



COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK



XENON

Search for Dark Matter and Solar Neutrino with XENONnT

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KIPAC FPD Seminar,
Mar 17, 2026



Dark matter evidence at all scales

Dark matter: $\sim 27\%$ of the Universe and 84% of the matter content

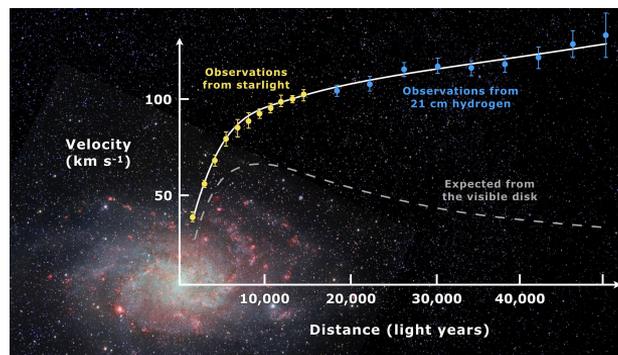
Consistent with a cold, non-baryonic component

Mass density $\sim 0.3 \text{ GeV/cm}^3$ for halo dark matter in the solar system

In an Earth-sized volume $\sim 0.5 \text{ kg}$ – about **the weight of a squirrel**

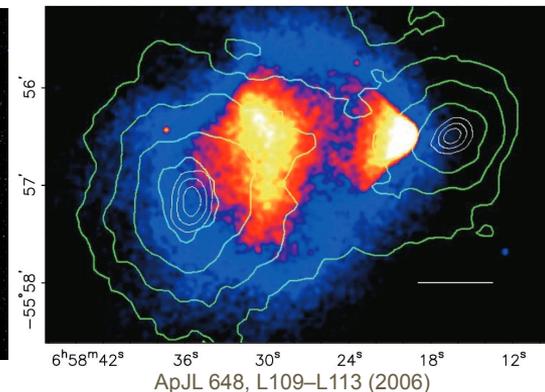


Galaxy rotation curves

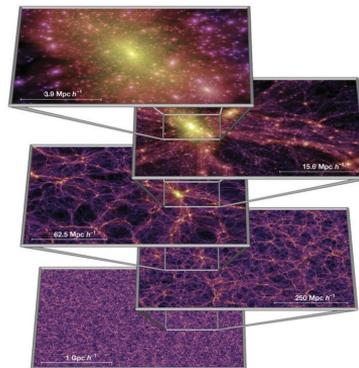


ApJ 159, L 379 (1970); ApJ 238, L 471 (1980)

Gravitational lensing of cluster merging

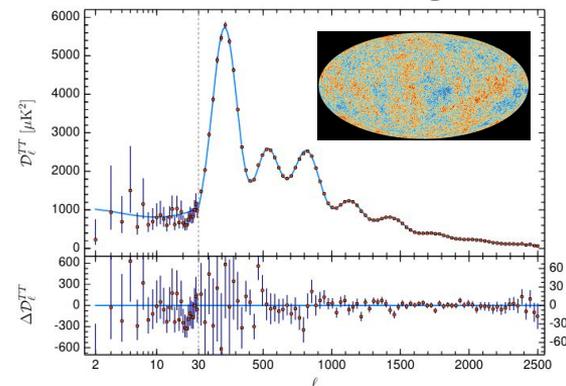


Galactic large scale structure



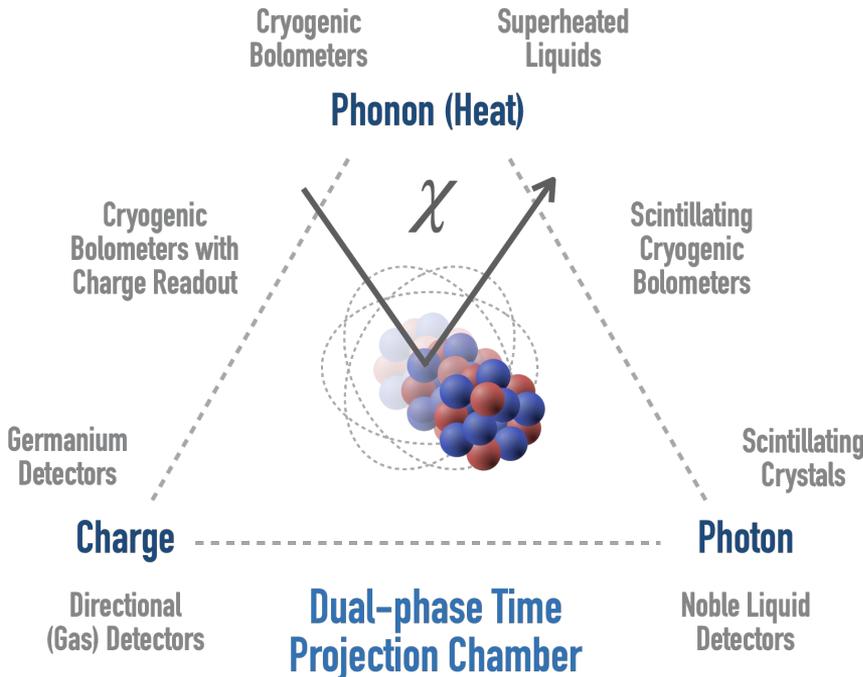
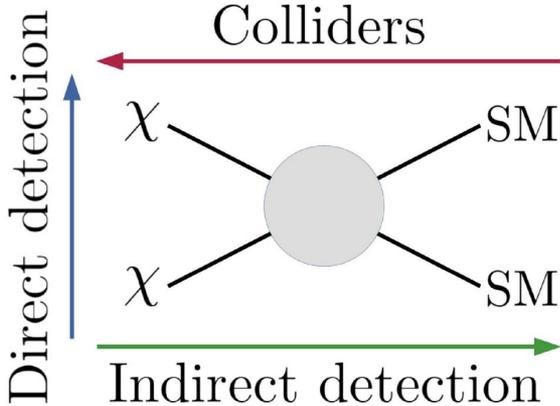
Nature 435 (2005) 629-636

Cosmic microwave background

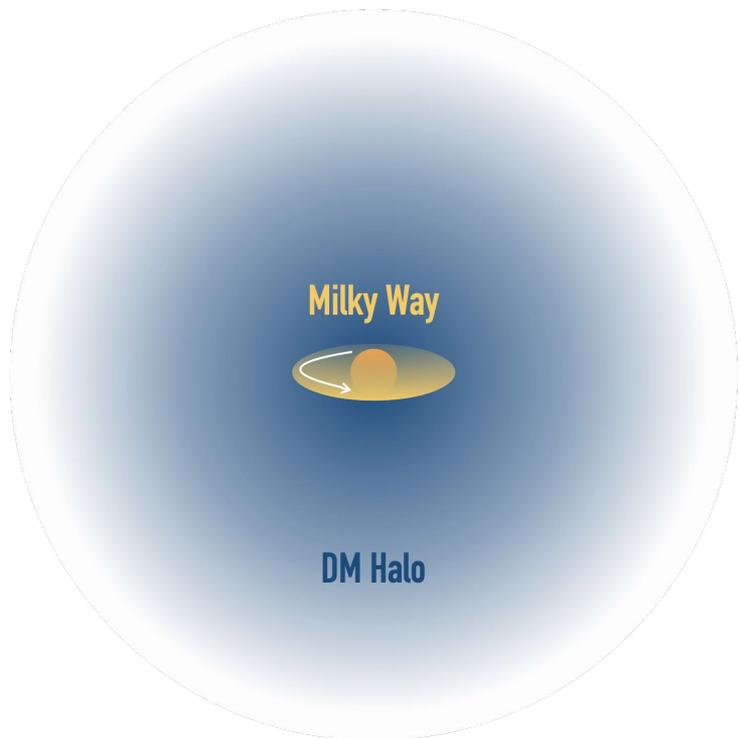


A&A 641, A6 (2020)

Search for particle Dark Matter candidates



Laboratory-based direct search experiment



Event rate per unit target mass

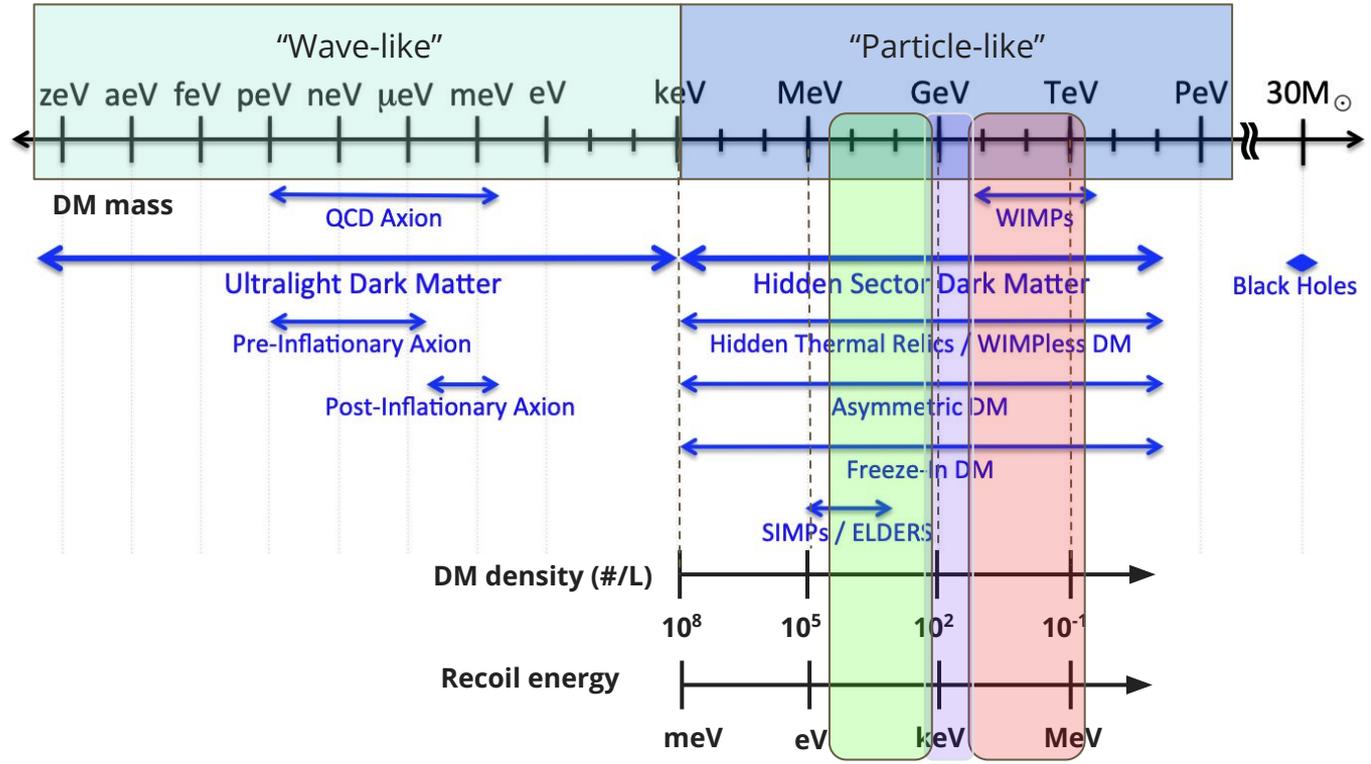
Velocity average

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_P} \left\langle v \frac{d\sigma_{\chi P}}{dE_R} \right\rangle$$

Recoil energy Dark matter mass Target particle mass

Dark matter candidates

US cosmic visions 2017 report



Focus of this talk

Contents

- **XENONnT Experiment**

LXe TPCs, instrumentations, status

- **Search for Weakly Interacting Massive Particles (WIMPs)**

10 GeV – TeV scale Dark Matter

- **Search for Light Dark Matter and Solar Neutrino**

GeV Dark Matter, solar B^8 neutrinos fog

- **Search for Light Dark Matter with Ionization-only Signals**

MeV-GeV Dark Matter, instrumental challenges,

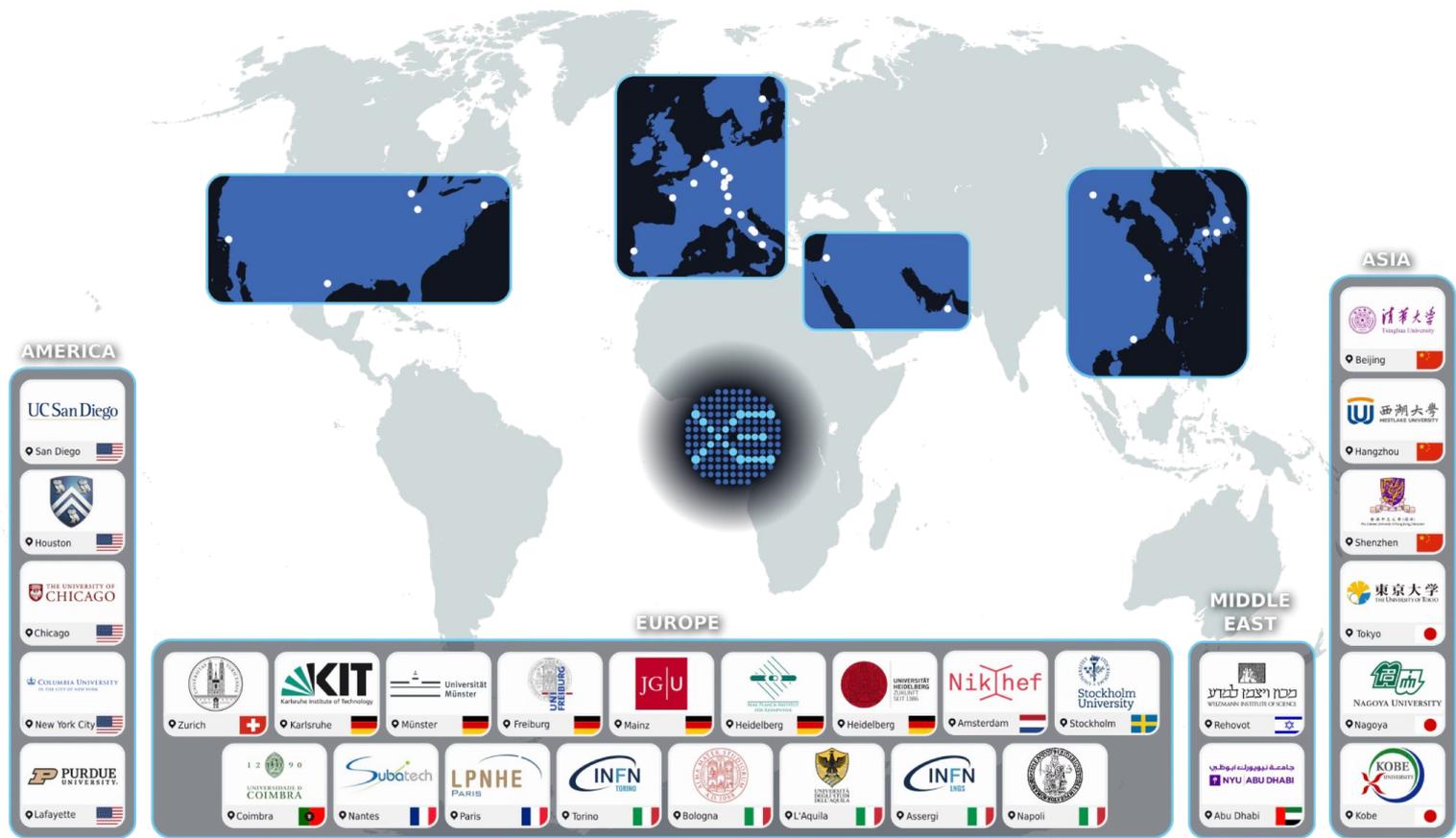


High mass

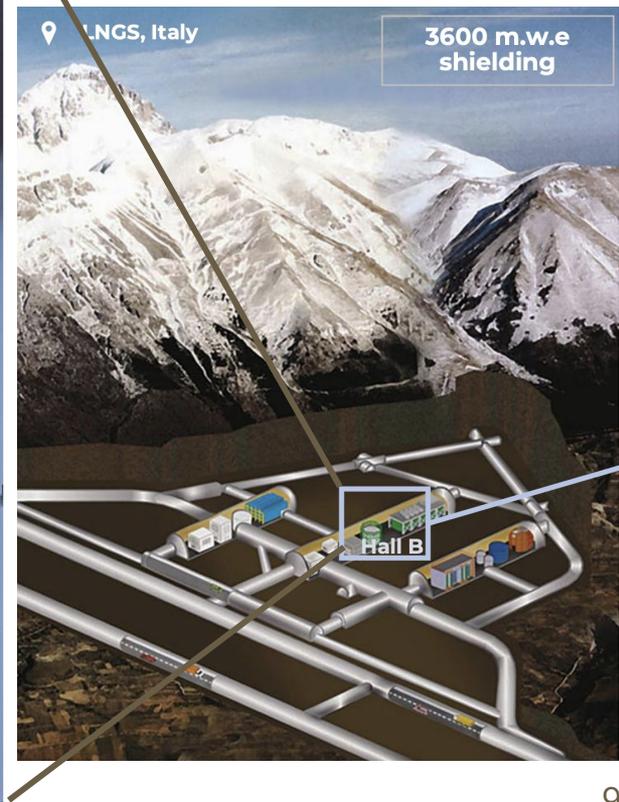
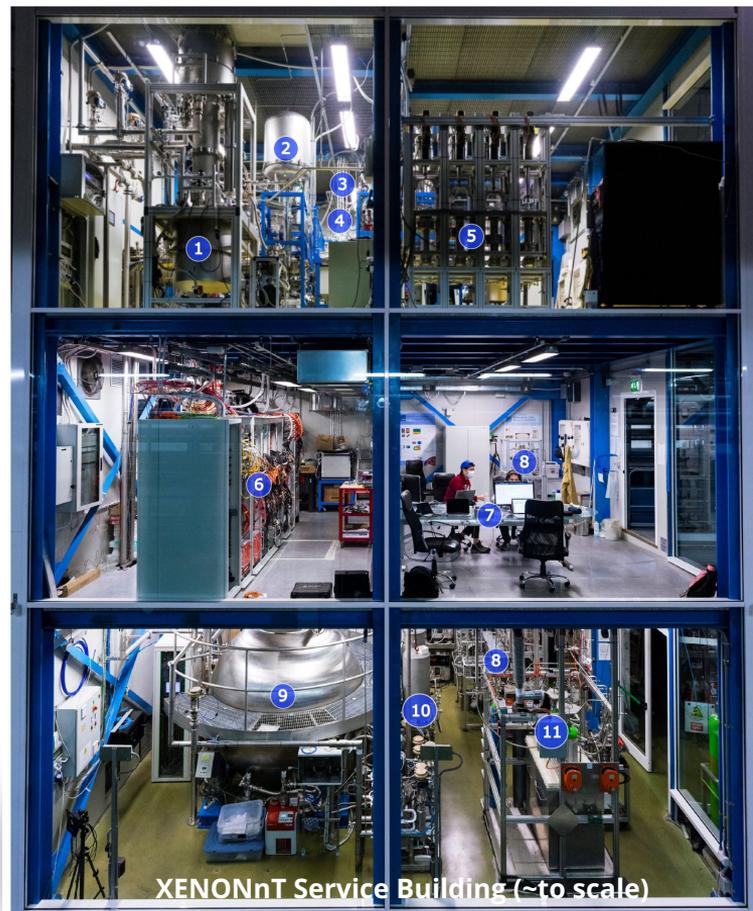
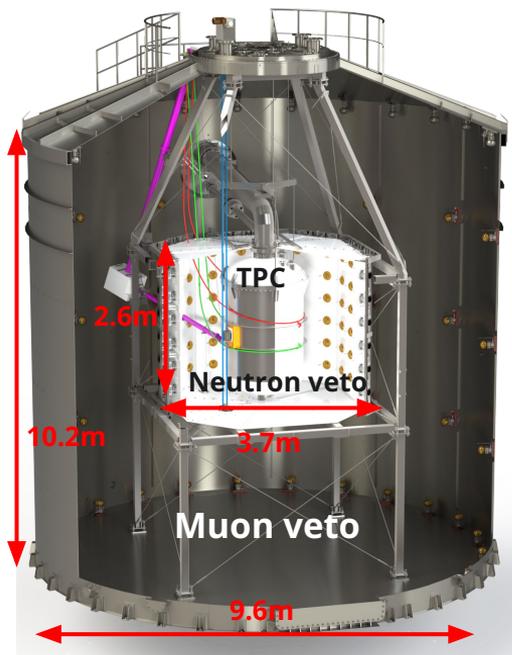
Low mass

XENONnT Experiment

The XENON Collaboration



XENONnT detector

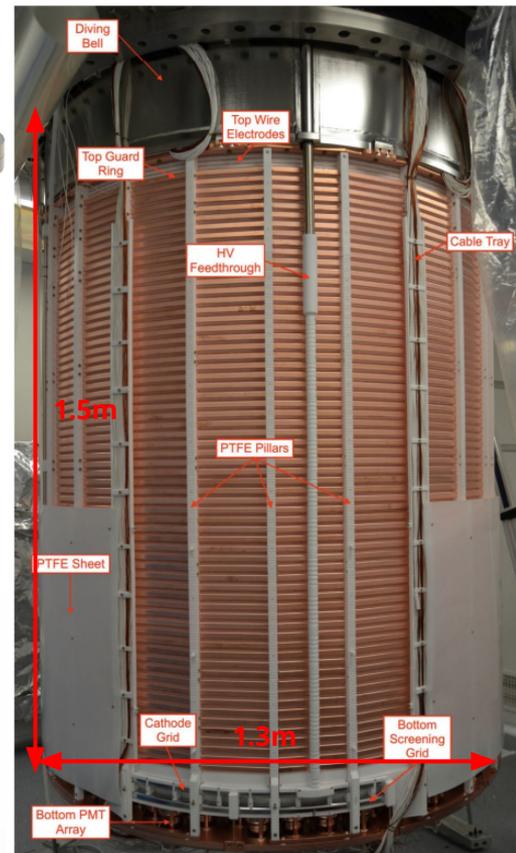
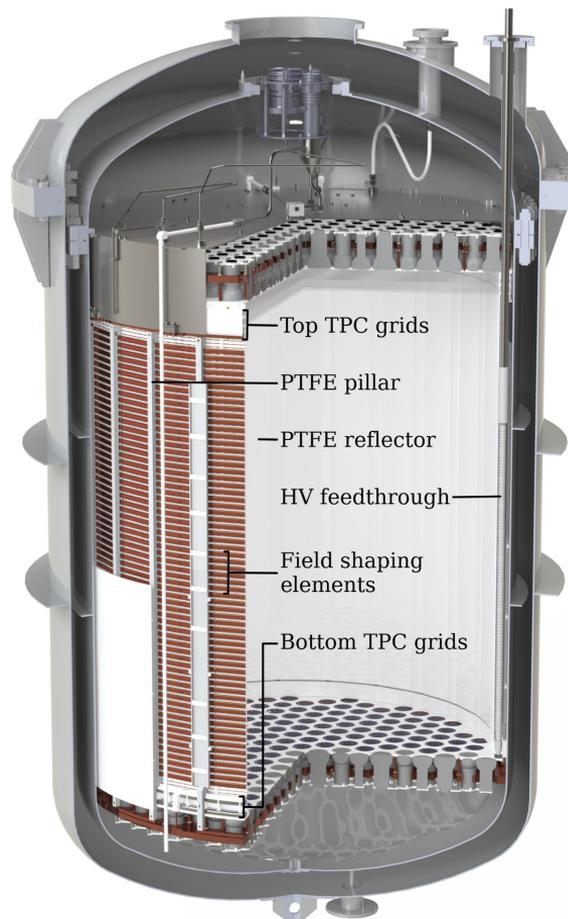


XENONnT detector

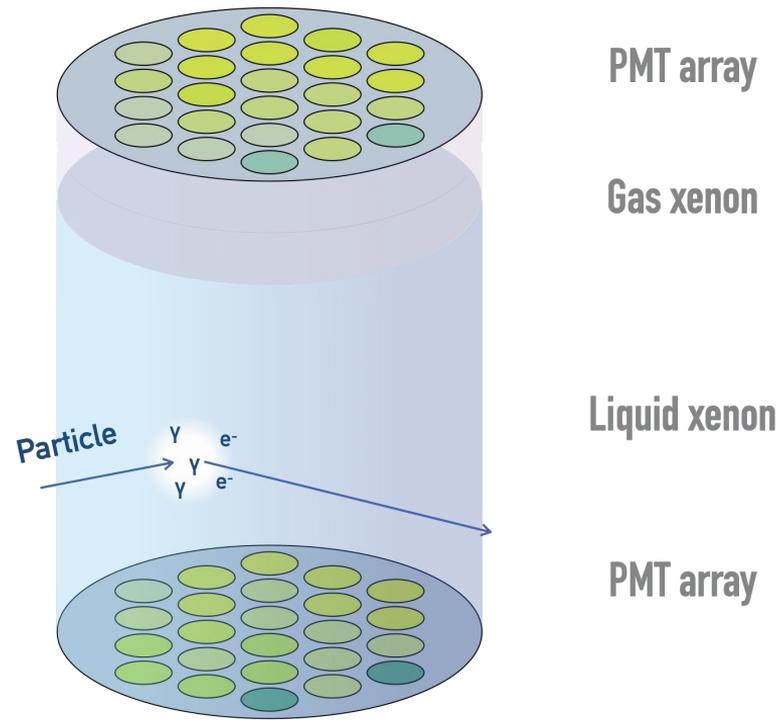
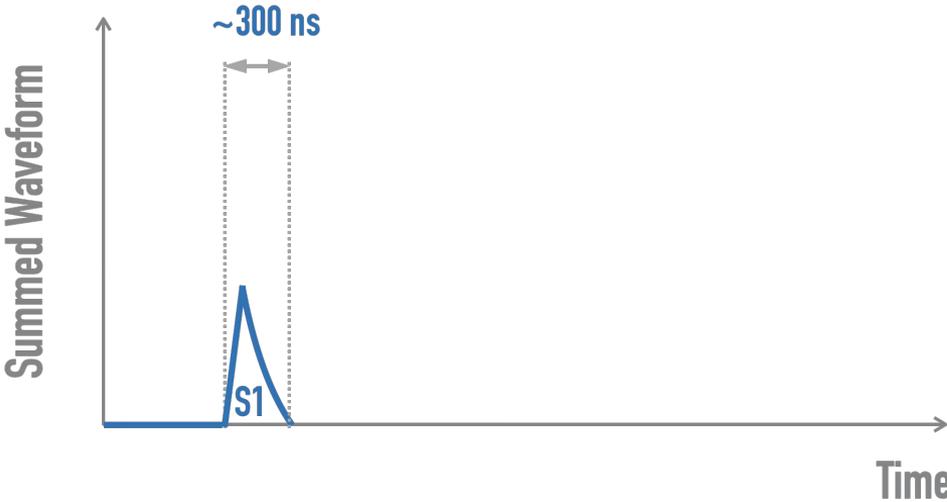
Time projection chamber (TPC)

- 8.6 tonne xenon in total, 6 tonne in active volume
- 23 V/cm drift field, ~ 2.9 kV/cm extraction field

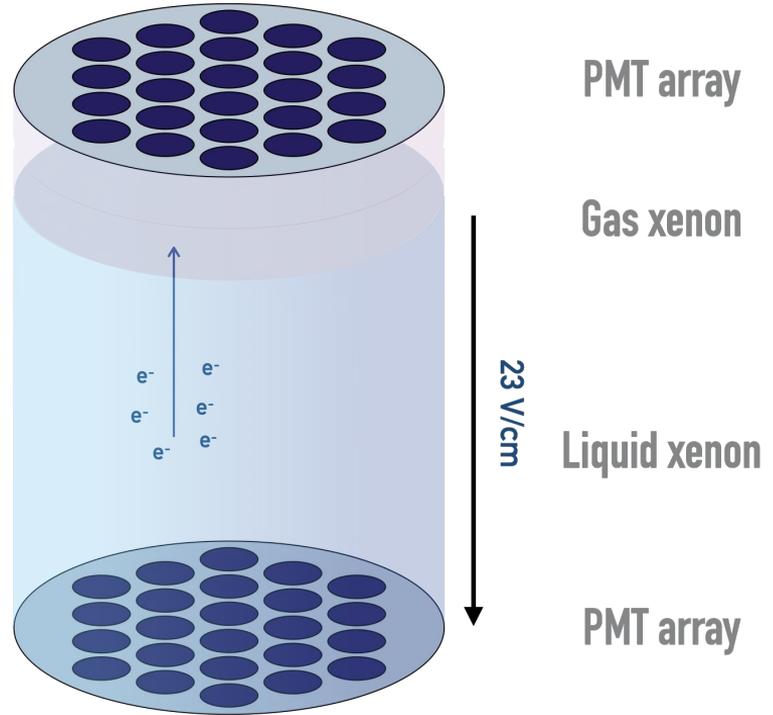
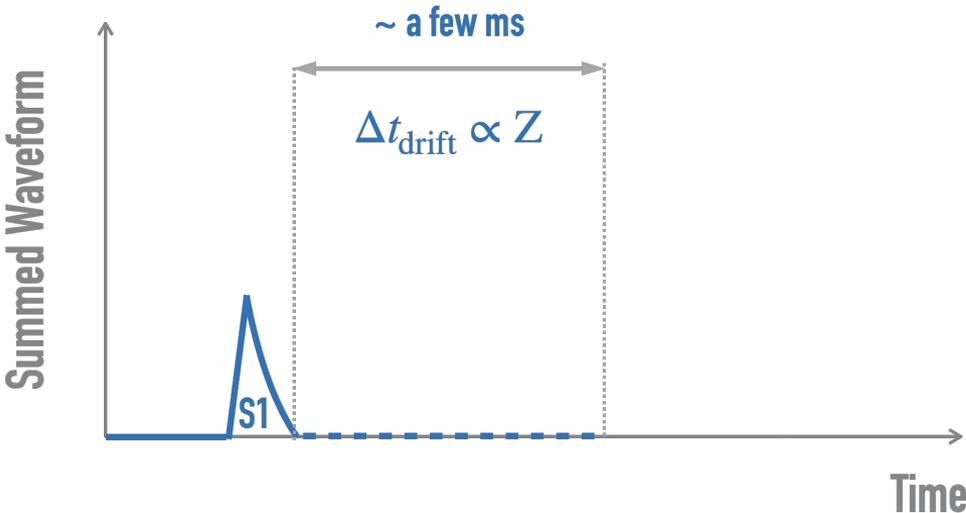
| Drift Length | Diameter | Sensitive Target | Drift Field |
|--------------|----------|------------------|-------------|
| 1.5 m | 1.32 m | 5.9 tonne | 23 V/cm |



