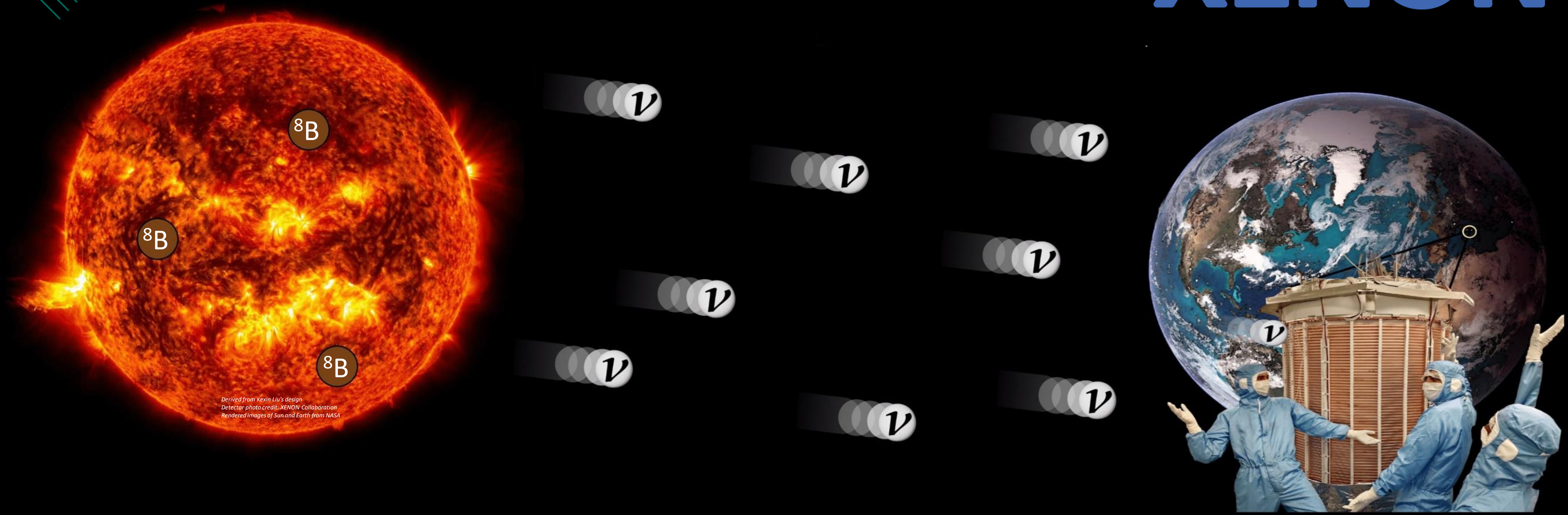
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

XENON



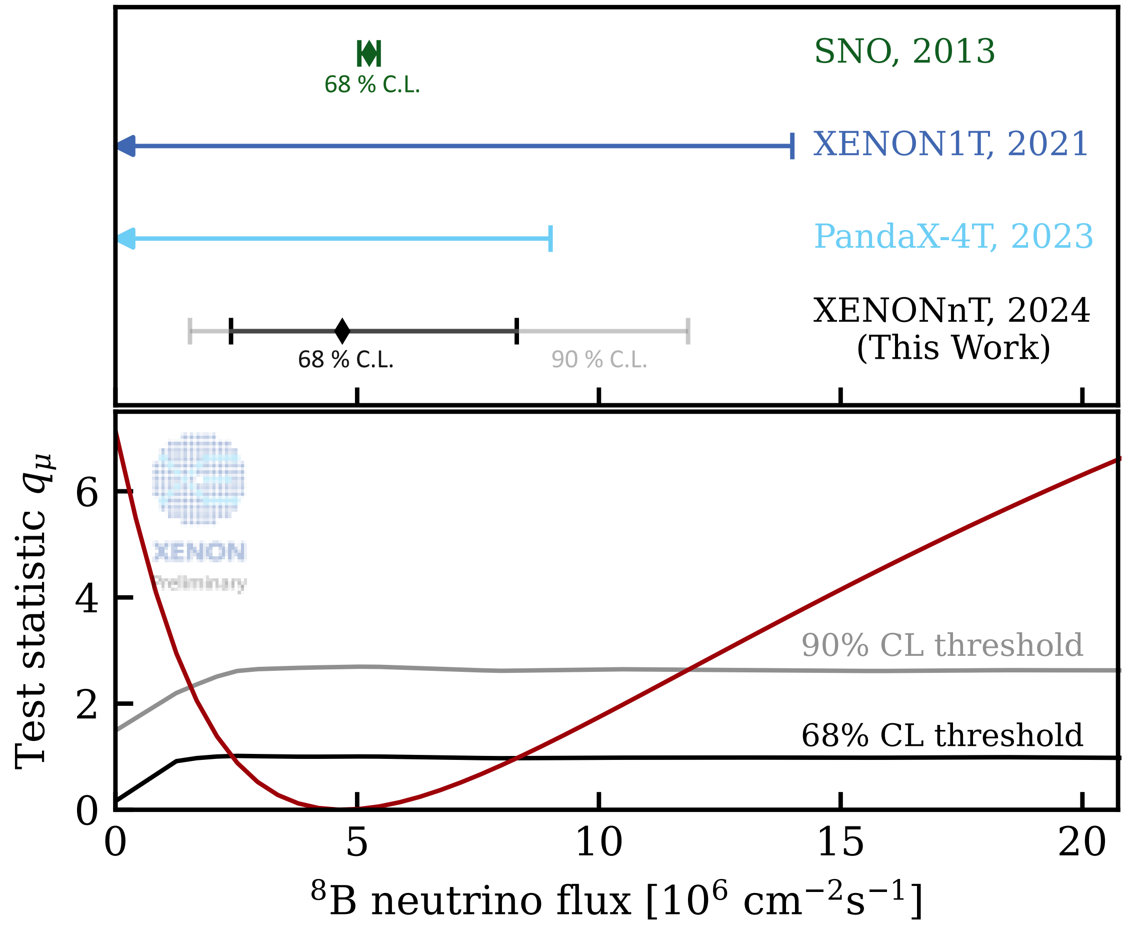
Entering the Neutrino Fog

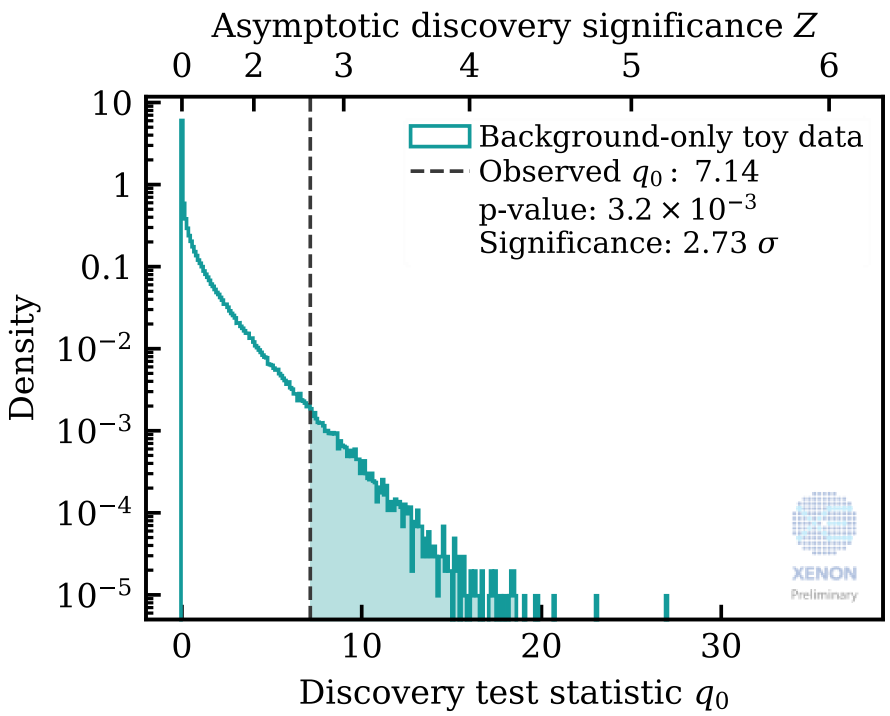
First Measurement of Solar Neutrinos via CEvNS in XENONnT

Matteo Guida
on behalf of the XENON collaboration

19th Patras Workshop on Axions WIMPs and WISPs 17.09.2024

XENONnT Solar ^{8}B CEvNS Search Results





- ^{8}B neutrinos measured via CEvNS at **2.73σ**.
- **FIRST** detected astrophysical ν in a dark matter detector.
- **FIRST** measured CEvNS from astrophysical ν source.
- **FIRST** measured CEvNS with a xenon target.

arXiv:2408.02877

The XENON Team

≈ 200 scientists
29 institutions
12 countries

XENON

AMERICA

UC San Diego	San Diego	USA
Rice University	Houston	USA
The University of Chicago	Chicago	USA
Columbia University in the City of New York	New York City	USA
Purdue University	Lafayette	USA

EUROPE

Universität Zürich	Zurich	Switzerland
KIT Karlsruhe Institute of Technology	Karlsruhe	Germany
WWU Münster	Münster	Germany
Uni Freiburg	Freiburg	Germany
JGU	Mainz	Germany
Max-Planck-Institut für Kernphysik	Heidelberg	Germany
Nikhef	Amsterdam	Netherlands
Stockholm University	Stockholm	Sweden
Universidade de Coimbra	Coimbra	Portugal
Subatech	Nantes	France
LPNHE Paris	Paris	France
INFN Torino	Torino	Italy
Alma Mater Studiorum	Bologna	Italy
Università degli Studi dell'Aquila	L'Aquila	Italy
INFN LNGS	Assergi	Italy
Federico II	Napoli	Italy

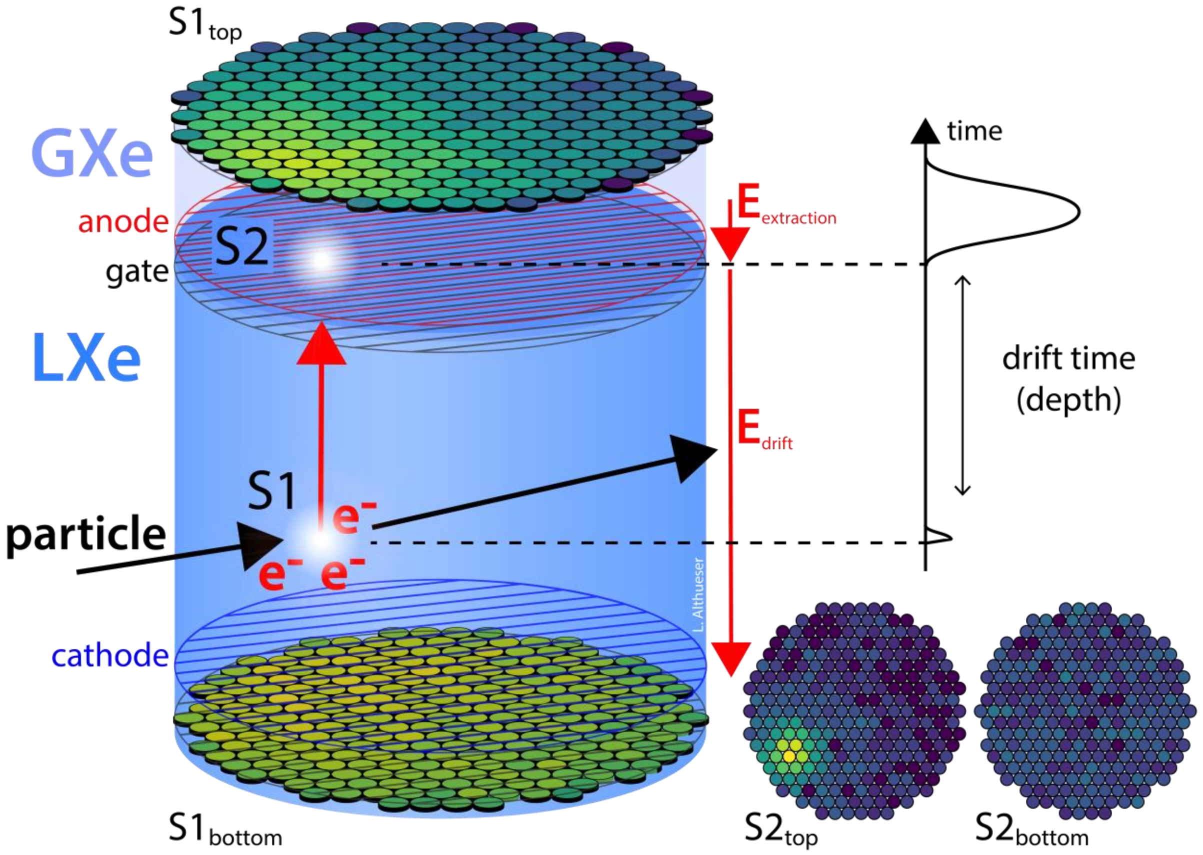
MIDDLE EAST

מכון ויצמן למדע Weizmann Institute of Science	Rehovot	Israel
جامعة نيويورك ابوظبي NYU Abu Dhabi	Abu Dhabi	UAE

ASIA

清华大学 Tsinghua University	Beijing	China
西湖大学 Westlake University	Hangzhou	China
The Chinese University of Hong Kong, Shenzhen	Shenzhen	China
東京大学 The University of Tokyo	Tokyo	Japan
Nagoya University	Nagoya	Japan
Kobe University	Kobe	Japan

The XENONnT Experiment



- **S1 SIGNAL**
  prompt scintillation photons.
- **S2 SIGNAL**
  secondary scintillation photons from electroluminescence in gaseous xenon (GXe) due to drifted electrons.
- **3D VERTEX RECONSTRUCTION**
  X,Y: S2 hit pattern in the top PMT array.
  Z: drift time S2-S1.
- **ENERGY RECONSTRUCTION**
  from combined S1 and S2 signals.

Eur. Phys. J. C 84, 784 (2024)

Recoil Type Discrimination

Gamma

Beta

★ / Neutrino elastic scattering

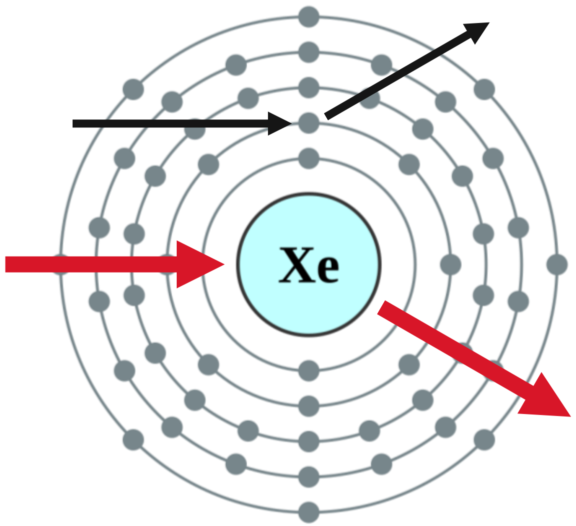
★ ★ Solar axions, ALPs, ...

