary

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RELICS : Measuring Coherent Neutrino-Nucleus Scattering Utilizing Dual-Phase Xenon TPC

1.RELICS will find ~4600 CEvNS events in 32 kg sensitive volume one year of exposure

✅ **sufficient signal observation**

2.Delayed Electron pile-up events will be the dominant background, but can be suppressed by waveform and pattern-spacetime cuts

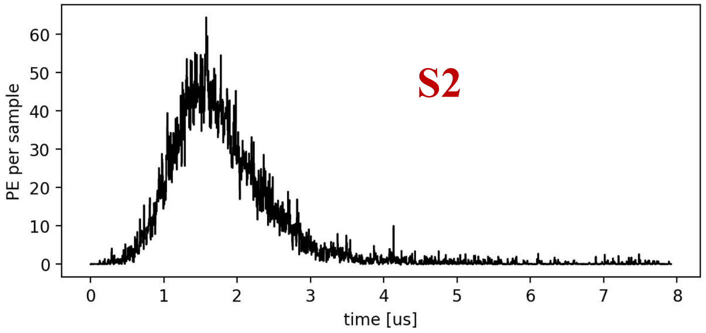
✅ **low background (shielding & cut selection)**

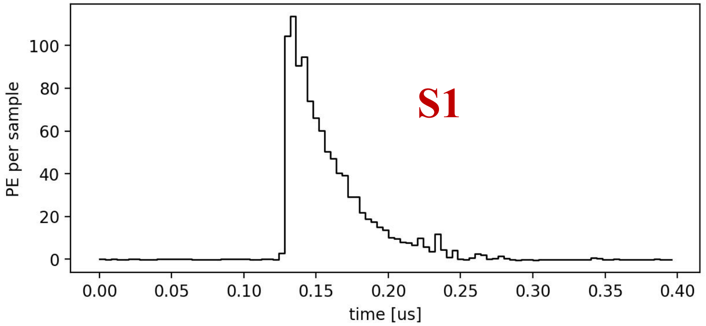
3.The prototype has verified the feasibility of each sub-system for the RELICS experiment and the capability to detect single-electron signals and signals from calibration sources in the low-energy region.

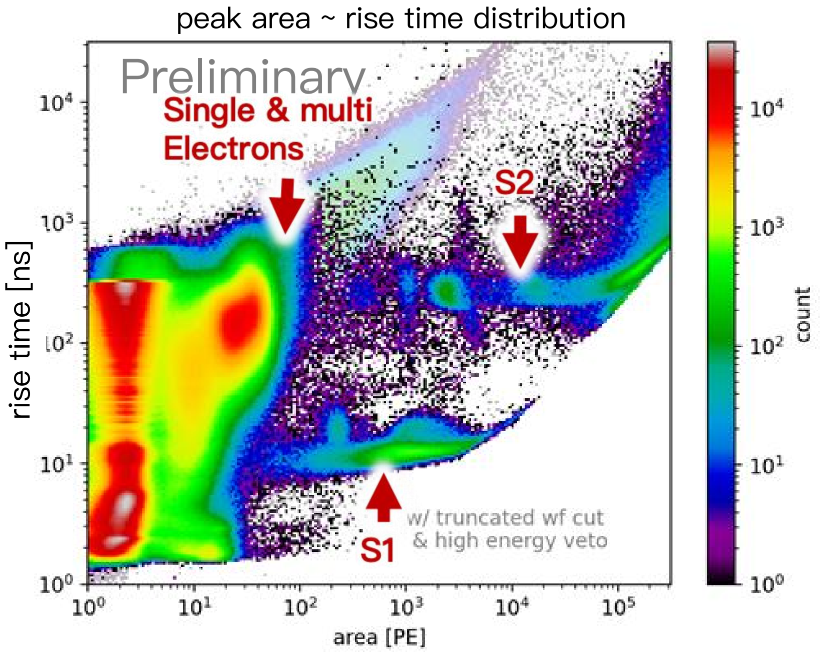
✅ **low threshold (single PE trigger rate& single-electron detection gain)**

