XENON

Latest results from the XENONnT experiment

Dr. Maxime Pierre

On behalf of the XENON collaboration

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GDR DUPhy - Lyon

11th of October, 2024

XENON TPC in a nutshell

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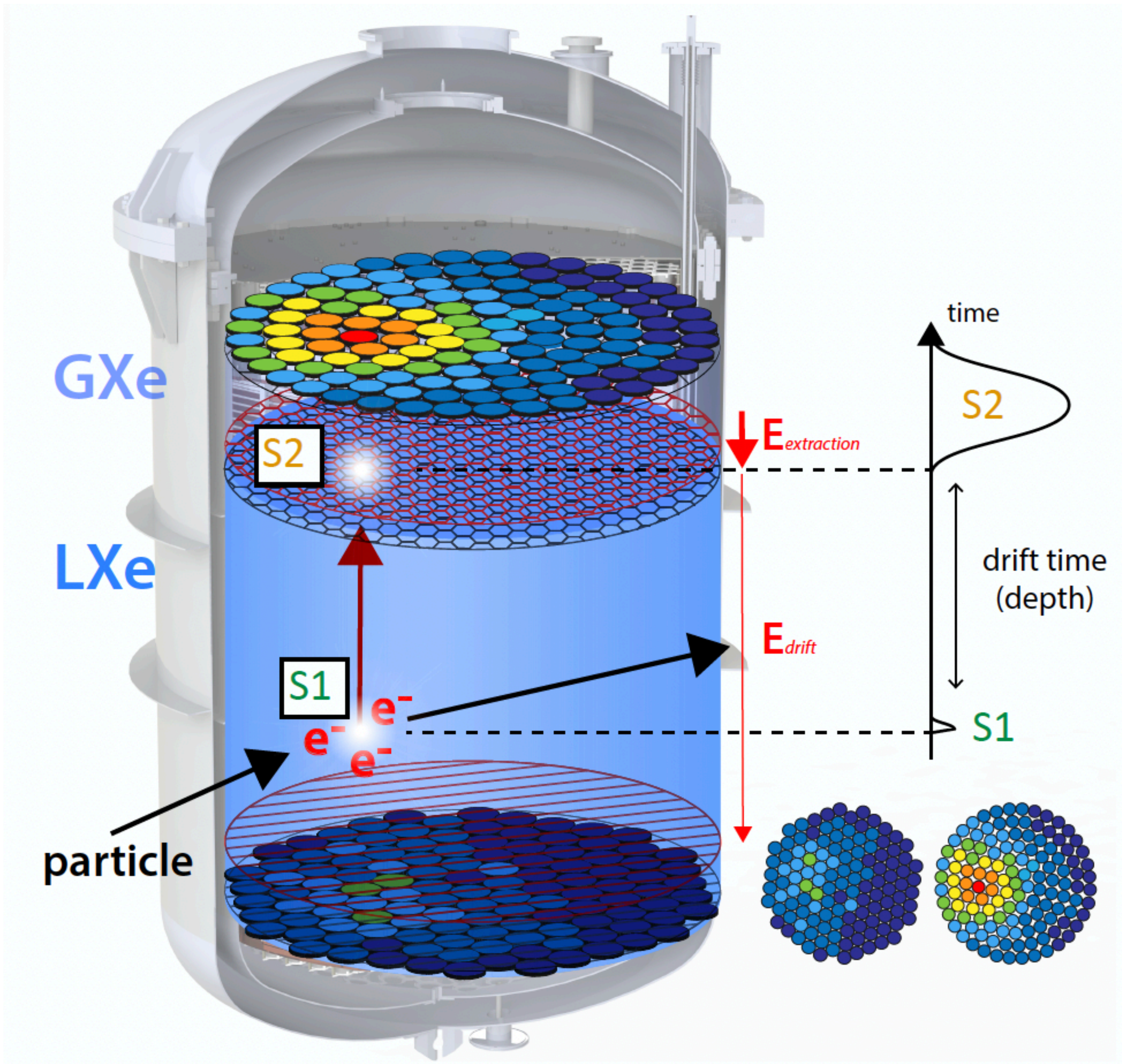

Light and Charge readout

- Prompt scintillation signal (**S1**)
- Secondary proportional scintillation signal in GXe from drifted electrons (**S2**)

Event reconstruction

- **3D Position:**
  - **Z** from drift time
  - (**X**, **Y**) from PMTs hit pattern
- **Energy** → $E = W \cdot (n_{ph} + n_e)$

Particle discrimination

- Interaction type **Nuclear Recoil (NR)**/**Electronic Recoil (ER)** through **S1**/**S2** ratio

$$\left(\frac{S2}{S1}\right)_{NR} < \left(\frac{S2}{S1}\right)_{ER}$$

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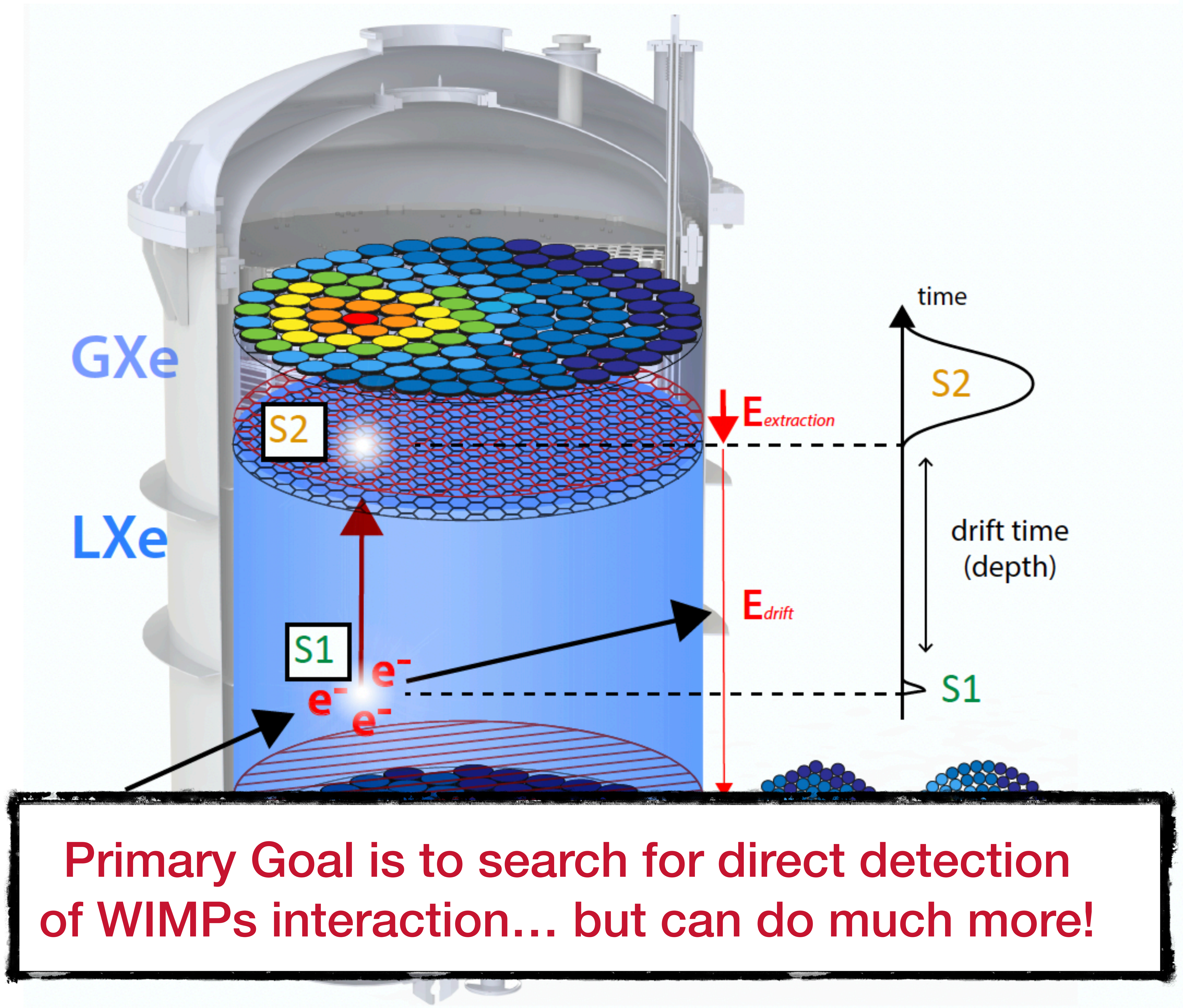

Primary Goal is to search for direct detection of WIMPs interaction… but can do much more!

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First Science Run -SR0- Results

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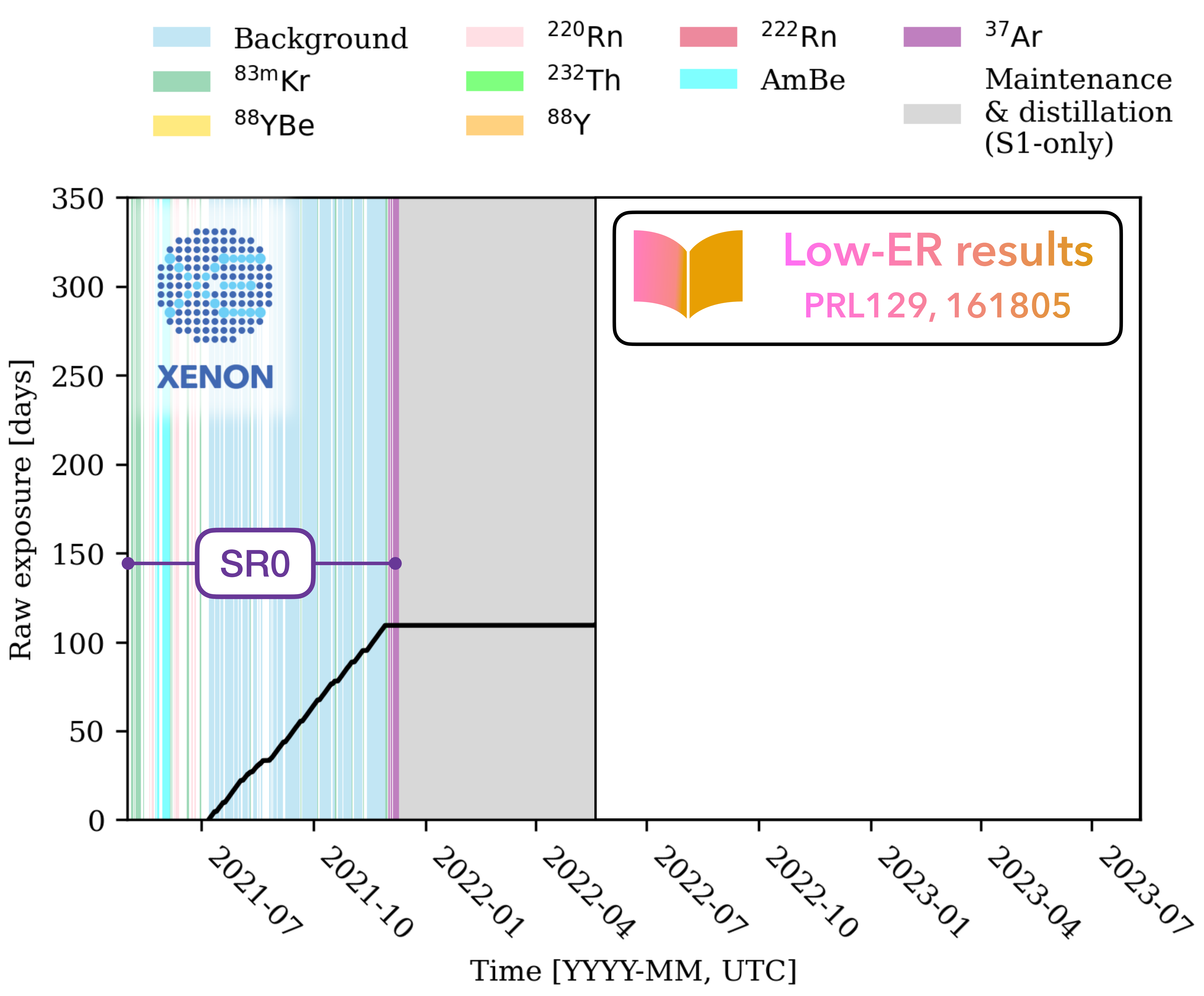

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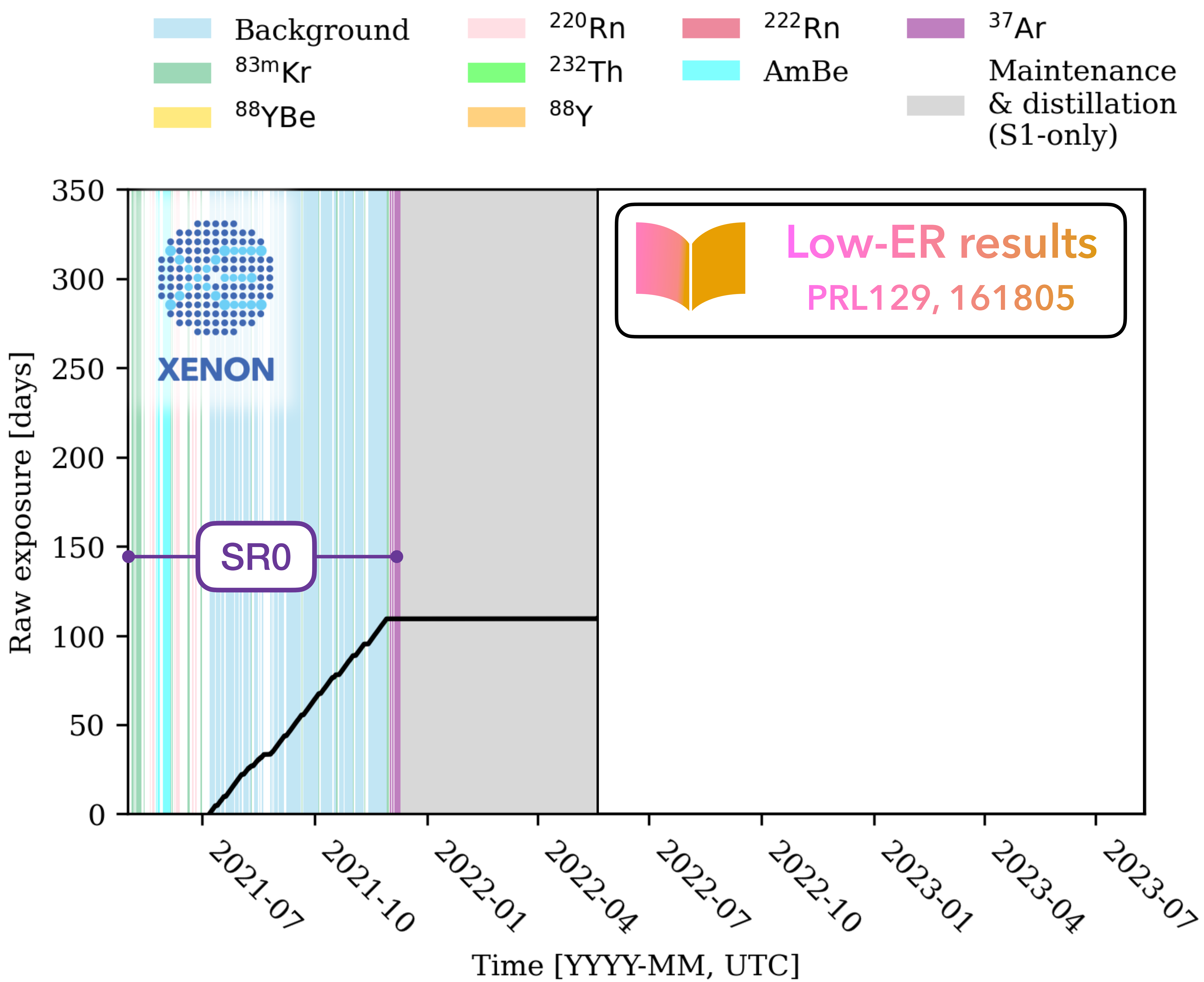

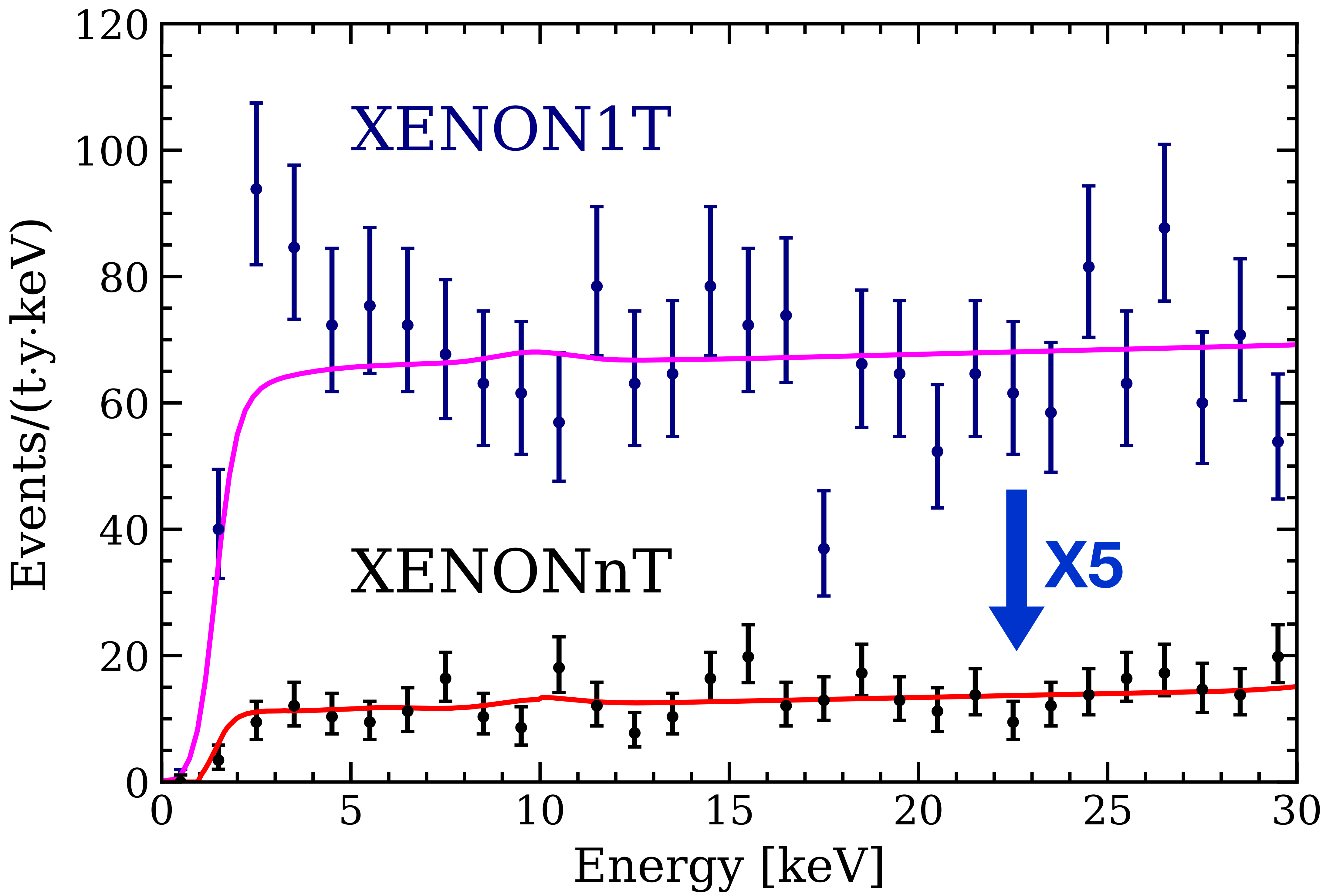

- Excluded XENON1T ER excess at ~4σ
  - ➡ Stringent limit with non-astronomical observations on solar axions, neutrino magnetic moment, boson DM

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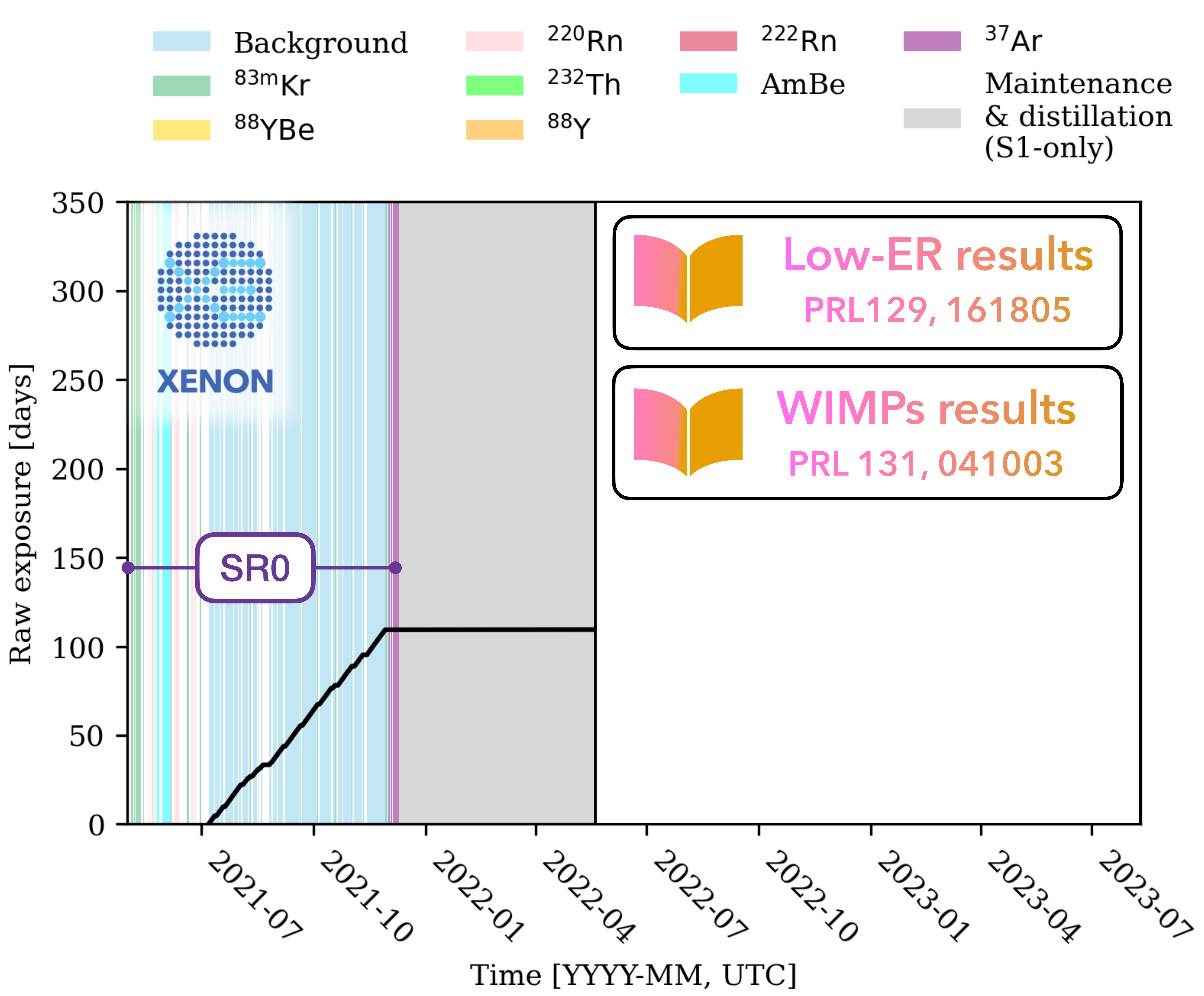
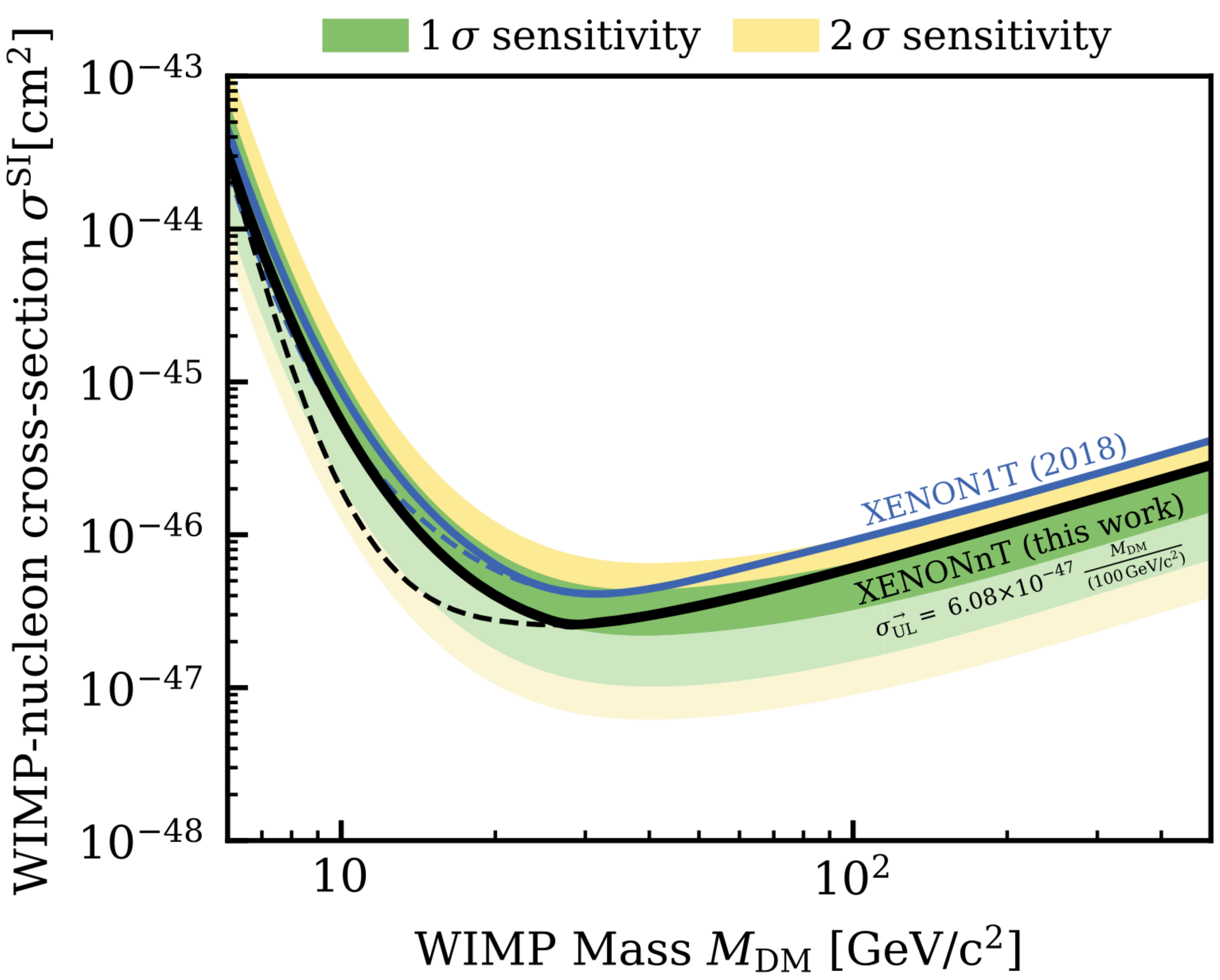


Low-ER results
PRL129, 161805

WIMPs results
PRL 131, 041003



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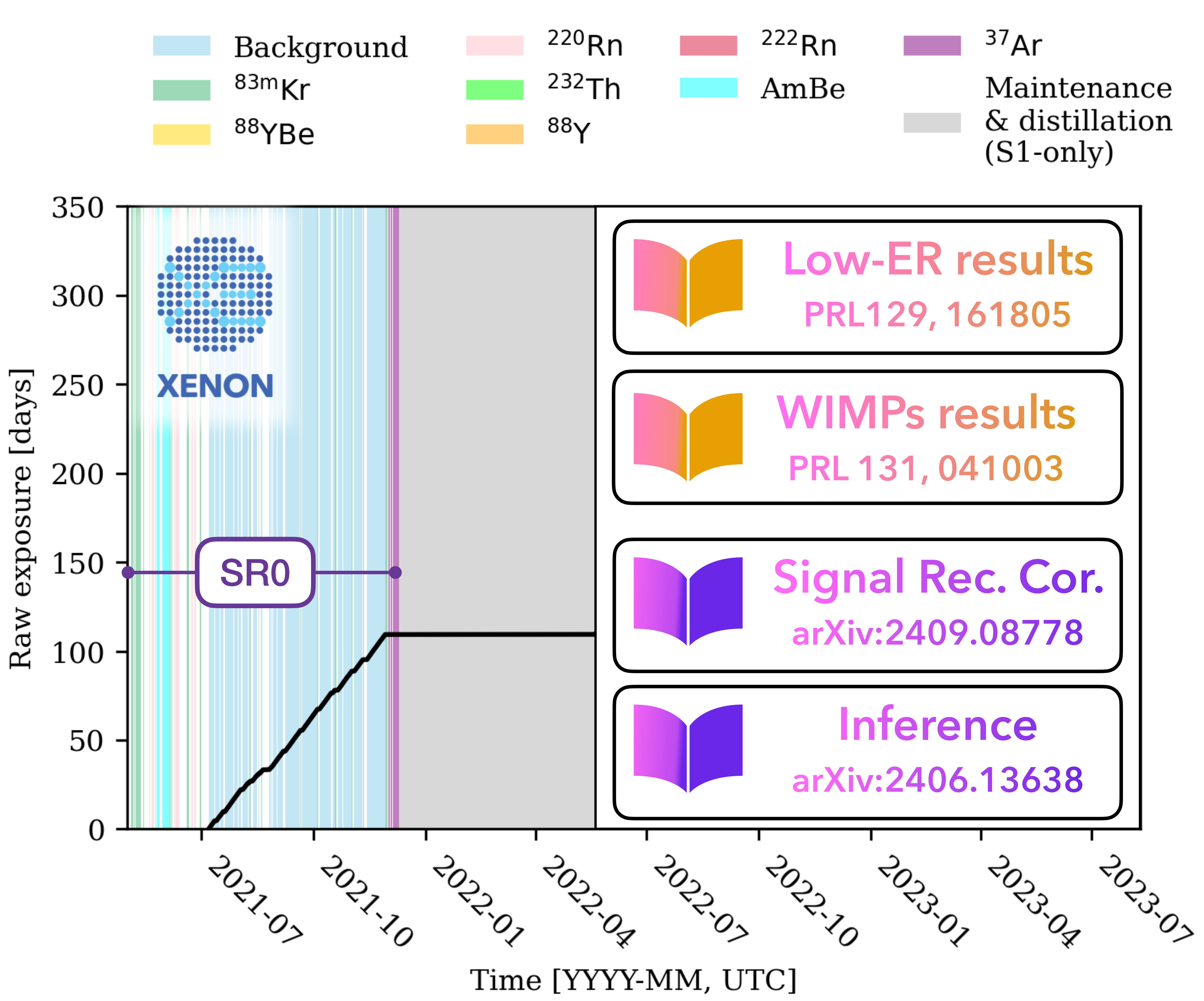