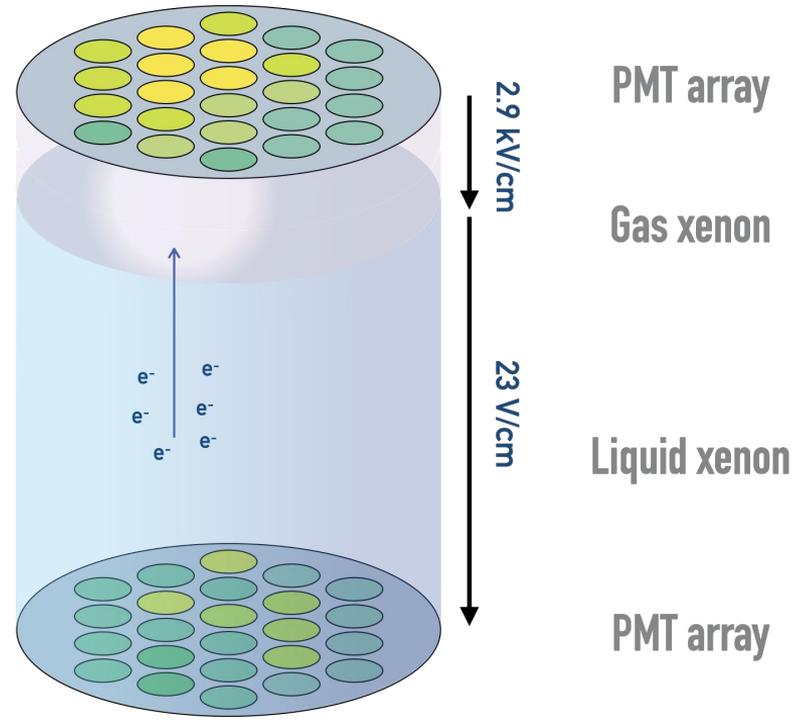
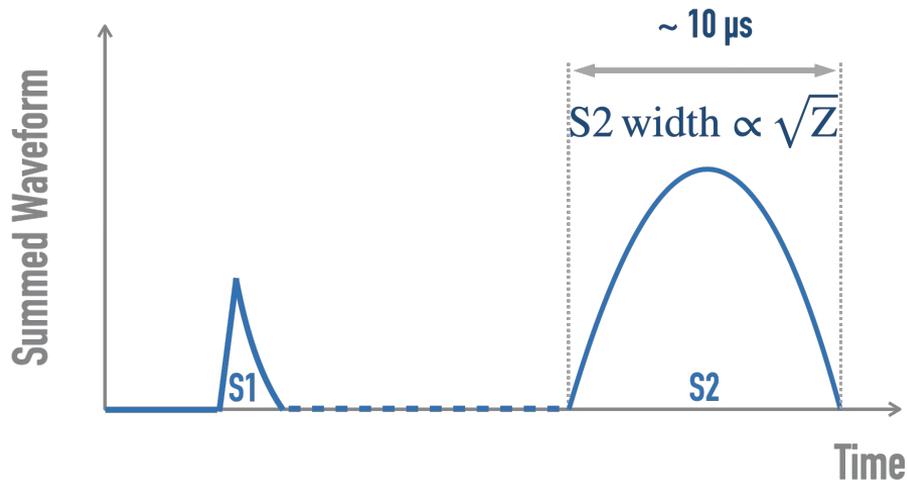
Dual-phase Xenon Time Projection Chamber (TPC)



Dual-phase Xenon Time Projection Chamber (TPC)



Dual-phase Xenon Time Projection Chamber (TPC)



Dual-phase Xenon Time Projection Chamber (TPC)

Detector observables

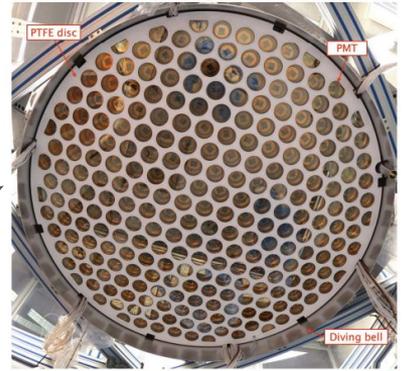
- S1:** prompt scintillation photons in LXe
- S2:** proportional scintillation from electrons in GXe-LXe
- Z:** drift time \times drift velocity
- X, Y:** from top PMT hit pattern
- Energy:** $S1 / [\# \text{ photons} / \text{keV}] + S2 / [\# \text{ electrons} / \text{keV}]$

Particle discrimination power

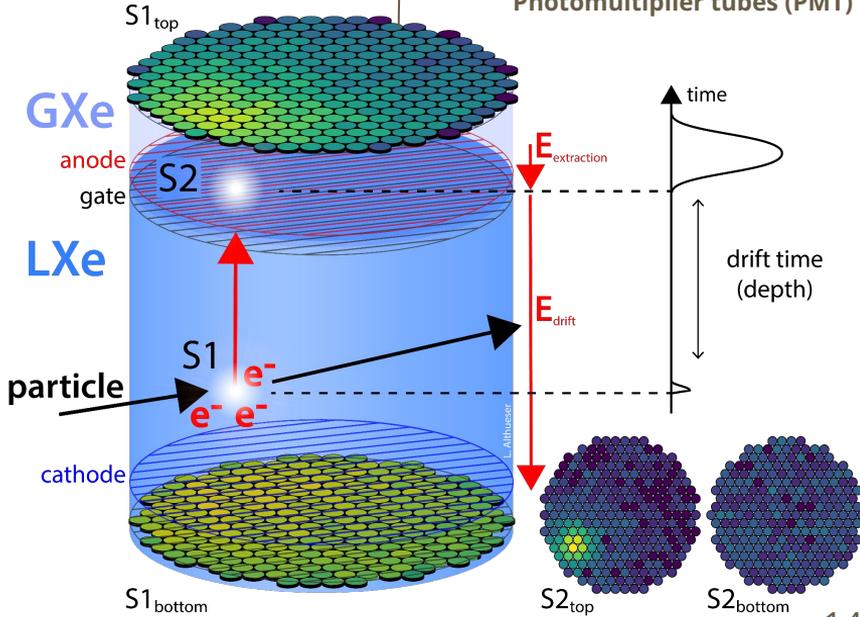
- Nuclear recoil (NR):** neutron, WIMP, ...
- Electronic recoil (ER):** beta, gamma, ...

Detectors:

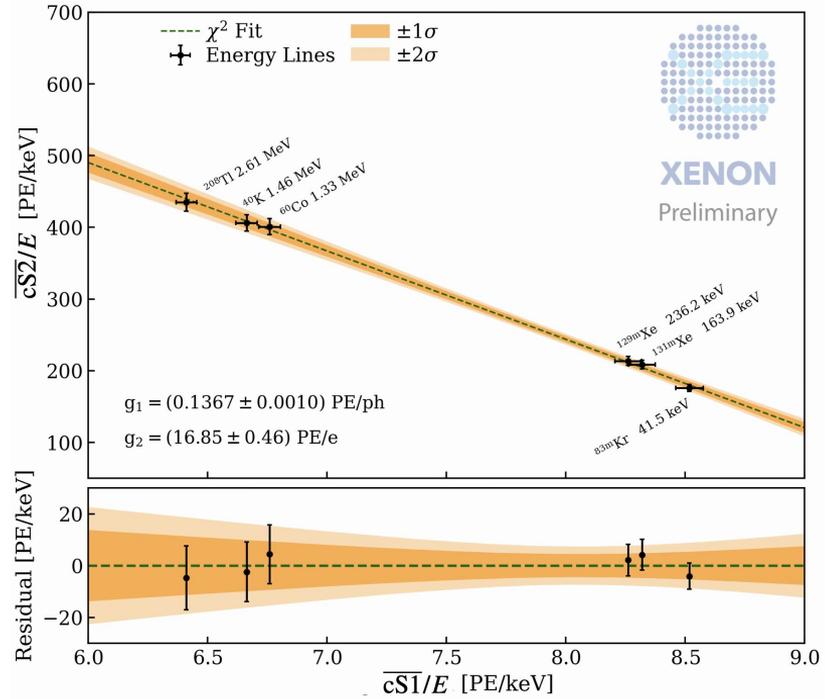
- XENONnT** (Gran Sasso, Italy), **LUX-ZEPLIN** (SURF, US), **PandaX-4T** (Jinping, China), **XLZD/PandaX-xT** (Planning), ...



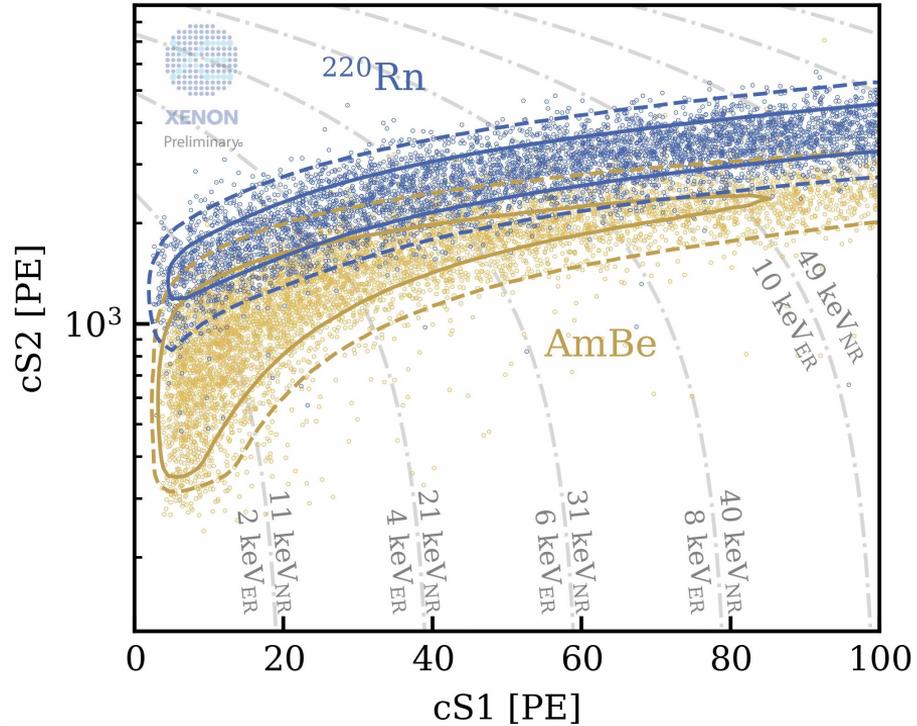
Photomultiplier tubes (PMT)



Energy calibrations and Particle discrimination



Mono-energetic peaks from xenon activation lines and calibration sources such as gamma-rays



^{220}Rn calibration - beta source
 AmBe calibration - neutron source via (α, n) reaction

XENONnT Science Runs

Upgrades and Status

SR0->SR1:

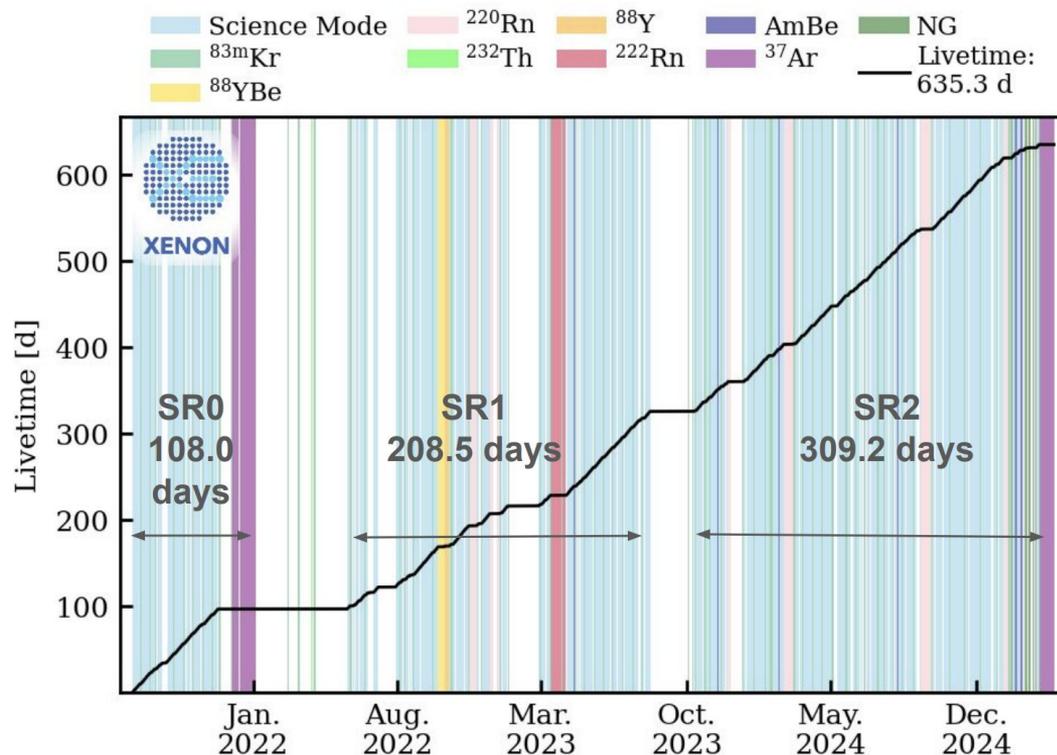
Liquid radon distillation, $1.8 \rightarrow 0.9 \mu\text{Bq/kg}$

SR1->SR2:

Injected Gd into the neutron Cherenkov veto, doubling the neutron tagging efficiency

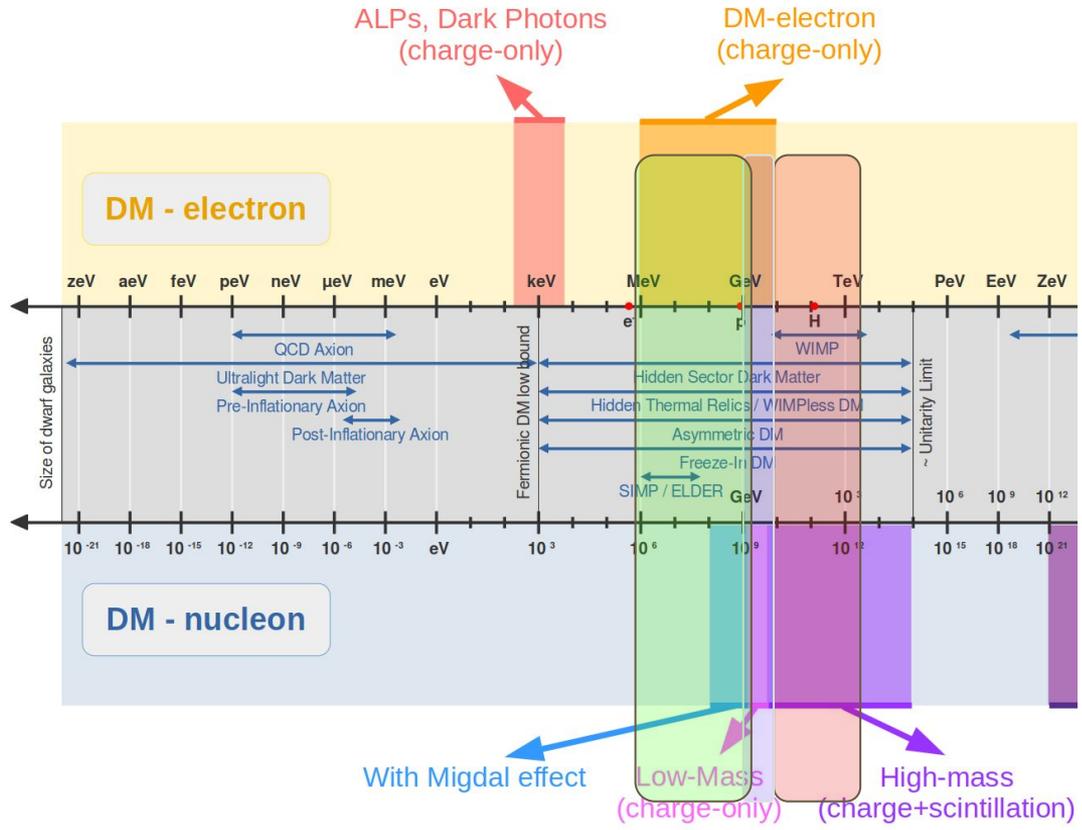
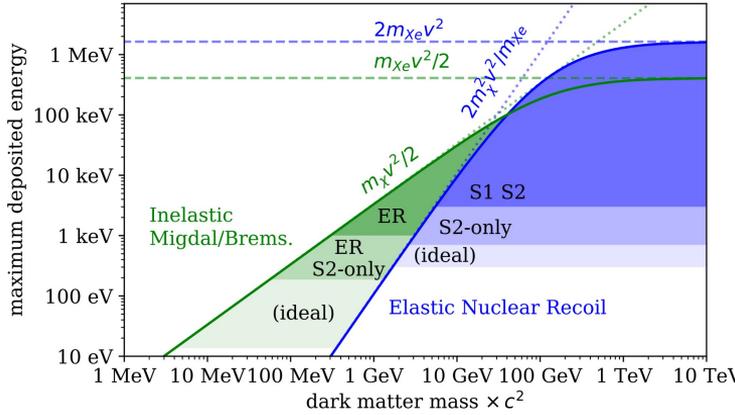
SR2-> SR3:

Detector upgrade and maintenance since early 2025, to enhance the drift field and fix flashing PMTs



Probe Dark Matter from MeV to TeV scale using XENONnT

XENONnT is kinematically sensitive to a wide range of dark matter candidates



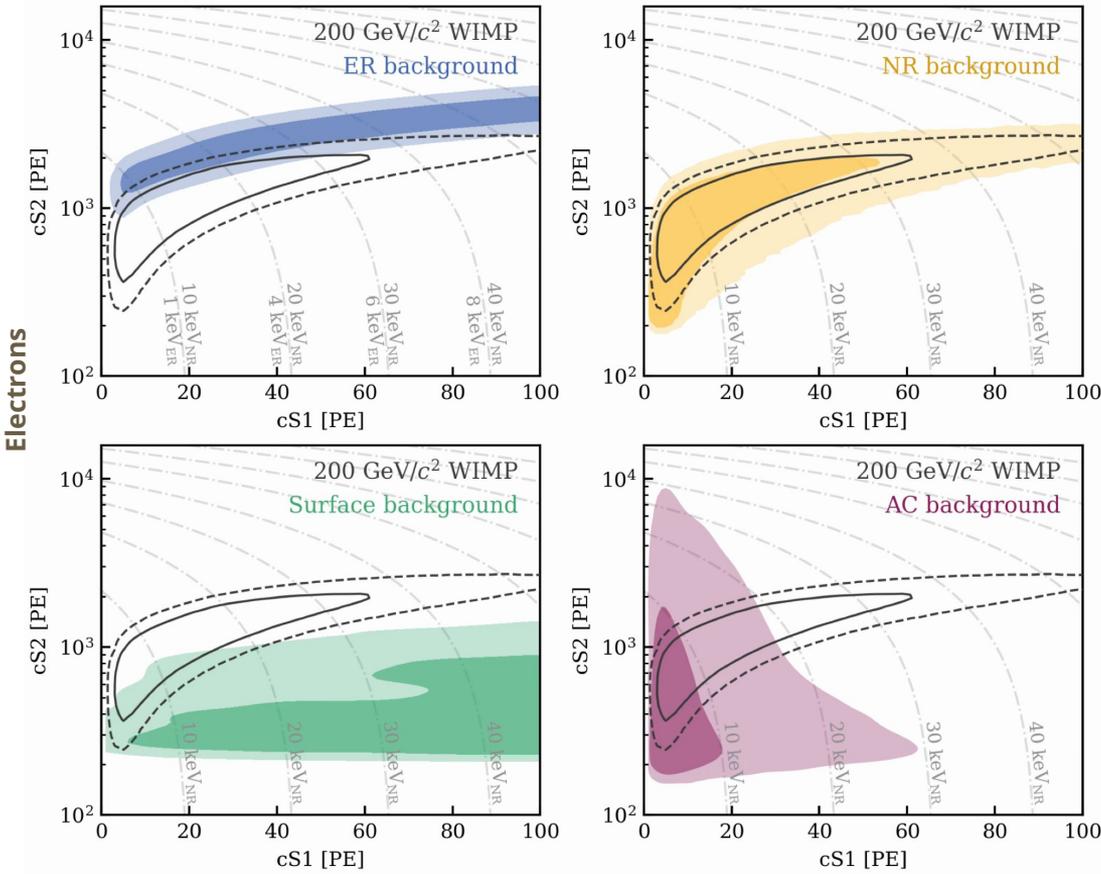
Search for Weakly Interacting Massive Particles (WIMPs)

Background models

Background discrimination is performed on the cS1-cS2 space

- Electronic recoil
- Nuclear recoil
- Surface background
- Accidental coincidence

In this section, I will focus on the WIMP search using 3.1 tonne*year of exposure using SR0+SR1.



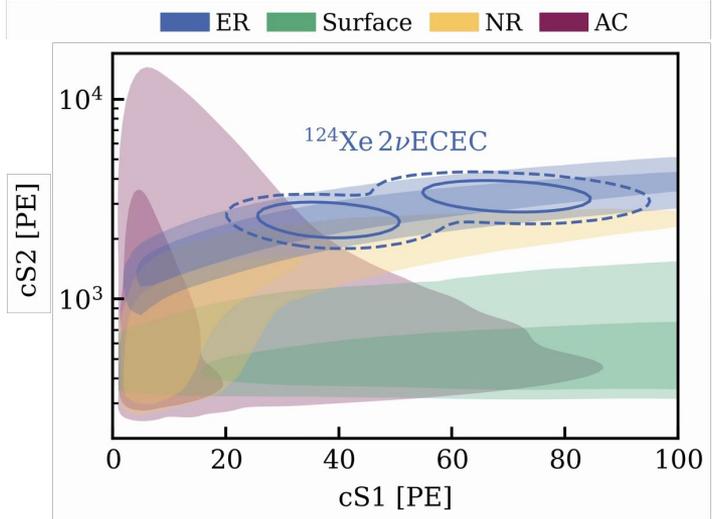
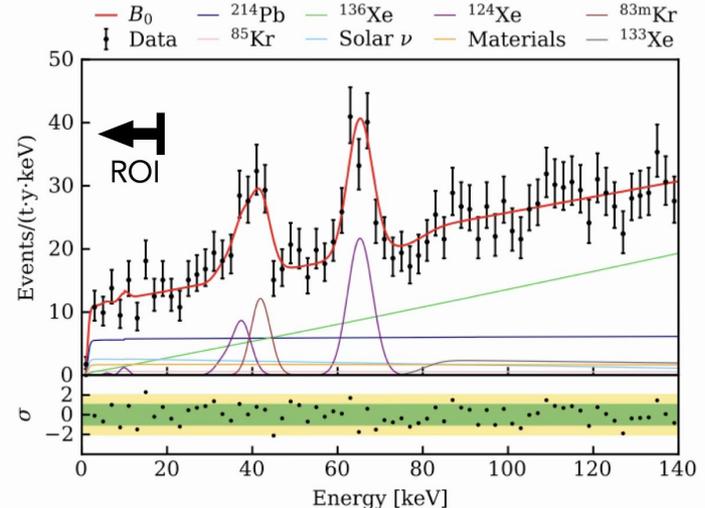
Photons

Background model - electronic recoil

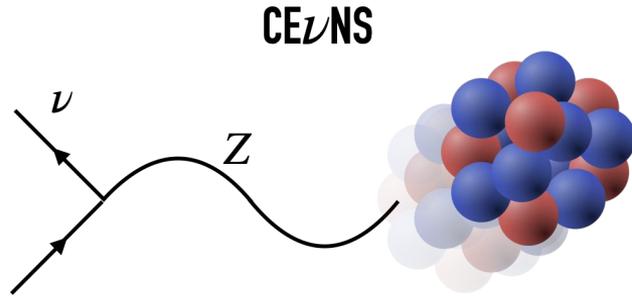
Background origins

- ^{214}Pb : dominant ER background, daughters of ^{222}Rn
- ^{85}Kr β -decays
- ^{124}Xe Double Electron Captures
- solar-pp $\nu - e$ elastic scattering, subdominant but irreducible

Shape modeled by ^{220}Rn ER calibration

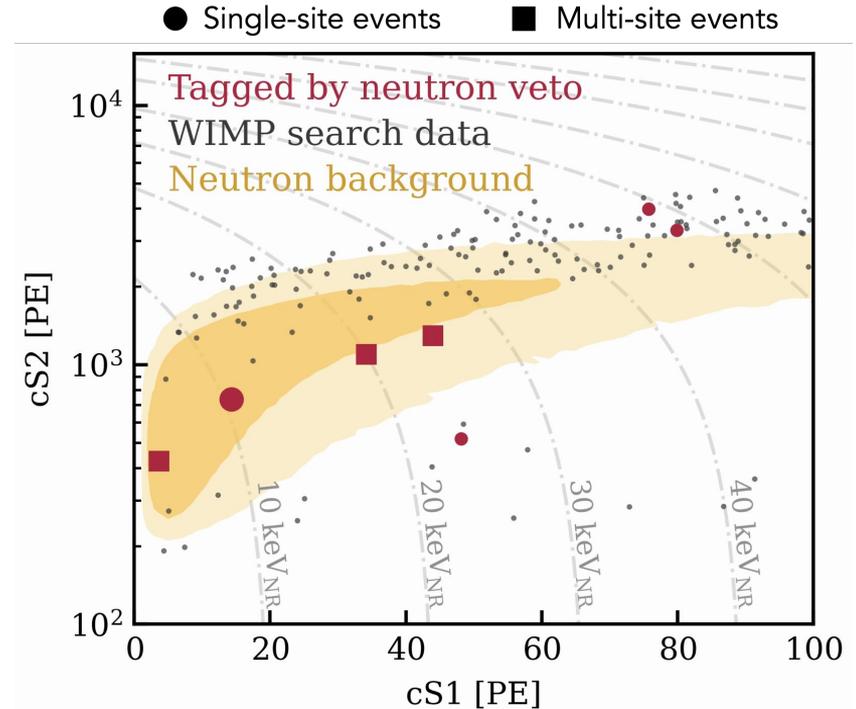


Background model – nuclear recoil

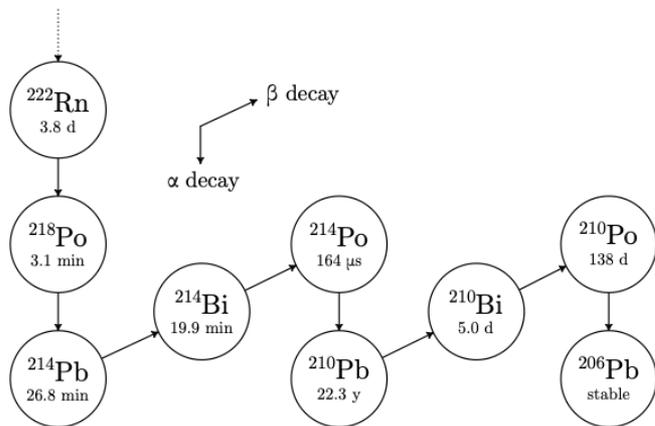


Background origins

- Coherent elastic neutrino-nucleus scattering (CE ν NS) from solar neutrinos (irreducible)
- Radiogenic neutrons, suppressed by neutron veto, single-site selection

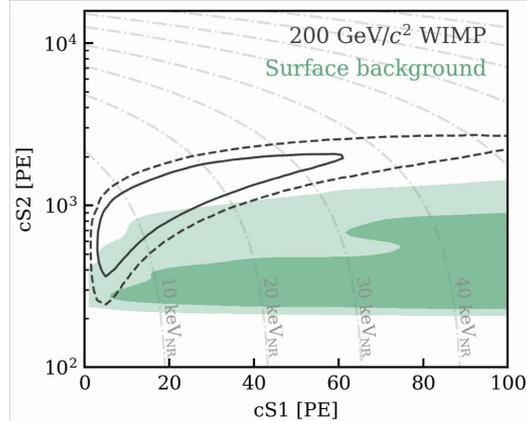
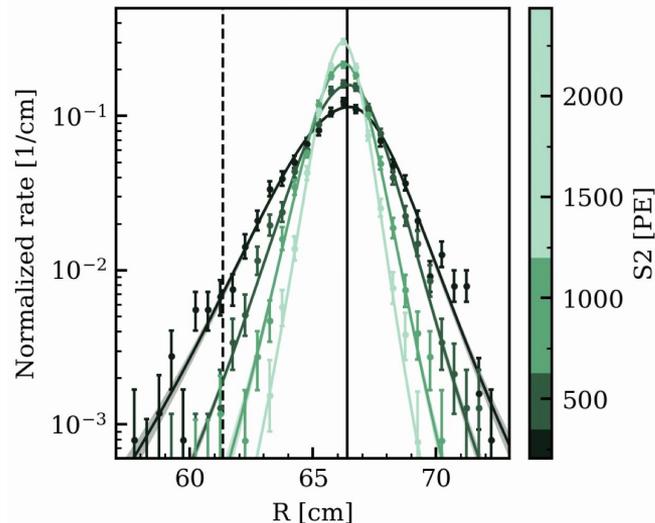


Background model – surface background



Background origins

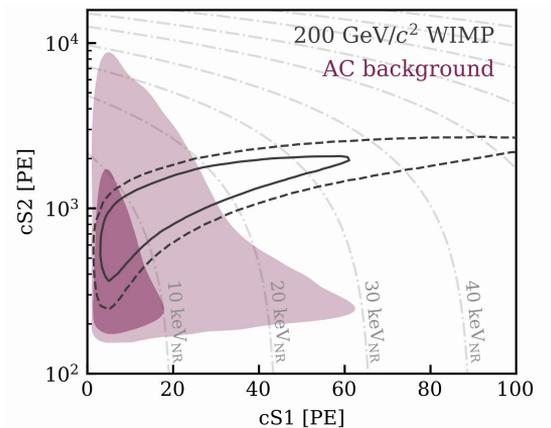
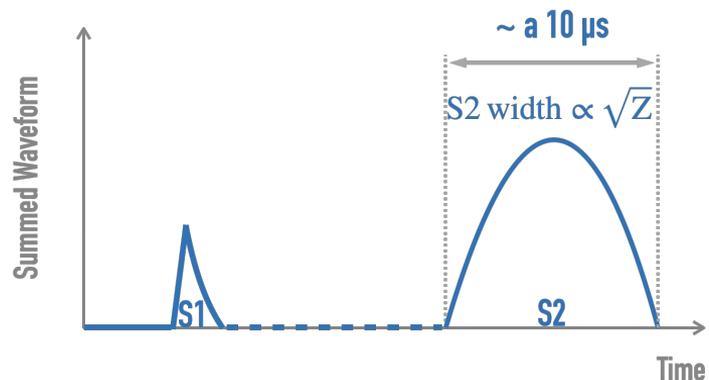
- From plate-out of ^{210}Pb daughters on PTFE wall
- Rejected by a radial cut
- Near-wall electrons could terminate at the wall during drift \rightarrow surface background features lower S_2
- Modeled by a KDE on selected surface events



Background model – accidental coincidence (AC)

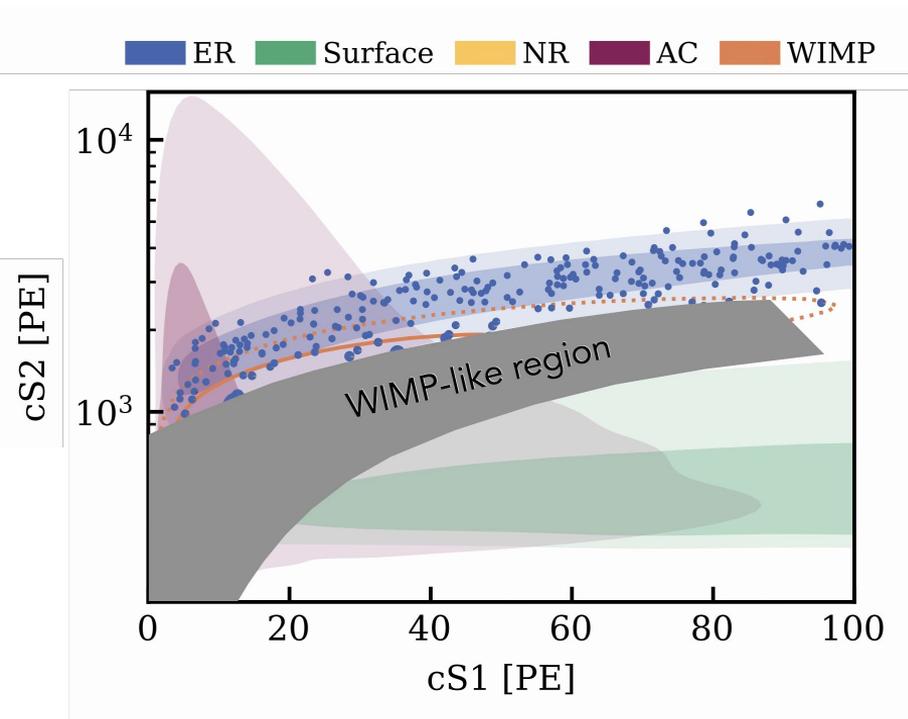
Background origins

- From accidental pairing of isolated S1 and isolated S2
- Will be dominant in the GeV DM searches (next section).
- AC origin understood in S2-only searches (the last section).



