Universität Zürich[UZH]

Physik Institut

Latest results from XENONnT

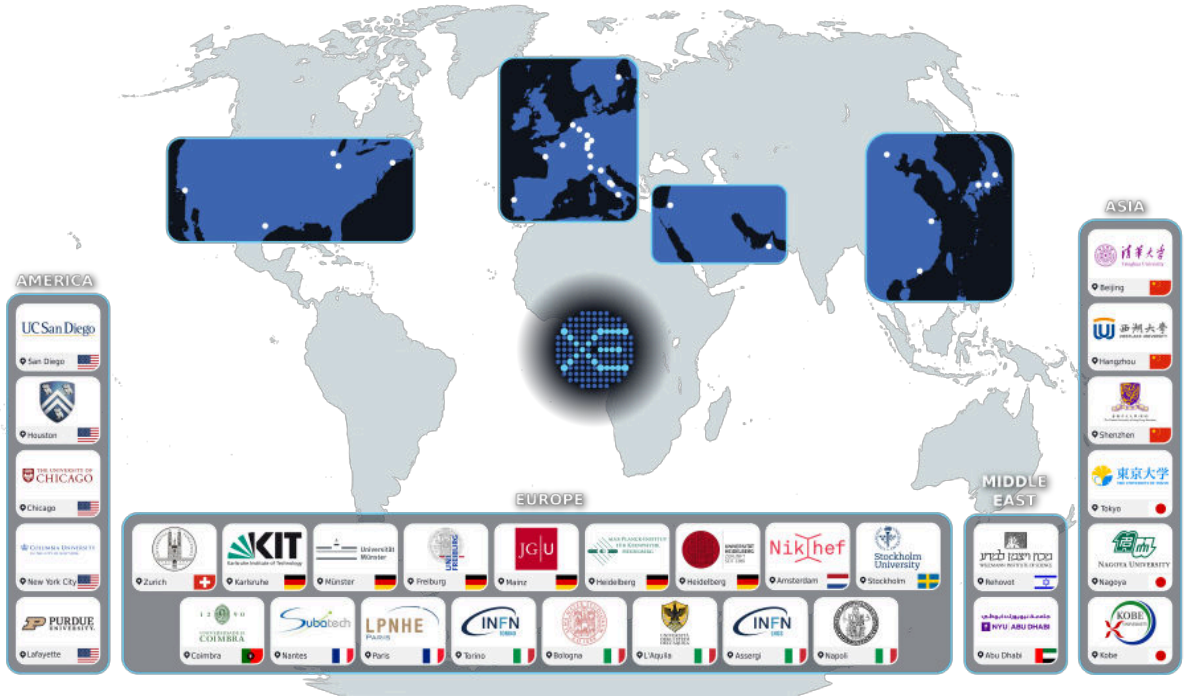
Probing Neutrino and Dark Matter Interactions

Florian Jörg florian.joerg@physik.uzh.ch

March 26, 2025 - Recontres de Moriond (Electroweak Interactions)

The XENON-family

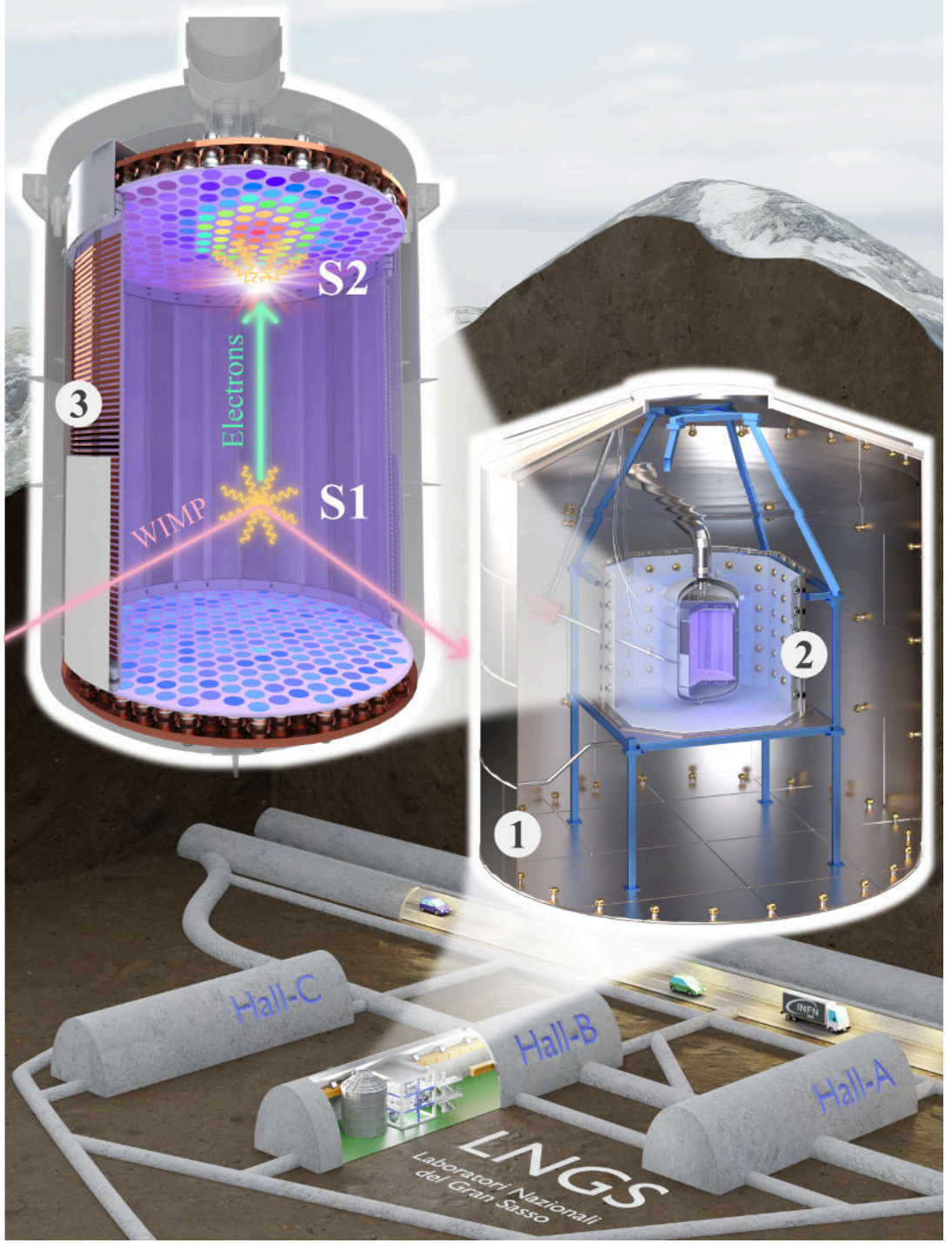
- 200+ scientists
- 30 institutions
- 12 countries



XENONnT Experiment

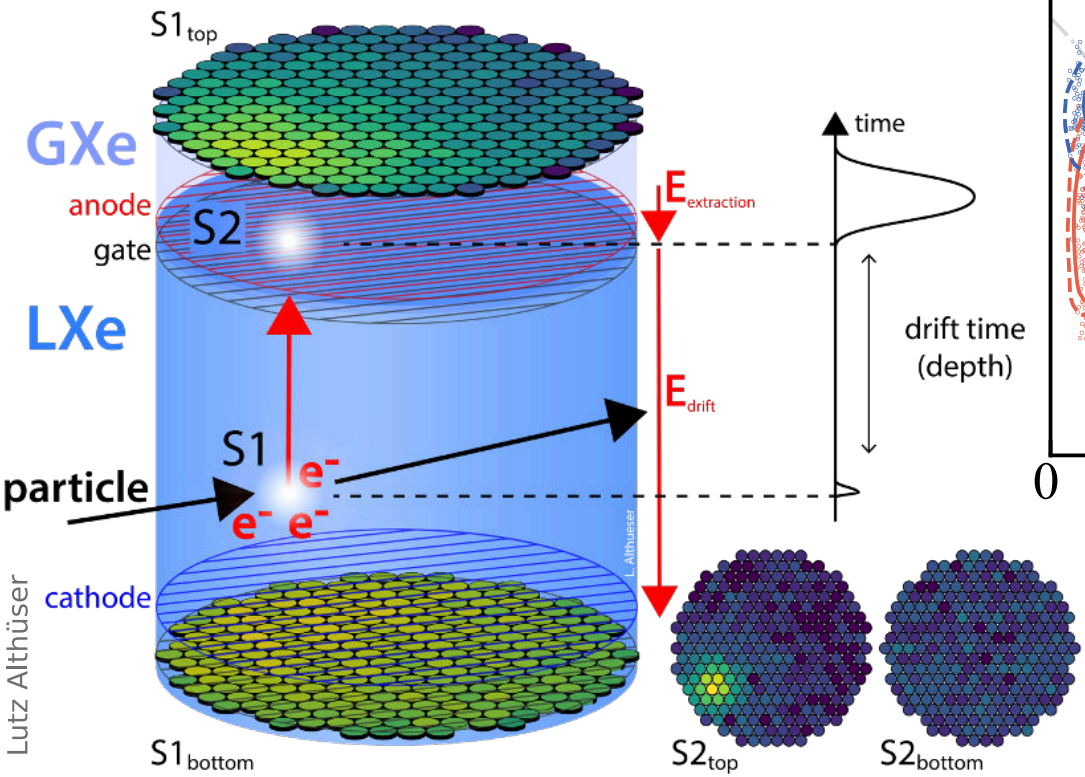
- Laboratorio Nazionali del Gran Sasso (LNGS, Italy)
- Depth: 1400m (3800 m.w.e)

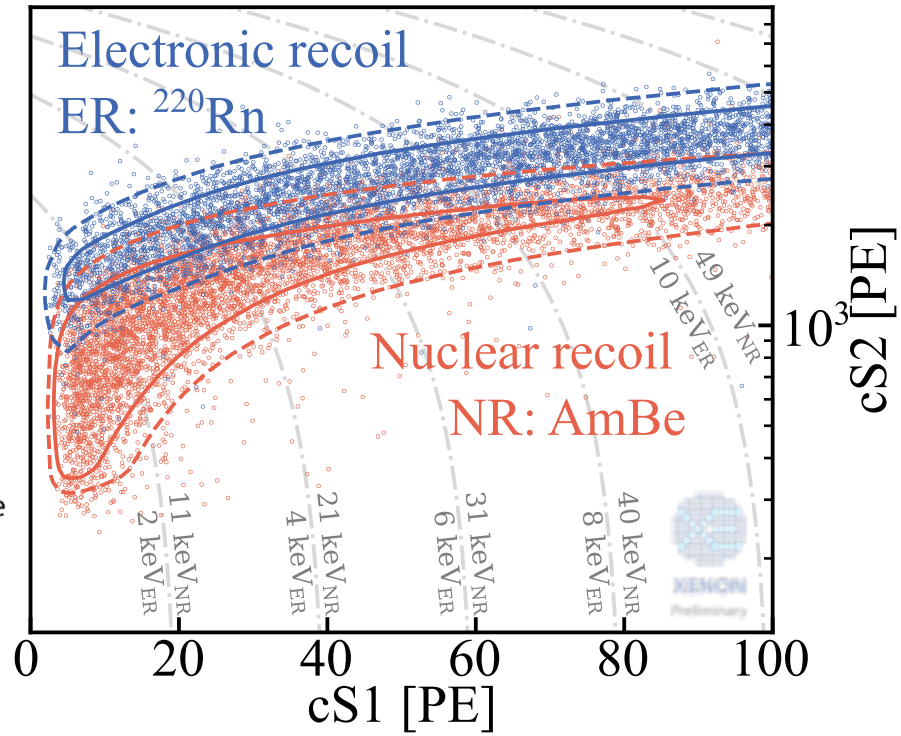
1. Active Muon Veto (MV)
   JINST 9 P11006, [1406.2374]
2. Gadolinium-doped Water Cherenkov Neutron Veto (NV)
   [2412.05264]
3. LXe Dual Phase Time Projection Chamber (TPC) with 5.9 tonnes active volume
   Eur. Phys. J. C 84, 784 (2024), [2402.10446]

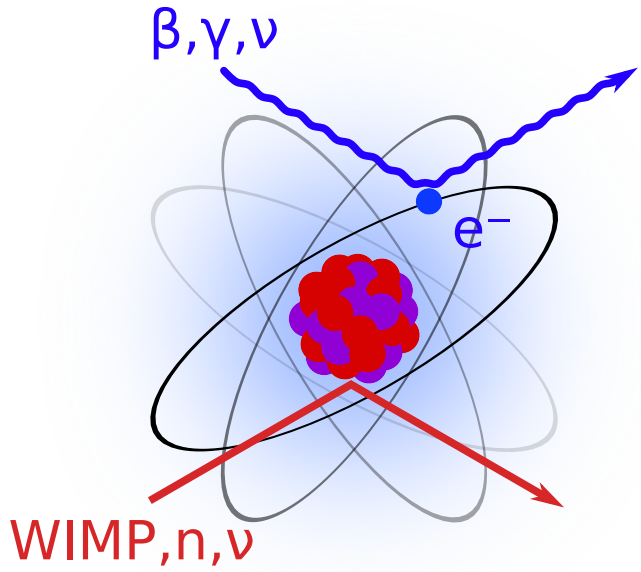


[2502.04209]