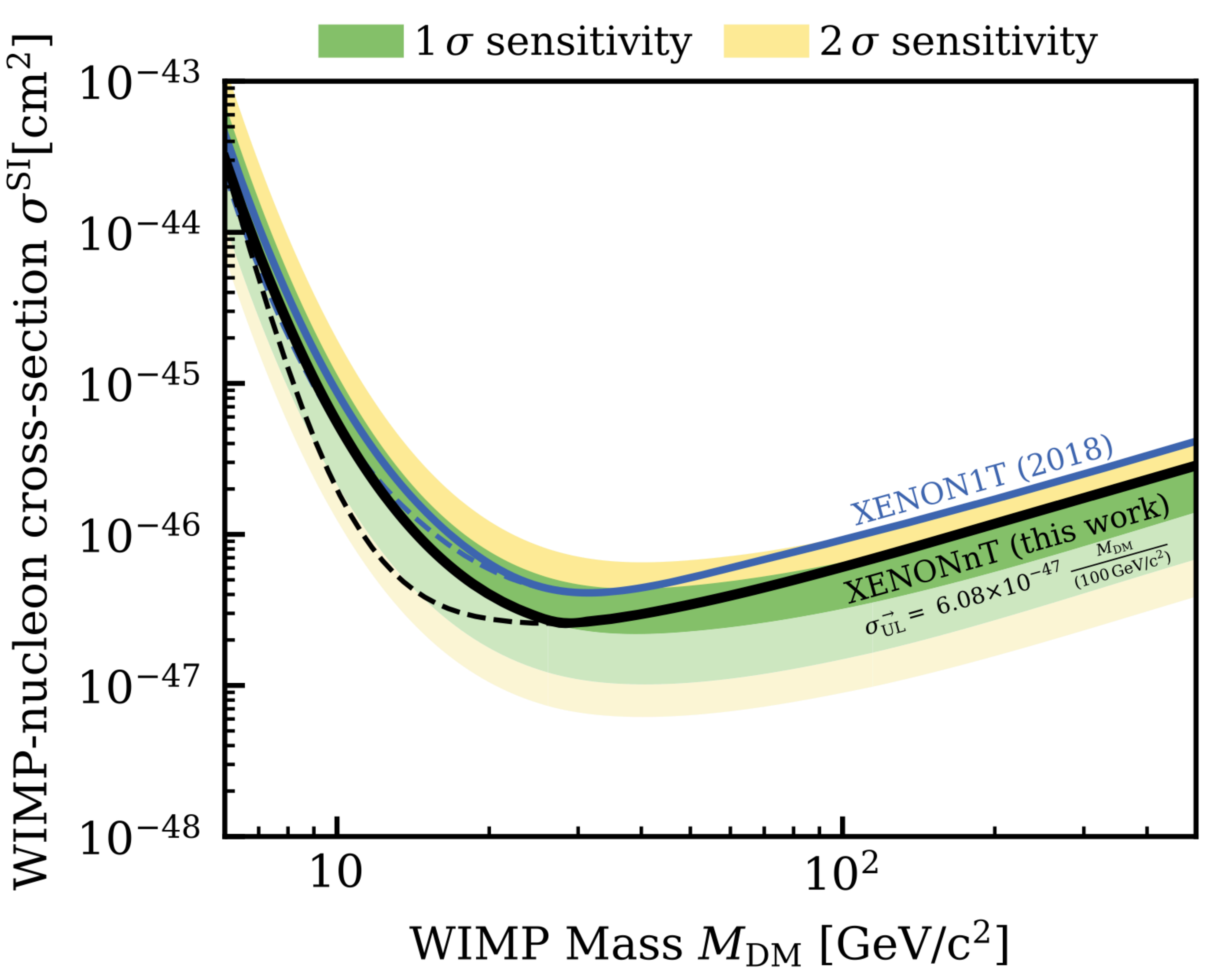

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New Science Run: SR1

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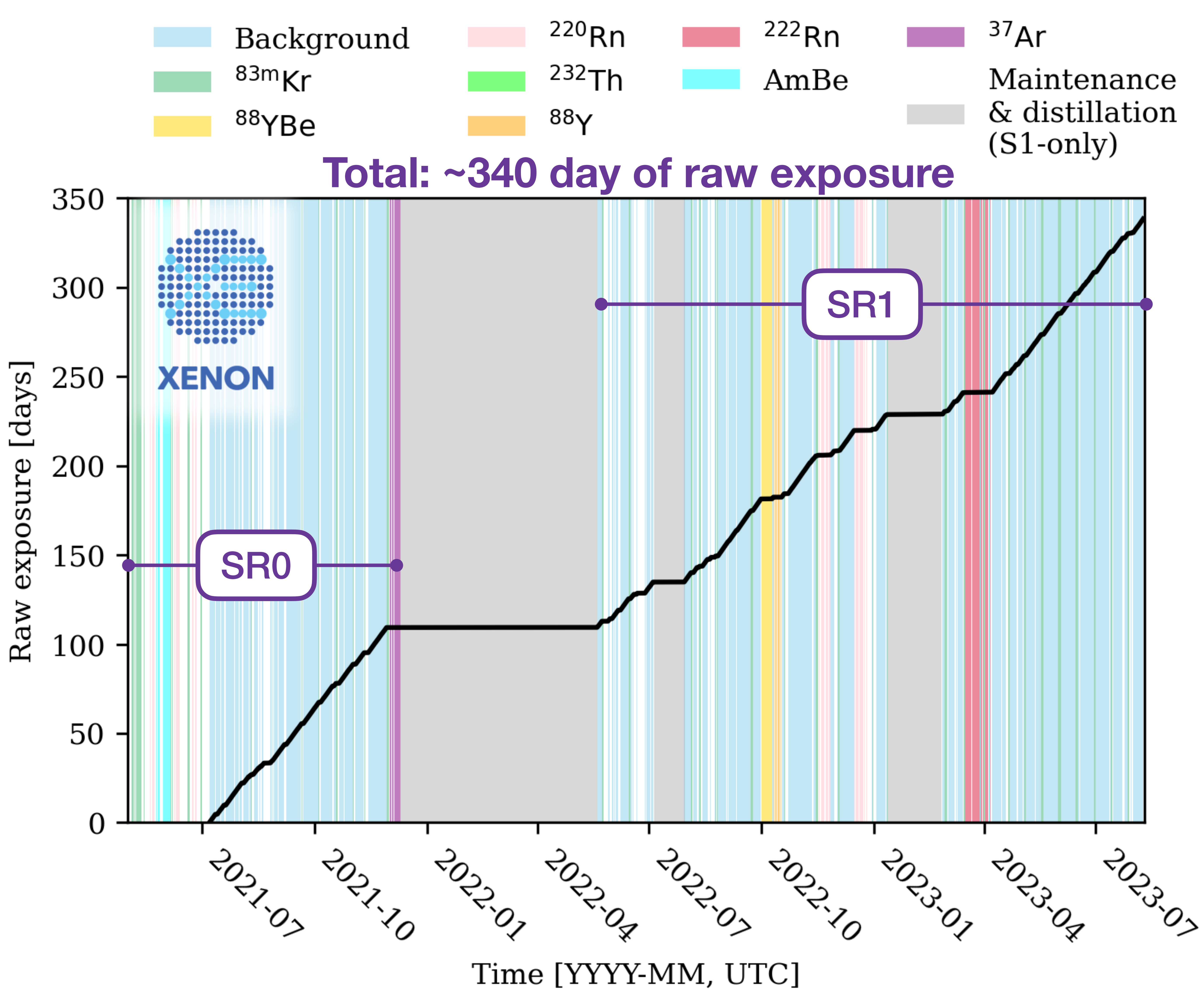
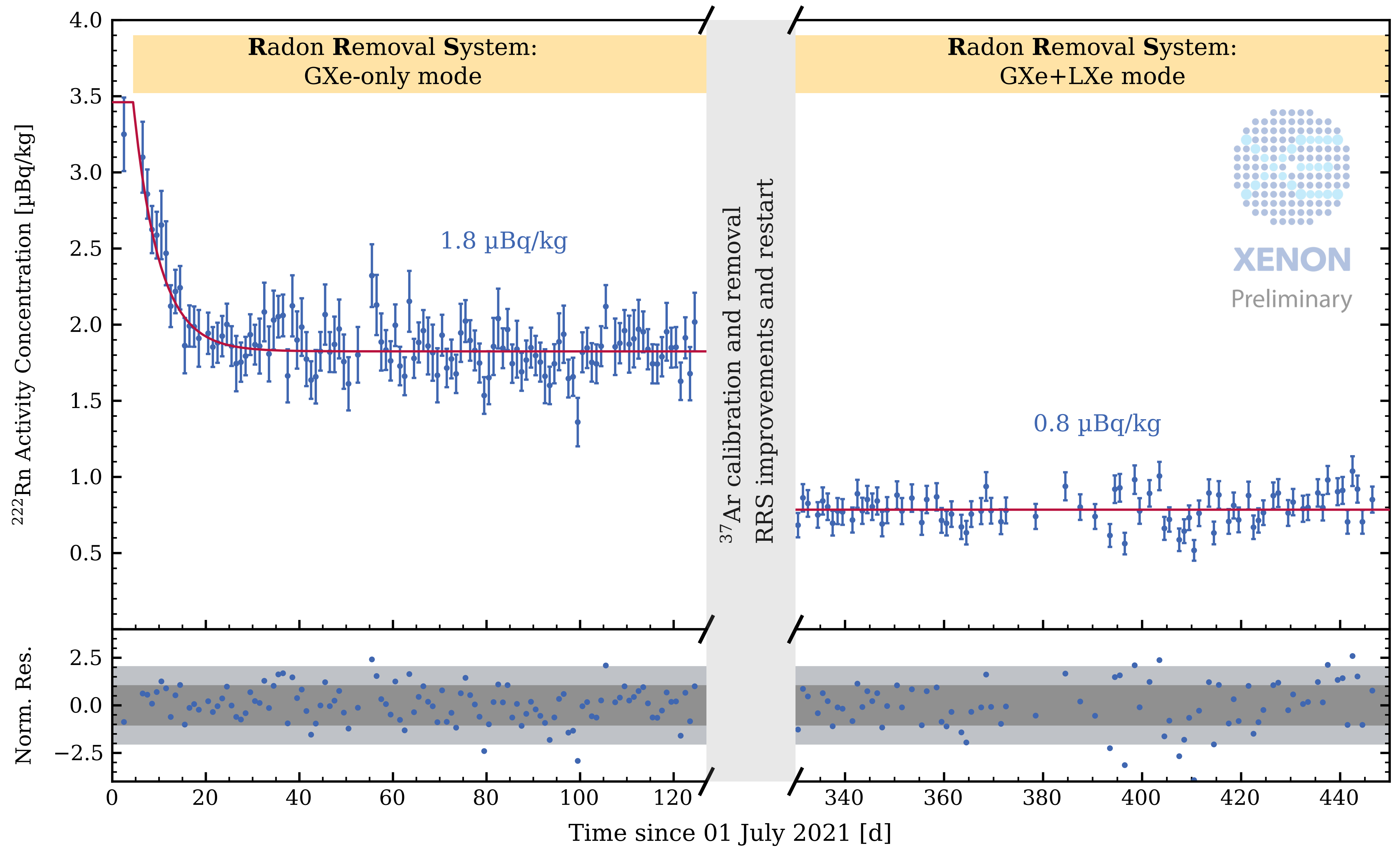


Science Run 1 Highlights

- Radon suppression milestone: distillation with combined gaseous and liquid xenon flow



< 1 μBq/kg

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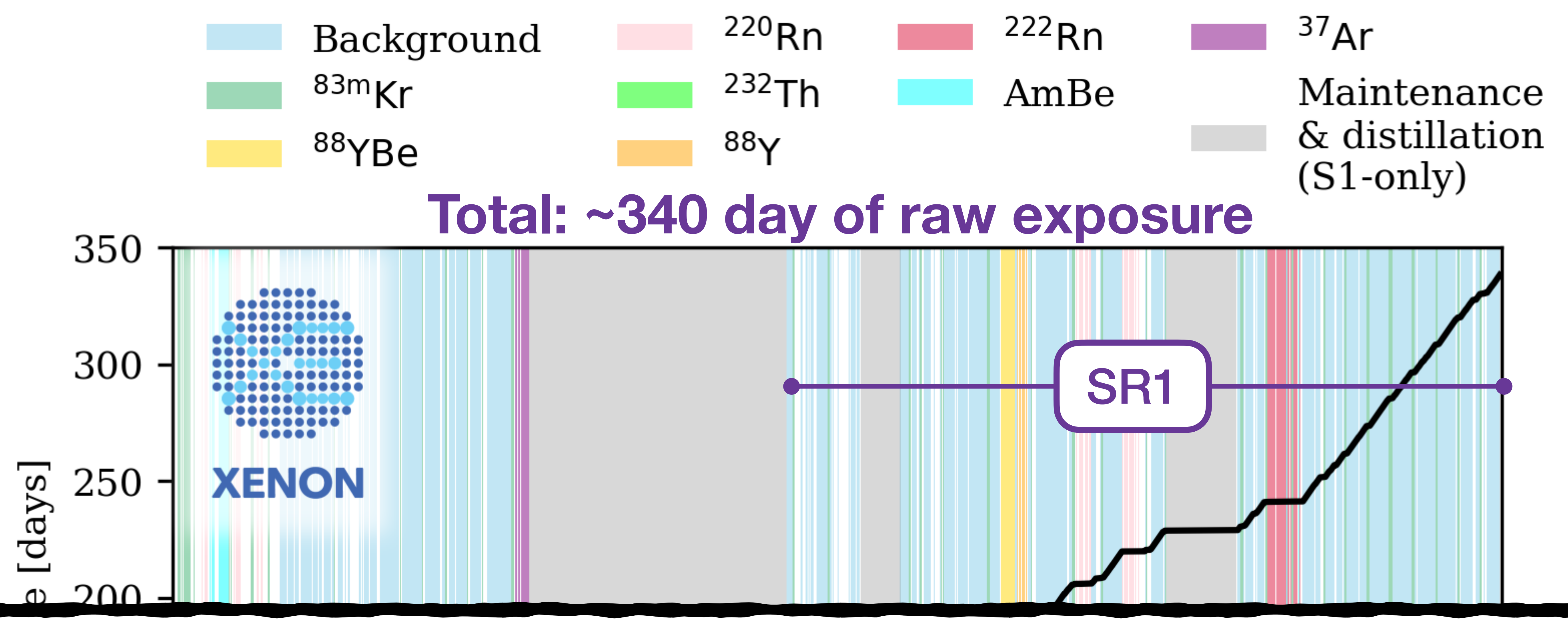

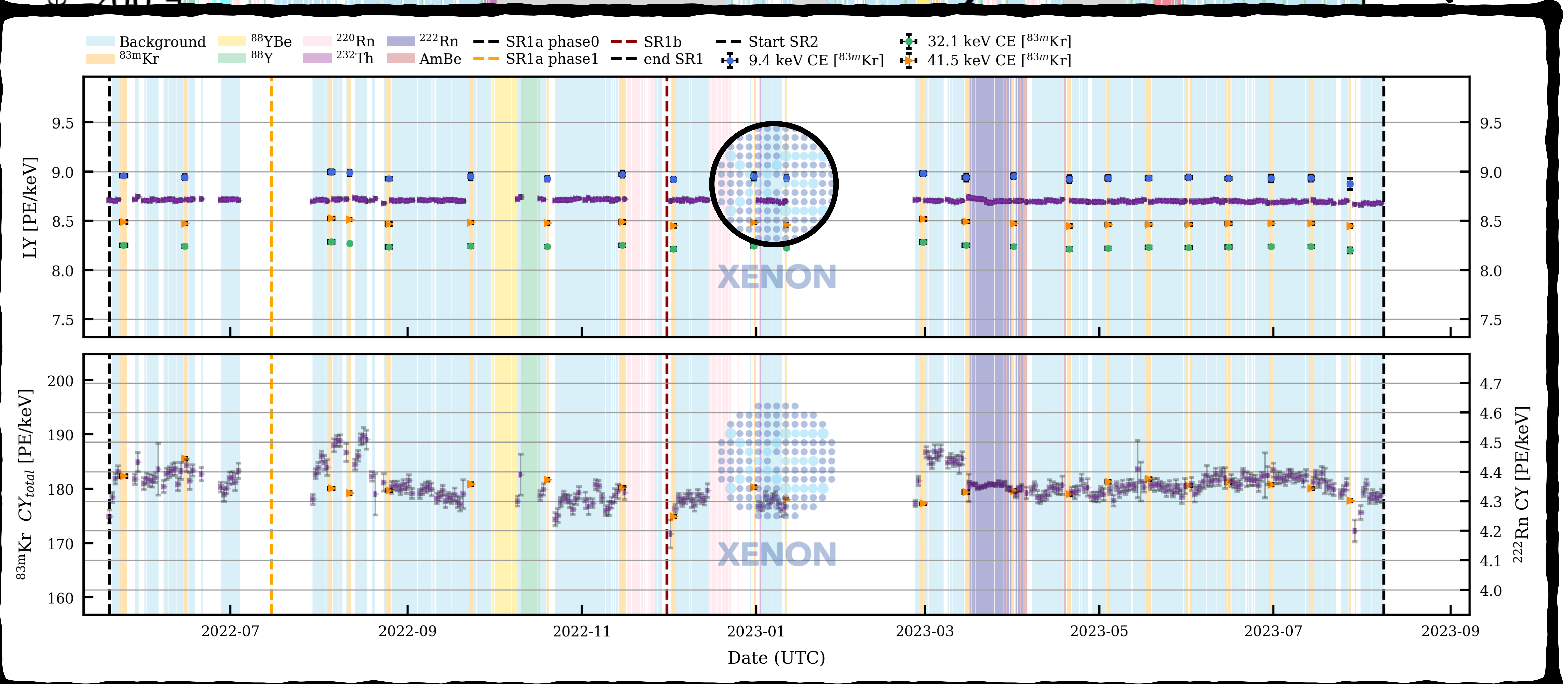

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- Radon suppression milestone: distillation with combined gaseous and liquid xenon flow
- Stable detector response: achieving <0.3% (1.1%) variation in Light and Charge Yields

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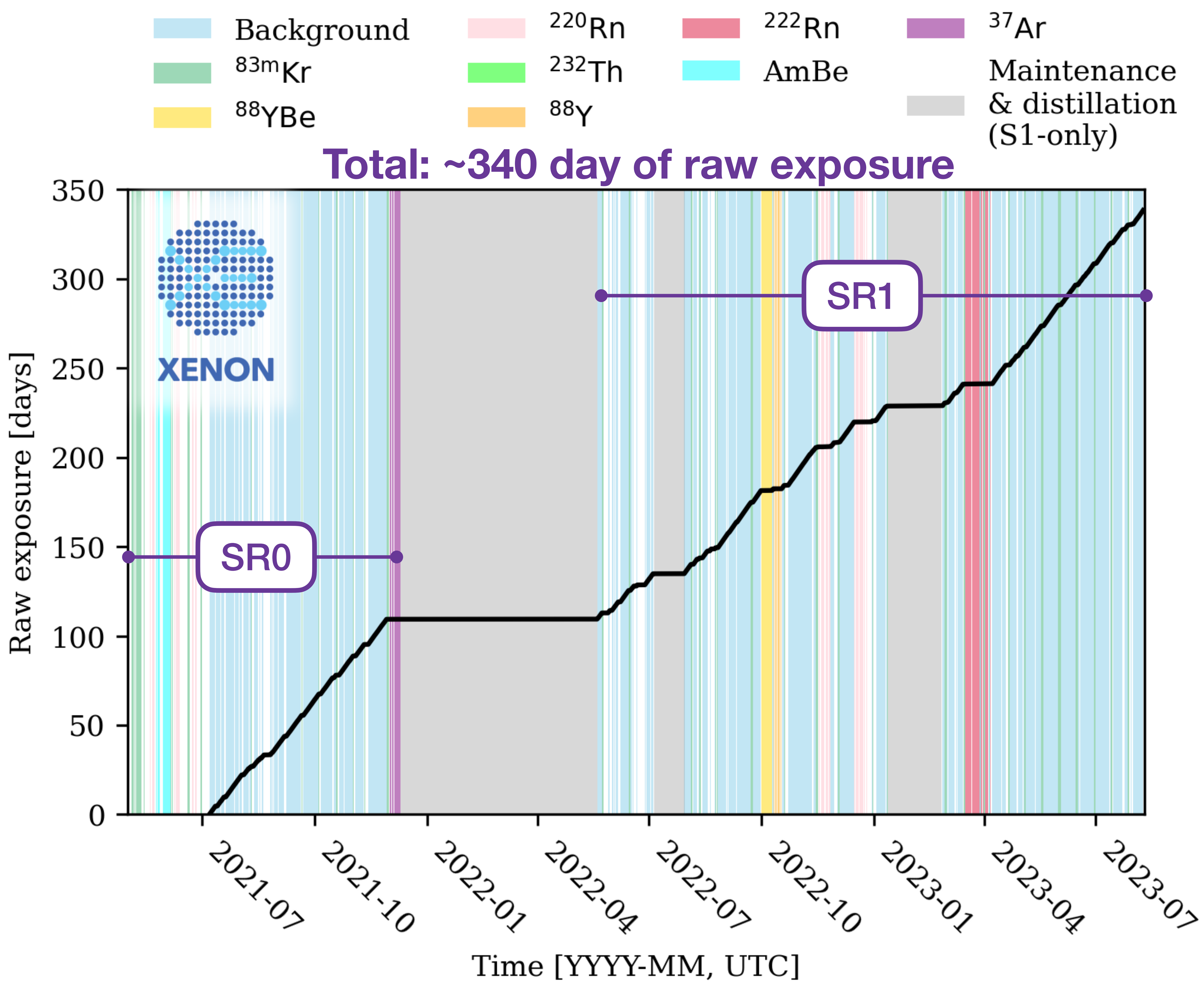

Science Run 1 Highlights

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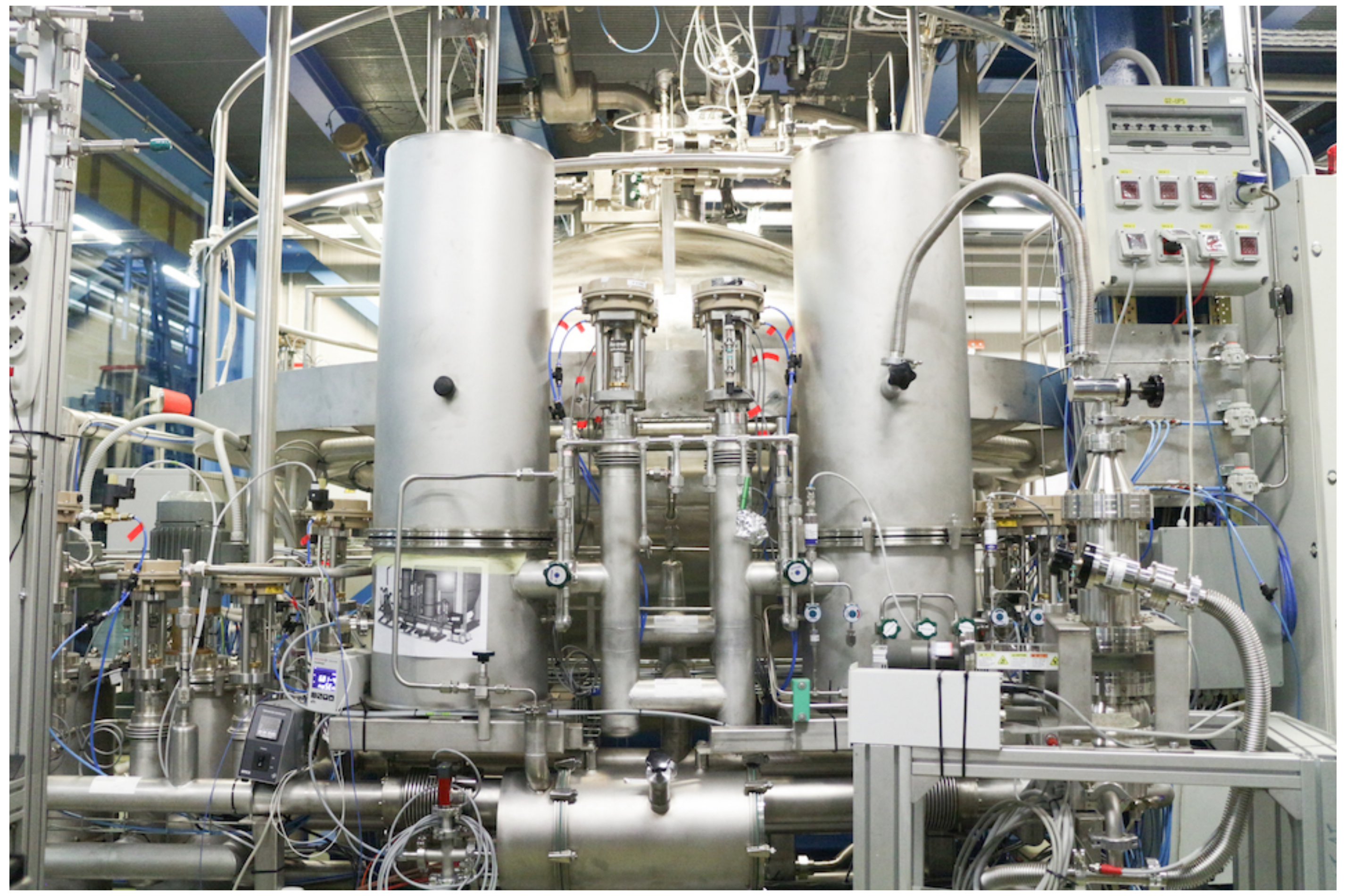
- Excellent electron lifetime ~$\mathcal{O}(10)$ ms



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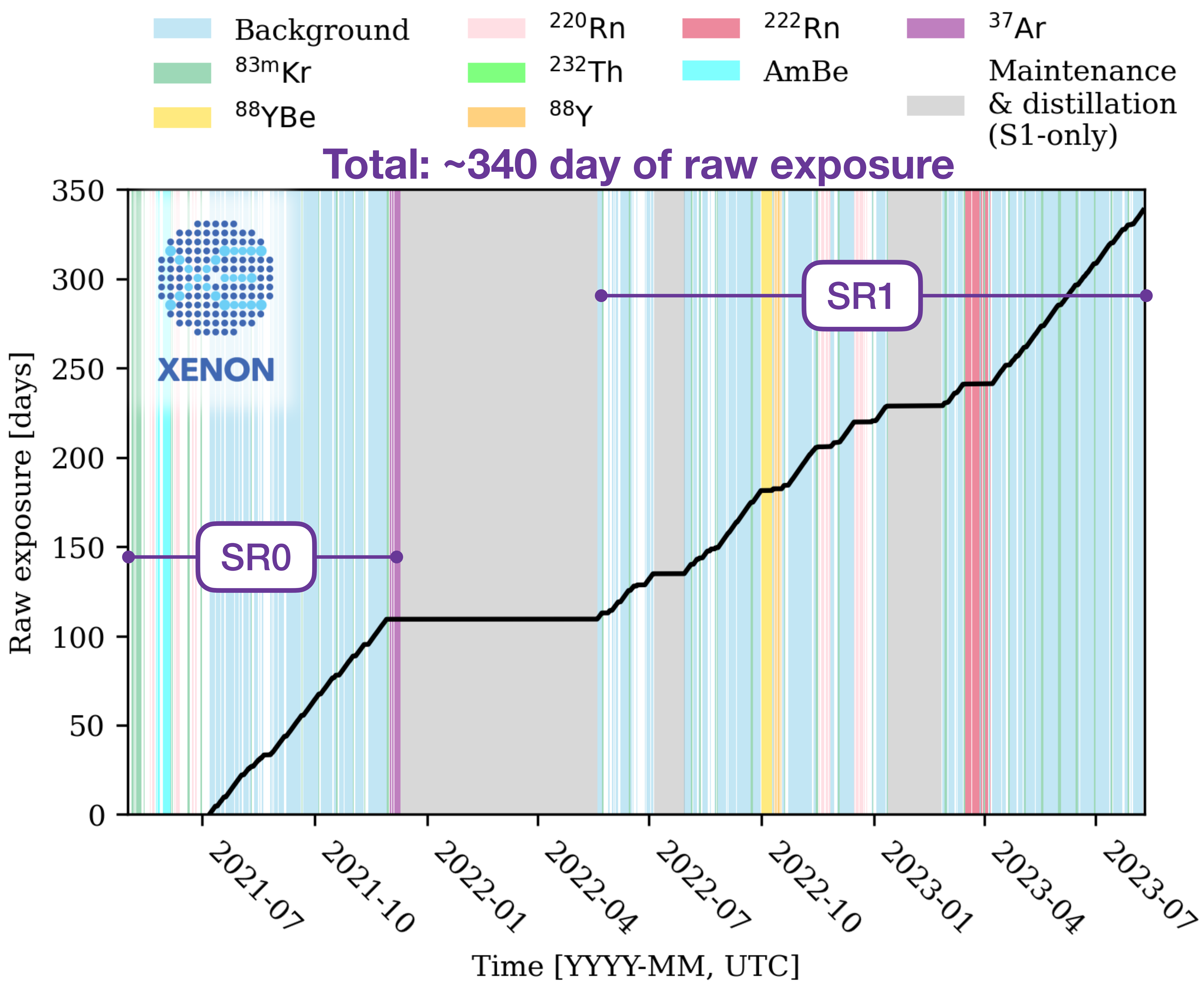

Science Run 1 Highlights

- Radon suppression milestone: distillation with combined gaseous and liquid xenon flow
- Stable detector response: achieving <0.3% (1.1%) variation in Light and Charge Yields
- Excellent electron lifetime ~$\mathcal{O}(10)$ ms
- Calibration plan follows SR0 strategy with three new features:
  - ➡ New ER calibration source: ^{222}Rn (β) and ^{232}Th (ɣ)
  - ➡ New low-energy NR calibration source: ^{88}YBe

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Next science case focus?

