RELICS
REactor neutrino **LI**quid xenon
Coherent elastic **S**cattering

西湖大学 | 暗物质与中微子实验室

RELICS: a REactor neutrino LIquid xenon Coherent elastic Scattering experiment

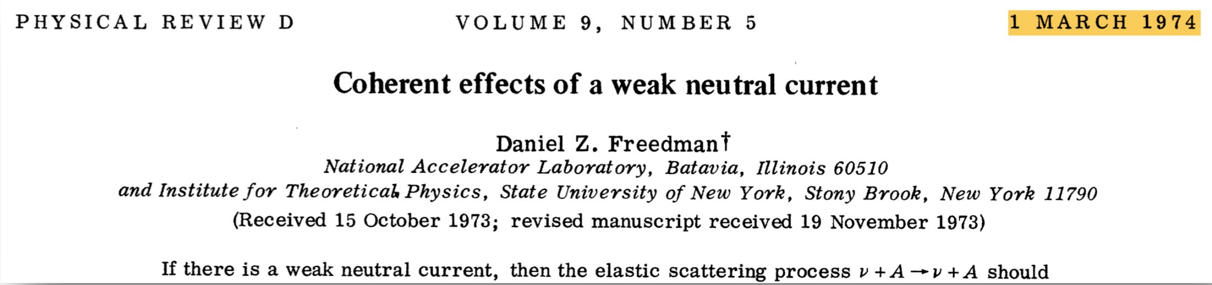
Shengchao Li

Westlake University
lishengchao@westlake.edu.cn

vSTEP 2024, Hangzhou – 2024.5.19

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

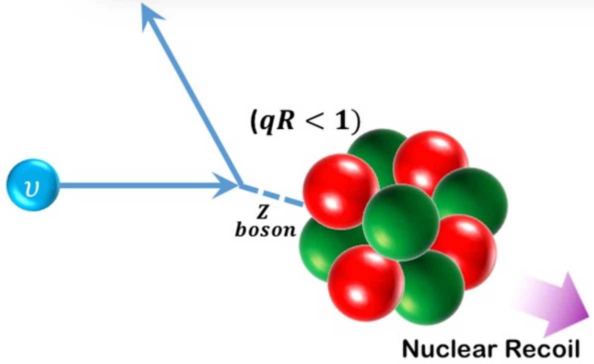
西湖大学 | 暗物质与中微子实验室

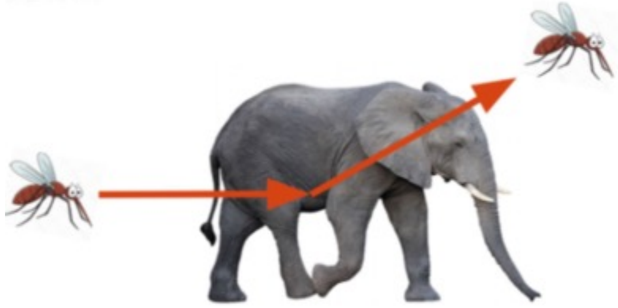

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should



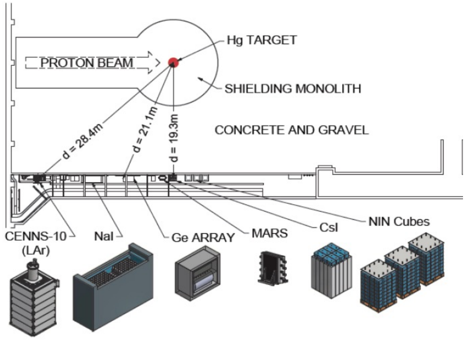


$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2.$$

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

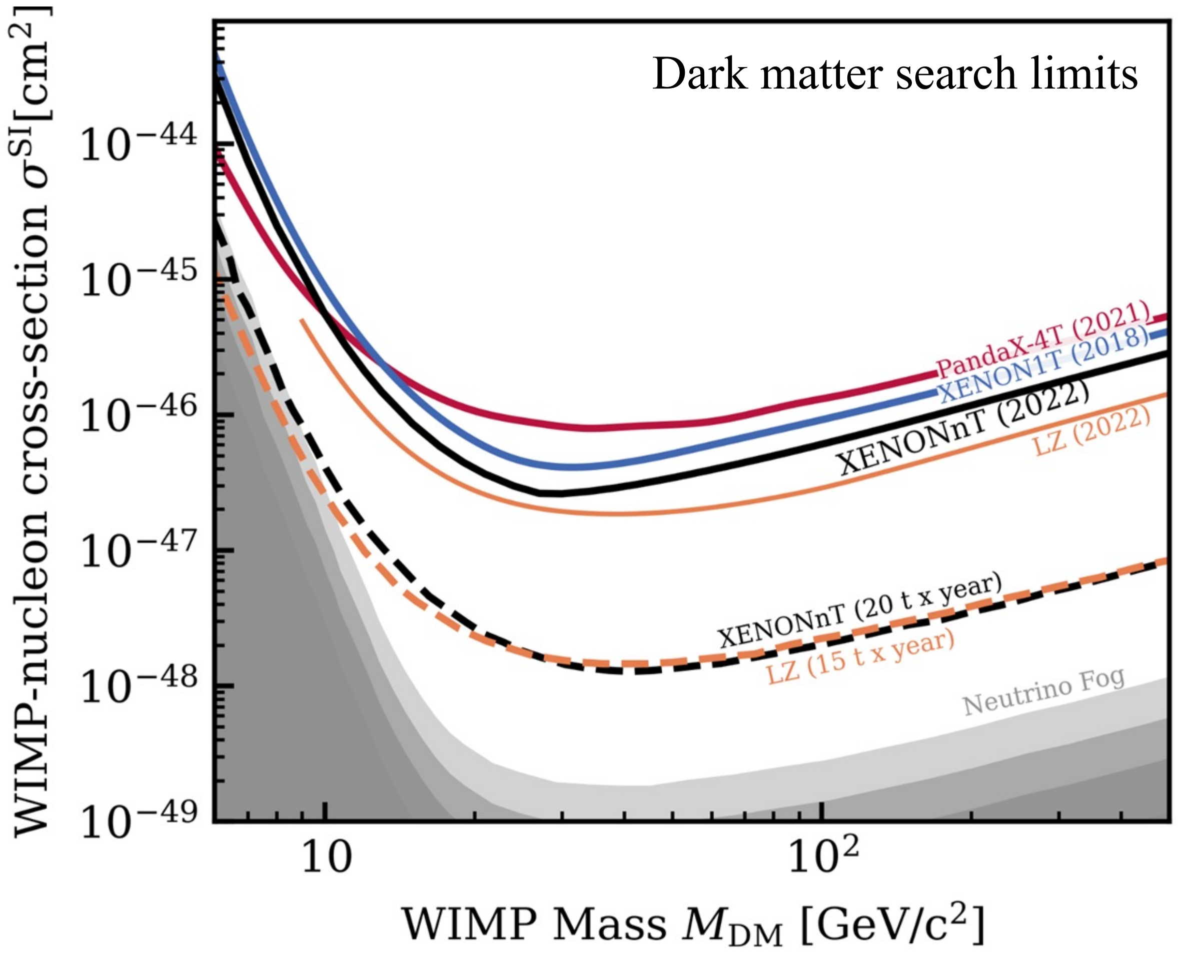
$$Q_W \propto N \implies \boxed{\frac{d\sigma}{dT} \propto N^2}$$

- qR < 1
- Z-exchange between neutrino and **entire** nucleus
- Coherent up to $E_\nu \sim 50$ MeV
- First discovery in 2017 by COHERENT



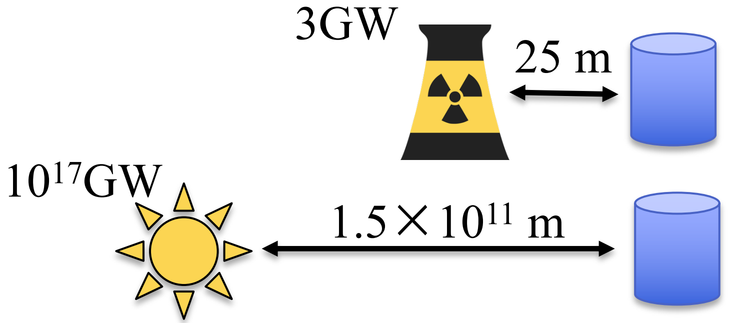
SCIENCE 357, no. 6356, 1123-1126 (2017)

Why xenon detector?



- Liquid xenon TPC is a leading technology for low-threshold rare event detection
- Neutrino fog/floor is around the corner for ton-scale dark matter experiments
- First CEνNS signal expected soon from ^{8}B solar neutrino, only 1~10 events to appear; but we can have much more CEνNS signal

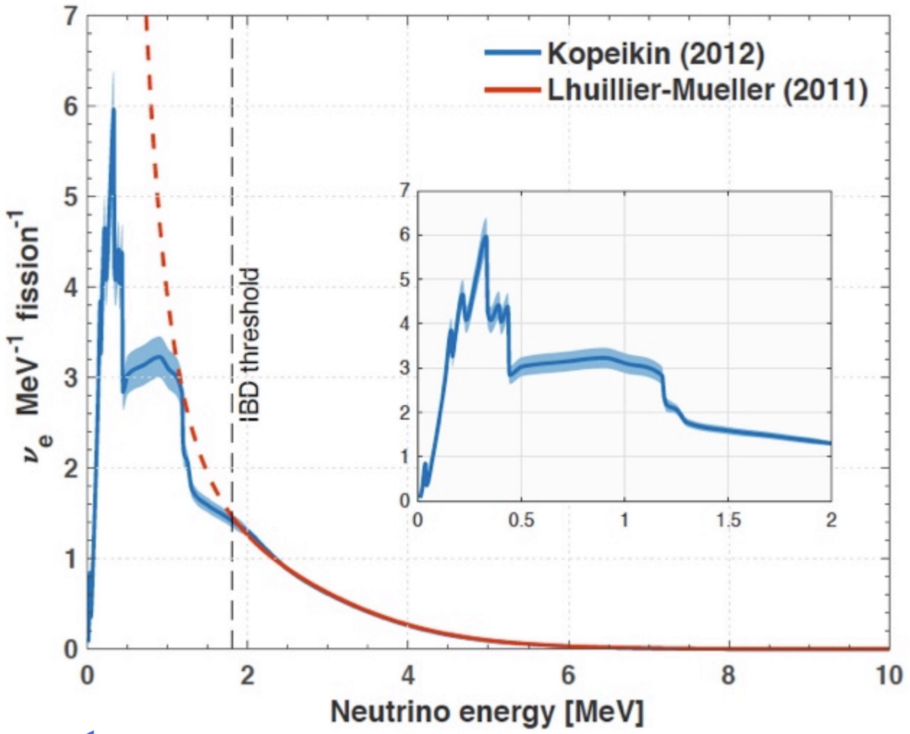
Why reactor?



$\Phi_\upsilon \approx 1\times10^{13}/s/cm^2$

6-7 orders

$\Phi_\upsilon \approx 5\times10^{6}/s/cm^2$

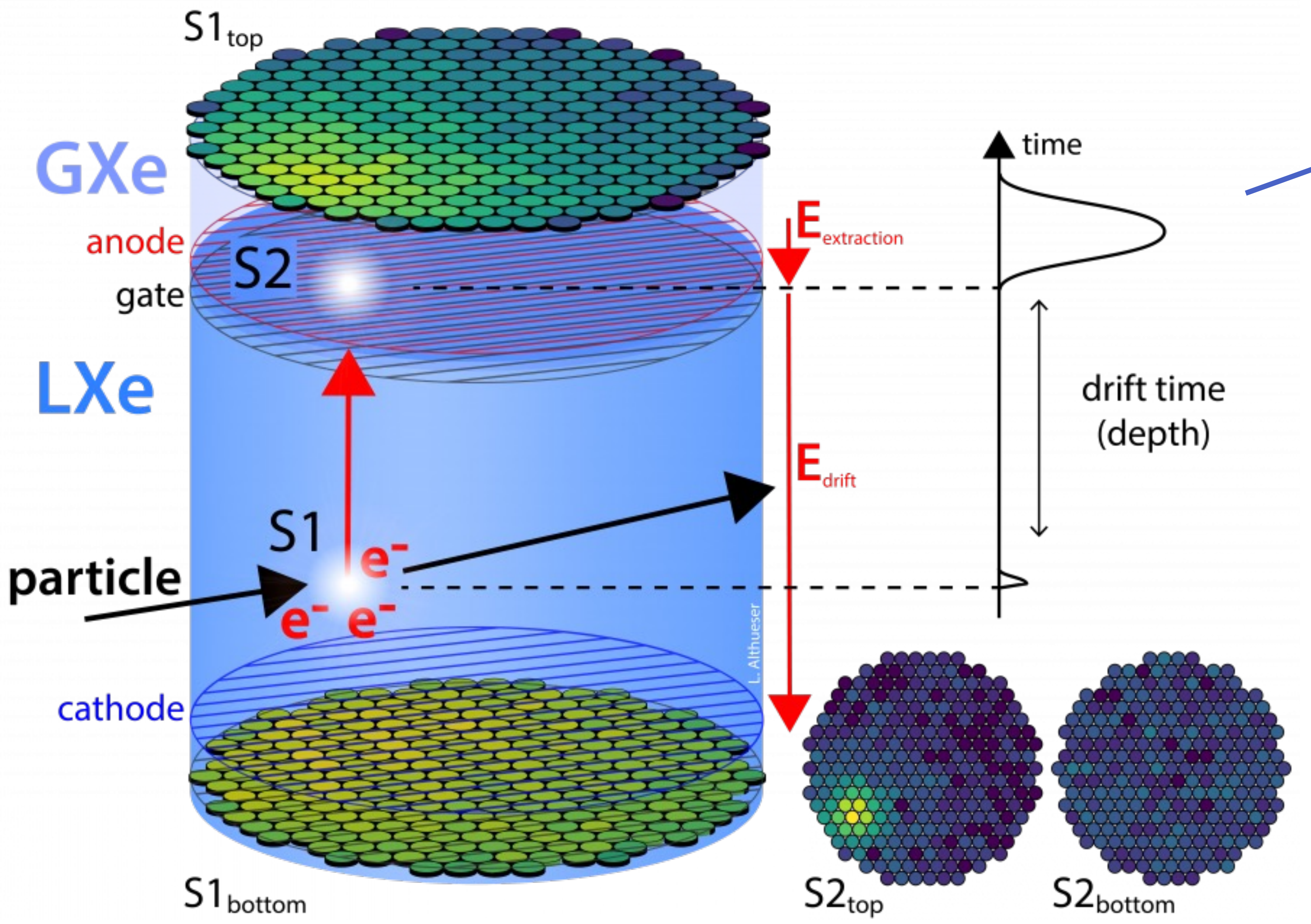


CEvNS-dominate energy

- Reactors are neutrino factories for copious MeV neutrinos; on-off measurement possible
- Reactors neutrinos are mostly below 6MeV energy, CEvNS is the dominating interaction channel
- For reactor neutrino flux, traditional IBD cannot probe <1.8MeV; CEvNS has no interaction threshold, more insights (fission, nuclear model, etc.)
- New reactor monitoring?