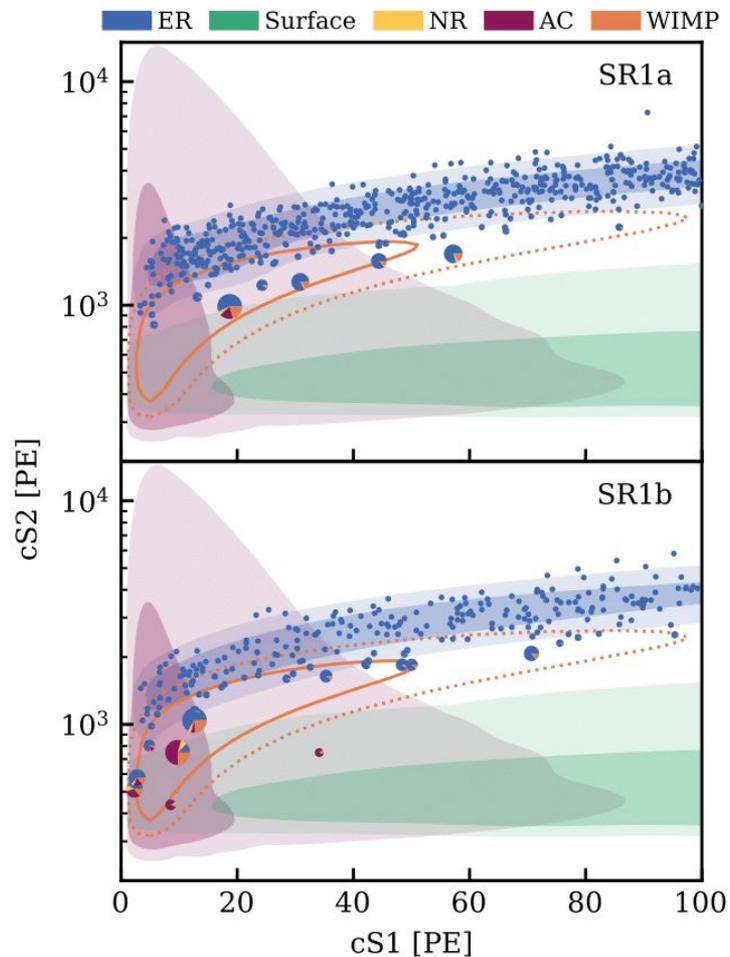
Blinding strategy

- To avoid human bias, the dataset is initially *blinded*
- To verify the models, staged unblinding is applied
 - Multi-site and neutron-veto-tagged events are unblinded to test neutron model
 - Goodness-of-fit tests are applied for each model.
- After all models are validated, the WIMP-like region is unblinded.



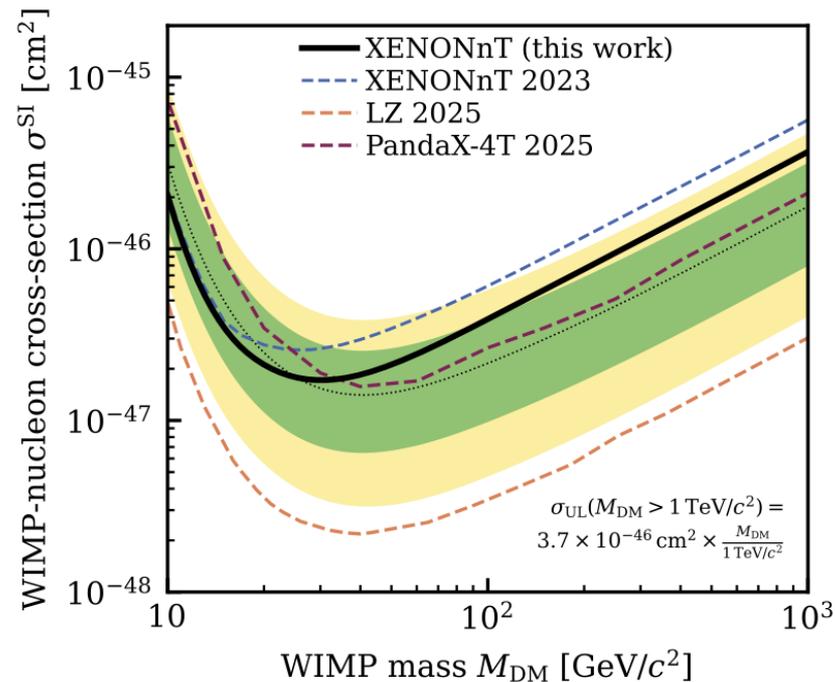
After unblinding

- To avoid human bias, the dataset is initially *blinded*
- To verify the models, staged unblinding is applied
 - Multi-site and neutron-veto-tagged events are unblinded to test neutron model
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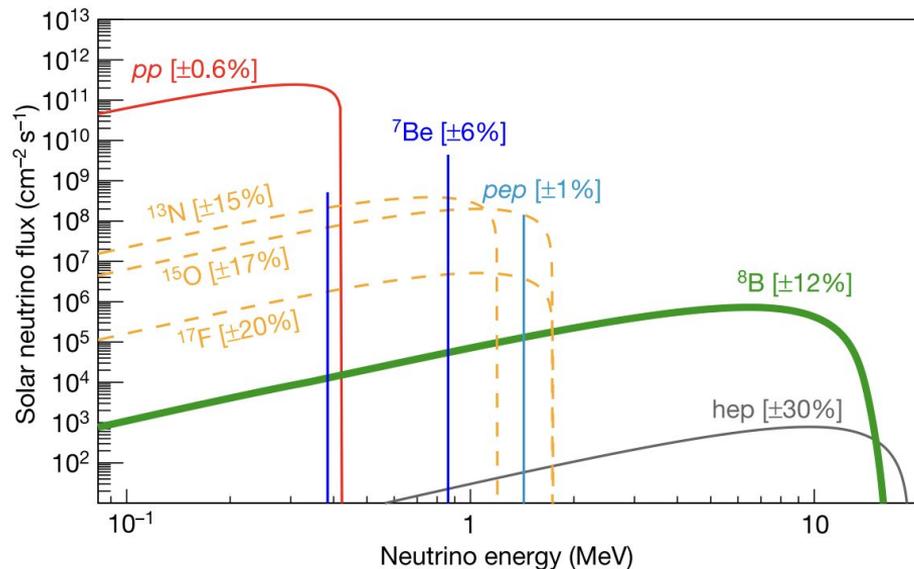
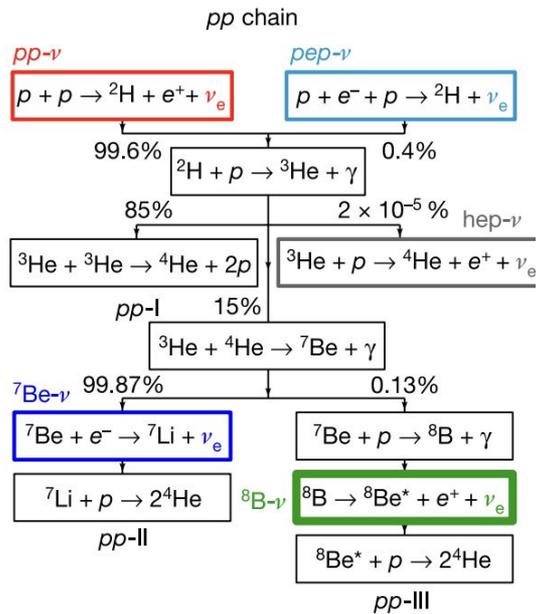
WIMP search result

- Unbinned likelihood function in (cS1, cS2, R) space
- **No significant excess**
- We report the upper limit of WIMP-nucleon cross section (90% confidence level).
 - For higher masses, $\sigma_{\text{UL}} \sim n_{\text{DM}}^{-1} \sim M_{\text{DM}}$
 - For lower masses, the sensitivity is limited by the energy threshold



Search for Solar Neutrino and Light Dark Matter

Solar neutrinos



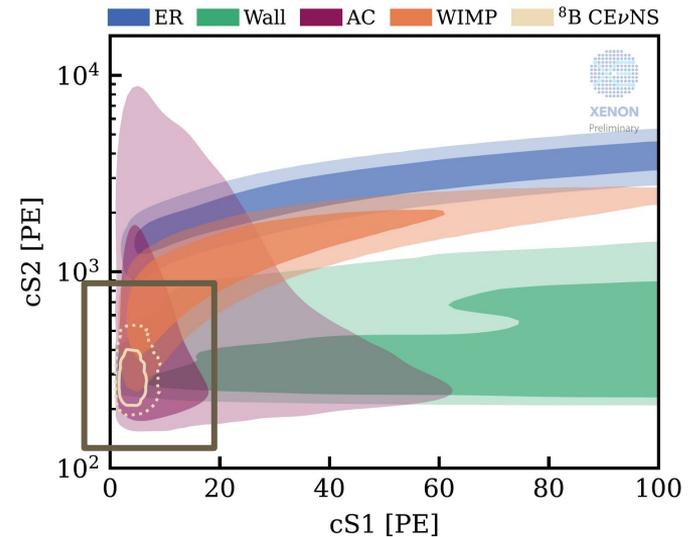
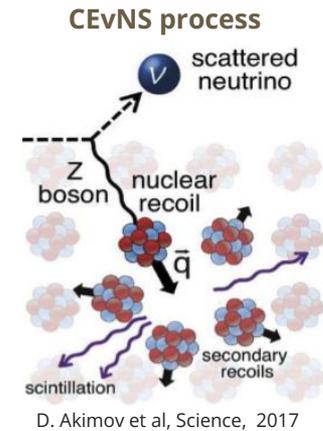
- Neutrino flux on Earth predicted by the Standard Solar Model
- Measured by experiments such as Sudbury Neutrino Observatory and Borexino
- **ERs** via ν -**e scattering**, and **NRs** via **coherent elastic neutrino-nucleus scattering (CE ν NS)**
- Irreducible background for low-energy dark matter searches

Neutrino CEvNS and Dark Matter

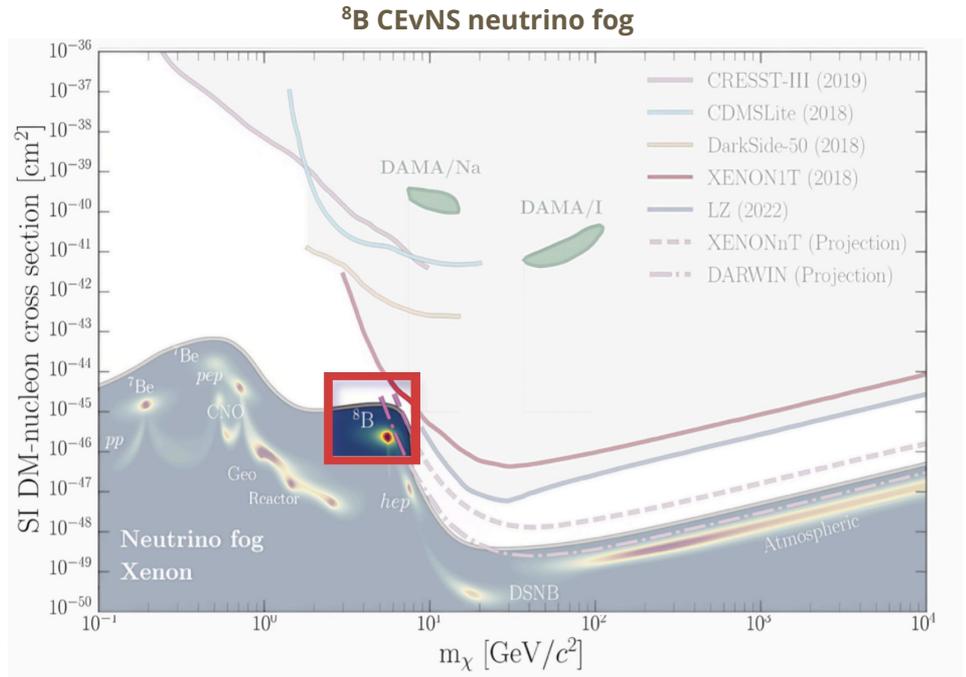
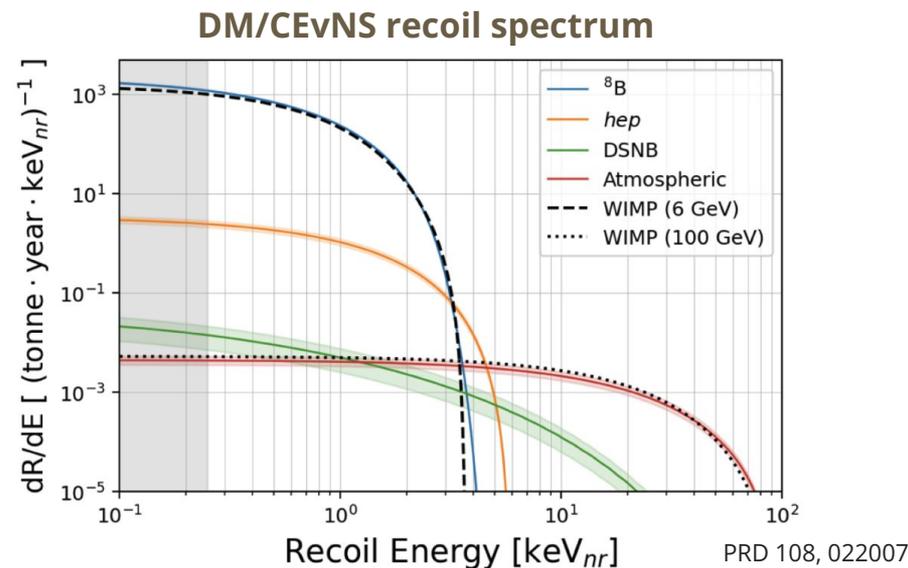
Neutrino CEvNS and dark matter detection stories are connected from the start:

- **In 1984**, Drukier and Stodolsky proposed to use coherent elastic neutrino-nucleus scattering (CEvNS) to detect low-energy neutrinos
- **In 1985**, Goodman and Witten proposed to search for the scattering of DM particles with atomic nuclei in the same formalism
- **In 2017**, observed by COHERENT with neutrino from spallation neutron source

The main experimental challenge is the detection of keV scale nuclear recoils



Neutrino fog and the low energy frontier



Neutrino CEvNS: Irreducible background for dark matter searches

Solar ^8B neutrino fog \sim 6 GeV dark matter \sim 300 recoils/(tonne*year) in [0.5, 5] keV_{NR}

Physics at the detector threshold

Challenges: Low detection efficiency

- $\text{keV}_{\text{nr}} \sim 5$ photons and 6 electrons / keV_{NR}
- Light collection efficiency $\sim 15\%$
- S1 photon detection is the limitation!

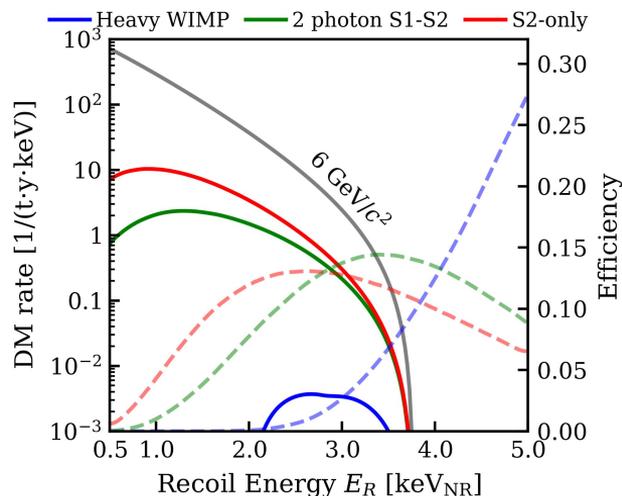
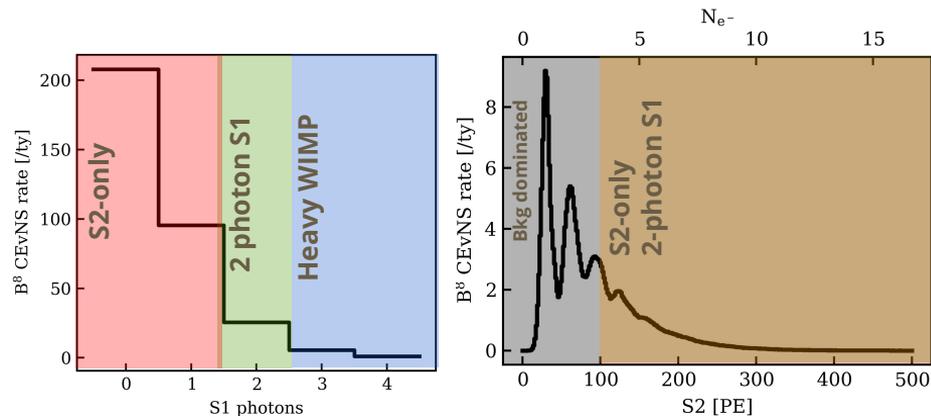
Solution: Lower S1 threshold

- Two 2 photon S1-S2 (x20 signal)
- S2-only (x90 signal)

Challenges: keV NR model and instrumental background

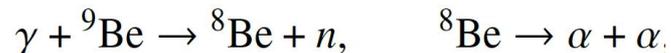
Solutions:

- Dedicated low-energy NR calibration
- Advanced background modeling and mitigation

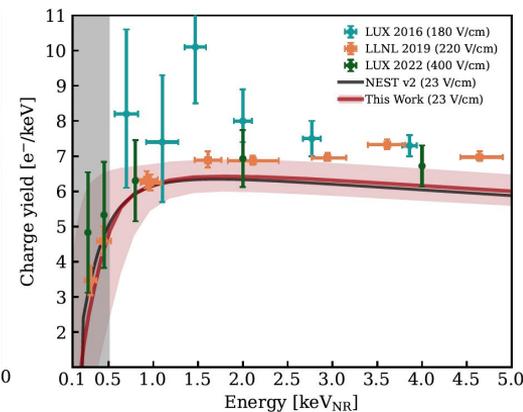
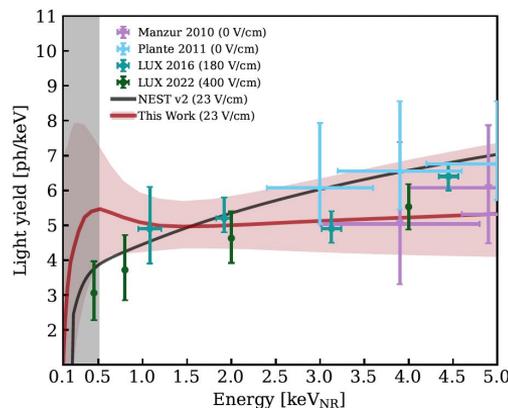
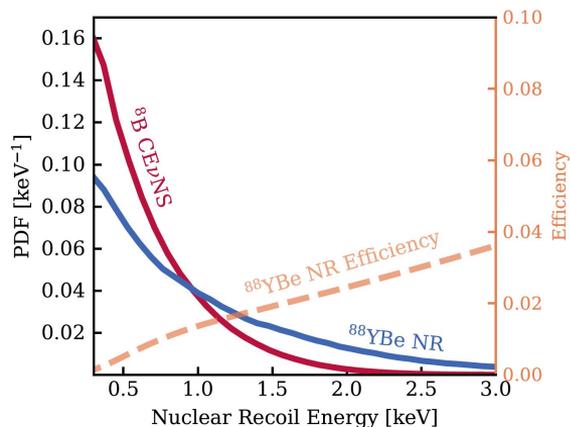
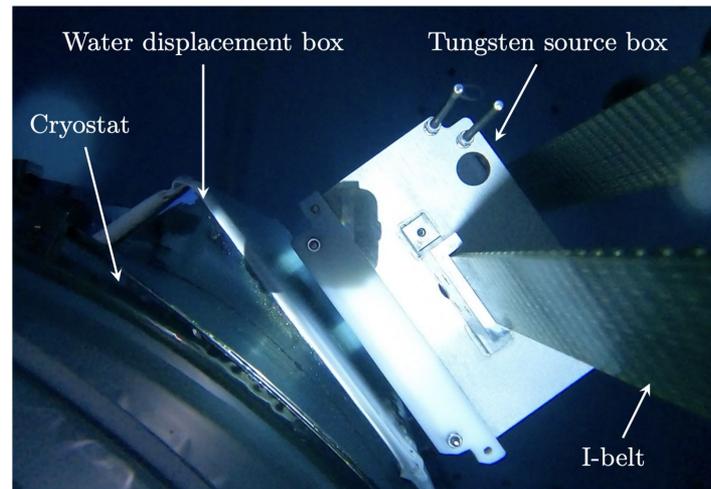


YBe: keV-scale neutron calibration

- A photoneutron source ^{88}YBe is used to calibrate the detector.
- ^{88}Y decays emit 1.84 MeV γ -rays, producing 152 keV quasi-monoenergetic neutrons via photoneutron production of Be



- On average, ~ 5 photon and ~ 6 electrons will be created per keV nuclear recoils.



Accidental background

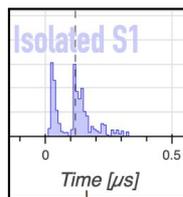
Main background: Accidentally pair of S1 and S2

S1 rate ~ 15 Hz, S2 rate ~ 0.15 Hz

Rate before mitigation \Rightarrow 400 events per day

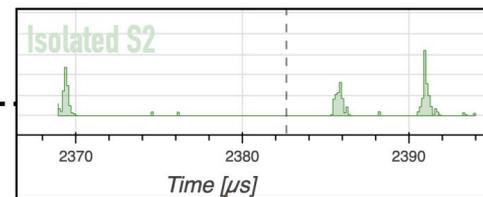
An instrumental fog before reaching the physics

Solution: Machine-learning driven,
multidimensional mitigation campaign



NOT physically
correlated

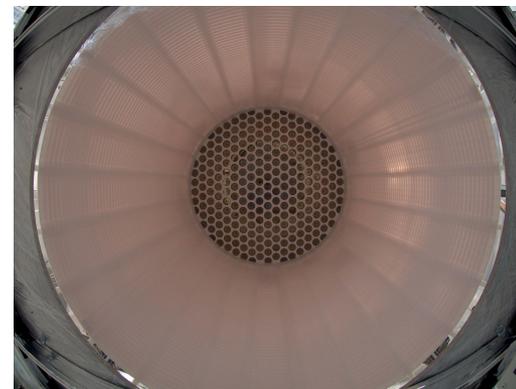
“Accidental”



PMT photon emission?



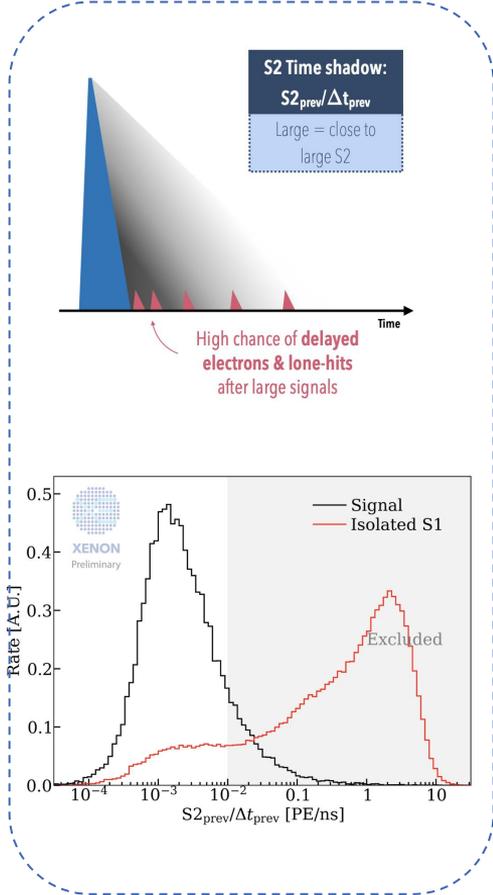
Electrode charge emission?
Liquid xenon impurity?



Backgrounds mitigation S1-S2

Correlation:

Temporal and spatial correlation to other high-energy events

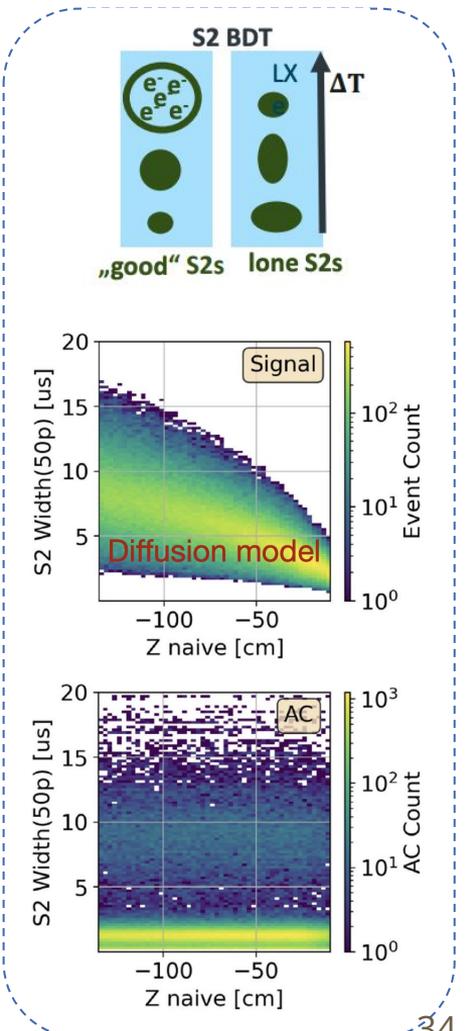
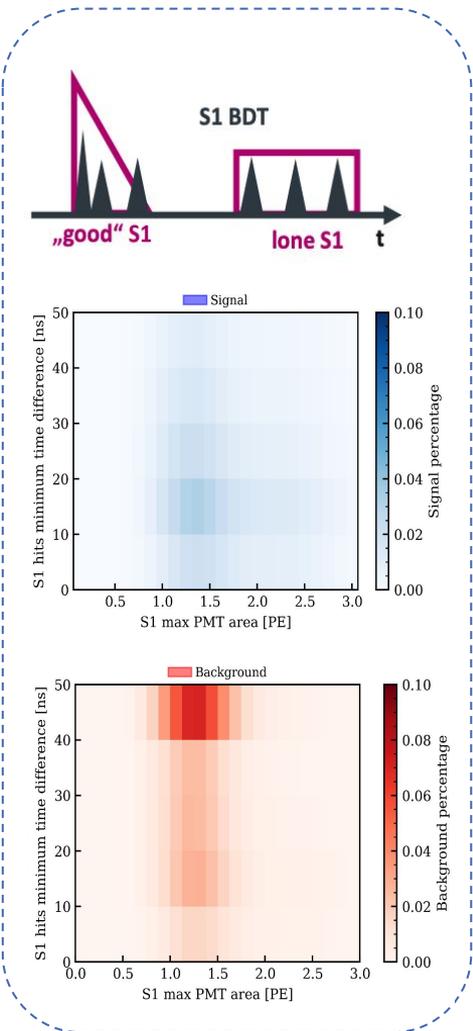


S1 waveform:

S1 width and optical patterns

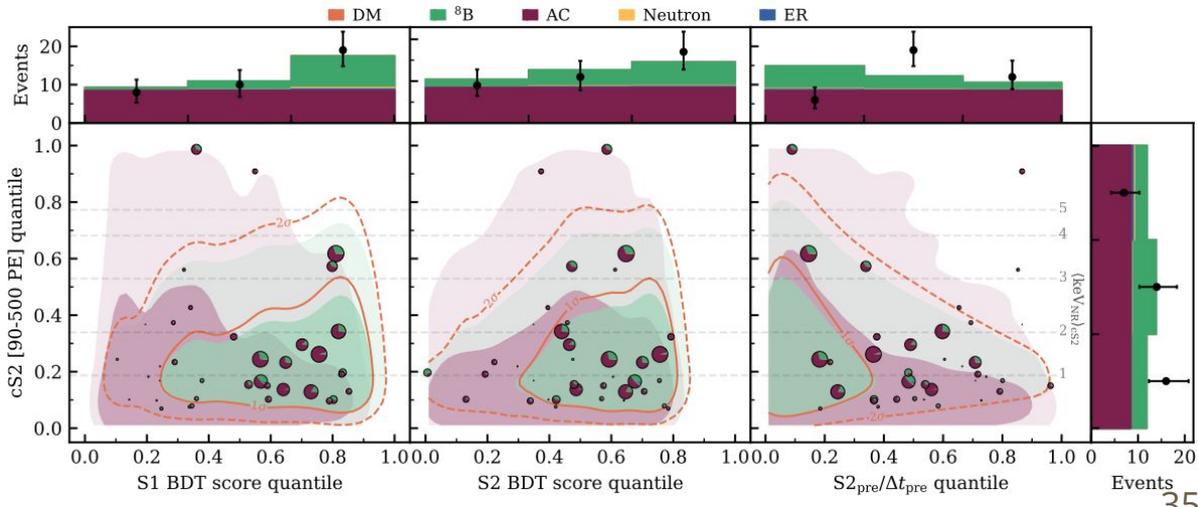
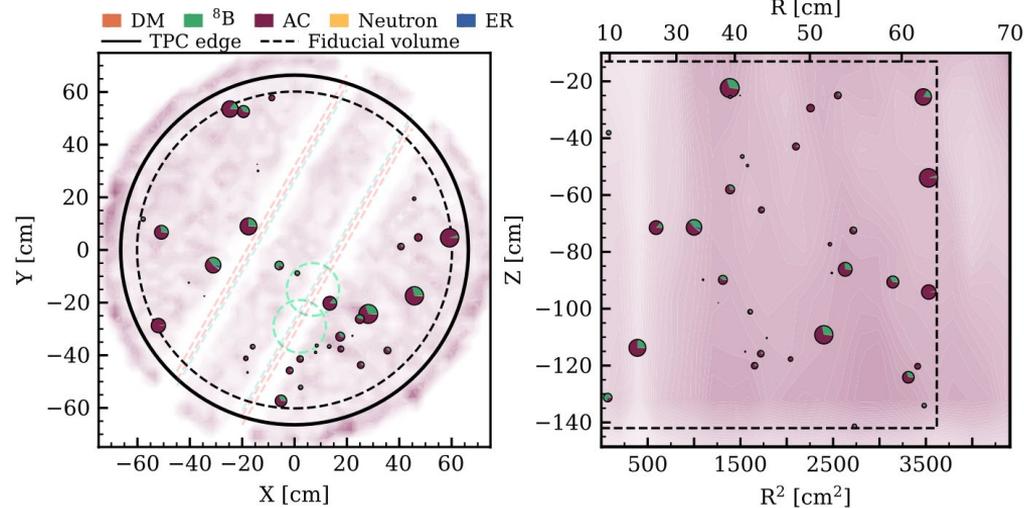
S2 waveform:

Drift time ~ S2 width



Observed events

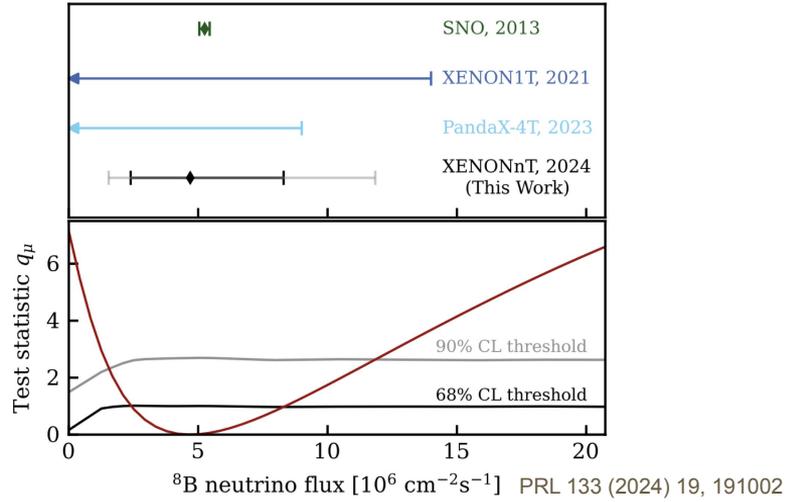
Unblinding reveals **37** observed events, with expectation of **38** events.



