First Search for Light Dark Matter in the Neutrino Fog with XENONnT

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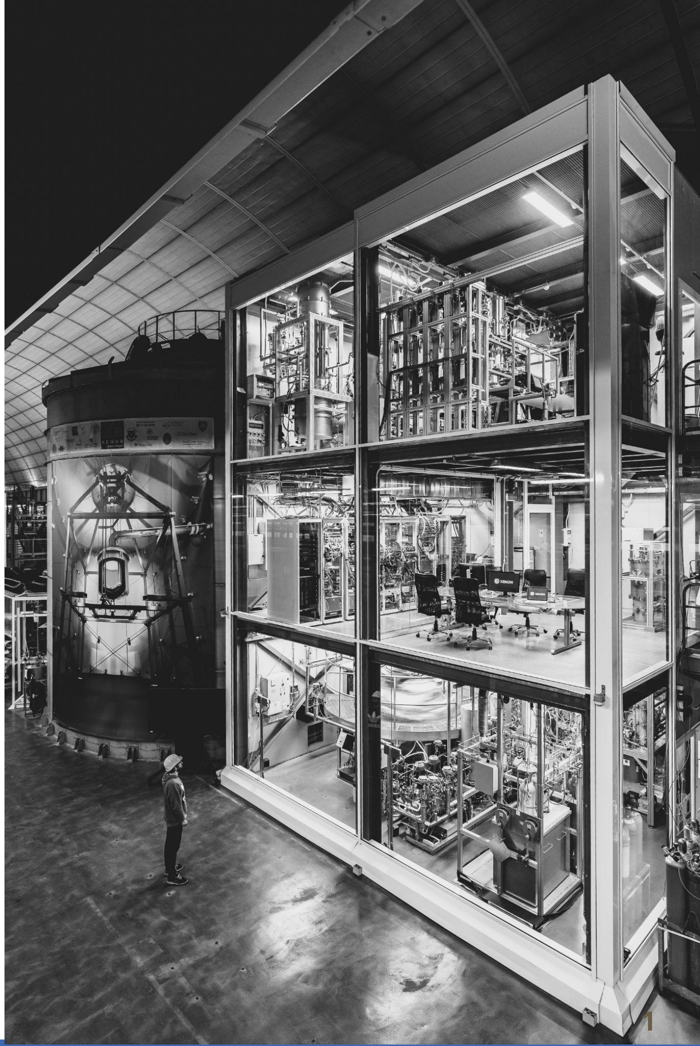
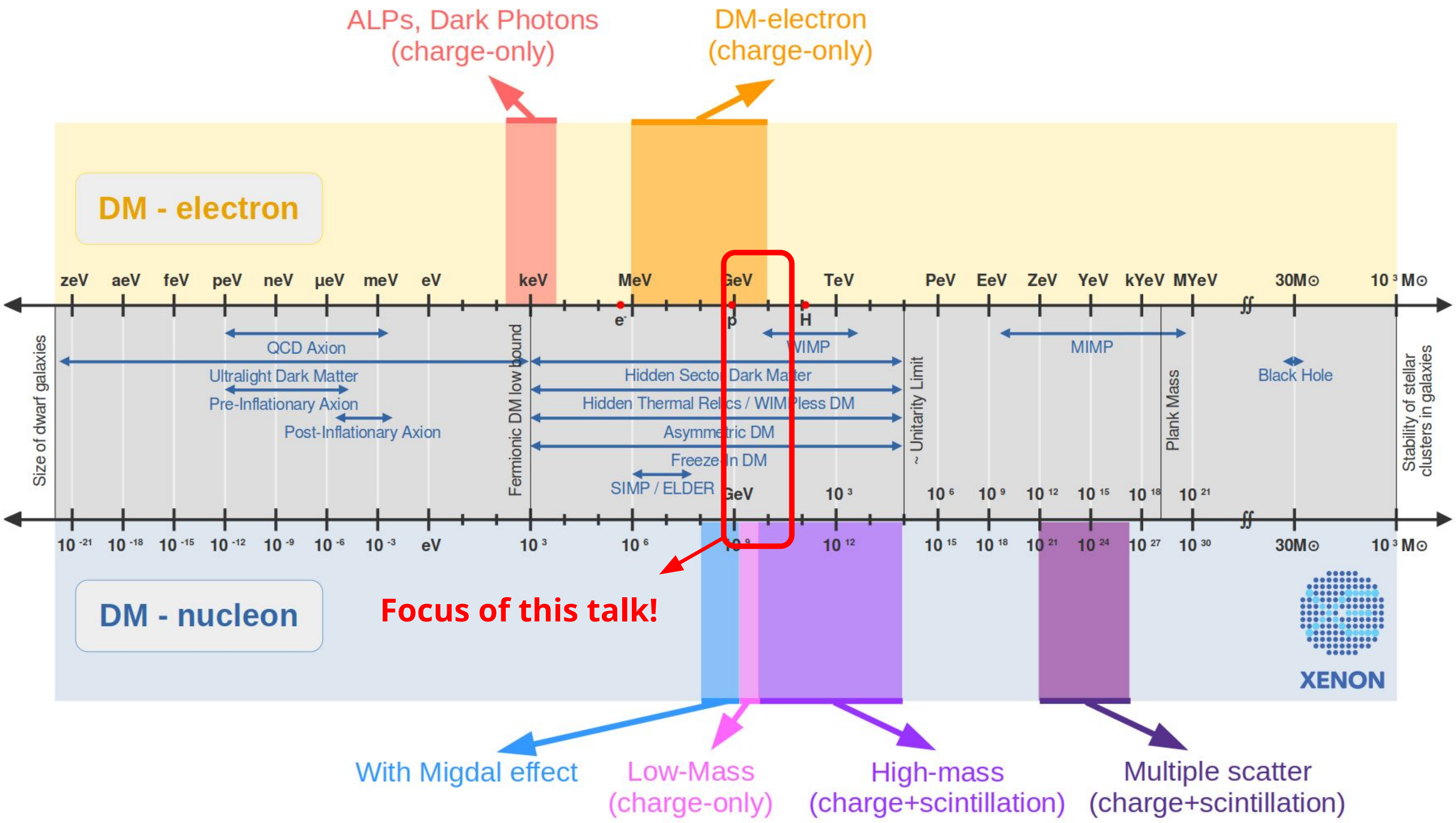
Shenyang Shi
Columbia University in the City of New York
On behalf of the XENON Collaboration
TAUP 2025