LXeTPC in a nutshell

西湖大学 | 暗物质与中微子实验室



XENONnT

Prompt-delayed coincidence

Scintillation (S1) + Ionization (S2)

3D position reconstruction

e^- drift velocity
z position (depth)

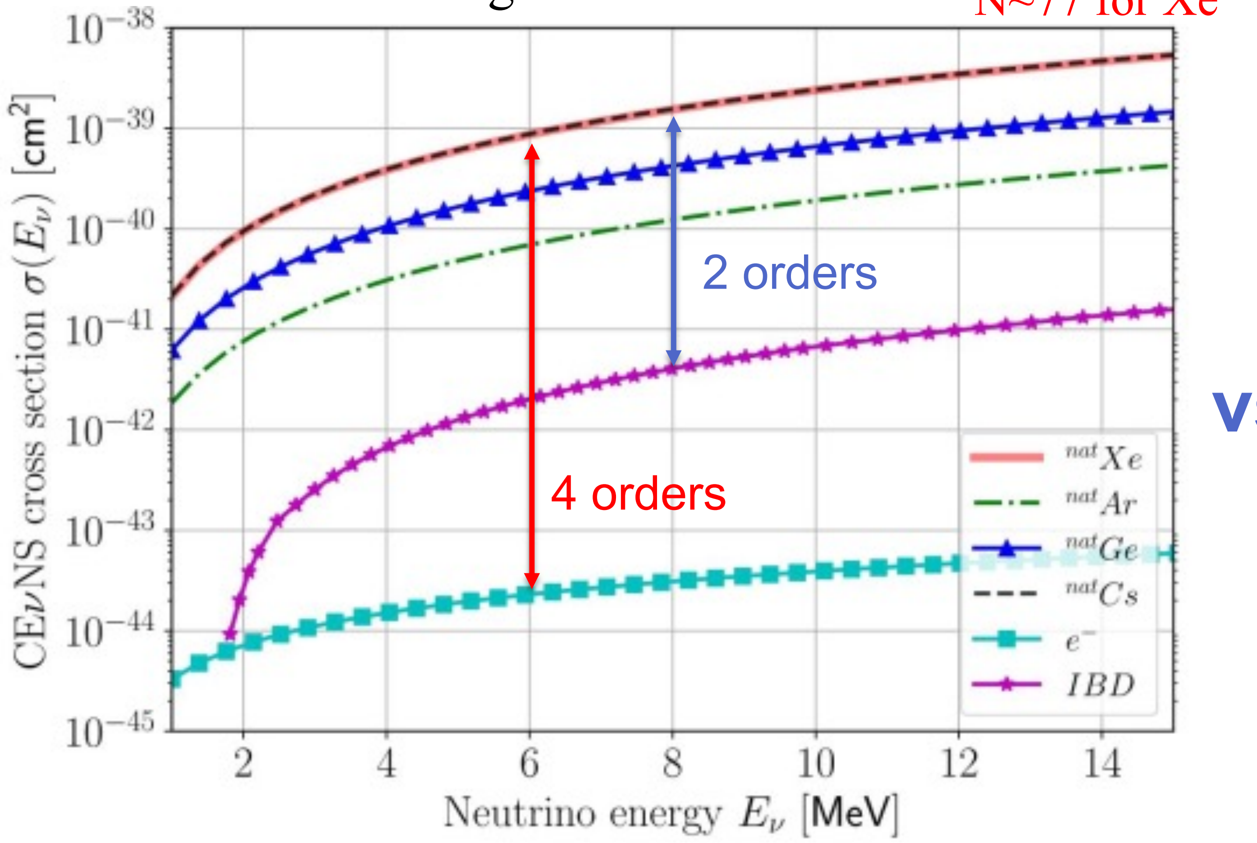
+

$S2_{top}$ PMT pattern
x-y position

Advantages and challenges

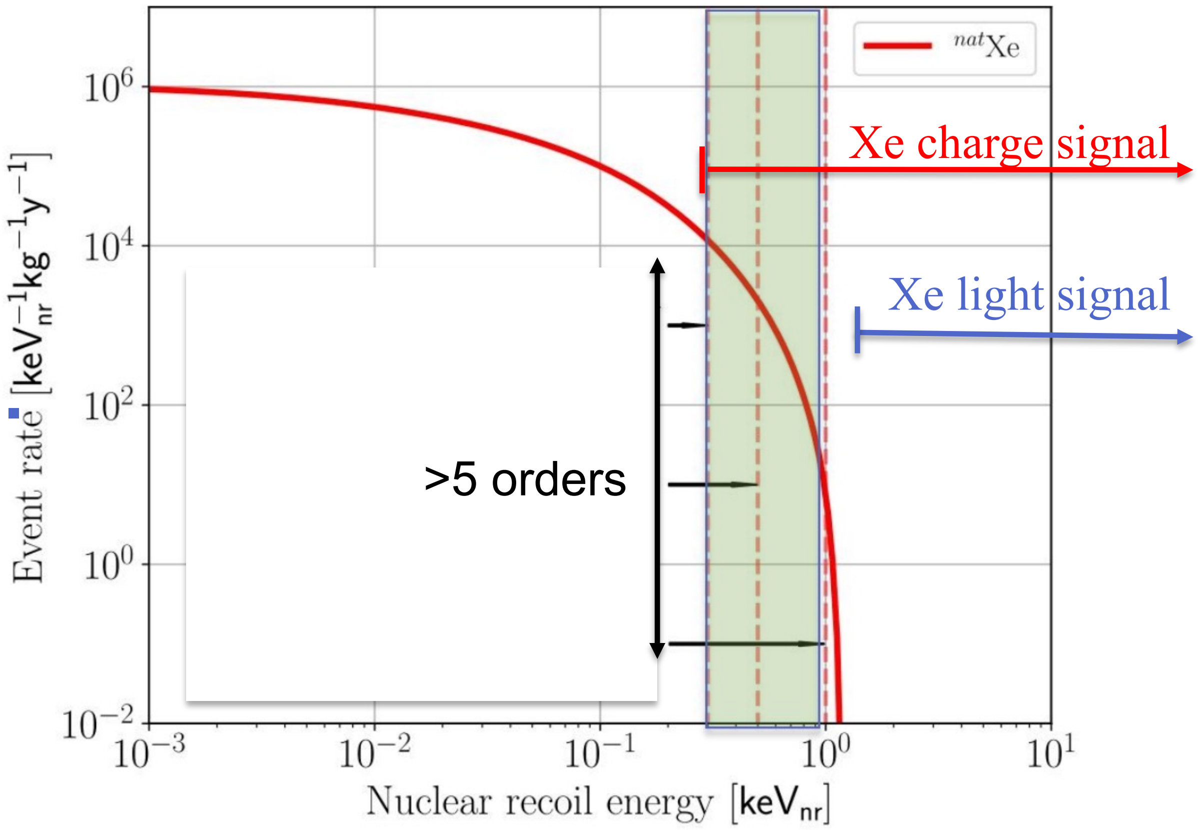
High cross-section ☺

N~77 for Xe



vs.

Weak signal ☹



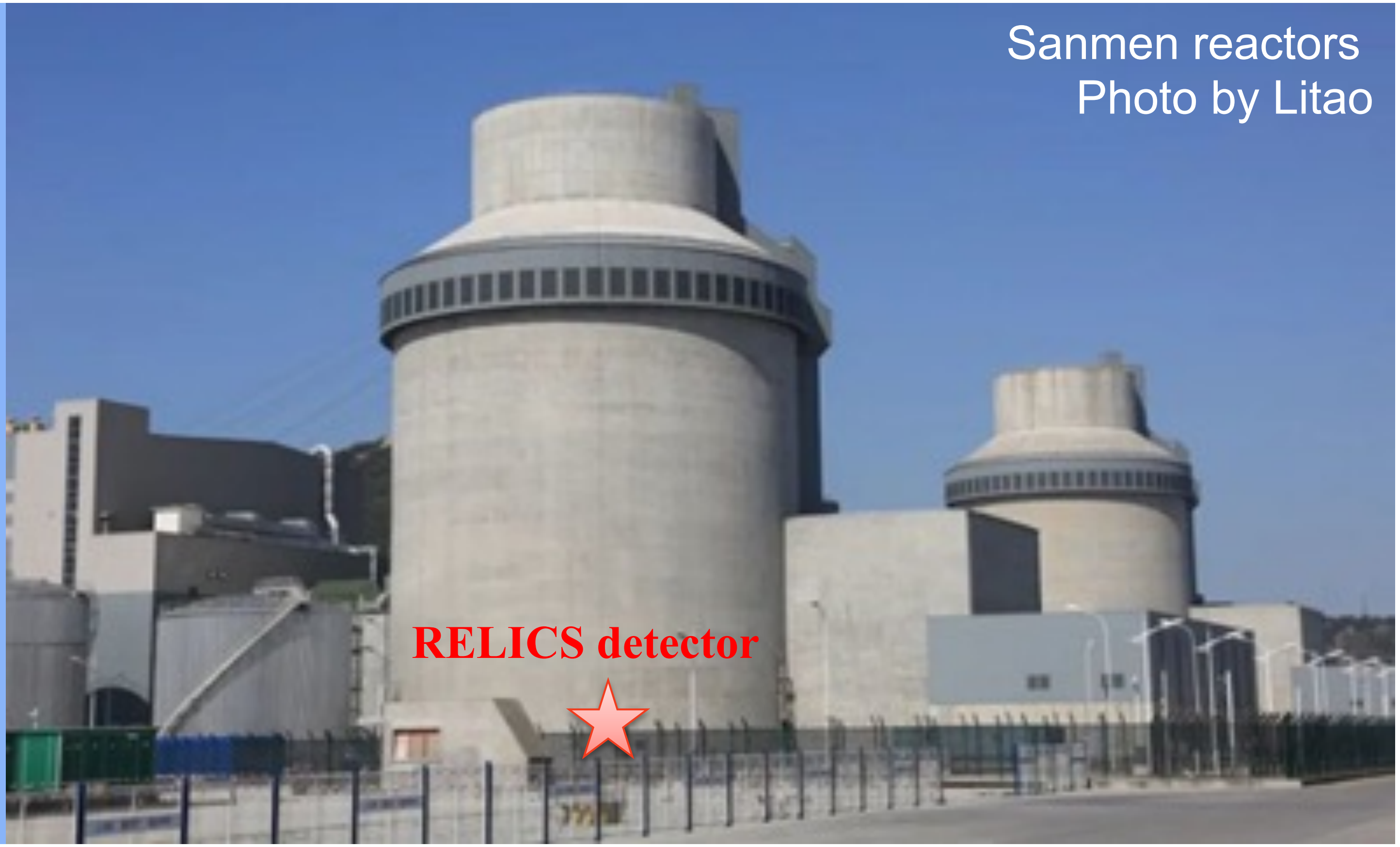
$$E = 13.7\text{eV}\left(\frac{cS1}{0.1} + \frac{cS2}{25}\right)$$

→ Every 13.7eV energy produce **0.1** S1 and **25** S2 in xenon

→ Use S2 signal only for low-threshold

RELICS Collaboration

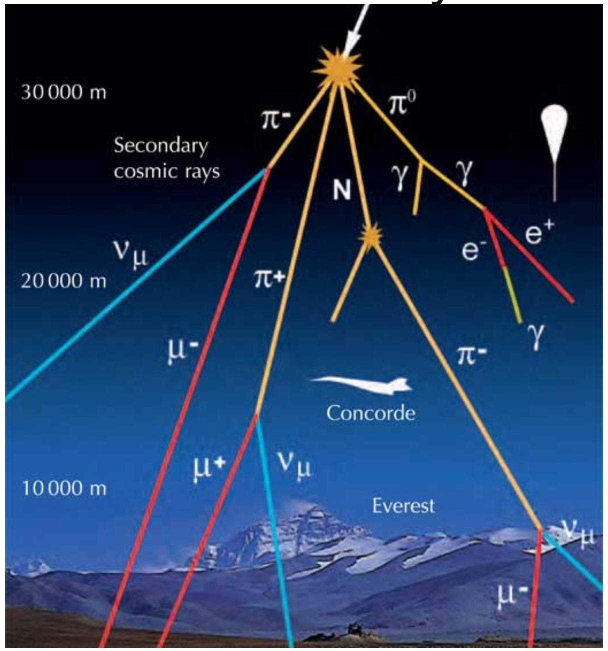
RELICS Site

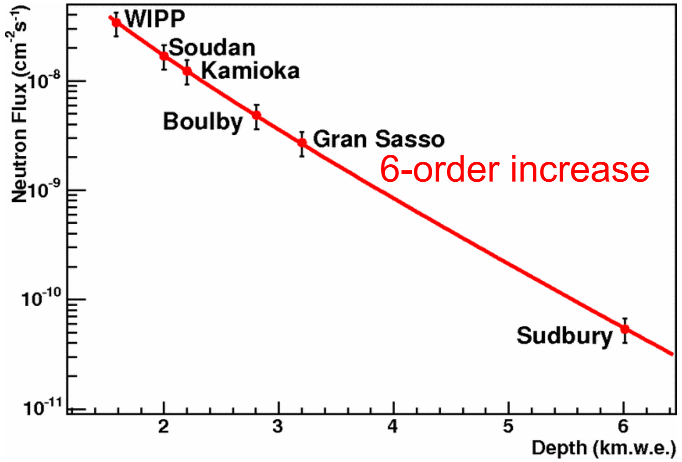


- Reactor power ~3GW， baseline ~25m
- Expected neutrino flux ~$\mathbf{10^{13}} \boldsymbol{\upsilon}/cm^2/s$

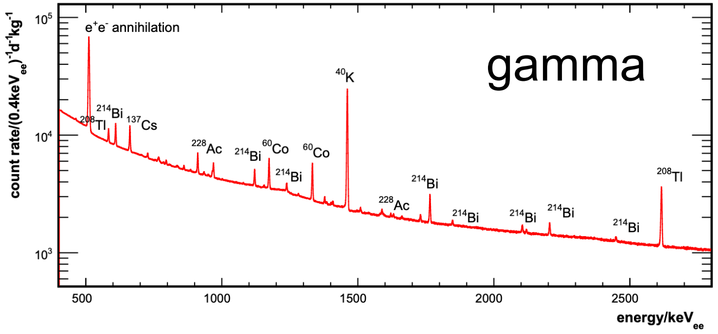
From underground (low-background) to near-reactor (high-background)