Dual-phase TPC principle







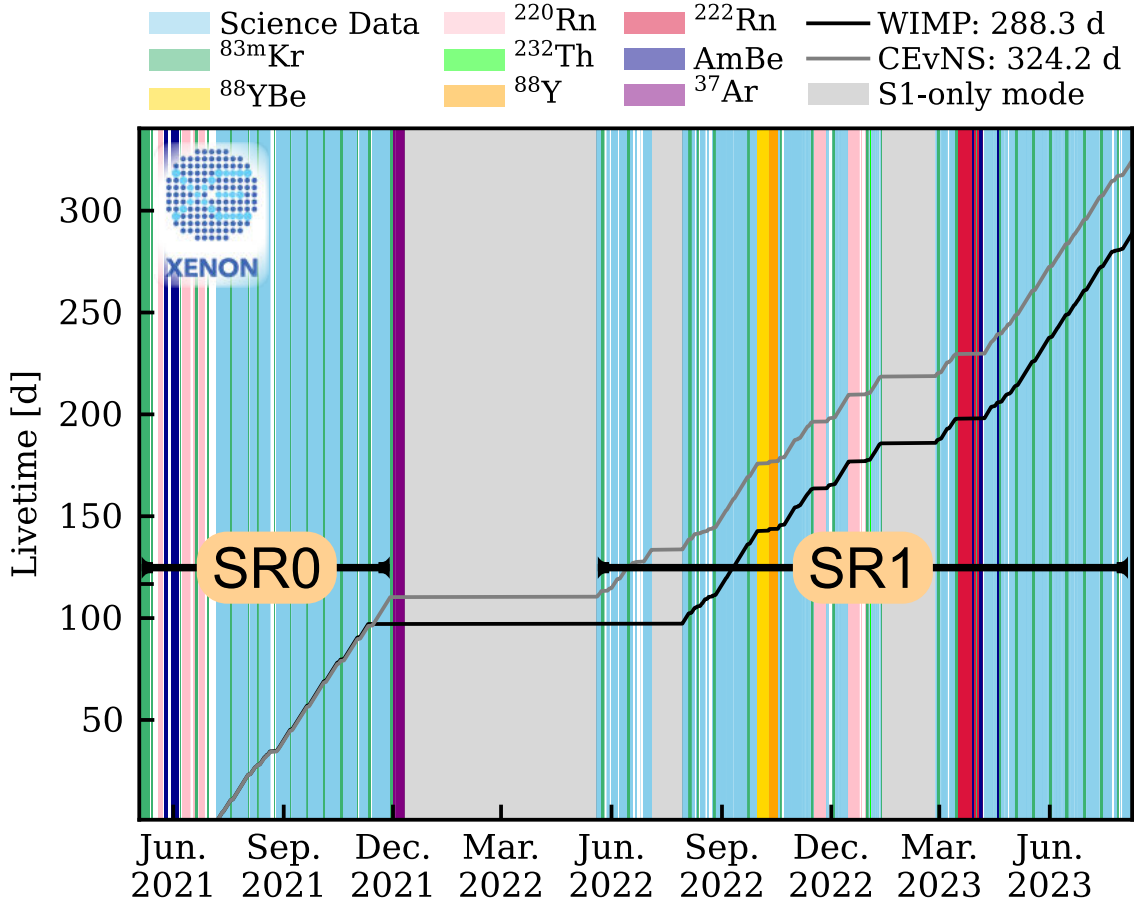
- Electron drift time ⇒ z-position
- Distribution of S2 signal ⇒ x-y-position
- S1/S2 ratio ⇒ signal discrimination

Science Data

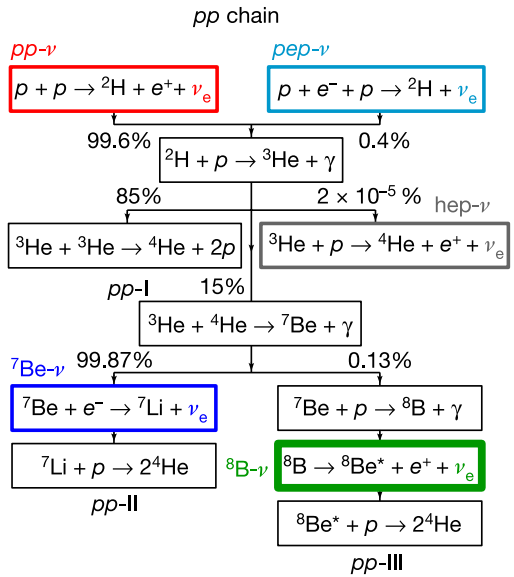
- Using data from first two science runs of XENONnT
  - **SR0**: 108.0 days
  - **SR1**: 208.5 days
- Fiducial mass: $\sim$ 4 tonnes
- Exposure: 3.5 tonnes $\times$ years
- Blind analysis

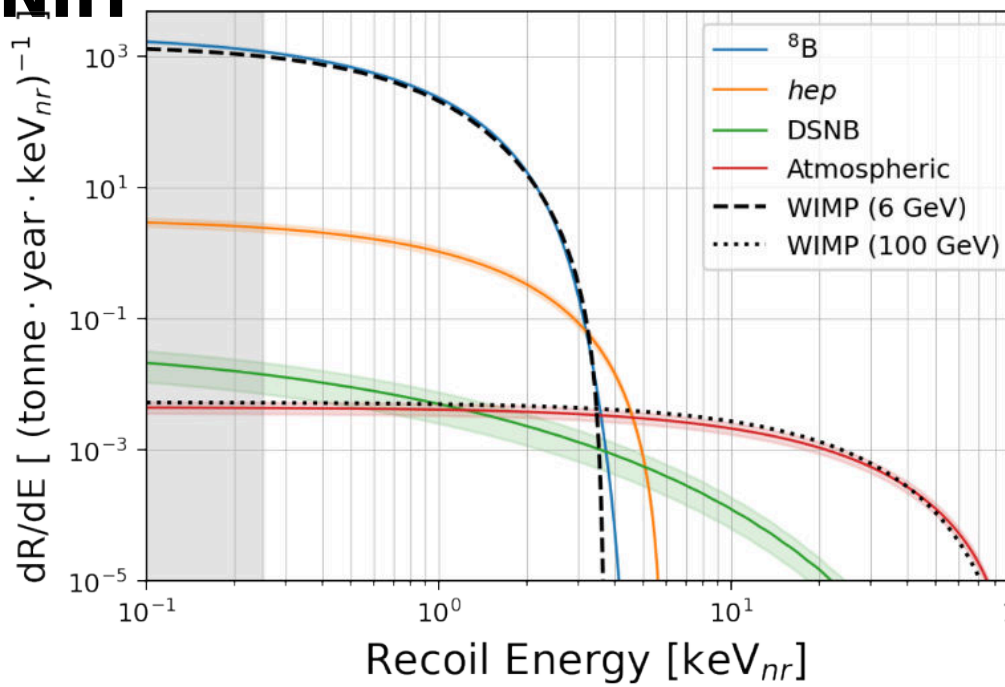
Goals:

- Detect CEνNS from ^{8}B solar neutrinos ✓
- Search for WIMPs ✓ see: [2502.18005]
- Further channels (pp-neutrinos, 0$\nu\beta\beta$, ...)

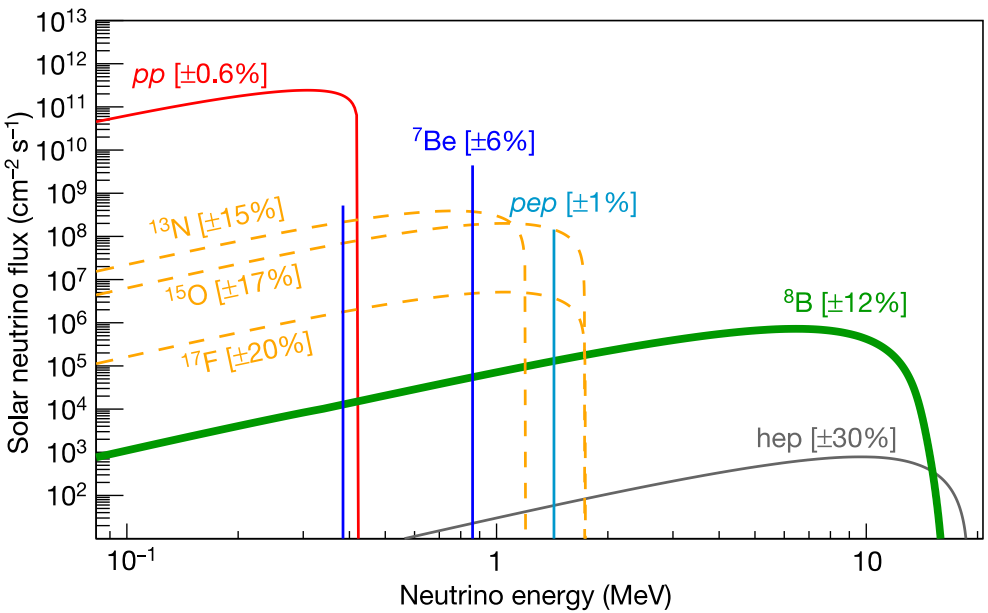


^{8}B Solar neutrinos in XENONnT





Phys.Rev.D 108 (2023) 2, 022007, [2304.06142]

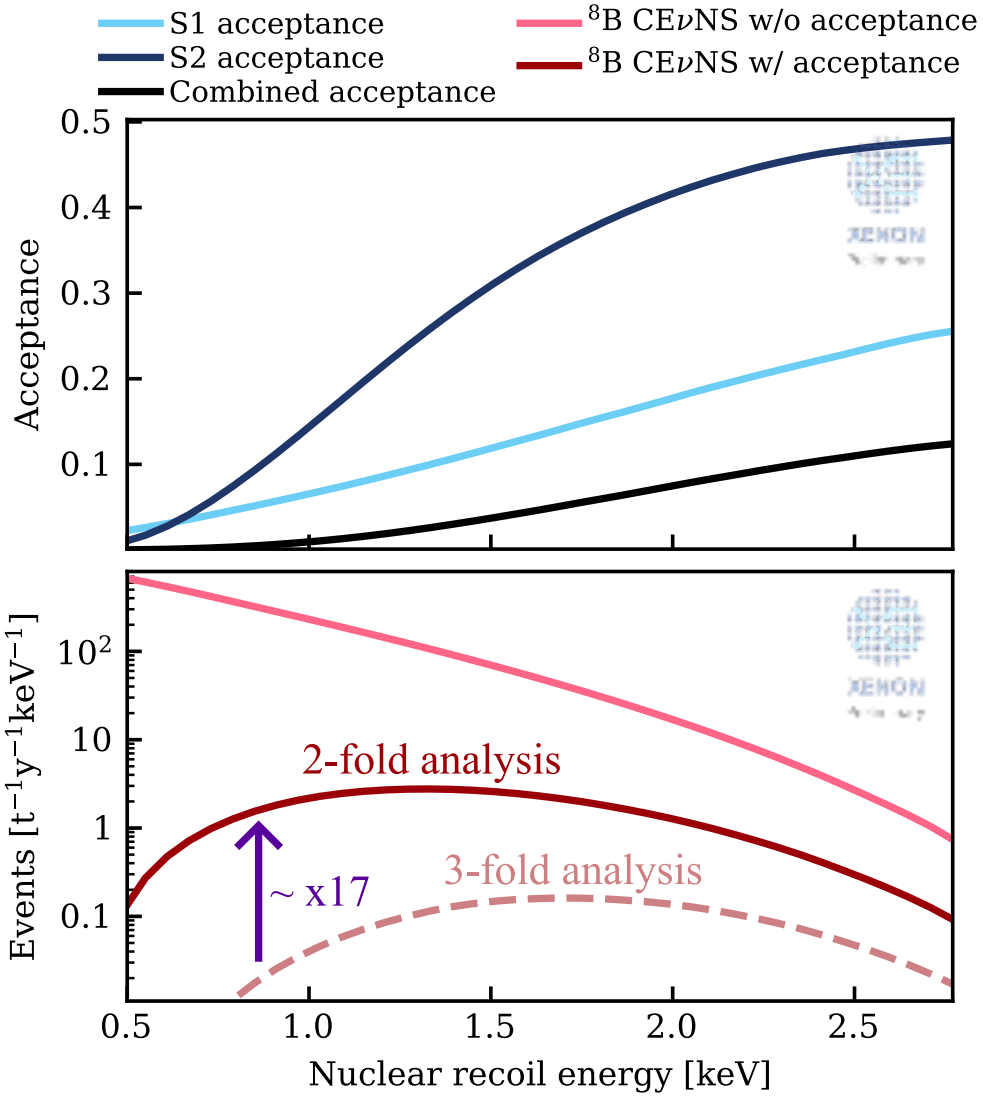


Nature volume 562, pages505–510 (2018)

The ^{8}B spectrum is (almost) identical to the one of 6 GeV/c^2 WIMPs!

⇒ "Neutrino fog"

Efficiency at low recoil energies

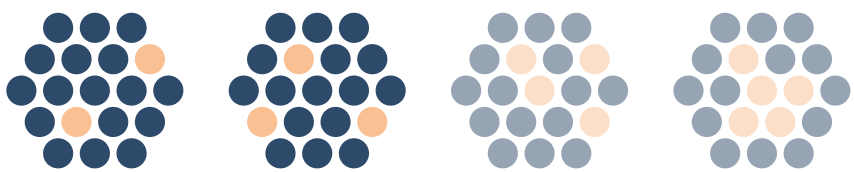


- ^{8}B spectrum drops steeply above 3 keV!
- Looking only at events with:
  S1: 2 or 3 PMT hits and
  S2: Between 120 - 500 PE
  $\approx$ 4 - 17 electrons.
- $\sim$17$\times$ higher CEvNS rate compared to 3-fold coincidence (dashed lines)!

