



XENON

Search for Light Dark Matter in XENONnT experiment

Based on the recent ArXiv Paper: <https://arxiv.org/abs/2601.11296>

Yongyu Pan

(LPNHE, Sorbonne University)

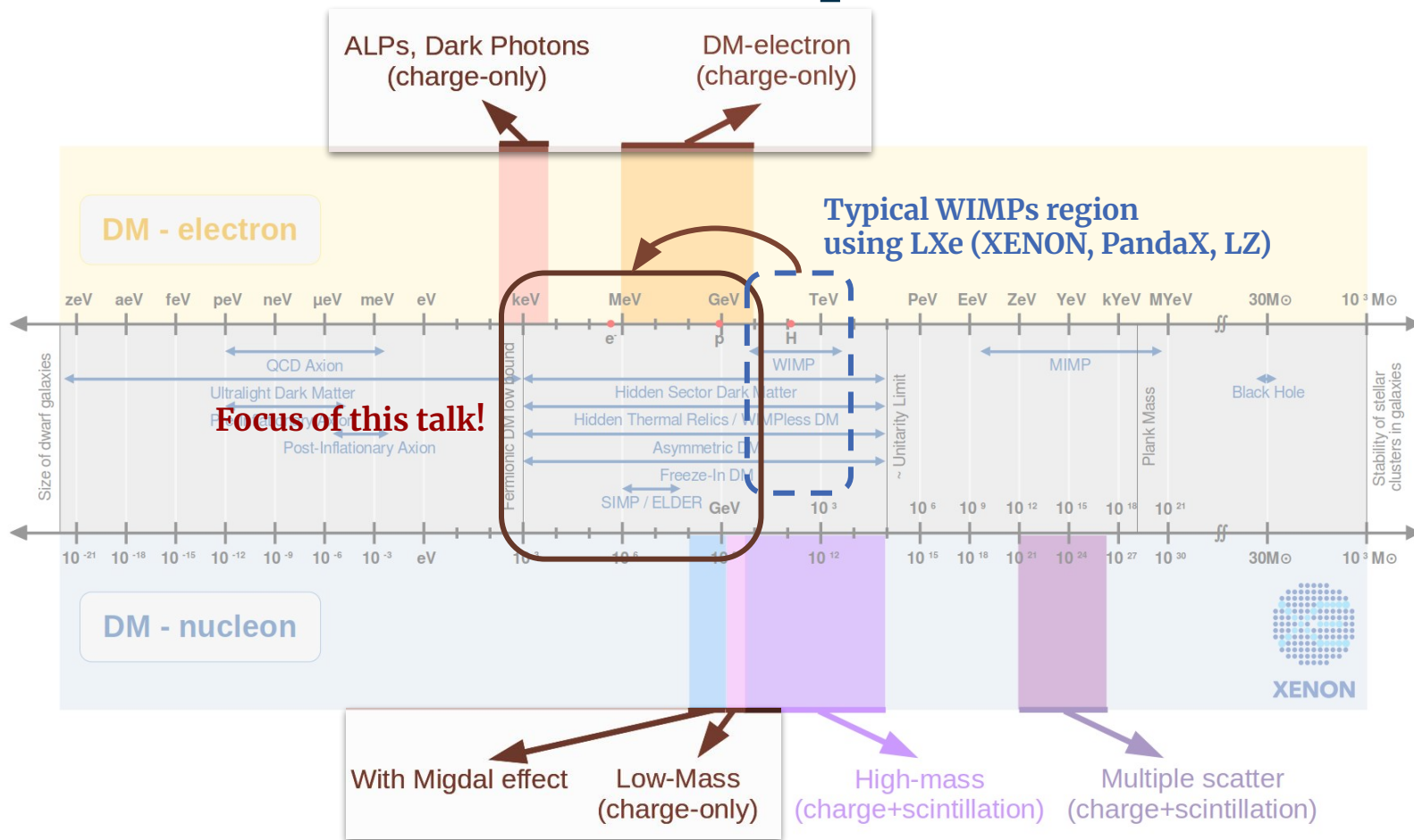
on behalf of XENON Collaboration

IRN Terascale

22 April 2026



Dark matter search landscape



XENONnT Experiment | Direct detection of dark matter



XENON

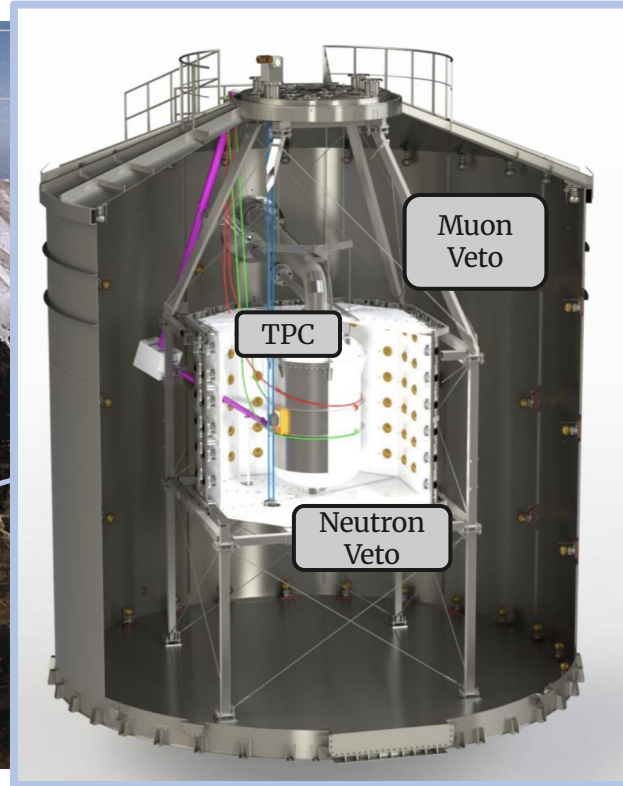
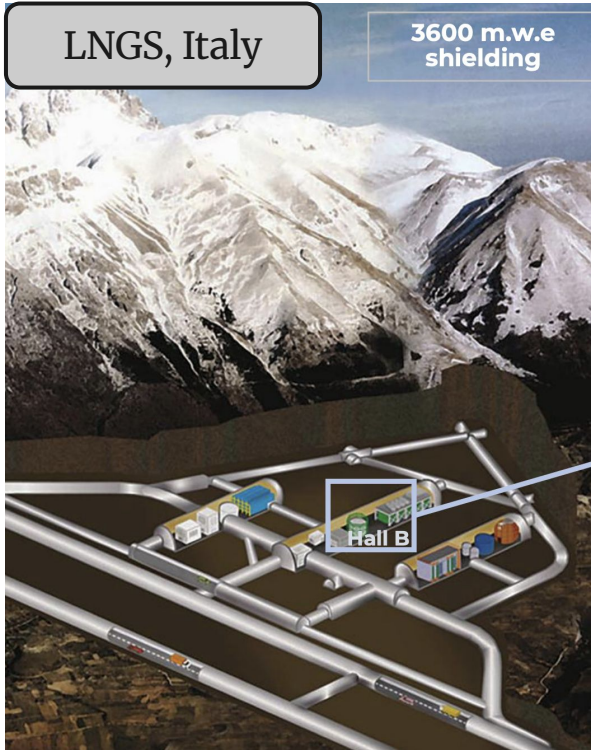
~ 200
Scientists

30
Institutions

12
Countries

LNGS, Italy

3600 m.w.e
shielding



Main Objective:
Discover Weakly Interacting Massive
Particles (WIMPs)

XENON program timeline

XENON10
2005
14 kg

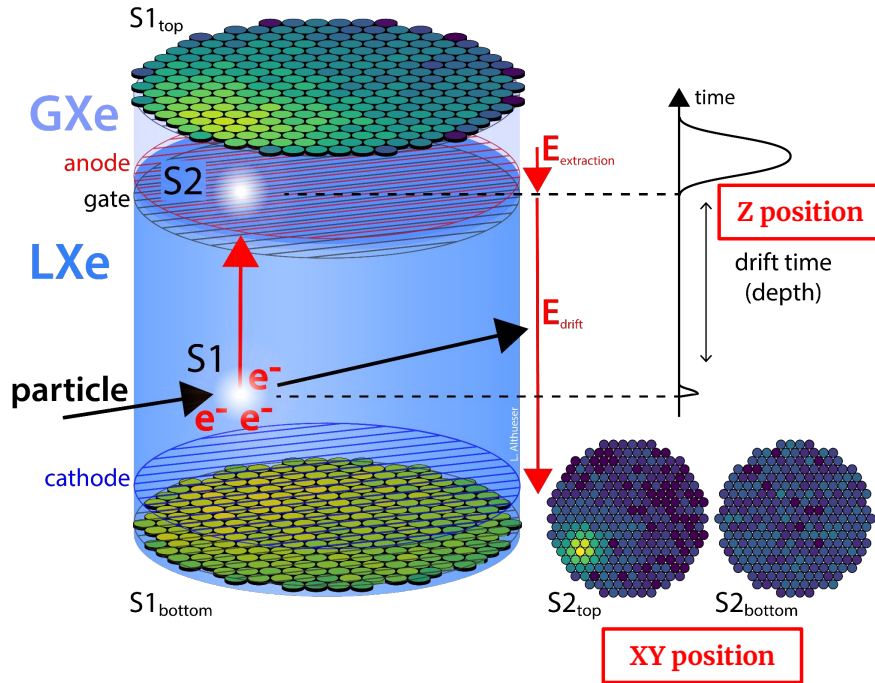


XENON100
2008
62 kg

XENON1T
2016
2 t



XENONnT
2020
6 t



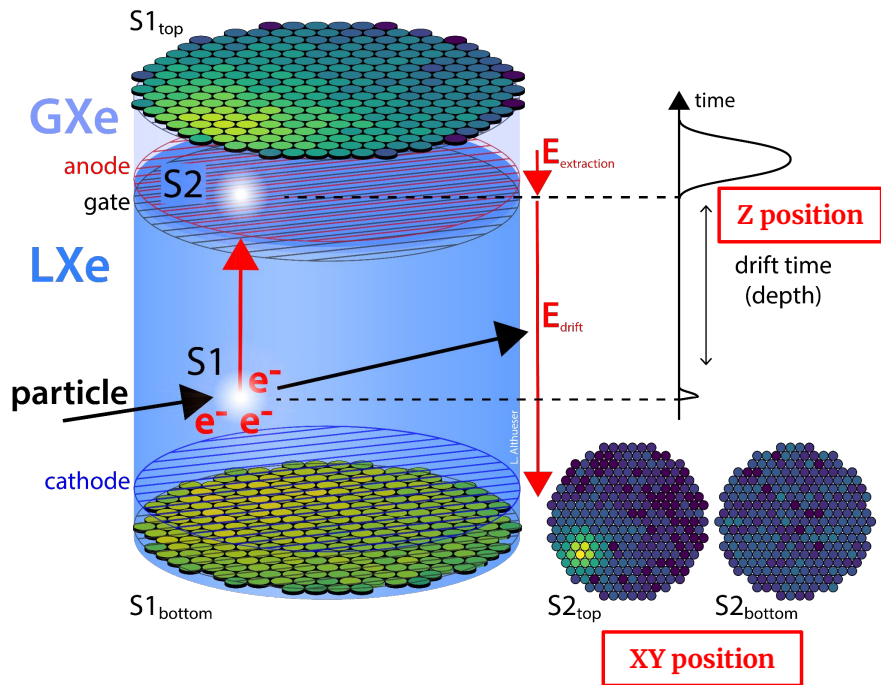
Dual phase Xe TPC (Time projection chamber)

- **S1:** Prompt scintillation light
- **S2:** Secondary scintillation light by ionized electrons
- **3D Position reconstruction:** Drift time + PMT pattern
- **Energy reconstruction:**

$$E = W \left(\frac{cS_1}{g_1} + \frac{cS_2}{g_2} \right)$$

W: Average energy to produce a quanta
 cS1, cS2: Corrected area of S1 and S2
 g1, g2: Gain of S1 (~0.1) and S2 (~15)

XENONnT Experiment | Direct detection of dark matter



Dual phase Xe TPC (Time projection chamber)