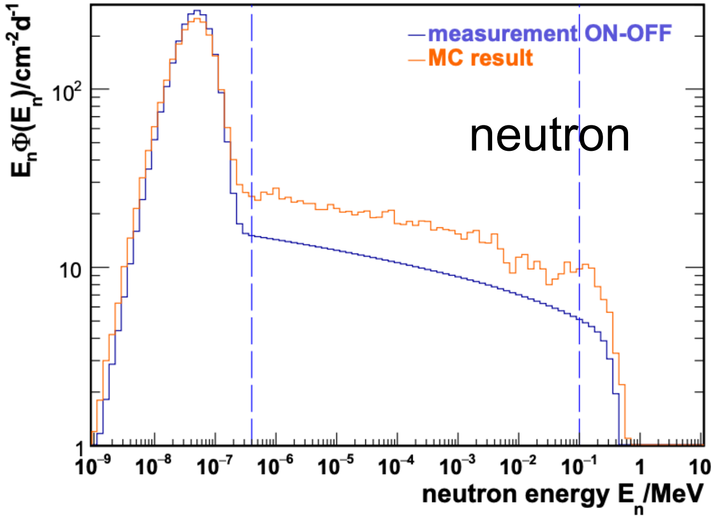
Cosmic Ray





Reactor





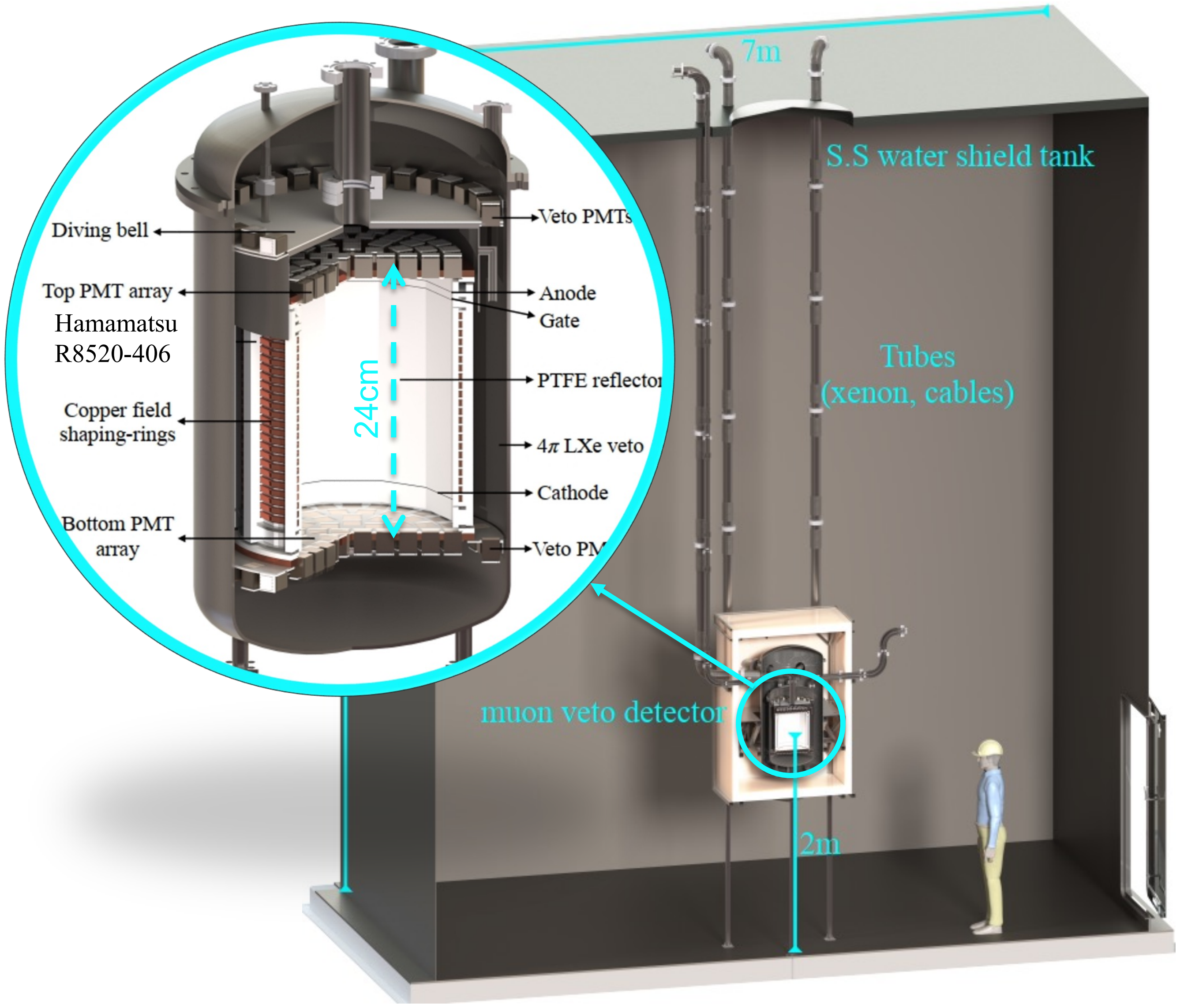
[Bonet+, 2112.09585]

[Haghighat, LSC+, 1812.02163]

event. Together these topological selections have enabled us to identify the IBD events in a surface-level detector where correlated background events outnumber the true IBD events by more than 400 to 1.

RELICS is a **low-threshold** liquid xenon experiment in **high-background** environment.

RELICS Detectors Design

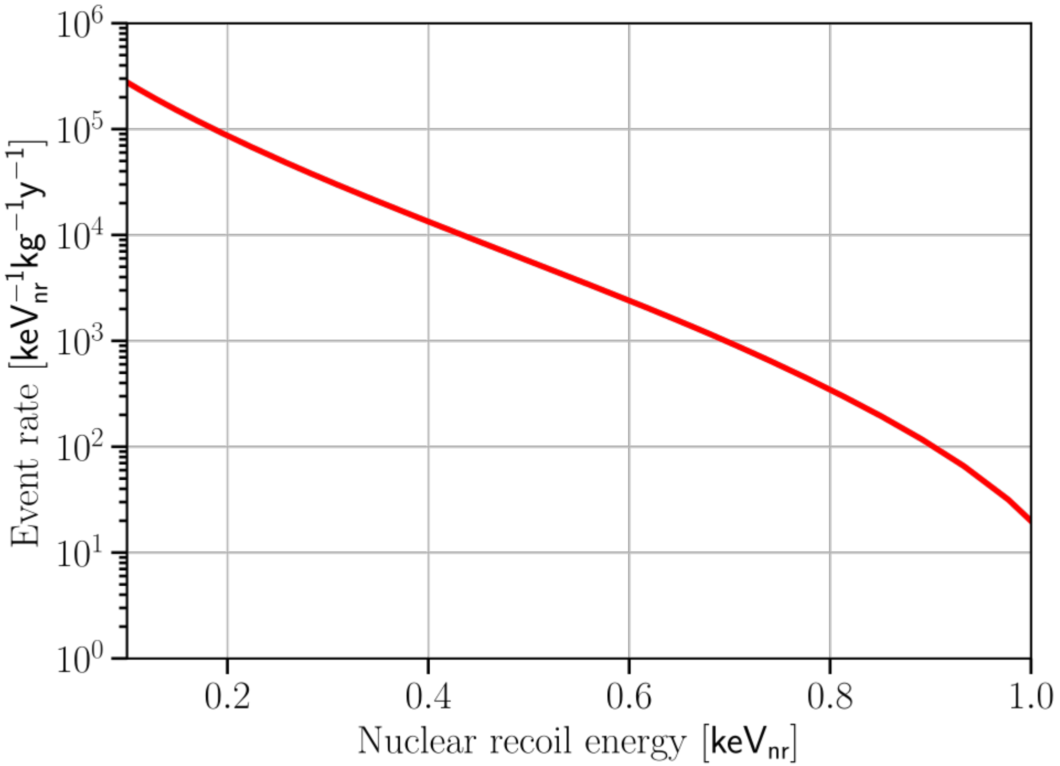


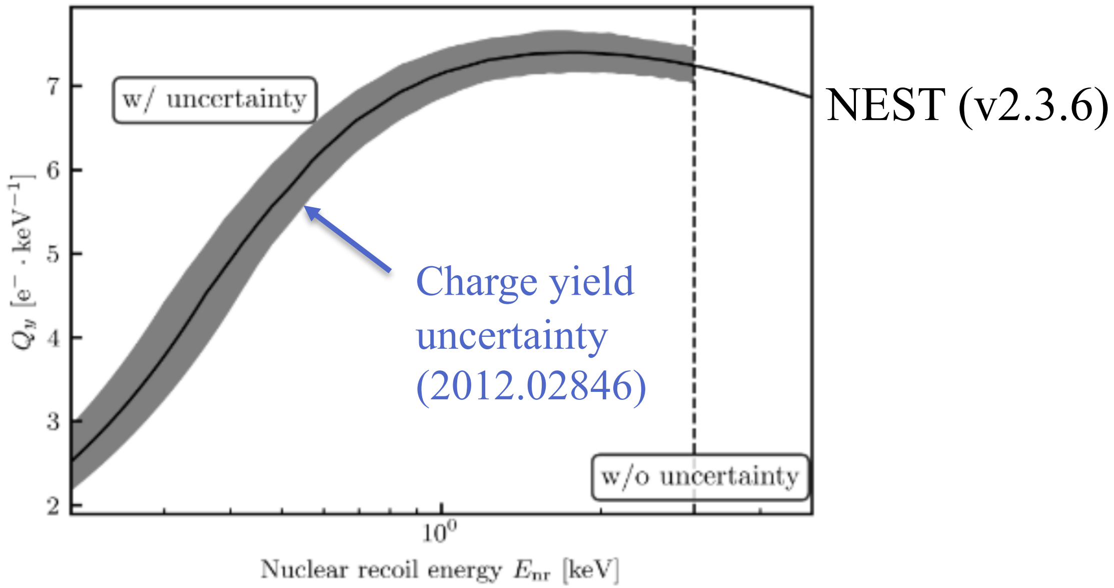
- 7m passive water shield
- Circulation and purification on top
- Plastic scintillator muon veto
- Xe skin (c.f. LZ) for gamma, beta
- 32kg fiducial volume TPC
- Top & bottom 64 PMTs each
- Extraction field 10kV/cm
- Drift field 500V/cm
- Low background materials

CEνNS Signal

西湖大学 | 暗物质与中微子实验室

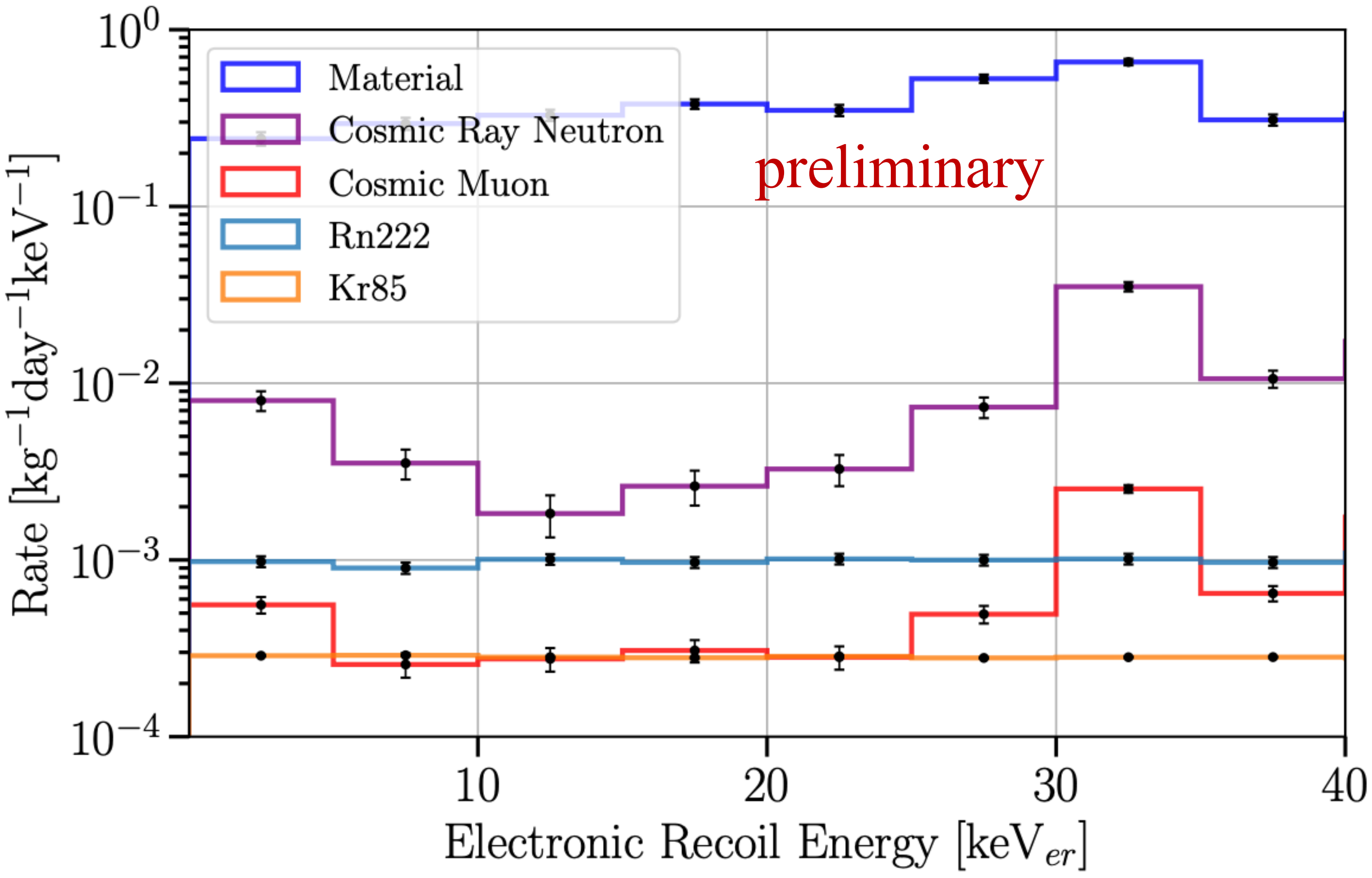
$$\frac{dN}{dE_R} = N_t \int \phi(E_\upsilon) \frac{d\sigma}{dE_R} dE_\upsilon$$