New Result from XENONnT

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XENON

Entering the Neutrino Fog

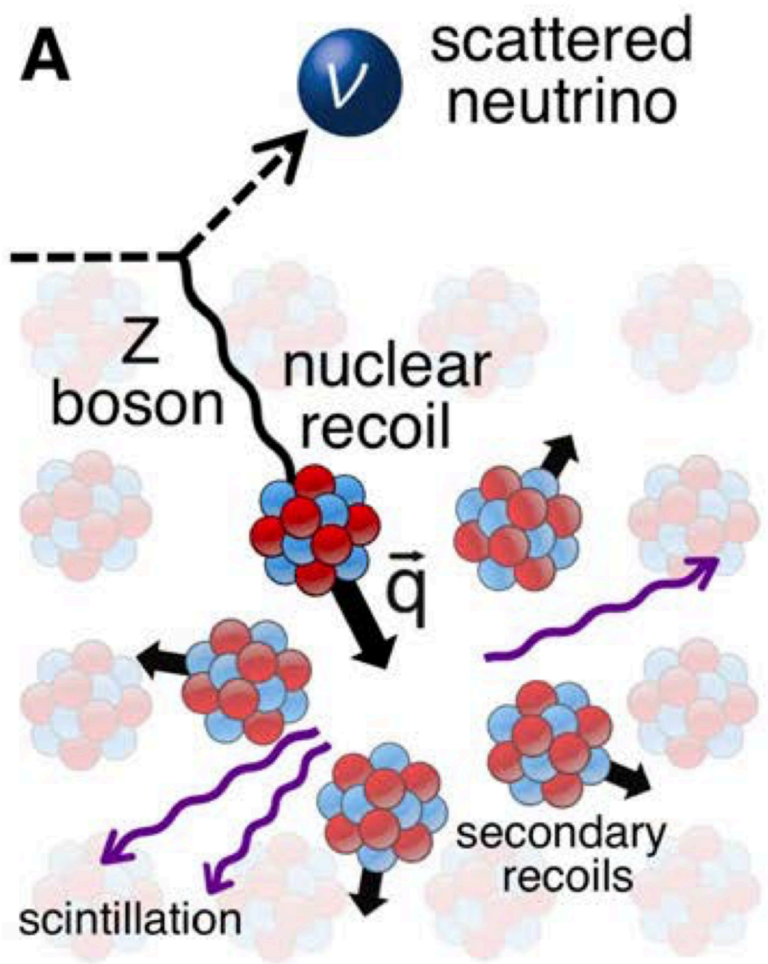
Coherent **E**lastic **n**eutrino **N**ucleus **S**cattering

Never measured in a DM direct detection experiment
Never measured in a xenon target
Never measured from astrophysical source

CEνNS search in XENON:

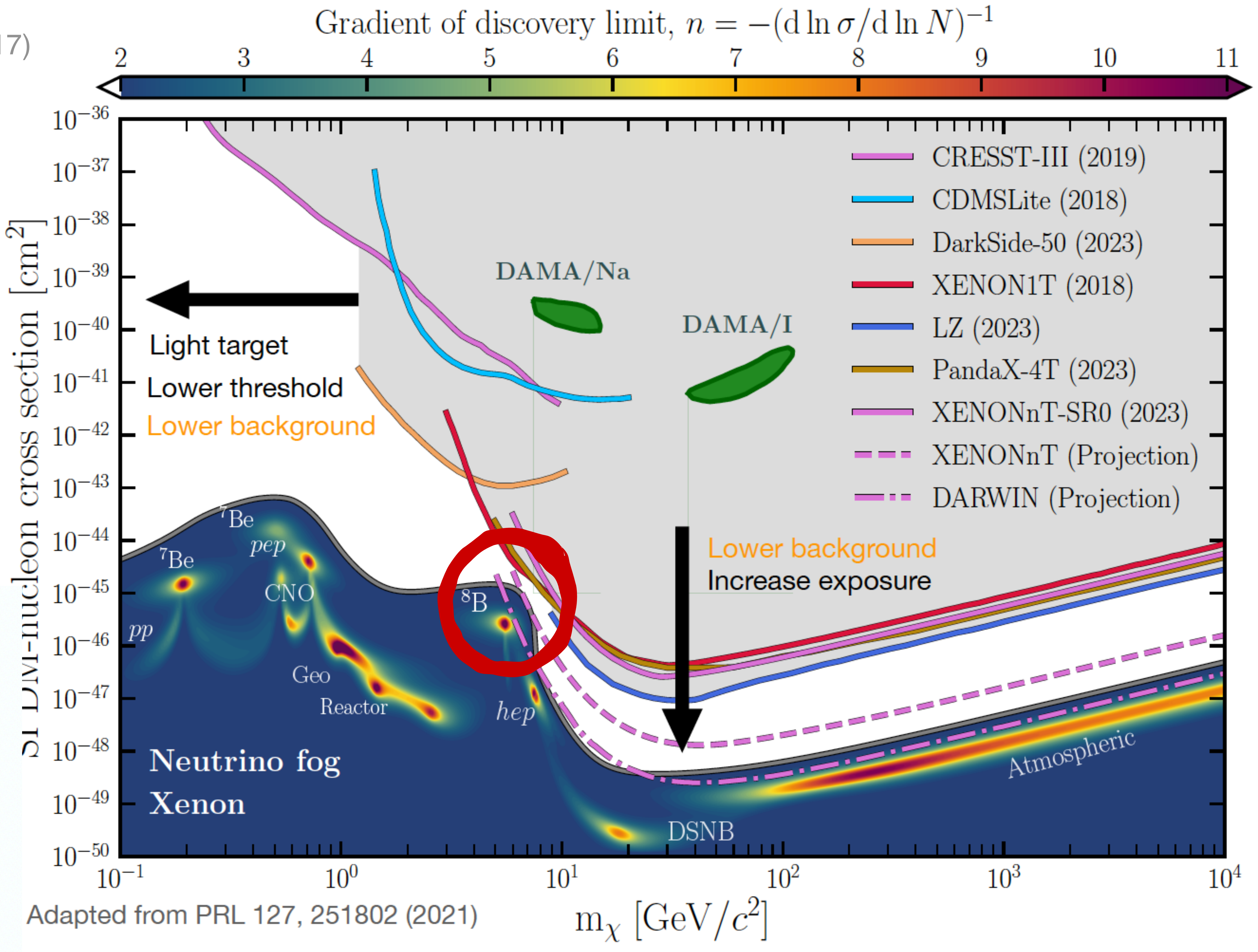
- Nearly indistinguishable from a ~6 GeV WIMP with σ_{SI} = 4.4 x 10^{-45} cm^2
- **Boost in cross section from coherent effect…but low energy recoil (< 1.5 keV$_{NR}$ in LXe)**

D. Akimov et al, Science 357 (2017)



$$\frac{d\sigma\left(E_\nu, E_R\right)}{dE_R} \propto N^2$$

N: Number of neutrons
→ Xe suitable for CEvNS



Adapted from PRL 127, 251802 (2021)

^{8}B CEνNS - Signal Region of Interest

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Boost sensitivity by lowering our energy threshold

- ^{8}B event rate in the conventional WIMP “3-fold analysis" (SR0): ~1% detection efficiency → 0.2 events / (t x yr)
- Lowering our S1 and S2 threshold → improve our expected event rate to 3.7(3.3) events / (t x yr) in SR0(1)

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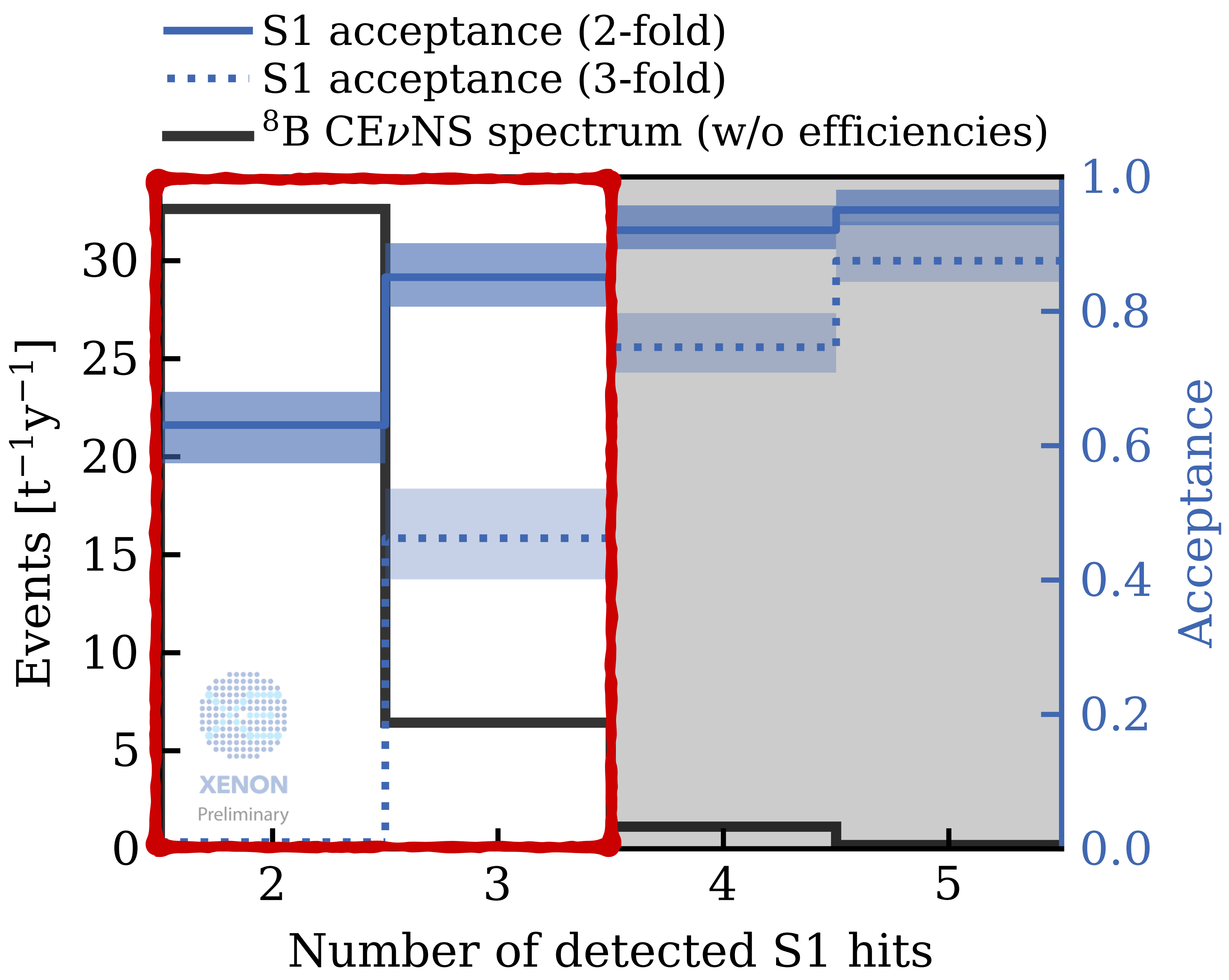
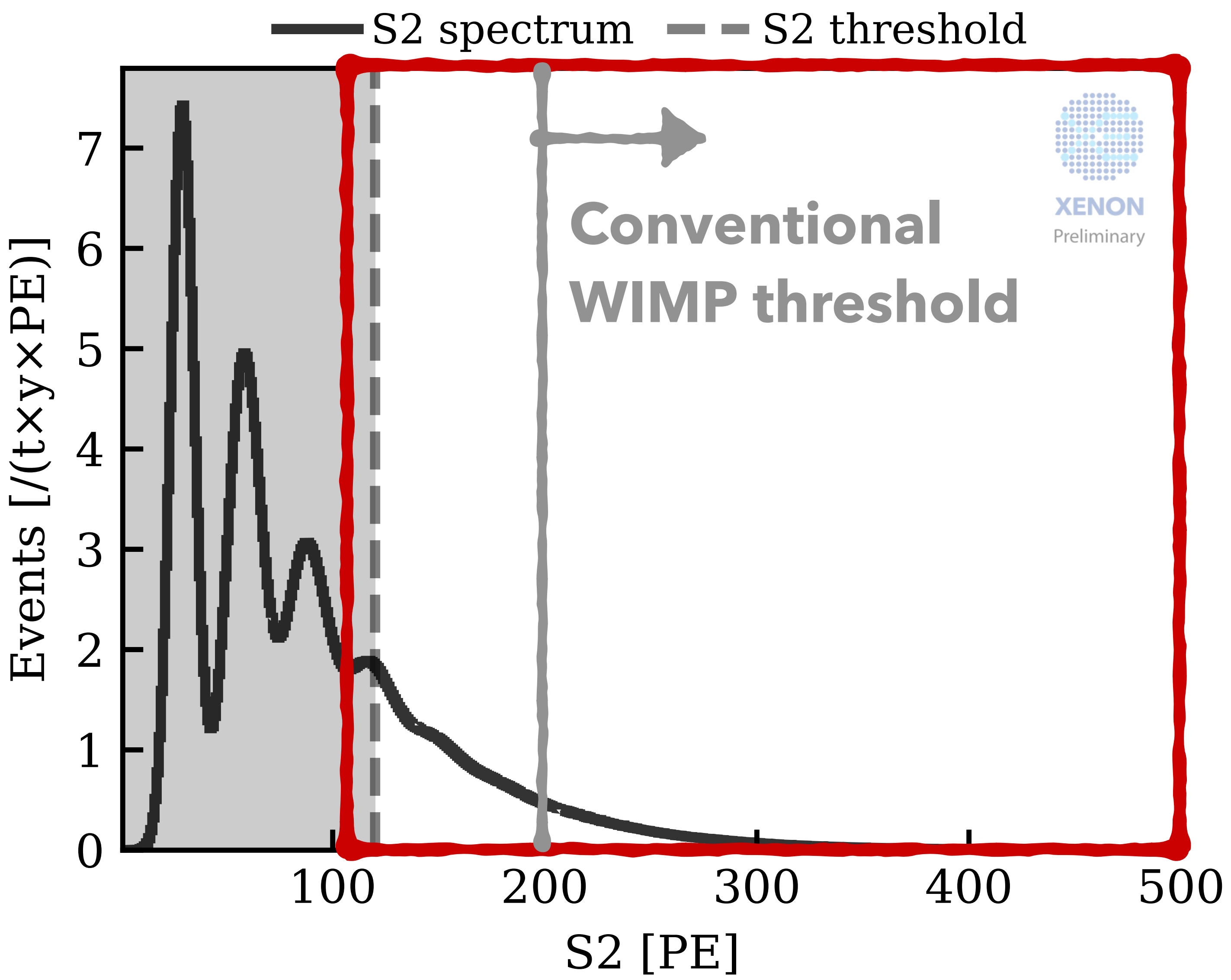
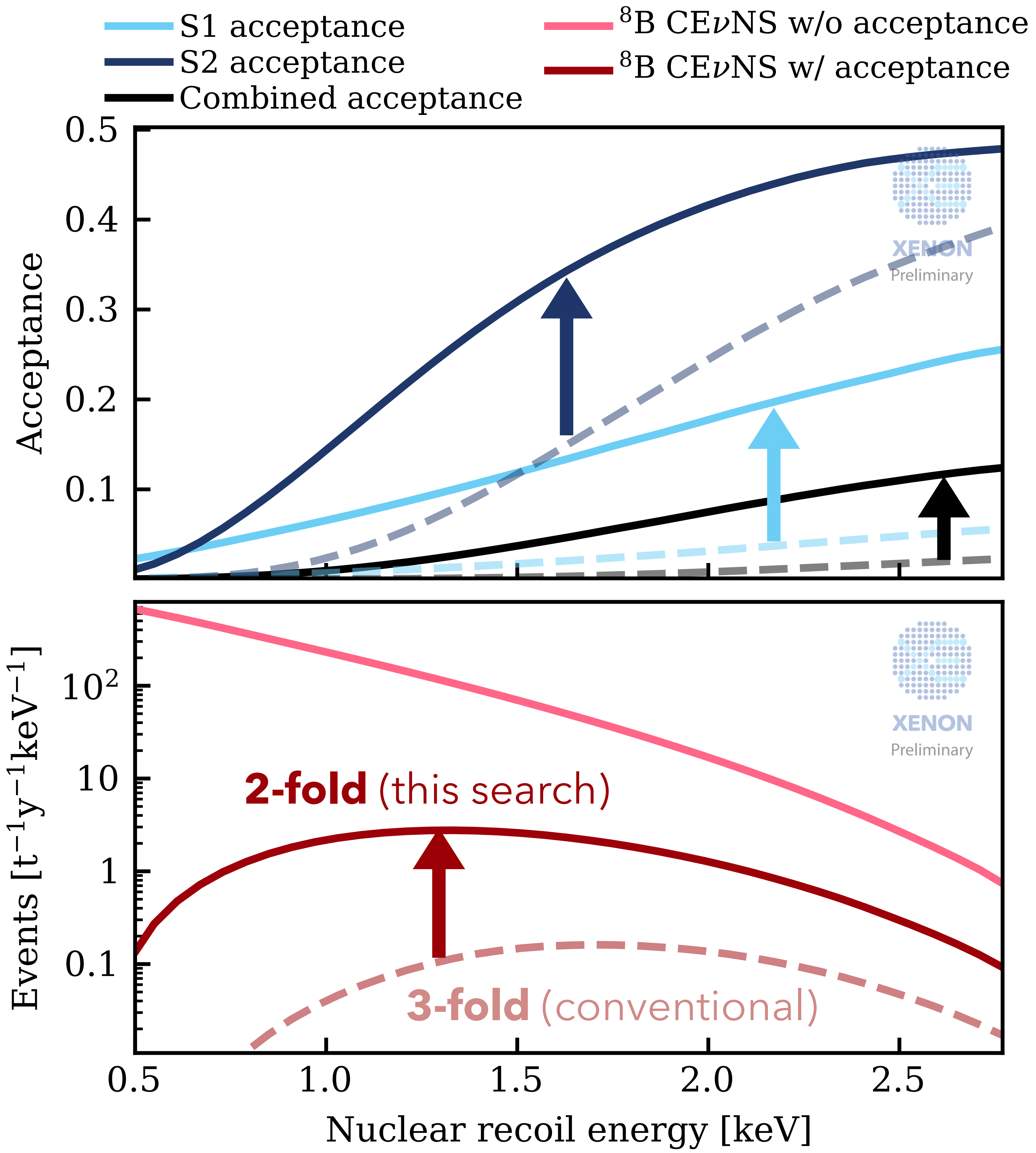
Blinded Region of Interest

S1 ROI: 2 or 3 hits ; A hit corresponds to a recorded photon by PMT+DAQ+software

S2 ROI: [120 - 500] PE → Reject high rate of isolated S2 background signal







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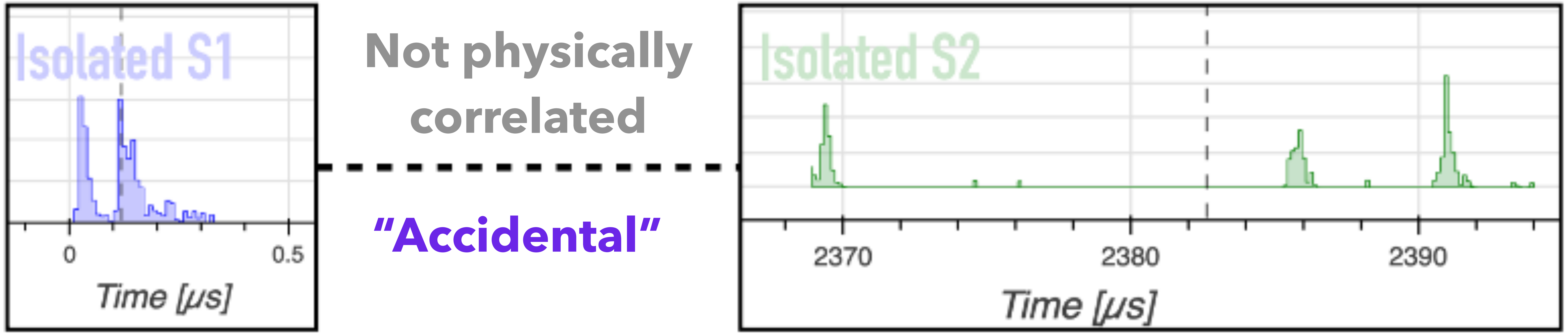
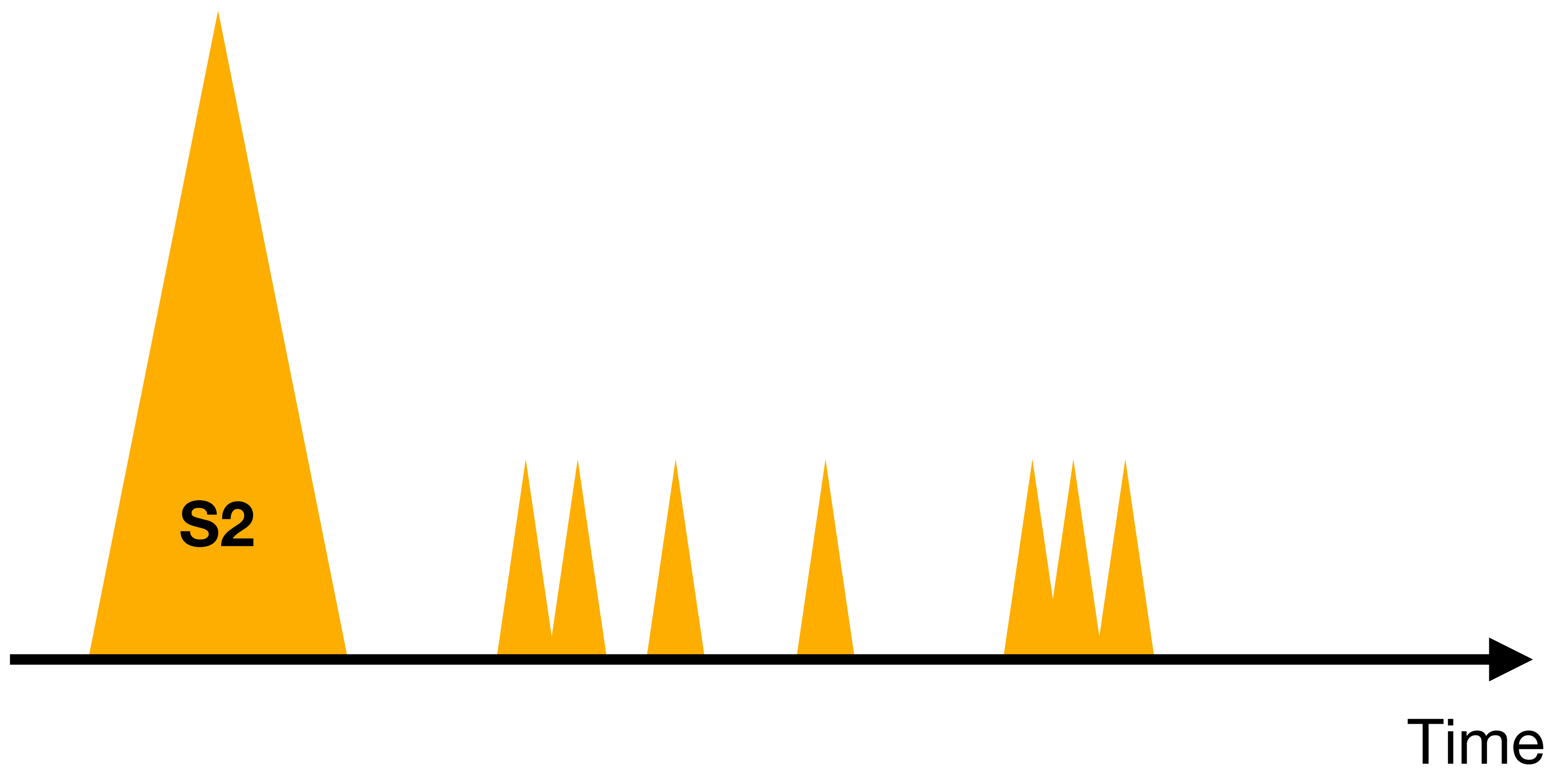
Main Source: Accidental Coincidences



- Accidental Coincidence (AC): Random pairing of **isolated S1** and **isolated S2**, whose exact origin is under investigation. Current culprit:
  - ➡ **Isolated S1 signals**: from pile-up induced single PMT hits, misclassified single electrons,…
  - ➡ **Isolated S2 signals**: from few-electron pile-up events, notably following high-energy interactions,…



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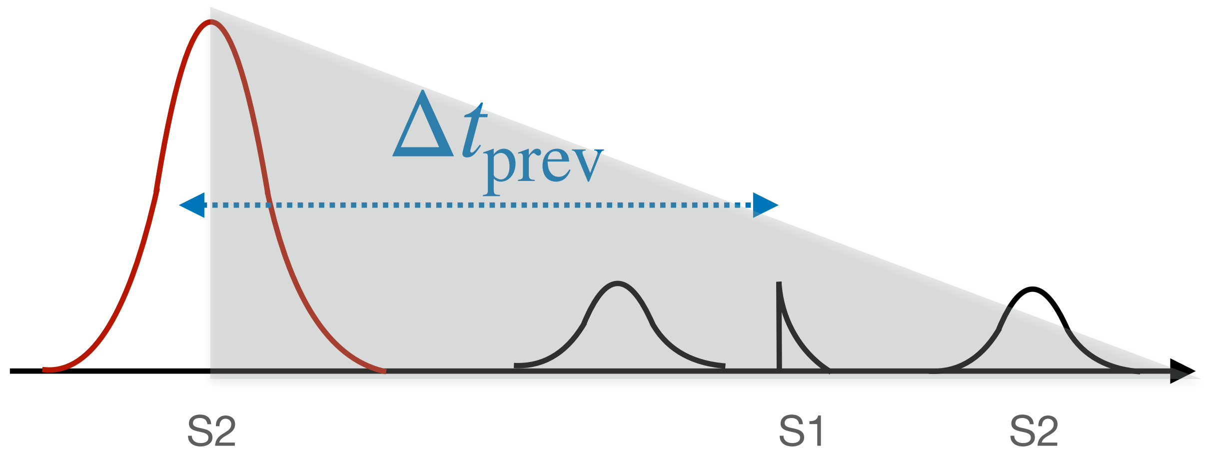
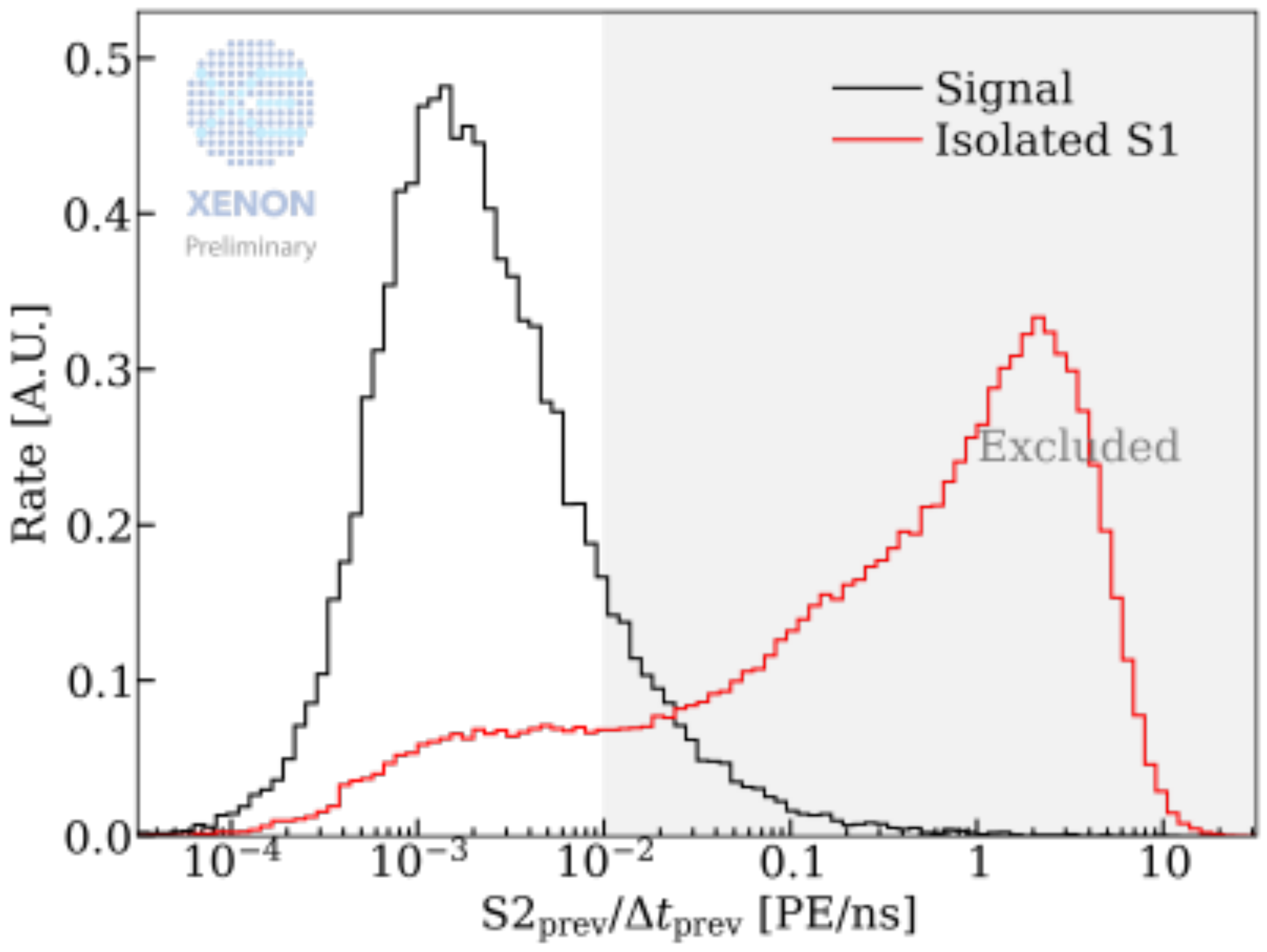
Accidental Coincidences Suppression:

1- Time Shadow

- Use space/time correlation with previous high-energy interaction
  - ➡ **Isolated S1 rate**: 15 Hz → 2.3 Hz
  - ➡ **Isolated S2 rate**: 150 mHz → 25 mHz





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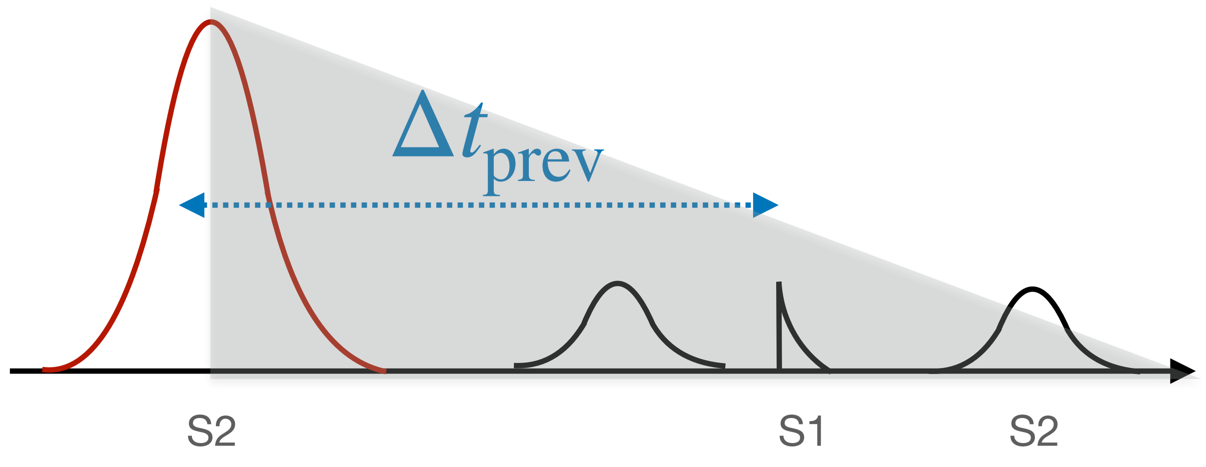
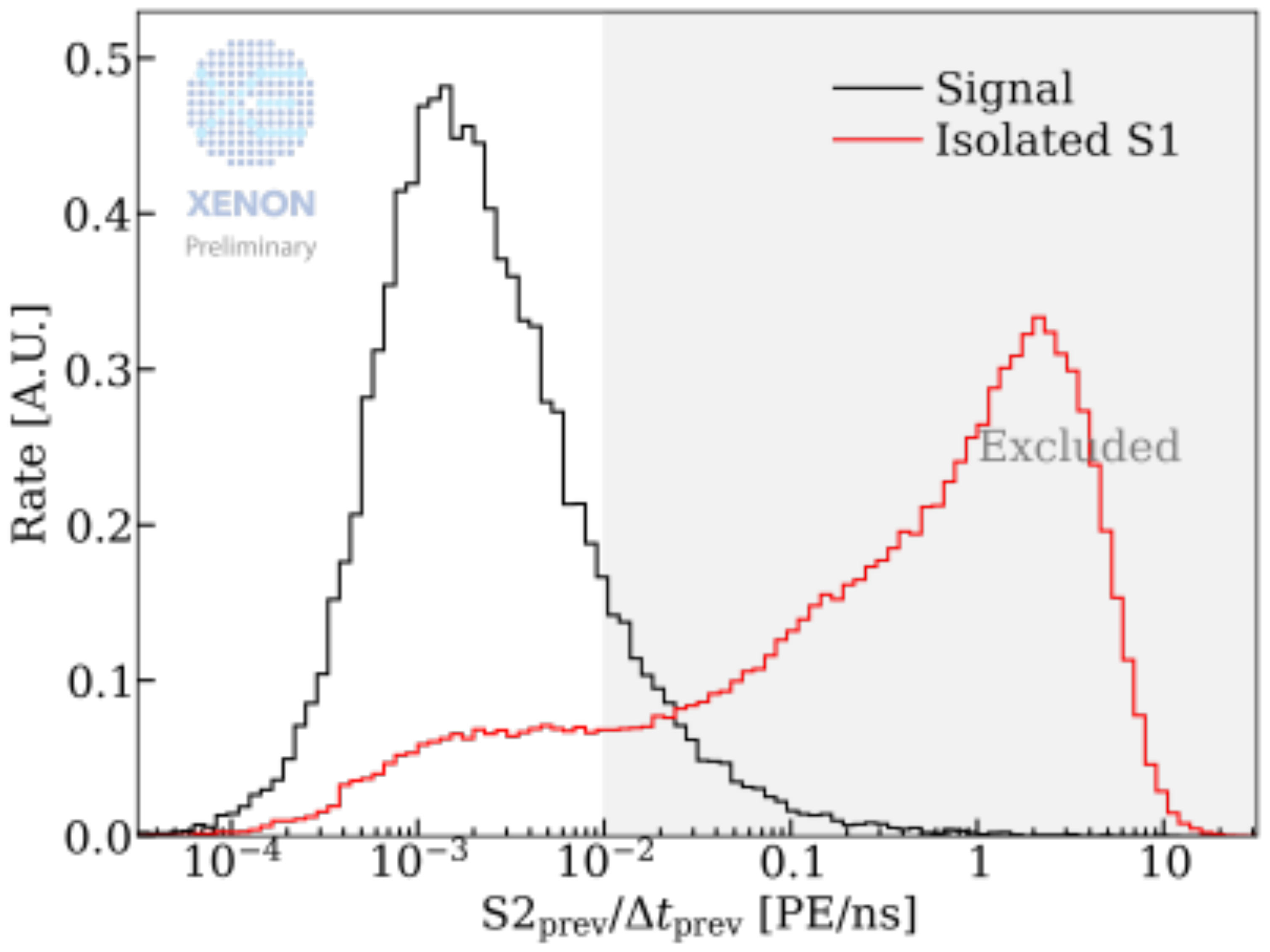


