XENON

西湖大學 WESTLAKE UNIVERSITY

Exploring Dark Matter and Neutrinos with XENONnT

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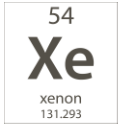
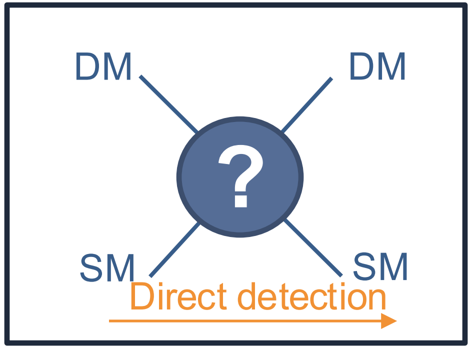
July 17, 2025

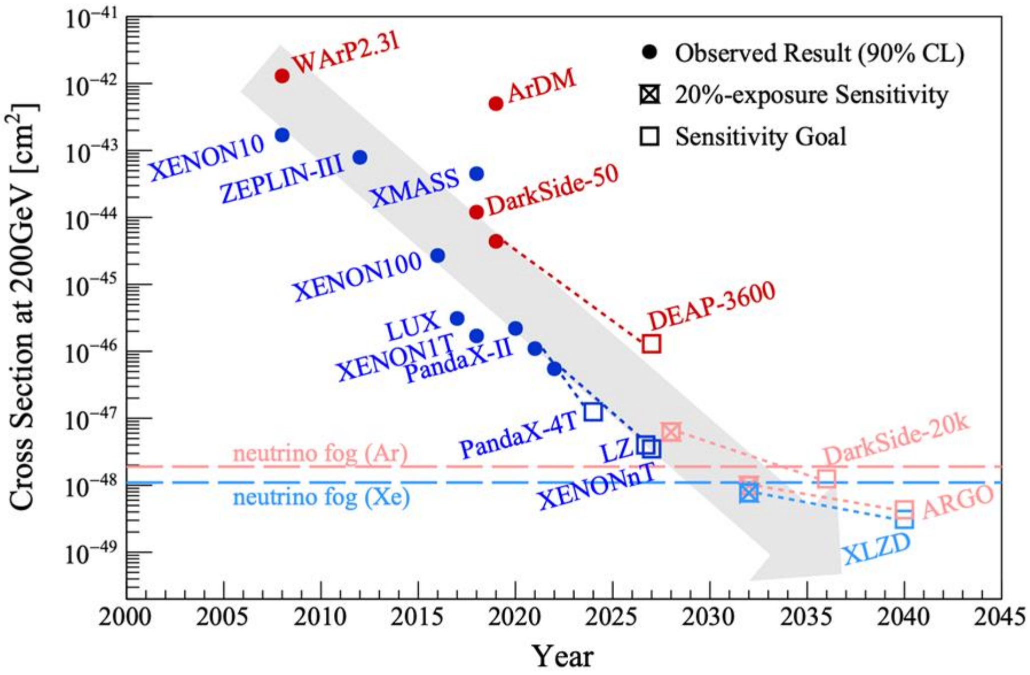
PRL 133, 191002 (2024)
PRL 134, 111802 (2025)
arXiv: 2412.10451 (2024)
arXiv: 2502.18005 (2025)

第六届粒子物理前沿研讨会@吉林大学

Westlake University | DM and neutrino lab

WIMP Search with 





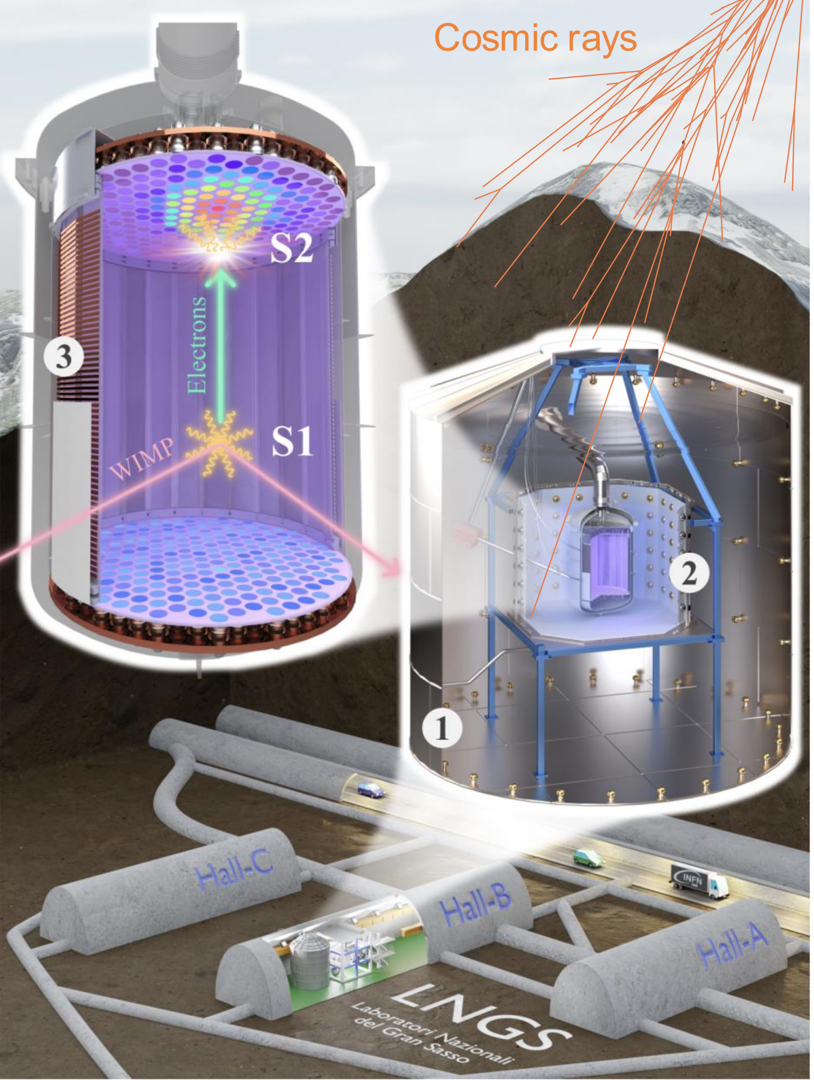
- Maximum signal via kinetic matching
- Coherent scattering

$$\frac{\lambda_{\text{deBrogile}}}{2\pi} = \frac{\hbar c}{p'c} \sim \frac{197\text{MeV fm}}{100\text{GeV} \cdot 10^{-3}} \approx \text{fm}$$

- Rate prefers high-A (high-J) targets

$$N \propto A^2 \sigma_{\chi,N} \text{ or } (J+1)J\sigma_{\chi,N}$$

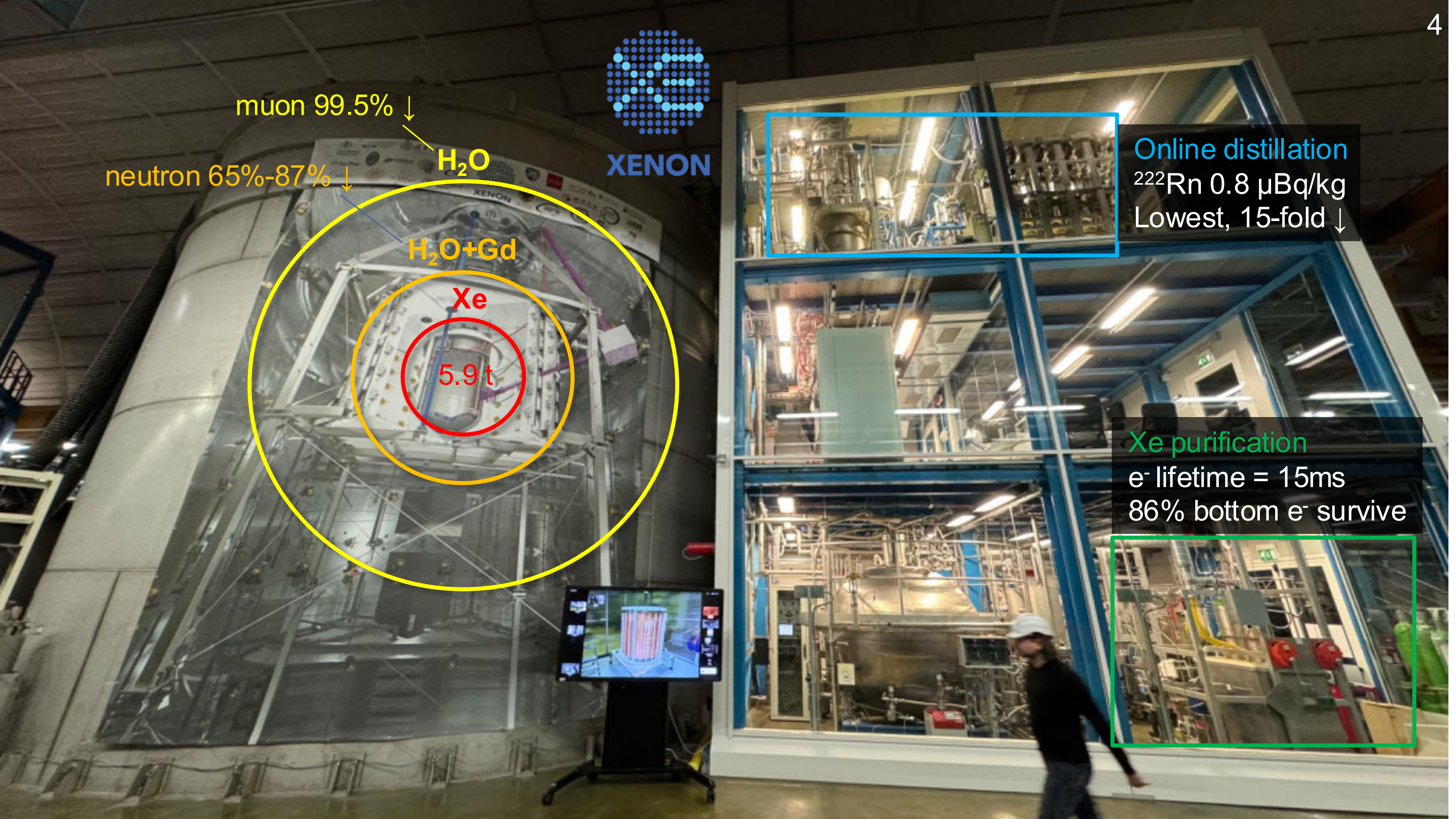
- Xe experiments lead the field
- 5 orders improvement in 20 years



12 countries
29 institutions
170 members

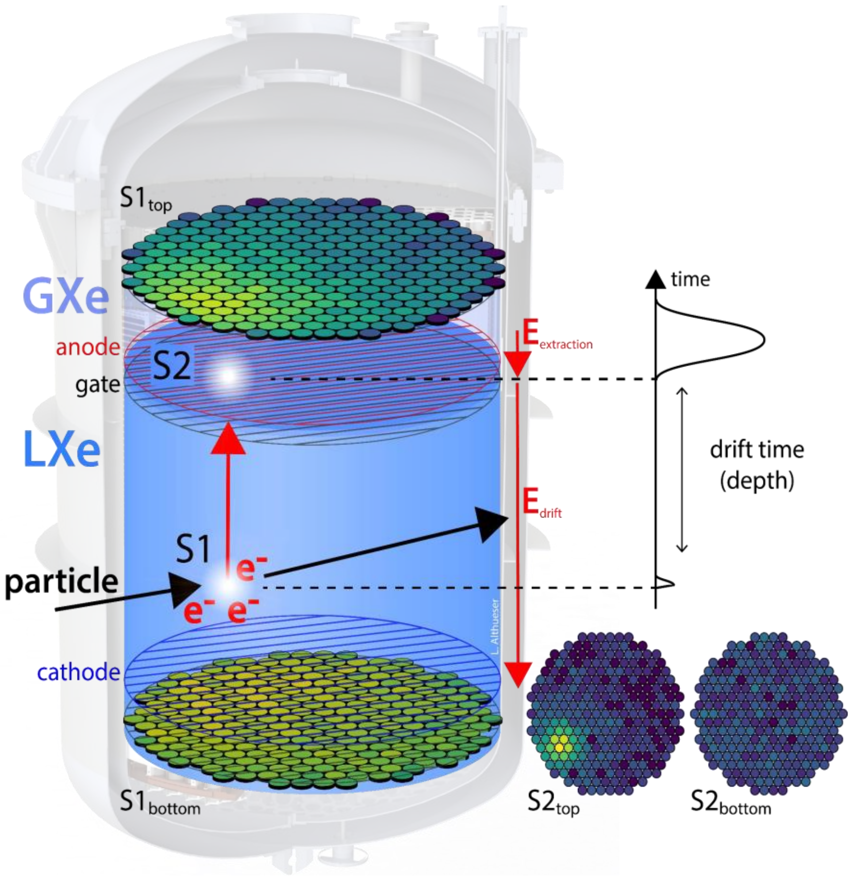
XENON

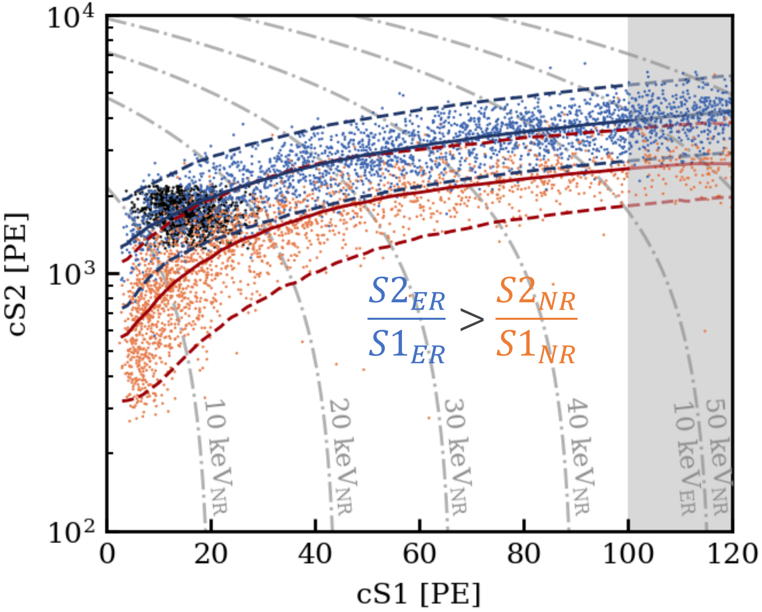
recent papers:
PRD 129, 161805 (2022)
PRD 108, 012016 (2023)
PRL 131, 041003 (2023)
PRL 133, 191002 (2024)
arXiv: 2412.10451 (2024)
PRD 111, 062006 (2025)
PRL 134, 111802 (2025)
arXiv: 2502.18005 (2025)