A glimpse of the solar neutrinos

| Component | Expectation | 6 GeV/c ² | |
|----------------------------|--------------------------------------|--------------------------------------|---|
| SI-DM | ... | 0.0 | (0.0) |
| ⁸ B CE ν NS | 11.9 ^{+4.5} _{-4.2} | 11.4 ^{+2.7} _{-2.6} | (6.0 \pm 1.4) |
| AC | 25.3 \pm 1.2 | 25.3 \pm 1.2 | (4.1 \pm 0.2) |
| ER | 0.7 \pm 0.7 | 0.5 ^{+0.6} _{-0.5} | (0.3 \pm 0.3) |
| Neutron | 0.5 ^{+0.2} _{-0.3} | 0.5 \pm 0.3 | (0.2 \pm 0.1) |
| Total background | 38.3 ^{+4.7} _{-4.4} | 37.7 ^{+3.0} _{-2.9} | (10.6 ^{+1.5} _{-1.4}) |
| Observed | ... | 37 | (10) |

In signal-like region
Neutrinos > Instrumental bkg!



No significant excess above the background model

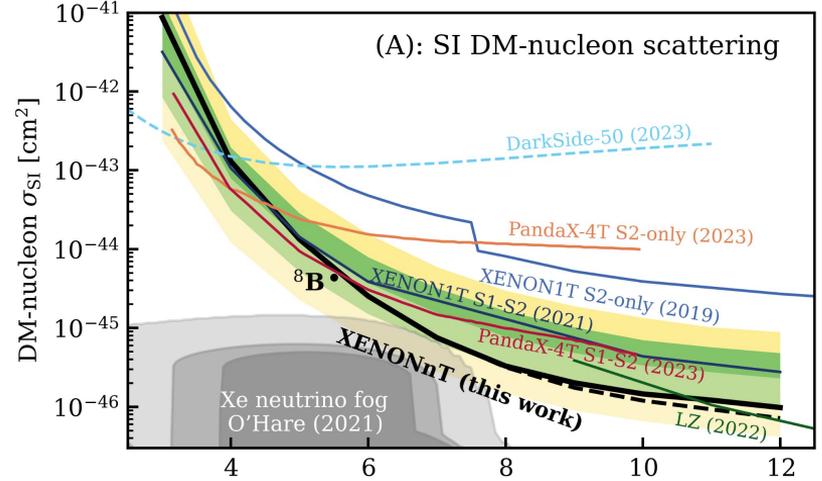
Indication of solar neutrinos, significance **2.73 σ**

Measured ⁸B flux: $4.7^{+3.6}_{-2.6} \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$

Further questions:

Origin of the instrumental backgrounds?

Ways to get closer to the neutrino fog?



Search for Light Dark Matter with Ionizations

Science case of “S2-only”

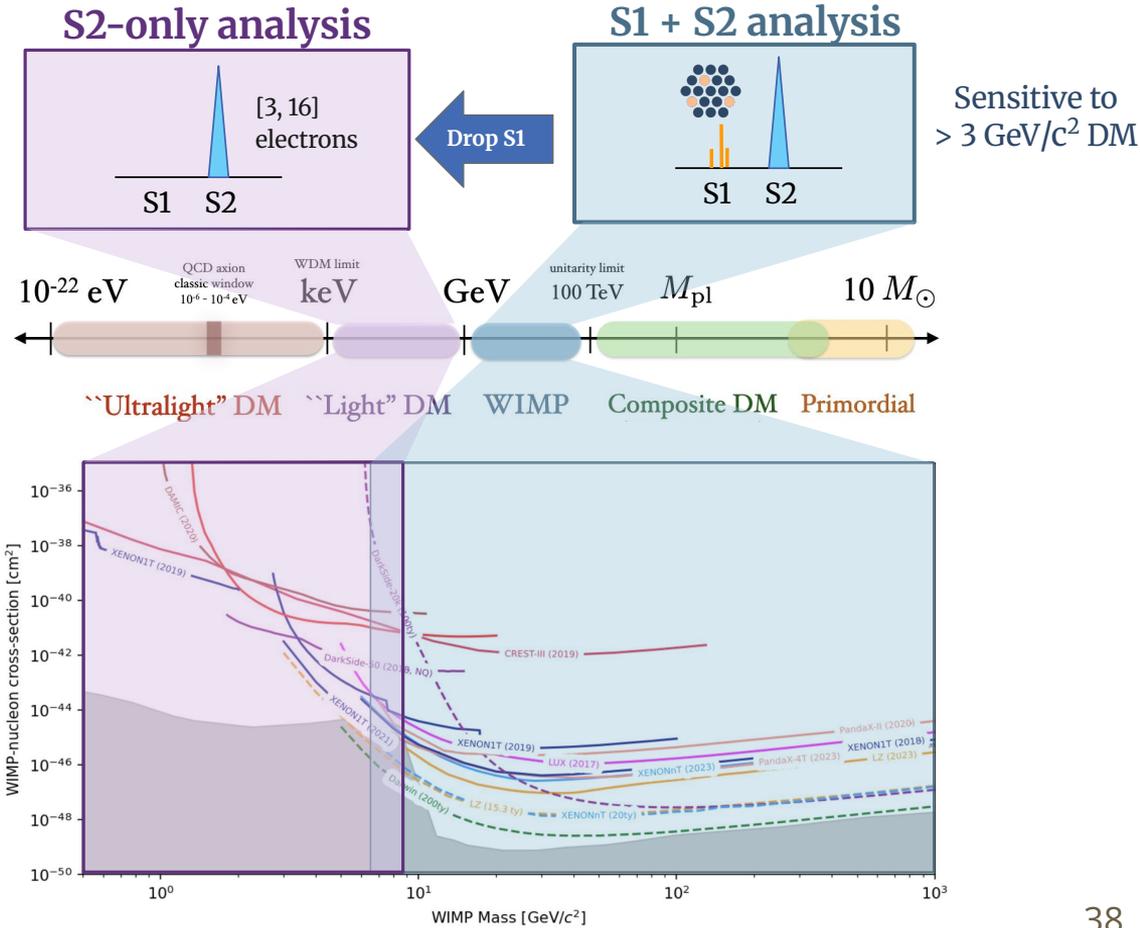
Advantages

Dropping S1 opens the door to a wide range of dark matter candidates of NR recoil [0.5, 5] keV or ER recoil [0.04, 0.7] keV.

- DM-nucleon [3, 12] GeV
- DM-electron [0.05, 10] GeV
- Axion-like particles/dark photons [0.03, 0.7] keV
- Other neutrino physics...

Challenges:

- No established analysis methods
- No event depth info without drift time
- Non-existent background model



Implication of a background model

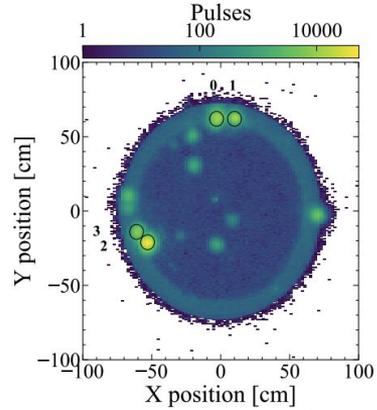
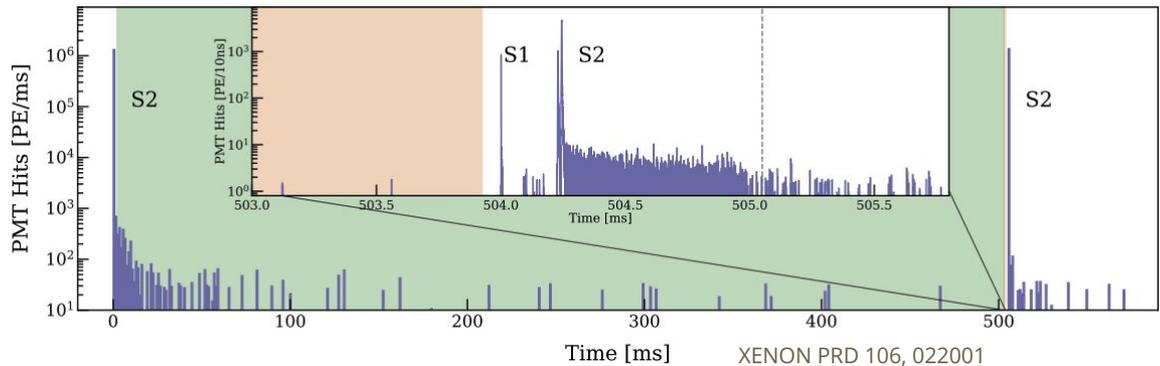
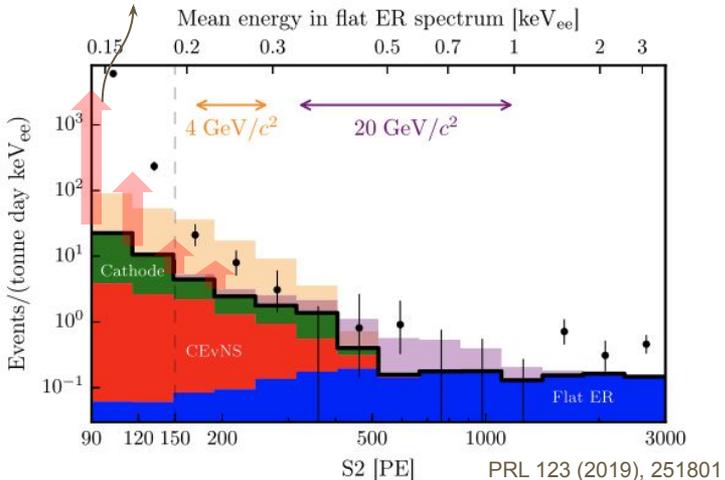
Without a complete background model:

- Any excess can be DM signal
- Limit setting only, no discovery power

Known phenomenology includes:

- Electron emission after high-energy events (delayed electron)
- Electrode radioactivity (cathode, gate, ...)

Are these dark matter or backgrounds?



Instrumental background origins

Electrodes/Gas background

Suppressed by S2 width and optical pattern (negligible)

Delayed electrons (DE) pile-up Accidental electrons (AE) pile-up

Suppressed by correlation and optical pattern

Wall background

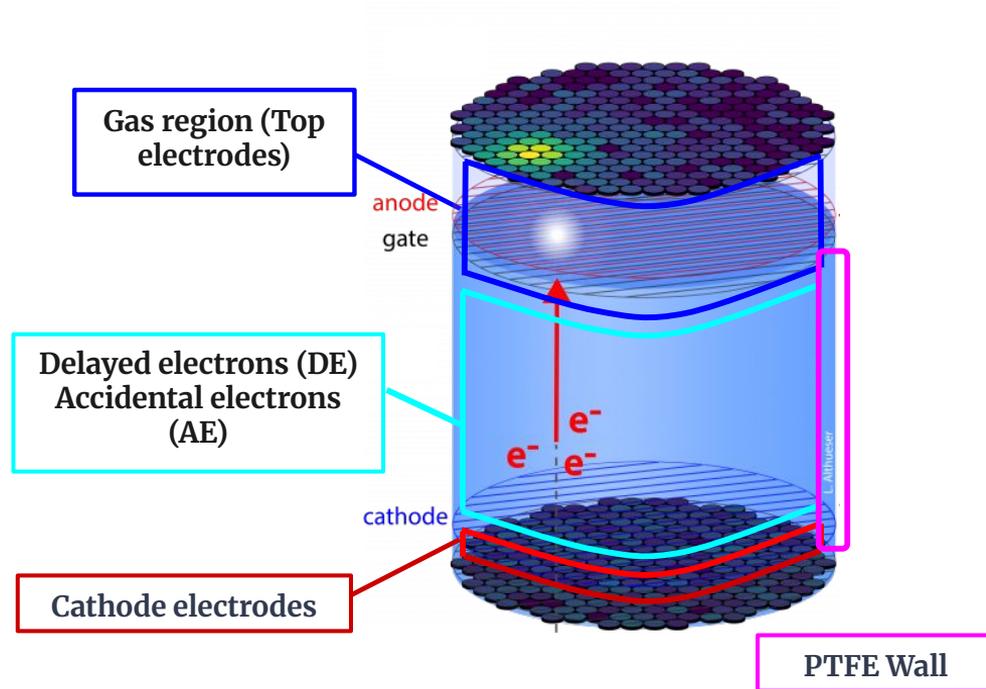
Suppressed by spatial selection (negligible)

Cathode electrodes

Suppressed by S2 width

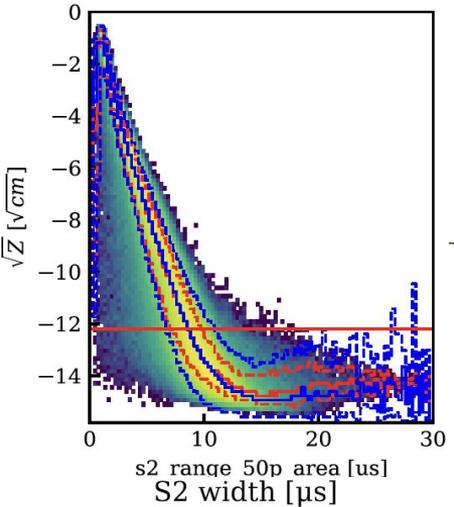
Complex detector physics involved, solutions:

- Data-driven modeling instead of first-principle simulations
- *Five machine-learning models are developed to model and mitigate instrumental backgrounds*

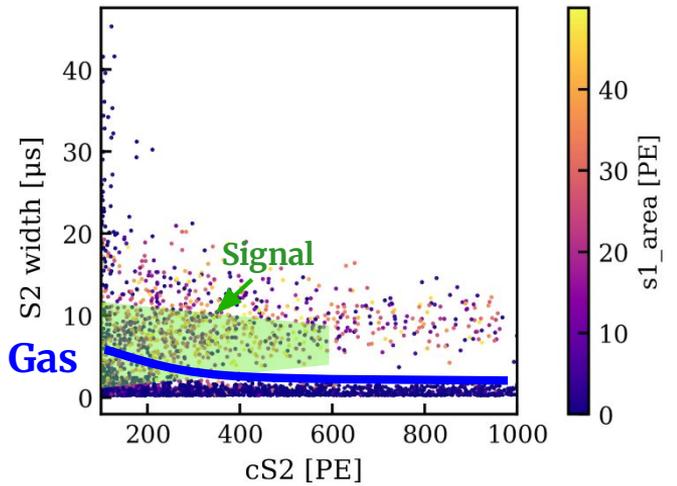
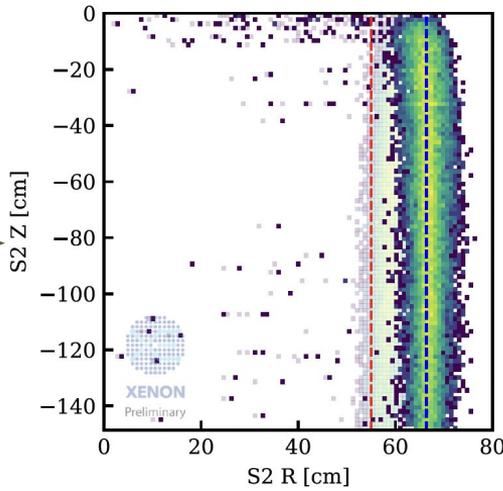


Gas and wall events - Z reconstruction model

- Position reconstruction is a key advantage for LXe TPCs to fiducialize, rejecting the majority of backgrounds.
- **A Boosted-decision-tree (BDT) model reconstructs event depth (z) using S2 width.**
- Gas and wall events can be excluded by fiducialization



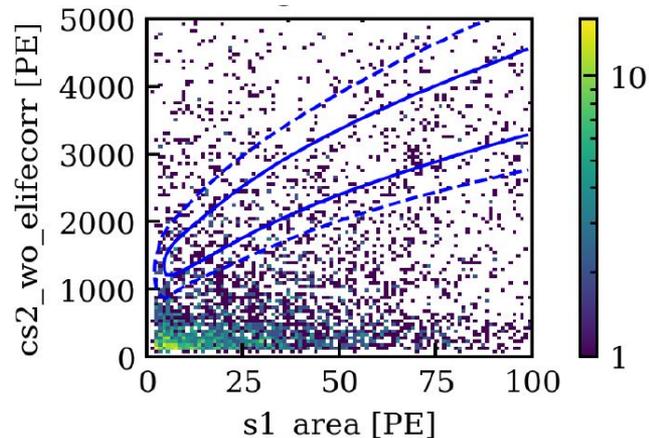
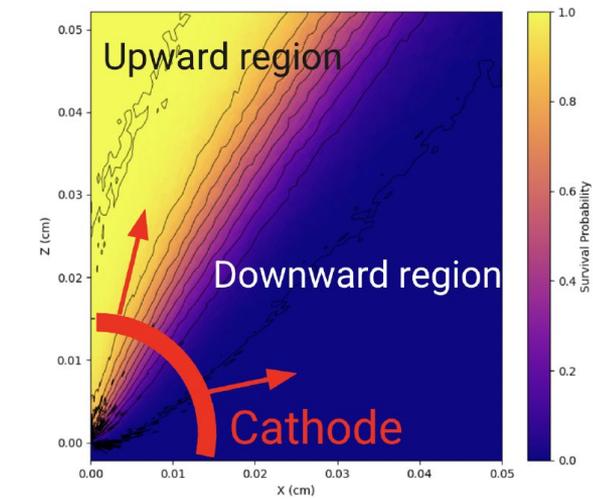
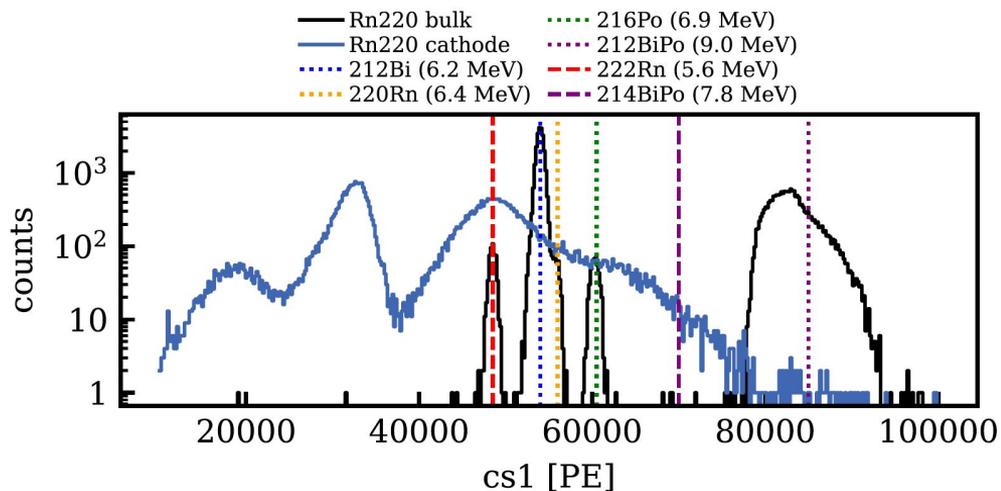
S2 width - Z reconstruction
 Field distortion correction



Cathode background origins

Events near cathode electrode suffer strong photon and charge loss

- **S1**: distorted microphysics of electron-ion recombination, or optical effect due to electrodes
- **S2**: charge loss of downward pointing electric fields

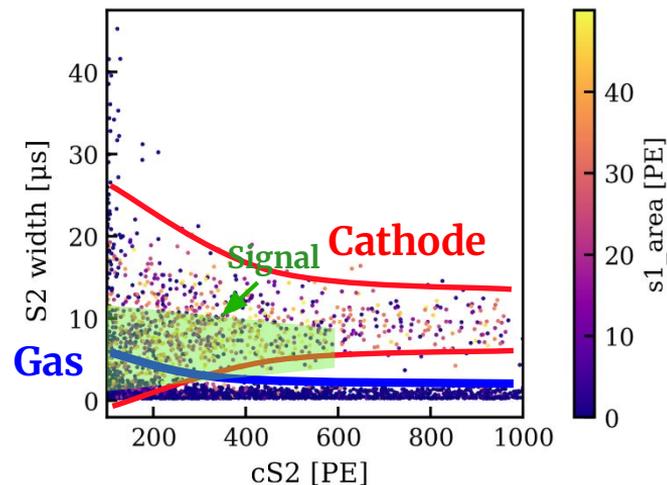
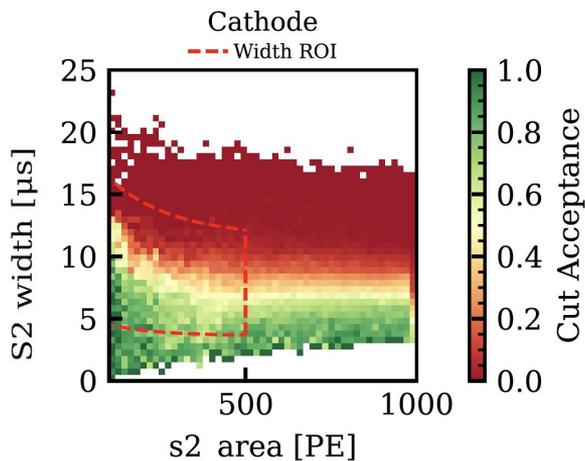
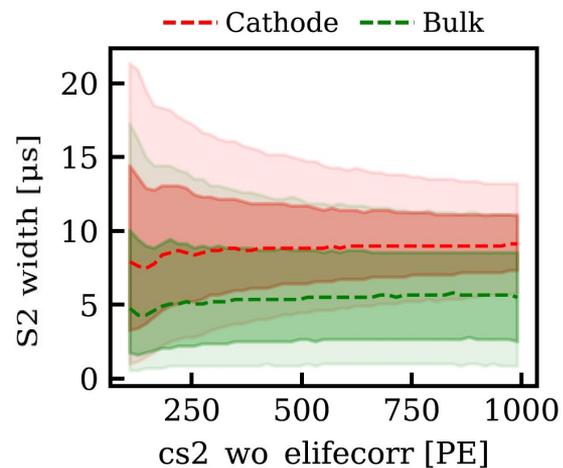


See also a recent paper by LUX-ZEPLIN
arxiv2602.21177 on the similar topic

Cathode background - S2 cathode BDT

A waveform-based S2 BDT model is developed to suppress cathode background

- Waveform simulation of the DM and cathode events
- 70% cathode events rejected, with 80% signal efficiency.



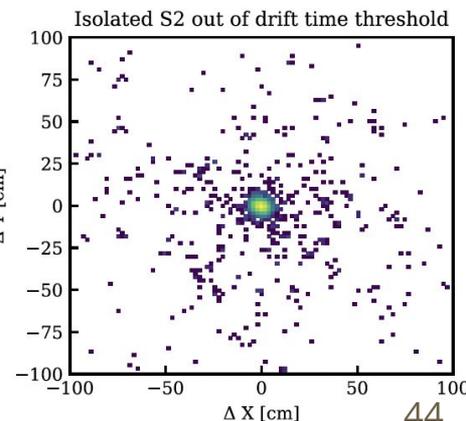
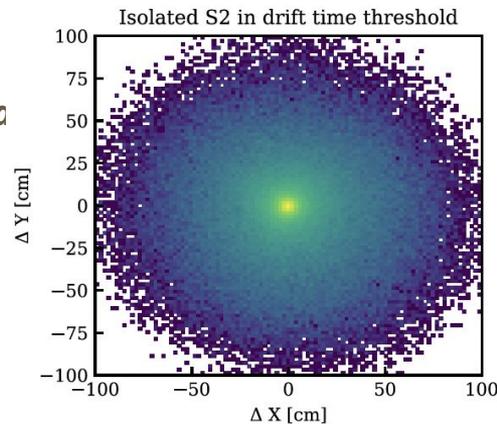
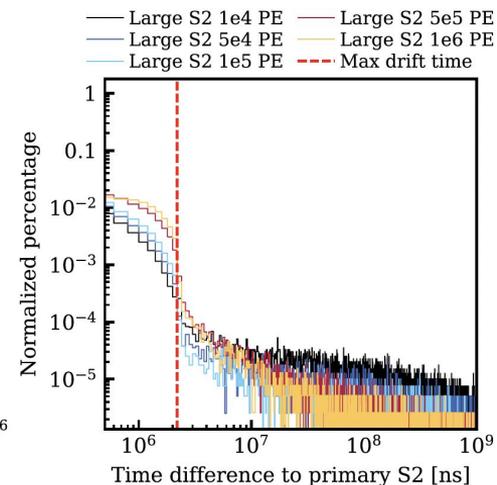
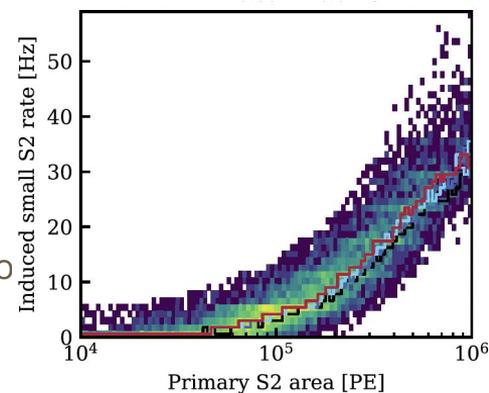
Delayed electrons - DE conditional normalizing flow

Isolated electrons emitted after a high-energy event up to 1 second

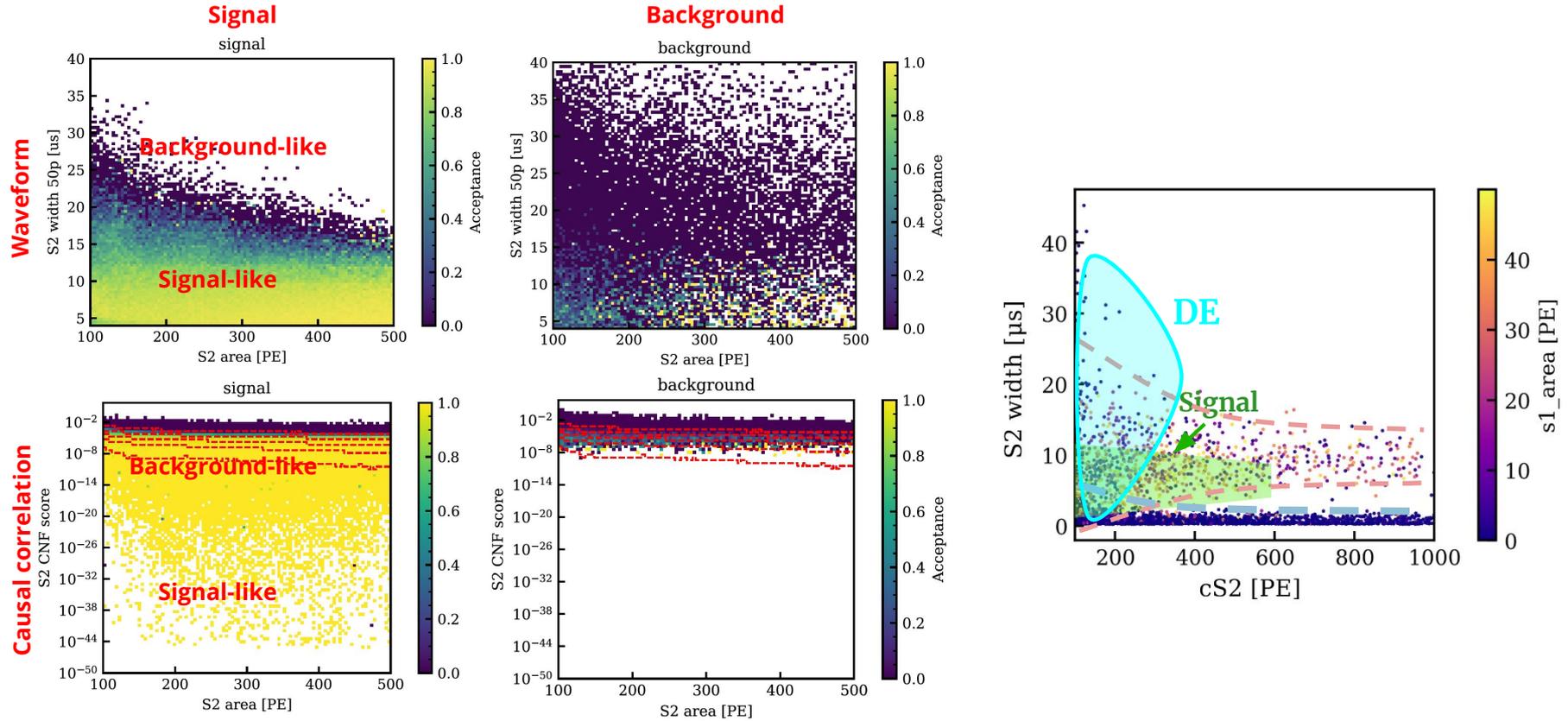
- Widely observed in liquid noble gas detectors
- Experiments points to impurities in LXe
- A simple quantitative modeling is unavailable due to multi-dimensional dependence, e.g., high-energy event energy, location, time difference, delayed electron properties, etc.

Modeled by developing a generative model, *conditional normalizing flow*, data-driven method:

- Simulate DE by a large S2 input.
- Evaluate large S2-DE causality.