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<p>Small S1 Low detection efficiency</p> <p>Photon $\times 100 \rightarrow S1 = 10 \text{ PE}^{(1)}$</p>	<p>Large S2 Strong scintillation in gas</p> <p>$e^- \times 100 \rightarrow S2 = 1500 \text{ PE}$</p>
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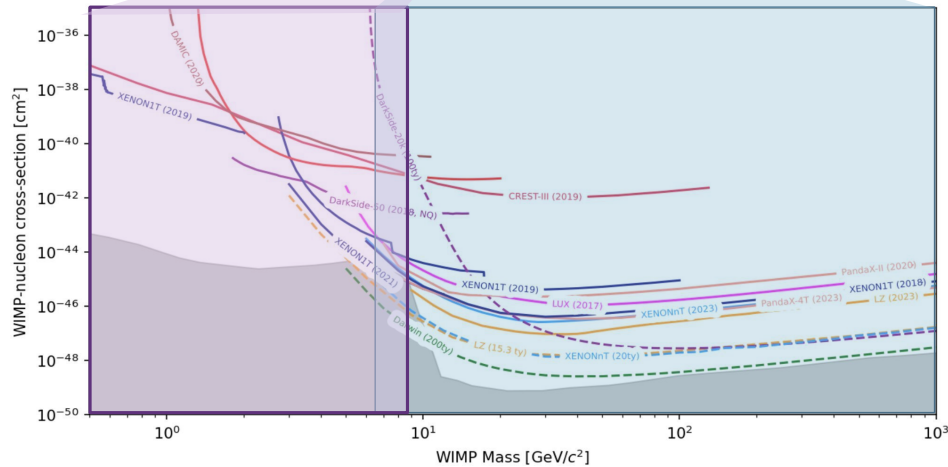
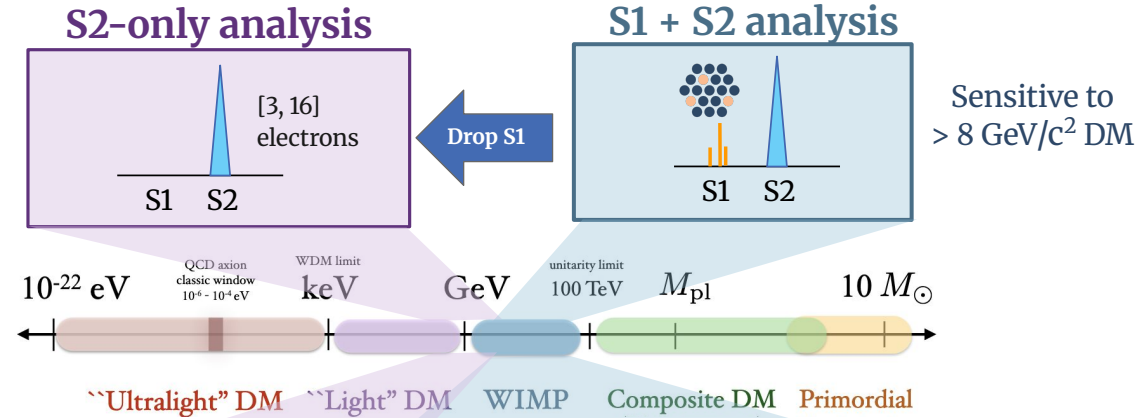
⇒ Motivation of **S2-only** analysis

(1) Detected Photoelectron [PE]

Motivation of S2-only analysis



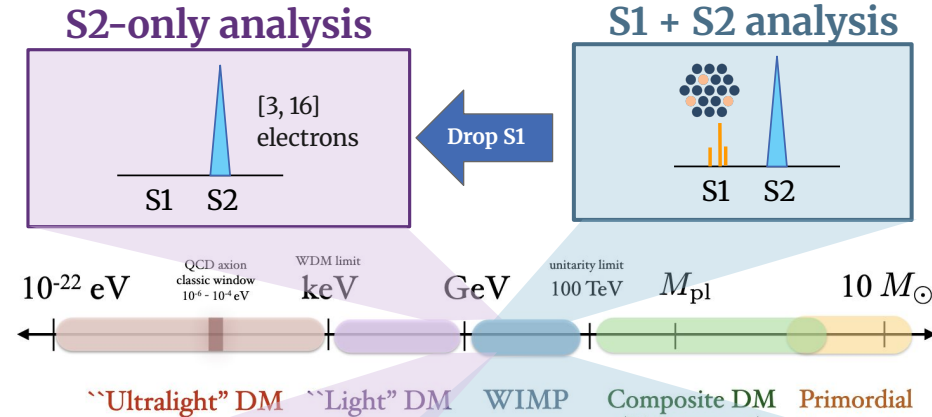
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Motivation of S2-only analysis



XENON



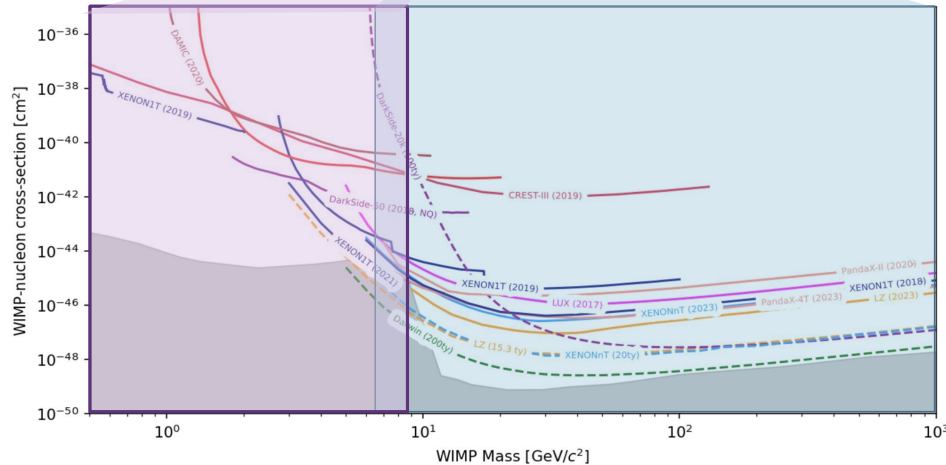
Advantage:

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

Challenges:

No z-Position due to the lose of S1 reducing the ability to reject top/bottom backgrounds

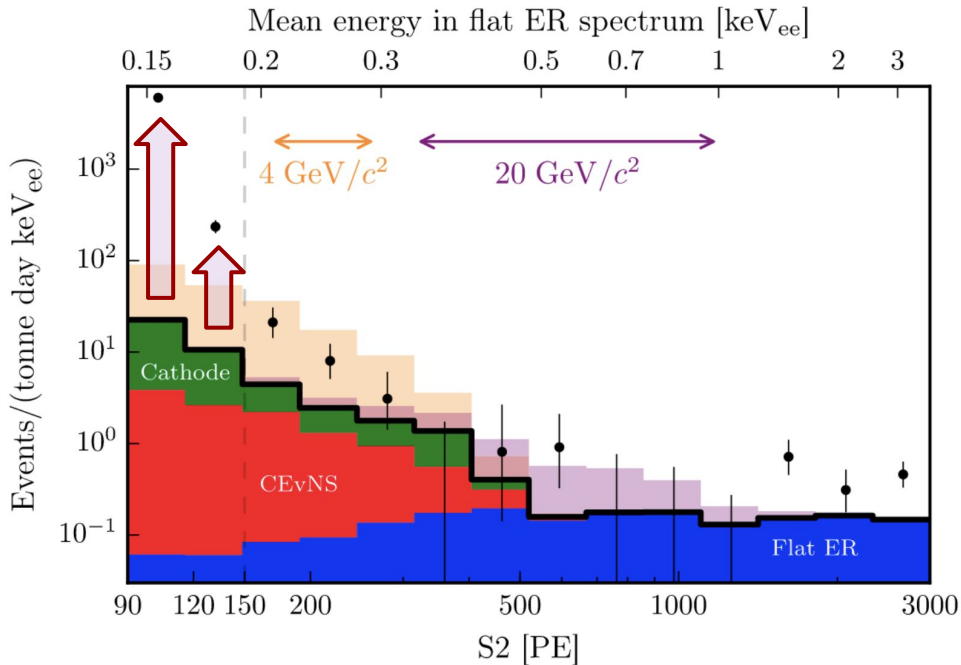
⇒ Difficult to build a **complete background model**



Motivation of S2-only analysis



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Advantage:

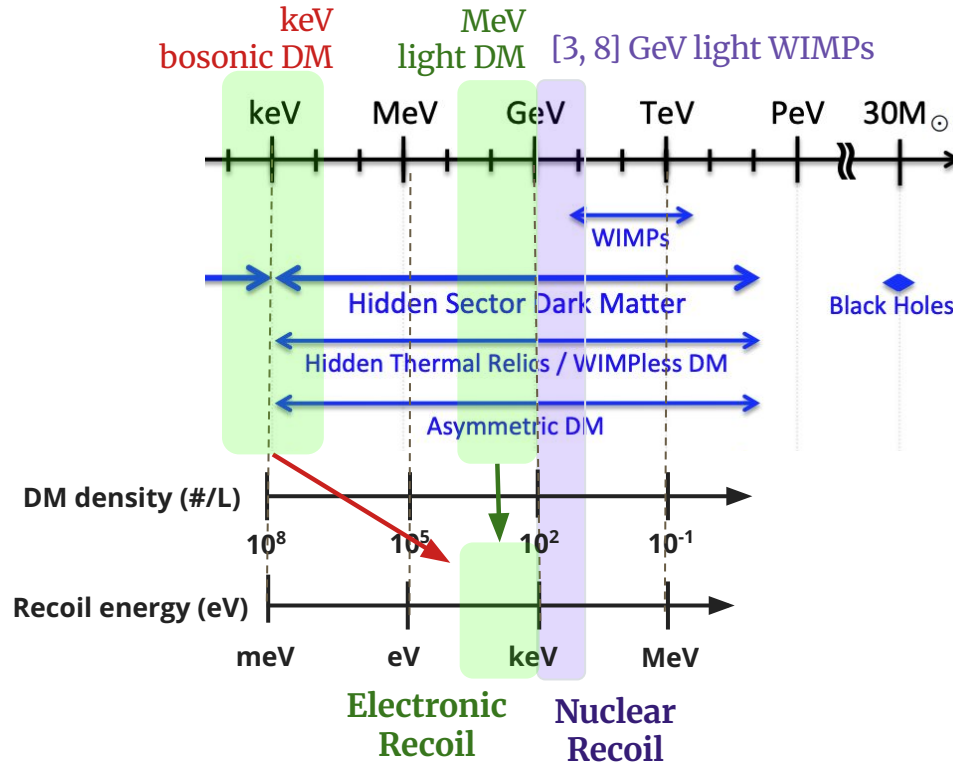
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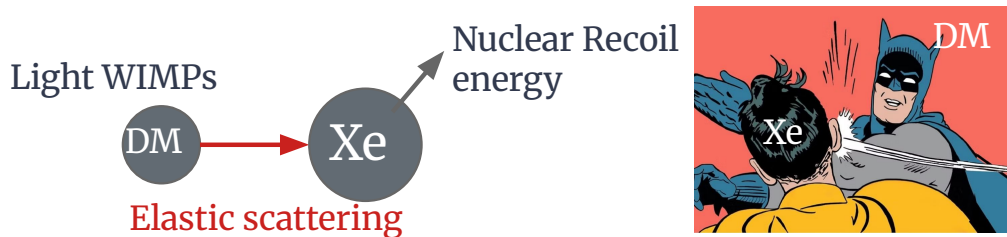
⇒ Difficult to build a **complete background model**

Signal Model



Signal Model

Nuclear Recoil

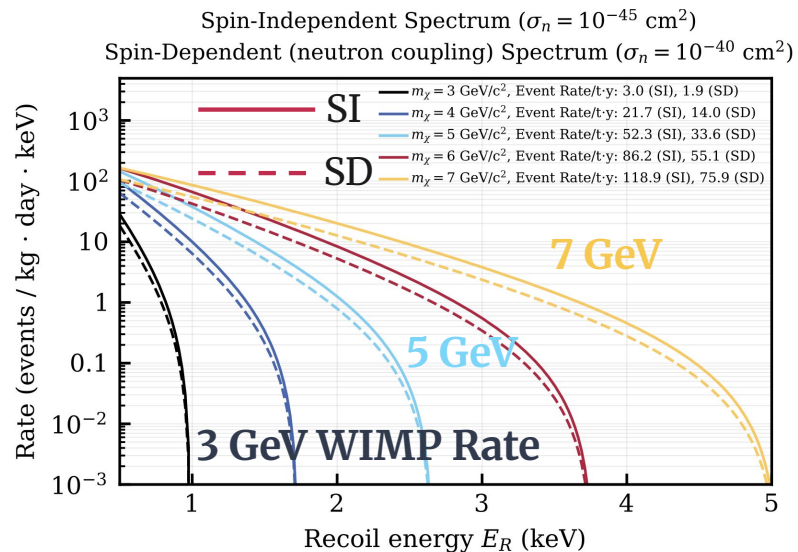


$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_{\text{Xe}}} \int_{v_{\min}}^{v_{\text{esc}}} f(v) v \frac{d\sigma_{\chi-\text{Xe}}(v)}{dE_R} dv$$

DM & Xe Properties

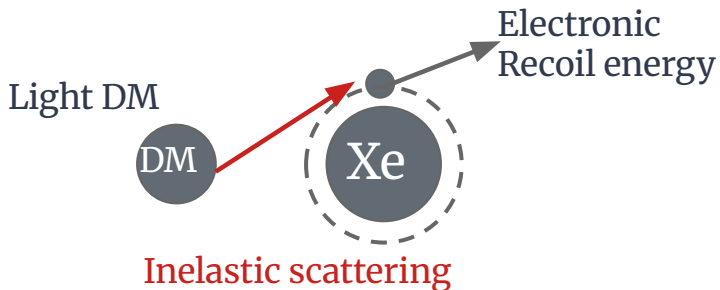
DM Velocity

Model Dependent Cross section



Signal Model

Electronic Recoil



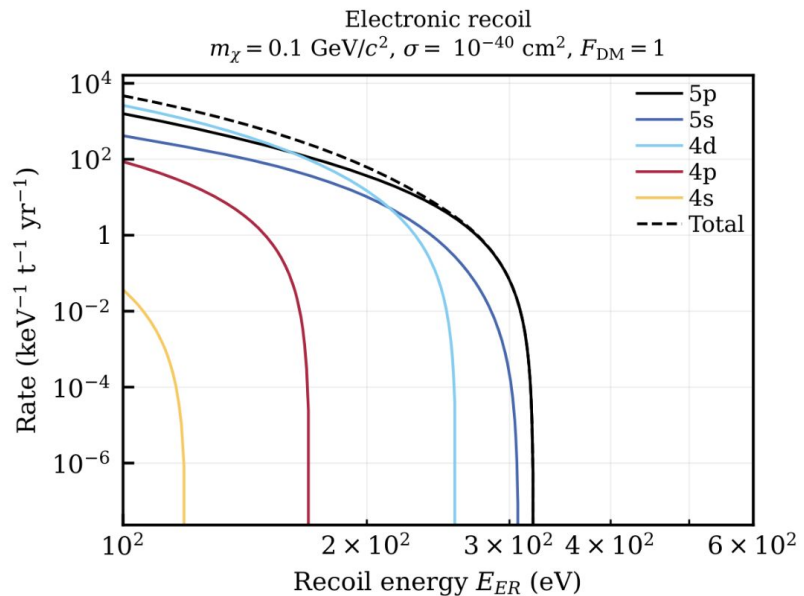
$$\frac{dR}{d \ln E_{er}} = \frac{N_{Xe} \rho_{\chi}}{m_{\chi}} \cdot \frac{\sigma_e}{8\mu_{\chi e}^2} \cdot \int q dq \eta(v_{\min}) \cdot |F_{DM}(q)|^2 \cdot \mathcal{A}(E, q)$$