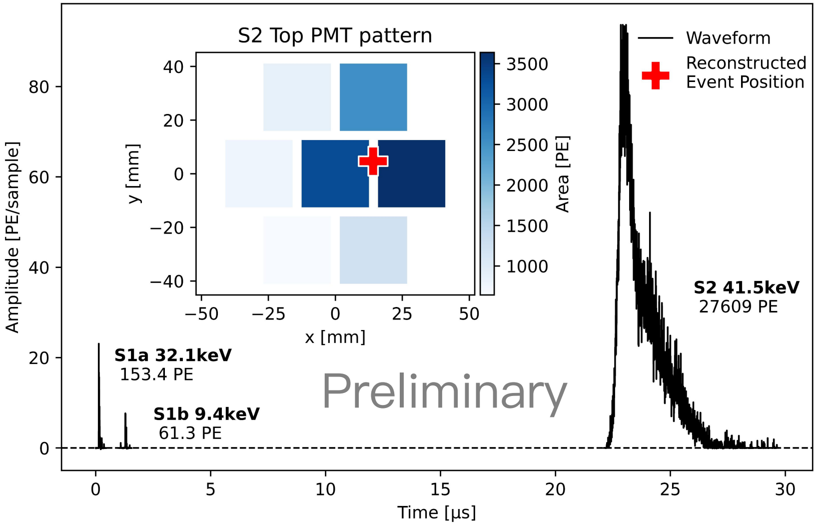
The RELICS detector is scheduled for construction this year and will begin taking data in 2026

Back Up


S2
PE per sample
time [us]

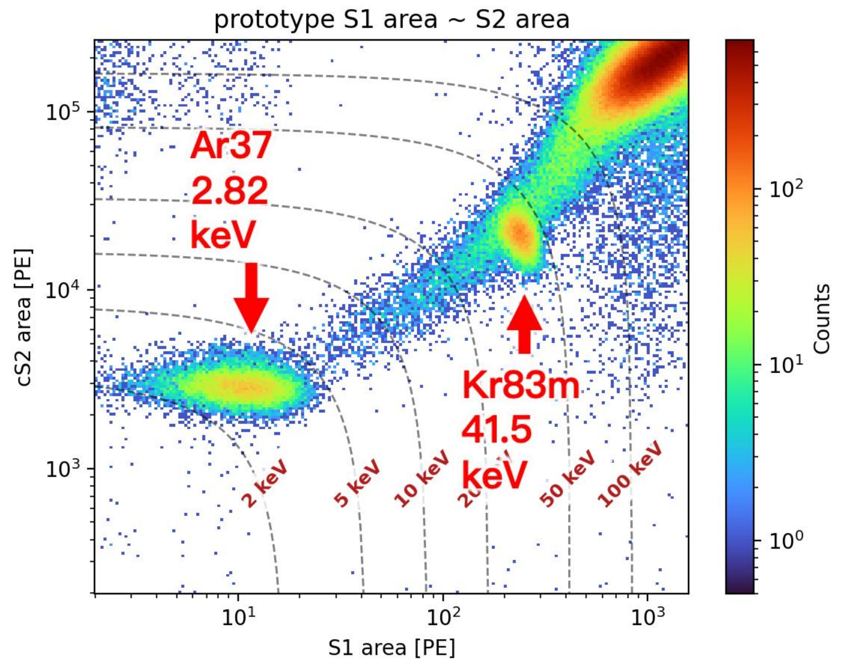

S1
PE per sample
time [us]