Dark matter search landscape



Neutrino fog

Solar neutrino: An “irreducible” background for DM discovery:

- Solar ^{8}B neutrino coherent elastic neutrino-nucleus scattering (**CEvNS**).
- A ~5.5 GeV/c^2 (σ_χ~4.4e-45 cm^2) halo dark matter (**DM**).

CEvNS and DM share very similar differential recoil energy spectrum.

DM sensitivity improves slower with more exposure:

$$\frac{S}{\sqrt{B}} \sim \frac{\sigma_\chi T}{\sqrt{\sigma_\nu T}} \sim \frac{1}{\sqrt{T}}$$

Some intuition: Maximum E_R

DM:

$$E_R^{max} = \frac{2\mu^2 v^2}{m_N}$$

CEvNS:

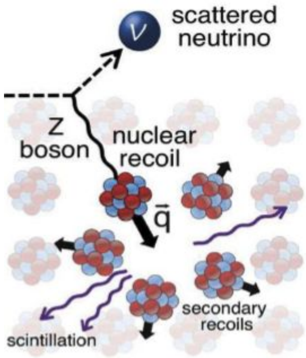
$$E_R^{max} \simeq \frac{2E_\mu^2}{m_N}$$

Equating: $m_\chi \approx \dfrac{E_\mu}{v}$

- Solar ^{8}B neutrino E_μ~ 5-10 MeV
- DM m_χ ~ 5-10 GeV, halo v ~ 1e-3c

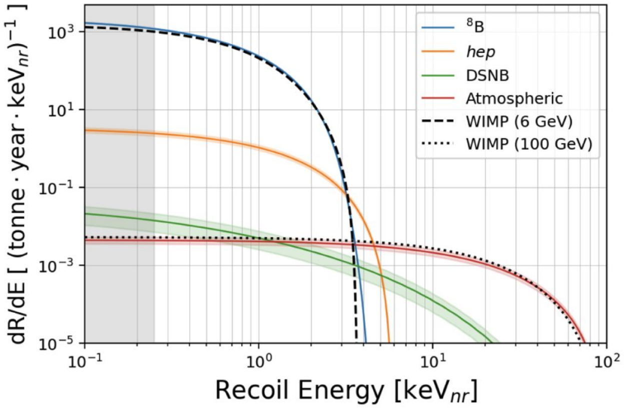
creates similar nuclear recoils.