But:

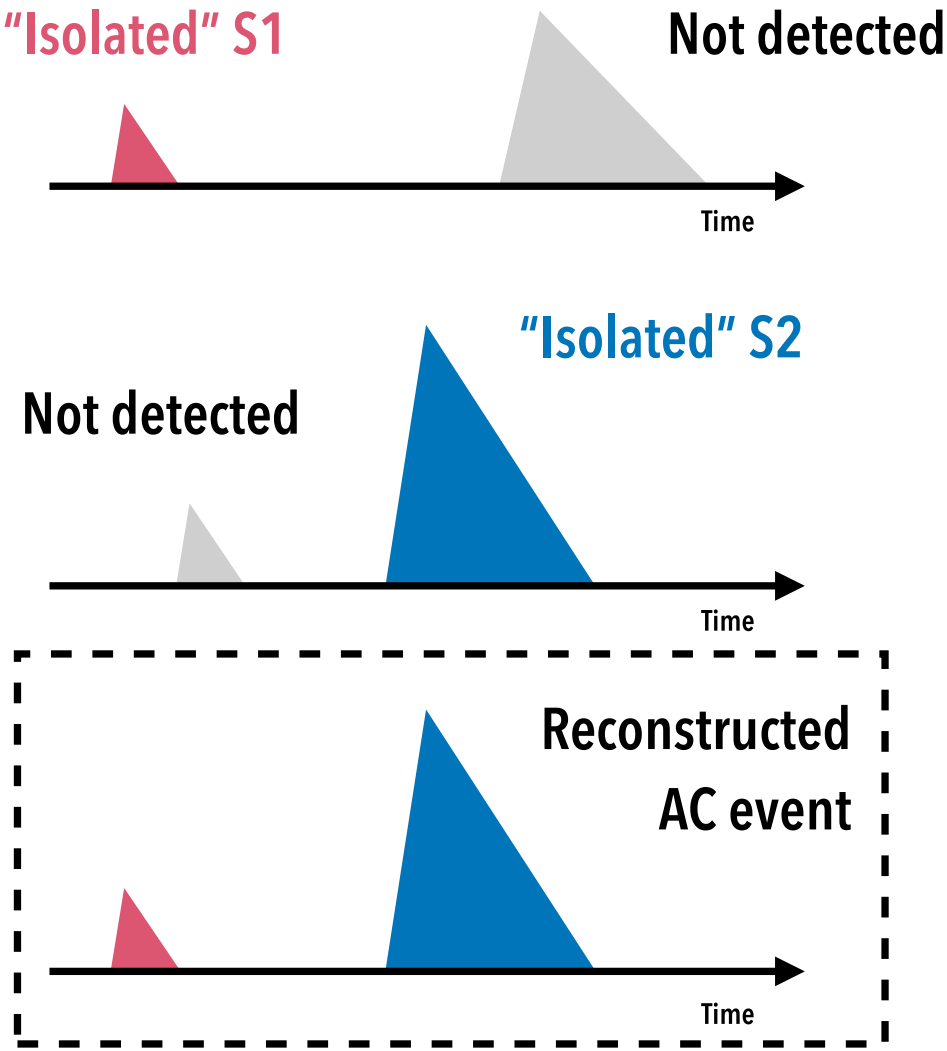
- Higher background
- Require low energy calibration

$\Rightarrow$ Done using YBe source [2412.10451]

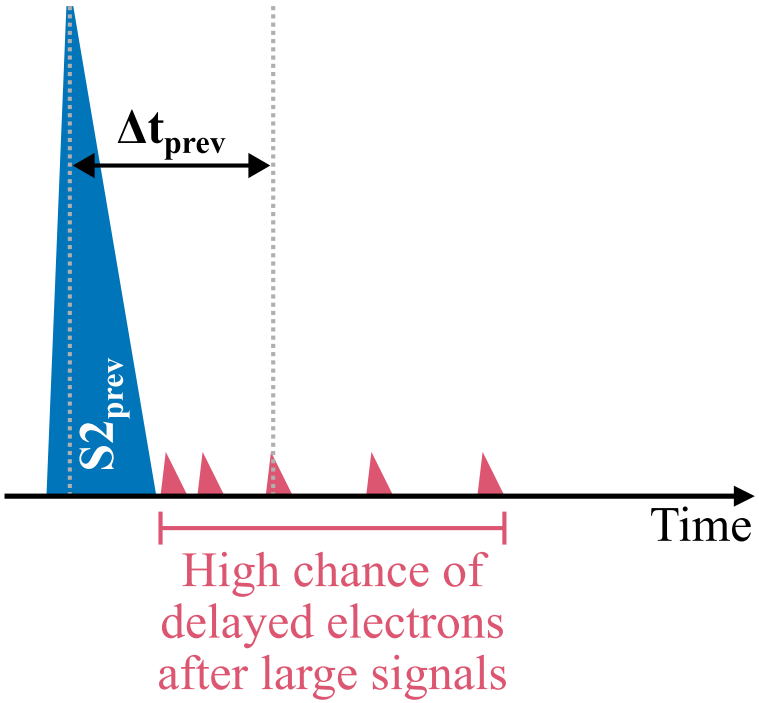


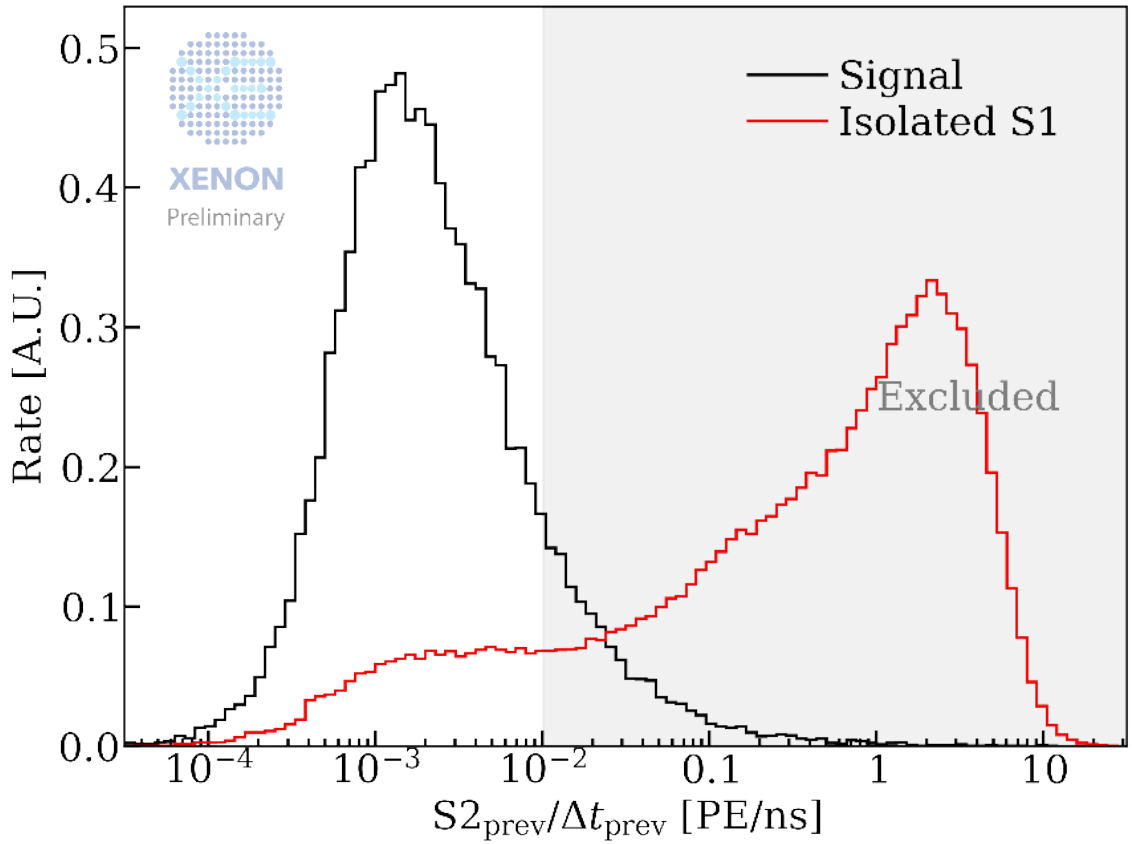
Accidental Coincidence (AC) Background

- Dominant background close to threshold
- Events from incorrectly paired S1 and S2 signals
- Raw AC rate $\sim$ 400 per day
  - "Isolated" S1: $\sim$ 15 Hz
  - "Isolated" S2: $\sim$ 0.15 Hz
- Events are mitigated using:
  - Boosted decision tree using S1 waveform
  - Boosted decision tree using S2 waveform
  - Correlation with a preceding high energy interaction (see next slide)



Accidental Coincidence (AC) Background



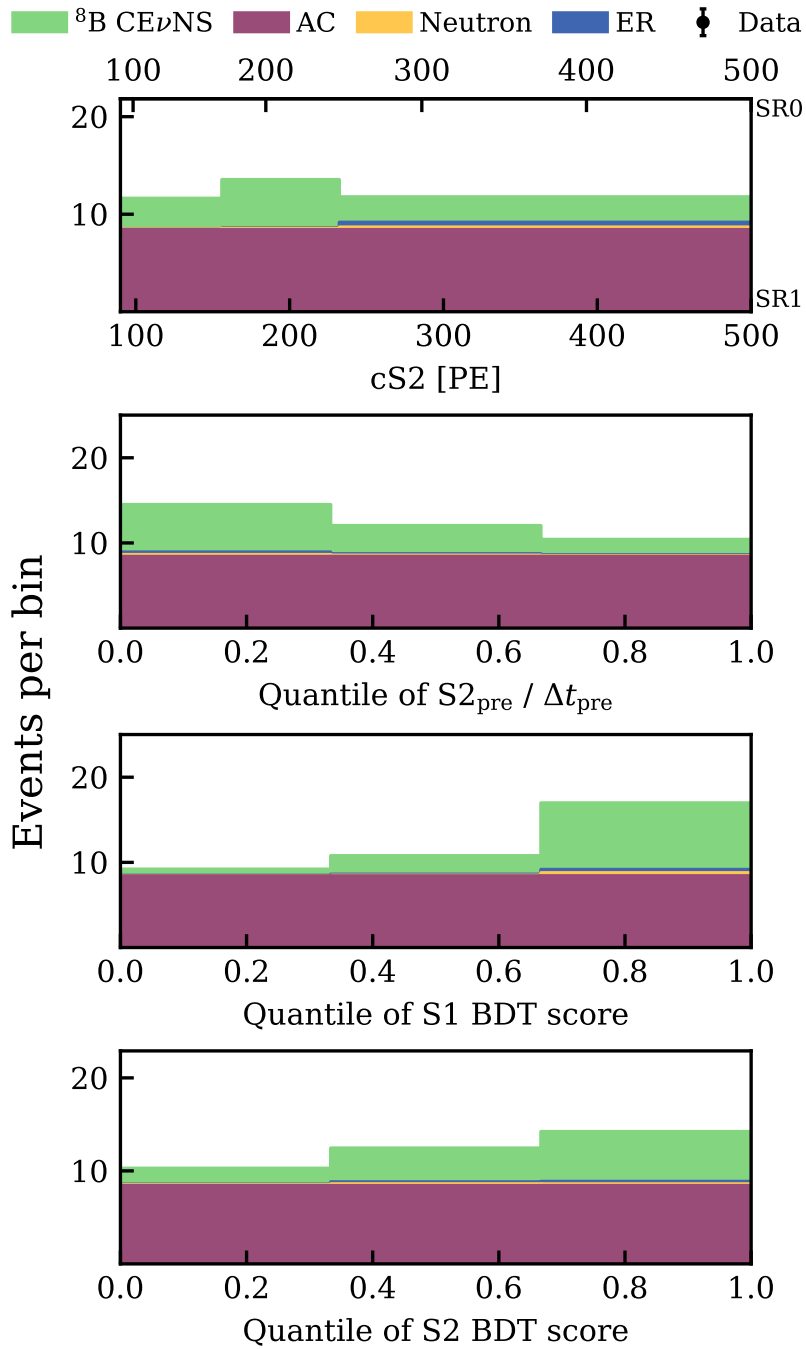


- Delay time: Δt_{prev} wrt. preceding large S2.
- Variable $\mathrm{S2}_{\mathrm{prev}}/\Delta t_{\mathrm{prev}}$ is part of likelihood function
- Large value = **close** to a **large** preceding S2

Unblinded dataset

Expected events: 38.3 ± 4

- Background: (26.4 ± 1.4)
- Signal: (11.9 ± 4)



