XENON

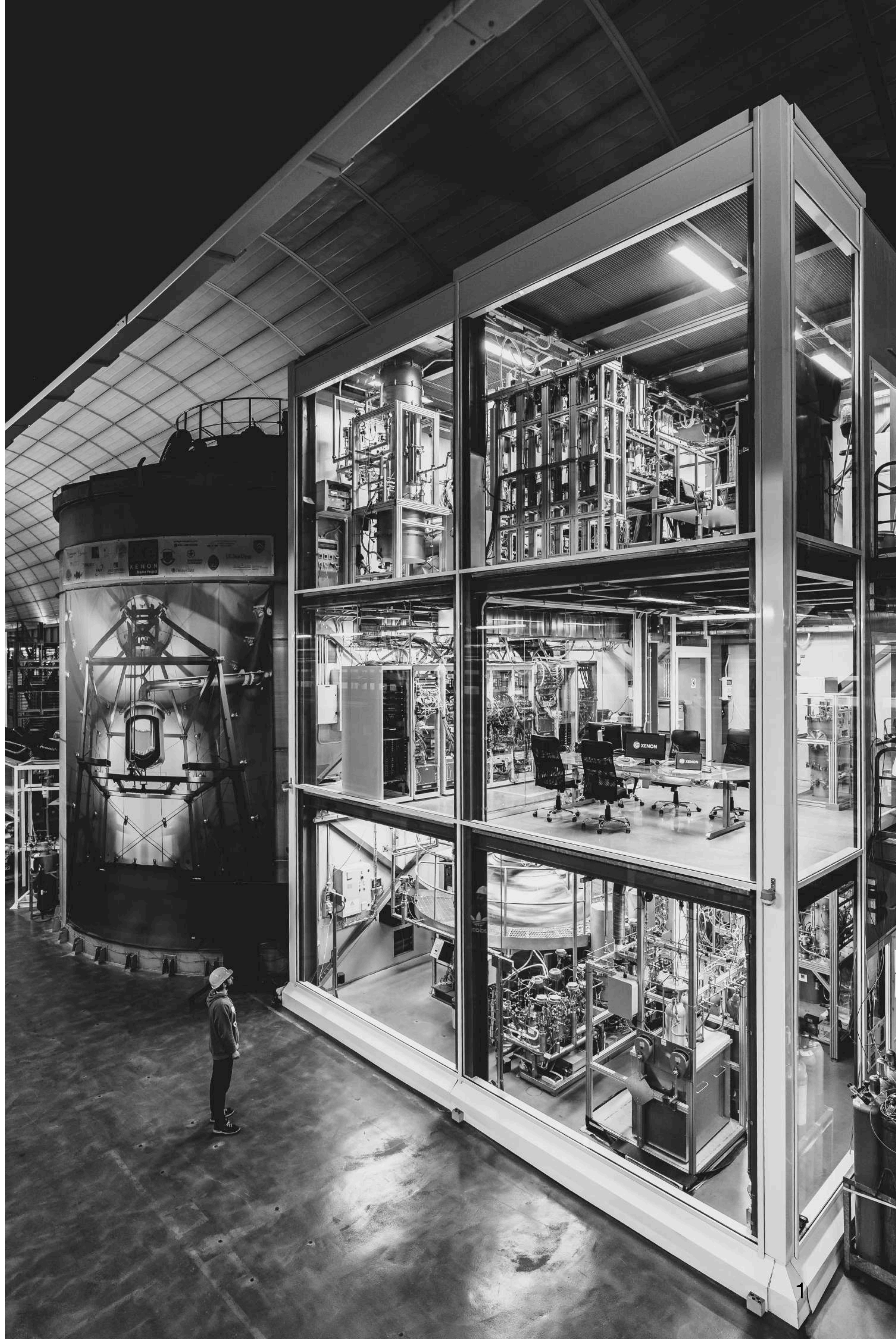
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Venturing into the Neutrino Fog

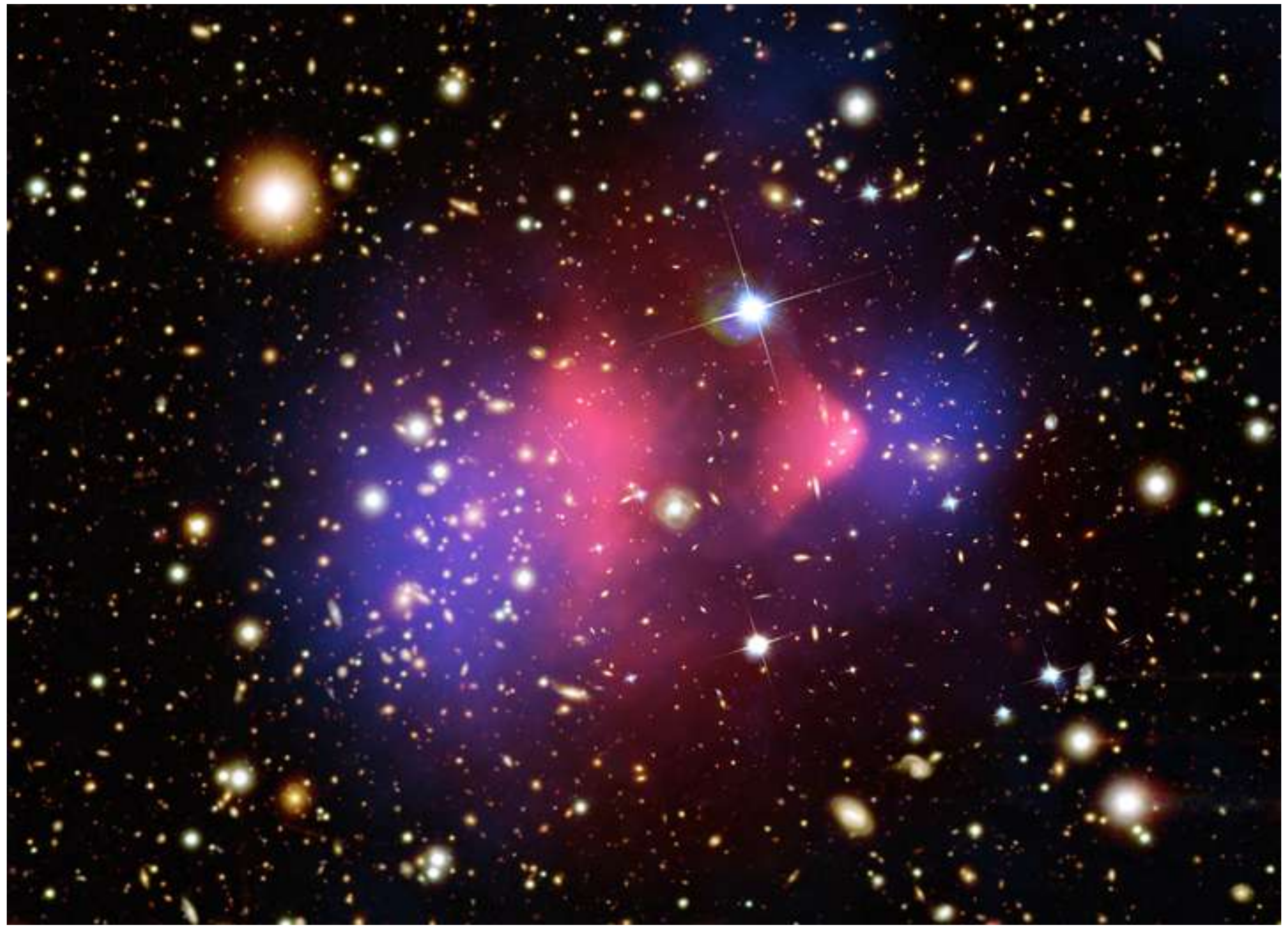
Solar ^{8}B neutrino search in XENONnT

Phys. Rev. Lett. 133, 191002

Dacheng Xu
Columbia University
Particle Physics Seminars @ BNL
November 7th, 2024



Why DM and How to Search for it?

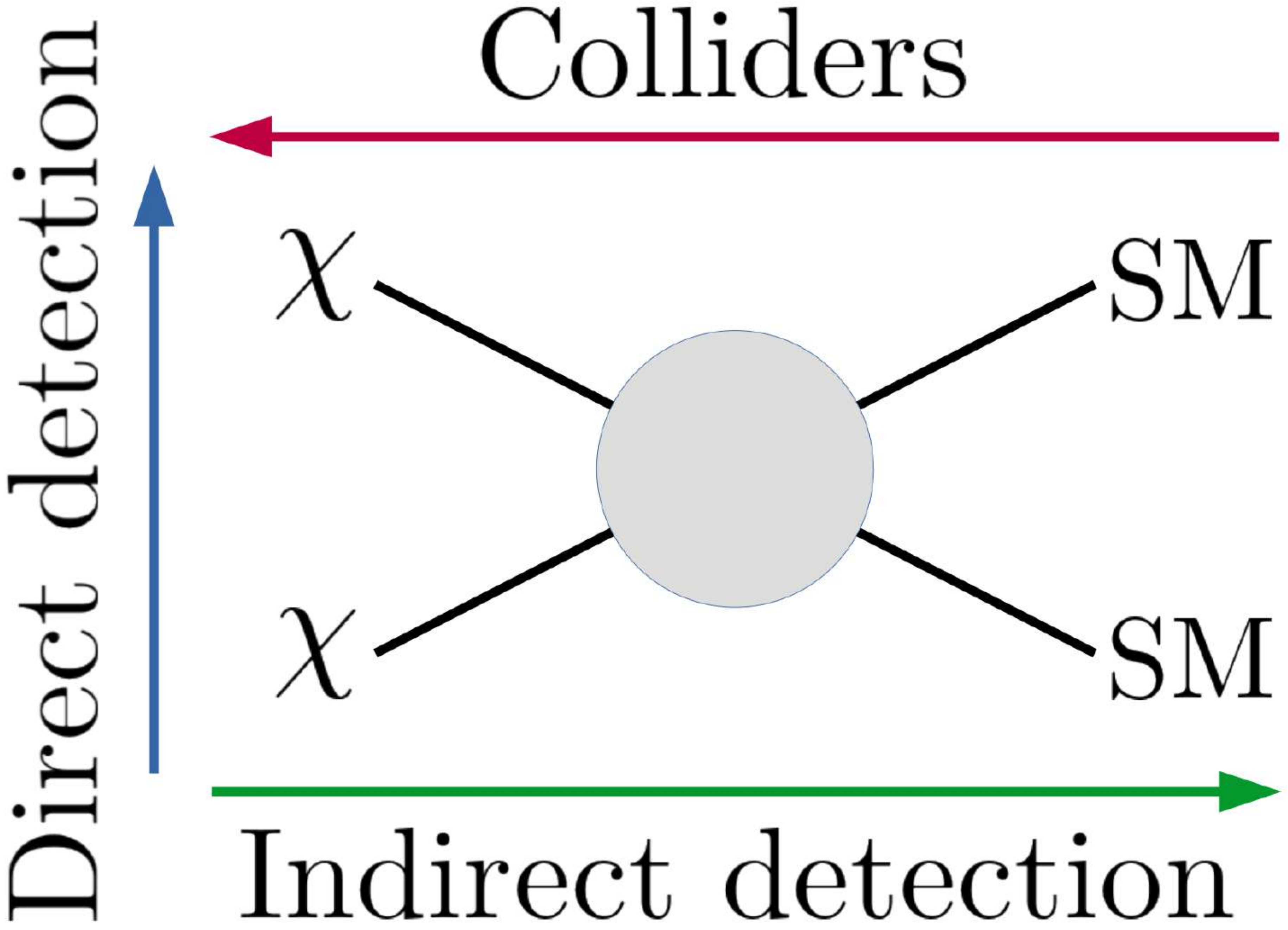


NASA, https://chandra.harvard.edu/photo/2006/1e0657/

Astrophysical and Cosmological evidence:

Without dark matter, the night sky would be dark,

and there would be no one to see it.



Prog.Part.Nucl.Phys. 119 (2021) 103865

Produce DM, wait for its annihilation,

or detect the interaction of DM

with Standard Model Particles.

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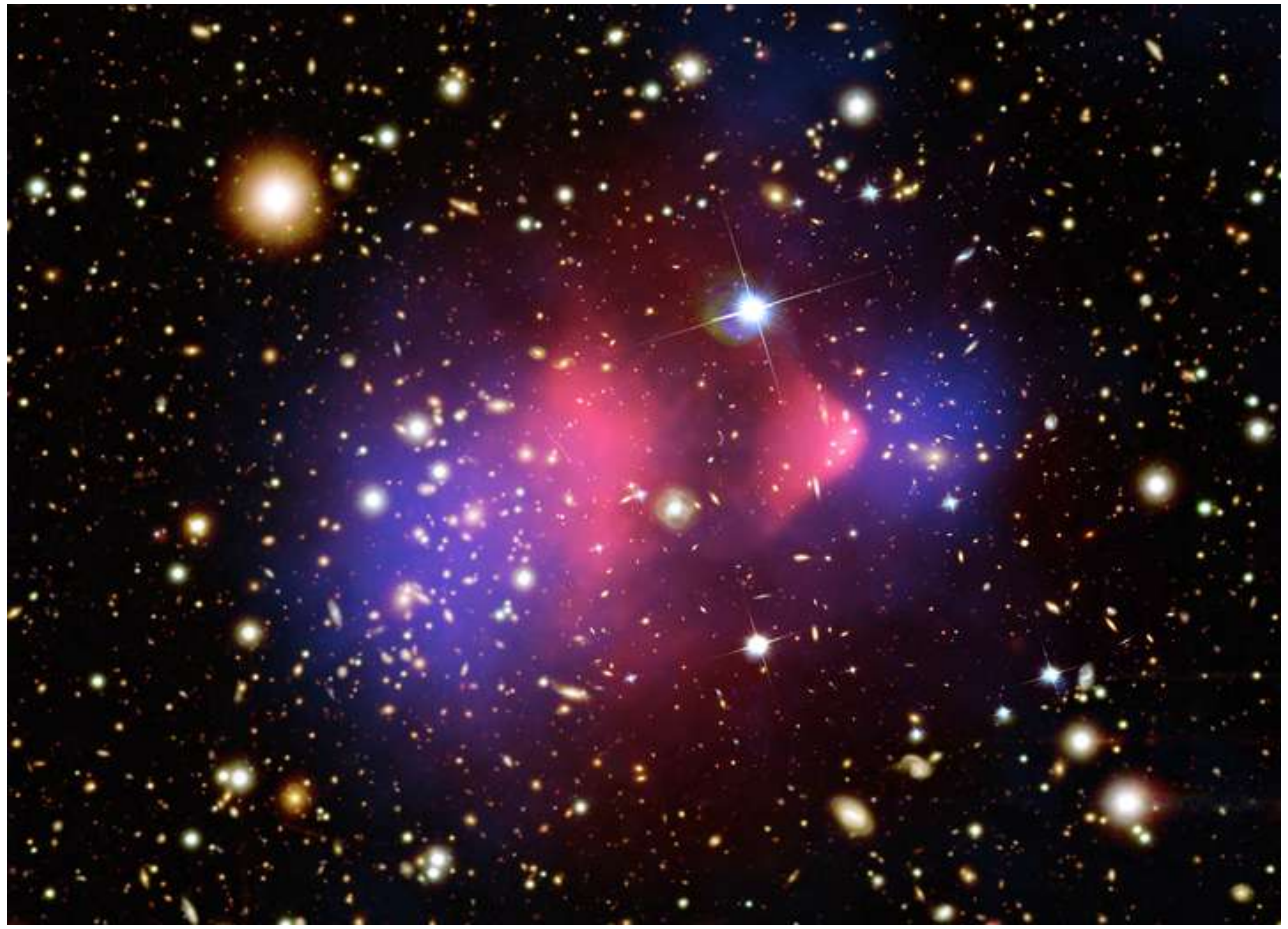

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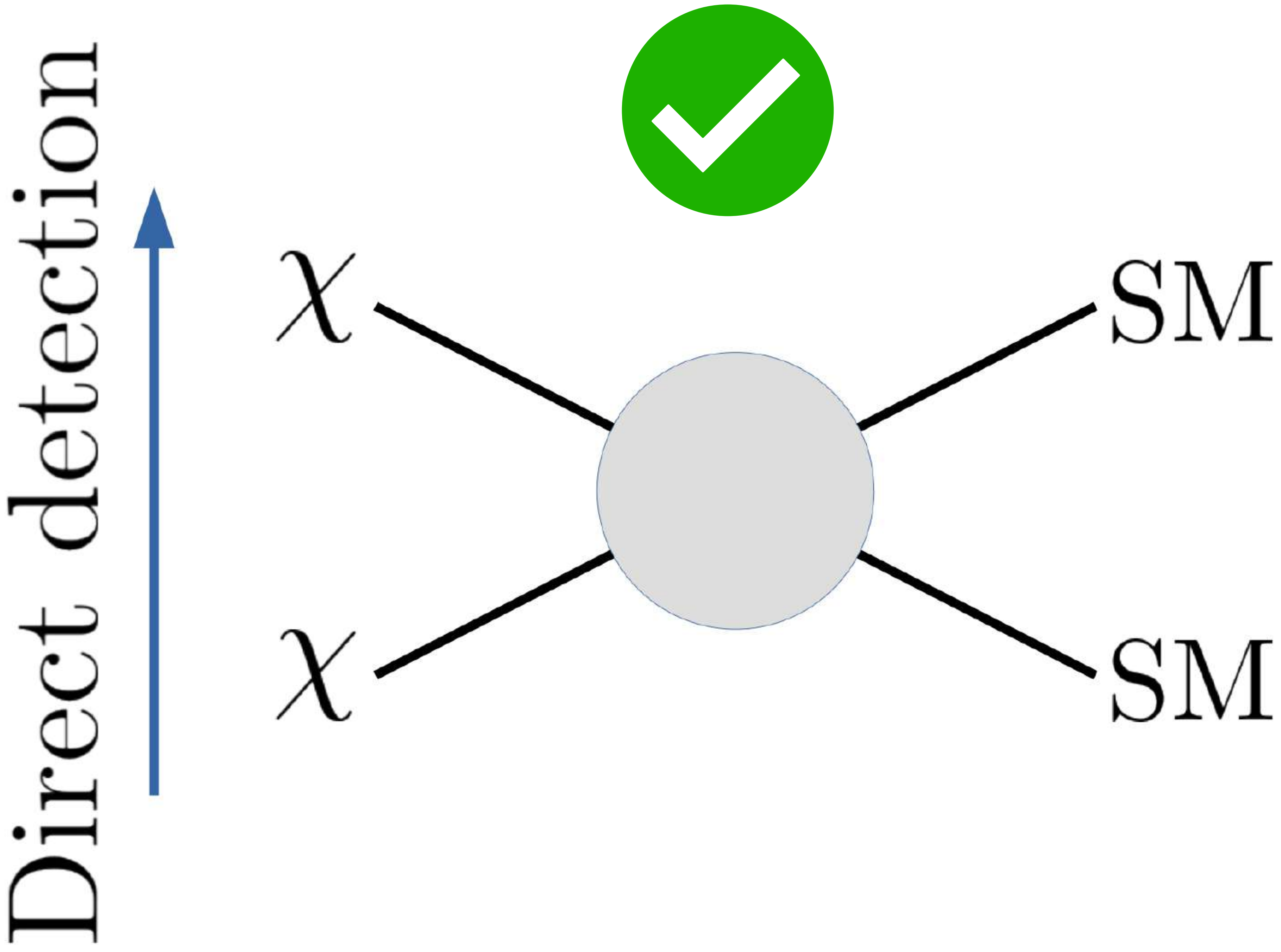

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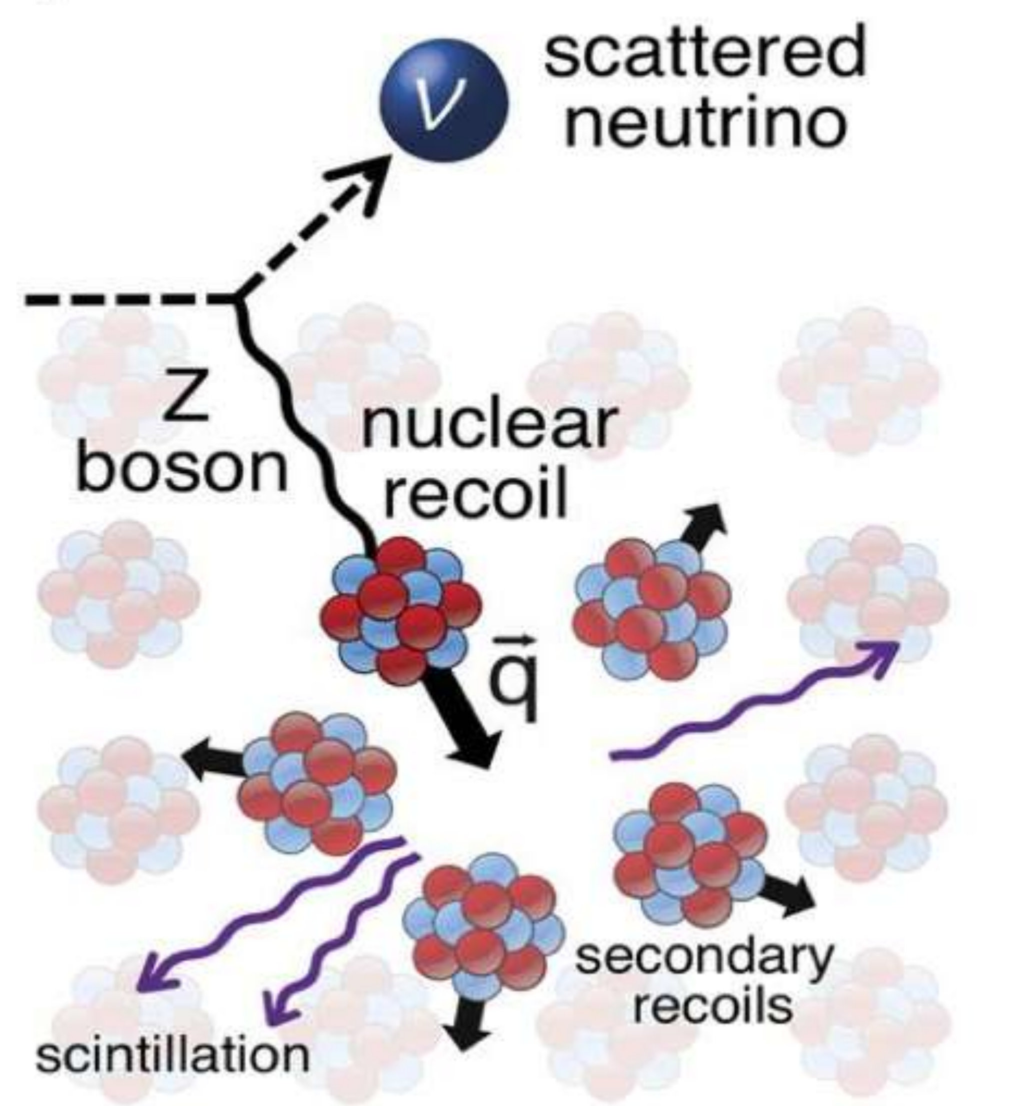
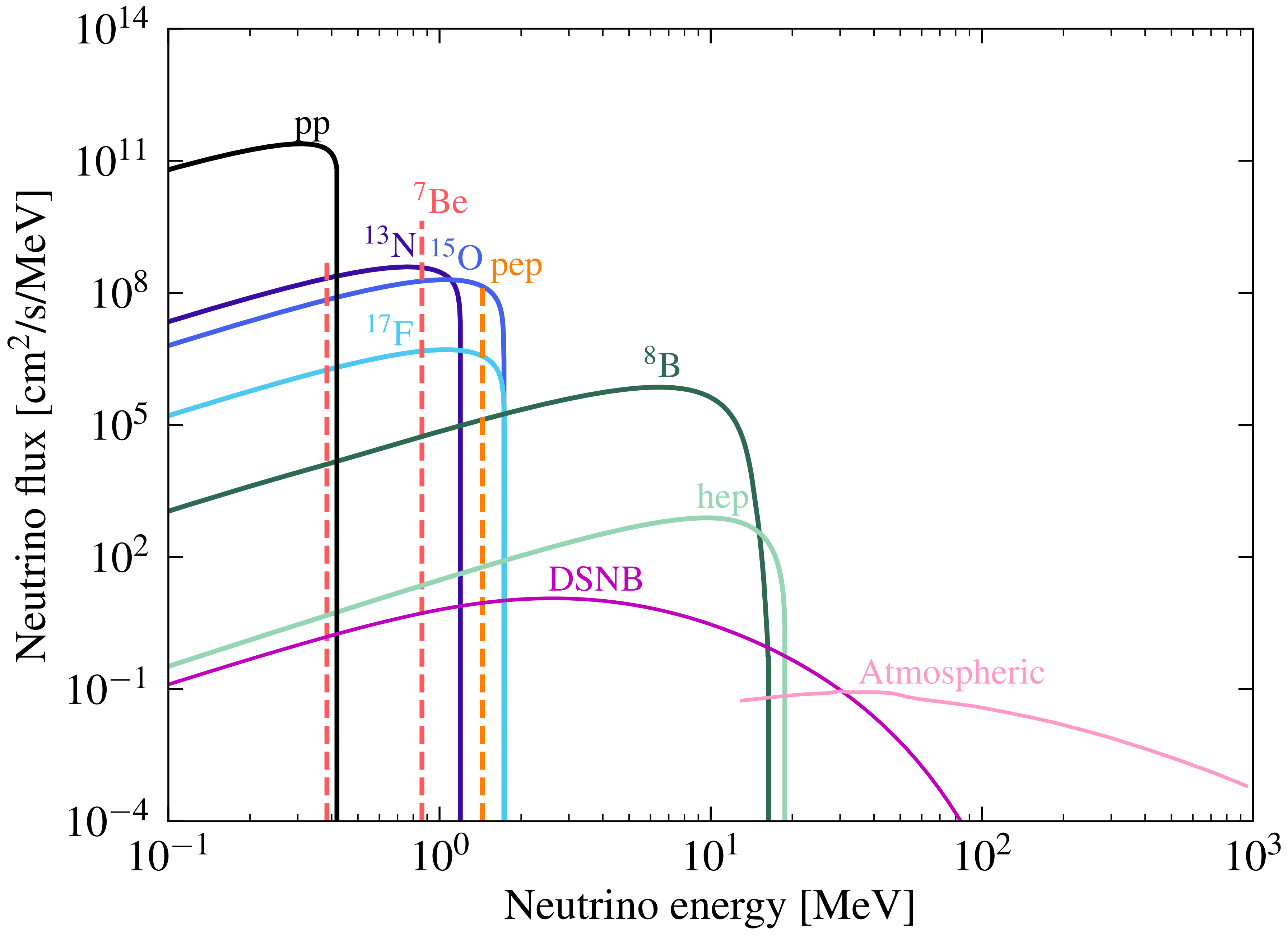
Neutrino Fog for WIMP

COHERENT, Science 357 (2017)

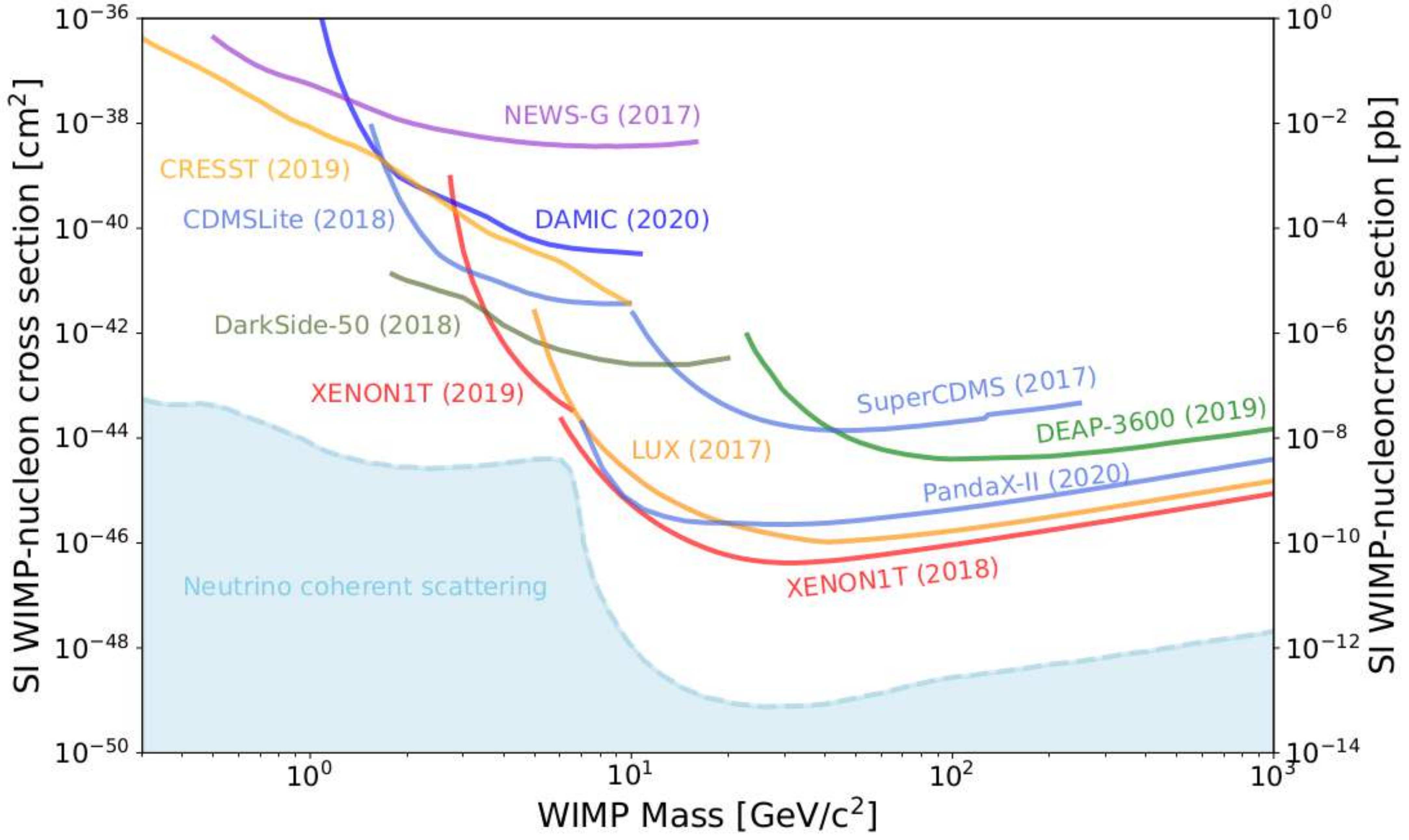


- To-date no evidence for WIMPs so we have set limits
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Solar neutrino is the unavoidable background for DM

European Physical Journal C, 81, 907 (2021)



Symmetry 2024, 16(2), 201



Neutrino Fog for WIMP

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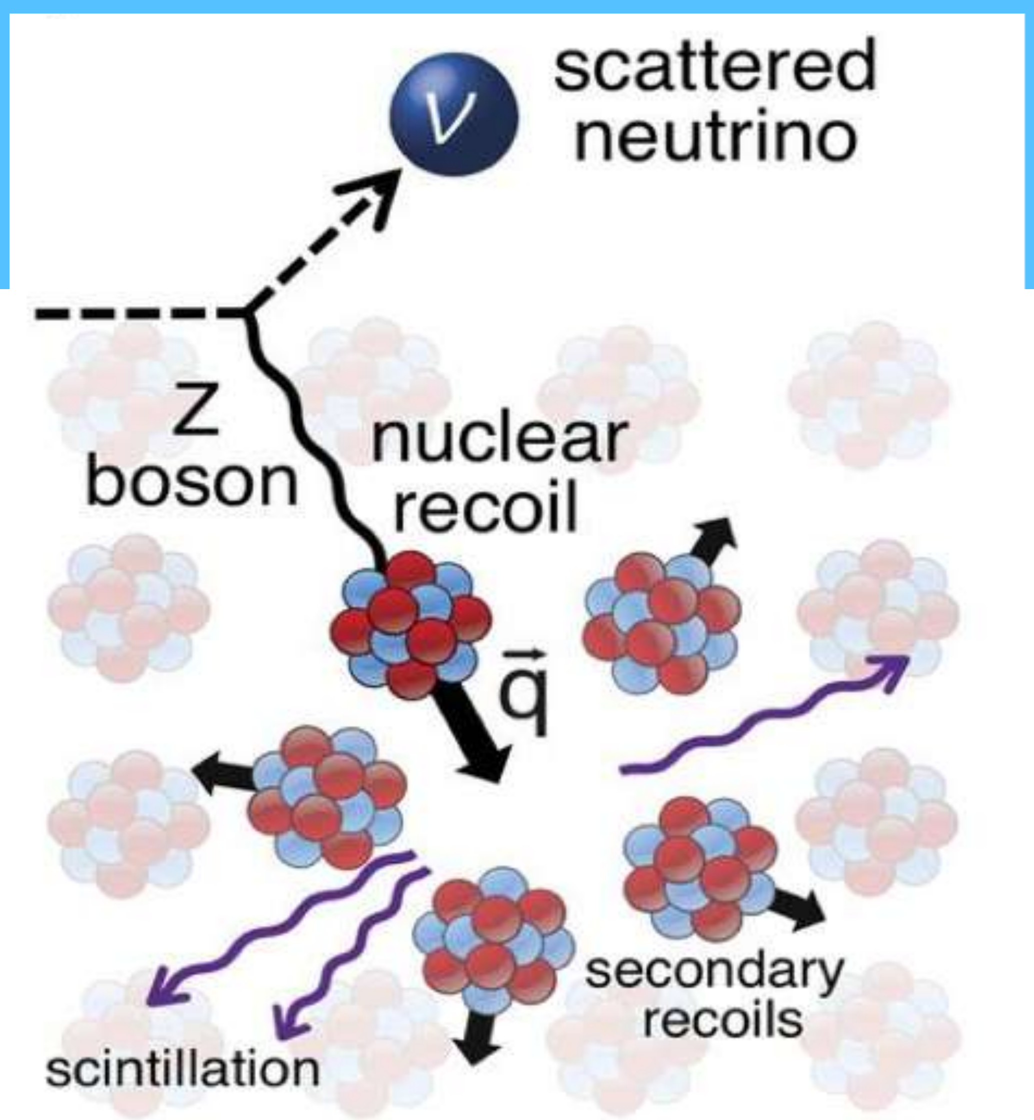

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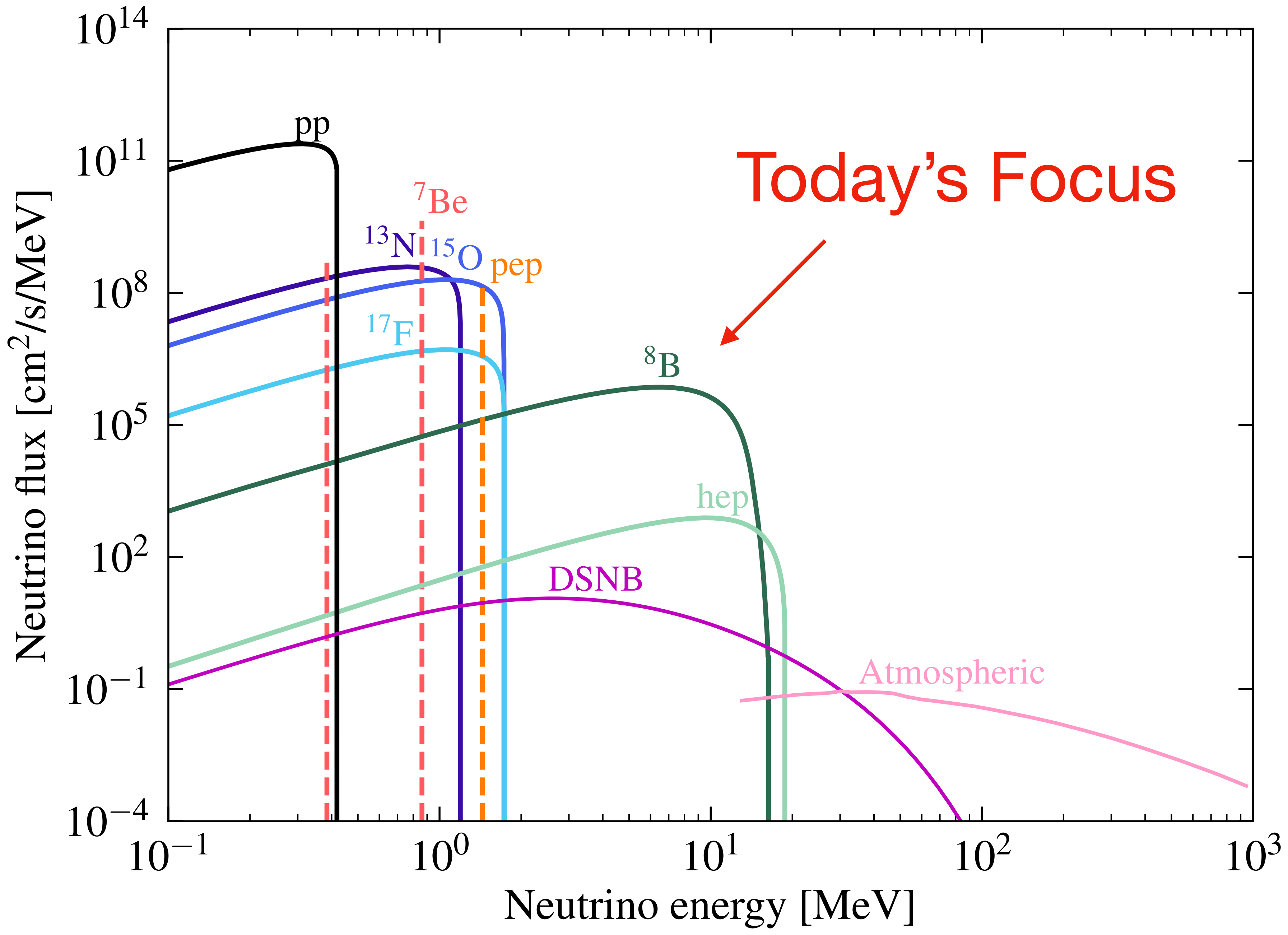

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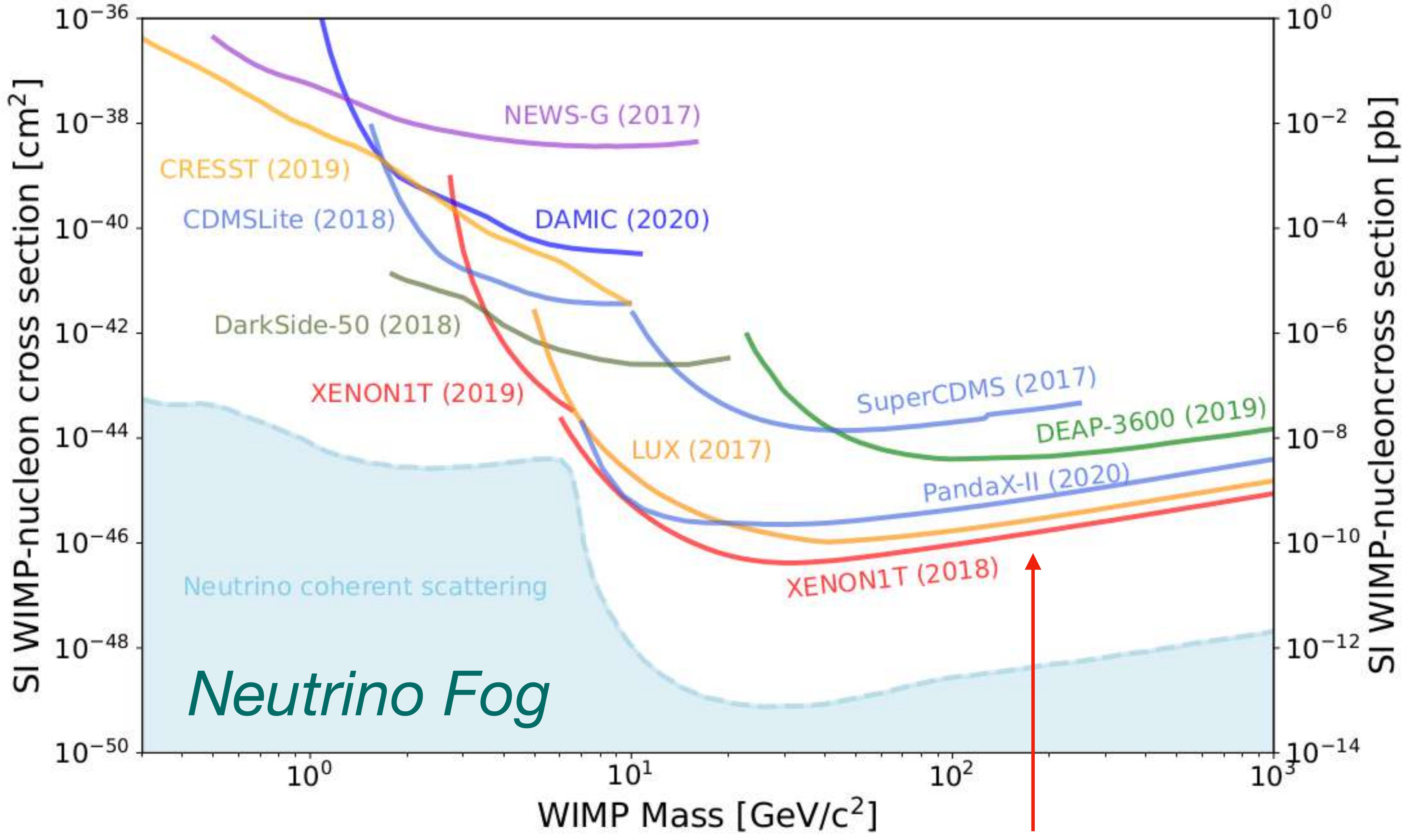
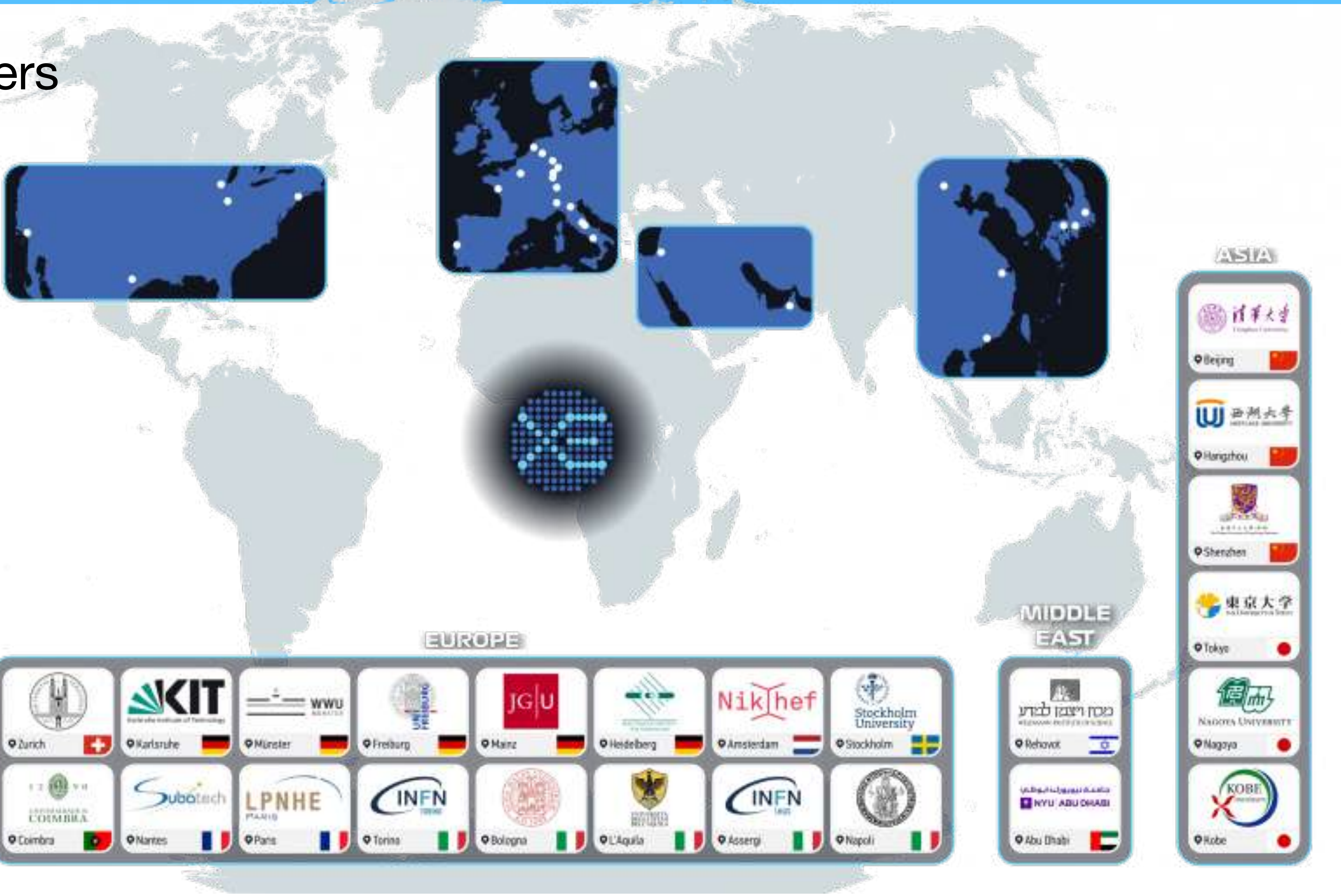