Delayed electrons - DE BDT

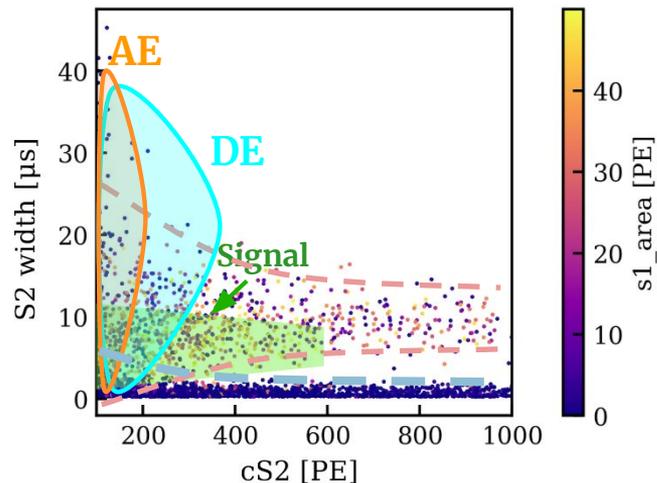
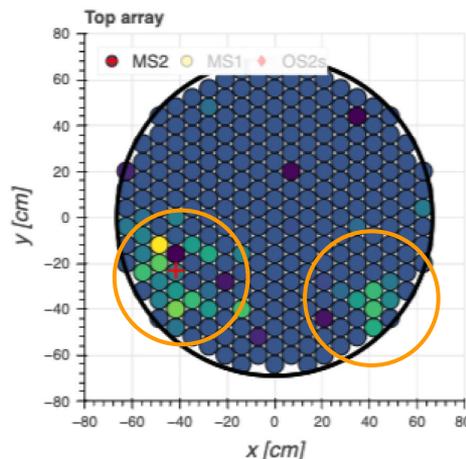
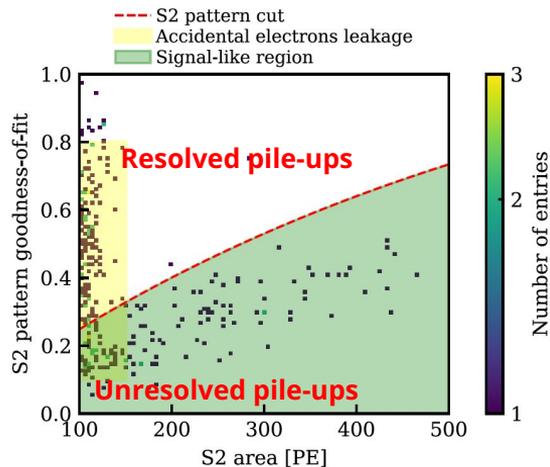


A DE BDT model is developed for DE mitigation (> 95%) using **waveform** and **causal correlations (CNF score)**

Accidental electrons - S2 pattern likelihood

Accidental pile-up of random electrons

- Developed a data-driven S2 optical map ($(x, y) \rightarrow$ PMT) using multilayer perceptron (MLP), trained by single scatter ^{83}mKr calibration data
- Single electron pile-up at different locations can be rejected
- Accidental pile-up at the same location \rightarrow irreducible



Background validation

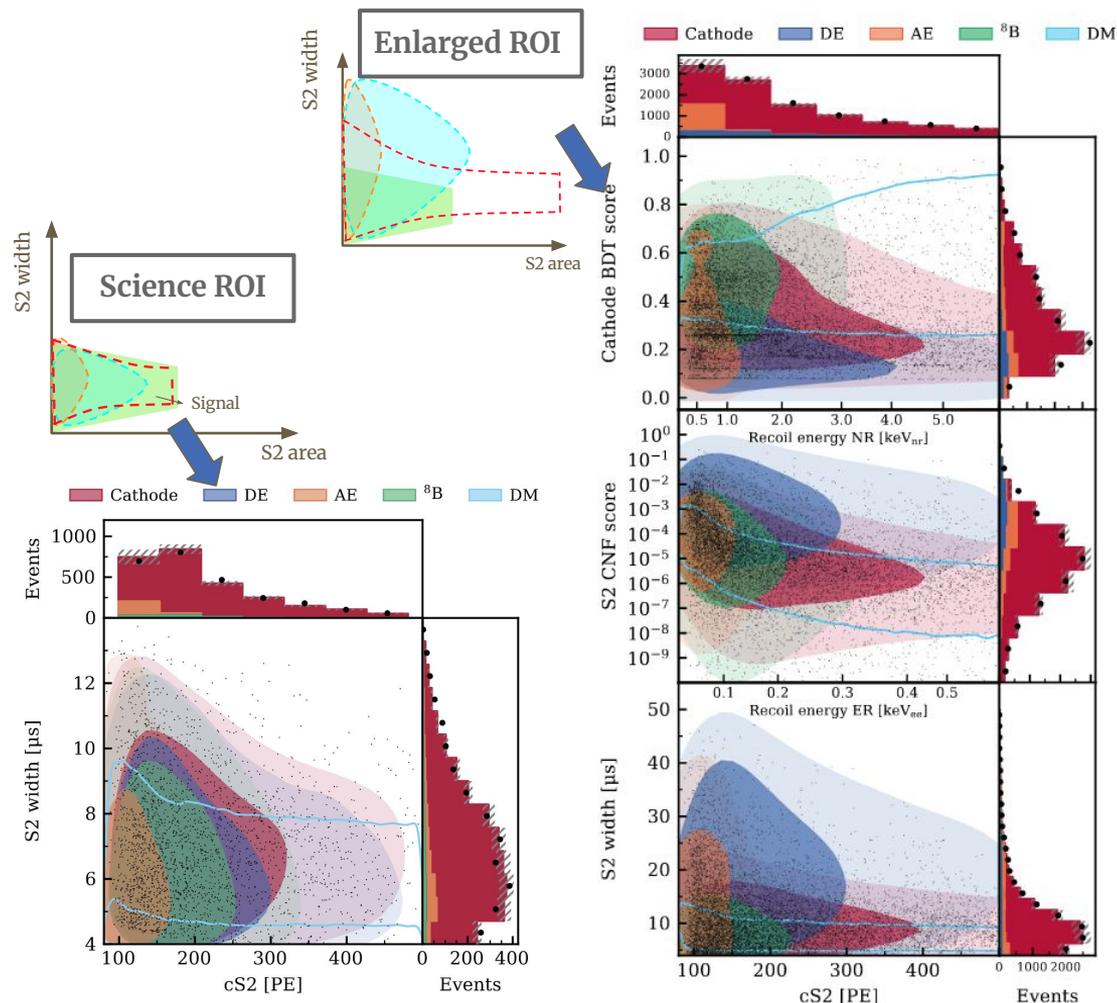
Background model validated in calibration data before unblinding

Enlarged ROI:

- BDT cuts not applied
- Background enriched for validation

Science ROI:

- All cuts applied
- Gain maximum background rejection
- Perform dark matter search.

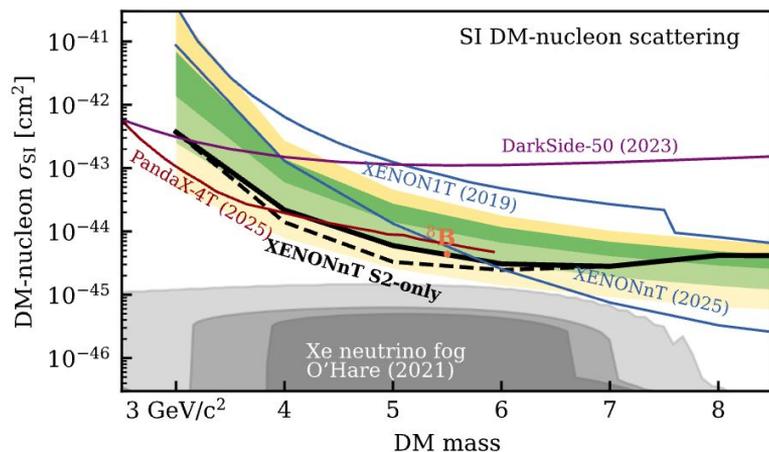


S2-only results

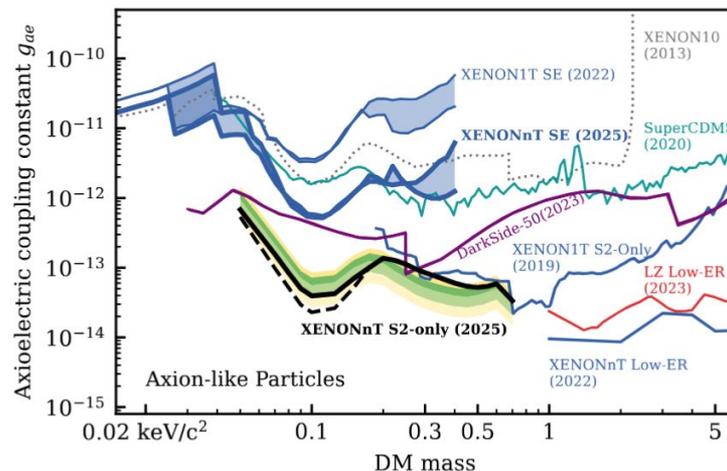
| Science run (exposure) | SR0 (1.50 t · y) | | SR1 (2.44 t · y) | | SR2 (3.89 t · y) | |
|--------------------------|------------------|-------------------|------------------|-------------------|------------------|----------------|
| Component | Expectation | Best fit | Expectation | Best fit | Expectation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

Good agreement
 ⇒ No signal excess

Most stringent limit set on ~5 GeV light WIMPs



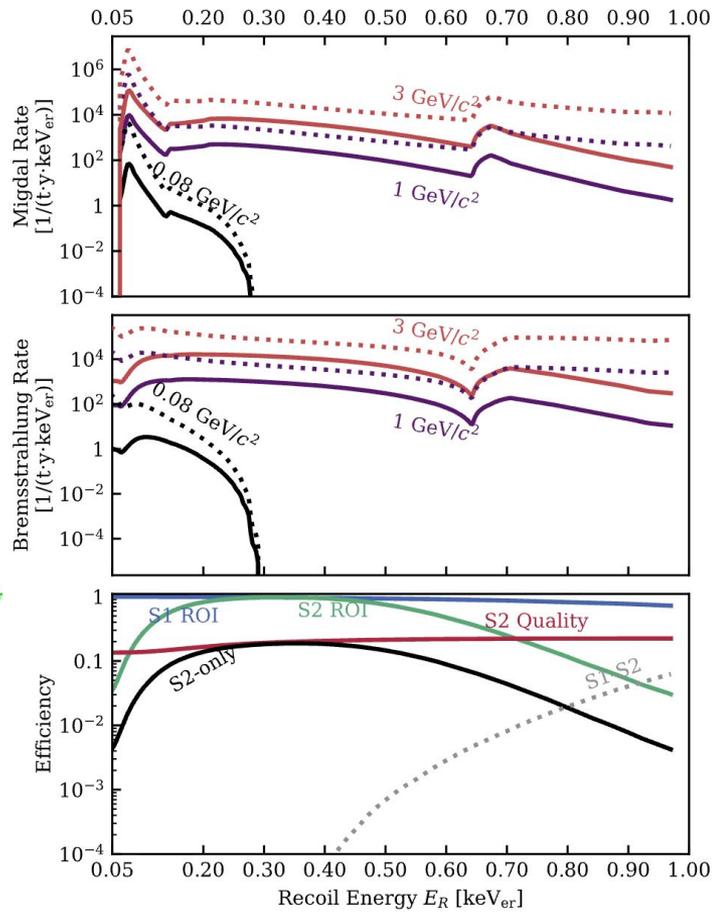
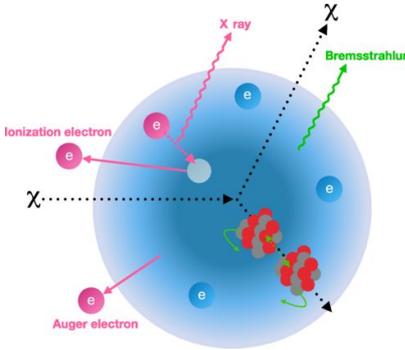
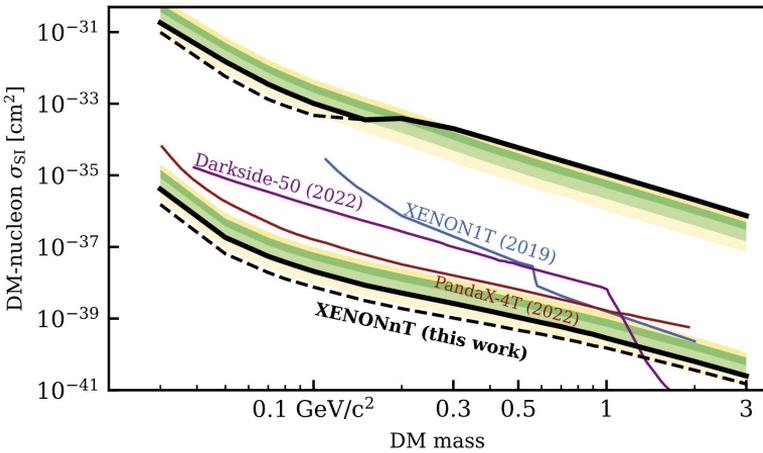
[0.04, 0.7] keV axion-like particles (ALP)



Migdal and Bremsstrahlung effect

Search for sub-GeV dark matter using ER signals produced by NR

- Migdal effect: sudden nucleus recoil can ionize atomic electrons
- Bremsstrahlung: recoiling positively-charged nucleus emits breaking radiations
- World-leading constraints of MeV-GeV dark matter



Conclusion

A large portfolio of XENONnT DM searches from TeV to MeV

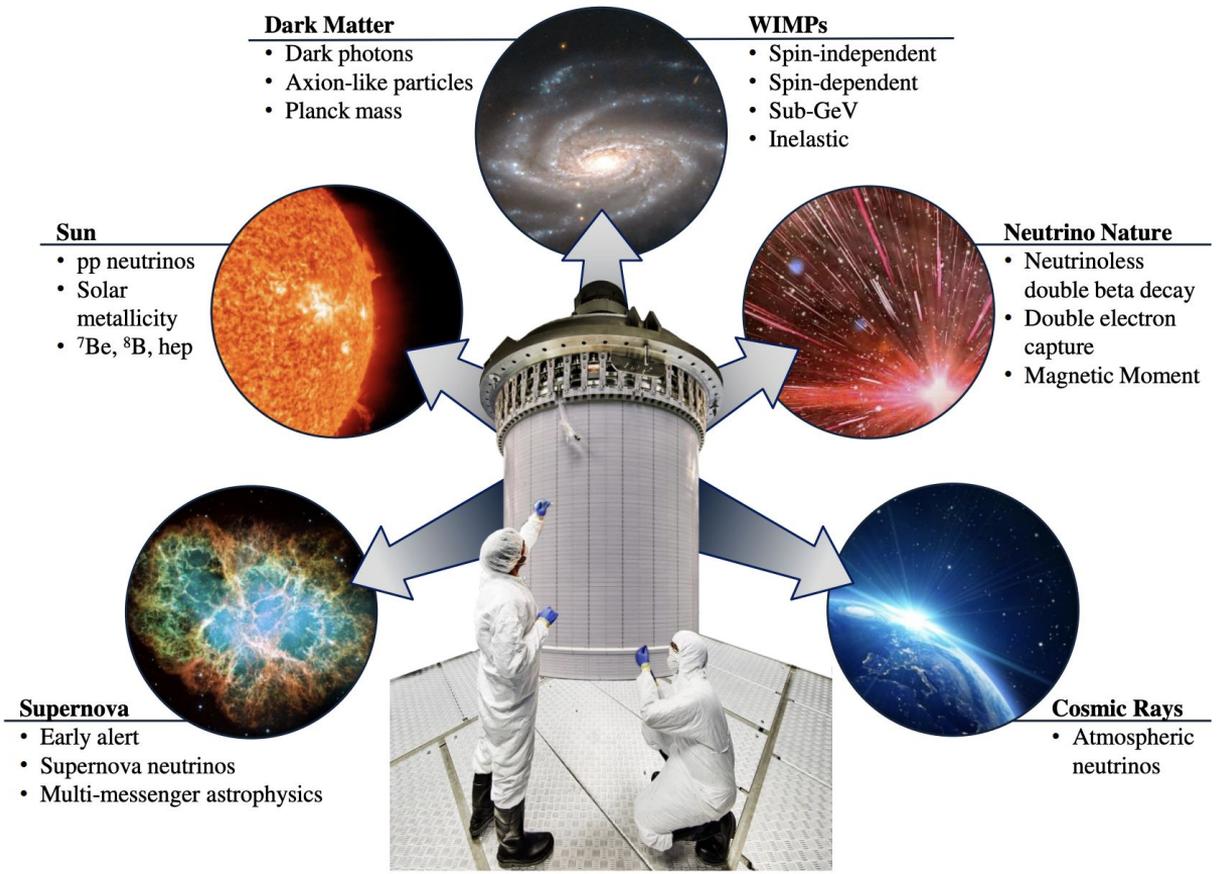
- **Search for Weakly Interacting Massive Particles (WIMPs):** *Phys. Rev. Lett.* 135, 221003 (2025)
- **Search for light dark matter in the neutrino fog with XENONnT:** *Phys. Rev. Lett.* 134, 111802 (2025), *Phys. Rev. Lett.* 133, 191002 (2024)
- **Search for light dark matter with ionization-only signals:** *arxiv.* 2601.11296 (2026), submitted to PRL, *Sub-GeV DM searches with Migdal and Bremsstrahlung in preparation*

Enabled by a set of hardware and analysis innovations:

- Record-low ER contaminations by liquid xenon distillation
- Accidental coincidence background mitigation
- An ionization-only background model using data-driven methods

More results to come in the future!

Future science potentials



Thank you for your attention!



Backup slides

| | SR0 | | SR1a | | SR1b | |
|--------------------------|-----------------|---------------------|-------------------|-------------------|-------------------|-------------------|
| | Nominal | Best fit | Nominal | Best fit | Nominal | Best fit |
| ER (flat) | 134 | 136 ± 12 | 430 ± 30 | 450 ± 20 | 151 ± 11 | 154 ± 10 |
| ER (^3H -like) | – | – | 62 | 40 ± 30 | 101 | 80^{+18}_{-17} |
| ER (^{37}Ar) | – | – | 58 ± 6 | 55 ± 5 | – | – |
| Neutron | 0.7 ± 0.3 | 0.6 ± 0.3 | 0.47 ± 0.19 | 0.45 ± 0.19 | 0.7 ± 0.3 | 0.7 ± 0.3 |
| CE ν NS (solar) | 0.16 ± 0.05 | 0.16 ± 0.05 | 0.010 ± 0.003 | 0.010 ± 0.003 | 0.019 ± 0.006 | 0.019 ± 0.006 |
| CE ν NS (atm.+DSNB) | 0.04 ± 0.02 | 0.04 ± 0.02 | 0.024 ± 0.012 | 0.024 ± 0.012 | 0.05 ± 0.02 | 0.05 ± 0.02 |
| AC | 4.3 ± 0.9 | $4.4^{+0.9}_{-0.8}$ | 2.12 ± 0.18 | 2.10 ± 0.18 | 3.8 ± 0.3 | 3.8 ± 0.3 |
| Surface | 13 ± 3 | 11 ± 2 | 0.43 ± 0.05 | 0.42 ± 0.05 | 0.77 ± 0.09 | 0.76 ± 0.09 |
| Total background | 152 | 152 ± 12 | 553 | 550 ± 20 | 257 | 239 ± 15 |
| WIMP (200 GeV/ c^2) | – | 1.8 | – | 1.1 | – | 2.1 |
| Observed | | | | | | arXiv: 2502.18005 |

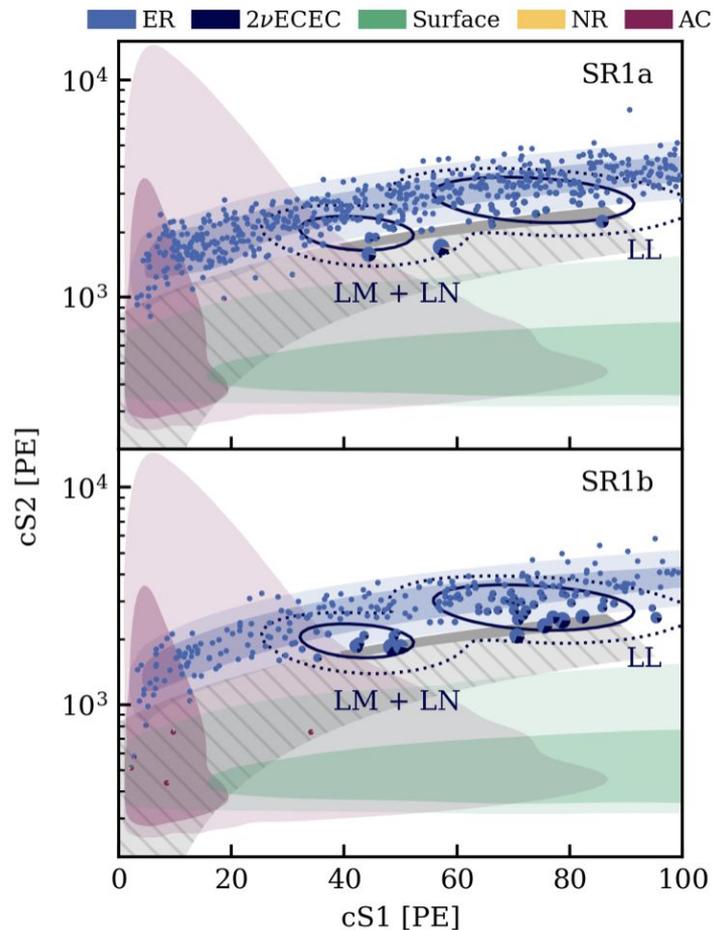
$$\mathcal{L}(\sigma, \theta) = \prod_{\text{SR} \in \{\text{SR0}, \text{SR1a}, \text{SR1b}\}} \mathcal{L}_{\text{SR}}(\sigma, \theta)$$

$$\mathcal{L}_{\text{SR}}(\sigma, \theta) = \mathcal{L}_{\text{SR}}^{\text{far-wire}}(\sigma, \theta) \times \mathcal{L}_{\text{SR}}^{\text{near-wire}}(\sigma, \theta) \times \mathcal{L}_{\text{SR}}^{\text{anc}}(\theta)$$

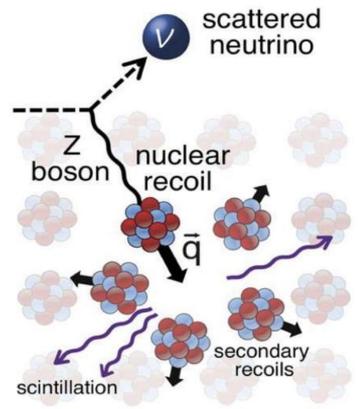
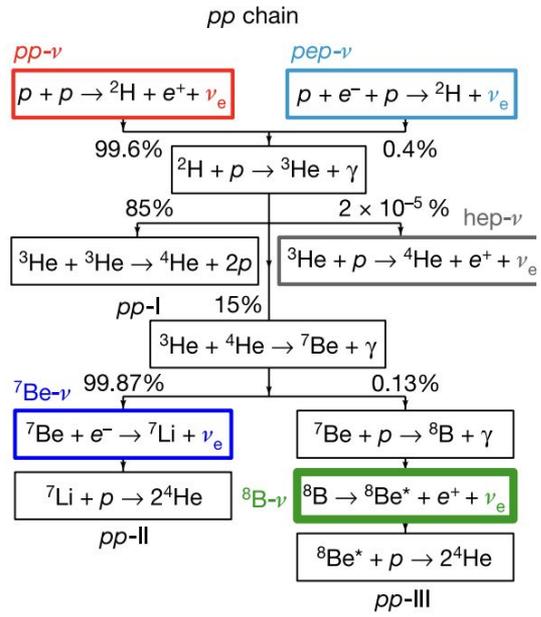
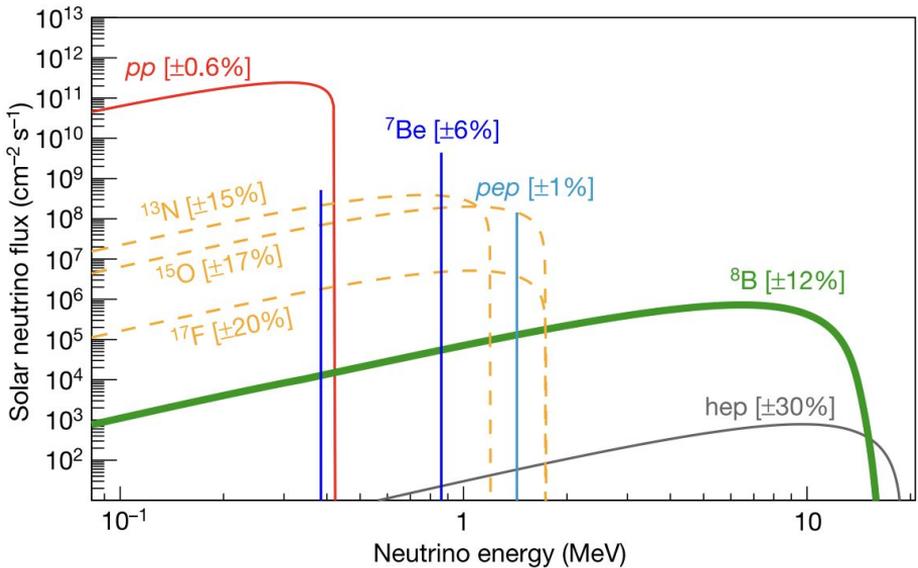
$$r_{LL} = CY_{LL}/CY_{\beta} \quad r_{LM} = CY_{LM}/CY_{\beta}$$

$$\Lambda = -2 \ln \left(\frac{\mathcal{L}(r_{LL} = 1, r_{LM} = 1), \hat{\theta}}{\mathcal{L}(r_{LL}, r_{LM}, \hat{\theta})} \right)$$

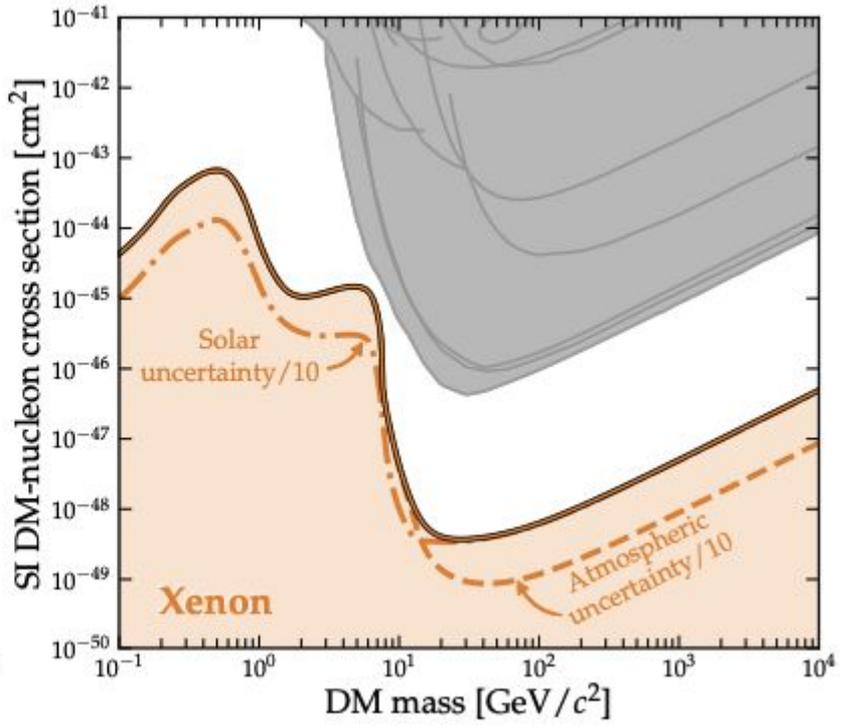
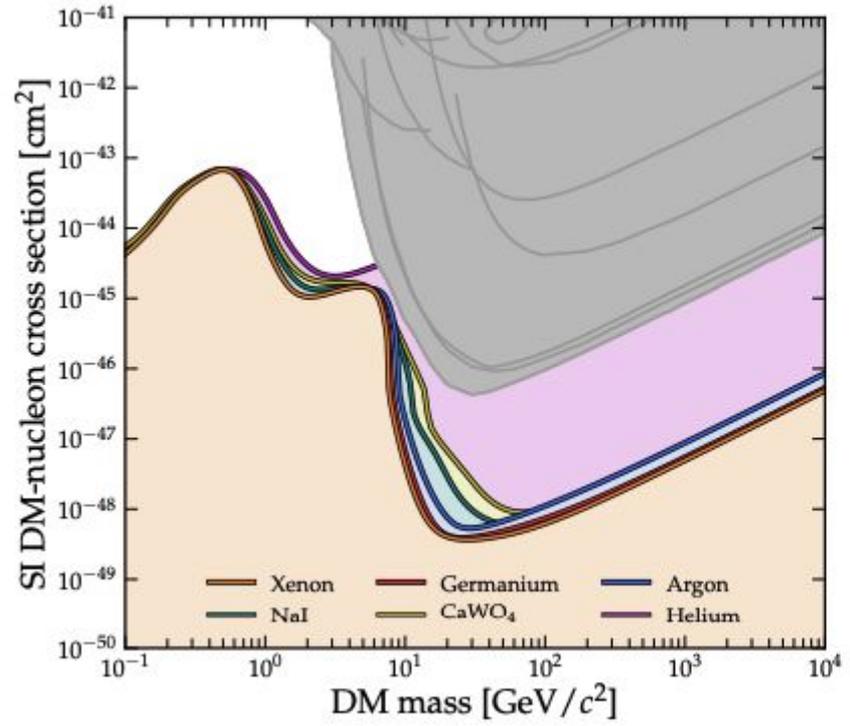
- ▶ Test size is set to $\alpha=0.05$ before unblinding, considering:
 - Maximize the rejection power in case of real 2 ν ECEC CY suppression.
 - Minimize the false WIMP discovery rate.
 - Keep the false rejection (test size) to a minimum.
- ▶ After unblinding, p-value = 0.09 -> failed to reject nominal CY model
- ▶ Best fit values: $r_{LL} = 0.80^{+0.08}_{-0.04}$ $r_{LM} = 0.72^{+0.11}_{-0.04}$



Neutrino and CEvNS process

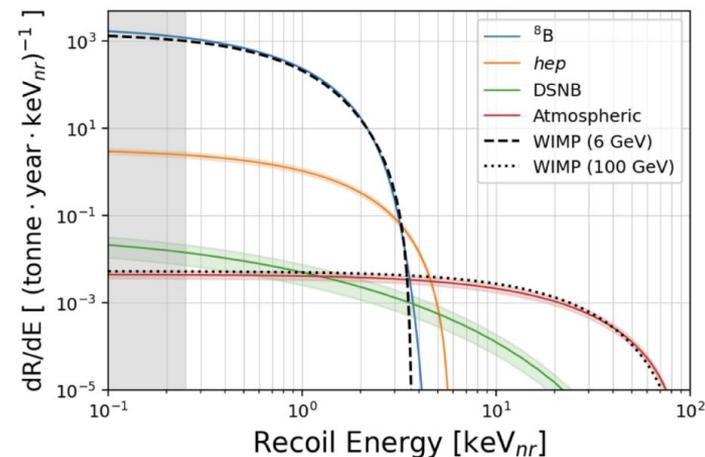
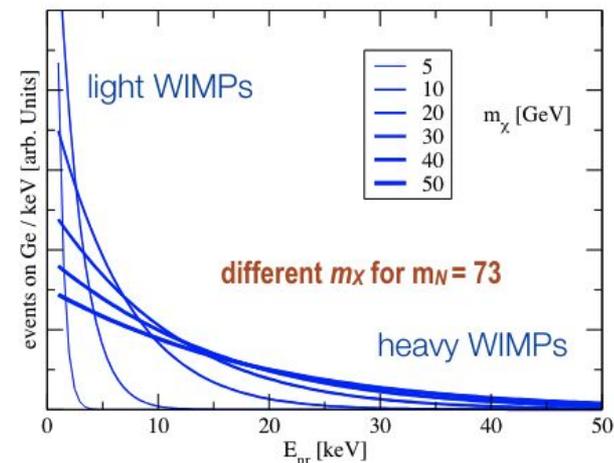


Neutrino fog: Detector material and solar neutrino uncertainty

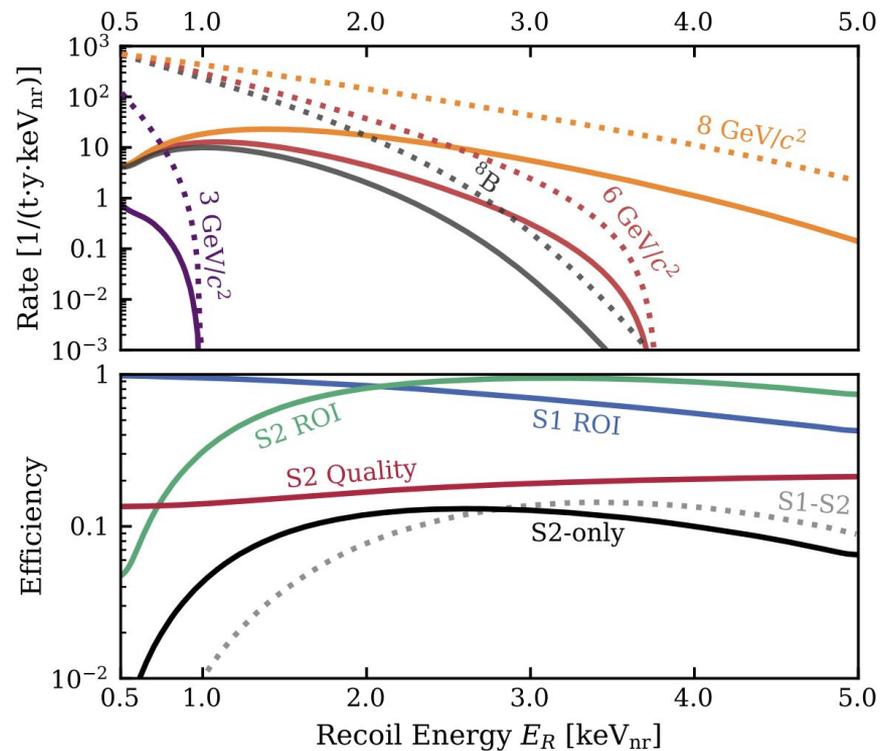
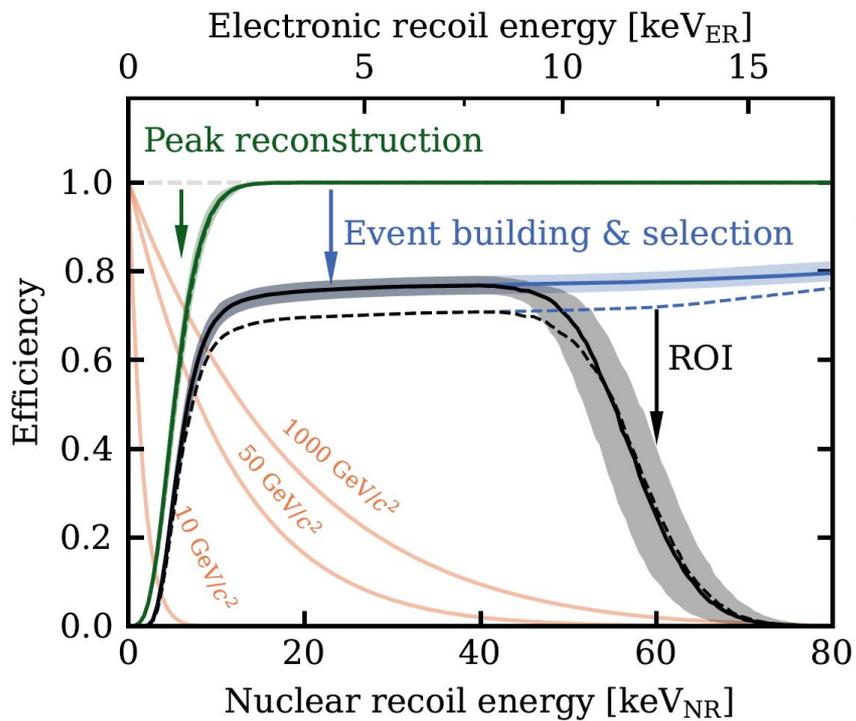