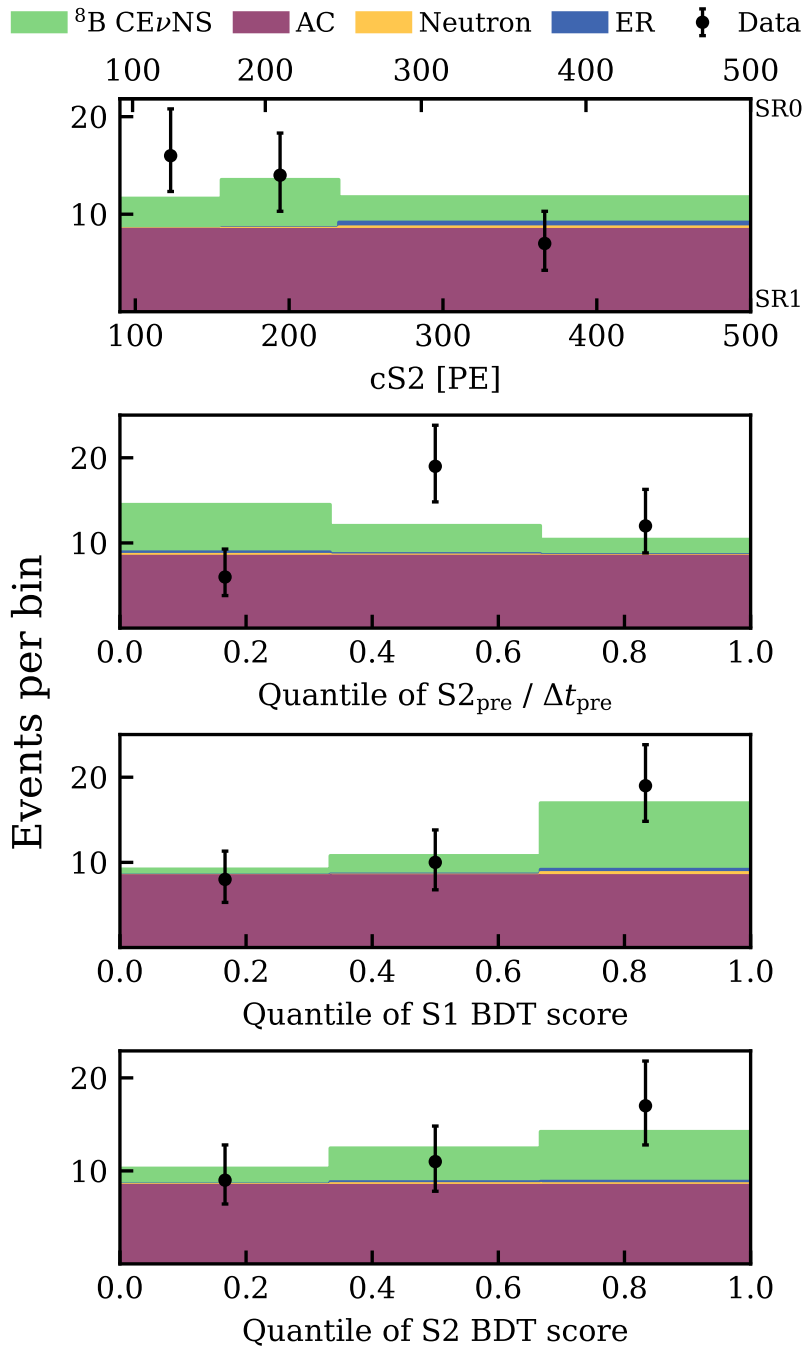
Unblinded dataset

Expected events: 38.3 ± 4

- Background: (26.4 ± 1.4)
- Signal: (11.9 ± 4)

Observed events: 37

- Background only hypothesis rejected at **2.73** σ!
- Goodness of fit (GOF) test performed to check for mismodelling (95% CL)



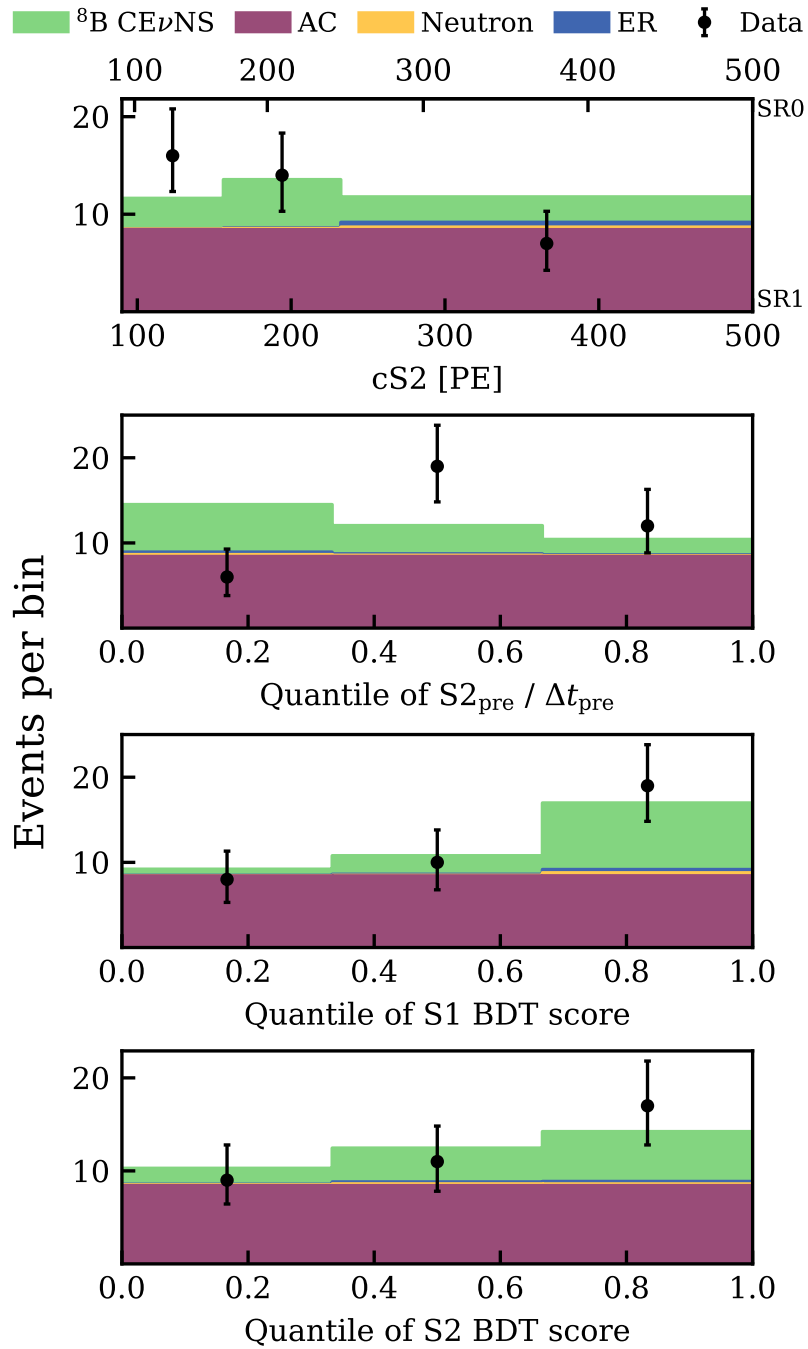
Unblinded dataset

Expected events: 38.3 ± 4

- Background: (26.4 ± 1.4)
- Signal: (11.9 ± 4)

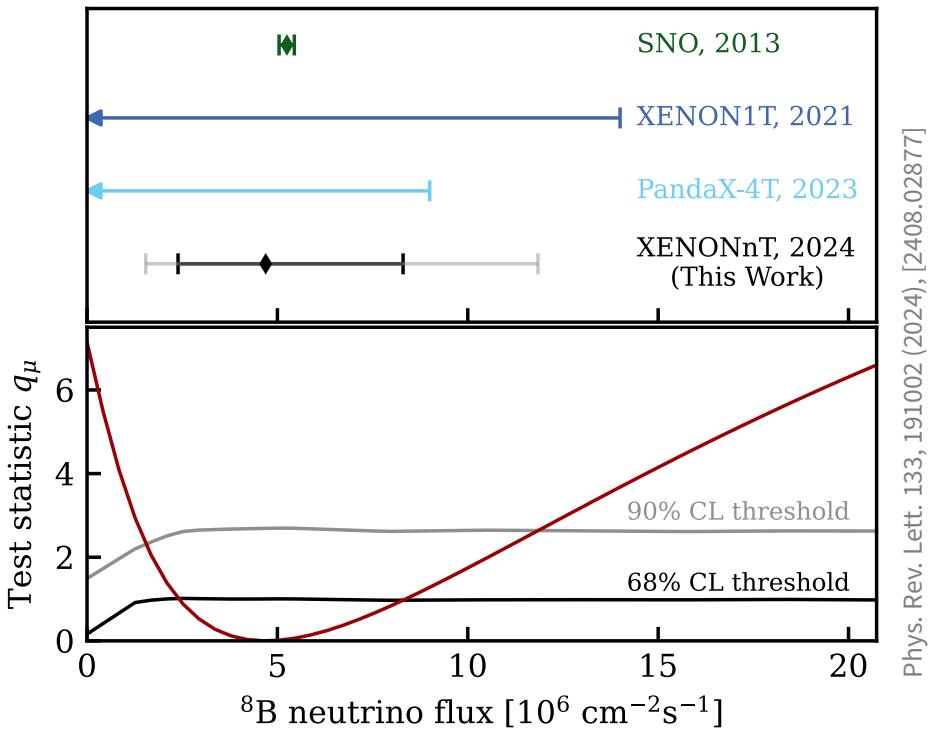
Observed events: 37

- Background only hypothesis rejected at **2.73** σ!
- Goodness of fit (GOF) test performed to check for mismodelling (95% CL)
- $\mathrm{S2_{pre}}/\Delta t_{\mathrm{pre}}$ below GOF threshold. No indication for mismodelling found.
- Investigation ongoing, higher statistics might resolve the tension
- Note: Removing this dimension from analysis would **increase** the significance to 3.22σ



^{8}B CEνNS Results

- Fix cross-section $\rightarrow$ Measurement of the solar ^{8}B flux:
  $(4.7^{+3.6}_{-2.3}) \times 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Compatible with SNO measurement ✓

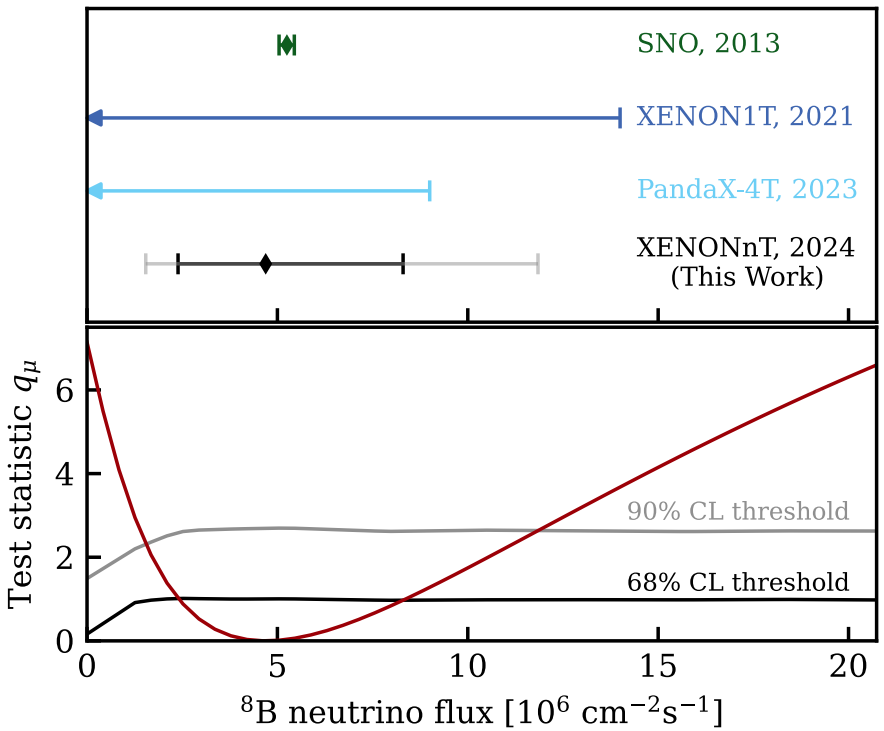


XENONnT: Phys. Rev. Lett. 133 (2024), 191002

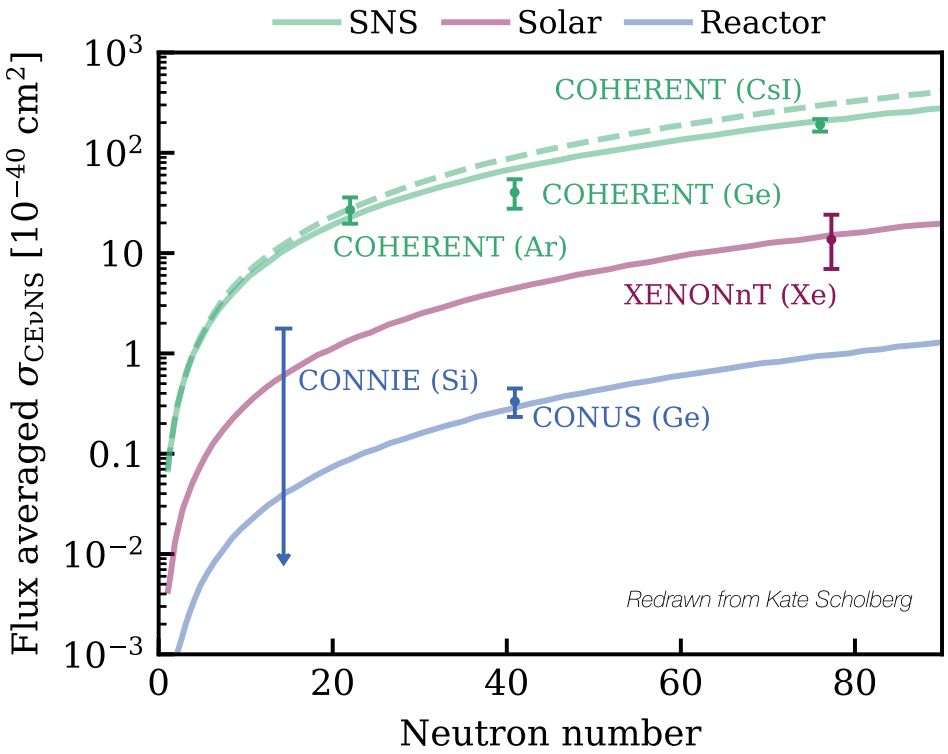
PandaX: Phys. Rev. Lett. 133 (2024) 19, 191001

^{8}B CEνNS Results

- Fix cross-section → Measurement of the solar ^{8}B flux:
  $(4.7^{+3.6}_{-2.3}) \times 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Compatible with SNO measurement ✓



Phys. Rev. Lett. 133, 191002 (2024), [2408.02877]