XENON Collaboration

- 200+ members
- 29 institutes
- 12 countries

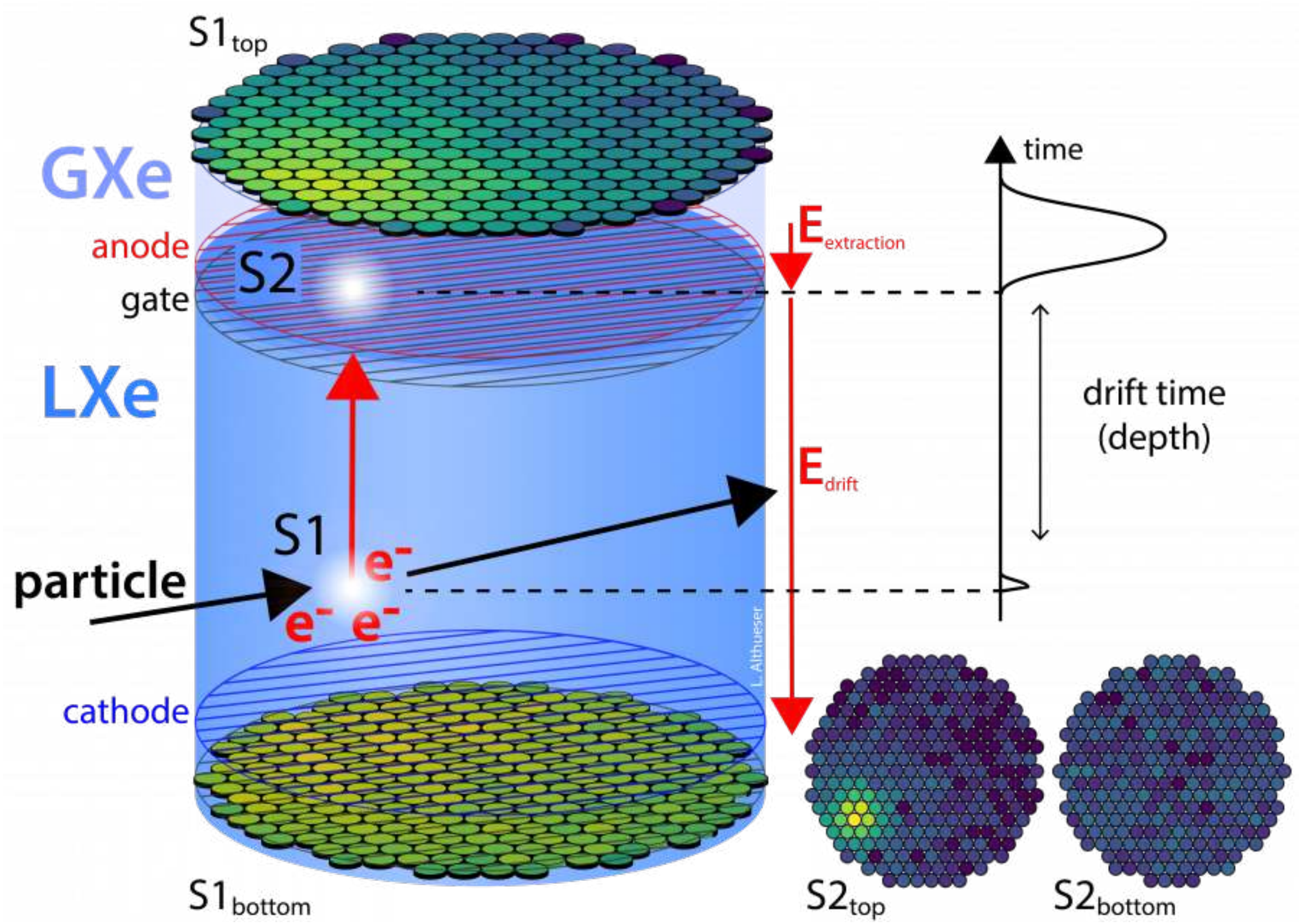


Content - Physics result & technical improvement

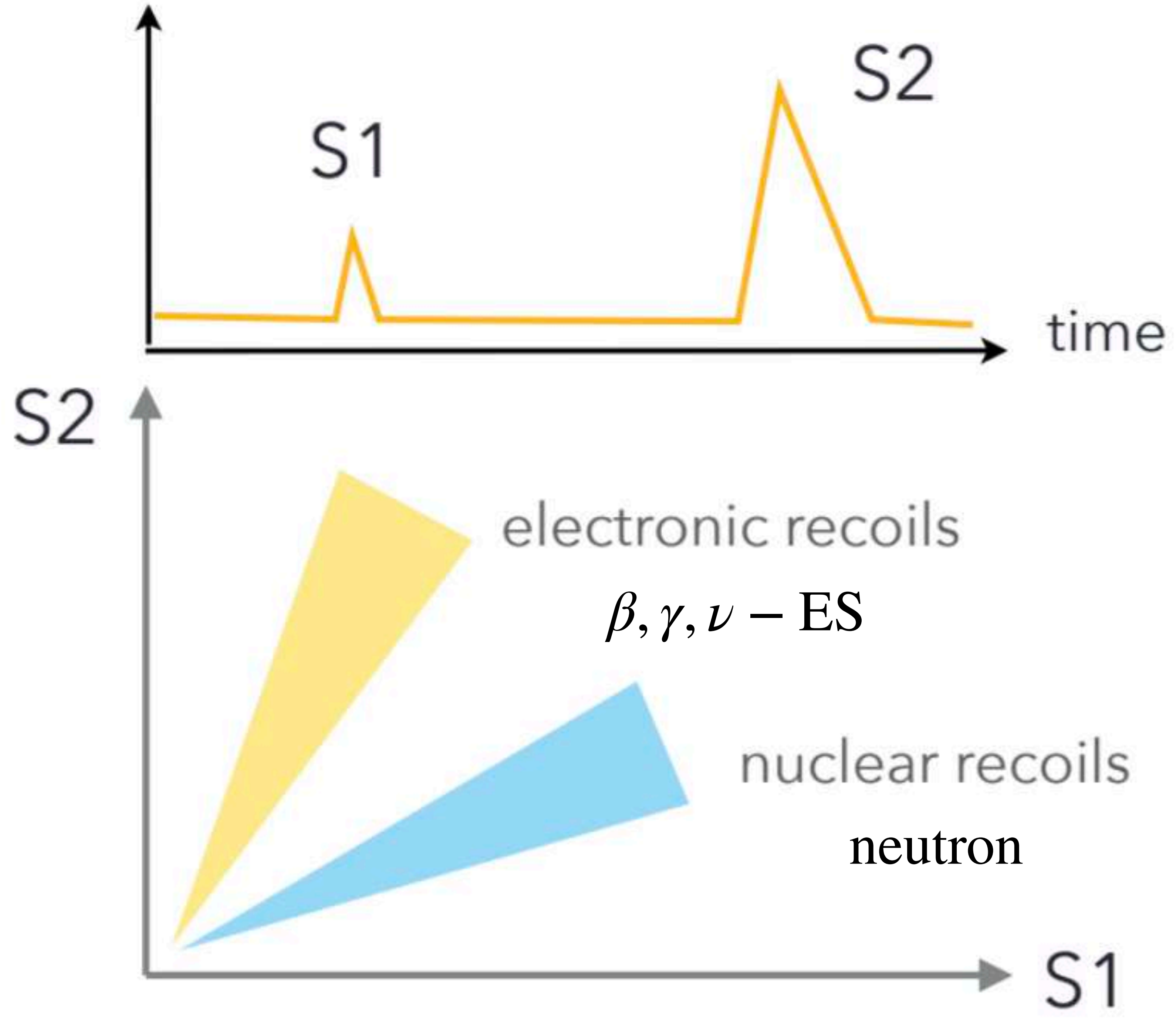
- Introduction
  - The XENONnT experiment, detector characteristic
- Signal & Background
  - Calibration in low energy nuclear recoil
  - Background: Accidental Coincidence(dominant), ER, Neutron, Surface
- Inference and Result

XENON Detector Principle

Two-Phase LXe Time Projection Chamber (TPC)



- 3D position resolution via light (S1) and charge (S2) signals
- S1/S2 depends on particle type
- Fiducialization (select volume with the least background)

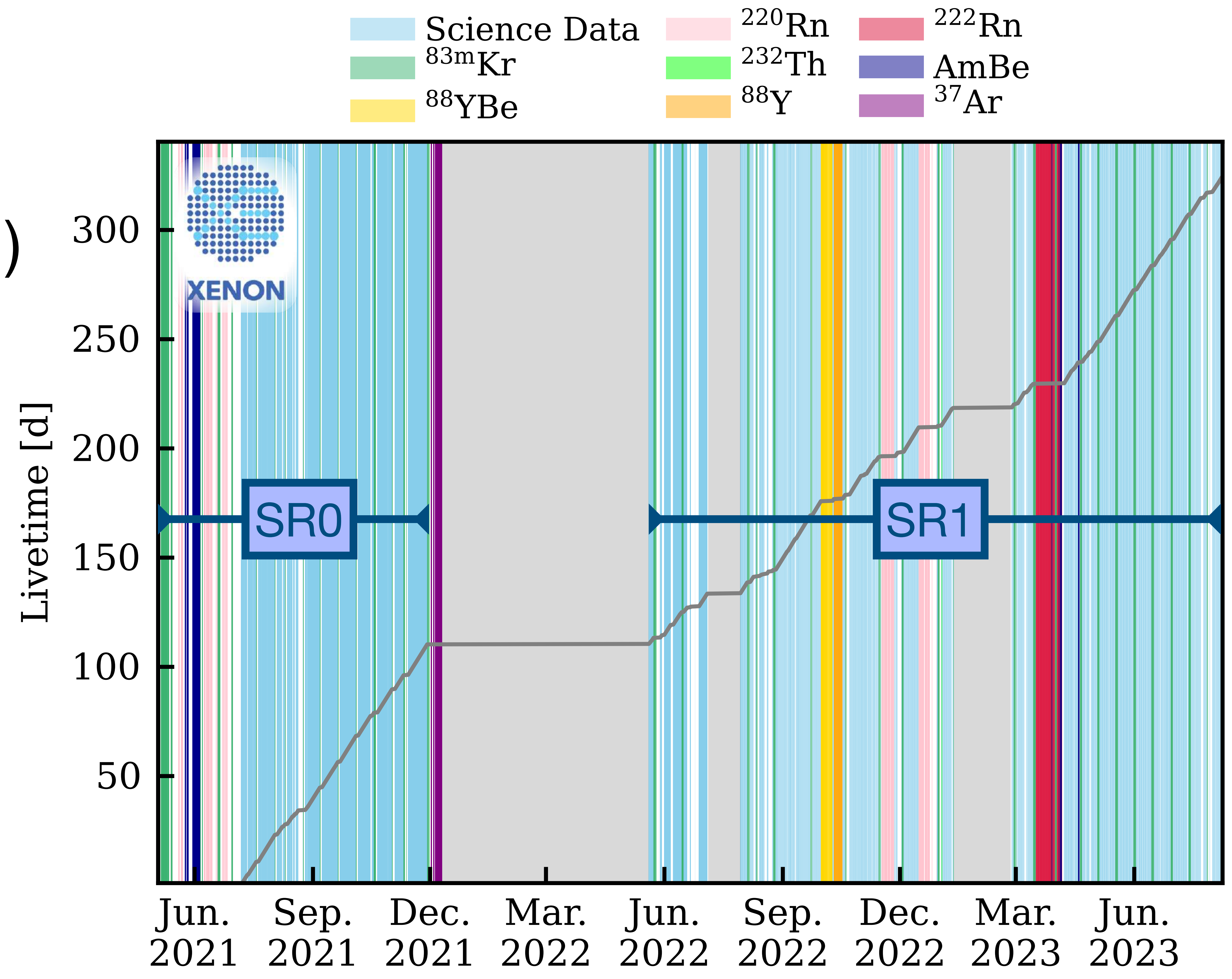


XENONnT Under the Gran Sasso

Drift Length	Diameter	Sensitive Target	Fiducial Mass	Drift Field
1.5 m	1.32 m	5.9 tonne	~4 tonne	23 V/cm

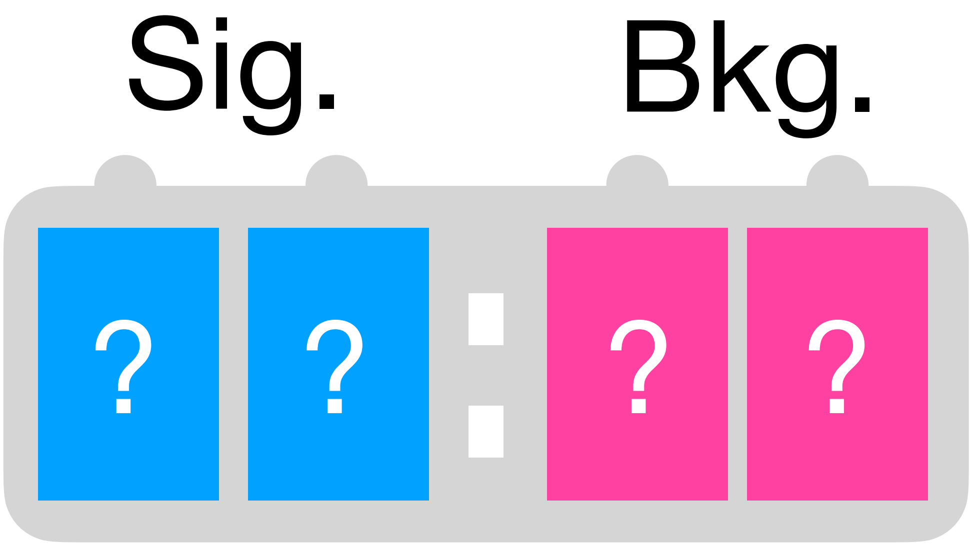
Search for ^{8}B CEvNS

- Use Science Run 0 & 1:
  - 108.0 days (SR0) + 208.5 days (SR1)
  - Fiducial mass: ~4 tonne
  - Exposure: ~3.5 t·y
- Perform blind analysis
  - The features of data will be hidden from analysts to ensure unbiased signal and background prediction

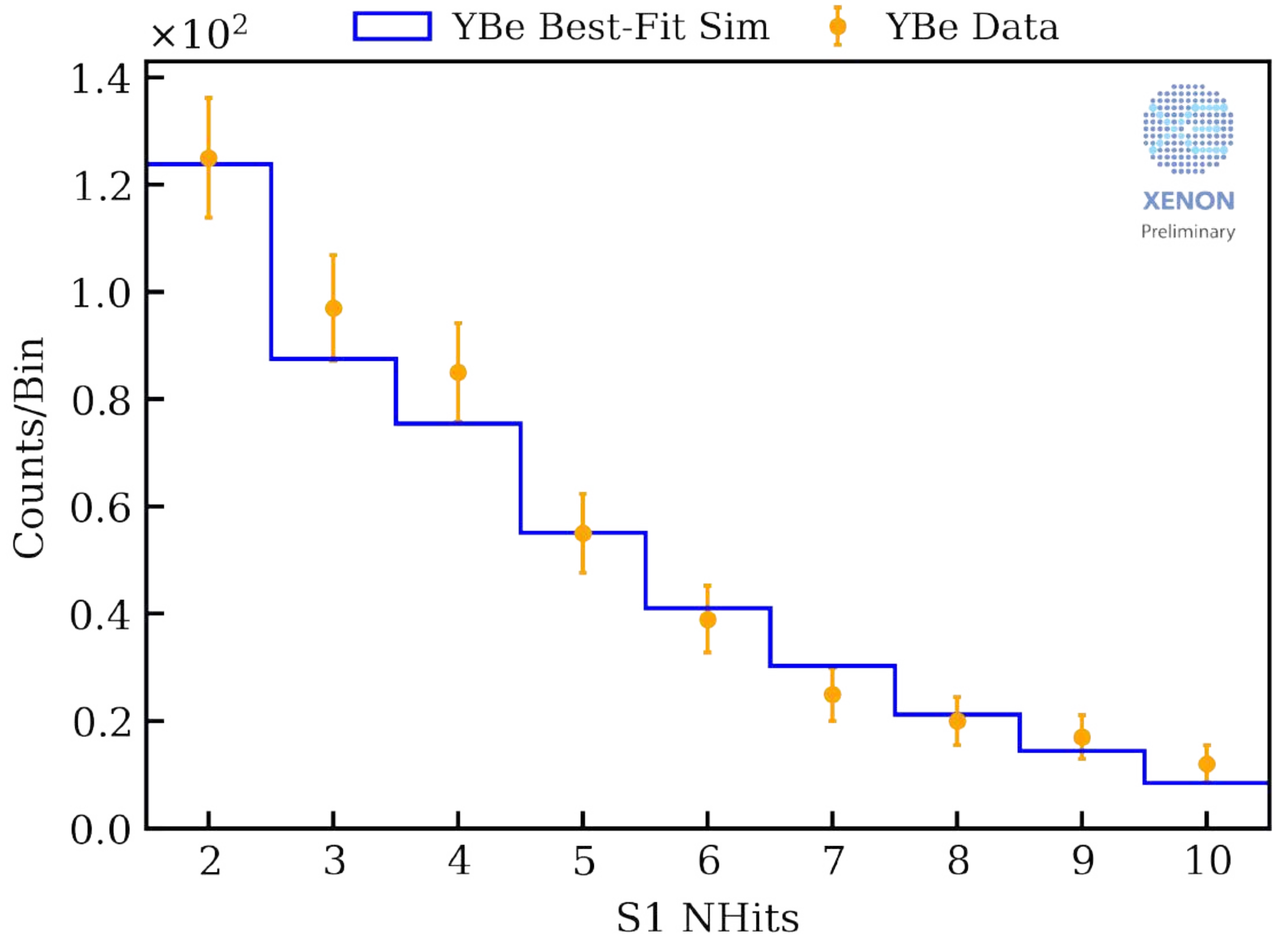


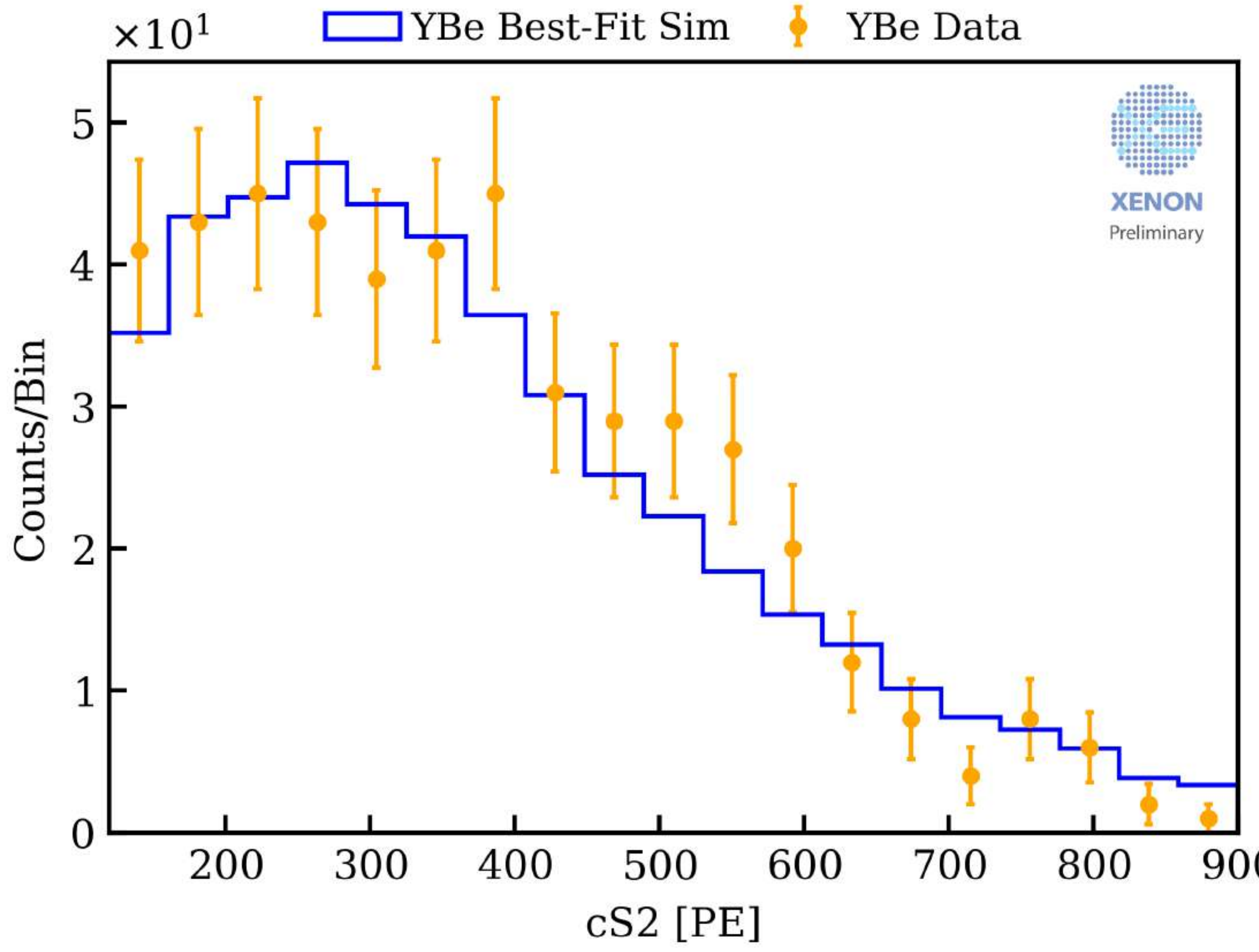
Signal & Background

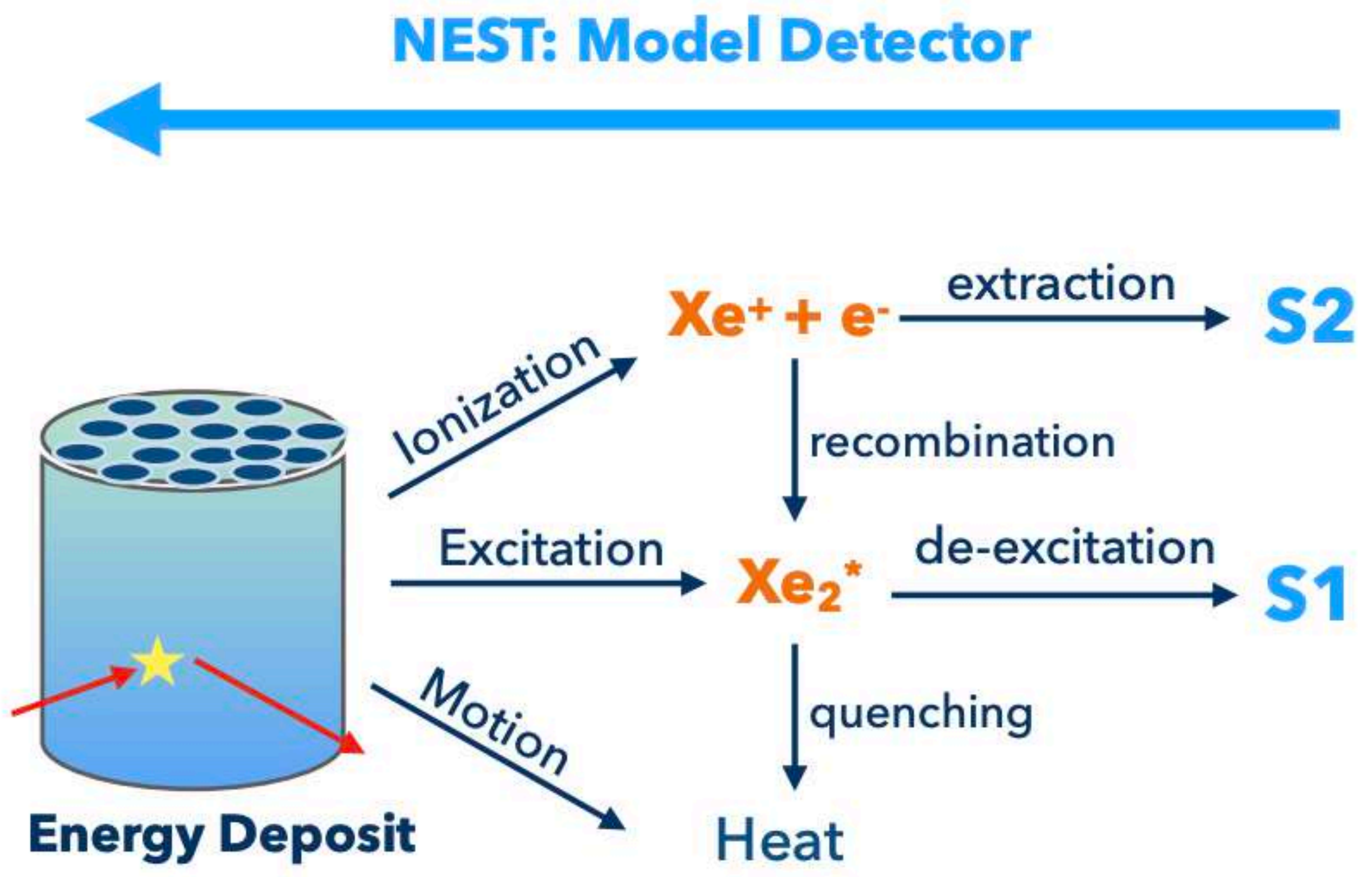
- Discovery significance ~ $S/\sqrt{B}$

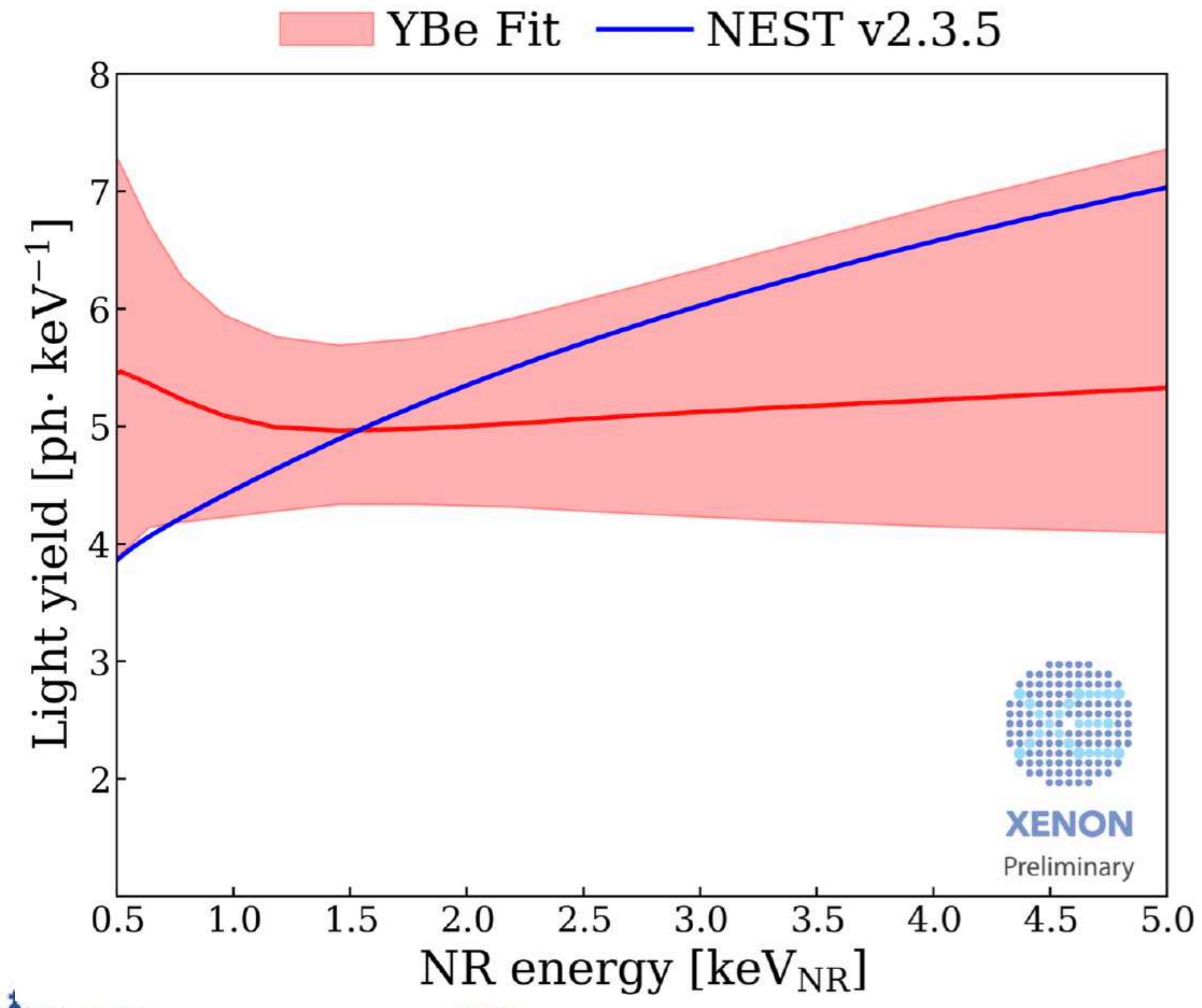


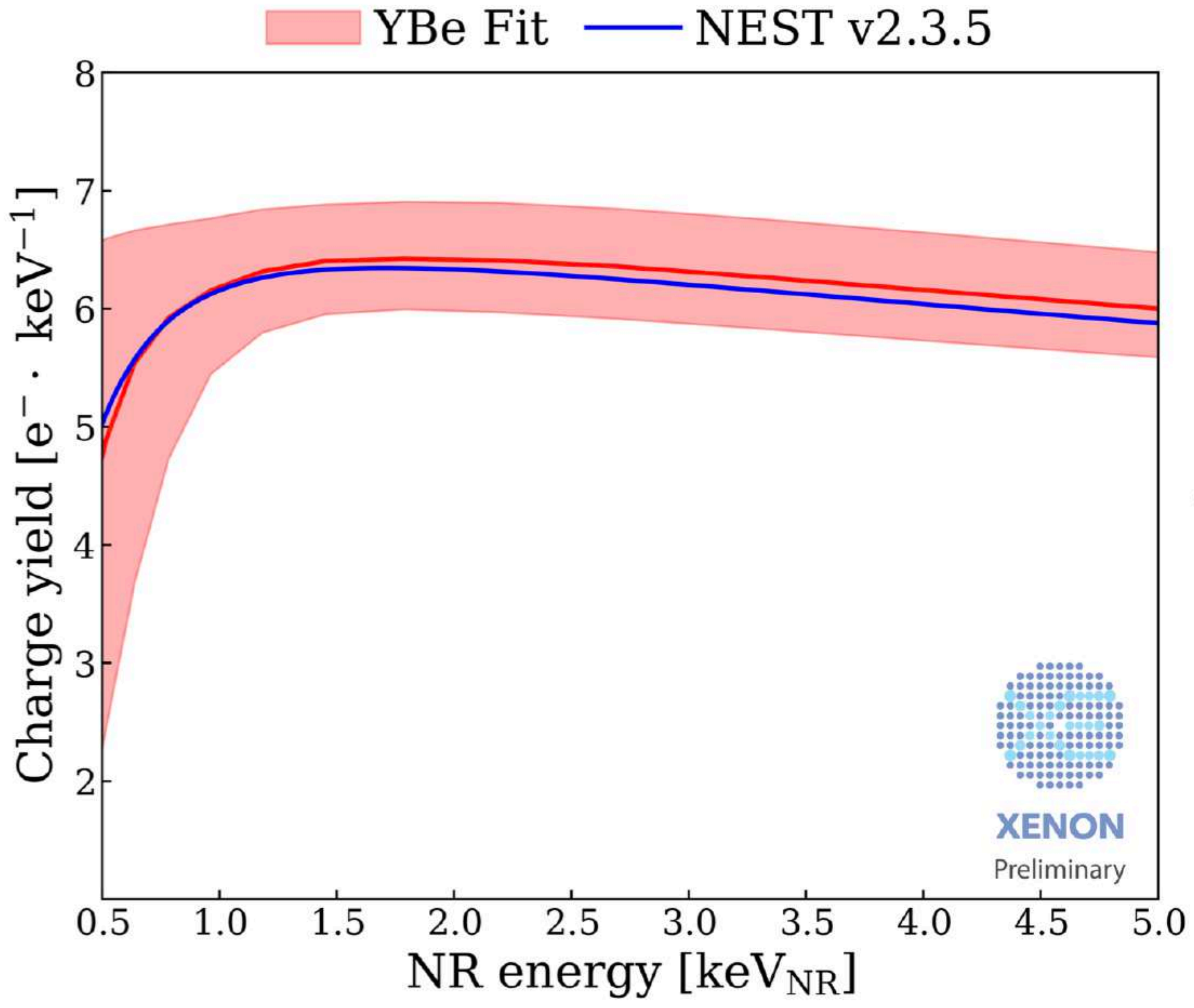
Calibration with Neutron Source: ^{88}YBe











- Excellent match between data and model
- Fit the NEST model with the ^{88}YBe data to predict the light and charge yield in the ^{8}B CEvNS energy range at the XENONnT drift field

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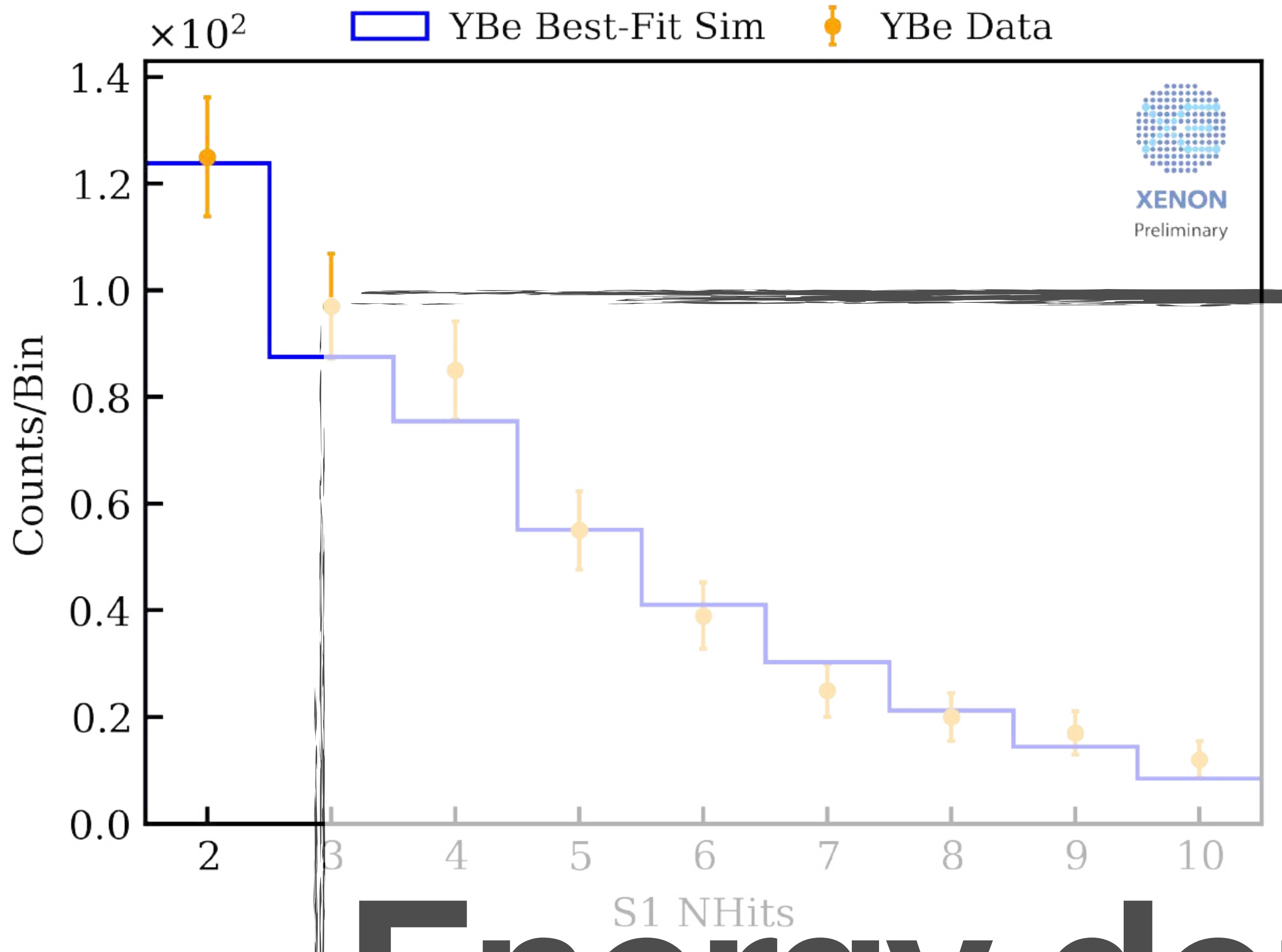
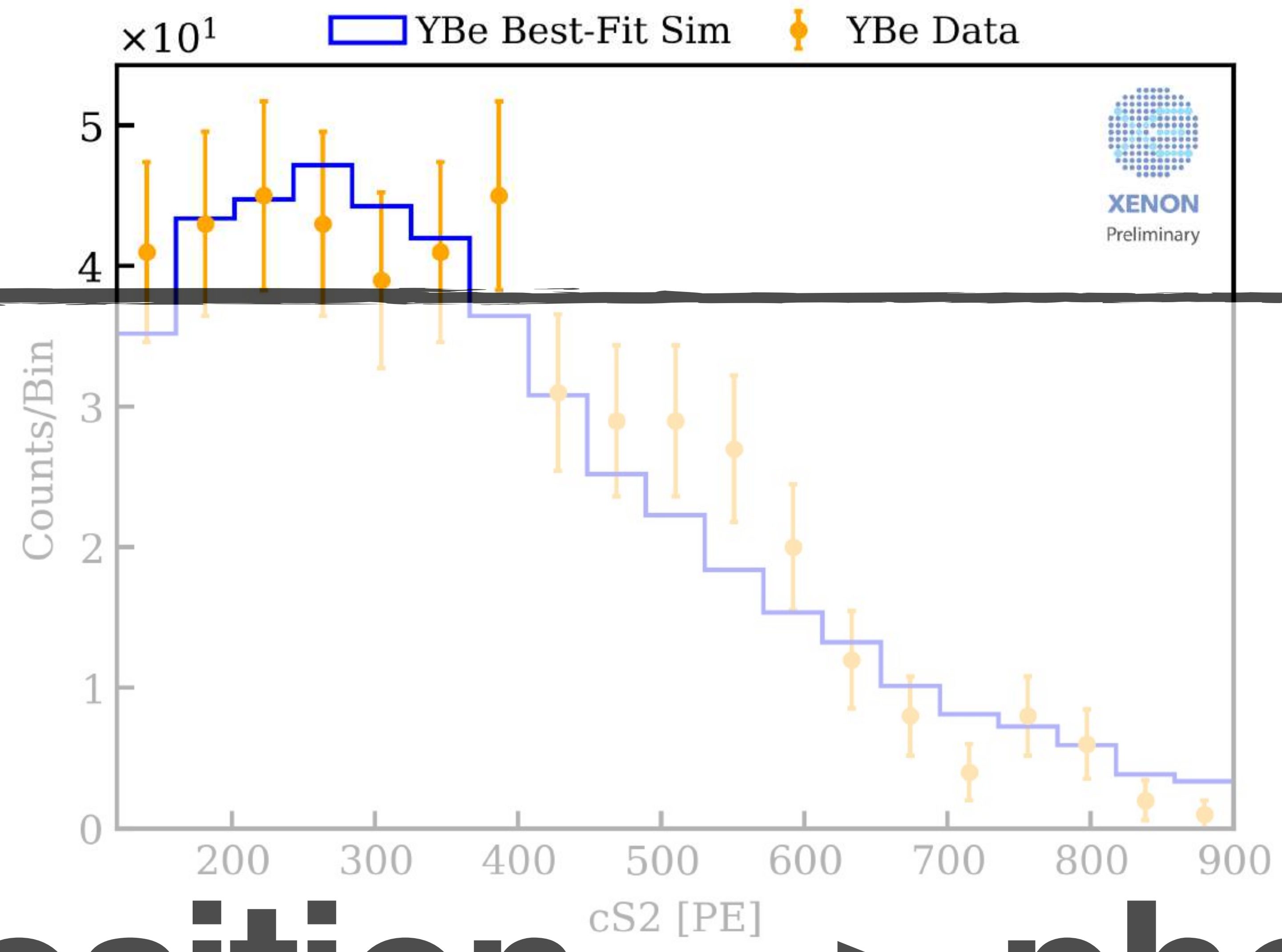
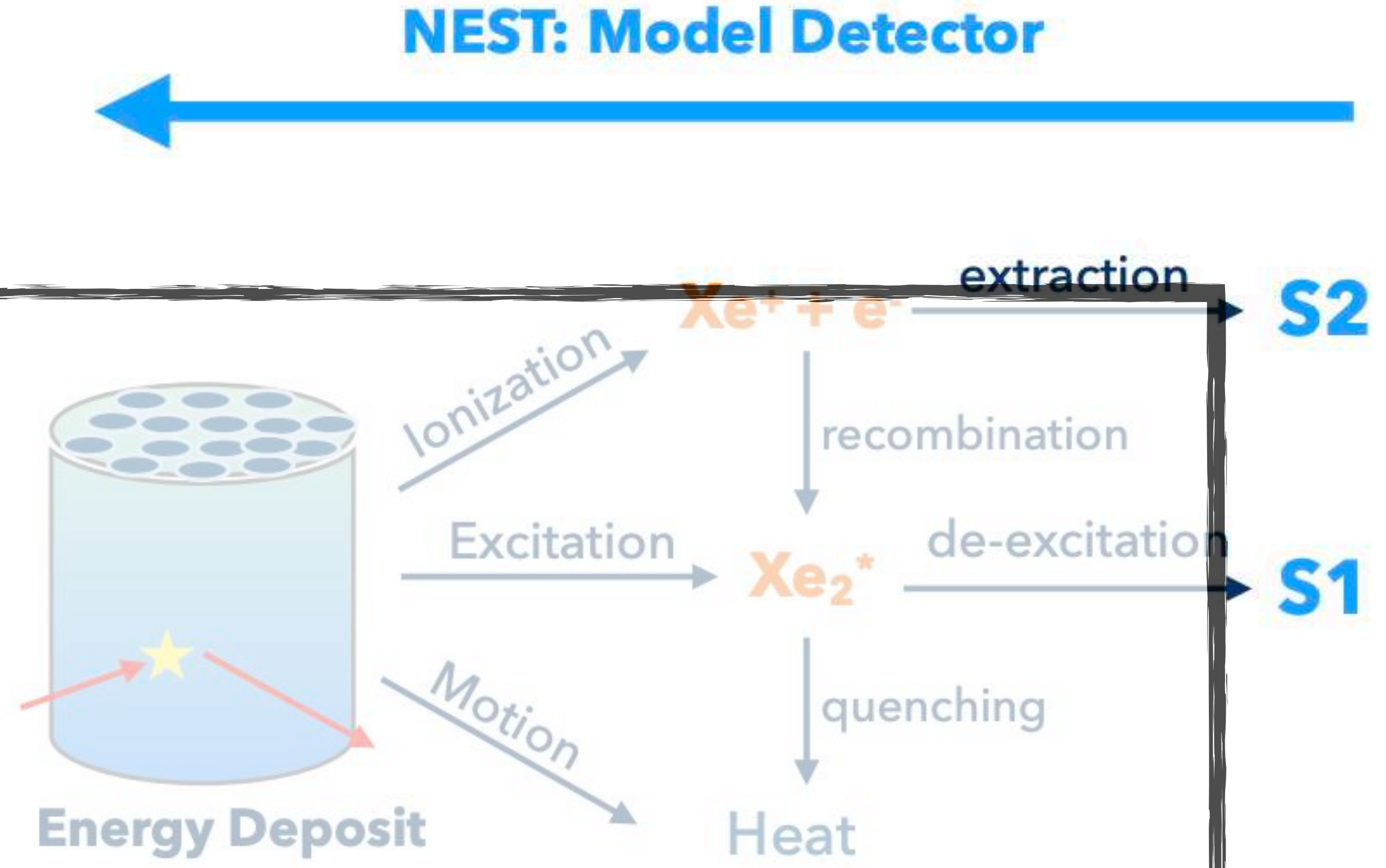
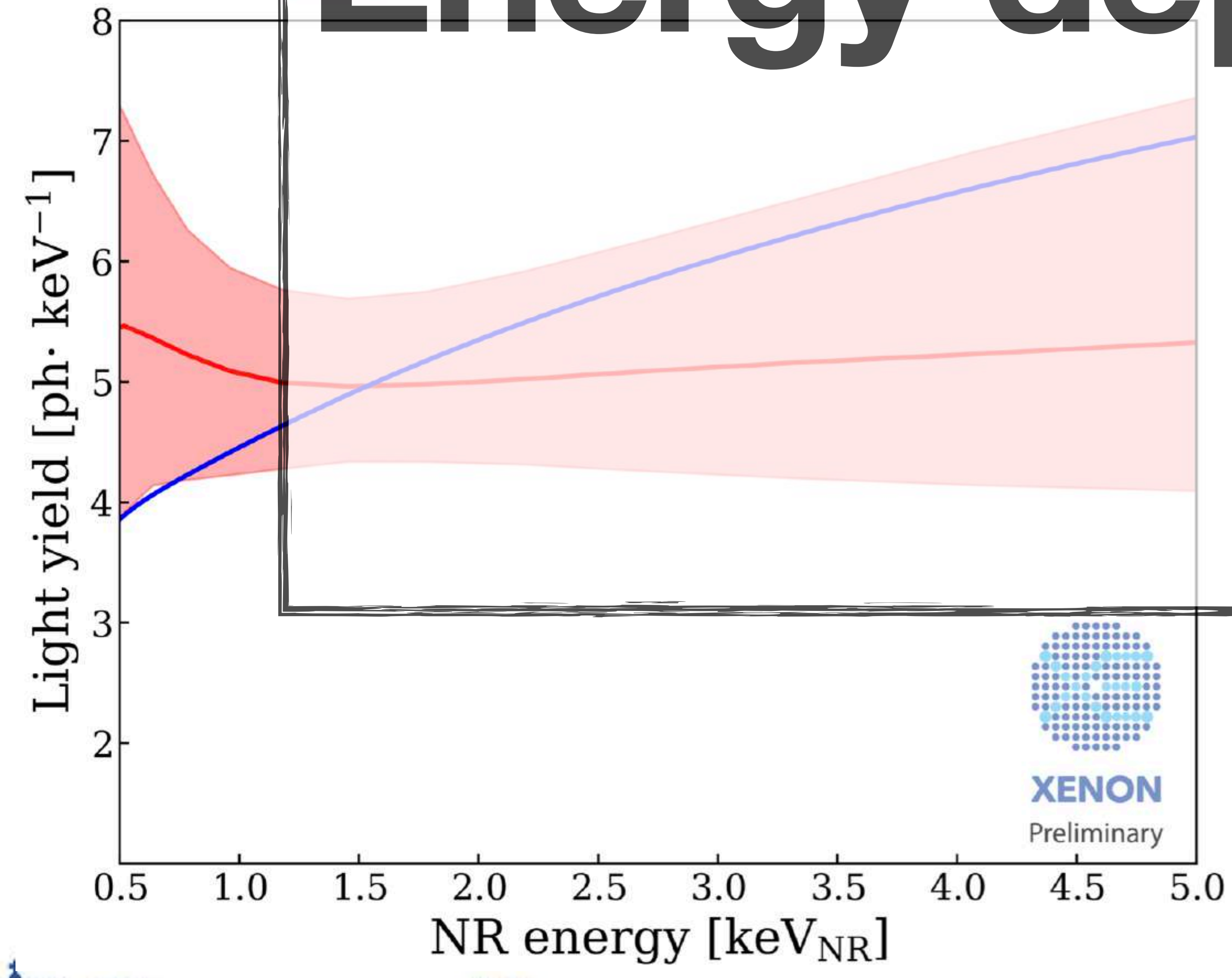
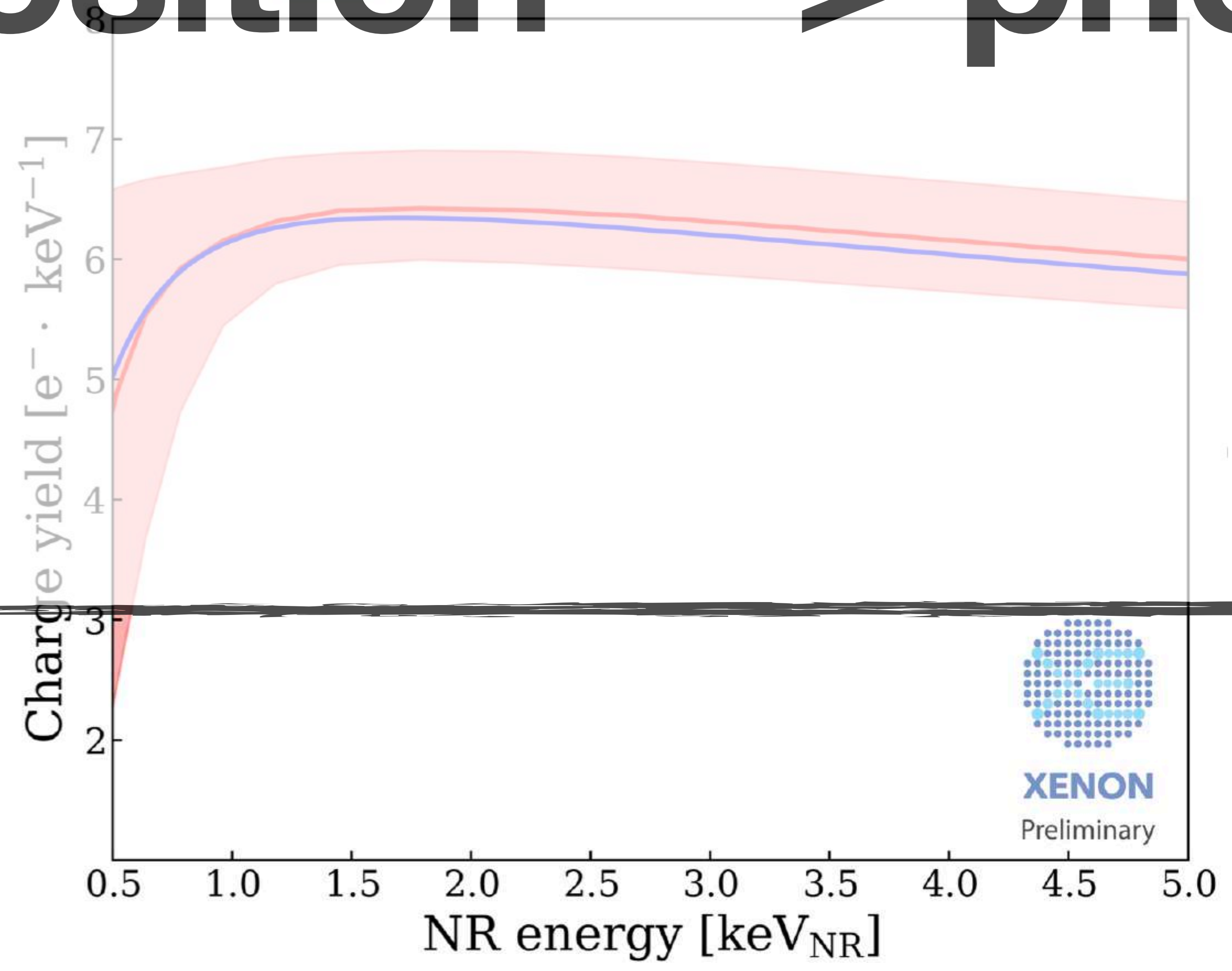