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

Dual-phase Time Projection Chamber (TPC)

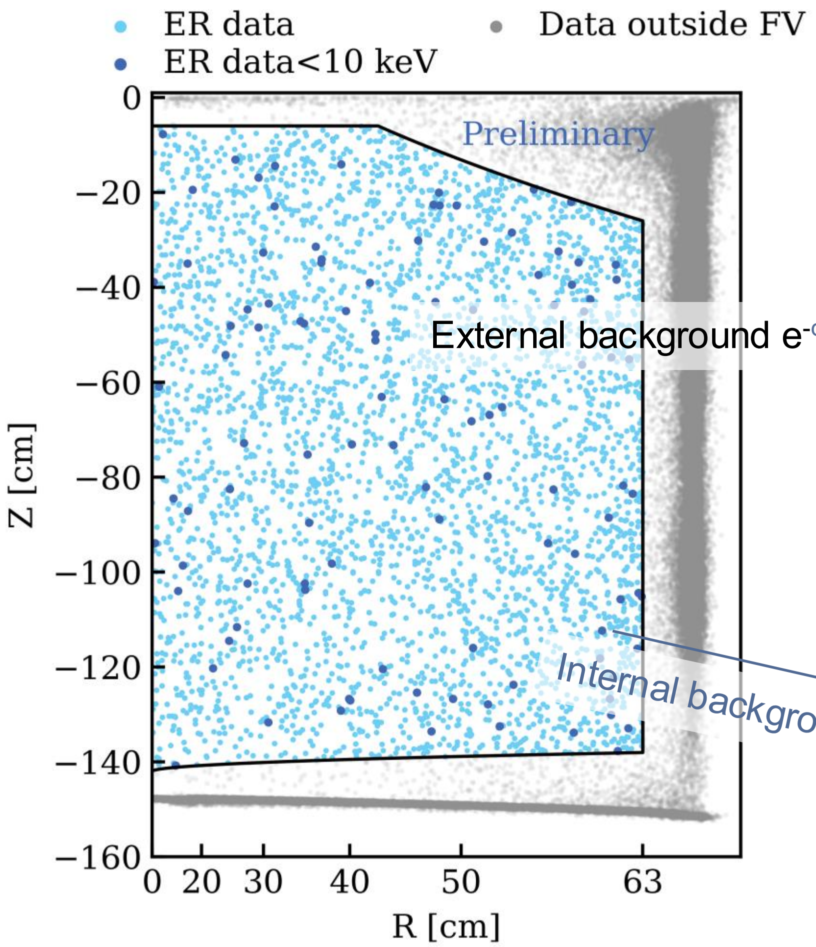




Particle discrimination:

ratio of charge/light (ERs vs. NRs)

