XENON

西湖大學
WESTLAKE UNIVERSITY

arXiv: 2412.10451

Low-energy Yttrium-Beryllium calibration in XENONnT

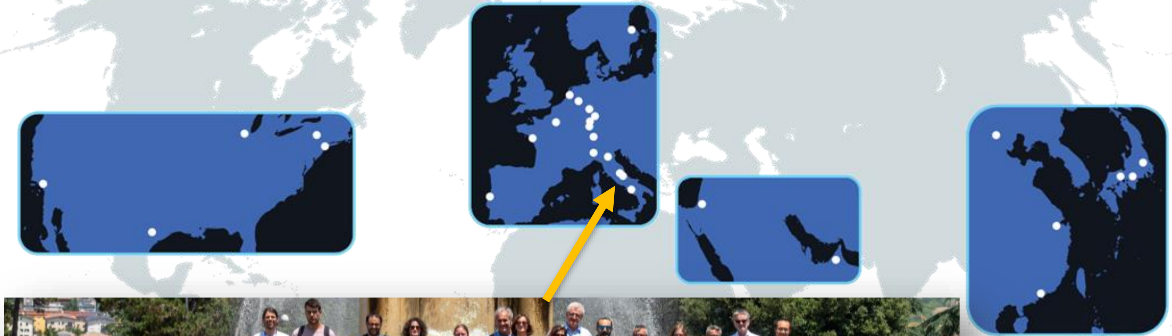
Shengchao Li
Westlake University
On behalf of the XENON Collaboration

Aug. 28, 2025
TAUP2025, Xichang

XENON collaboration

XENON
Westlake | DM and neutrino lab

12 countries
30 institutions
200+ members



AMERICA
- UC San Diego — San Diego
- Houston
- The University of Chicago — Chicago
- Columbia University — New York City
- Bucknell University — Lewisburg

EUROPE
- Zurich
- KIT Karlsruhe Institute of Technology — Karlsruhe
- Universität Münster — Münster
- Uni Freiburg — Freiburg
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- 東京大学 The University of Tokyo — Tokyo
- Nagoya University — Nagoya
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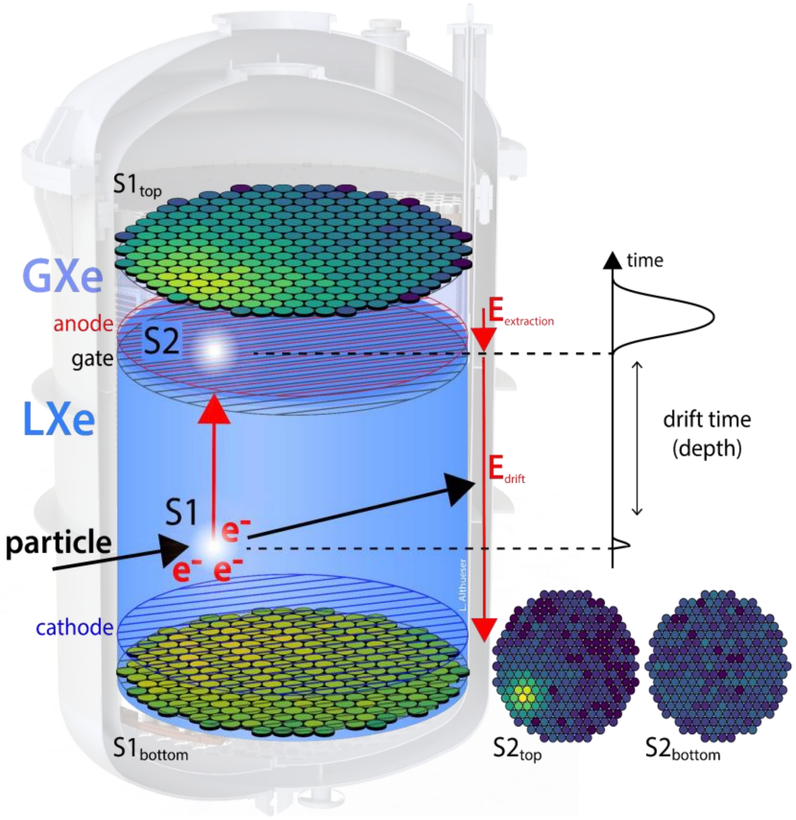
XENON Time Projection Chamber (TPC)

XENON Westlake | DM and neutrino lab



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)

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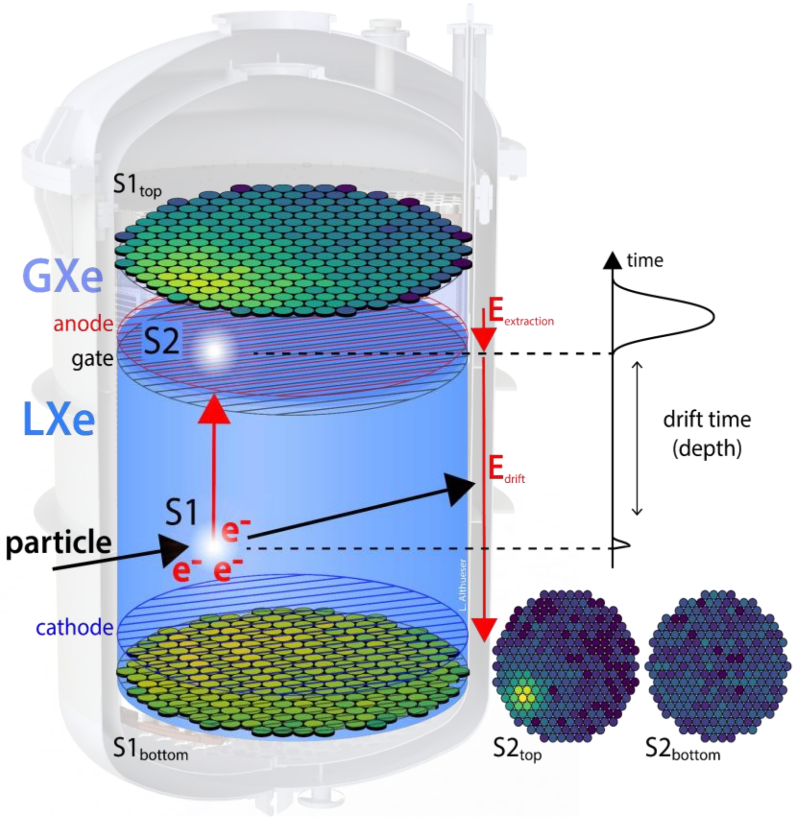

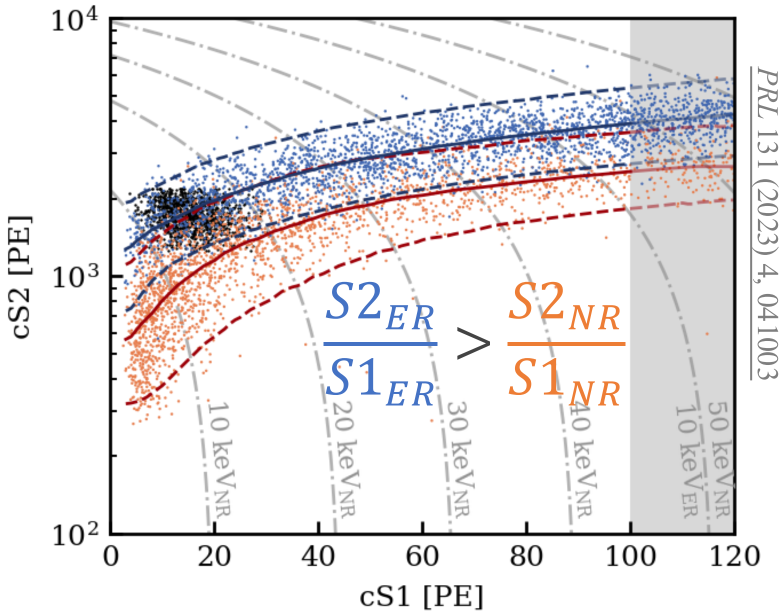

Particle discrimination:

ratio of charge/light (ERs vs. NRs)

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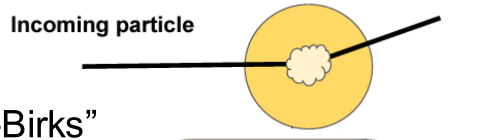
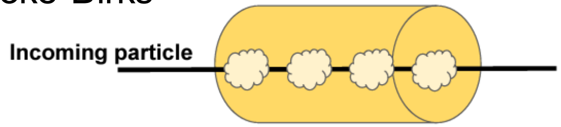
XENON Time Projection Chamber (TPC)