Energy deposition --> photon + electron





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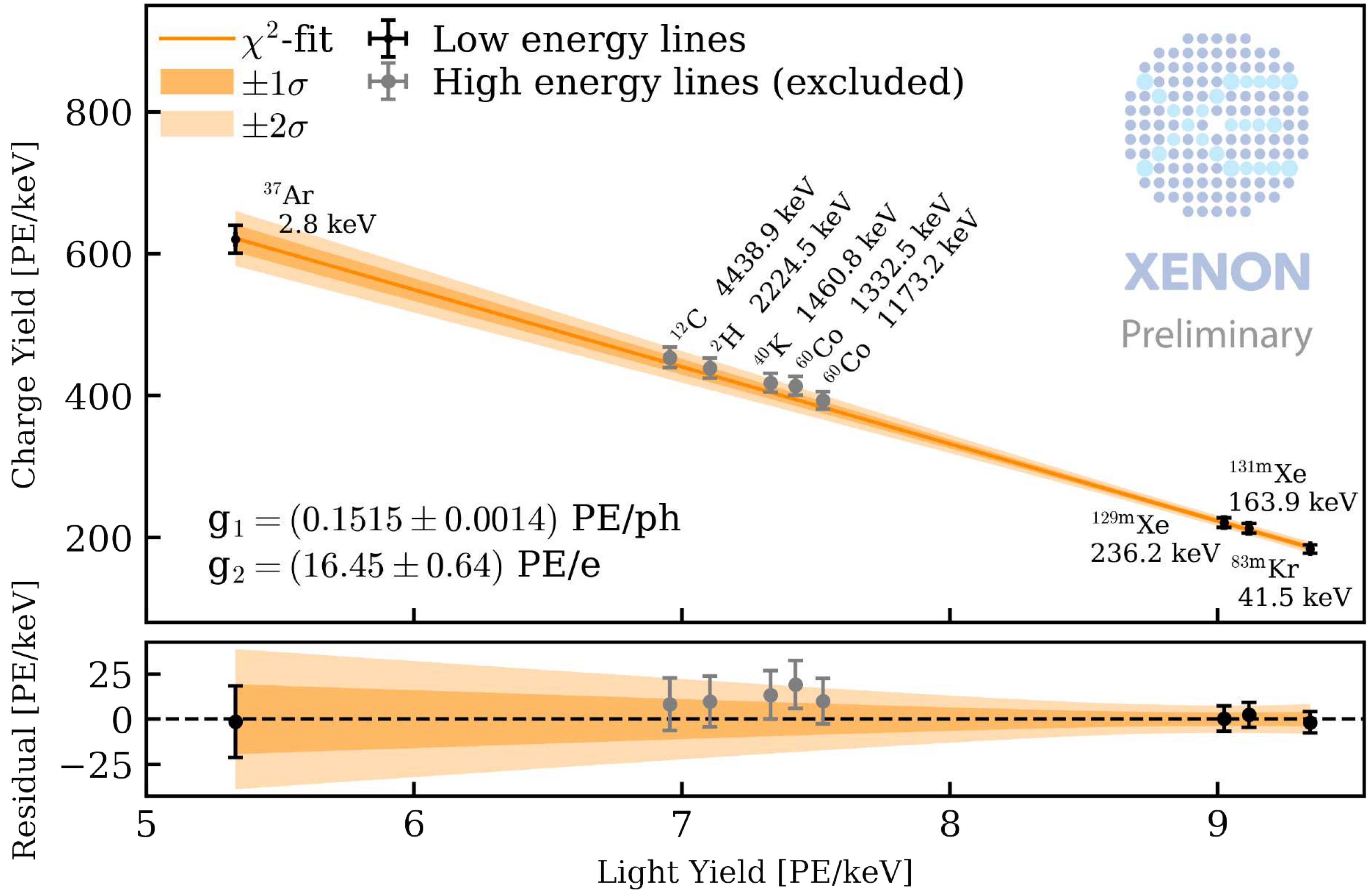
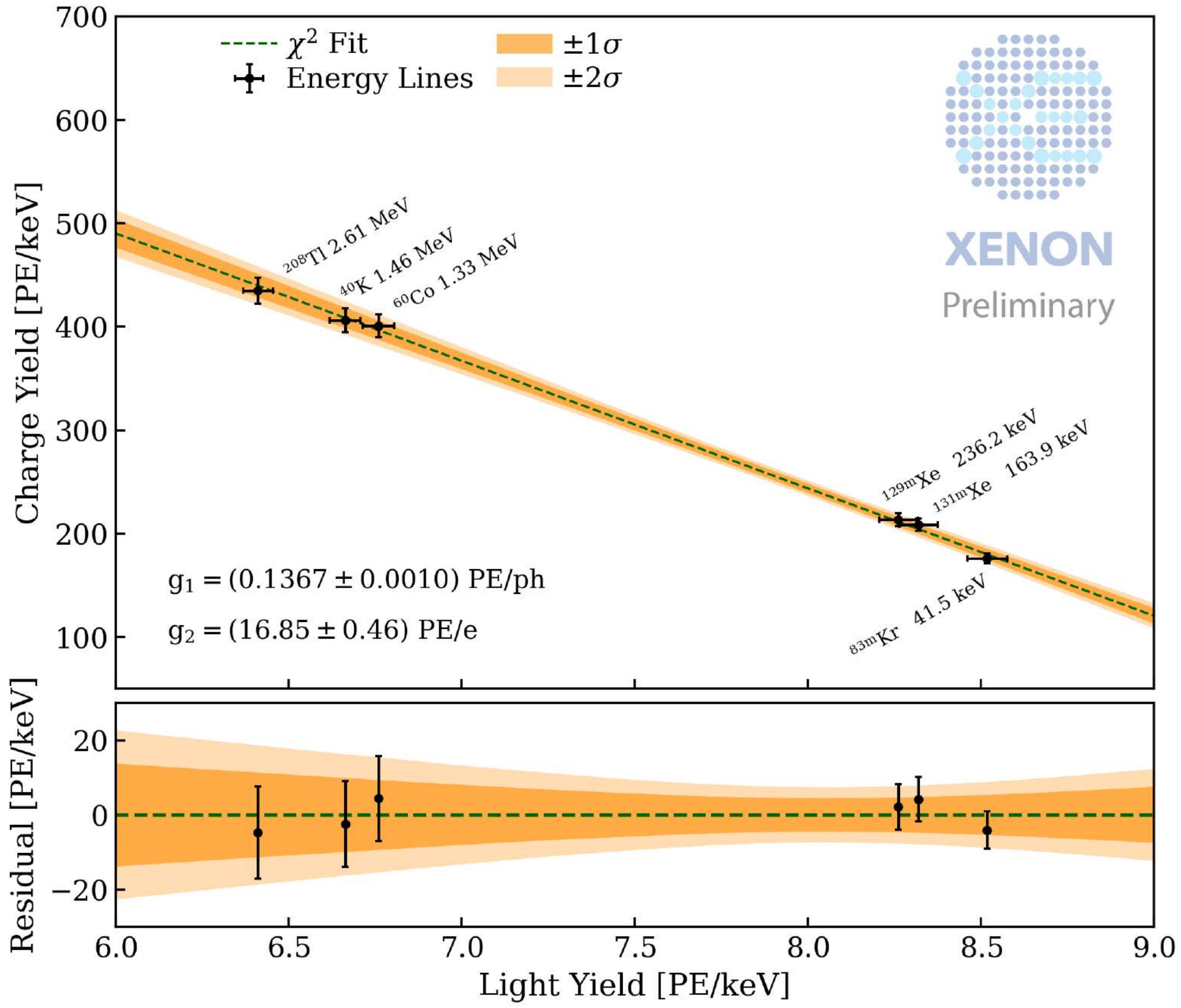
Calibration with Mono-E Electronic Recoils

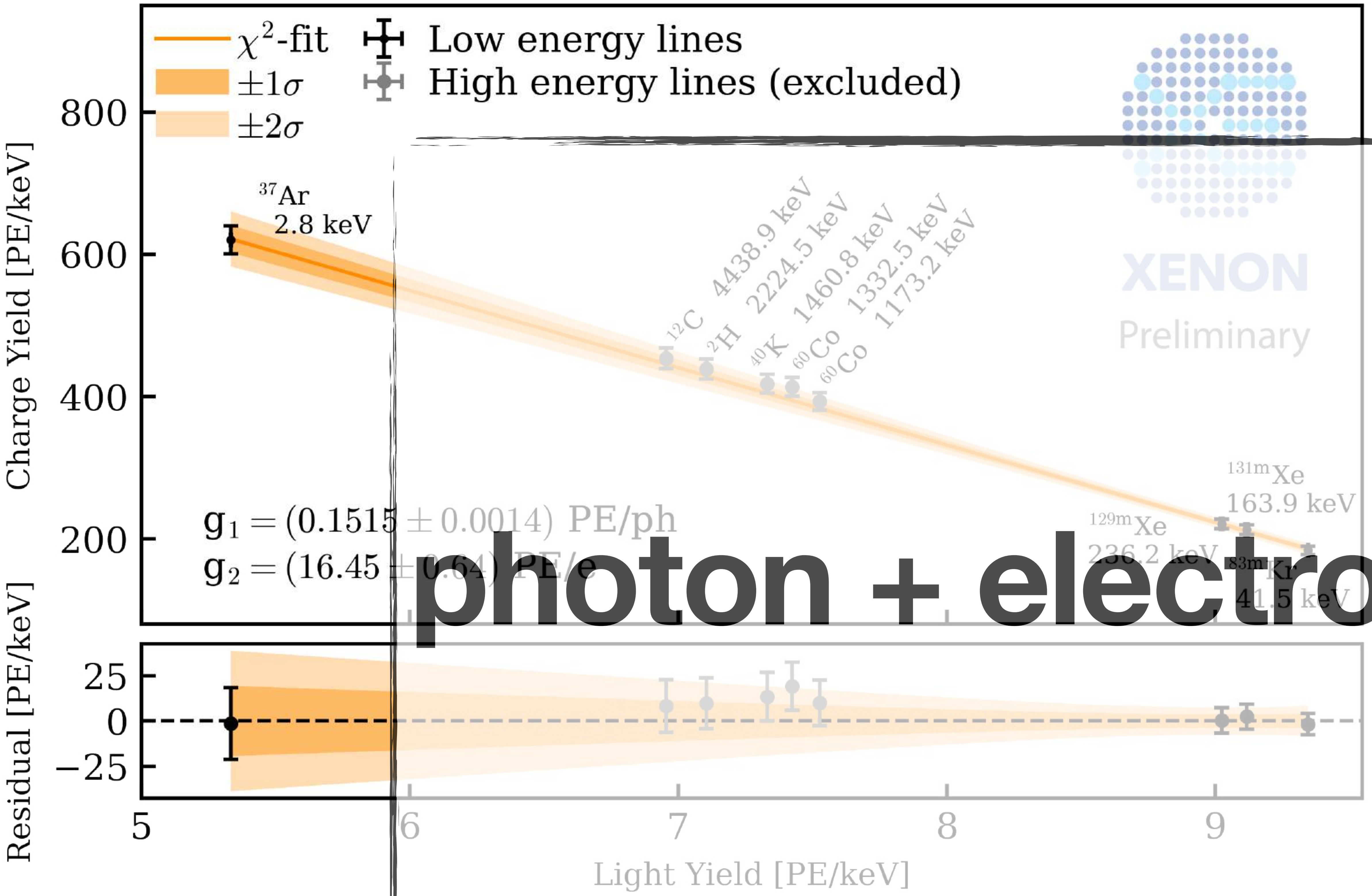


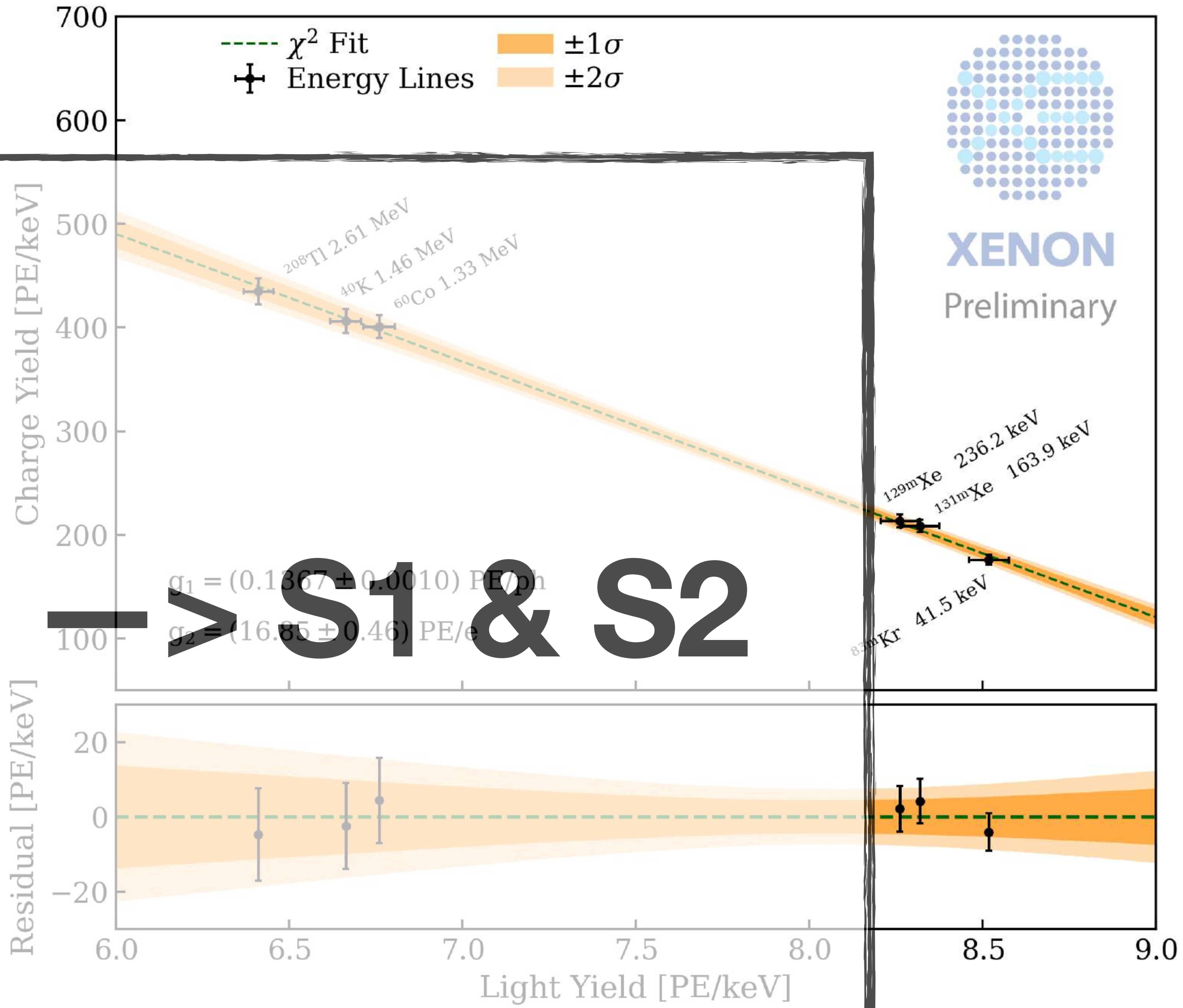


Science Run	g1 [PE/ph]	g2 [PE/e]
SR0	0.1515 ± 0.0014	16.45 ± 0.64
SR1	0.1367 ± 0.0010	16.85 ± 0.46

- $S1 = g_1 \times n_\gamma$ (photon detection efficiency)
- $S2 = g_2 \times n_e$ (charge amplification)

Calibration with Mono-E Electronic Recoils





photon + electron —> S1 & S2

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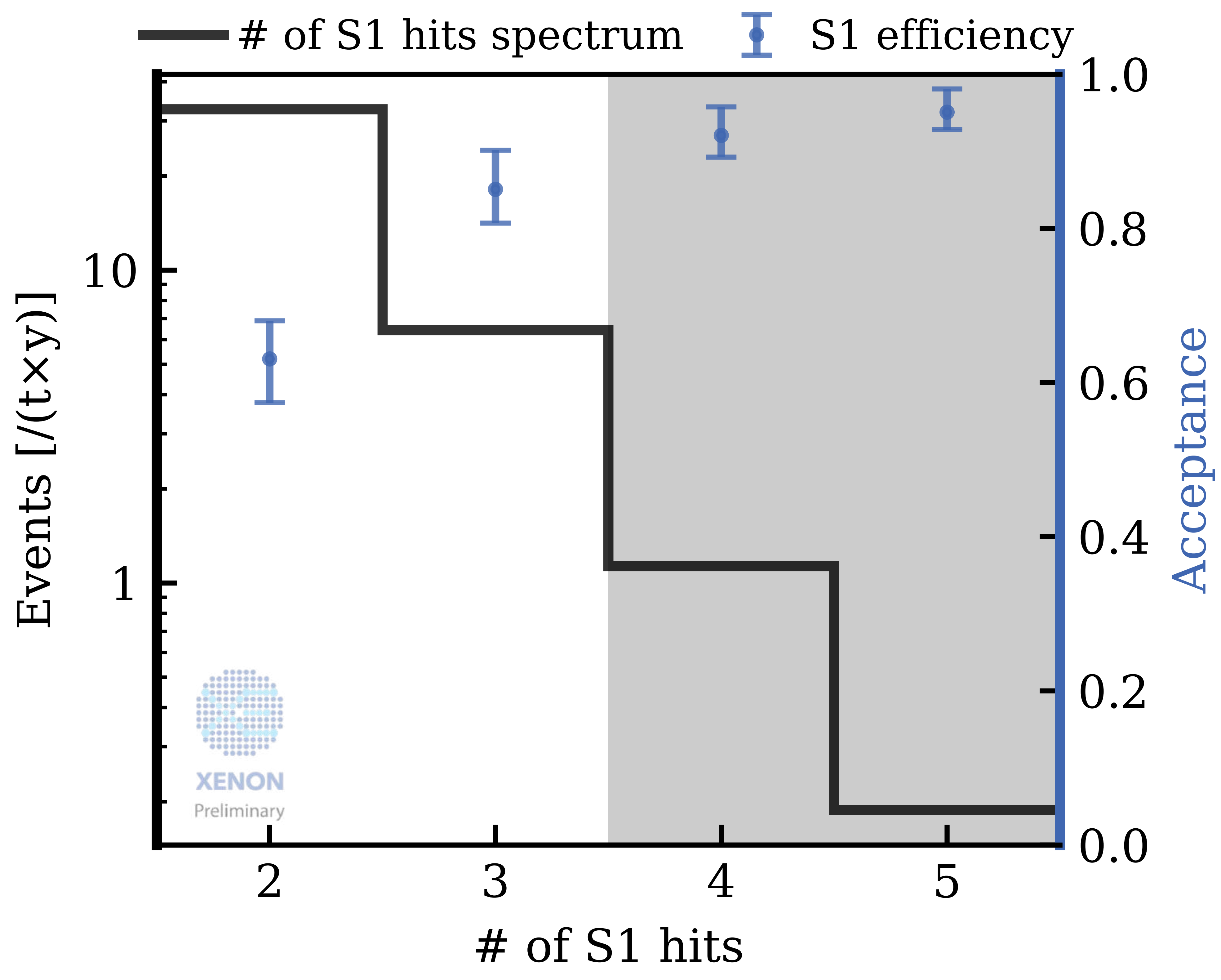
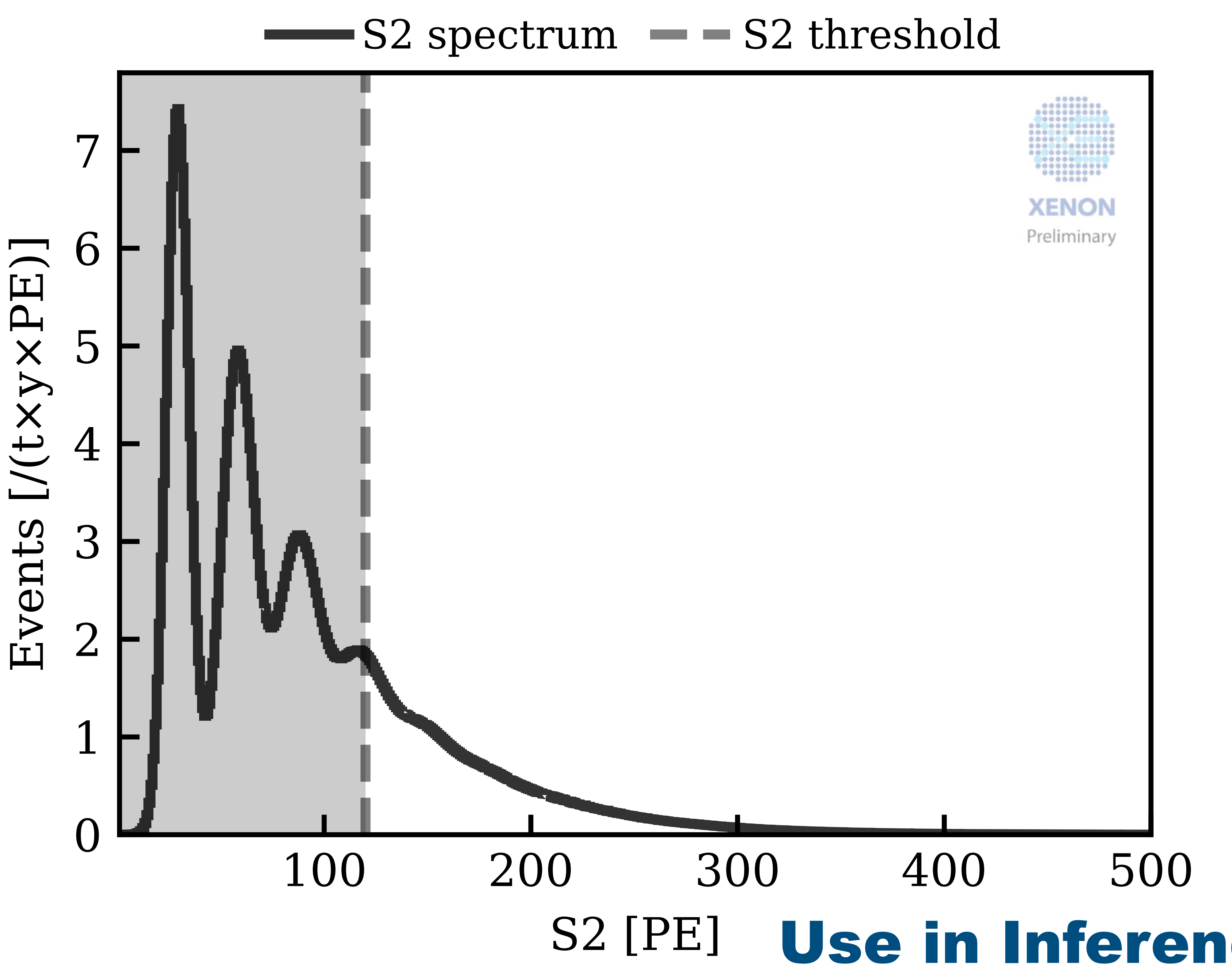
^{8}B CEvNS Signal Region of Interest





Use in Inference

S1 Range: 2 & 3 hits

- A hit usually corresponds to a photon hitting the PMT and is recorded by our DAQ and software

S2 Range: 120 - 500 PE

- S2 threshold of 120PE is used to reject high isolated S2 background

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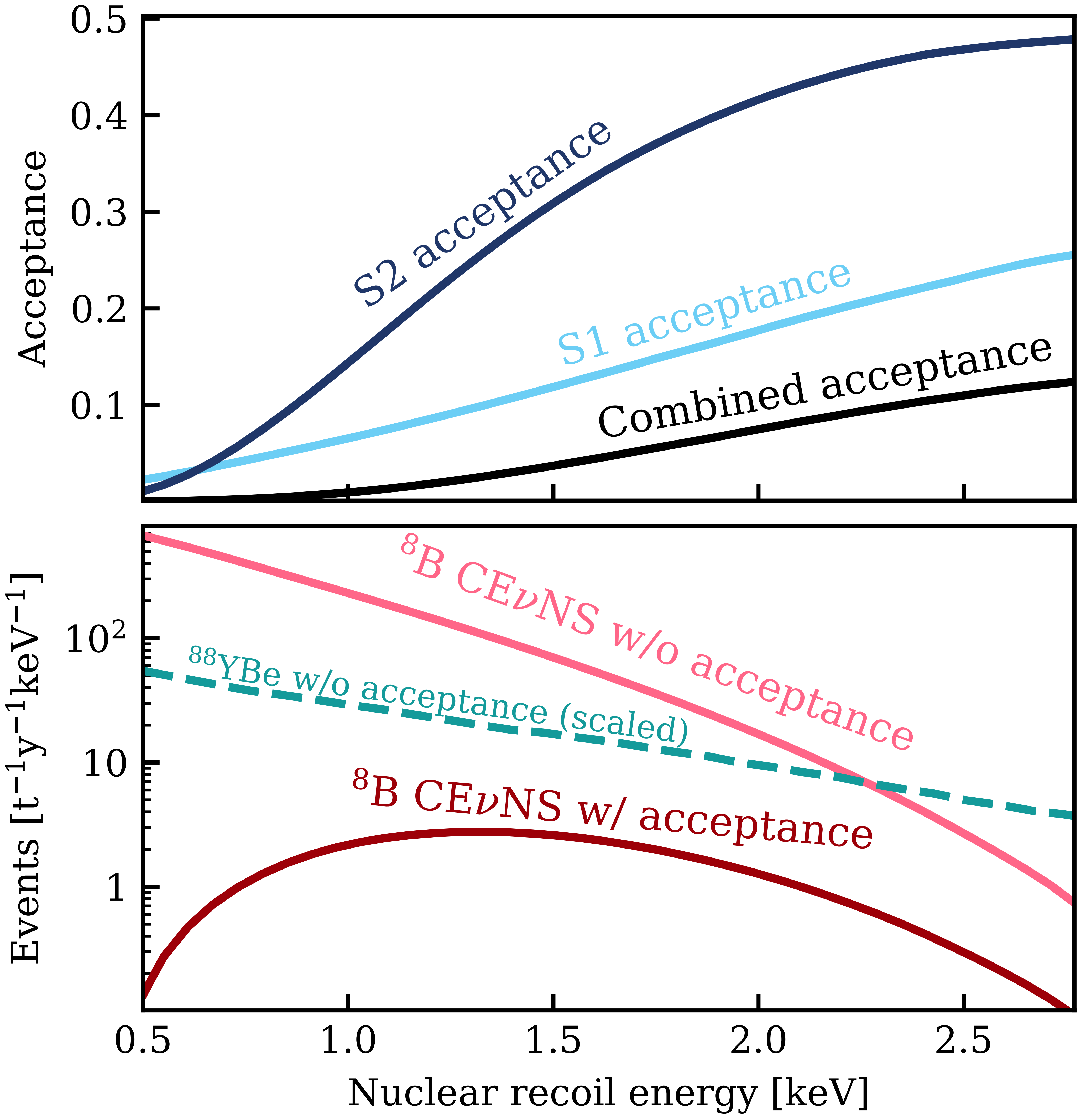
^{8}B CEvNS Signal Model



- SR0: 1.17 t·y
- SR1: 2.34 t·y

appletree 0.5.1

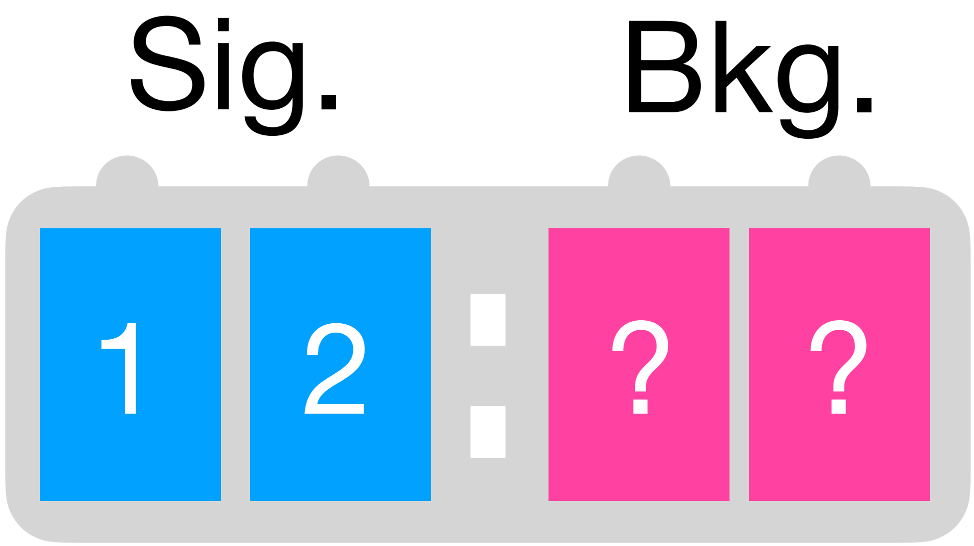
```
pip install appletree
```

Solar SM + SNO measurement

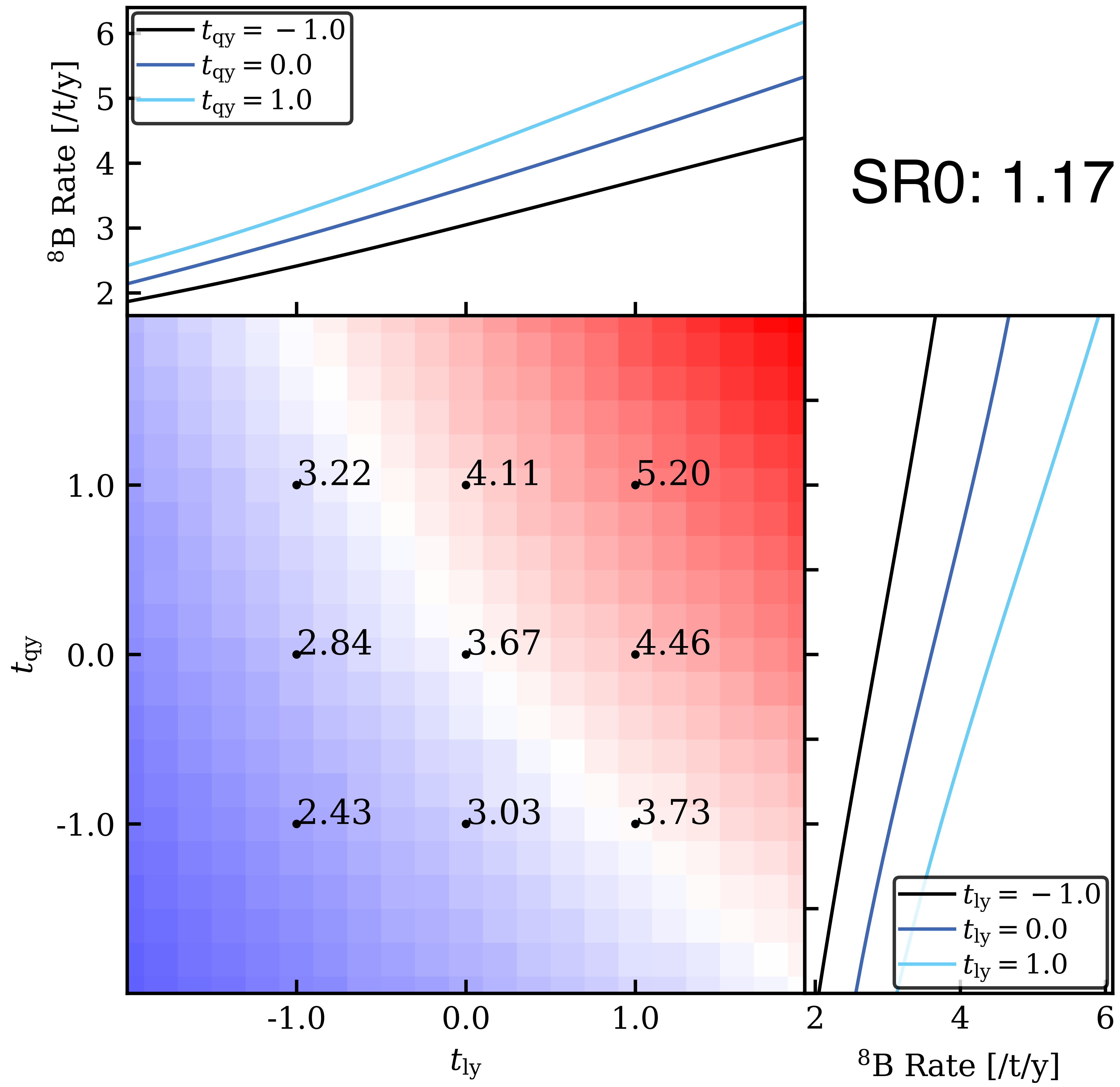
SM CEvNS cross-section

Detector Response

Efficiency



^{8}B CEvNS Signal Model



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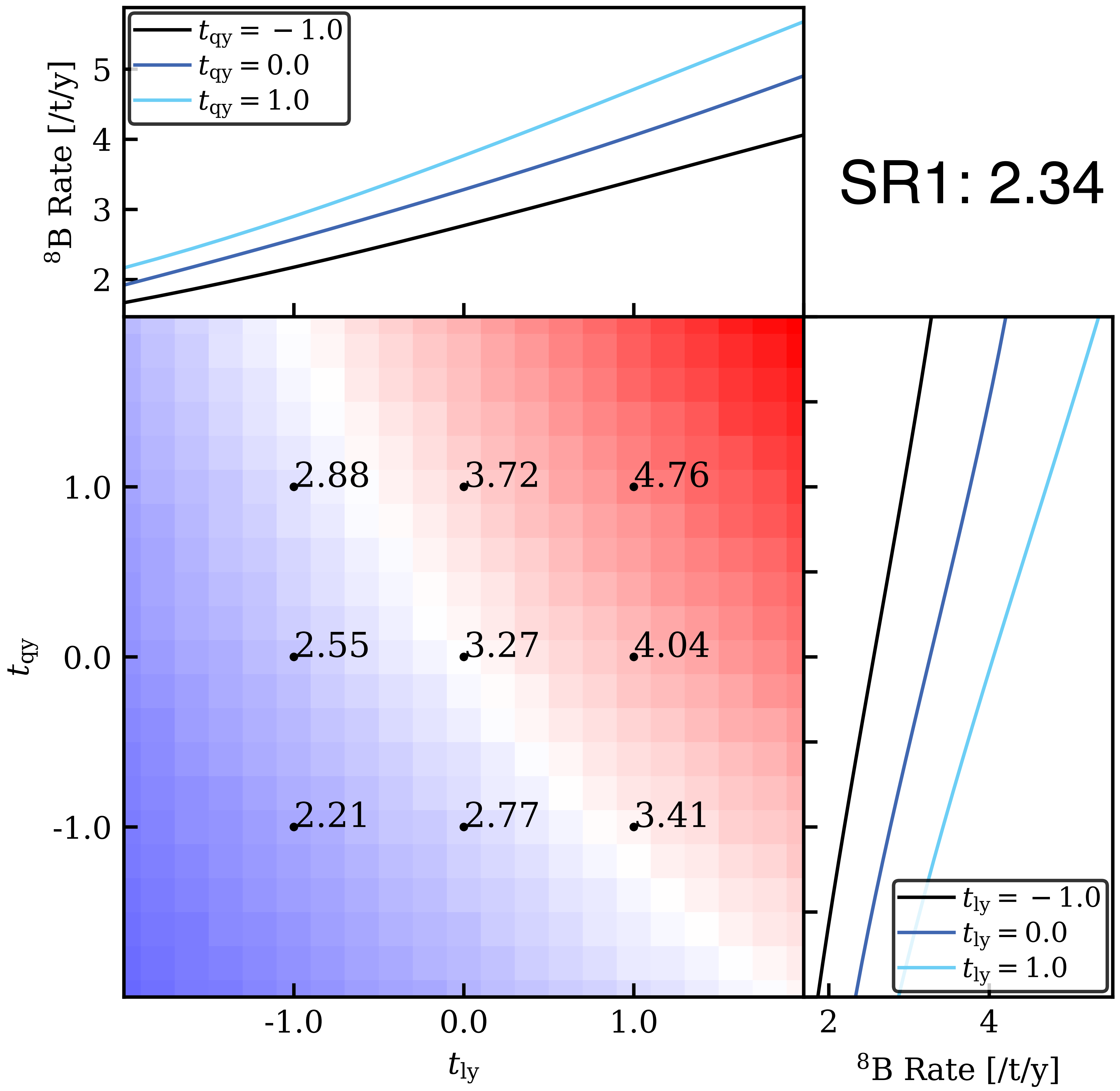