Neutron elastic scattering

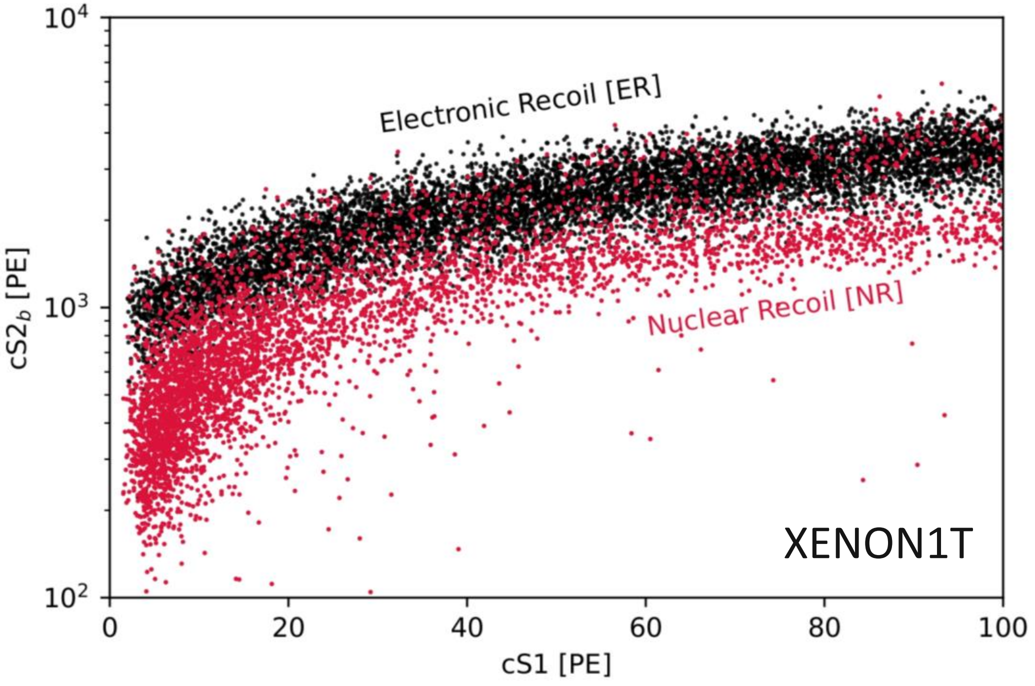
★ / Neutrino CEvNS

★ ★ WIMP dark matter, ...

Electronic Recoils (ER)



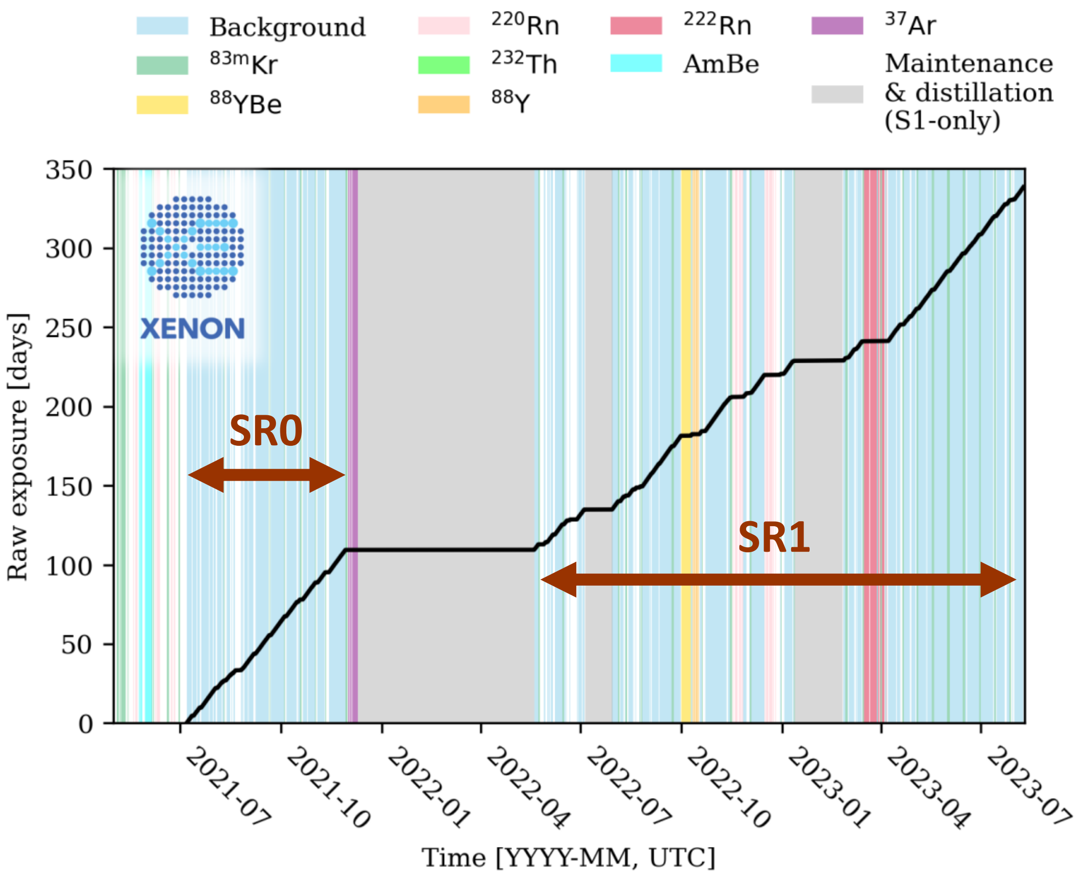
Nuclear Recoils (NR)



Recoil type discrimination

S1/S2 ratio depends on dE/dx.

XENONnT Timeline



Science data in the **ROI** is **BLINDED.**

- Stable detector response: achieving <1% (<3%) variation in light (charge) yield.
- Electron lifetime excellence ≈ 20ms.
- **Radon suppression milestone**: distillation with combined gaseous and liquid xenon flow.

↓

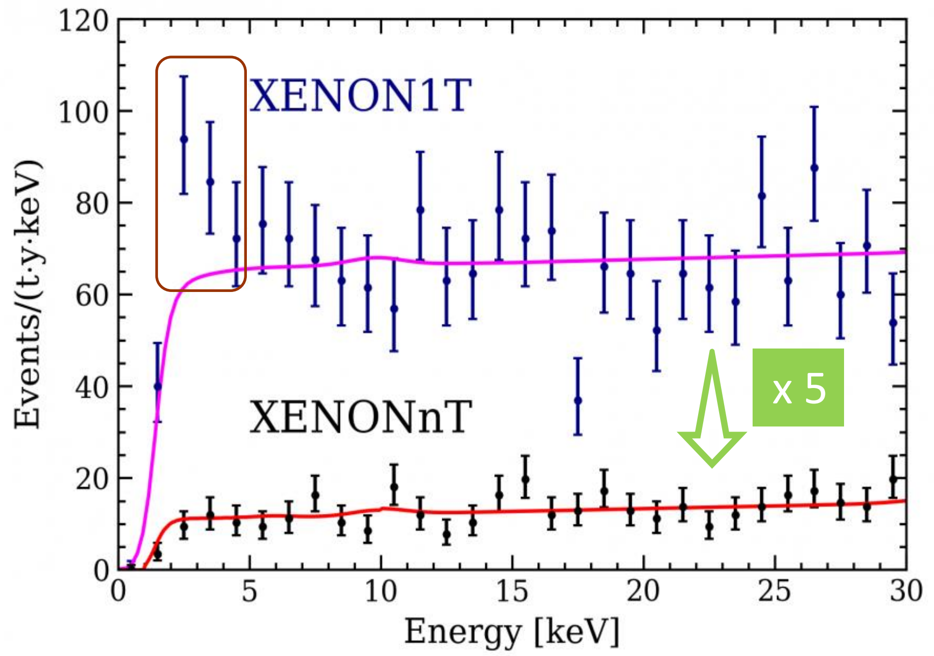
^{222}Rn ER background is pushed to record-low levels $< 1\ \mu\mathrm{Bq\ kg^{-1}}$.

Physics Results So Far

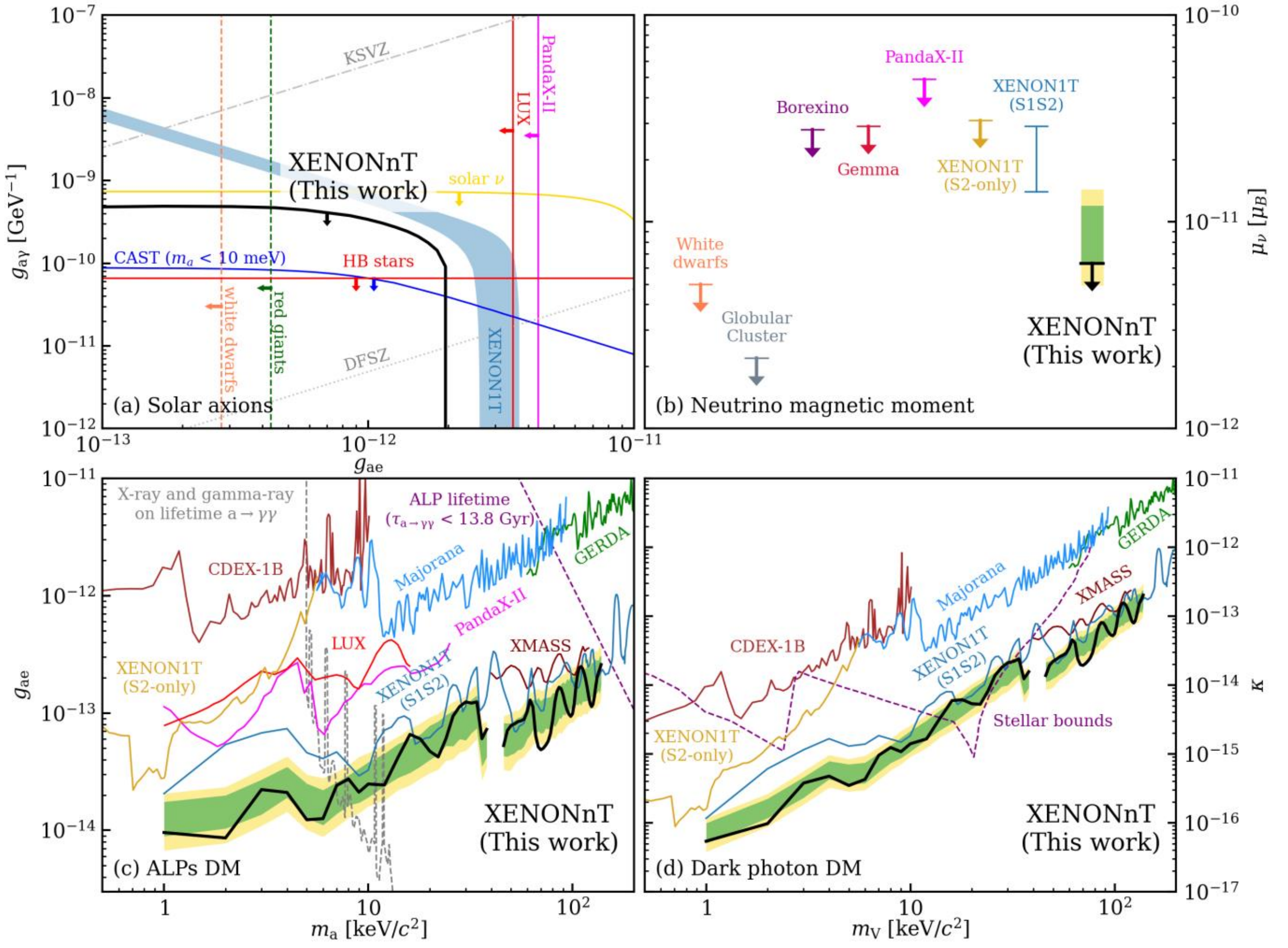
	α Electronic Recoils	χ WIMP Dark Matter	ν Solar CEvNS
DATA	**SR0**	**SR0**	**SR0 + SR1**
LIVETIME	**97.1** days	**97.1** days	**316.7** days
FIDUCIAL MASS	**4.2** t	**4.2** t	**4.0 t** (SR0) - **4.1 t** (SR1)
BLIND ANALYSIS	😎	😎	😎

New Physics Search in Electronic Recoils Data

- The XENON1T excess excluded at $\approx 4\,\sigma$.
  Tiny tritium leak suspected in XENON1T.
  Tritium mitigation implemented in XENONnT.



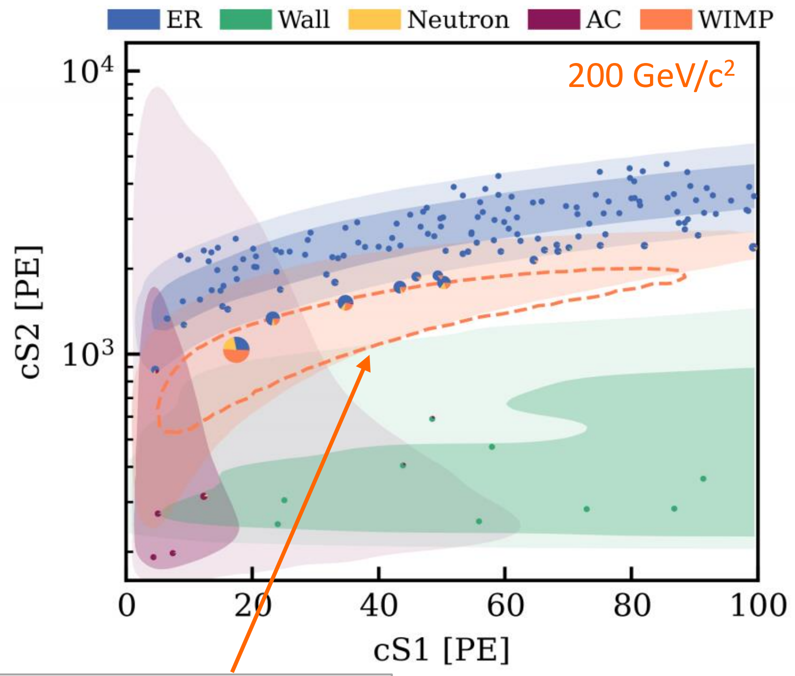
- Record-low ER background:
  15.8 events/(t y keV) in (1, 30) keV ROI.