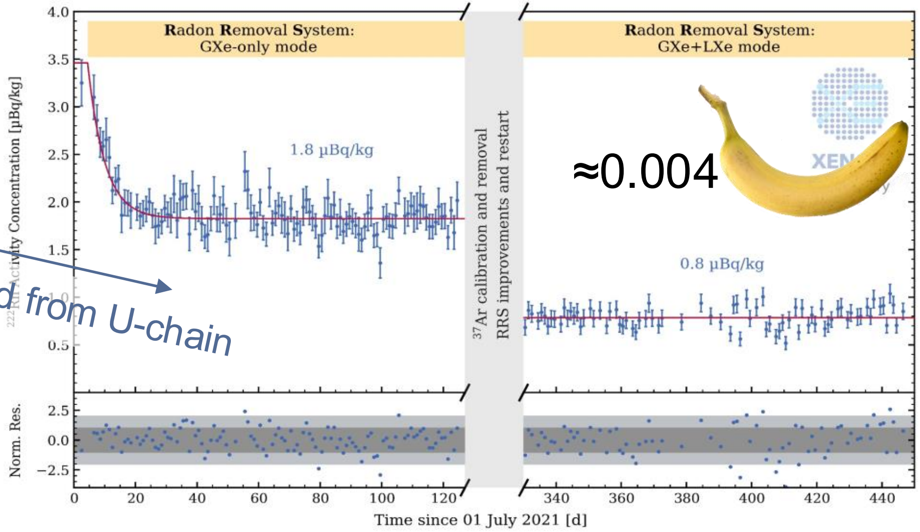
Ultra-low Background



External background e^{-d/λ_γ}

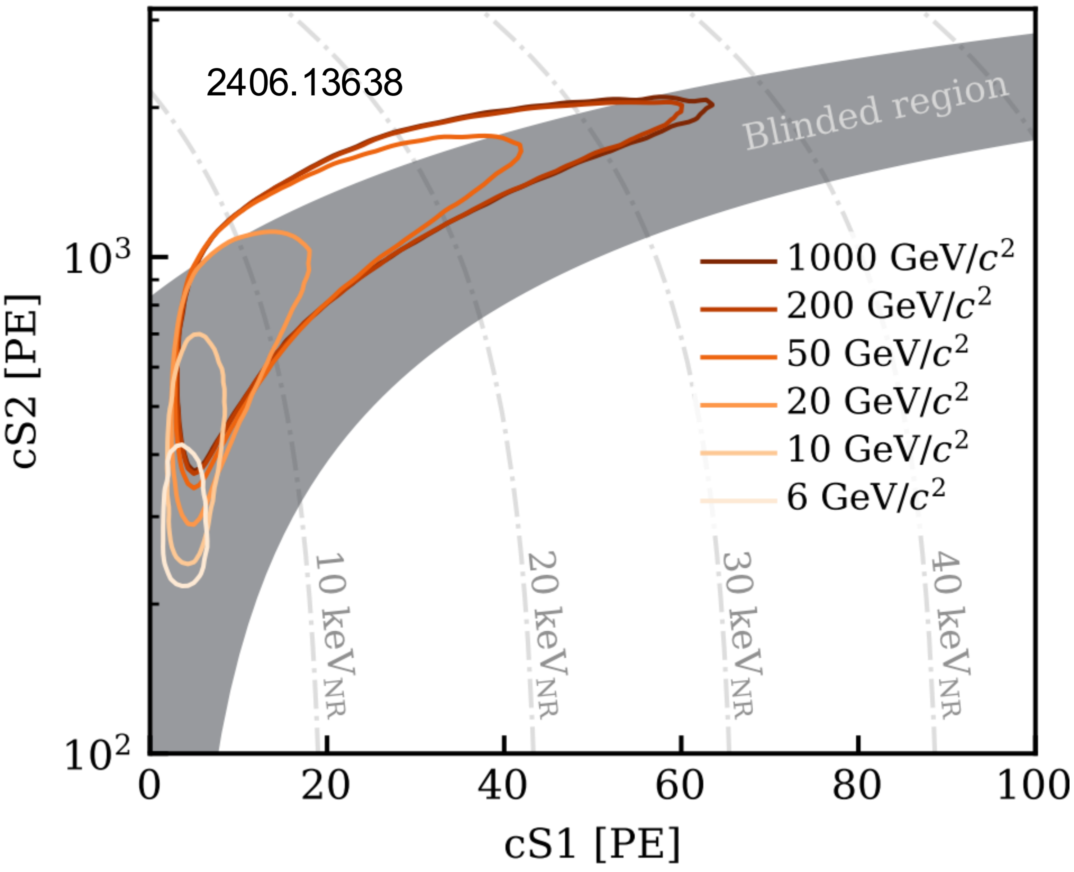
Internal background from U-chain

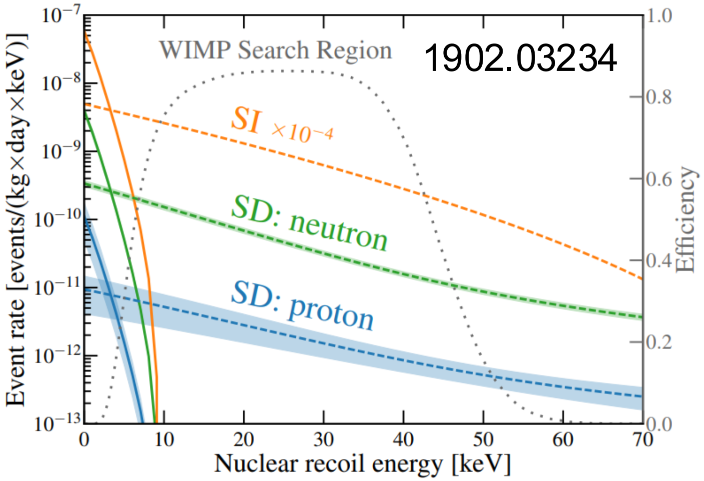
^{222}Rn Gas/liquid distillations



≈0.004

WIMP Signal Model

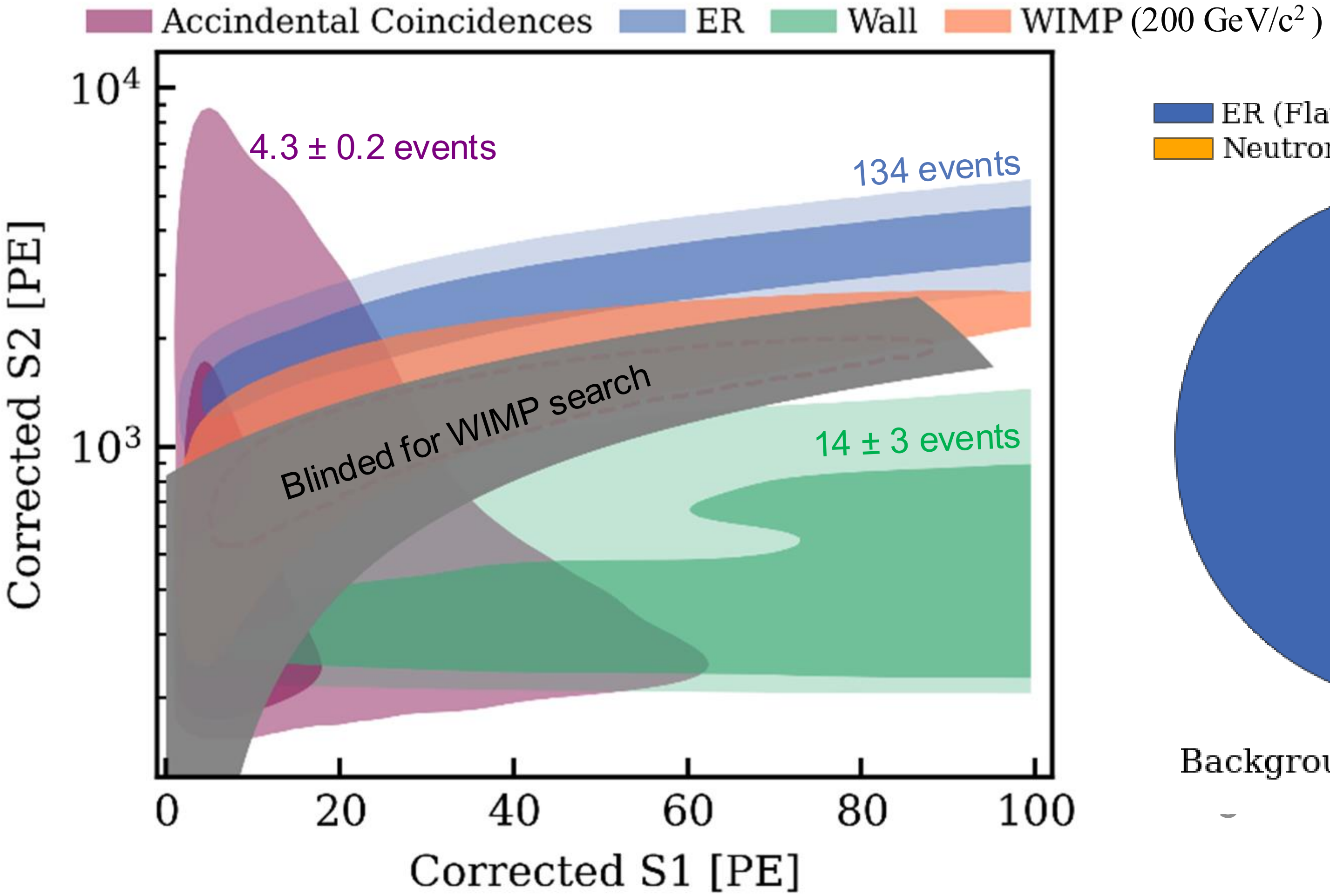


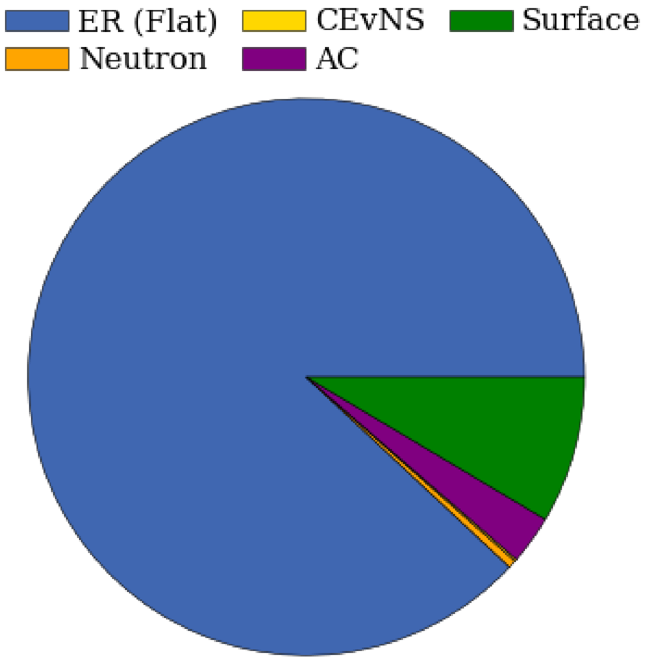


$$\frac{dR_{\mathrm{WIMP}}}{dE} = \frac{\rho_\chi}{2m_\chi \mu_{\chi N}^2} \left\langle \frac{1}{v} \right\rangle \sigma A^2 F^2(q)$$

- Kinetically saturated above 200 GeV
- Challenge: low cS1 with light WIMP

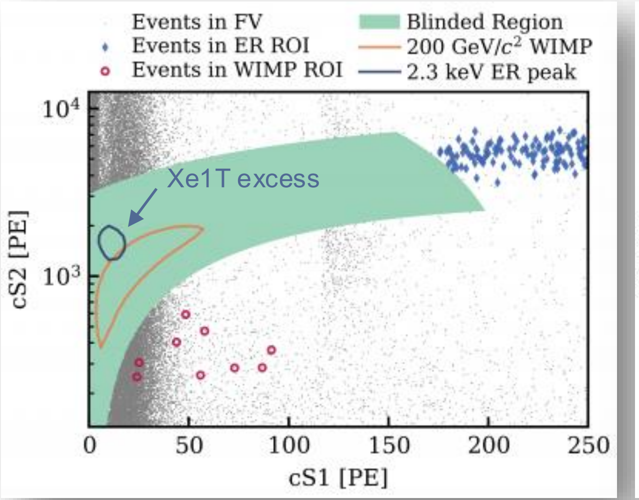
SR0 WIMP Search Backgrounds

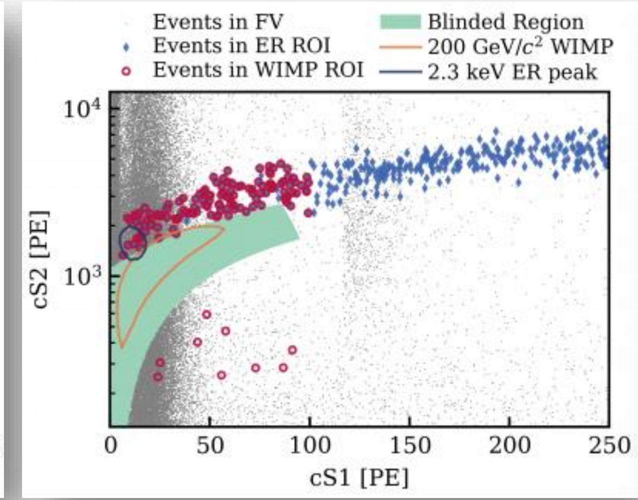


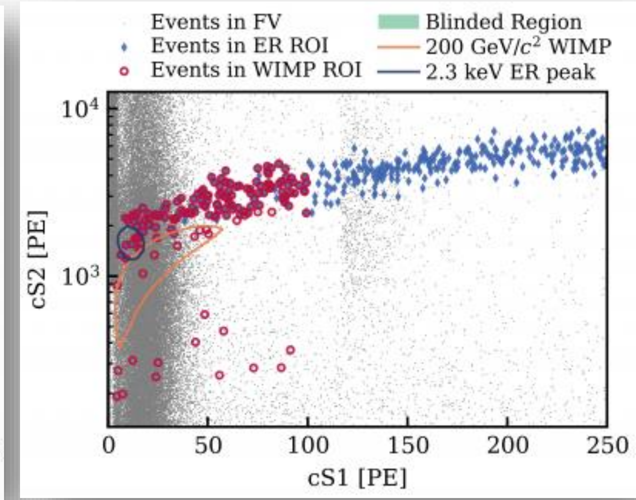


Background expectation: SR0

Unblinding Procedure







Unblind high-energy ER

- Fix ER sideband model and event selection

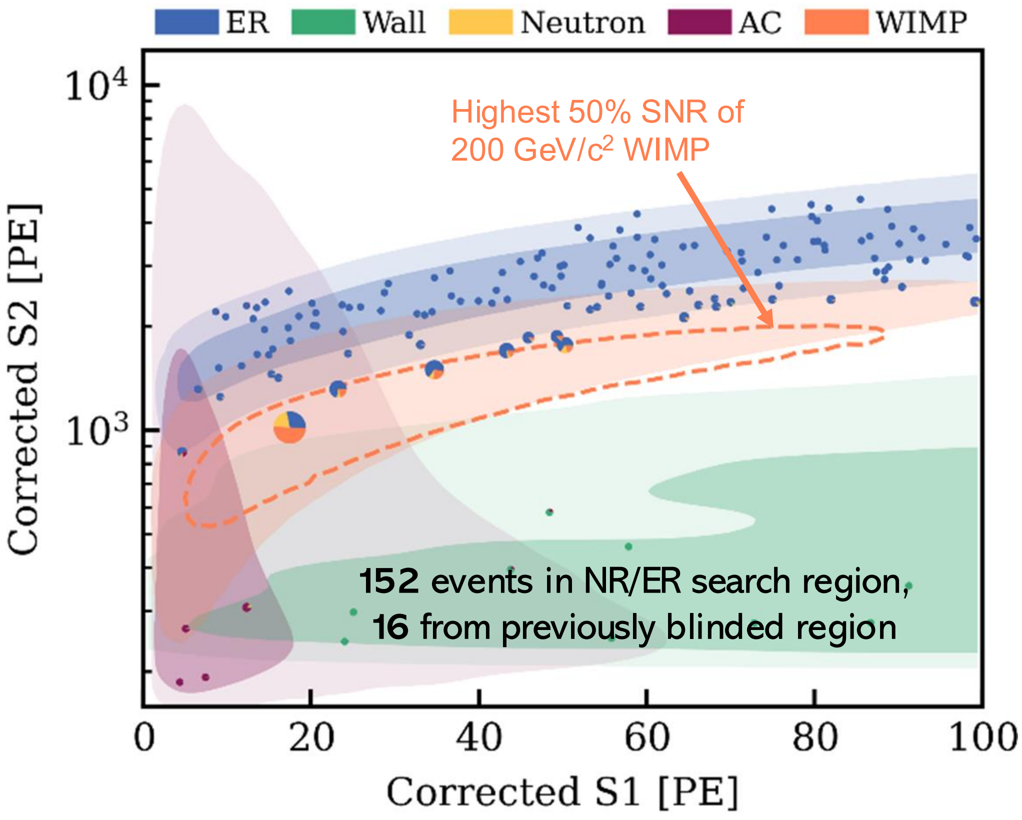
Unblind low-energy ER

- Search for signal in low-energy ER channel
- “ER leakage” checked for the blinded WIMP region

Unblind low-energy NR

- All selection, models, and inference frozen
- Search for WIMPs

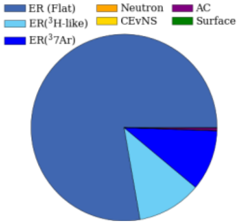
First WIMP Search Result (95 days)

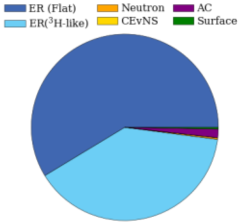


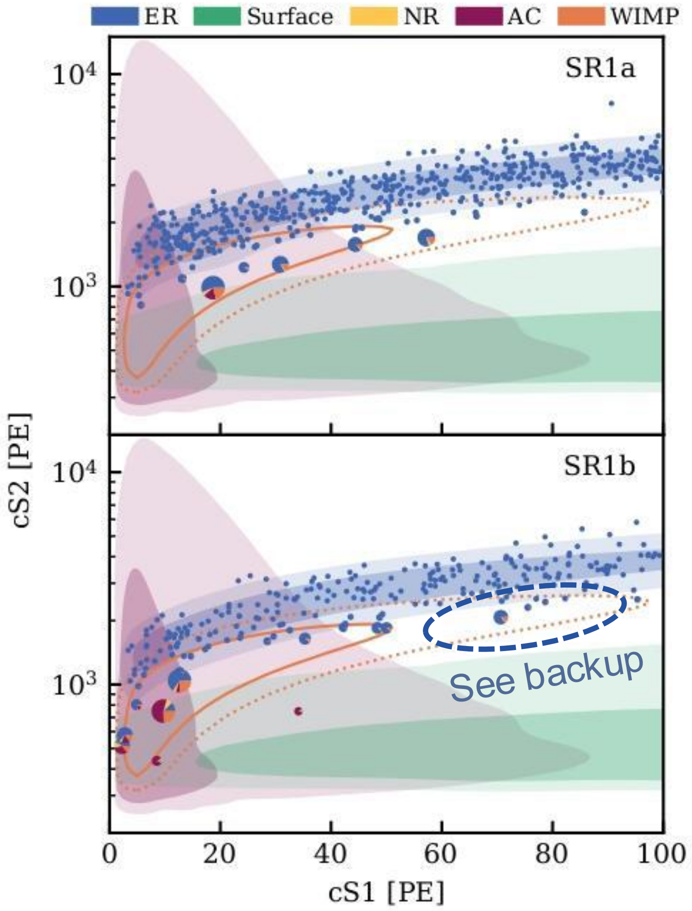
	SR0	
	Nominal	Best fit
ER (flat)	134	136 ± 12
ER (^{3}H-like)	–	–
ER (^{37}Ar)	–	–
Neutron	0.7 ± 0.3	0.6 ± 0.3
CEνNS (solar)	0.16 ± 0.05	0.16 ± 0.05
CEνNS (atm.+DSNB)	0.04 ± 0.02	0.04 ± 0.02
AC	4.3 ± 0.9	$4.4^{+0.9}_{-0.8}$
Surface	13 ± 3	11 ± 2
Total background	152	152 ± 12
WIMP (200 GeV/c^2)	–	1.8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

No excess found

Second WIMP Search Result (67+120 days)







	SR1a		SR1b	
	Nominal	Best fit	Nominal	Best fit
ER (flat)	430 ± 30	450 ± 20	151 ± 11	154 ± 10
ER (^{3}H-like)	62	40 ± 30	101	80^{+18}_{-17}
ER (^{37}Ar)	58 ± 6	55 ± 5	–	–
Neutron	0.47 ± 0.19	0.45 ± 0.19	0.7 ± 0.3	0.7 ± 0.3
CEνNS (solar)	0.010 ± 0.003	0.010 ± 0.003	0.019 ± 0.006	0.019 ± 0.006
CEνNS (atm.+DSNB)	0.024 ± 0.012	0.024 ± 0.012	0.05 ± 0.02	0.05 ± 0.02
AC	2.12 ± 0.18	2.10 ± 0.18	3.8 ± 0.3	3.8 ± 0.3
Surface	0.43 ± 0.05	0.42 ± 0.05	0.77 ± 0.09	0.76 ± 0.09
Total background	553	550 ± 20	257	239 ± 15
WIMP (200 GeV/c^2)	–	1.1	–	2.1
Observed	560		245	