"Thomas-Imel"



"Doke-Birks"



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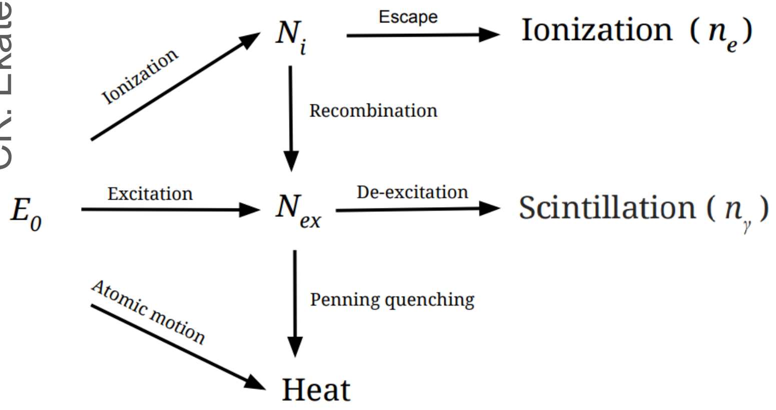
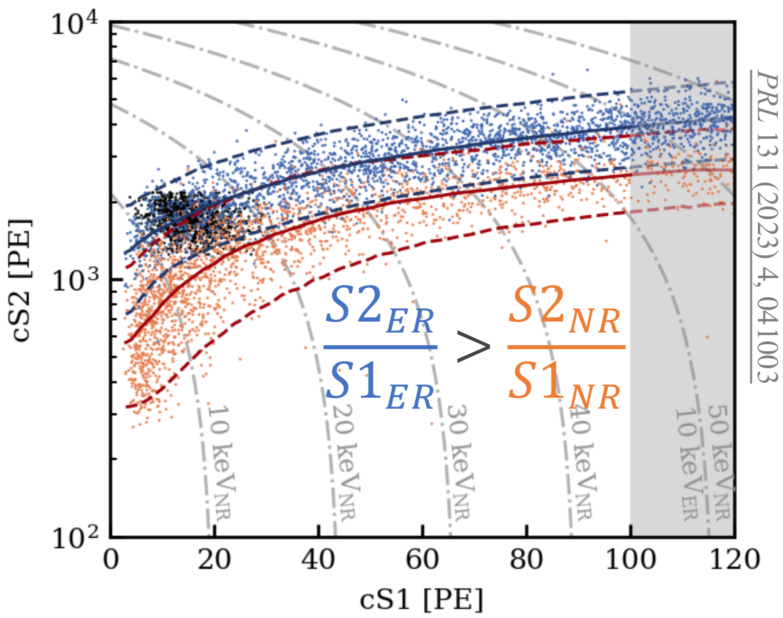




Particle discrimination:

ratio of charge/light (ERs vs. NRs)

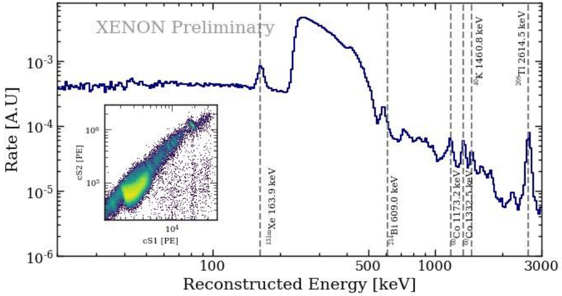
Inputs: energy, electric field, "Lindhard factor"

XENON WIMP calibration

In the WIMP search (*see Maxime's talk 8/25*), radioactive sources are introduced to model the **light/charge** response and **threshold** effect

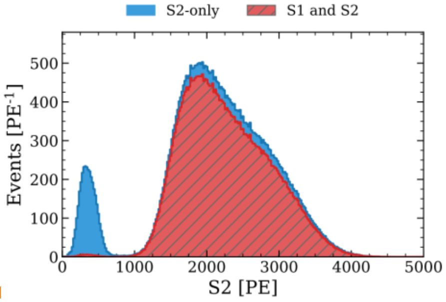
^{220}**Rn**: flat spectrum from beta

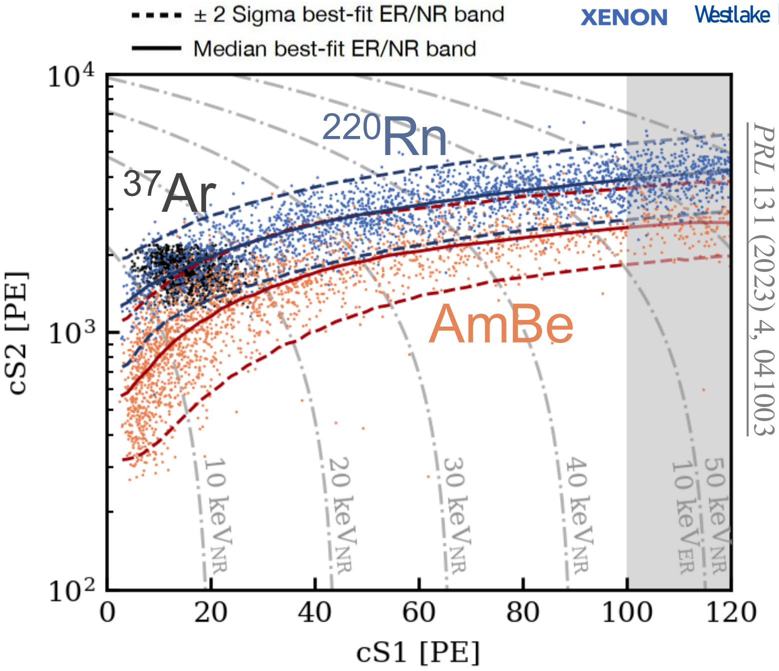
JINST 18 (2023) 11



^{37}**Ar**: electron-capture line(s) **2.82 keV** (K-shell) 0.27 keV (L-shell)

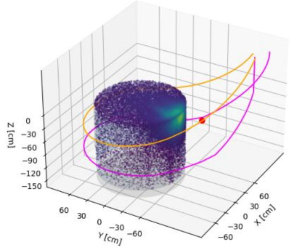
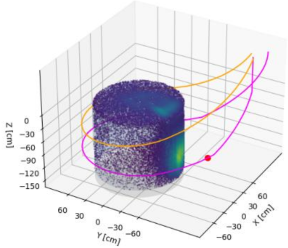
EPJC 83 (2023) 6, 542