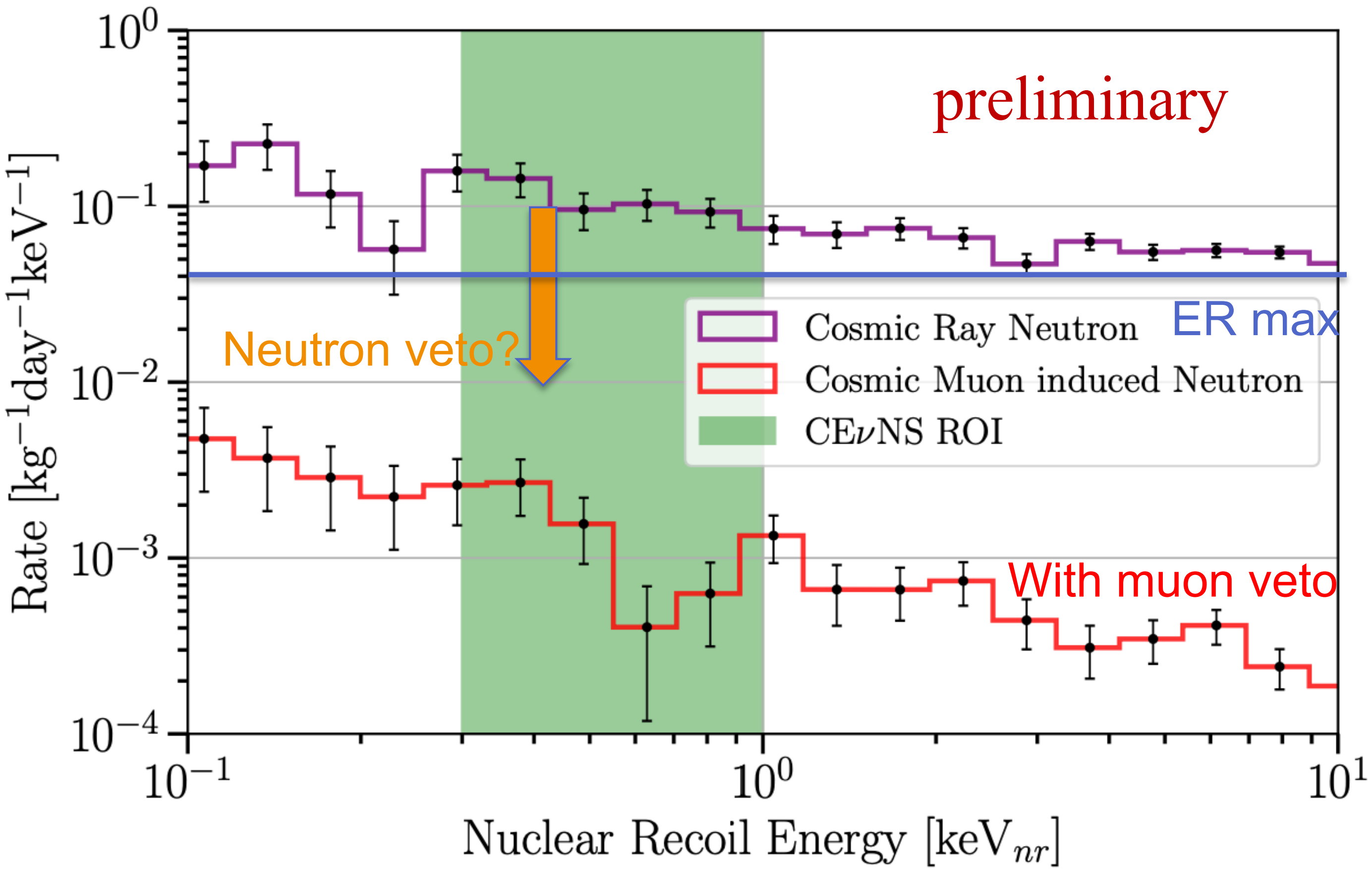
- Huber-Muller model for flux
- ^{235}U (56.1%), ^{239}Pu (30.7%), and ^{241}Pu, ^{238}U
- 13673.5 signal in [0.3,1] keV$_{nr}$ with 32 kg ∗ year exposure, 25m@3GW

Electronic Recoil (ER) Backgrounds



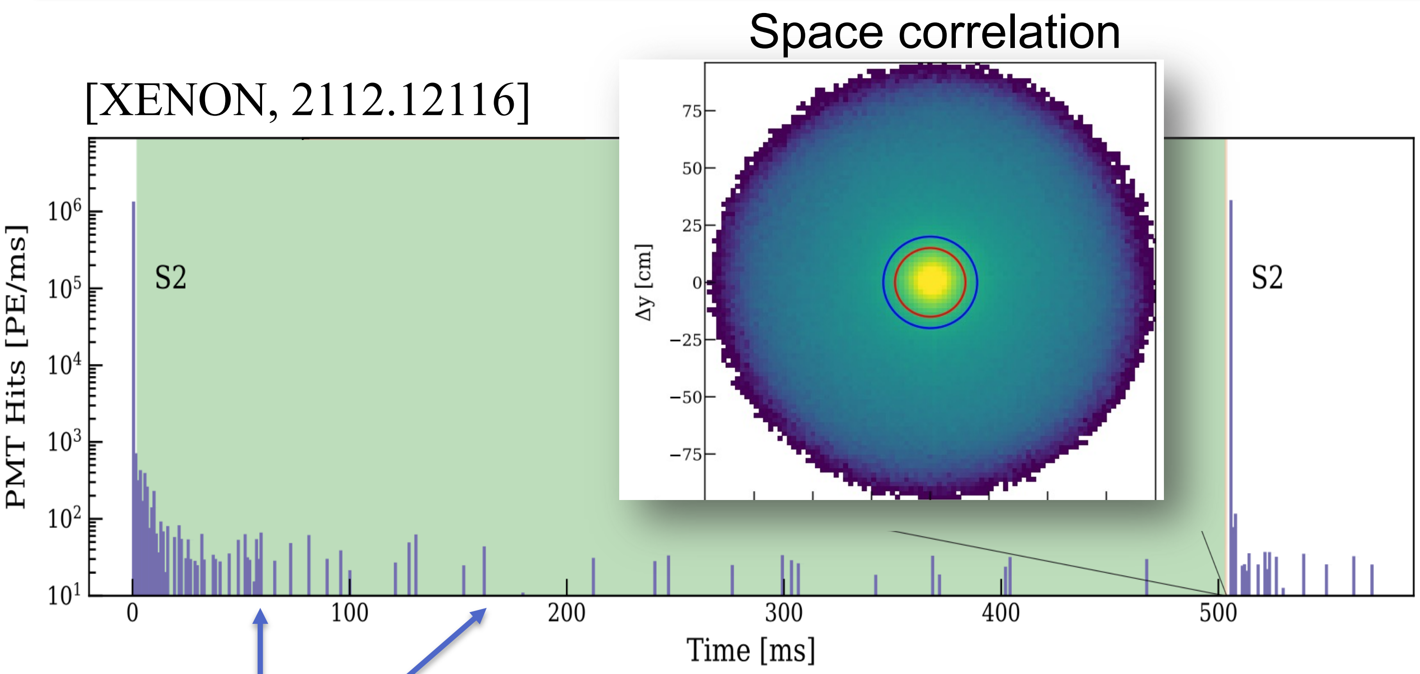
- ER background suppressed with passive shielding, and **1/5** after veto layers
- Detector material inside the cryostat (e.g. ^{238}U, ^{232}Th chain) is the major contribution
- Intrinsic radiation (^{85}Kr, ^{222}Rn) is not dominant
- Neutron-induced deexcitations also considered

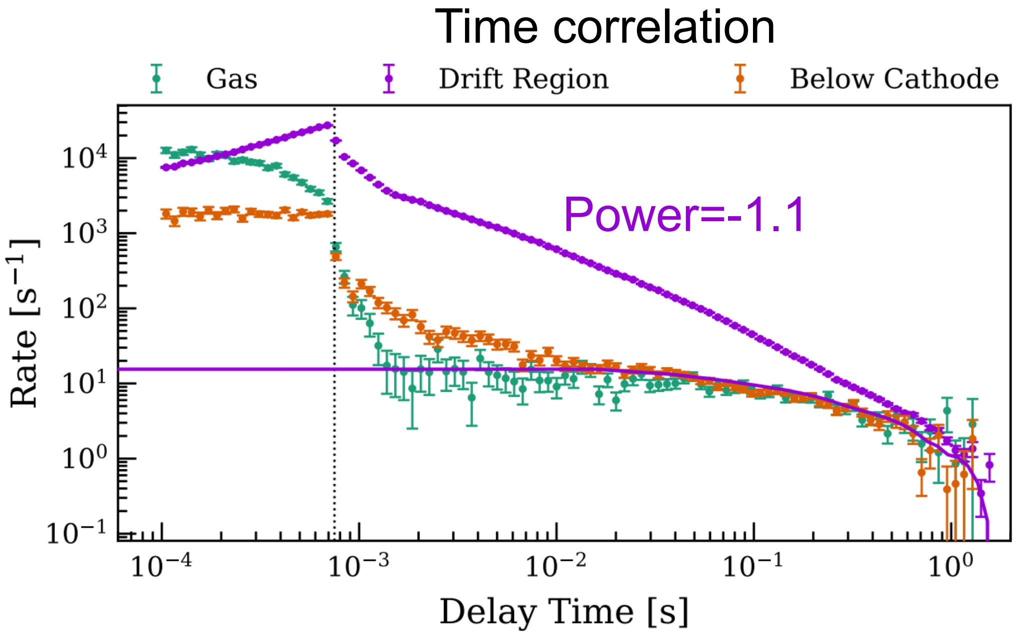
Nuclear Recoil (NR) Backgrounds



- Cosmic-ray neutrons are the major background:
  - ~1 order suppression with water
  - Another order possible with an active shielding*
- Plastic scintillator boards serve as muon veto — 99% suppression for muon-induced neutron

Delayed electron (DE) background

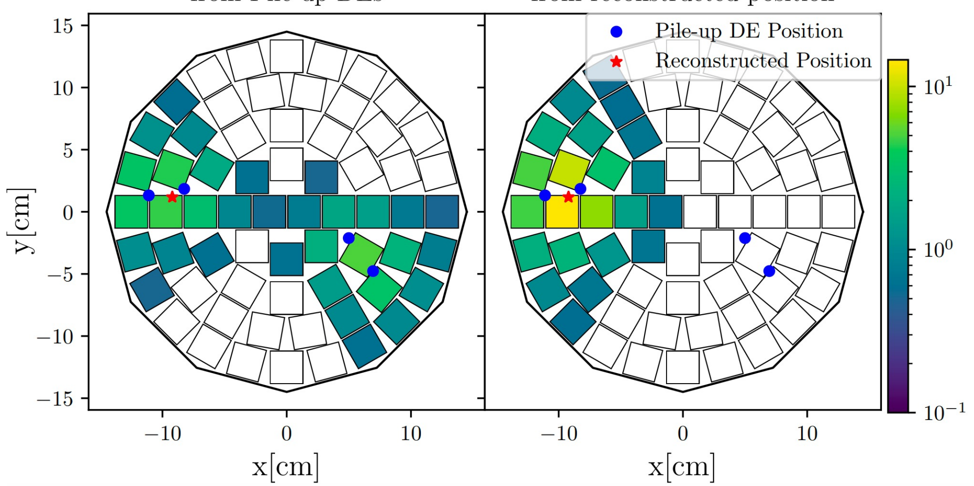




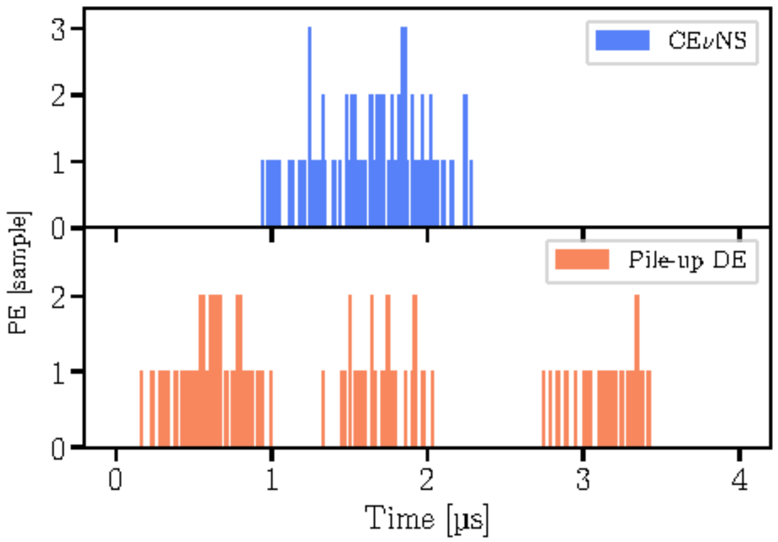
- Delayed electrons pollutes the S2-only channel; they have space and time correlation with prior large-energy events
- Muon (10Hz) can produce DE pile-ups, overlapping with CEvNS ROI (4-6e$^-$)

DE background suppression

Hit-pattern

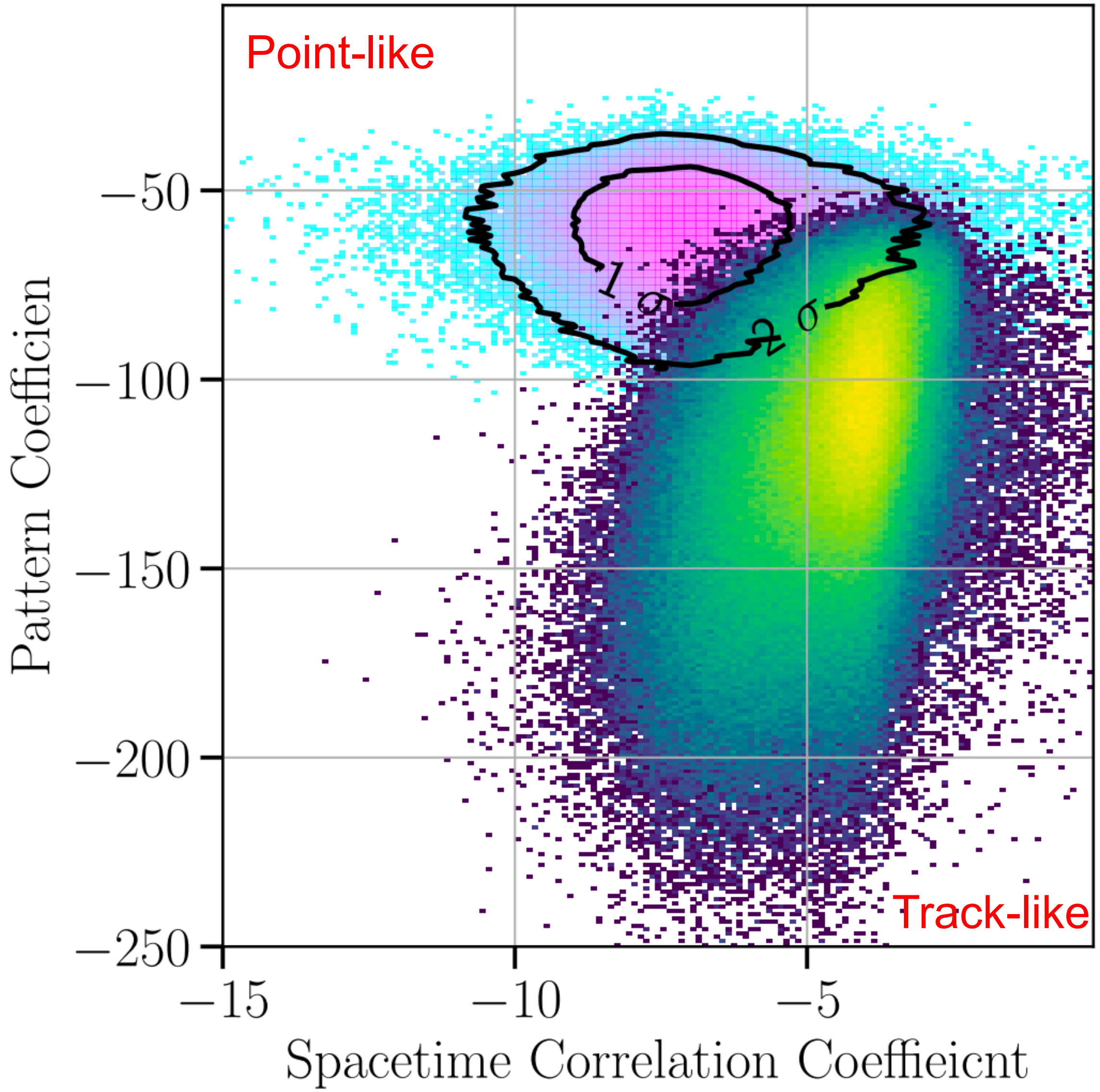


Time correlation



- Delayed electron pileups modeled from XENON1T pathological study [XENON, 2112.12116]
- Point-like CEvNS and track-like muon induced DE signals are modeled
- Use hit-pattern and space-time correlation to suppress DE background by ~4 orders

