Westlake University | DM and neutrino lab

XENON RELICS

# Exploring neutrinos with CEvNS in liquid xenon TPCs

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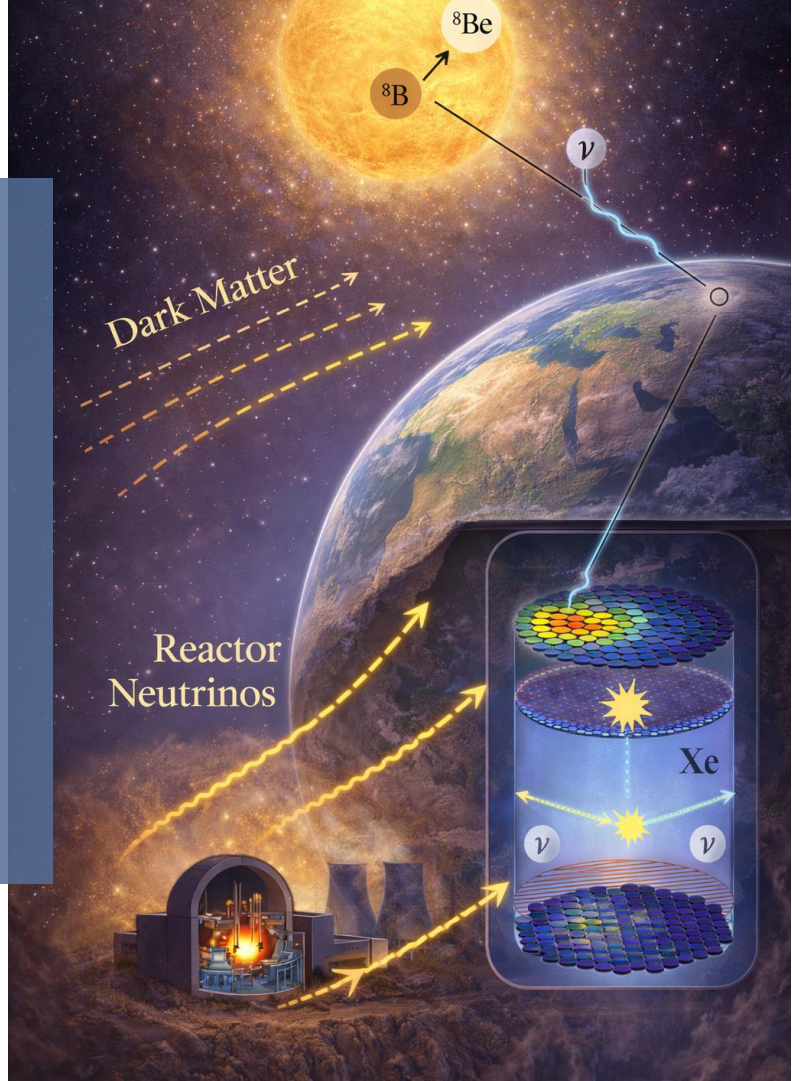
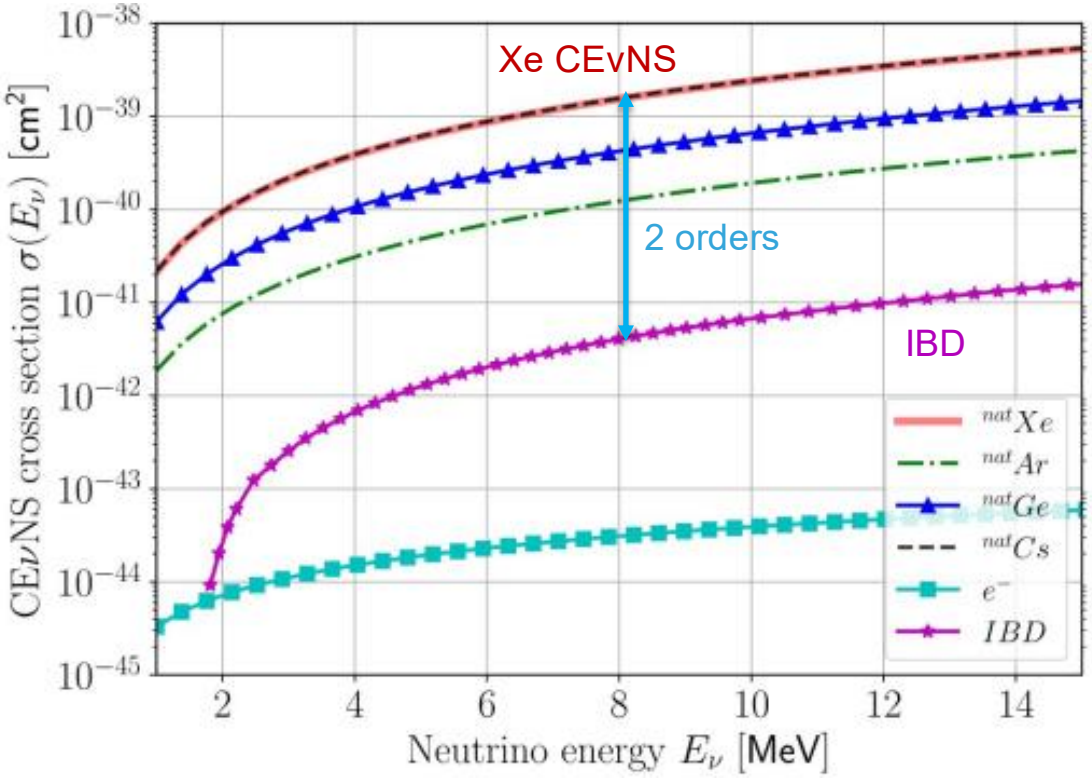
Westlake University

with inputs from XENON and RELICS collaborations




JUNO workshop@HIAS-UCAS
2026.1.28

# Experiments with CEvNS




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

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

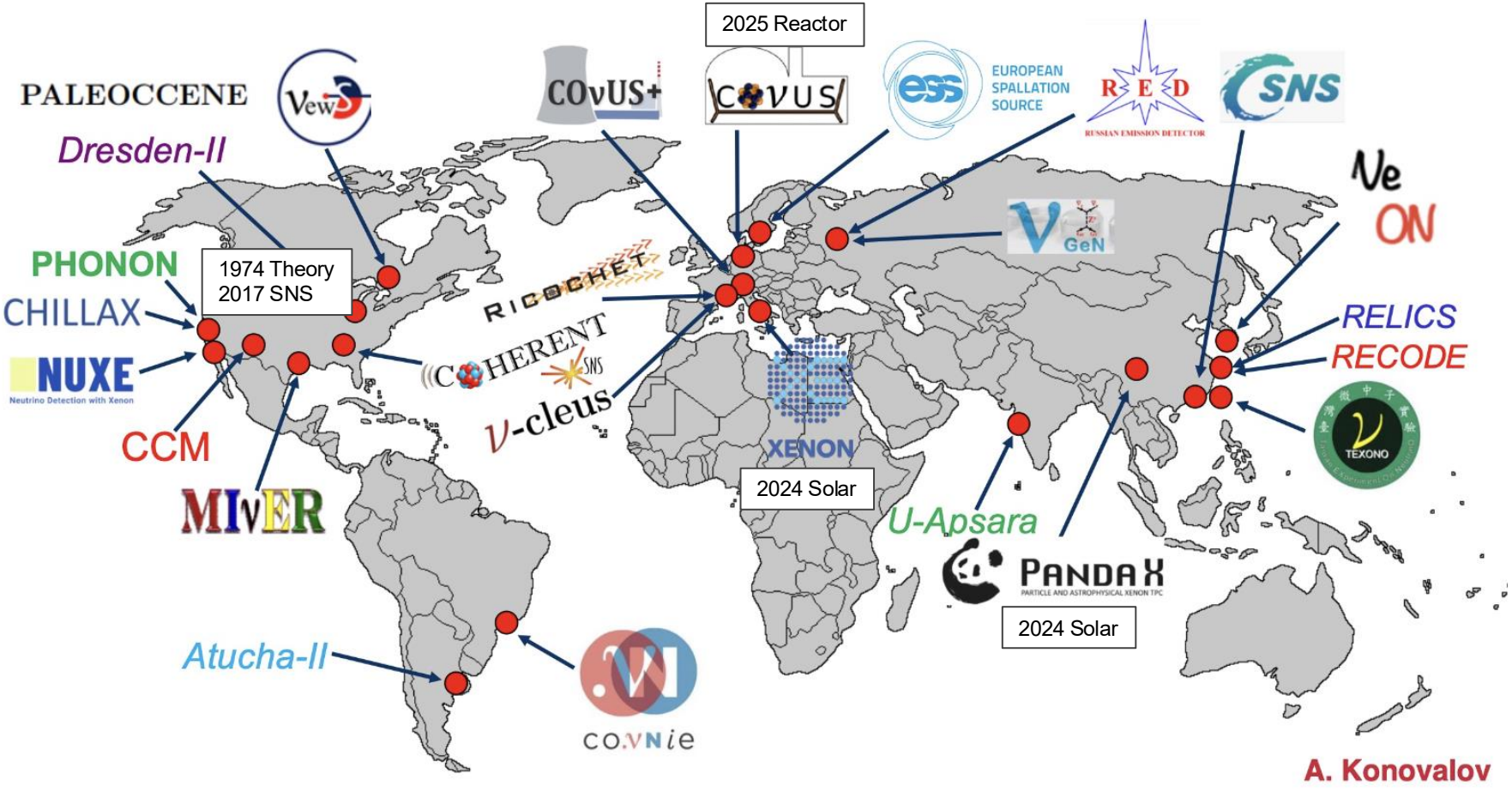
$$Q_W \propto N \implies \boxed{\frac{d\sigma}{dT} \propto N^2}$$