PRL 131 (2023) 4, 041003

AmBe: MeV neutron coincident with γ-ray in nVeto

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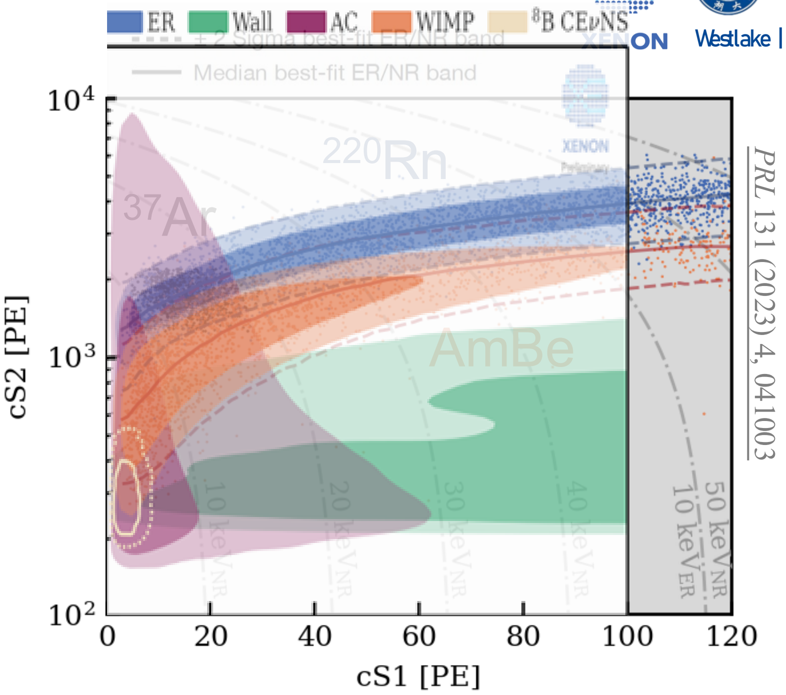
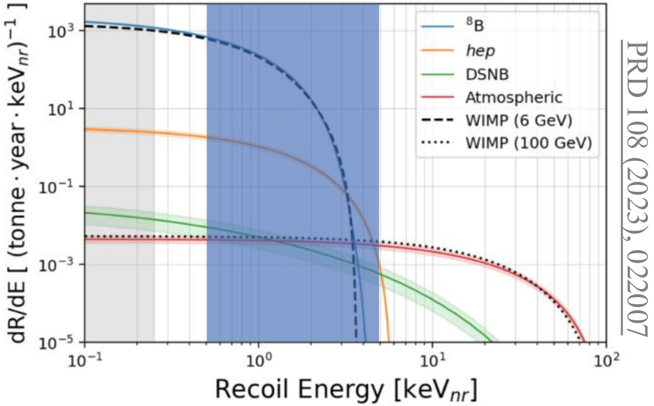
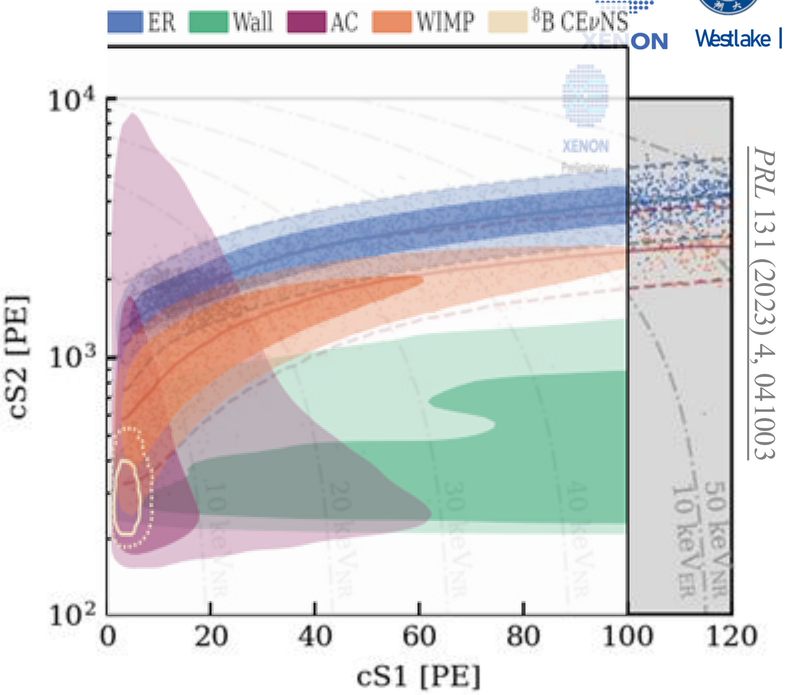


Low-energy NR calibration

For the search for ^{8}**B neutrino** (*see Kexin's talk 8/26*), and **~6GeV** WIMP (*see Shenyang's talk 8/27*), the momentum transfer is O(1/10) of ~100 GeV WIMP nuclear recoils





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Low-energy NR calibration

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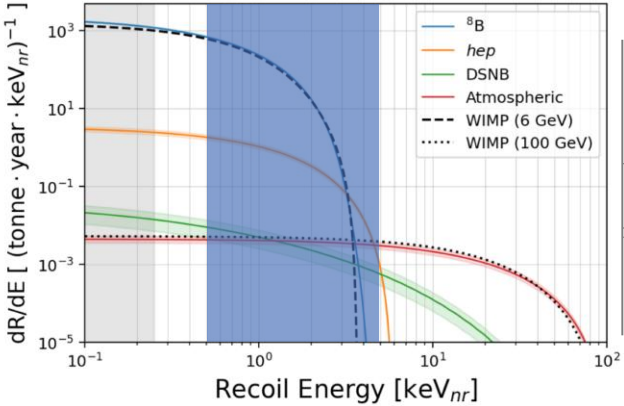
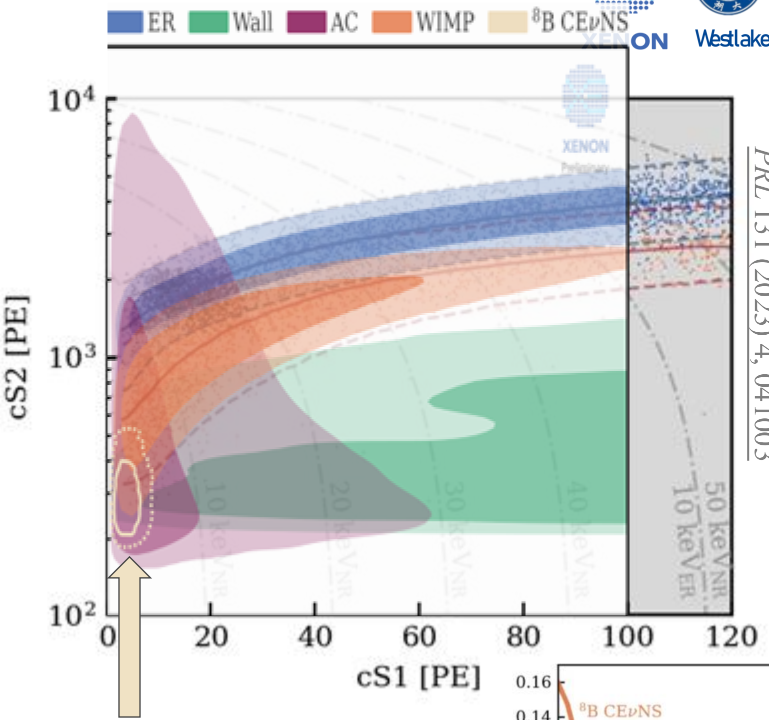


PRD 108 (2023), 022007

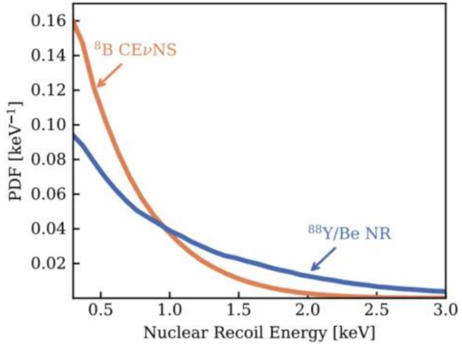
Need:

- Demonstrate **sub-keV NR detection** with reduced (3→2) coincidence requirement
- Extract **light and charge yields** of 0.5-5keV in LXe at field condition of 23V/cm



PRL 131 (2023) 4, 041003

Yttrium-Beryllium 152 keV neutrons to cover the signal region of ^{8}B and light WIMP



Yttrium-Beryllium photoneutron source

1.84 MeV **^{88}Y** γ-ray triggers **^{9}Be** photo-disintegration:

$$\gamma + {}^{9}\mathbf{Be} \rightarrow \mathbf{n} + {}^{8}\mathbf{Be} \quad (Q=-1.667\ \mathrm{MeV})$$

→ quasi-monoenergetic 152 keV neutrons,
but only 0.65 mb cross-section (γ:n ~ 10^5:1)

→ **need:** more Be, gamma shielding

$$\mathcal{S} = \frac{p_{\gamma,n} N_{\mathrm{NRSS}}/S_n}{p_{\gamma,n} N_{\mathrm{ER}}/S_n + N_\gamma/S_\gamma}$$