DM & Xe Properties

DM Velocity

Form Factor related to mediator

Atomic Response Term



Signal Model

Absorption of bosonic DM



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Axion-like Particle
Dark Photon



Recoil energy

$$E_{ER} = m_\chi$$

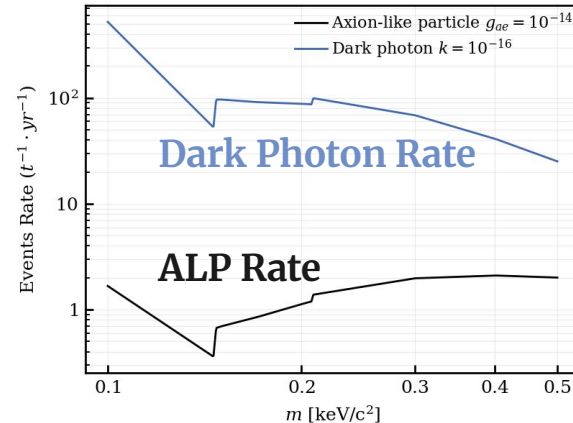
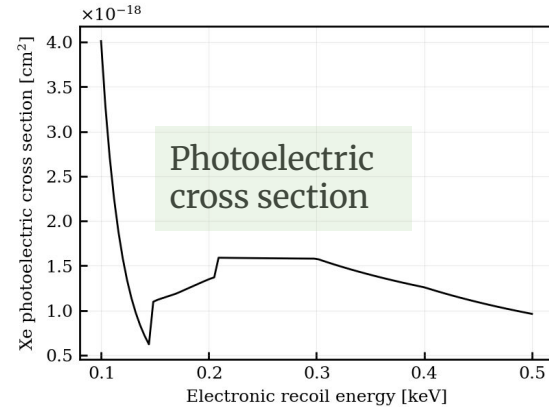
Absorption
(Axio-electric or
kinetic mixing + photo-electric)

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

Kinetic Mixing constant

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

Axio-electric coupling constant



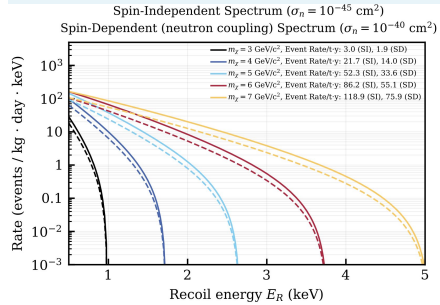
Signal Model | Signal spectrum



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Recoil Energy Spectrum

Light DM



Signal Model | Signal spectrum



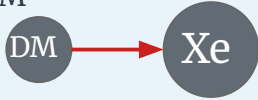
XENON

Recoil Energy Spectrum

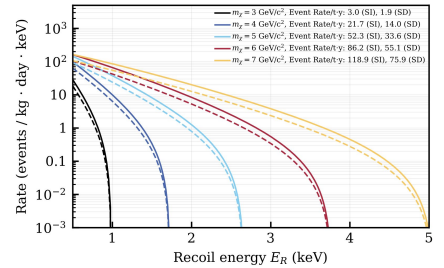


- Charge Yield
- Detection & Data Selection Efficiency

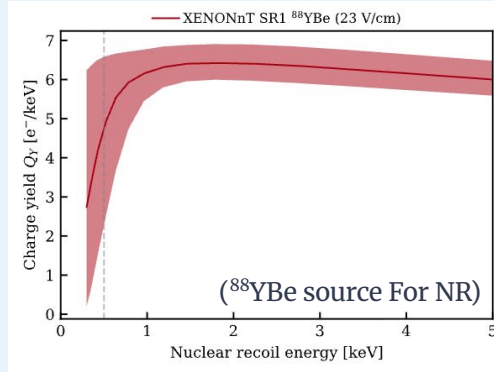
Light DM



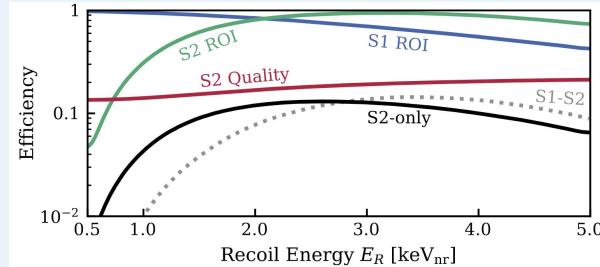
Spin-Independent Spectrum ($\sigma_n = 10^{-45} \text{ cm}^2$)
Spin-Dependent (neutron coupling) Spectrum ($\sigma_n = 10^{-40} \text{ cm}^2$)



Charge Yield:
 $E_{\text{recoil}} \Rightarrow N_{\text{electrons}}$



Data Selection Efficiency



Signal Model | Signal spectrum



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Recoil Energy Spectrum



- Charge Yield
- Detection & Data Selection Efficiency

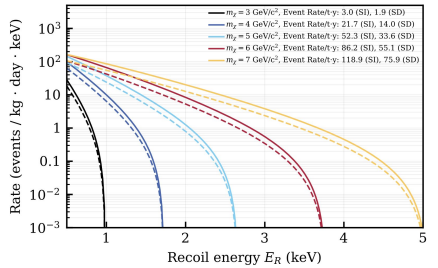


Signal Prediction

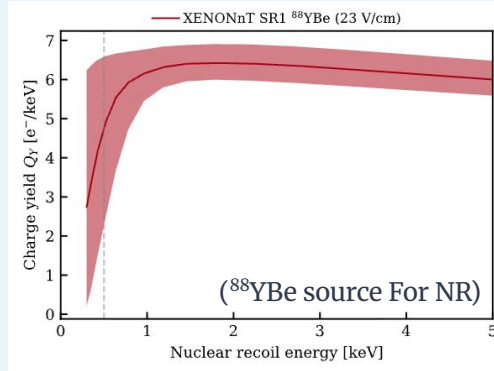
Light DM



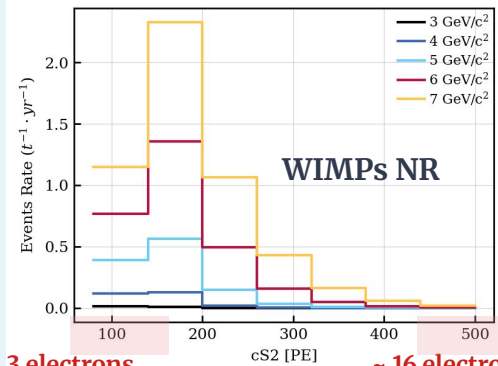
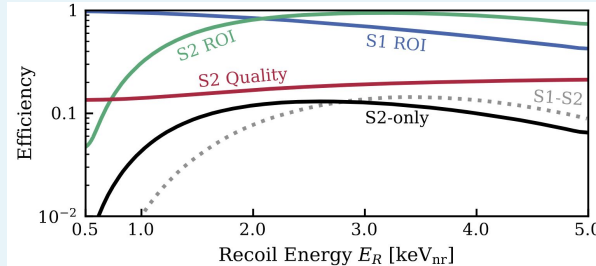
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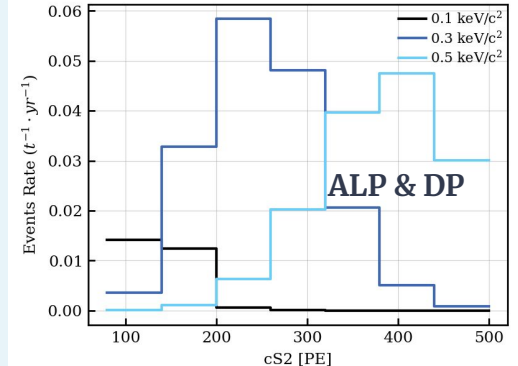


Data Selection Efficiency



~ 3 electrons

~ 16 electrons



Signal Model | Signal spectrum



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Recoil Energy Spectrum



• Charge Yield

• Detection & Data Selection

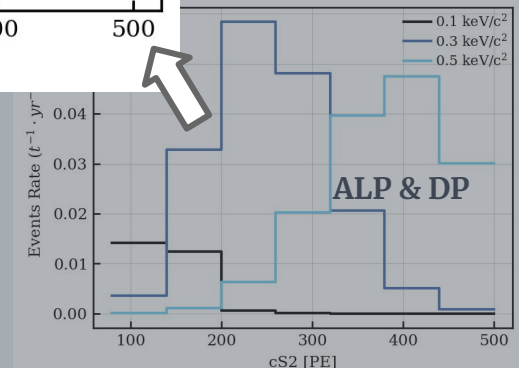
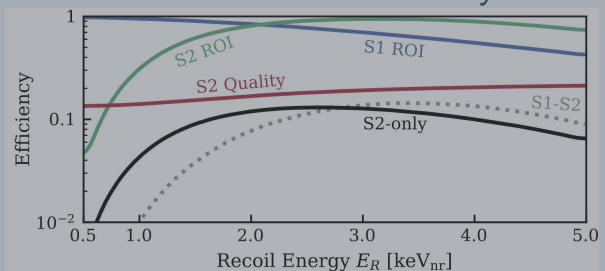
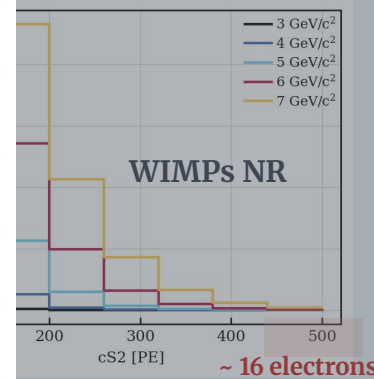
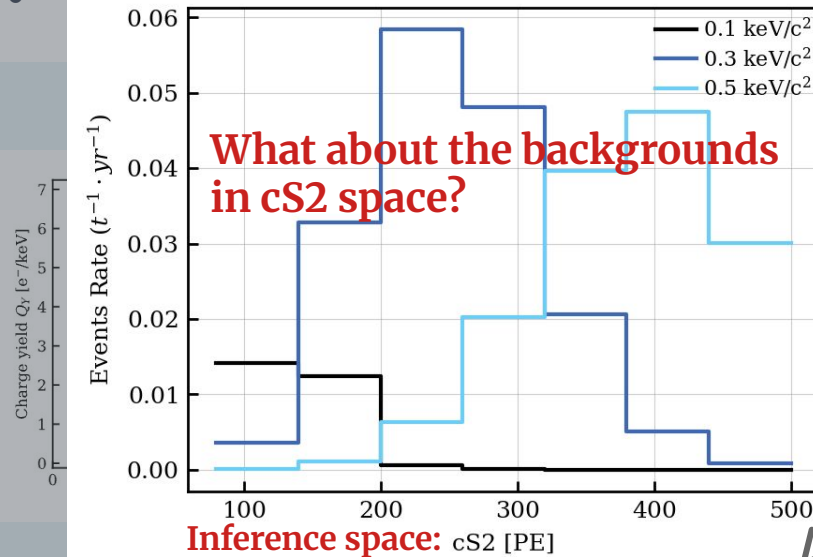
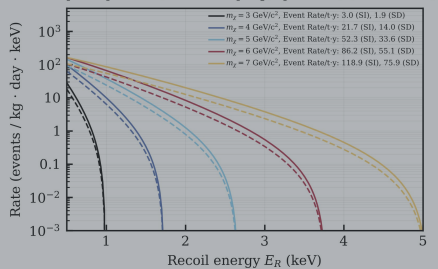


