



# Latest results from XENONnT on dark matter search and solar neutrinos

B. Andrieu

XIX International Conference on Interconnections  
between Particle Physics and Cosmology (PPC2026)  
Sydney, Australia



**XENON**

- ◇ XENONnT
- ◇ CE $\nu$ NS
- ◇ S2-only
- ◇ Summary



# XENONnT Collaboration



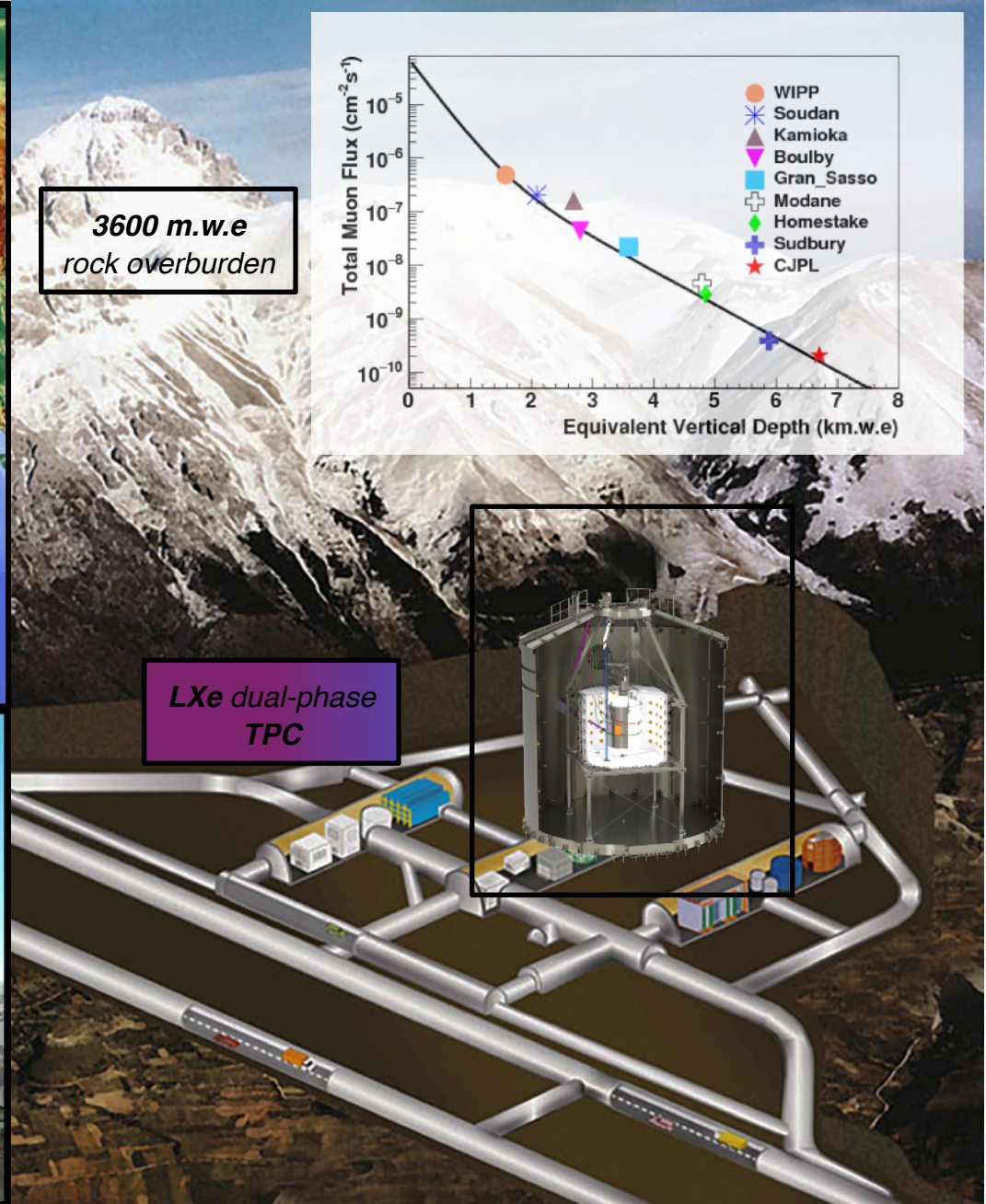
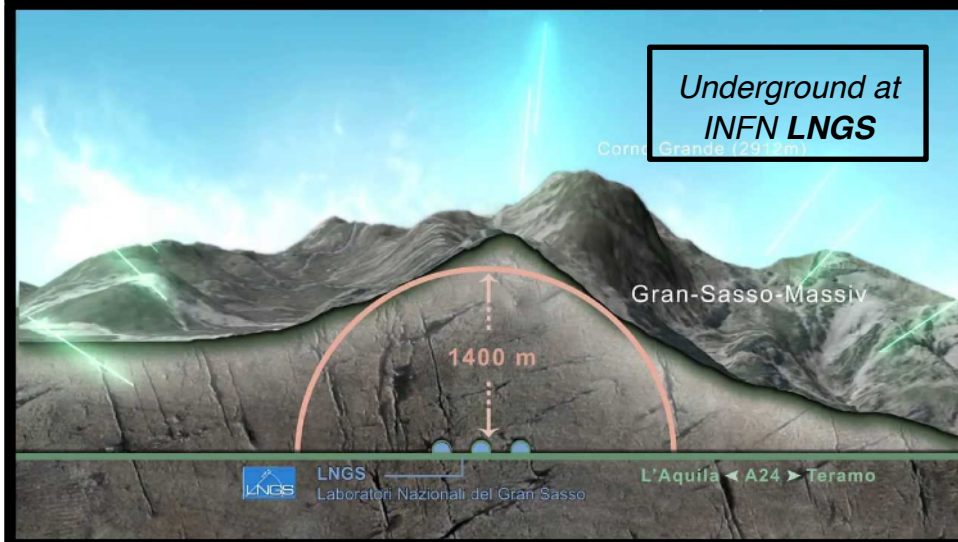
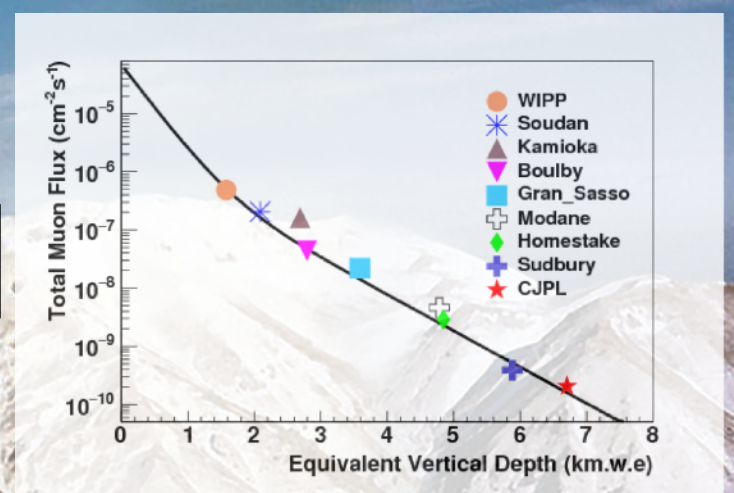
200+ scientists    31 institutions    12 countries



# XENONnT Location



**3600 m.w.e  
rock overburden**





# XENONnT Detector

## 3 Nested Detectors sharing the same DAQ

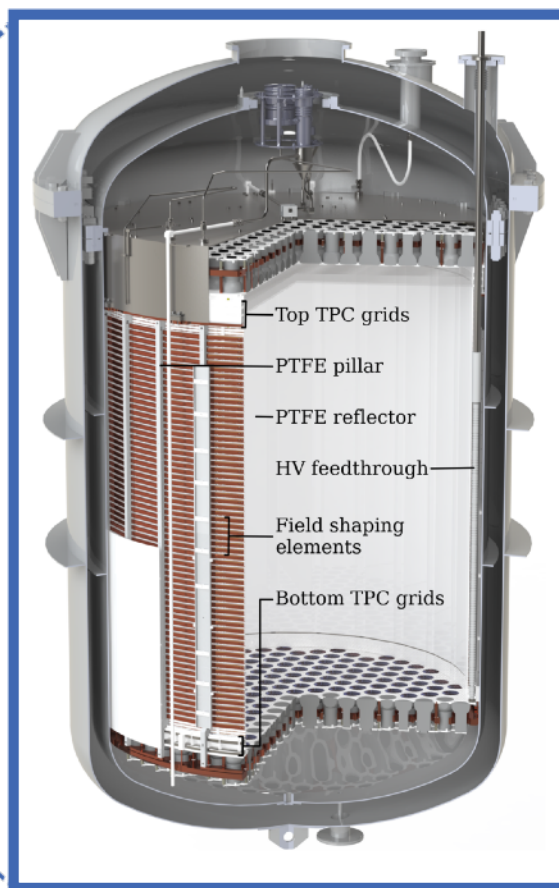
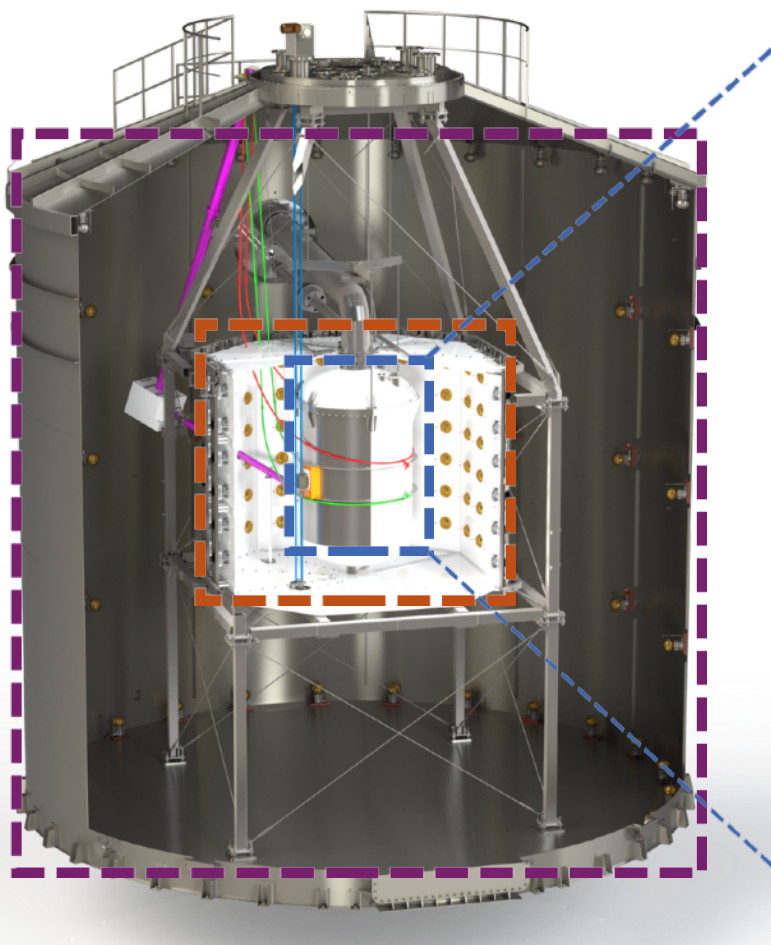
All materials very carefully selected for excellent radio-purity

### Muon and neutron veto (MV & NV):

- MV: JINST 9 P11006, [1406.2374]  
NV: Eur. Phys. J. C 85, 695 (2025), [2412.05264]
- 700 t Gd loaded **water Cherenkov veto detectors**.
- Both passive and active shield **against cosmogenic and radiogenic neutrons**.
- 84 and 120 PMTs covering their surface

### TPC:

- TPC: Eur. Phys. J. C 84, 784 (2024), [2402.10446]
- **LXe Dual phase time-projection chamber**.
- 8.5 t of liquid and gaseous xenon, 5.9 t of active target.
- 494 PMTs divided in two arrays (top and bottom).
- 23 V/cm drift electric field.