← TPC NR

← TPC ER (direct+induced)

optimized with MC simulations:
t = 50 mm, d = 25.4 mm

→ final **ER:NR ~ 1600:1** with 9.45 cm of tungsten

Also proposed for NaI[Tl]:
PRL 110 (2013) , 211101

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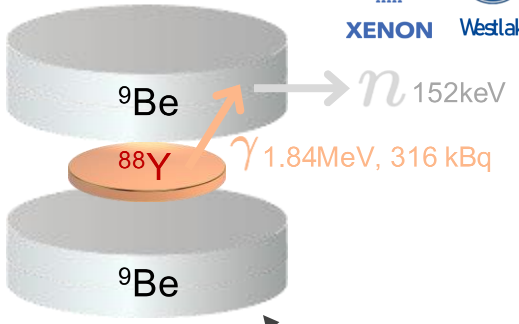
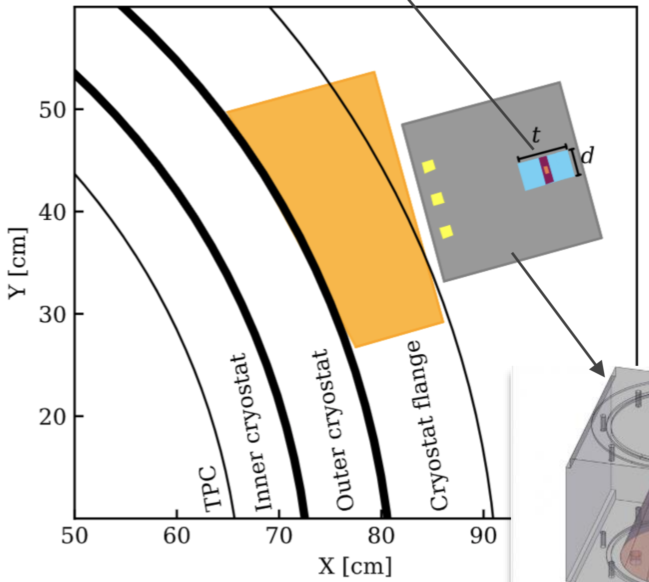
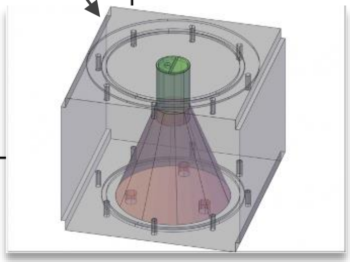




tungsten block



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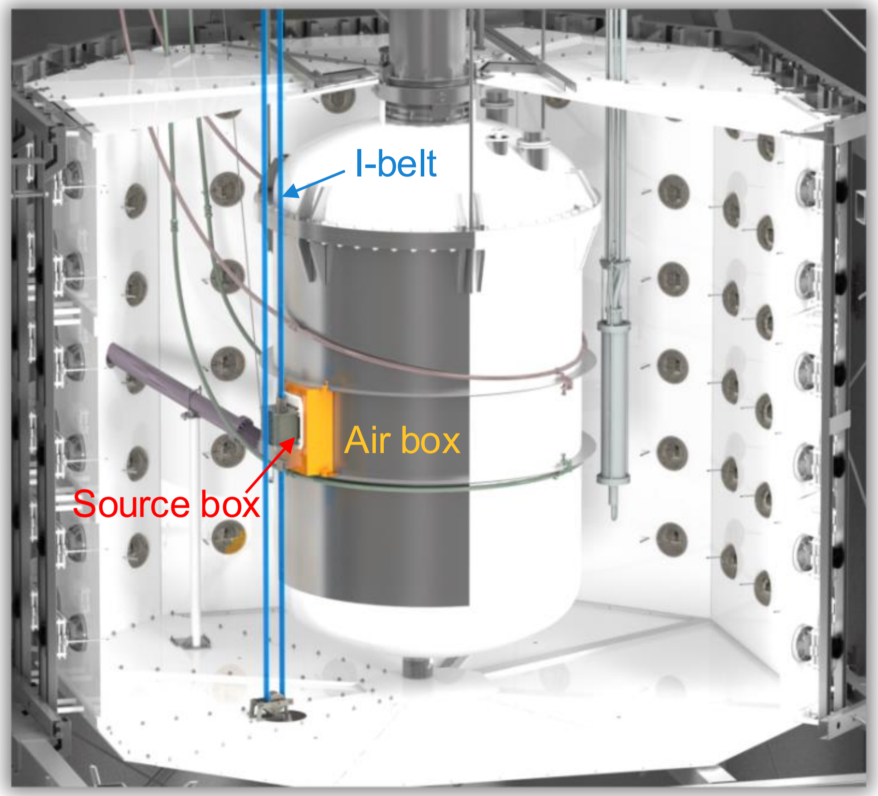
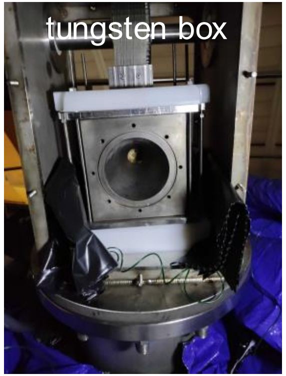
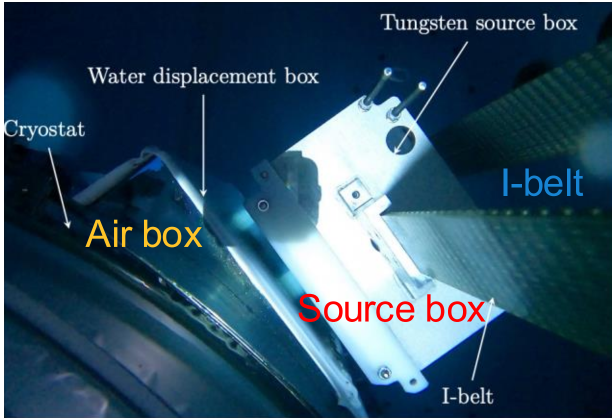
YBe source deployment

Design: *EPJC* 84 (2024) 8, 784



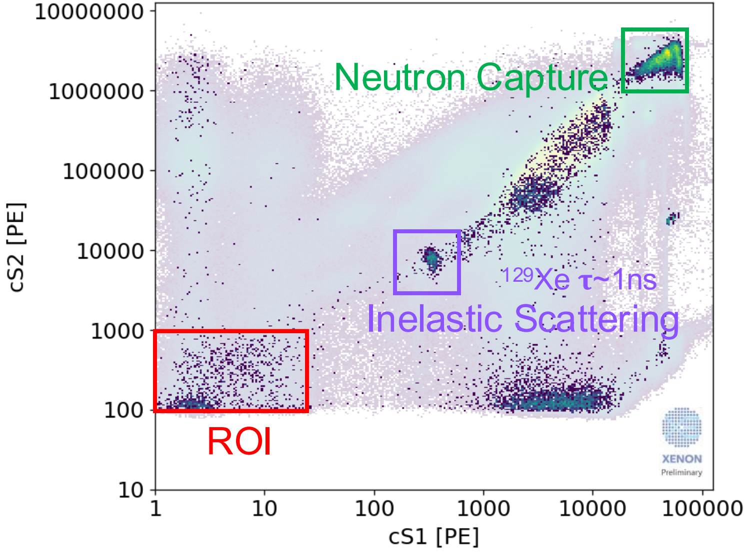


CR: Daniel W., Yossi M.

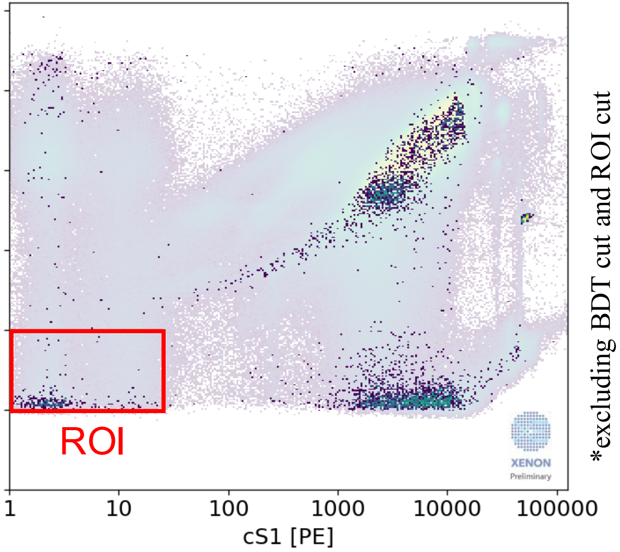


^{88}Y+Be and ^{88}Y+PVC calibrations

^{88}Y+Be (NR+ER) – 183h

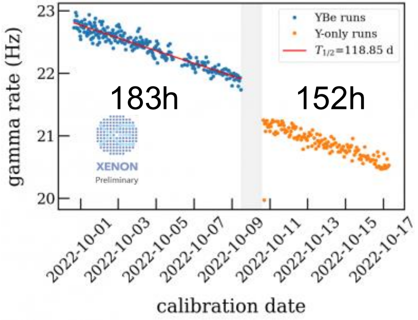


^{88}Y+PVC (ER) – 152h



*excluding BDT cut and ROI cut

- PVC plastic replaces Be target, similar gamma attenuation, but **no neutrons**
- To **model** background components related to **^{88}Y gamma**