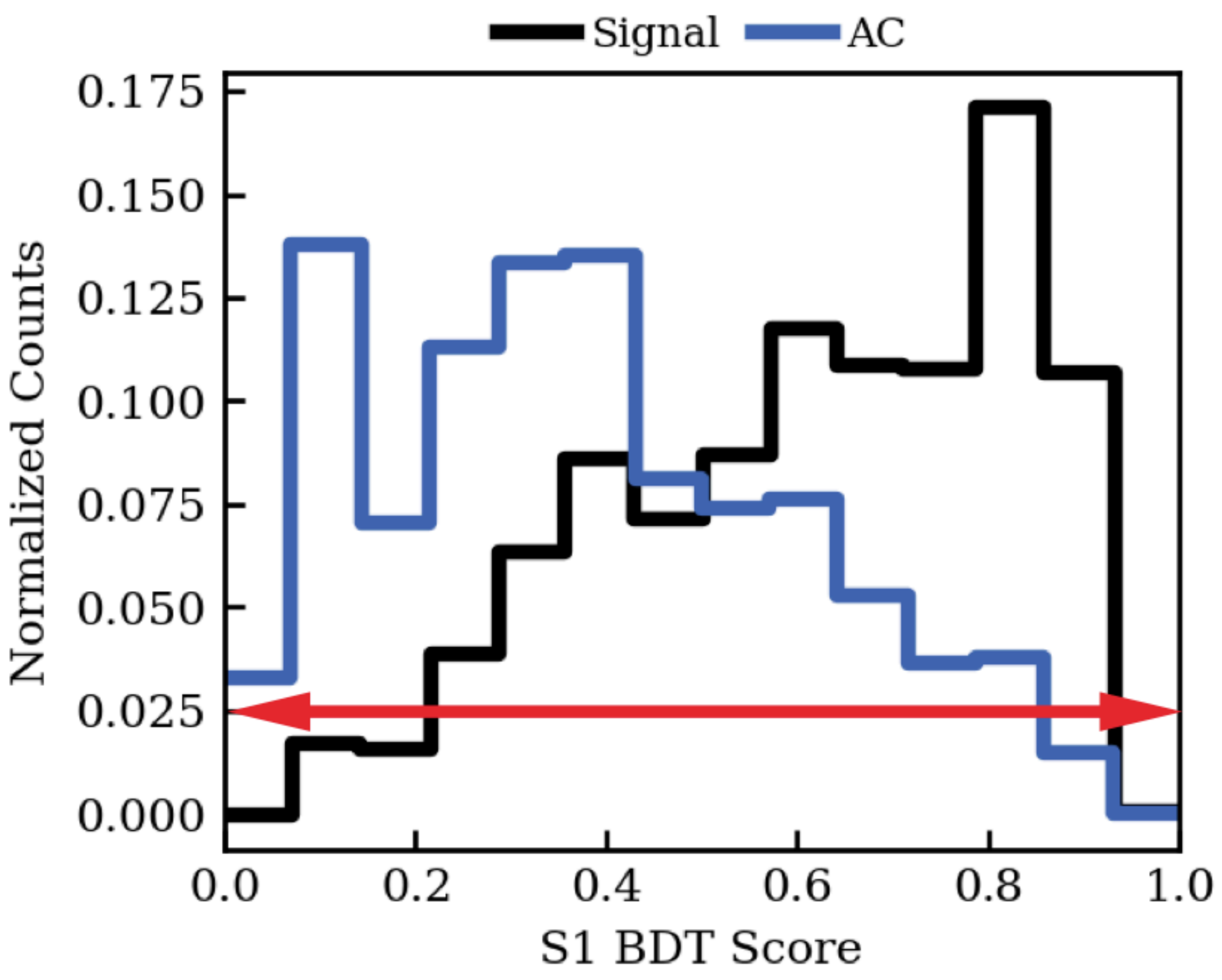


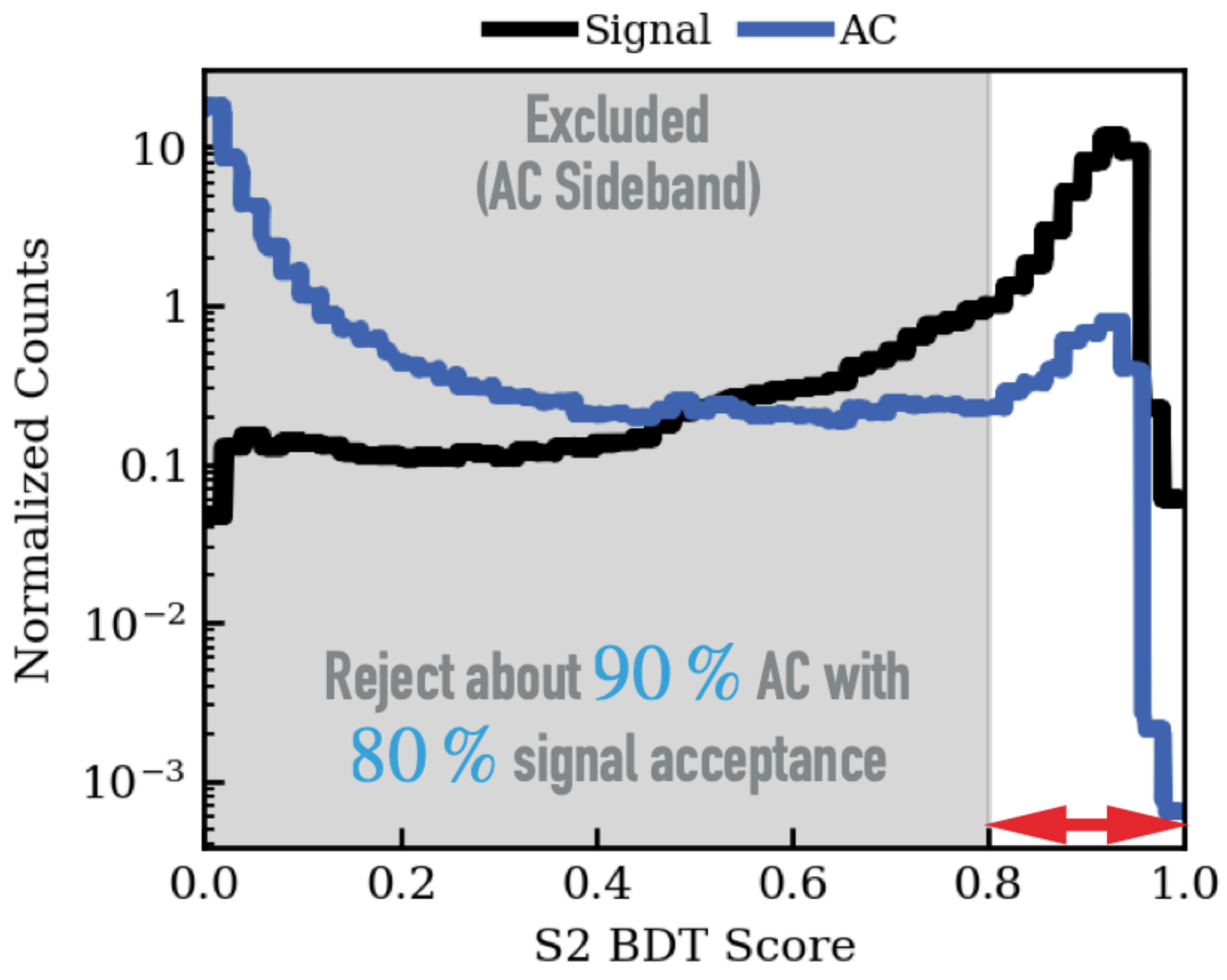
2- Two Boosted Decision Tree (BDT)

- **S1 BDT:** leverage S1 pulse shape and spatial distribution across the PMT arrays.
- **S2 BDT:** check that S2 pulse shape correlated with the diffusion of the drifting electron cloud law.

Expected # of AC events:

7.5 ± 0.7 (SR0) and 17.8 ± 1.0 (SR1)





Background Model

Accidental Coincidences Suppression:

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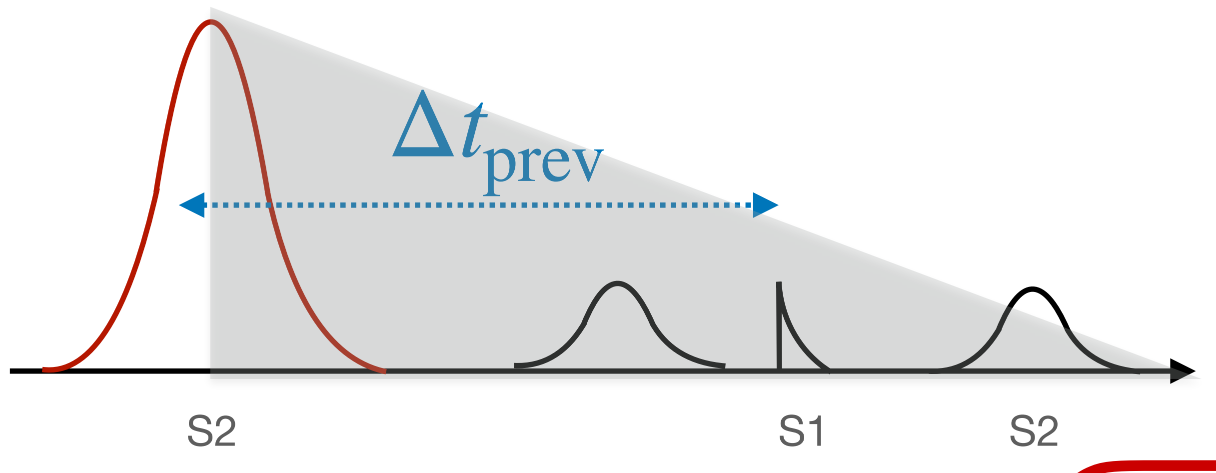

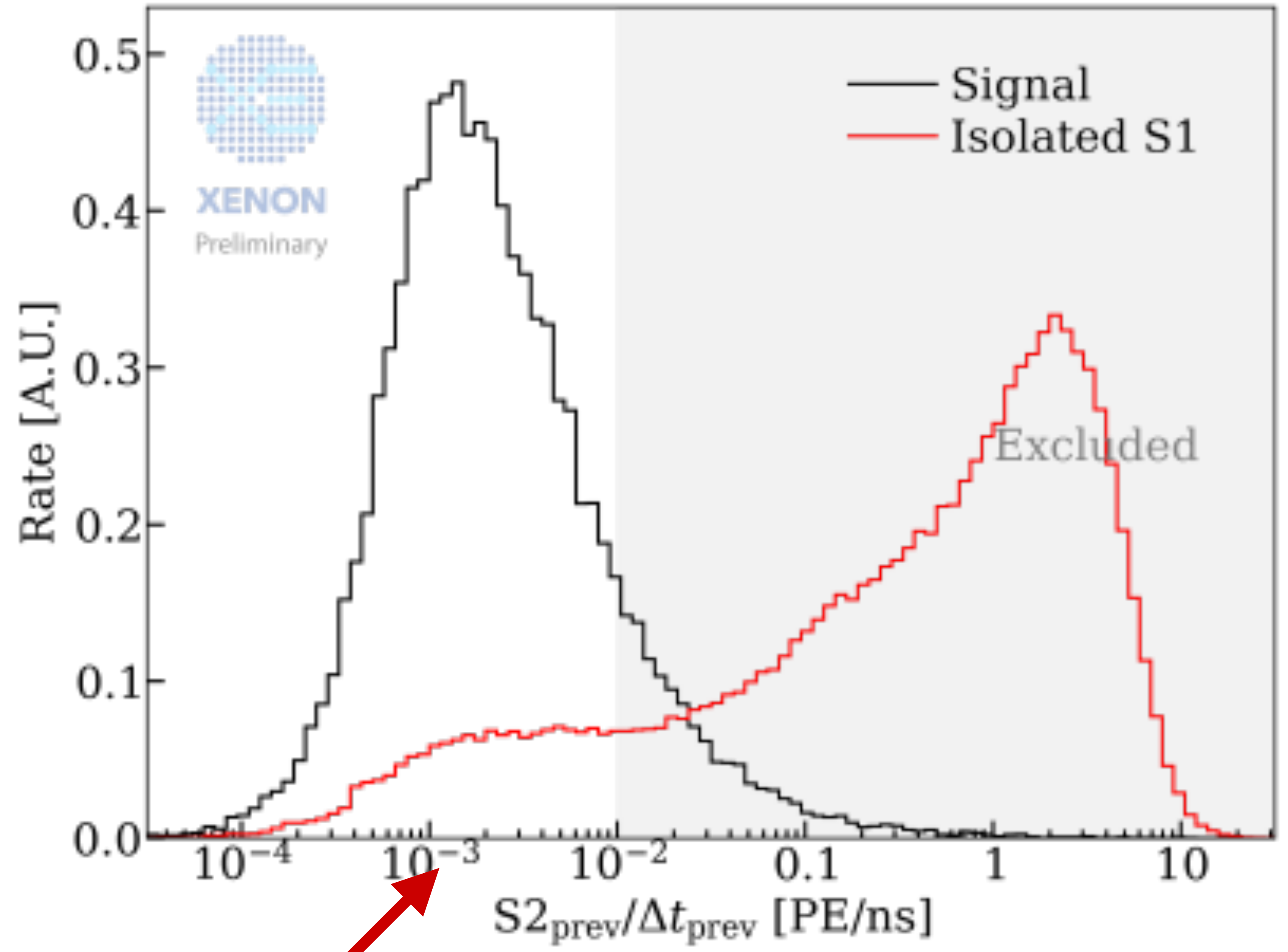

Those 3 dimensions are used in the inference

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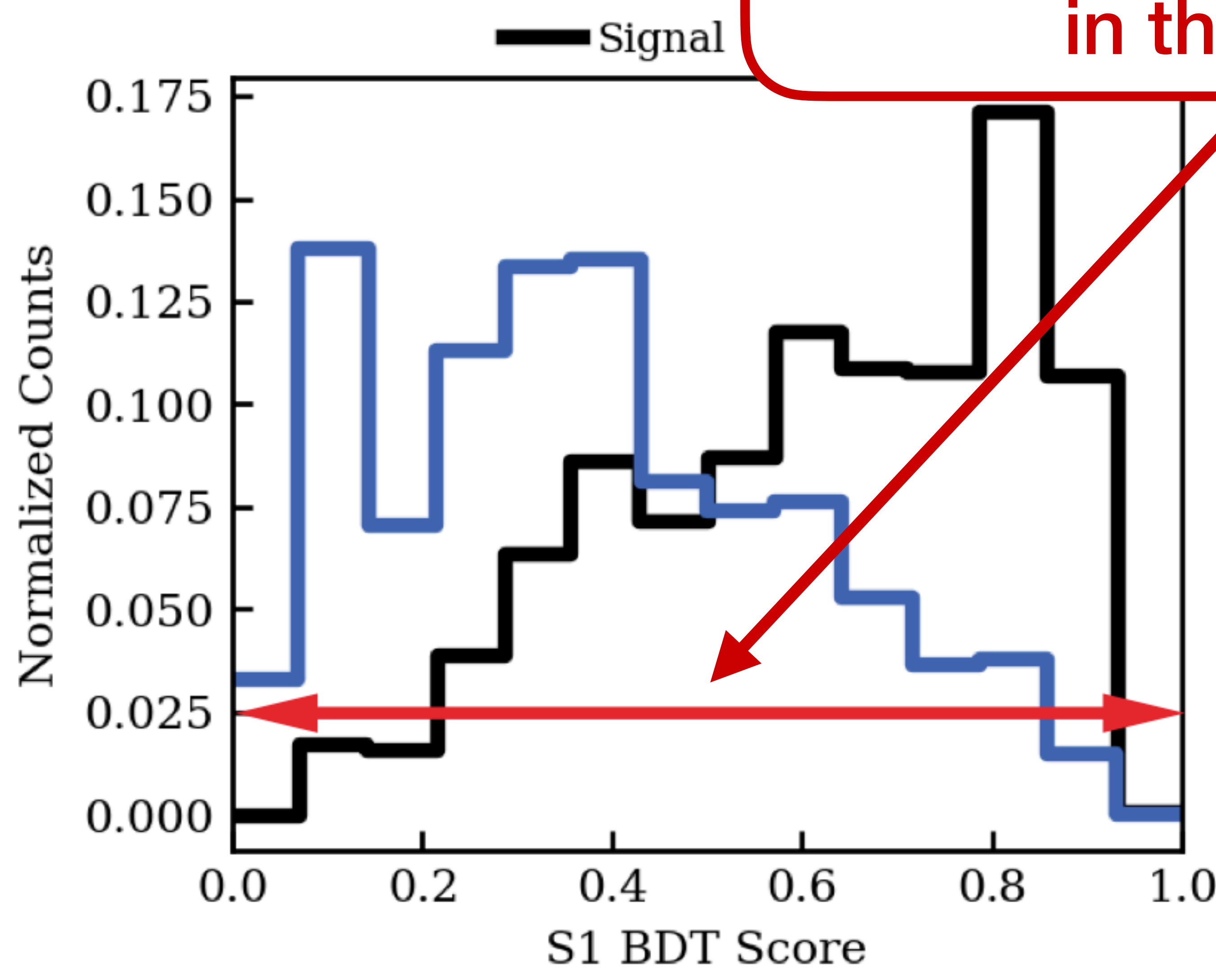

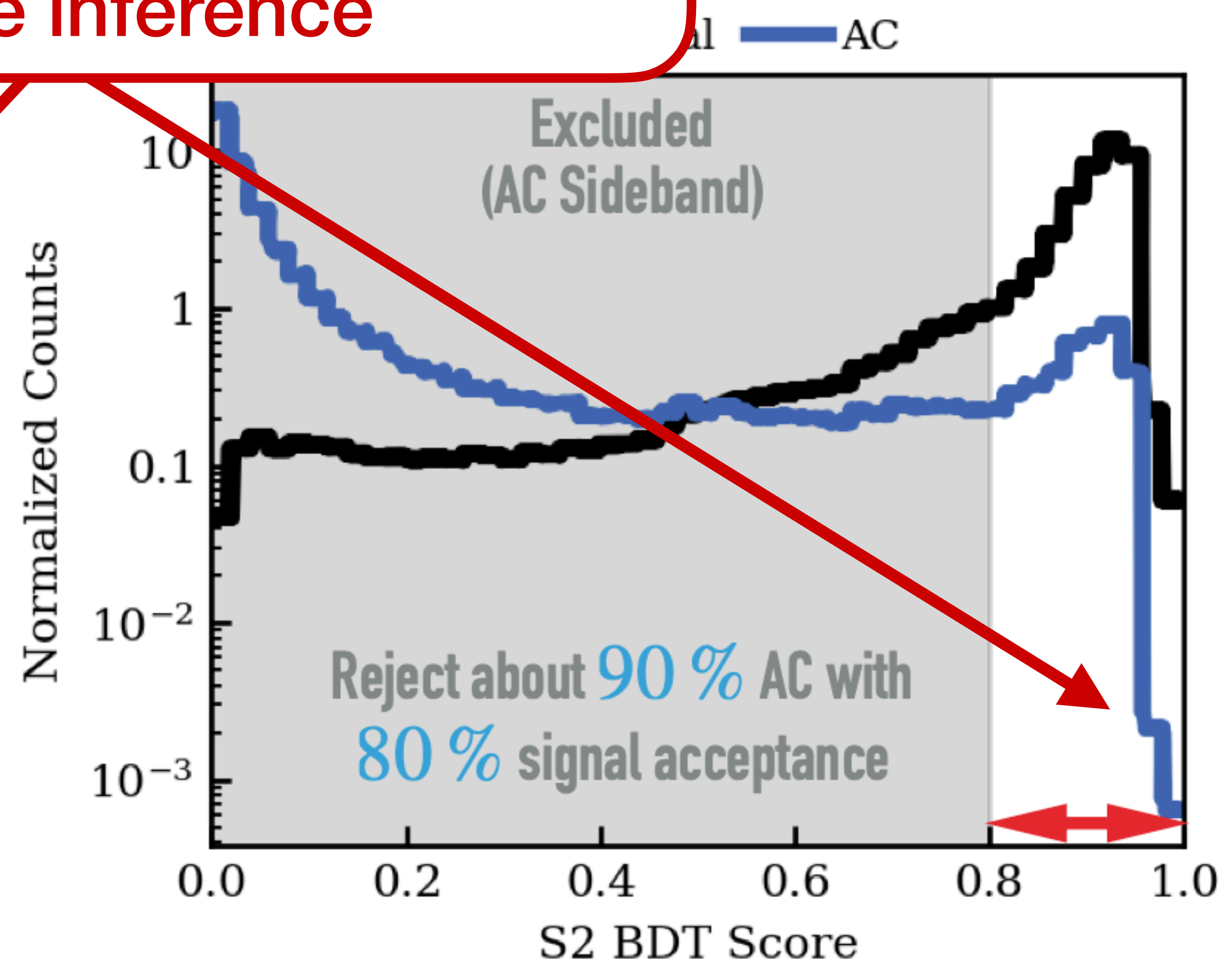

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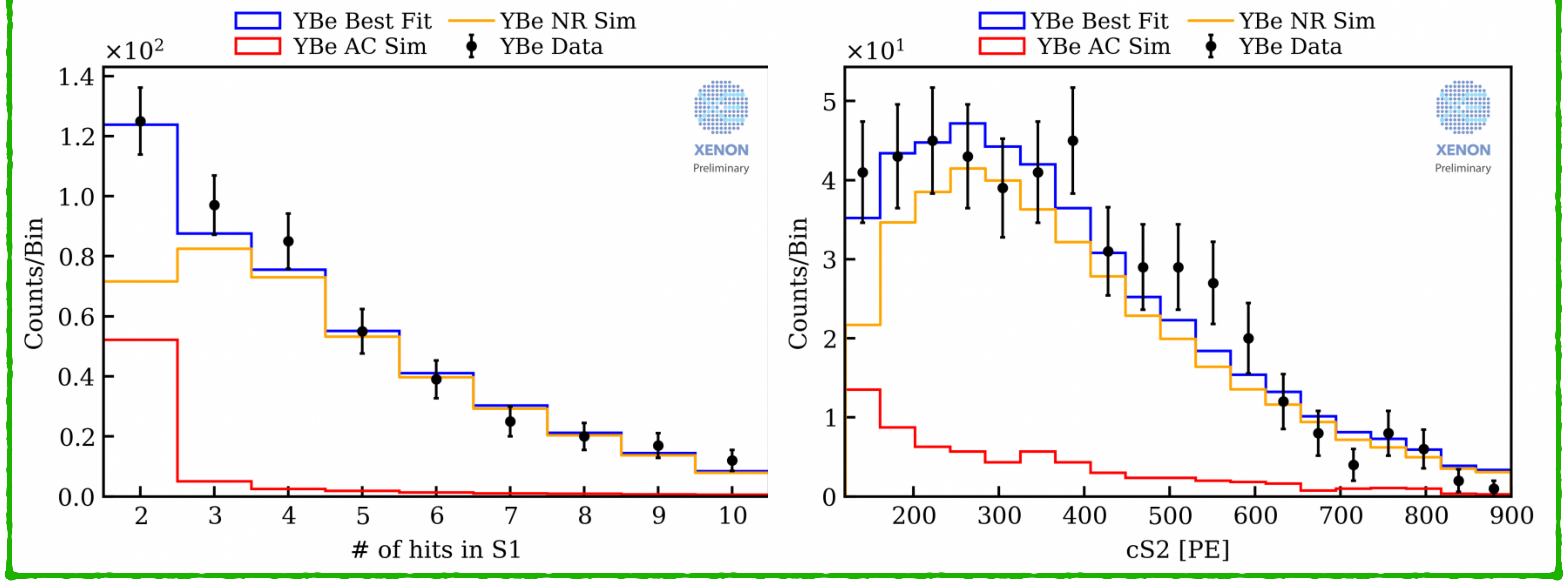
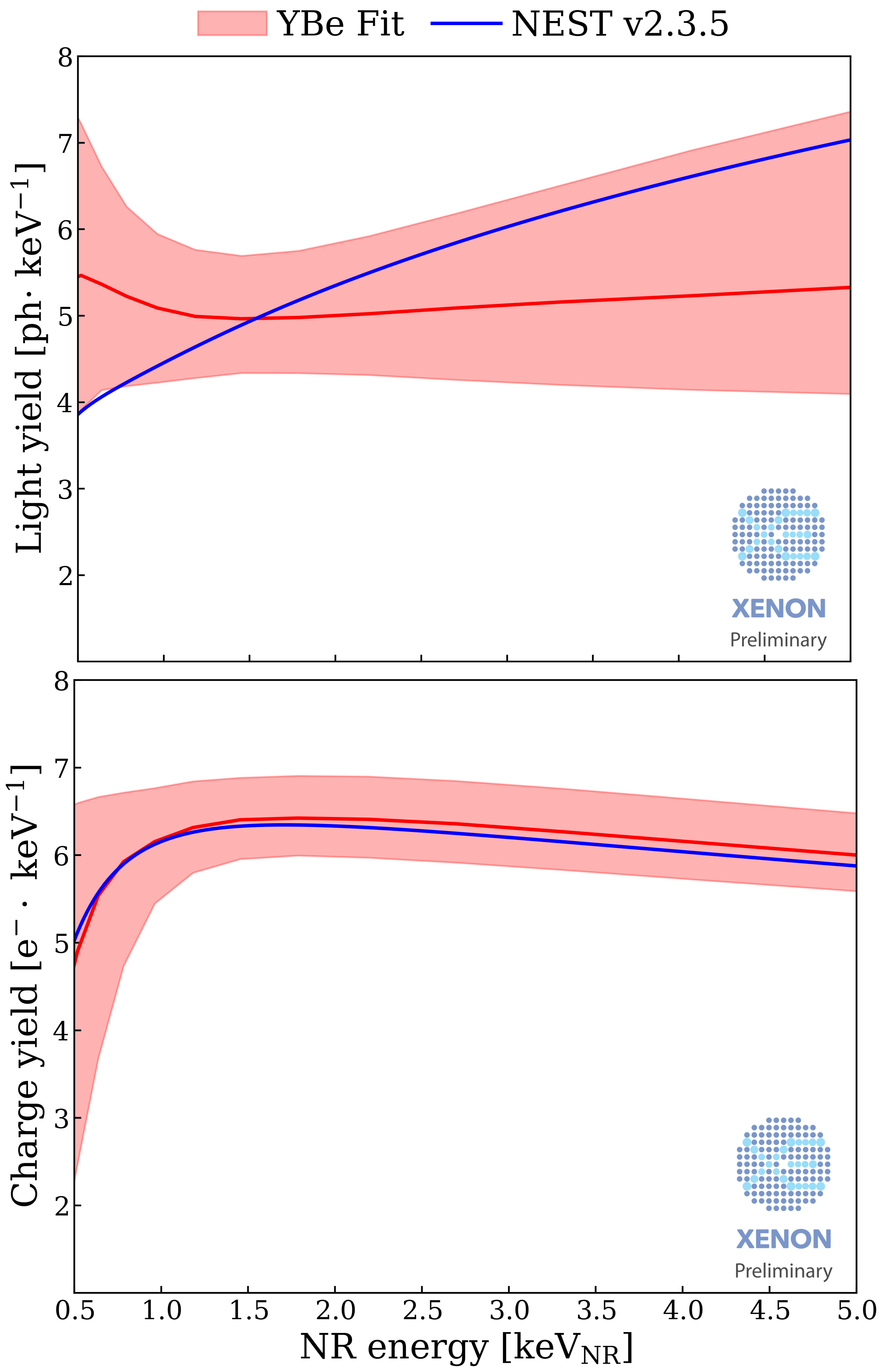
Constrain Yield Models:

$$\gamma(^{88}\mathrm{Y}) + {}^{9}\mathrm{Be} \rightarrow n + {}^{8}\mathrm{Be}$$

- Great agreement between data and model.
  - ➡ Background originating from Accidental Coincidences (AC) are modelled with data-driven simulation framework.
- **Light (LY) and Charge Yields (CY)** were **extracted** down to 0.5 $\mathrm{keV_{NR}}$ at XENONnT electric field of 23 V/cm **with latest NEST parametrisation**.
- Yield model uncertainty leads to ~ 30% signal rate uncertainty.