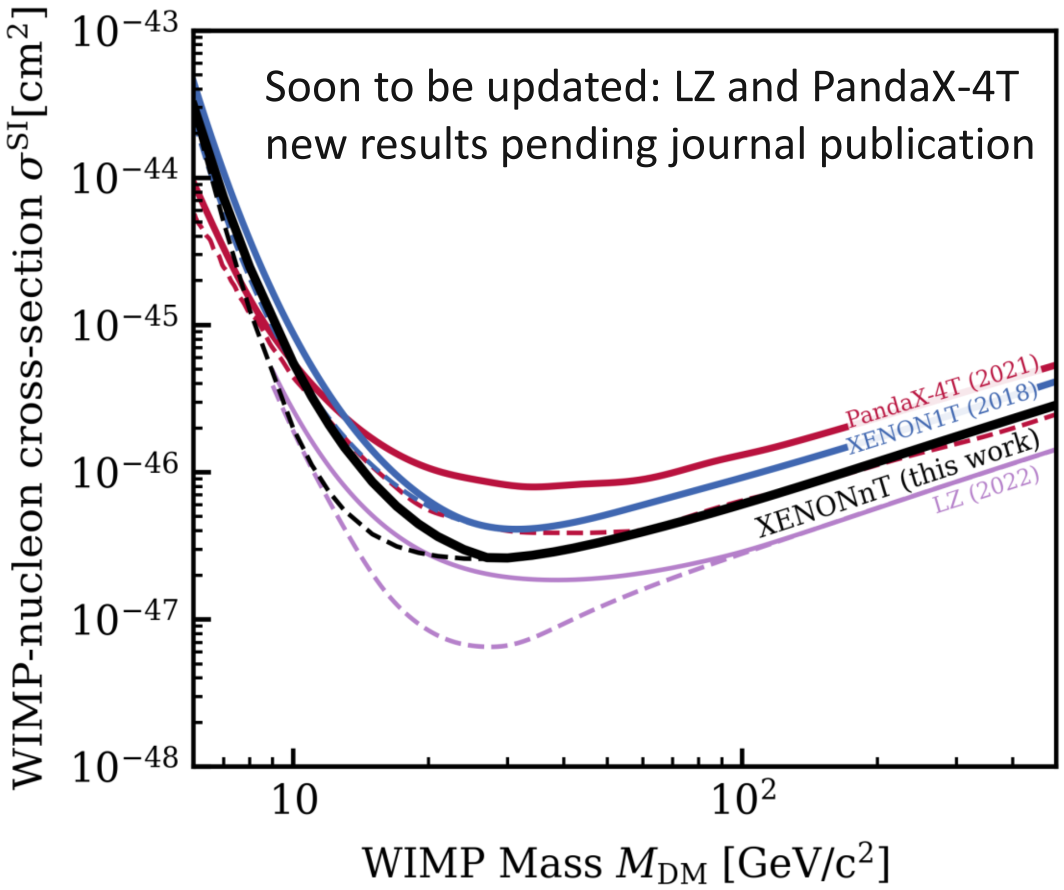
World leading laboratory limits on BSM signals:
solar axion, ALPs, NMM.

Phys. Rev. 482 Lett. 129, 161805 (2022)

WIMP Dark Matter Search



50% of WIMP signal with highest signal-to-noise



- Strongest limit for spin-independent WIMP-nucleon cross section: 2.6×10^{-47} cm^2 at 28 GeV/c^2.
- Power-constrained limit (PCL) to median sensitivity: excluding only parameter space that the detector is sensitive to.
- The convention needs to be rediscussed within the community.

Phys. 362 Rev. Lett. 131, 041003 (2023)

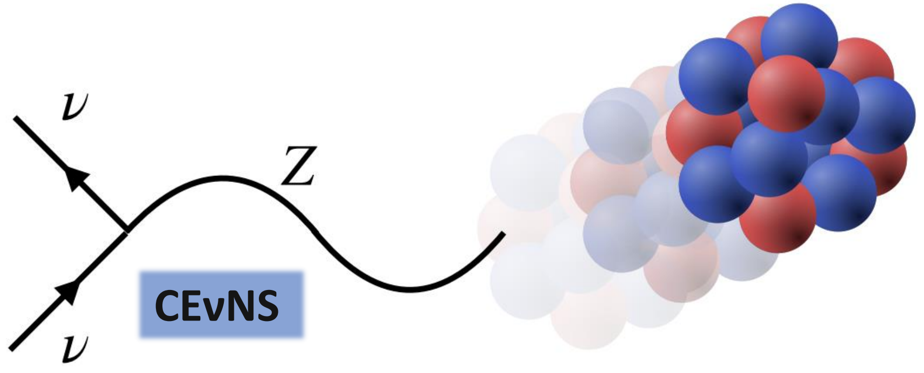
SOLAR ^{8}B CEνNS

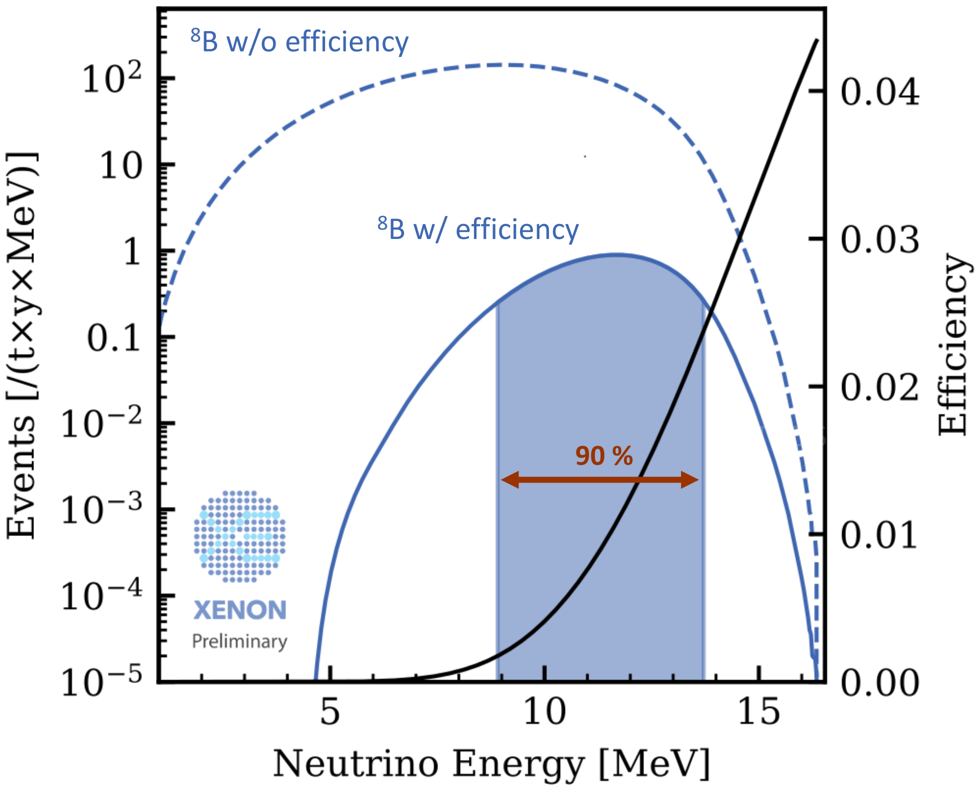
- Coherent Elastic Neutrino-Nucleus Scattering → CEνNS
  "high" cross section for ν physics but low recoil energy < 1.5 keV_{NR}.
- Flavour-independent process, exchange of a Z boson.
- Nuclear cross−section dependence

$$\sigma_{CE\nu NS} \propto N^2 \qquad N \equiv \text{neutrons}$$

  - **Never** measured in a xenon target.
  - **Never** measured from astrophysical source.

- First measured by COHERENT (2017) from Spallation Neutron Source (SNS). Science 357 (2017) 6356, 1123-1126
- ^{8}B CEνNS in XENONnT: 90% of events from the range [8.9, 13.7] MeV.





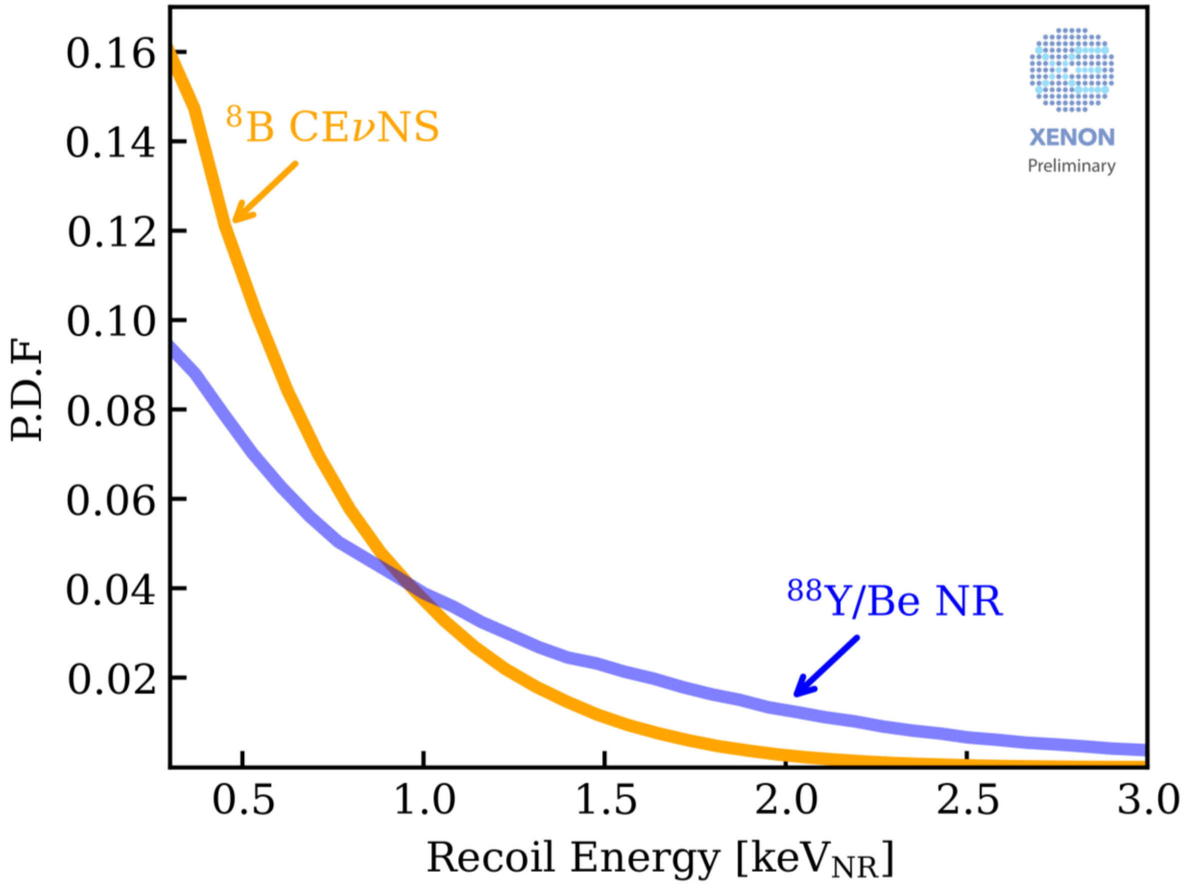
^{88}YBe Low Energy Nuclear Recoil Calibration

- First ^{88}YBe low-energy nuclear recoil (NR) calibration for 7 days using a external photoneutron source to get the low-energy yields in the liquid xenon.

- Quasi-monoenergetic 152 keV neutrons are produced by photo-disintegration of ^{9}Be by the 1.84 MeV γ-rays of the ^{88}Y.

$$\gamma + {}^{9}\text{Be} \rightarrow n + {}^{8}\text{Be}$$

- Challenging external calibration due to proximity to the detector threshold, high background rates, and low statistics.



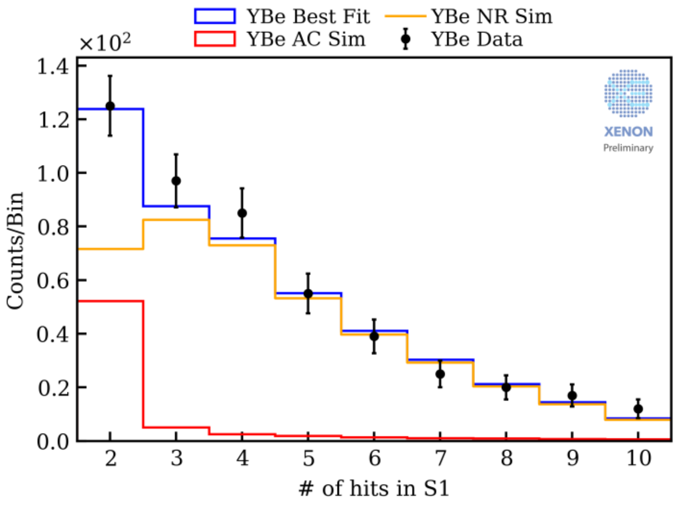
Yield model with ^{88}YBe Calibration

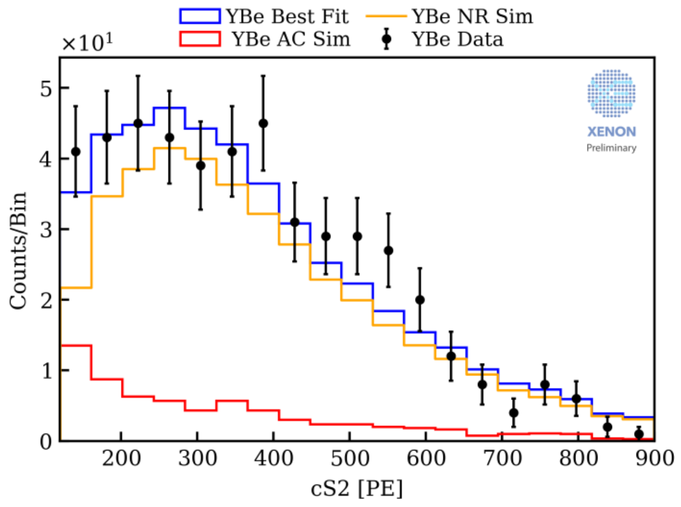
IMPRS for Precision Tests of Fundamental Symmetries
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

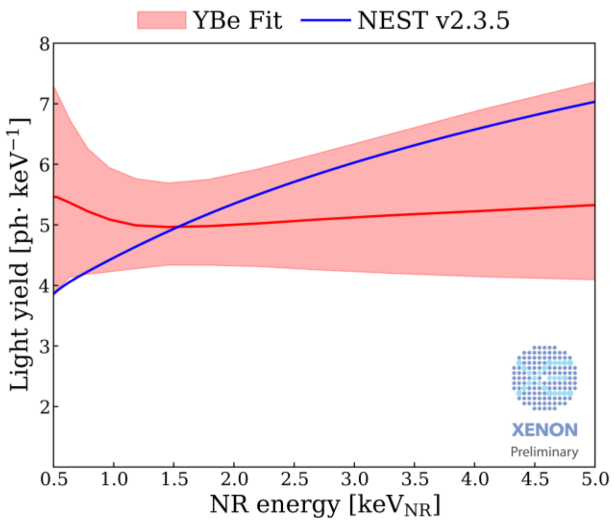
XENON

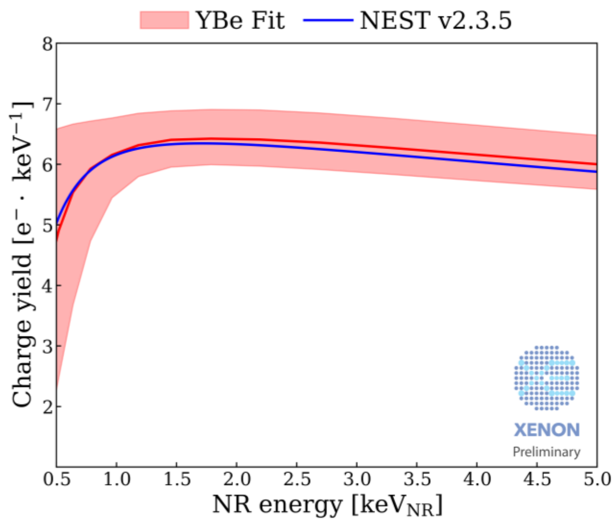
- Great agreement between data and model.