SR1: 2.34 t·y

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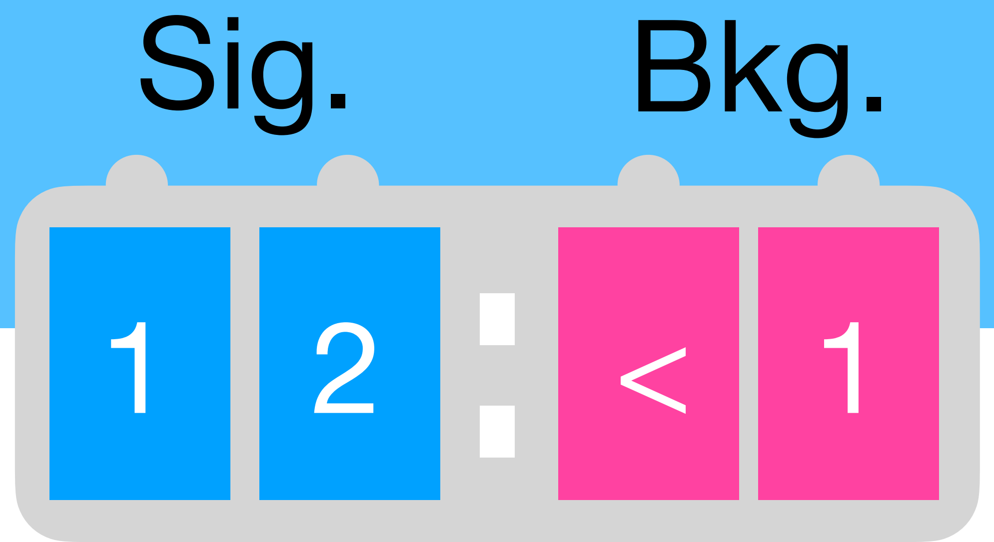
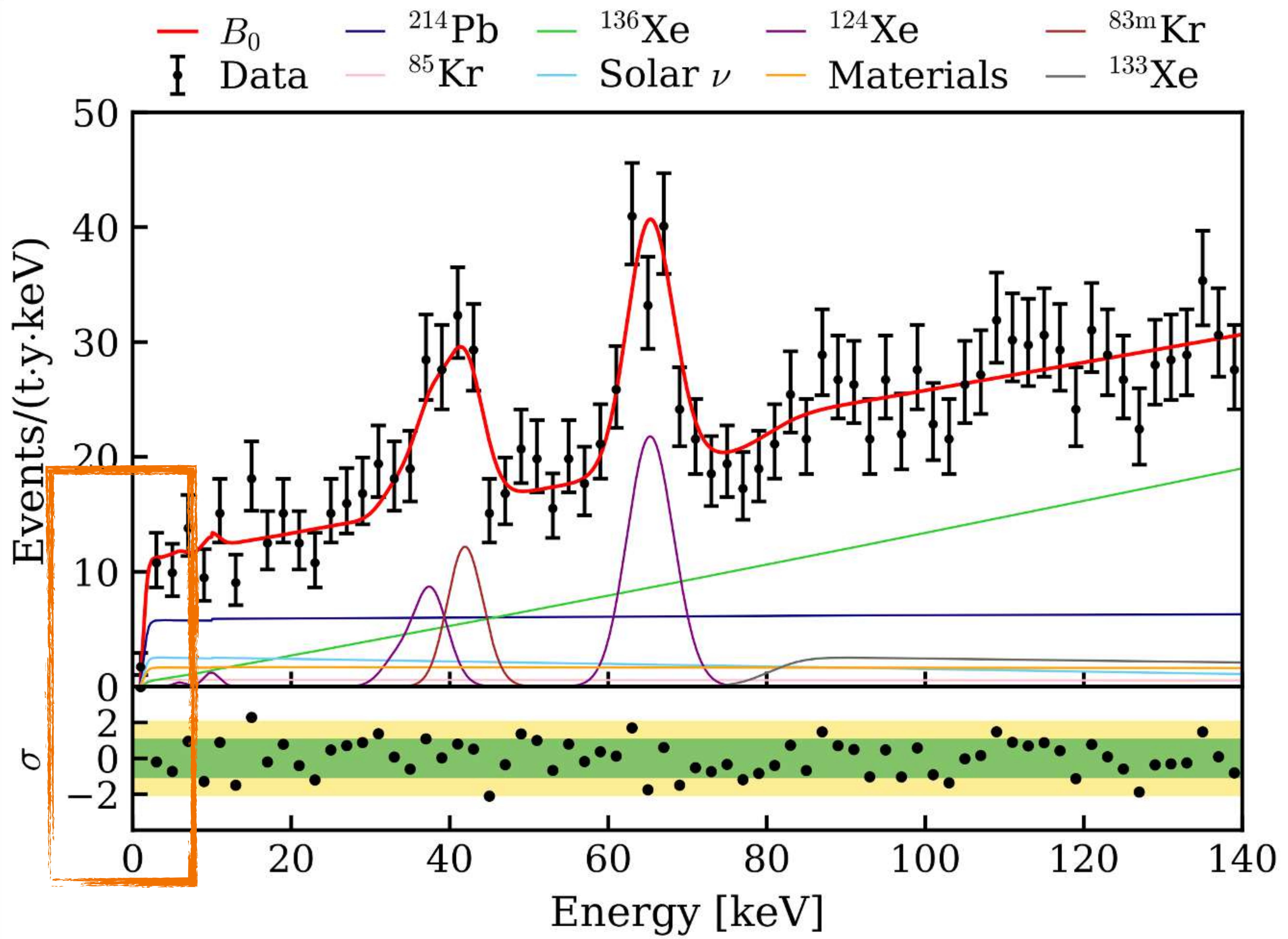
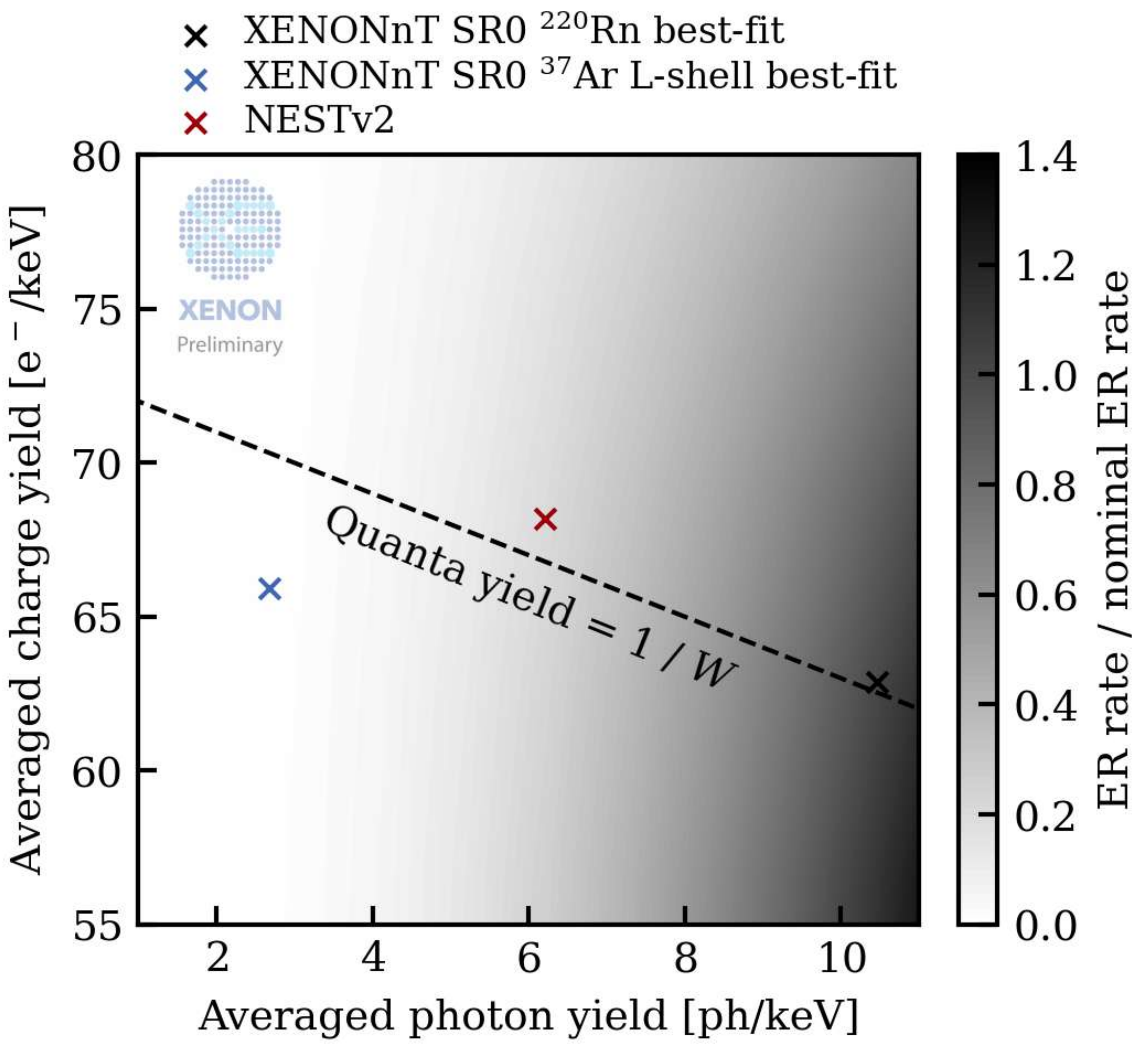
Electronic Recoil Background



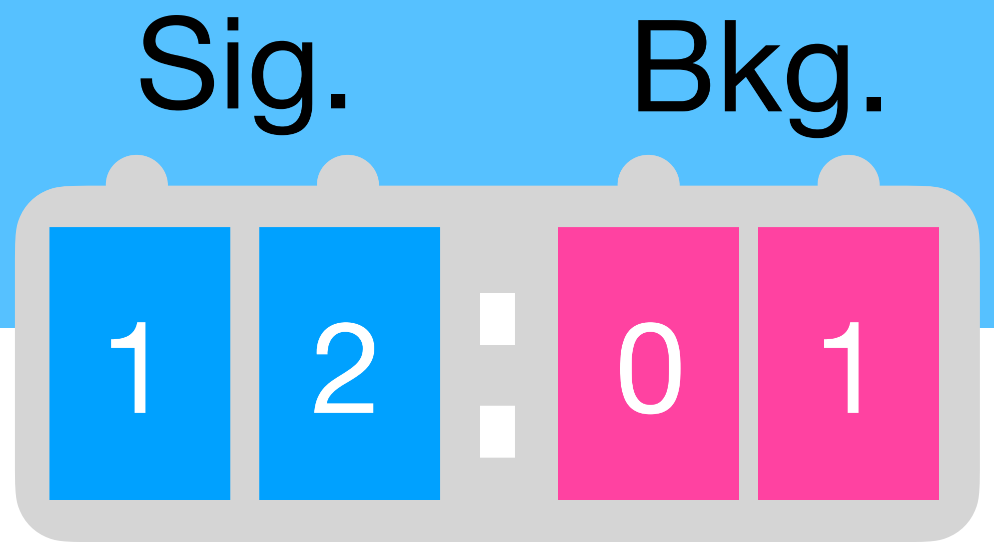




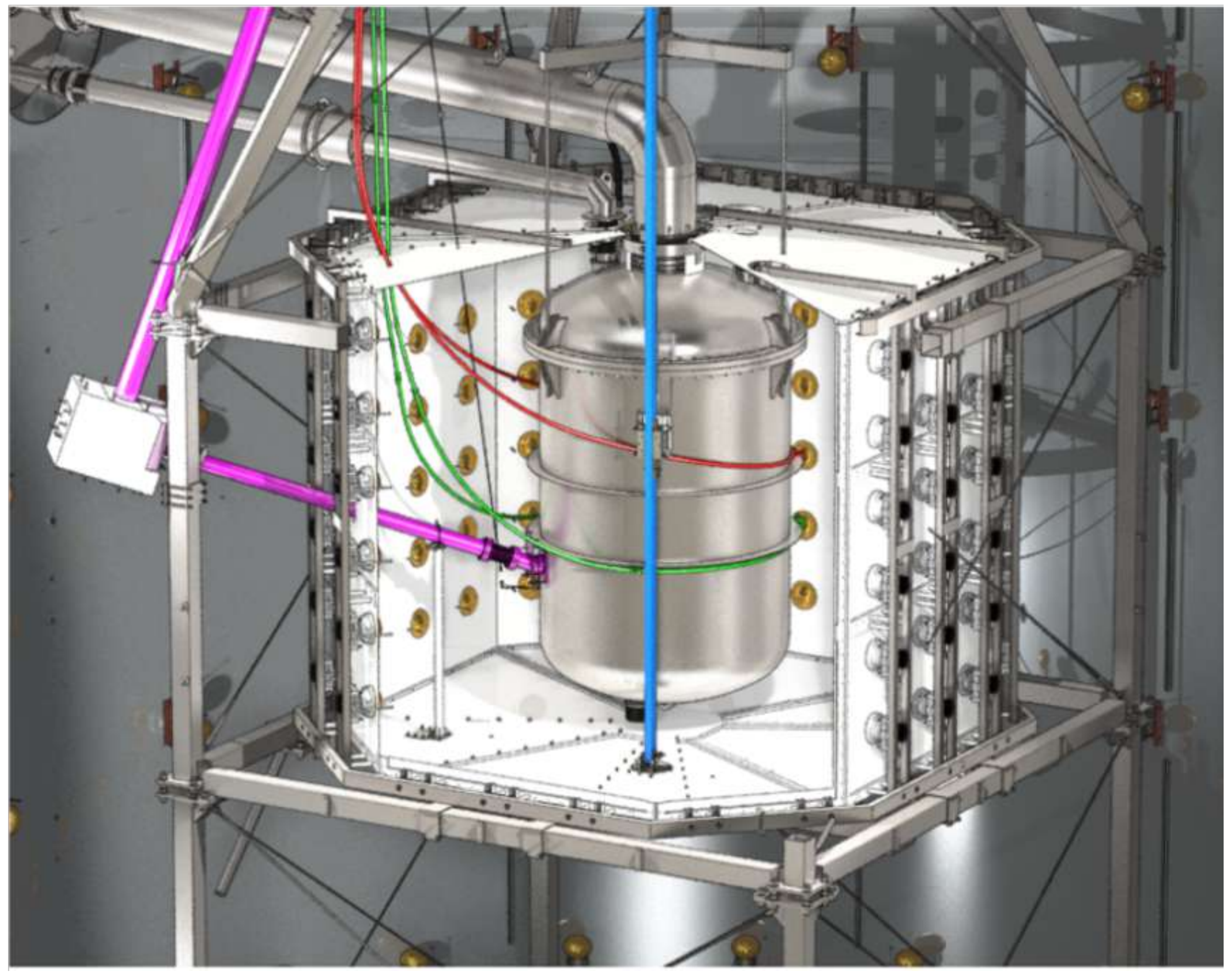
Science Run	CEvNS ROI (^{220}Rn Model)	CEvNS ROI (NESTv2 Model)
SR0	0.13	~0
SR1	0.56	~0

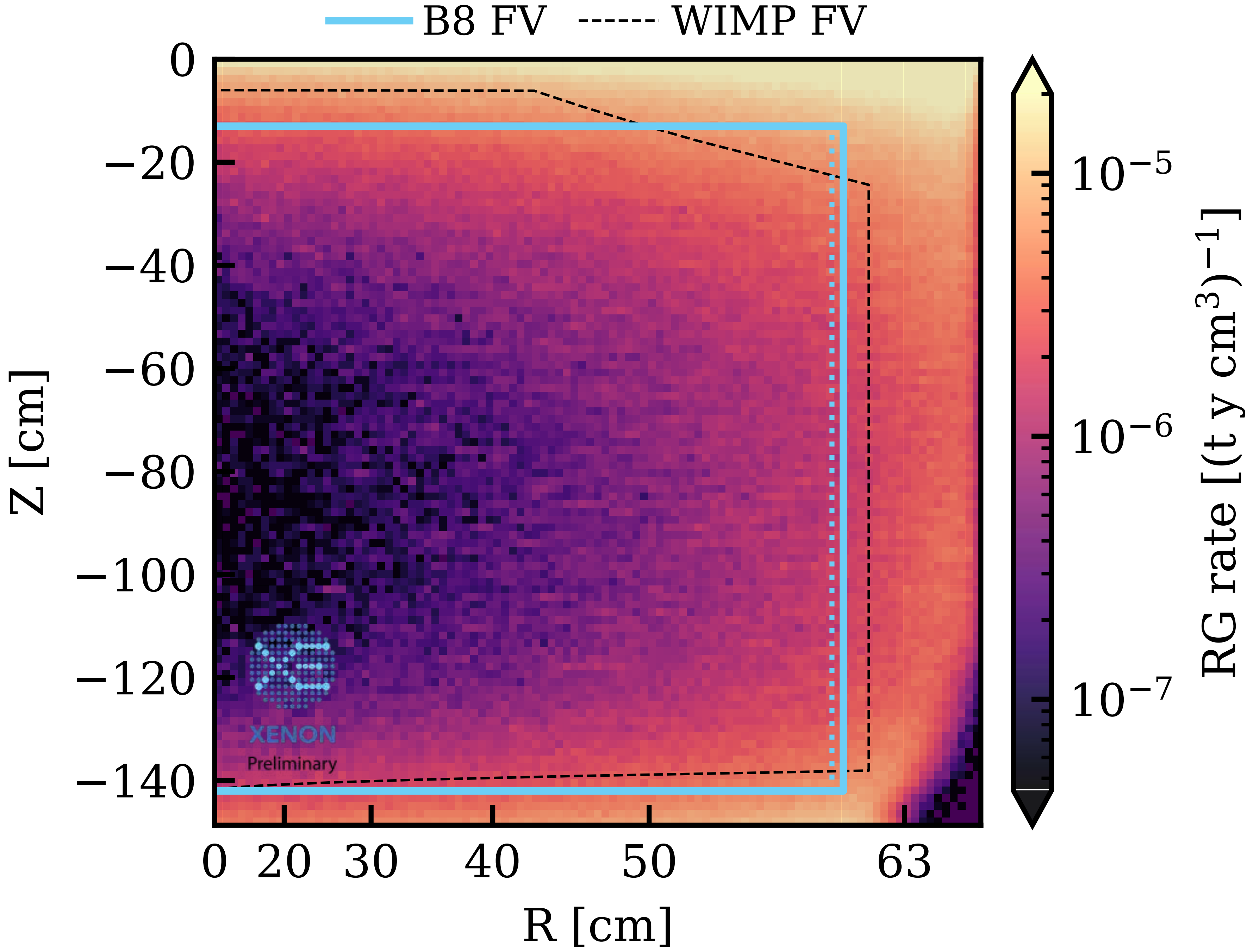
Final background prediction (conservative):
- SR0: 0.13 ± 0.13 Events
- SR1: 0.56 ± 0.56 Events

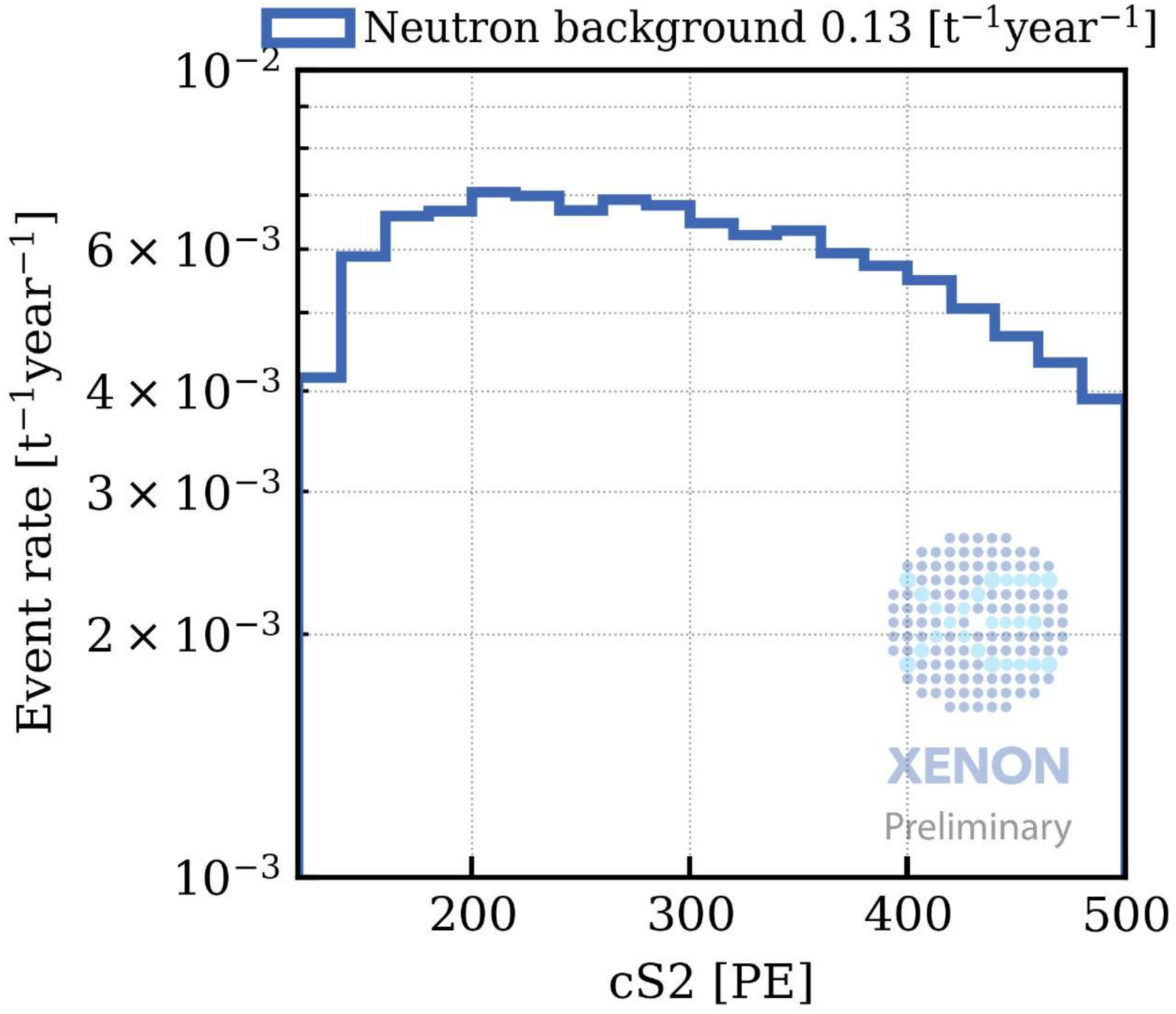
Neutron Background



^{8}B FV mass ~ 4t





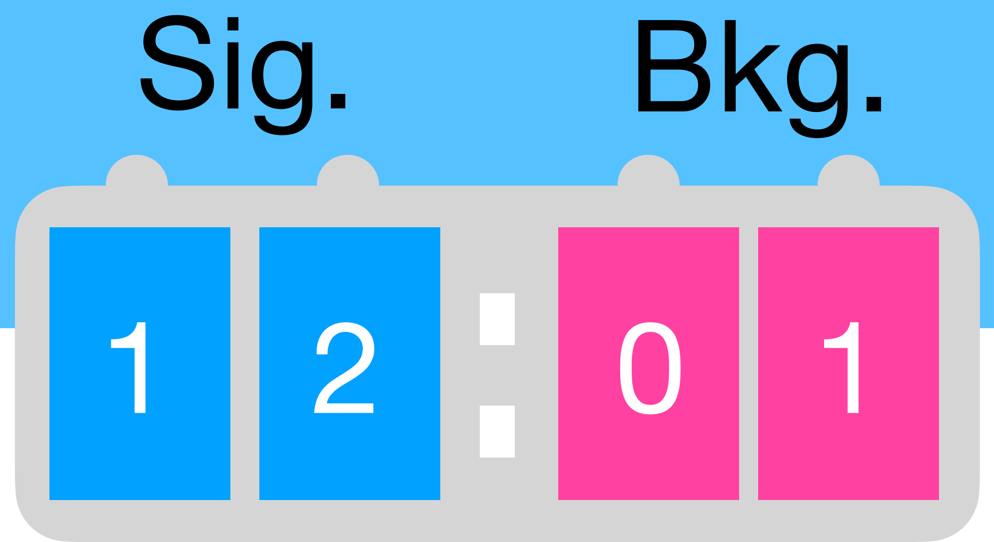


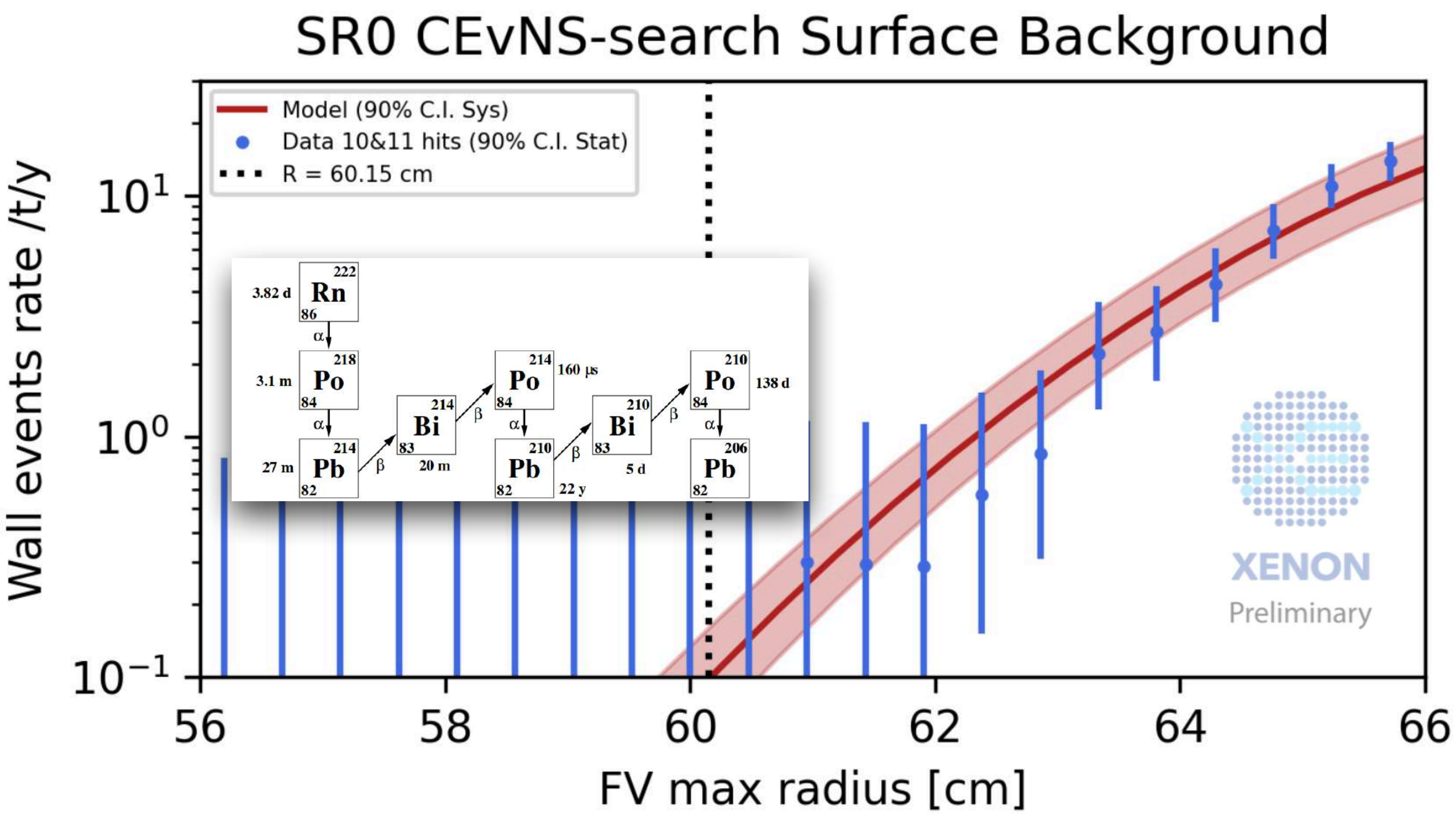
- Rate estimated by full chain simulation
- Uncertainty is determined with sideband data tagged with Neutron Veto

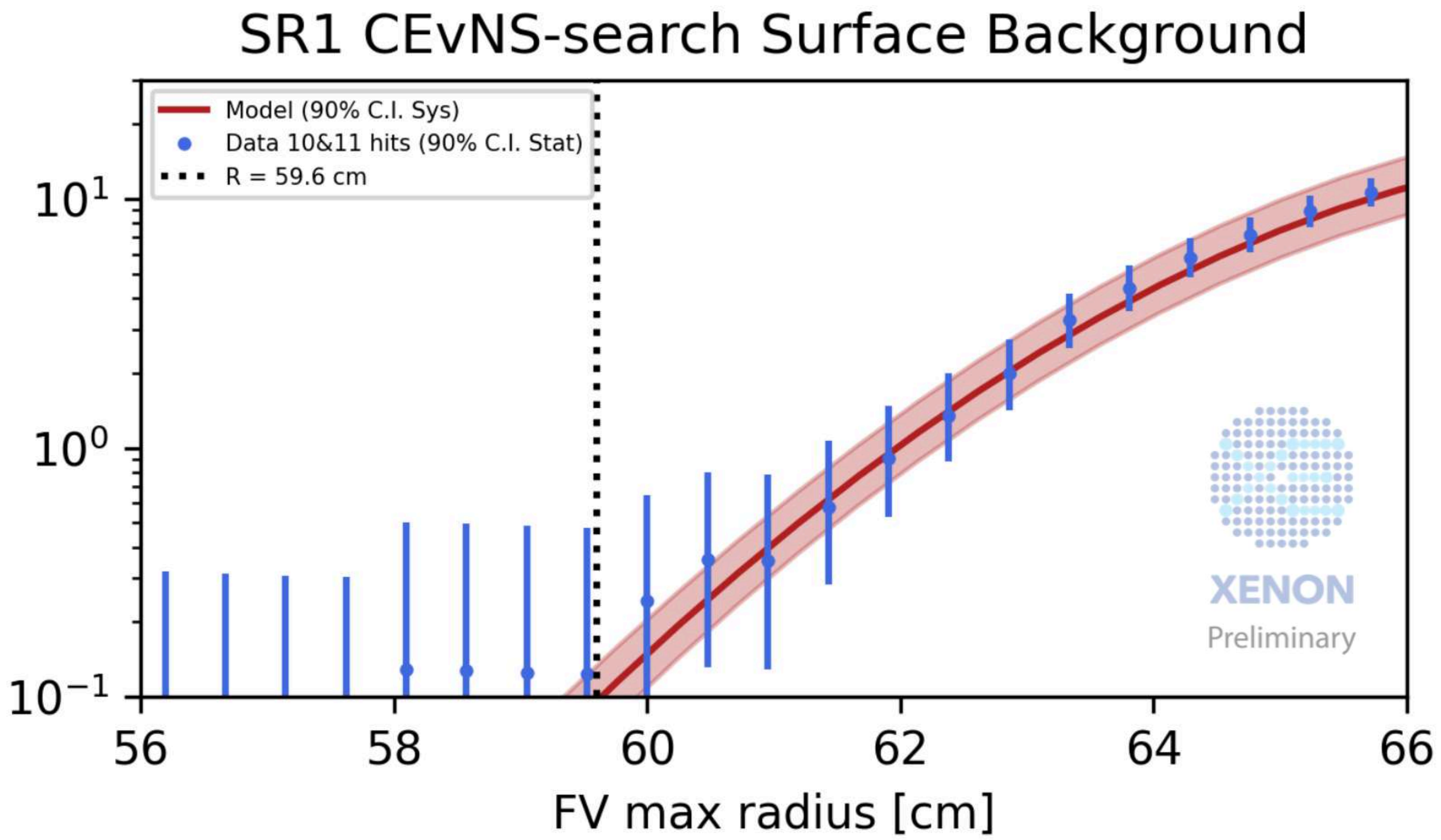
Final background prediction:

- SR0: 0.13±0.07 Events
- SR1: 0.33±0.19 Events

Surface Background







A radial cut is placed to reduce the background on the inner surface of the PTFE panels

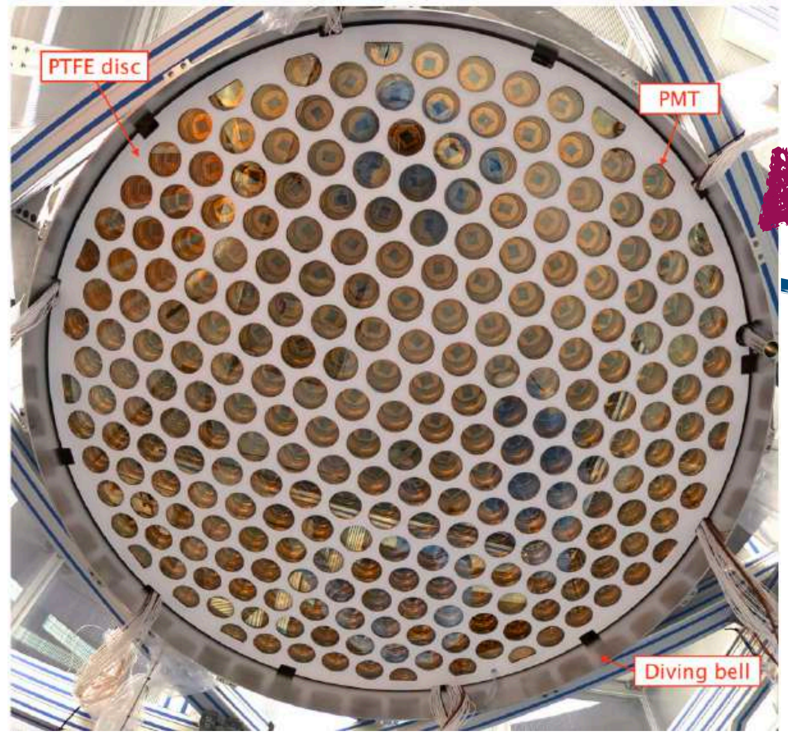
Final background prediction:

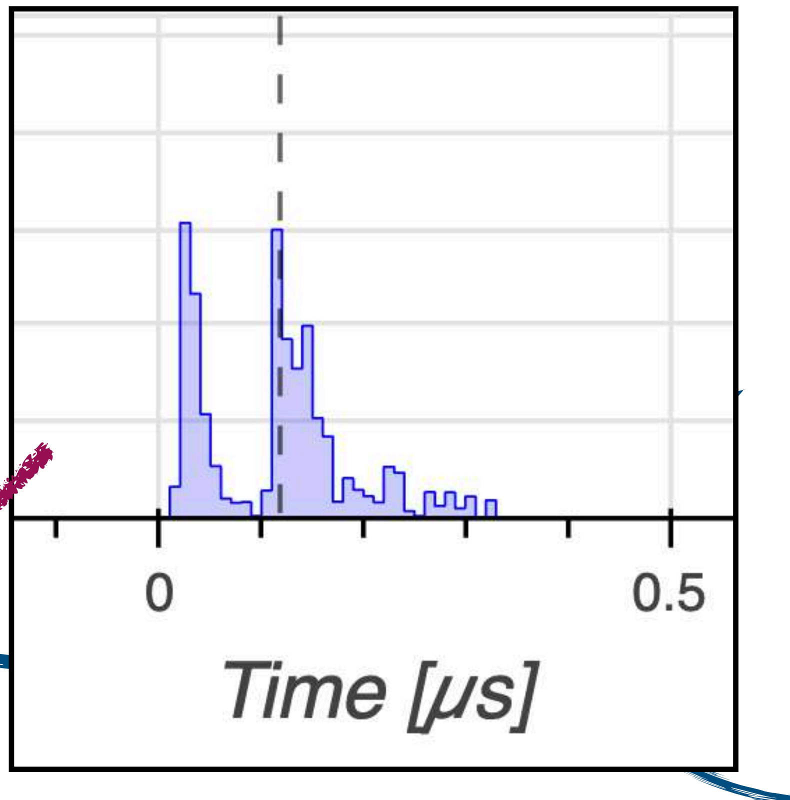
- SR0: 0 (< 0.12 Events), $R_{max} = 60.15$cm
- SR1: 0 (< 0.23 Events), $R_{max} = 59.60$cm

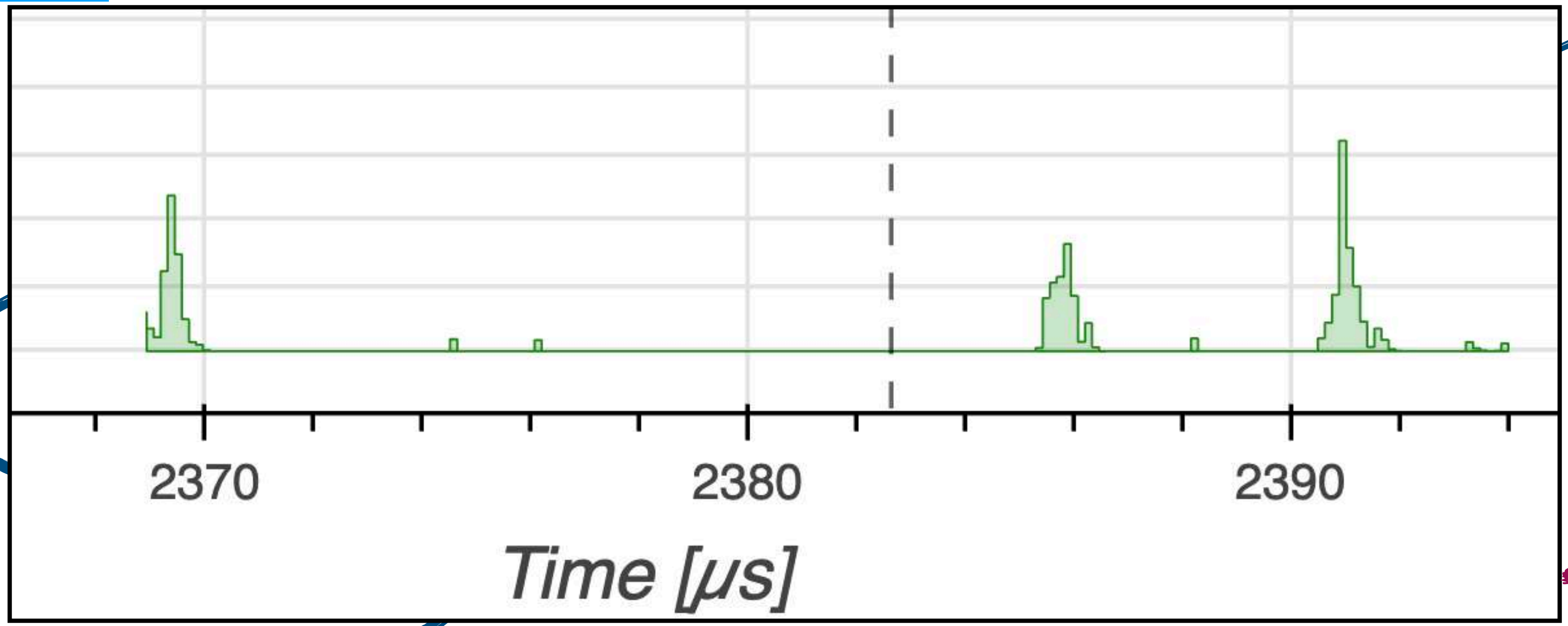
A negligible component in this analysis

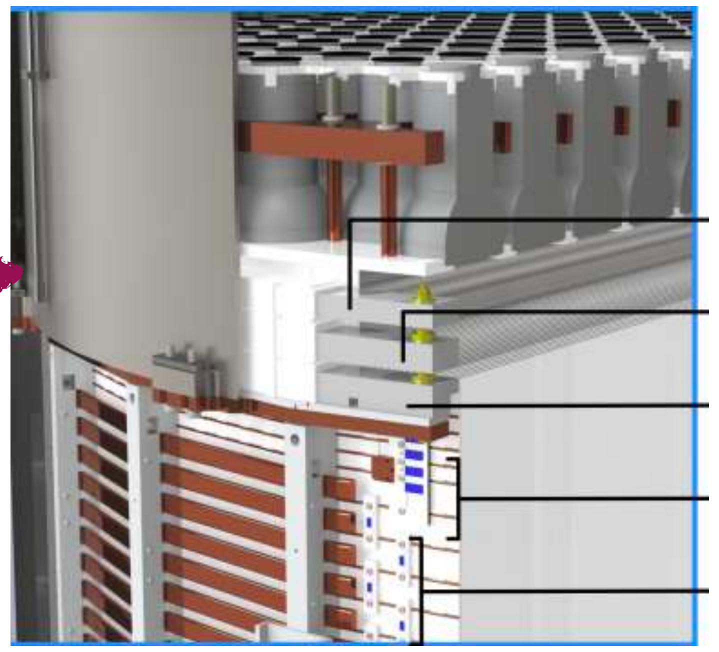
Accidental Coincidence in XENONnT

Accidentally pair S1 and S2 peaks







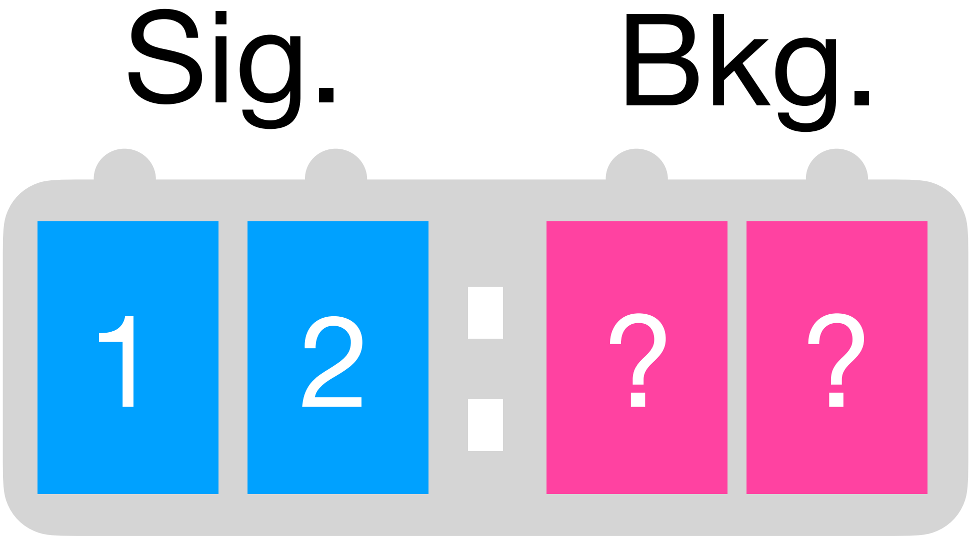


$$N_{AC} = \int_{t_0}^{t_1} R_{S1}(t) \cdot R_{S2}(t) \cdot T_{max} dt$$

In low energy NR ROI： (S1 2/3 hits, S2 from few to dozens electrons)

Iso-S1 Rate	Iso-S2 Rate	T max	Raw AC Rate
~ 15 Hz	~ 0.15 Hz	2.2 ms	5 mHz (~400/day)

23 V/cm drift field



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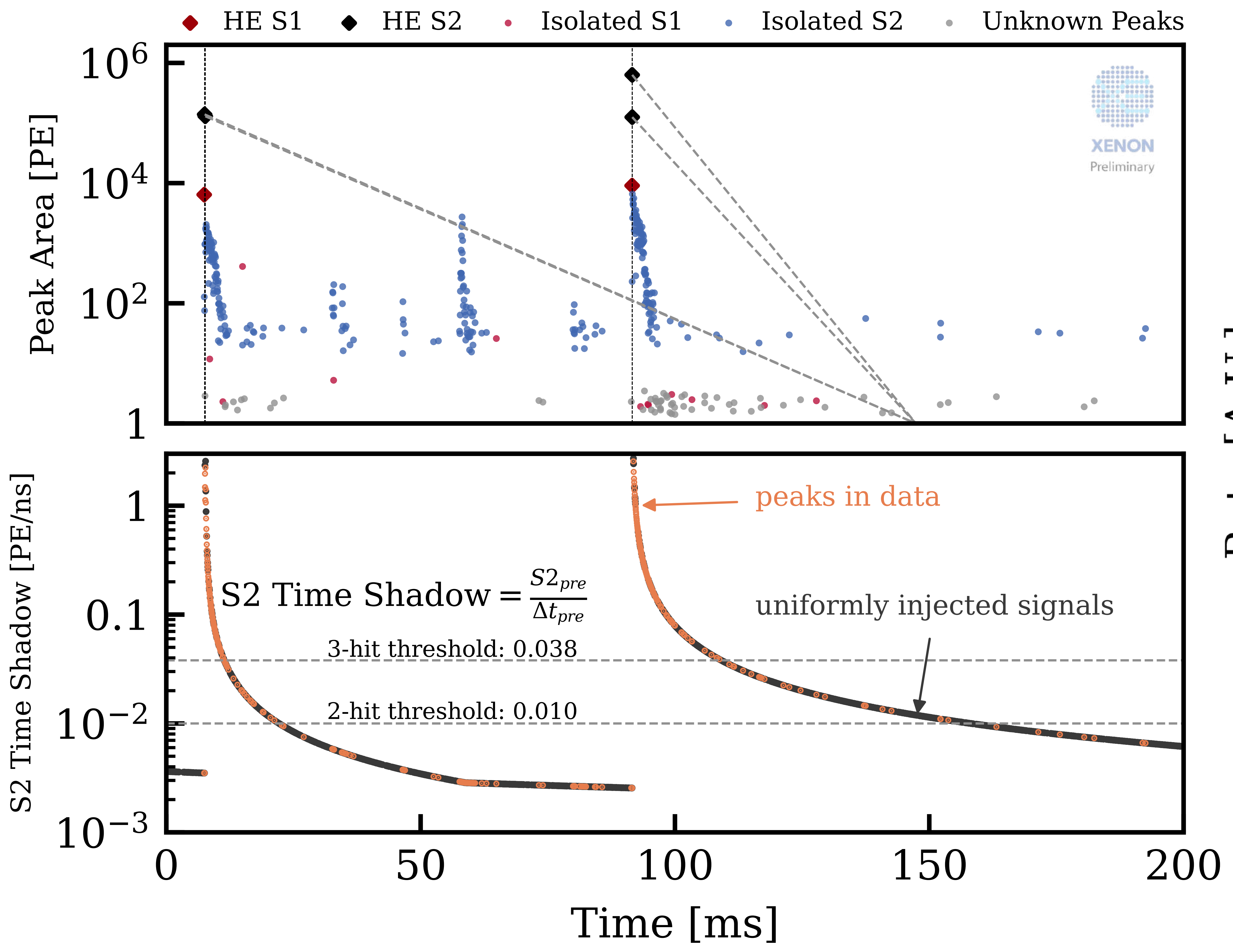
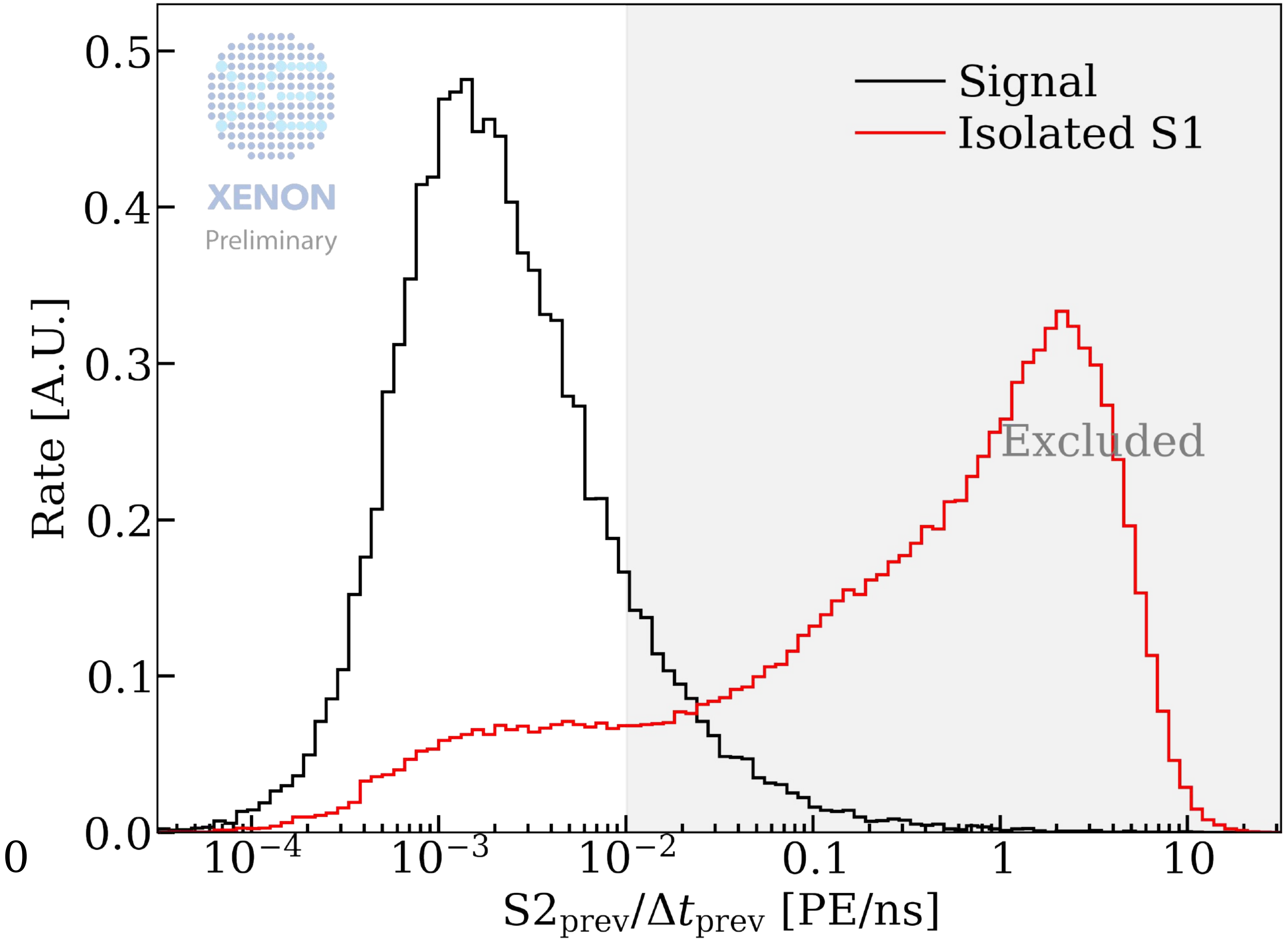
Time Shadow - Quantify the cleanliness of the exposure