- Fix flux → First measurement of the CEνNS cross-section in xenon:
  $(1.1^{+0.8}_{-0.5}) \times 10^{-39}\,\mathrm{cm}^2$
- Compatible with standard model prediction ✓
- $\frac{d\sigma}{dE_R} \sim N^2$

XENONnT: Phys. Rev. Lett. 133 (2024), 191002

PandaX: Phys. Rev. Lett. 133 (2024) 19, 191001

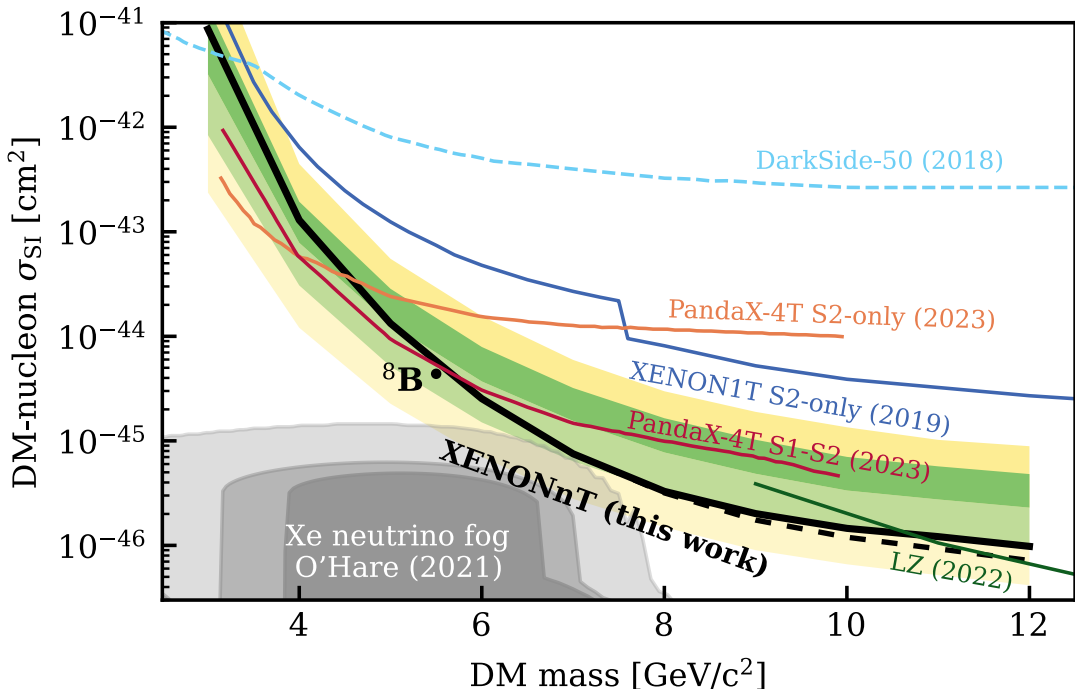

Dark matter search
in the neutrino fog

Search for light WIMPs among the neutrinos

Component	^{8}B**-only**	**4** GeV/c^2	**6** GeV/c^2	**10** GeV/c^2
SI DM	–	3.2	0.0	0.0
^{8}B CEνNS	$11.4^{+2.0}_{-3.6}$	10.2 ± 2.7	$11.4^{+2.7}_{-2.6}$	$11.4^{+2.7}_{-2.6}$
Total background	$37.7^{+2.5}_{-3.9}$	$36.4^{+3.0}_{-3.0}$	$37.7^{+3.0}_{-2.9}$	$37.7^{+3.0}_{-2.9}$
Observed	37	37	37	37

- Upward fluctuation below 5 GeV/c^2
- Downward fluctuation above 5 GeV/c^2
- Apply Power constrain (PCL) to "clip" reported limit at the -1σ sensitivity
- Data & software for re-casting are available

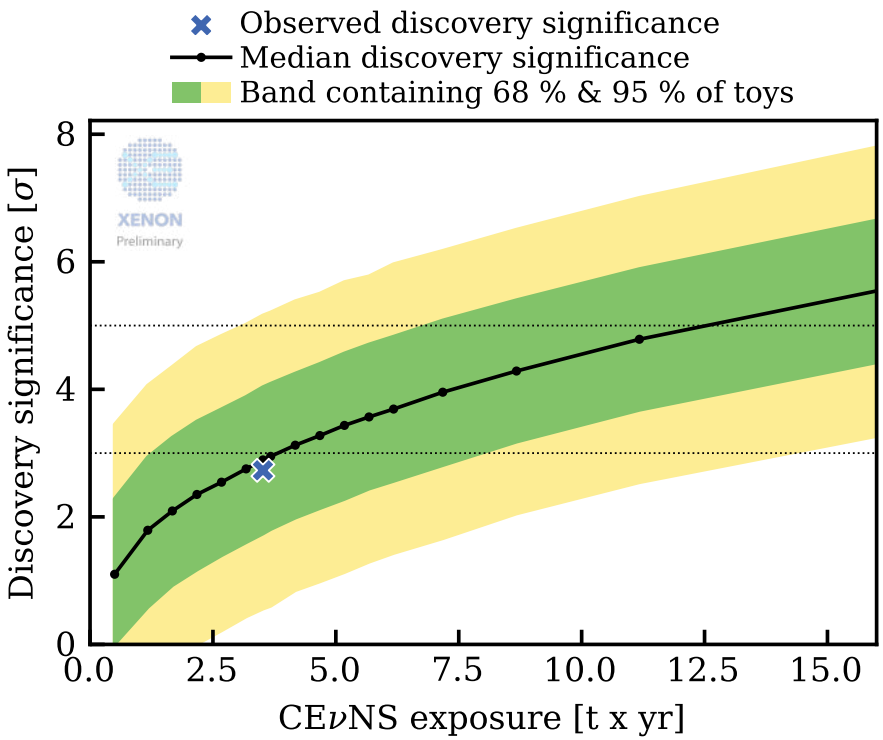
DOI 10.5281/zenodo.14522707

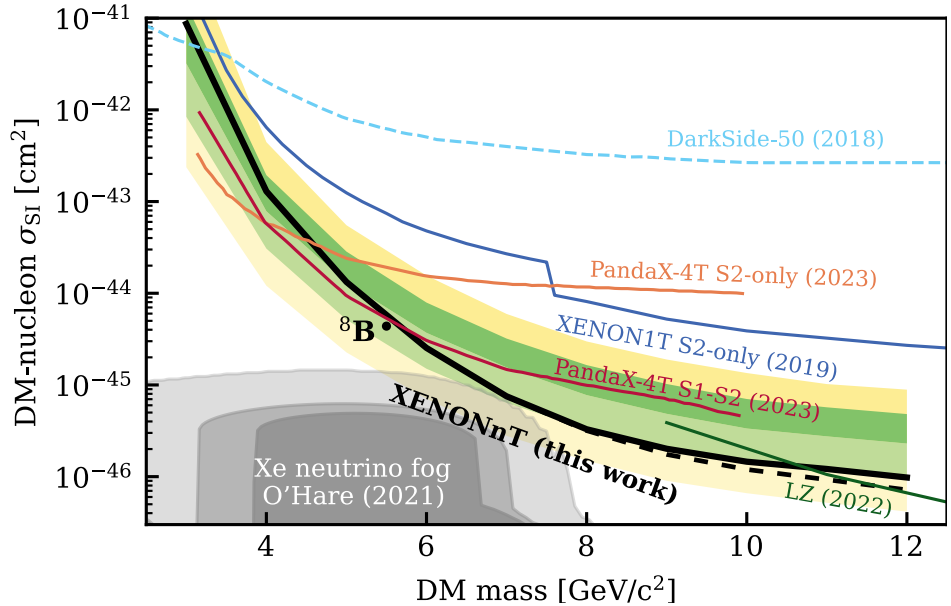


[2409.17868]

Summary & Outlook

- XENONnT & PandaX-4T are first to measure CEνNS on xenon from astrophysical source
- Measurement of ^{8}B CEνNS at 5σ is in reach within the lifetime of the experiment!





- XENONnT conducted first dark matter search in the "neutrino fog"
- XENONnT will be collect more data, operation until $\sim$ 2028.
- Further exciting results will come soon!

Thank you for your attention!
Looking forward to your questions.

Backup slides

WIMP spectrum and detection efficiency

$$\frac{dR}{dE_{\text{recoil}}} = \frac{M_T}{m_A} \frac{\rho_0}{m_\chi} \int_{v_{\text{min}}}^{v_{\text{esc}}} \epsilon(E_{\text{Recoil}})\, v \cdot f(\vec{v})\, \frac{d\sigma_{\chi,N}}{dE_{\text{Recoil}}}\, dv$$

Astrophysical inputs

- Local DM density $\rho_0 \sim 0.3\text{GeV}/\text{cm}^3$
- DM velocity distribution $f(\vec{v})$

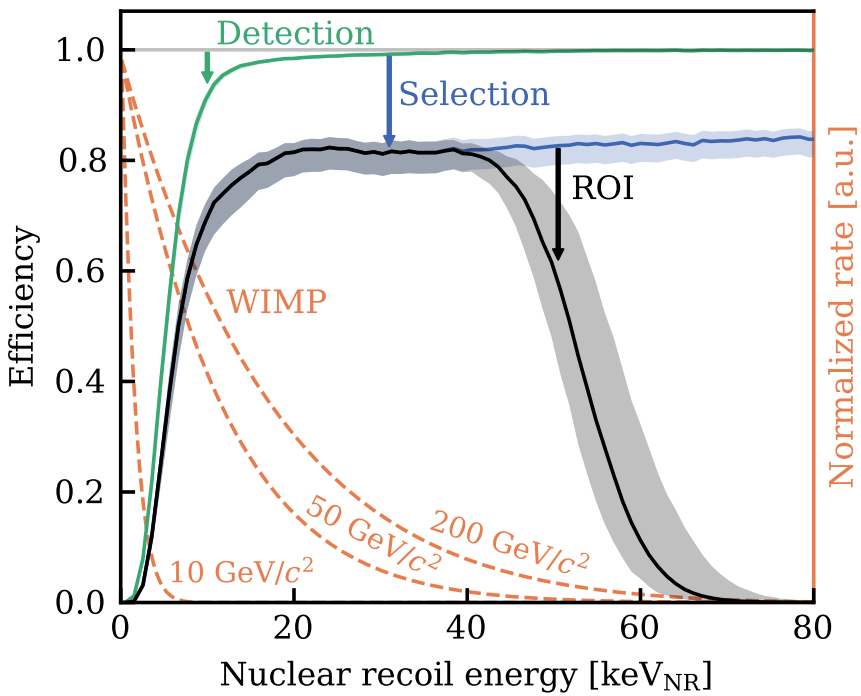
Particle physics

- WIMP - nucleon cross section $\sigma_{\chi,N}$

Detector physics

- Target material: atomic mass m_A and total mass M_T
- Energy threshold: v_{min} and detection efficiency $\epsilon(E_{\text{Recoil}})$

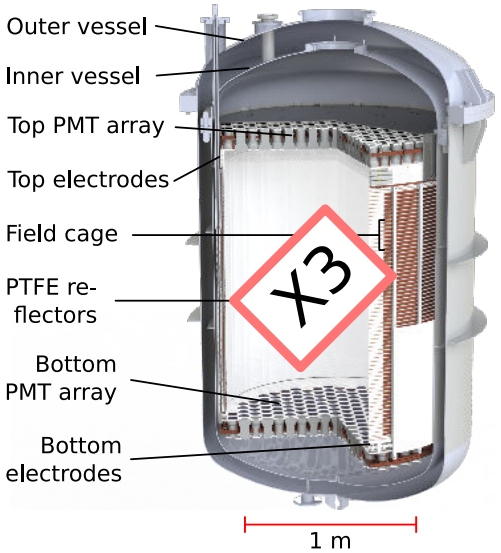
XENONnT: PRL 131, 041003 (2023)



Some subsystems of the XENONnT detector

Dual-phase TPC

JCAP11(2020)031, arXiv: 2007.08796

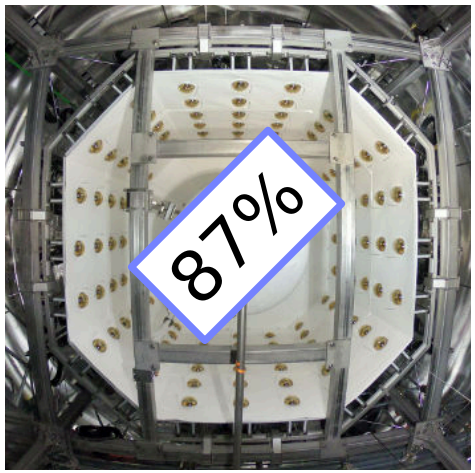


LXe purification

EPJC 82 (2022) 860, arXiv: 2205.07336

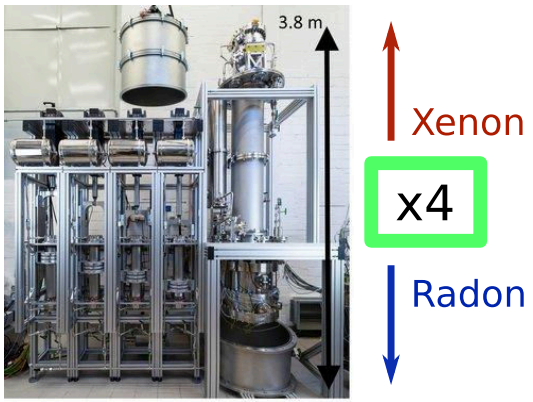
Neutron veto

arXiv: 2412.05264

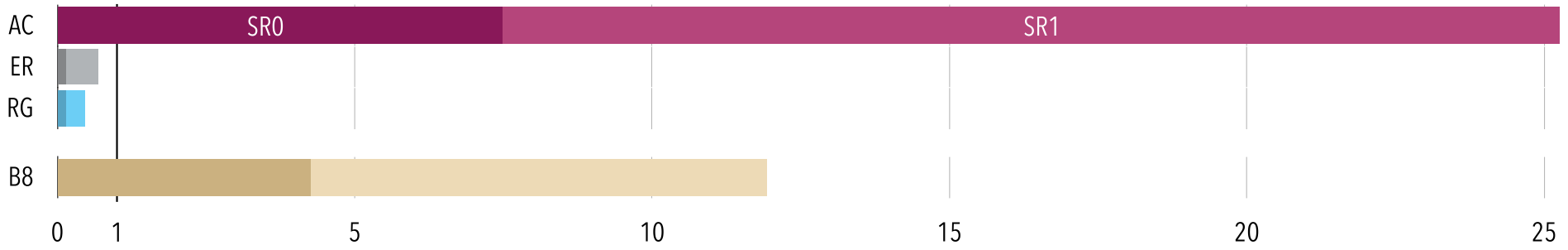


Radon distillation

EPJC82(2022)12,1104, arXiv:2205.11492



Signal and background prediction



Electronic recoils (ER)