### XENON program timeline

XENON10  
2005  
14 kg



XENON100  
2008  
62 kg



XENON1T  
2016  
2 t

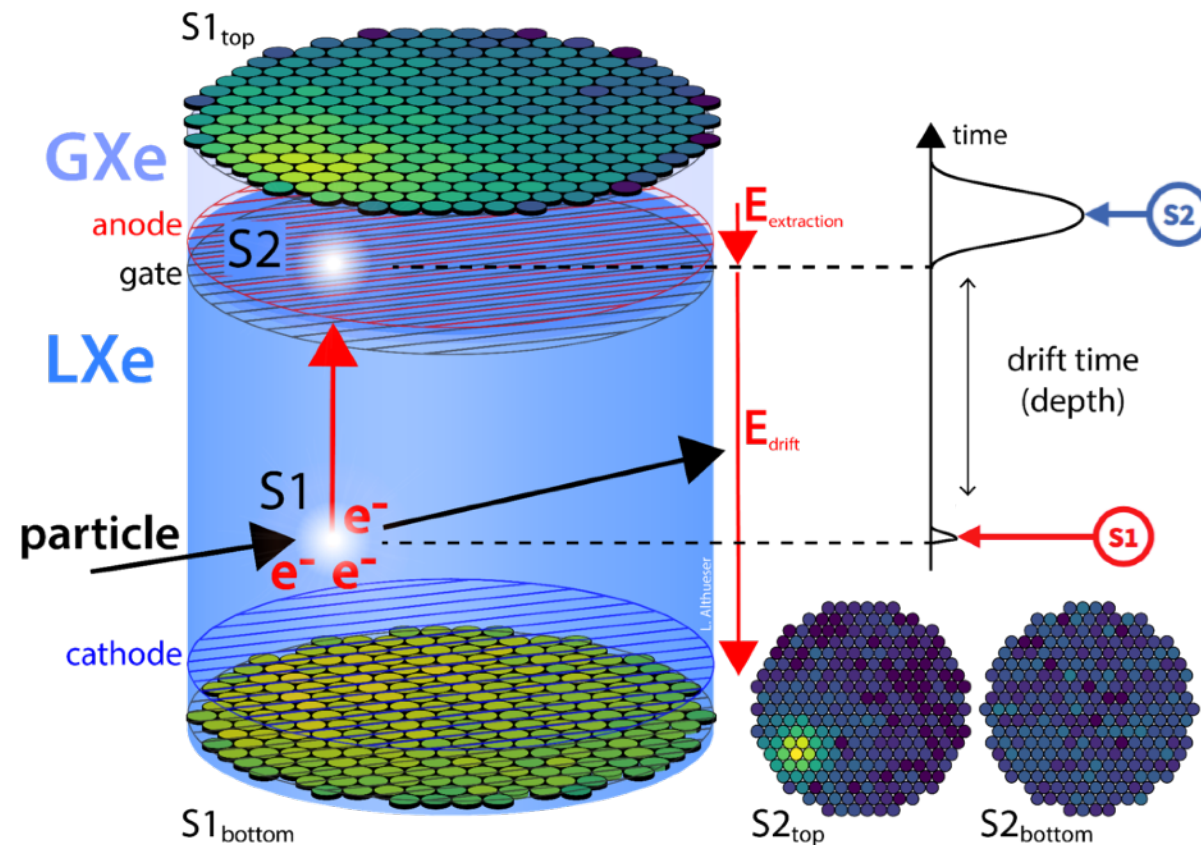


XENONnT  
2020  
6 t

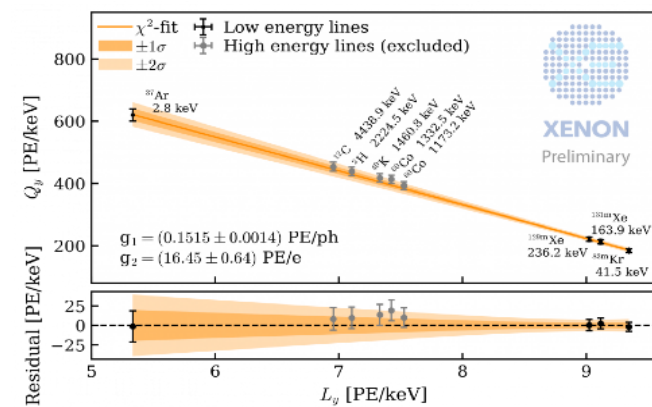




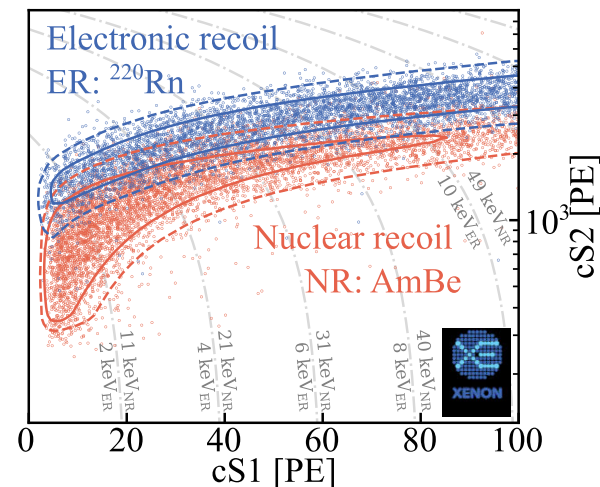
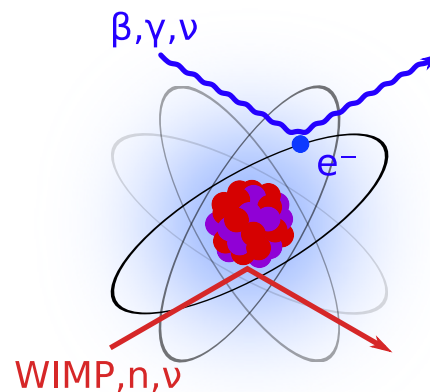
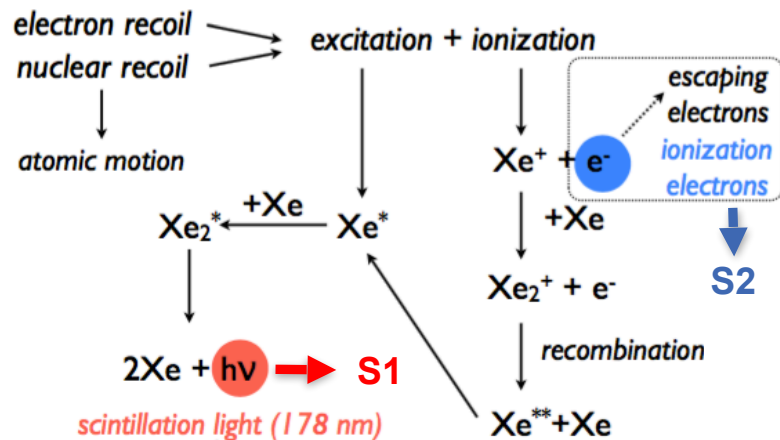
# XENONnT Dual-Phase Xe TPC



- ❖ **S1 Signal:** prompt scintillation photons.
- ❖ **S2 Signal:** secondary scintillation photons from electroluminescence of e- extracted in GXe.
- ❖ **3d vertex reconstruction:**
  - x, y : S2 hit pattern in top PMT array
  - z: drift time (S2-S1)
- ❖ **Energy reconstruction:** from combined **S1** and **S2** signals:  $E = W ((S1/g1) + (S2/g2))$   
(W = mean quantum energy = 13.7 eV,  
g1 (~0.1) & g2 (~15) gain from calibration)



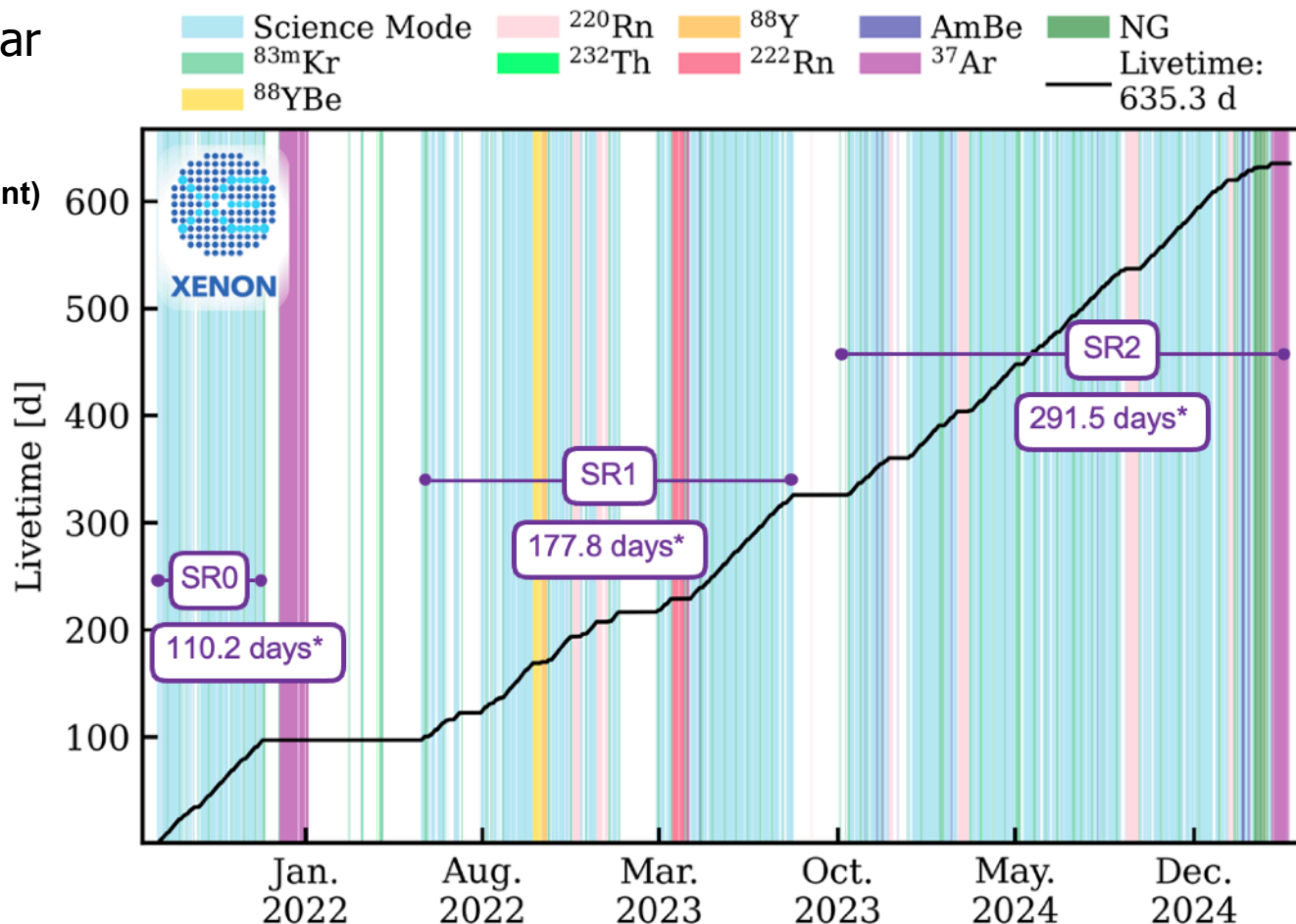
- ❖
- Recoil identification:**
- from
- S2/S1**
- ratio



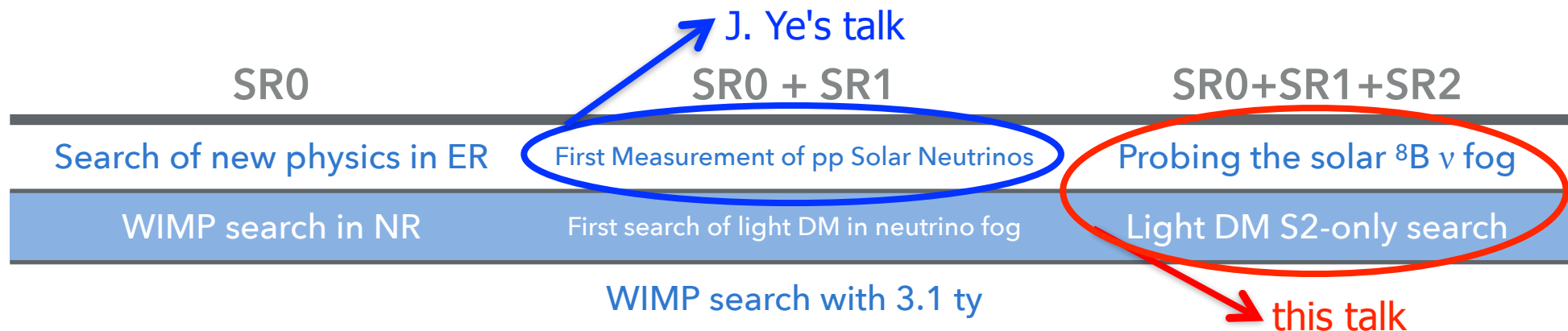
# XENONnT Science Data

SR0+1+2: up to 7.83 Tonne-year

- Fiducial mass of 4-5 tonne (analysis-dependent)
- Three science runs (SR):
  - SR0:  $^{222}\text{Rn}$  activity =  $1.8 \mu\text{Bq/kg}$
  - SR1: Radon Removal System high-flow mode  
 $\rightarrow ^{222}\text{Rn}$  activity =  $0.9 \mu\text{Bq/kg}$ !
  - SR1a:
    - Higher ER rate from  $^{85}\text{Kr}$ ,  $^{37}\text{Ar}$ ,  $^3\text{H}$ .
  - SR1b:
    - Low  $^{85}\text{Kr}$ ,  $^{37}\text{Ar}$  after cryogenic distillation.
    - $^3\text{H}$  still present.
  - SR2: Gd-loaded water (0.02%.)  
 $\rightarrow$  NV tagging efficiency:  $77 \pm 1 \%$   
 $(53 \pm 1 \%$  for SR0-1)

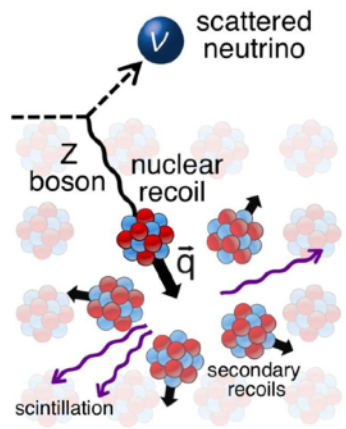


## Science Publications





# Probing the Solar $^8\text{B}$ Neutrino Fog: CEVNS

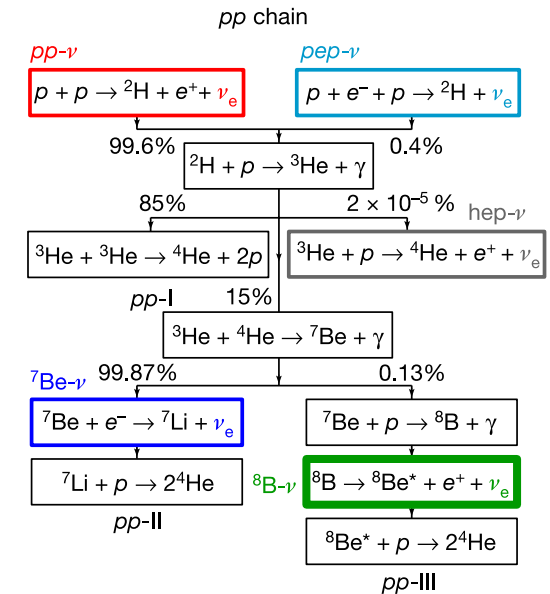


$$\sigma_{CEvNS} \propto N^2$$

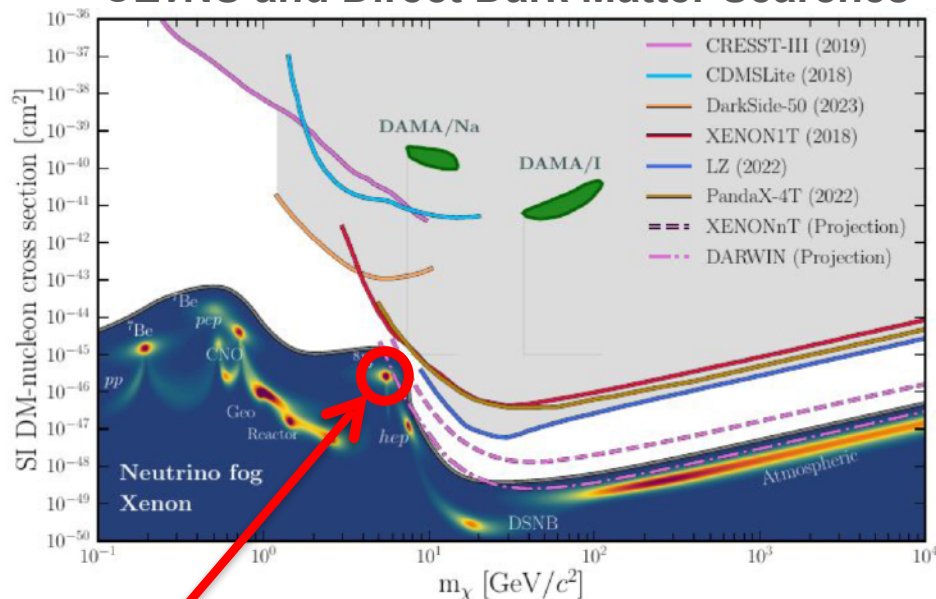
## Coherent Elastic $\nu$ -Nucleus Scattering

- Standard model process predicted in 1974, first measured by COHERENT in 2017.
- Never measured on Xe target or from astrophysical source.
- $^8\text{B}$  Solar  $\nu$  : Expected to have the largest detectable number of CE $\nu$ NS in Xe

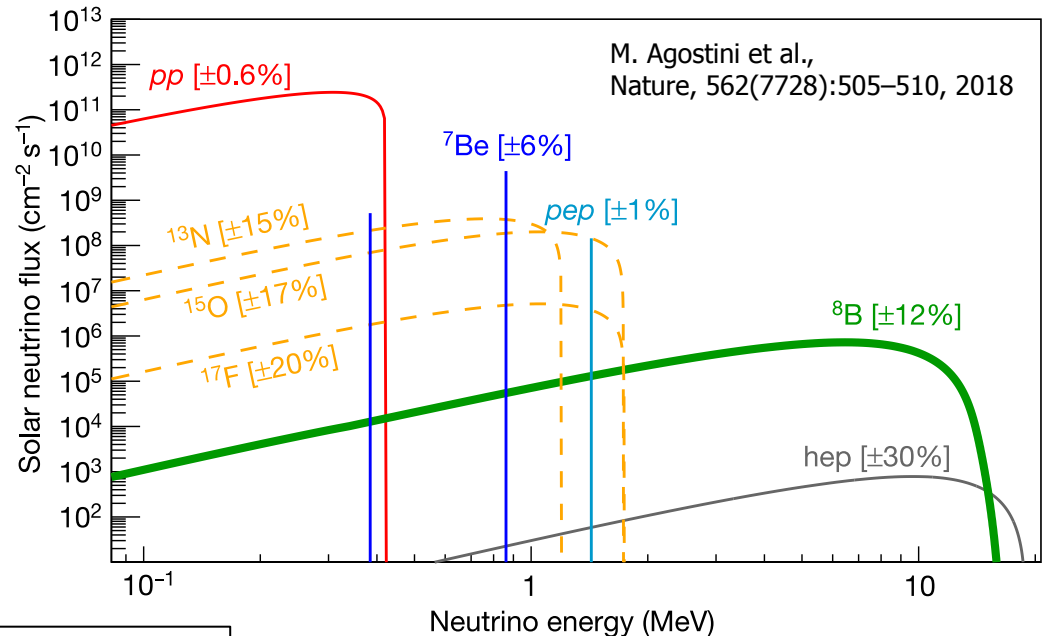
→ V. De Romeri's talk



## CEvNS and Direct Dark Matter Searches



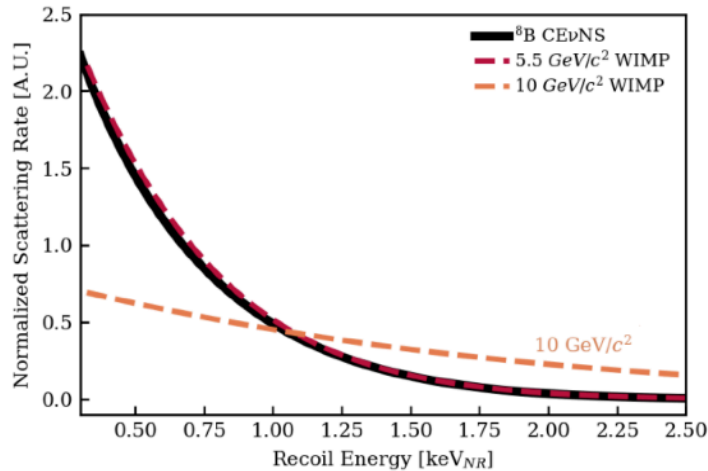
Main background for low-mass WIMP  
Nearly indistinguishable from 5.5 GeV/c<sup>2</sup> WIMP → Neutrino fog!