CEvNS process

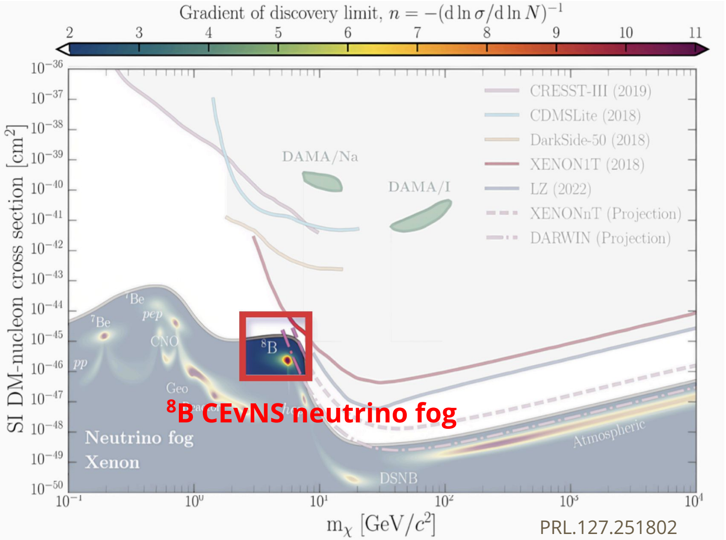


D. Akimov et al, Science, 2017

DM/CEvNS dR/dE



PRD 108, 022007



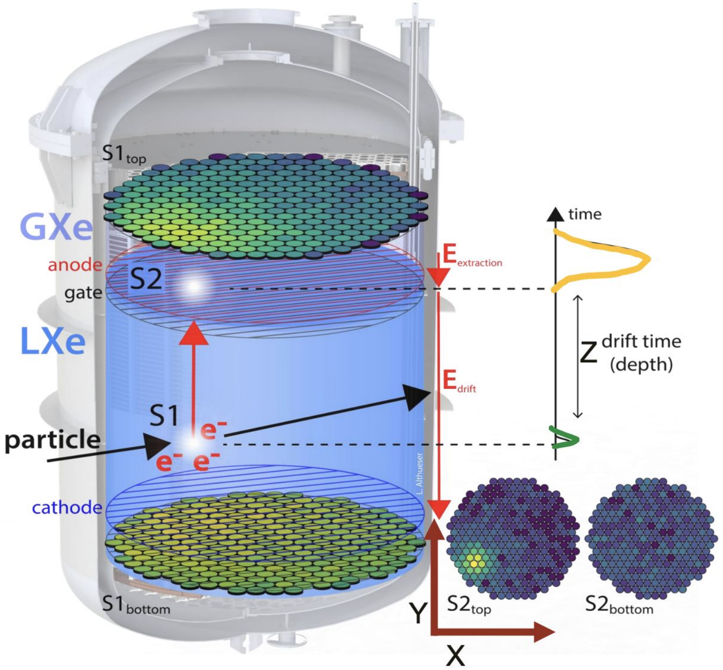
PRL.127.251802

Reach to the neutrino fog

DM search near the neutrino fog in XENONnT faces three major challenges:

- **Solar neutrino background**
  - Solar ^{8}B neutrino **~ 300 recoils/(tonne*year) in [0.5, 5] keV$_{NR}$.**
- **Low nuclear recoil energy**
  - ~ 5 photons and 6 ionizating electrons / keV$_{NR}$.
  - Light collection efficiency ~ 15%, extraction efficiency ~ 50%.
  - **Detection efficiency ~1%, ^{8}B CEvNS -> 3 events/(tonne*year).**
  - Dedicated yield calibrations (***See Shengchao's talk on 8/28 on YBe calibration***) and large exposure needed.
- **High detector background level**
  - Accidental coincidence (AC) background.
  - Advanced background suppression techniques needed.

XENONnT dual-phase liquid xenon Time Projection Chamber (TPC)

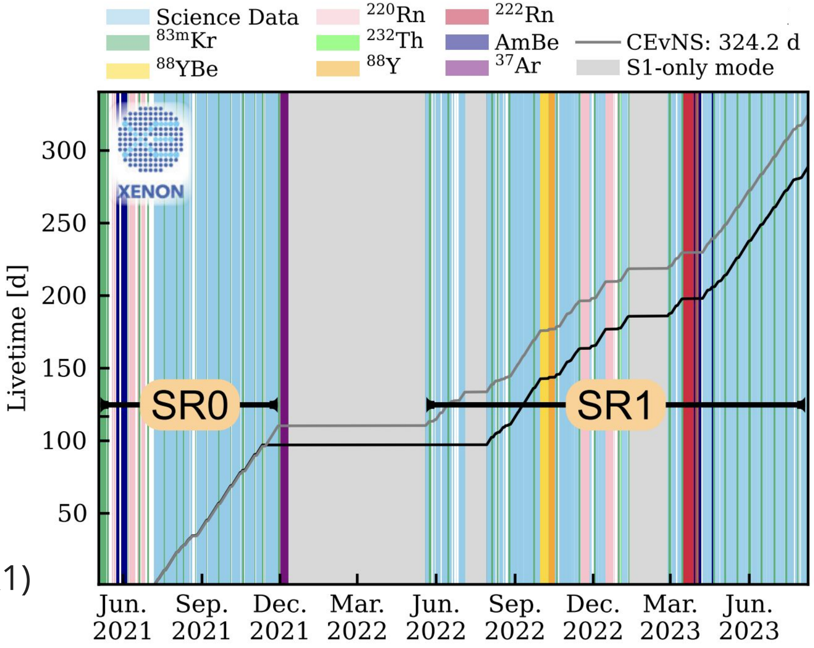


Drift Length	Diameter	Sensitive Target	Drift Field
1.5 m	1.32 m	5.9 tonne	23 V/cm

Exposure

- **Data taking**
  - May 1, 2021 - December 10, 2021 (SR0, 108.1 days)
  - May 19, 2022 - August 8, 2023 (SR1, 208.5 days)
- **Total exposure: ~ 3.51 tonne*year**
- **Stable detector condition**
  - < 1% (<3%) light (charge) yield variation
- **High liquid xenon purity**
  - Electron lifetime ~ 20 ms
- **Regular calibrations**
  - g1: 0.1515 ± 0.0014 PE/ph (SR0) & 0.1367 ± 0.0010 PE/ph (SR1)
  - g2: 16.45 ± 0.64 PE/e (SR0) & 16.85 ± 0.46 PE/e (SR1)