- Flat spectrum from 0 to 10 keV
- Response of LXe to low energy ERs uncertain. Assign a conservative 100% uncertainty

Radiogenic neutrons (RG)

- 58% uncertainty from side band of neutron veto tagged events

Surface background

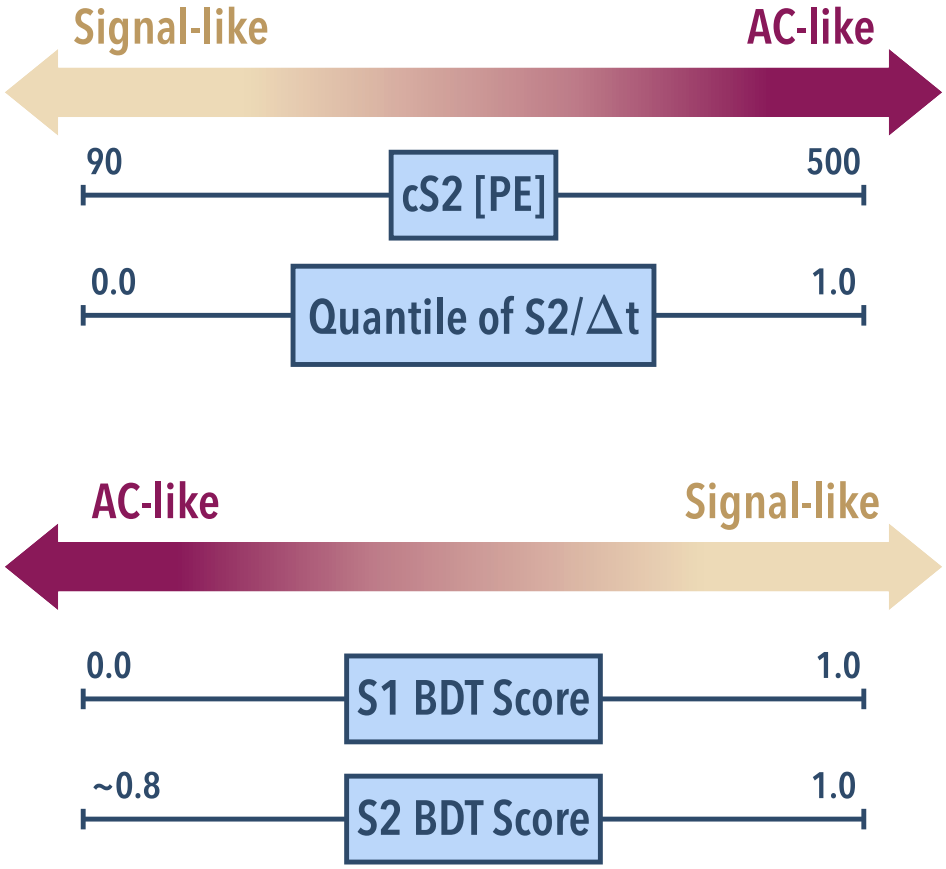
- Reduced to negligible levels by spatial selection (fiducial volume)
- Not included in the likelihood

^{8}B neutrino signal

- 35% uncertainty from detection efficiency and signal yield in LXe.
- Flux is kept as a free parameter

The Likelihood function

- Binned likelihood in 4D parameter space
  - 3 x 3 x 3 x 3 = 81 bins
  - Separate terms for SR0 & SR1
  - Constraints on rates and yields from ancillary measurements
- Data-driven AC background
- Other background and signal models from simulations
- Surface background: Derived from data; FV chosen such that it can be neglected in the likelihood



Validation of AC background

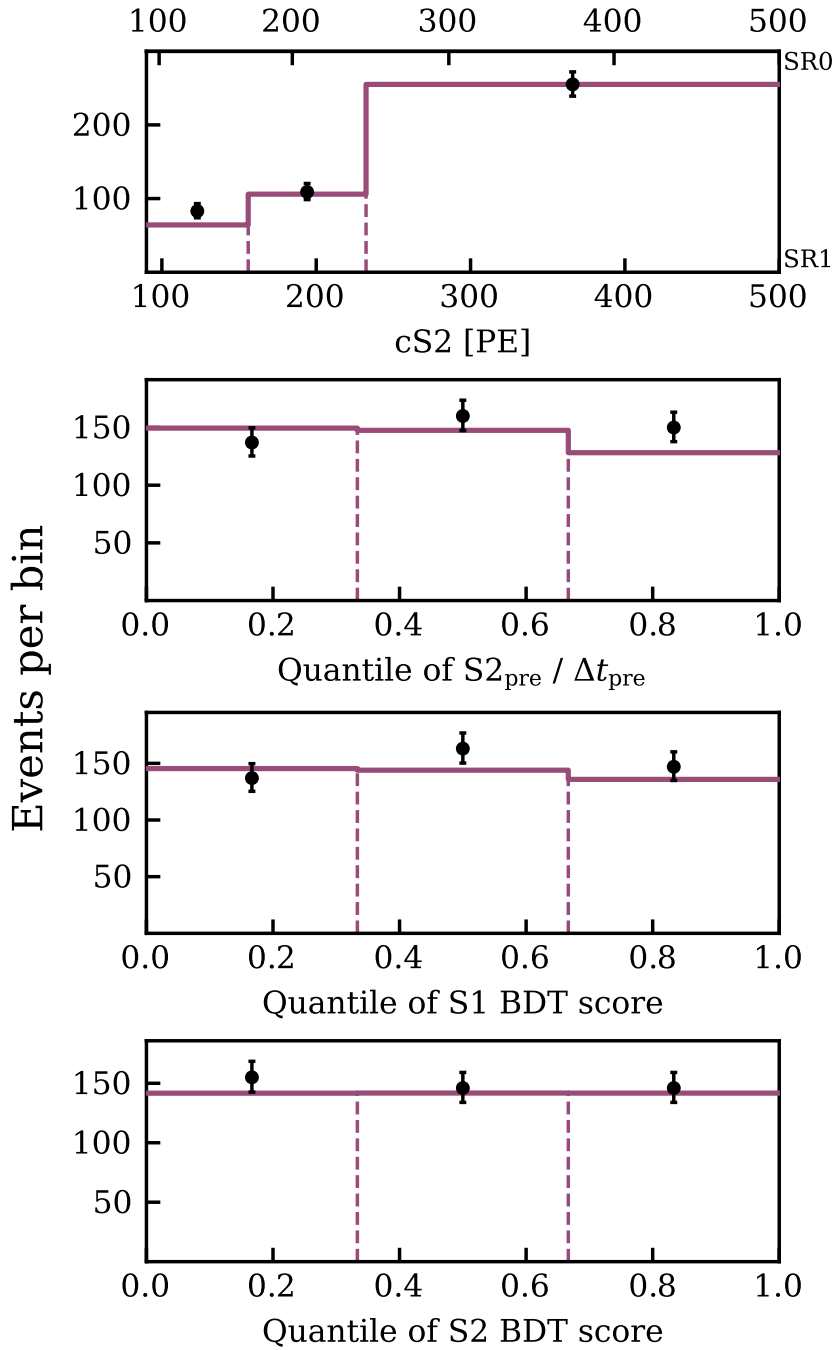
- Data driven AC model: Resampling isolated S1/S2 pulses into synthetic events
- Dominant background, needs validation!
- Define an **AC sideband** by inversion of anti-AC cuts

AC sideband

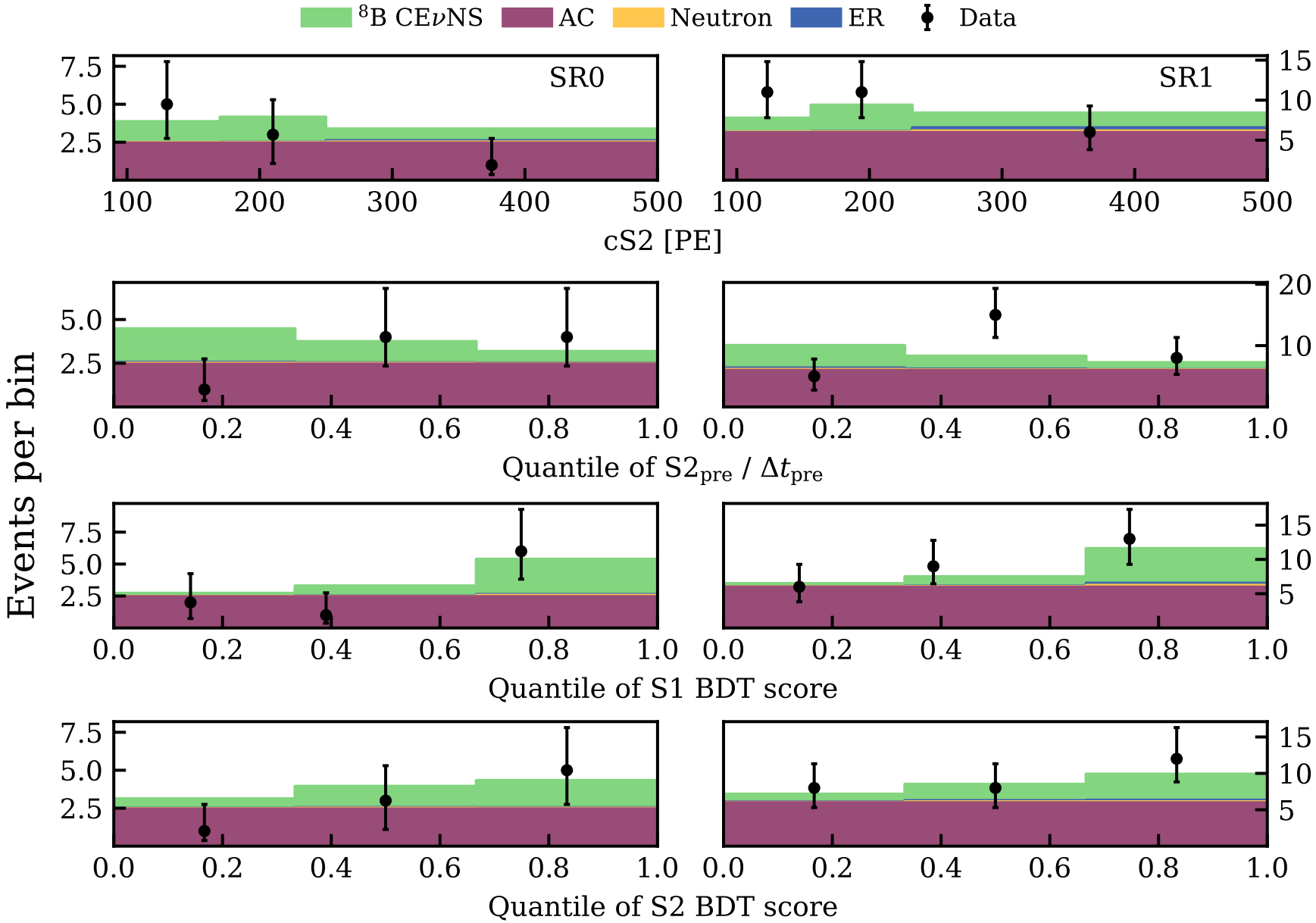
Expected: 425.2 events

Observed: 447 events

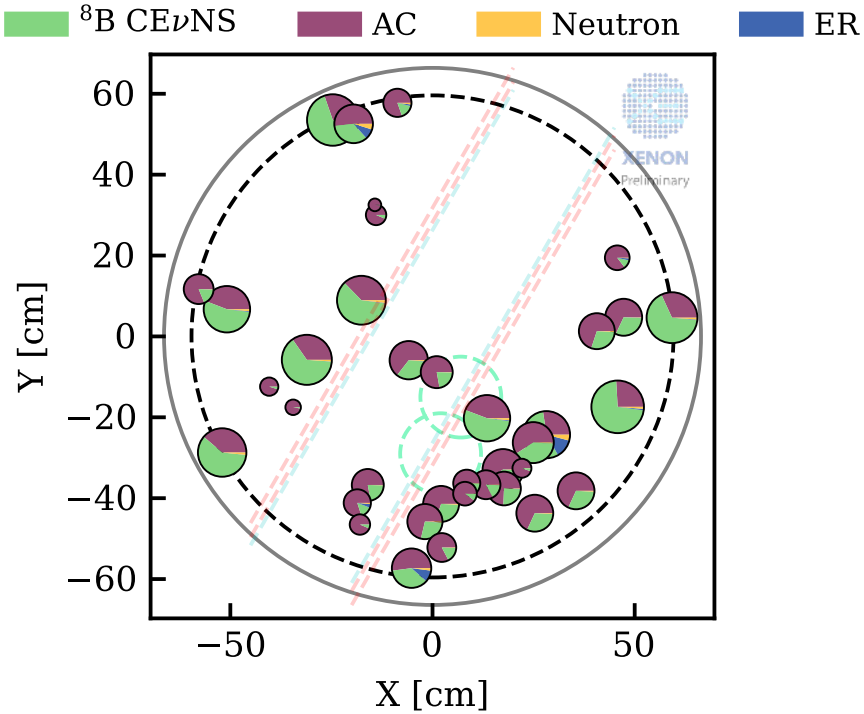
- Propagate uncertainties from the sideband into background prediction