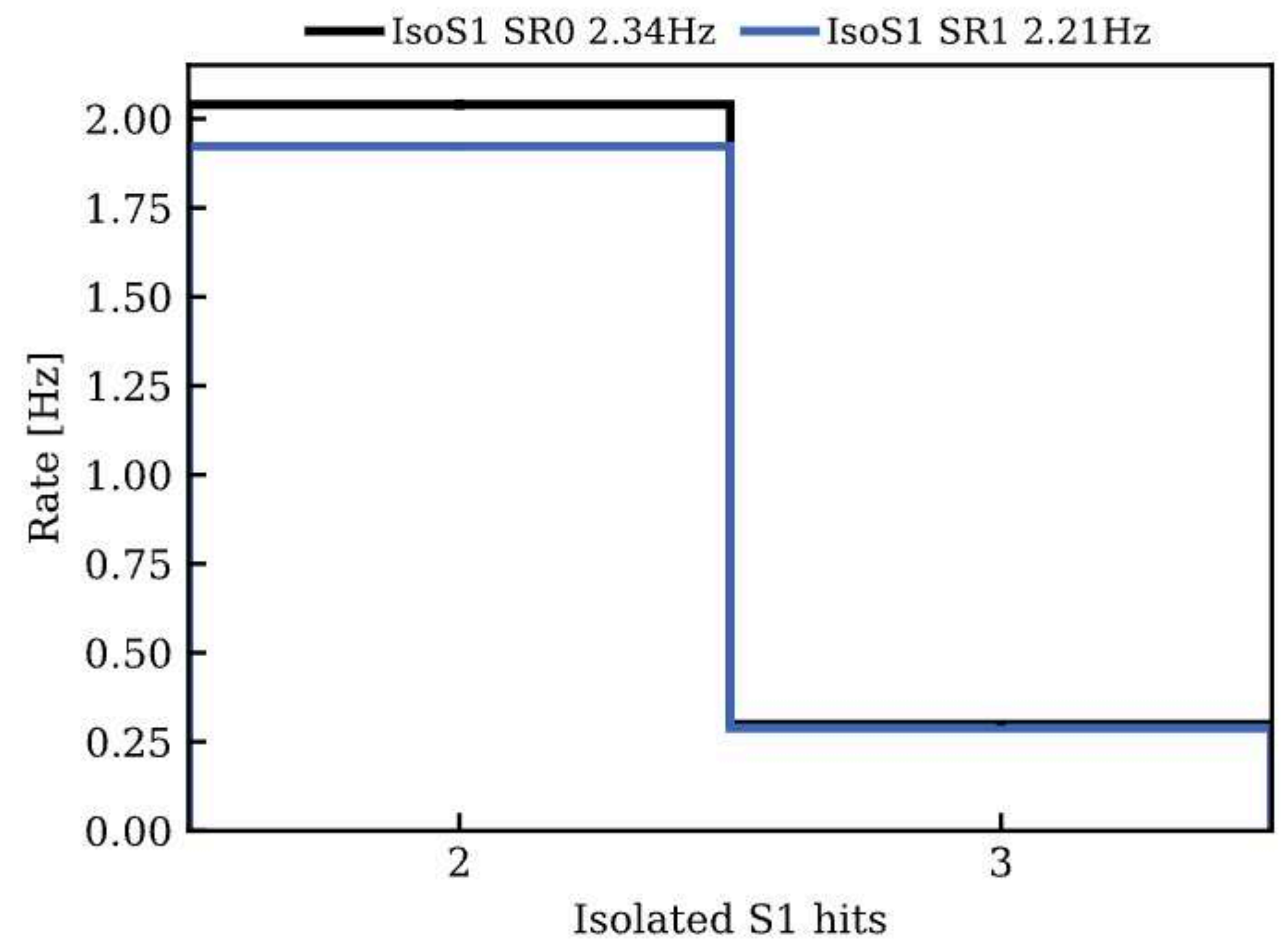




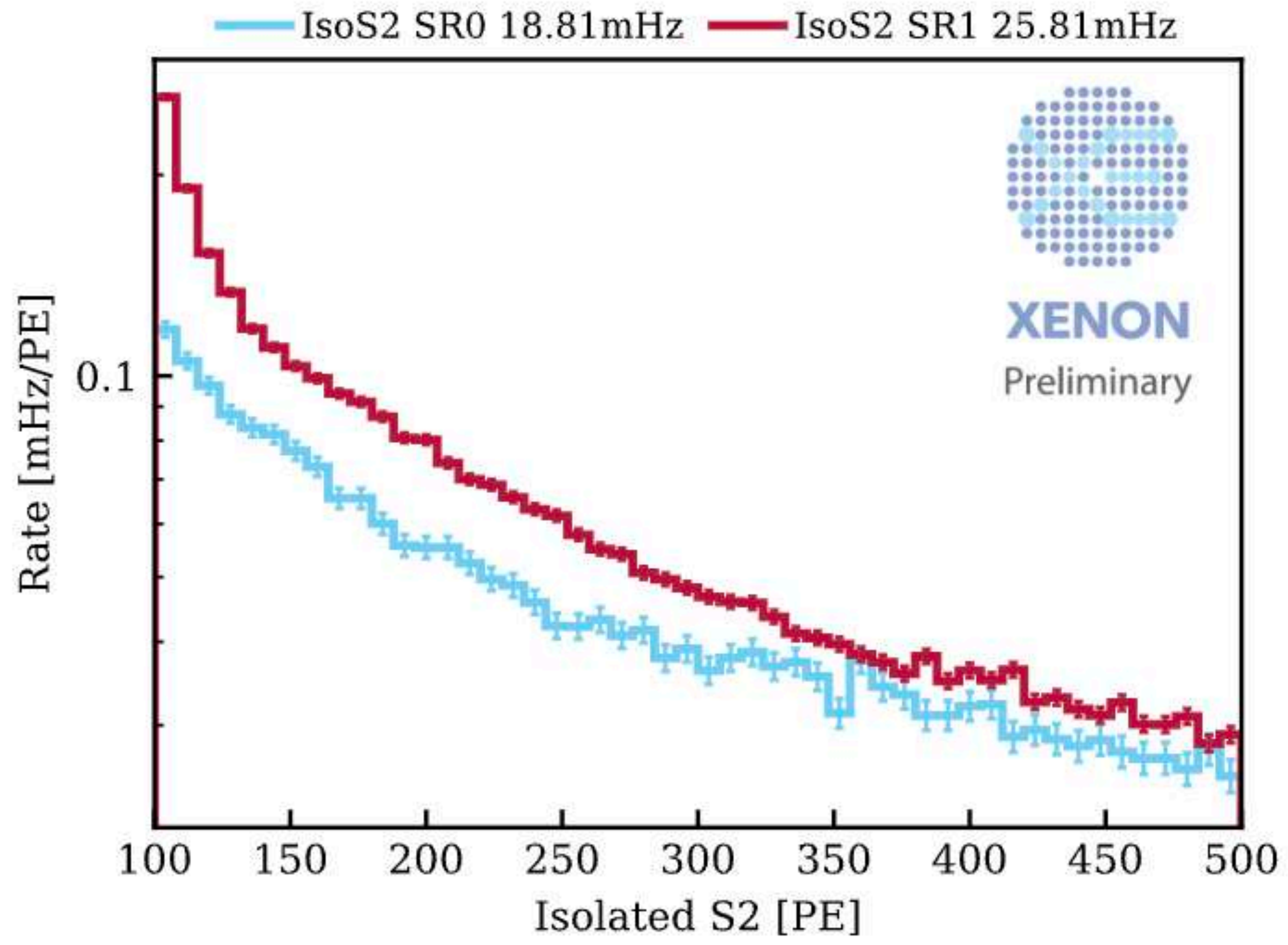
Use in Inference

Suppress isolated peaks & Simulation

Isolated S1: 15 Hz →2.3 Hz

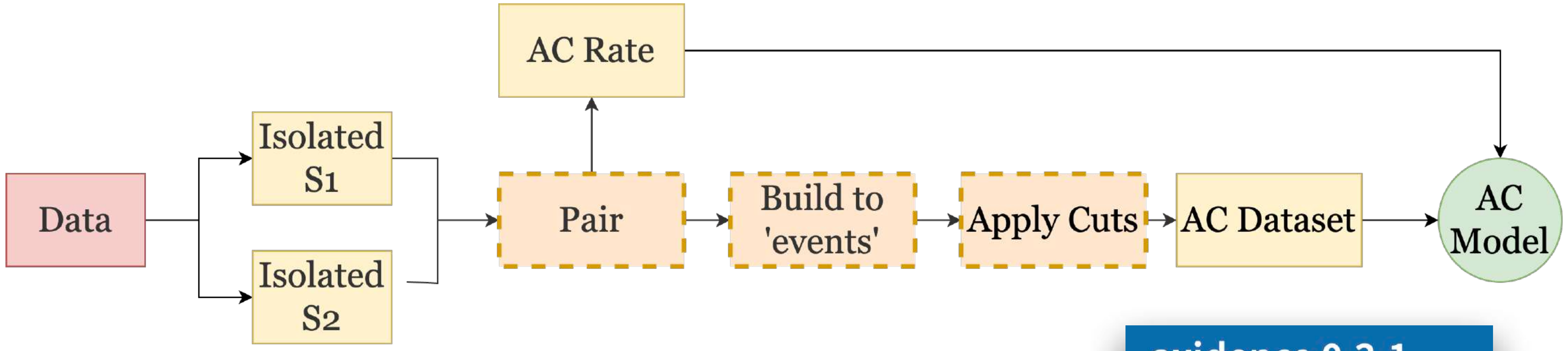


Isolated S2: 0.15 Hz → 25 mHz

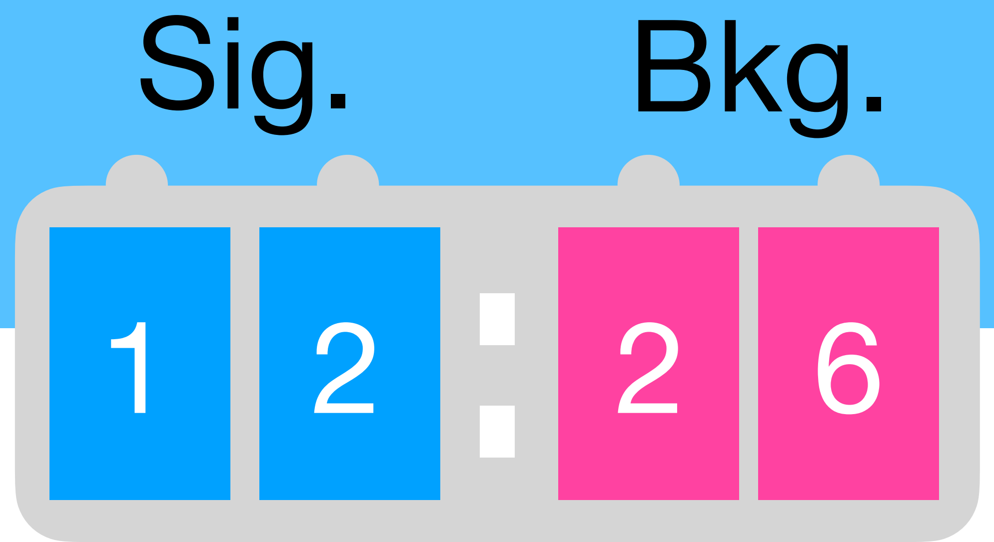


- After the time-space correlation cuts, the majority of isolated peaks is removed.
- Signal acceptance ~ 75%-85%

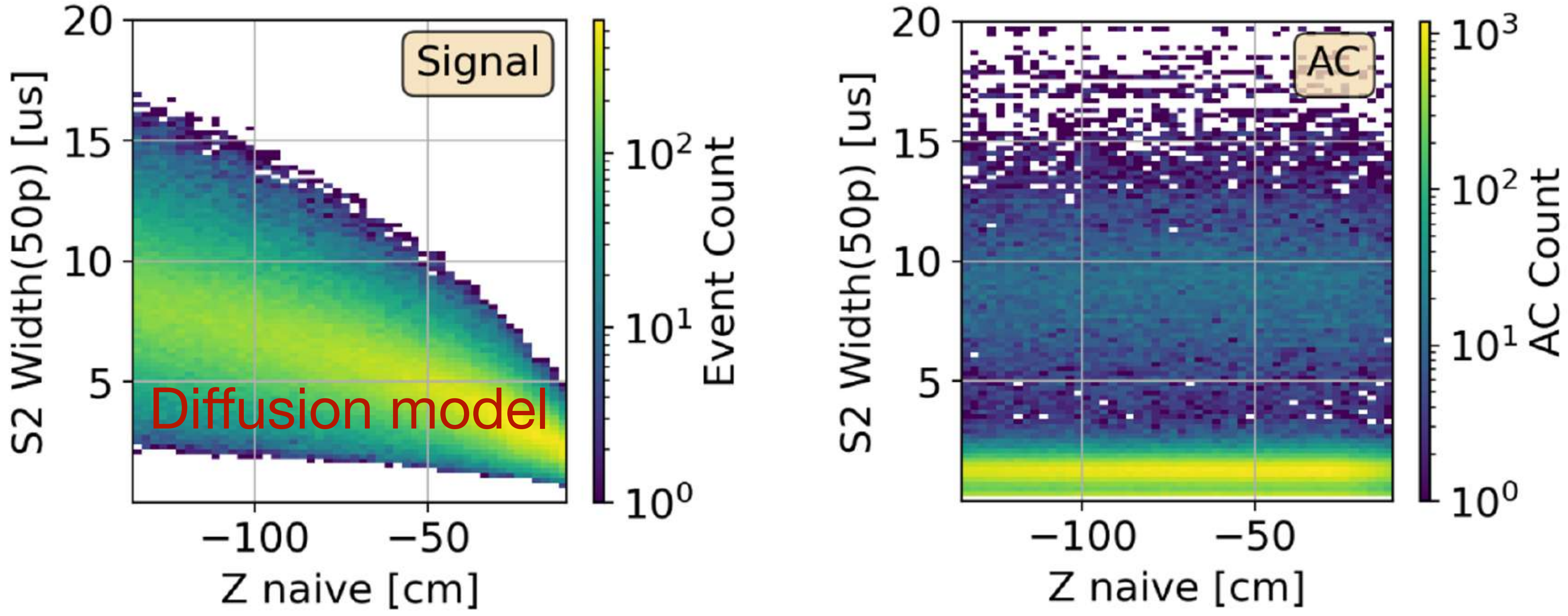
- Then we run Data-driven simulation to get the background prediction

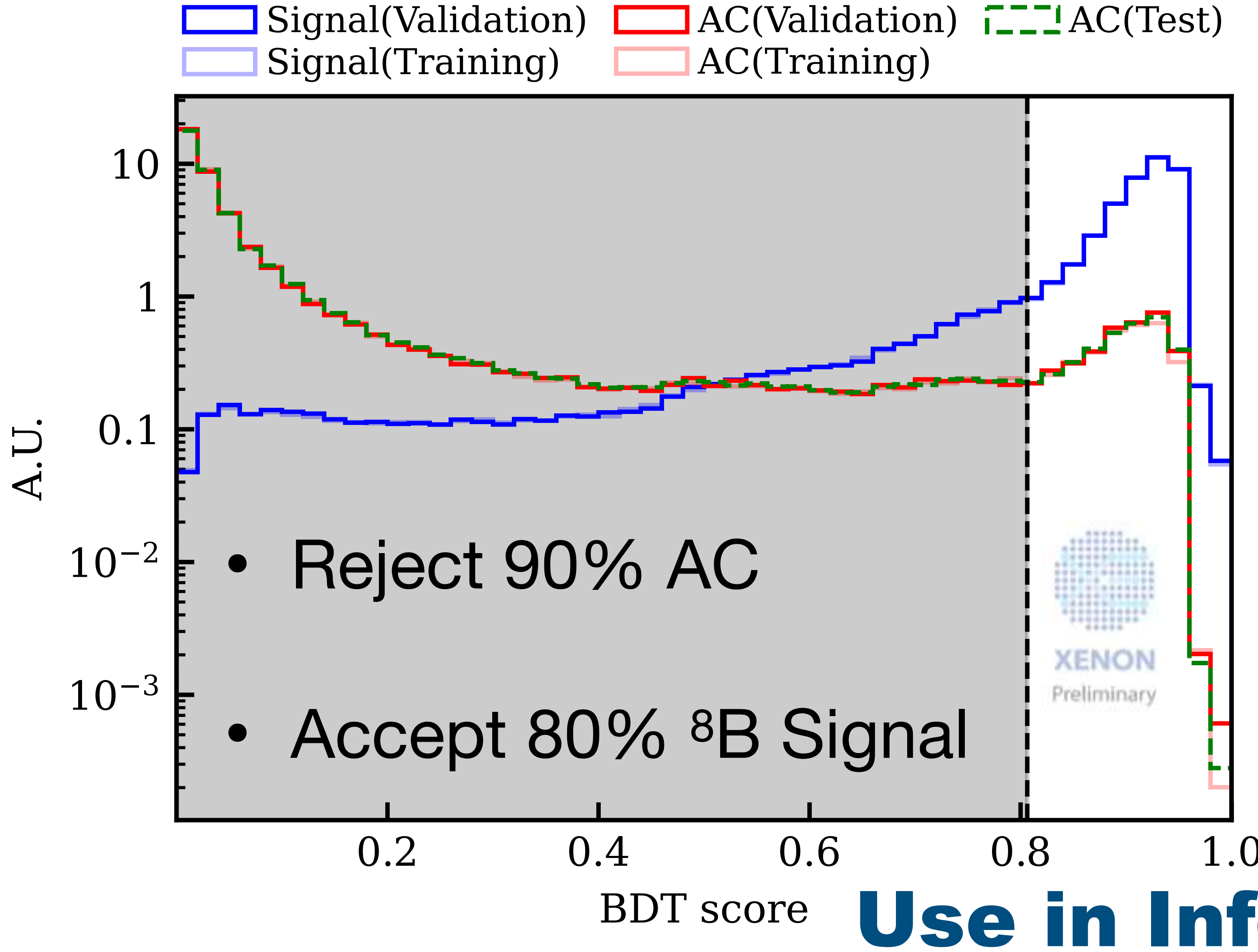


S1/S2 Pulse shape into GBDT

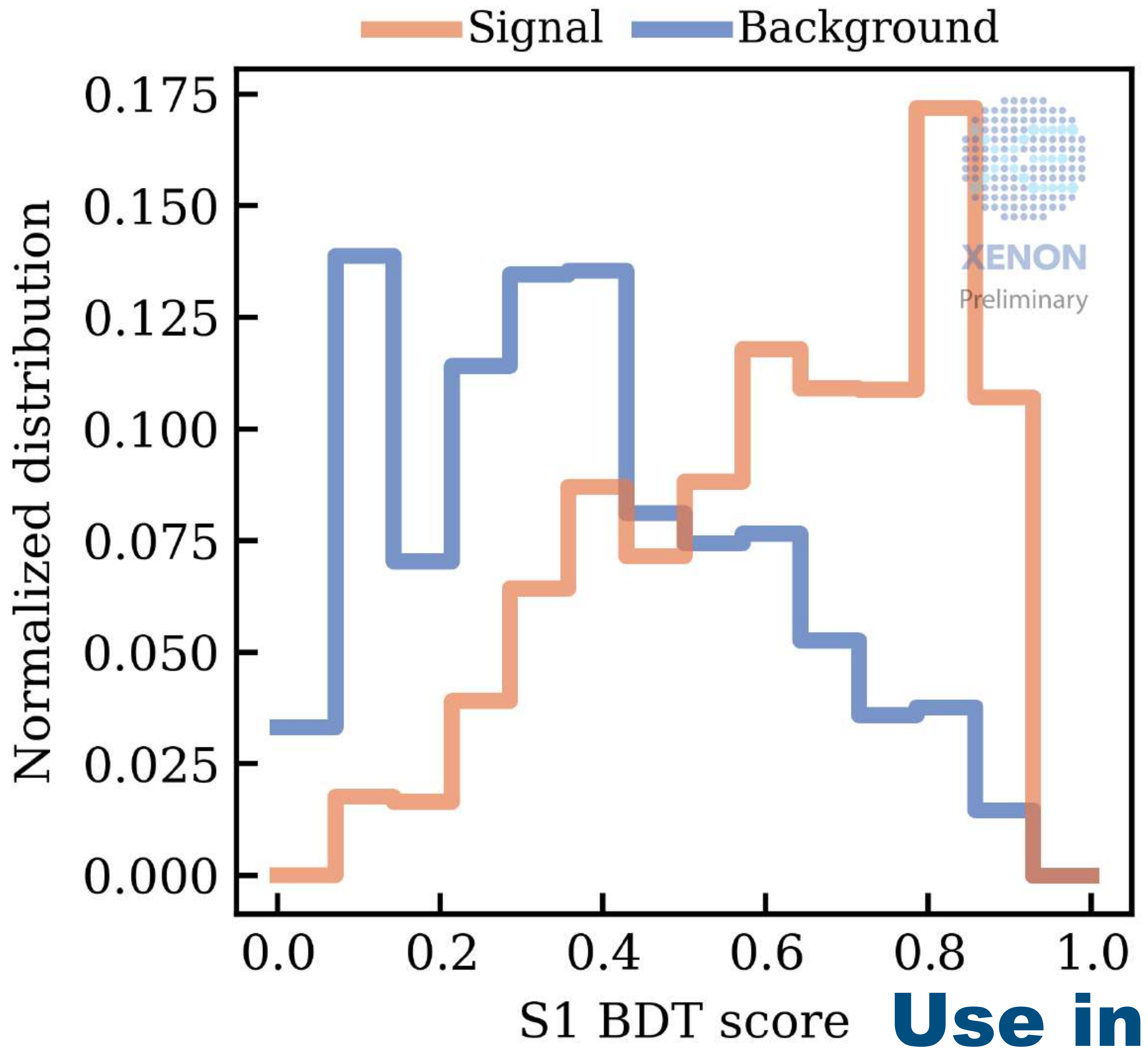


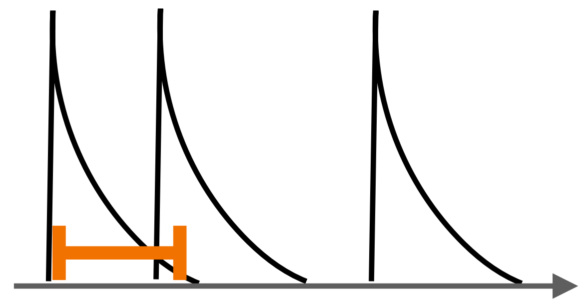
Gradient Boosting Decision Tree





Use in Inference



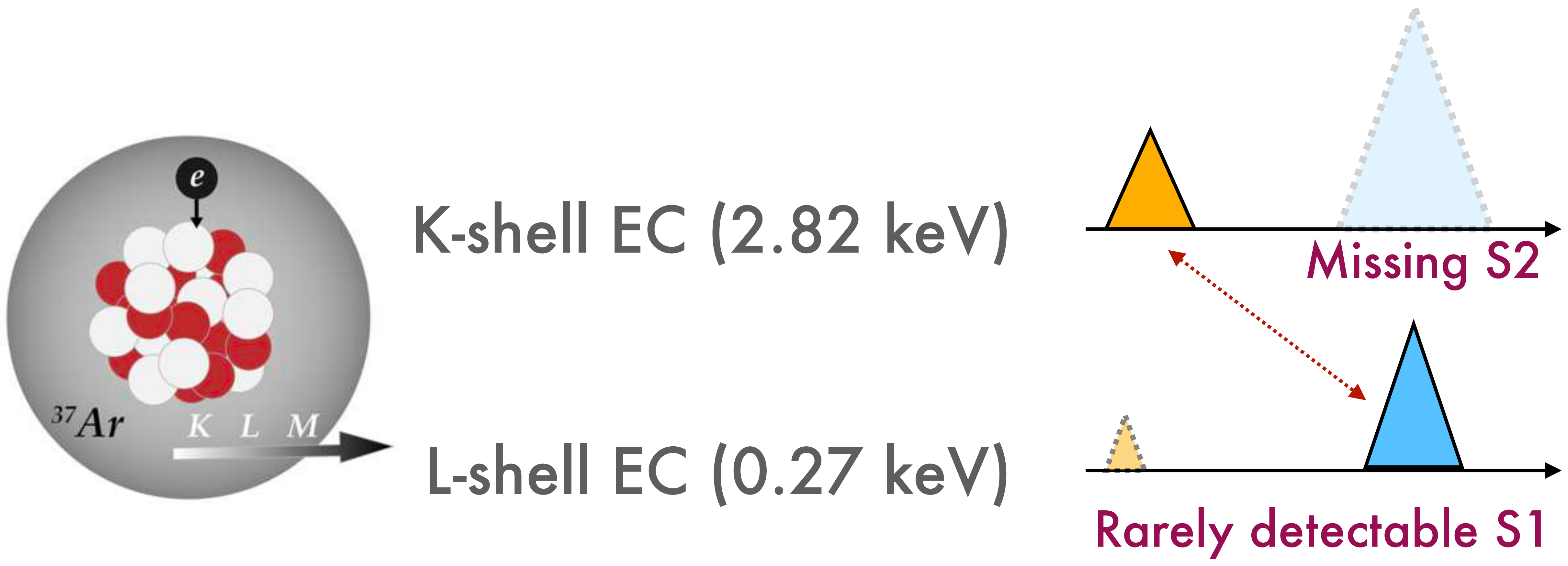


Use in Inference

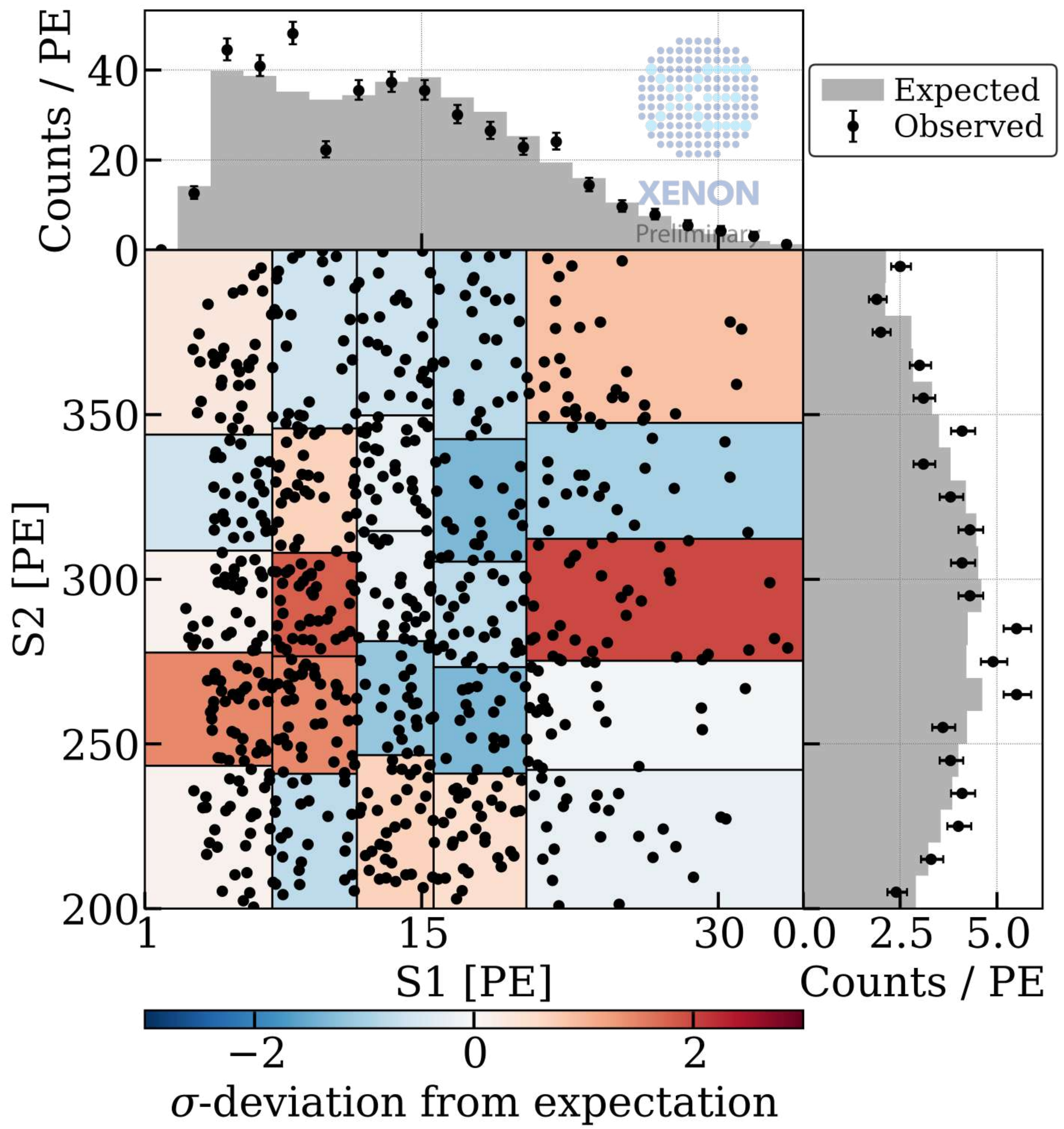
- Trained with AC vs Simulated ^{8}B
- Also use the S1BDT score and S2BDT score as inference dimensions

Validation on ^{37}Ar datasets

Provide High AC Counts to validate the framework

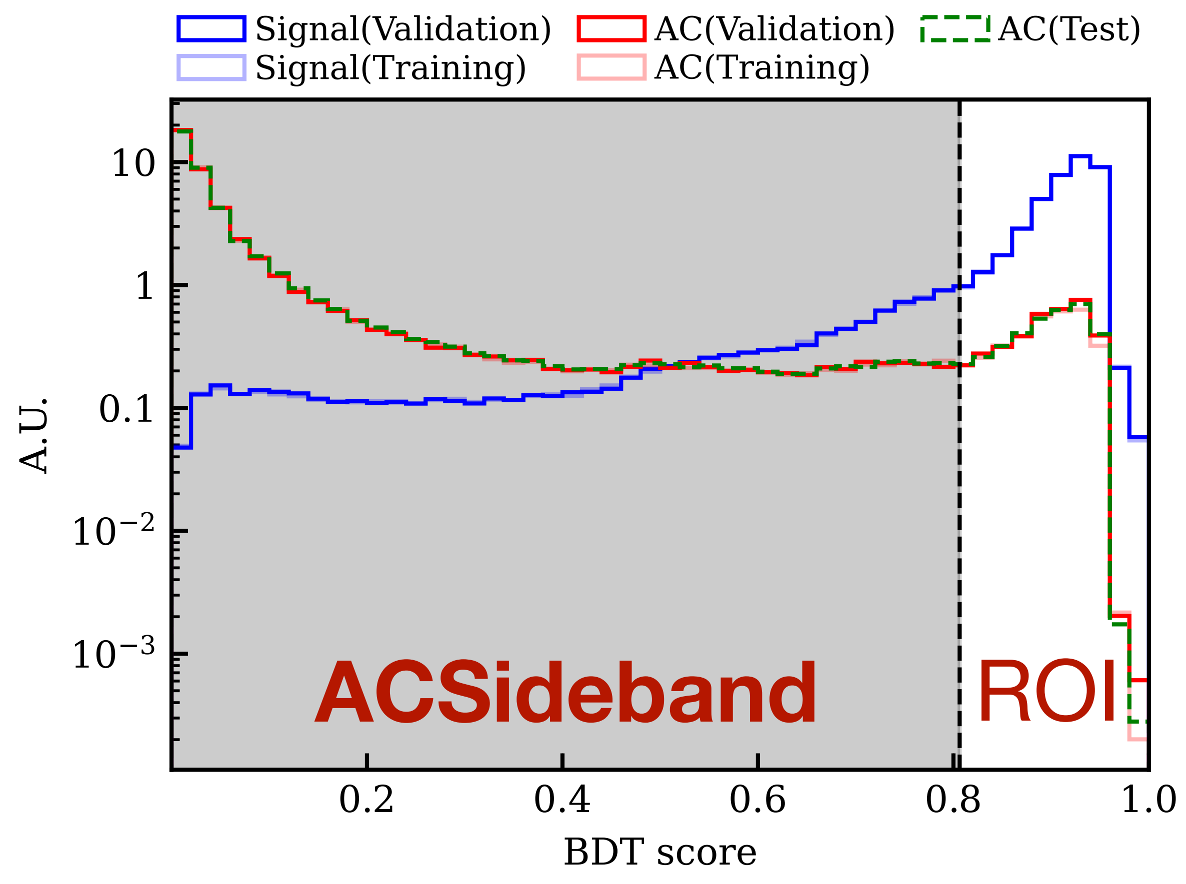


Dataset	Predicted	Observed
PureAC	1522.7	1459
In-ROI	731.6	733
ACSideband	349.7	366

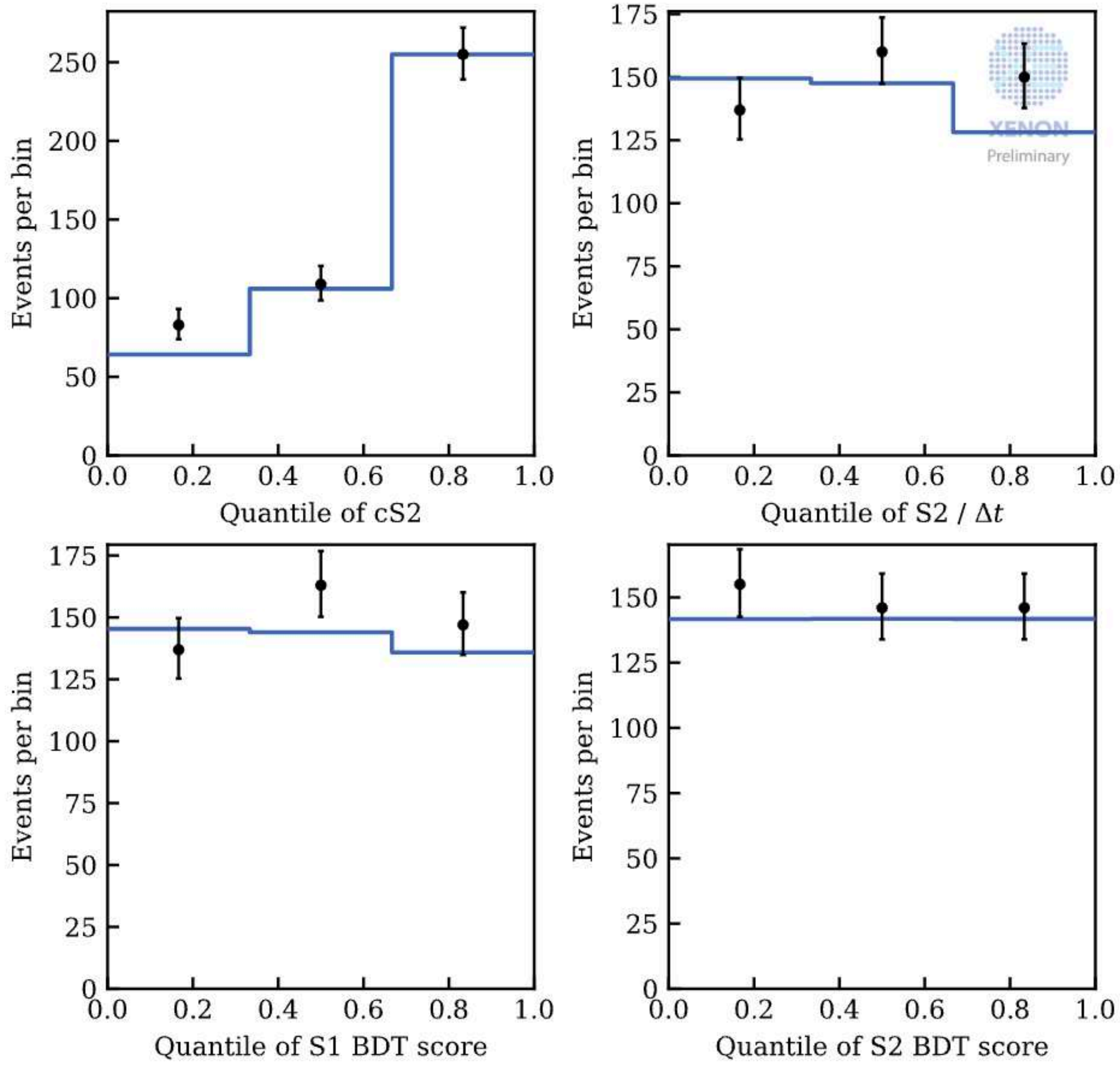


Validation on Science data ACSideband

Determine Systematic Uncertainty



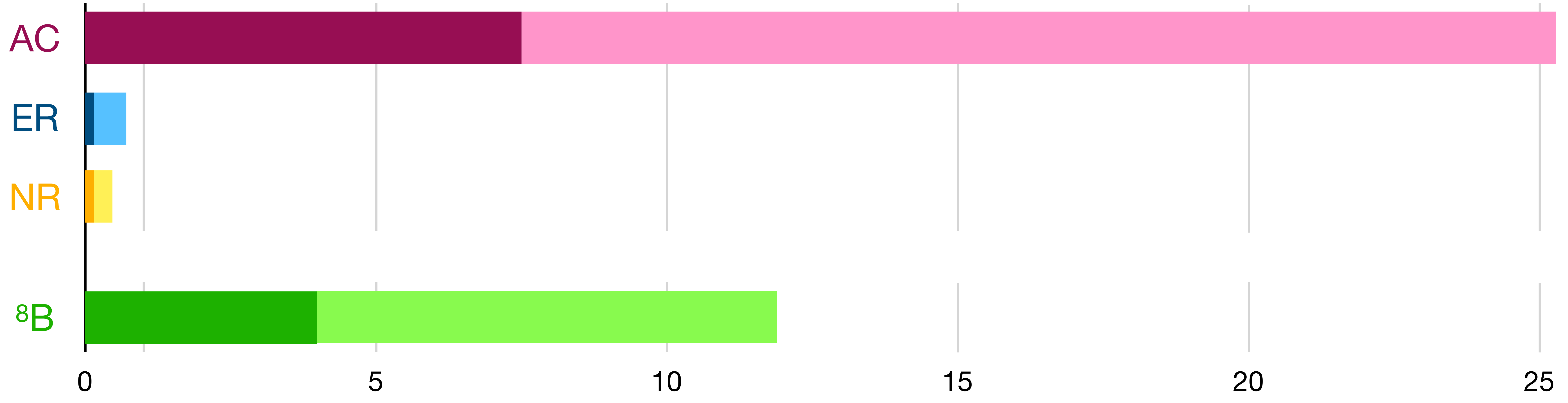
	AC Rate[/t/y]
SR0	6.37
SR1	7.58



Unblinding shows within 2-sigma, use the statistic uncertainty of ACSideband to be the systematics

Dataset	Predicted	Observed	p-value (4D)	Relative Uncertainty
SR0	122.7	121	0.33	9.0%
SR1	302.5	326	0.25	5.8%

Signal and Backgrounds Prediction



AC: Accidental Coincidence Background

- Validated by AC-rich Sideband
- Uncertainty: 9% (SR0), 6% (SR1)

ER: Electronic Recoil Background

- Flat spectrum at O(0.1)keV
- 100% conservative uncertainty

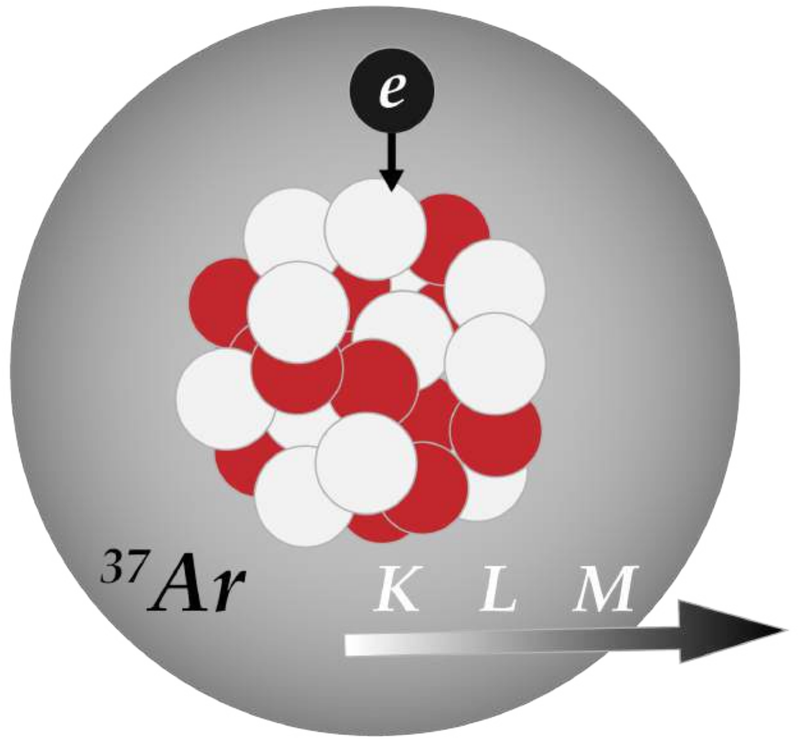
NR: Nuclear Recoil Background

- Full-chain simulated
- 58% uncertainty from sideband

^{8}B: CEvNS Signal

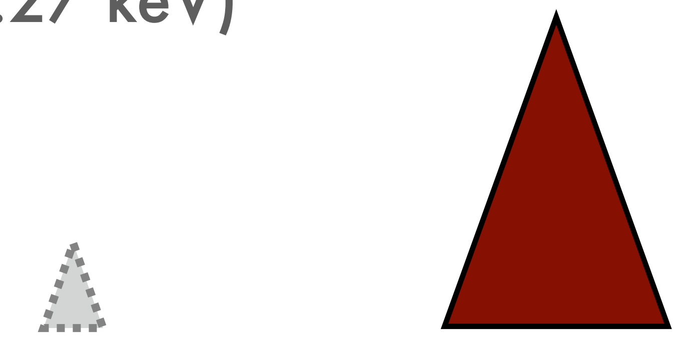
- Yields calibrated from ^{88}YBe neutron source
- ~35% uncertainty from yields and efficiencies