- The same data-driven simulation pipeline for accidental coincidence, the largest background source, was applied uniformly across all science searches and calibrations.





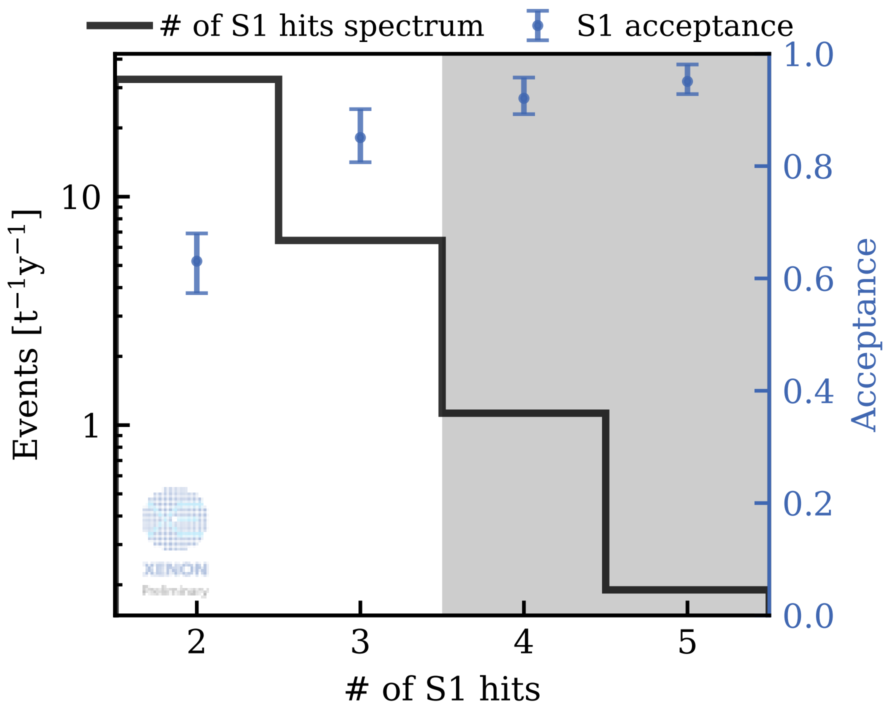


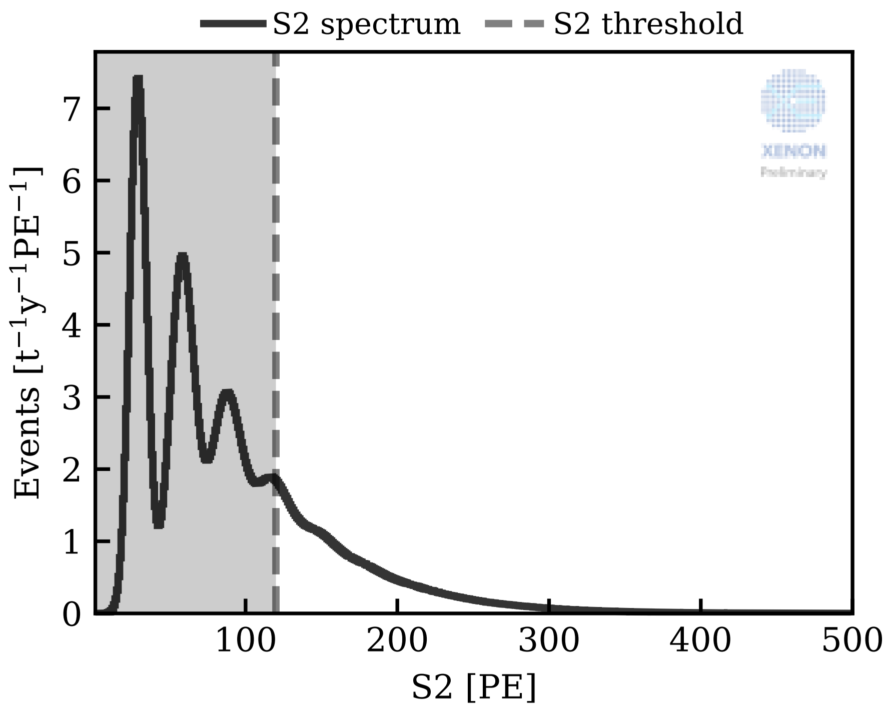


- The Light Yield (LY) and Charge Yield (CY) were extracted down to 0.5 keV_{NR} at XENONnT electric field of 23 V/cm.

- Yield model uncertainty leads to $\approx$ 30% signal rate uncertainty.

^{8}B CEvNS: Signal Region of Interest





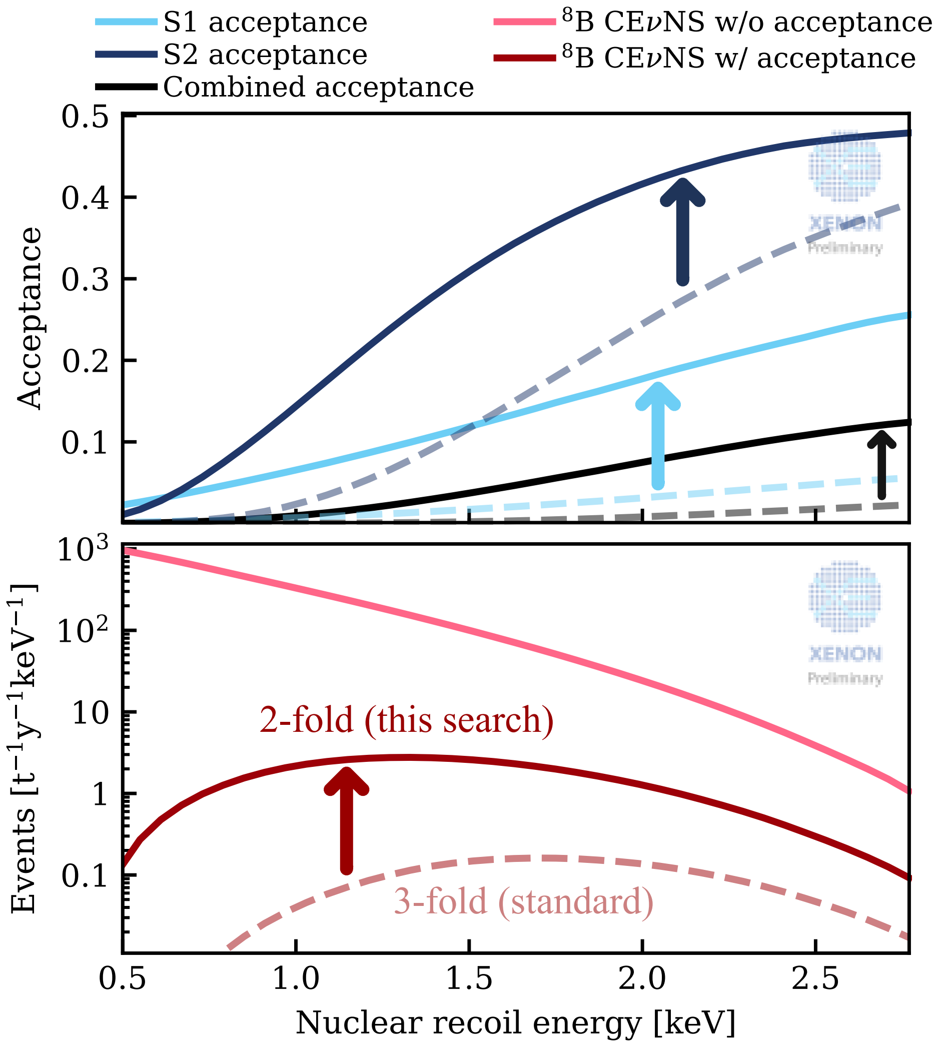
S1 ROI: **2** or **3 hits**

S1 hit: photon hitting the PMT and recorded by DAQ and software.

S2 ROI: [**120 – 500**] **PE**

120 PE used to reject high isolated S2 background below it.

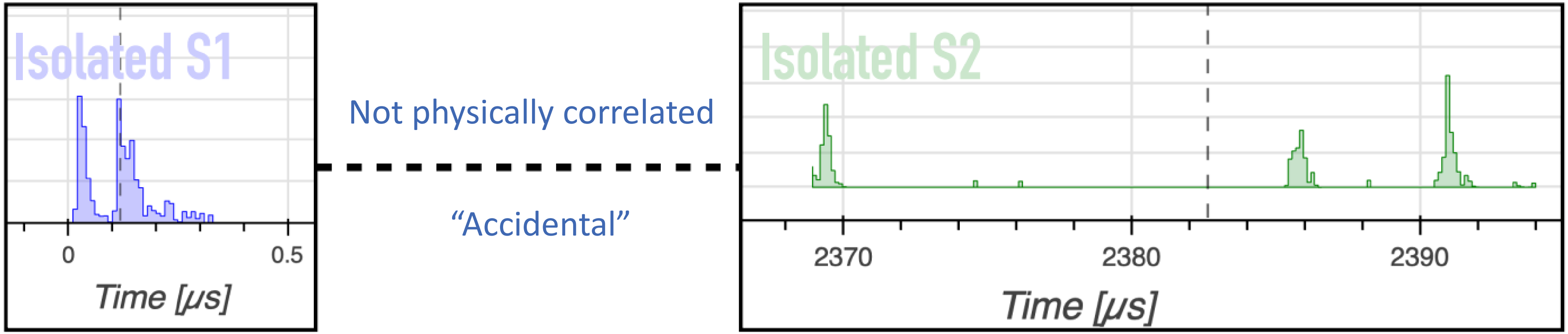
Lowering the Energy Threshold



- Relaxed the S1 waveform shape requirement from conventional analysis:
  - 3-fold → 2-fold
  - keeping AC background under control
- Lowered S2 threshold from conventional analysis 200 PE → 120 PE.

17 TIMES MORE EVENTS

Accidental Coincidence (AC) Background



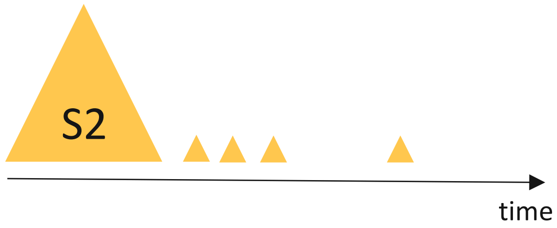
Dominant background close to the threshold.

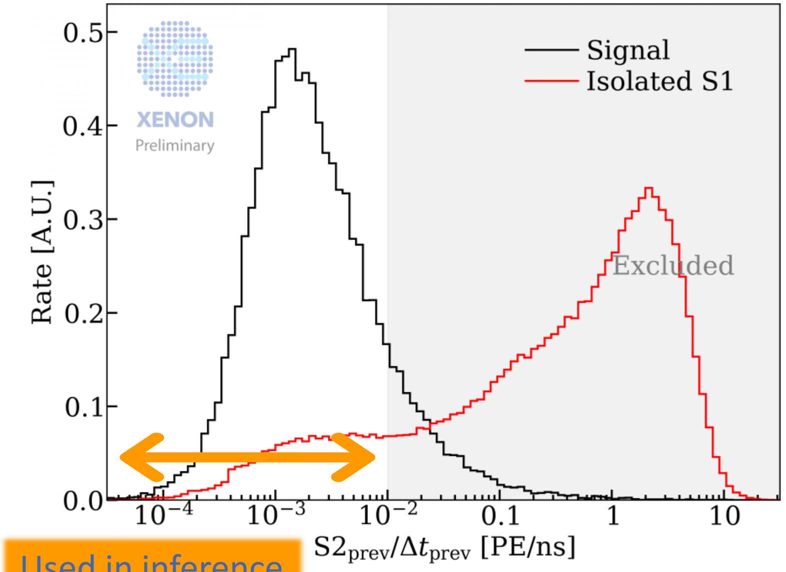
- Exact physical mechanisms of isolated peaks are under investigation.
  - "isolated S1 signals": from pileup-induced single PMT hits, misclassified single electrons, …
  - "isolated S2 signals": from few-electron pileup events, notably following high-energy (HE) interactions, …
- Raw AC rate ≈ 400 per day
  - "Isolated" S1 ≈ 15 Hz
  - "Isolated" S2 ≈ 0.15 Hz
  - Max. drift time: 2.25 ms

Reducing AC Background

❖ High chance of delayed electrons after large S2 signals (high energy radioactivity).

Time shadow → S2/Δt



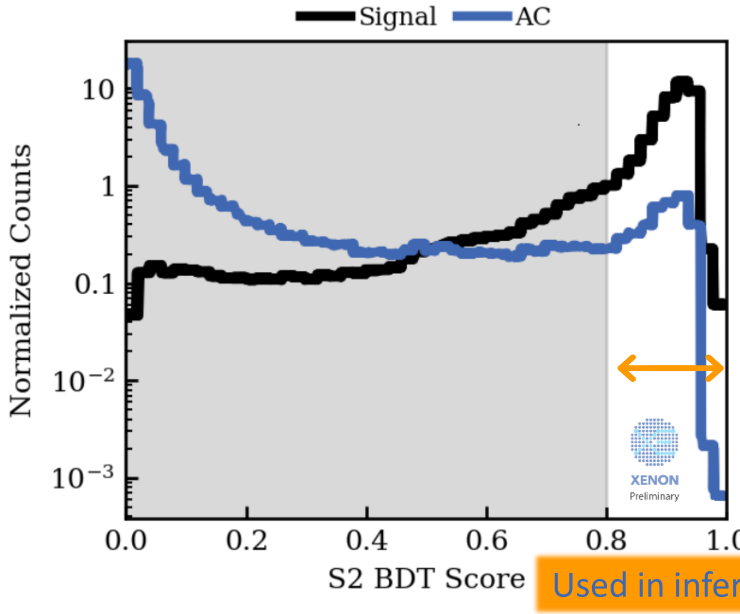


Used in inference

❖ Further suppression by 2 Boosted Decision Tree (BDT):

- **S2 BDT** → check that S2 pulse shape correlated with the diffusion of the drifting electron cloud law. No correlation in AC background.

- **S1 BDT** → leverage S1 pulse and S1 spatial distribution across the PMT arrays to discriminate signal from isolated S1 signals induced by a random pileup of PMT hits.