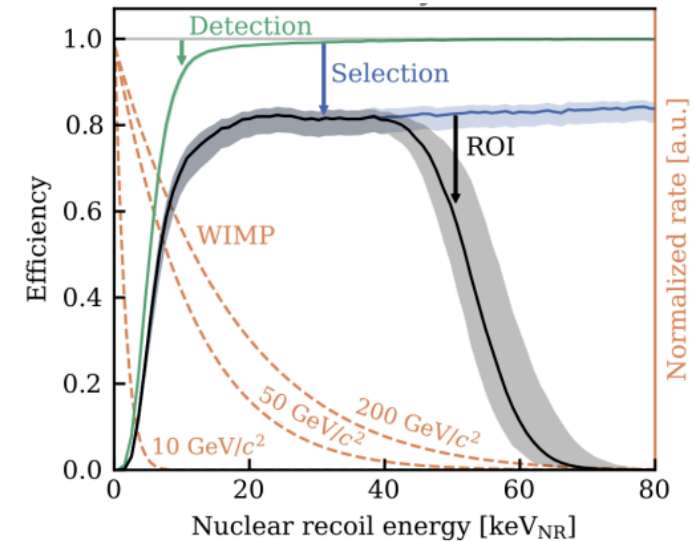
M. Agostini et al.,  
Nature, 562(7728):505–510, 2018

# Probing the Solar $^8\text{B}$ Neutrino Fog: from 3 to 2-fold efficiency

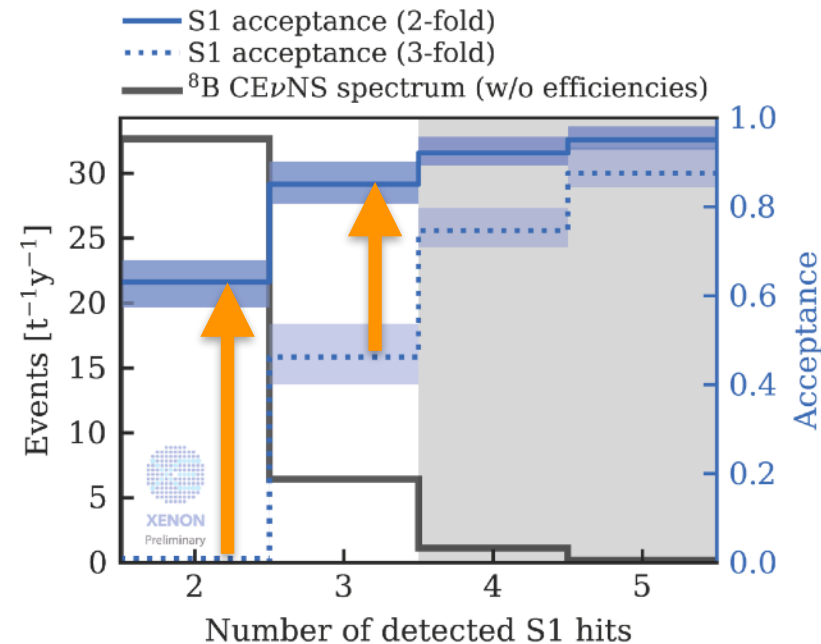
Low energy deposit  
> 90% of detectable recoils below 2.1 keV



Nearly invisible in NR standard analysis that requires 3 or more photons (PMT hits)  
→ detection efficiency ~ 1%!



→ Lower PMT coincidence from **3-fold** (standard NR) to **2-fold** to reach CEvNS sensitivity



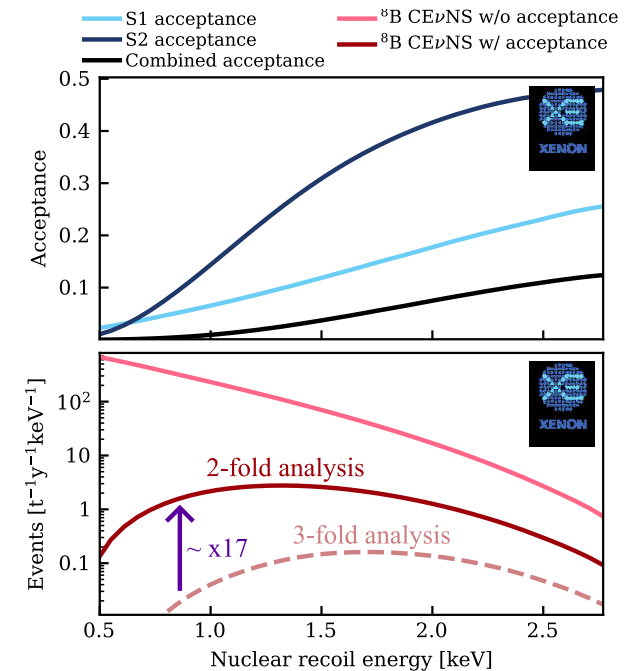
## Event selection

- **S1:** 2 or 3 PMT hits
  - **S2:** [120,500] PE ~ 4-18 e<sup>-</sup>
- **17 x higher CEvNS rate!**  
compared to 3-fold coincidence  
(dashed to solid lines)

## Caution

- **Higher background**
- **Low energy calibration needed**  
→ **Done using  $^{88}\text{YBe}$  source**

Low-energy nuclear recoil calibration of XENONnT with a  $^{88}\text{YBe}$  photoneutron source, *Phys. Rev. D* 113 (2026) 112017





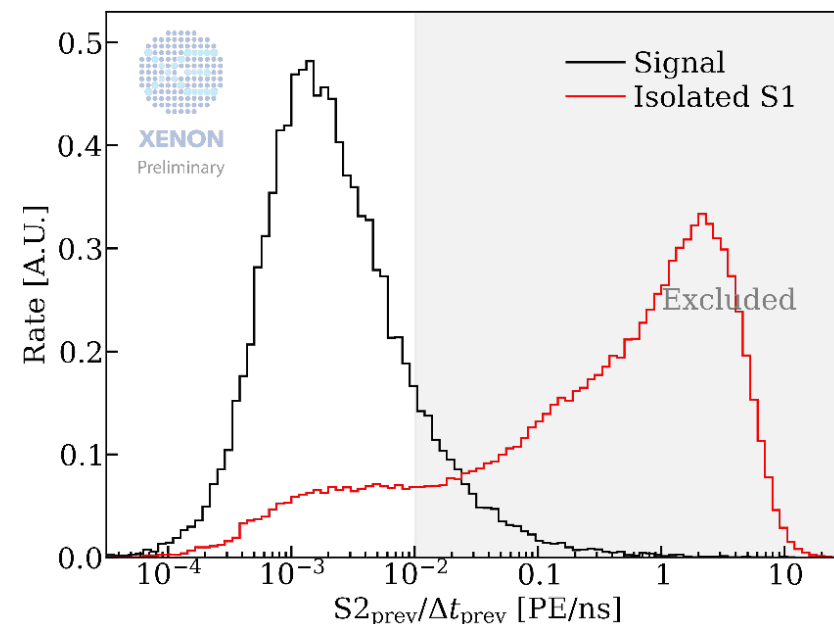
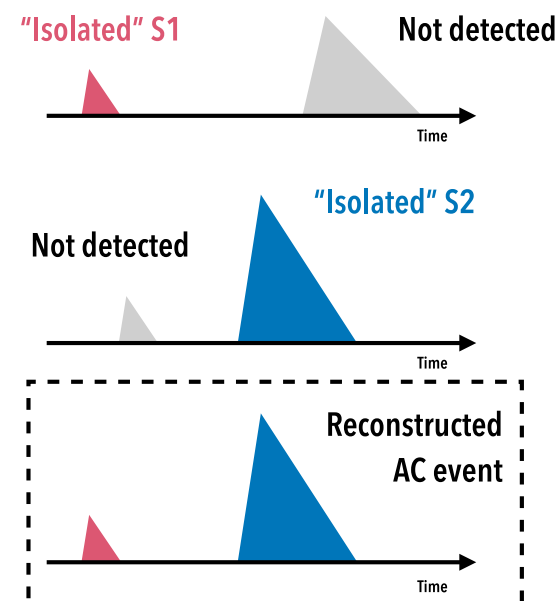
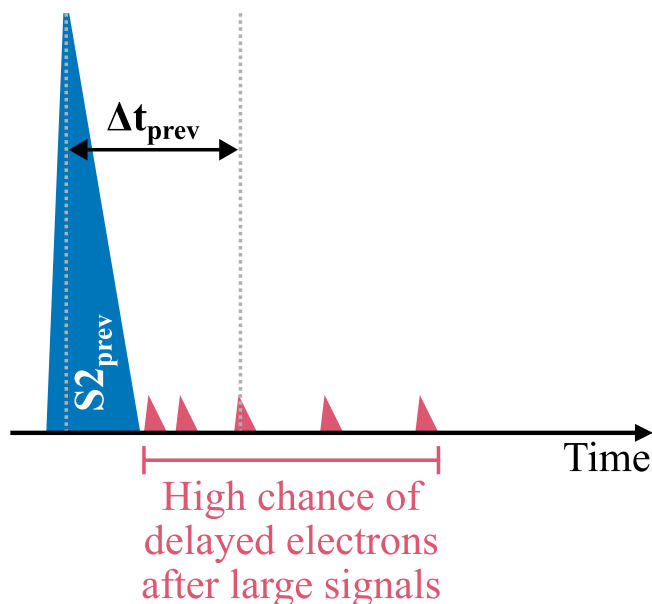
# Probing the Solar $^8\text{B}$ Neutrino Fog: Accidental Coincidence (AC) BG

## AC Dominant background close to threshold

- Events from incorrectly paired S1 and S2 signals
- Raw AC rate ~400 per day
  - "Isolated" S1: ~15 Hz
  - "Isolated" S2: ~0.15 Hz

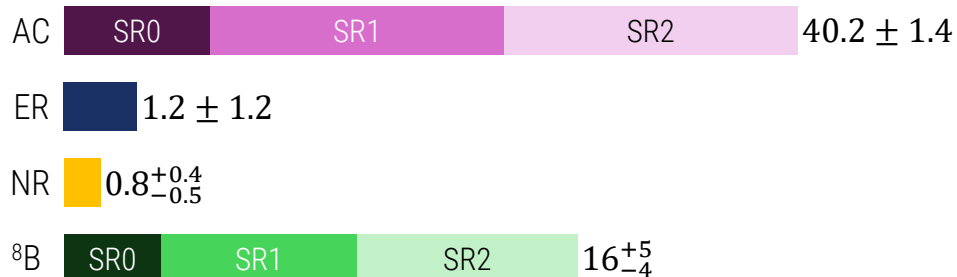
## AC Events are mitigated using

- Boosted decision tree (BDT) based on S1 waveform
- Boosted decision tree (BDT) based on S2 waveform
- Correlation with a preceding high energy interaction
  - Delay time:  $\Delta t_{\text{prev}}$  wrt. preceding large S2
  - Variable  $S2_{\text{prev}}/\Delta t_{\text{prev}}$  is part of likelihood function
  - Large value = **close** to a **large** preceding S2



# Probing the Solar $^8\text{B}$ Neutrino Fog: Unblinding

Expected number of events



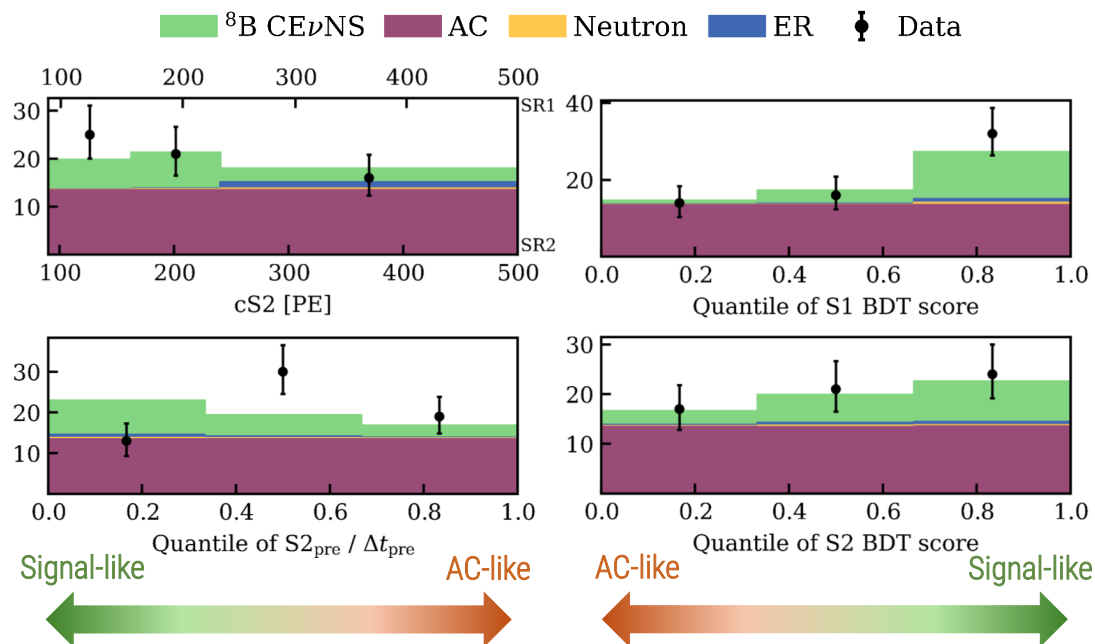
Events Observed: 62

Best-fit number of  $^8\text{B}$  signal events:  $17 \pm 5$

→ **Background only hypothesis rejected at  $3.3 \sigma$ !**

## Extended binned likelihood in 4D parameter space

- cS2 [PE], quantile of S2/ $\Delta t$ , S1 BDT score, S2 BDT score
- Separate terms for each SRs
- Constraints on rates and yields from ancillary measurements



- Agreement between best-fit model and data through Goodness-of-fit (GOF) test based on binned likelihood (95% CL requirement)
- **Test definition fixed before unblinding**, sensitivity to potential mis-modeling validated with toy MC
- $S2_{\text{prev}}/\Delta t_{\text{prev}}$  was below GOF threshold in SR0 & SR1  
→ **No indication for mismodelling in SR2.**
- Note: Removing this dimension from analysis would **increase the significance!**