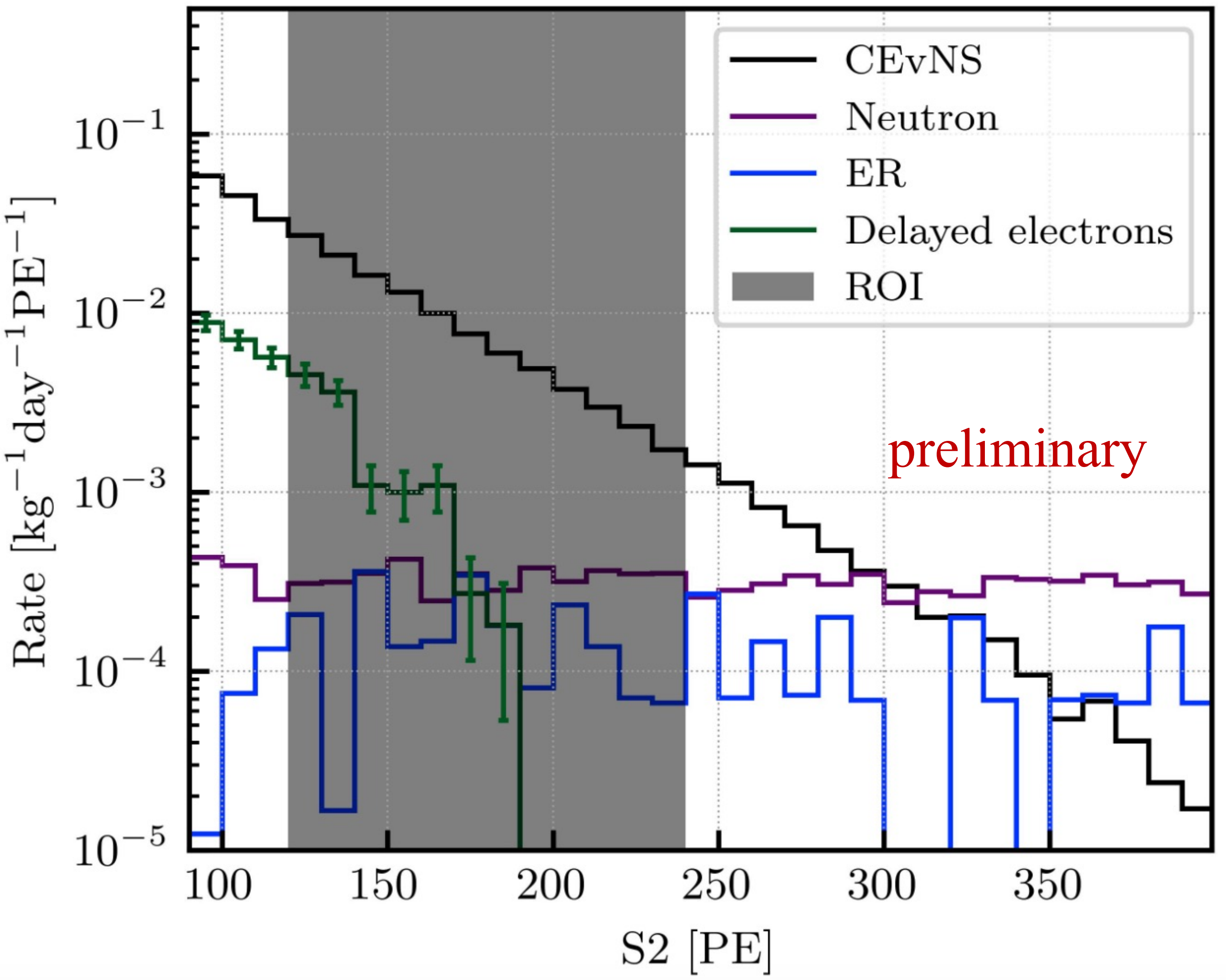
DE background suppression



- Delayed electron pileups modeled from XENON1T pathological study [XENON, 2112.12116]
- Point-like CEvNS and track-like muon induced DE signals are modeled
- Use hit-pattern and space-time correlation to suppress DE background by ~4 orders

Signal and background estimation

西湖大学 | 暗物质与中微子实验室



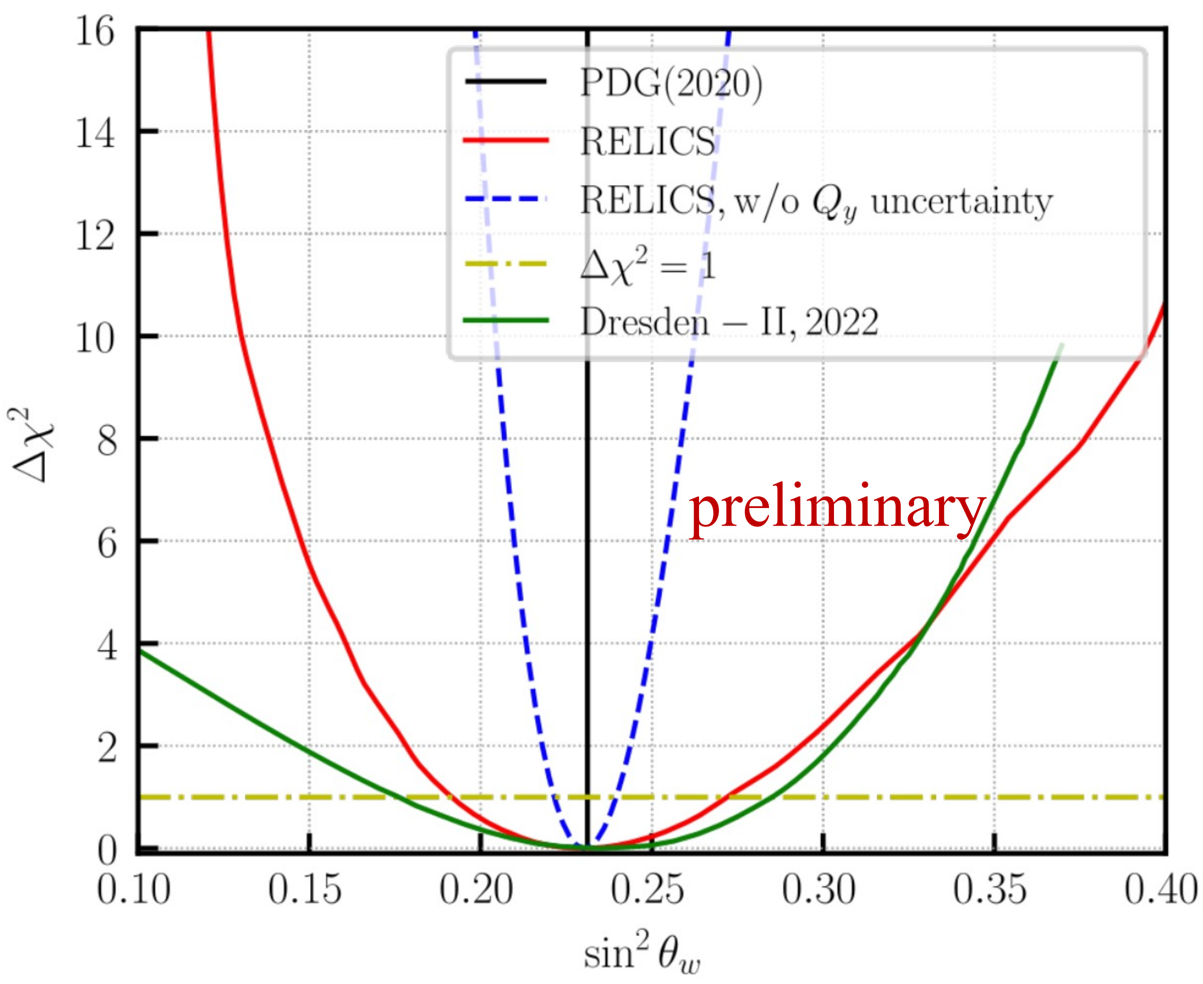
	Events/($32kg \cdot year$)
CEνNS	13673.5
CR neutron	470.4
μ-induced neutron	2.3
Beta, gamma	232.0
Delayed electron	1429
Total background	2133.7

Expected signal : background = 6 : 1

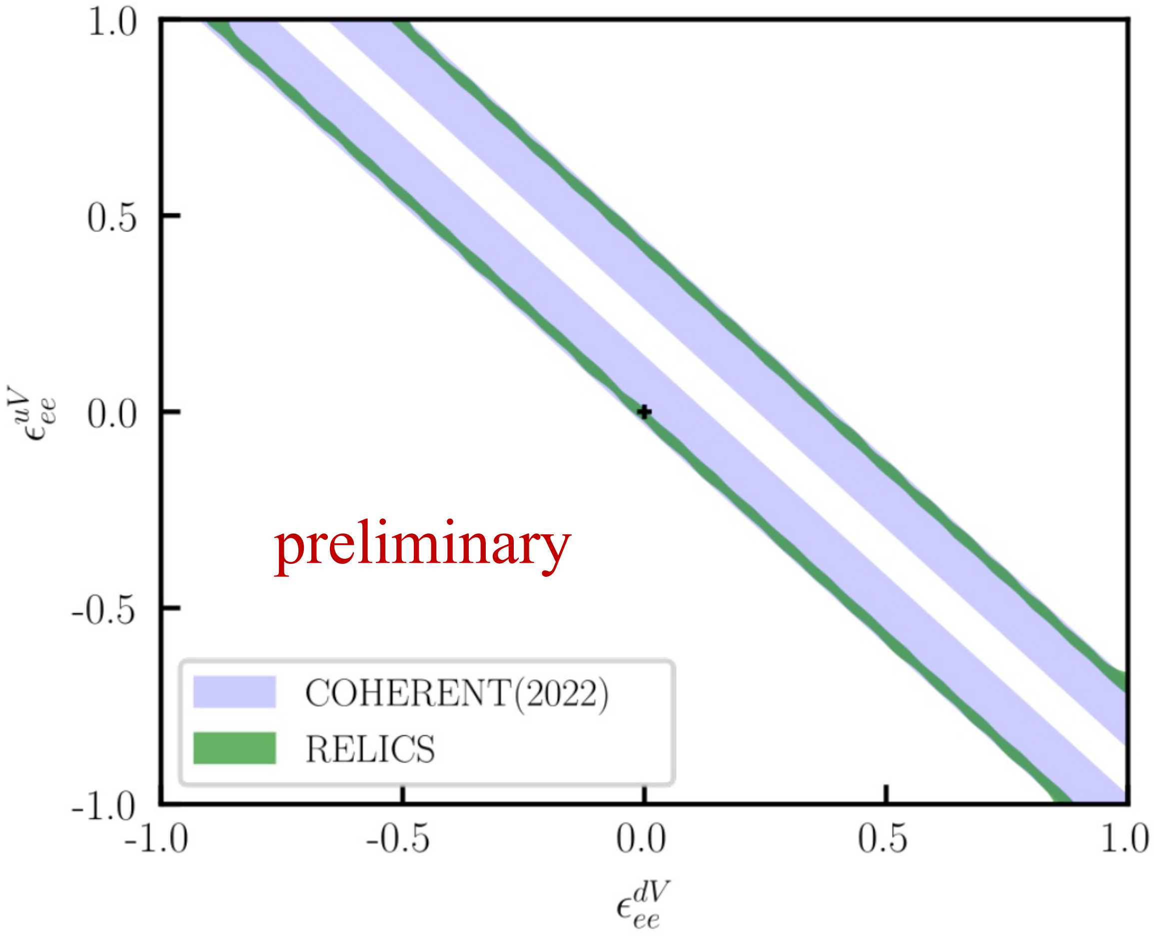
Sensitivity Estimation

西湖大学 | 暗物质与中微子实验室

Weak mixing



NSI $$\frac{d\sigma}{dE_R} = \frac{G_F^2 \cdot m_t}{2\pi} F^2(2m_t E_R)\left[2 - \frac{m_t E_R}{E_\nu^2}\right] \times \left[Z(g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}) + N(g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})\right]^2$$



Sensitivity Paper https://arxiv.org/abs/2405.05554

西湖大学 | 暗物质与中微子实验室

[Submitted on 9 May 2024]

RELICS: a REactor neutrino LIquid xenon Coherent elastic Scattering experiment

Chang Cai, Guocai Chen, Jiangyu Chen, Fei Gao, Xiaoran Guo, Tingyi He, Chengjie Jia, Gaojun Jin, Yipin Jing, Gaojun Ju, Yang Lei, Jiayi Li, Kaihang Li, Meng Li, Minhua Li, Shengchao Li, Siyin Li, Tao Li, Qing Lin, Jiajun Liu, Minghao Liu, Sheng Lv, Guang Luo, Jian Ma, Chuanping Shen, Mingzhuo Song, Lijun Tong, Xiaoyu Wang, Wei Wang, Zihu Wang, Yuehuan Wei, Liming Weng, Xiang Xiao, Lingfeng Xie, Dacheng Xu, Jijun Yang, Litao Yang, Long Yang, Jingqiang Ye, Jiachen Yu, Qian Yue, Yuyong Yue, Bingwei Zhang, Shuhao Zhang, Yifei Zhao

Coherent elastic neutrino-nucleus scattering (CEvNS) provides a unique probe for neutrino properties Beyond the Standard Model (BSM) physics. REactor neutrino LIquid xenon Coherent Scattering experiment (RELICS), a proposed reactor neutrino program using liquid xenon time projection chamber (LXeTPC) technology, aims to investigate the CEvNS process of antineutrinos off xenon atomic nuclei. In this work, the design of the experiment is studied and optimized based on Monte Carlo (MC) simulations. To achieve a sufficiently low energy threshold for CEvNS detection, an ionization-only analysis channel will be adopted for RELICS. A high emission rate of delayed electrons after a big ionization signal is the major background, leading to an analysis threshold of 120 photo-electrons in the CEvNS search. The second largest background, nuclear recoils induced by cosmic-ray neutrons, is suppressed via a passive water shield. The physics potential of RELICS was explored with a 32 kg-yr exposure at a baseline of 25 m from a reactor core with a 3 GW thermal power. In an energy range of 120 to 240 PEs, we the expected 13673.5 CEvNS and 2133.7 background events.The sensitivity of RELICS to the weak mixing angle was investigated at a low momentum transfer. Our study has shown that RELICS can further improve the constraints on the non-standard neutrino interaction (NSI) compared to the best results. RELICS set out to develop a powerful surface-level detection technology for low-energy neutrinos from reactors.