Signal Prediction

Light DM



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



Signal Model | Signal spectrum



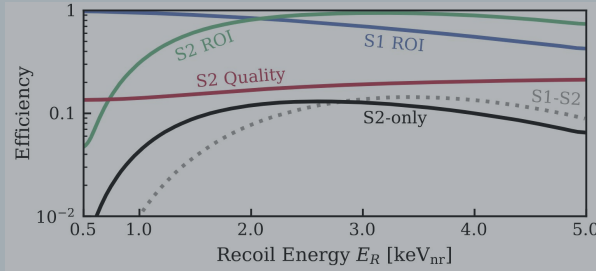
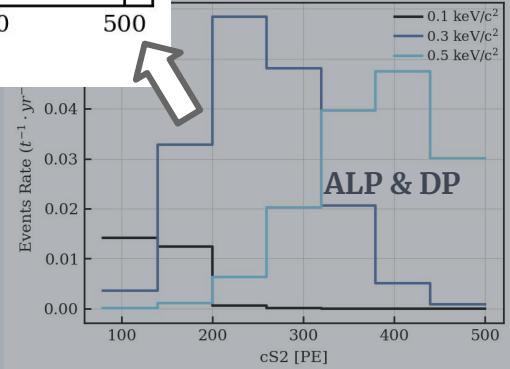
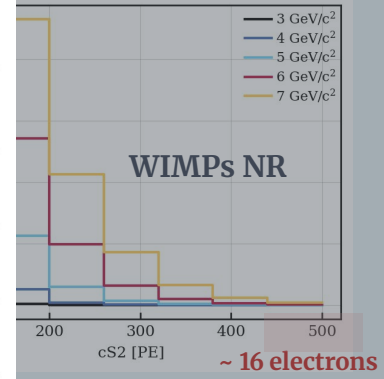
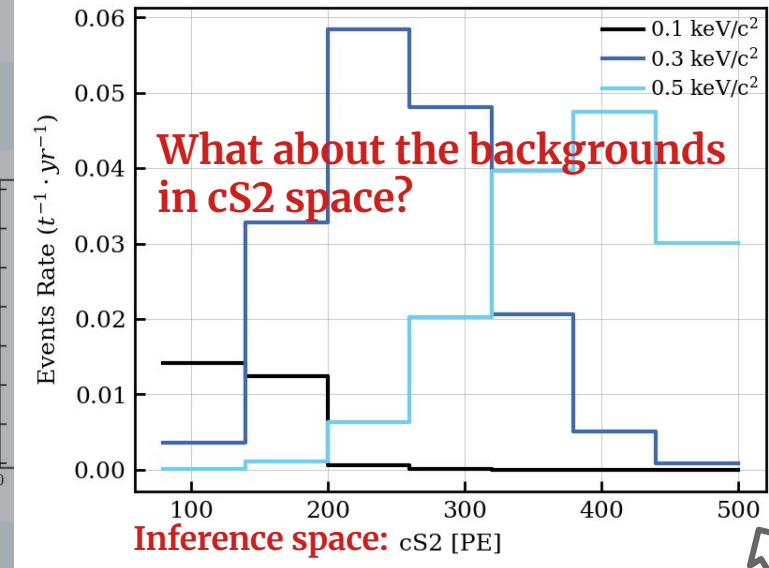
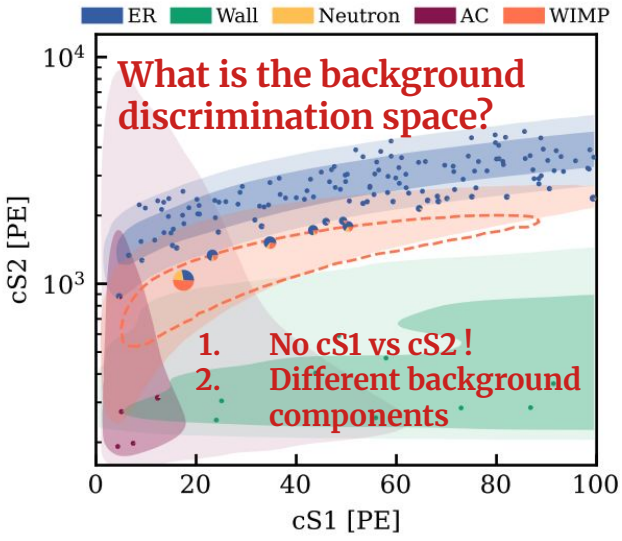
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- Charge Yield

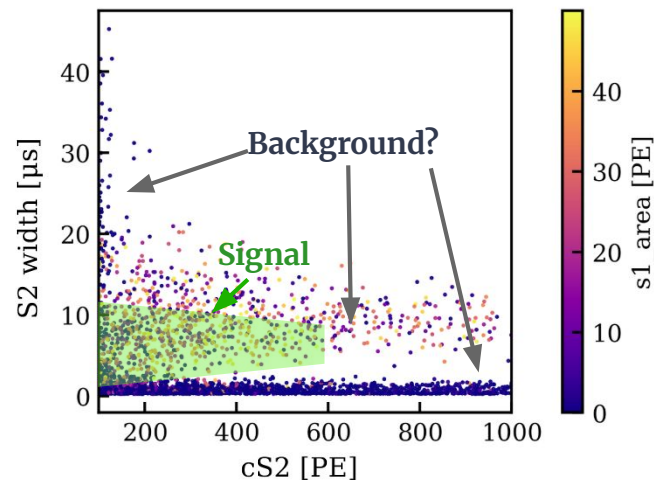
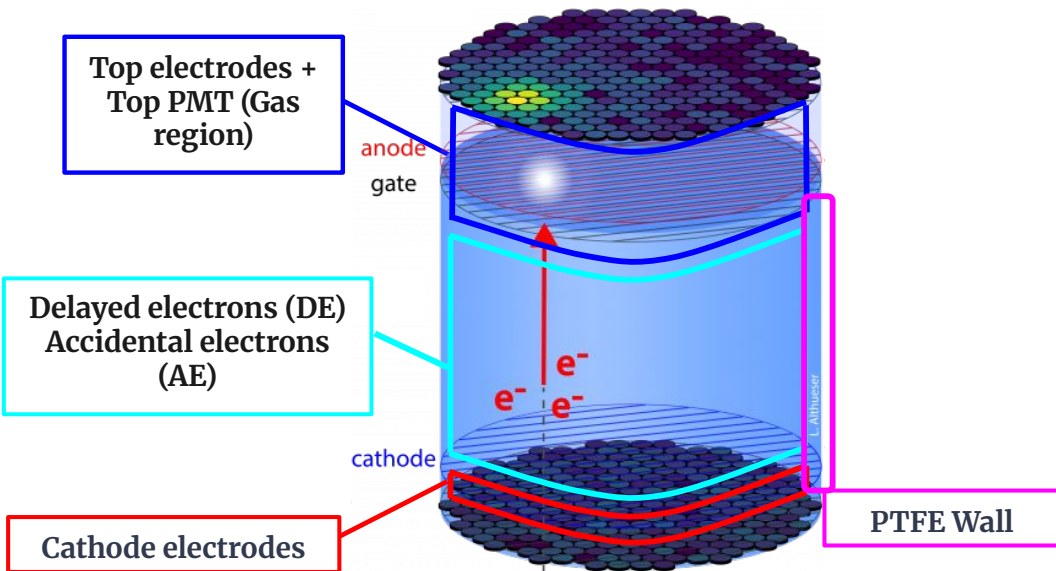
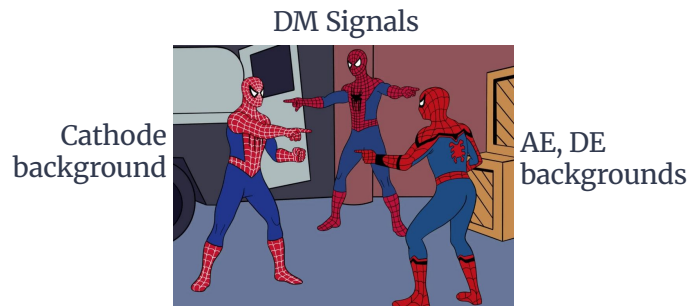
- Detection & Data Selection

Signal Prediction

Recoil Energy Spectrum

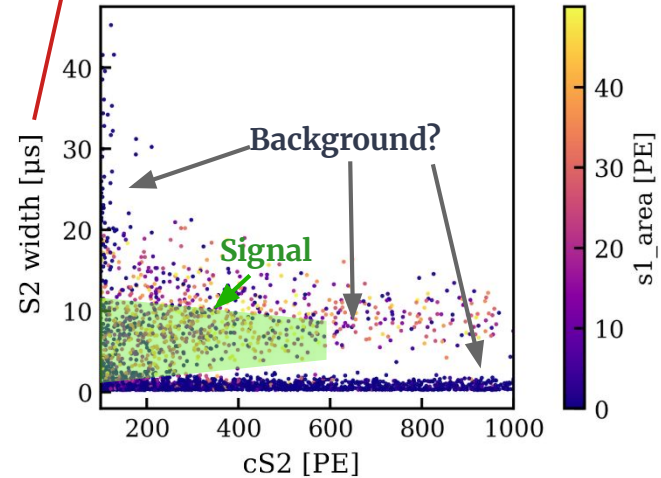
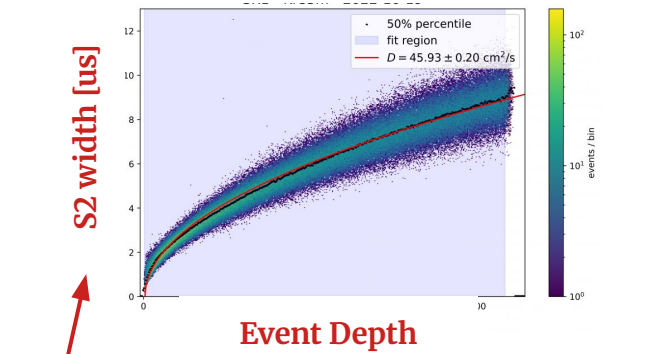
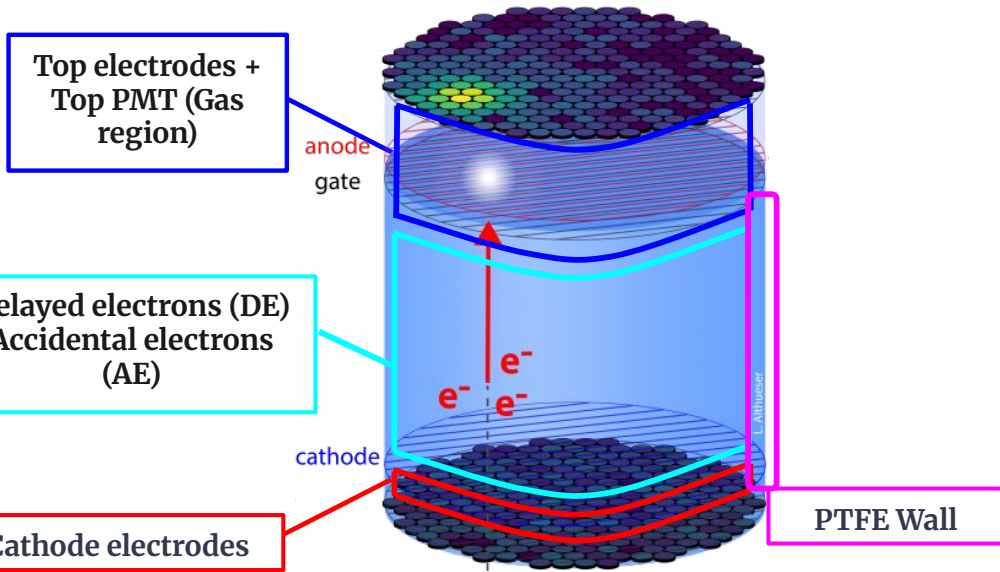


Background Suppression & Modeling



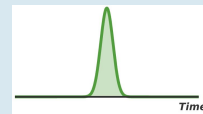
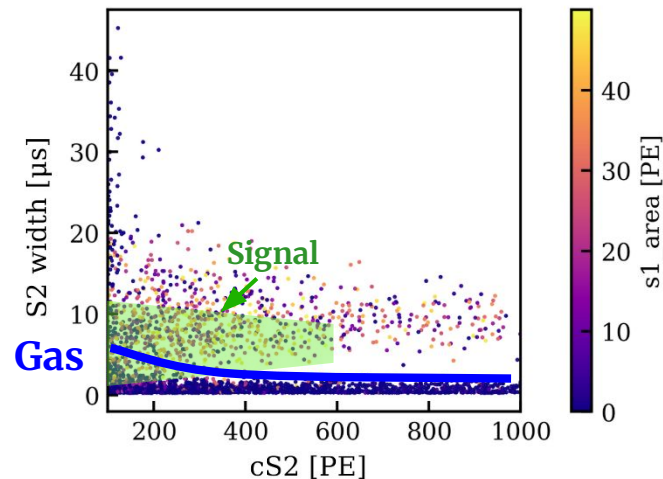
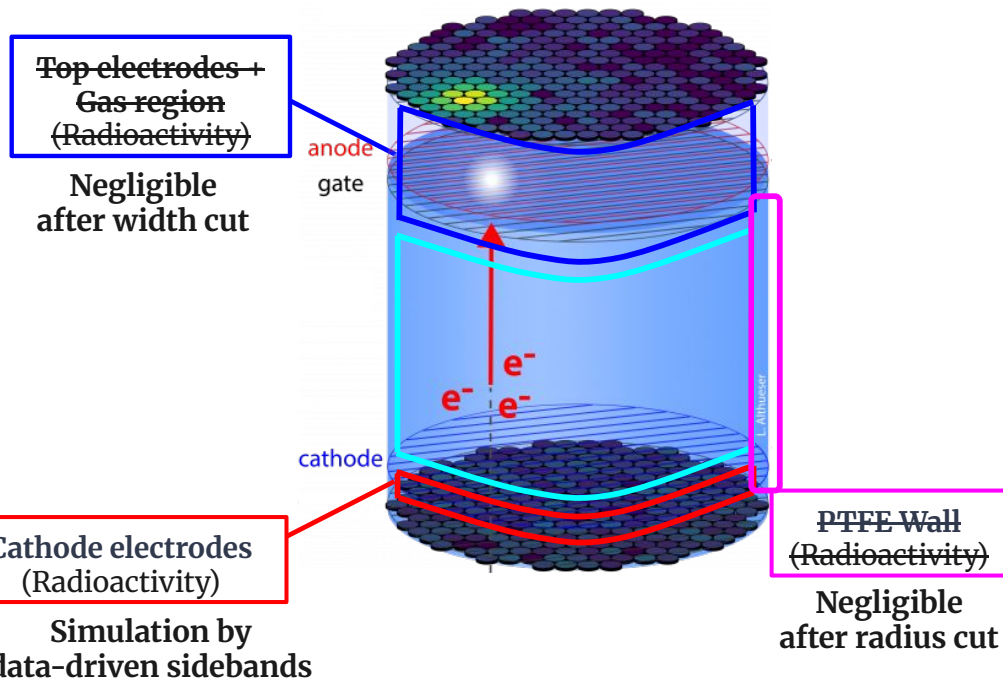
2D Background
discrimination space