**Compare with IBD:**

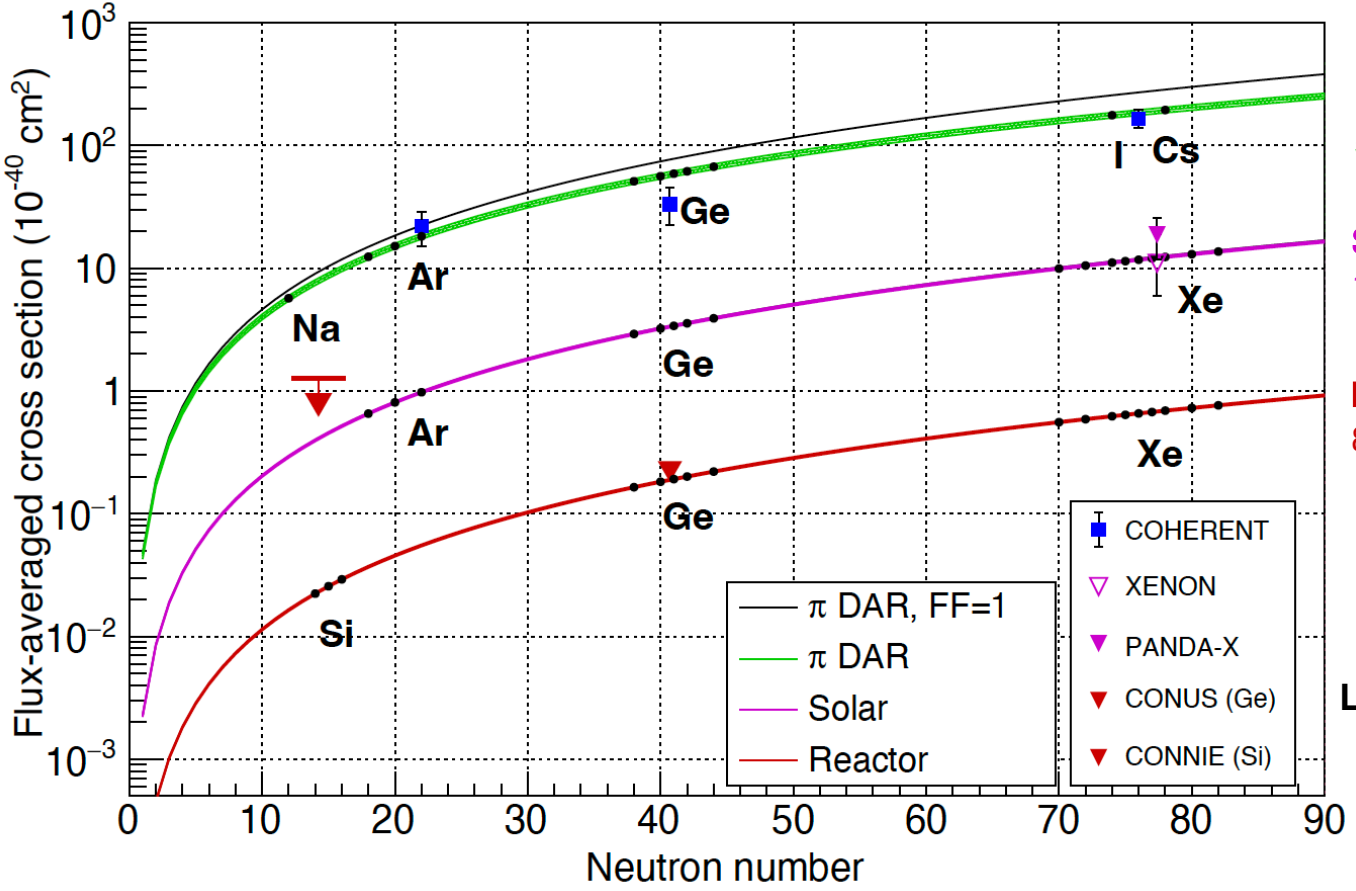
- ✓ Cross-section 100x → compact
- x Energy 0.1% → low-threshold
- ✓ No interaction energy threshold
- x No coincidence, recoil-based
- ✓ Complementary physics

particle, astrophysics…

# Landscape of CEvNS experiments



# Landscape of CEvNS experiments




SNS
50MeV

Solar
15MeV

Reactor
8MeV

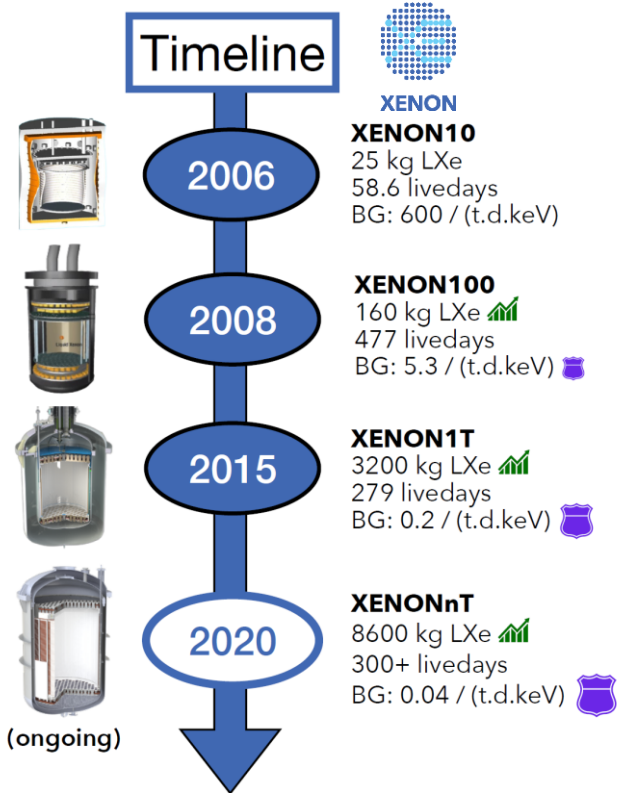
$$< T >= \frac{2}{3}\frac{E_\nu^2}{M_A}$$

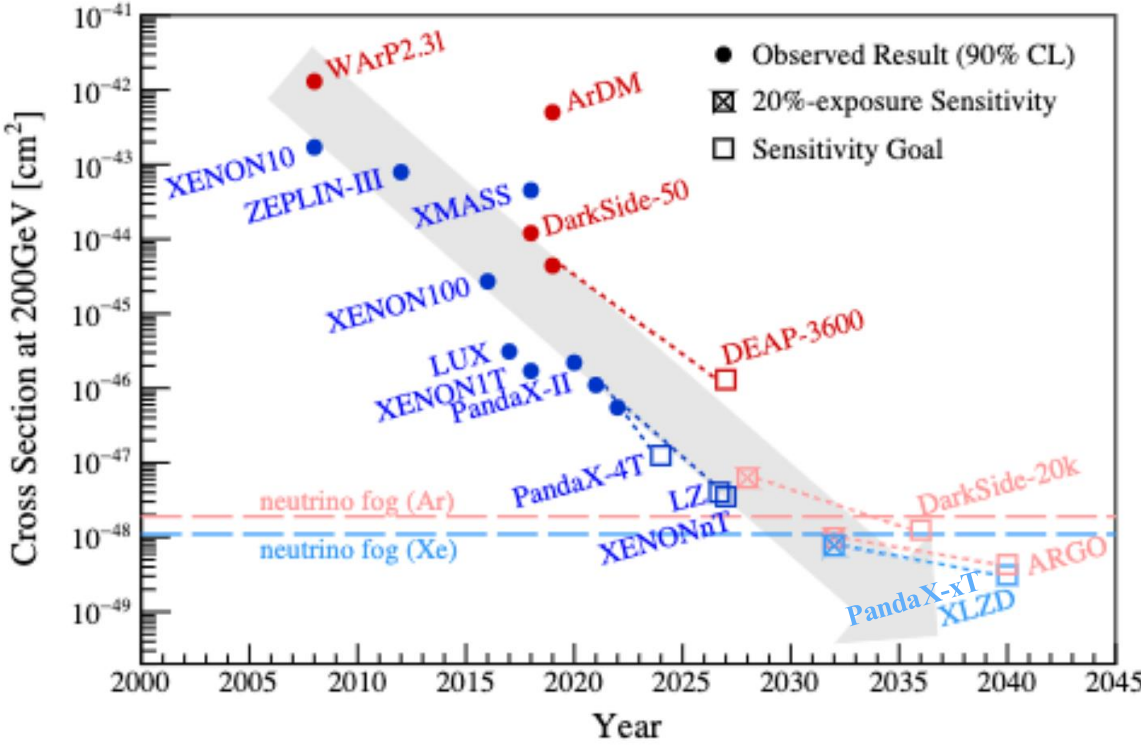
$$< T > \sim \text{keV}$$

This talk:

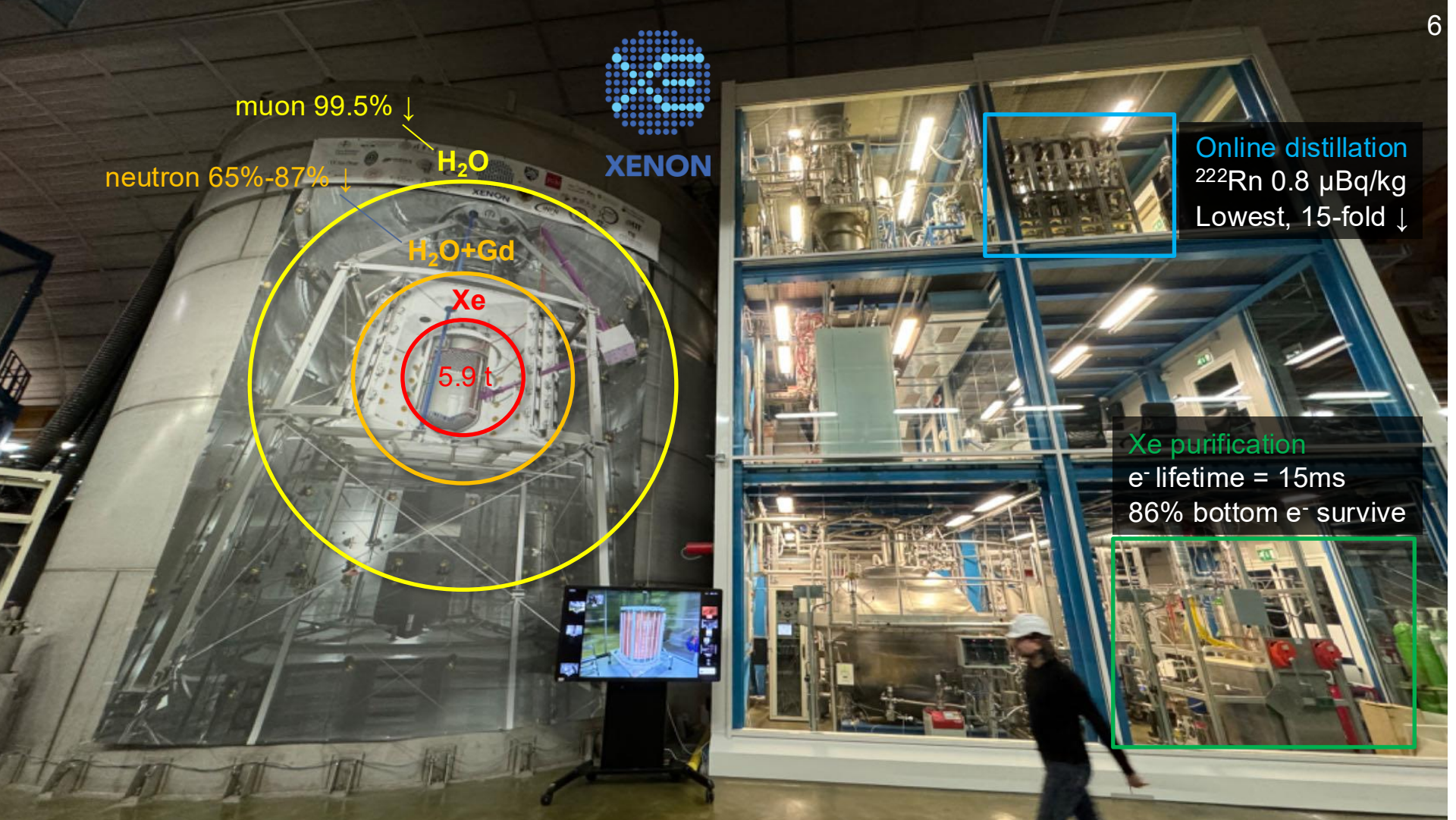
**Low-threshold Xenon detector**

# Xenon-based detectors



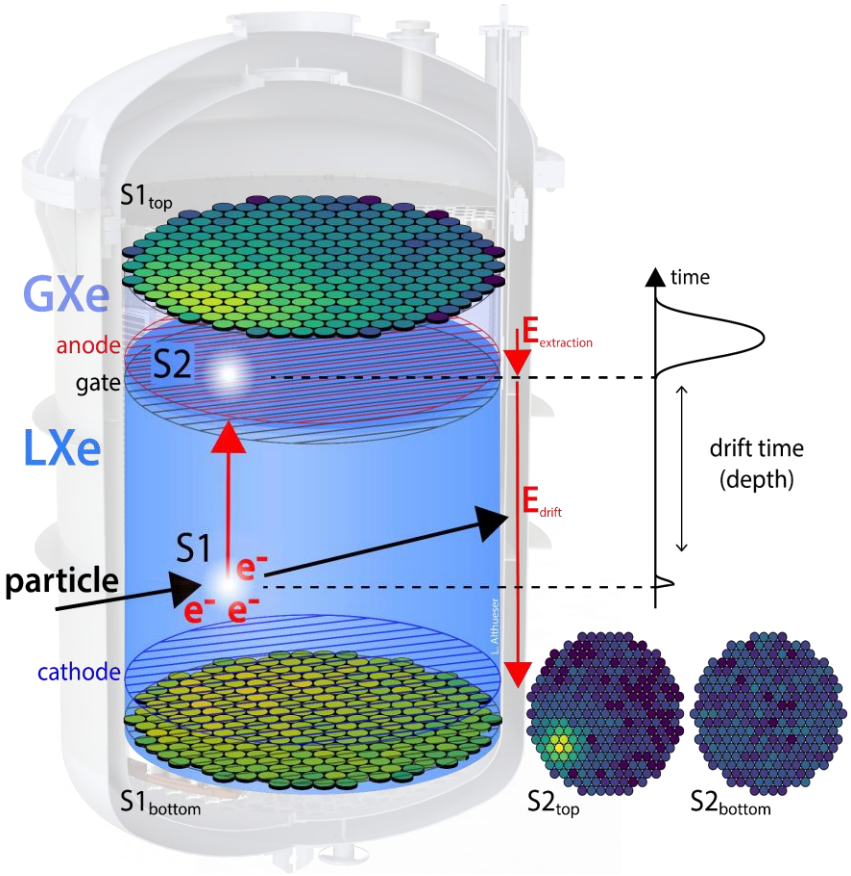




Factor of 10 every **3.3** years, lead GeV dark matter limits


muon 99.5% ↓
neutron 65%-87% ↓
$H_2O$
$H_2O$+Gd
Xe
5.9 t
XENON
Online distillation
$^{222}$Rn 0.8 μBq/kg
Lowest, 15-fold ↓
Xe purification
$e^-$ lifetime = 15ms
86% bottom $e^-$ survive

# Xenon Time Projection Chamber (TPC)






**Redundant readout:**

**S1:** light signal (prompt)

**S2:** charge signal (delayed)

**3D position info:**

-XY from PMT hit pattern

-Z from drift time

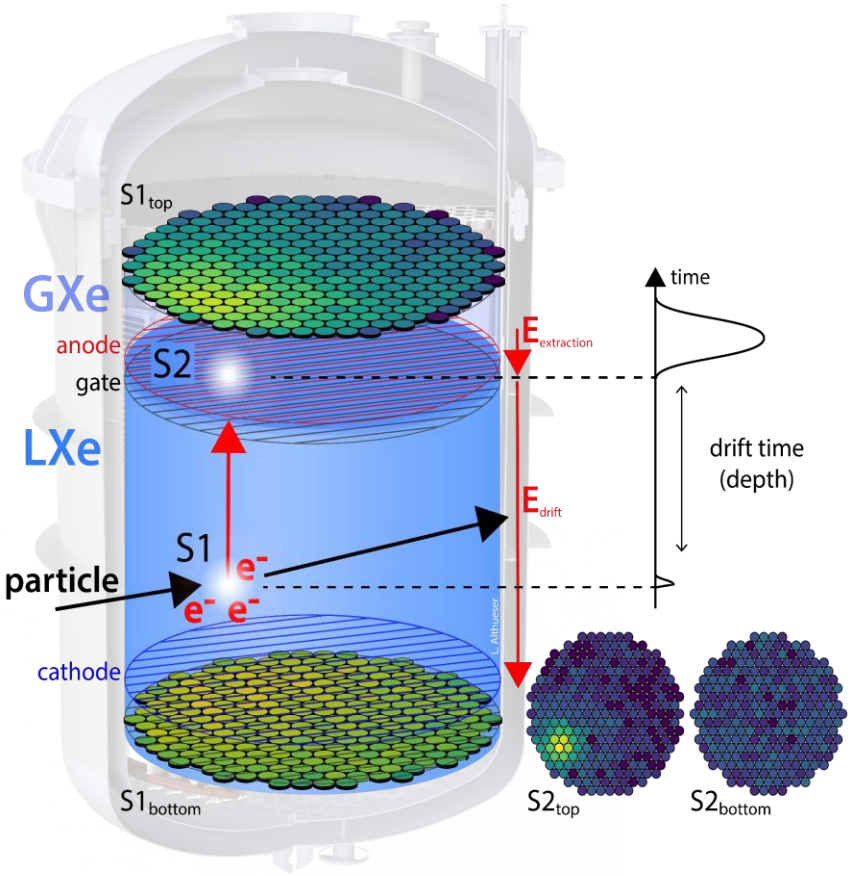
**Energy reconstruction:**

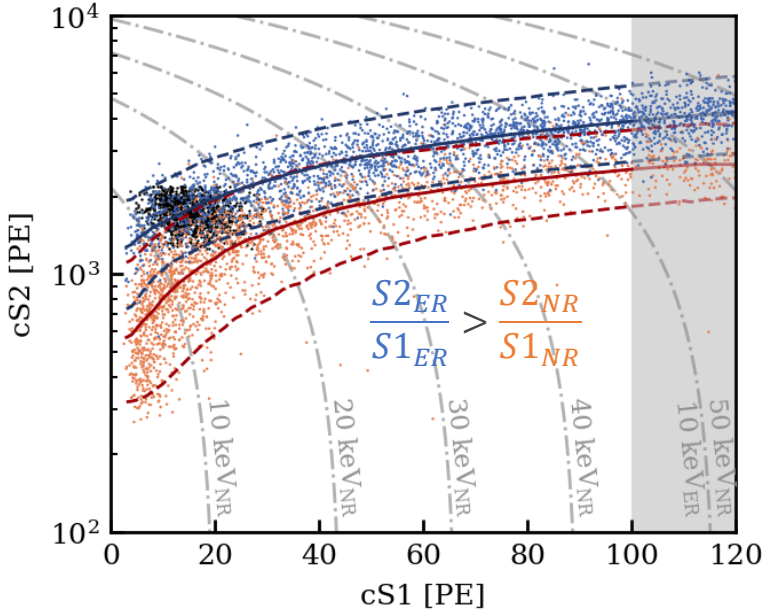
$E = 13.7eV \times (N_{ph}+N_e)$

**Particle discrimination:**

ratio of charge/light (ERs vs. NRs)