Light dark matter

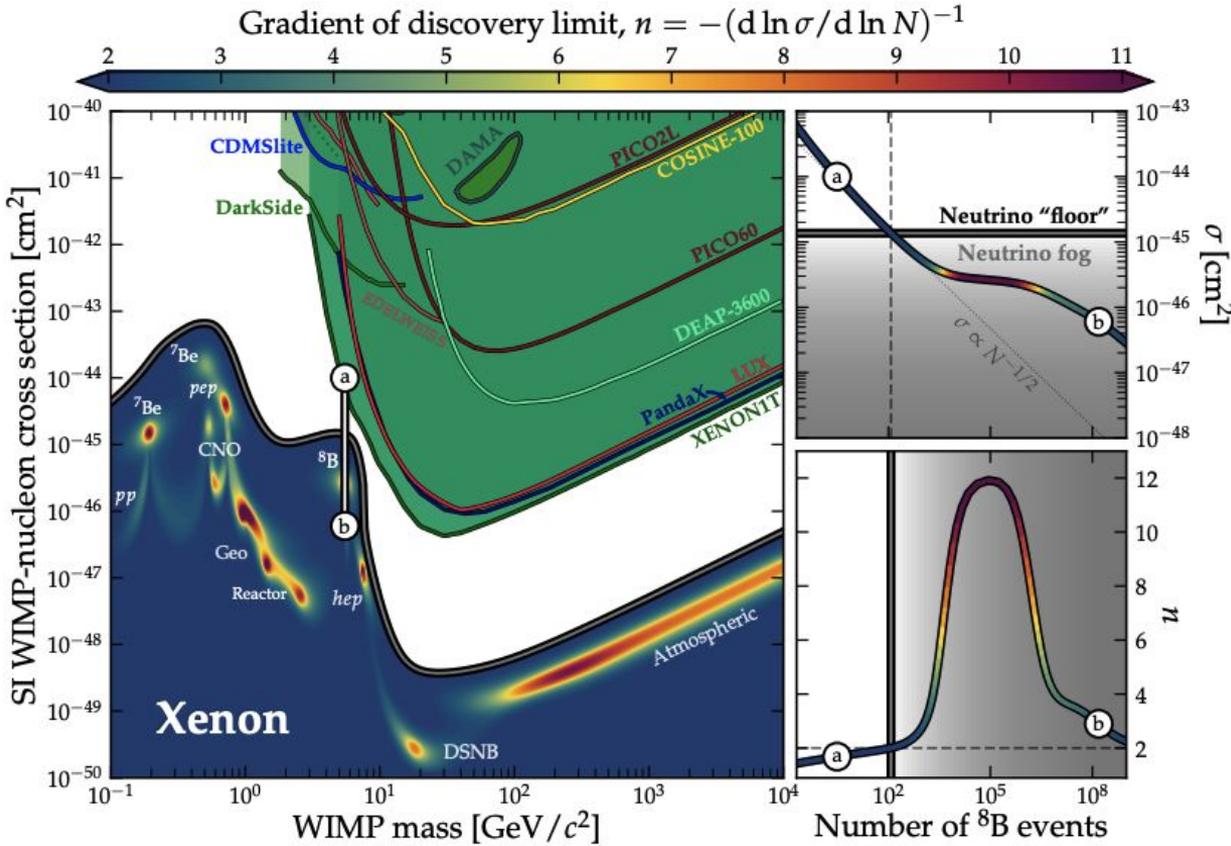
- GeV-scale light dark matter (DM) is well-motivated:
 - ◆ Low-mass WIMPs: Lee-Weinberg bounds $\sim 2\text{-}3 \text{ GeV}/c^2$.
 - ◆ Asymmetric DM: Phys. Rev. D 79, 115016 (2009)
 - ◆ Self-interacting DM: Phys. Rev.Lett. 84, 3760 (2000)
 - ◆ Mirror DM: Phys. Lett. B 766 (2017)
- However the direct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



Light WIMP analysis



Neutrino fog vs Neutrino floor

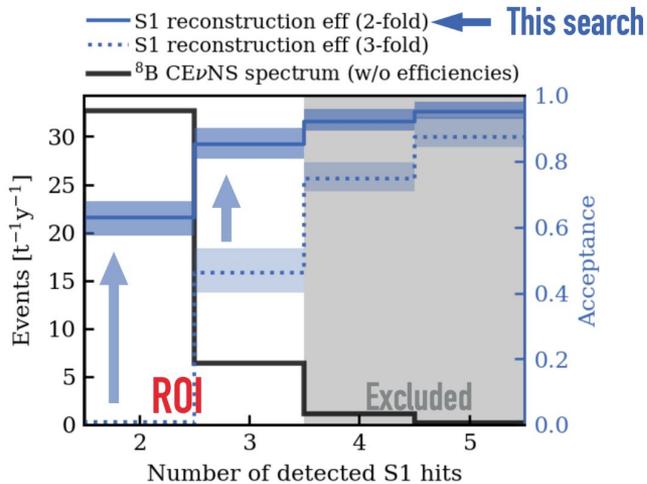


Signal efficiency

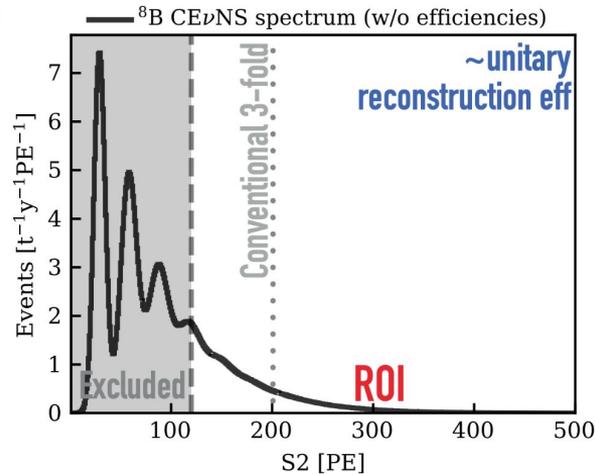
Energy threshold is the major efficiency loss mechanism!

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

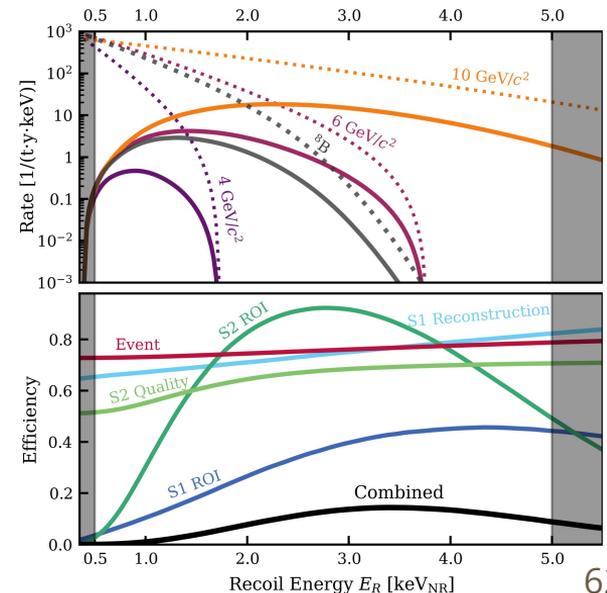
S1 efficiency vs CEvNS spectrum



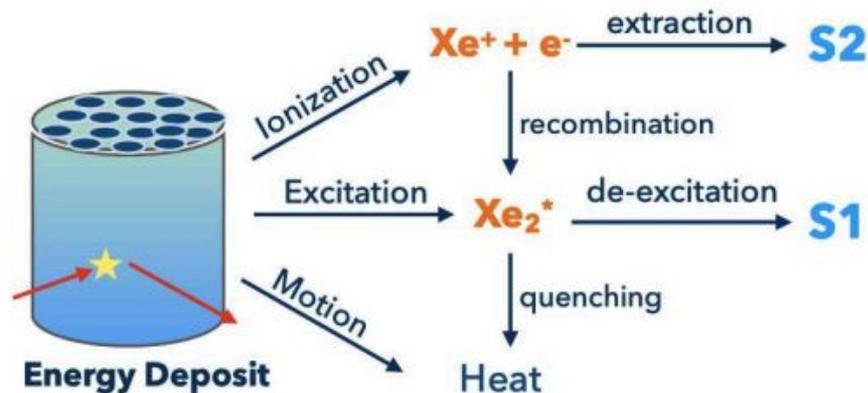
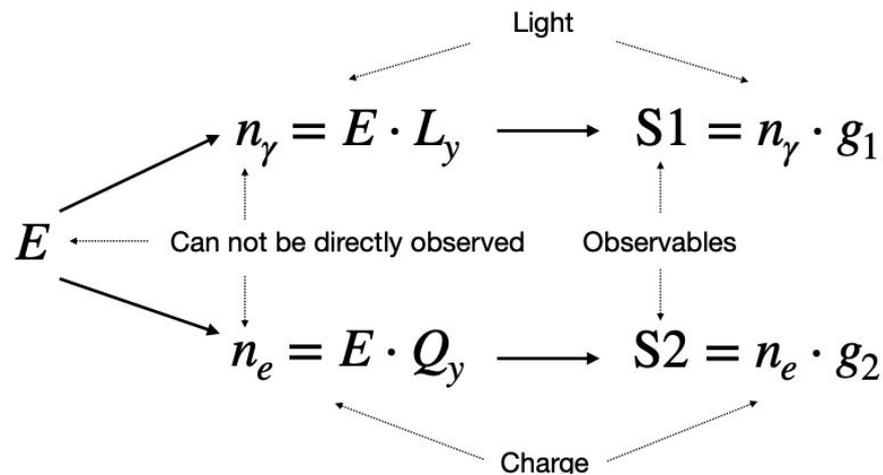
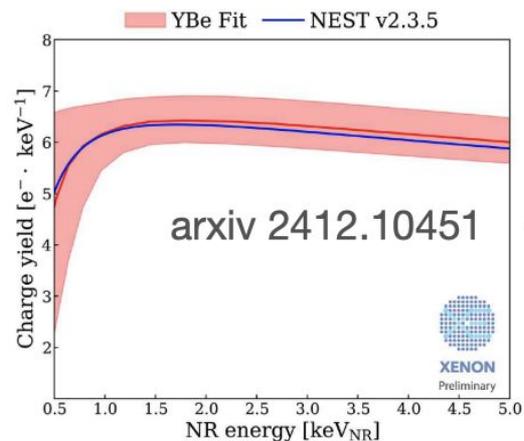
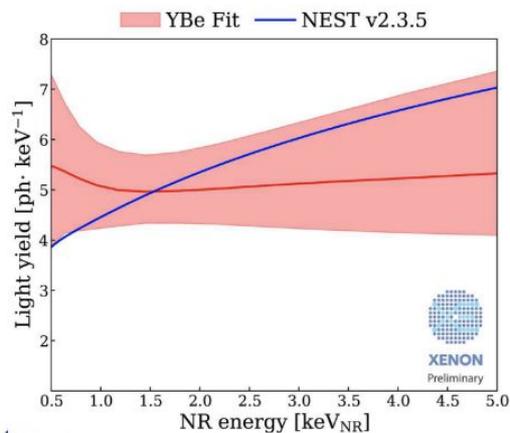
S2 range vs CEvNS spectrum



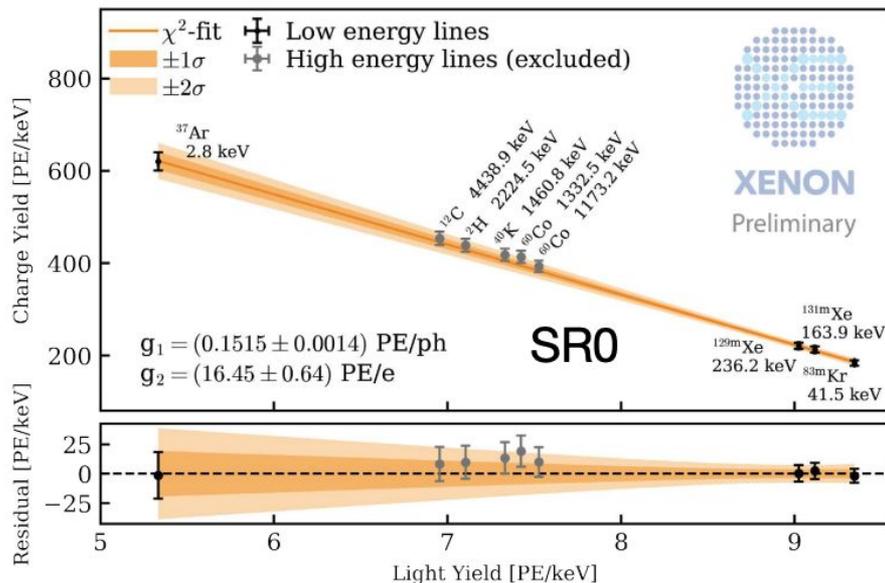
DM spectrum after efficiency Efficiency decomposition



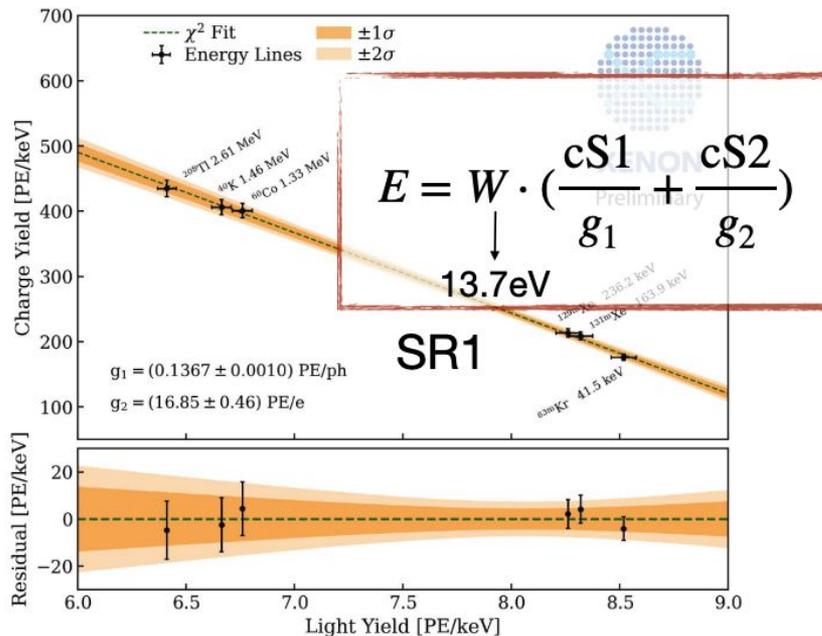
Yield model



Calibration of g1 and g2

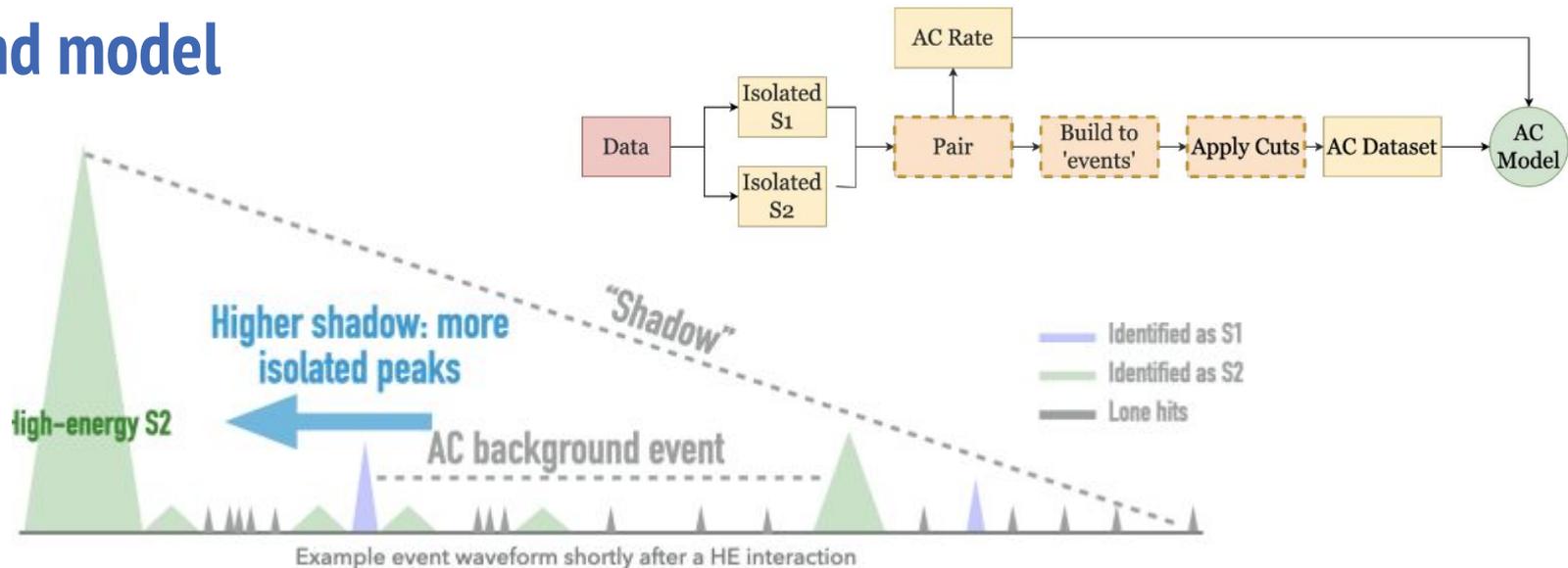


| Science Run | g_1 [PE/ph] | g_2 [PE/e] |
|-------------|---------------------|------------------|
| SR0 | 0.1515 ± 0.0014 | 16.45 ± 0.64 |
| SR1 | 0.1367 ± 0.0010 | 16.85 ± 0.46 |



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

Background model



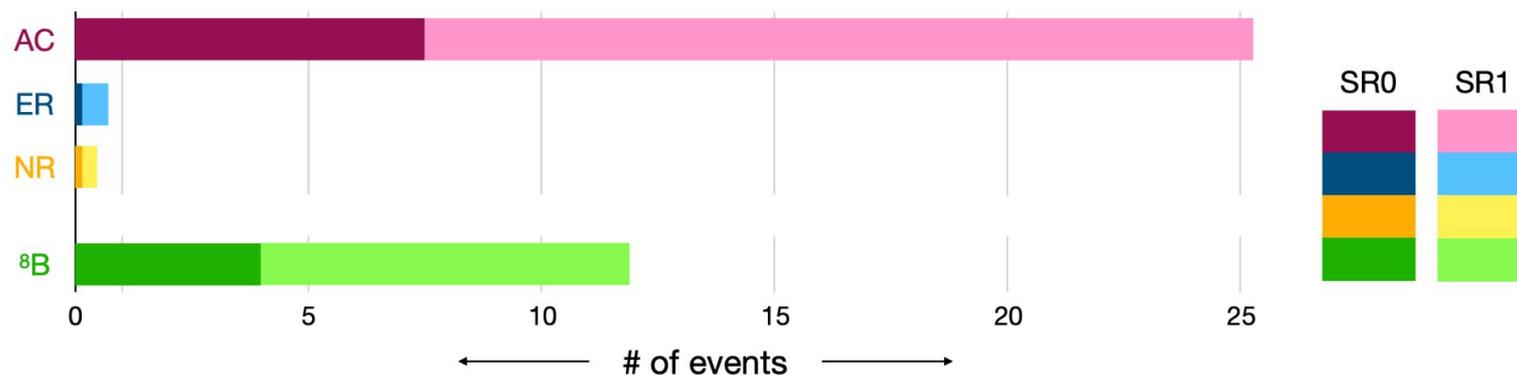
$$N_{AC} = \int_{t_0}^{t_1} R_{S1}(t) \cdot R_{S2}(t) \cdot T_{max} dt$$

| 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

Background summary

Background dominated by AC and ^8B neutrinos!



AC: Accidental Coincidence Background

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

NR: Nuclear Recoil Background

- Full-chain simulated
- 58% uncertainty from sideband

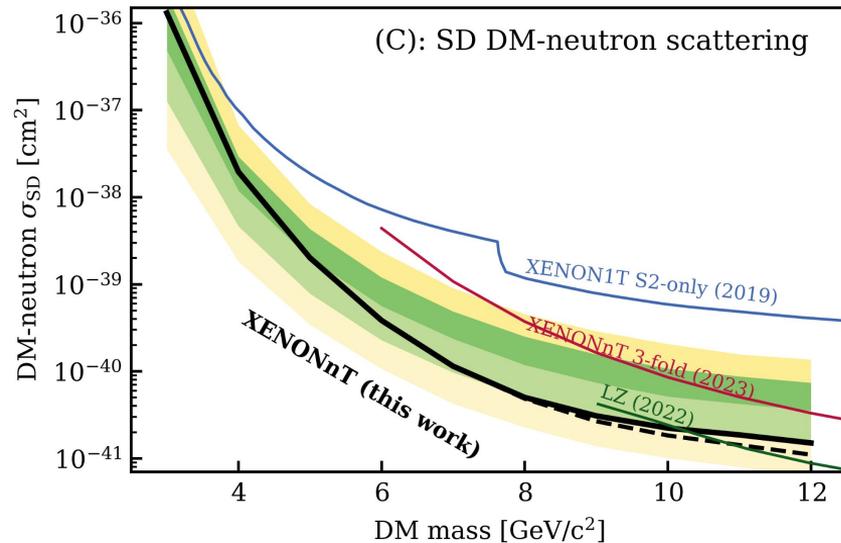
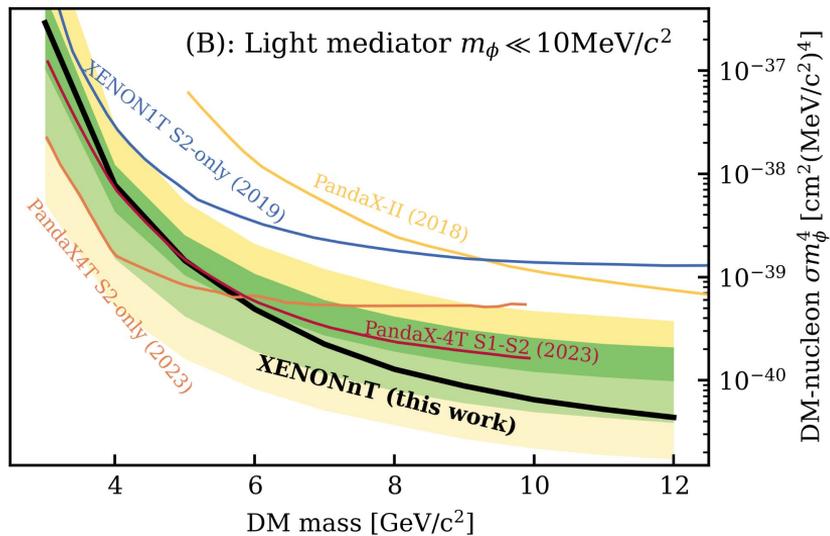
ER: Electronic Recoil Background

- Flat energy spectrum at $O(0.1)\text{keV}$
- 100% conservative uncertainty

^8B : CEvNS Signal

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

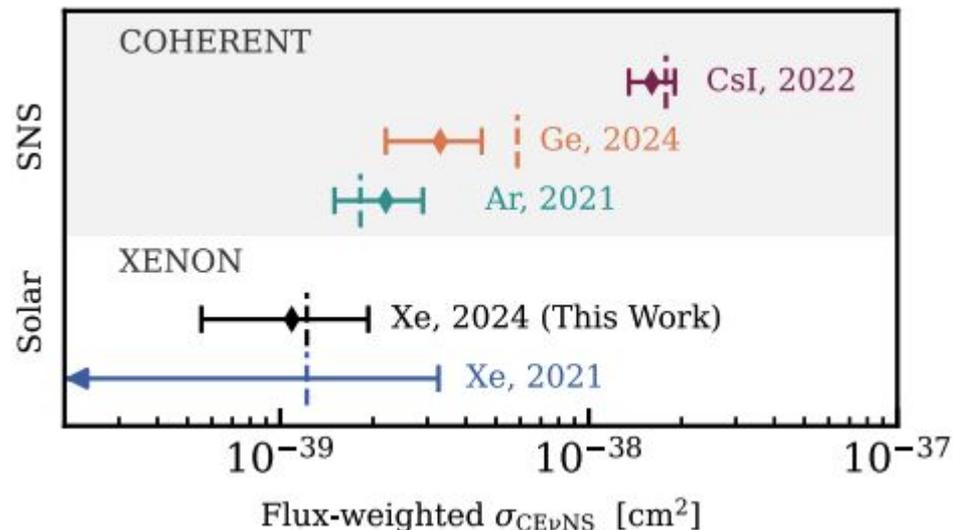
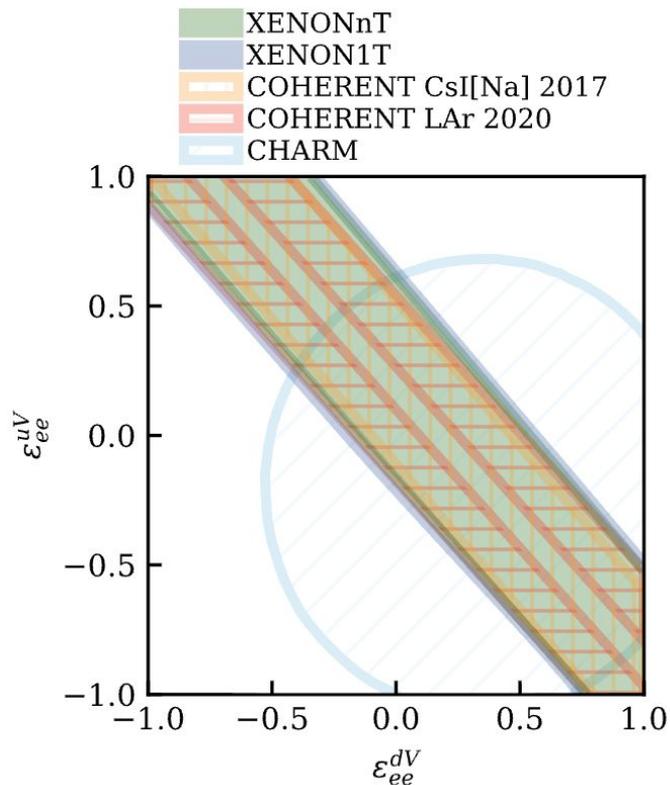
S1-S2: Other DM models



Constrain Standard model

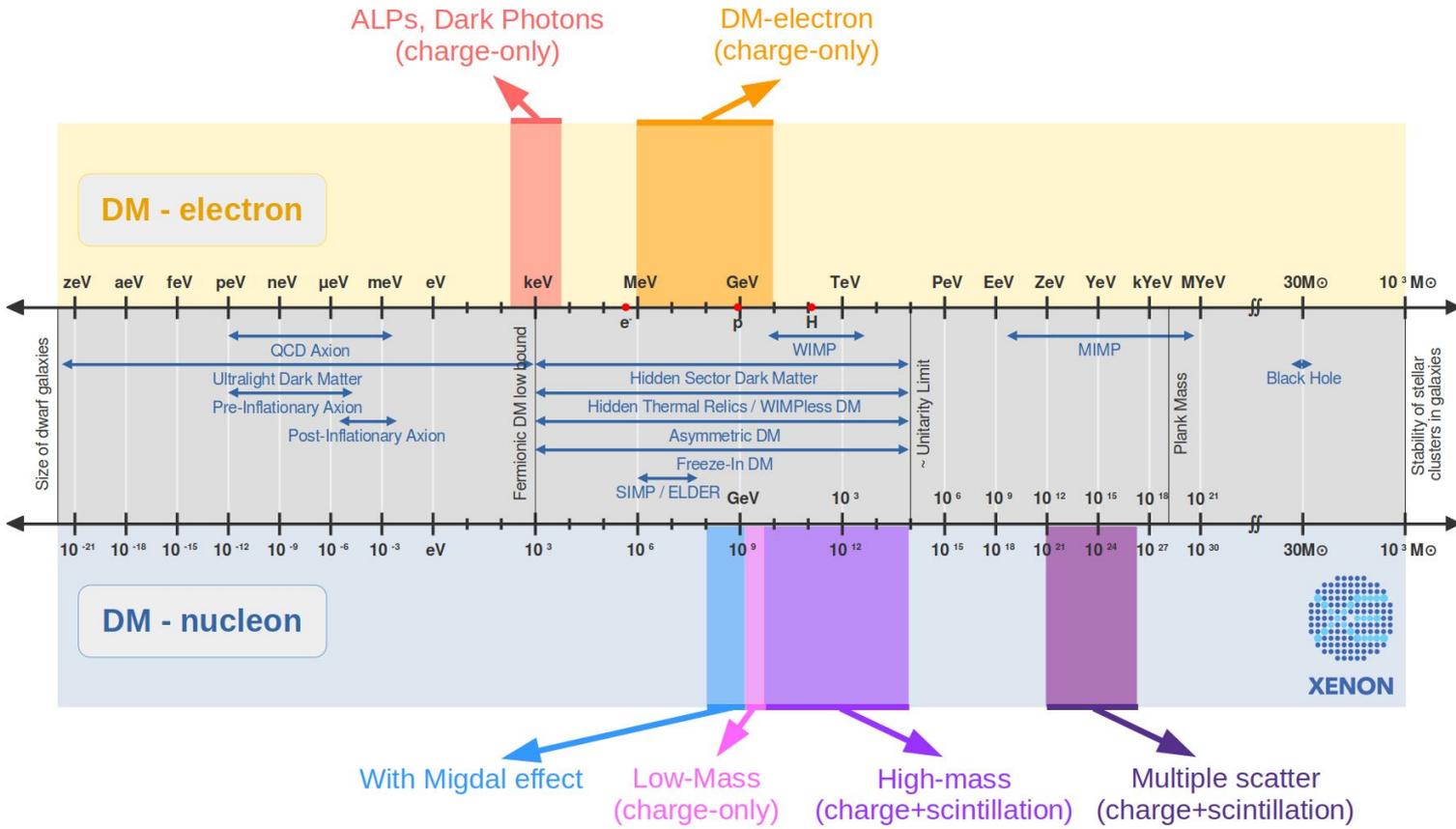
$$\frac{d\sigma(E_\nu)}{dT} = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) (G_V^{BSM})^2$$

$$G_V^{BSM} = [Z (g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}) + N (g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})]$$



S2-only analysis

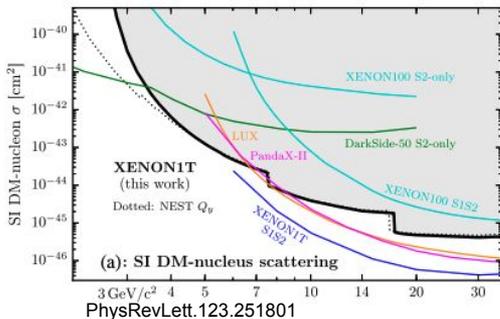
S2-only search



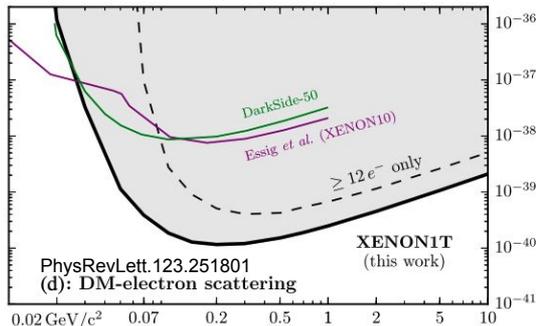
S2-only search

- Neutrino
- Axion-like particle / Dark photon...