Analysis Validation by Search for ^{37}Ar L-Shell

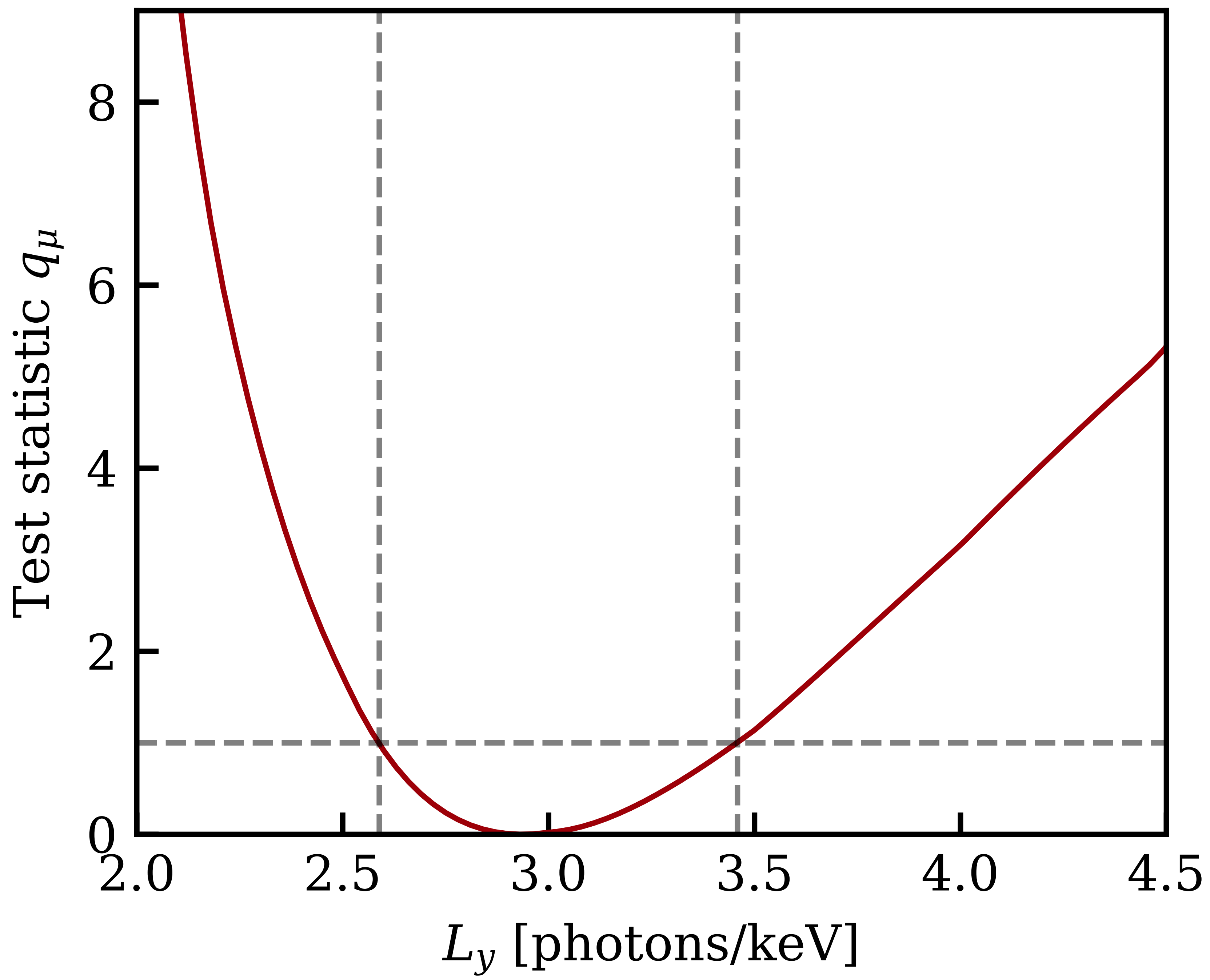


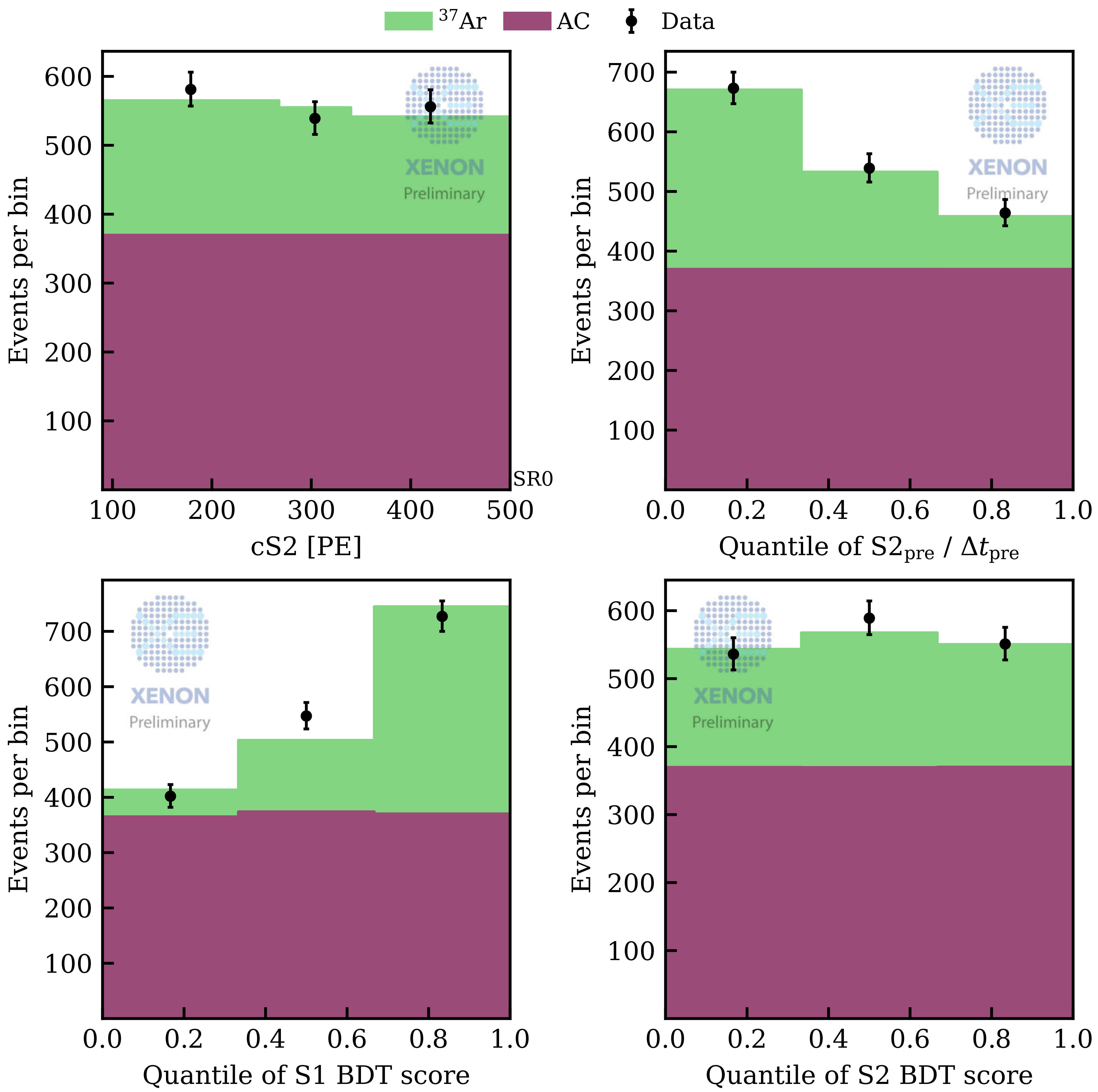
L-shell Electron Capture

(0.27 keV)



S1 Rarely detectable

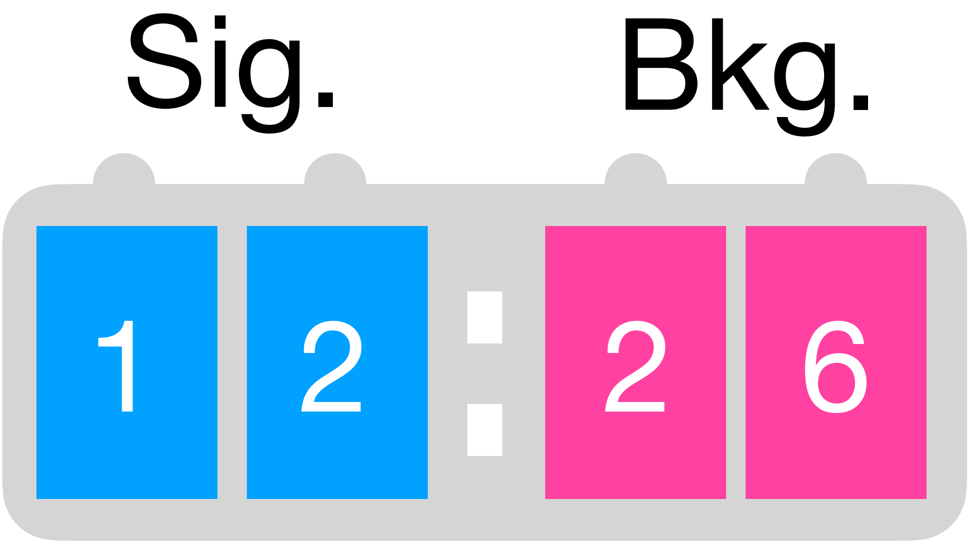




Extended binned likelihood with $3^4 = 81$ bins

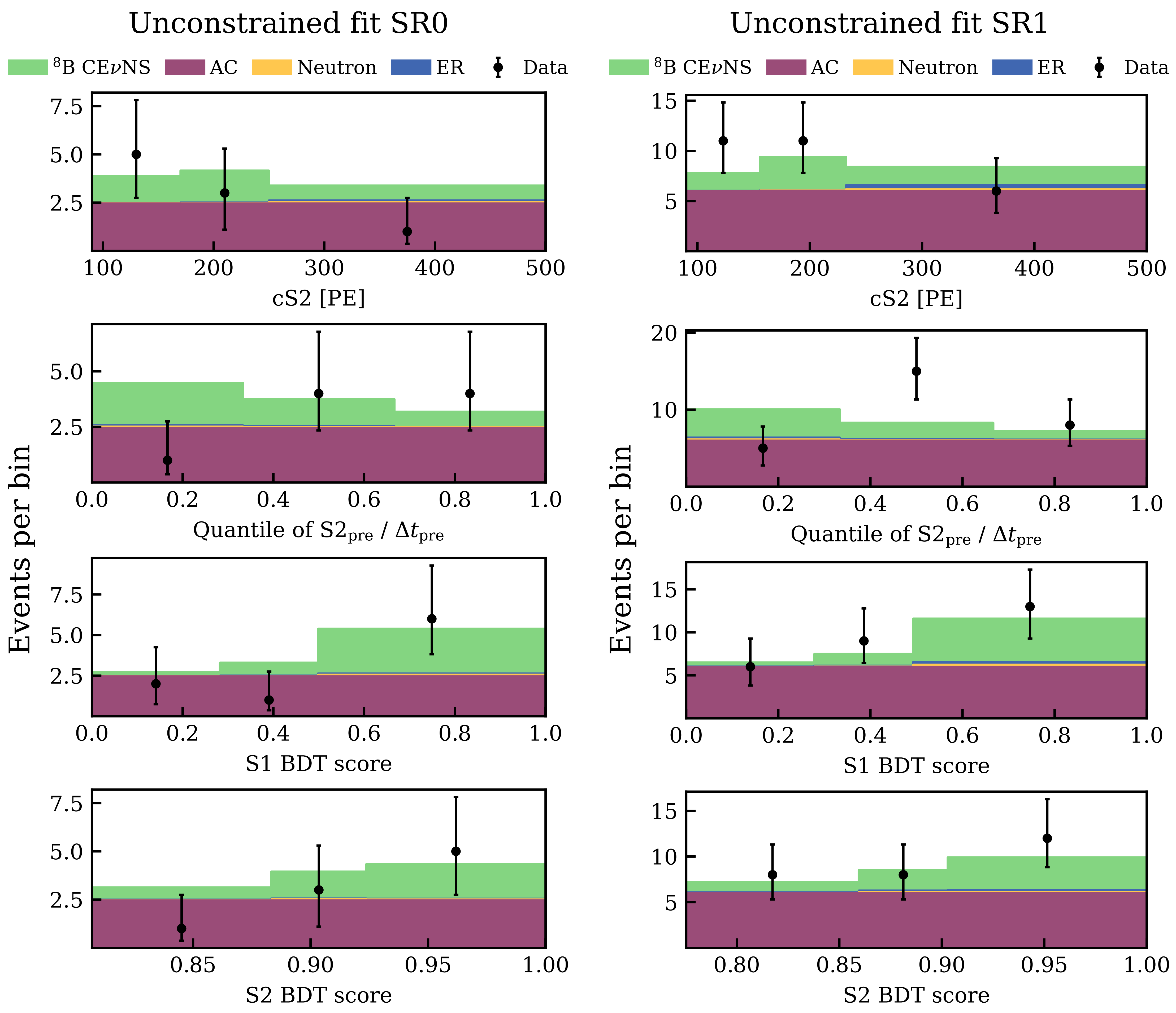
4D GoF p-value: 0.7

Inference and Result



Unblind Result

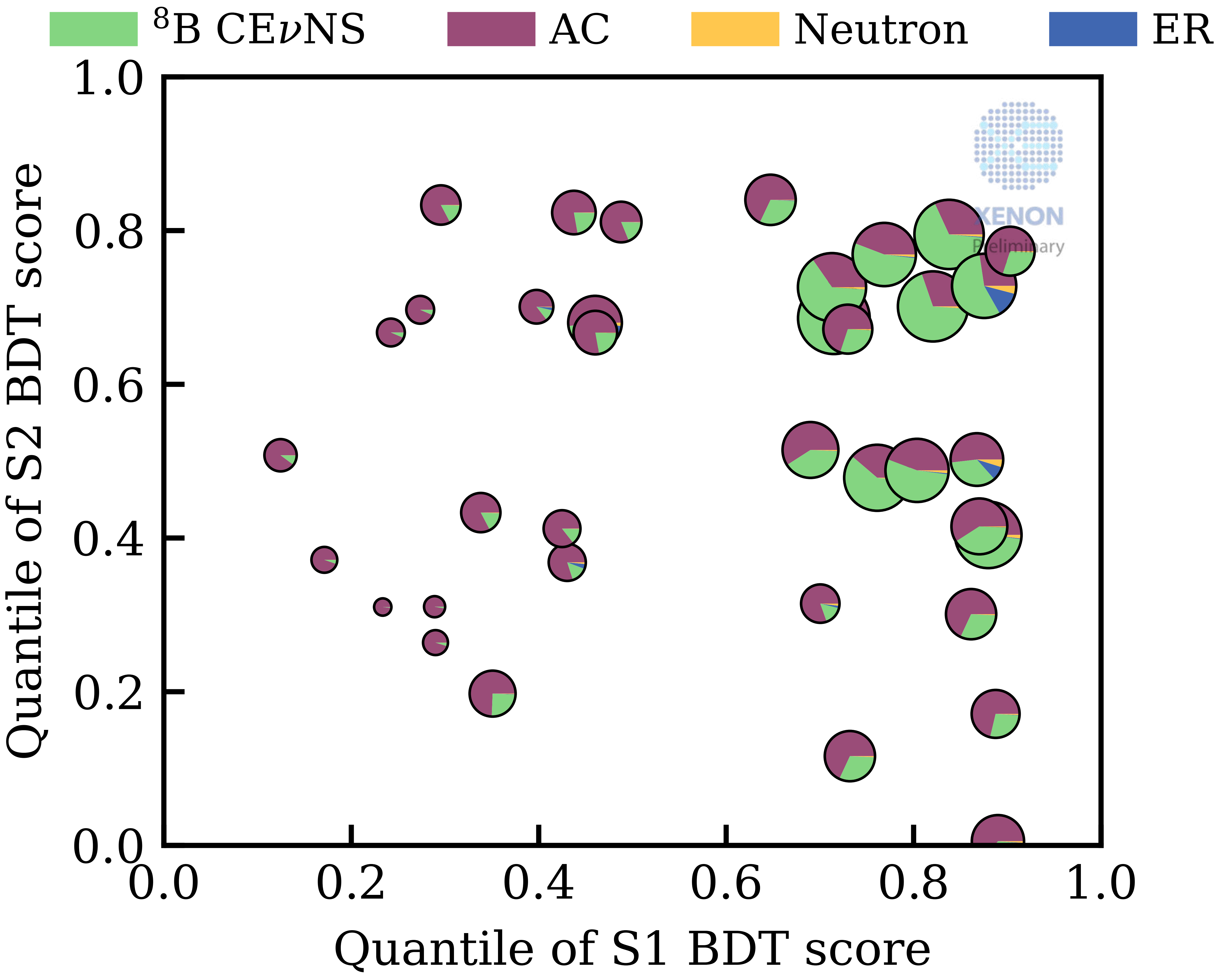
Component	Nominal Expectation	Background + ^{8}B fit
AC - SR0	7.5 ± 0.7	7.4
AC - SR1	17.8 ± 1.0	17.9
ER	0.7 ± 0.7	0.5
NR	0.5 ± 0.3	0.5
Total Background	26.4 ± 1.4	26.3
^{8}B	11.9 ± 4.5	10.7
Observed	37	

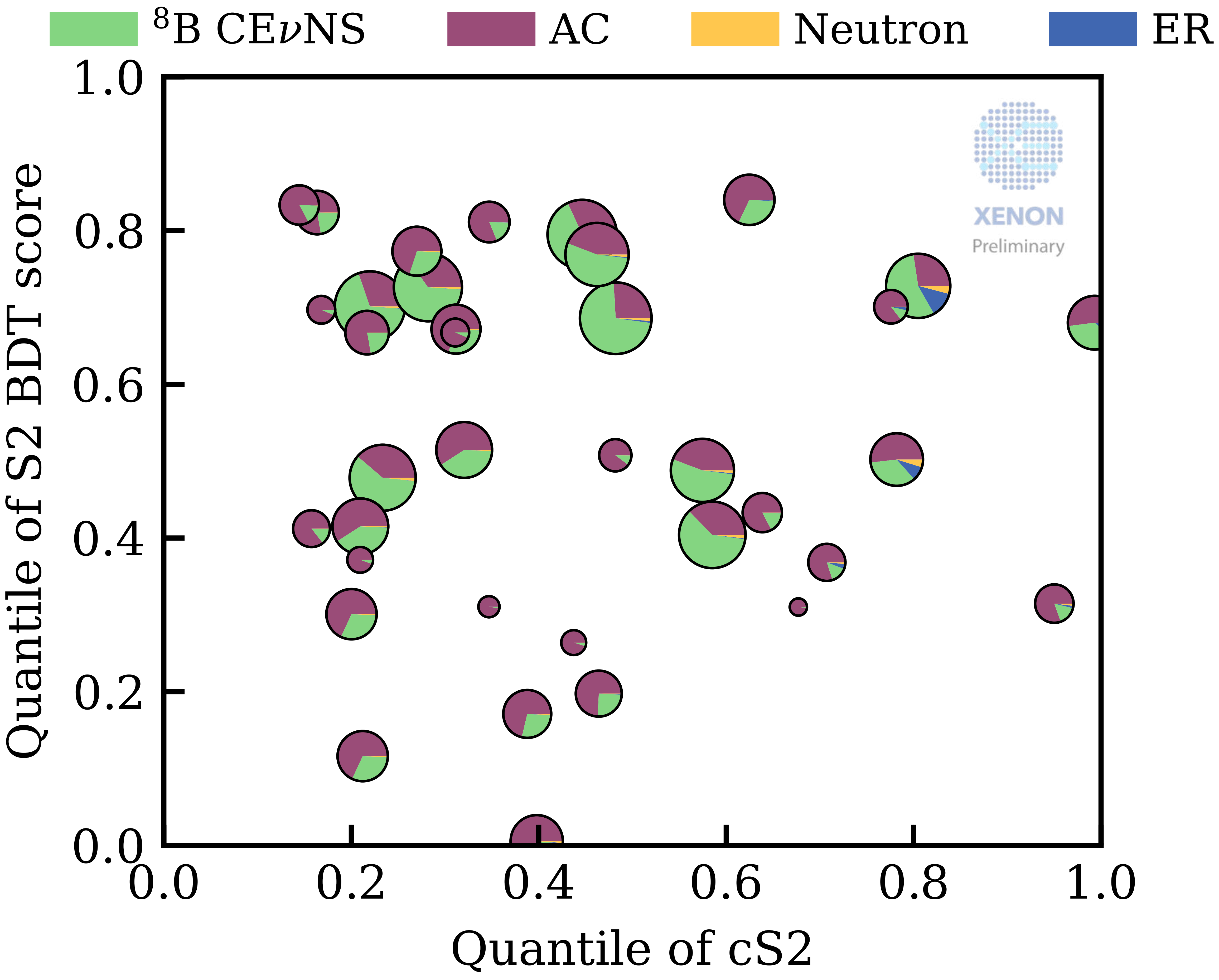


The significance of the solar ^{8}B neutrinos via CEvNS in XENONnT at 2.73σ

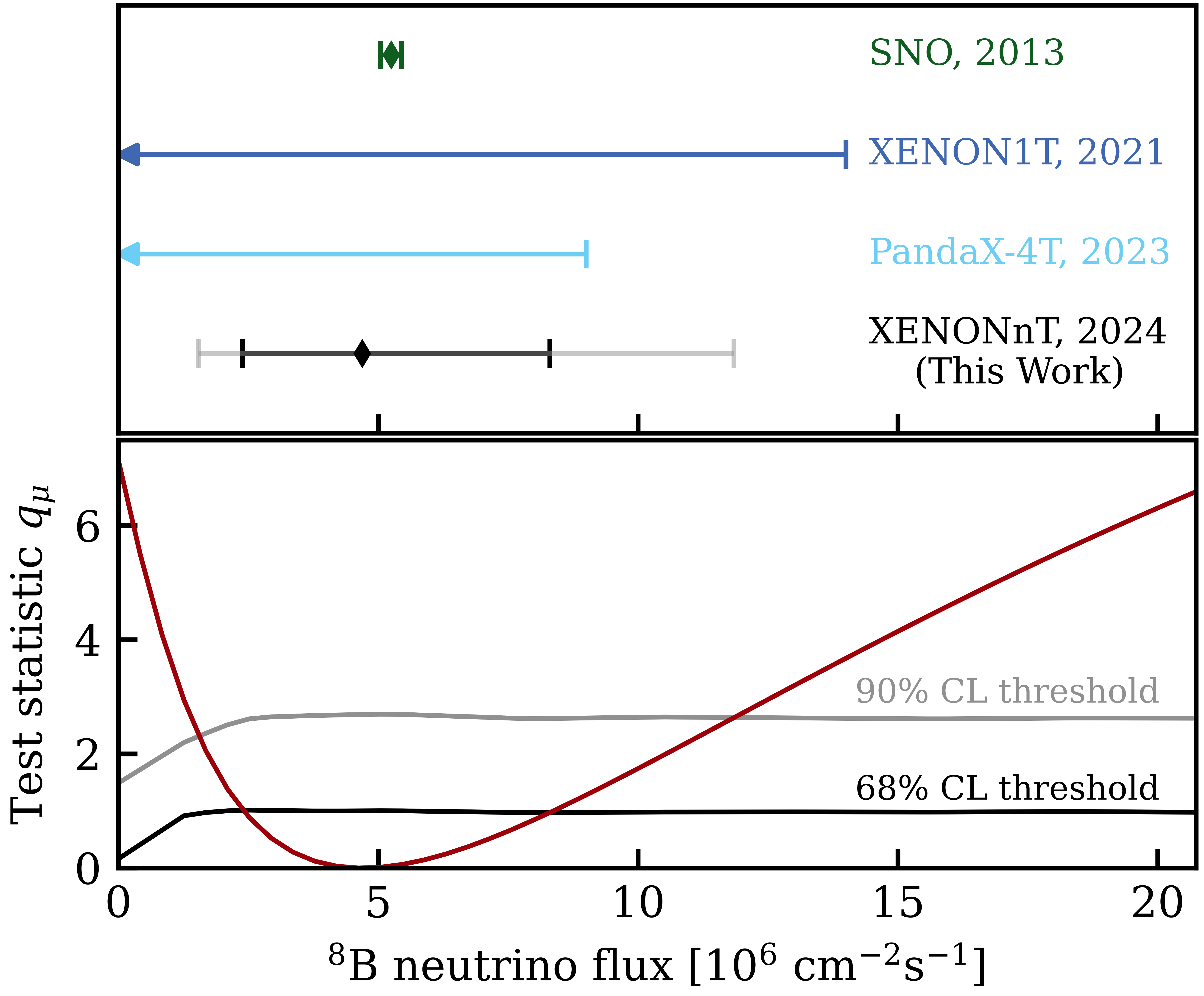
1/300 chance to be fluctuated background

Event distribution in important parameters

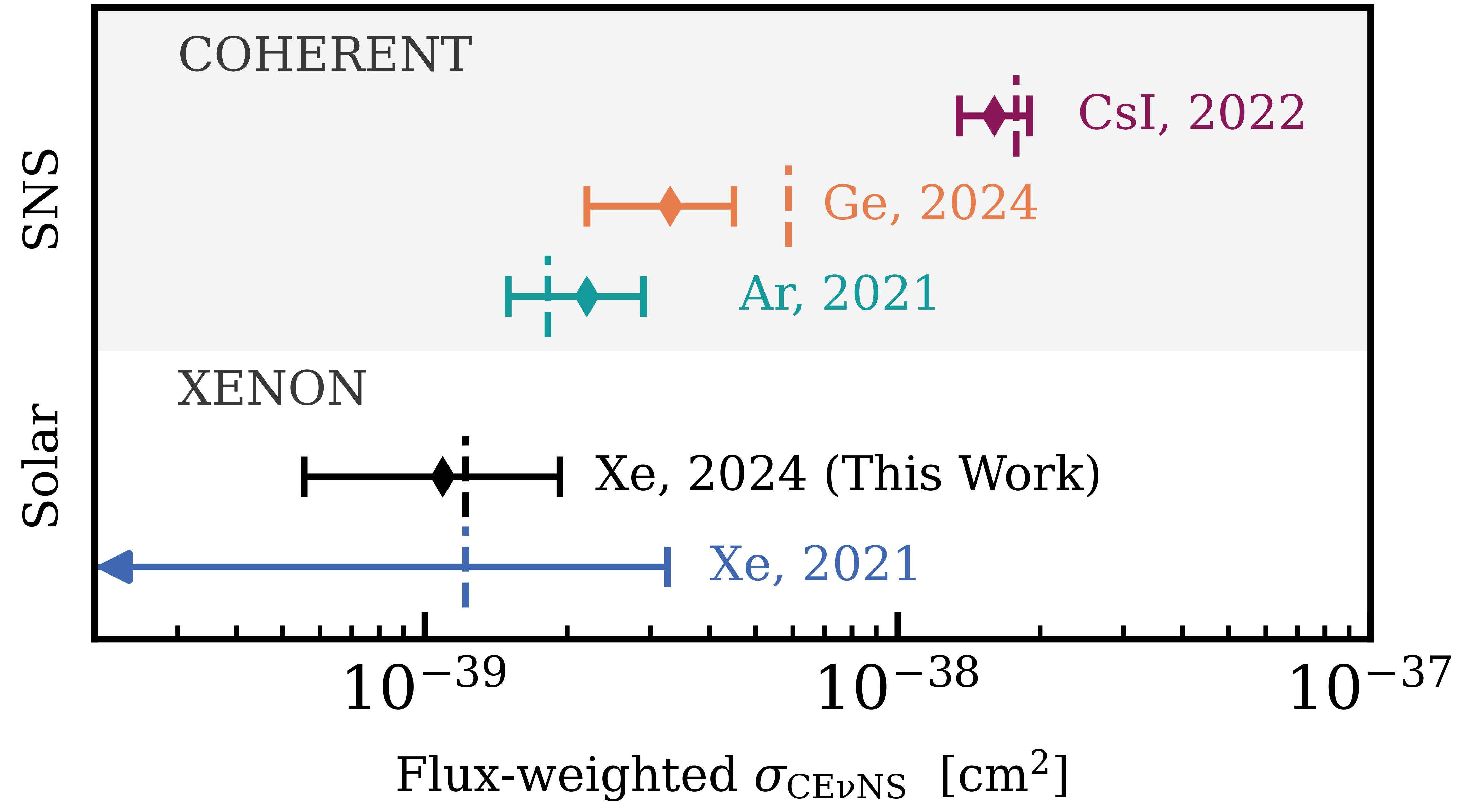




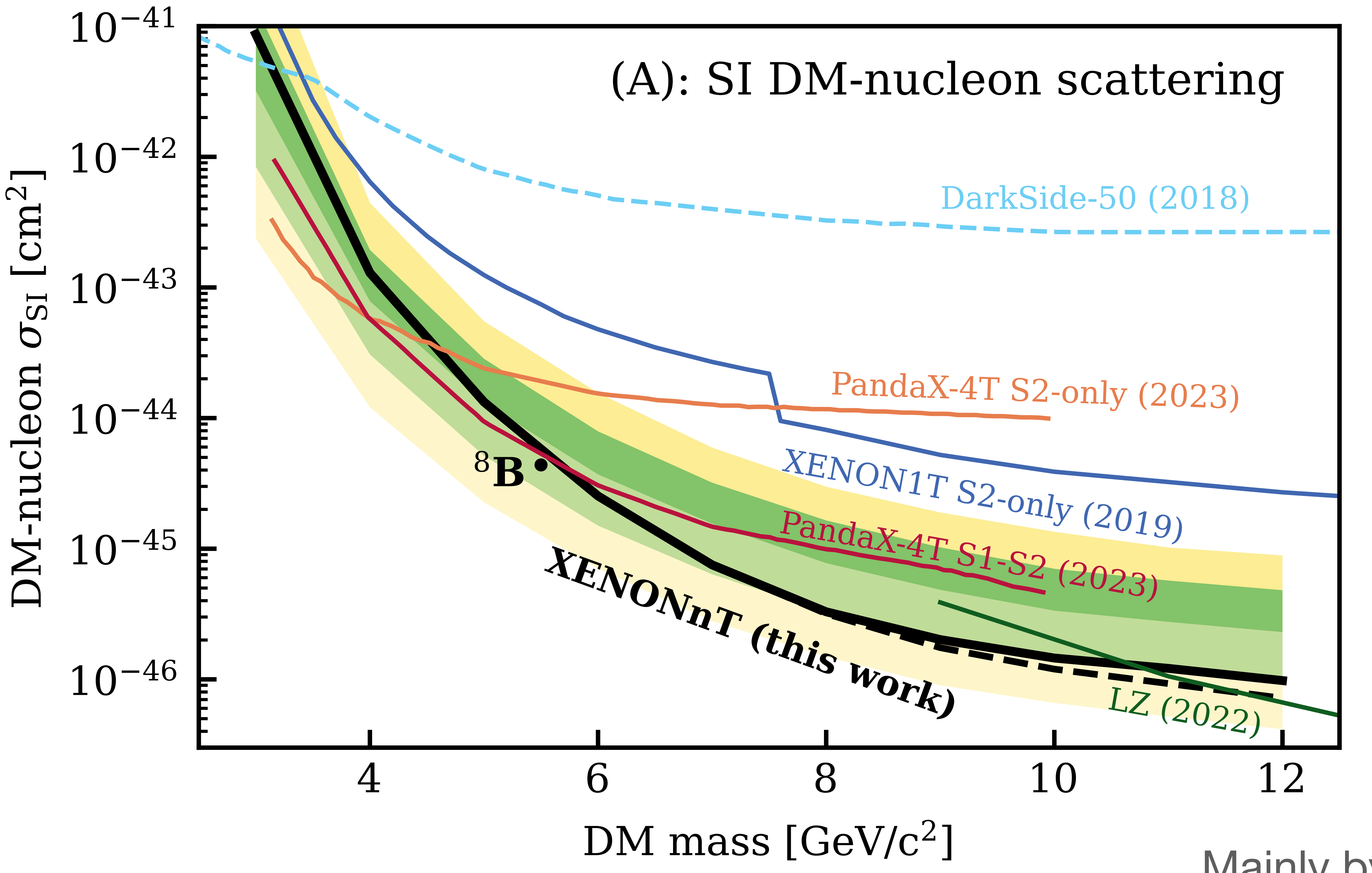
Set Constrain on solar ⁸B neutrinos flux and CEvNS cross-section



- Assume the CEvNS cross-section predicted by the SM
- *Or* assume the solar ^{8}B neutrinos flux measured by SNO



Constrain Light Dark Matter

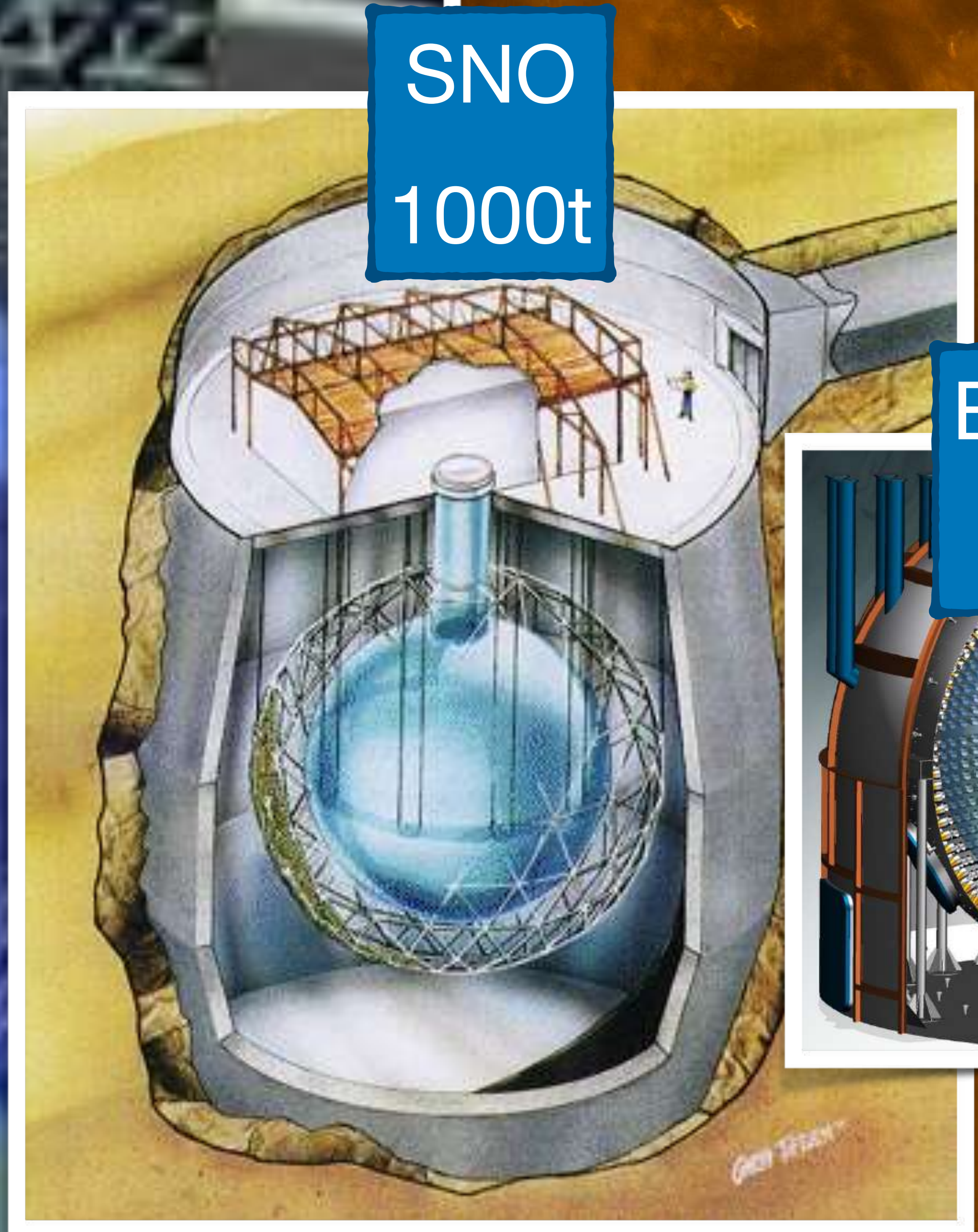


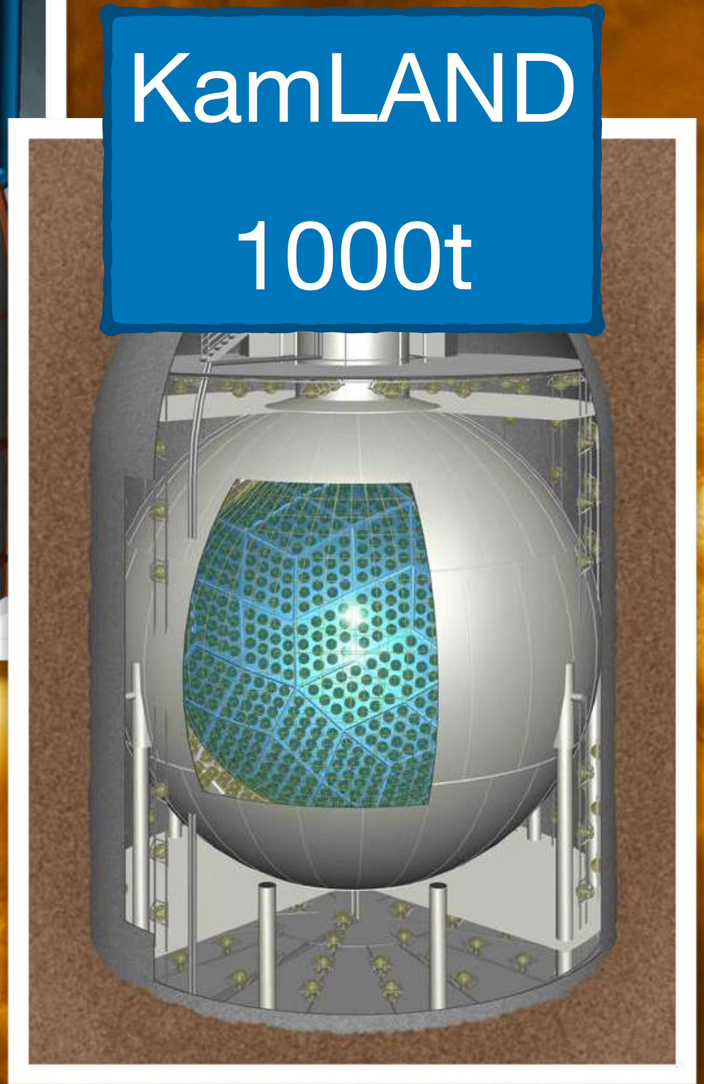
- Another study based on same data
- First Search for Light Dark Matter in the Neutrino Fog with XENONnT
- arXiv: 2409.17868 submitted to PRL

Mainly by Shenyang Shi

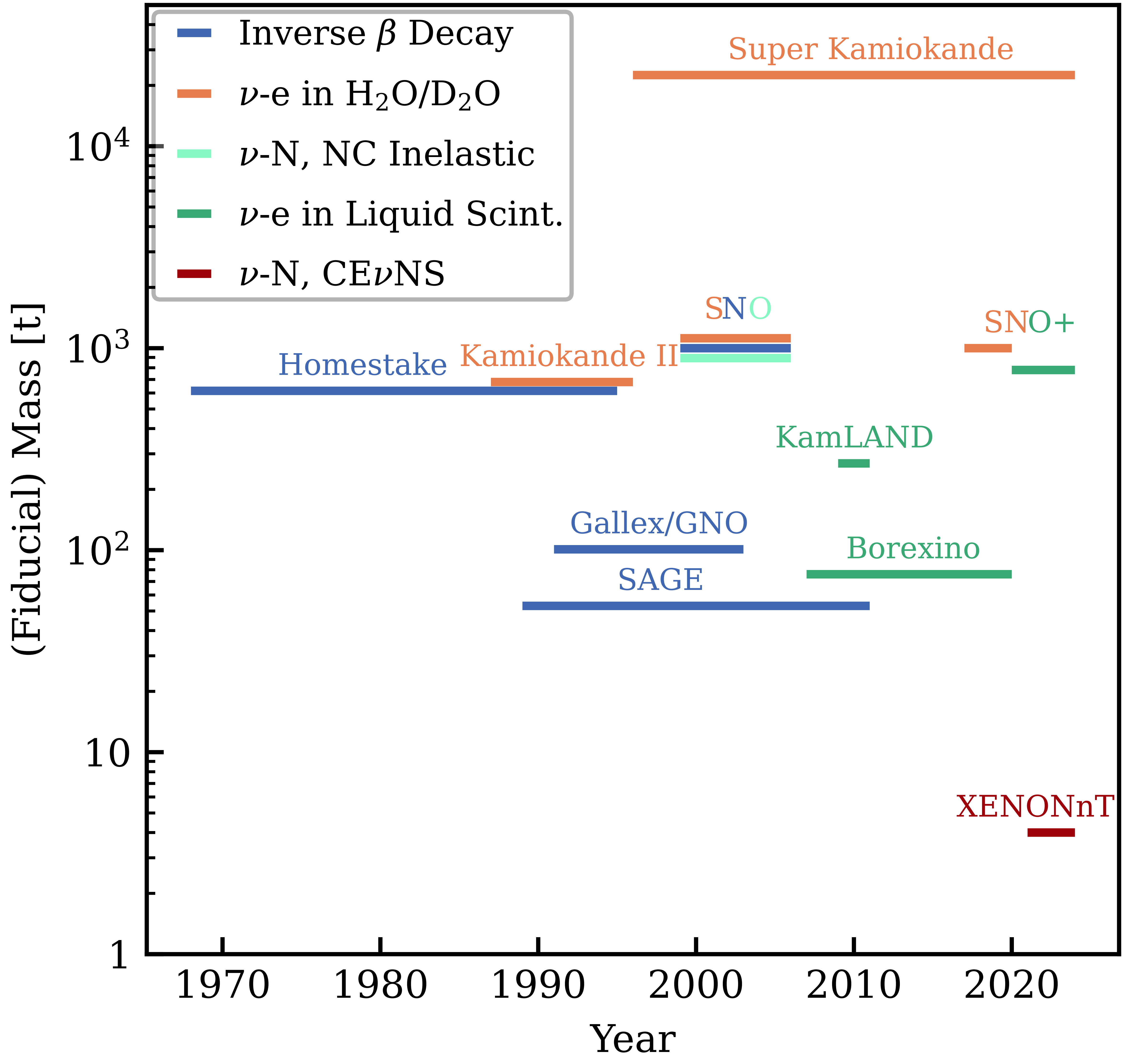
XENONnT:

The Smallest Solar Neutrino Detector





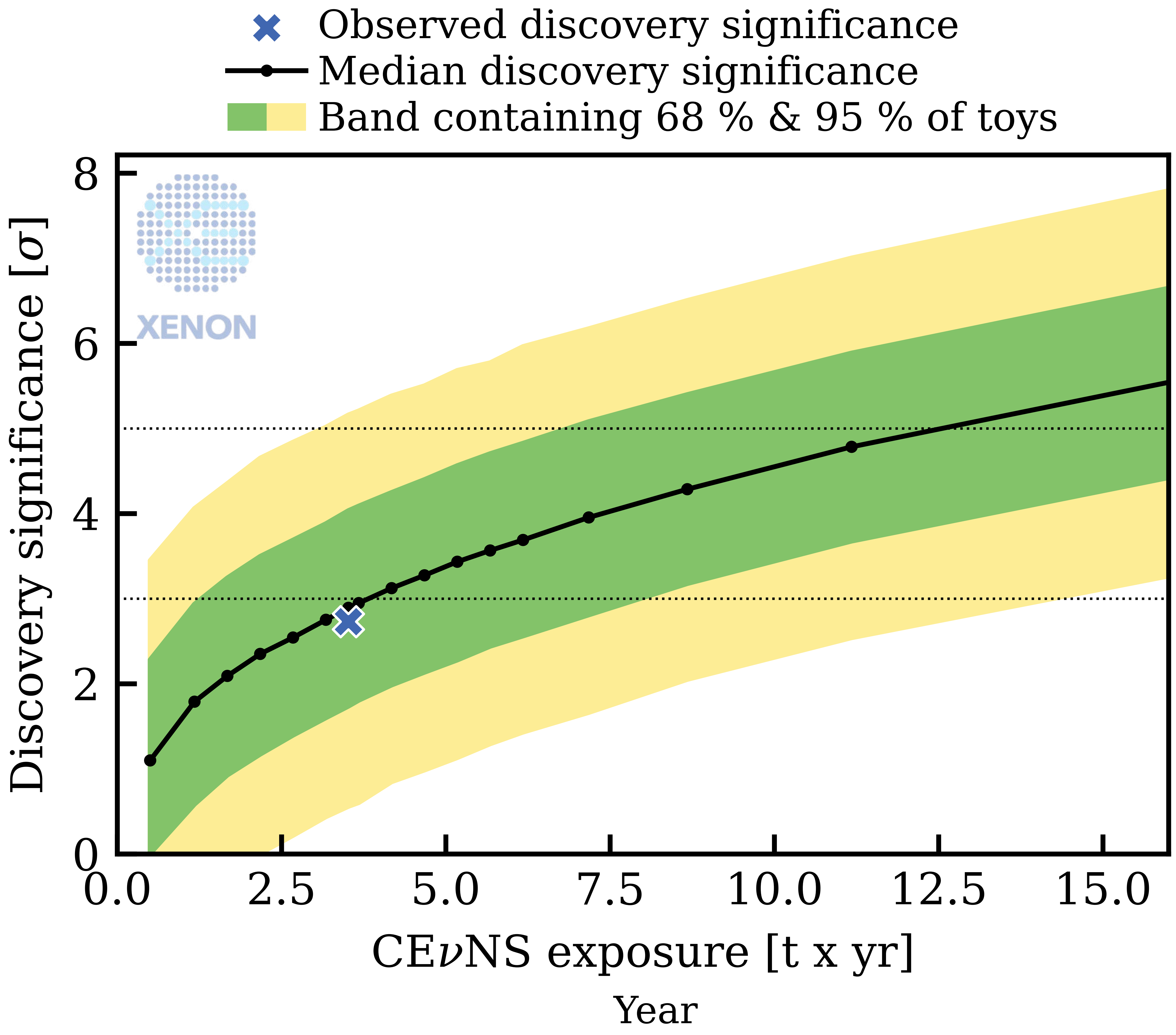
Summary and Outlook



- Check our paper online:
  - Phys. Rev. Lett. 133, 191002
- With more exposure, we expect to measure the solar ^{8}B neutrinos at higher significance and to better constrain its flux.