Steady source decay monitored with gamma

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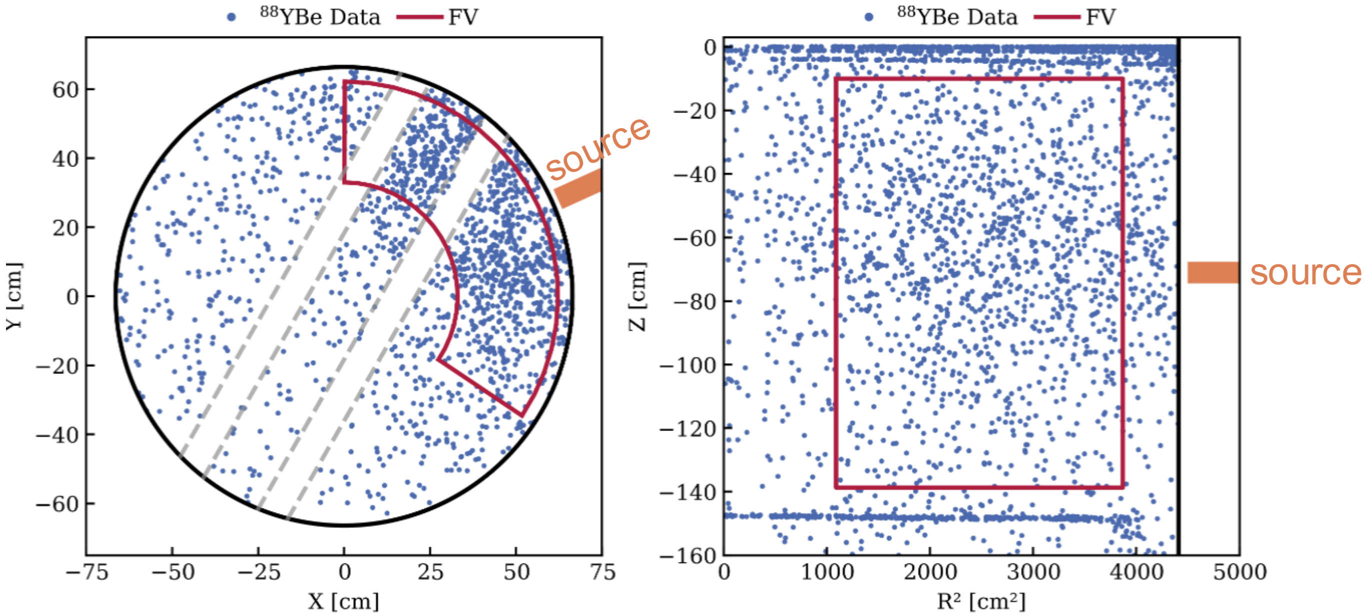
Fiducial volume selection

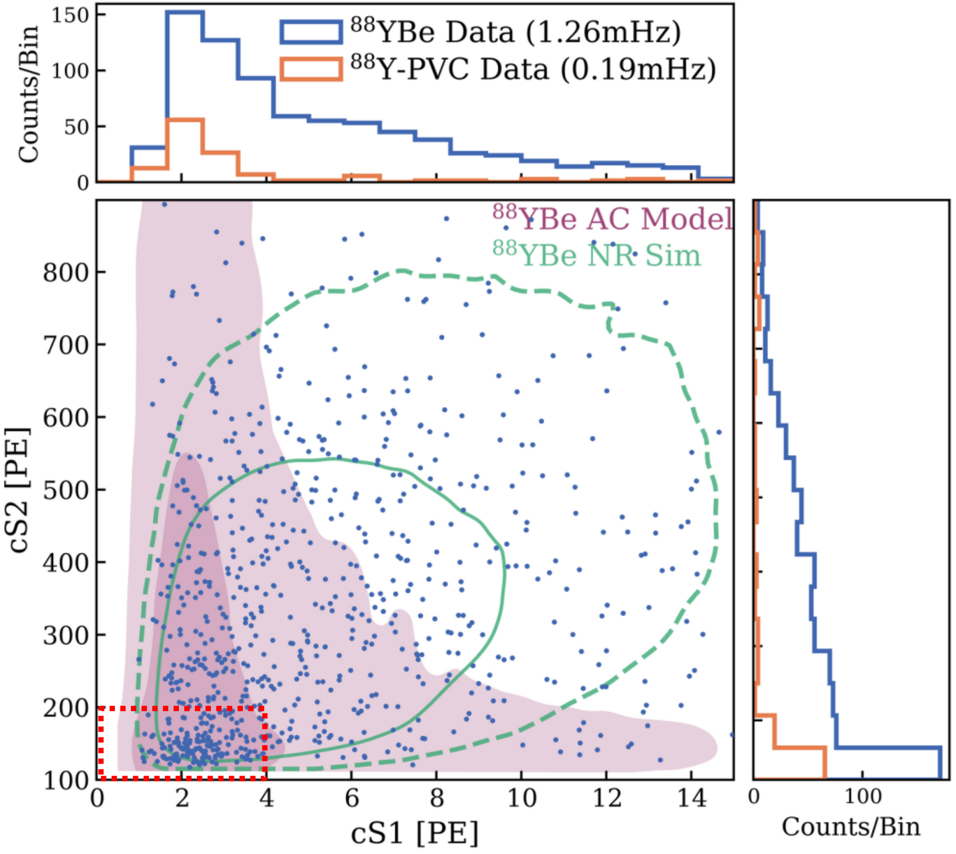


Partial cylindrical shell with a 33 (62.2) cm inner (outer) radius:

- Optimized with neutron simulation (retain ~90% signal)
- Neutron mean-free-path **~10 cm** → not too deep in R
- Reduce **wall events** with reduced S2 → not too shallow in R
- Reduce electrode/surface events → centered in depth

Event distribution in ROI

- Much higher event rate in the low-energy NR ROI of YBe data implies successful NR calibration
- In YBe dataset, additional **accidental coincidence (AC) events** concentrate in dashed box, overlapping with the expected YBe NR signal region from simulation
- **origin**: isolated S1 and S2 due to high energy gammas
- The gamma-only Y-PVC dataset is expected to contain only ACs
- **Need:** AC suppression, AC model



AC suppression with machine learning

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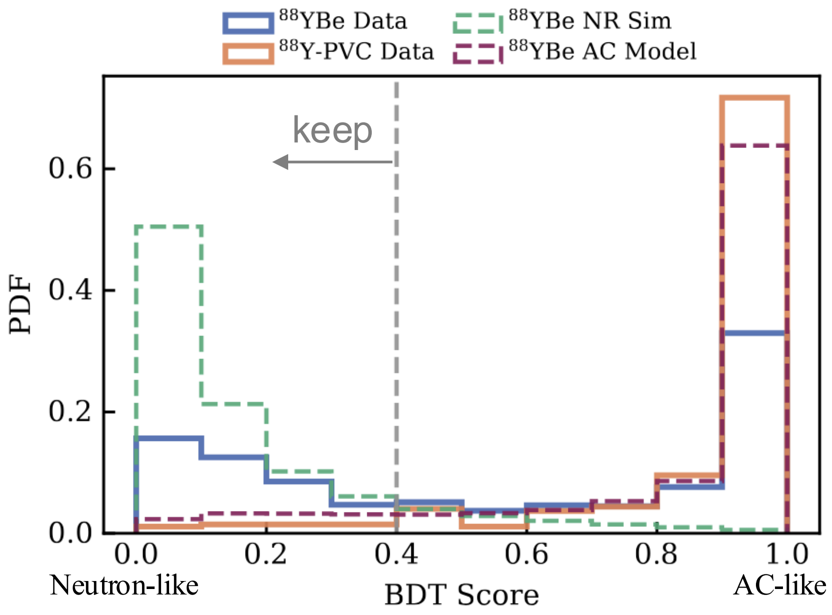
- Prepare **two** datasets:

1. ^{88}YBe neutron simulation
2. Data-driven AC model from ^{88}YBe and ^{88}YPVC runs, to predict **rate** and **shape** of AC events*

   *using *Axidence*, validated with science and calibration data

- Train a **Boosted Decision Tree (BDT)** classifier to discriminate AC events from NR events, using **physics-inspired** parameters, such as:

  Diffusion: correlation between the S2 pulse width and electron drift time
  NR multi-scatter (MS): space and time correlation between the largest two S2s, at the cost of single-scatter NRs (~20% of total NRs)

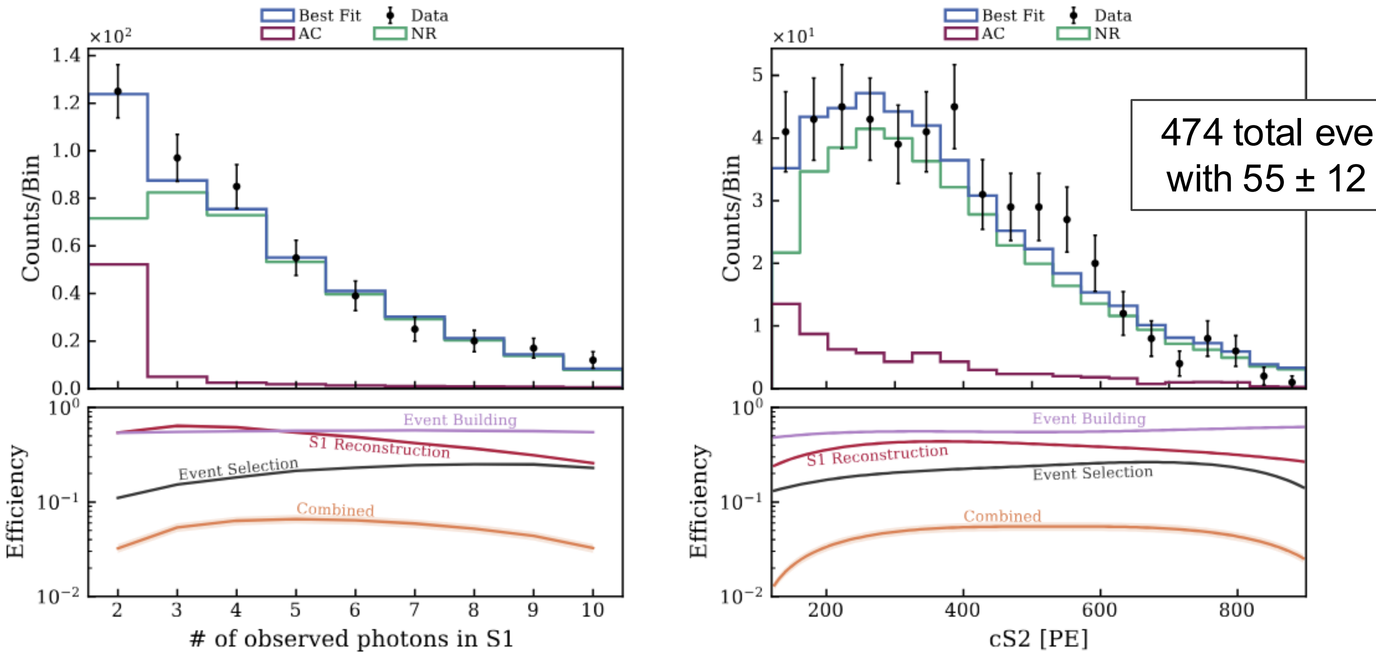


Separation in **BDT score** dimension:

- rejects 91% of AC events
- retaining 89% of ^{88}YBe MS NRs

^{88}Y-PVC data score suggest AC feature extracted in BDT and accurate AC model

Best-fit YBe spectrum w/ AC model



474 total events, with 55 ± 12 AC

Yield + reconstruction effects included to fit YBe data:

- **S1 reconstruction efficiency** by bootstrapping PMT hits to mimic MS neutrons
- **Event building efficiency** evaluated by salting*
- **Event selection efficiency** due to delayed electron (high R dependence)

*injecting NR into high γ-induced S1/S2 environment using Saltax

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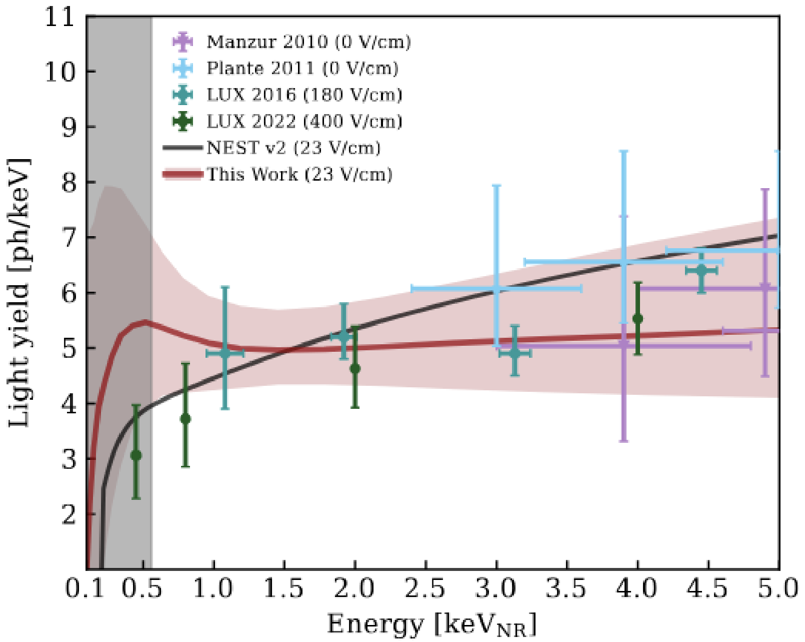
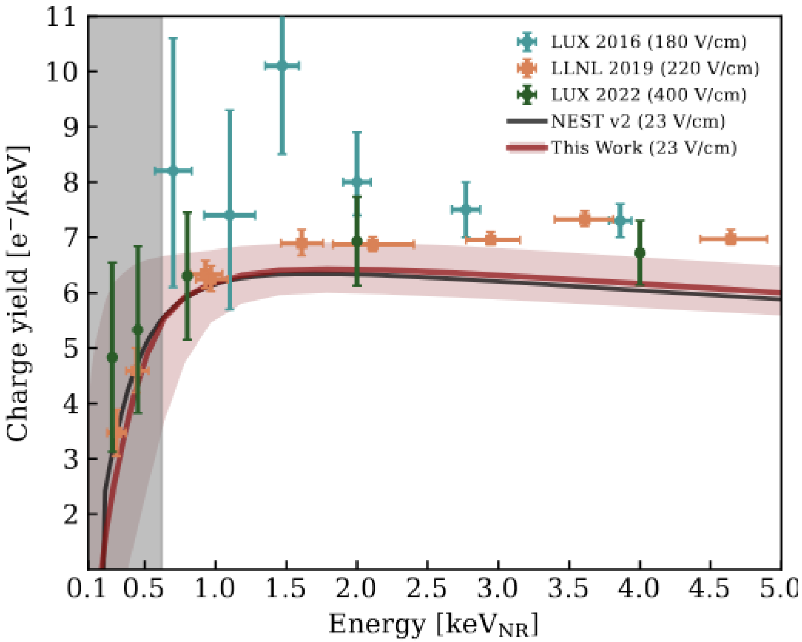
Best-fit NR yields





- **MCMC best-fit p-value = 0.93**
- **NEST v2** parameterization, ~30% uncertainty band sampled from fitted posterior
- **Minimum threshold** for light (*charge*) yield at 0.56 (*0.62*) keV$_{NR}$

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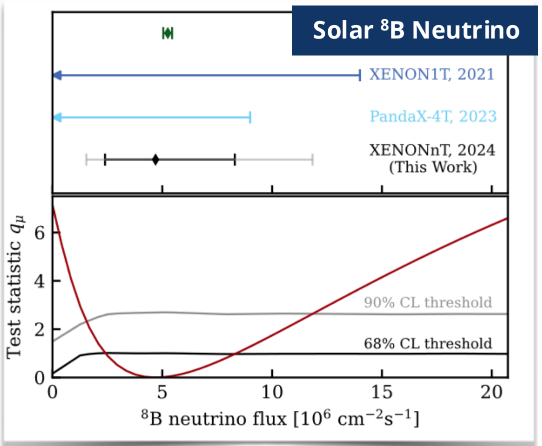
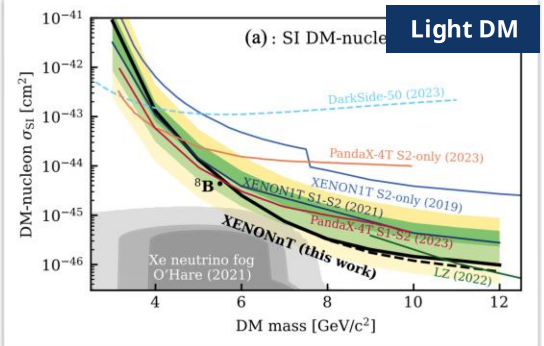
Summary