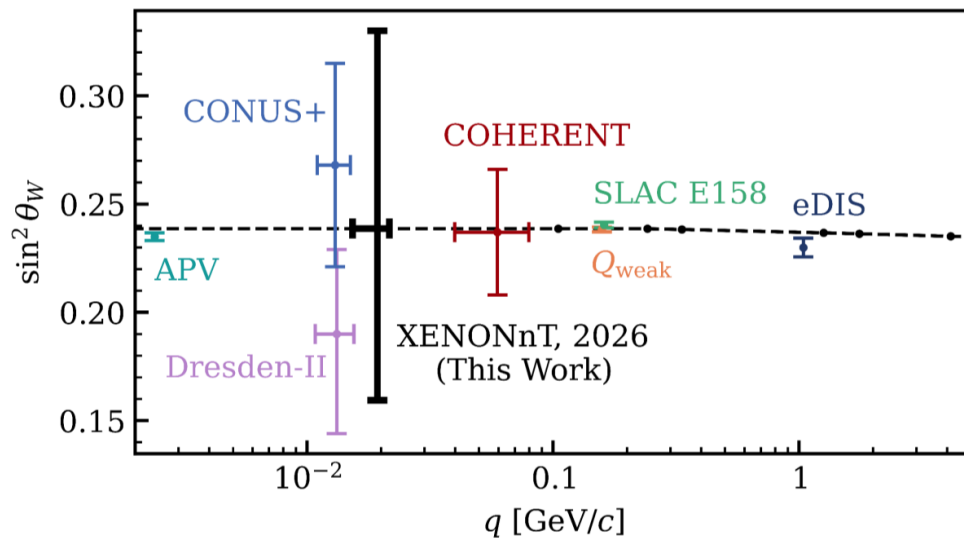
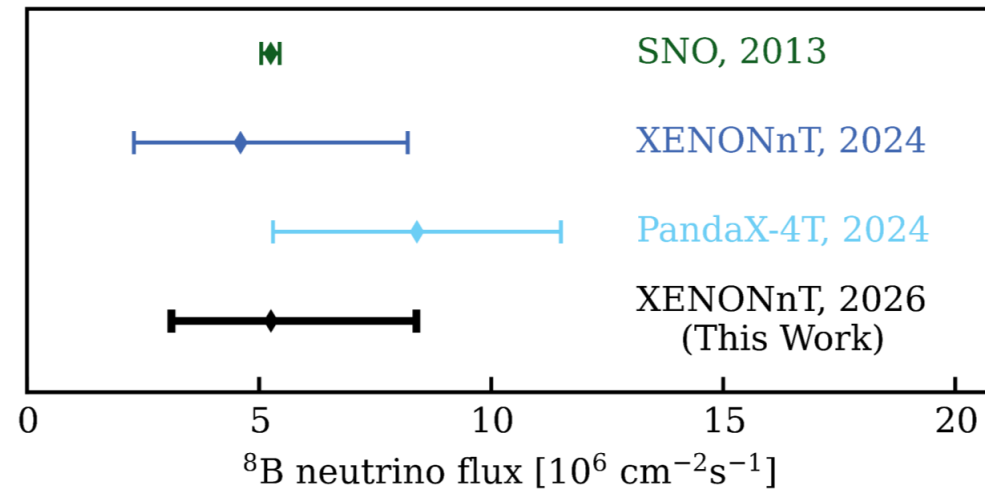


# Probing the Solar $^8\text{B}$ Neutrino Fog: Results

Fix cross-section  $\rightarrow$  **Measurement of solar  $^8\text{B}$  flux**

$$\phi = 5_{-2}^{+3} \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

Compatible with SNO measurement



Fix flux  $\rightarrow$  **Measurement of weak mixing angle**  
at low momentum transfer ( $\sim 0.02 \text{ GeV}/c$ )

$$\theta_W \in [0.159, 0.330]$$

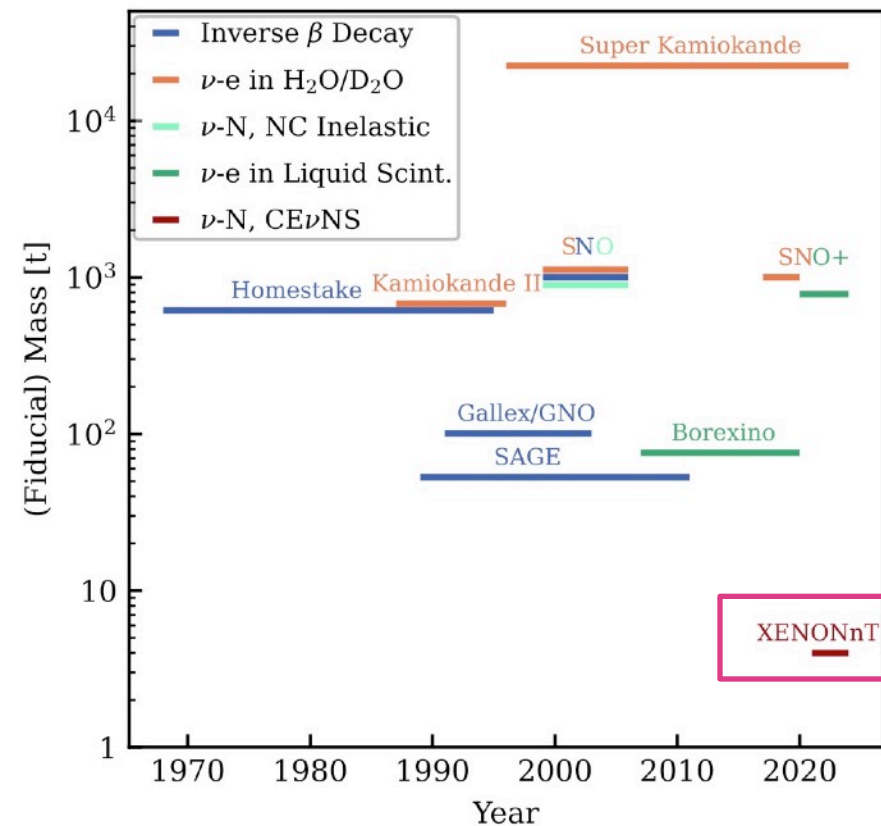
Constraints on neutrino charge  
radius and  $Z'$  coupling

# Probing the Solar $^8\text{B}$ Neutrino Fog: Summary

**First** detection of **astrophysical  $\nu$**  via elastic NR

**First blinded** measurement of  **$\text{CE}\nu\text{NS}$  with Xe**

**First step into "neutrino fog"** by a **DM** experiment

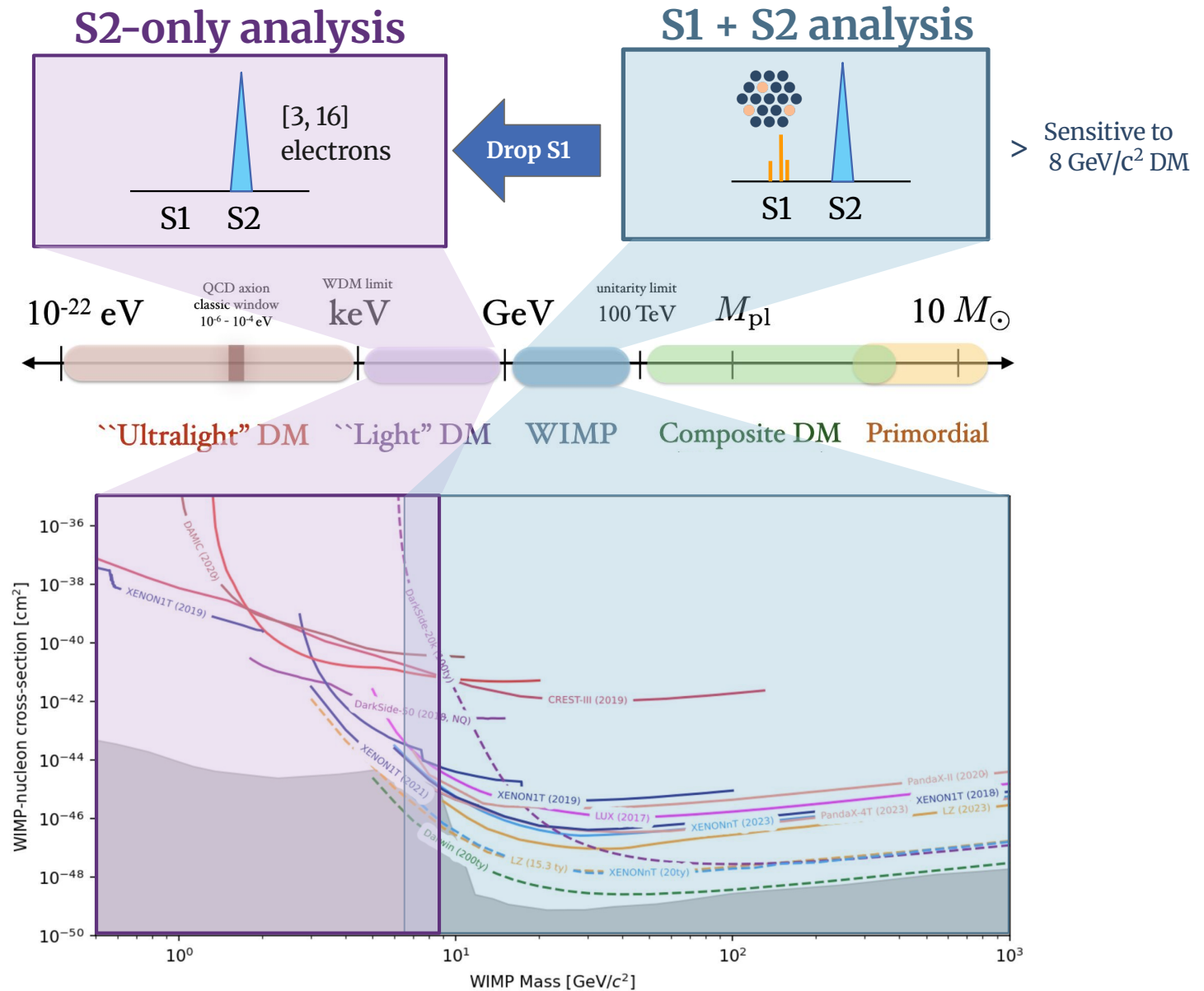


**XENONnT as  
SOLAR NEUTRINO DETECTOR**

XENONnT is joining the restricted club  
of experiments able to detect solar neutrinos,  
but with

**MUCH SMALLER TARGET MASS**  
**MUCH LOWER ENERGY THRESHOLD**

# S2-only Analysis : Motivation

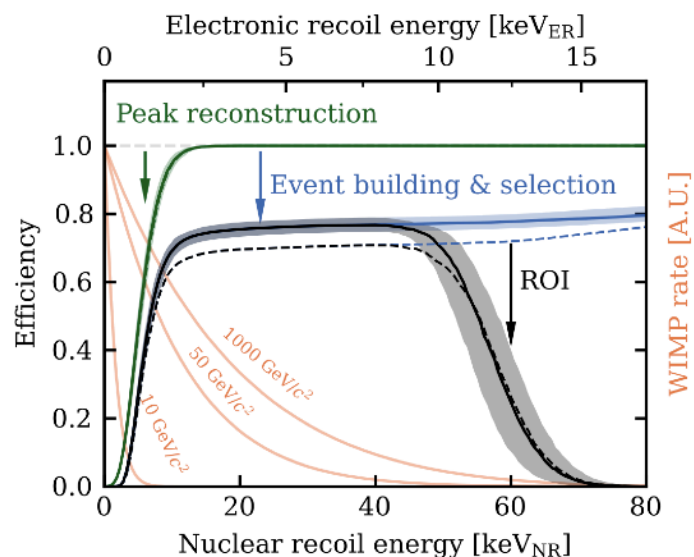


→ **Extend the parameter space to lighter ( $[3, 8] \text{ GeV}/c^2$ ) DM and  $O(\text{keV})$  bosonic DM models**



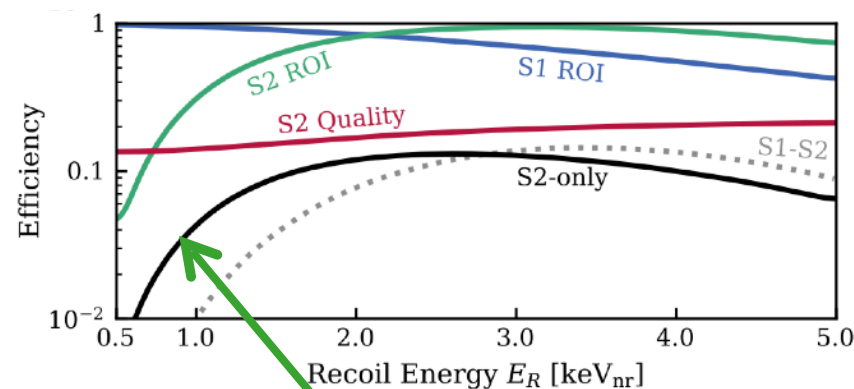
# S2-only Analysis : Challenges

**S1+S2**



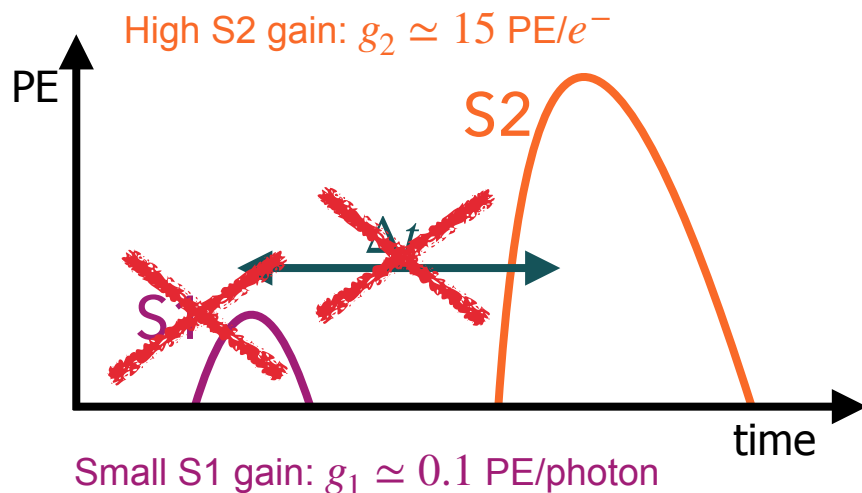
S1 (>3 PE) + S2 pairing → few keV threshold

**S2-only**



✓ Remove S1 → < 1 keV threshold

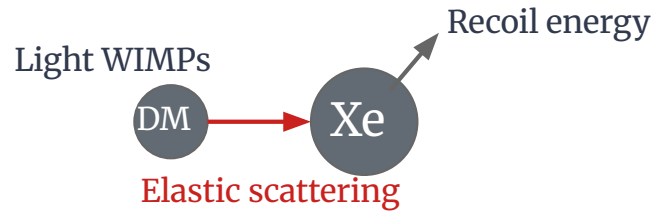
**S2-only search:**



**Downsides:**

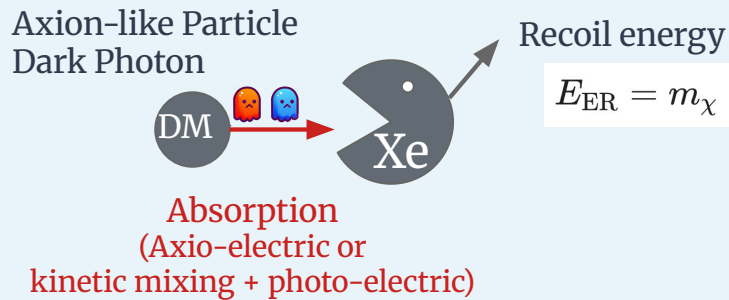
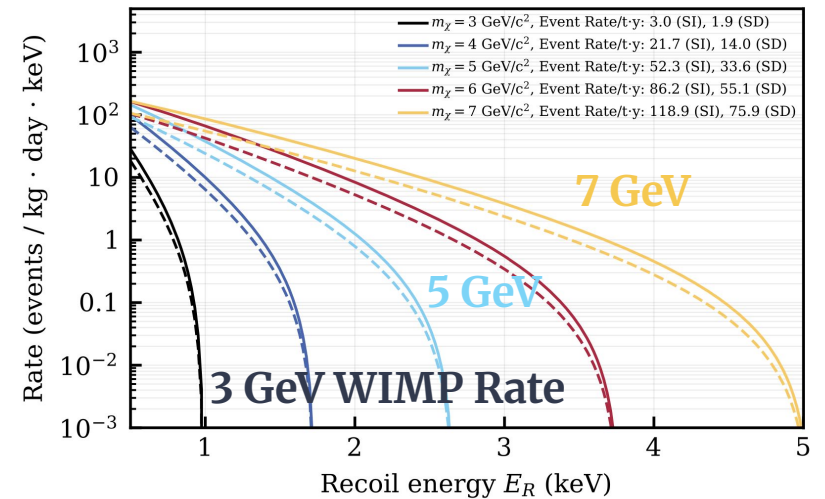
- ✗ no S1 no NR/ER discrimination
- ✗ no  $\Delta t$  → no z position
- less powerful top-bottom bkg discrimination