Science data in ROI was blinded

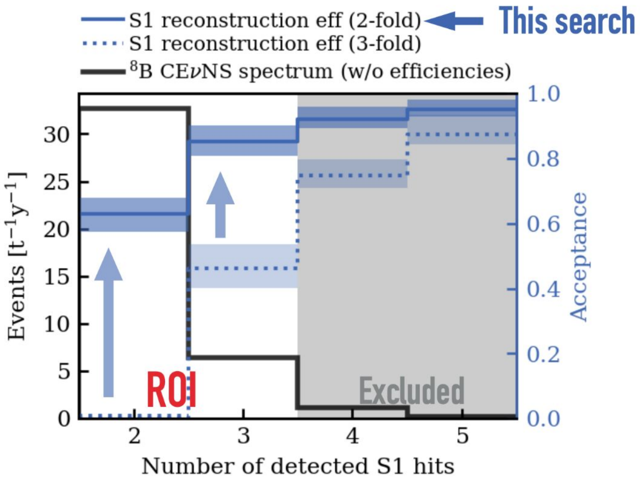


Signal efficiency

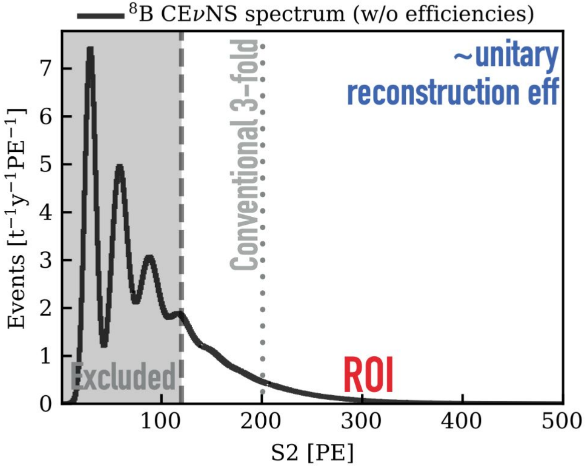
Energy threshold is the major efficiency loss mechanism!

- **S1: 2 or 3** detected photons; **S2:** [120, 500] PEs ~ [8, 33] ionized electrons.
- Heavy WIMP analysis: S1 >= 3 detected photons; S2 >= 200 PE.
- Region of interest optimized by signal to background ratio.
- Gain **17 times higher DM/CEvNS acceptance** than heavier WIMP analysis.

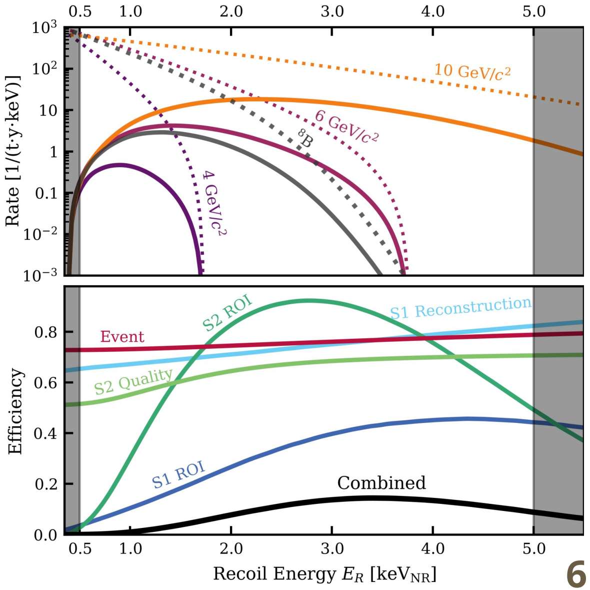
S1 efficiency vs CEvNS spectrum



S2 range vs CEvNS spectrum



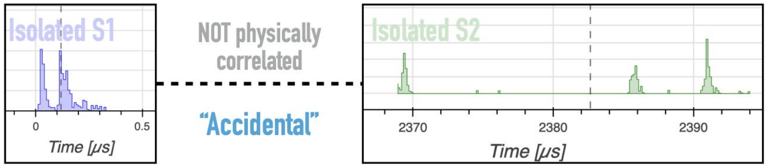
DM spectrum after efficiency
Efficiency decomposition



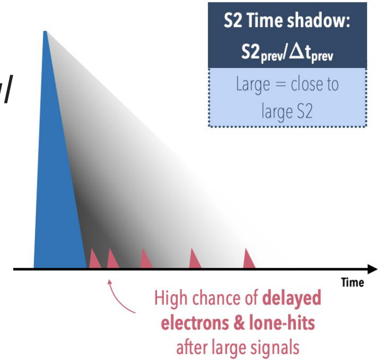
Accidental coincidences

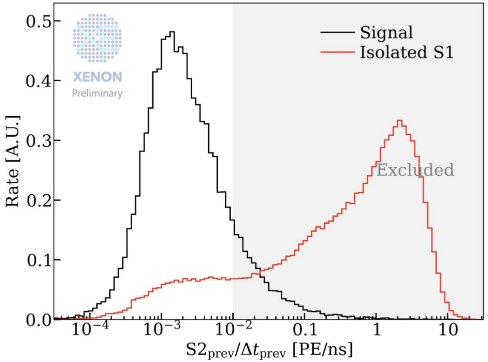
- **Origin:**
  - Random pairing of isolated S1s and isolated S2s.
  - Hypothesized isolated peaks origin: *Induced by high-energy events, single photon/electron accidental pile-ups, gas and cathode events.*
- **Suppression:**
  - Space and time correlation to previous high-energy events.
  - **Correlation score used in inference.**
- **Rate:**
  - Before mitigation:
    - Isolated S1 15 Hz / Isolated S2 150 mHz
  - After mitigation:
    - Isolated S1 2.3 Hz / Isolated S2 18 mHz