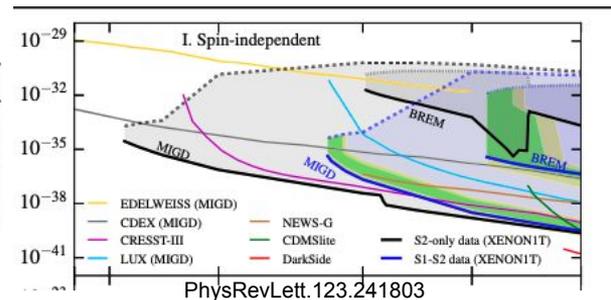
DM-nucleon



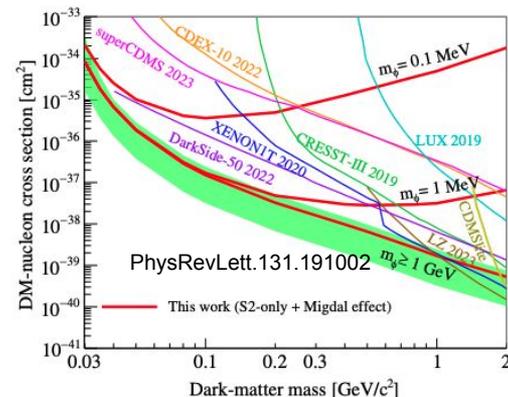
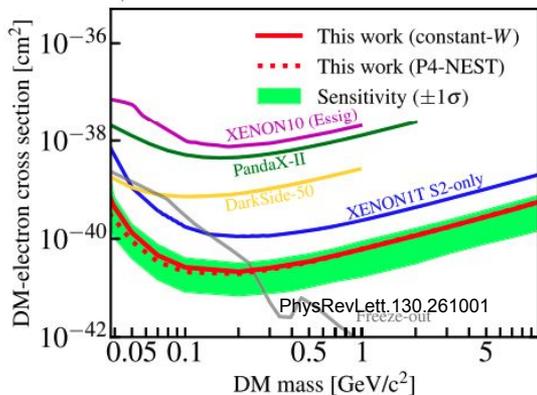
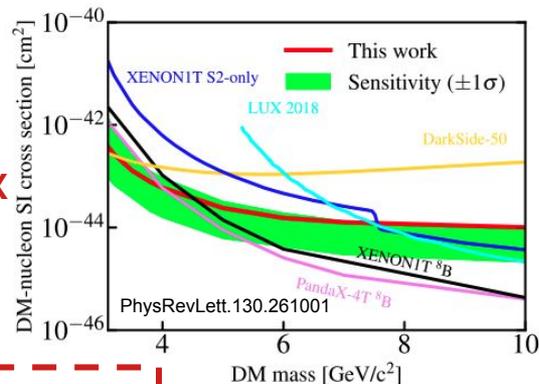
DM-electron



Migdal



XENON



PandaX

- DAMIC
- SENSEI
- Darkside

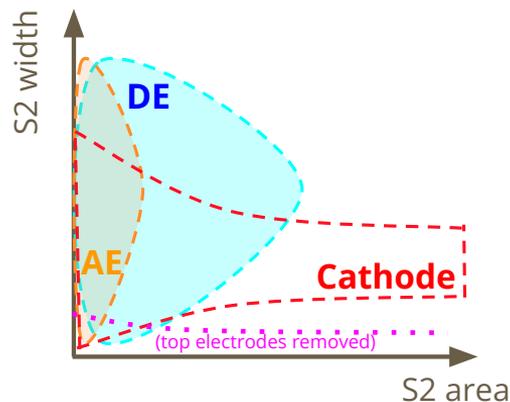
Broad physics opportunities at low energy

S2-only background model methodology

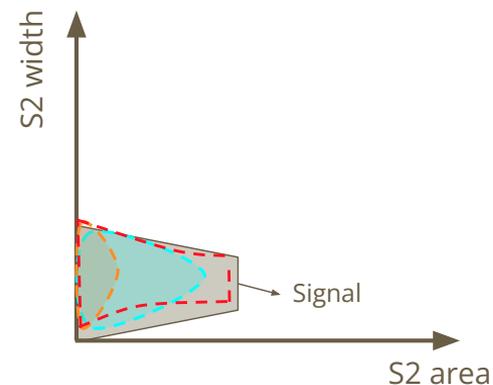
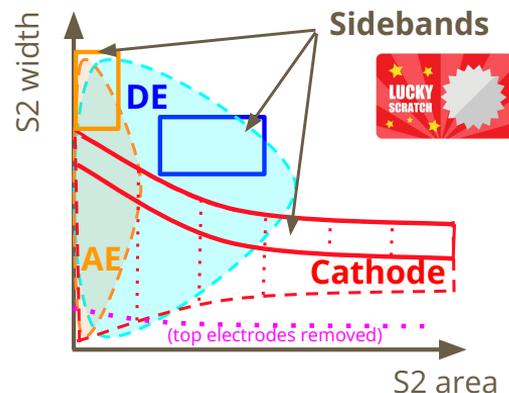
1. Distributions in parameter space through data-driven or simulation-driven approach

2. Renormalization of background model
 1. Sideband selection
 2. Unblind S2-only science data in sideband
- ⇒
3. Reweight the distribution

2. Application of full science cut



Enlarged ROI



Science ROI

Delayed electron background

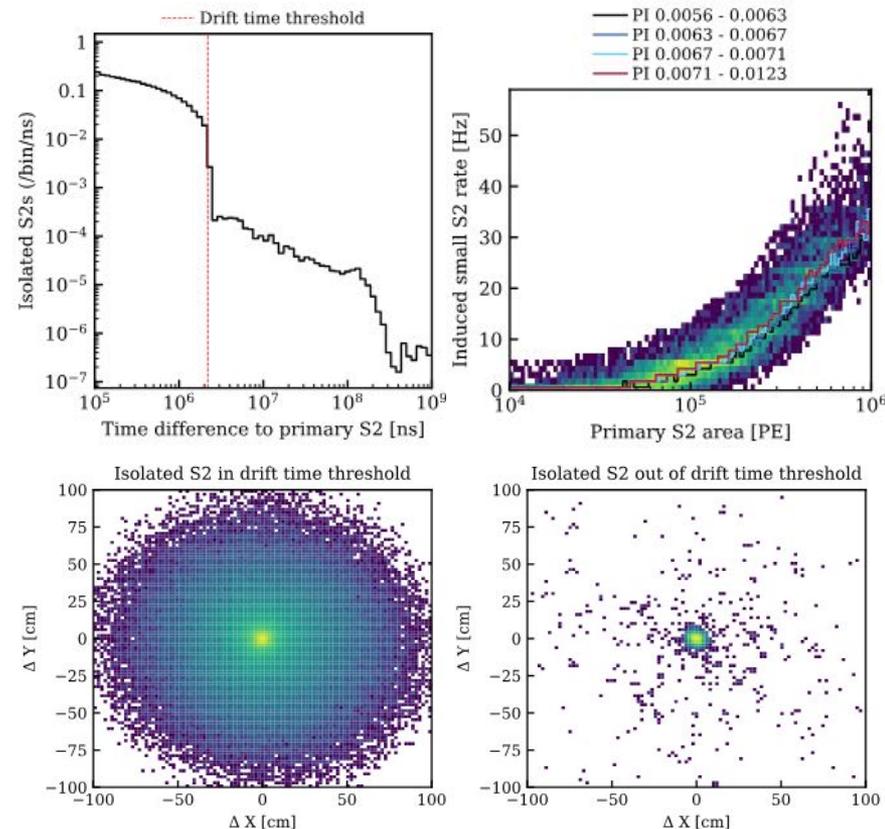
Primary S2s \Rightarrow isolated S2 following 1 second window⁽¹⁾, causing the DE background.

Source of isolated S2s mostly from trapped single electrons by impurities⁽²⁾.

Isolated S2s' feature depends on:

- Primary S2s' feature
- Run condition

Machine-learning generative algorithm, predicting the rate and the shape of isolated S2s given any primary S2.



(1) [PhysRevD.102.092004](#), [PhysRevD.106.022001](#)
(2) [PhysRevD.111.012005](#)

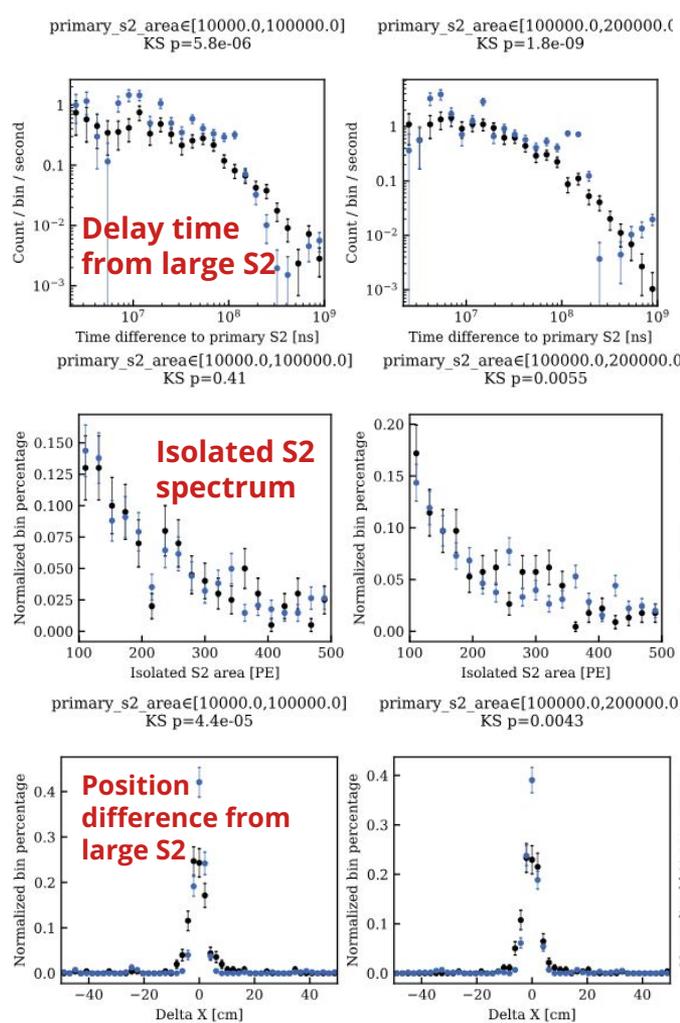
Delayed electron background

A **CNF** (conditional-normalizing-flow machine) is built to *learn the multi-dimensional correlation* between primary S2 and isolated S2.

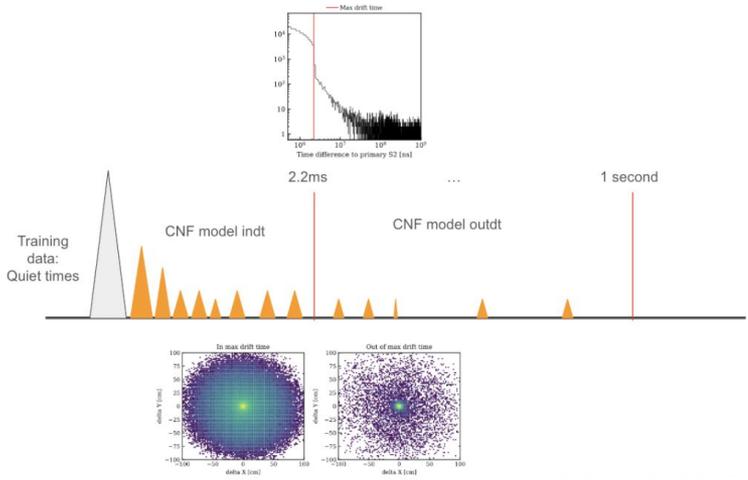
Isolated S2s can be modeled:

- **Simulated** by feeding all primary S2s in real data, getting their S2 waveforms
- **Salted back to real data** to build delayed electron events by Straxen.
- Applying cuts to get DE **background template**

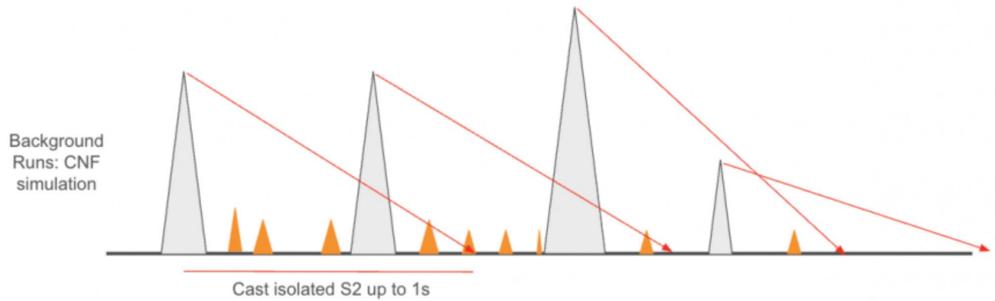
Shape determined by data-driven CNF simulation.



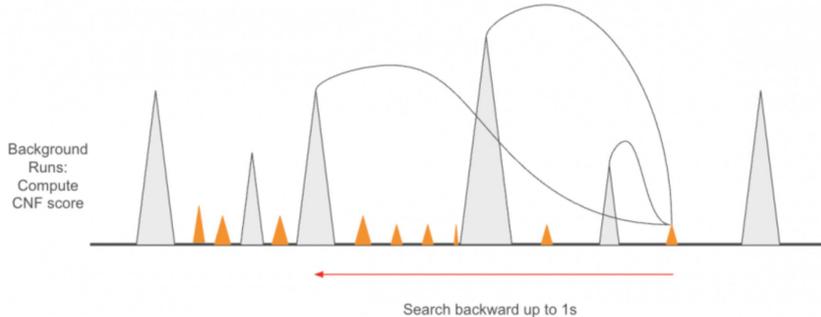
Delayed electron background



For each primary S2, generate isolated S2 simulations based on CNF best fit, including their time, positions, width, AFT, pattern, etc.



Choose the maximum CNF score considering the area, width, position, S2 pattern, etc



Delayed electron background

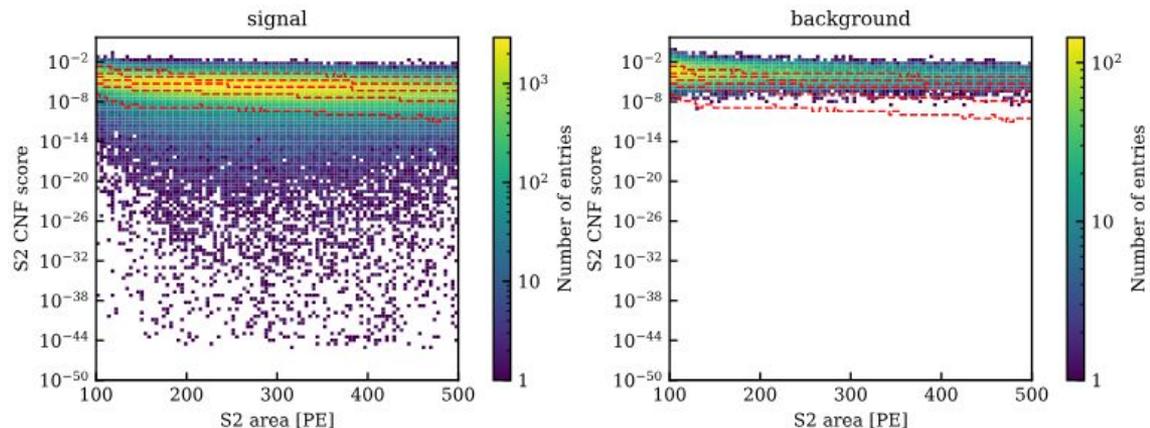
BDT machine learns the features:

- S2 area
- S2 width
- CNF score

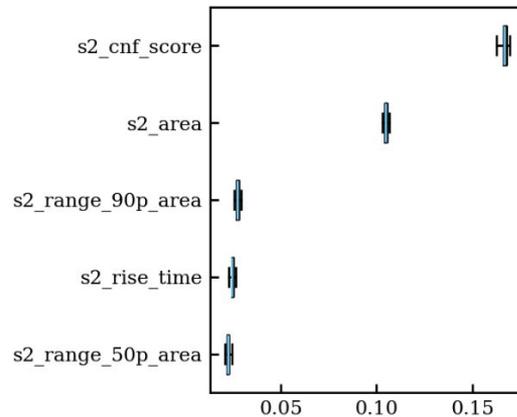
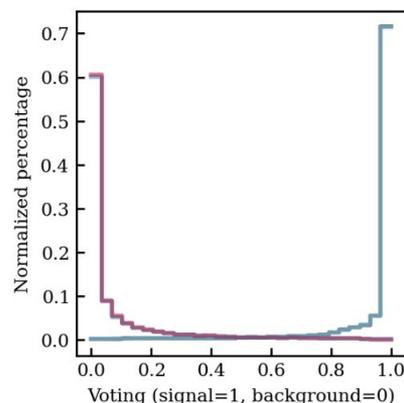
evaluating the correlation to previous primary S2s.

Can suppress the DE background to near negligible level:

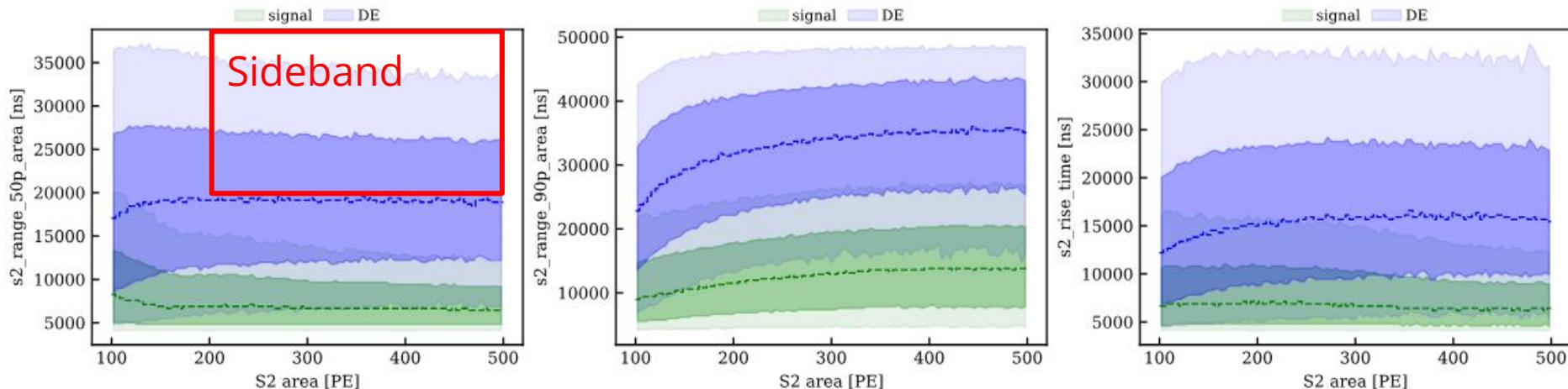
- DE rejection: 97%
- Signal acceptance: 90%



— Signal Test dataset — Signal Training dataset
— AC Test dataset — AC Training dataset



Delayed electron background



Delayed electron has wider S2 width due to unphysical SE pile-up, and exponential-decaying S2 area spectrum.

- Sideband selection: S2 area in [200, 500] PE, S2 width in [20, 40] us
- The DE rate can be renormalized by the observed events in sideband.

Accidental electron background

Random pile-up of single electrons from:

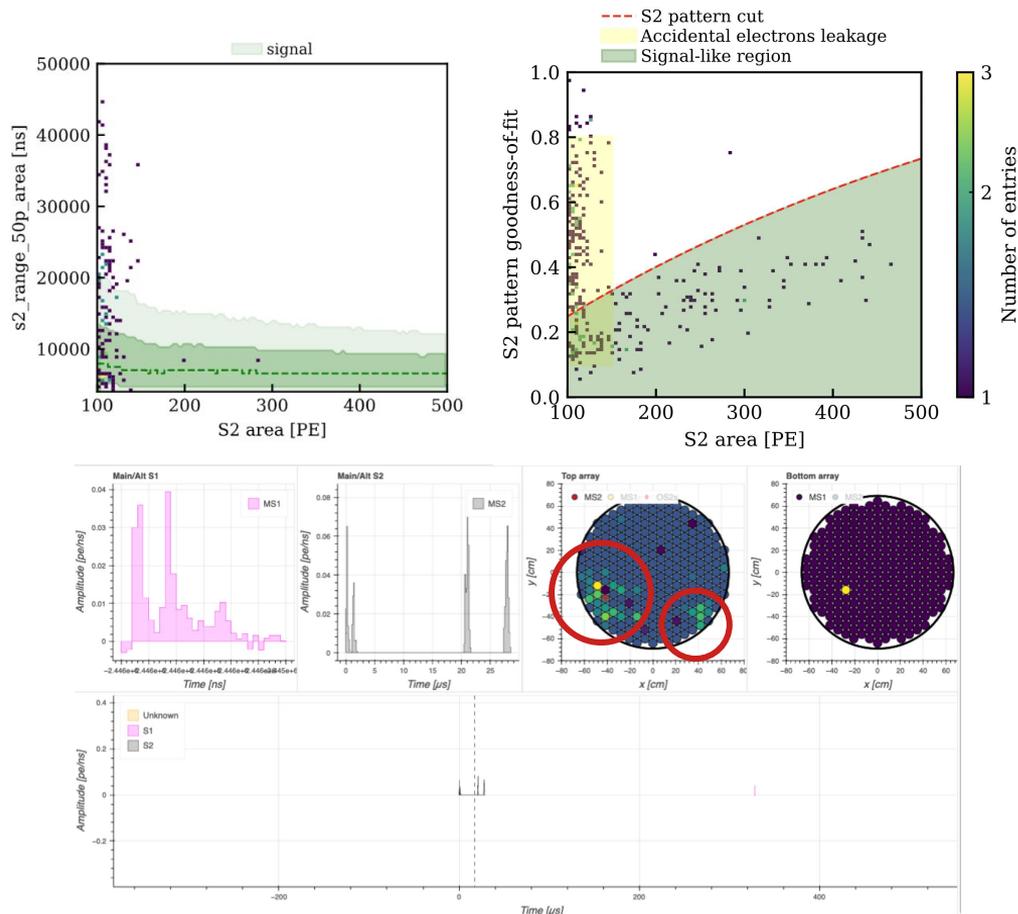
- Intrinsic detector SE emission not correlated to primary S2.
- SE far from originating primary S2.

Irreducible compared to the DE components.

Sideband selection:

- Events rejected by S2 pattern cut

Maybe the culprit of the excess of the AC sideband validation below 120 PE in CEvNS.



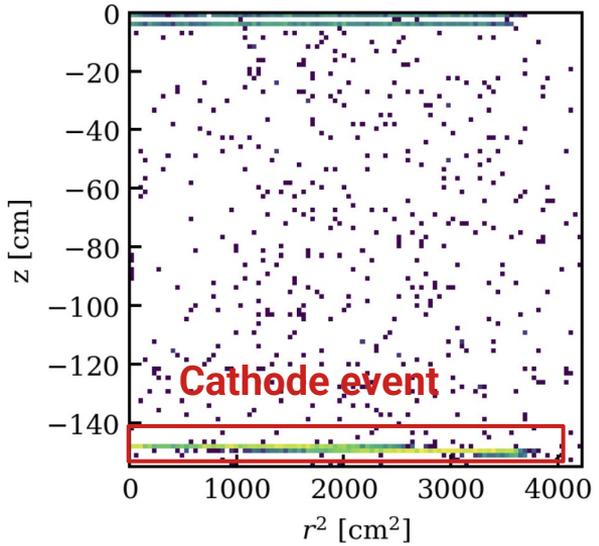
Cathode background

Pb-210 (Rn-222 decay chain)

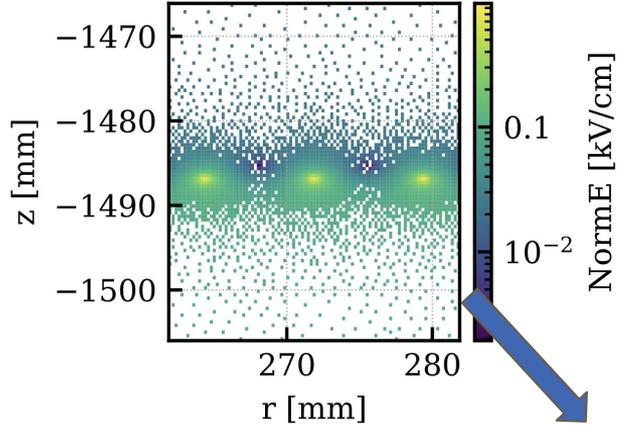


Cathodes

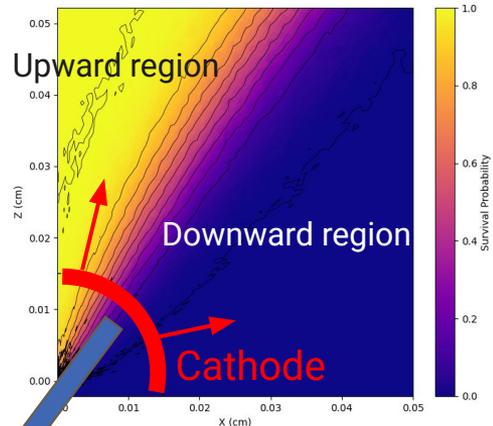
SR0 Rn220



Electric field map

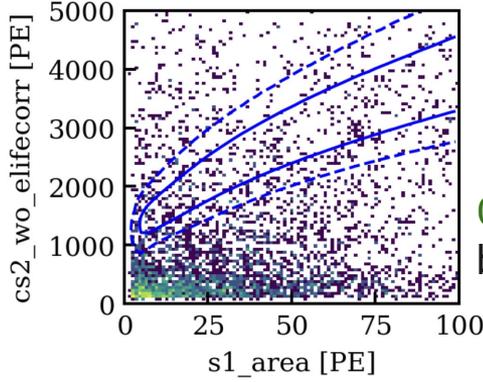


Electron survival probability map



S1 loss
 Strong field
 ⇒ suppress recombination
 Geometry effect
 ⇒ Low S1 detection efficiency

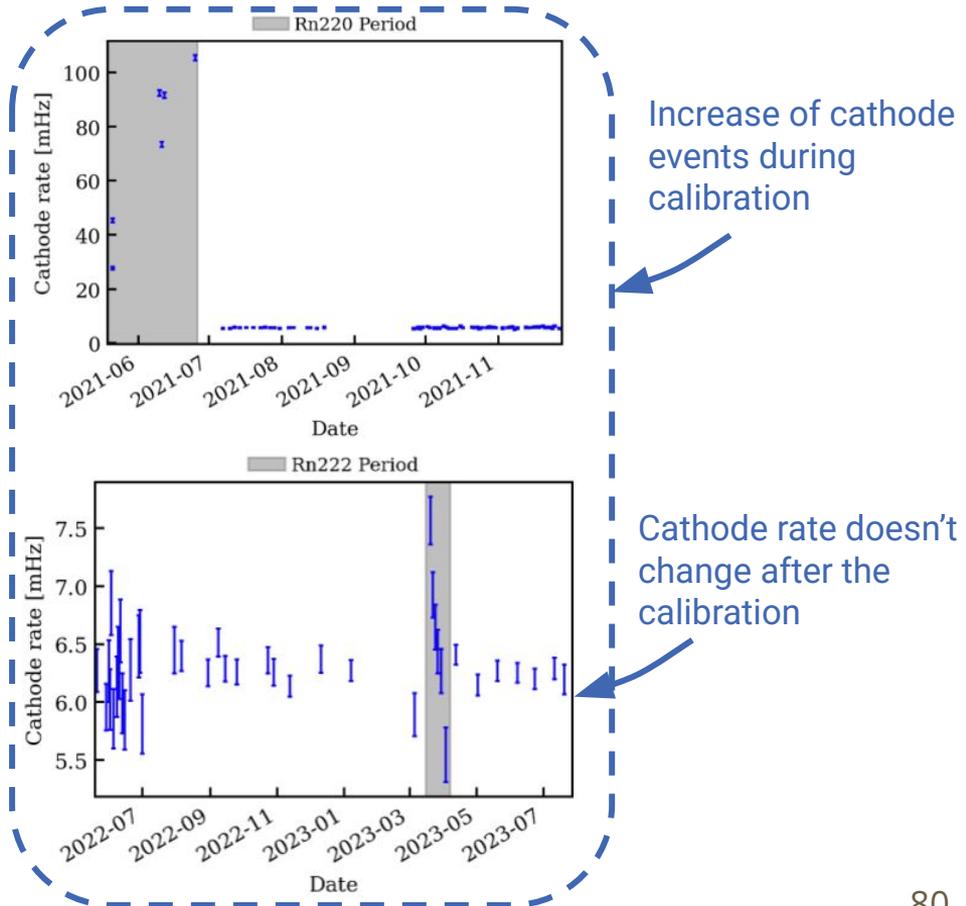
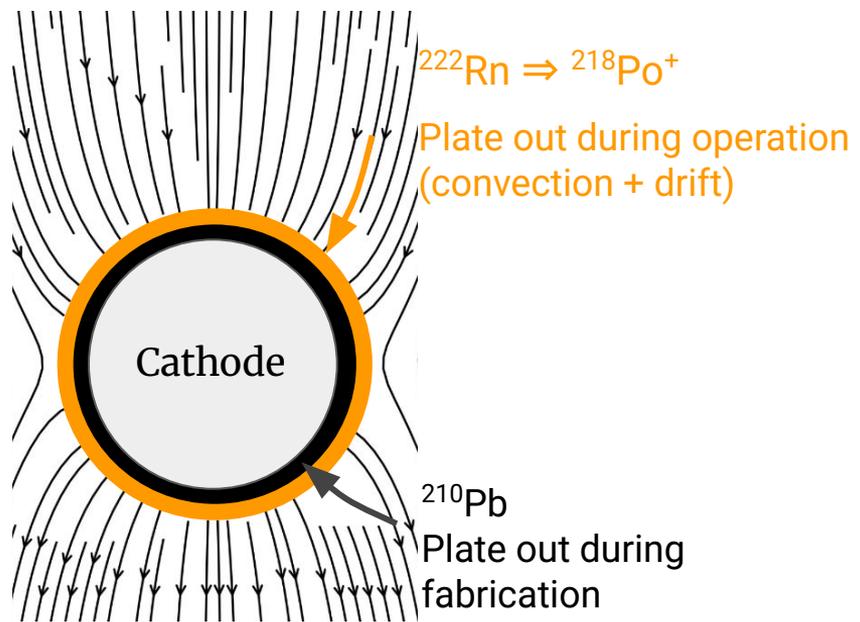
S2 loss
 Electrons drifting downward