Thanks for listening!

Summary and Outlook



- Check our paper online:
  - Phys. Rev. Lett. 133, 191002
- With more exposure, we expect to measure the solar ^{8}B neutrinos at higher significance and to better constrain its flux.

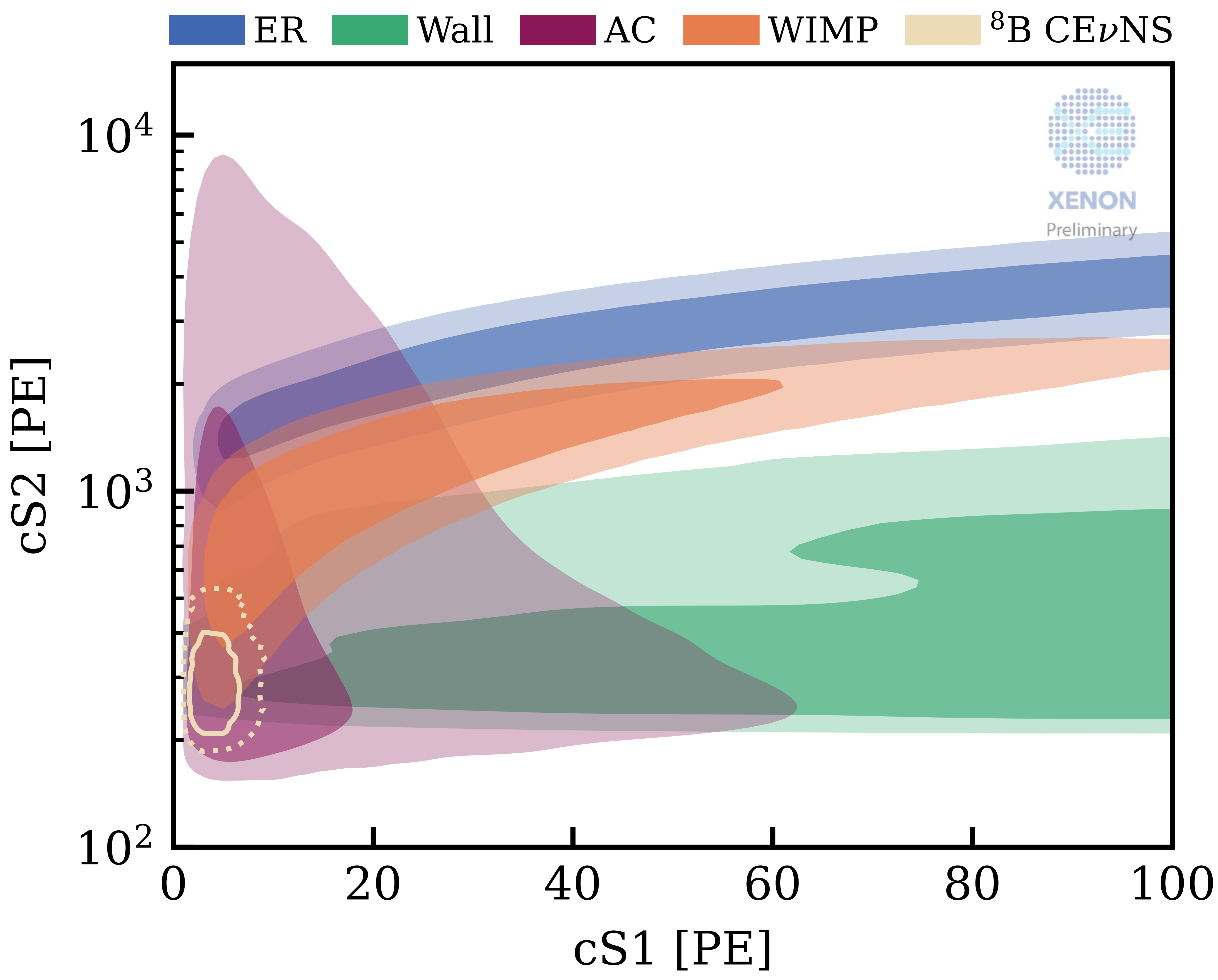
Thanks for listening!

Supplementary

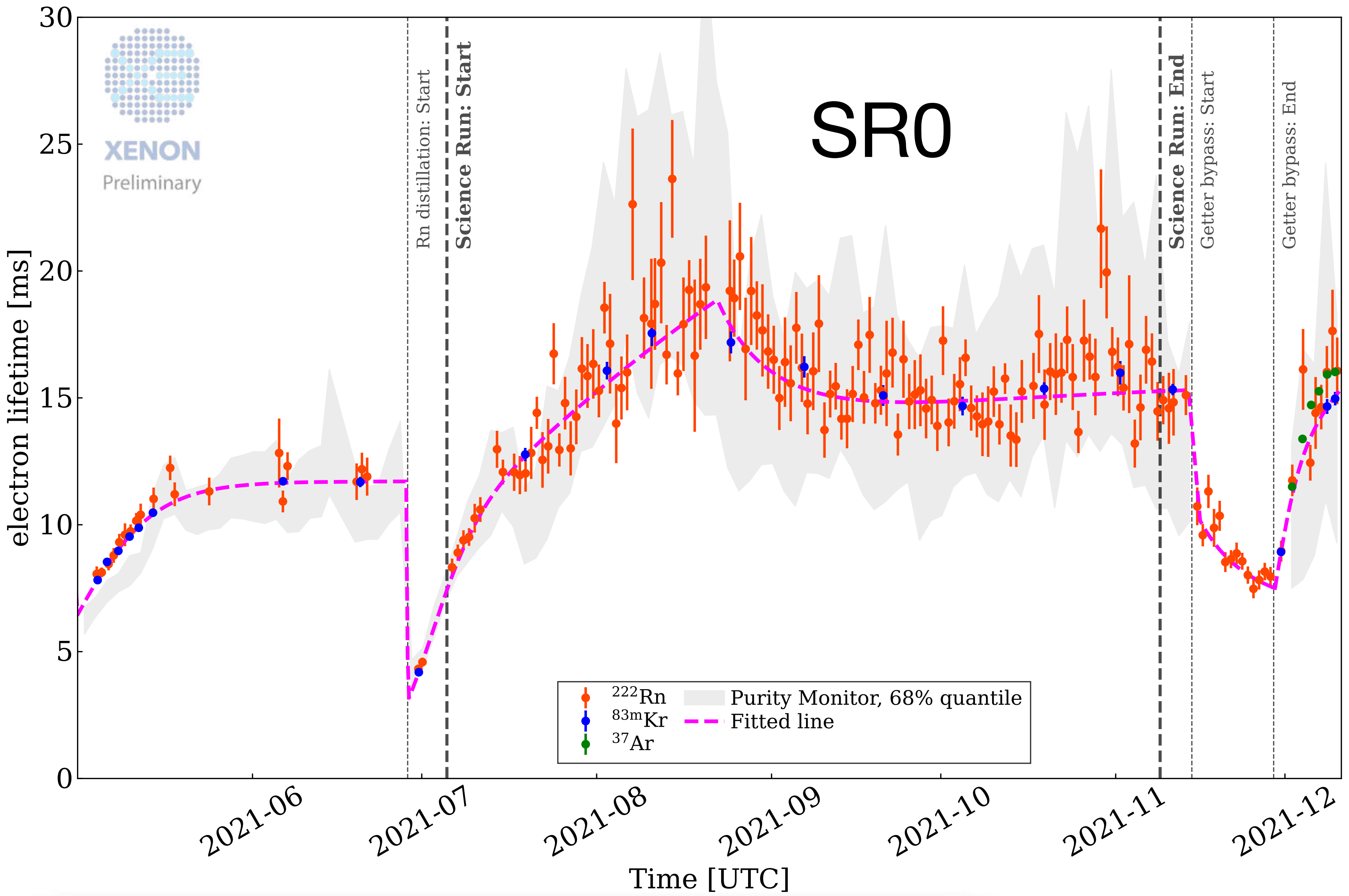
Content - Physics result & technical improvement

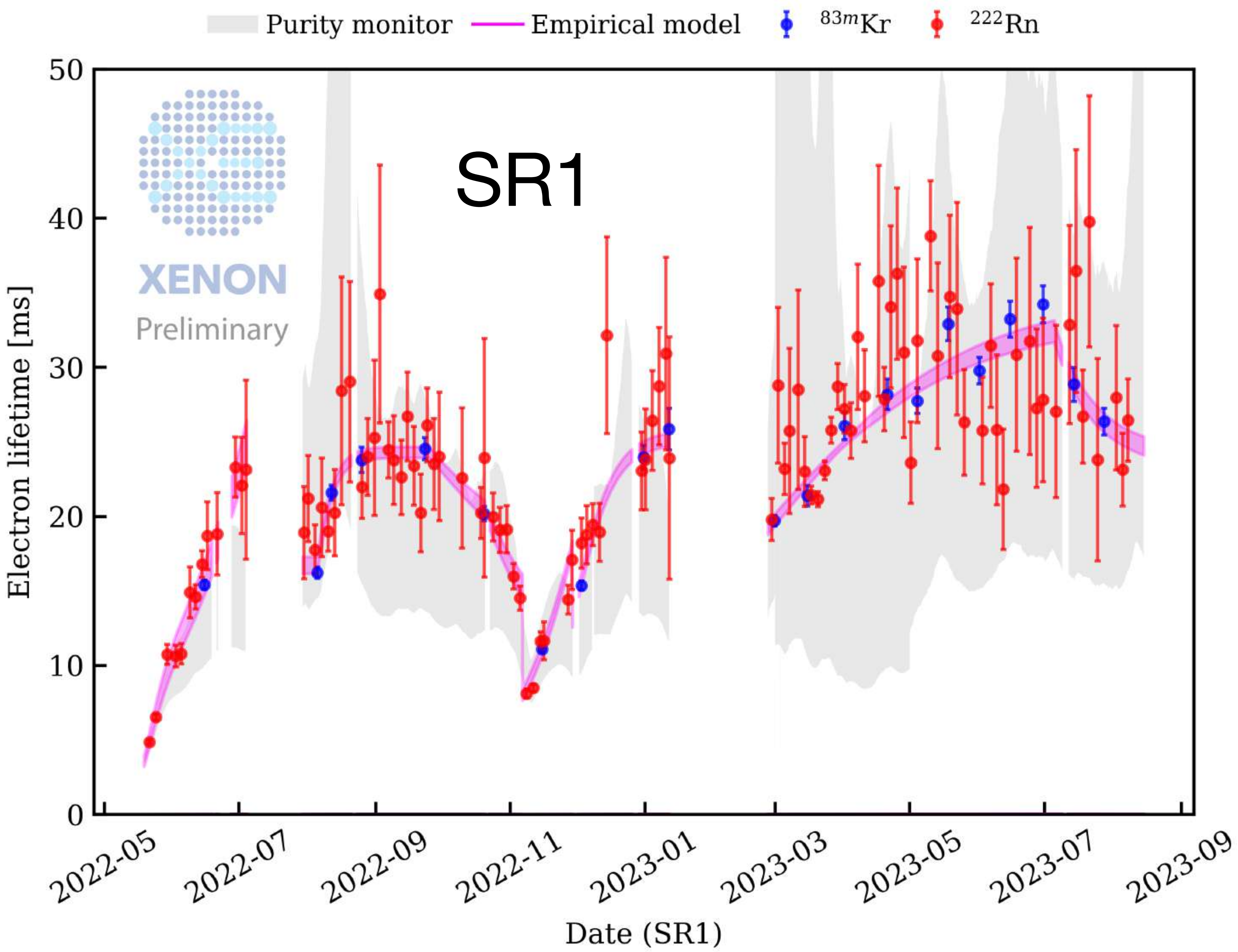
- Introduction
  - The XENONnT experiment, detector characteristic
- Signal & Background
  - Calibration in low energy nuclear recoil
  - Background: Accidental Coincidence(dominant), ER, Neutron Surface
- Inference and Result

200 GeV WIMP



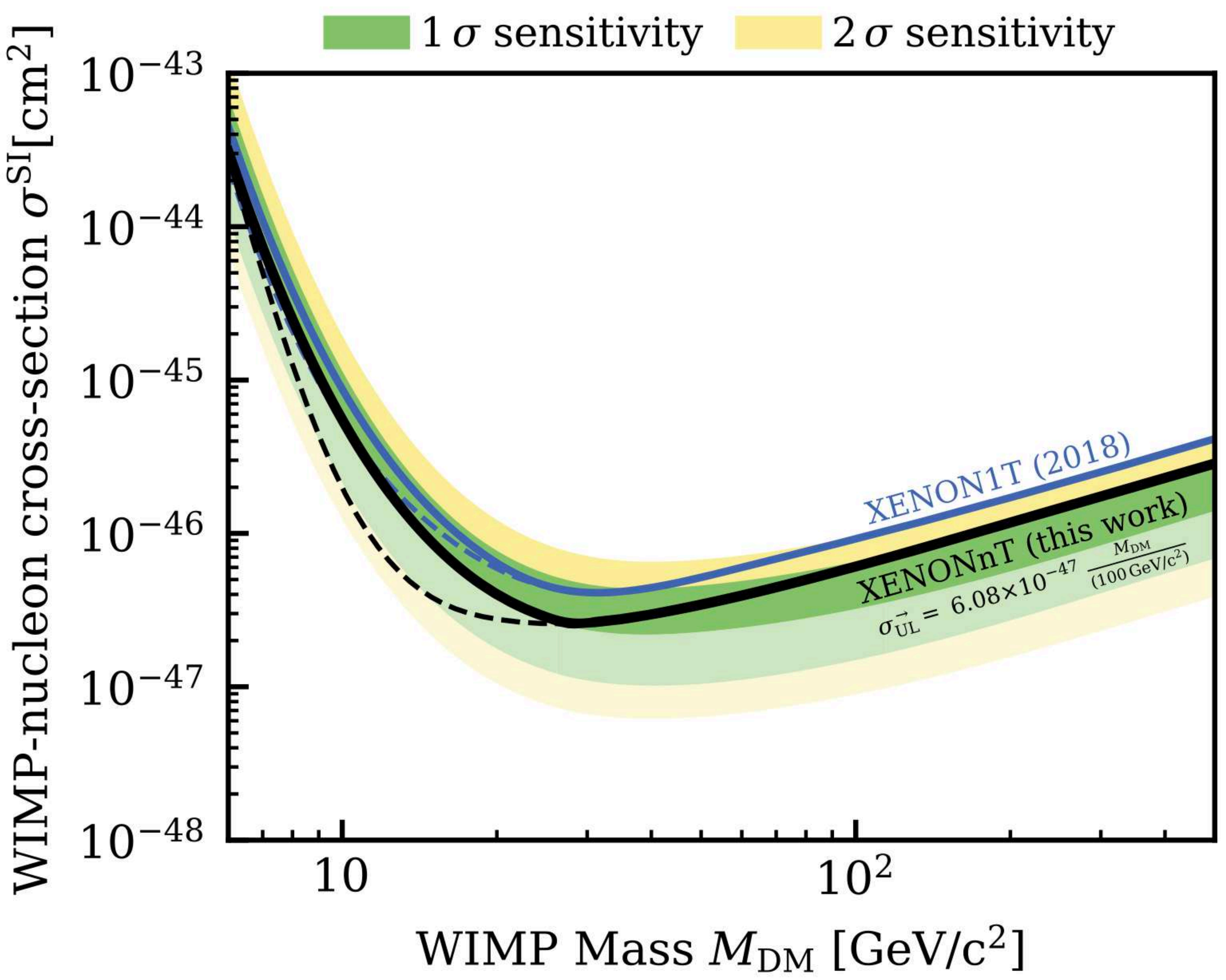
High Liquid XENON Purity

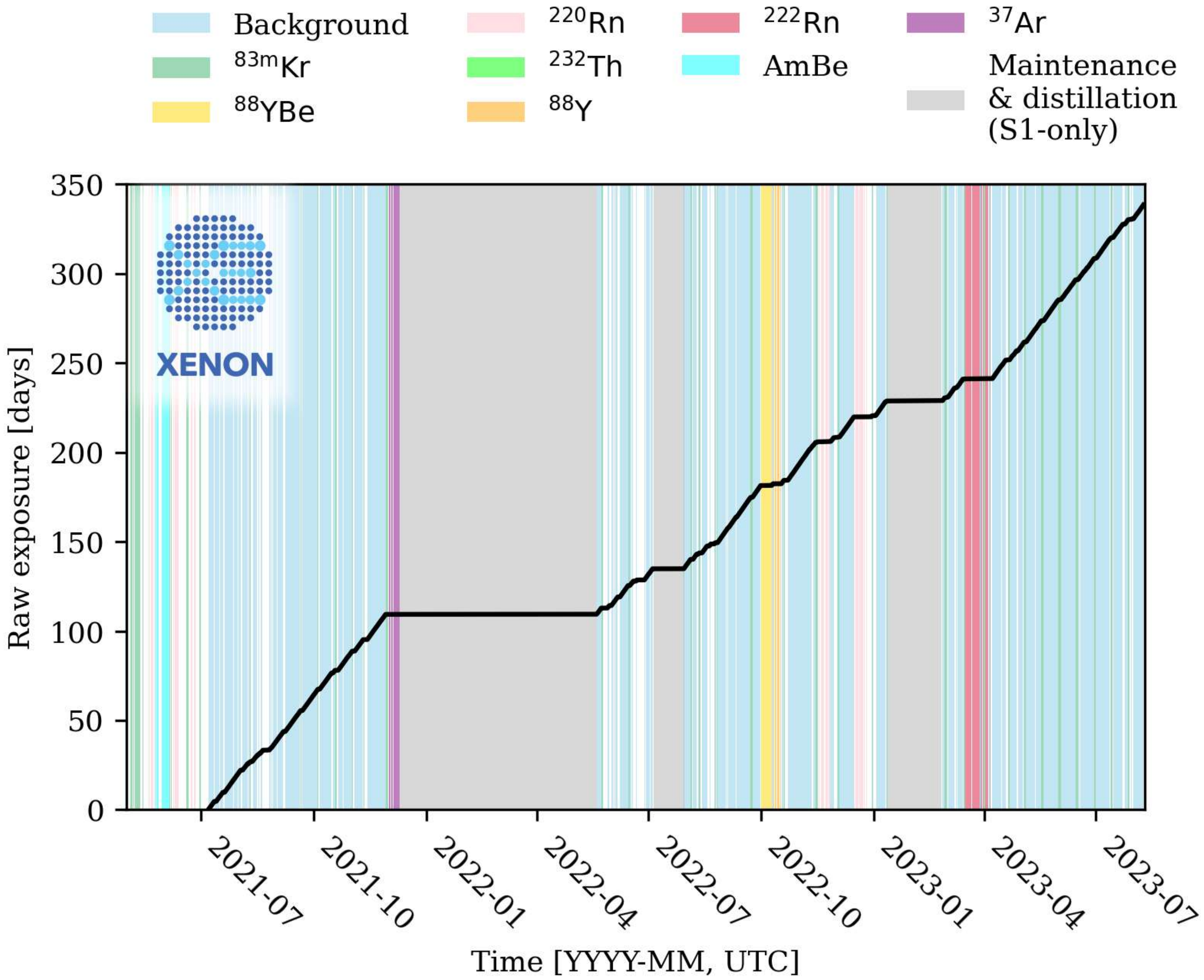




- XENONnT maintains high electron lifetime thanks to its novel liquid phase purification
- Turn-around time of 0.9 days for entire 8.6 tonnes
- About 90% of the electrons survive the full drift

XENONnT Science Data



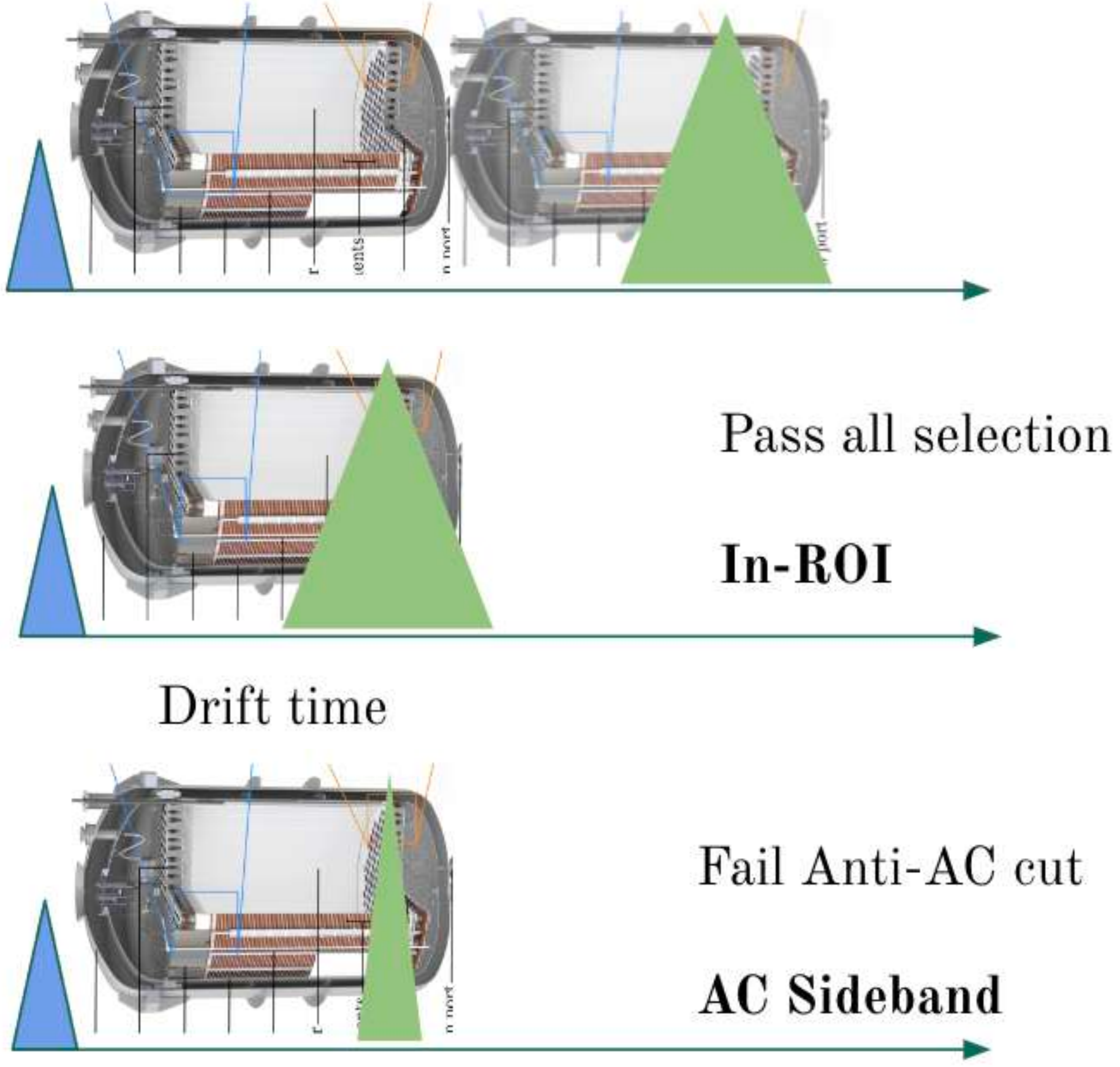


Both SR0 and SR1 data are used to search for solar ^{8}B CEvNS and WIMPs Dark Matter, etc

Model Validation & Systematic Error

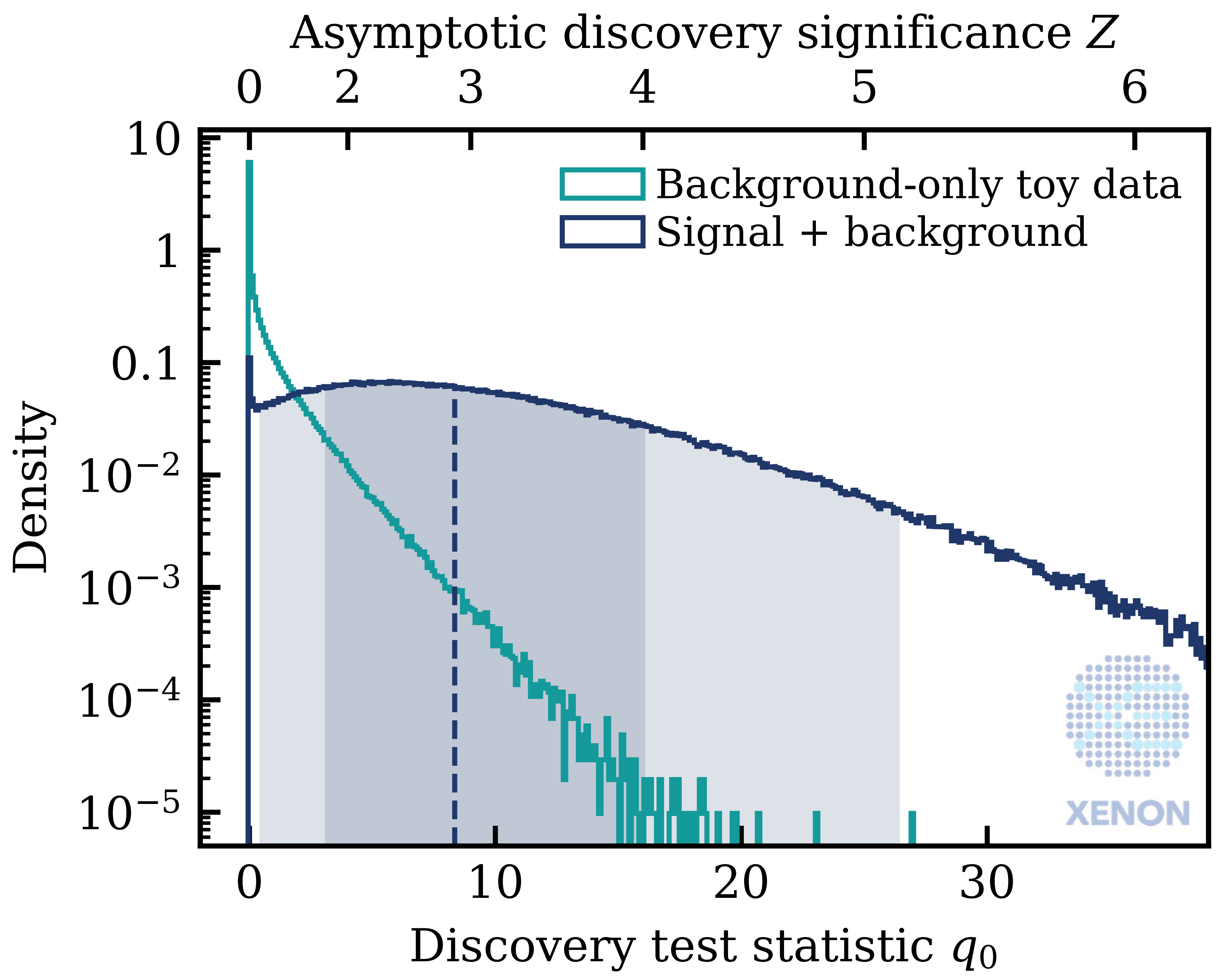
Test the mode with AC-rich datasets

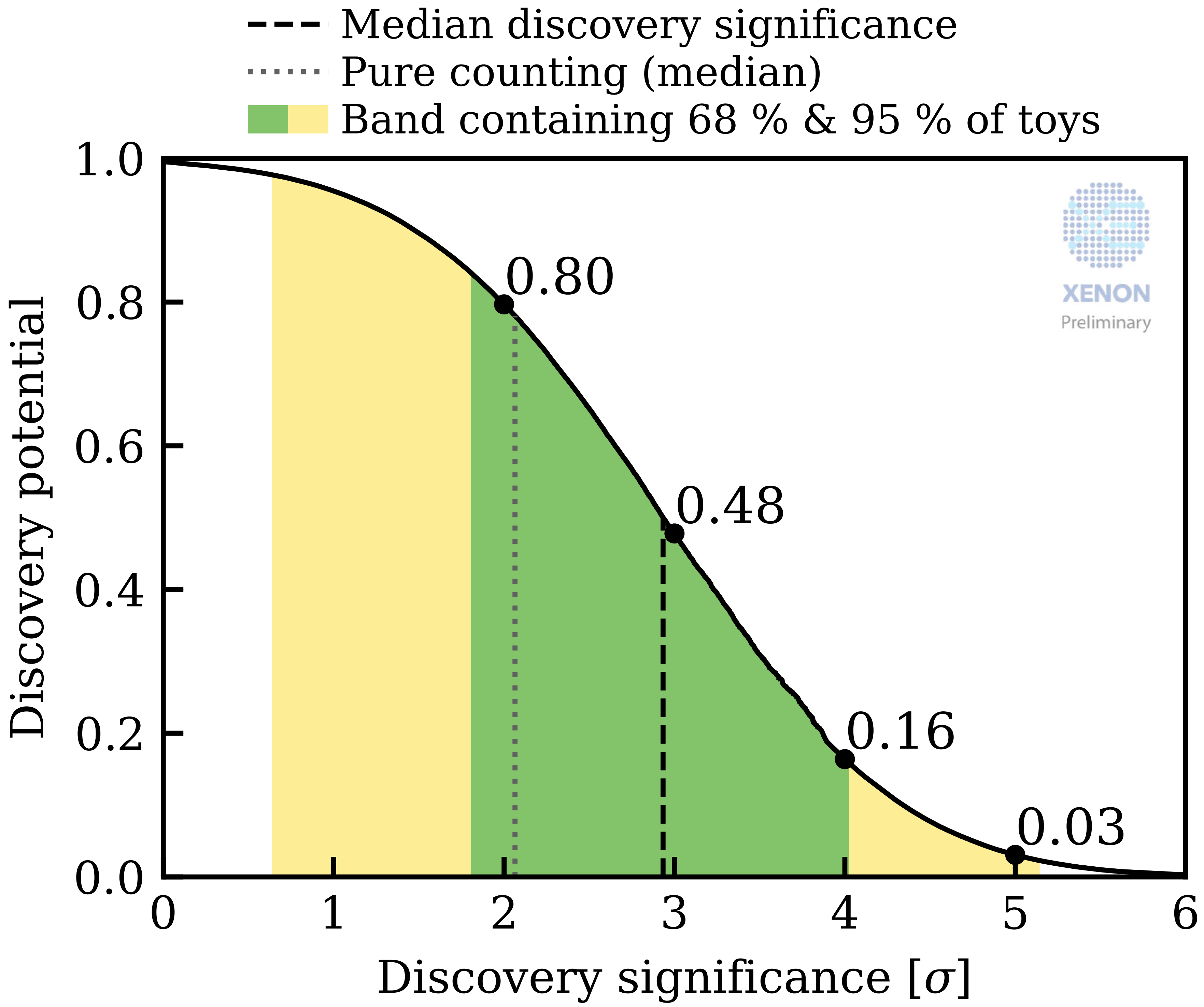
- Build events longer than the TPC, thus build Pure-AC events
- In high rate calibration data
- In science search data, select events which only failed anti-AC cuts: ACSideband



Final Prediction & Projected Discovery Potential

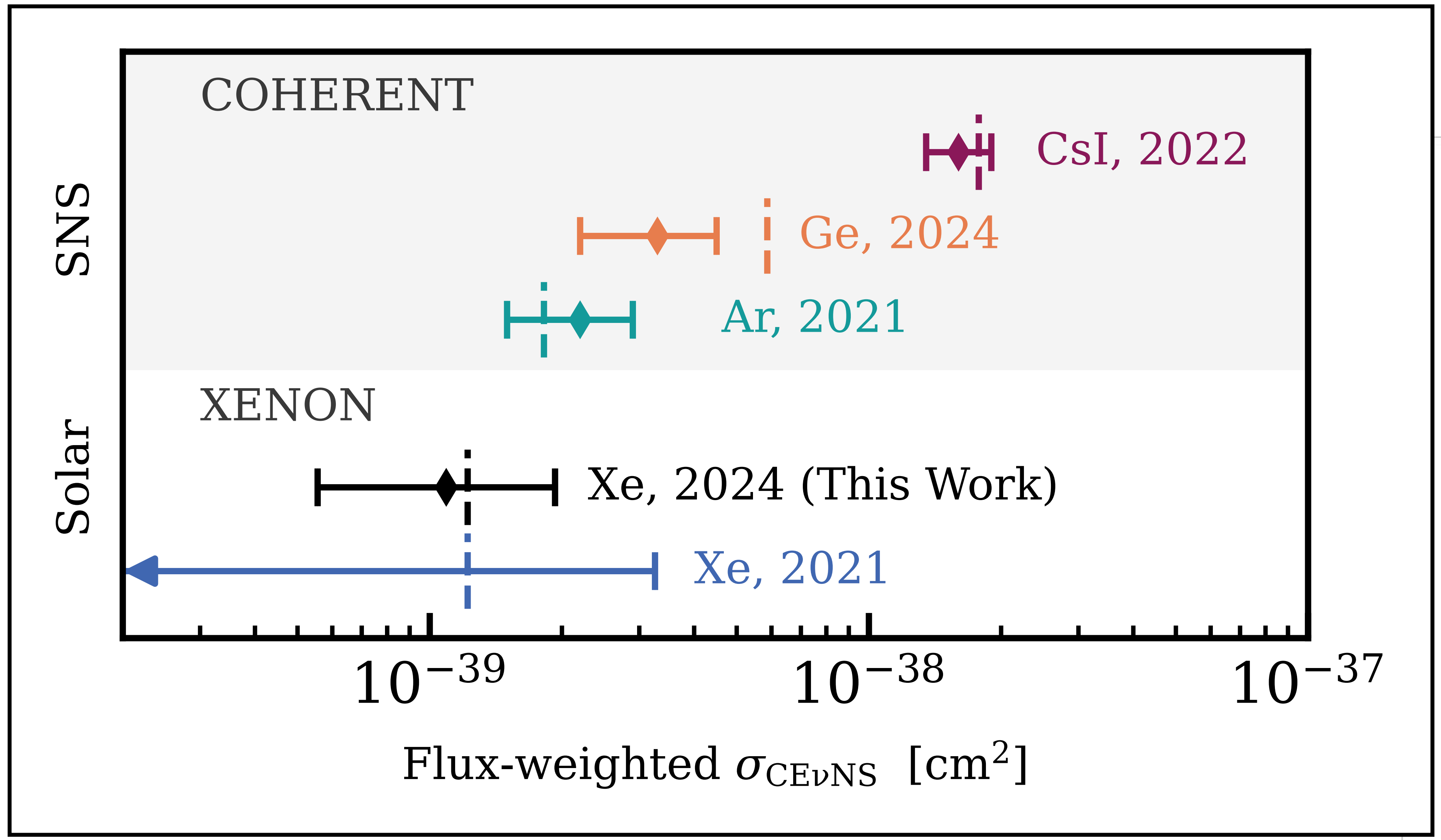
Component	Rate [Events]
AC - SR0	7.5 ± 0.7
AC - SR1	17.8 ± 1.0
ER	0.7 ± 0.7
NR	0.5 ± 0.3
Total Background	26.4 ± 1.4
^{8}B	11.9 ± 4.5

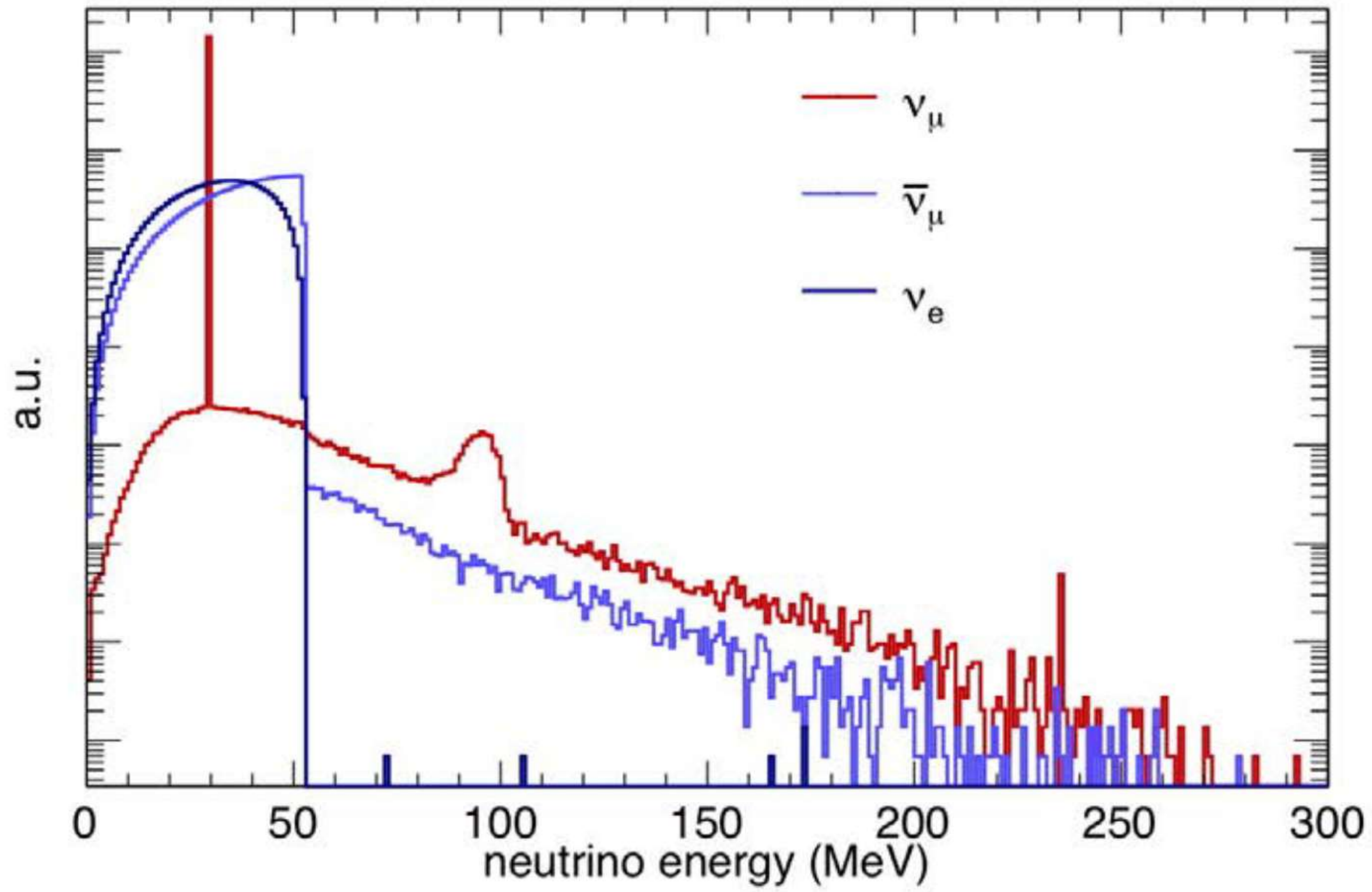




We expect to see solar ^{8}B neutrinos at $>2(3)\sigma$ significance with a probability of 0.80 (0.48), with a full 4-D analysis

Set Constrain on CEvNS Cross section of Xe





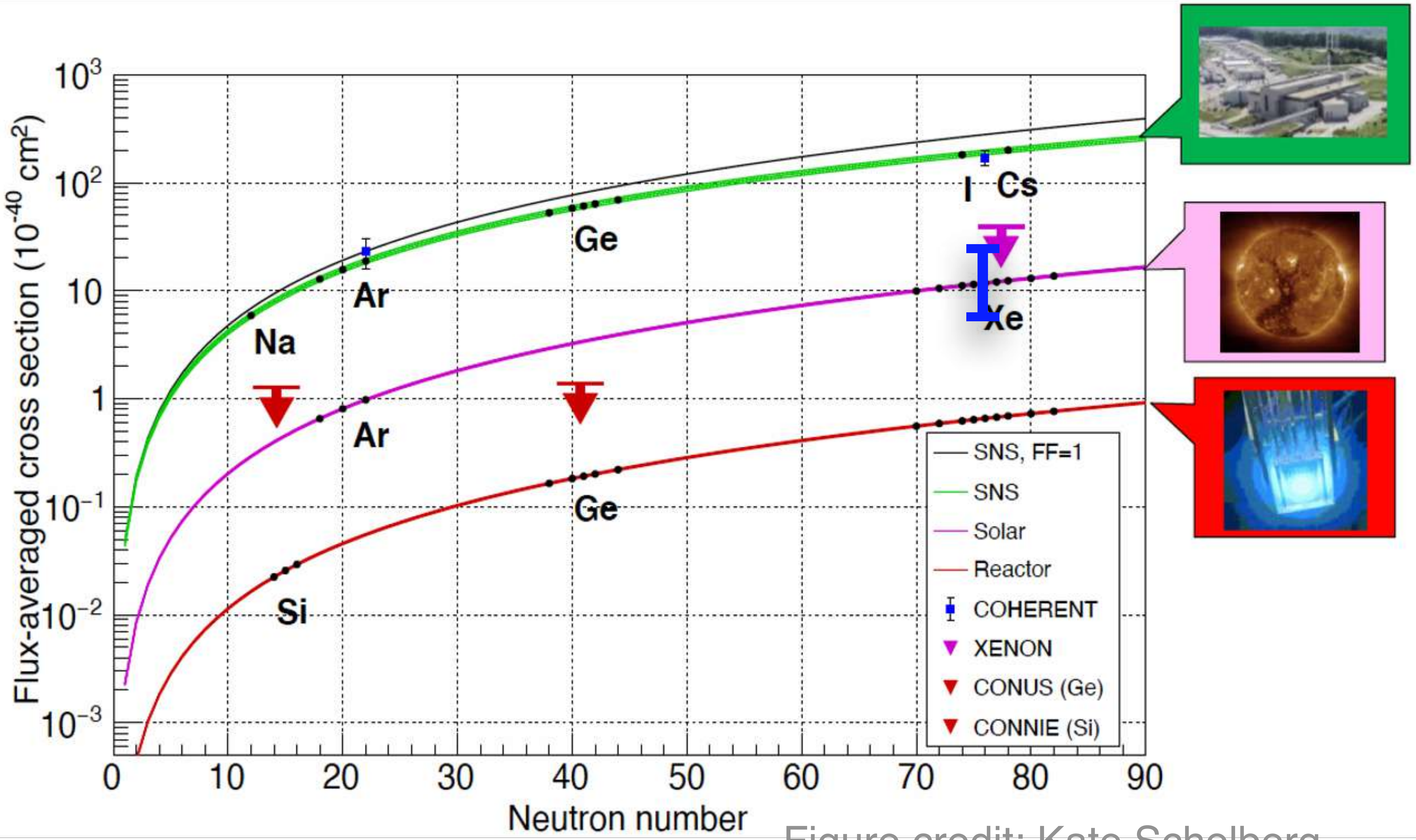
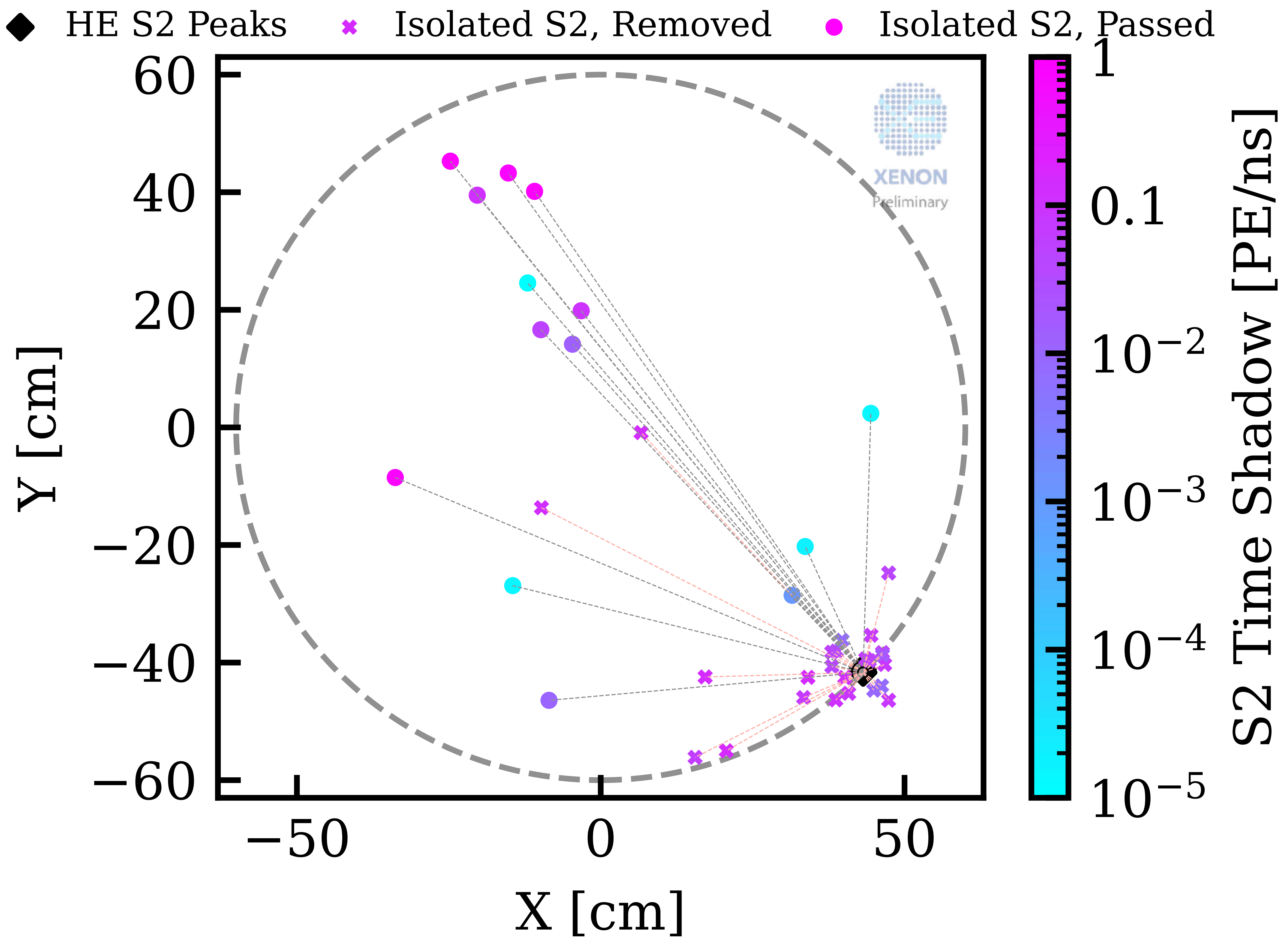
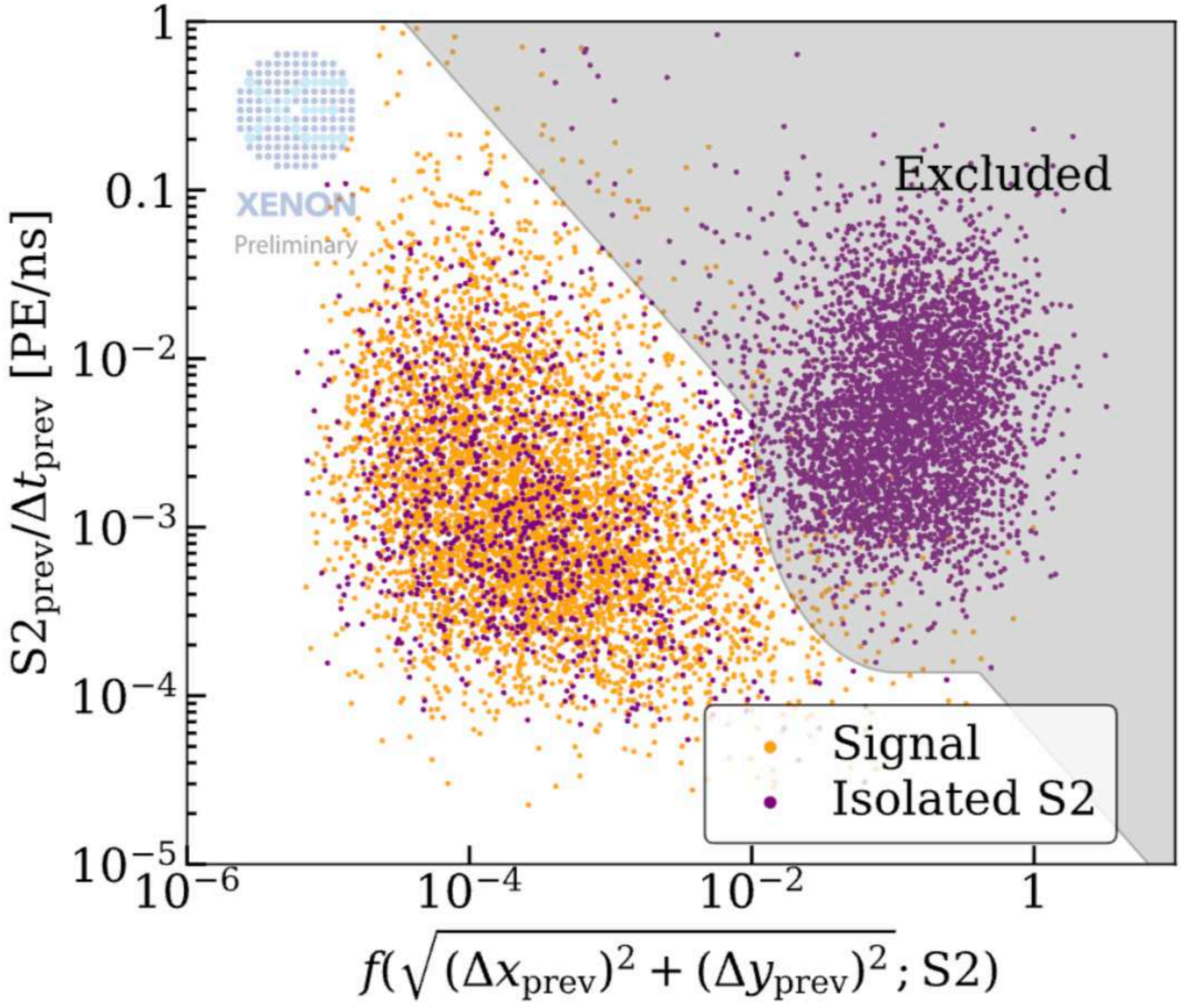