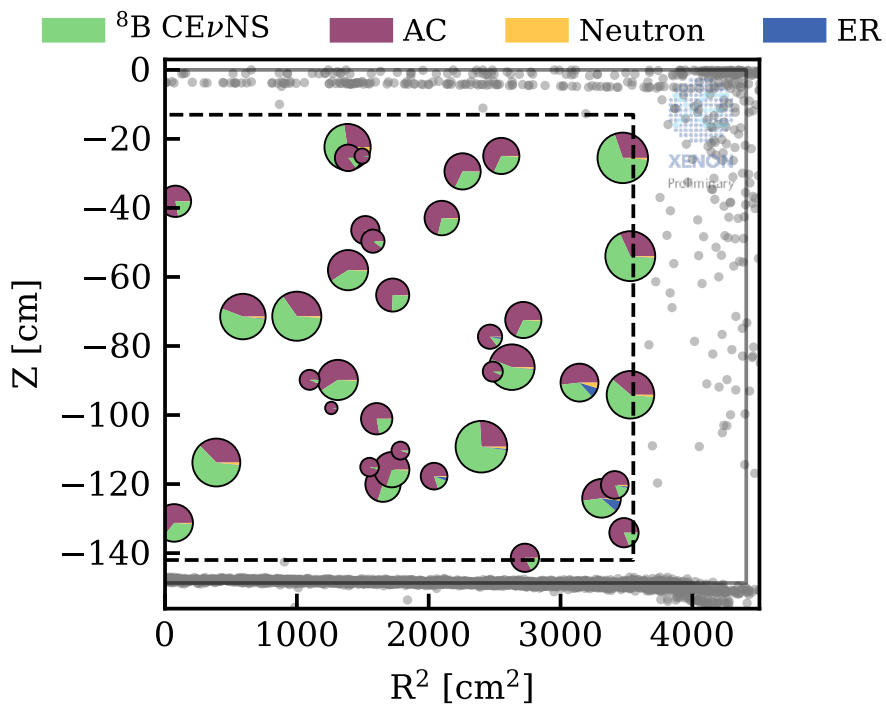


Additional event distributions - SR0 vs. SR1

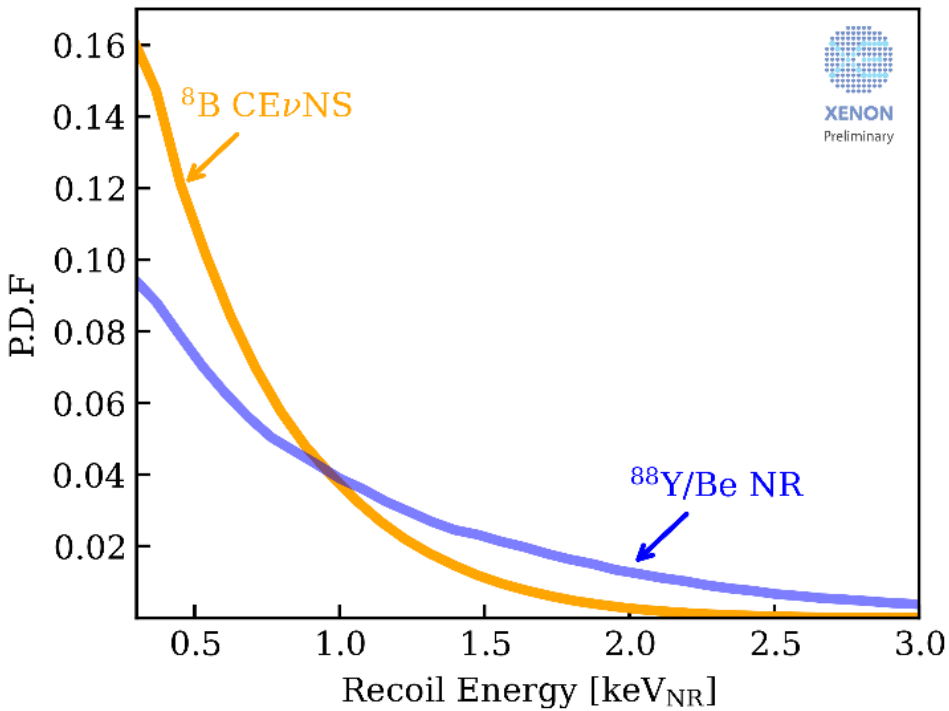


Additional event distributions - Event position



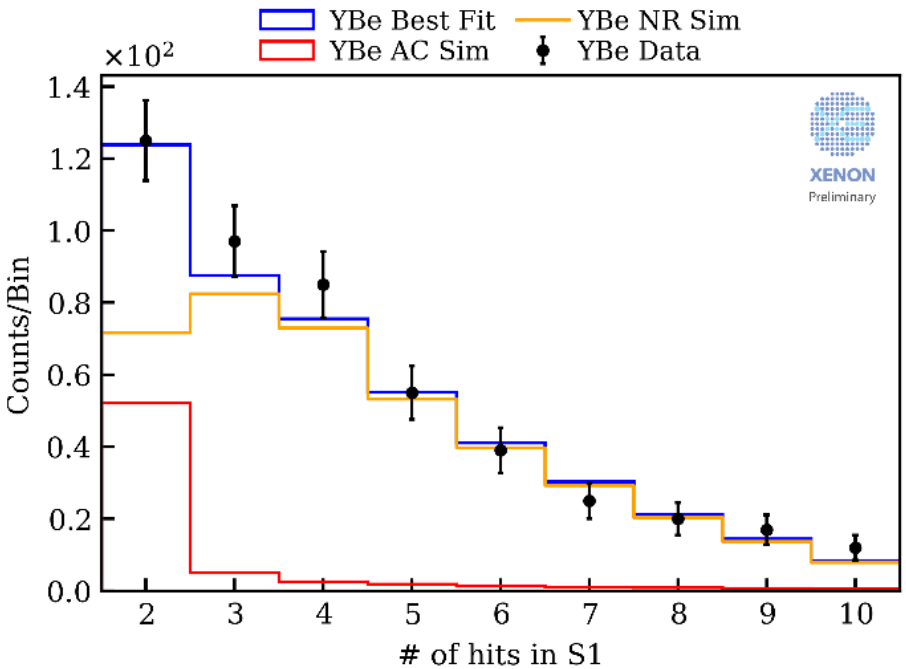


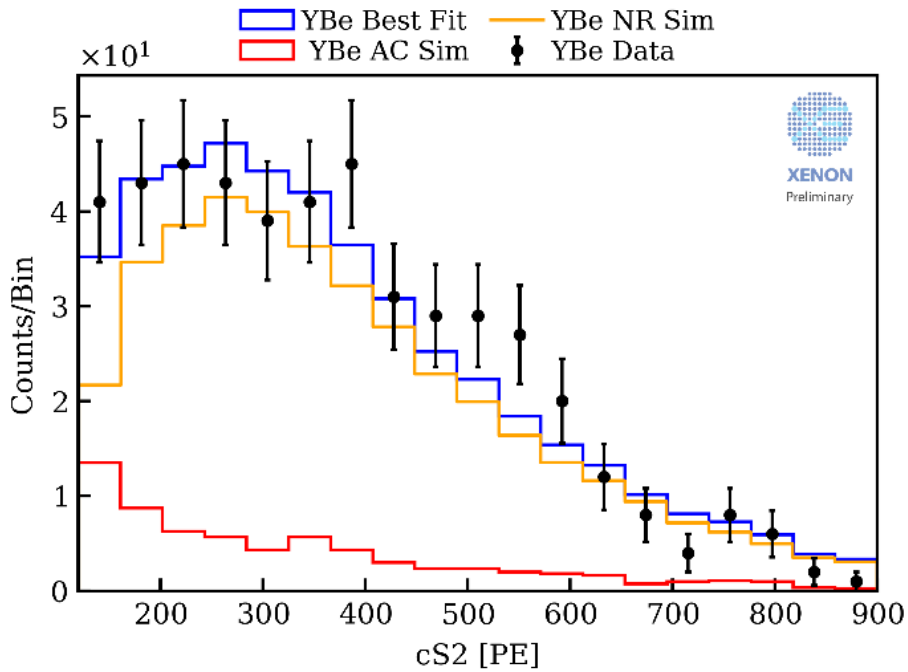
Calibration at lowest energies



- Calibration with an external YBe source
- ^{88}Y emits a high energy gamma: $\gamma + {}^{9}\mathrm{Be} \rightarrow \mathrm{n} + {}^{8}\mathrm{Be}$
- Delivers quasi-monoenergetic low energy neutrons ($\sim$ 152 keV)
- Similar recoil spectrum like ^{8}B neutrinos