# Xenon Time Projection Chamber (TPC)

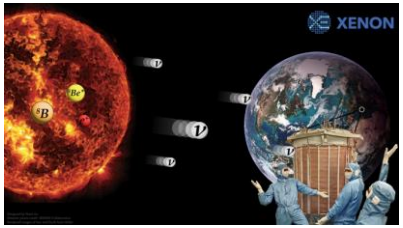


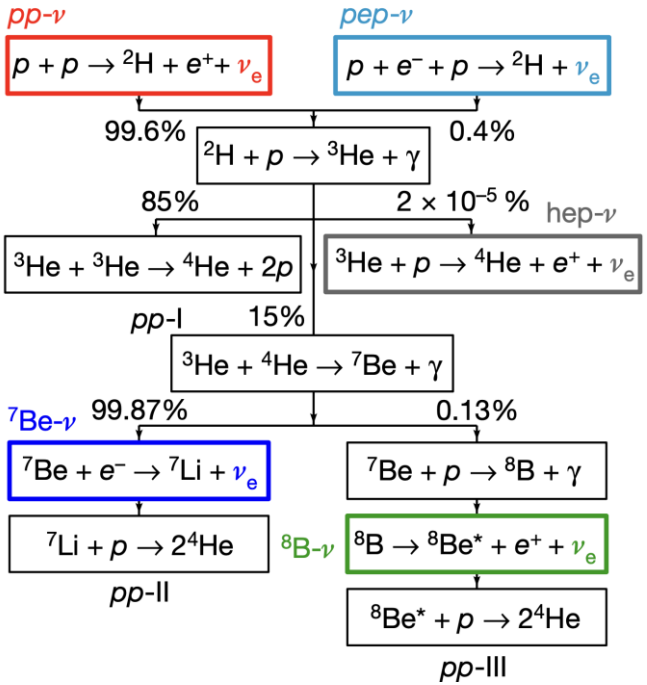



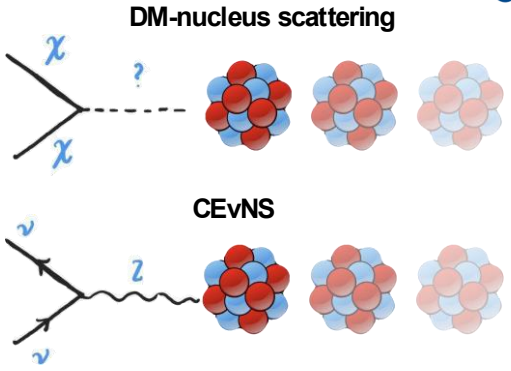

**Particle discrimination:**

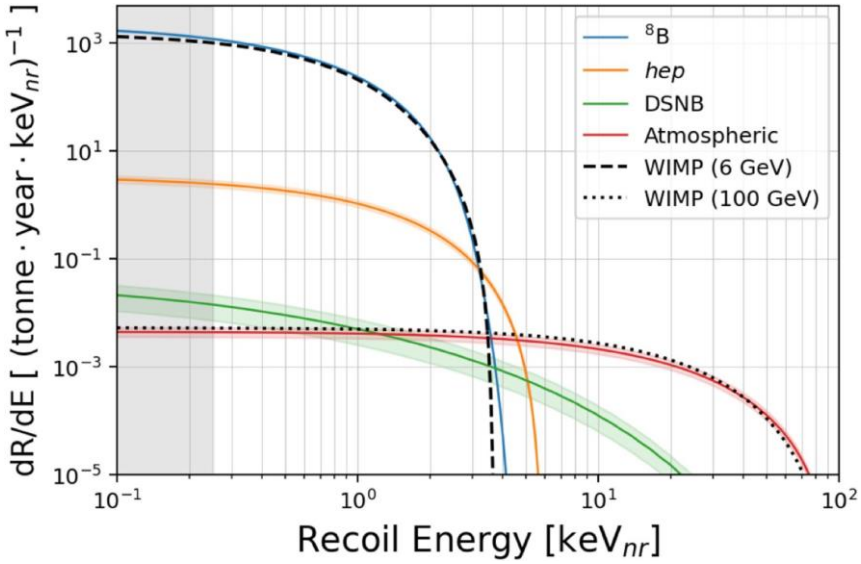
ratio of charge/light (ERs vs. NRs)

# Solar neutrino in xenon TPC

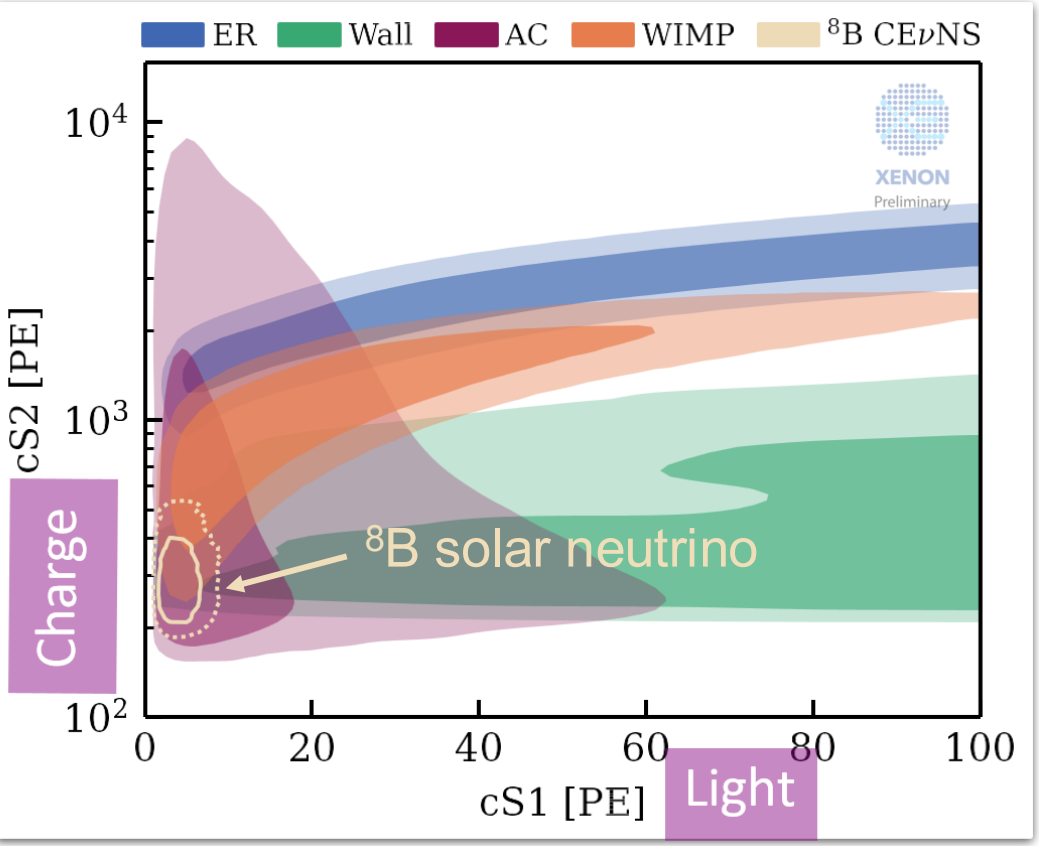


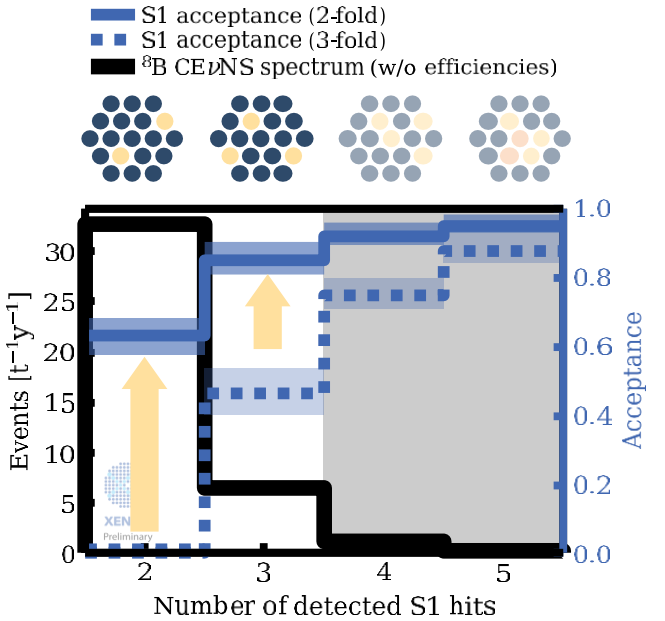



# Solar Neutrino in WIMP Search

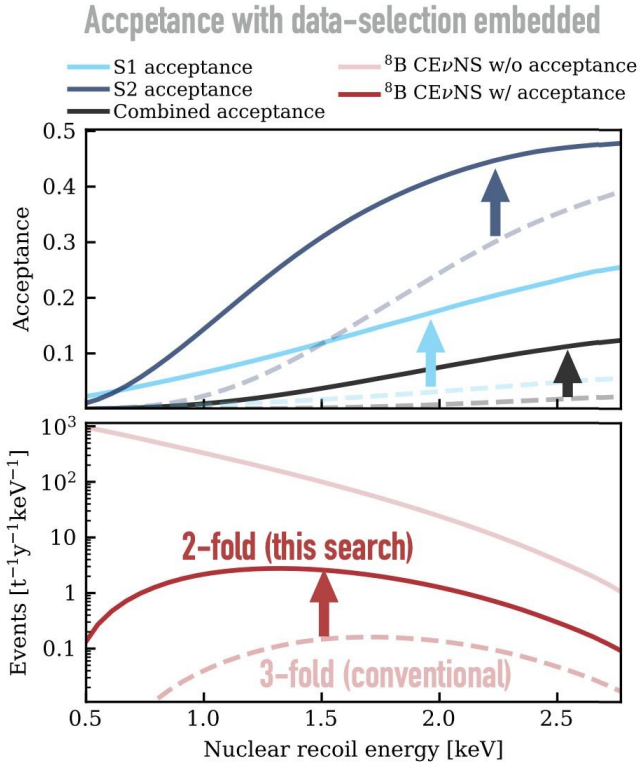



| | SR0 | |
|---|---|---|
| | Nominal | Best fit |
| ER (flat) | 134 | $136 \pm 12$ |
| ER ($^3$H-like) | – | – |
| ER ($^{37}$Ar) | – | – |
| Neutron | $0.7 \pm 0.3$ | $0.6 \pm 0.3$ |
| CE$\nu$NS (solar) | $0.16 \pm 0.05$ | $0.16 \pm 0.05$ |
| CE$\nu$NS (atm.+DSNB) | $0.04 \pm 0.02$ | $0.04 \pm 0.02$ |
| AC | $4.3 \pm 0.9$ | $4.4^{+0.9}_{-0.8}$ |
| Surface | $13 \pm 3$ | $11 \pm 2$ |
| Total background | 152 | $152 \pm 12$ |
| WIMP (200 GeV/$c^2$) | – | 1.8 |
| Observed | 152 | |

# $^8$B Search: Win with Lower Threshold




| | |
|---|---|
| CE$\nu$NS (solar) | $0.16 \pm 0.05$ |

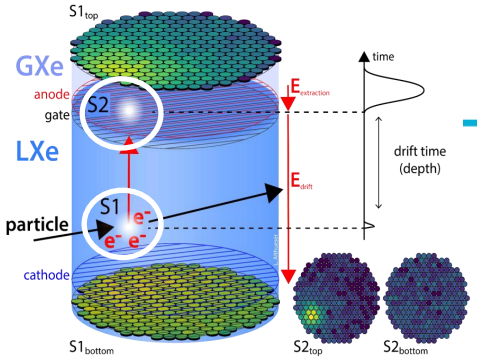


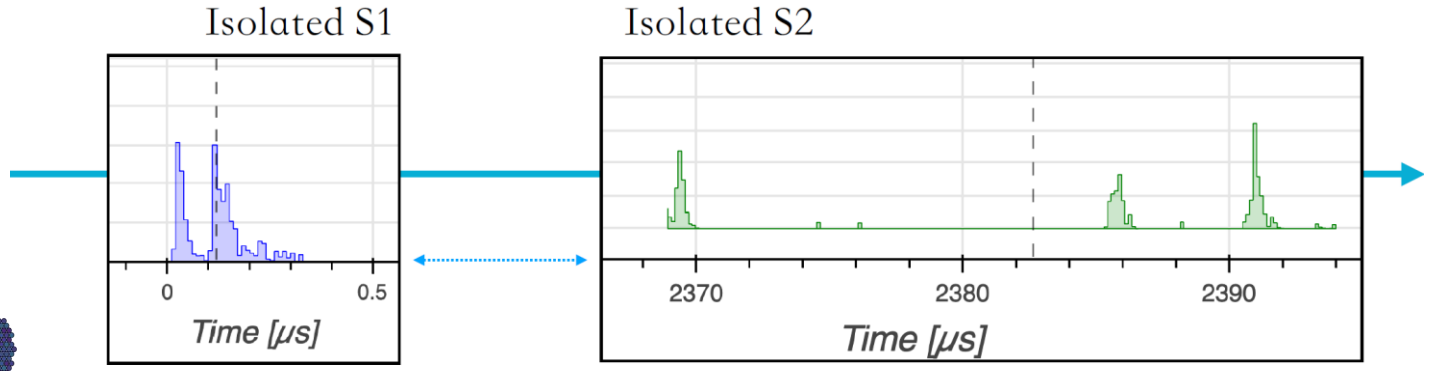

Most $^8$B CEvNS below **3-fold WIMP** threshold:

- **S1** coincidence PMTs: lower to **2-fold** → **~20x** higher $^8$B CEvNS signal
- **S2** = (**120**,500) PE ≃ (**4**,17) electrons → ? higher background

# Challenge 1: Accidental Coincidence (AC)

i.e., incorrectly paired **S1** and **S2**




PMT lone-hits pile-ups, …

Hypothesis: delayed electrons, from electrodes …

$$Count_{AC} = \int_{t_0}^{t_1} R_{S1}(t) \times R_{S2}(t) \times T_{max} dt$$

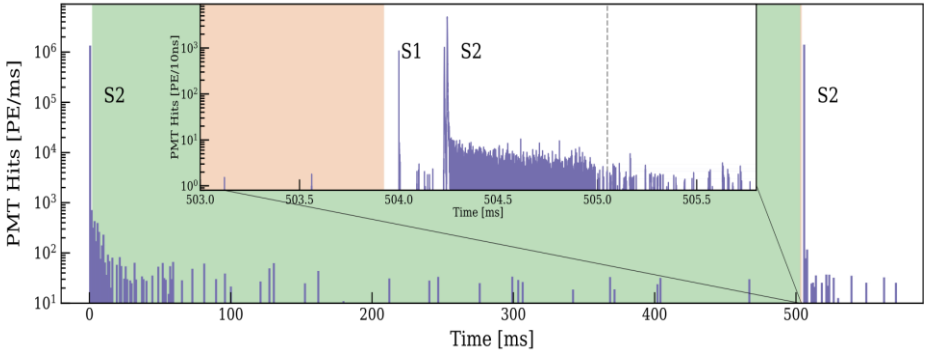
15 Hz

2.2 ms

0.15 Hz

Before suppression ~ **400/day** ☹

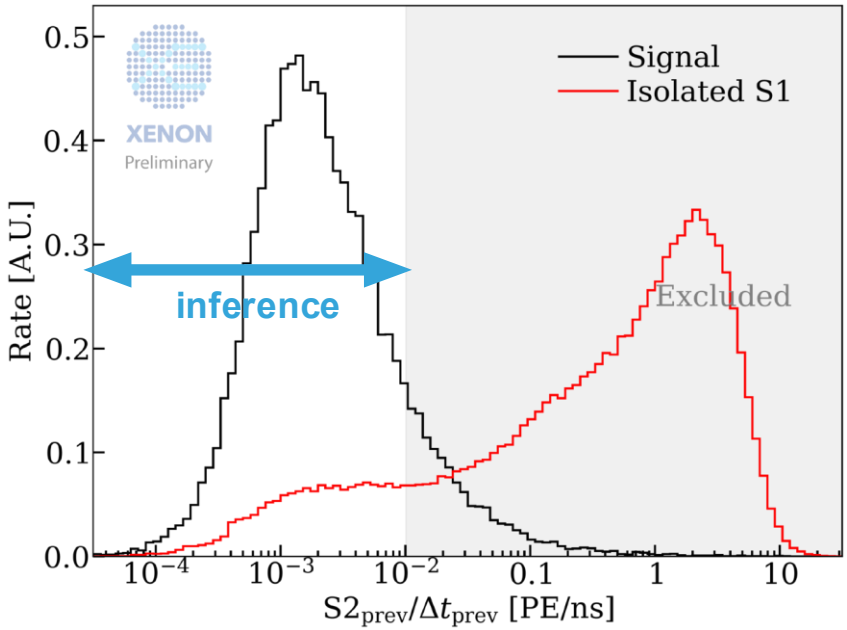
# AC removal: High Energy Correlation




XeTPCs have low-energy signals following high-energy peaks → time correlation

**S2 Time shadow:**

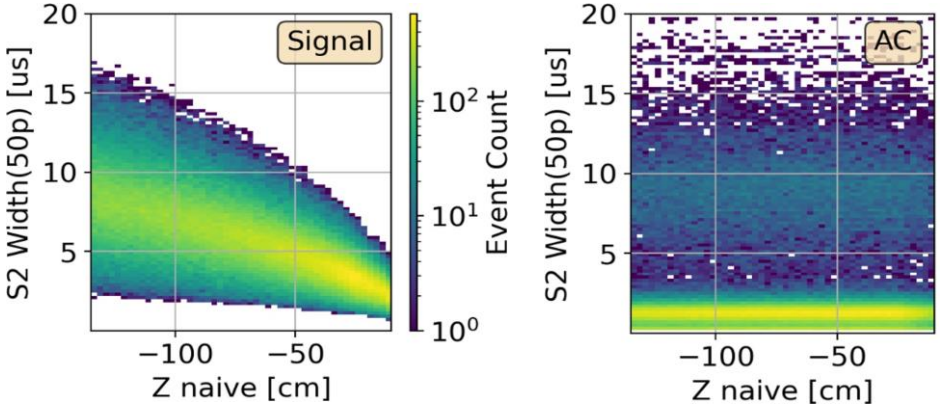
$S2_{prev}/\Delta t_{prev}$

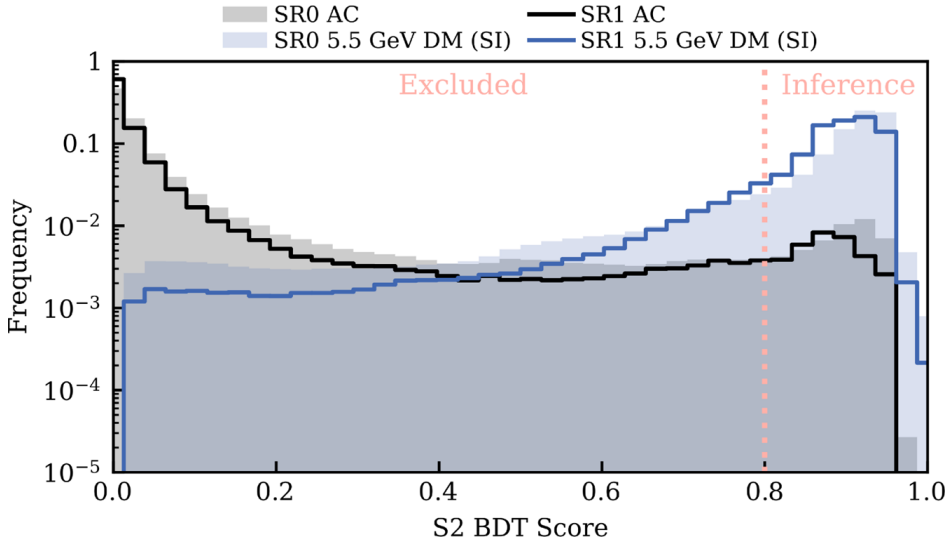


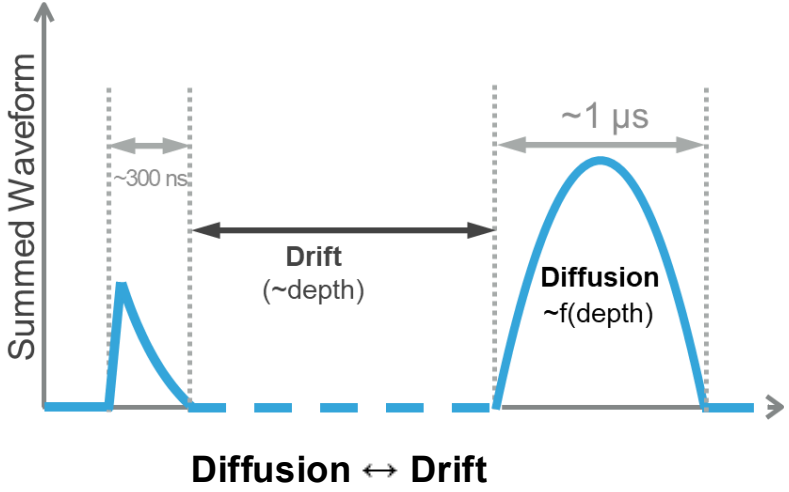

- Exposure remain = 80%
- Data-driven simulation verified with calibration
- "Isolated" S1/S2 suppressed by **1-2 orders**

| "Isolated" S1 | "Isolated" S2 |
|---|---|
| 15 Hz → **2.3 Hz** | 150 mHz → **25 mHz** |

# AC removal: Waveform Learning



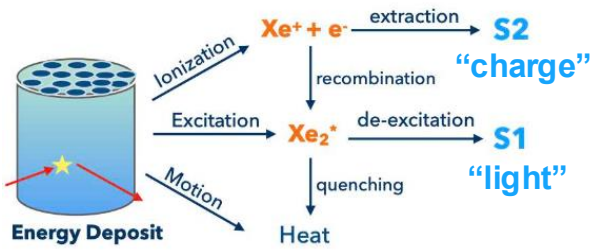




## Boosted Decision Tree Machine

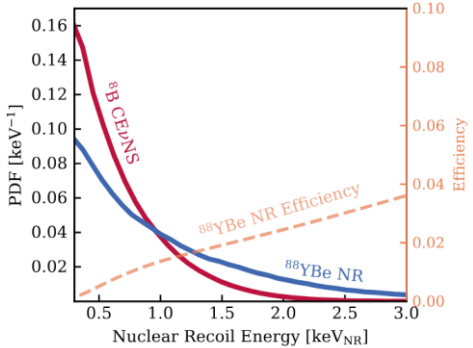
- Learning waveform features
- Electrons diffuse over the drift
- Reject **90%** AC, retain **80%** signal