- **First successful** sub-keV nuclear recoil calibration with an ^{88}YBe photoneutron source in XENONnT
- Accumulated 183 hours of **neutron calibration**, and 152 hours of **gamma-only** exposure
- Data-driven **AC model** used to train **BDT classifier**, verified on gamma-only dataset
- **Light** and **charge yields** of liquid xenon (23 V/cm) from **~0.5 to 5.0 keV$_{NR}$** constrained with MCMC fit
- Yield model fed into recent **low-energy NR searches in XENONnT**



(Kexin's talk 8/26) PRL 133 (2024), 191002



(Shenyang's talk 8/27) PRL 134 (2025), 111802

backups

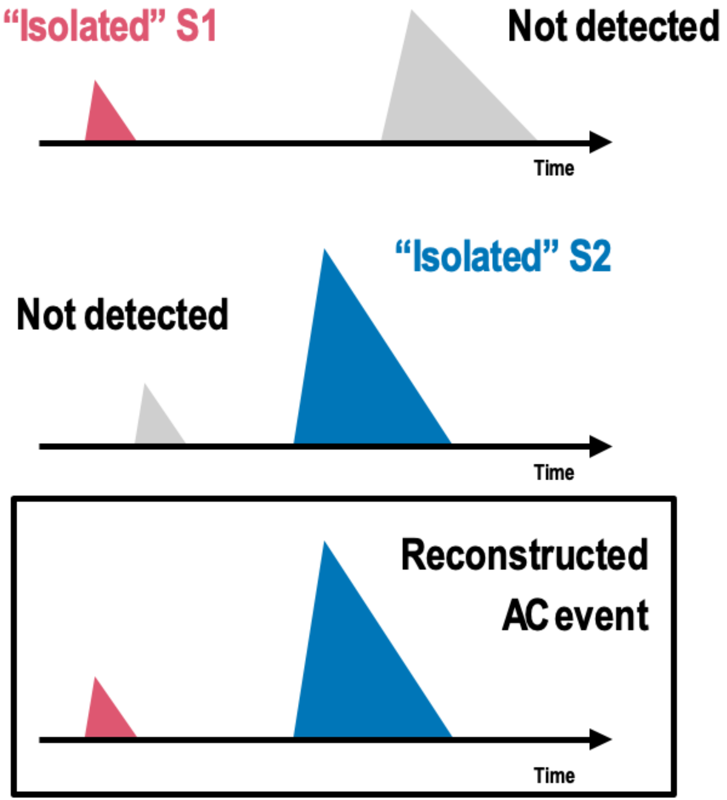
AC background in calibration

*before suppression cuts

- “Isolated” S1
  ~300 Hz* (reduced coincidence)
- “Isolated” S2

  ~1 Hz* (cathode, delayed e^-)
- Max. Drift time: 2.25 ms

A strong position dependence of delayed e^-, due to correlation with ^{88}Y gamma on detector surface



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NEST parameterization

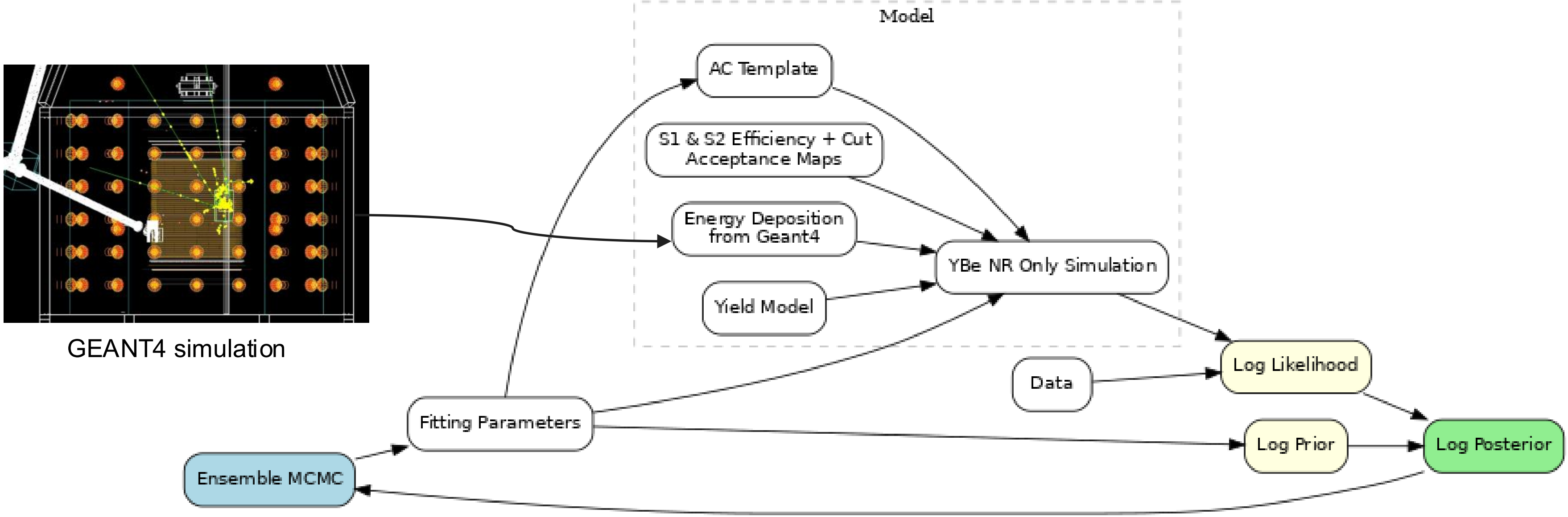
Parameter	NEST v2	Prior	Marginal posterior
α	$11.0^{+2.0}_{-0.5}$	[8.5, 21]	$12.1^{+1.5}_{-2.3}$
β	$1.10^{+0.05}_{-0.05}$	[0.85, 1.35]	$0.98^{+0.09}_{-0.15}$
γ	$0.0480^{+0.0021}_{-0.0021}$	[0.0375, 0.0585]	$0.0447^{+0.0052}_{-0.0077}$
ϵ	$12.6^{+3.4}_{-2.9}$	[0, 29.6]	$13.3^{+5.2}_{-5.8}$
ζ	$0.3^{+0.1}_{-0.1}$	[0, 0.8]	$0.4^{+0.3}_{-0.2}$
η	2^{+1}_{-1}	[-3, 7]	3^{+2}_{-2}
θ	$0.30^{+0.05}_{-0.05}$	[0.05, 0.55]	$0.28^{+0.16}_{-0.17}$
ι	$2.0^{+0.5}_{-0.5}$	[-0.5, 4.5]	$2.2^{+1.8}_{-1.6}$
F_{ex}	0.4	[0, 1]	$0.5^{+0.3}_{-0.3}$
F_i	0.4	[0, 1]	$0.6^{+0.4}_{-0.3}$
ξ	0.50	[0, 1]	$0.48^{+0.33}_{-0.34}$
ω	0.19	[0, 1]	$0.40^{+0.28}_{-0.39}$