Prototype Testing

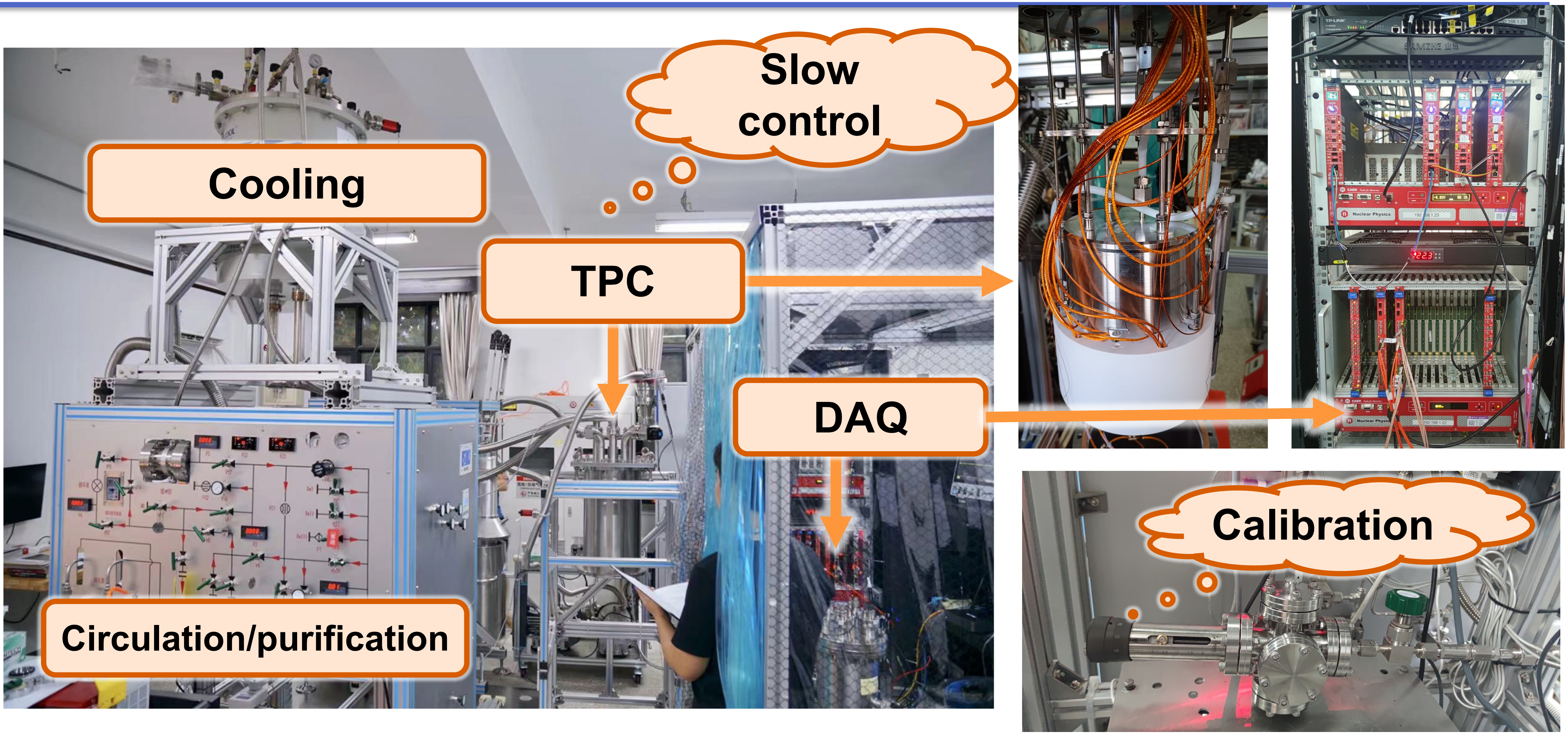
西湖大学 | 暗物质与中微子实验室

Prototype		Full Detector
✓	Cooling, circulation	✓
✓	DAQ	✓
✓	**Calibration**	✓
✓	Liquid level control	✓
SOON	Veto (muon, gamma)	✓
✗	Shielding	✓
~0.56 kg	Total mass	~50 kg
8	PMT number	128

CR: Yifei@COUSP24

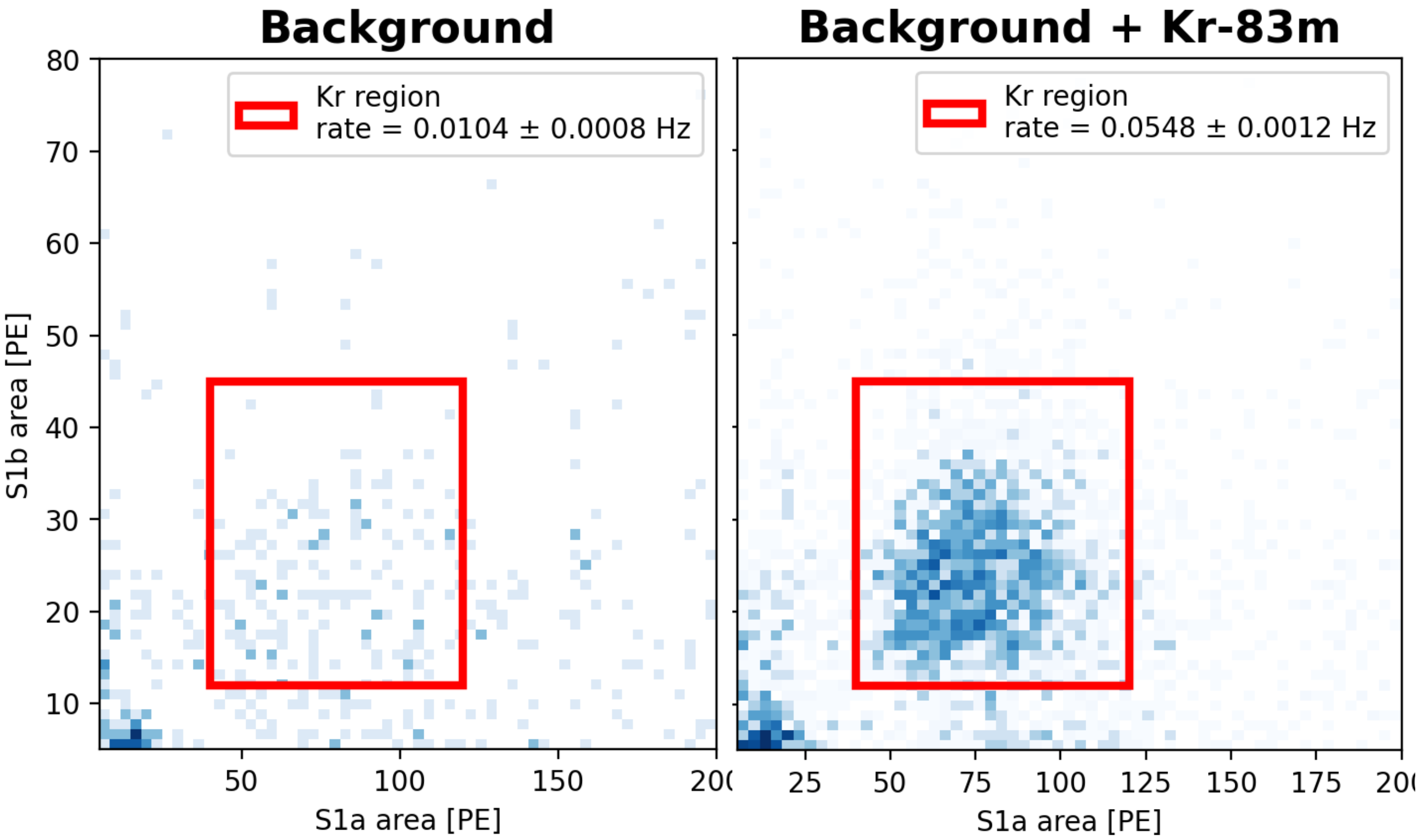
Tsinghua RELICS Prototype

西湖大学 | 暗物质与中微子实验室

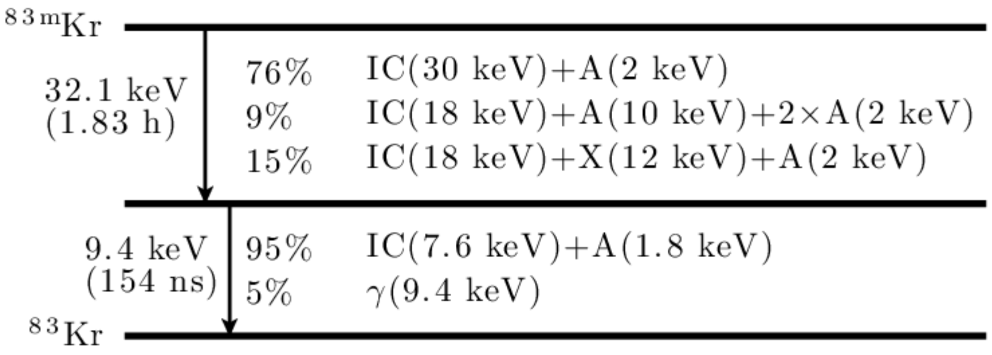


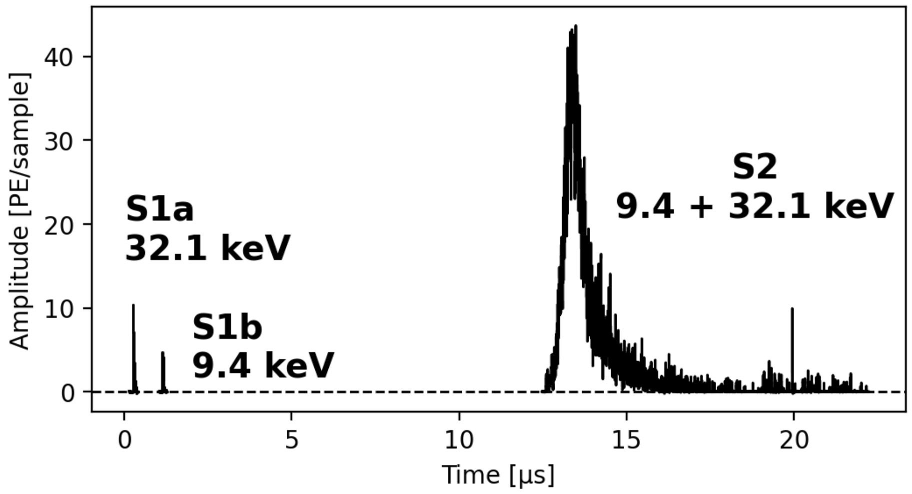
CR: Yifei@COUSP24

Kr83m Calibration



Clear sign of Kr signal after injection



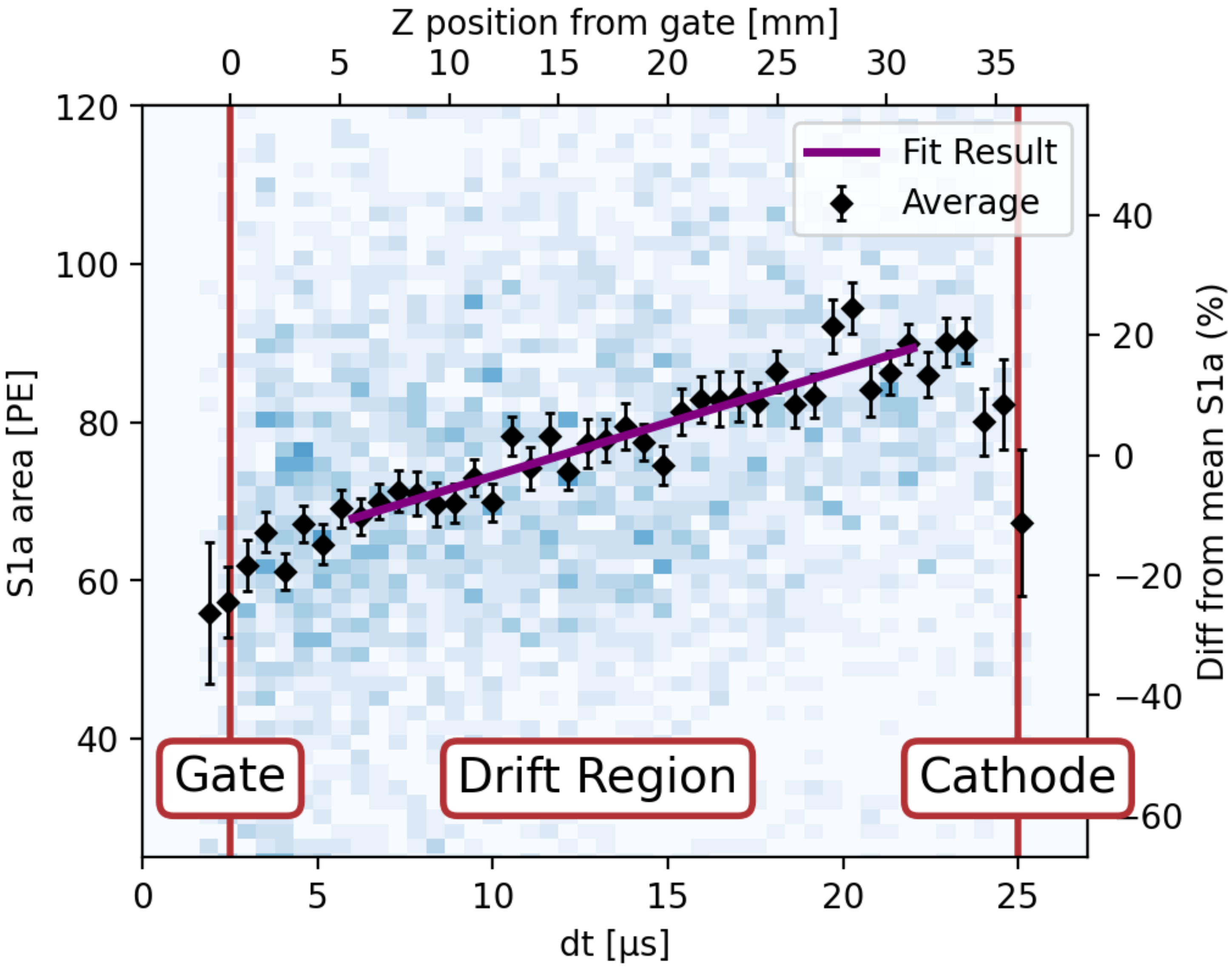


Consecutive decay event observed

CR: Yifei@COUSP24

Prototype measurements

西湖大学 | 暗物质与中微子实验室



- Use electron drift time to estimate depth
- Use Kr energy and S1 size to infer light collection efficiency
- Space uniformity