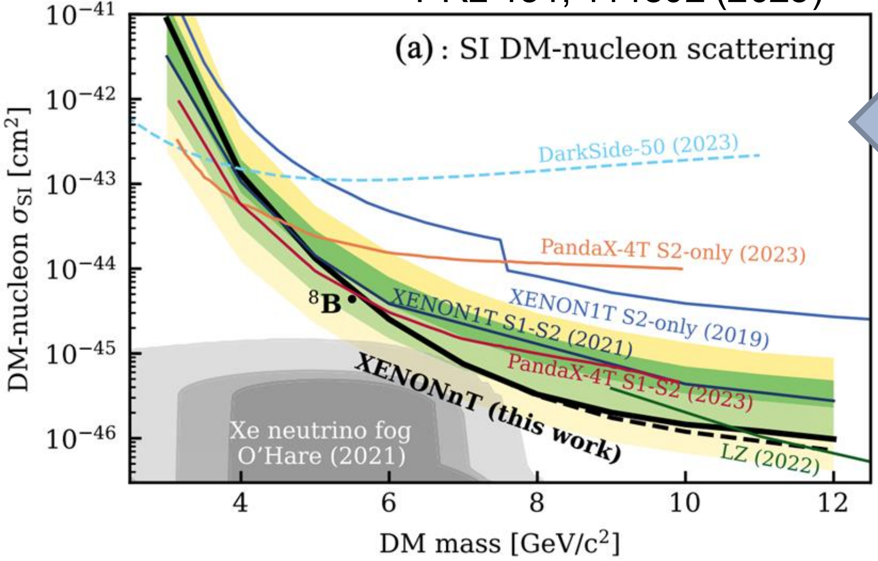
SR1a: Higher ER rate of ^{85}Kr and ^{37}Ar observed

SR1b: Removed with distillation, except ^{3}H

No excess found with 3x exposure

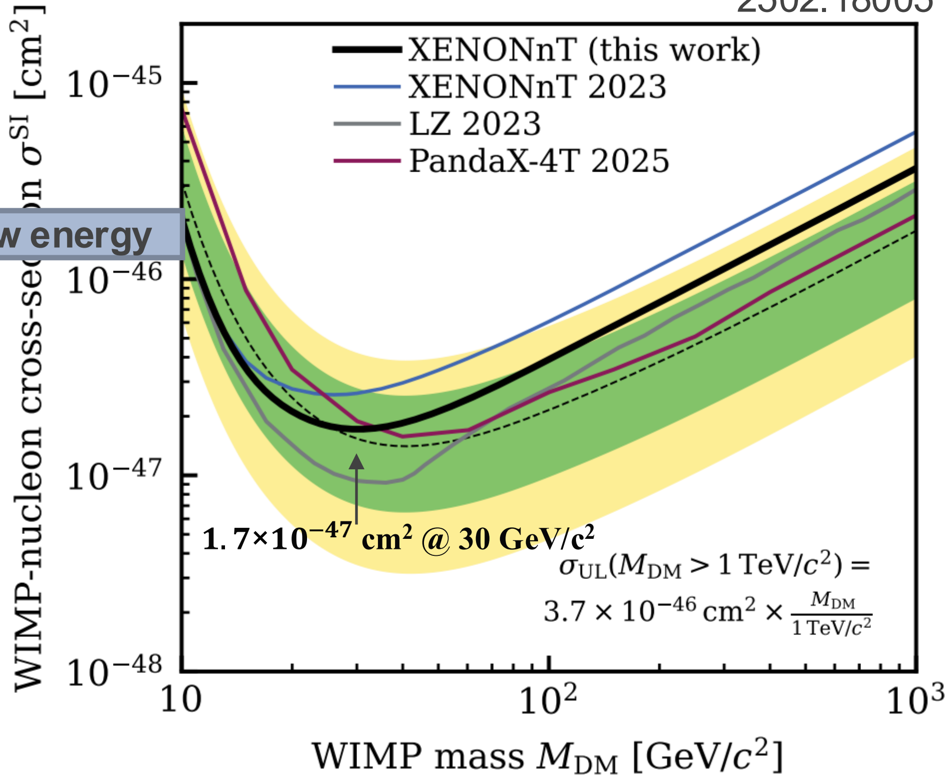
WIMP Limits (2025)

PRL 134, 111802 (2025)

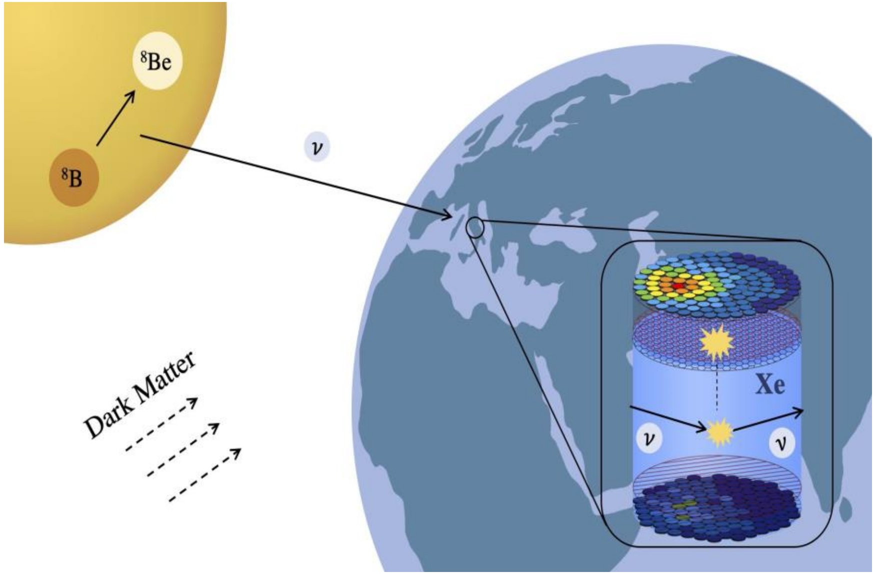


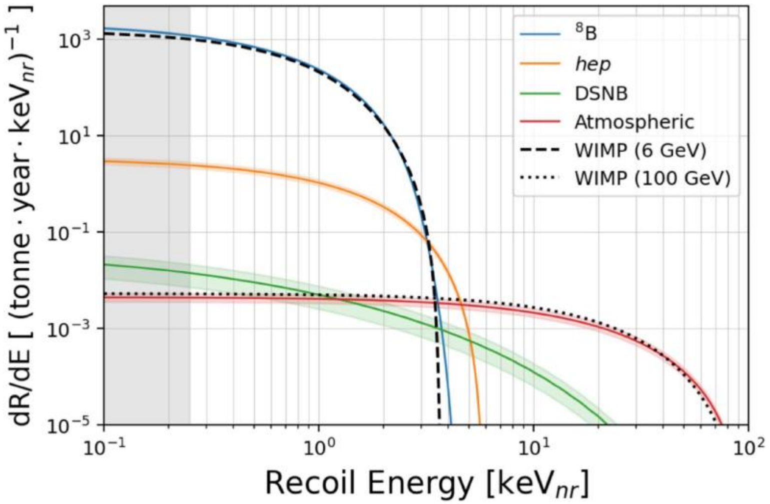
Low energy

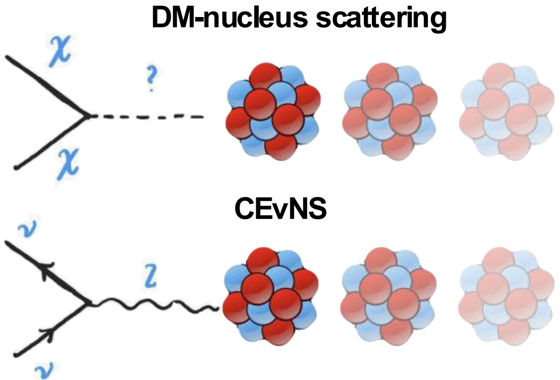
2502.18005



Neutrino NR ~~Background~~ Signal







- **CEvNS**: **C**oherent **E**lastic **Neutrino-N**ucleus **S**cattering (1973 - 2017)
- Large cross-section: $\sigma \propto N^2 \simeq 6000$
- Single scatter NR signal mimic WIMP
- Low momentum transfer, e.g., **^{8}B solar neutrino**: E_ν < 15 MeV
  [see Wed. Wu's talk]

^{8}B SEνNS: Win with Lower Threshold

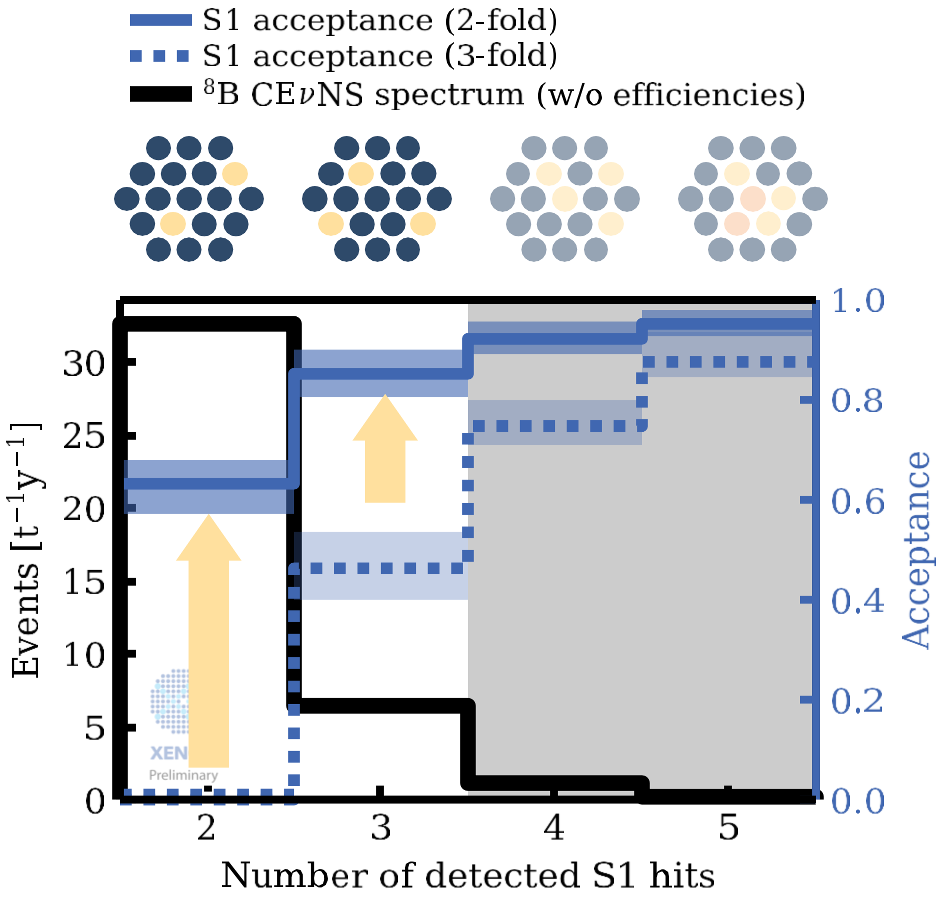
- **WIMP search**:

	SR0	
	Nominal	Best fit
CEνNS (solar)	0.16 ± 0.05	0.16 ± 0.05

- most ^{8}B events below energy threshold
- **CEvNS search**:
- Lowering **S1** coincidence requirement from **3** to **2** PMTs
- **S2** = (120,500) PE ≃ (4,17) electrons

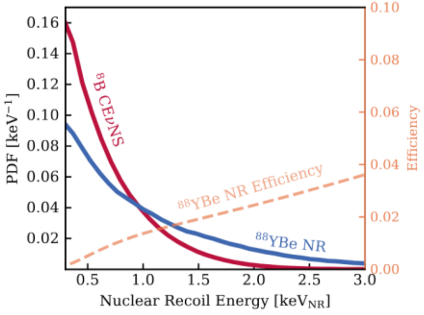
→ **~20x** higher ^{8}B rate

New challenges Different approach



Signal: Neutron Calibration for Low-energy

2502.18005

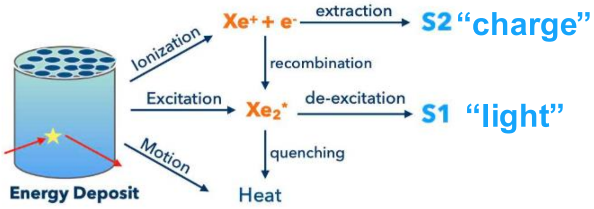


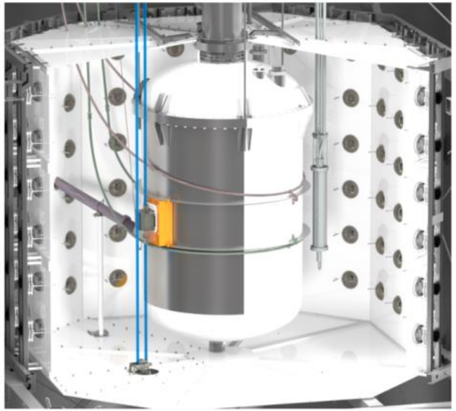
Yttrium-Beryllium (YBe) source

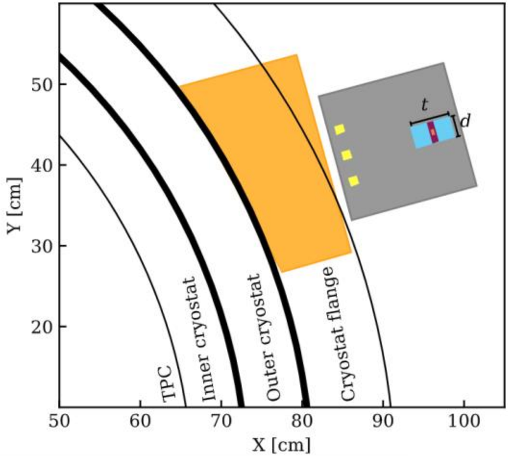
- γ + ^{9}Be → n + ^{8}Be
- emits 152 keV neutrons that mimics NR from ^{8}B