Background Suppression & Modeling



2D Background
discrimination space

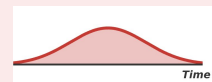
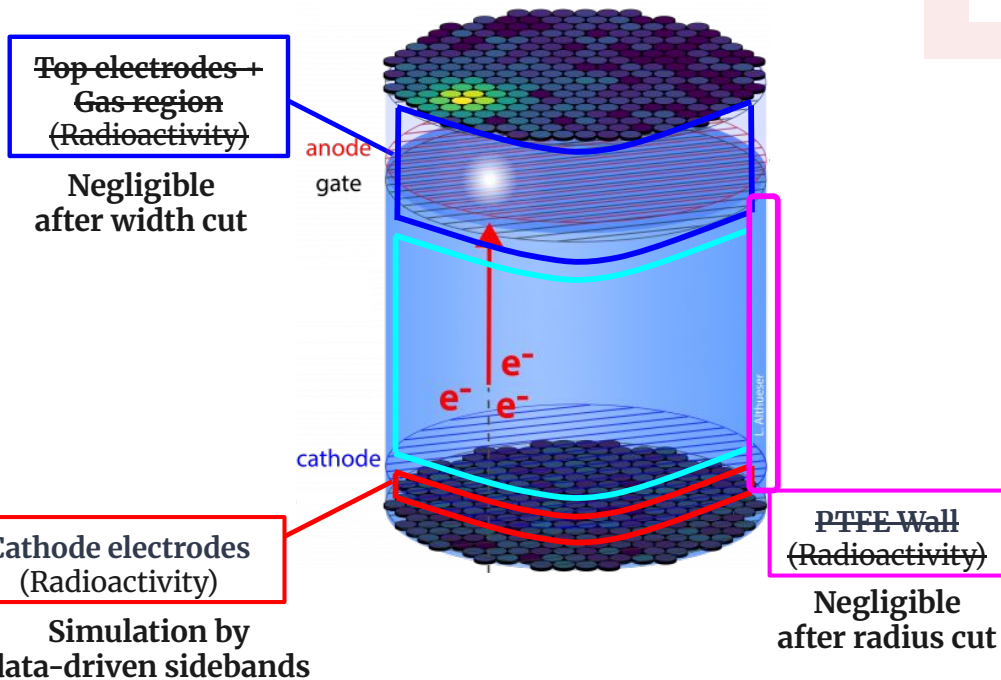
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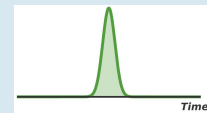
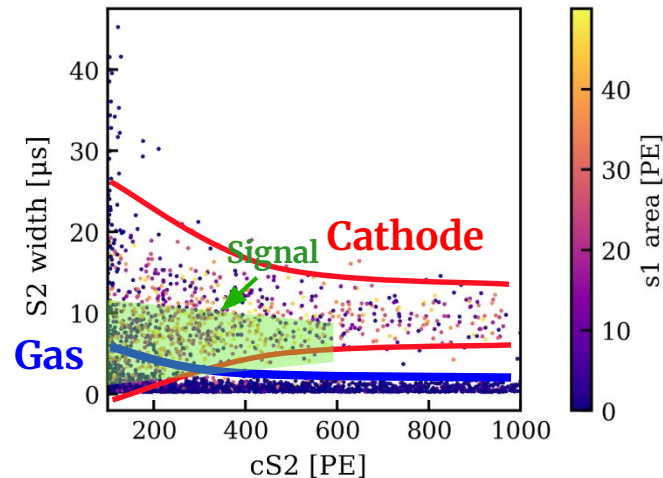
Gas: S2 width < 3 μ s due to smaller diffusion

Background

Suppression & Modeling

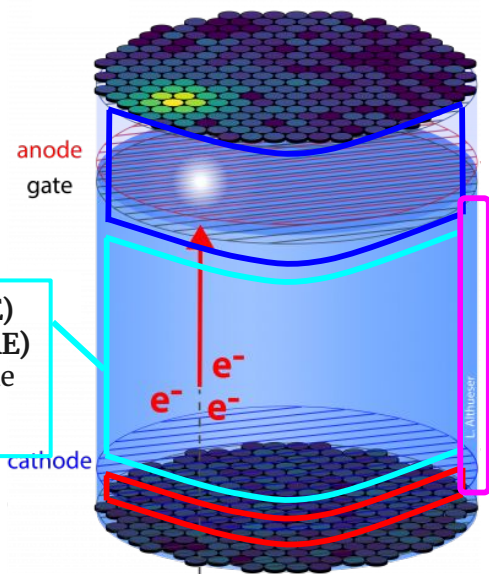


Cathode: S2 width ~ 10 μ s
large overlap with signal region
waveform-based BDT machine

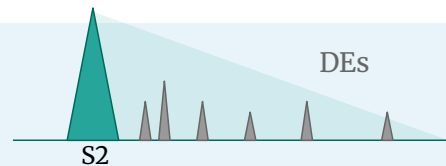


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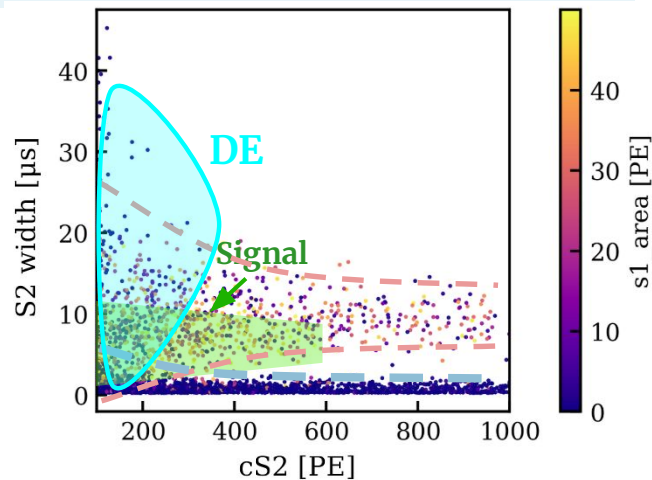


Delayed electrons (DE)
Accidental electrons (AE)
(Electrons trapped in the impurities)



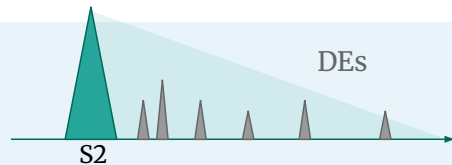
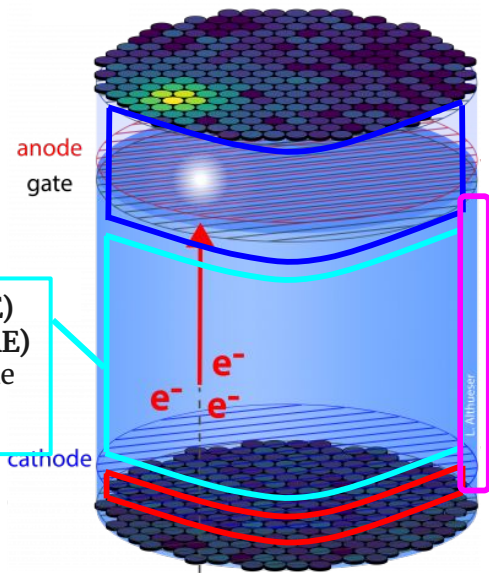
DE:

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



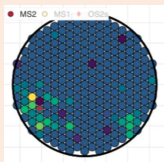
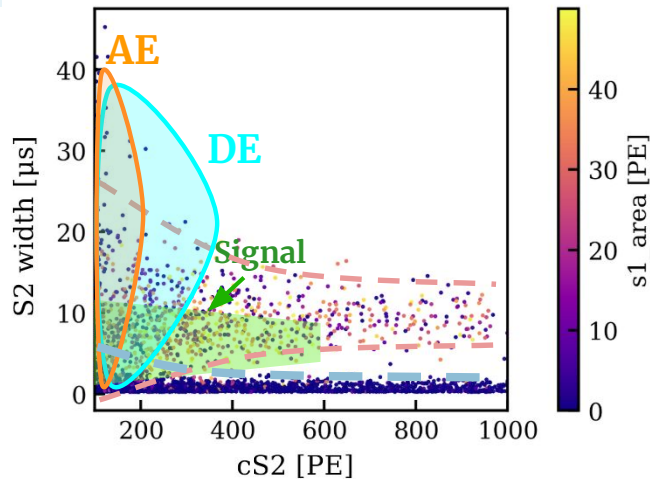
Background

Suppression & Modeling



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

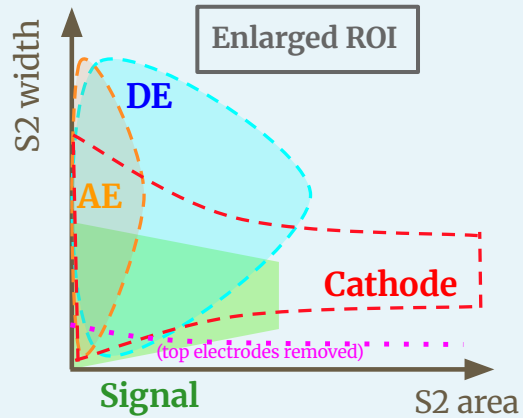
Background Modeling



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What we have now:

DE, AE, cathode background modeling in full space



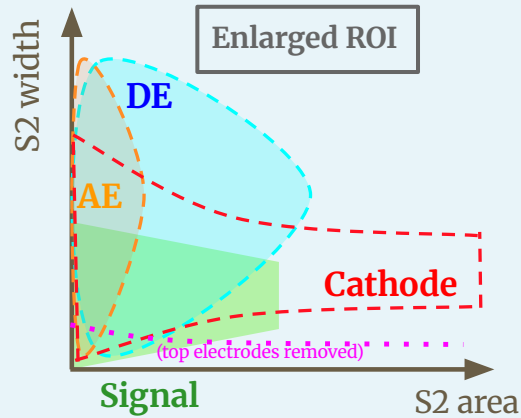
Background Modeling



XENON

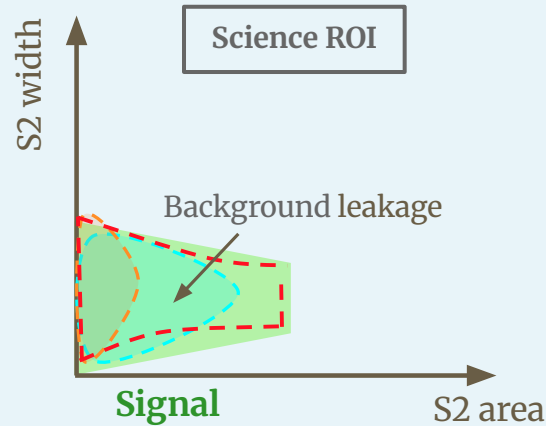
What we have now:

DE, AE, cathode background modeling in full space



Objective:

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



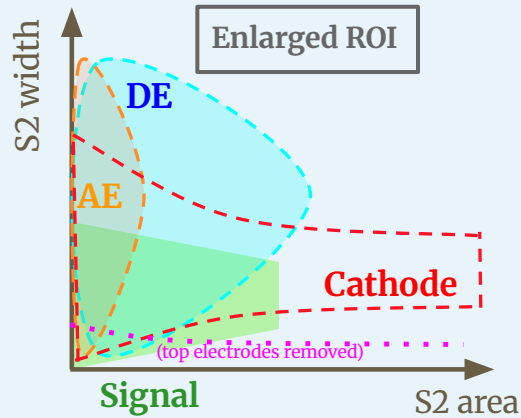
Background Modeling



XENON

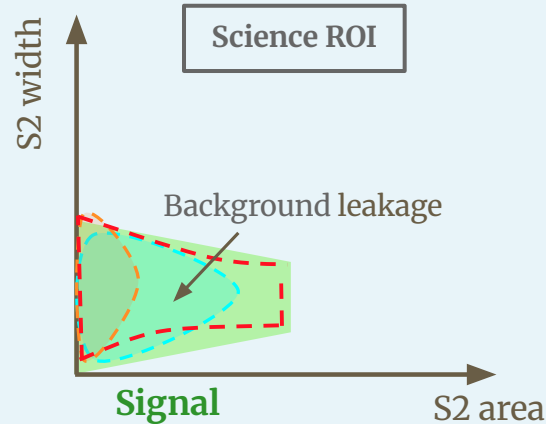
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DE, AE, cathode background modeling in full space



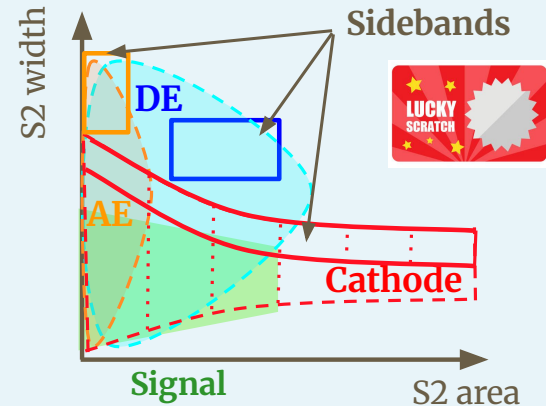
Objective:

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**.