# S2-only Analysis : Signals



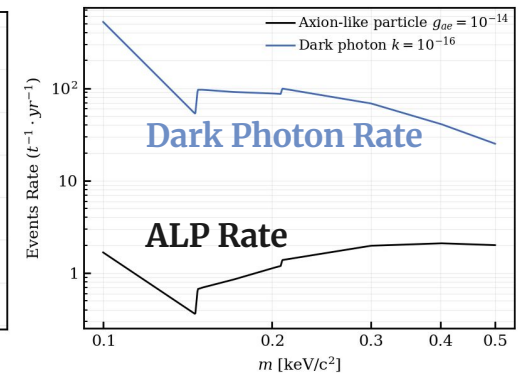
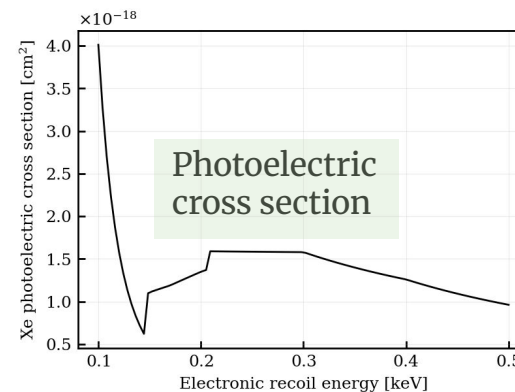
$$\frac{dR}{dE_R} = \underbrace{\frac{\rho_0}{m_\chi m_{\text{Xe}}}}_{\text{DM \& Xe Properties}} \underbrace{\int_{v_{\min}}^{v_{\text{esc}}} f(v) v}_{\text{DM Velocity}} \underbrace{\frac{d\sigma_{\chi\text{-Xe}}(v)}{dE_R}}_{\text{Model Dependent Cross section}} dv$$

Spin-Independent Spectrum ( $\sigma_n = 10^{-45} \text{ cm}^2$ )  
Spin-Dependent (neutron coupling) Spectrum ( $\sigma_n = 10^{-40} \text{ cm}^2$ )



$$R_{\text{DP}} \propto \epsilon^2 \cdot \frac{\sigma_{\text{PE}}}{m_{\text{DP}}}$$

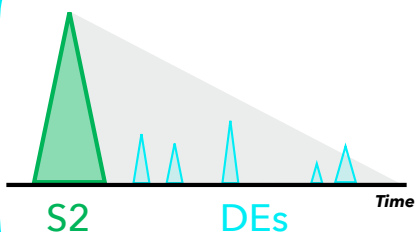
$$R_{\text{ALP}} \propto g_{ae}^2 \cdot m_{\text{ALP}} \cdot \sigma_{\text{PE}}$$



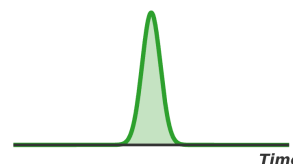
# S2-only Analysis : Backgrounds

## Delayed Electrons (DE):

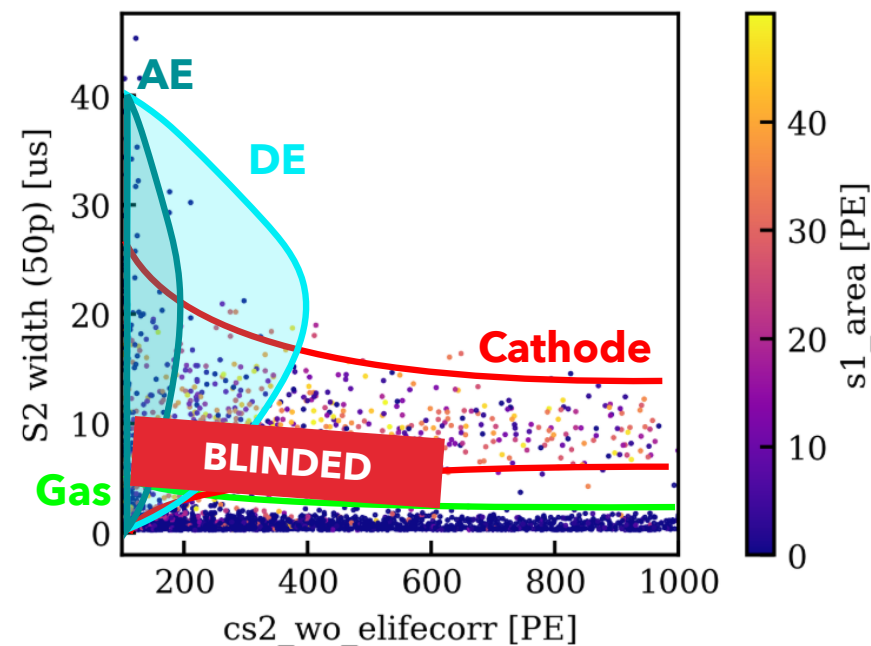
- ▶ Position & Time correlated with the parent S2.
- ▶ Large S2 width due to the peak merging
- ▶ Correlation-based CNF and BDT machine



**Gas:** S2 width < 3 us due to smaller diffusion



sr1 Rn220



Gas region  
(Top electrodes)

Negligible  
after width cut

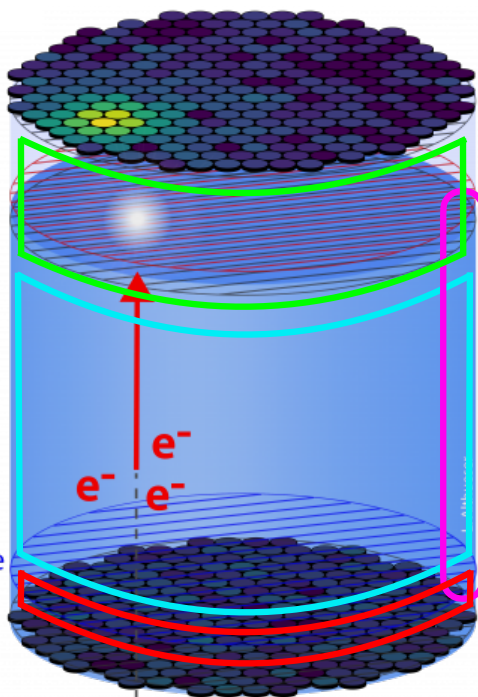
anode  
gate

Delayed electrons (DE)  
Accidental electrons (AE)  
(Electrons trapped in the  
impurities)

cathode

Cathode electrodes

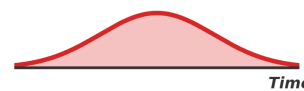
Simulation by  
data-driven sidebands



PTFE Wall

Negligible  
after radius cut

**Cathode:** S2 width ~ 10 us large  
overlap with signal region  
waveform-based BDT machine



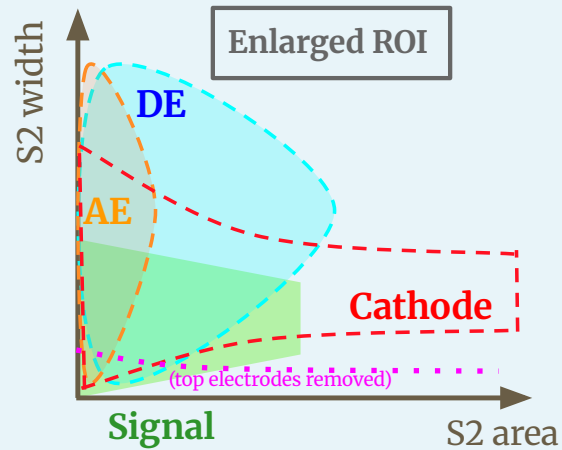
Images credits: Yongyu Pan



# S2-only Analysis : Background modeling

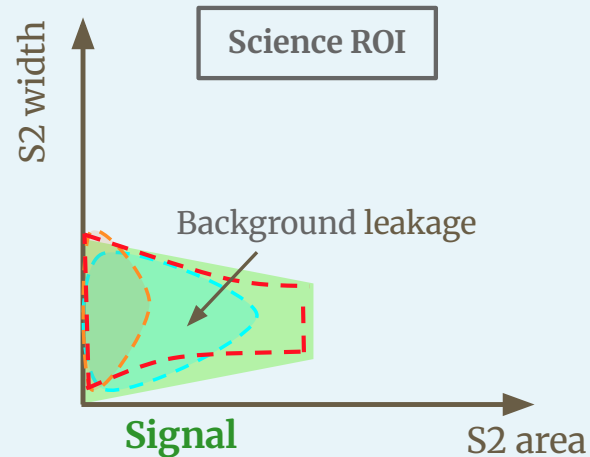
## What we have now:

DE, AE, cathode background modeling in full space



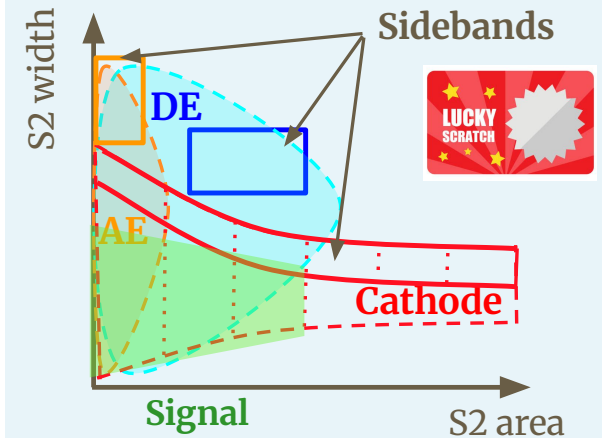
## Objective:

Estimate the DE, AE, cathode background in **blinded Signal ROI**



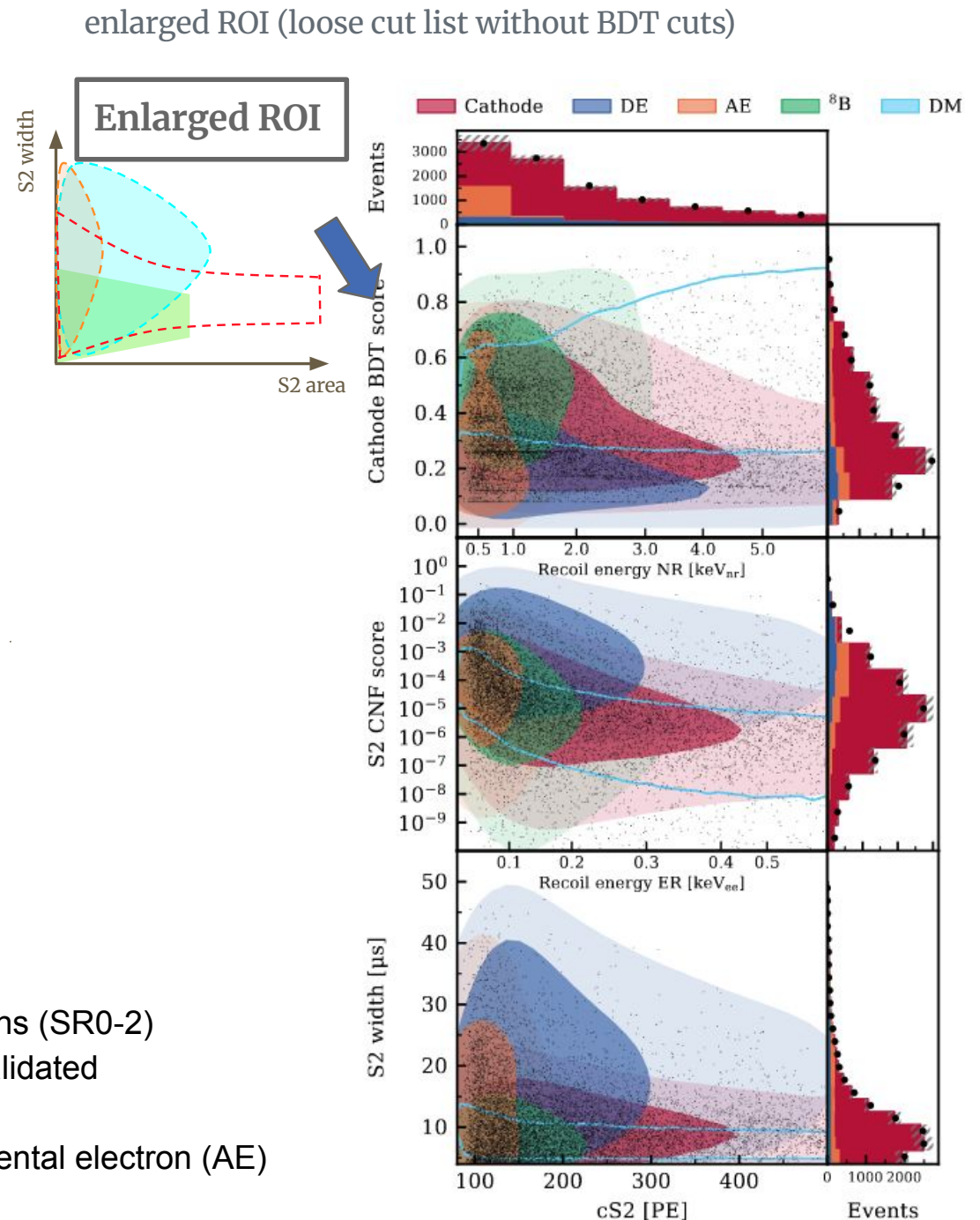
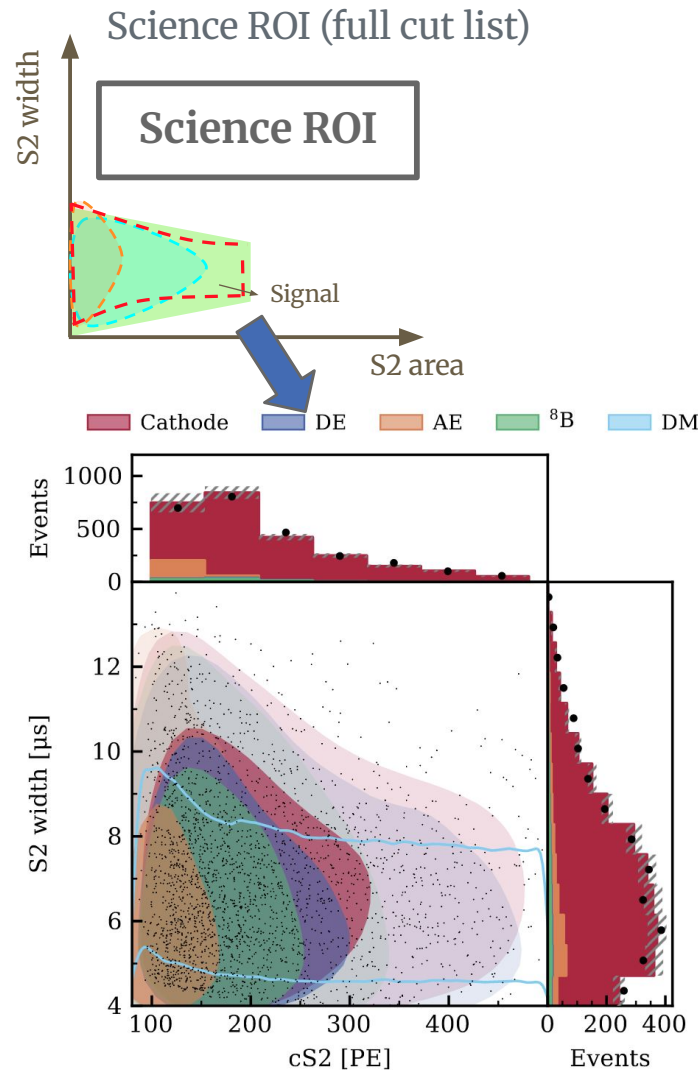
## Sideband technique:

**Unblind** the sideband region, correct and normalize the background modeling in **Signal ROI**.



- (1) Background modeling from simulation can be different from the actual distribution from data
- (2) Science ROI (full cut list), enlarged ROI (loose cut list without BDT cuts)
- (3) Background validation is done on Rn220, Rn222 calibration in different SRs