# Challenge 2: Low-energy Response

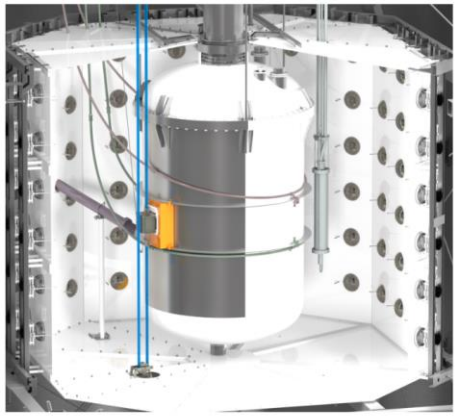


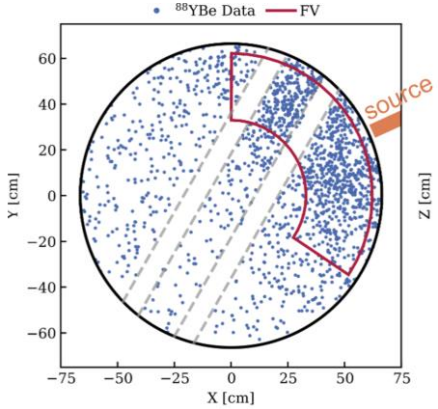

**YBe neutron calibration**

- Measure light/charge yields ~1keV$_{NR}$
- Demonstrate low-energy detection

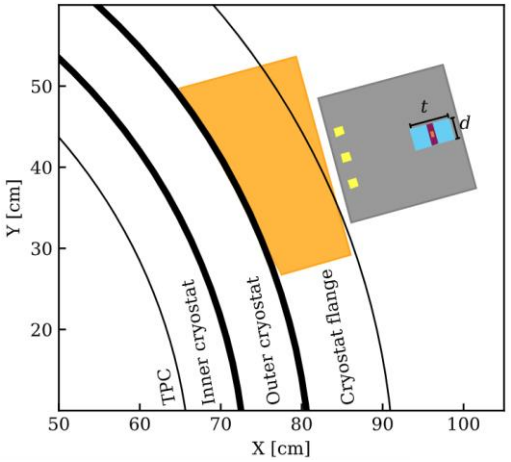


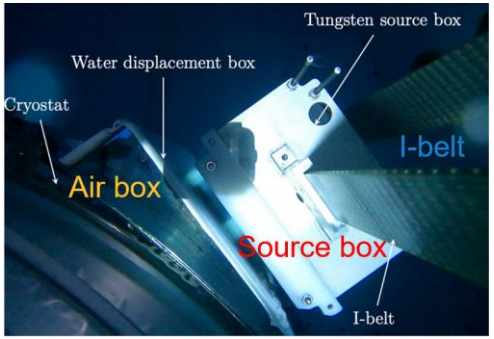

**YBe source:** $\gamma$ + $^{9}$Be → n + $^{8}$Be





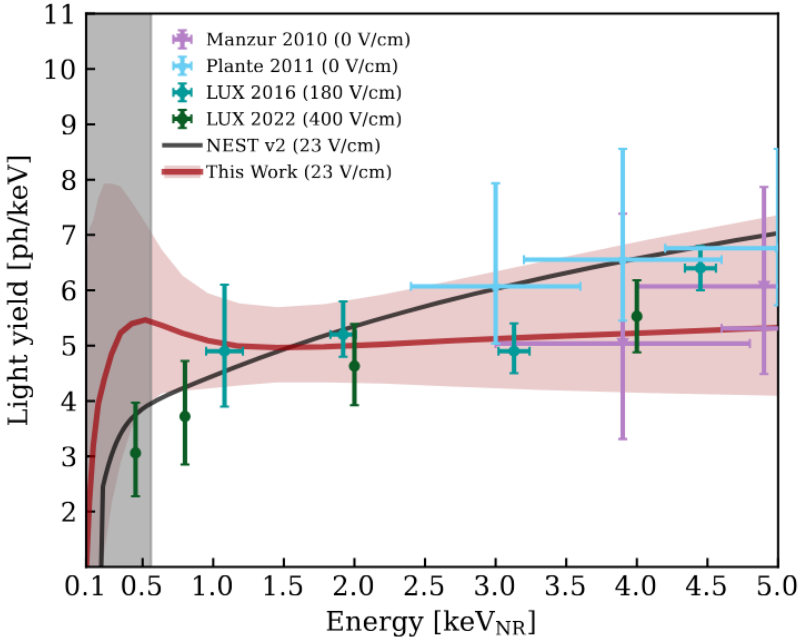

2502.18005

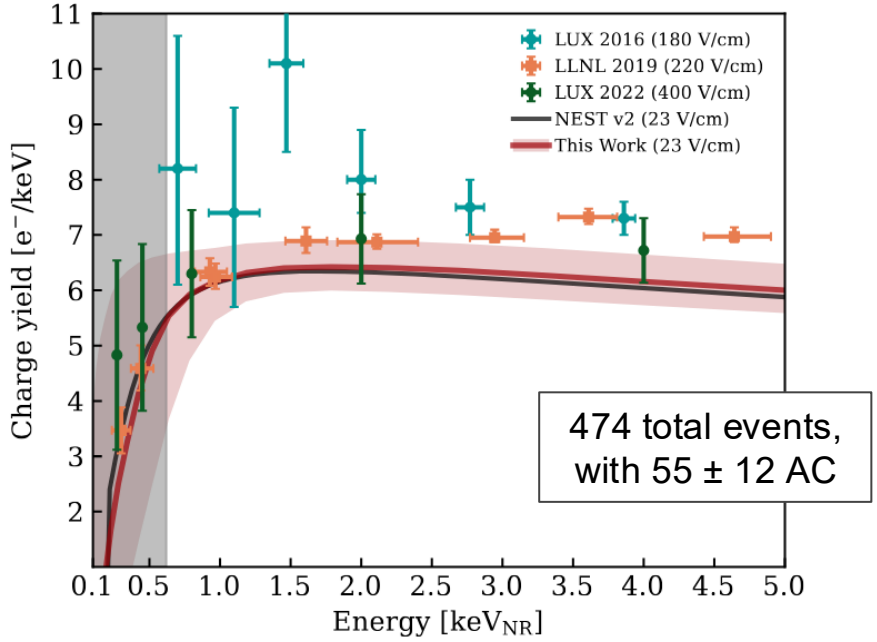



Deployed near TPC with tungsten gamma-shielding

# Signal: Emission model from YBe

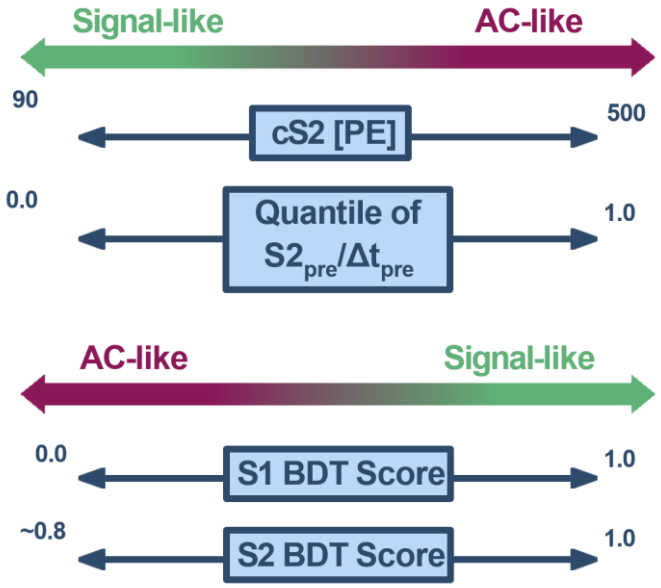


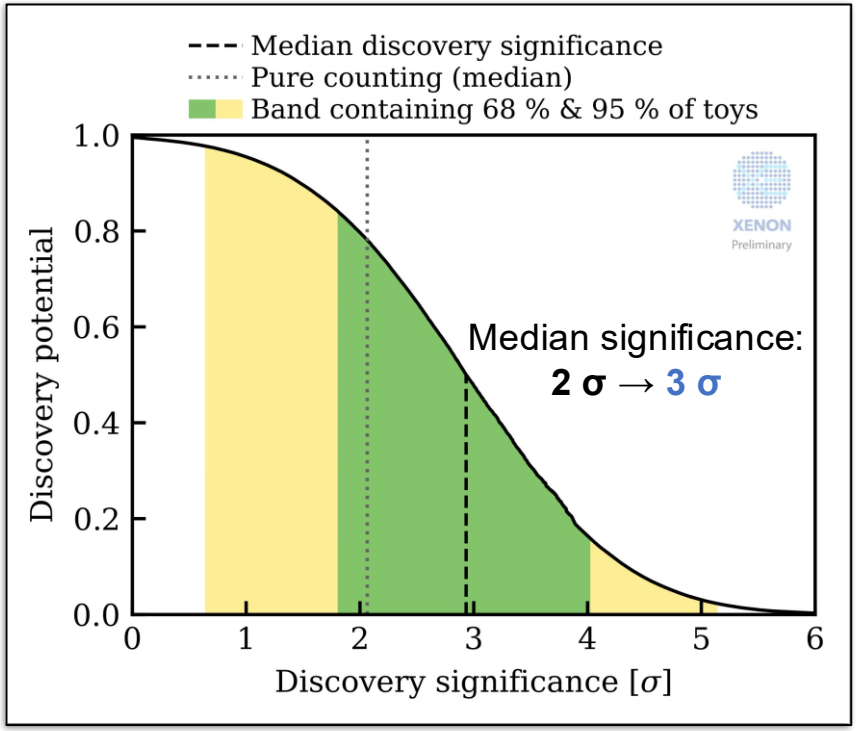




- Demonstration to extract **signal** **near 0.5 keV**
- Extracted light and charge **yields**
- **35% uncertainty** for $^8$B CEvNS model