Blinded analysis on 3 Science Runs

Upgrades and Status

SR0->SR1:

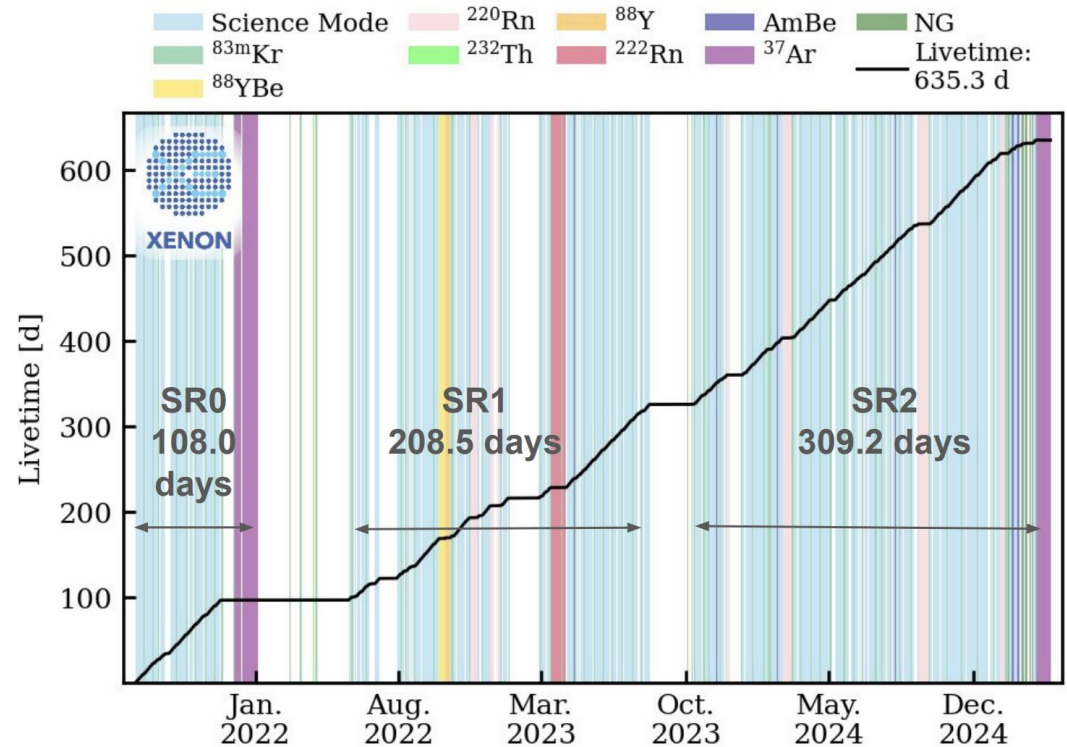
Liquid radon distillation, $1.8 \rightarrow 0.9 \mu\text{Bq/kg}$

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

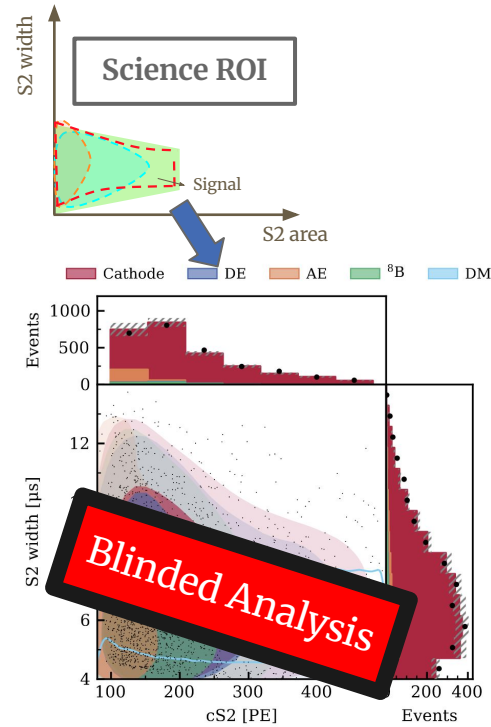


Unblinding

Validation of background model



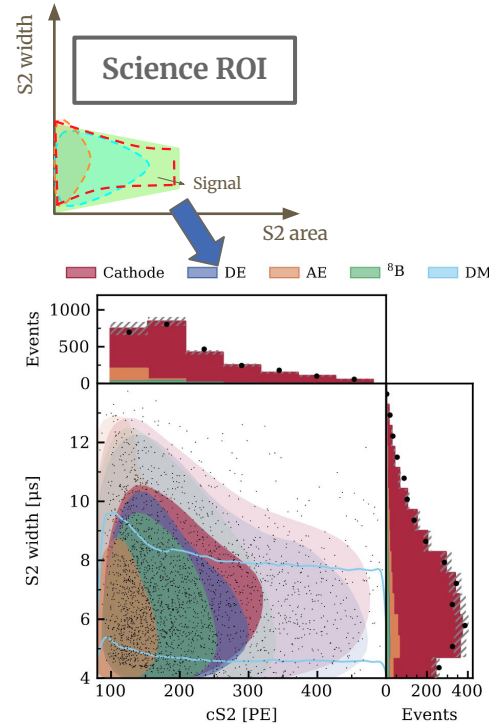
XENON



Unblinding

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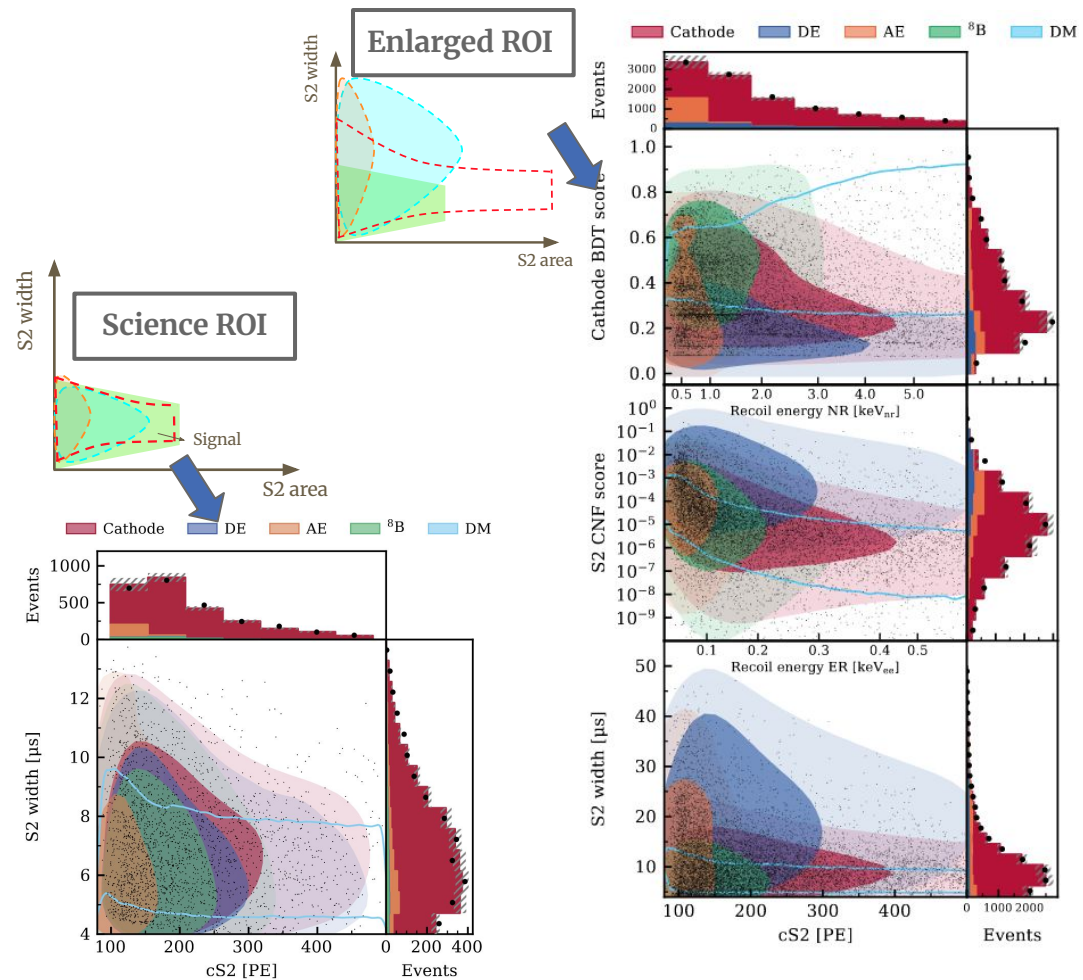
1. Unblind **7.83 tonne-year** of S2-only data
2. **Good agreement** between the observed events and background model
3. **Cathode** background is dominant while **AE** primarily contribute to the lowest energy bin



Unblinding

Validation of background model

1. Unblind **7.83 tonne-year** of S2-only data
2. **Good agreement** between the observed events and background model
3. **Cathode** background is dominant while **AE** primarily contribute to the lowest energy bin
4. First complete S2-only background model, **validated across different dimensions**



Unblinding Events

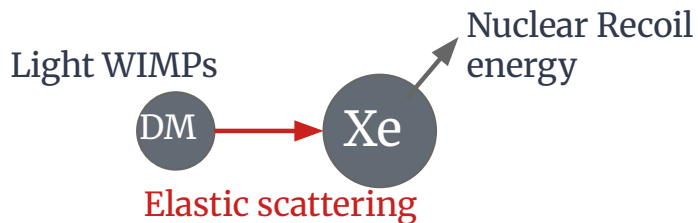


XENON

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^{+25}_{-24}	660 ± 70	726^{+28}_{-27}	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^{+5}_{-4}	29 ± 7	26^{+7}_{-6}	32.3 ± 8	29^{+8}_{-6}
Total background	600 ± 80	586 ± 28	800 ± 80	858^{+30}_{-29}	1260 ± 100	1130 ± 30
Observed	583		864		1107	

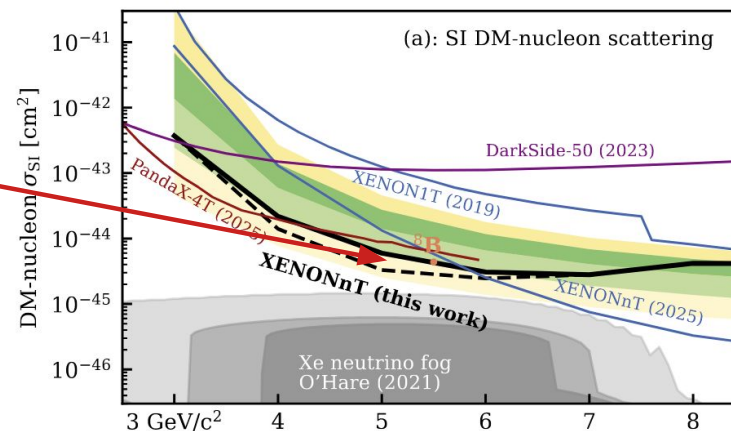
Good agreement
 \Rightarrow **No signal excess**

Limits on light DM (NR channel)



- Exclude cross sections above $6.0 \times 10^{-45} \text{ cm}^2$ at $m_\chi = 5 \text{ GeV}/c^2$
- Approaching the neutrino fog
- Downward fluctuations at low end
- PCL (Power-Constrained Limit) applied

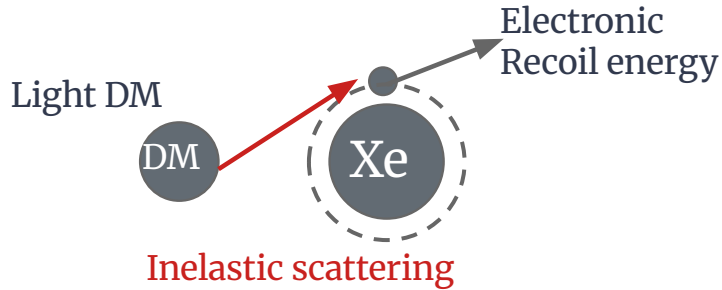
Spin-independent + heavy mediator



Limits on light DM (ER channel)

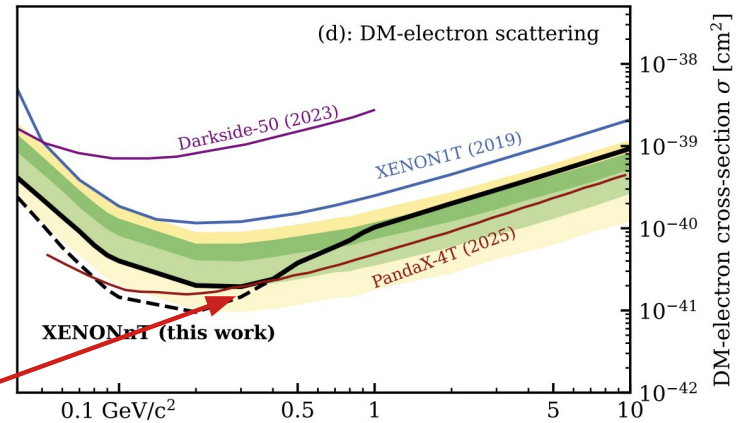


XENON



- Low-energy ER models benefit most from the S2-only analysis
- Excluding DM–electron scattering σ above $2.4 \times 10^{-41} \text{ cm}^2$ at $m_\chi = 0.4 \text{ GeV}/c^2$.