Used in inference

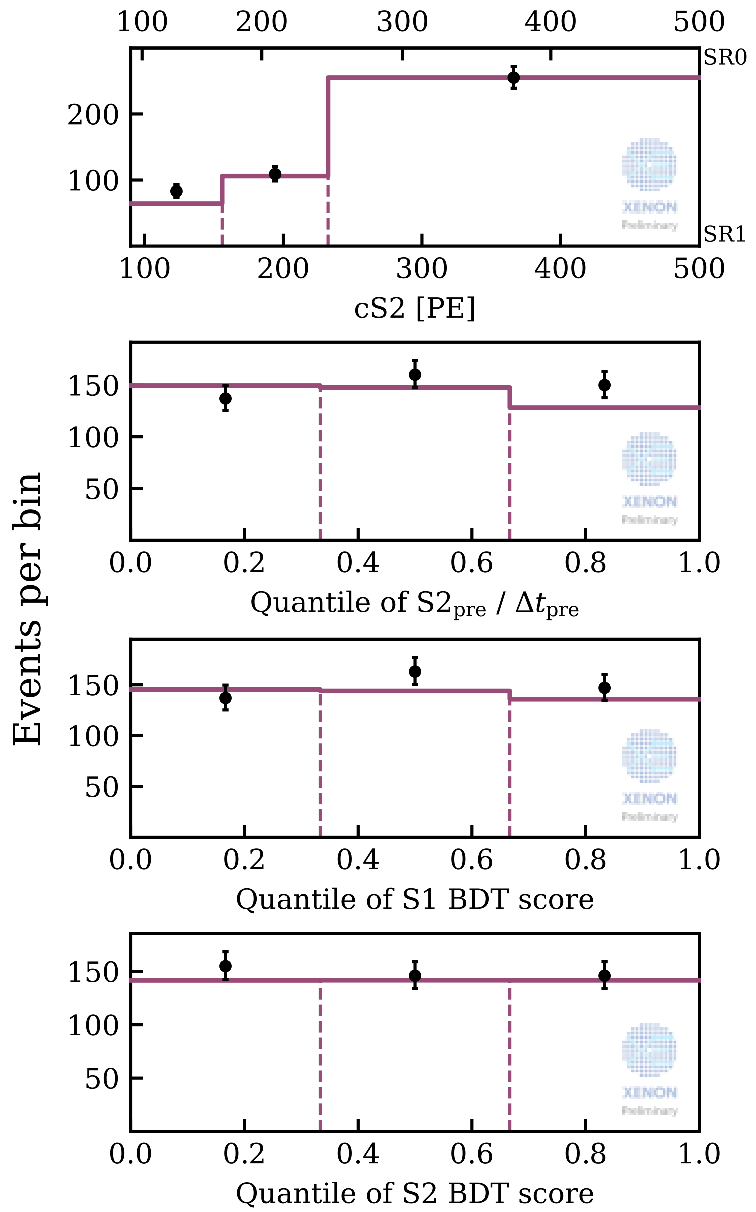
Validation of AC: AC-Sideband Unblinding

- AC model is datadriven → validation is crucial
  AC sideband (invert highest AC rejection power cuts)

Dataset	Expectation	Observation	p-value (4D)
SR0	122.7	121	0.33
SR1	302.5	326	0.16

- The S2 threshold is increased to 120 PE after sideband unblinding → avoid mismodeling.

- The remaining differences propagate as **uncertainty** to the final likelihood:
  - SR0: 9%
  - SR1: 6%



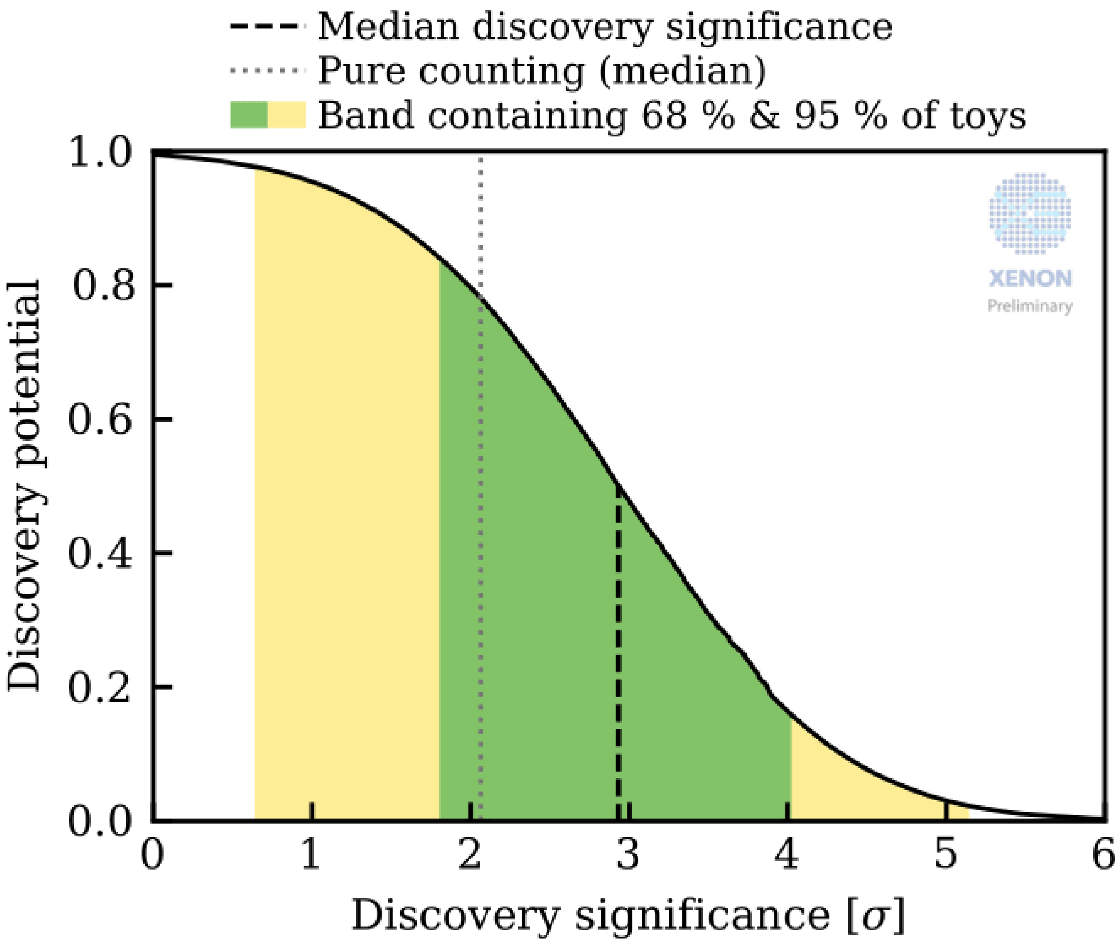
Discovery Potential

- Extended binned likelihood in 4D parameter space
  3 x 3 x 3 x 3 = 81 bins.

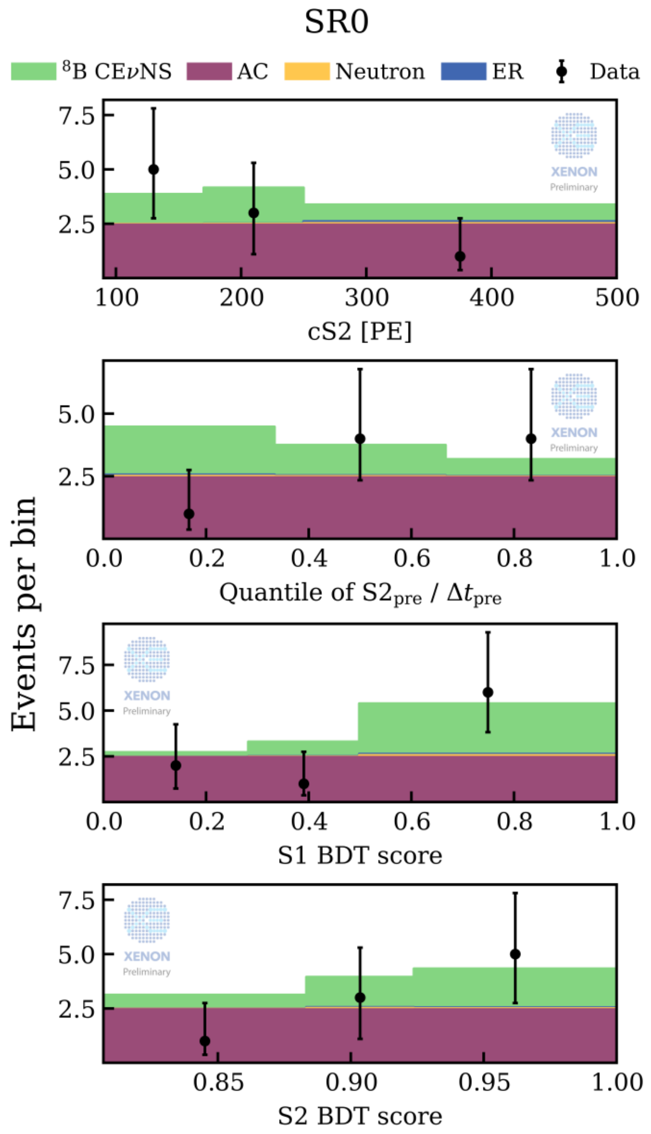
- Separate terms for SR0 & SR1.
  Constraints on rates and yields from ancillary measurements.