^{8}B CEνNS search - Prediction

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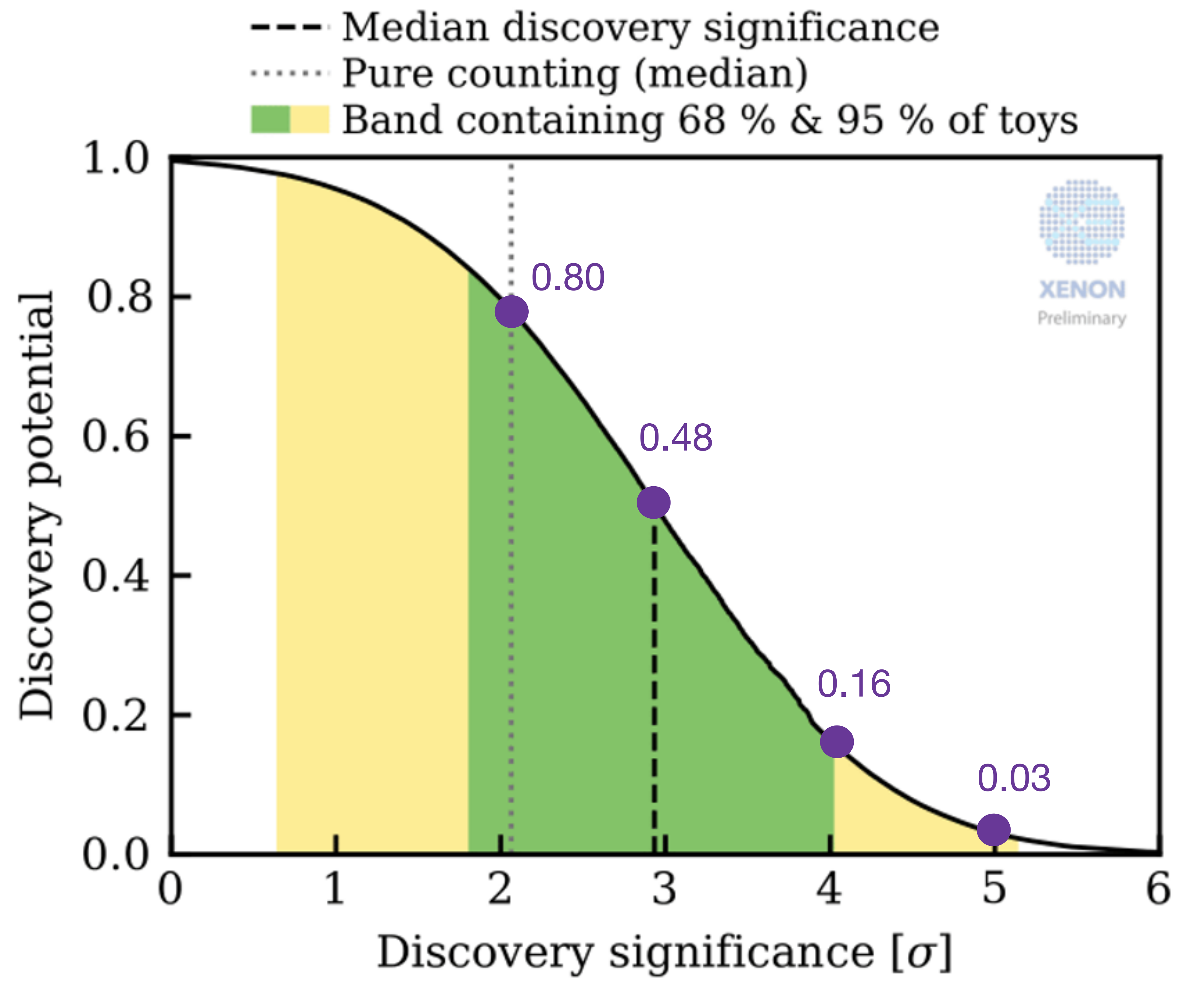
- Use both science run to perform a blinded analysis, with **316.16 days of livetime** and a fiducial mass of **4.0 (4.1) tonnes in SR0 (SR1)** leading to a **total exposure of 3.51 t x yr**
- Extended binned likelihood in 4D parameter space 3 x 3 x 3 x 3 = 81 bins (cS2, $S2_{prev}/\Delta t_{prev}$, S1 BDT, S2 BDT)

48% to observe > 3σ significance

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



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- **^{8}B neutrino flux**: $4.6^{+3.6}_{-2.3} \times 10^{6}$ cm^{-2} s^{-1} at 68% C.L. no tension with literature value

Background only hypothesis rejected with 2.73σ significance

Strong evidence of CEνNS Interaction

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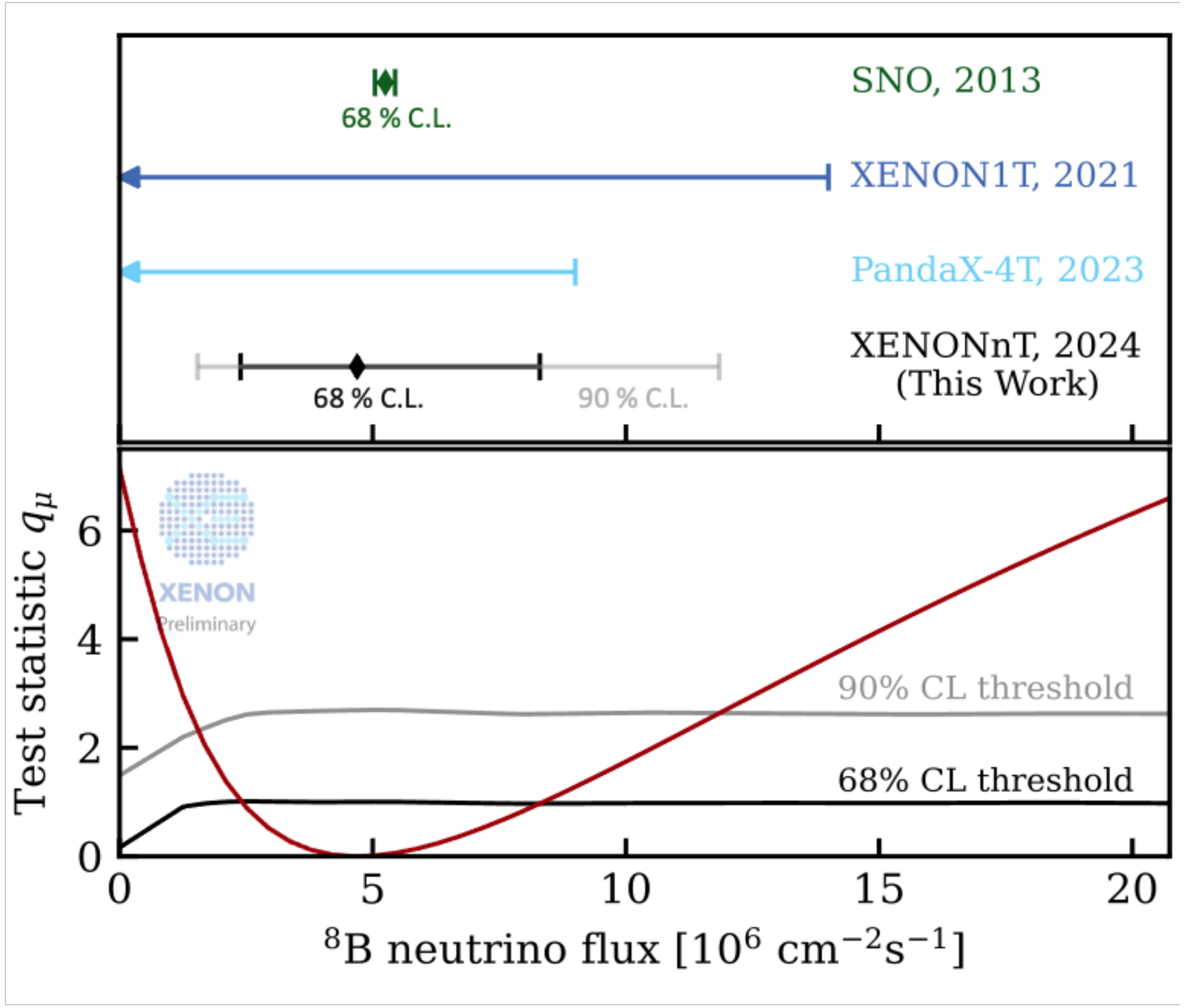
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3
Total background	$26.4^{+1.4}_{-1.3}$	26.3 ± 1.4
^{8}B	$11.9^{+4.5}_{-4.2}$	$10.7^{+3.7}_{-4.2}$
Observed	37	



^{8}B CEνNS search - Unblinding

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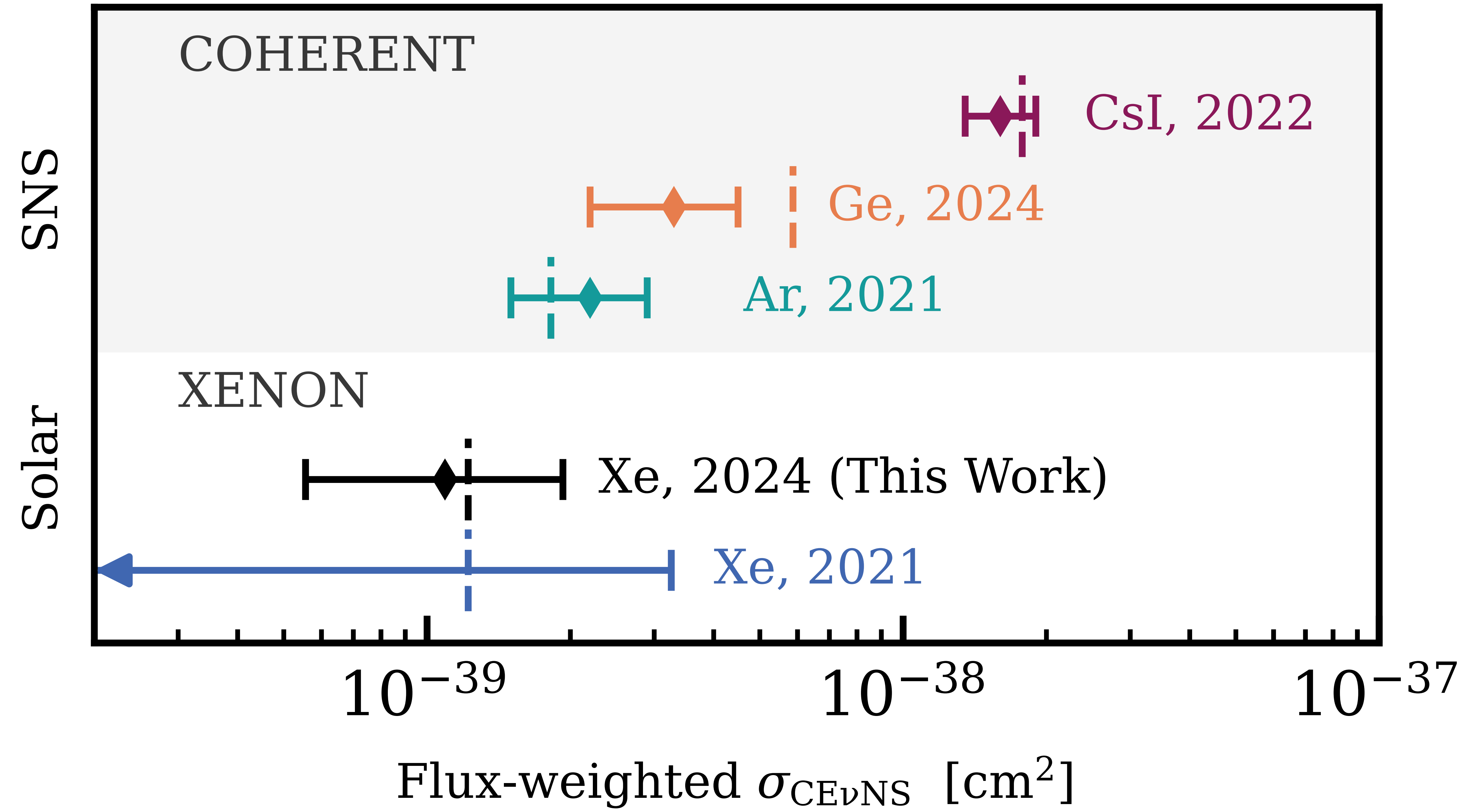
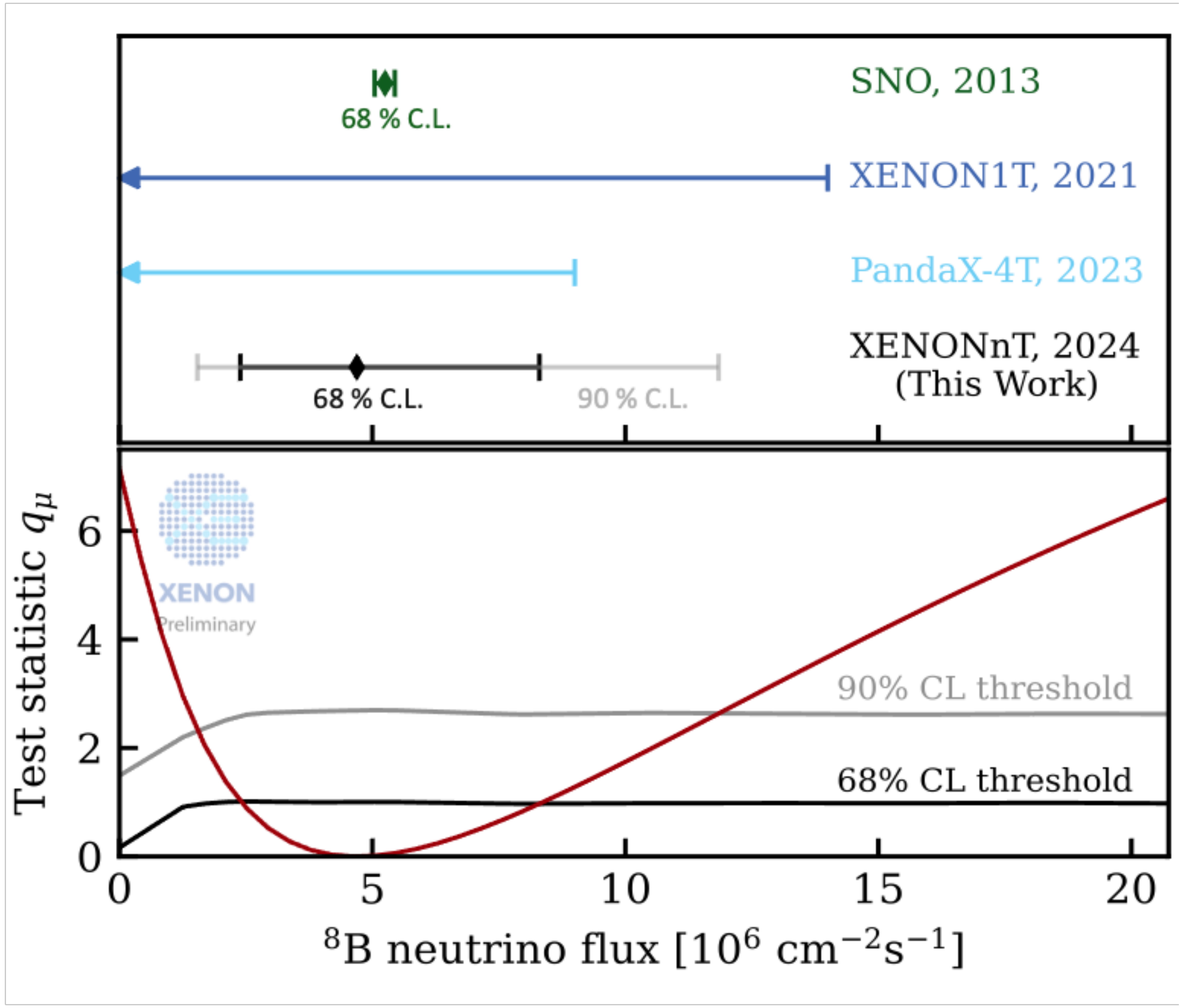
- **^{8}B neutrino flux**: $4.6^{+3.6}_{-2.3} \times 10^{6}$ cm^{-2} s^{-1} at 68% C.L. no tension with literature value
- With constrain from SNO flux → Measure the **flux-weighted CEνNS cross section**: $1.1^{+0.8}_{-0.5} \times 10^{-39}$ cm^{2}

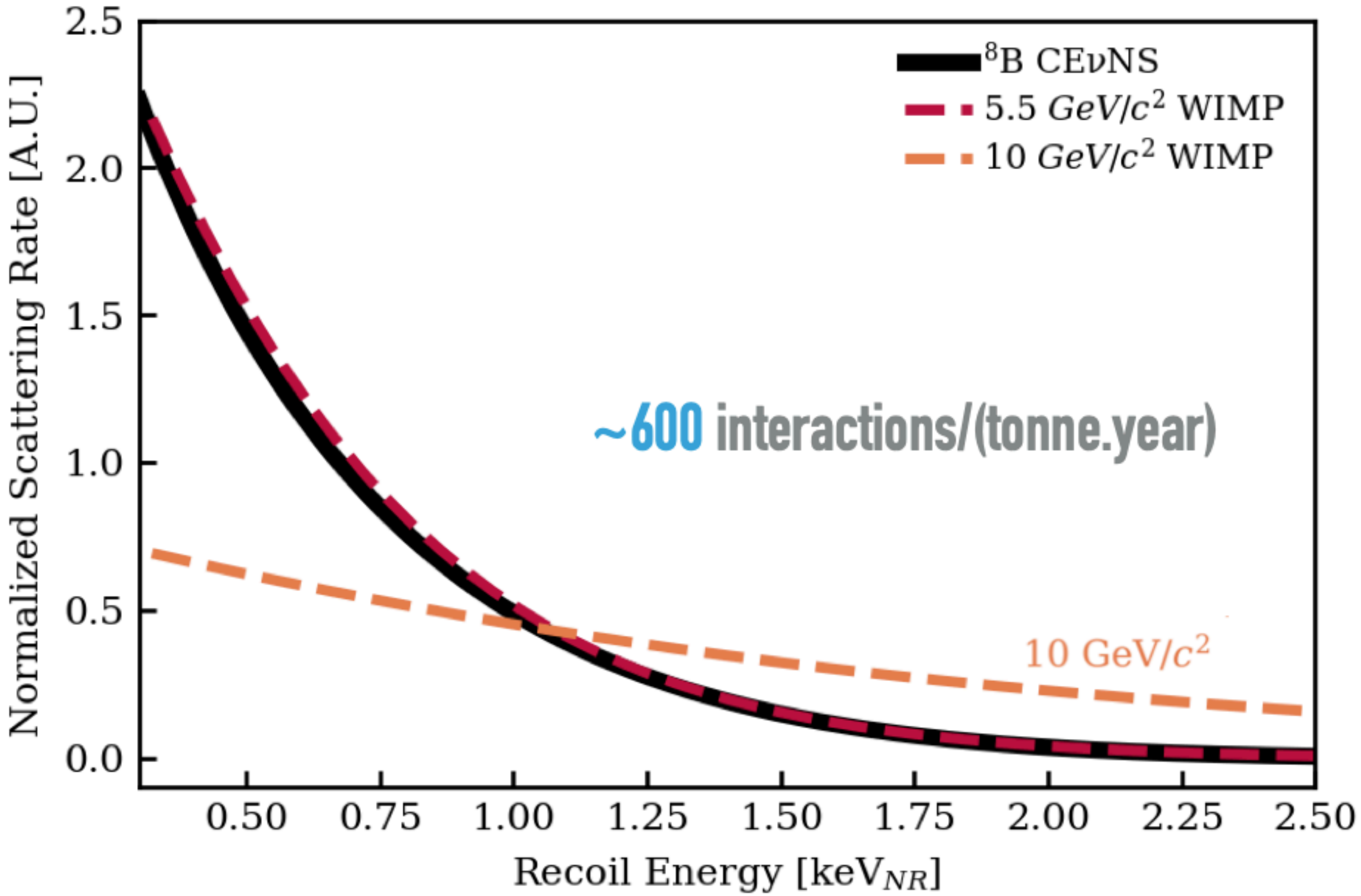
Background only hypothesis rejected with 2.73σ significance

Strong evidence of CEνNS Interaction





A reminder that CEνNS is a background for DM search



- Focus on light DM models such as asymmetric and self-interacting DM
- Benefit from the work done for the 8B CEνNS analysis

Low-mass DM results

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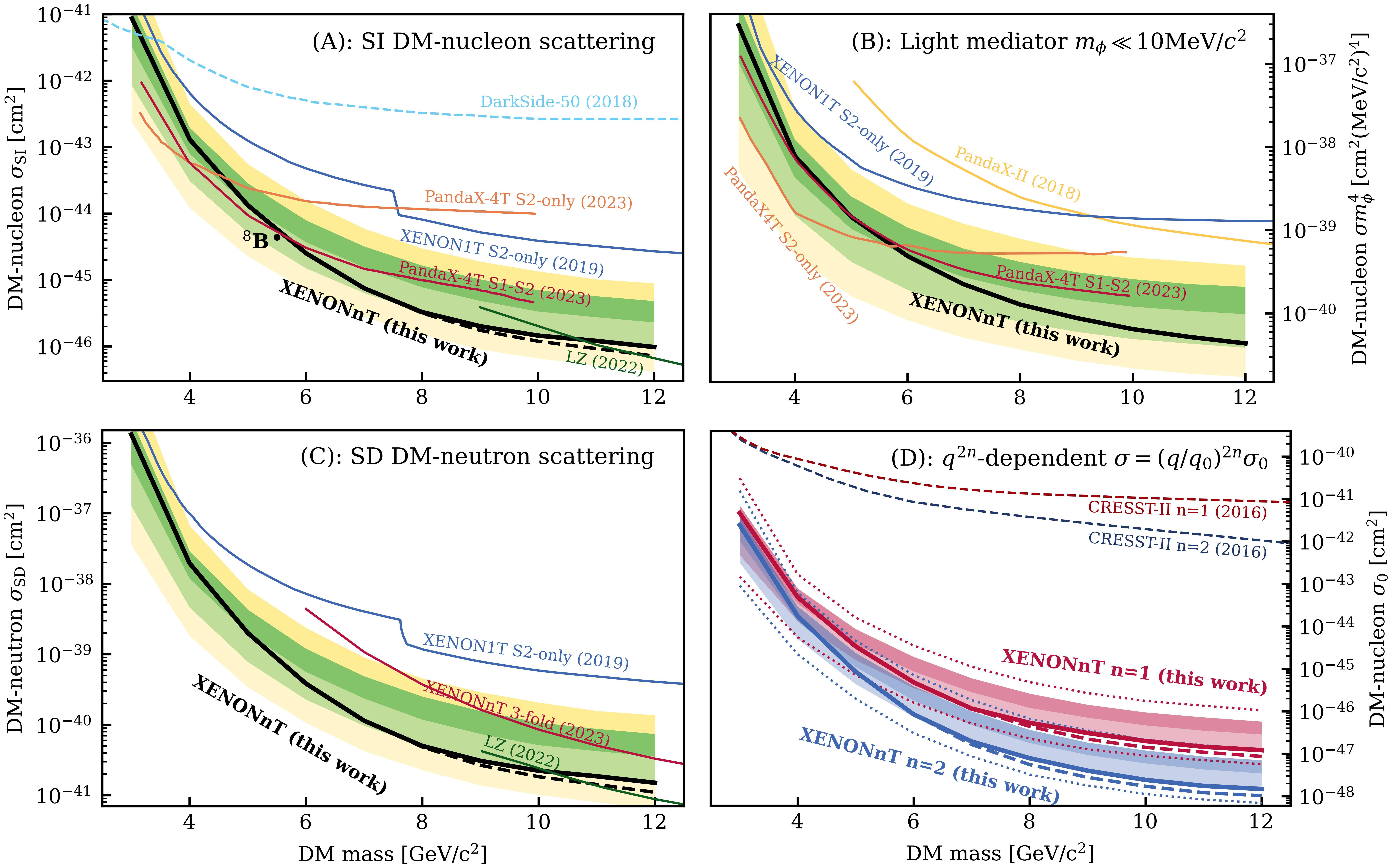

Summary & Outlook

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Strong evidence for CEνNS interaction in XENONnT: A first step into the neutrino fog

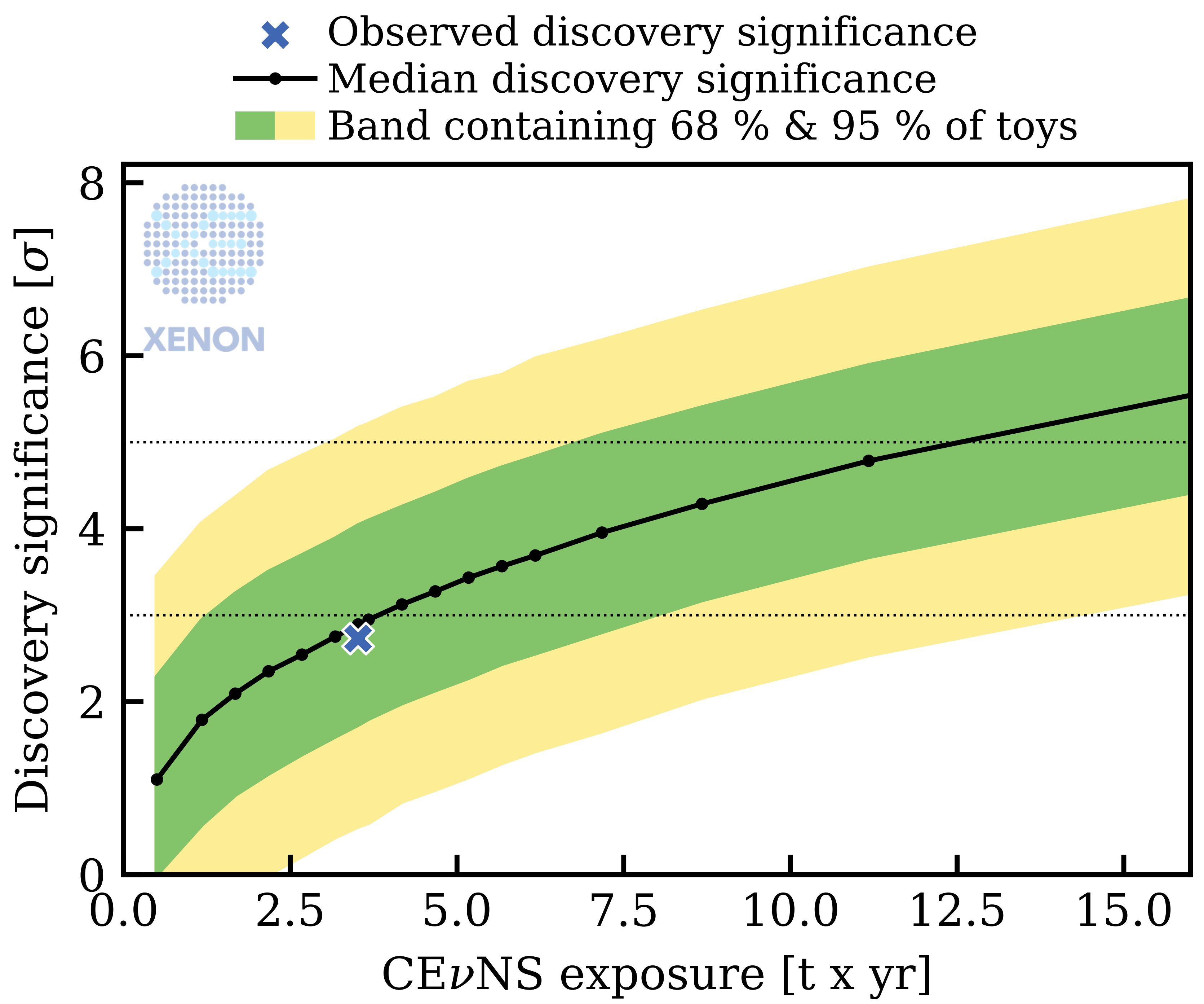
^{8}B CEνNS
arXiv:2408.02877

First Light DM results near the neutrino fog

Low-mass DM
arXiv:2409.17868

More results to come:

- Stay tuned for the **incoming WIMP results** with SR0+SR1 datasets
- We continue to take data, **SR2 ongoing** with Gd-loaded Water in nVeto to improve our neutron tagging efficiency.
  - ➡ Improved significance for ^{8}B CEνNS with increased exposure
  - ➡ Broad physics program with active analyses ongoing whose scope goes beyond WIMP search



Back-Up

XENON

Subdominant Source:

Background Model

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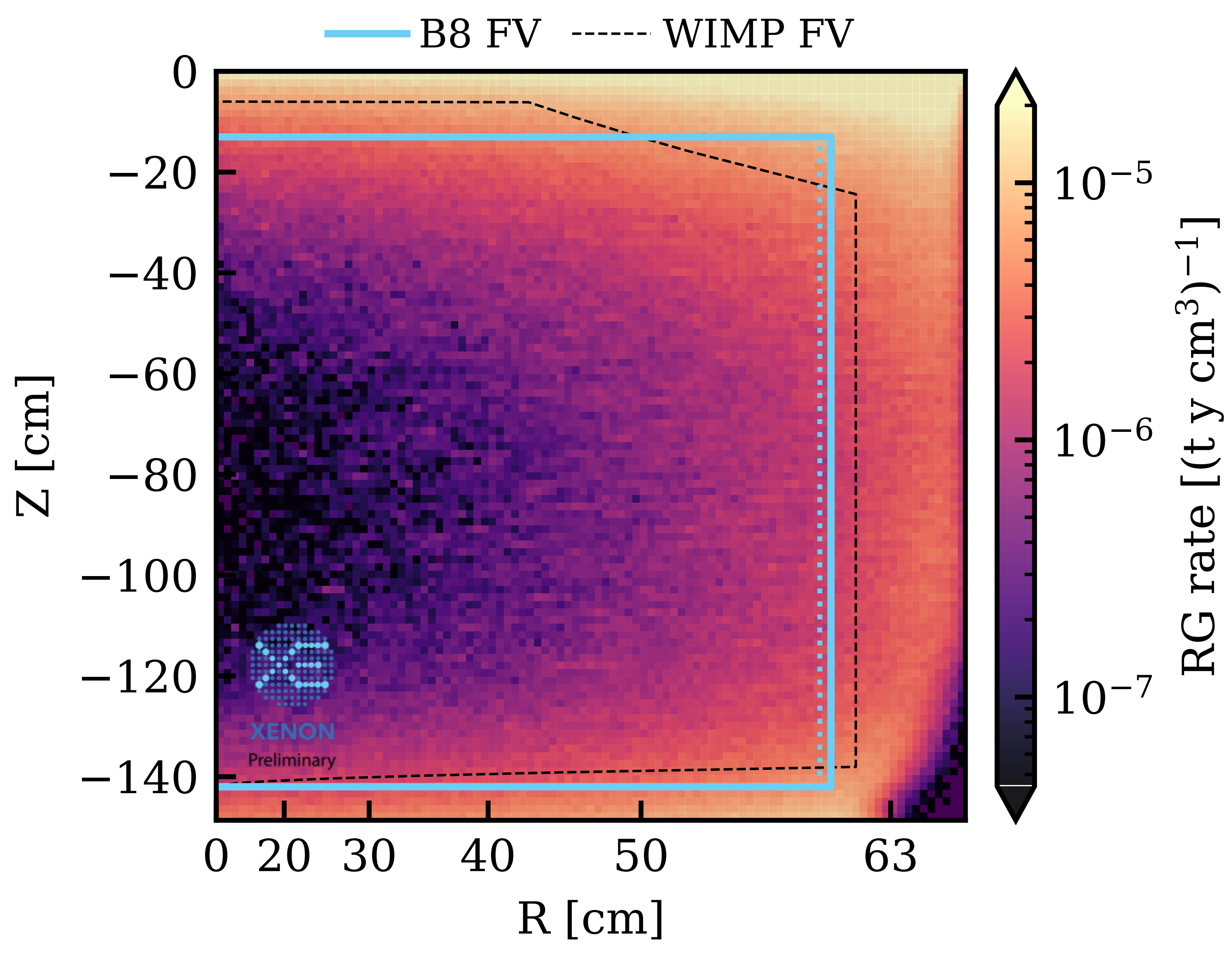
Subdominant Source:

Nuclear Recoil:

- Radiogenic neutrons (**fission, α-n**), simulation and data-driven (NV) model
  - ➡ Projection SR0: 0.13 ± 0.07 events
  - ➡ Projection SR1: 0.33 ± 0.19 events