Cathode band
 below ER band

Cathode background

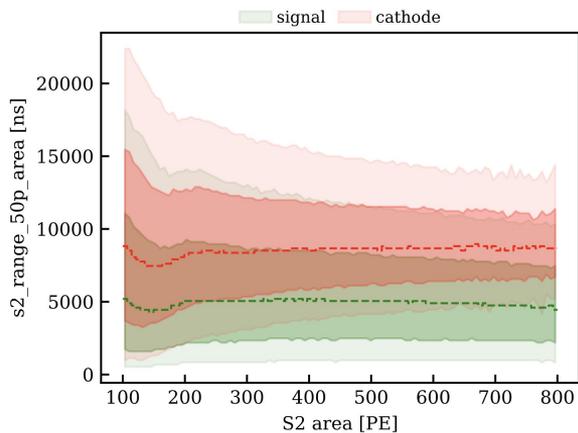
Enhanced cathode background during calibration:
Plate out of positive ion from Rn-222/Rn-220 decay chain during operation



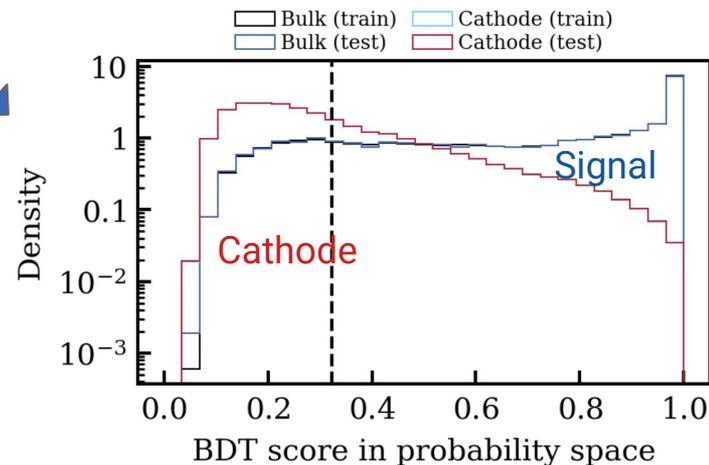
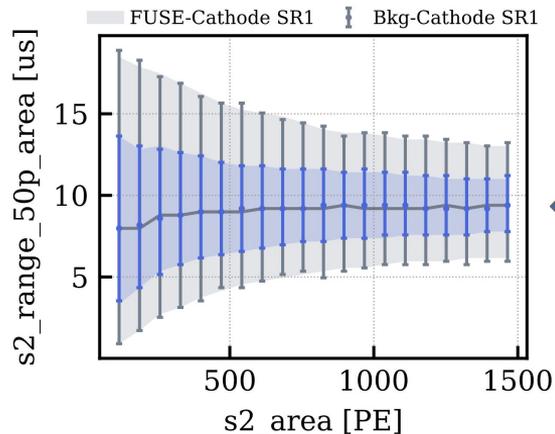
Cathode background

Waveform features provide discrimination power of cathode and signal:

- S2 area
- S2 width (50p)
- S2 width (90p)
- S2 rise time

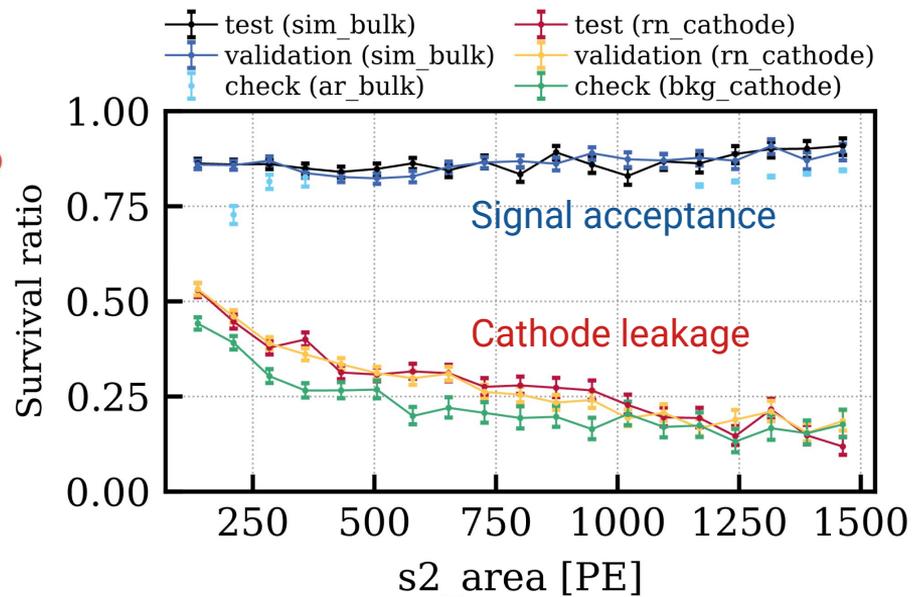
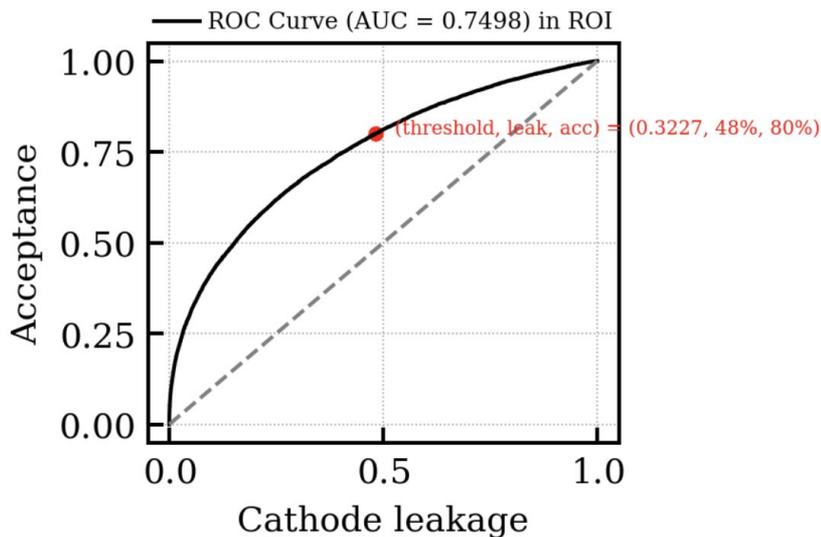


Fuse validation on waveform feature spaces
⇒ more statistics

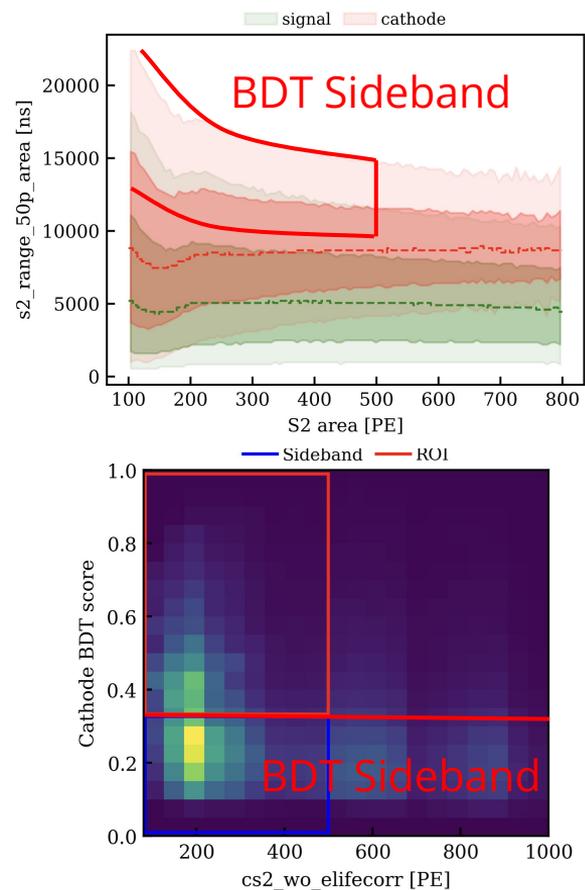


Cathode background

- Better performance than simple S2 width cut
- Cathode rejection: 50%
- Signal acceptance: 80%



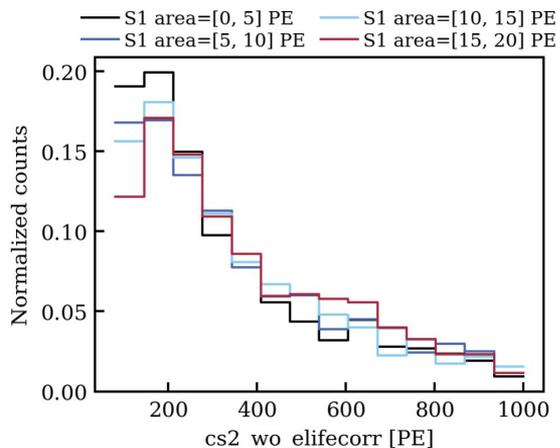
Cathode background



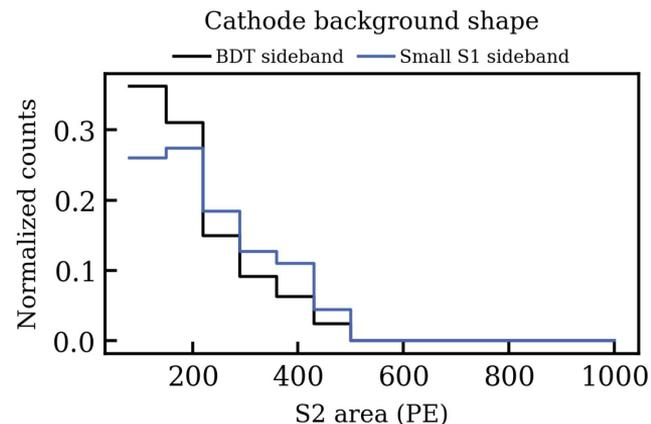
1. Cathode dominant region (sideband) selection:
 - Small S1 Events with z at cathode position
 - **Events rejected by cathode BDT cut**

For each S2 area bin, simulation can give the ratio of BDT rejected events/BDT allowed events.

2. Rescaling to ROI



S1 dependent spectrum not reliable
Smaller S1 predicts more cathode background in low S2 region

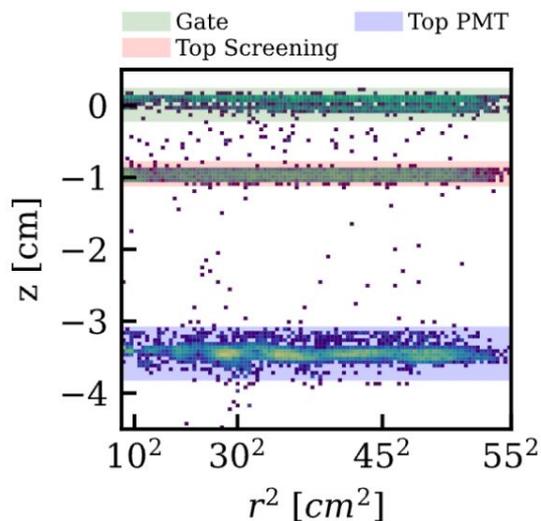


BDT sideband predicts a S2 spectrum weighting more towards the lower end.

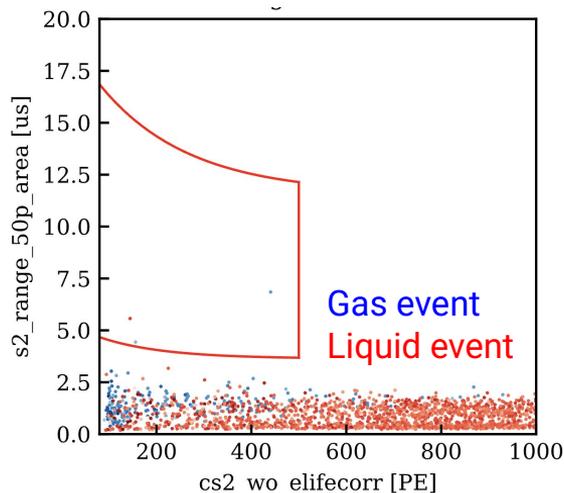
Gate/gas background

Origin:
Pb-210 beta decay from ^{222}Rn decay chain from **gate**, anode, **top screening wires**, **top PMTs**.

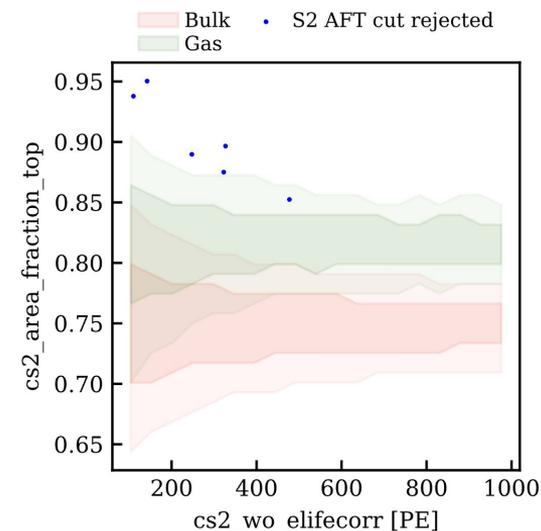
Primarily identified by the S2-width selection and cS2 AFT cut. Can be suppressed to negligible level.



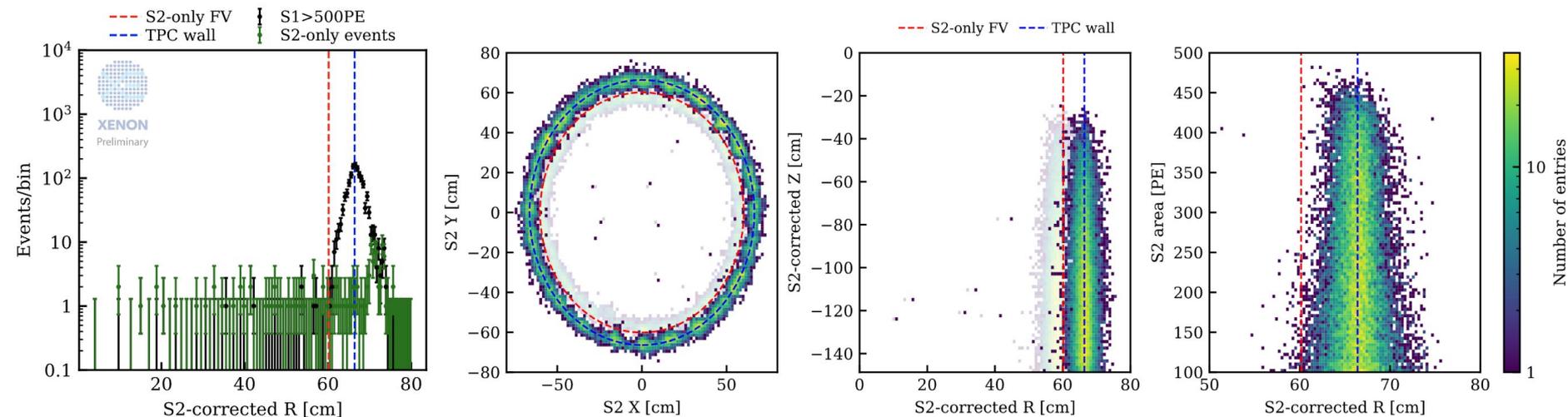
S2 width lower boundary



S2 AFT upper boundary



Wall background



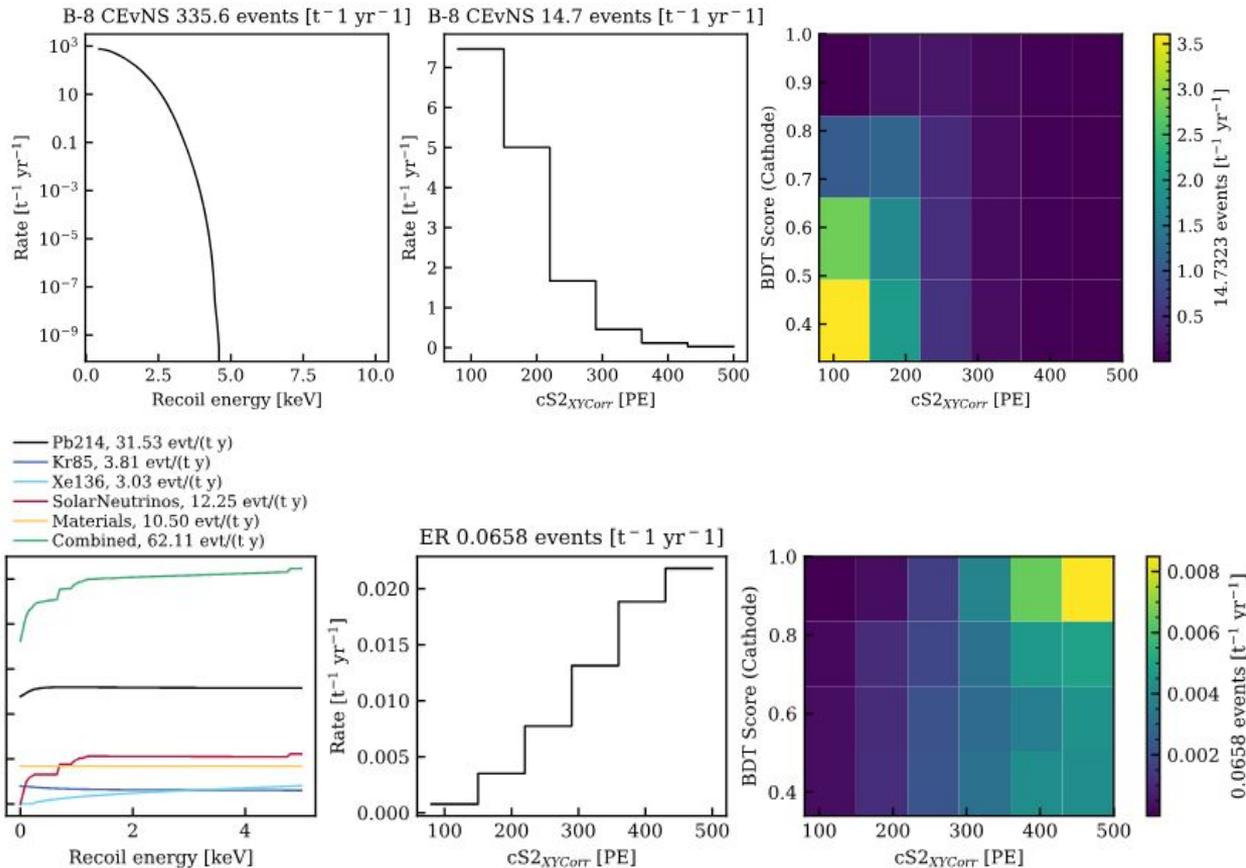
A S2-only position reconstruction algorithm is developed using S2 waveform, allowing **Z reconstruction** and **field distortion correction**.

Wall background reduced to **negligible level** using 2-fold analysis fiducial choices.

CEvNS/ER background

Simulation shows CEvNS and ER are **subdominant** compared to detector backgrounds.

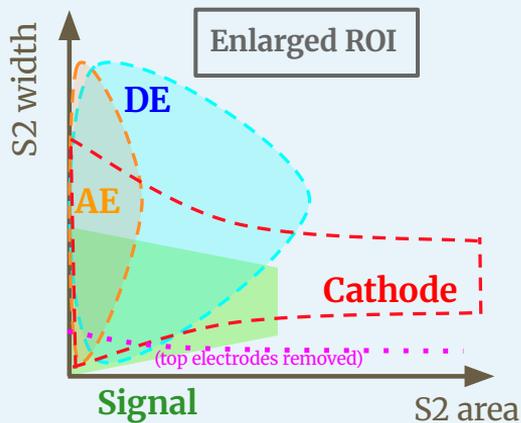
- CEvNS prediction: 14.7 /ty, ~4 times of 2 fold.
- ER background is negligible.



Background Modeling

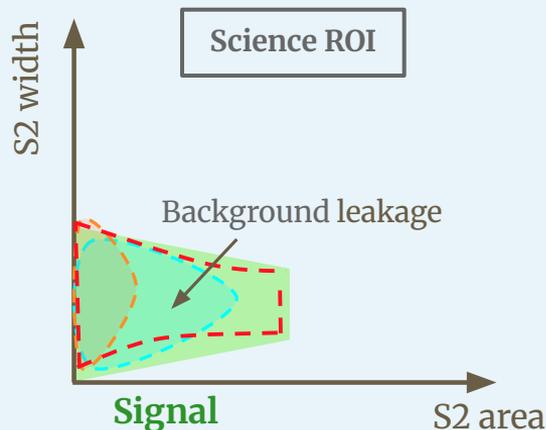
What we have now:

DE, AE, cathode background modeling in full space



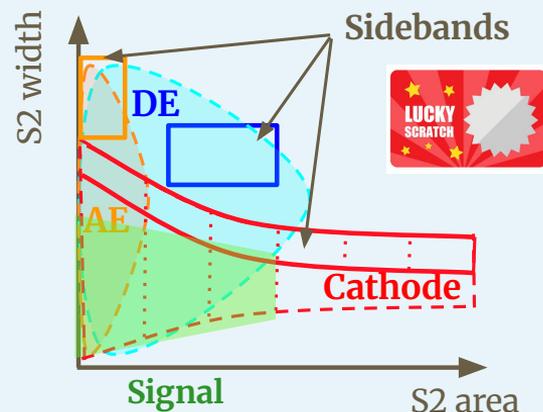
Objective:

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.

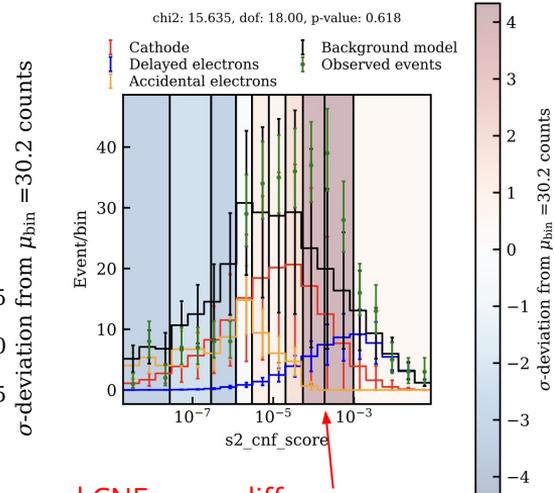
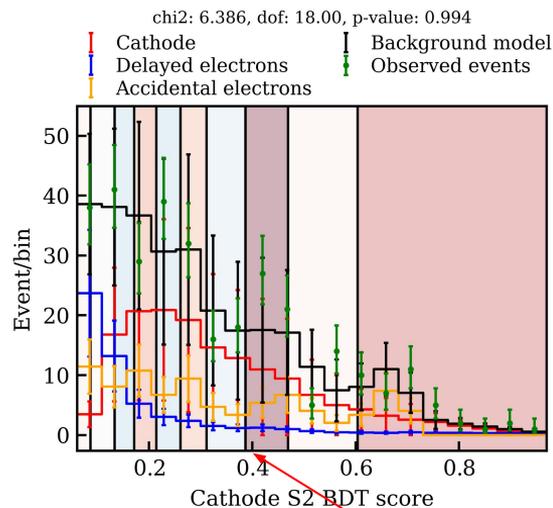
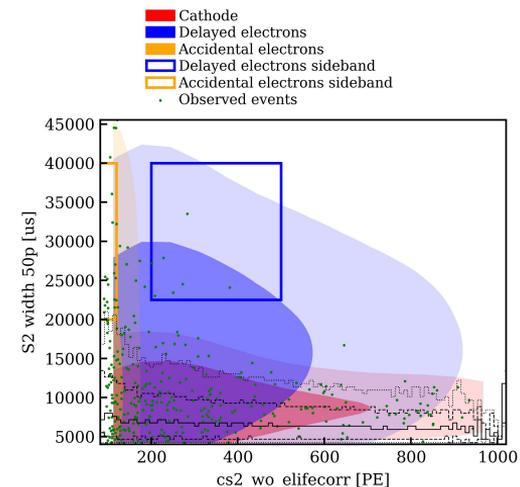
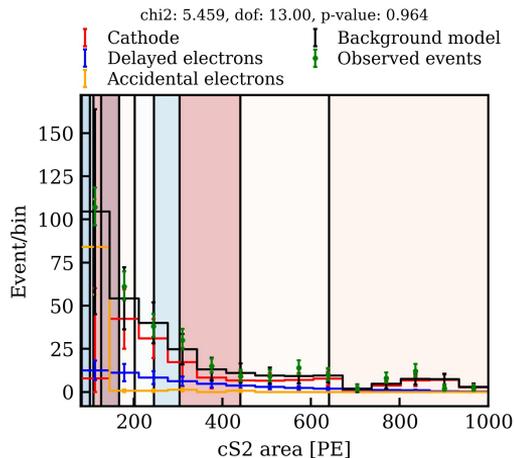


- (1) Background modeling from simulation can be different from the actual distribution from data
- (2) Science ROI (full cut list), enlarged ROI (loose cut list without BDT cuts)

SRO Rn220 enlarged

We perform a two-step validation:

- **Enlarged ROI: No S2 width related cuts applied**
- **Science ROI: Apply complete S2-only cut list**

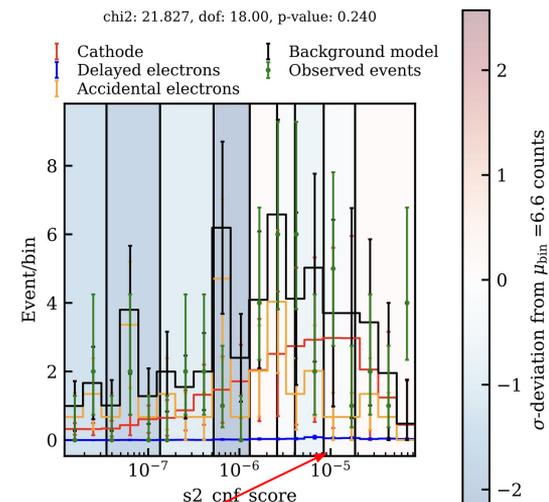
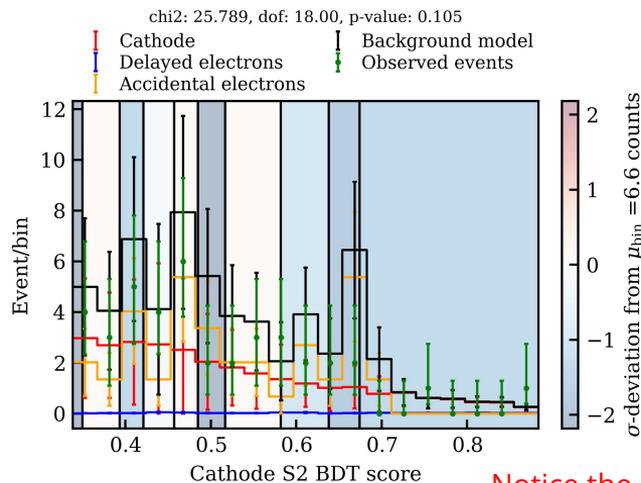
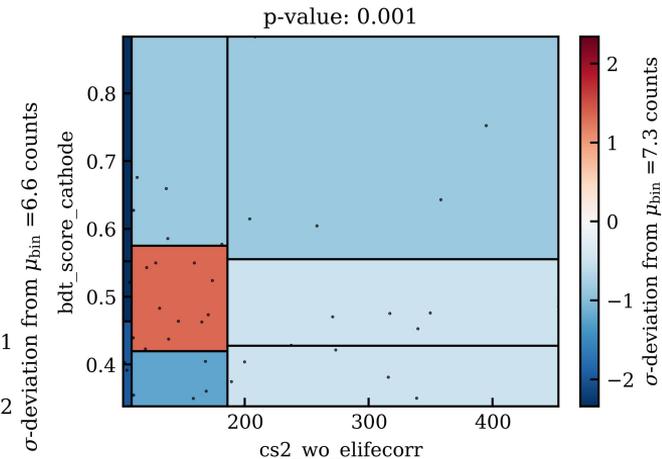
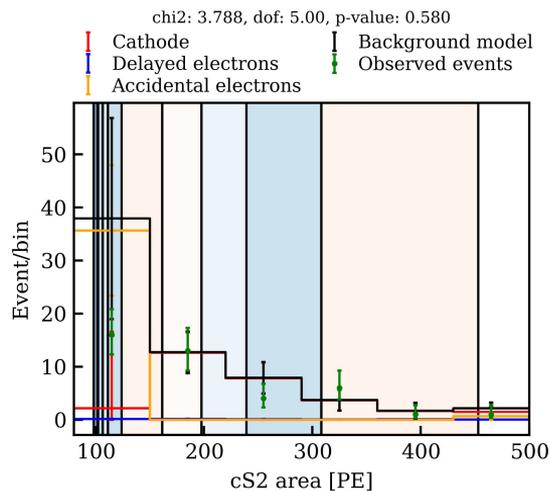


Notice the BDT score and CNF score differences

SRO Rn220 science

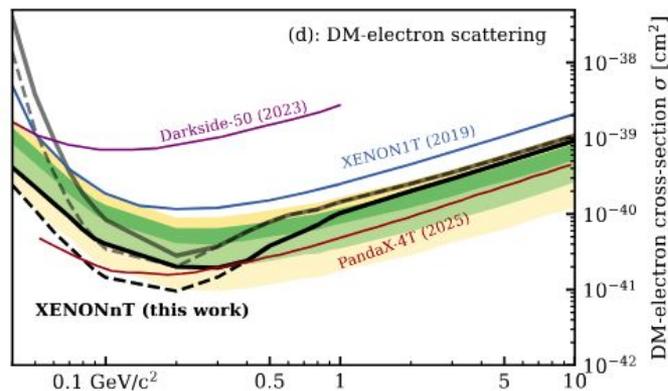
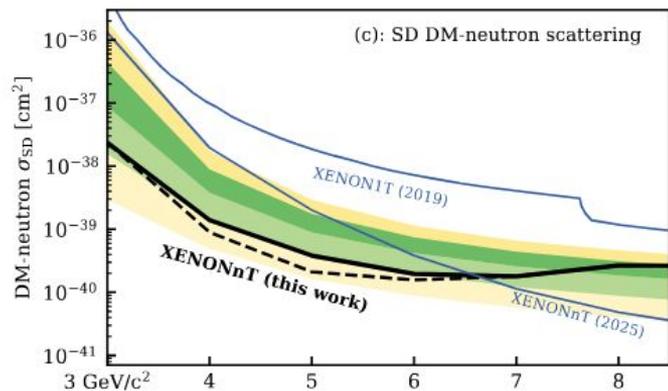
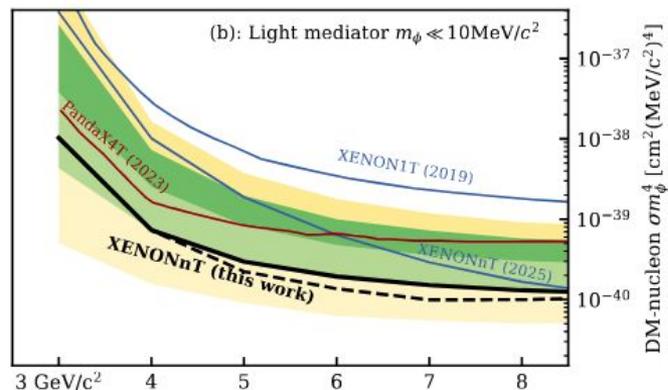
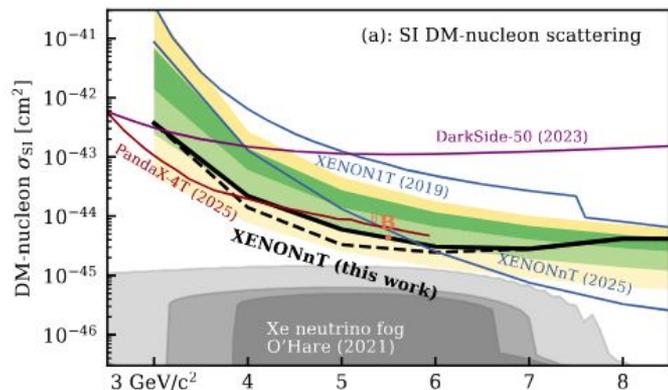
We perform a two-step validation:

- Enlarged ROI: No S2 width related cuts applied
- **Science ROI: Apply complete S2-only cut list**



Notice the DE is gone, AE survived

S2-only results



S2-only results