Calibration at lowest energies

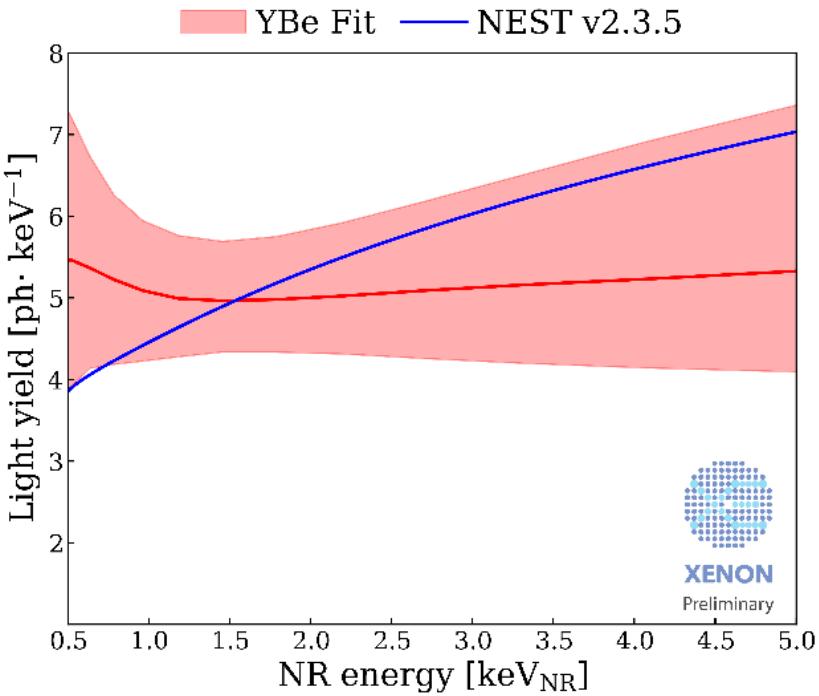


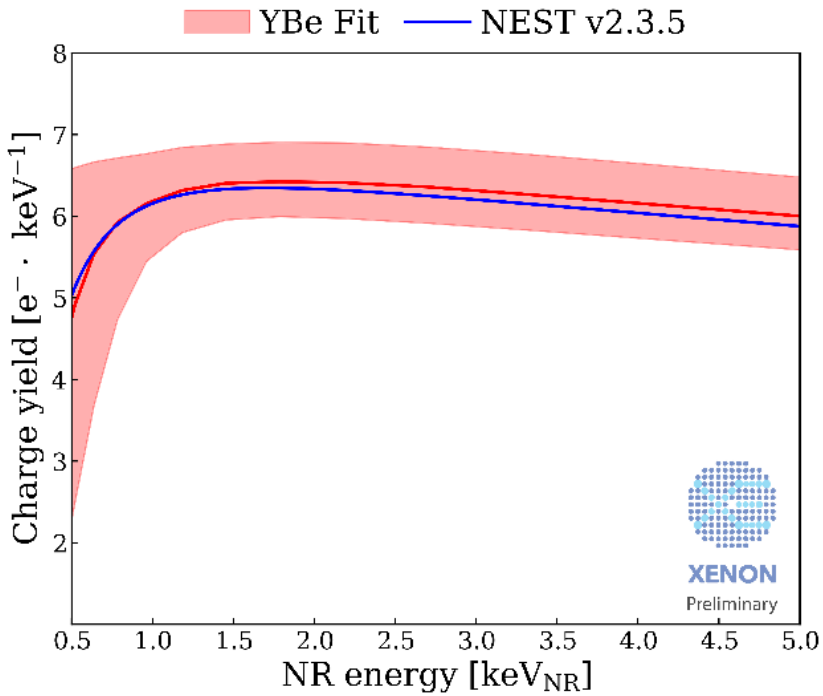


⇒ Constrain of light and charge yield at lowest energies

— Still, the uncertainty is the dominant systematic in the study

Calibration at lowest energies

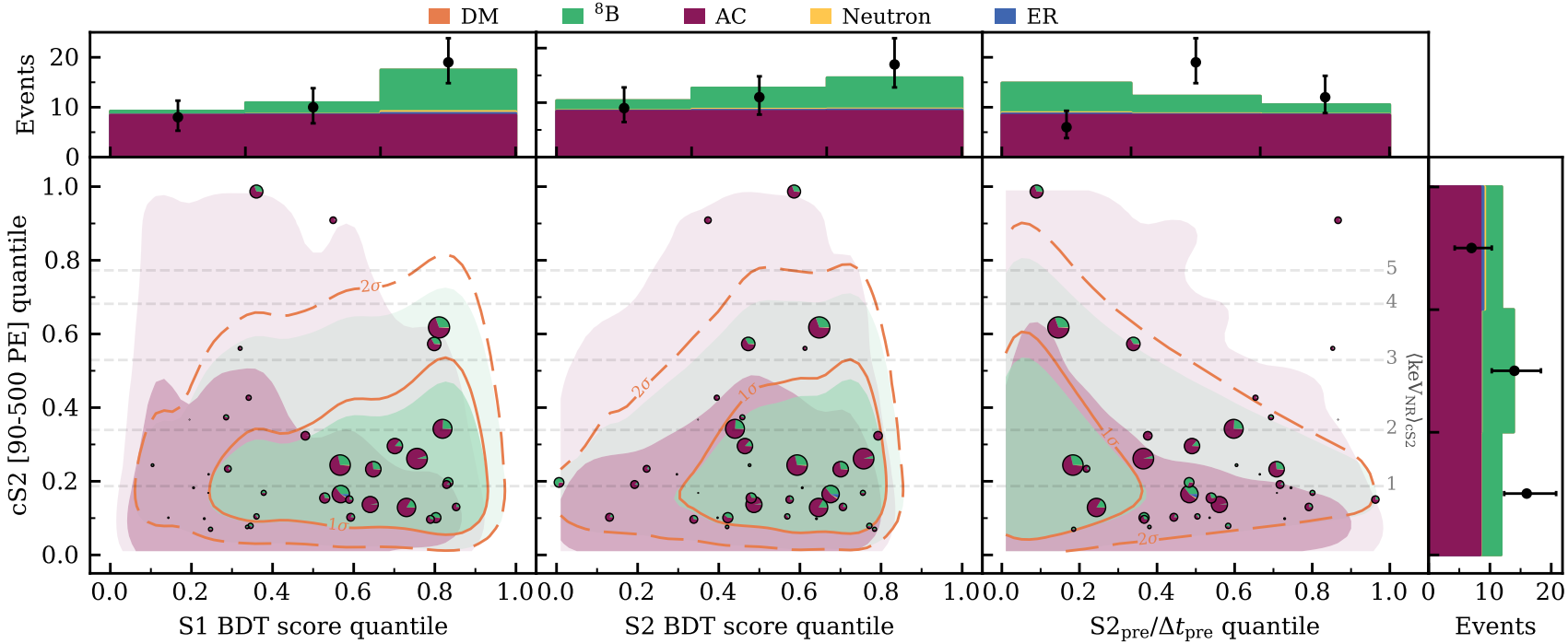


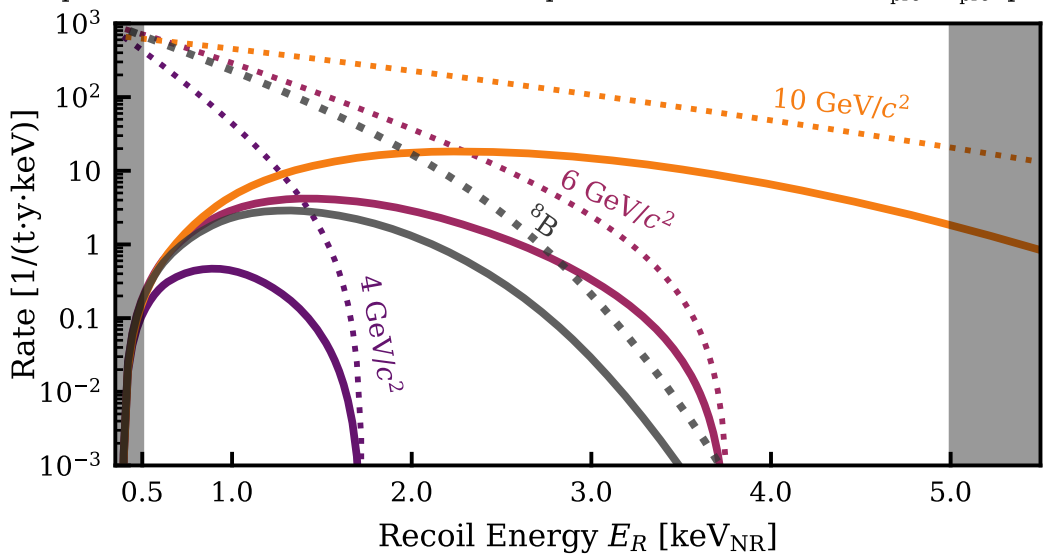


⇒ Constrain of light and charge yield at lowest energies

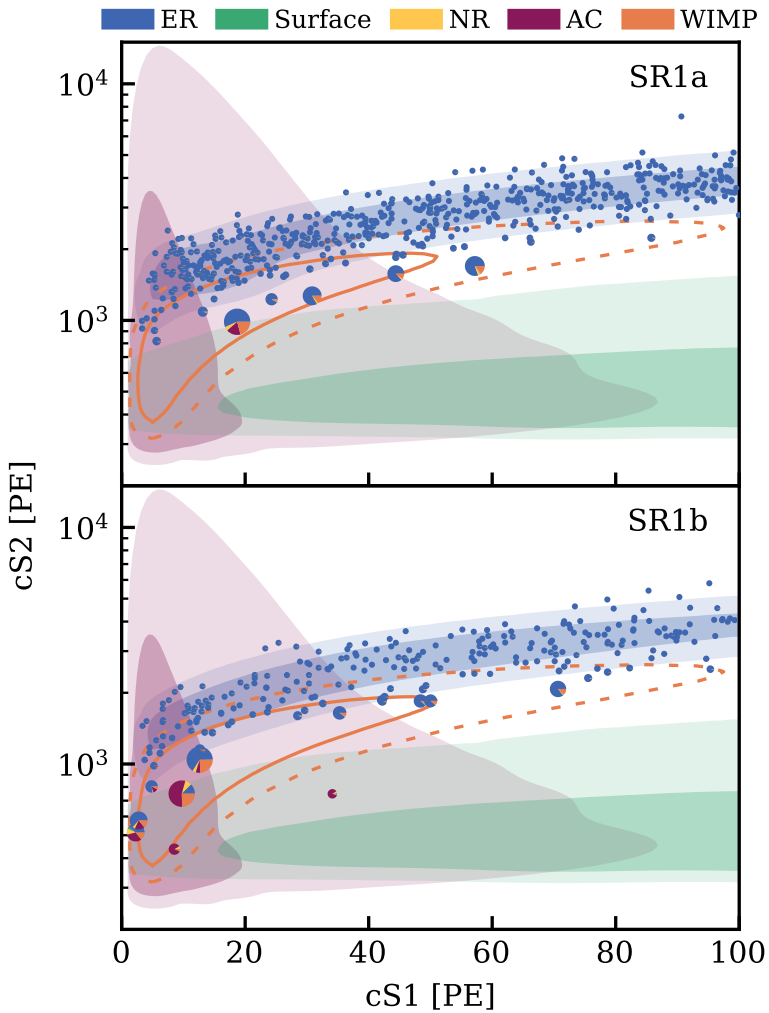
— Still, the uncertainty is the dominant systematic in the study

Additional event distributions - Analysis dimensions



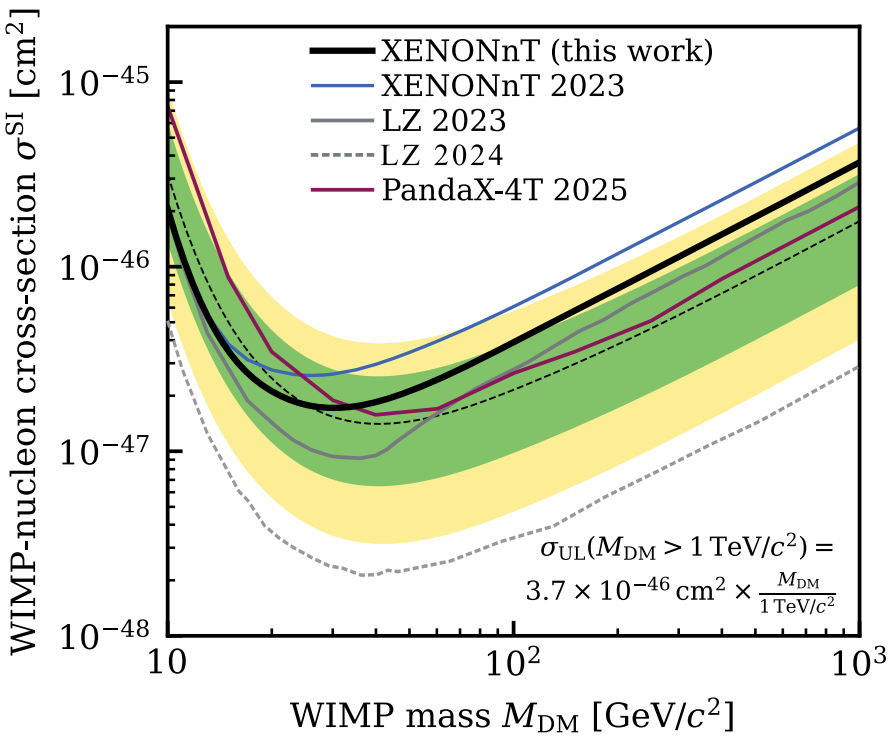


New: 3-fold WIMP search



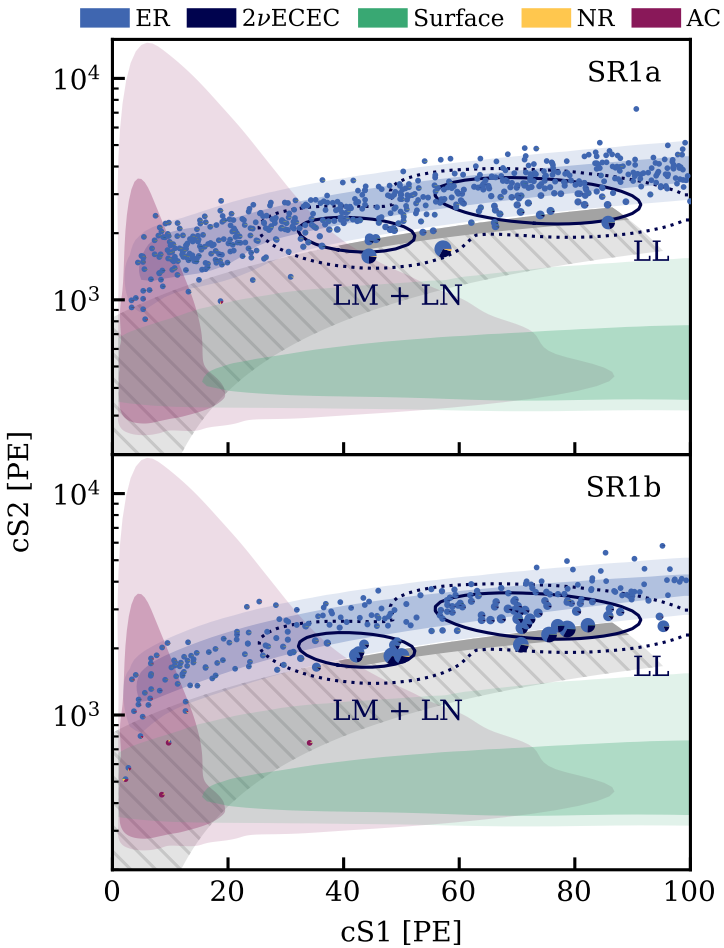
[2502.18005]

- Search for WIMP-nucelon interaction using the SR0+SR1 data (3.1 tonne × year)
- Several side-band and goodness of fit validations
- No excess over expected background observed ⇒Upper limit improved by ∼x1.5

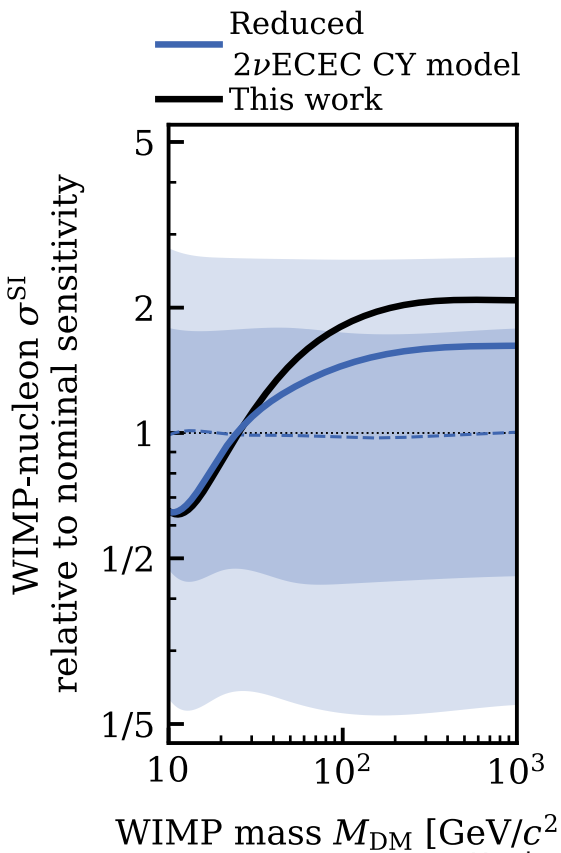


Charge yield of ^{124}Xe DEC

- Suppressed charge yield observed for **single** electron capture of ^{125}Xe
- New pre-print from LZ on the details: [2503.05679]
- **But:** No measurement available at the XENONnT electric field



- CY-suppression can "absorb" other background sources ⇒ bias limit downward.
- Perform a PLR test at unblinding. Insufficient evidence to reject the pure β model!



Best Fit:
$Q_{LL} = 0.8^{+0.08}_{-0.04} Q_\beta, Q_{LM} = 0.72^{+0.11}_{-0.04} Q_\beta$