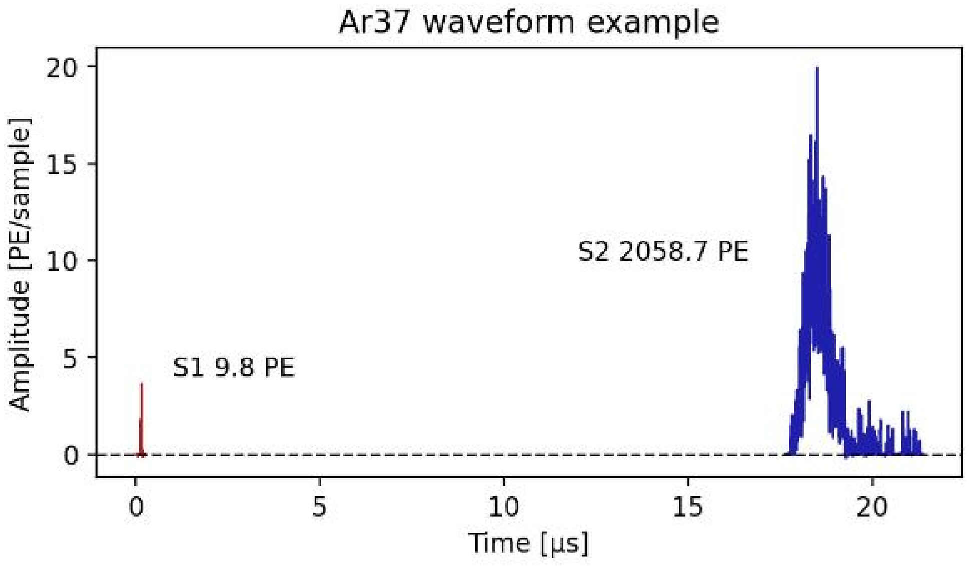

peak area ~ rise time distribution
Preliminary
Single & multi
Electrons
S2
S1
w/ truncated wf cut
& high energy veto
rise time [ns]
area [PE]
count

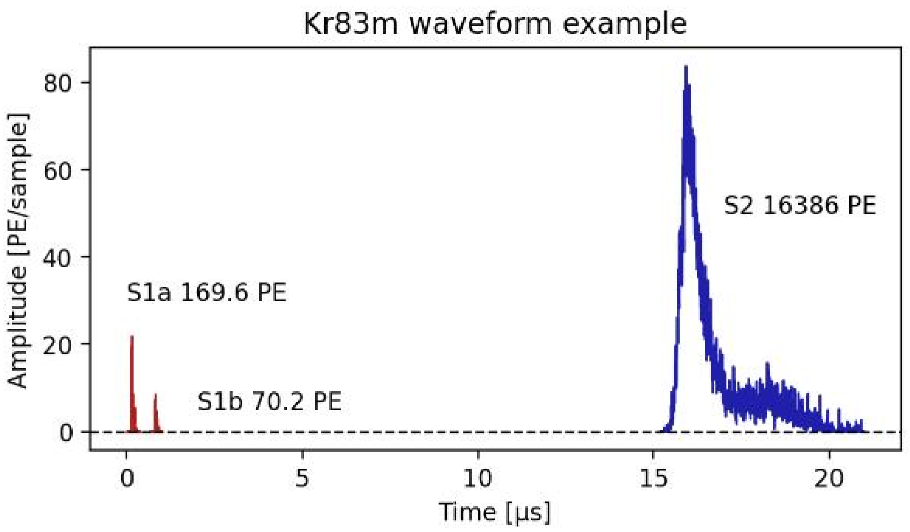

S2 Top PMT pattern
y [mm]
x [mm]
Area [PE]
Waveform
Reconstructed
Event Position
S2 41.5keV
27609 PE
S1a 32.1keV
153.4 PE
S1b 9.4keV
61.3 PE
Preliminary
Amplitude [PE/sample]
Time [μs]