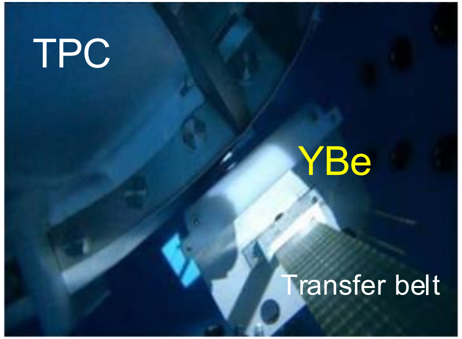
Purpose:

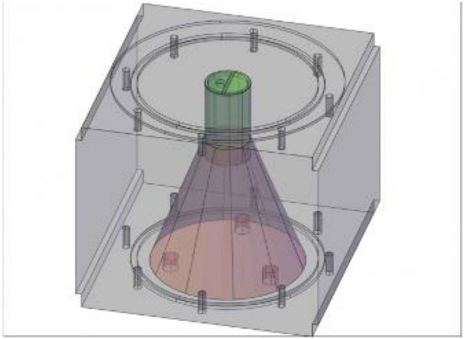
- Measure light/charge yield ~1keV$_{NR}$
- Test near-threshold detection







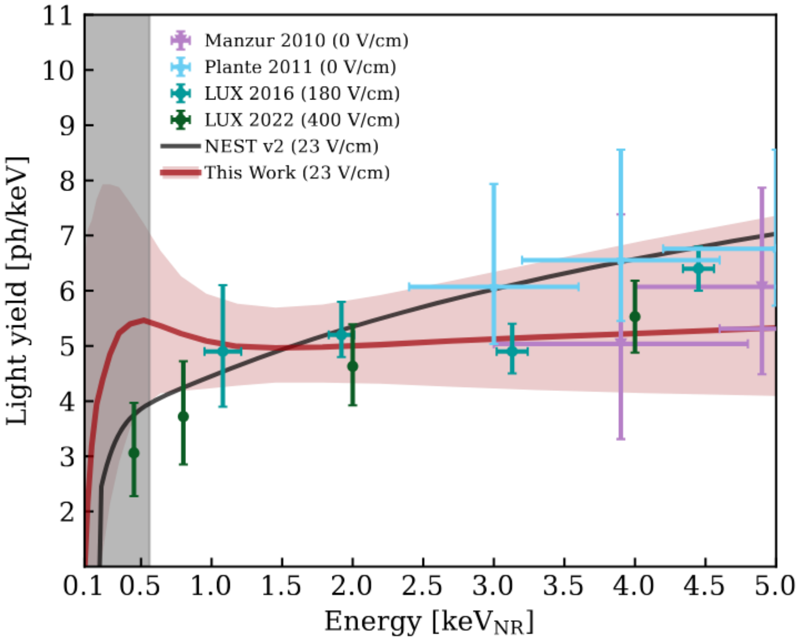


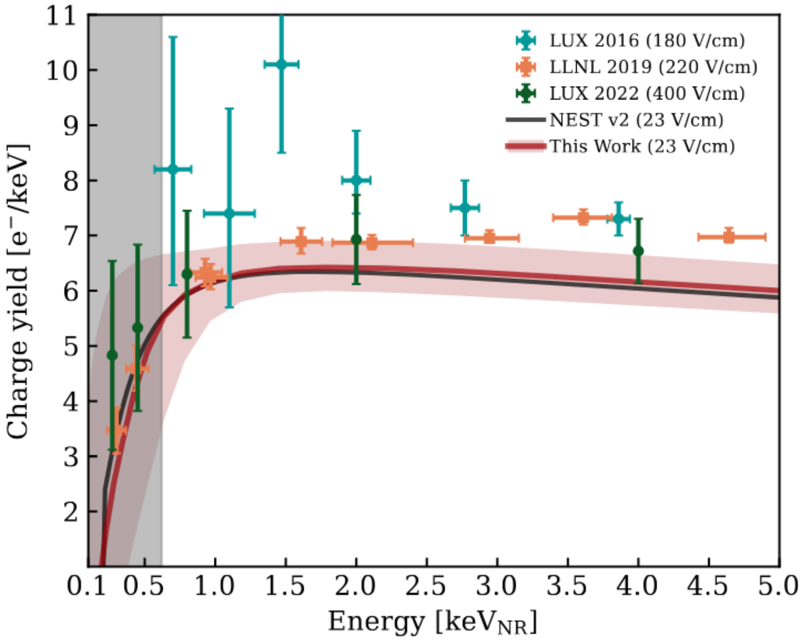


External source lowered in water tank with tungsten shielding

Gamma/neutron: 10^5:1 → 10^3:1

Signal: Emission model from YBe





MCMC fit to NEST(*) model: *for micro-physics in noble elements

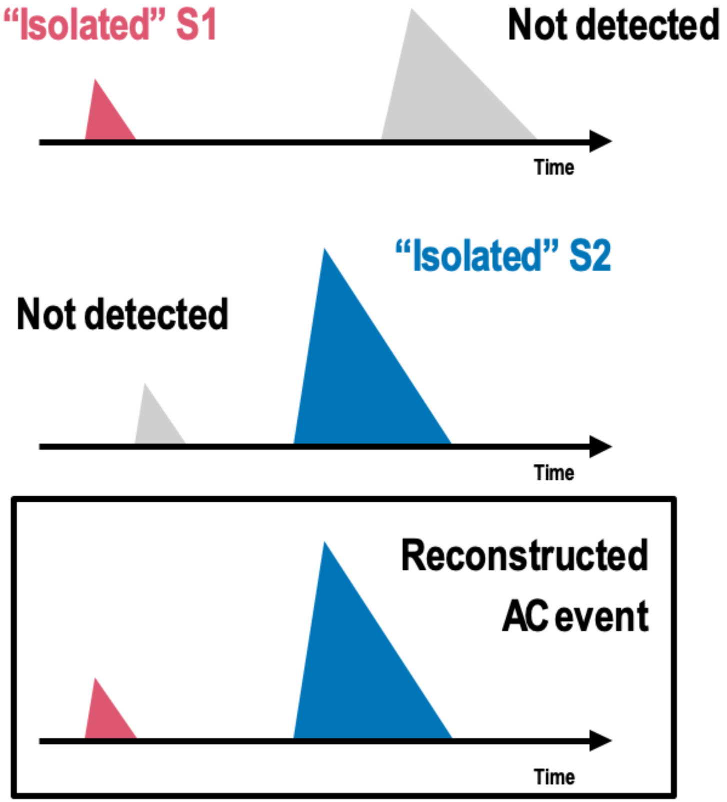
- Good agreement for multiple-scatter neutron data
- Extracted **light** and **charge yield**, first time down to ~0.5keV at 23 V/cm
- **35% yield uncertainty** propagate to ^{8}B search

Background: Accidental Coincidence (AC)

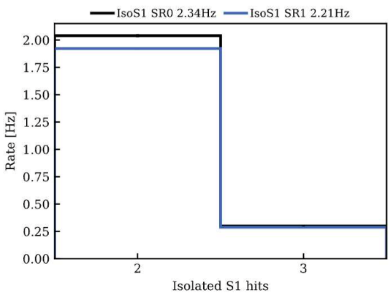
i.e., incorrectly paired **S1** and **S2**

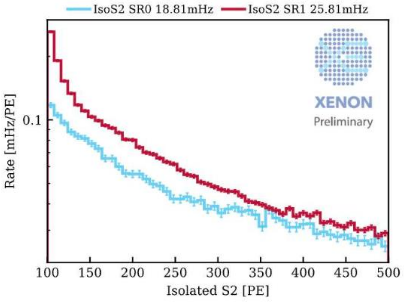
- **Dominant background** with **lowered** energy threshold
- "Isolated" S1
  ~15 Hz (reduced coincidence)
- "Isolated" S2
  ~0.15 Hz (cathode, delayed e^-)
- Max. Drift time: 2.25 ms

→ **Raw AC rate: ~400/day**



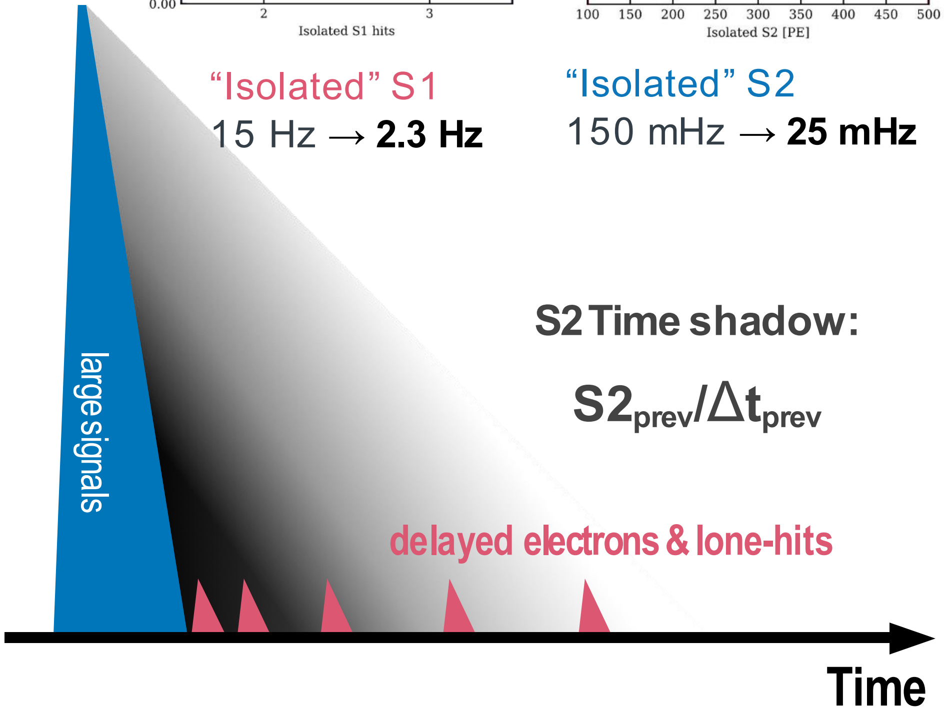
Background: Primary S2 Time Shadow





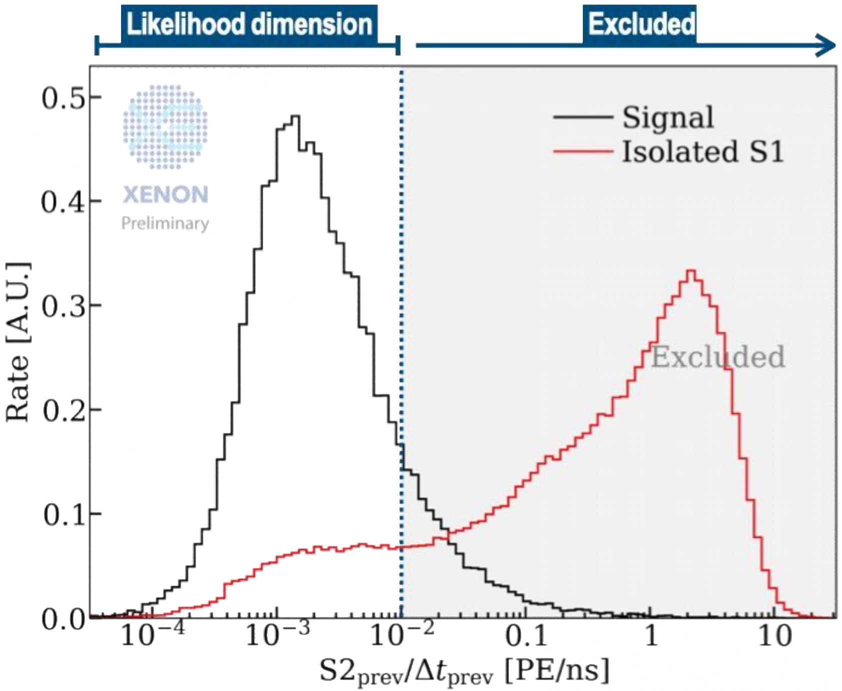
"Isolated" S1
15 Hz → **2.3 Hz**

"Isolated" S2
150 mHz → **25 mHz**



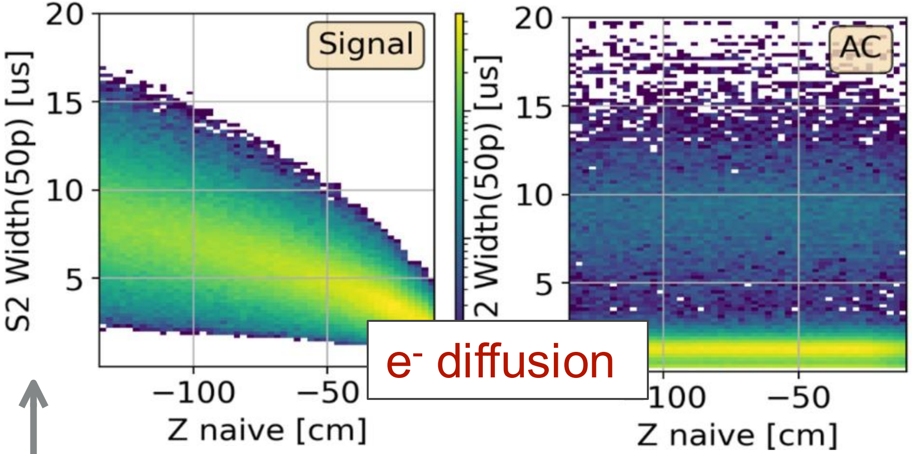
S2 Time shadow:

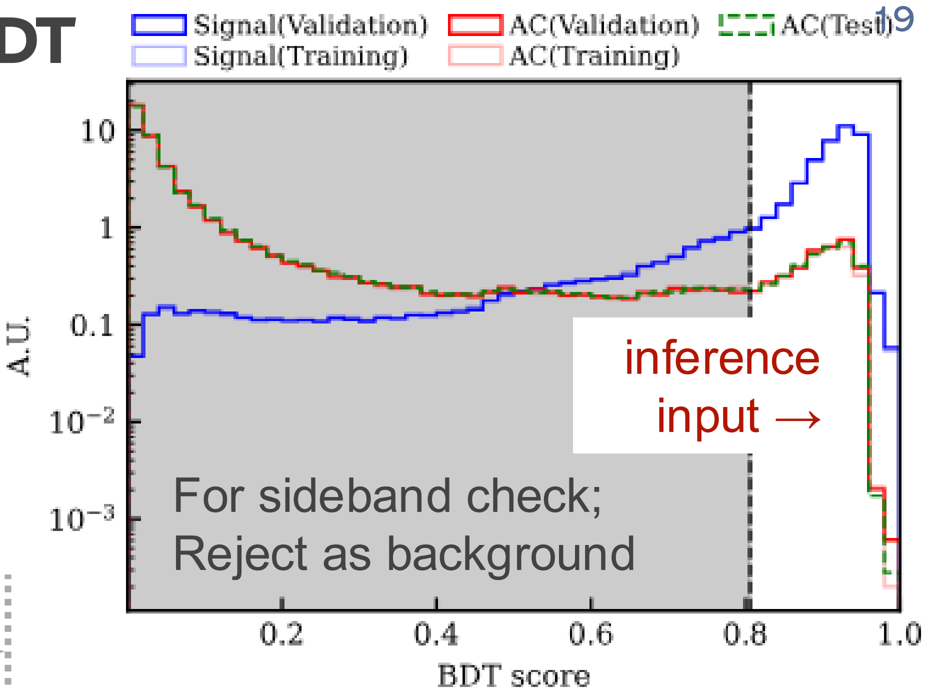
$S2_{prev}/\Delta t_{prev}$

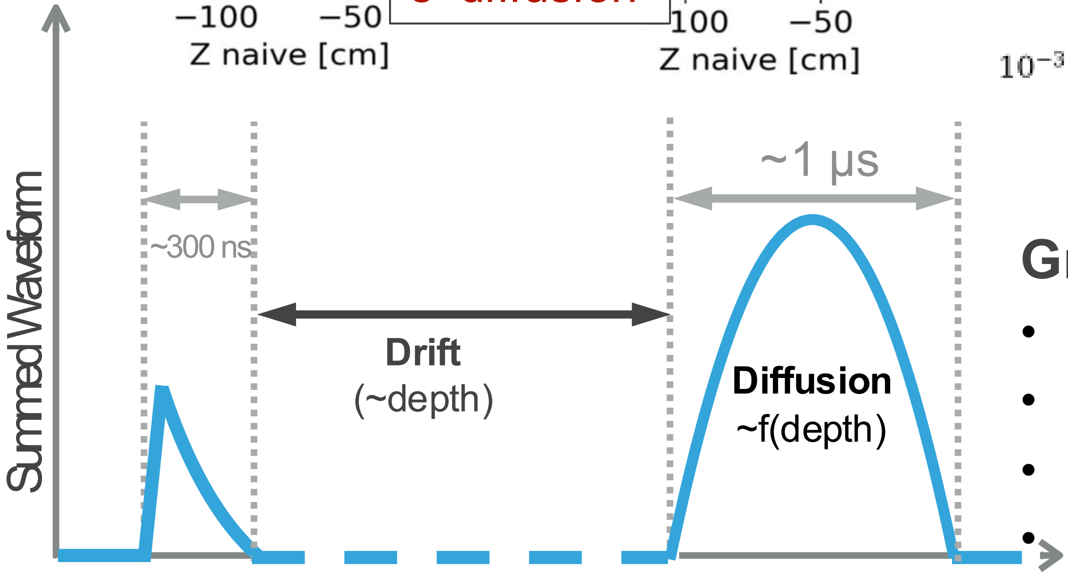


- Most isolated S1/S2 peaks removed
- Signal acceptance ~80%
- Data-driven simulation for remaining background prediction
  → **verified on calibration data**

Background: Pulse shape into GBDT





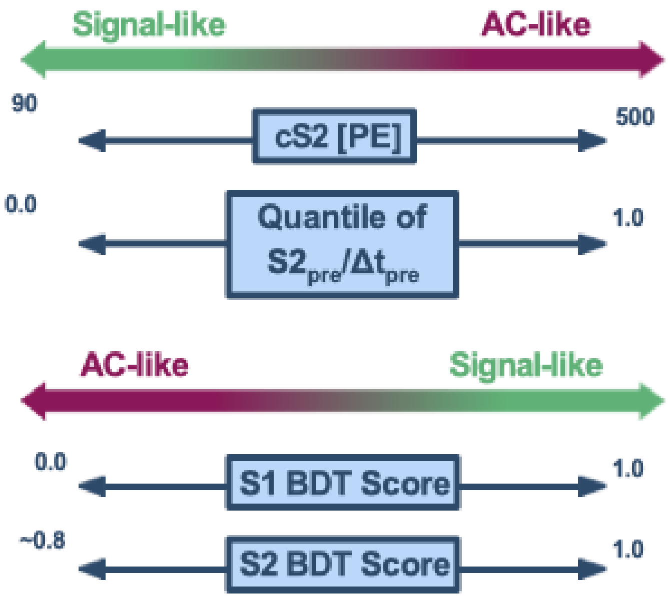


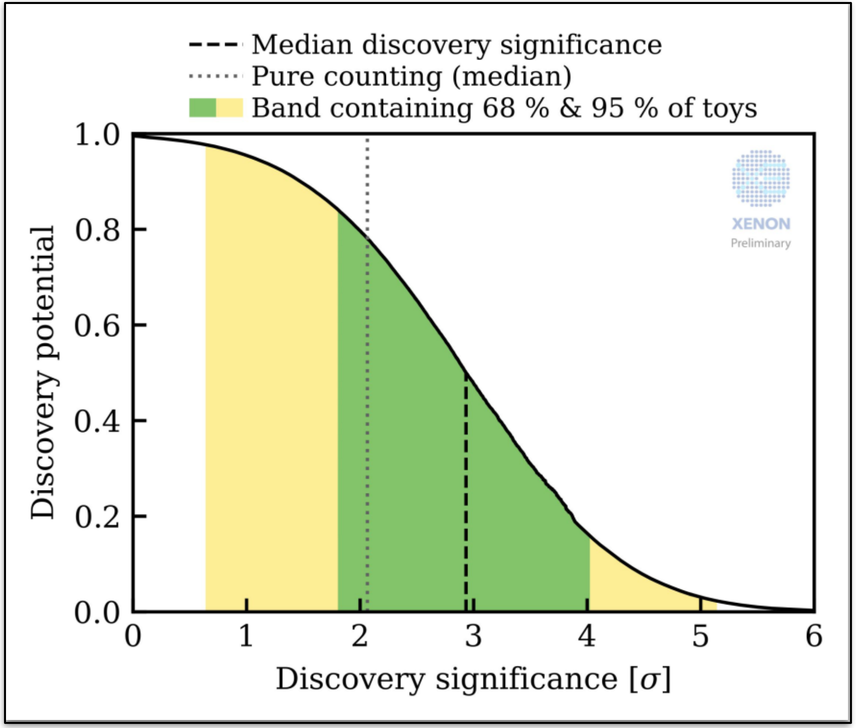
Gradient **B**oosting **D**ecision **T**ree:

- Extract waveform information
- Reject 90% AC, retain 80% signal
- Passed sideband check (p~0.3)
- Score used in final inference

^{8}B Likelihood and Sensitivity

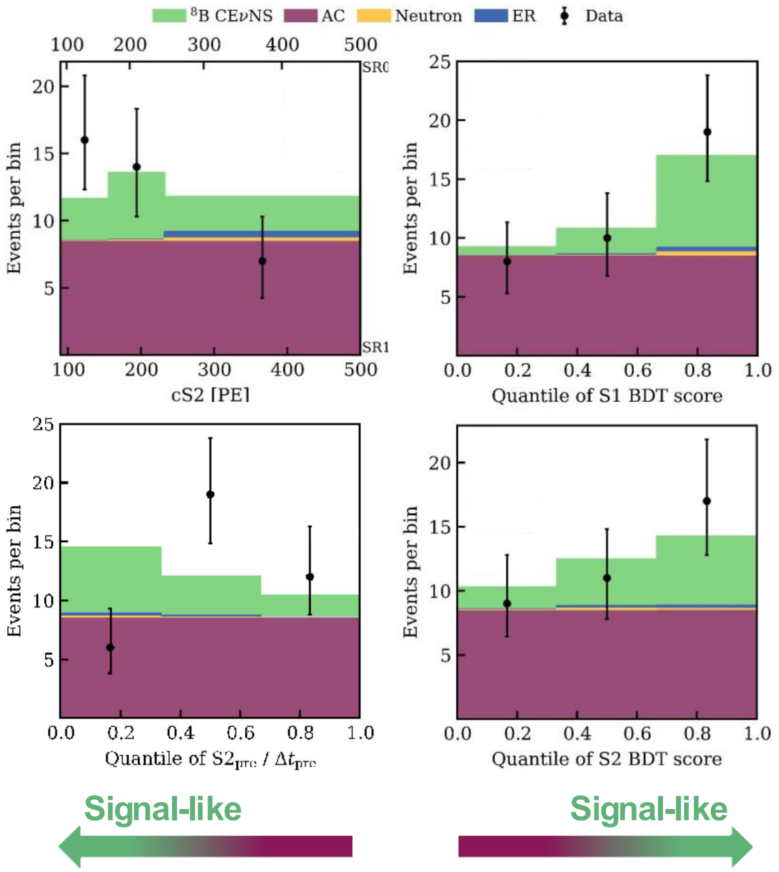
- Extended binned likelihood
  - 3 × 3 × 3 × 3 = 81 bins
  - Separate terms for SR0 and SR1
  - Constraints on YBe yield model





Multi-dimensional inference improves sensitivity:
2 σ → **3 σ**

^{8}B Neutrino Unblinding Results (SR0+SR1)



PRL 133, 191002 (2024) APS Highlight of 2024

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

38.3

high-flux calibration R&D @Westlake

XENONnT saw **~11** ^{8}B neutrinos from the Sun:

significance = 2.73σ

(1/300 chance to be background only)