# S2-only Analysis : Background validation after unblinding



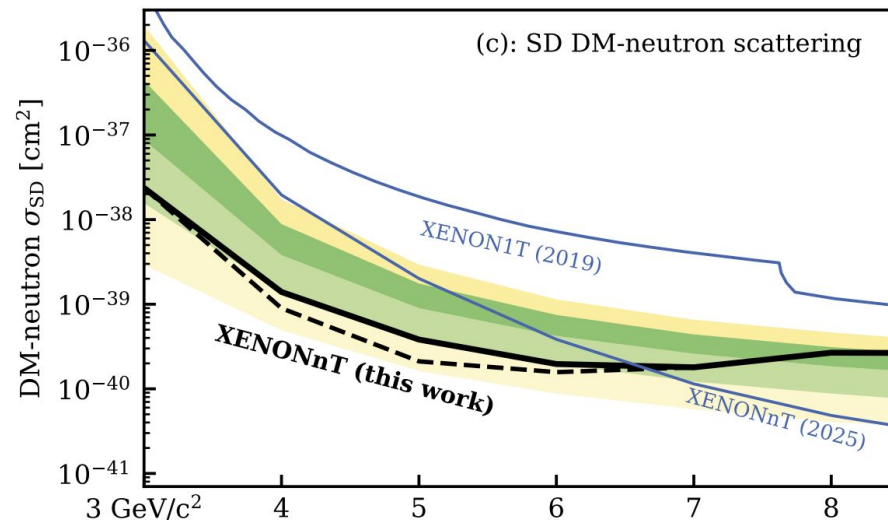
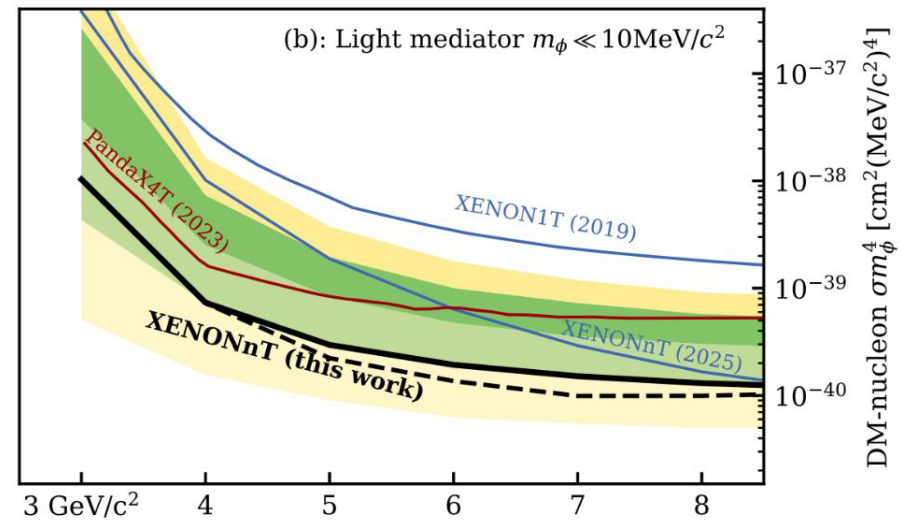
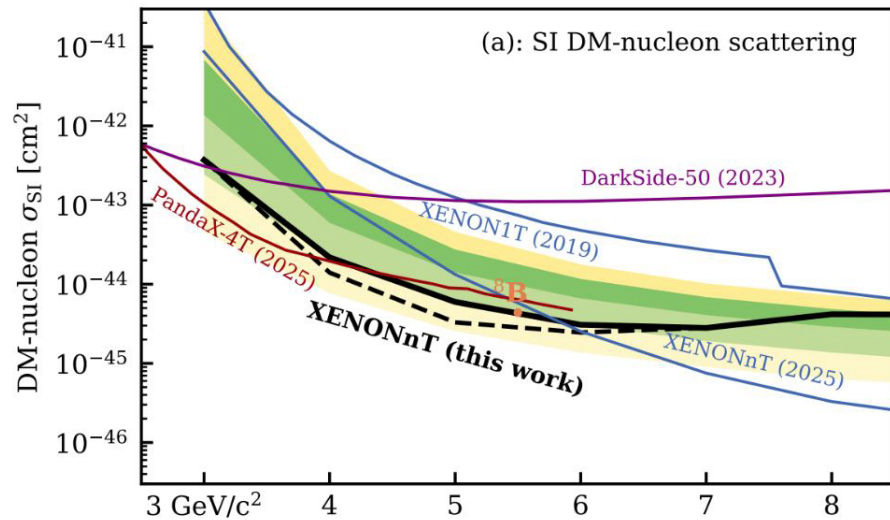
## Validation of background model:

- Unblind 7.83 t x yr of data over 3 Science Runs (SR0-2)
- First complete S2-only background model, validated across different dimensions
- Cathode background is dominant while accidental electron (AE) primarily contributes to the lowest energy bin.

# S2-only Analysis : Results & Limits (NR channel)

| Science run (exposure)   | SR0 (1.50 t · y) |                   | SR1 (2.44 t · y) |                   | SR2 (3.89 t · y) |                |
|--------------------------|------------------|-------------------|------------------|-------------------|------------------|----------------|
| Component                | Expectation      | Best fit          | Expectation      | Best fit          | Expectation      | Best fit       |
| Cathode                  | $480 \pm 70$     | $477^{+25}_{-24}$ | $660 \pm 70$     | $726^{+28}_{-27}$ | $1210 \pm 90$    | $1080 \pm 30$  |
| Delayed electron         | $1.3 \pm 0.5$    | $1.3 \pm 0.5$     | $0.34 \pm 0.07$  | $0.34 \pm 0.07$   | $17.2 \pm 2.3$   | $17.1 \pm 2.3$ |
| Accidental electron      | $97 \pm 17$      | $89 \pm 13$       | $108 \pm 8$      | $106 \pm 8$       | —                | —              |
| $^8\text{B}$ CE $\nu$ NS | $21 \pm 5$       | $18^{+5}_{-4}$    | $29 \pm 7$       | $26^{+7}_{-6}$    | $32.3 \pm 8$     | $29^{+8}_{-6}$ |
| Total background         | $600 \pm 80$     | $586 \pm 28$      | $800 \pm 80$     | $858^{+30}_{-29}$ | $1260 \pm 100$   | $1130 \pm 30$  |
| Observed                 | 583              |                   | 864              |                   | 1107             |                |

Good agreement  
⇒ No signal excess

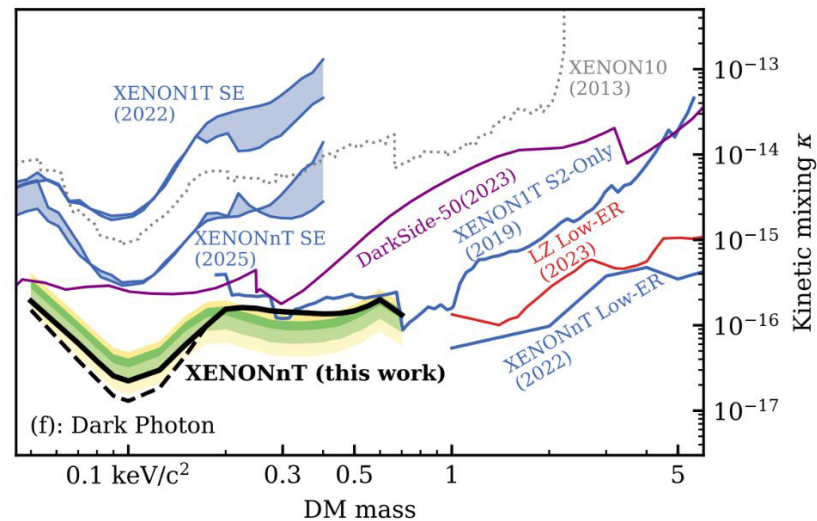
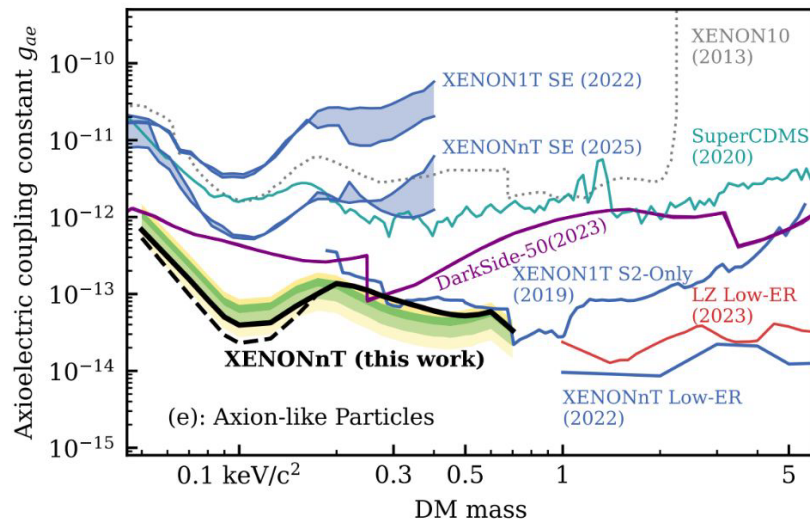
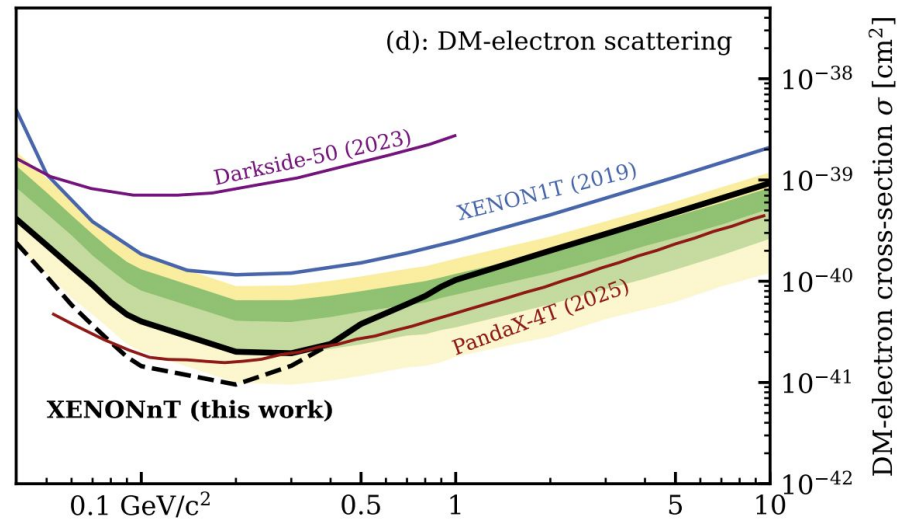




# S2-only Analysis : Results & Limits (ER channel)

| Science run (exposure)   | SR0 (1.50 t · y) |                   | SR1 (2.44 t · y) |                   | SR2 (3.89 t · y) |                |
|--------------------------|------------------|-------------------|------------------|-------------------|------------------|----------------|
| Component                | Expectation      | Best fit          | Expectation      | Best fit          | Expectation      | Best fit       |
| Cathode                  | $480 \pm 70$     | $477^{+25}_{-24}$ | $660 \pm 70$     | $726^{+28}_{-27}$ | $1210 \pm 90$    | $1080 \pm 30$  |
| Delayed electron         | $1.3 \pm 0.5$    | $1.3 \pm 0.5$     | $0.34 \pm 0.07$  | $0.34 \pm 0.07$   | $17.2 \pm 2.3$   | $17.1 \pm 2.3$ |
| Accidental electron      | $97 \pm 17$      | $89 \pm 13$       | $108 \pm 8$      | $106 \pm 8$       | —                | —              |
| $^8\text{B}$ CE $\nu$ NS | $21 \pm 5$       | $18^{+5}_{-4}$    | $29 \pm 7$       | $26^{+7}_{-6}$    | $32.3 \pm 8$     | $29^{+8}_{-6}$ |
| Total background         | $600 \pm 80$     | $586 \pm 28$      | $800 \pm 80$     | $858^{+30}_{-29}$ | $1260 \pm 100$   | $1130 \pm 30$  |
| Observed                 | 583              |                   | 864              |                   | 1107             |                |

Good agreement  
⇒ **No signal excess**

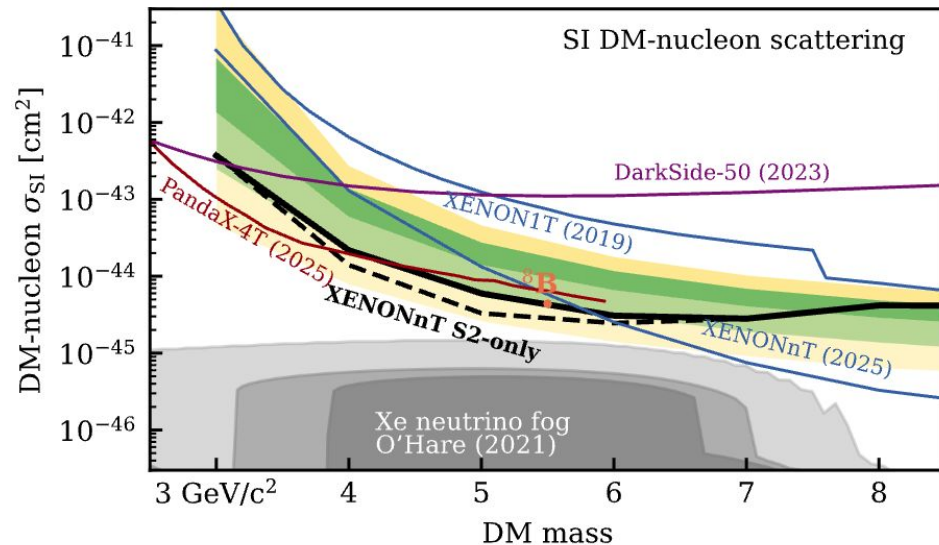




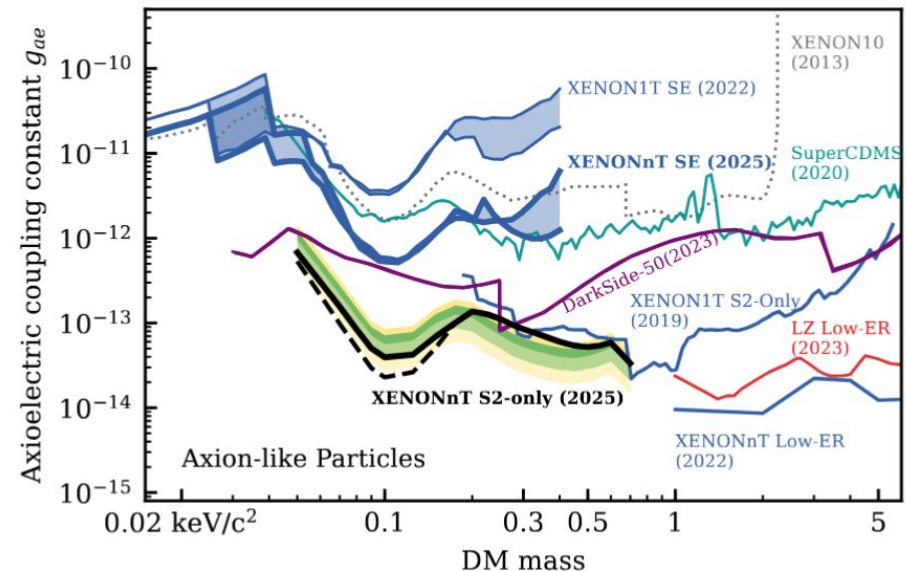
# S2-only Analysis : Summary

**S2-only** analysis allows XENONnT to probe  
**lighter (3-8 GeV/c<sup>2</sup>)** DM and **O(keV)** Bosonic DM  
**First complete background model** for **S2-only** analysis  
**Advanced ML techniques** used for background suppression  
**Blinded S2-only analysis** of data~7.83 tonne-year exposure, extending limits for multiple DM models.