AC origin

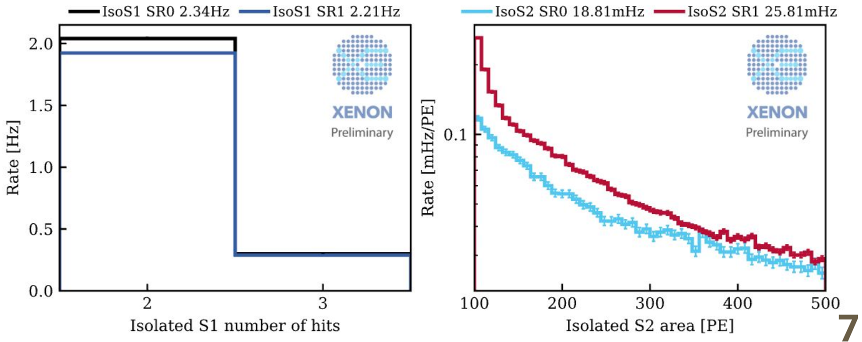


AC suppression via correlation





AC spectrum

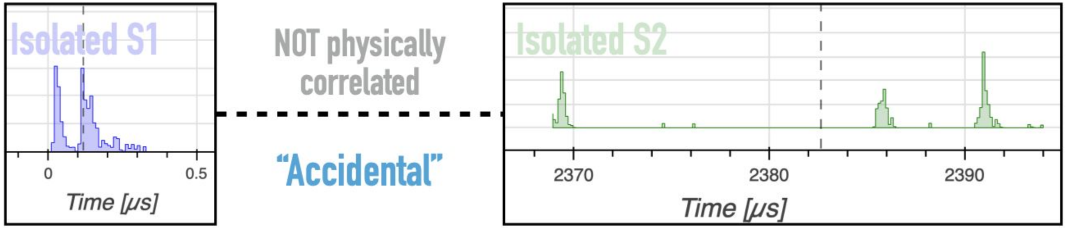


Machine learning AC background suppression

S1 and S2 features can distinguish signal and background using Boosted Decision Tree (BDT).

- **S1 BDT:**
  - Signal: Narrower S1 width, double-photoelectron (DPE) effect.
  - AC: Wider S1 width, no DPE effect.
- **S2 BDT:**
  - Signal: Deeper event ~ wider S2, due to electron diffusion.
  - AC: S2 width uncorrelated with event depth.
- **Both BDT scores are used in the inference.**

An AC waveform example



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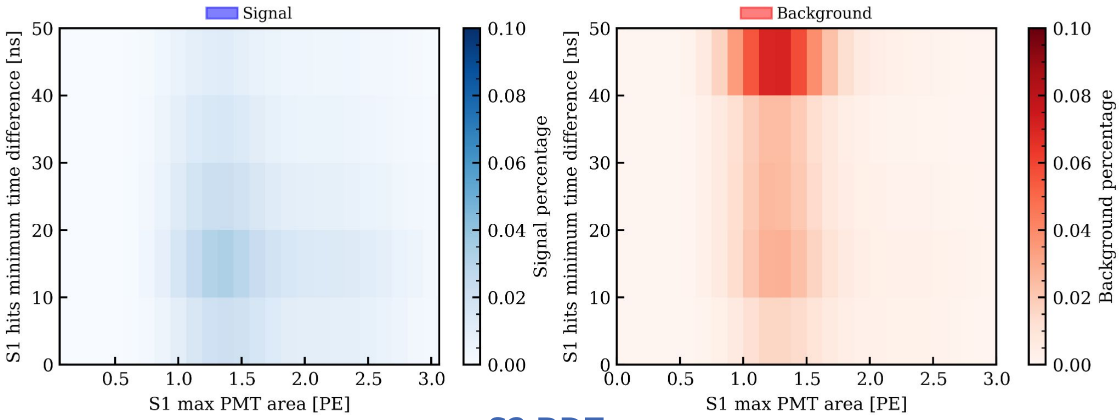
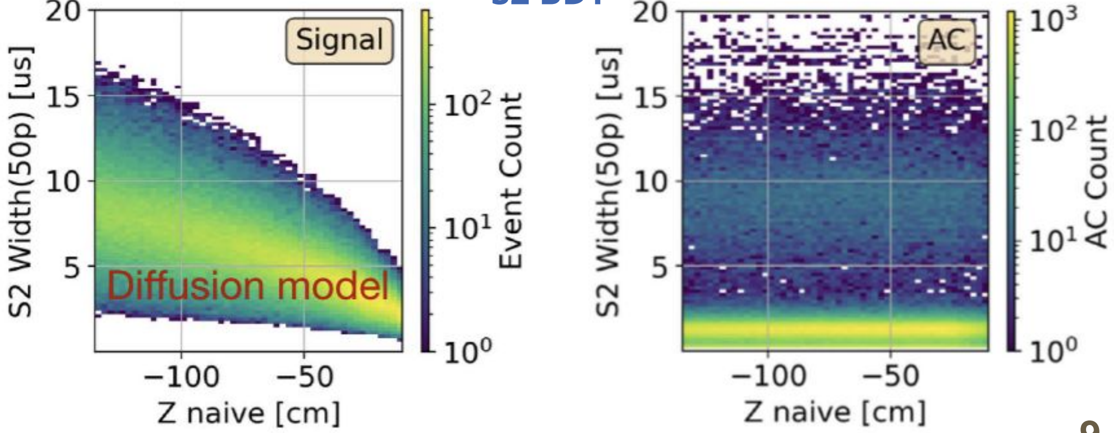
S1 BDT