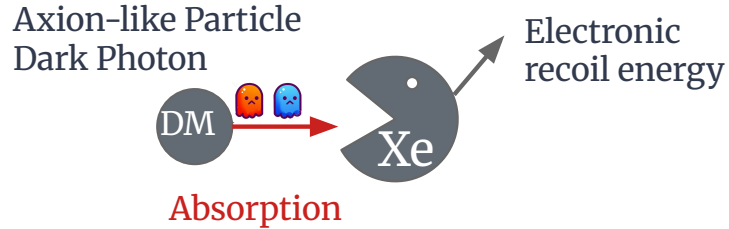
Electronic recoil + heavy mediator



Limits on light DM (ER channel)

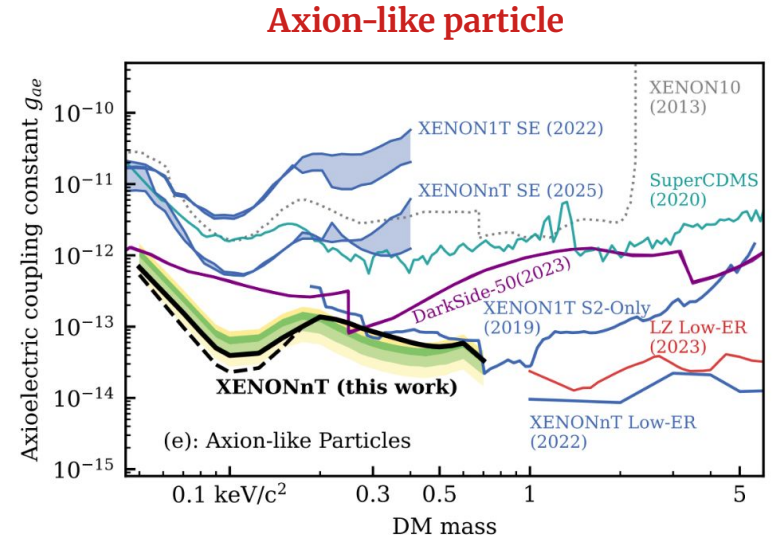


XENON



Exclude the parameter spaces for **bosonic DM**:

- Axion-like particles (axioelectric coupling constant)
 - $g_{ae} = 3.9 \times 10^{-14}$ @ $m_\chi = 0.1 \text{ keV}/c^2$
- Dark photon (kinetic mixing constant)
 - $\kappa = 2.2 \times 10^{-17}$ @ $m_\chi = 0.1 \text{ keV}/c^2$

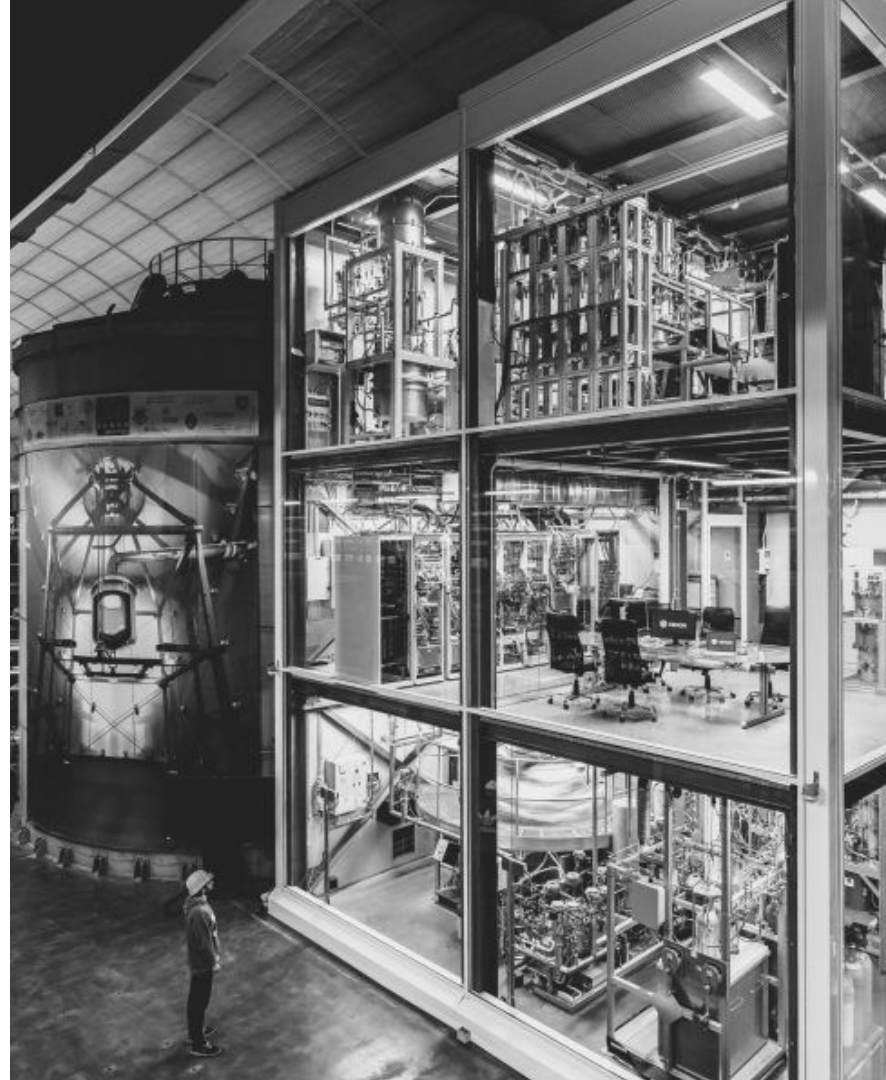


Summary

- S2-only analysis allows XENONnT to probe **lighter DM** ($3\text{--}8\text{ GeV}/c^2$) via NR channel, $O(\text{MeV})$ DM $O(\text{keV})$ Bosonic Dark Matter via ER channel.
- **First complete background model** for S2-only analysis in XENONnT is built. **Advanced ML techniques** are used for background suppression.
- S2-only data of **7.83 tonne-year** exposure are unblinded, setting new limits across multiple DM models.

Please see more details on the paper:

- <https://arxiv.org/abs/2601.11296>



Summary

- S2-o
light
Matt
- First
analy
tech
- S2-o
unbl
mod

Please see

- <https://>

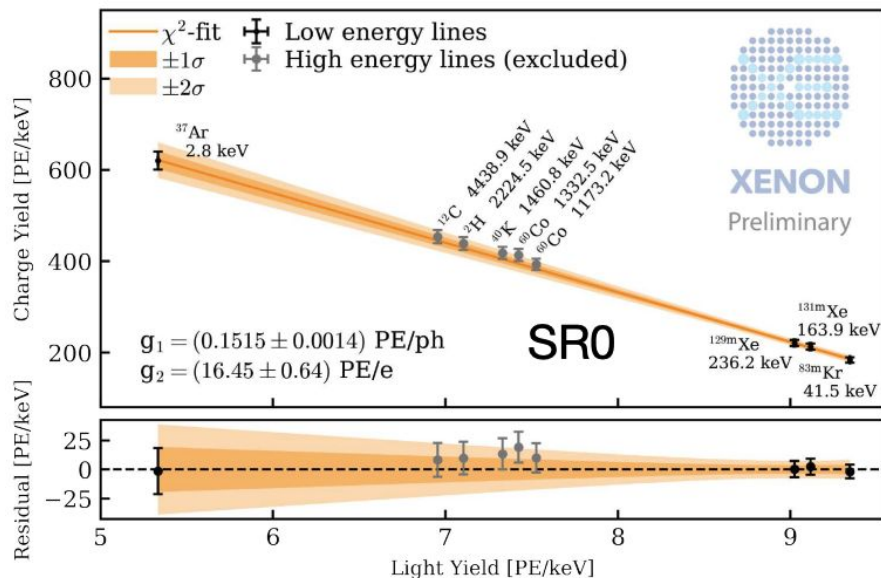




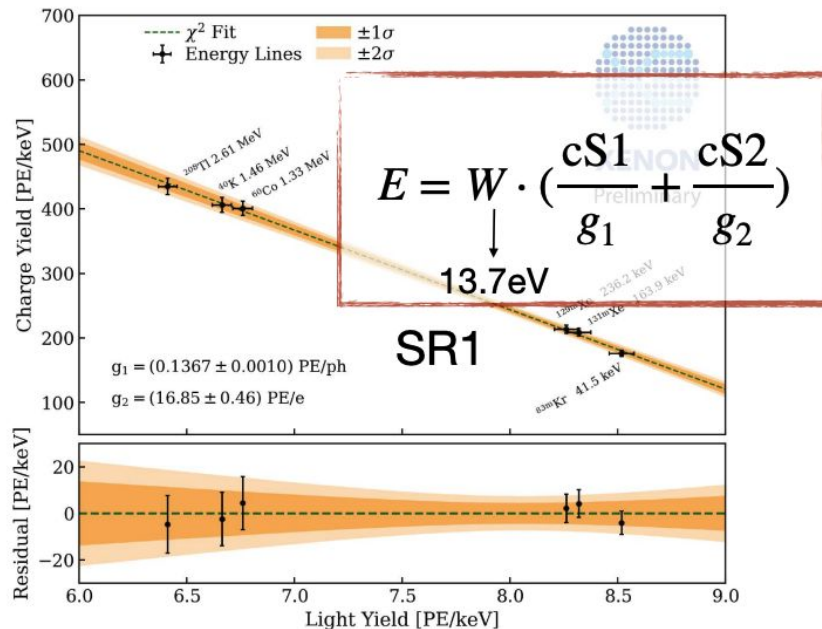
XENON

Back-up slides

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)

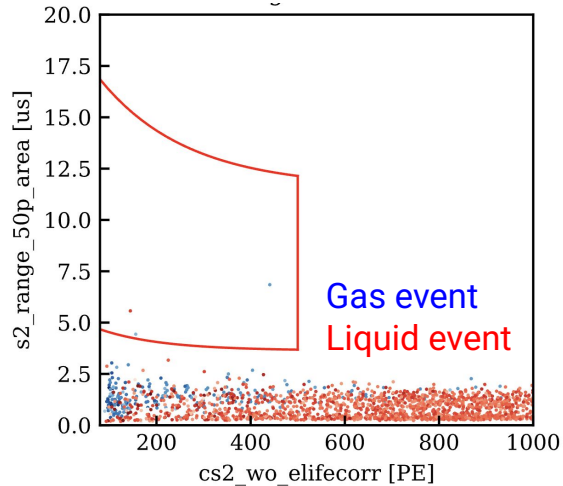
Gas cuts

Origin:

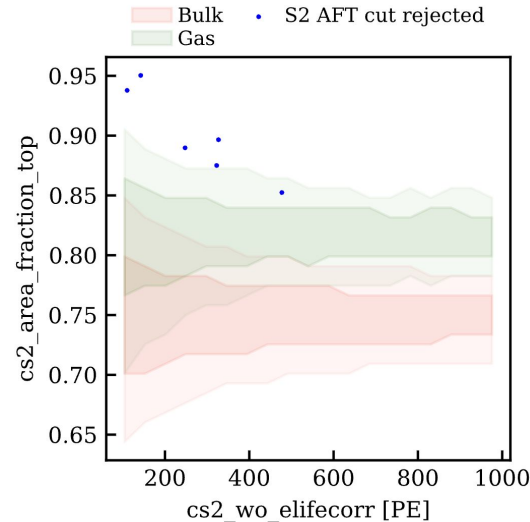
Pb-210 beta decay from ^{222}Rn decay chain from **gate**, anode, **top screening wires**, **top PMTs**.

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

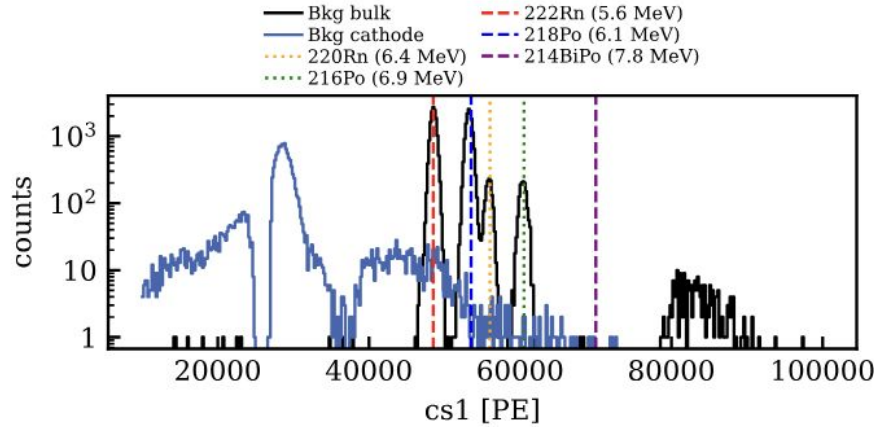
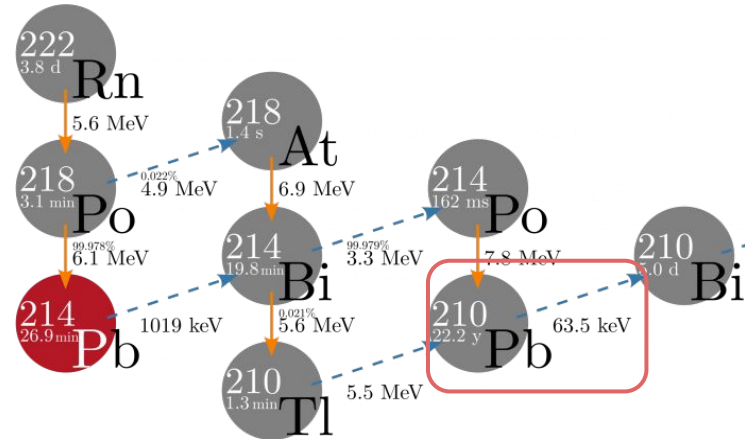
S2 width lower boundary