- Expected background: 26.4 events
  Expected signal: 11.9 events

- Likelihood analysis:
  - 2σ: 80%
  - > 3σ: 50%



Unblinding Results



Expected Background

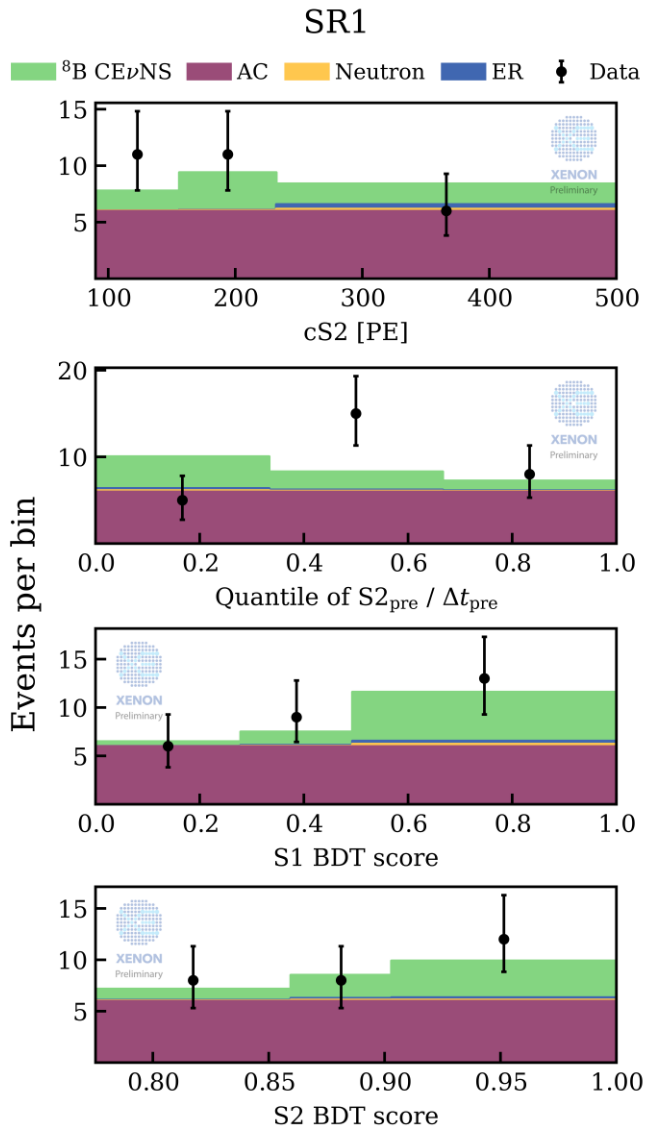
$26.4^{+1.4}_{-1.3}$

Expected Signal

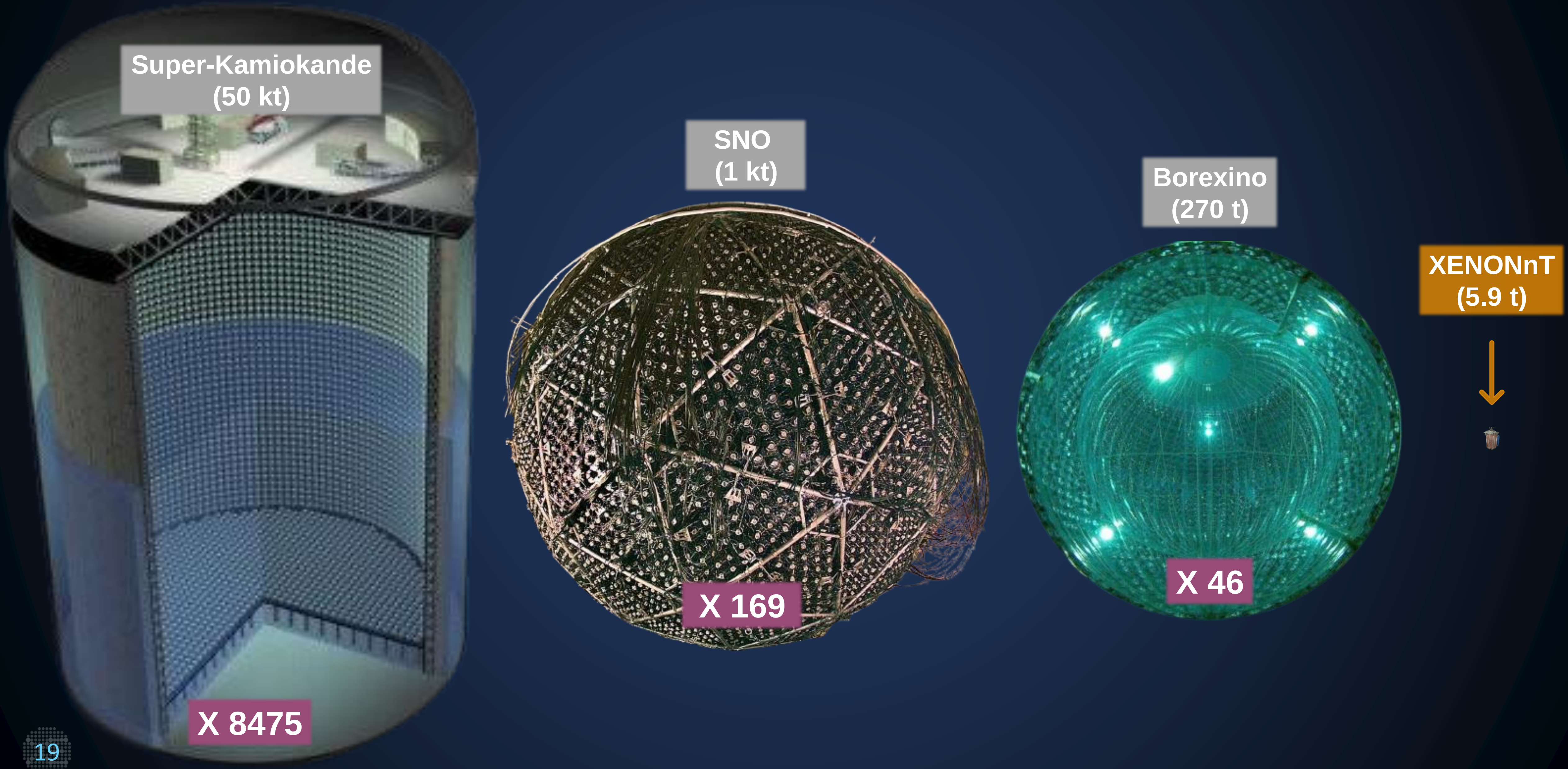
$11.9^{+4.5}_{-4.2}$

37

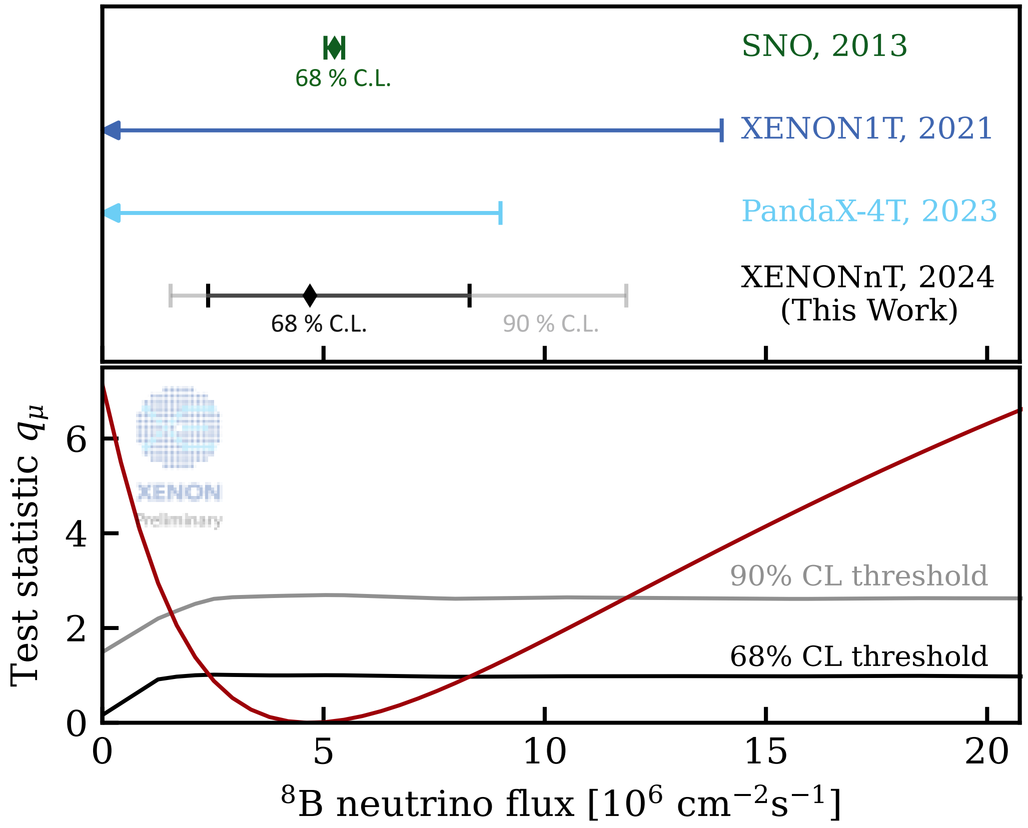
Events observed



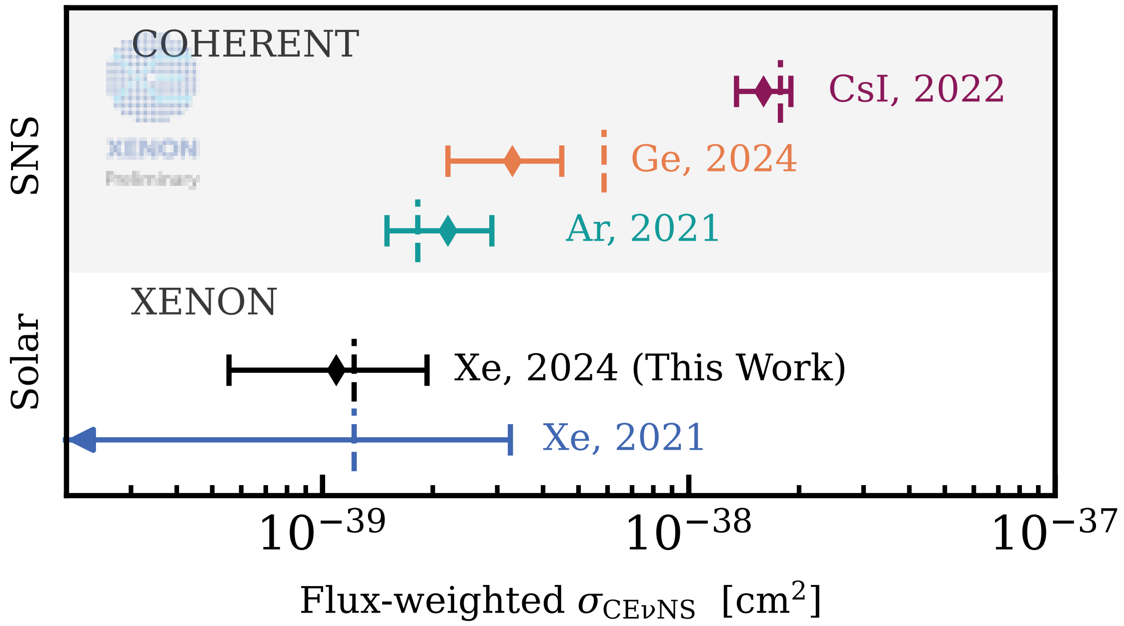
XENONnT: The Smallest "Solar" Neutrino Detector



Physics Results



- With the solar 8B neutrino flux constrained by SNO $\sigma_{\text{CE}\nu\text{NS}}$ measured.
- First measurement on xenon: consistent with the SM prediction.

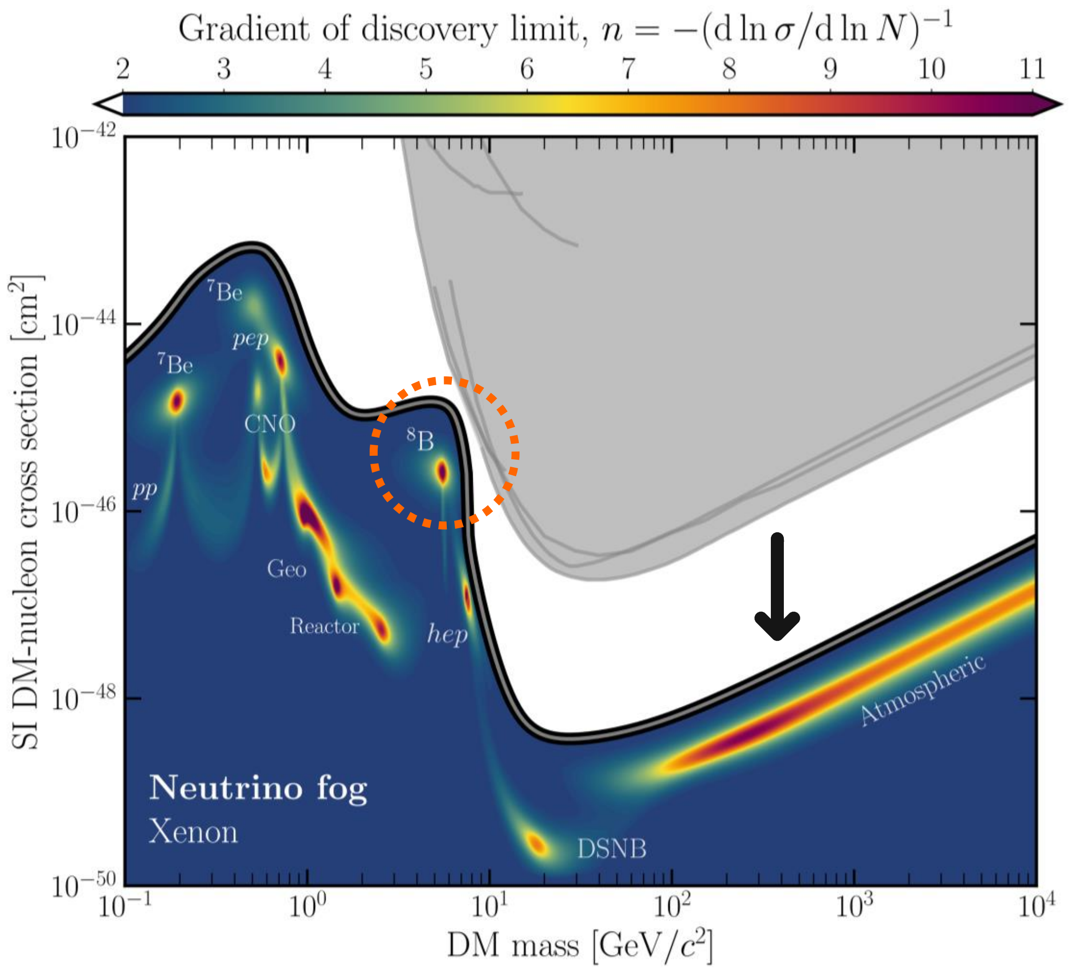


- ^{8}B neutrino flux: $(4.7^{+3.6}_{-2.3}) \times 10^6$ cm^{-2}s^{-1} at 68% C.L. no tension with literature value

arXiv:2408.02877

Summary and Outlook

- **FIRST** detection with **blind analysis** of ^{8}B solar neutrino CEvNS at **2.73σ**.
- **FIRST** observed astrophysical ν in a dark matter detector.
- **FIRST** measured CEvNS with a Xe target.
- The unexplored WIMP parameter space is awaiting — stay tuned!
- Reduced ER and NR background in new data:
  using GXe + LXe Rn distillation and neutron veto water Gd-doping.
- Much more **blinded data** collected!



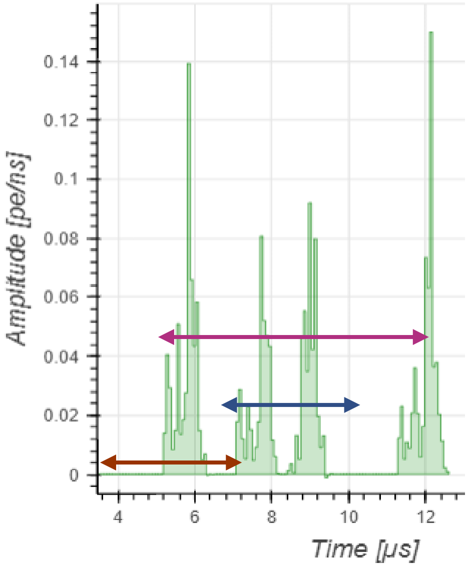
Phys. Rev. Lett. 127, 251802 (2021)

BACKUP SLIDES

S2 BDT

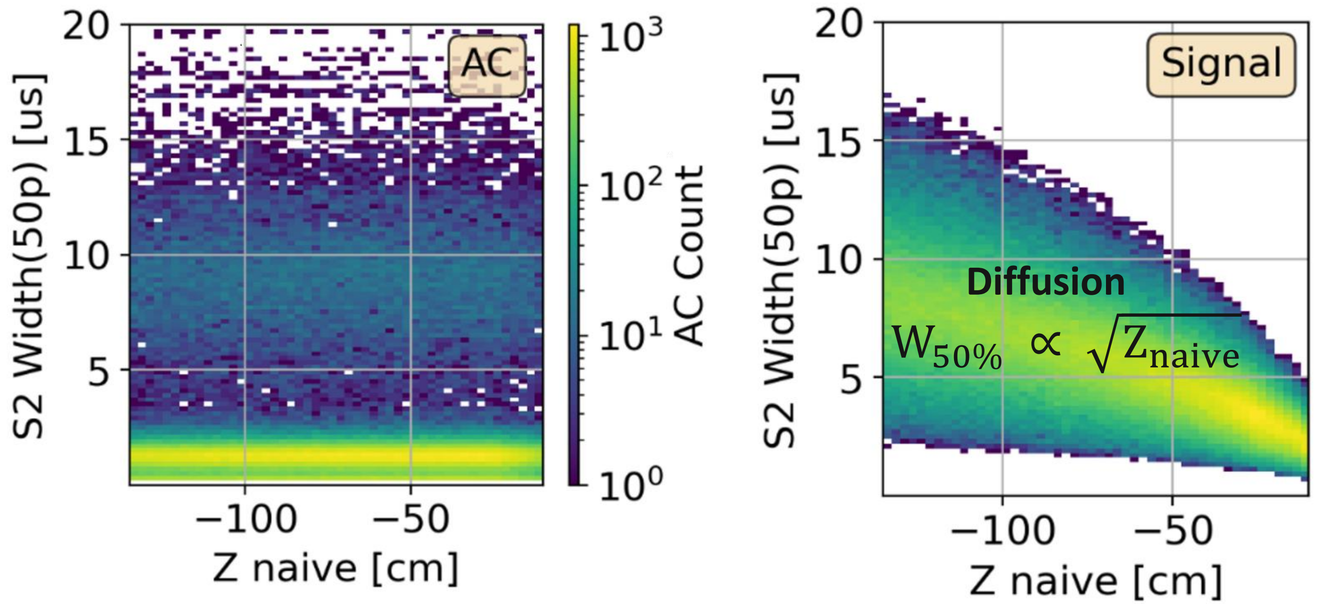
- BDT trained using simulated signal and data-driven AC background, with each feature rigorously validated between data and simulation.

S2 Signal



Feature relevance

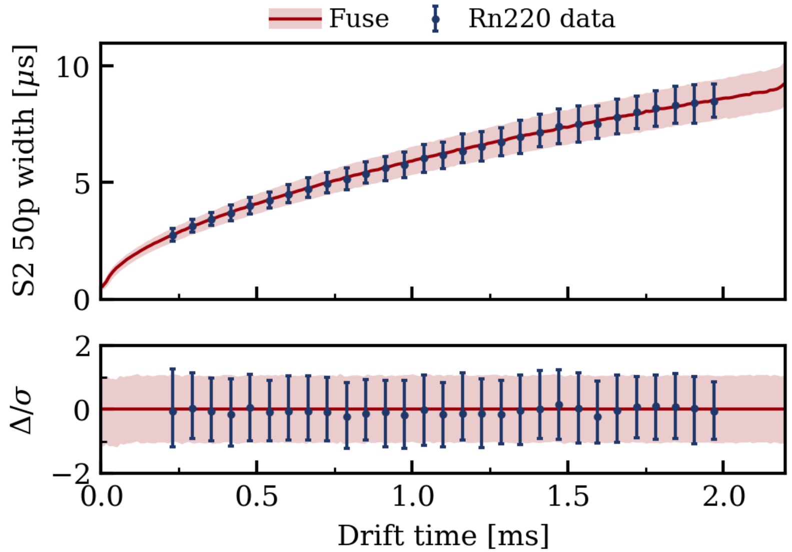
50% width
Rise time
90% width
z-naive



Great agreement between simulation and data.