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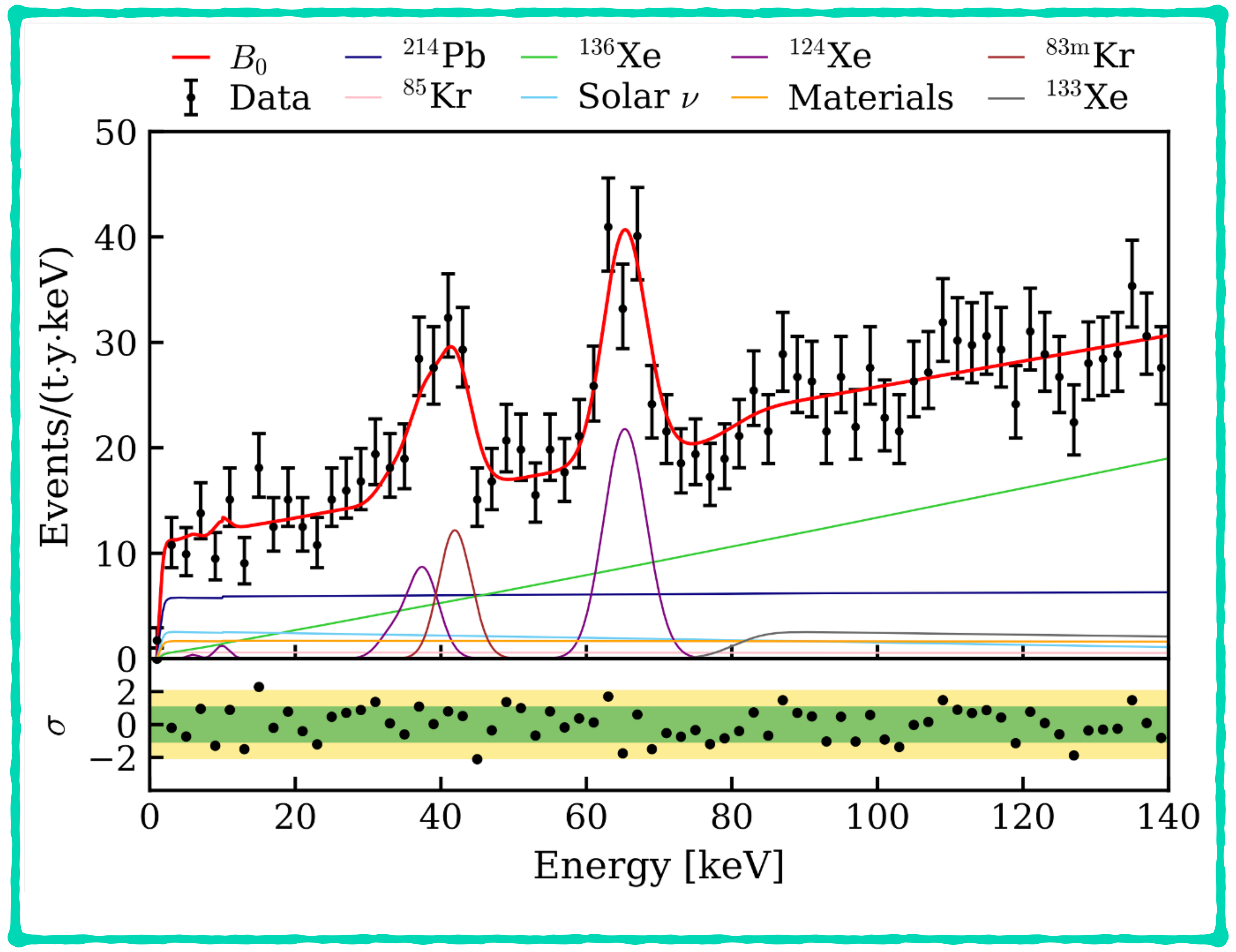
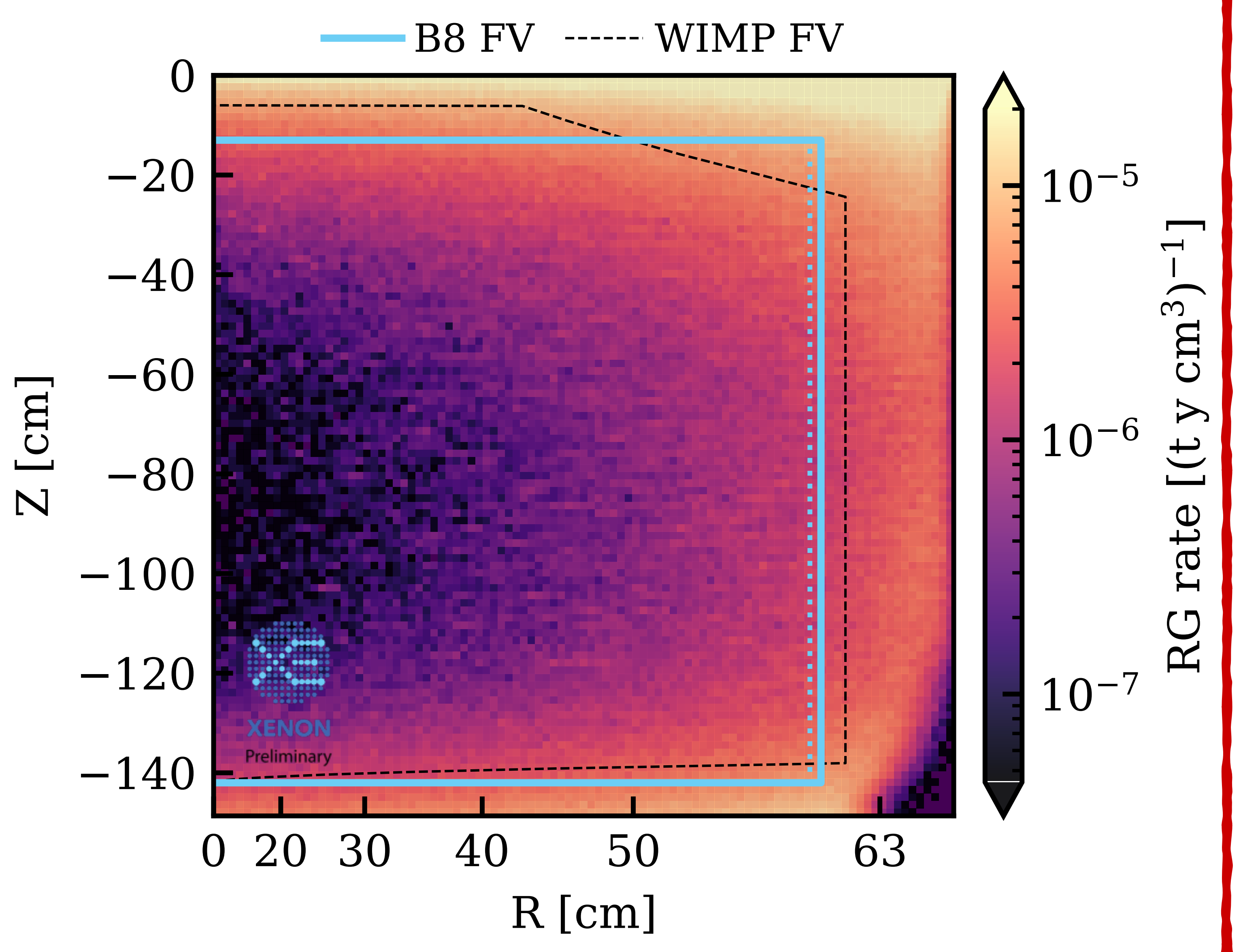
- Radiogenic neutrons (**fission, α-n**), simulation and data-driven (NV) model
  - ➡ Projection SR0: 0.13 ± 0.07 events
  - ➡ Projection SR1: 0.33 ± 0.19 events

Electronic Recoil:

- Dominated by **^{214}Pb** flat β-spectra
  - ➡ Projection SR0: 0.13 ± 0.13 events
  - ➡ Projection SR1: 0.56 ± 0.56 events





Background Model

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Subdominant Source:

Nuclear Recoil:

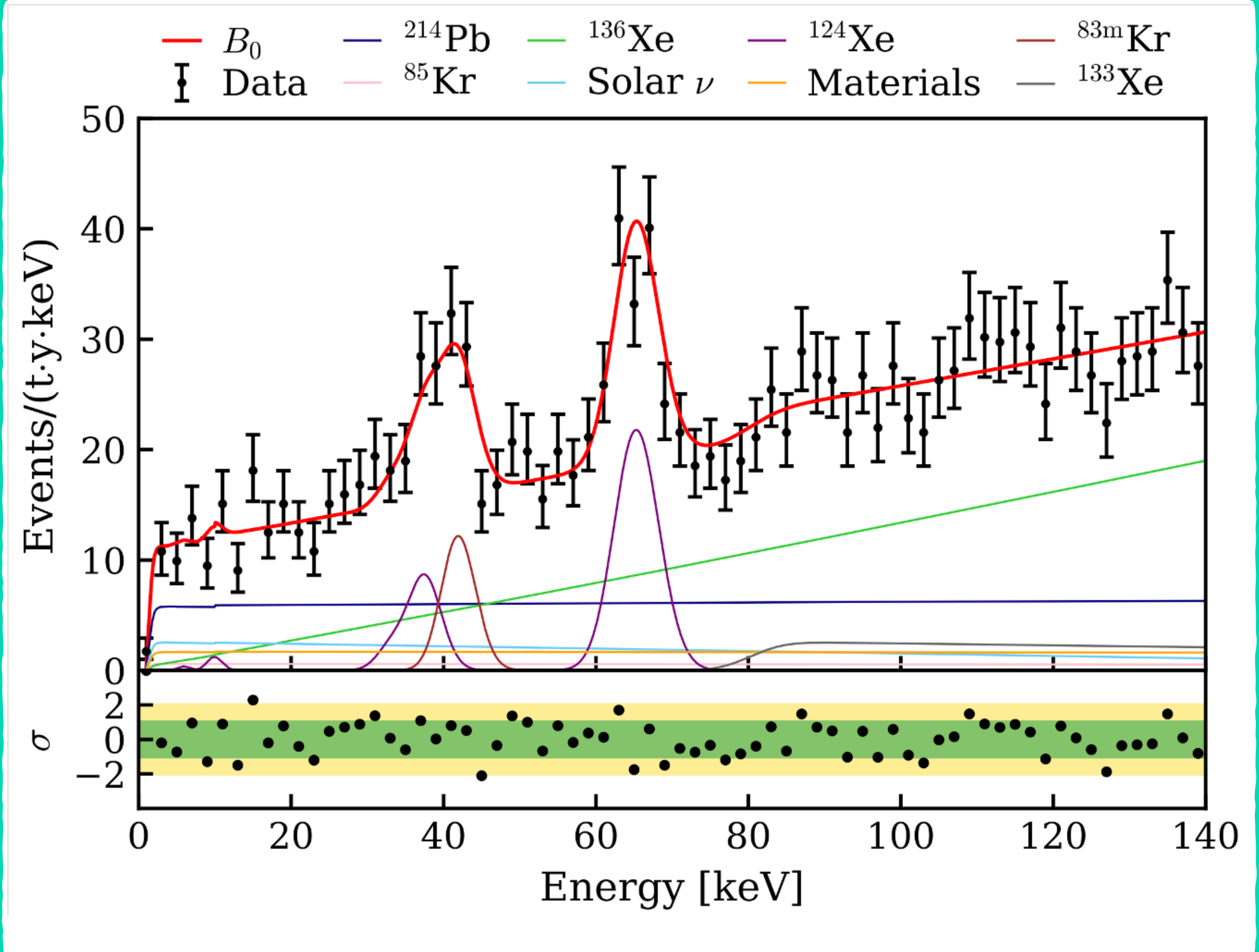
- Radiogenic neutrons (**fission, α-n**), simulation and data-driven (NV) model
  - ➡ Projection SR0: 0.13 ± 0.07 events
  - ➡ Projection SR1: 0.33 ± 0.19 events

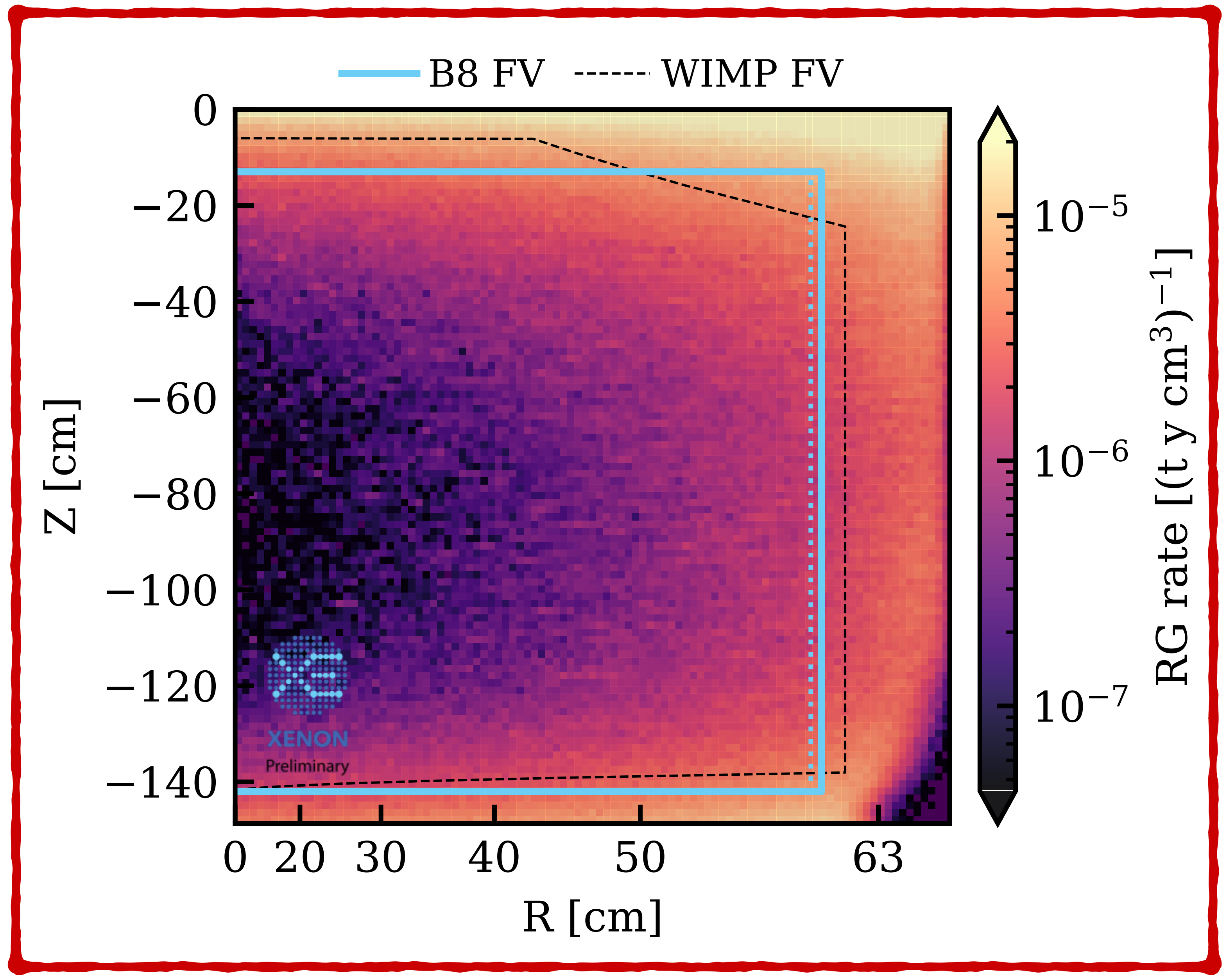
Electronic Recoil:

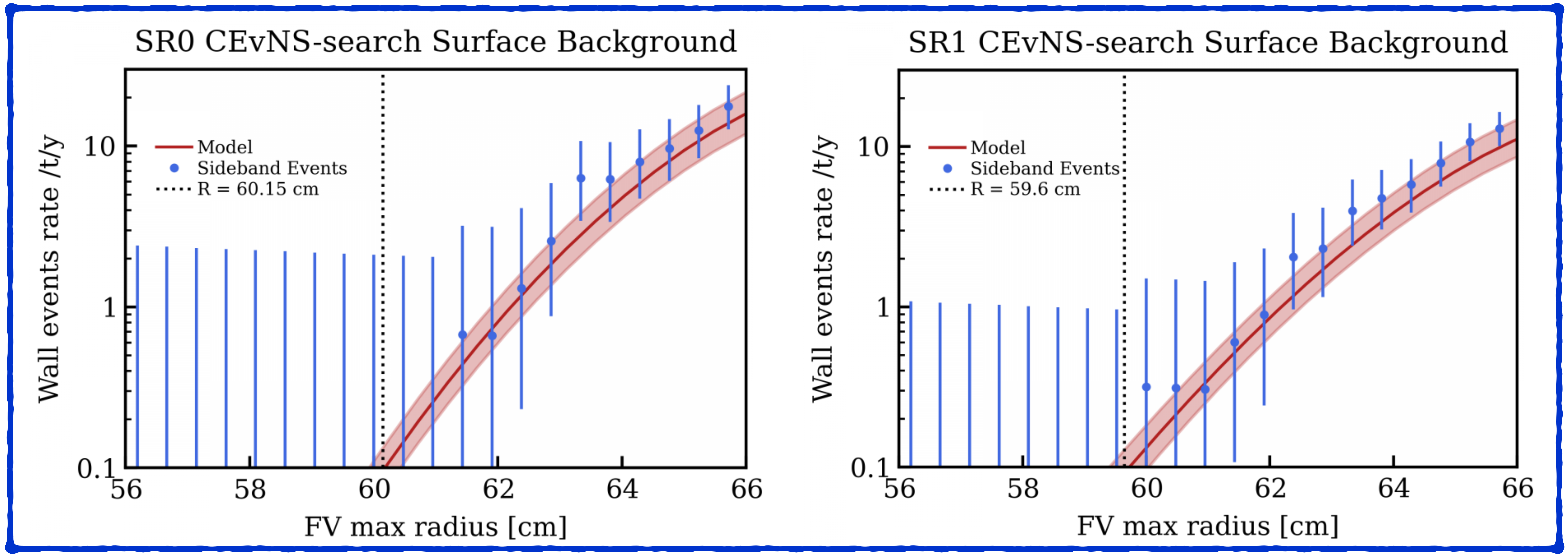
- Dominated by ^{214}**Pb** flat β-spectra
  - ➡ Projection SR0: 0.13 ± 0.13 events
  - ➡ Projection SR1: 0.56 ± 0.56 events

Surface Event:

- ER from ^{210}**Pb** plate out at detector walls
  - ➡ Data-driven model SR0/1: <0.3 events







Yields model from ^{88}YBe Calibration

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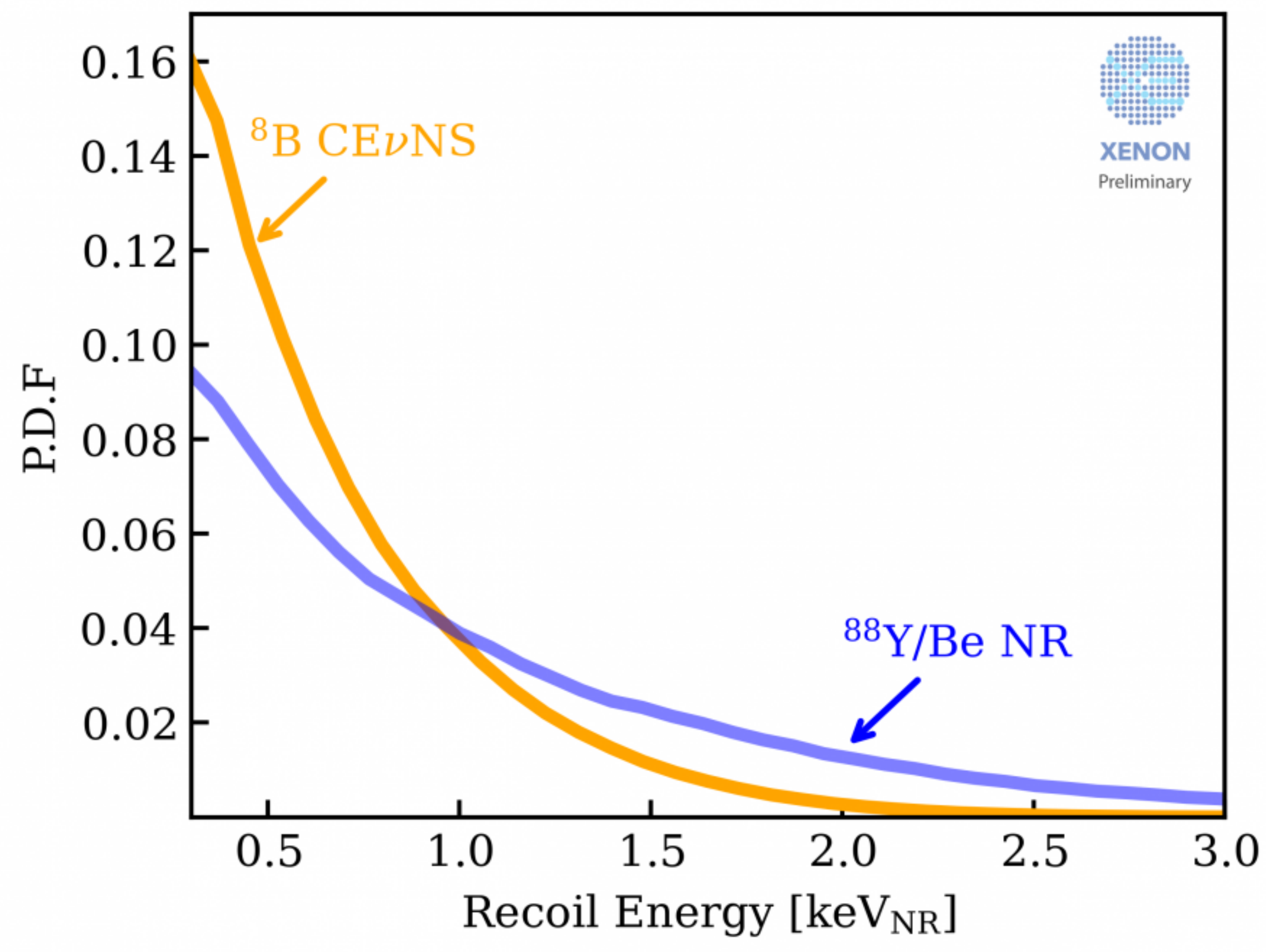
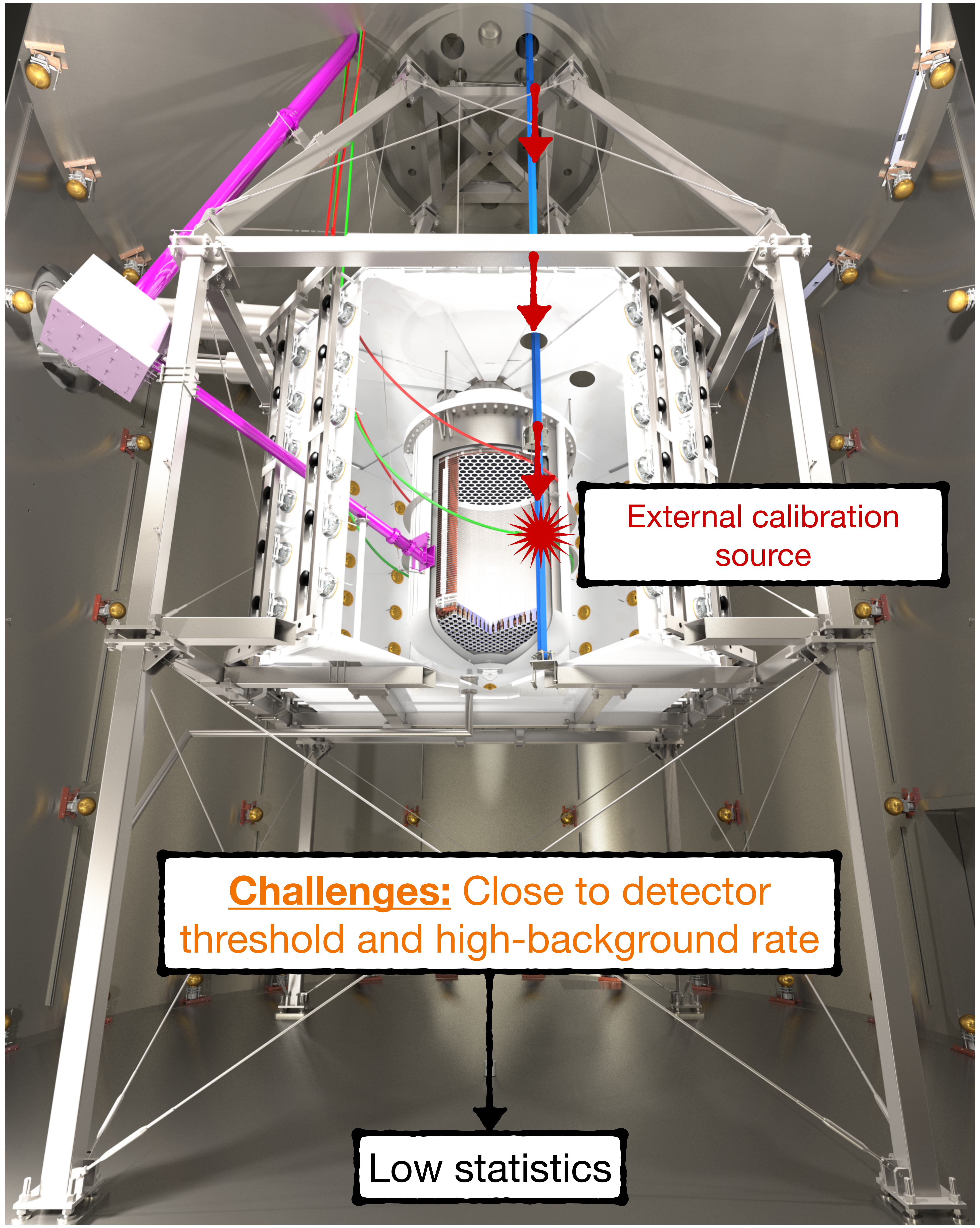
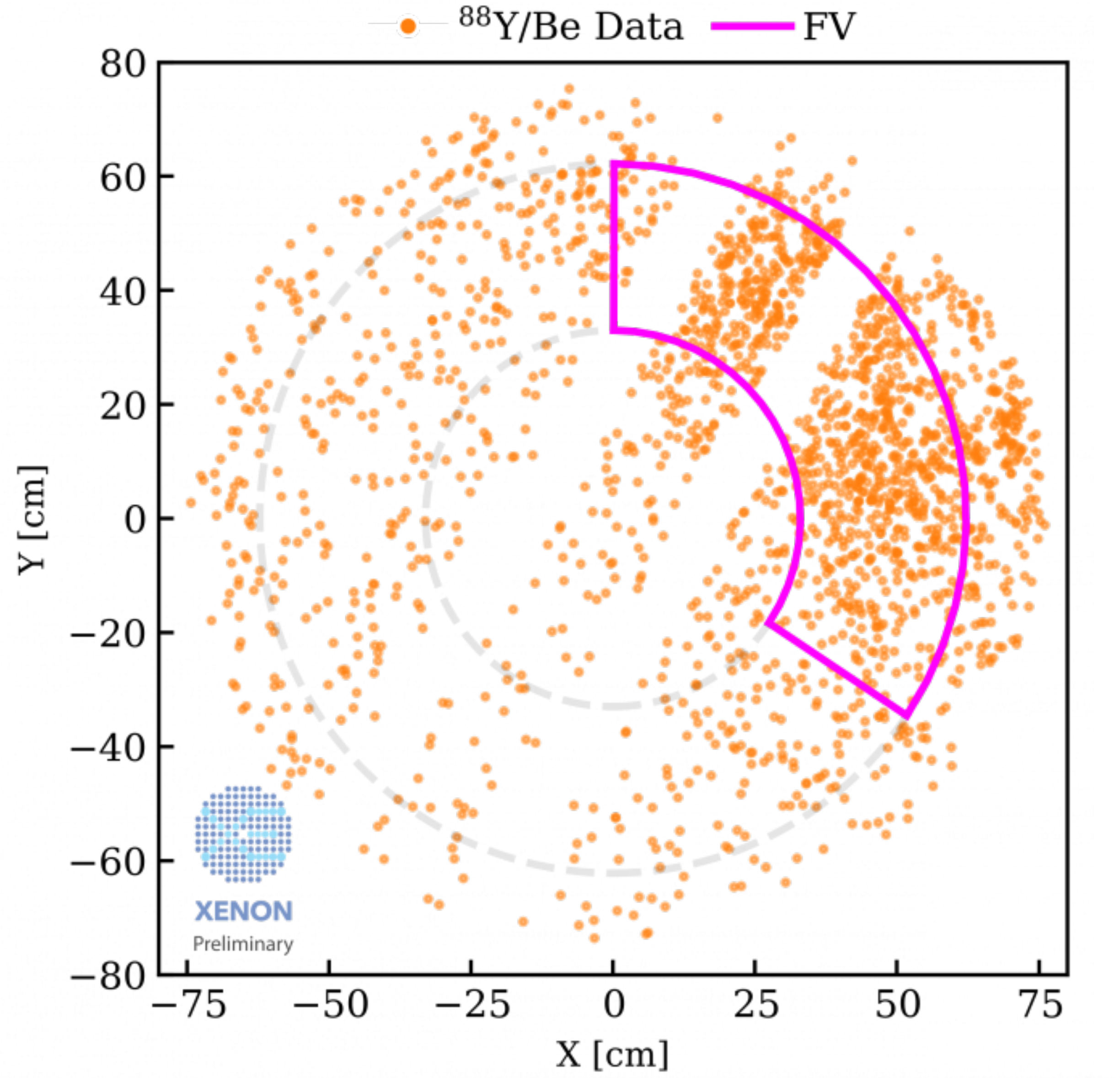
New calibration source:

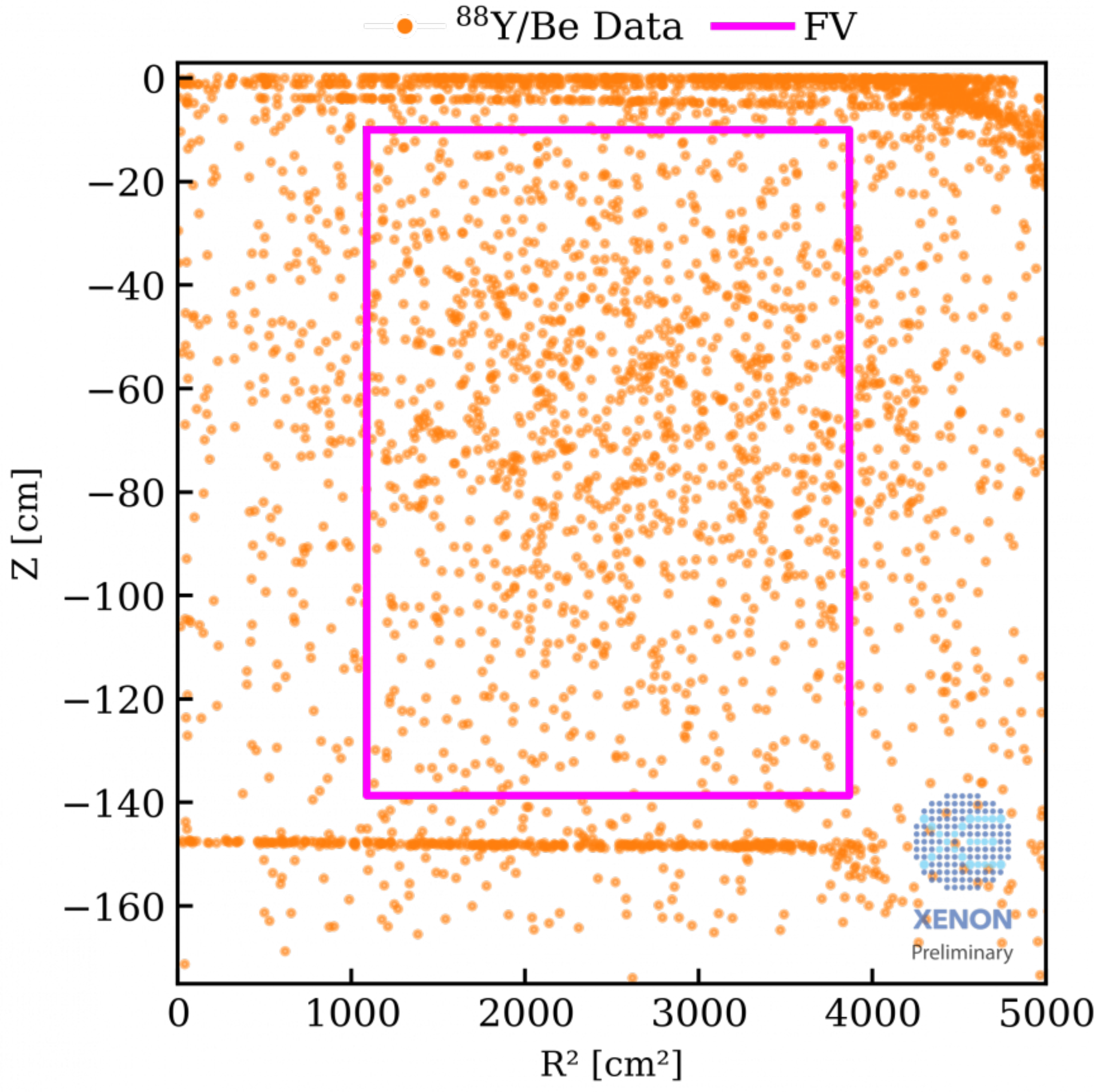
- **Low-energy NR calibration** using external photoneutron source.
- Quasi-monoenergetic 152 keV neutrons produced via:

$$\gamma(^{88}\text{Y}) + ^{9}\text{Be} \rightarrow n + ^{8}\text{Be}$$









^{8}B CEνNS search - Unblinding

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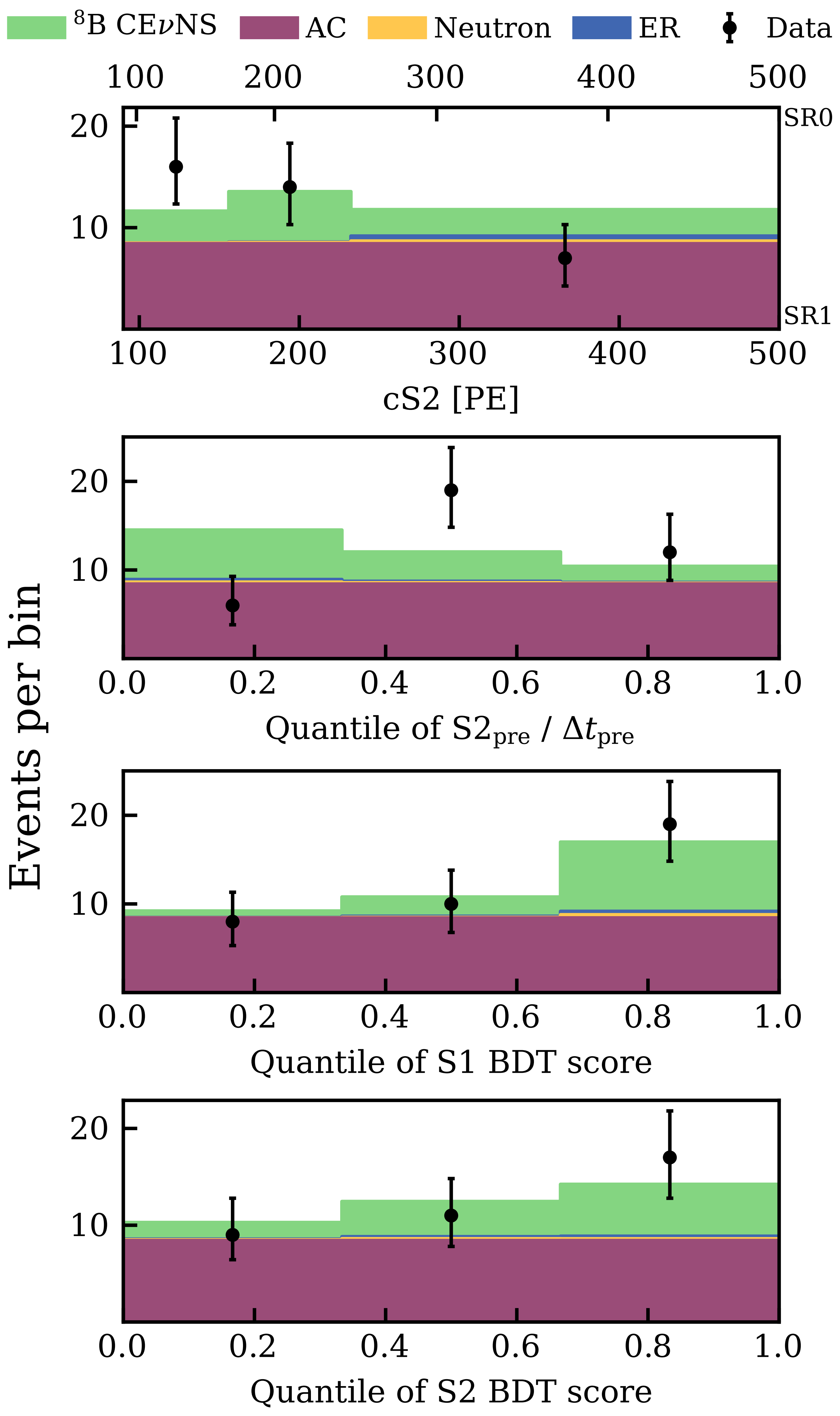