Most stringent limit set on **~5 GeV light WIMPs**



And also on **[0.04, 0.2] keV ALPs**



# Summary and Outlook

**Blinded analysis** across three XENONnT SRs yield a  **$3.3\sigma$  observation of  $^8\text{B}$  solar CEVNS** and new **best limits on light DM**

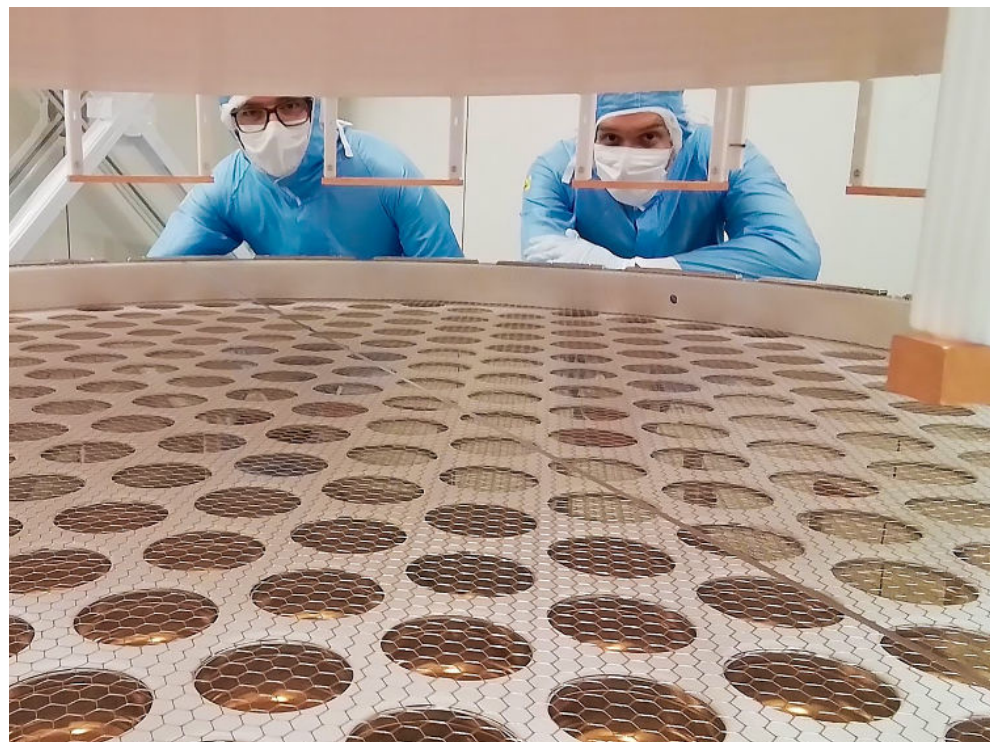
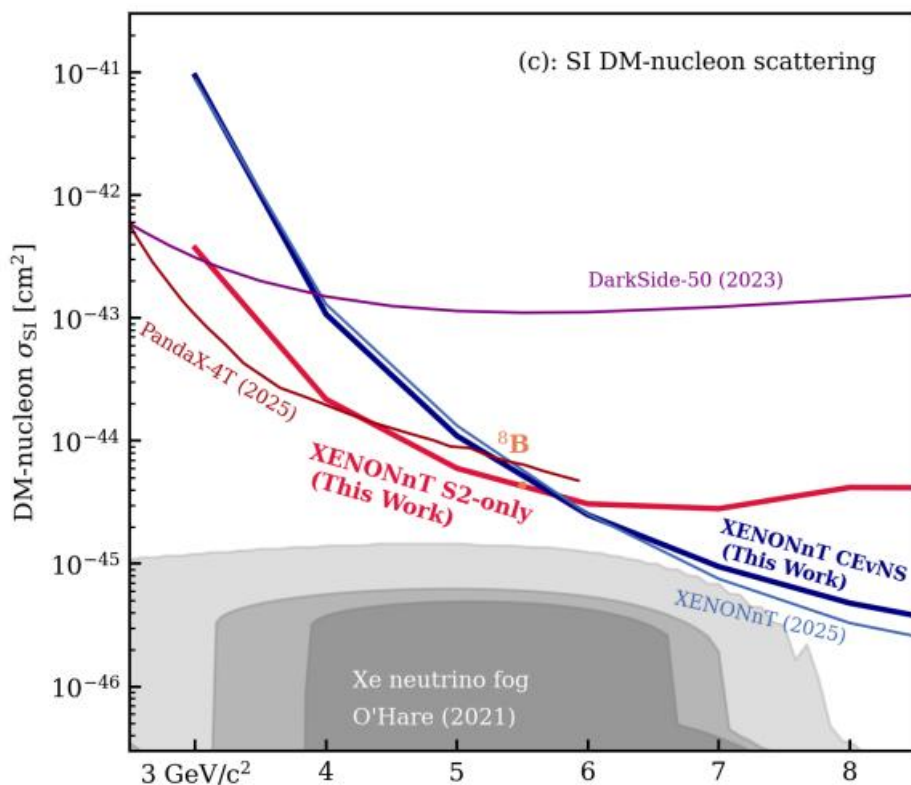
The search for dark matter with LXe detectors has officially reached the **neutrino fog**!

Following a 1-year upgrade after SR2, **XENONnT 2.0 is now in commissioning!**

- New electrodes
- Exchange of problematic PMTs
- Improvement in TPC condition stability
- Stronger drift field (as designed)
- Better Extraction Efficiency
- Improved ER/NR discrimination
- Enhanced Neutron Veto performance

**Measurement of  $^8\text{B}$  solar CEVNS at  $5\sigma$  is in reach within the lifetime of the experiment!**

Light WIMP results S2-Only+CEVNS







# XENONnT : Neutron Veto improvement

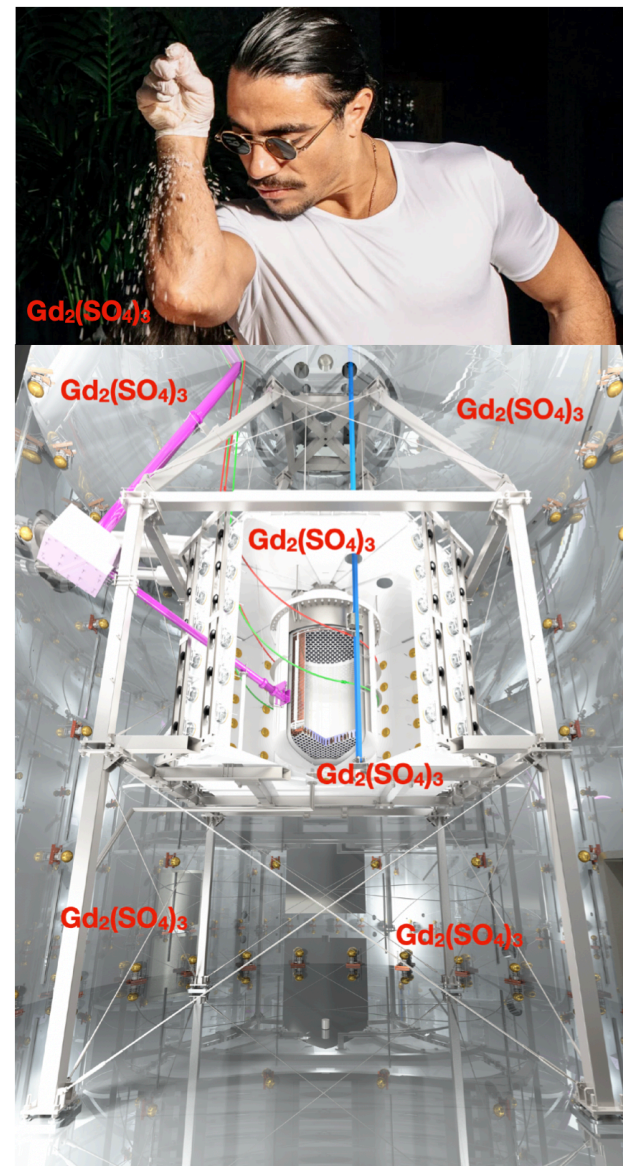
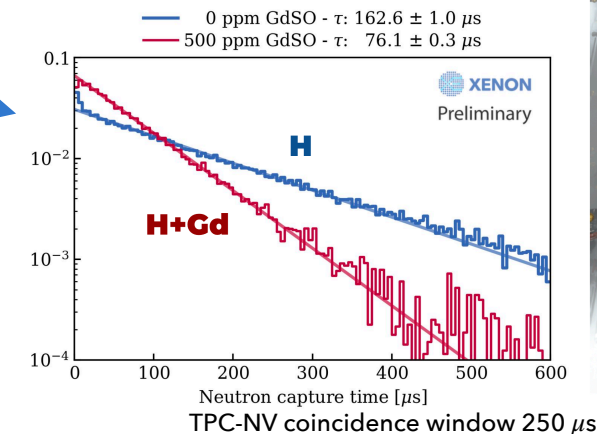
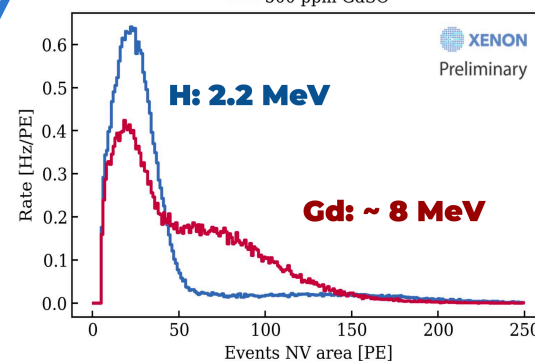
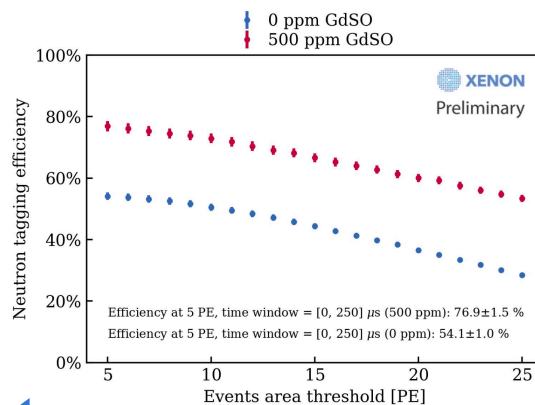
## SR0+SR1: Pure water

- ▶ NV tagging efficiency:  $53 \pm 1 \%$ .
- ▶ H capture: **2.2 MeV**,  $1 \gamma$ .
- ▶ Capture time H-only: **160  $\mu\text{s}$** .

Gd-sulphate loading: 350 kg in 700 tons of water (500 ppm), Gd mass concentration at 0.02%.

## SR2: Gd-loaded water (0.02%)

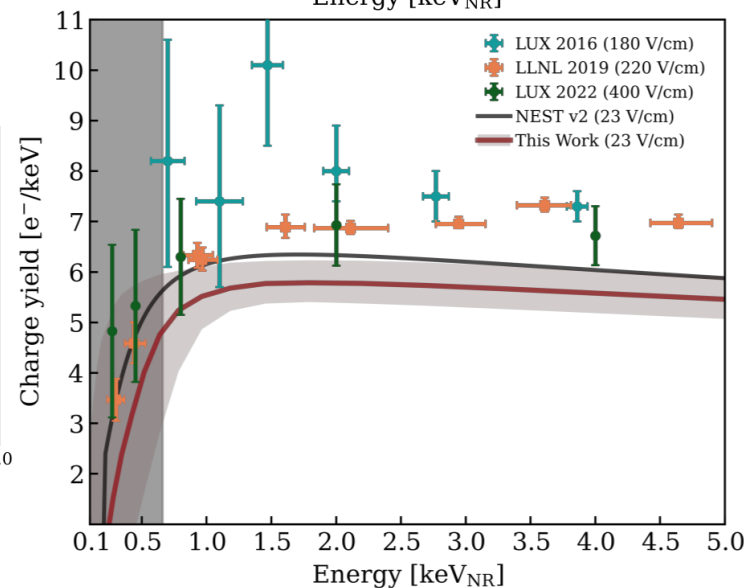
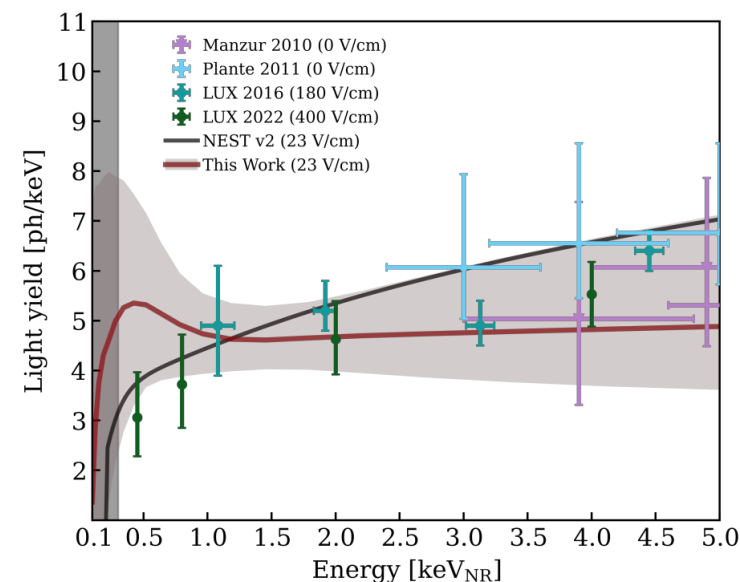
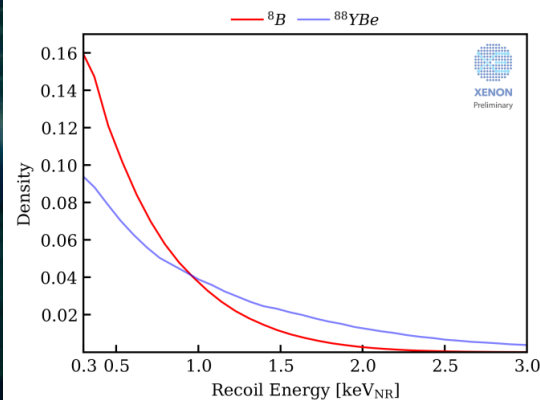
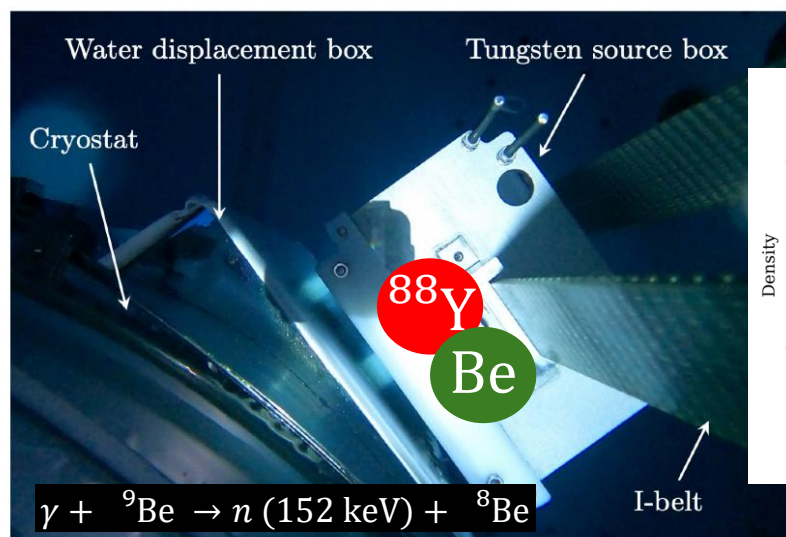
- ▶ NV tagging efficiency:  $77 \pm 1 \%$ .
- ▶ Gd capture: **8 MeV**, **3-4  $\gamma$** .
- ▶ Capture time H+Gd: **75  $\mu\text{s}$** .
- ▶ **A factor 2 neutron background reduction wrt SR0 with demi-water.**
- ▶ Planned 10x higher Gd mass: expected tagging efficiency of 87%.