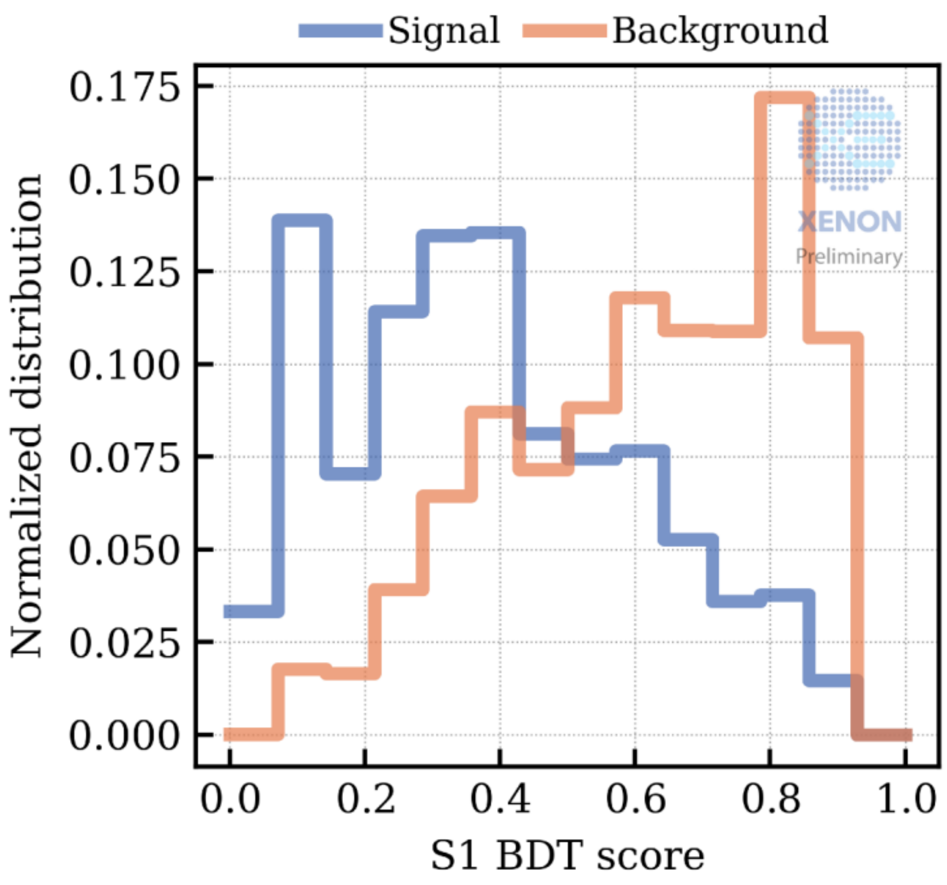
xenon-fuse 1.3.0

```
pip install xenon-fuse
```

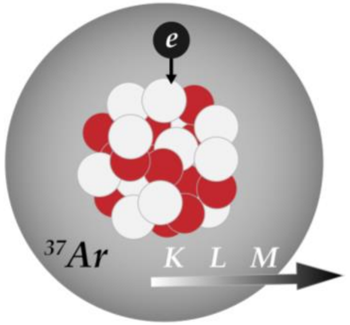


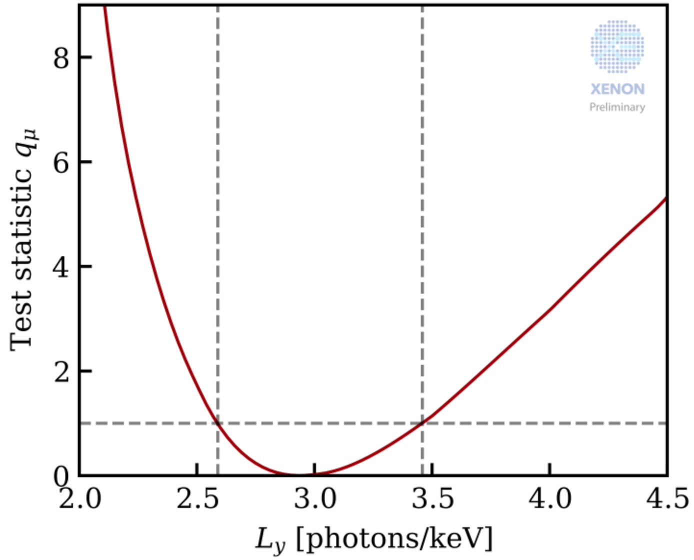
S1 BDT

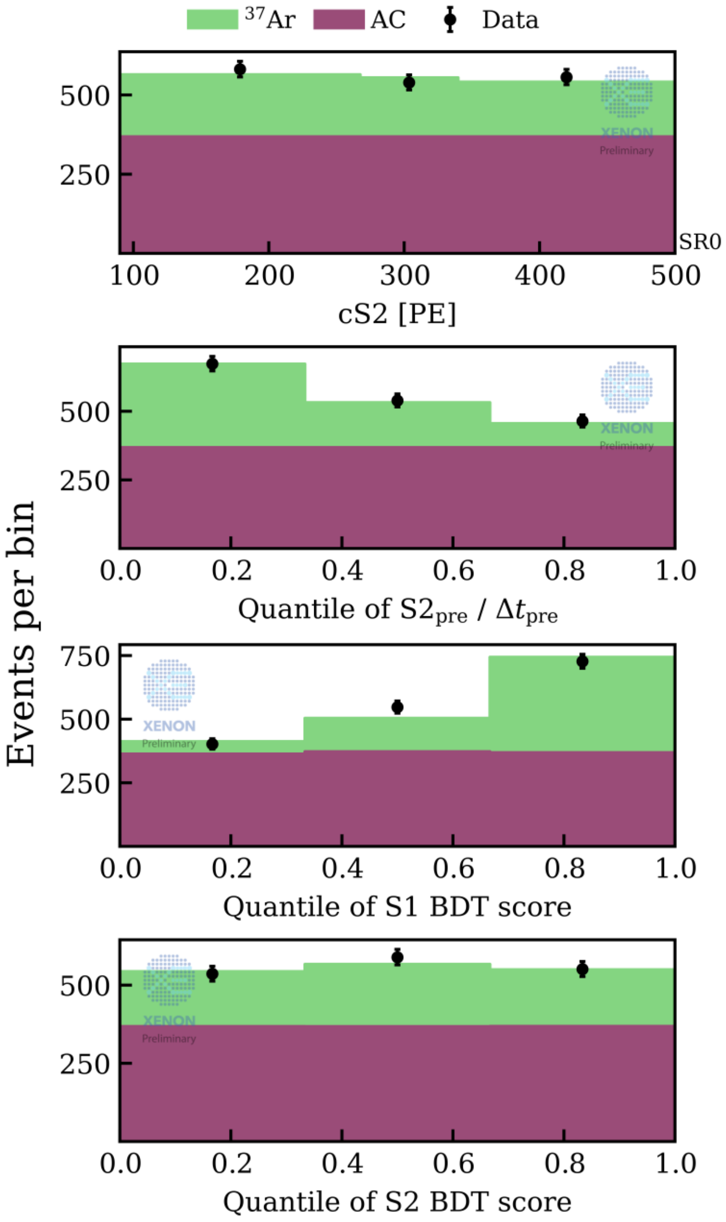
- Waveform-feature-based S1 BDT differentiates isolated S1 signals from random PMT hit clustering.
- Input features: double photo-electron emission, S1 pulse shape, S1 hit counts, PMT channel distribution of S1.
- Trained with a data-driven sample of isolated S1 and simulated ^{8}B S1
- S1 area in the 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 ≈ 0.2.
- Enhances signal vs. background discrimination but is significantly weaker than the S2 BDT.



^{37}Ar L-Shell



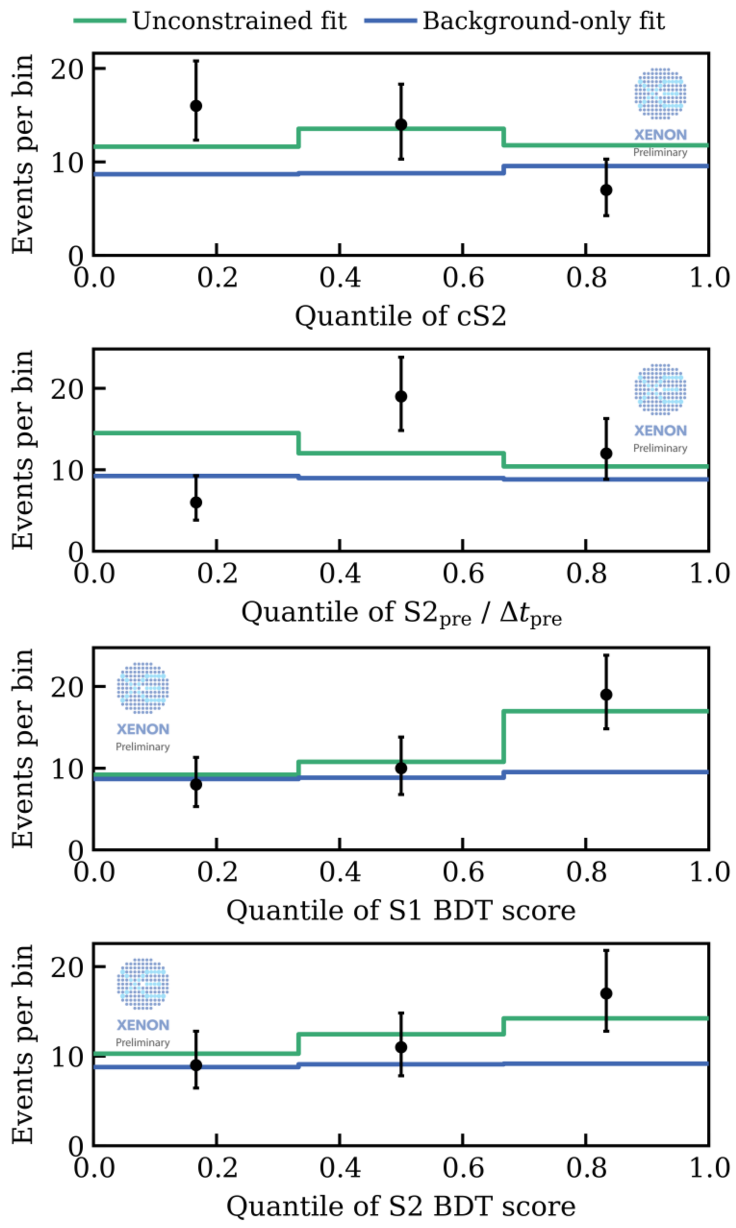




- Light yield from 0.27 keV ER signal in ^{37}Ar SR0 calibration.
- Comparison with B8 analysis:
  - Similarity: expected signal predicts 2-3 S1 hits and dominated by AC background.
  - Difference: high statistics.
- Very good agreement: four-dimensional GOF test p-value of 0.92.

GOF Test

- Mostly good agreement with signal+bkg fit.
- Perform 4 x 1D goodness of fit tests (95% CL), 4 p-values with threshold: 0.0127
- Quantile of S2/Δt → p-value: 0.008
- Detailed inspections of both the individual events in the dataset and the AC sideband data indicate no mismodeling.
- Excluding S2/Δt from the statistical analysis would result in a statistical significance of 3.22 σ.



Power-Constrained Limits (PCL)

- Standard business: report an upper limit (UL) on signal strength μ for New Physics. Downward fluctuations and mismodeling (e.g., overestimated bkg rates) can lead to very low ULs.

- **Issue**: when the chance of rejecting a small signal hypothesis is nearly the same whether it is true or the bkg-only hypothesis is true → lack meaningful discrimination between the signal + bkg and bkg-only hypotheses.

- **Goal**: only exclude the parameter space that the detector is sensitive to.

- **Error in White Paper** (1): mistakenly defined PCL based on discovery power (probability to reject $\mu = 0$ if the true signal strength is μ) instead of rejection power (probability to reject μ if the true signal strength is μ). This caused an absence of a common standard.

- **Conventions to date**:
  - LZ & PandaX-4T: rejection power which corresponds to -1σ of the quantile of the sensitivity band.
  - XENONnT: rejection power which corresponds to median of the sensitivity band

- New recommendations are needed, intercollaboration discussion is ongoing.

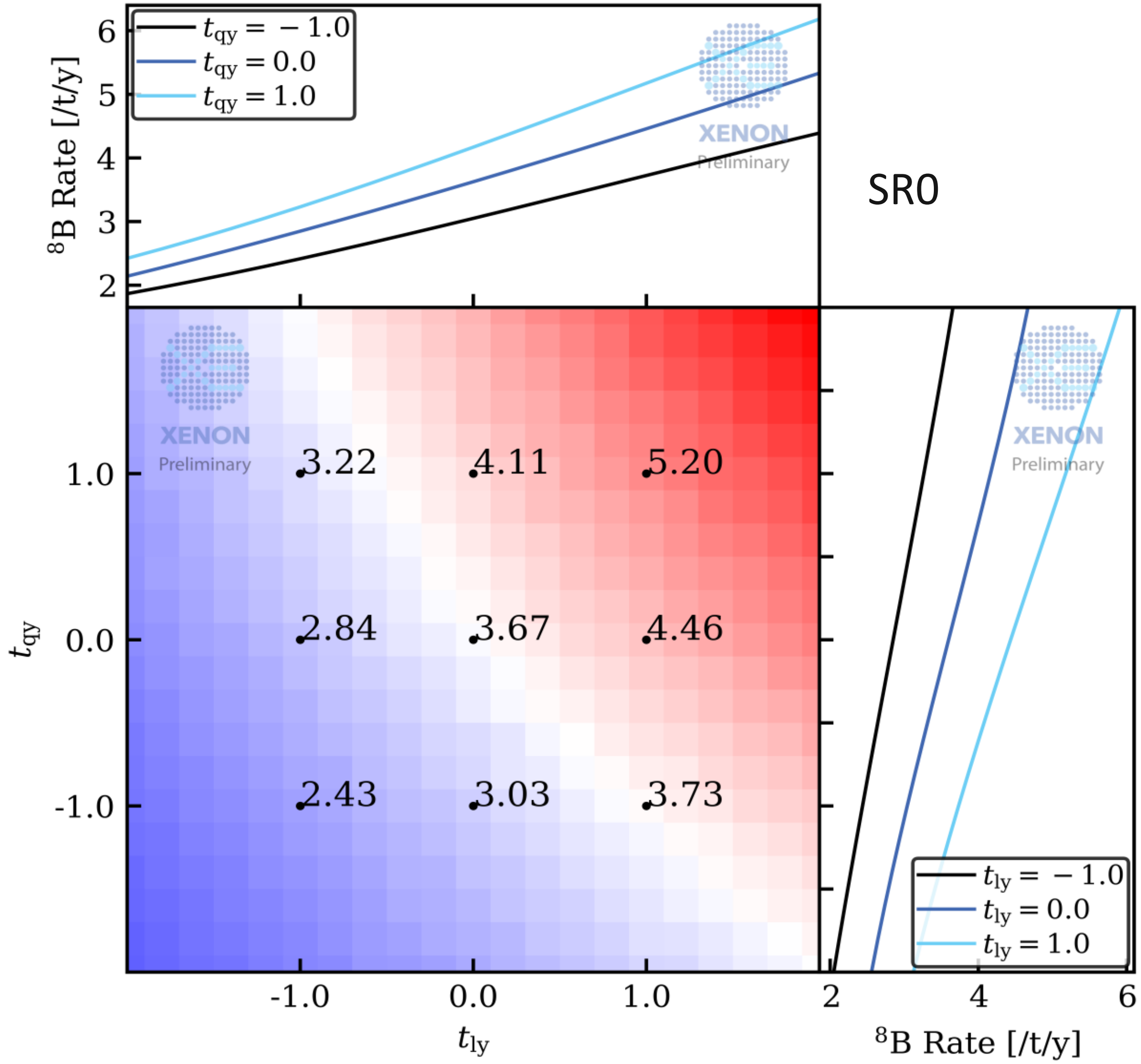
(1) Eur. Phys. J. C 81, 907 (2021), 2105.00599