Back Up

Kr-83m		32.1	1.83 h
		9.4	154 ns
Ar-37	K-shell	2.82	35 d
	L-shell	0.27	







Back Up

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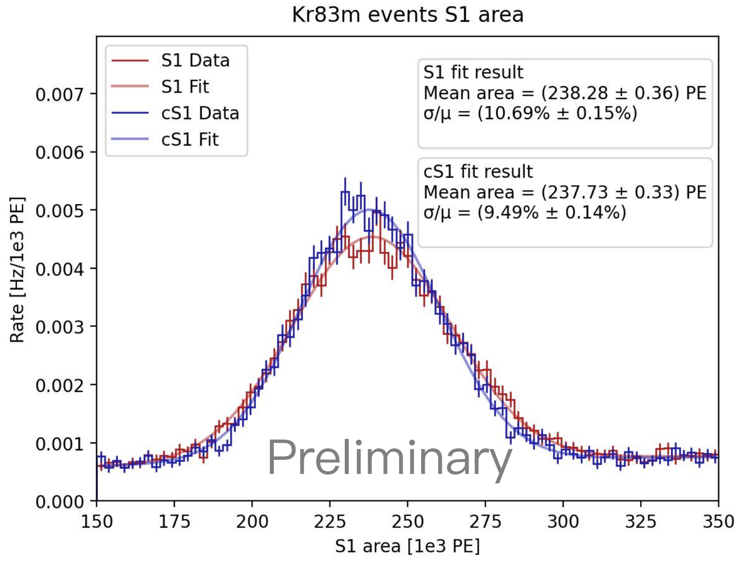
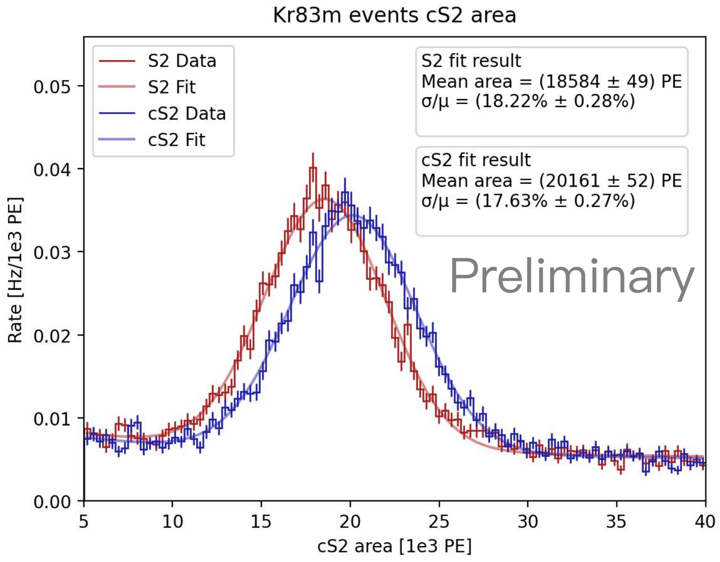
Electron Extraction Efficiency $\eta_{extra} = \sim 93.9\ \%$

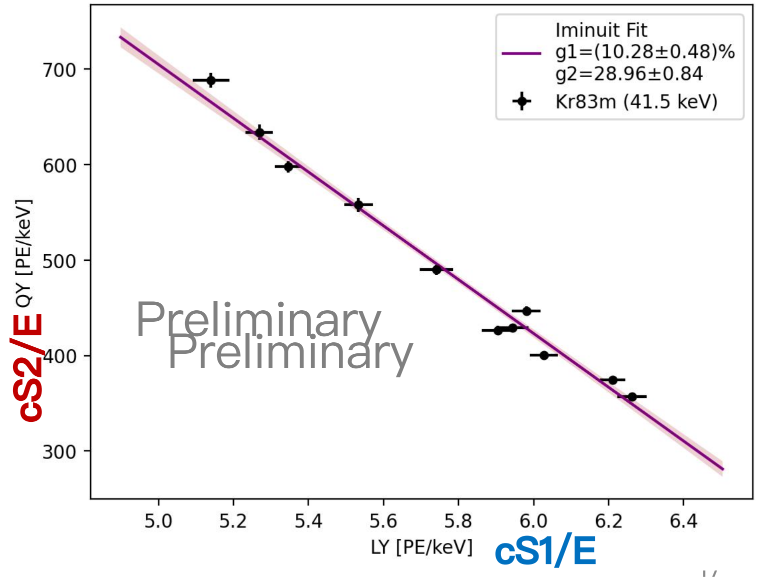
Scintillation Light Detection Efficiency $g1 = 10.28\ \%$