# XENON $^{8}$B Sensitivity

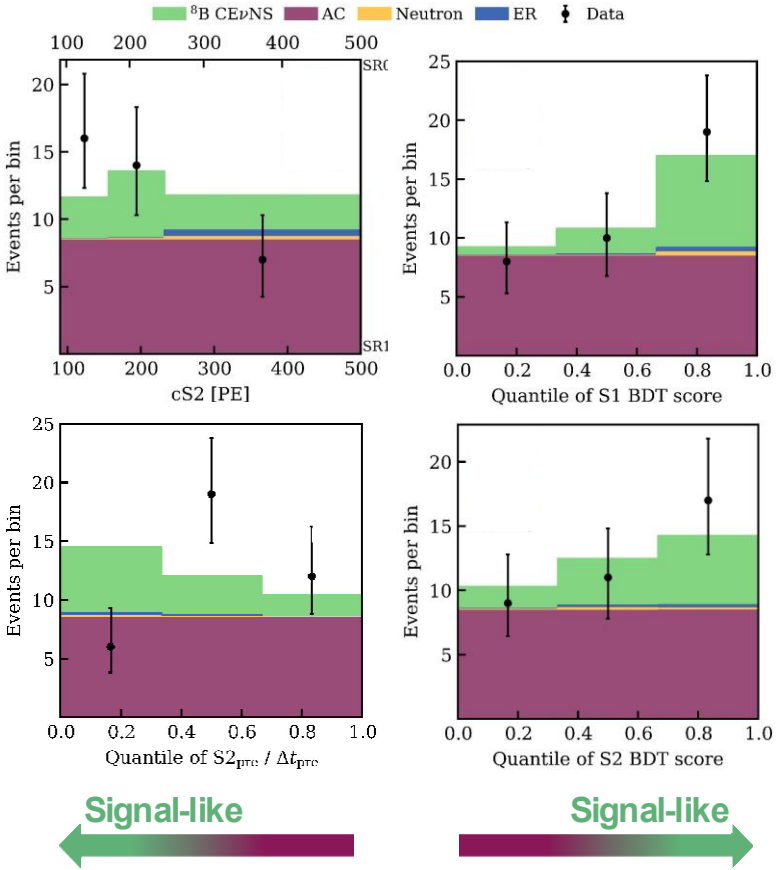
- Extended binned likelihood
- New analysis dimensions
- Constraints on YBe yield model



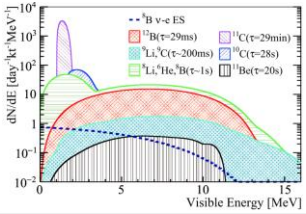




**Feature extraction ↔ Improved sensitivity**

# $^8$B CEvNS Results




Compare: JUNO ν-e




| Component | Expectation | Best-fit |
|---|---|---|
| AC (SR0) | $7.5 \pm 0.7$ | $7.4 \pm 0.7$ |
| AC (SR1) | $17.8 \pm 1.0$ | $17.9 \pm 1.0$ |
| ER | $0.7 \pm 0.7$ | $0.5^{+0.7}_{-0.6}$ |
| Neutron | $0.5^{+0.2}_{-0.3}$ | $0.5 \pm 0.3$ |
| Total background | $26.4^{+1.4}_{-1.3}$ | $26.3 \pm 1.4$ |
| $^8$B | $11.9^{+4.5}_{-4.2}$ | $10.7^{+3.7}_{-4.2}$ |
| Observed | Constrained by YBe 37 | |

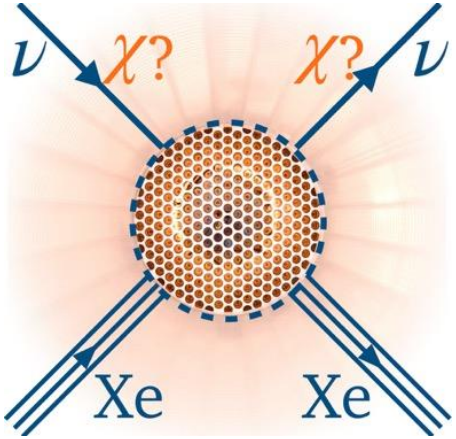
**First measurements of $^8$B CEvNS**

**PandaX-4T(2024) 2.6σ** PRL 133, 191001 (2024)

**XENONnT(2024) 2.7σ** PRL 133, 191002 (2024)

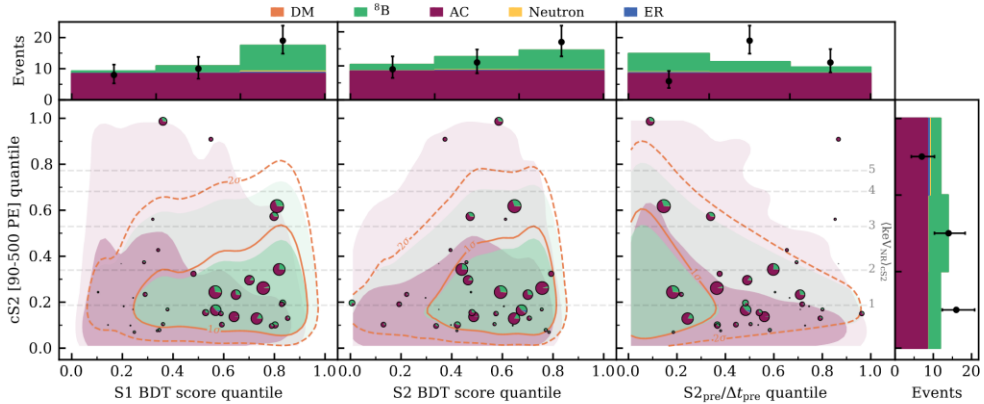
**LZ(2025) 4.5σ** arXiv:2512.08065

# “Neutrino Fog”

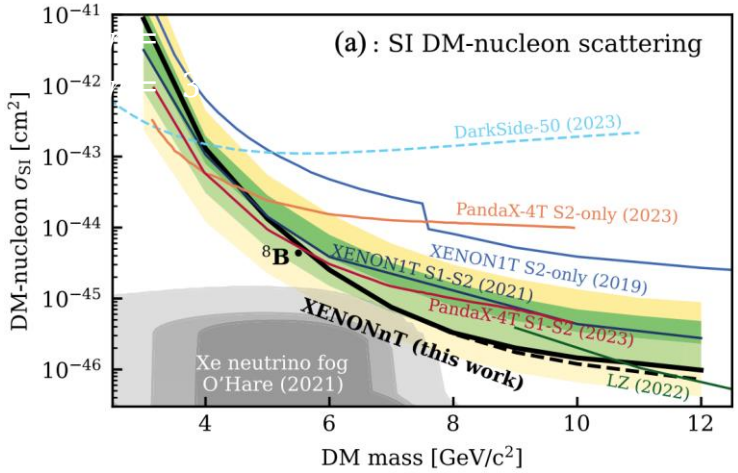



Xe TPC now and future:

- **CEvNS background:** slower improvement over exposure
- Opportunity for precise measurement with improved yield models

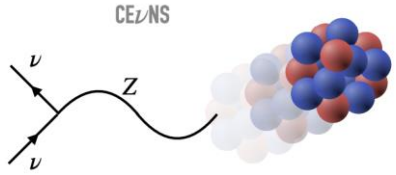


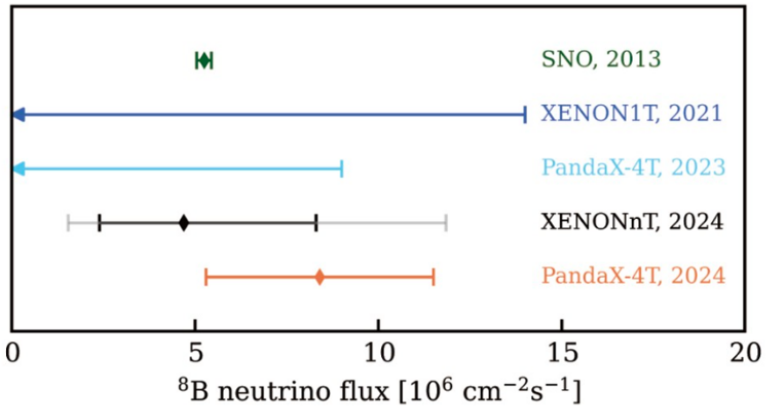

$^8$B becomes DM background

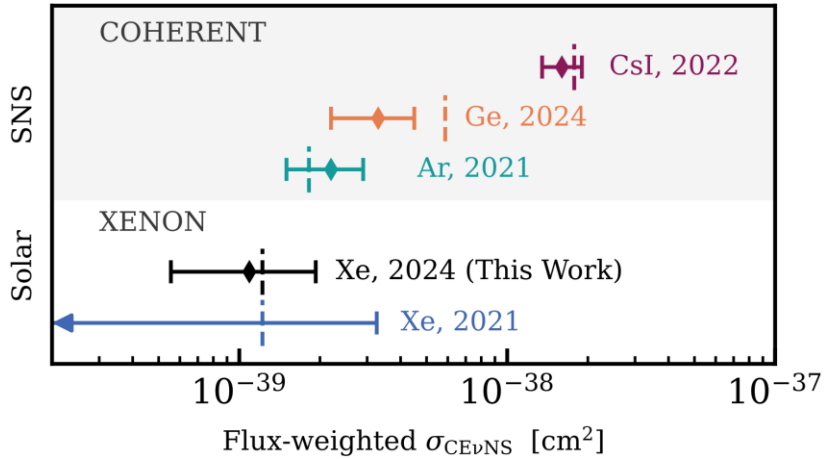



DM limit “first step” into neutrino fog

# CEvNS Measurements



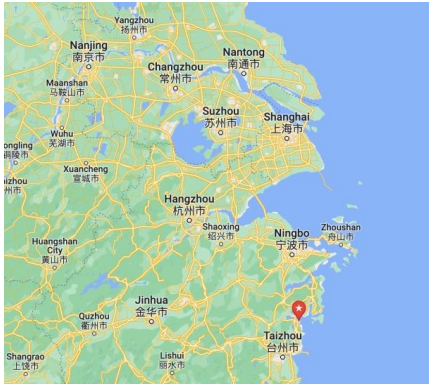




XENON: **11 CEvNS** over 3 years…

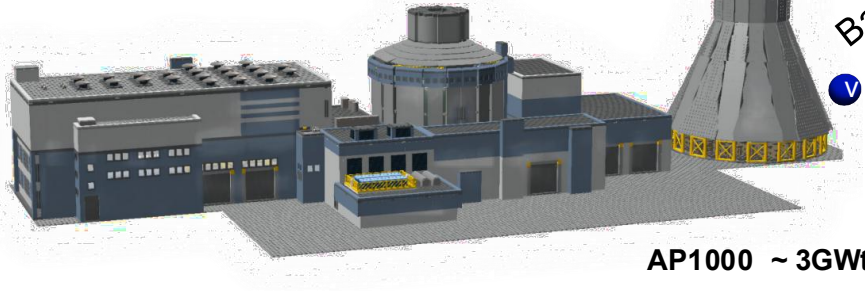
Can we have more?