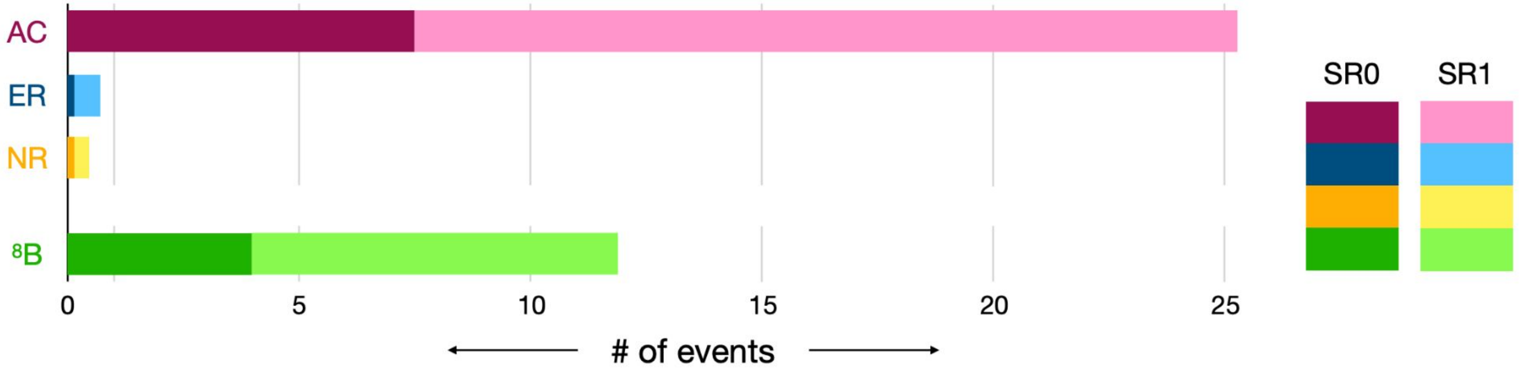


S2 BDT



Background summary

Background dominated by AC and ^{8}B neutrinos!