Yield Uncertainty of Signal

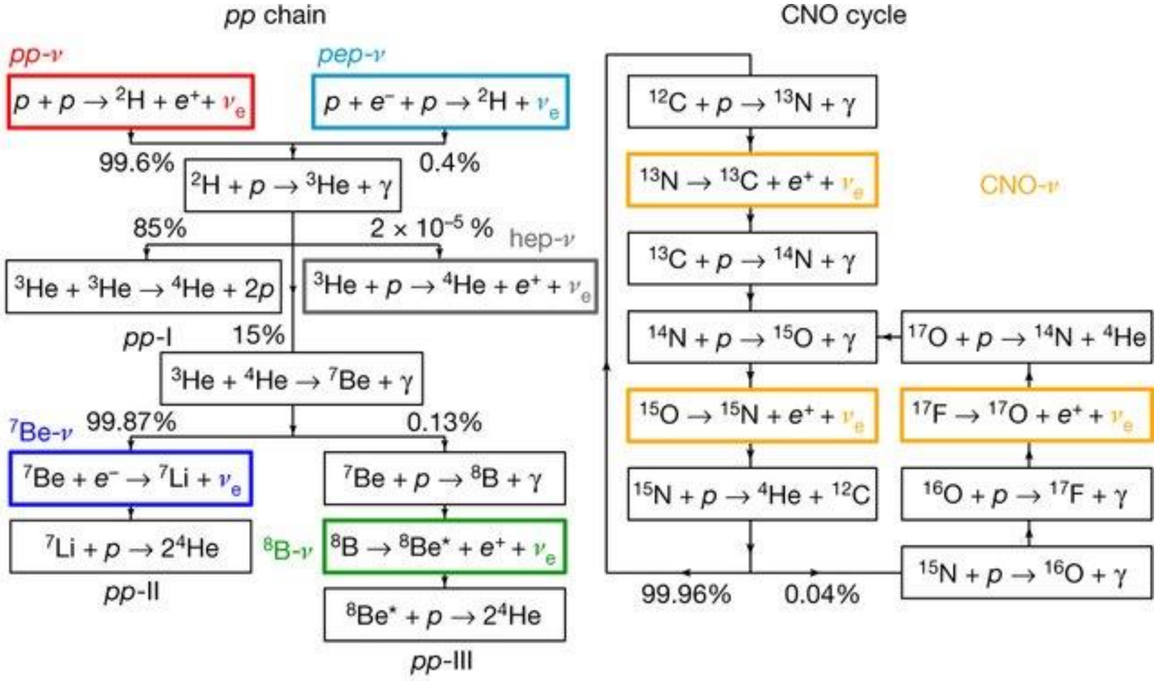
(t_{ly}, t_{qy}) two morphers of the yields: uncertainties of the emission model

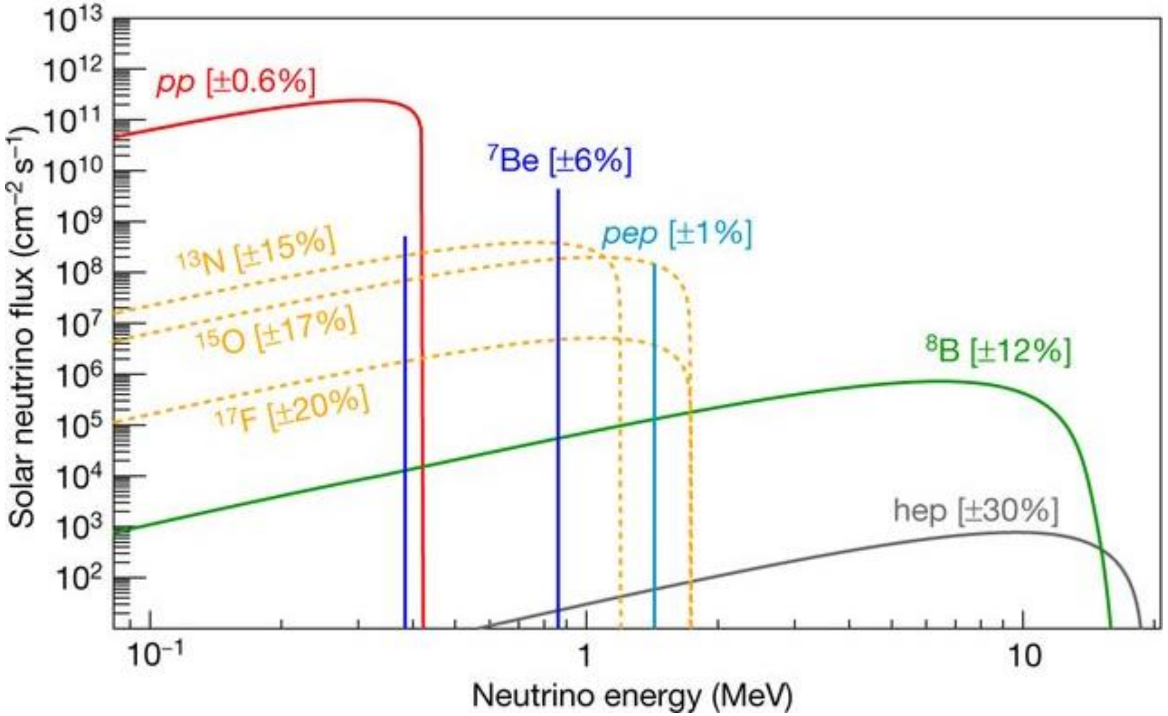
$$LY(t_{ly}) = \langle LY \rangle + t_{ly} \cdot \sigma_{LY}(\text{sign}(t_{ly}))$$
$$QY(t_{qy}) = \langle QY \rangle + t_{qy} \cdot \sigma_{QY}(\text{sign}(t_{qy}))$$

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



Solar Neutrinos

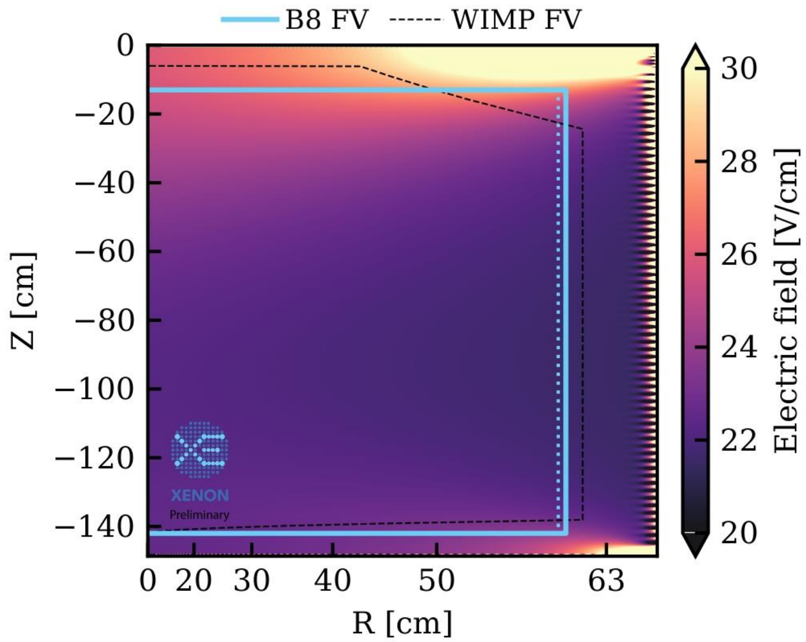




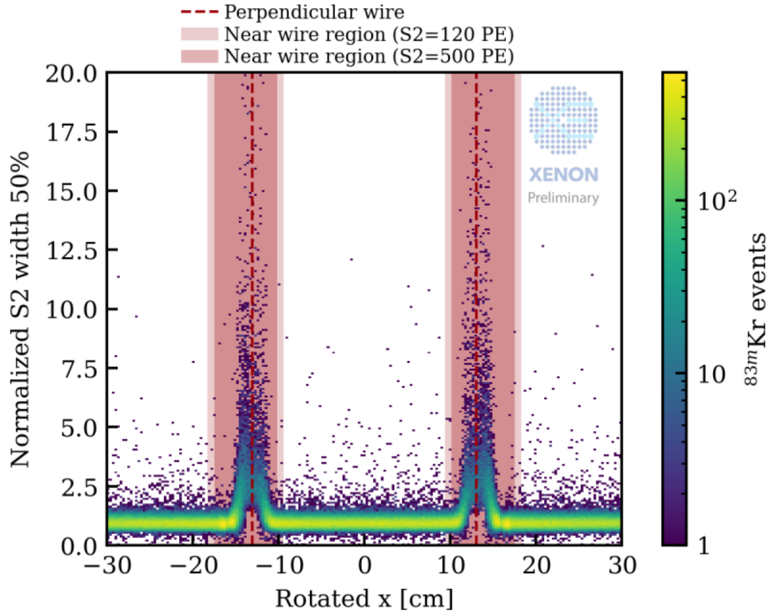
BOREXINO: Nature 562 (2018) 7728, 505-510

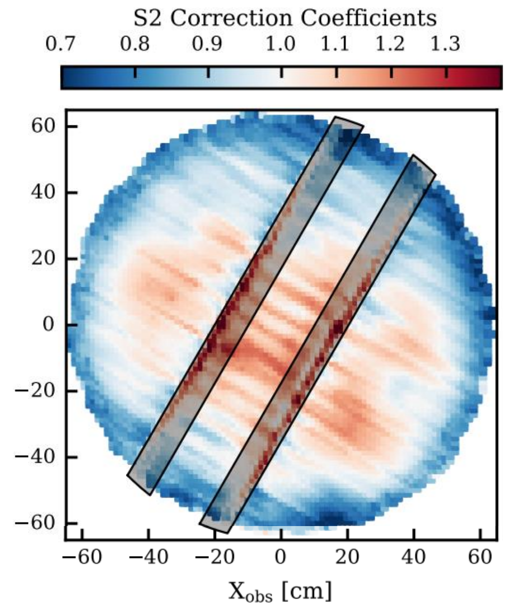
Fiducial Volume (FV)

- 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.



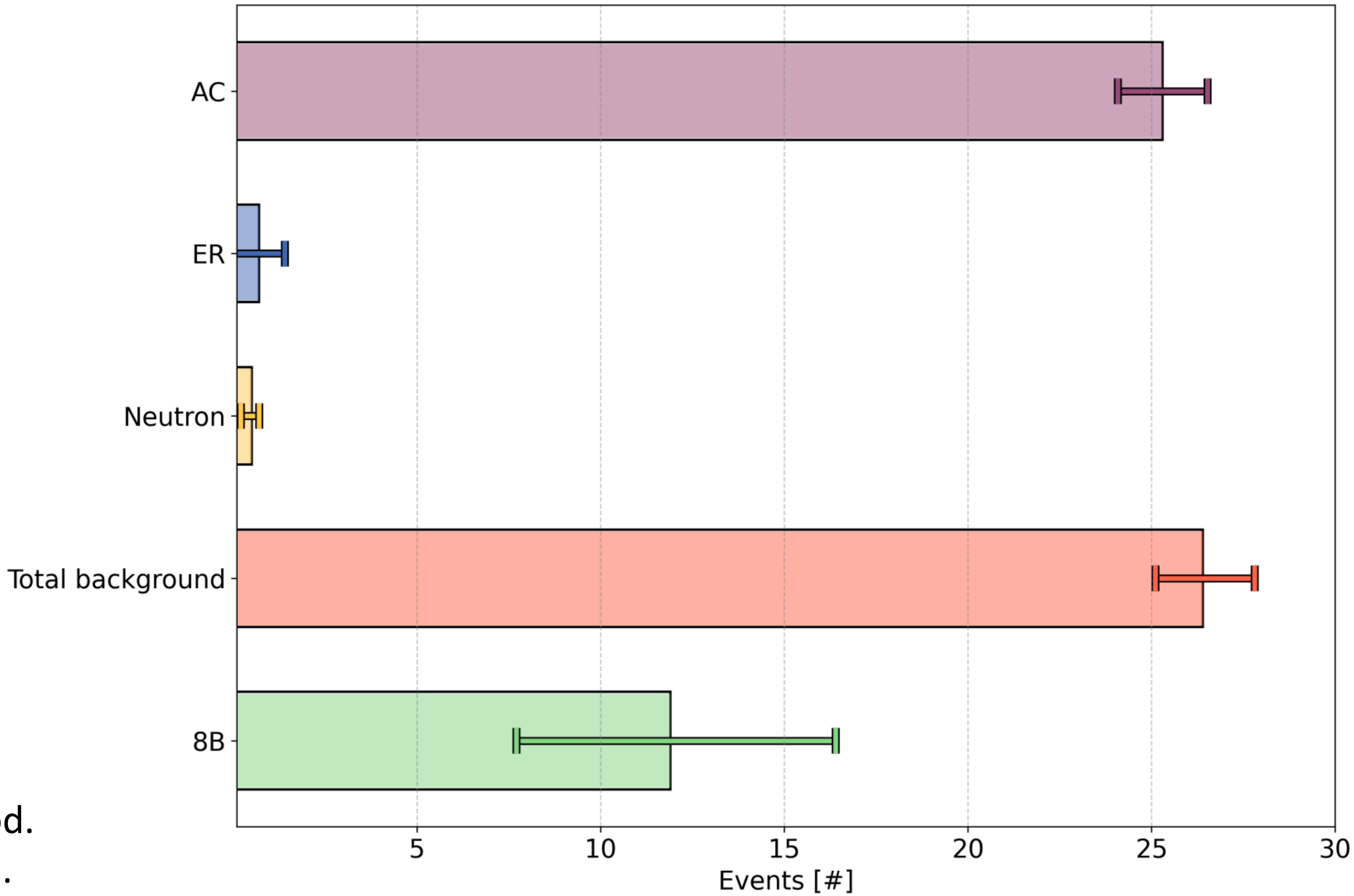
- Events near wires are excluded from analysis due to insufficient simulation fidelity.
- S2 pulse shape varies near perpendicular wires, causing systematic errors if S2 BDT (trained on simulation) is applied.





Signal & Background Prediction

- **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.



IMPRS for Precision Tests of Fundamental Symmetries
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XENON

Components Expectation and Best-fit

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