# Xe TPC for reactor CEvNS



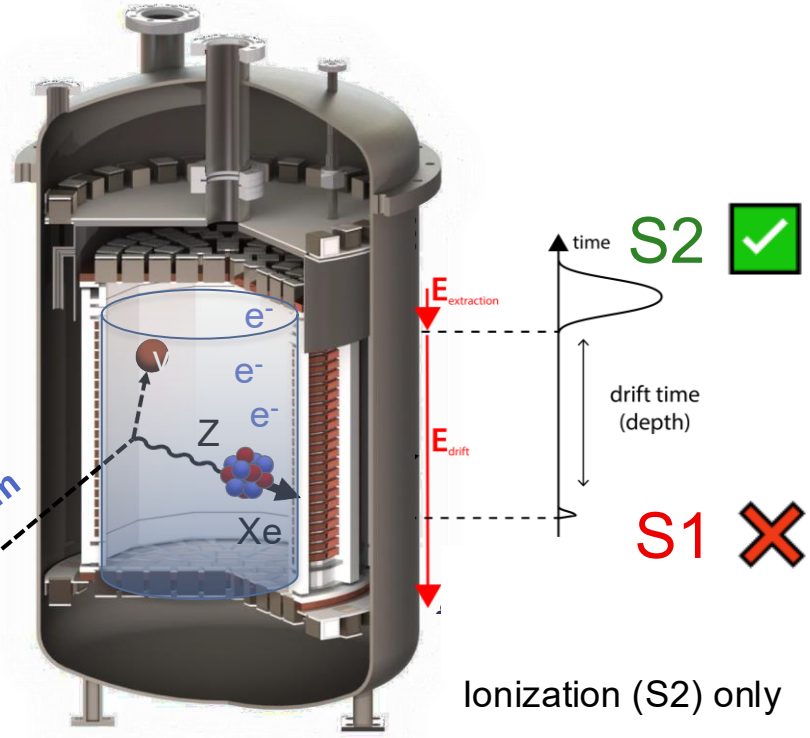

Sanmen Reactor, Zhejiang

Neutrino flux ~ $10^{13}\ cm^{-2}s^{-1}$



AP1000 ~ 3GWth

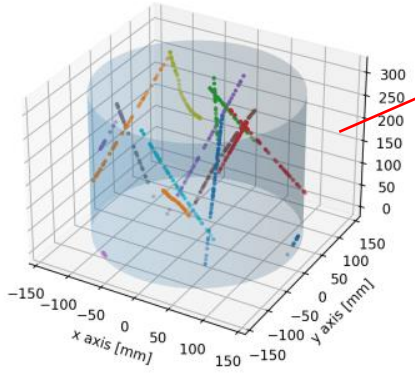
Baseline ~25m



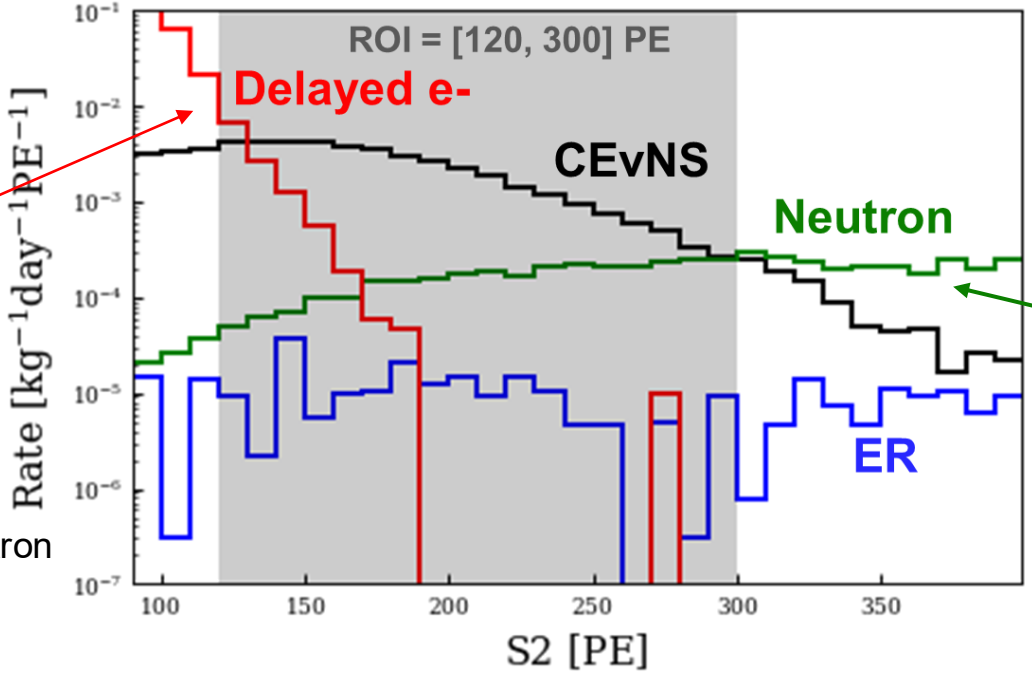

Ionization (S2) only

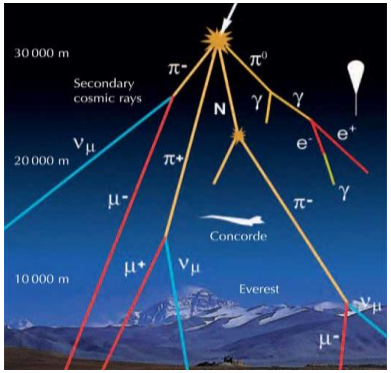
On-site commission 2026

# RELICS Signal and Backgrounds




Muon-related delay electron
- Correlation cuts
- Waveform



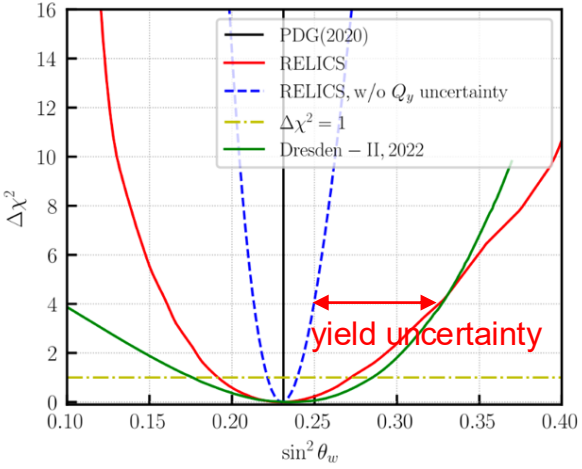




Cosmic-ray neutron
- Shielding

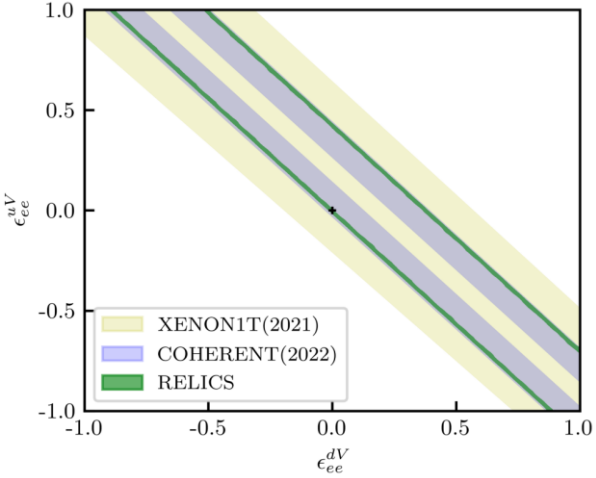
- ~5000 CEvNS with 30kg-year exposure @25m baseline
- ~1500 backgrounds in the same exposure, cosmic-ray related
- Active + passive shielding needed for suppression

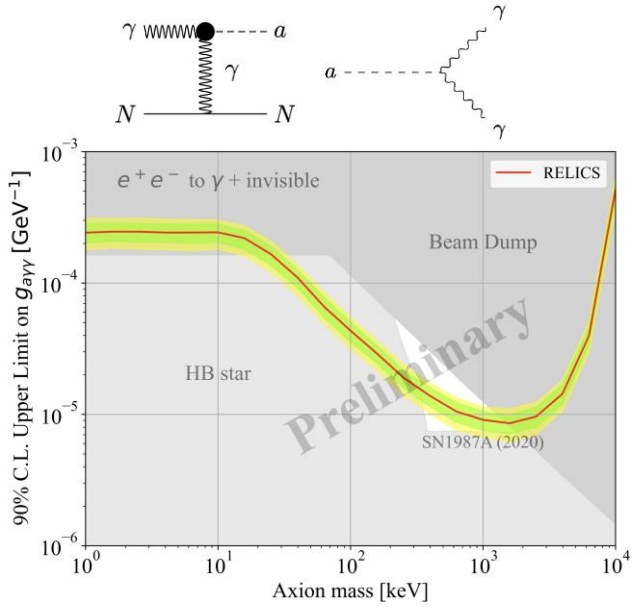
# RELICS Sensitivities

$$\sin^2\theta_W(\mu) = \frac{g'^2(\mu)}{g^2(\mu) + g'^2(\mu)}$$




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

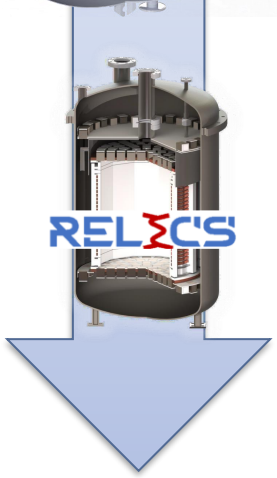



- Weak mixing angle at low-$Q^2$
- Non-standard neutrino interactions
- Axion coupling to gamma (reactor ALP)

# Summary

- CEvNS is complementary to IBD, c.f., Jiajun's talk
- Xe TPCs are advantageous in cross-section
- Three ton-scale Xe TPCs saw CEvNS from solar $^{8}B$ neutrinos
- kg-scale Xe TPC will measure reactor CEvNS cross-section with high-flux and low-Q




**Technology maturity**
20 years of development
Purification; Rn/Kr distillation
Accidental suppression

**Shared bottleneck/systematic**
Delayed electron
Detector response (lowE yields)

**Future work**
Local R&D (problem & solution)
Theoretical motivation

**Ultimate CEvNS detector**