AC: Accidental Coincidence Background

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

ER: Electronic Recoil Background

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

NR: Nuclear Recoil Background

- Full-chain simulated
- 58% uncertainty from sideband

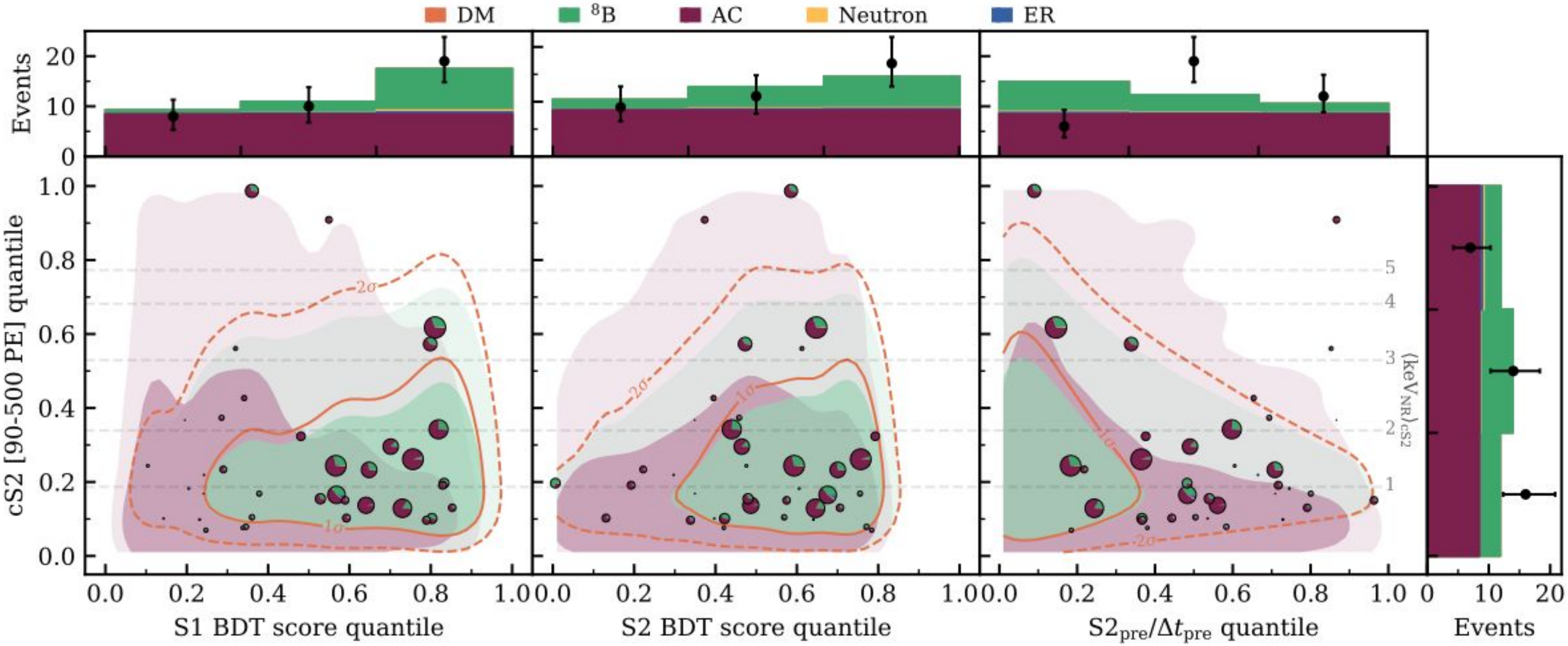
^{8}B: CEvNS Signal

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

Unblinded Events

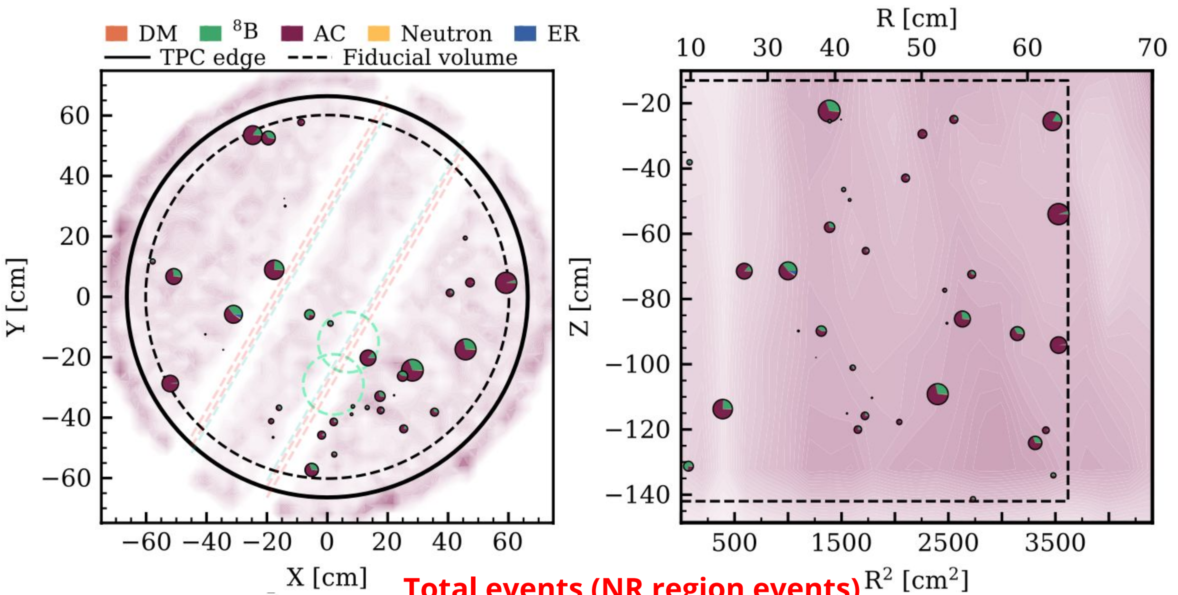
Unblinded events distribution on analysis dimensions.

Expected **38** events, observed **37** events.



Unblinded Events

- No excess above 3σ was observed for any DM mass in [3, 12] GeV/c^2.
- **Solar ^{8}B CEvNS is the most dominant background in the signal-like region!**

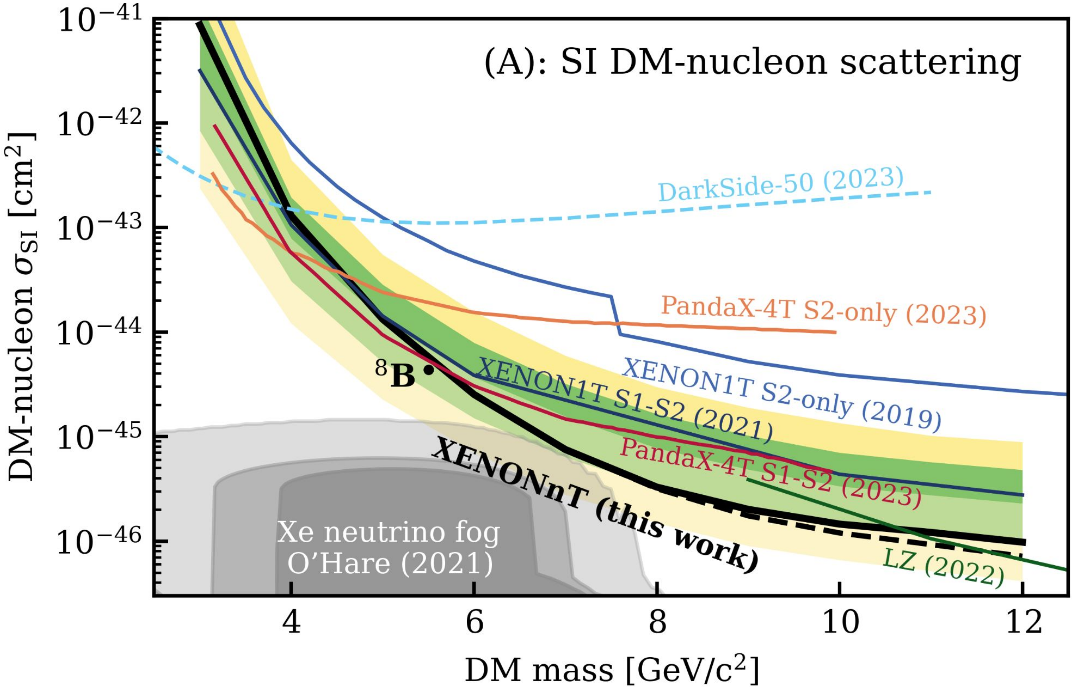


Total events (NR region events)