## Low energy NR calibration with $^{88}\text{YBe}$

- The low-energy NR response is calibrated with 152 keV neutrons from an external  $^{88}\text{YBe}$  source
- Calibrate detector with neutrons on/off (Yttrium-PVC gamma-only source)
- Light and charge yield (and uncertainties) from best fit of NESTv2.3 yield model

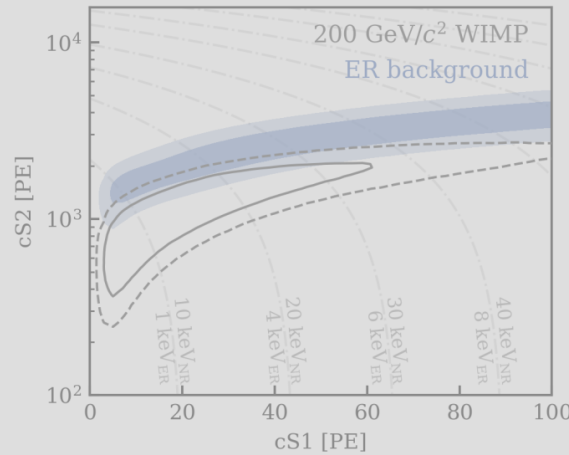


# Probing the Solar $^8\text{B}$ Neutrino Fog: Backgrounds

Background in traditional WIMP search

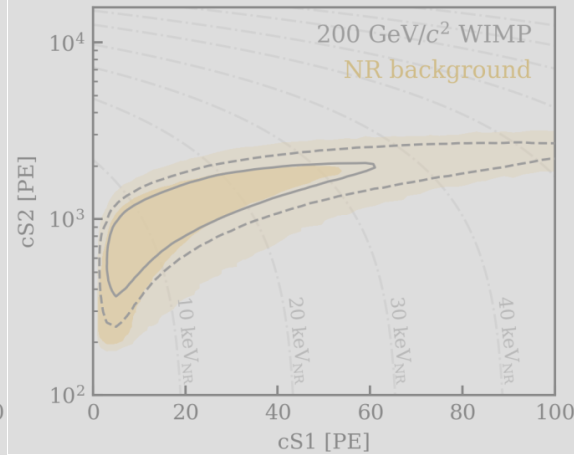
## ER Background

Intrinsic radioactive contaminants in xenon volume



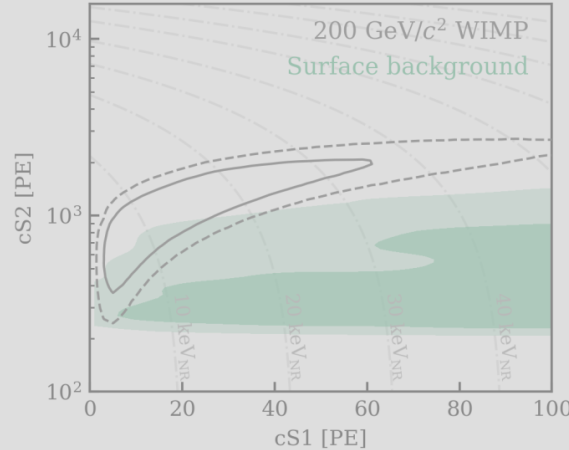
## NR Background

Radiogenic neutrons from detector materials



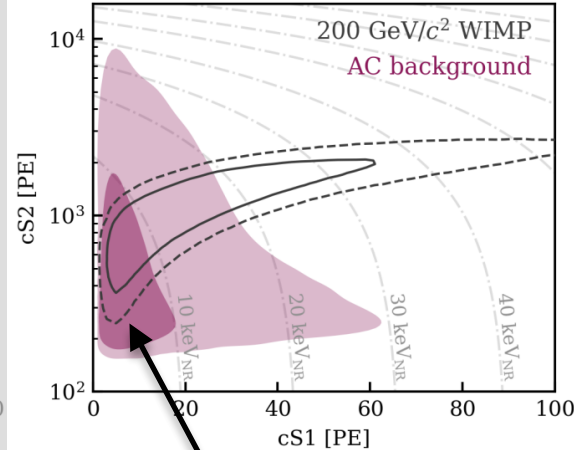
## Surface Background

Radon daughters plating out into PTFE wall



## Accidental Coincidences

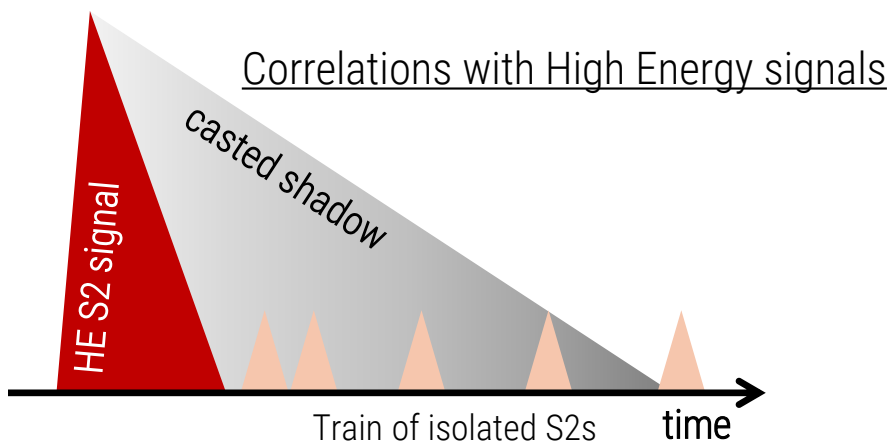
Random pairing of isolated S1 and S2 signals



**Dominant background for  $\text{CE}\nu\text{NS}$  analysis**

# Probing the Solar $^8\text{B}$ Neutrino Fog: AC Rejection

Isolate S1 and S2 rate and discrimination of AC events based on time and spatial correlation with preceding signals and boosted decision tree (BDT) trained on S1 and S2 waveforms: **rejection power around 90%** with a **signal acceptance of 80%** !

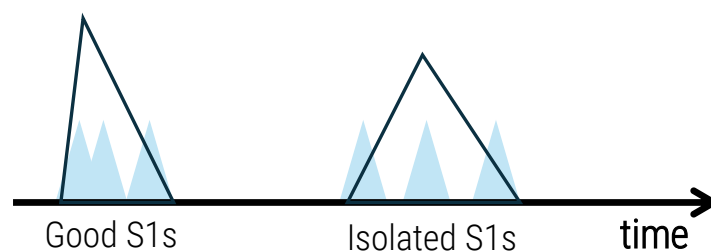


After suppression:

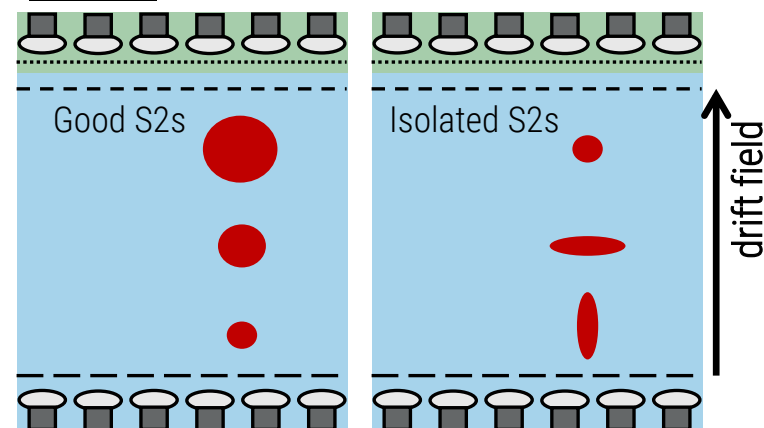
| SR  | S1 [Hz] | S2 [mHz] | AC [ $\mu\text{Hz}$ ] |
|-----|---------|----------|-----------------------|
| SR0 | 2.3     | 16.6     | 0.80                  |
| SR1 | 2.2     | 21.5     | 0.99                  |
| SR2 | 1.7     | 17.7     | 0.60                  |

Additional ~20% suppression in SR2 via advanced peak classification and S2 merging!

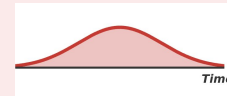
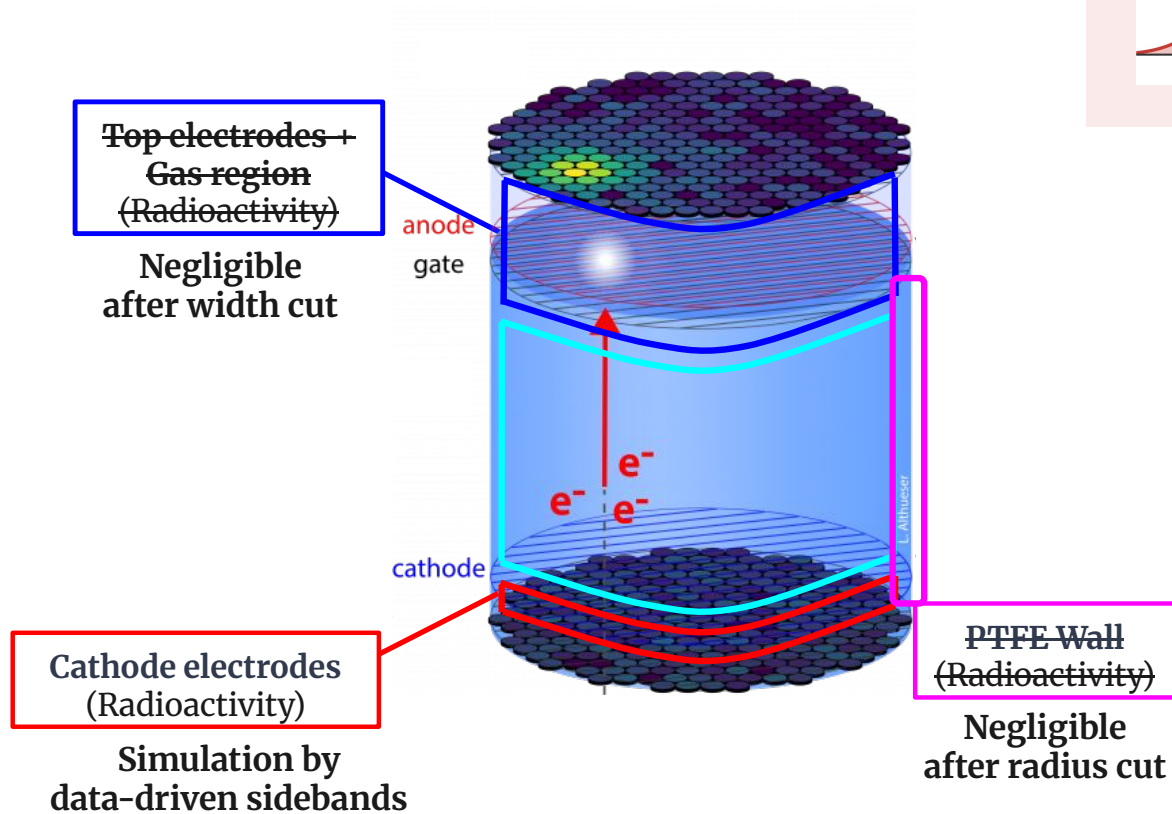
S1 BDT



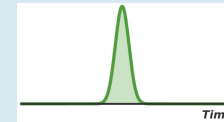
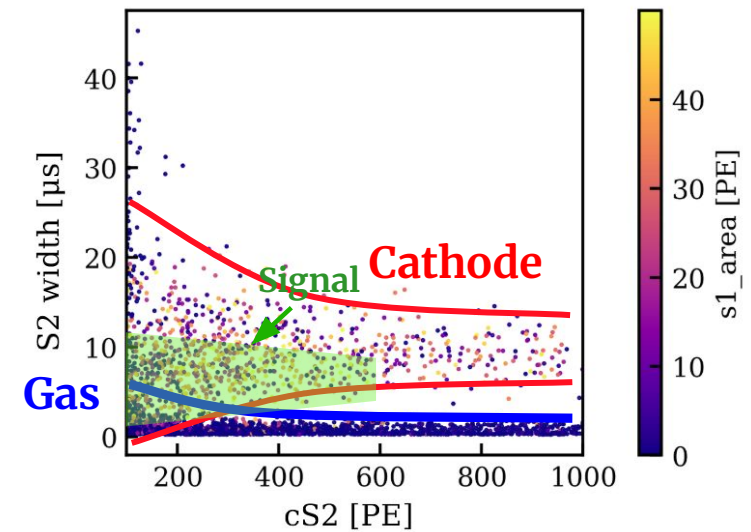
S2 BDT



# S2-only Analysis : Background suppression & modeling I



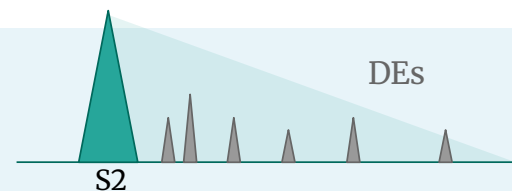
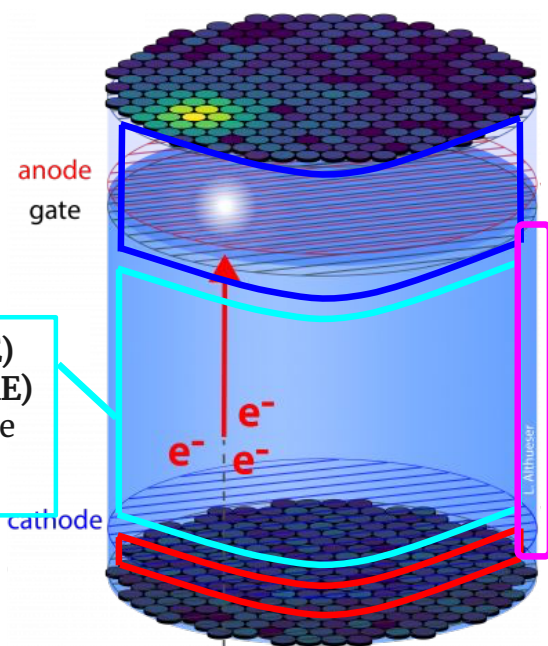
**Cathode:** S2 width  $\sim 10 \mu\text{s}$   
large overlap with signal region  
waveform-based BDT machine



**Gas:** S2 width  $< 3 \mu\text{s}$   
due to smaller diffusion

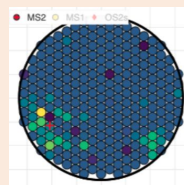
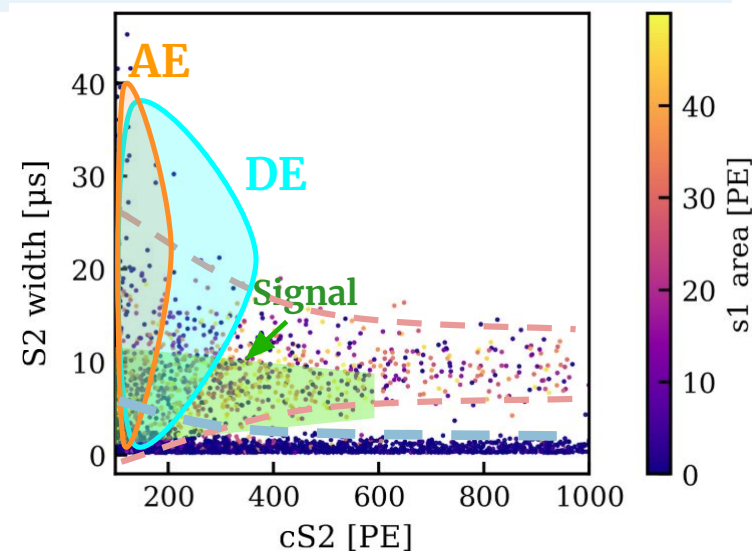


# S2-only Analysis : Background suppression & modeling II



**DE:**

- Position & Time correlated with the parent S2
- Large S2 width due to the peak merging
- Correlation-based CNF and BDT machine



**AE:** pile-up of single DEs

- Poor pile-up PMT pattern
- Mitigated by pattern likelihood cut
- Modeled in data-driven way

# S2-only Analysis : Background Summary

|                                   | Top electrodes / Gas events                             | Cathode electrodes                                                 |
|-----------------------------------|---------------------------------------------------------|--------------------------------------------------------------------|
| <b>Origins</b>                    | Radioactivity from $^{222}\text{Rn}$ decay chain        |                                                                    |
| <b>Key features</b>               | Small S2 width < 4 us due to small drift length ~few cm | Large S2 width spread [0, 20] us due to large drift length ~140 cm |
| <b>Cut Development</b>            | S2 width cut                                            | BDT machine using waveform features                                |
| <b>Remaining events after cut</b> | Negligible                                              | Simulation- and data-driven modeling                               |

|                                   | Delayed Electrons (DE)                                      | Accidental Electrons (AE) |
|-----------------------------------|-------------------------------------------------------------|---------------------------|
| <b>Origins</b>                    | (DE: one-time emission, AE: pile-up of different emissions) |                           |
| <b>Key features</b>               | Large S2 width due to peak merging                          |                           |
|                                   | Position & Time correlated with the parent S2               | Poor pile-up PMT pattern  |
| <b>Cut Development</b>            | BDT machine using the above correlation                     | S2 pattern cut            |
| <b>Remaining events after cut</b> | Data-driven modeling                                        |                           |