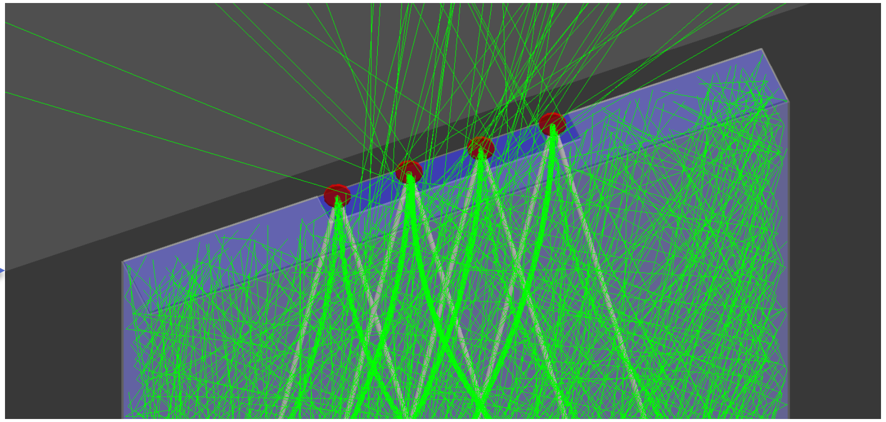
CR: Yifei@COUSP24

Westlake R&D

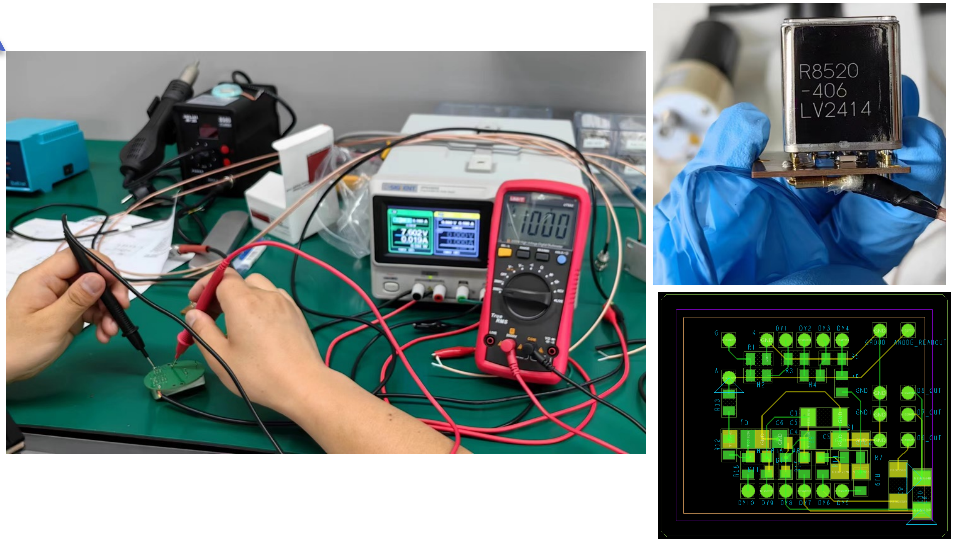
- Suppression of DE is key to CEvNS detection, require accurate muon track reconstruction (~2cm)
  1. 4-pi plastic scintillator muon veto
  2. PMT front-node readout to avoid saturation from muon signal
  3. Test with local TPC

- Delayed electron pathology with a specialized local TPC at Westlake -> CEvNS, MeV DM

- Calibration testing (e.g., a <300keV neutron source) – probe low-energy yields



Simulation done, lab test soon



PMT base design and testing

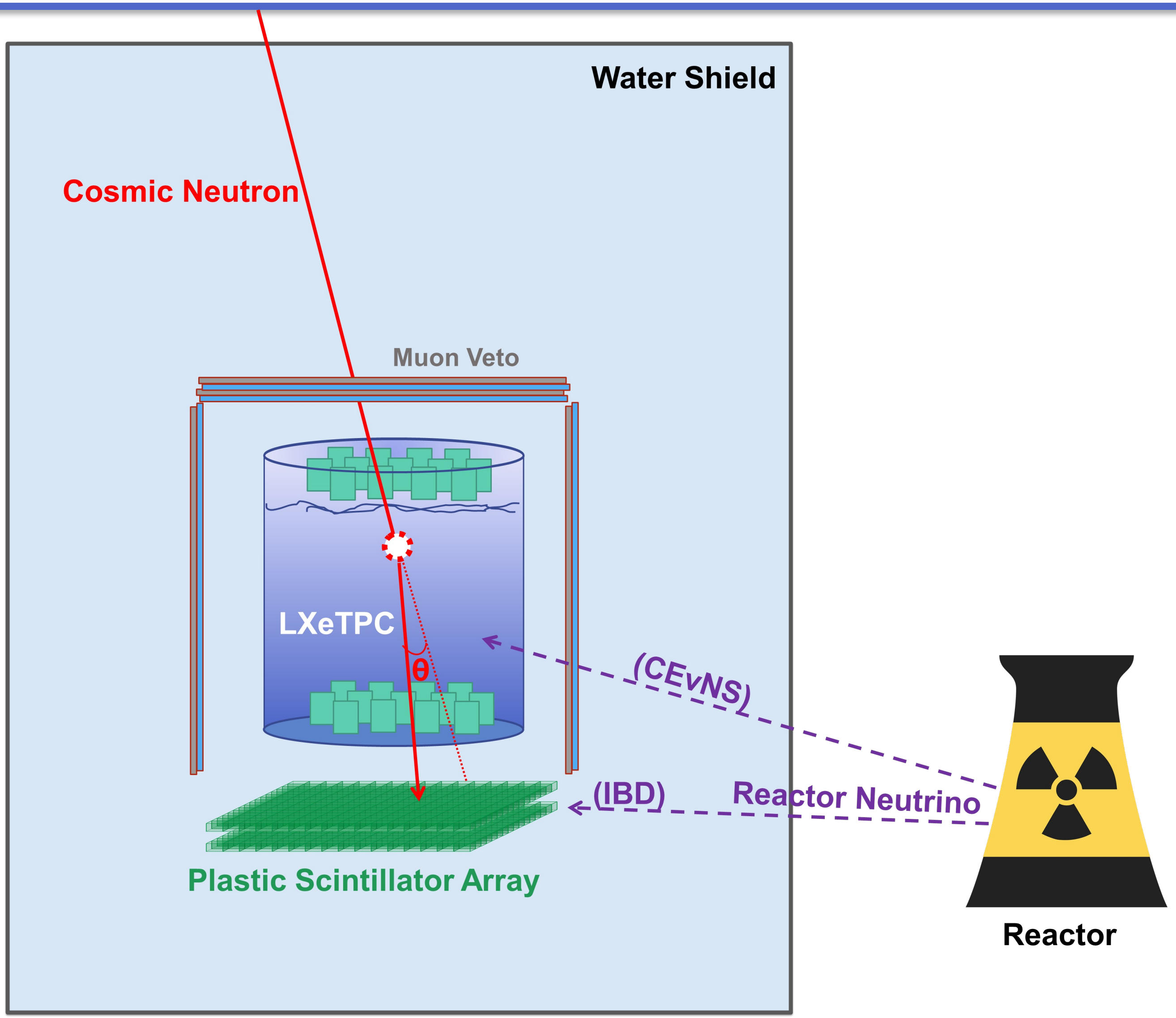
Conclusion

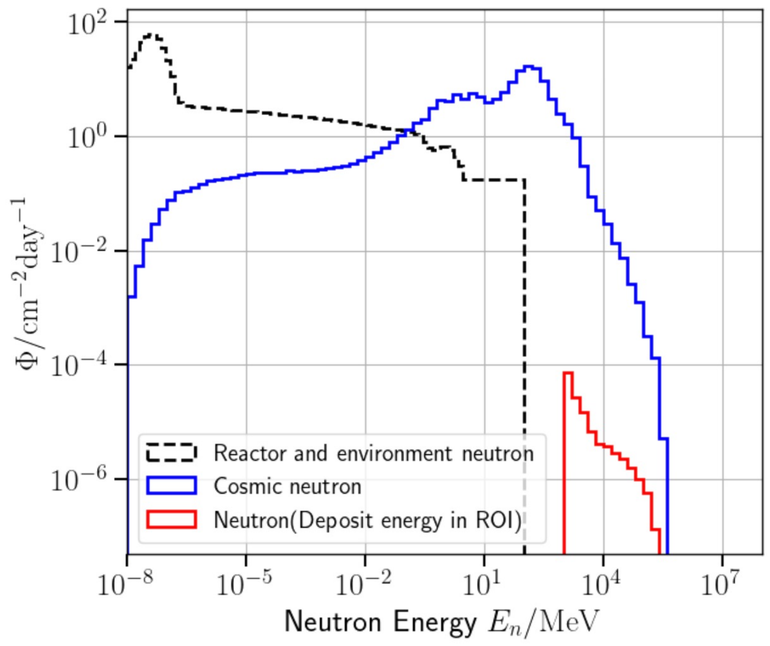
- RELICS is a **low-threshold**, **near-reactor** CEvNS LXe experiment.
- In 2405.05554 we studied backgrounds for the s2-only CEvNS signal; **delayed electrons**, **cosmic-ray** related backgrounds and **material radioactivity** have the top contribution.
- With a final **SNR of 6**, RELICS can probe weak mixing angle and NSI...
- Prototypes and tests **ongoing** for verification and improvements.

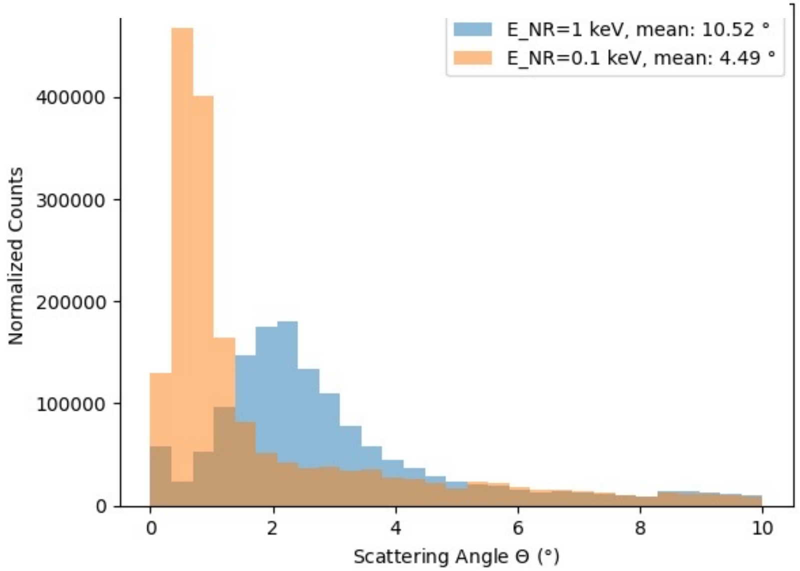
Your suggestions are very appreciated!