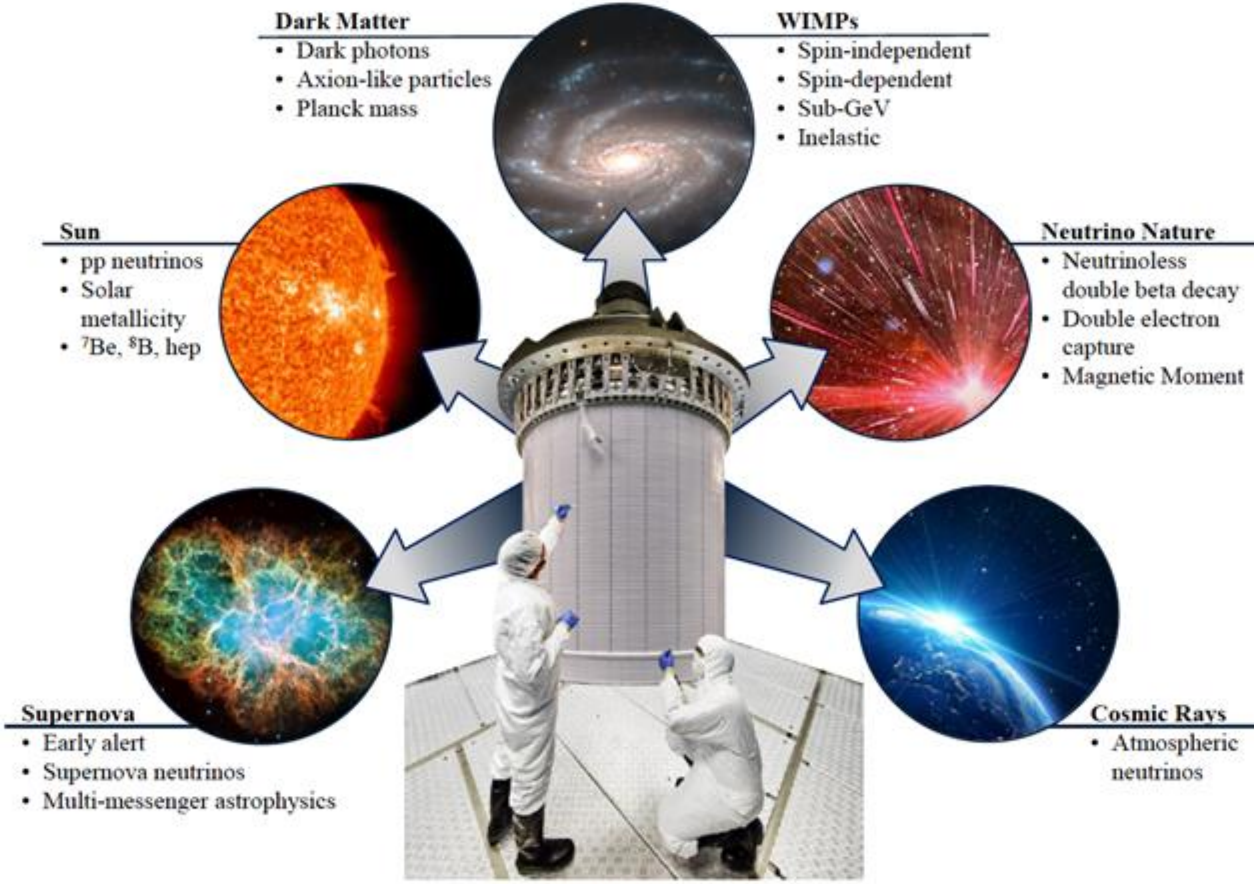
Conclusions?

✓**New WIMP limit**
Blinded analysis with 2.5x improvement

✓^{8}**B solar neutrino**
Dedicated calibration and optimized analysis

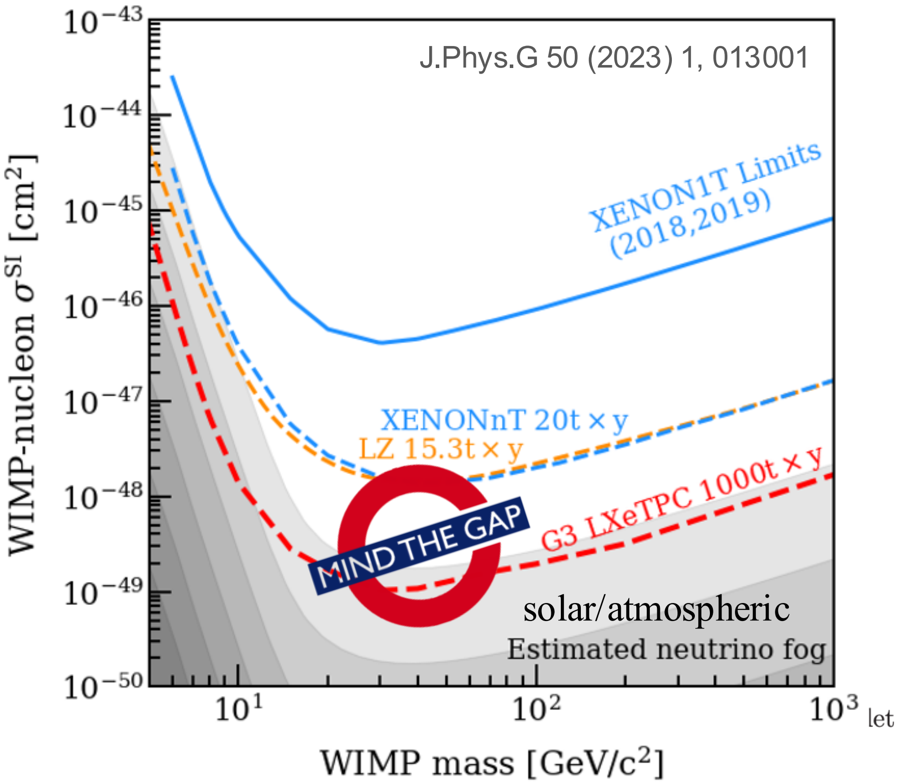
✓**New light-DM limit**
Into the “neutrino fog”

Xenon TPC = multi-purpose astrophysics observatory



Generation-3 Dark Matter Detector

What next?



Still many models (parameter space) out there

need: Gen-3 LXeTPC (50-100t) LArTPC (>100t)

Revisit some assumptions?

Increased systematics:

- Neutrino background (flux, cross-section uncertainty)
- Nuclear physics
- Xe emission model @low-E

Global constraints:

- Collider
- Cosmology/astronomy
- EFT

Frequentist → Bayesian

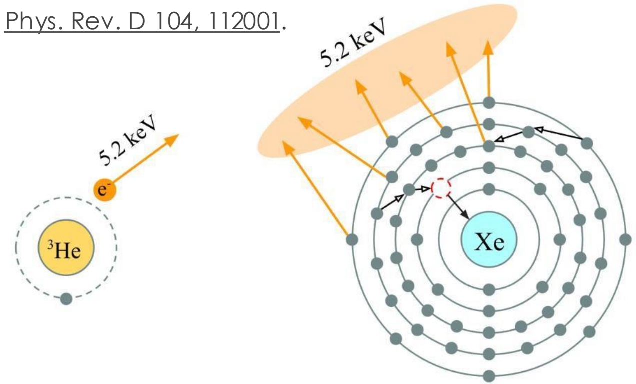
exclusion race → model check

Join force on theory & experiment

backups

ER Shift -- ^{124}Xe DEC?

Phys. Rev. D 104, 112001.

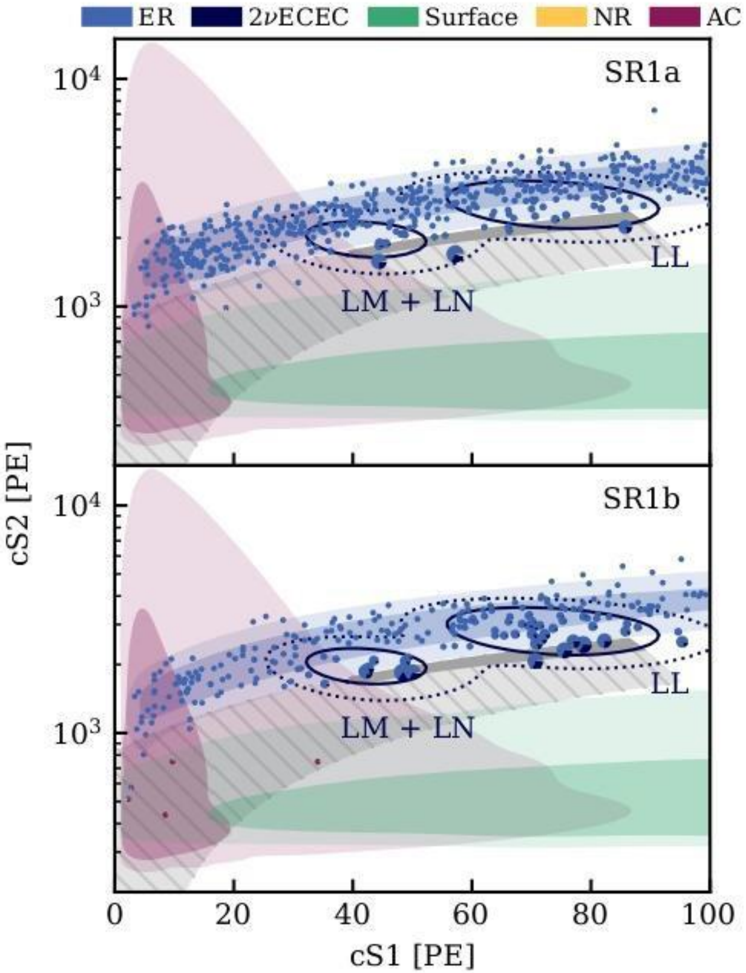


- **^{124}Xe** Double Electron Capture (DEC) from LL and LM+LN shells contributes **4.5** and **9.1** events in SR0 and SR1.

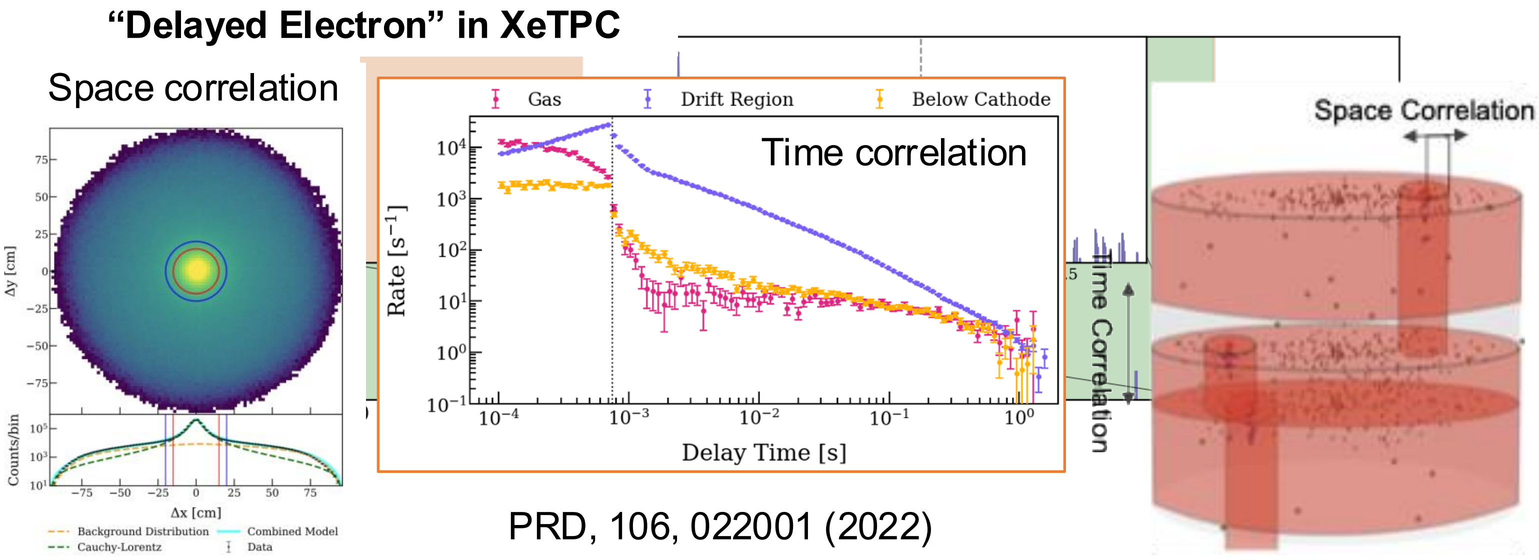
- Charge yield **Q** (link to cS2) suppressed, with best-fit values:

$$Q_{LL} = \mathbf{0.8}^{+0.08}\, Q_\beta \,,\; Q_{LM} = \mathbf{0.72}^{+0.11}\, Q_\beta$$

- Statistically not significant (p=0.09)



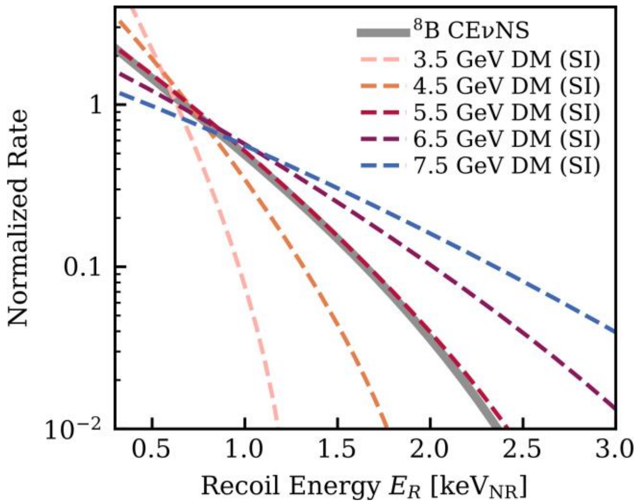
Background: Long-term Isolated Peak



PRD, 106, 022001 (2022)