Figure credit: Kate Scholberg

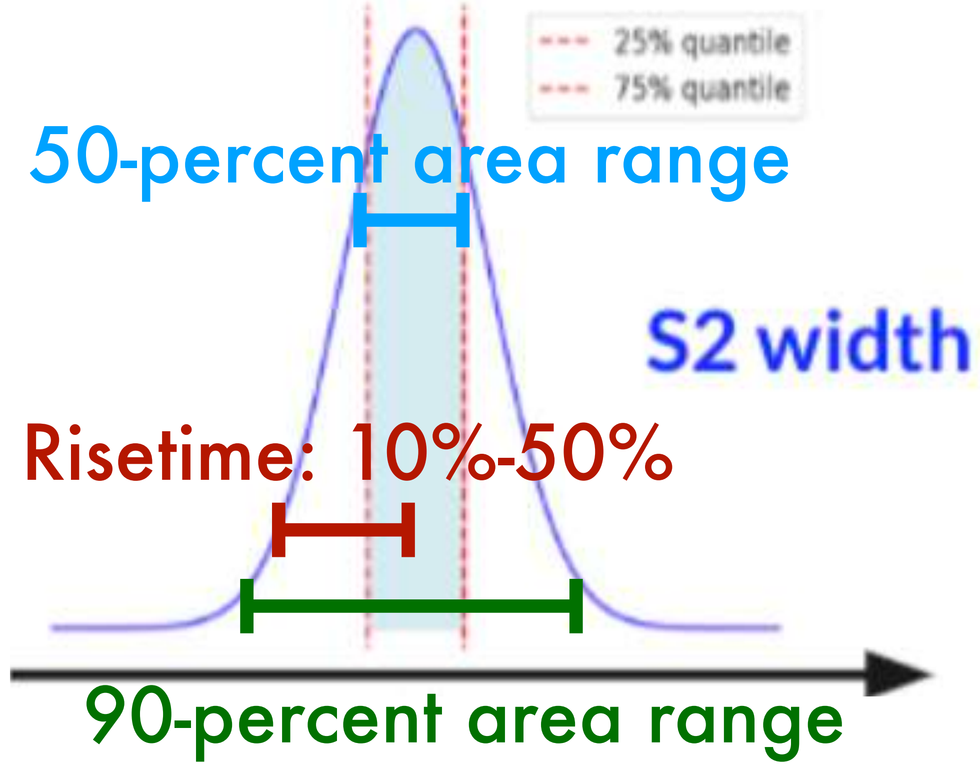
Time + Position Shadow





Cut threshold set to remove the worst 20% of time & space

Fuse: Framework for Unified Simulation of Events

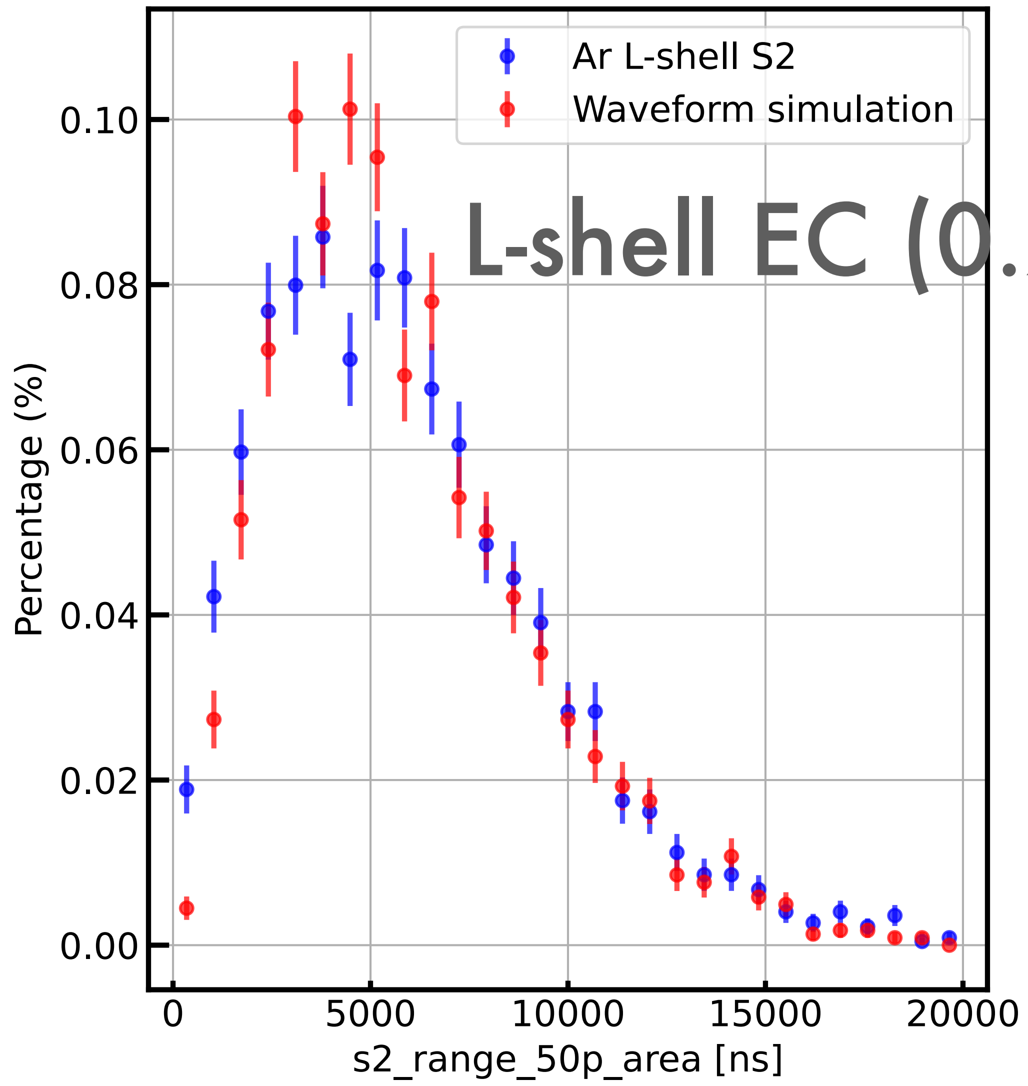


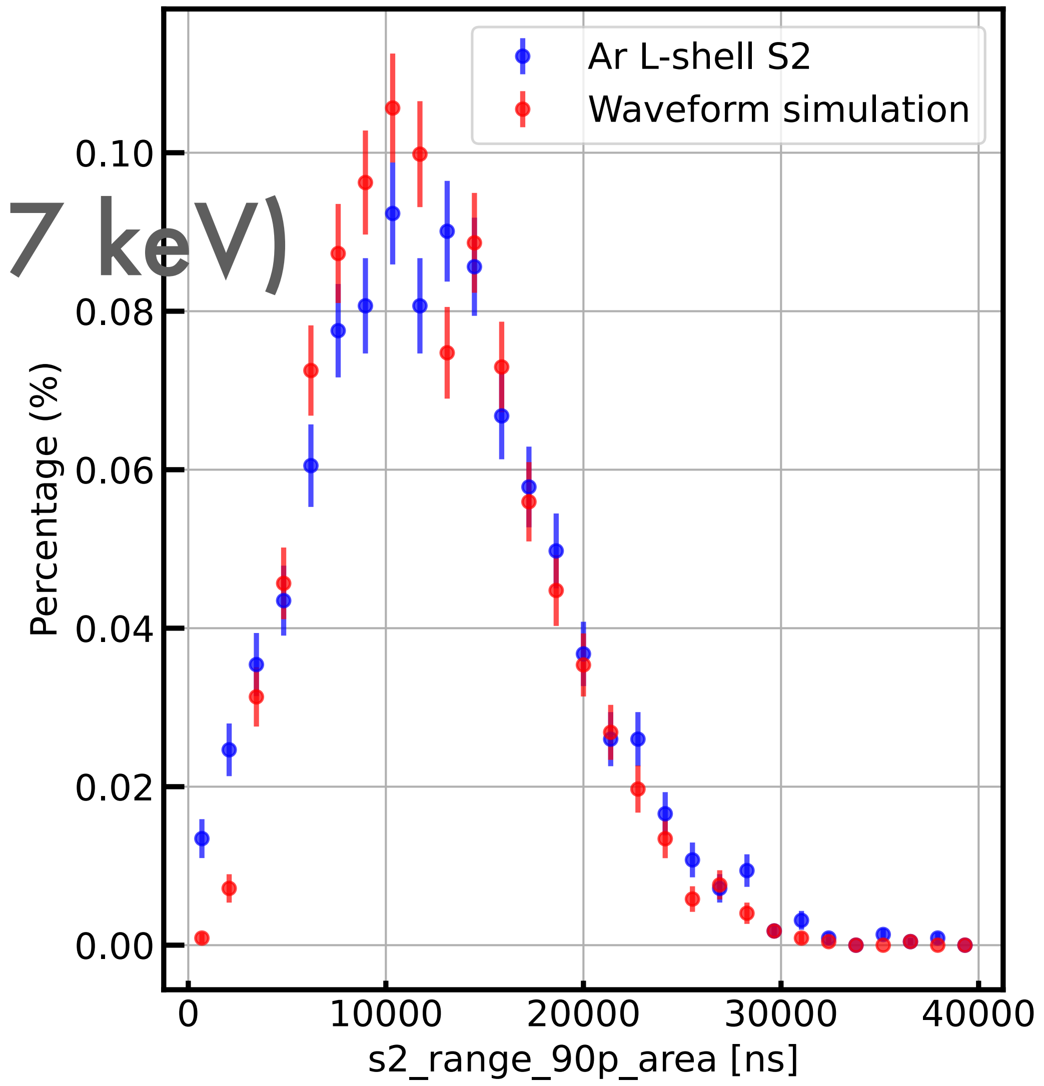
- Simulation include the microphysics, detector physics, PMT&DAQ response to get events.
- Simulation & data match well

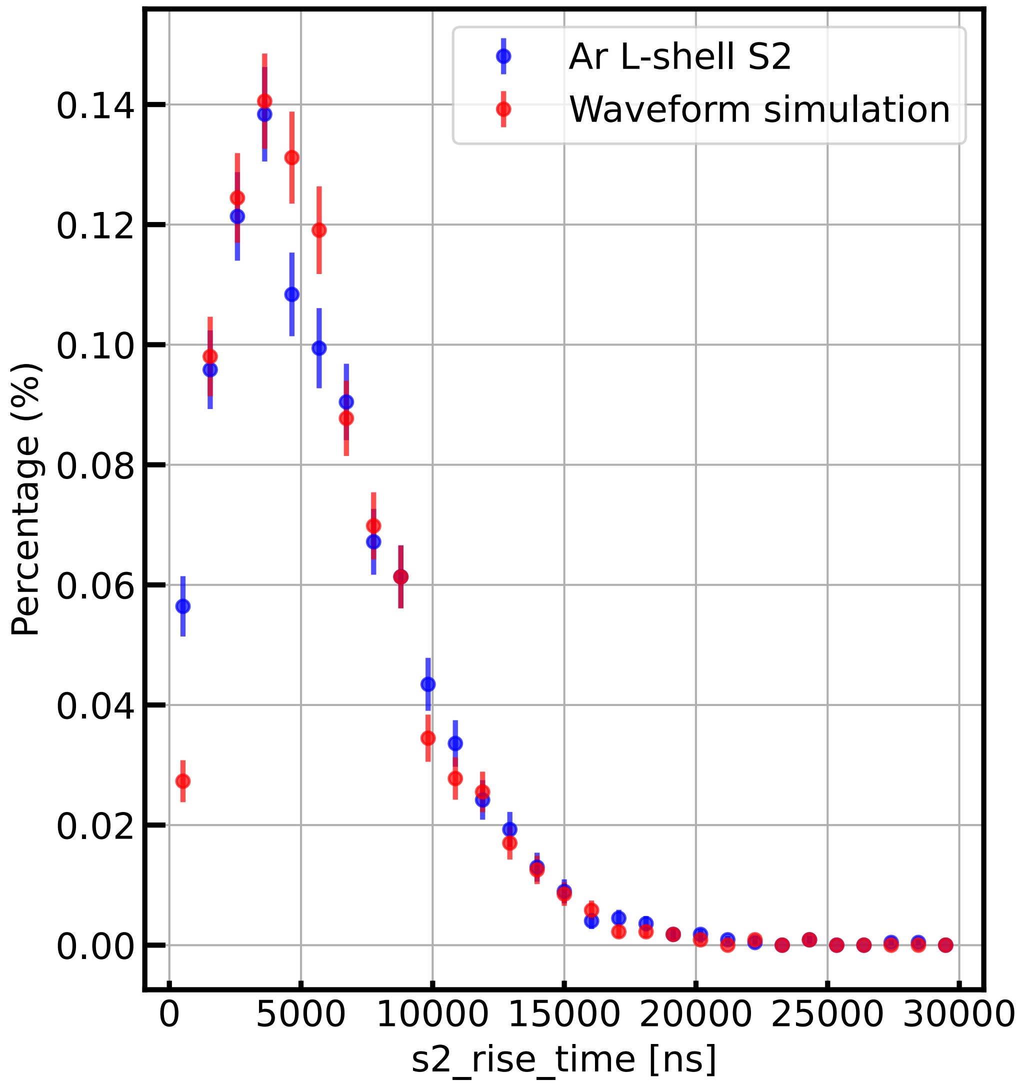
xenon-fuse 1.3.0

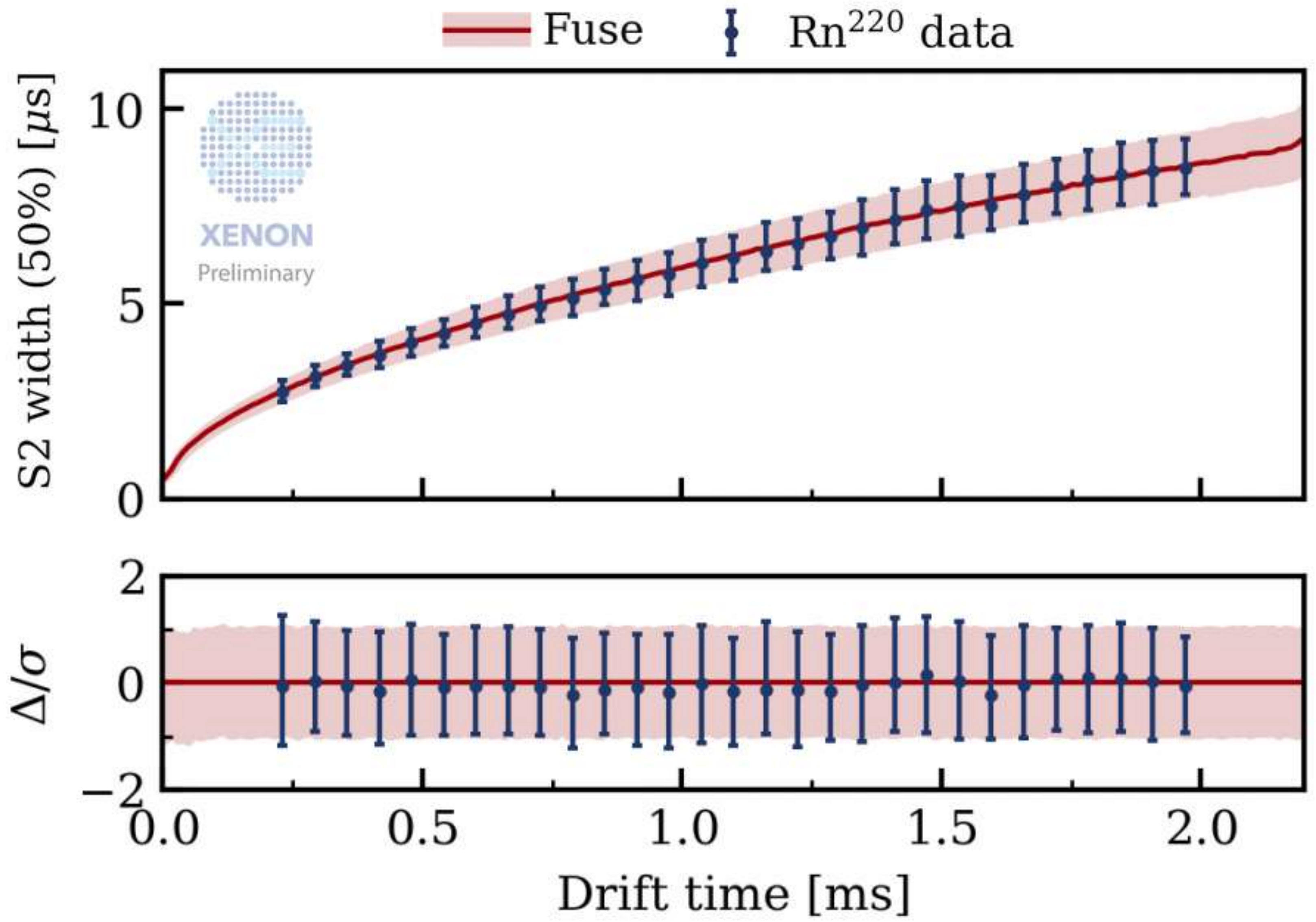
```
pip install xenon-fuse
```

L-shell EC (0.27 keV)



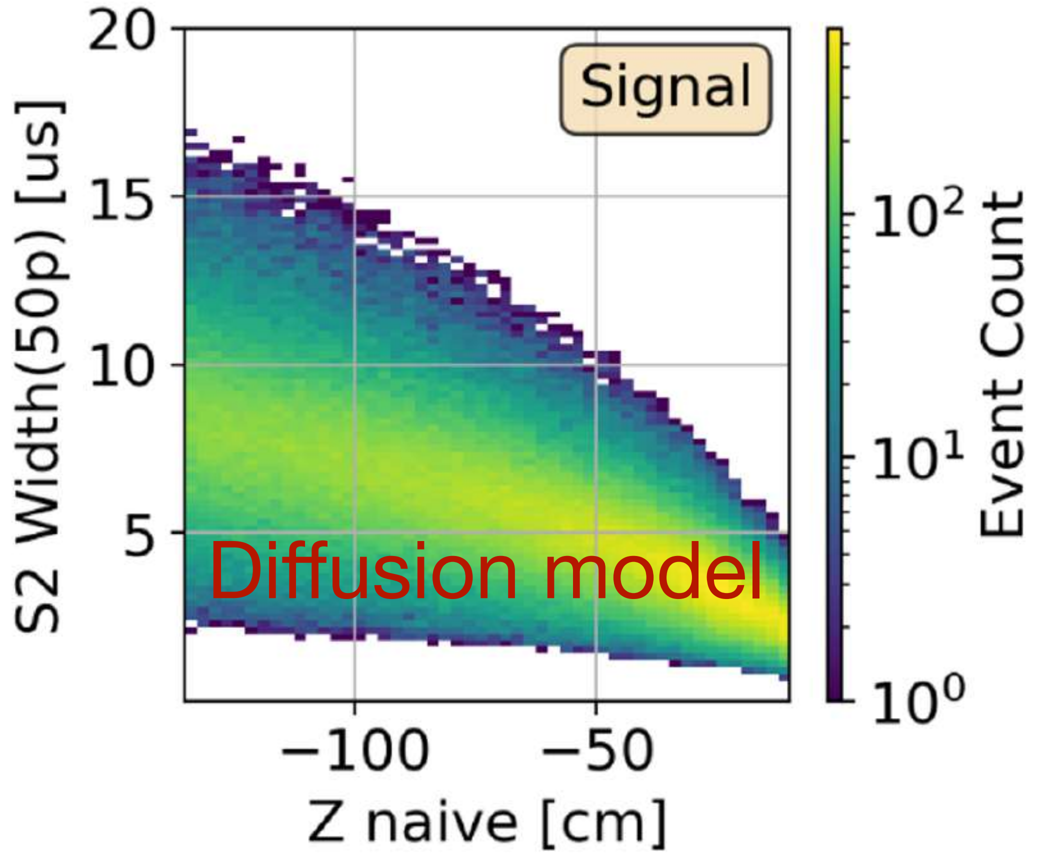


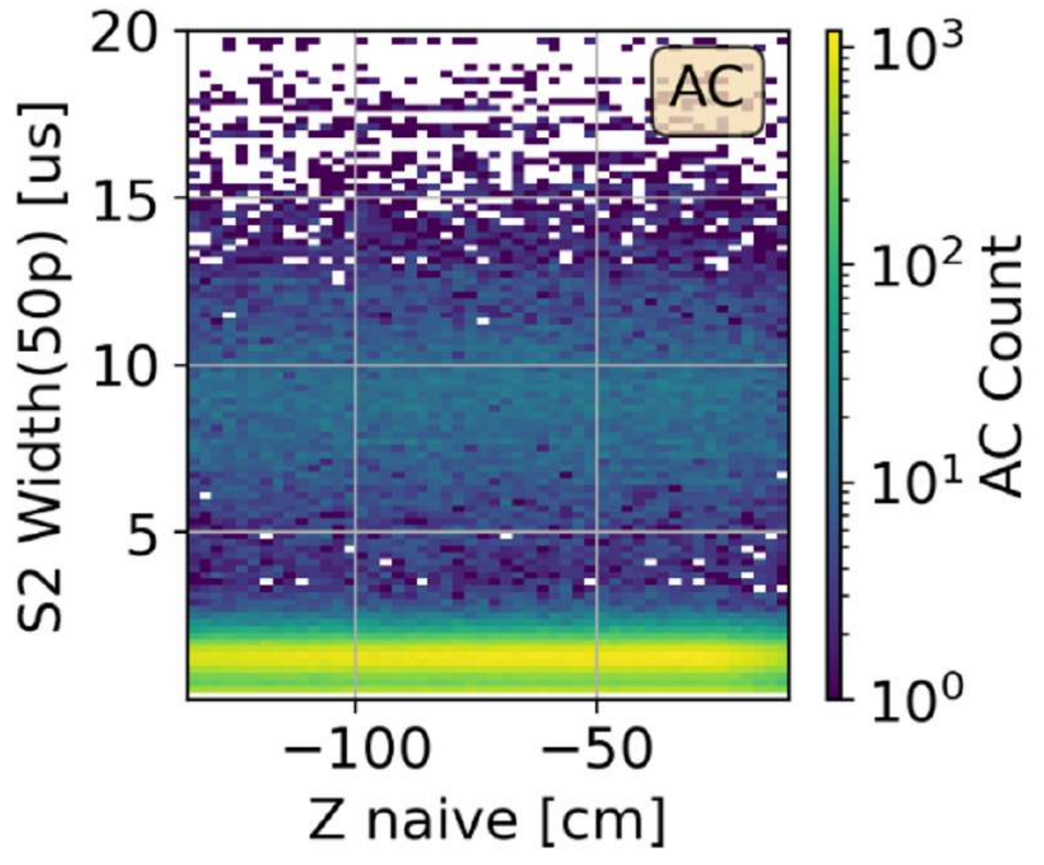


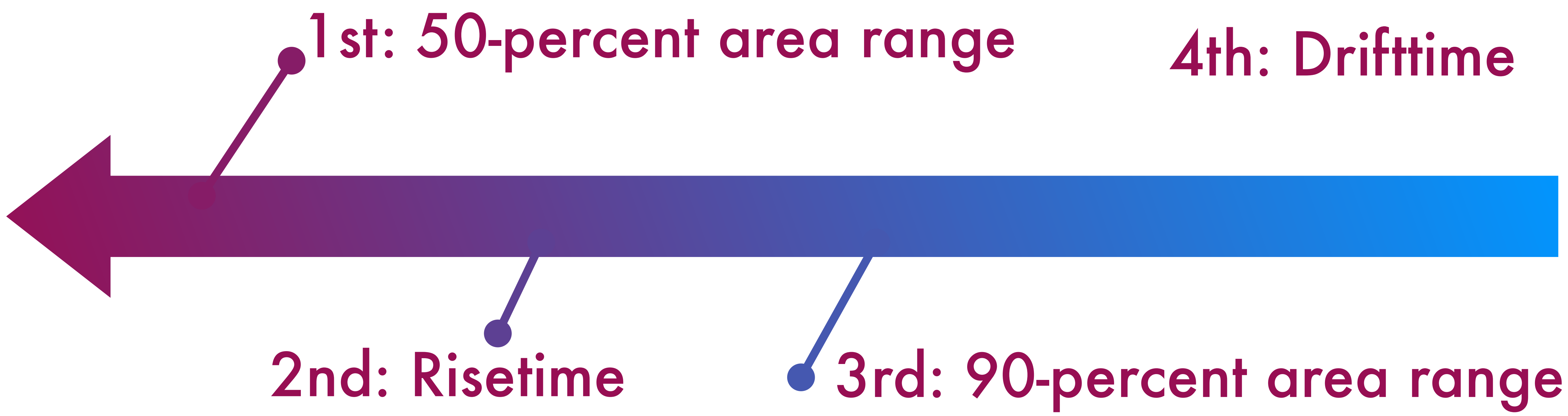


S1/S2 Pulse shape into GBDT

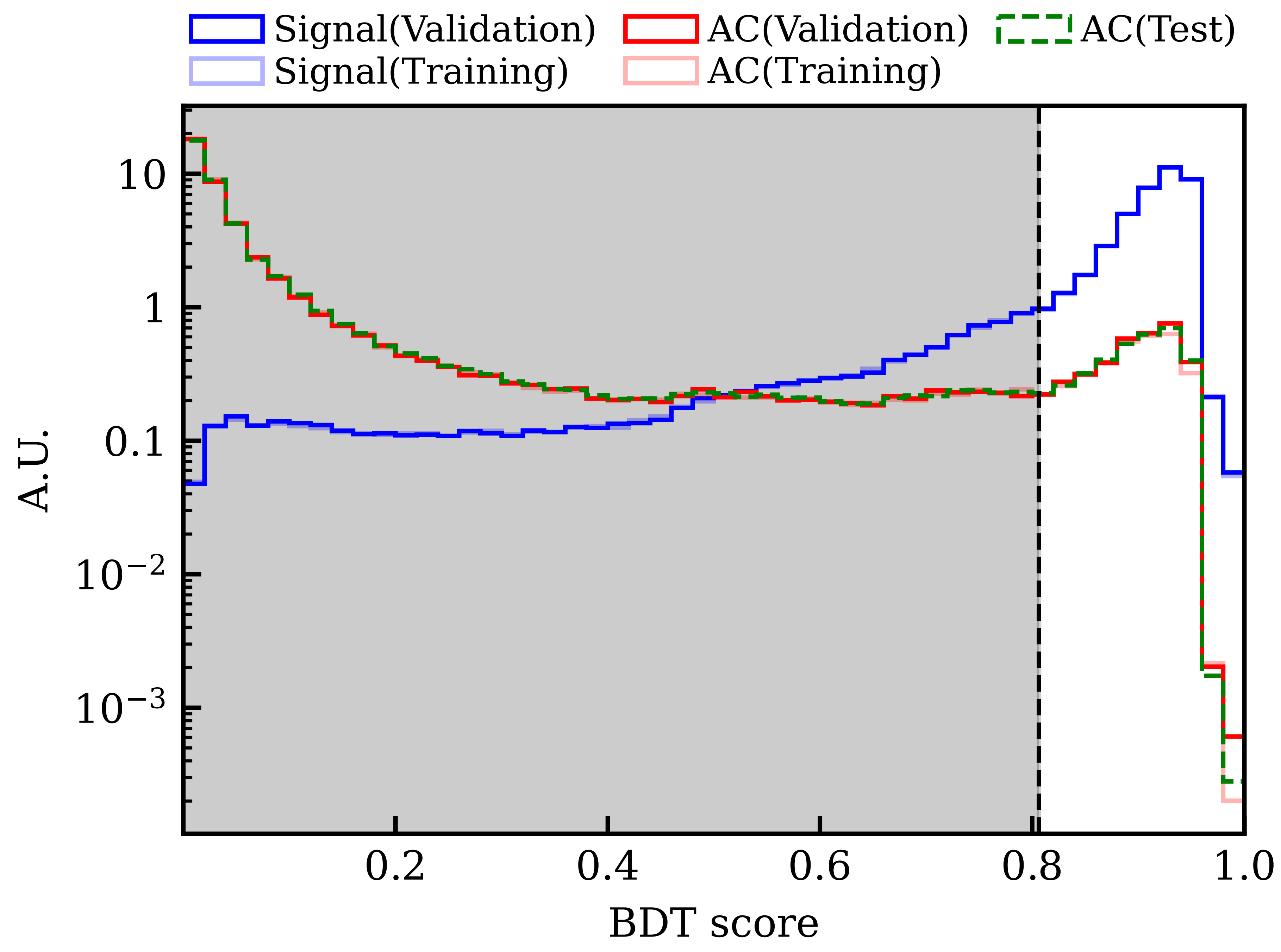
$$t_{50p} \propto \sqrt{T_{drift}}$$



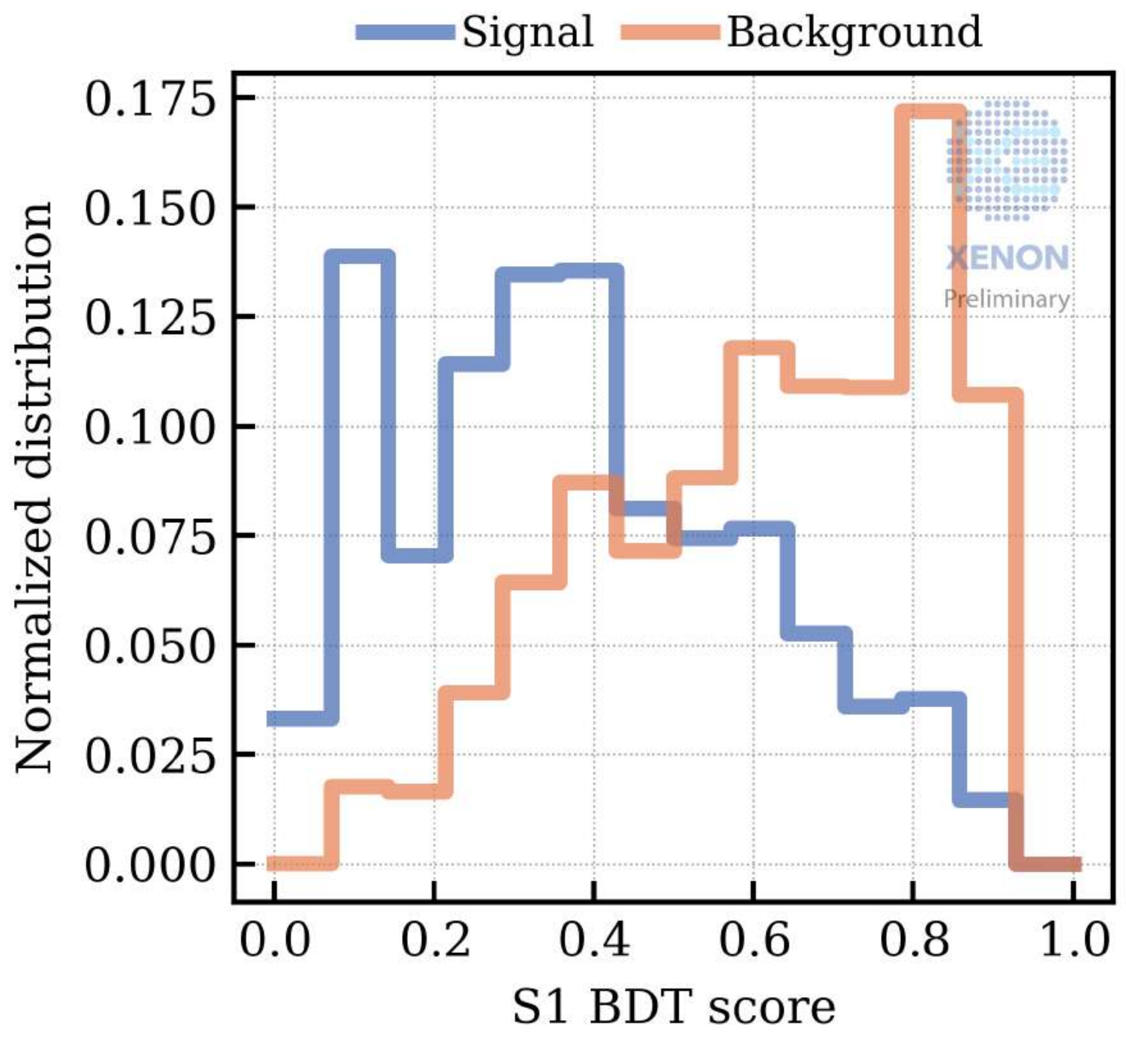




- Split datasets to prevent

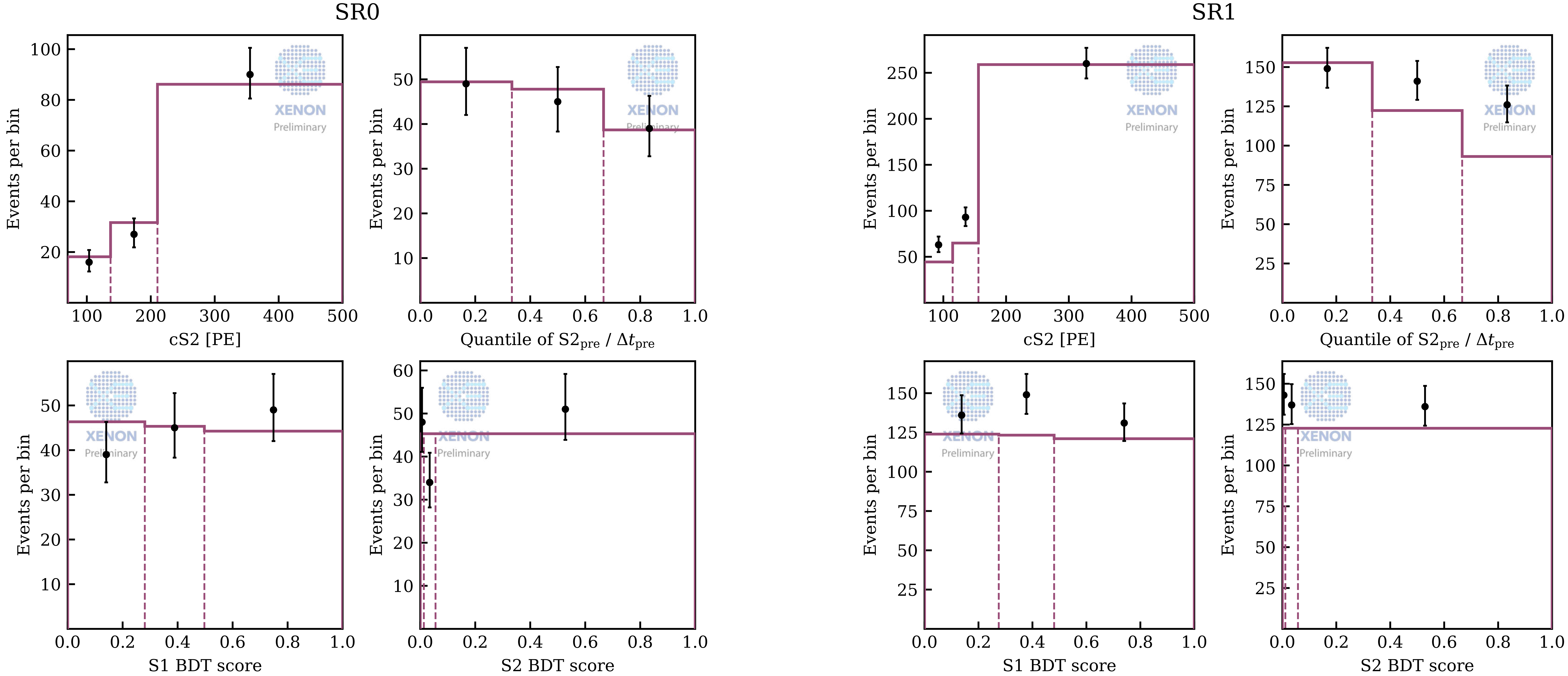


S1/S2 Pulse shape into GBDT



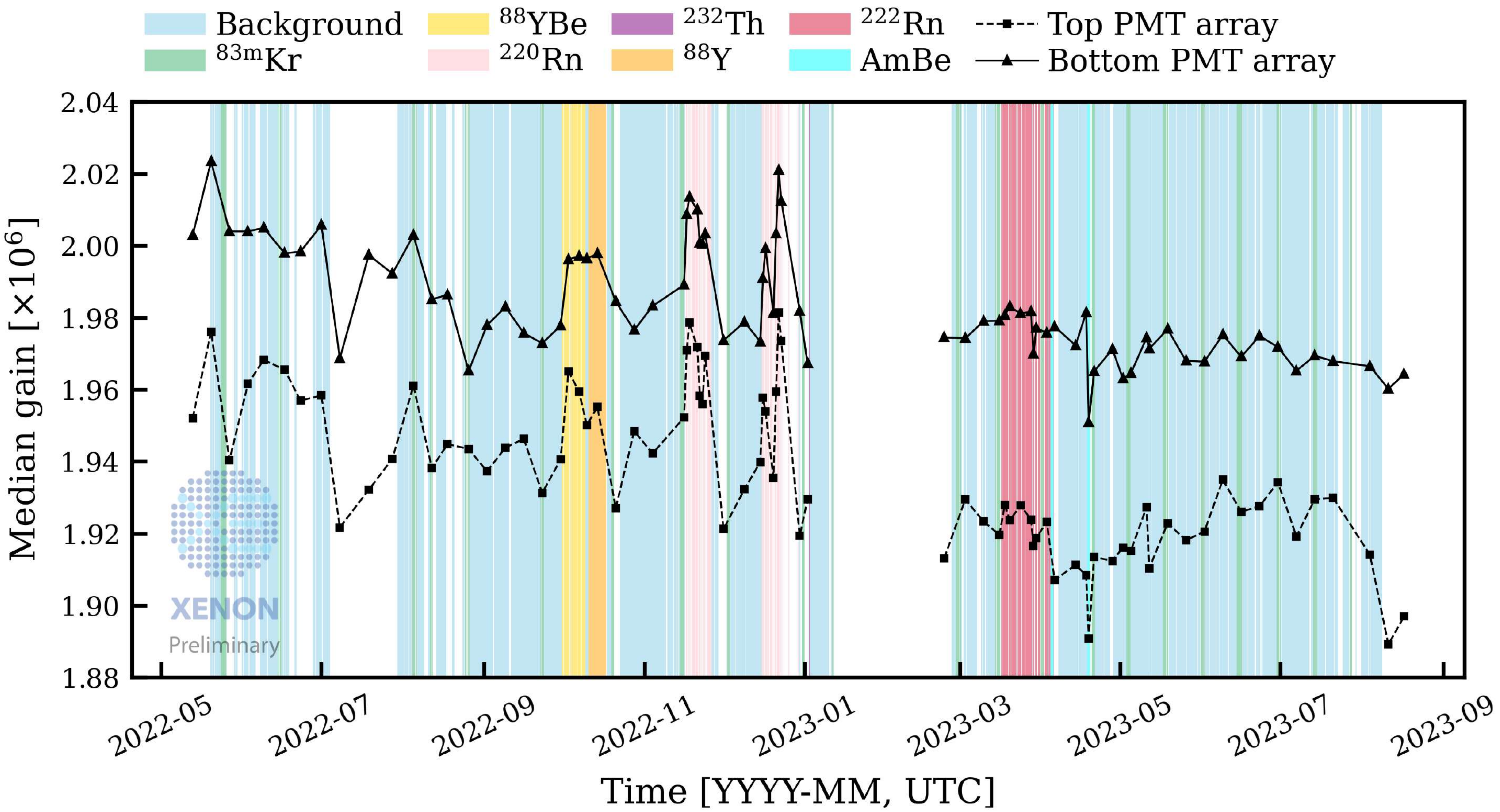
- Trained with IsoS1 vs. Simulated ^{8}B S1
- Utilize this discrimination power in the inference. So do the remaining parameter space of the TimeShadow and S2BDT cut.

ACSideband and new S2 threshold: 120PE



Science Run	Expectation	Data	P-value (4D)	Deviation
SR0	135.9	133	0.74	-0.25 sigma
SR1	368.2	416	0.03	+2.49 sigma

Stability of XENONnT During Science Runs



Stability of XENONnT is well established in both SR0 and SR1