Backups

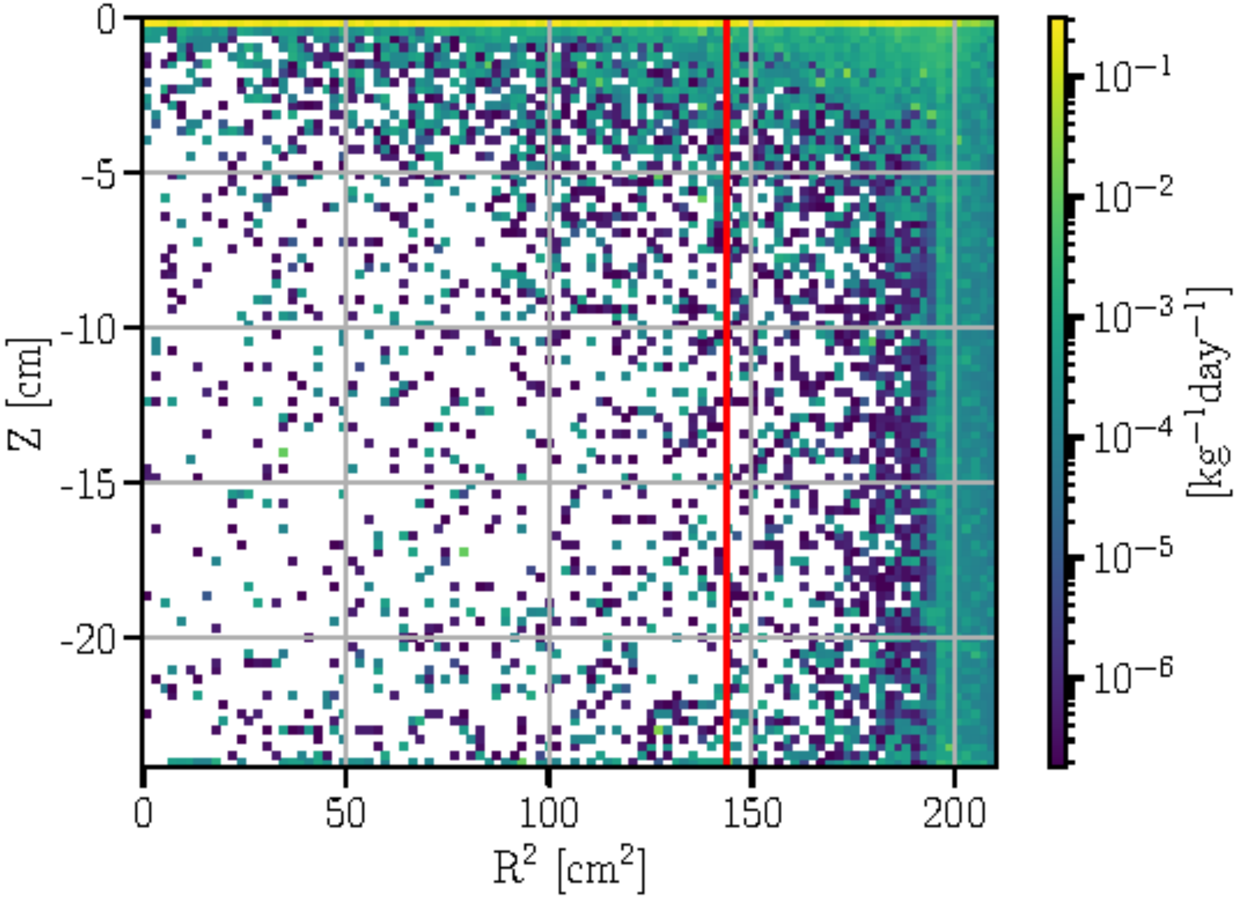
Cosmic Neutron Suppression

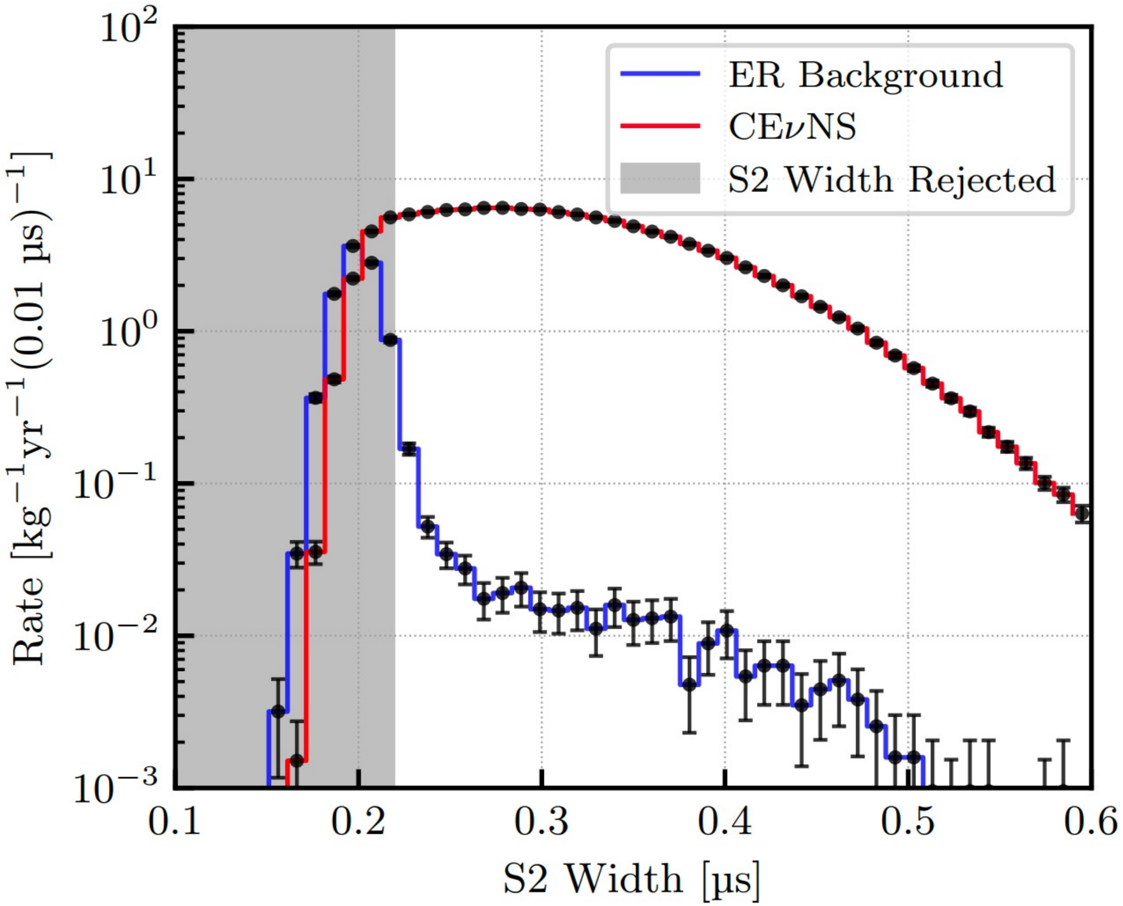






Fiducial Cuts

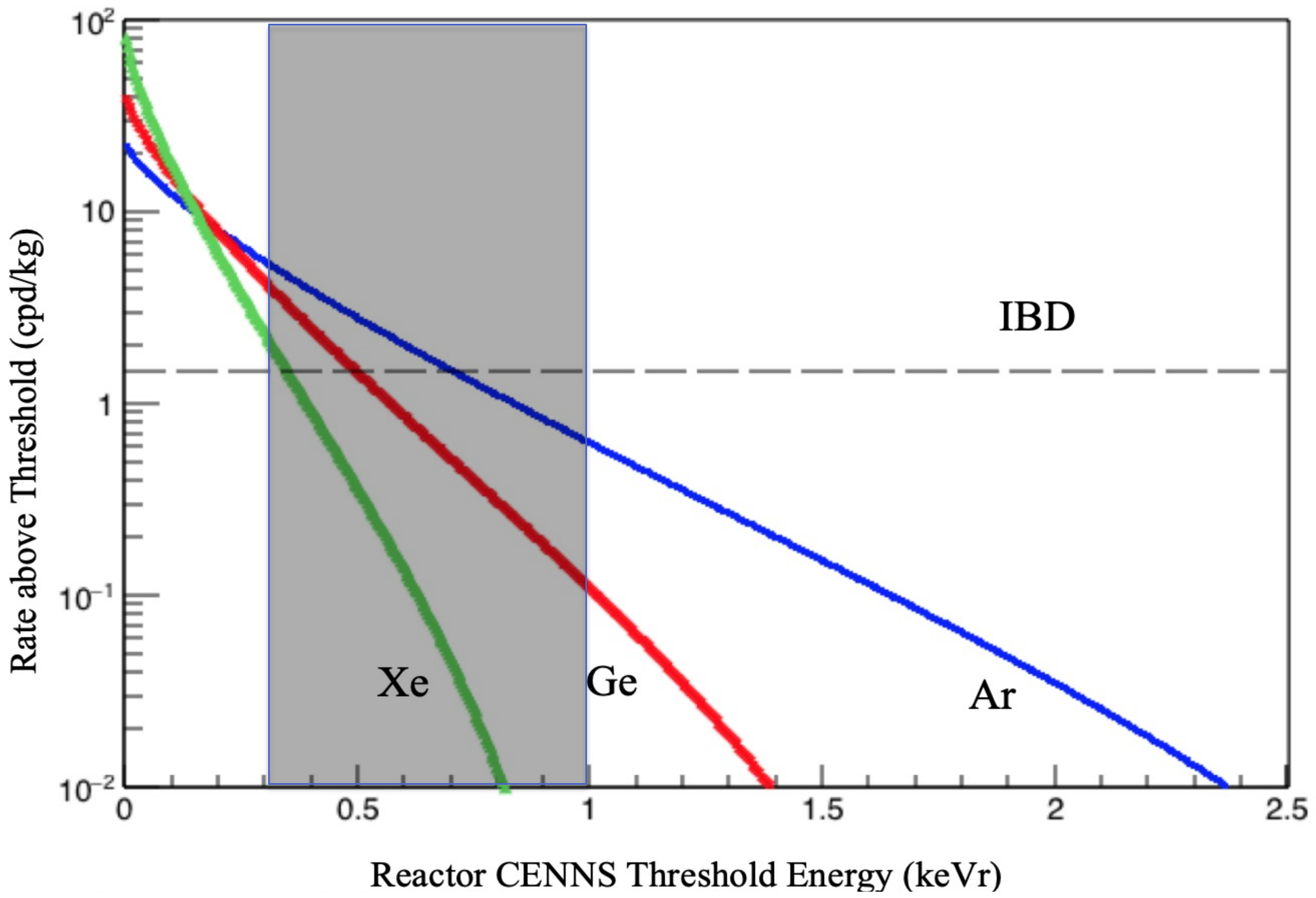




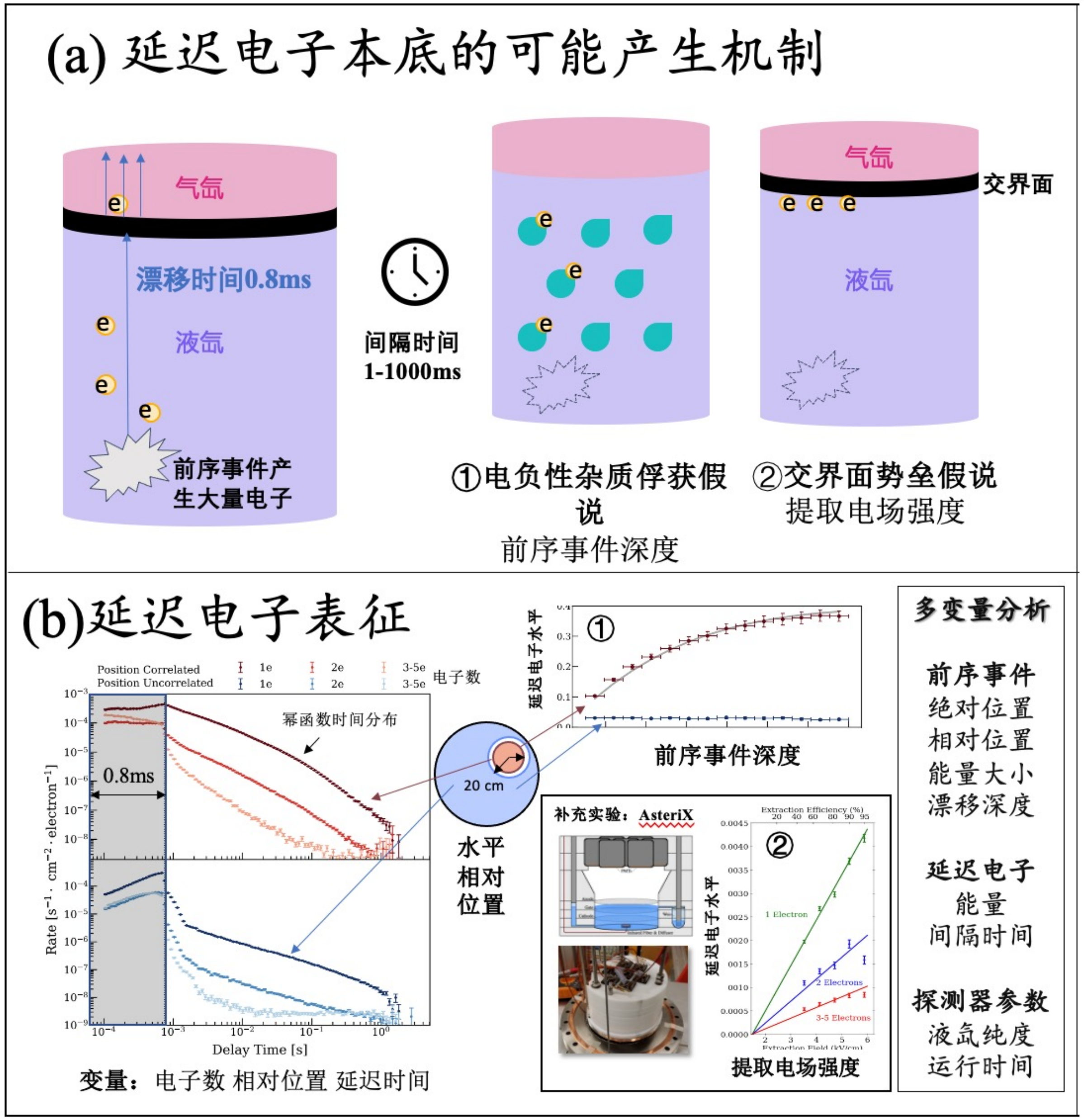
- Radius cut -> xy

- Pulse width -> depth;
- 6% background and 86% CEvNS after cut

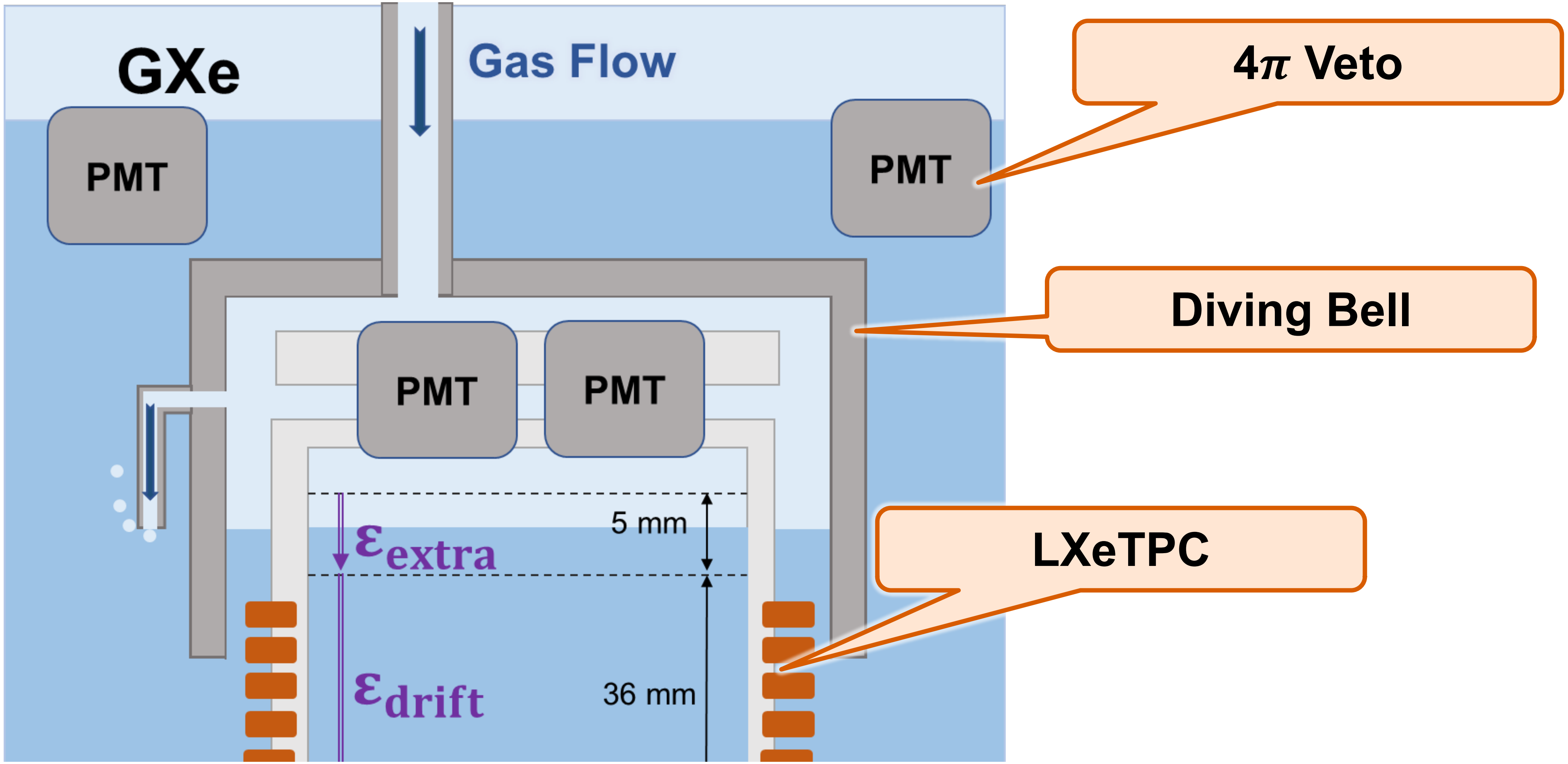
CEvNS rate vs. threshold



Delayed Electrons



Prototype TPC



Preparation and schedule

西湖大学 | 暗物质与中微子实验室