Component	Expectation	Background only	4 GeV/c^2		6 GeV/c^2		10 GeV/c^2	
SI-DM	⋯	⋯	3.2	(1.6)	0.0	(0.0)	0.0	(0.0)
^{8}B CEνNS	$11.9^{+4.5}_{-4.2}$	$11.4^{+2.0}_{-3.6}$	10.2 ± 2.7	(2.5 ± 0.7)	$11.4^{+2.7}_{-2.6}$	(6.0 ± 1.4)	$11.4^{+2.7}_{-2.6}$	$(5.4^{+1.3}_{-1.2})$
AC	25.3 ± 1.2	$25.3^{+1.1}_{-1.3}$	25.1 ± 1.2	(3.7 ± 0.1)	25.3 ± 1.2	(4.1 ± 0.2)	25.3 ± 1.2	(3.3 ± 0.1)
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$	$0.6^{+0.7}_{-0.6}$	(0.0 ± 0.0)	$0.5^{+0.6}_{-0.5}$	(0.3 ± 0.3)	$0.5^{+0.7}_{-0.5}$	$(0.4^{+0.5}_{-0.4})$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3	0.5 ± 0.3	(0.1 ± 0.1)	0.5 ± 0.3	(0.2 ± 0.1)	0.5 ± 0.3	(0.2 ± 0.1)
Total background	$38.3^{+4.7}_{-4.4}$	$37.7^{+2.5}_{-3.9}$	$36.4^{+3.0}_{-3.0}$	$(6.3^{+0.7}_{-0.7})$	$37.7^{+3.0}_{-2.9}$	$(10.6^{+1.5}_{-1.4})$	$37.7^{+3.0}_{-2.9}$	$(9.2^{+1.4}_{-1.3})$
Observed	⋯	37	37	(10)	37	(10)	37	(4)

Dark matter limit

- Excludes spin-independent DM-nucleon cross sections > 2.5e−45 cm^2 at 90% confidence level for a 6 GeV/c^2 DM.
- DM sensitivity and limit approach the "neutrino fog".
- However there is still room to improve!
    - Signal model systematics.
    - Background suppression methods and systematic uncertainties.
    - More exposure.
    - New analysis techniques.



Summary

Thank you for your attention!

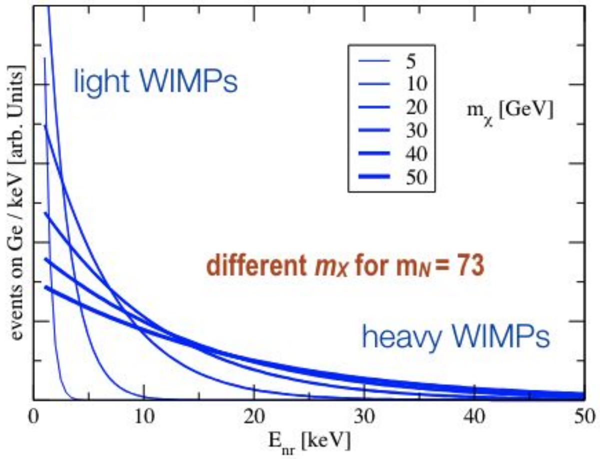
- Please find our paper on:
  - arxiv.2409.17868
  - PRL. 134, 111802.
- <u>Data release</u> including complete likelihood construction available for recasting more interesting physics.
- Further analysis going on in the S2-only channel to place tighter constraints on lighter mass DM and neutrino physics.

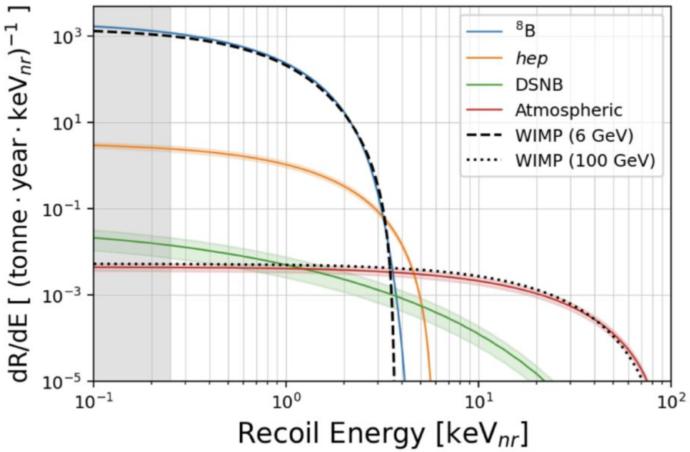
Stay tuned!

Appendix

Light dark matter

- ➔ GeV-scale light dark matter (DM) is well-motivated:
  - ◆ Low-mass WIMPs: Lee-Weinberg bounds ~2-3 GeV/c^2.
  - ◆ Asymmetric DM: Phys. Rev. D 79, 115016 (2009)
  - ◆ Self-interacting DM: Phys. Rev.Lett. 84, 3760 (2000)
  - ◆ Mirror DM: Phys. Lett. B 766 (2017)
- ➔ However the direct detection of GeV DM is challenging:
  - ◆ An “irreducible background” called **neutrino fog**.
  - ◆ **Near the detector energy threshold**. Hard to detect, ~keV recoil energy, < 5 photons/electrons detected; more backgrounds.





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Other DM models