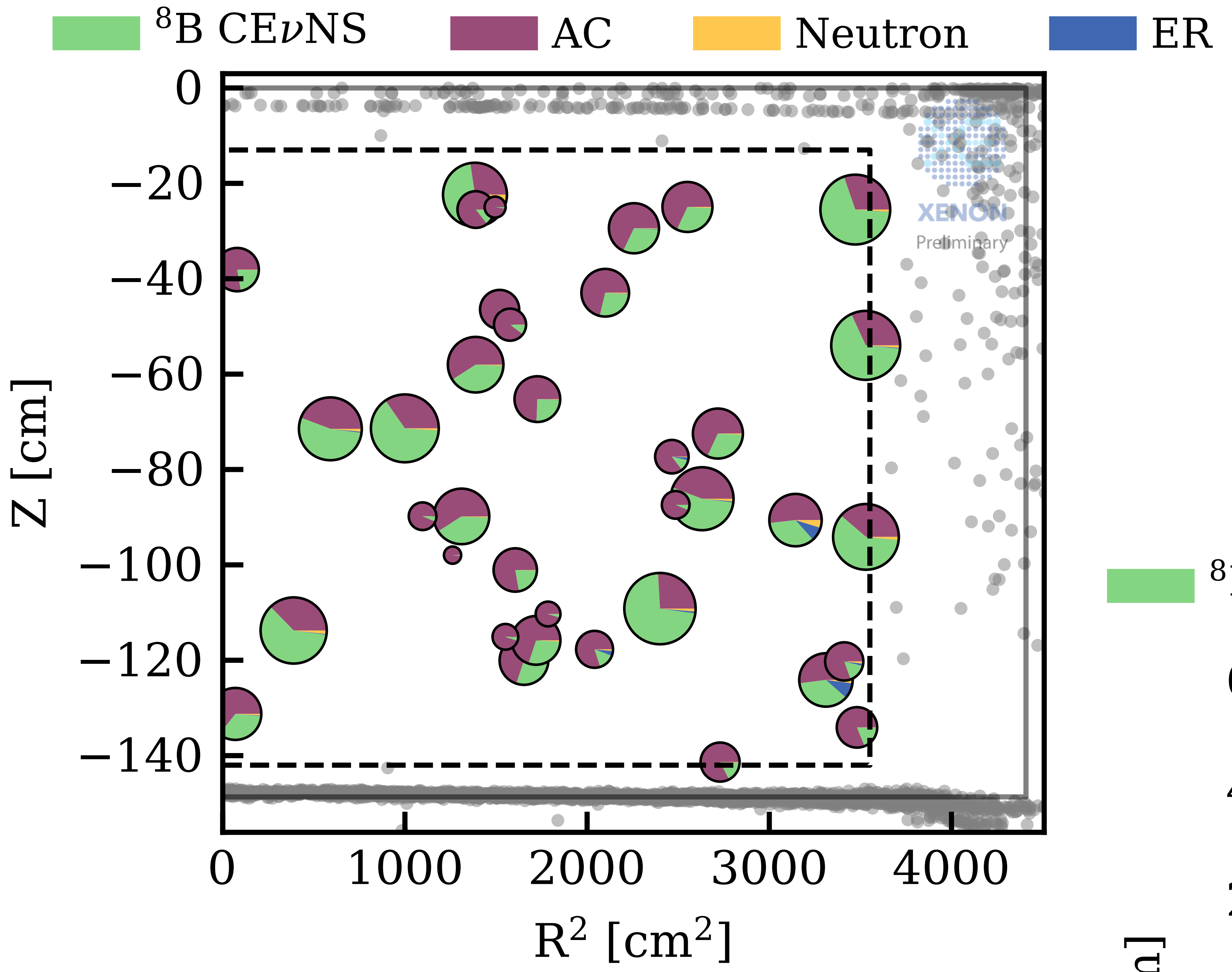

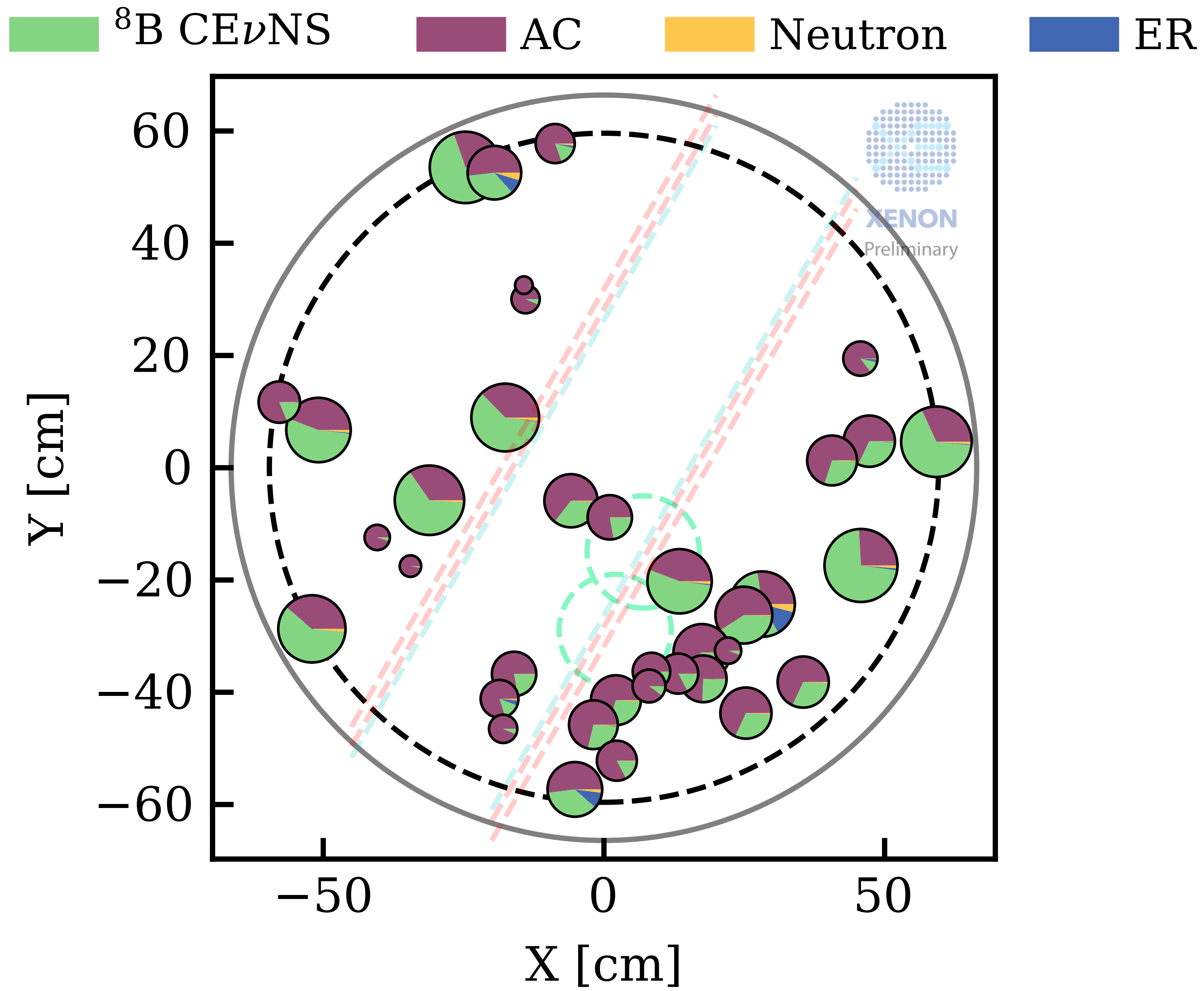

Yields uncertainties

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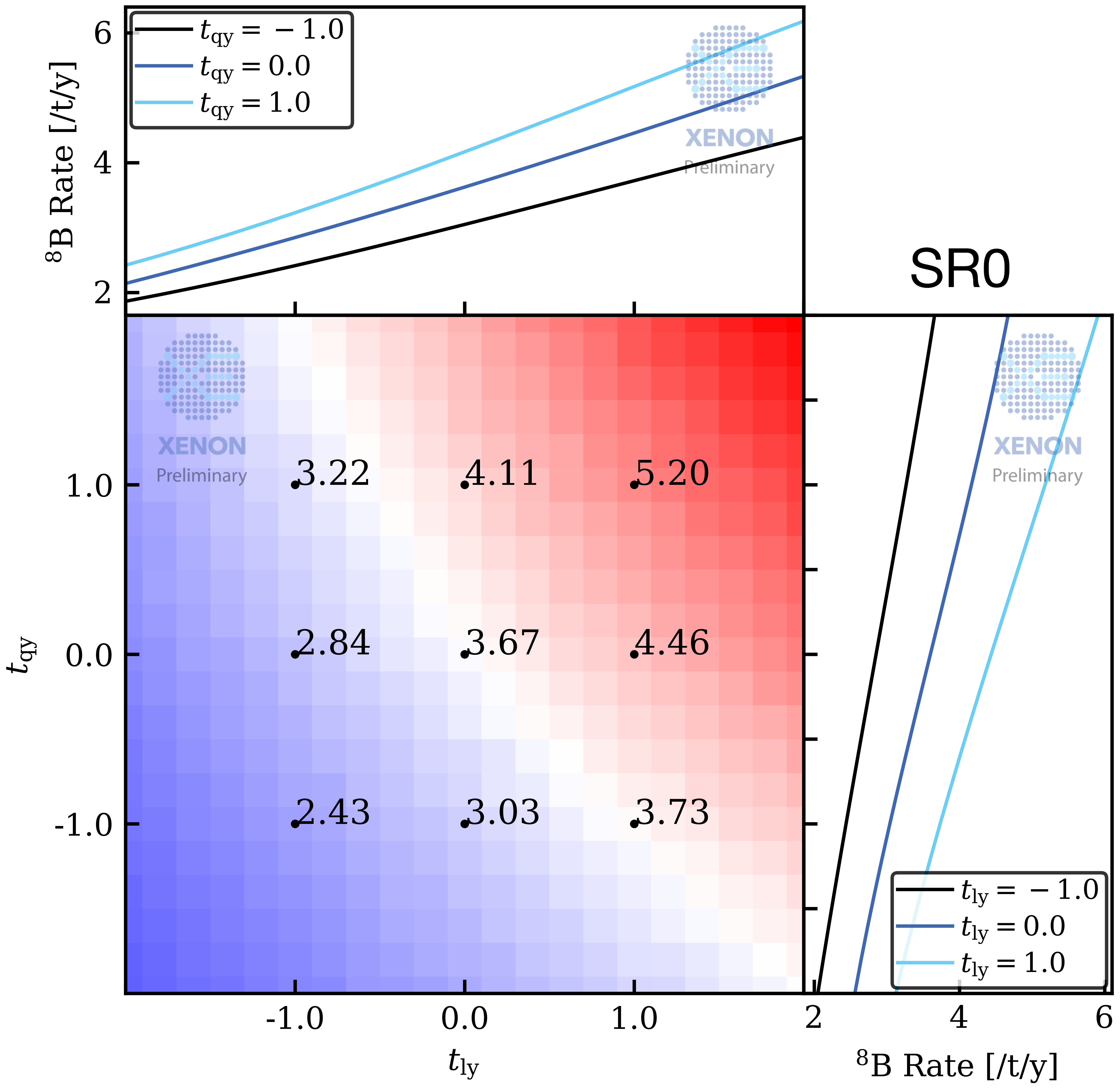


(t_{ly}, t_{qy}) two morphers of the yields: uncertainties of the emission model

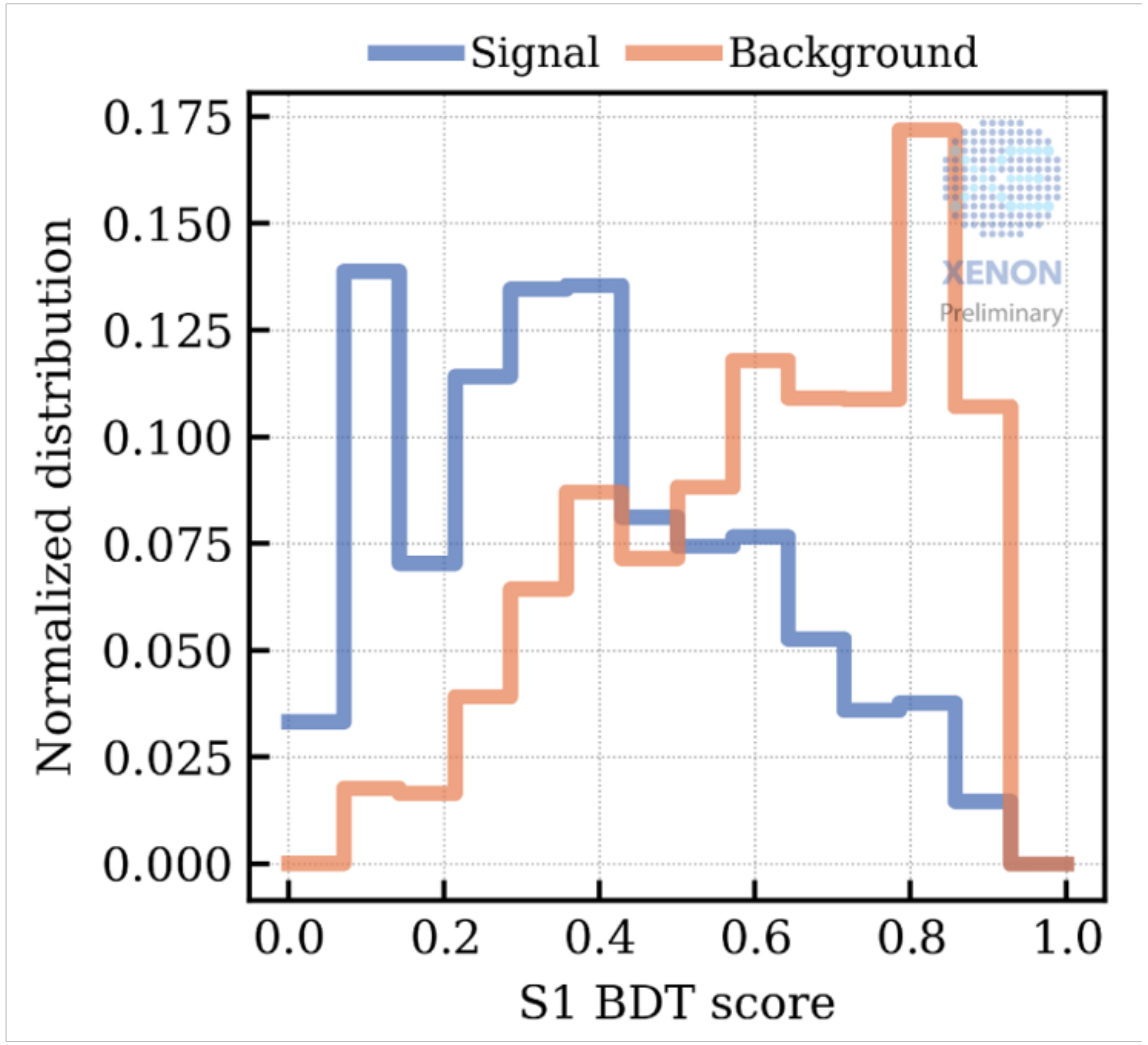
$$LY(t_{ly}) = \langle LY \rangle + t_{ly} \cdot \sigma_{LY}(\mathrm{sign}(t_{ly}))$$
$$QY(t_{qy}) = \langle QY \rangle + t_{qy} \cdot \sigma_{QY}(\mathrm{sign}(t_{qy}))$$

with:

$t_{ly} \sim N(0,1);\ t_{qy} \sim N(0,1)$

S1 BDT

- Waveform–feature–based S1 BDT differentiates isolated S1 signals from random PMT hit clustering.
- Input features: double photo–electron emission, S1 pulse shape, S1 hit counts, PMT channel distribution of S1.
- Trained with a data–driven sample of isolated S1 and simulated ^{8}B S1
- S1 area in the largest–contributing PMT is the most important feature due to the signal–only double photoelectron emission (DPE), where a single photon striking the PMT photocathode produces two photoelectrons with $p \approx 0.2$.
- Enhances signal vs. background discrimination but is significantly weaker than the S2 BDT.



Credit slide: Matteo Guida

S2 BDT

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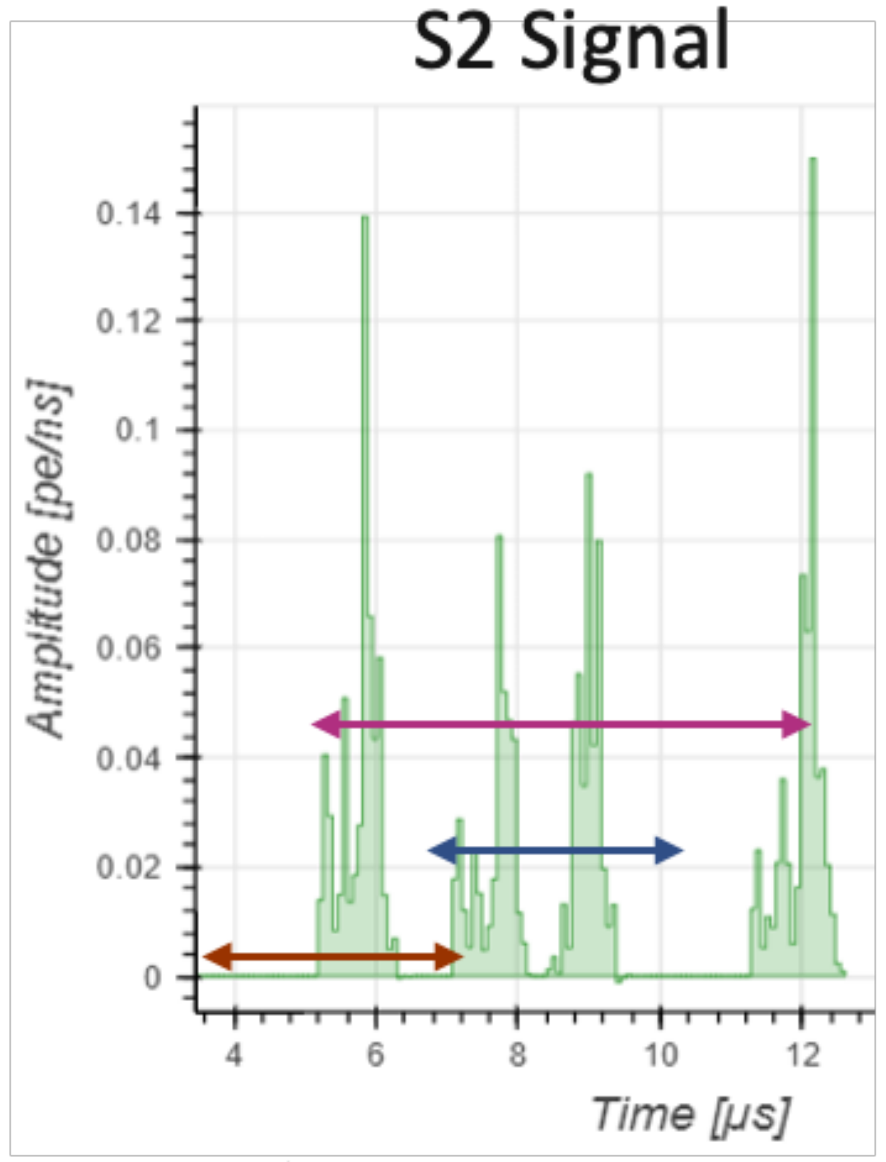
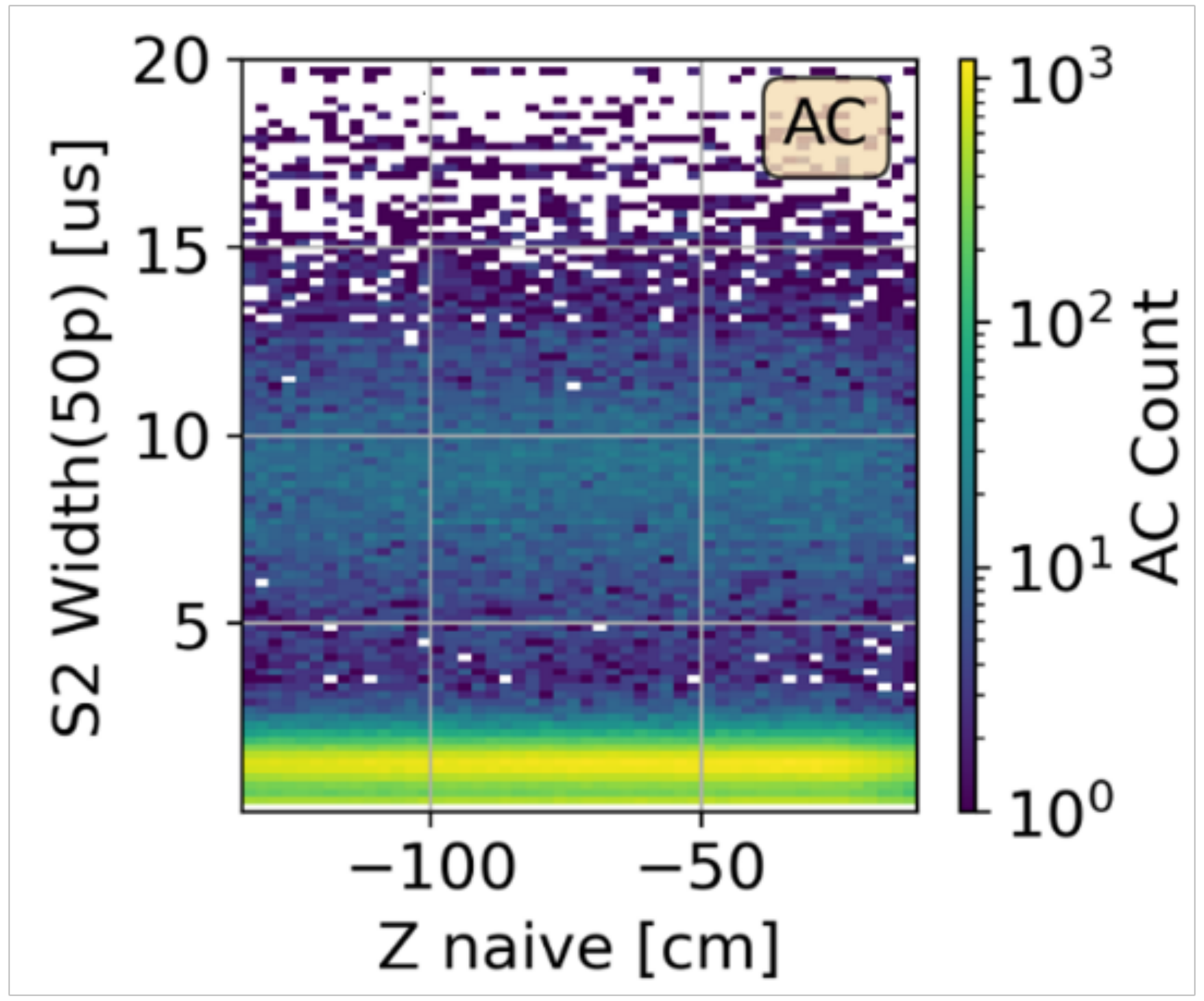
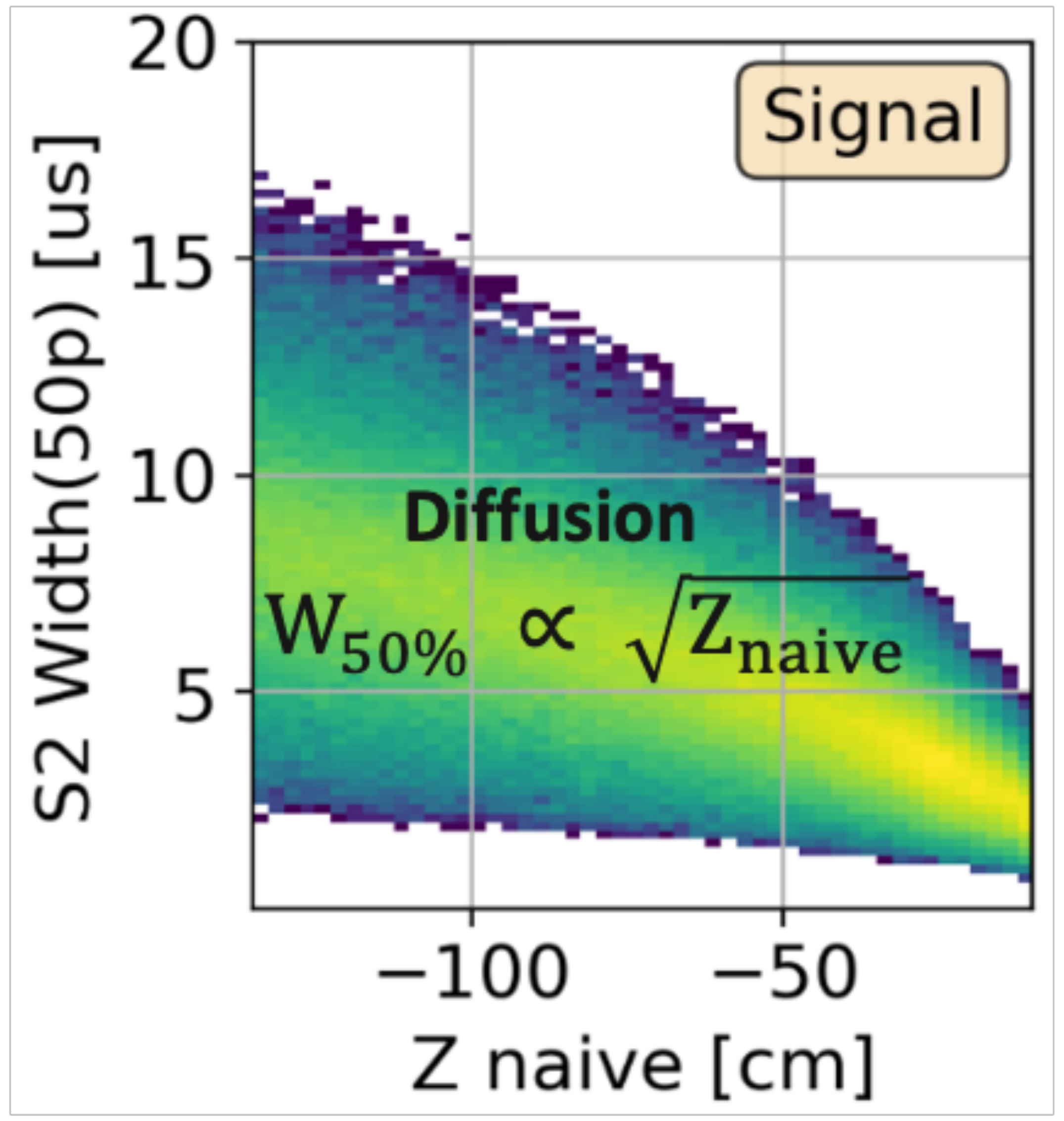
- BDT trained using simulated signal and data-driven AC background, with each feature rigorously validated between data and simulation.