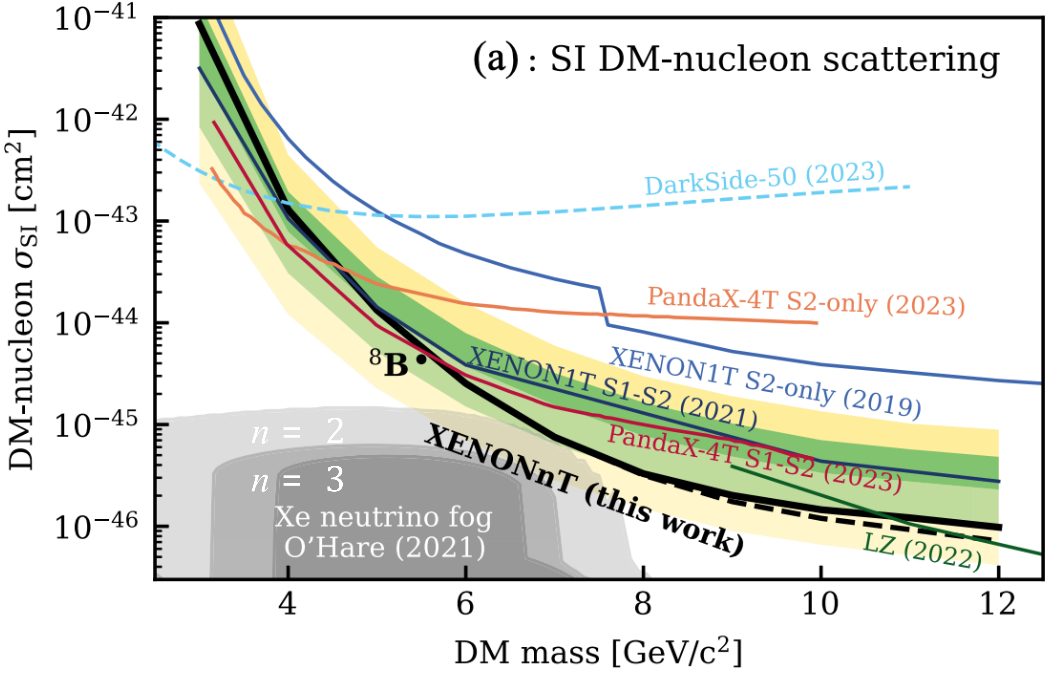
- Spatially **within 15 cm** of primary event
- Temporally follow a **power law decay**
- Use **space-time correlation** to suppress this background
- **Photoionization** with shorter time constant (~us)

Stepping into the "neutrino fog"



^{8}B neutrino signal coincide with WIMP of 5.5 GeV/c^2

PRL 134, 111802 (2025)



Same dataset and low-energy analysis framework:

No excess WIMP found

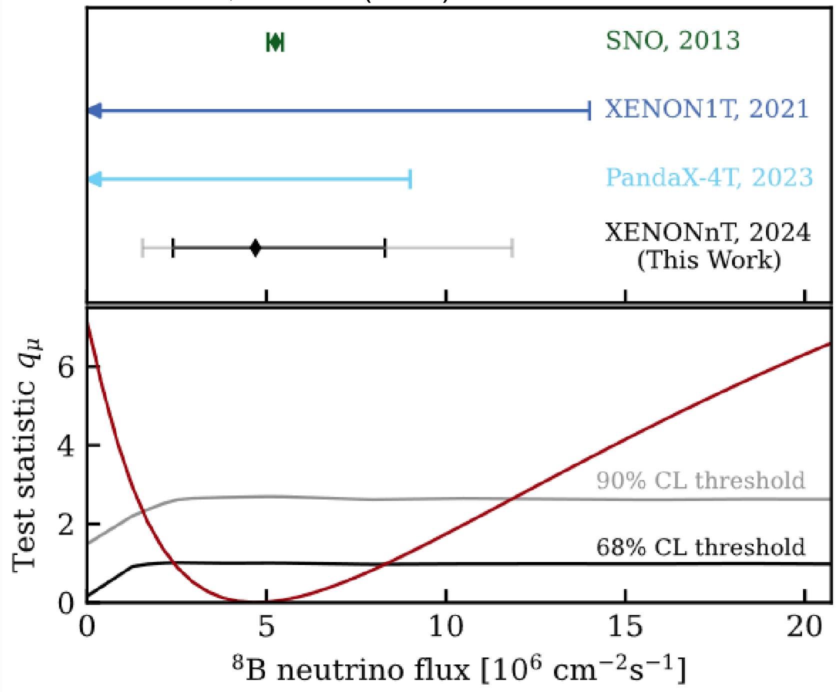
→ New parameter space excluded

(treat ^{8}B CEvNS as background)

→ Slower improvement with exposure now on

Constrain ^{8}B Neutrino Flux and CEvNS

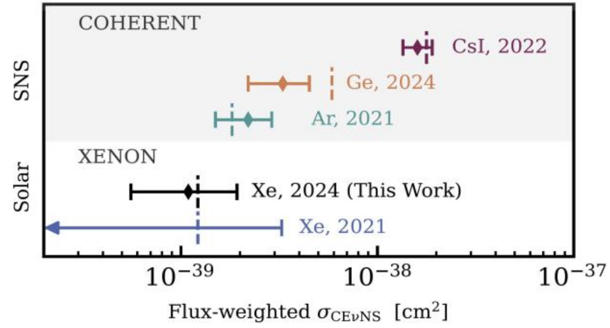
PRL 133, 191002 (2024)

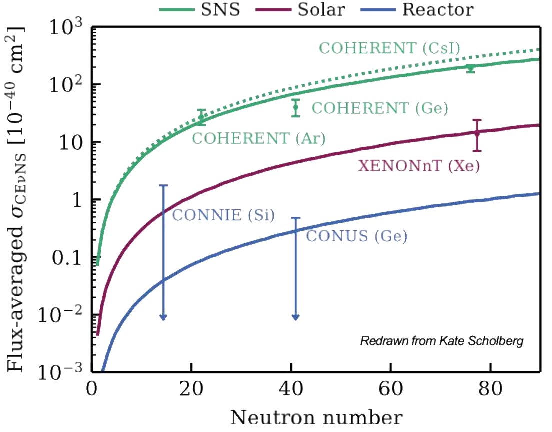


x-section

FIX

flux





Measured ^{8}B flux: $4.7^{+3.6}_{-2.6} \times 10^6$ cm^{-2} s^{-1}

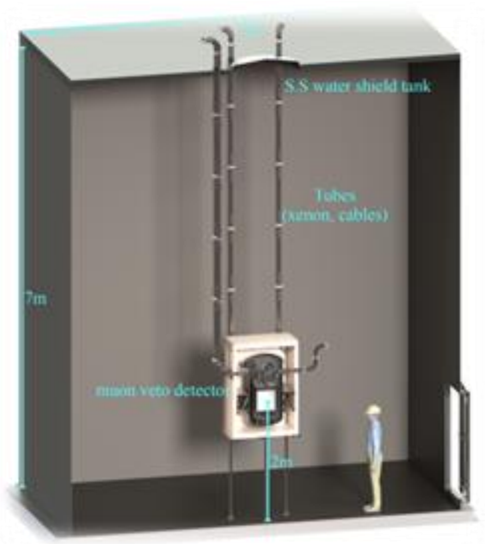
(assuming Standard Model CEvNS cross-section)

First measurement of CEvNS in xenon:

Cross-section agree with Standard Model (fixed flux)

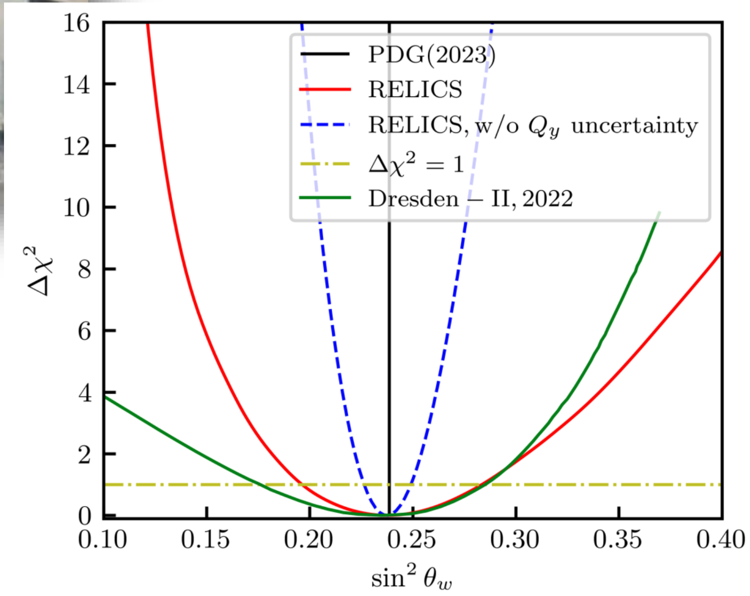
RECODE & RELICS use reactor ν_e (flux = sun x 10^7)

RELICS Reactor CEvNS Experiment

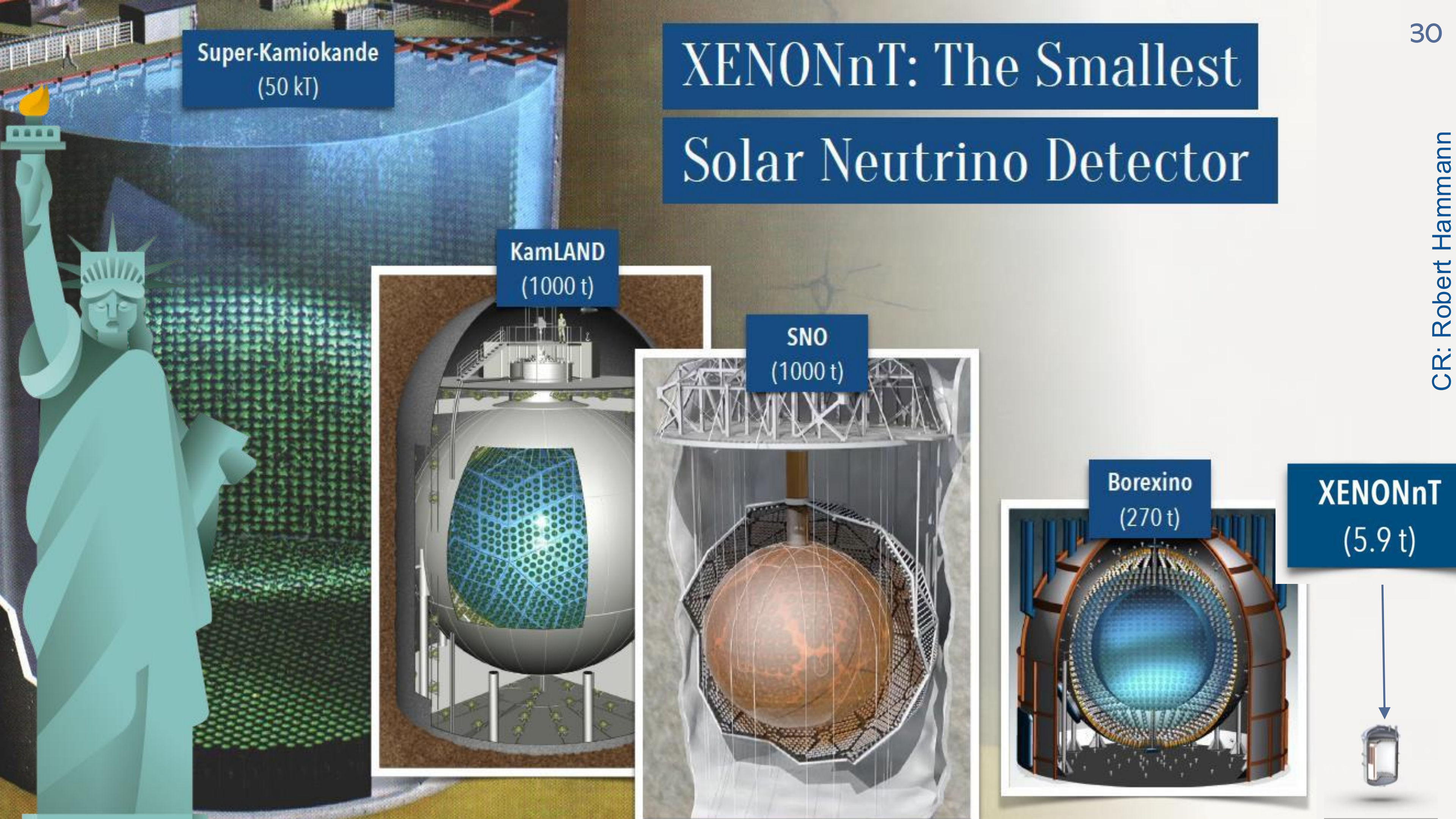


$$Q_W = N - (1 - 4\sin^2\theta_W)Z$$

RELICS

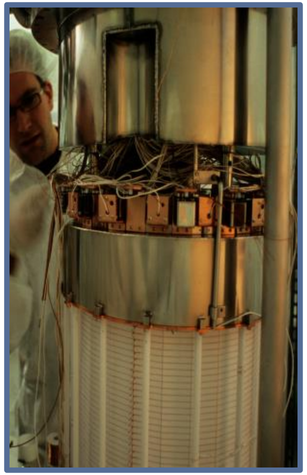


XENONnT: The Smallest Solar Neutrino Detector



CR: Robert Hammann

Evolution of XENON Detectors



	XENON10	XENON100	XENON1T	XENONnT
	2005 - 2007	2009 - 2016	2016 - 2018	2020 - Running
	0.015t	0.161t	3.2t	8.6t
Relative background	1	5×10^{-3}	2×10^{-4}	3×10^{-5}
Exposure	0.87 kg×year	48 kg×year	1 t×year	20 t×year