In YBe fitting, δ is fixed to -0.0533 to avoid degeneracy, because of single drift field strength of (23±1.5) V/cm

a	Scaling on NR total quanta. Default value is $11^{+2.0}_{-0.5}$ keV^{-b}.
b	Power-law exponent for the NR total quanta. Default value is 1.1 ± 0.05.
ς	Field dependence in NR light and charge yields, with mass-density-dependent scaling (Equation (11)).
ρ_0	Reference density for scaling density-dependent NEST functions: 2.90 g/cm^3.
υ	Hypothetical exponential control on density dependence in ς; the default value is 0.3.
γ	Power-law base for the field dependence in ς. Default value is 0.0480 ± 0.0021.
δ	Power-law exponent in the field dependence in ς; default value is -0.0533 ± 0.0068.
ϵ	Reshaping parameter for NR charge yields, controlling the effective energy scale at which the charge yield behavior changes. The default value is $12.6^{+3.4}_{-2.9}$ keV.
p	Exponent which controls the shape of the energy dependence of the NR charge yields at energies greater than $\mathcal{O}(\epsilon)$. Default value is 0.5.
ζ	Controls the energy dependence of the NR charge yields roll-off at low energies. Default value is 0.3 ± 0.1 keV.
η	Controls energy-dependent shape of the NR charge yields roll-off at low energies. Default value is 2 ± 1.
θ	Controls the energy dependence of the NR light yields roll-off. Default value is 0.30 ± 0.05 keV.
ι	Controls the shape of the energy dependence of the NR light yields roll-off. Default value is 2.0 ± 0.5.
F_q	Fano-like factor for statistical fluctuations. For ERs, this is proportional to $\sqrt{E \cdot \mathcal{E}}$; see Equation (7). For NRs, this is separated into fluctuations for N_{ex} and N_i; the default value is 0.4 for both in NEST v2.3.11, while the values were 1.0 in previous NEST versions. (F_{ex} was underestimated to be conservative for low-mass WIMPs.)
σ_p	Non-binomial contribution to recombination fluctuations, modeled as a skew Gaussian in electron fraction space.
A	Amplitude of non-binomial recombination skew Gaussian. For NRs, this is a constant 0.04 (v2.3.11) or 0.1 (v2.3.10). For ERs, it is field-dependent: $A = 0.09 + (0.05 - 0.09)/(1 + (\mathcal{E}/295.2)^{251.6})^{0.007})$, where 0.05 was 0.055 in 2.3.10
ξ	Centroid-location parameter of the non-binomial recombination skew Gaussian. Default value for ERs is an electron fraction of 0.45, but 0.5 for NRs.
ω	Width parameter for the non-binomial recombination skew Gaussian. Takes value of 0.205 for ERs and 0.19 for NRs.
α_p	Skewness parameters for the non-binomial recombination skew Gaussian. Takes the value -0.2 for ERs, while being zero for NRs.
α_r	Additional skewness in the recombination process itself. Field- and energy- dependent equations can be found in Ref. [59] for ERs, while this is fixed at 2.25 for NRs, with evidence of higher values in [59].

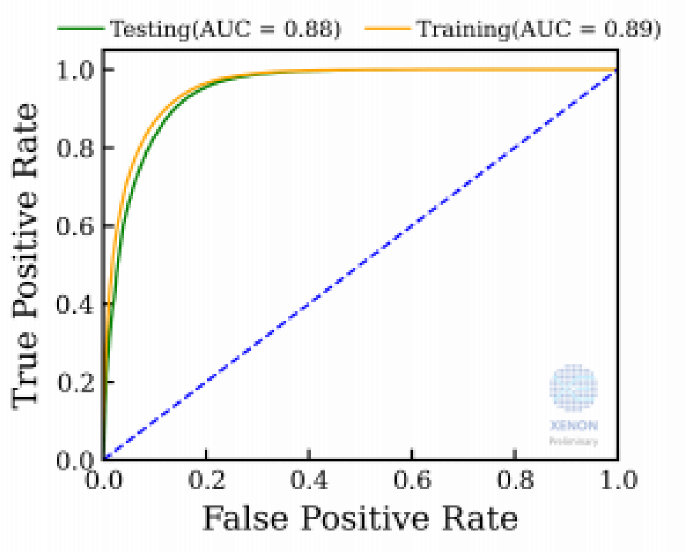
Front. Detect. Sci. Technol. Sec. Detector Physics, Volume 2 - 2024

Fitting procedure

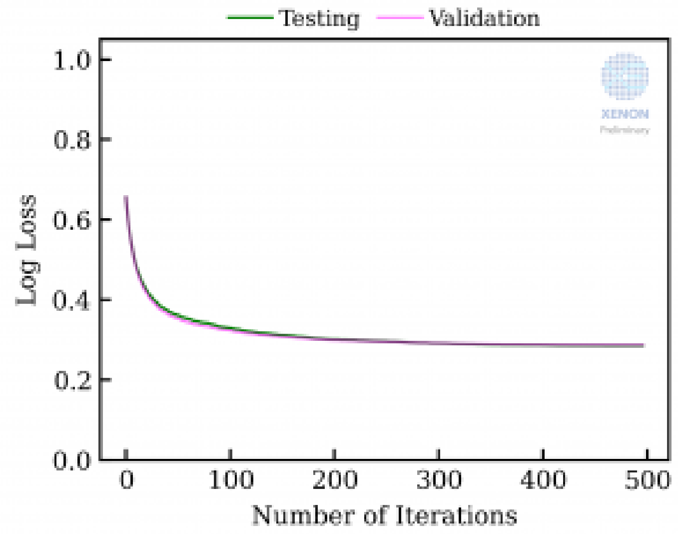


eXtreme Gradient Boosting (XGBoost) Classifier

area under the curve(AUC)



Log loss

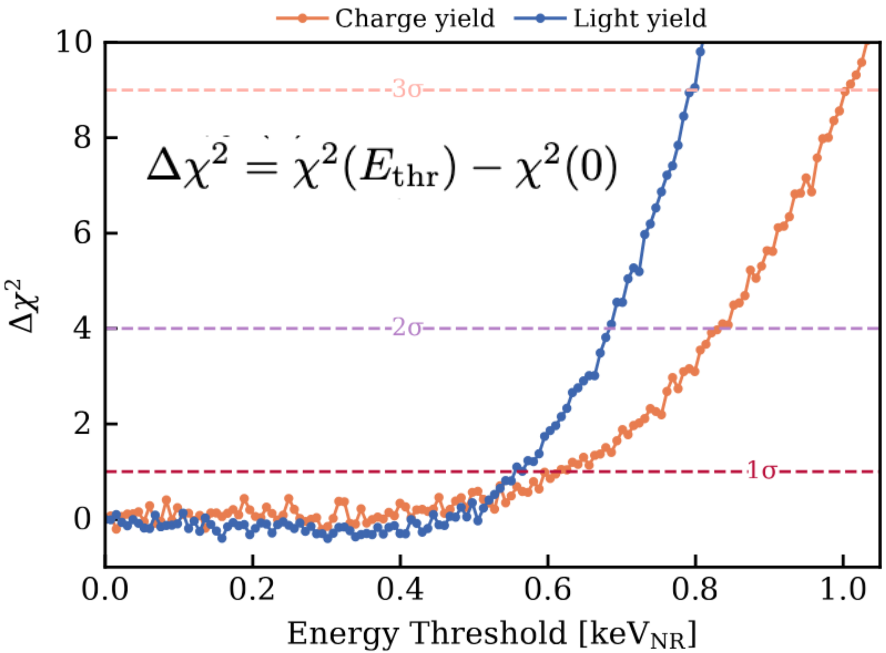


Features:

- width and rise time of the main S2 signals
- time, position, and width differences between the main and alternative S2 signals
- drift time between the main S1 and S2 signals

Lowest observable energy

XENON Westlake | DM and neutrino lab



threshold

light yield: $0.56 \pm 0.02\ \mathrm{keV_{NR}}$
charge yield: $0.62 \pm 0.03\ \mathrm{keV_{NR}}$

Low energy neutron calibration sources

Source	Energy		Yield	Timing
	Range (MeV)	Distribution		
^{252}Cf	0–10 (average of 2)	Continuous	10^3 n/s/μCi	γ-Tagging[a]
Fission reactors	0–10 (average of 2)	Continuous	10^{12}–10^{16} n/s/MW_{th}	NA
AmBe	0–10	Continuous	$\sim 5 \times 10^{-5}$ n/α	γ-Tagging[a]
PuBe	0–10	Continuous	$\sim 5 \times 10^{-5}$ n/α	γ-Tagging[a]
AmLi	0–1.5 (average of 0.45)	Continuous	$\sim 10^{-6}$ n/α	ND
SbBe	0.023	Monoenergetic	$\sim 10^{-5}$ n/γ	NA
YBe	0.152	Monoenergetic	$\sim 10^{-5}$ n/γ	NA
D-D	2–3	Monoenergetic	$\lesssim 10^9$ n/s	$\lesssim 10$ μs
D-T	13–15	Monoenergetic	$\lesssim 10^{10}$ n/s	$\lesssim 10$ μs
p-Li	0–2	Monoenergetic	Varies[b]	$\gtrsim 1$ ns
p-V	0–0.2	Monoenergetic	Varies[b]	$\gtrsim 1$ ns

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