Feature relevance

- 50% width
- Rise time
- 90% width
- z-naive

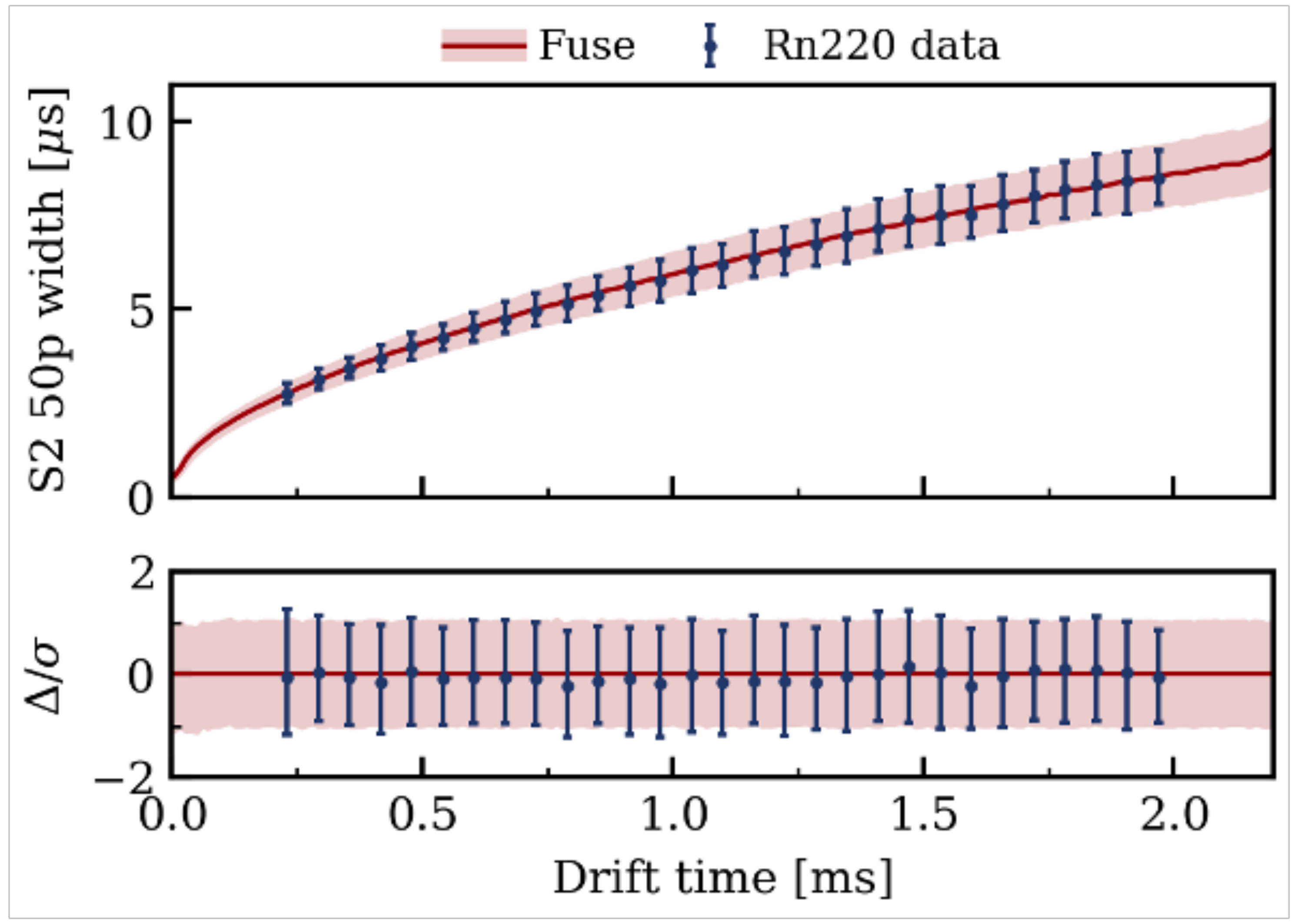




Great agreement between simulation and data.

xenon-fuse 1.3.0

```
pip install xenon-fuse
```

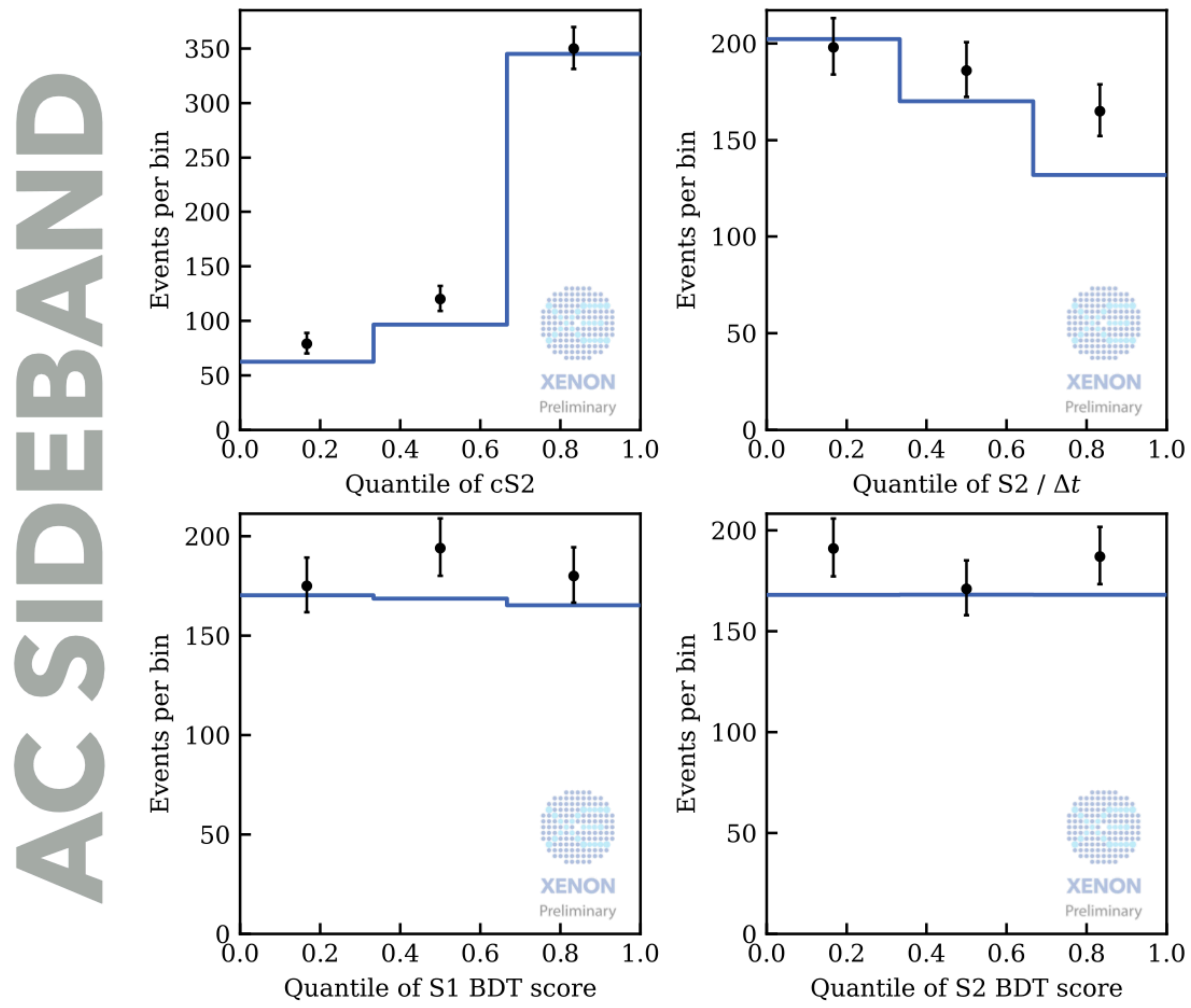


Credit slide: Matteo Guida

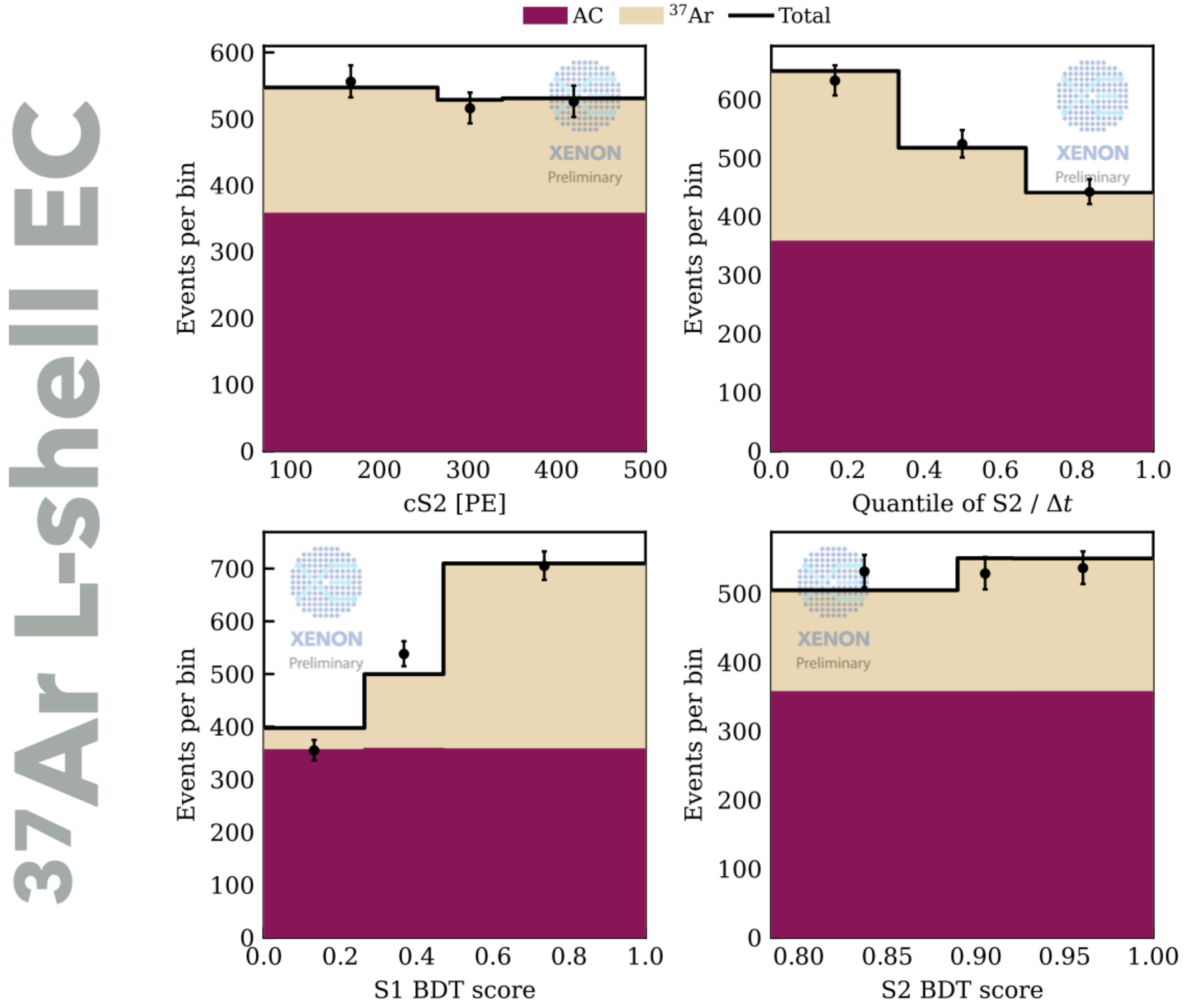
Credit slide: Lanqing Yuan

VALIDATION OF AC MODEL

arXiv:2408.02877



Publication in preparation



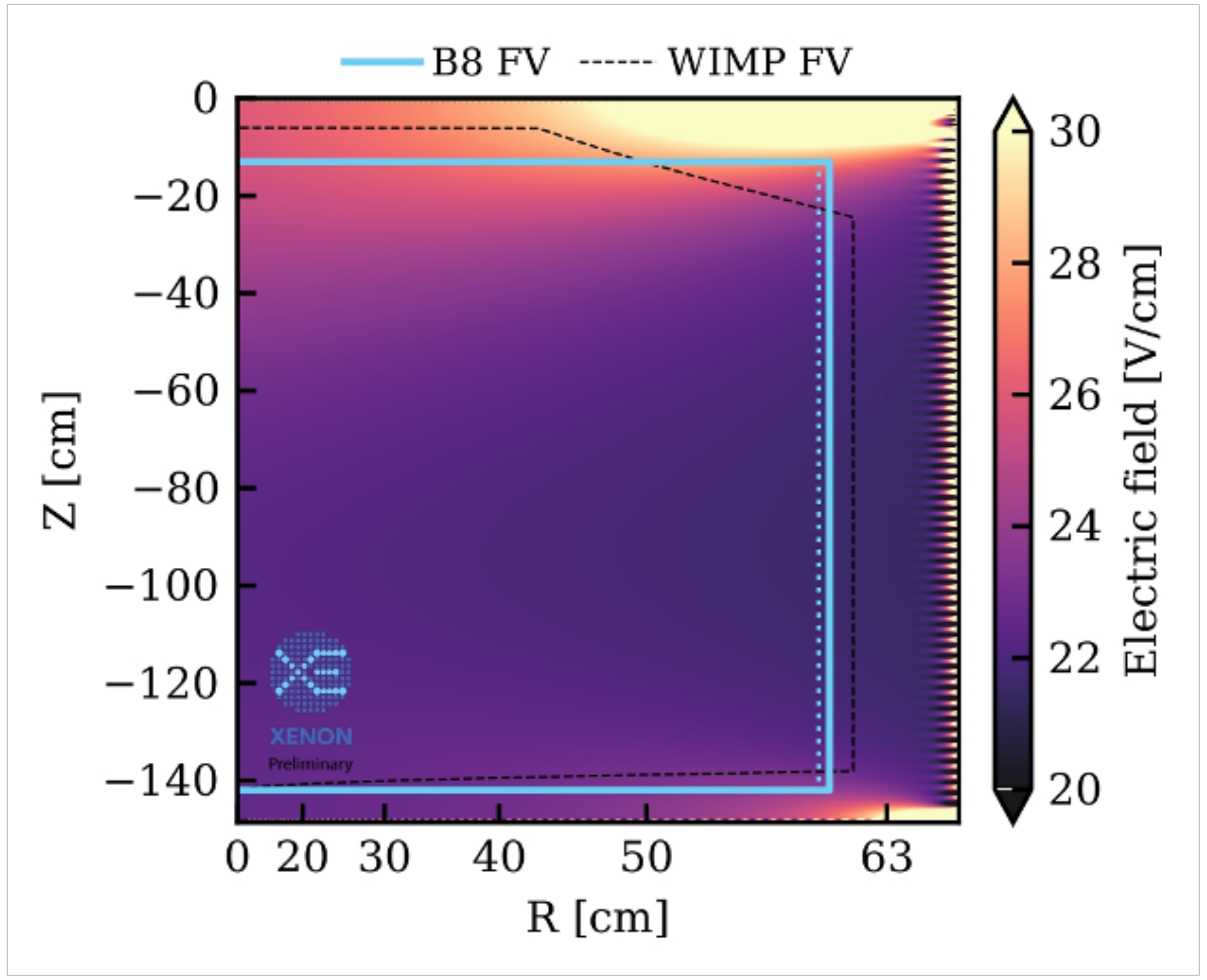
- **Validated** by AC sideband unblinding (events that failed S2 BDT cuts)
- The difference (<10%) is considered when determine systematic uncertainty
- **Validated** by ^{37}Ar L-shell 0.27 keV ER calibration data
- Constrained ER light yield with 1598 observed events

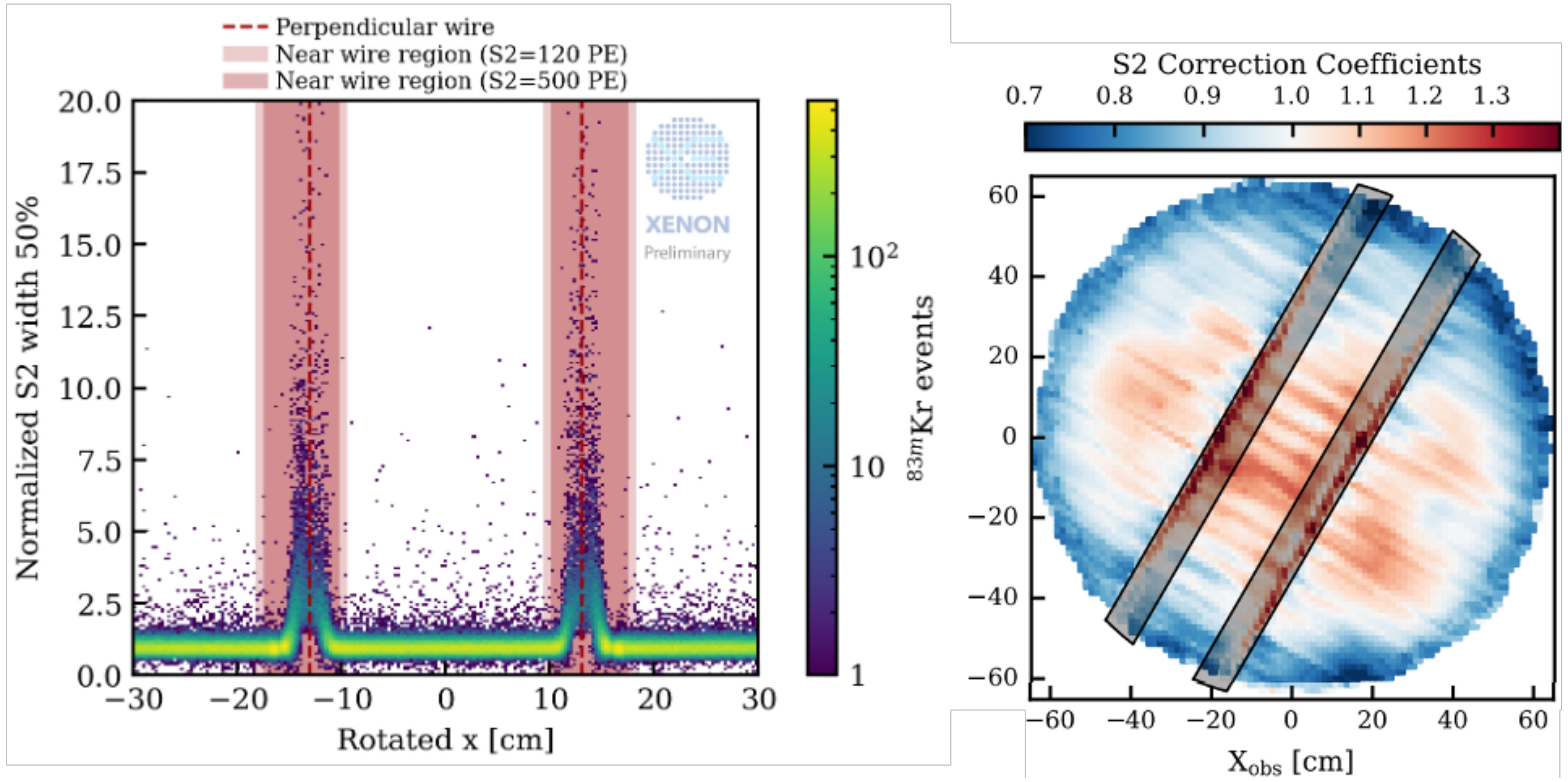
Fiducial Volume

- Unlike WIMP, the B8 FV was not optimized based on signal and bkg predictions. It was selected to:
  - top/bottom → no areas with limited detector modelling
  - radius → minimize surface bkg to a negligible level.

- Events near wires are excluded from analysis due to insufficient simulation fidelity.

- S2 pulse shape varies near perpendicular wires, causing systematic errors if S2 BDT (trained on simulation) is applied.





Credit slide: Matteo Guida

Signal and Background model

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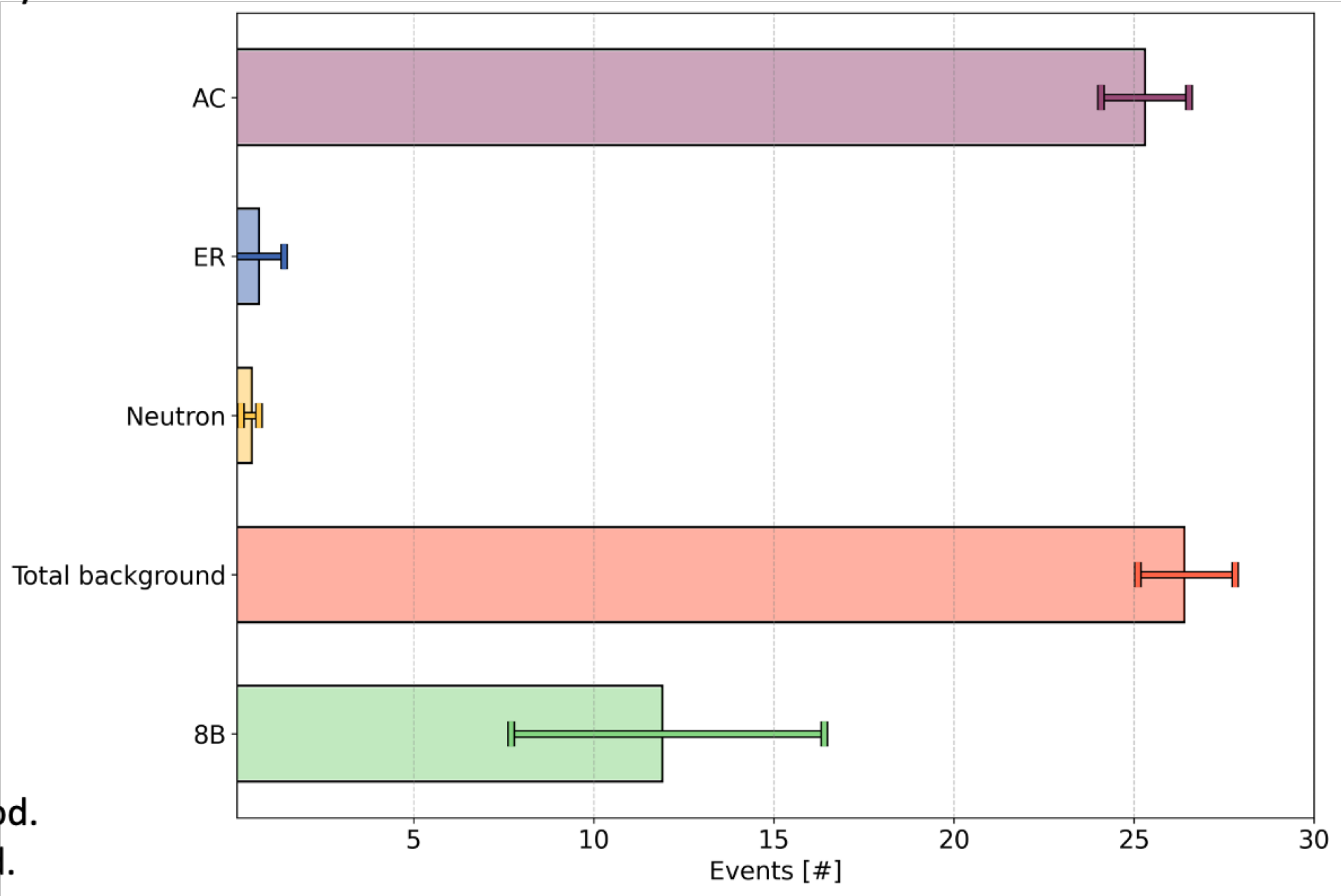
- **AC**: uncertainty from discrepancy in derived by the sideband unblinding.
- **B8**: 35% uncertainty from yields & efficiency. Flux is a free parameter.
- **ER**: Electronic recoil background with flat spectrum 0-10 keV Conservative 100% uncertainty from yields.
- **RG**: Radiogenic neutron background, 58% uncertainty derived from the sideband.
- Surface background: not included in likelihood. Fiducial volume such that it can be neglected.



Credit slide: Matteo Guida

Time Shadow Cut

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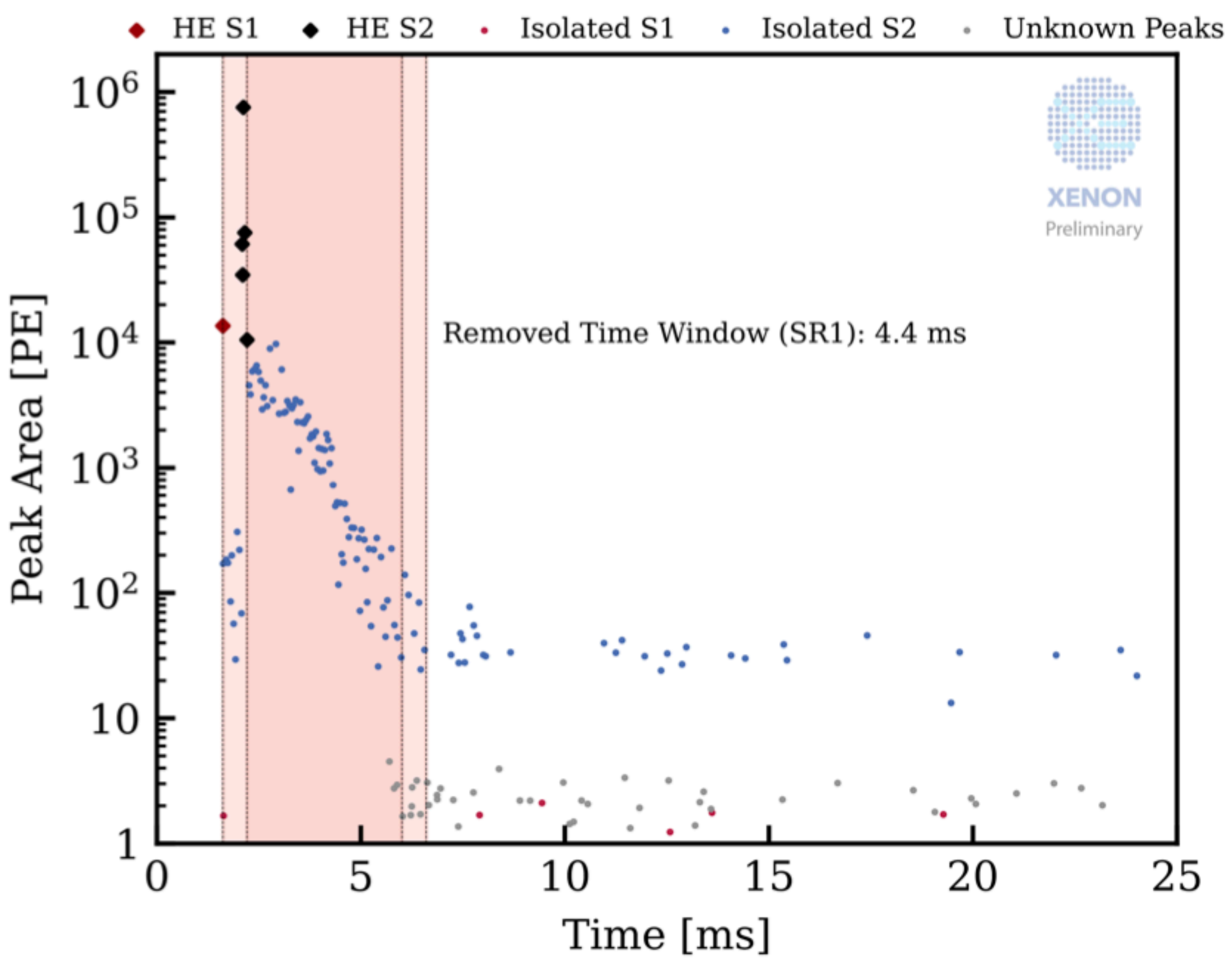

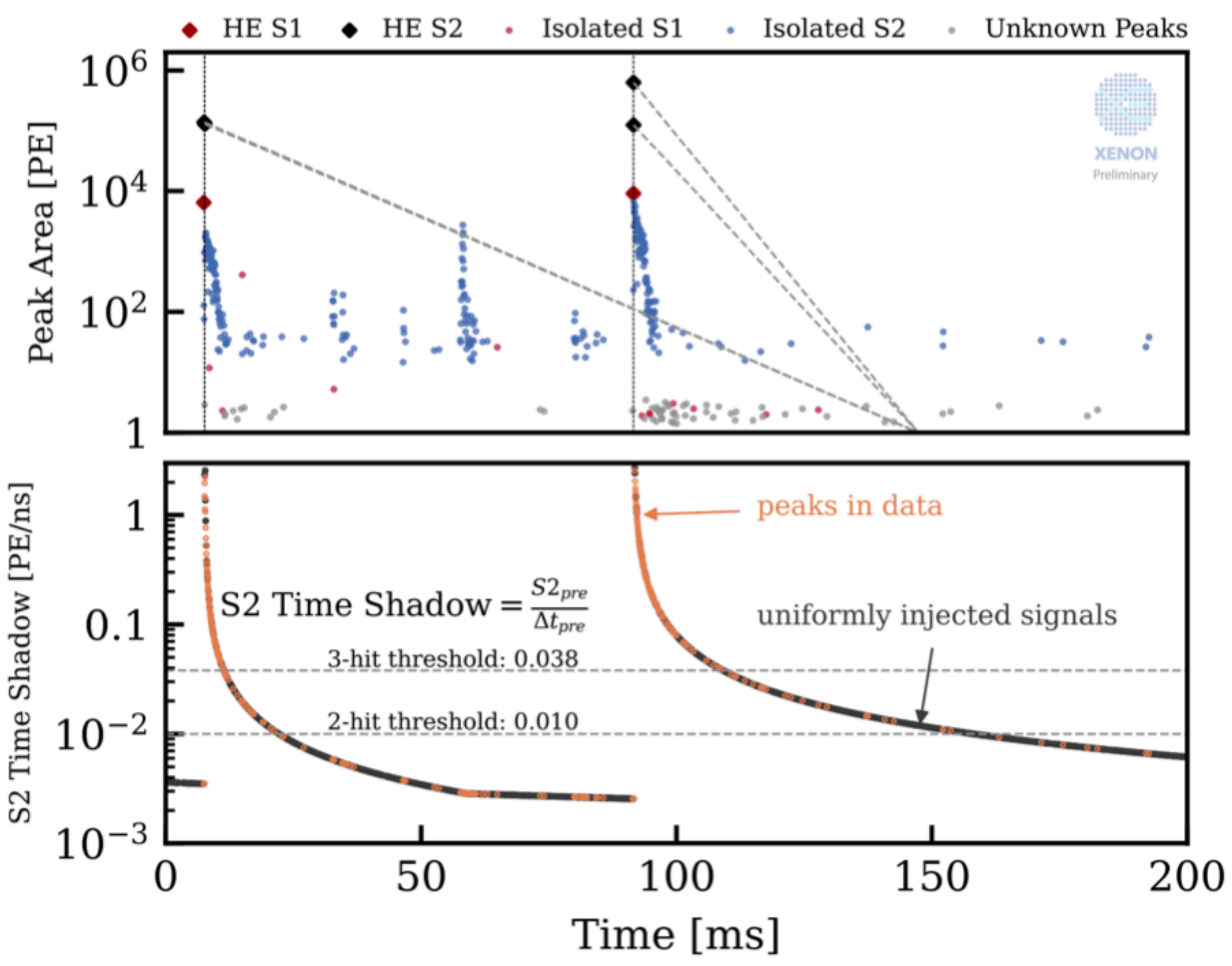

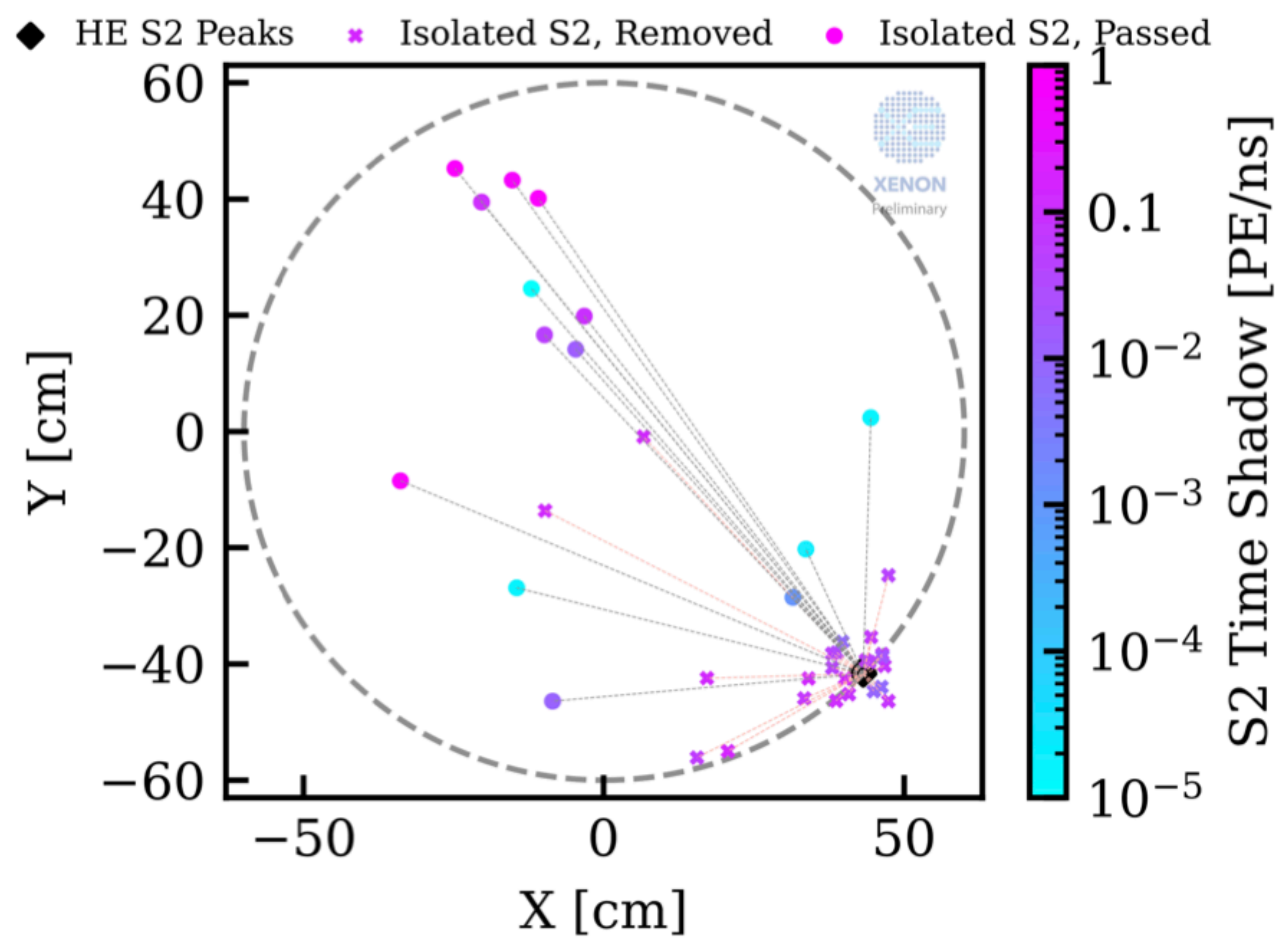

From XENON1T to XENONnT

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UPGRADE

x3 larger TPC
8.5 t LXe
494 PMTs

Xenon handling
New purification
& ER bkg. reduction
New recovery/storage

Water Cherenkov Neutron Veto
Gd-doping ongoing

Goal →

More target mass
Reduced background level