Total Electron Gain $g2 = 28.96$ PE

$$\frac{E}{W} = L + Q = \frac{cS1}{g1} + \frac{cS2}{g2}$$

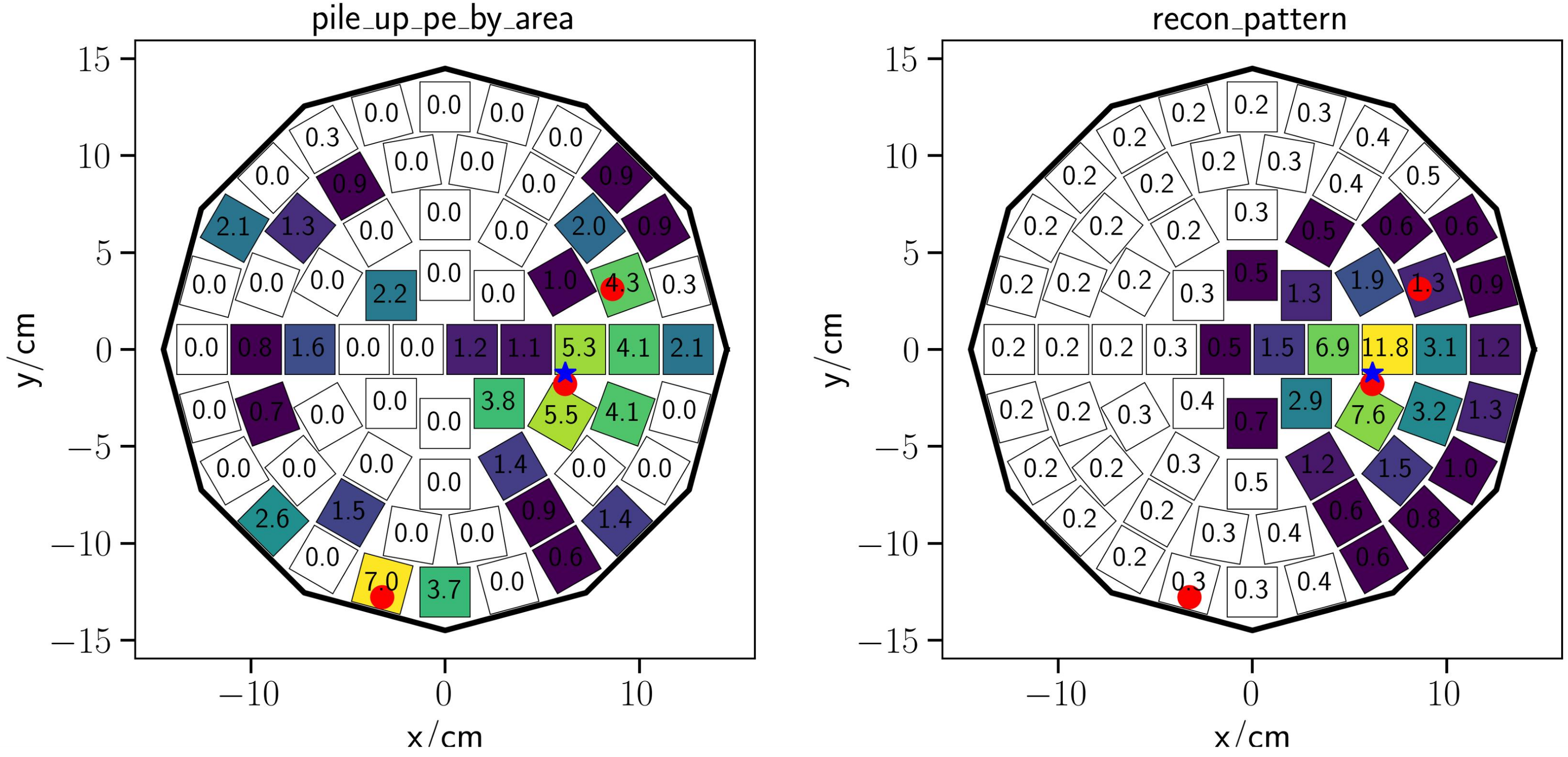






Back Up

Pattern Coefficient Calculation:



$$P = \sum_{ch=0}^{63} \log\left(\frac{{\lambda_{ch}}^{N_{ch}^{pe}} \times e^{-\lambda_{ch}}}{N_{ch}^{pe}!}\right)$$

$$P_i = N_i \times (t - t_i)^{-\gamma} \times \frac{1}{2\pi \cdot \sigma^2} e^{-\frac{(x-x_i)^2+(y-y_i)^2}{2\sigma^2}}$$