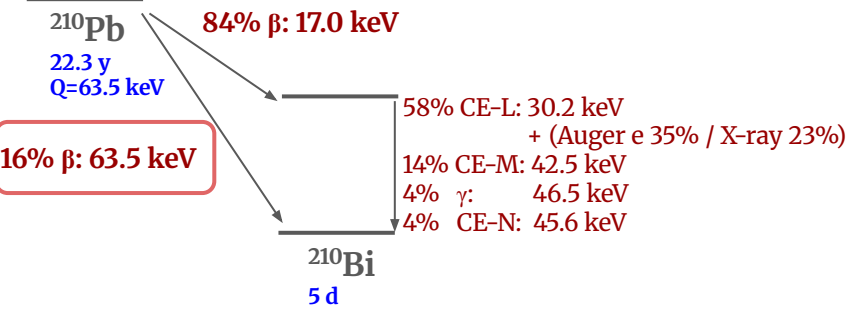
S2 AFT upper boundary



Cathode background (decay chain)



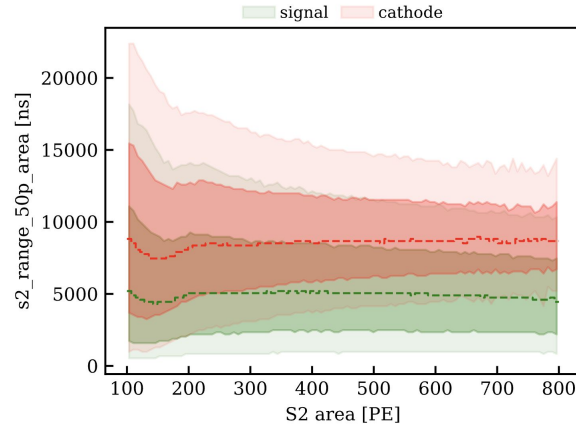
(a) High-Energy Alpha Spectrum in Background Run



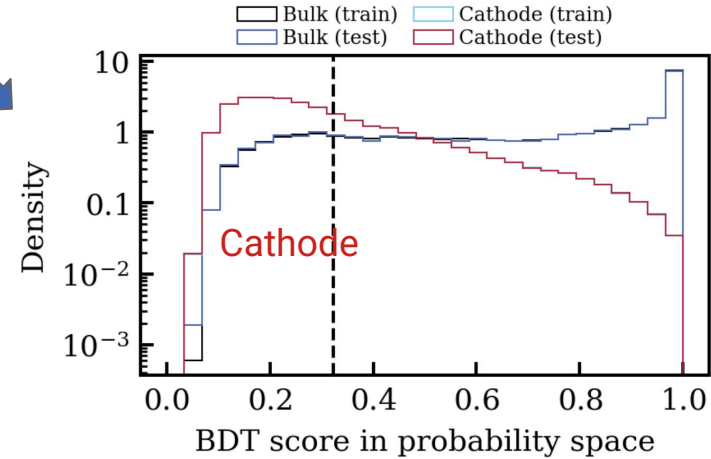
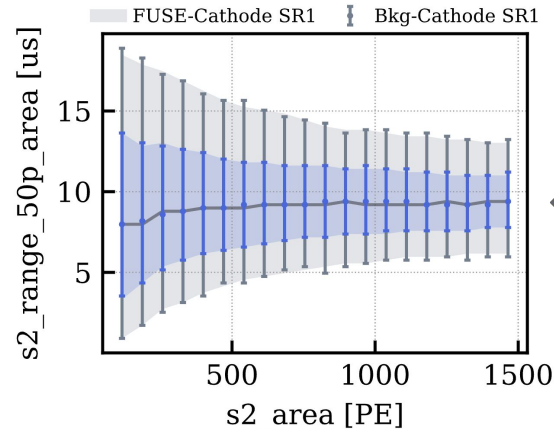
Cathode BDT

Waveform features provide discrimination power of cathode and signal:

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

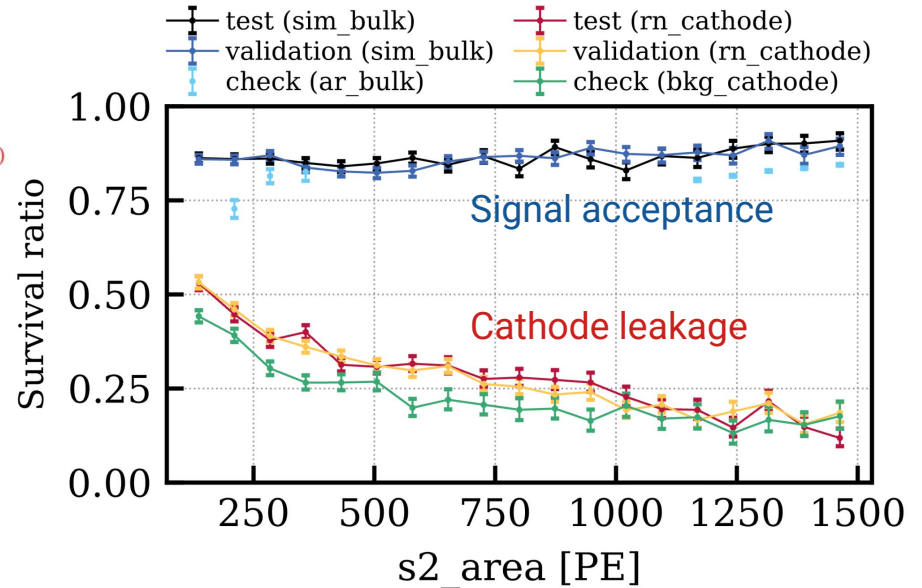
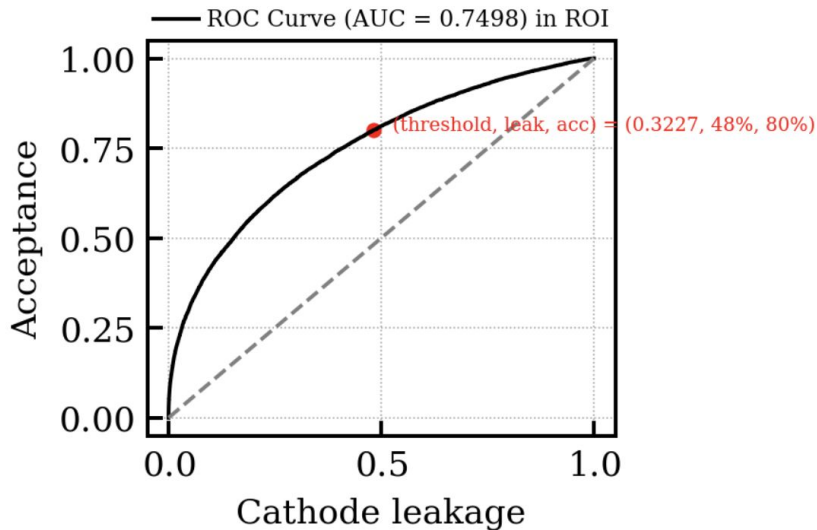


Fuse validation on waveform feature spaces
⇒ more statistics



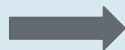
Cathode BDT

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



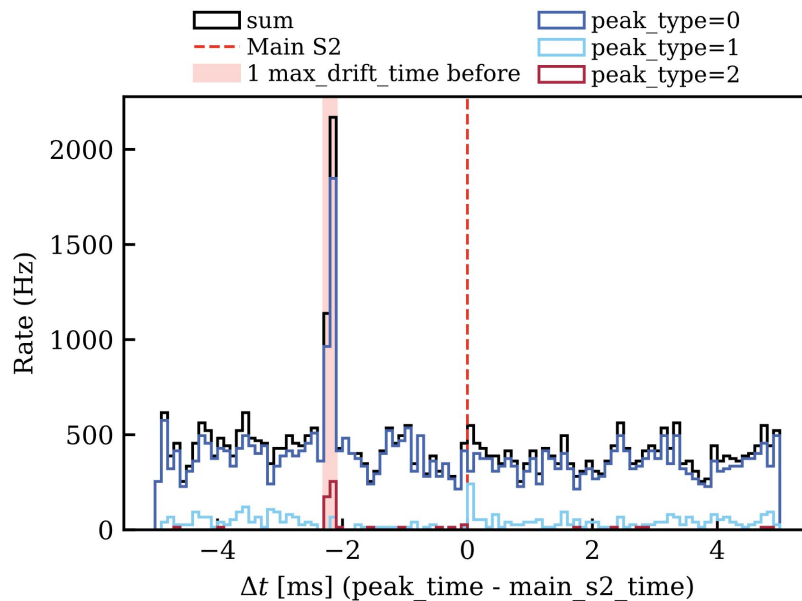
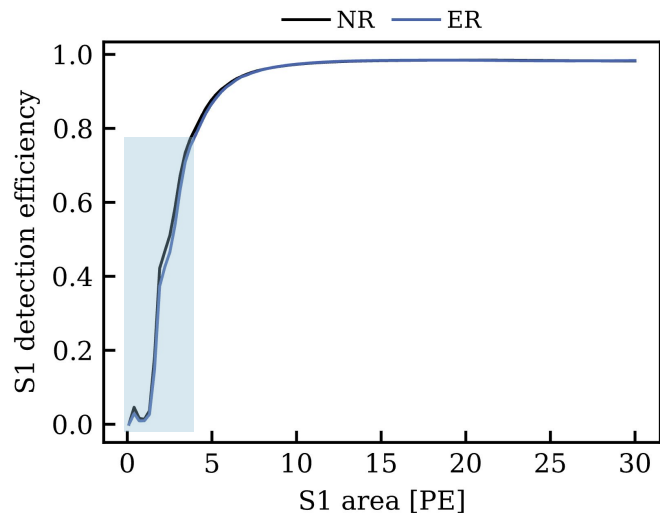
Cathode drift time veto cut

Low S1 detection efficiency
S1 is reconstructed as S0 or S2

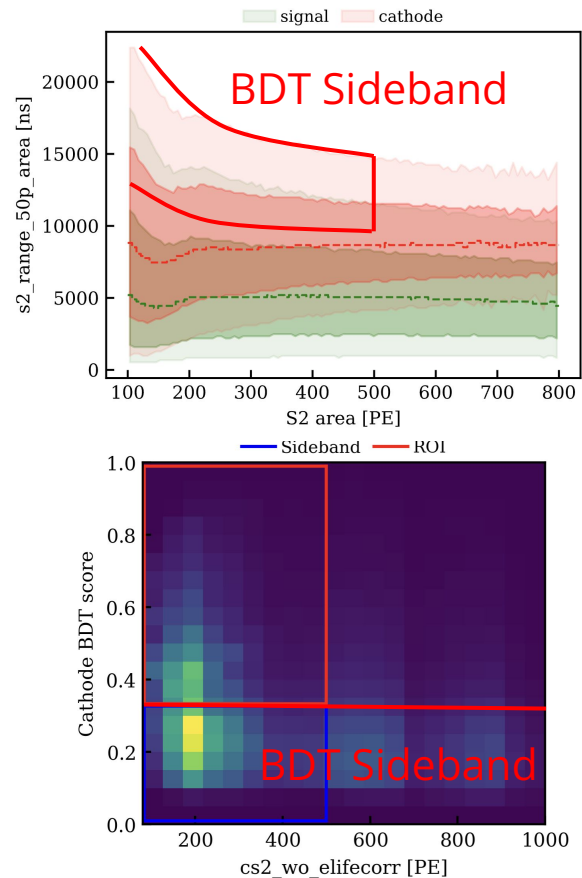


Reject event with S0/S2 at
cathode drift time

Cathode rejection: 15%
Signal acceptance: 99.5%



Cathode Modeling comparison

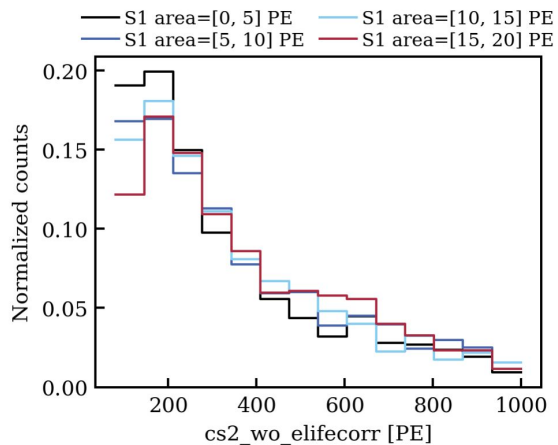


1. Cathode dominant region (sideband) selection:

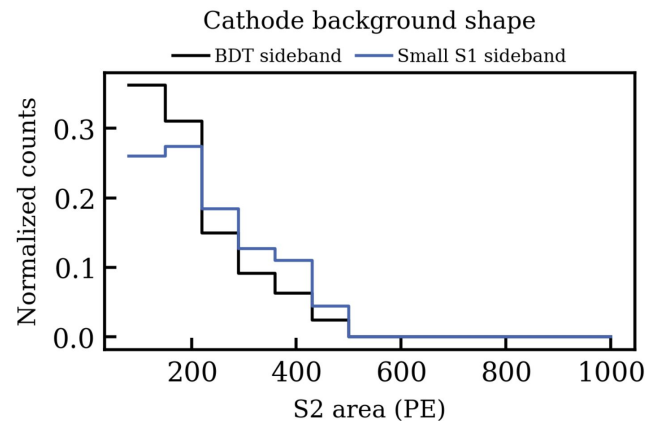
- Small S1 Events with z at cathode position
- **Events rejected by cathode BDT cut**

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.

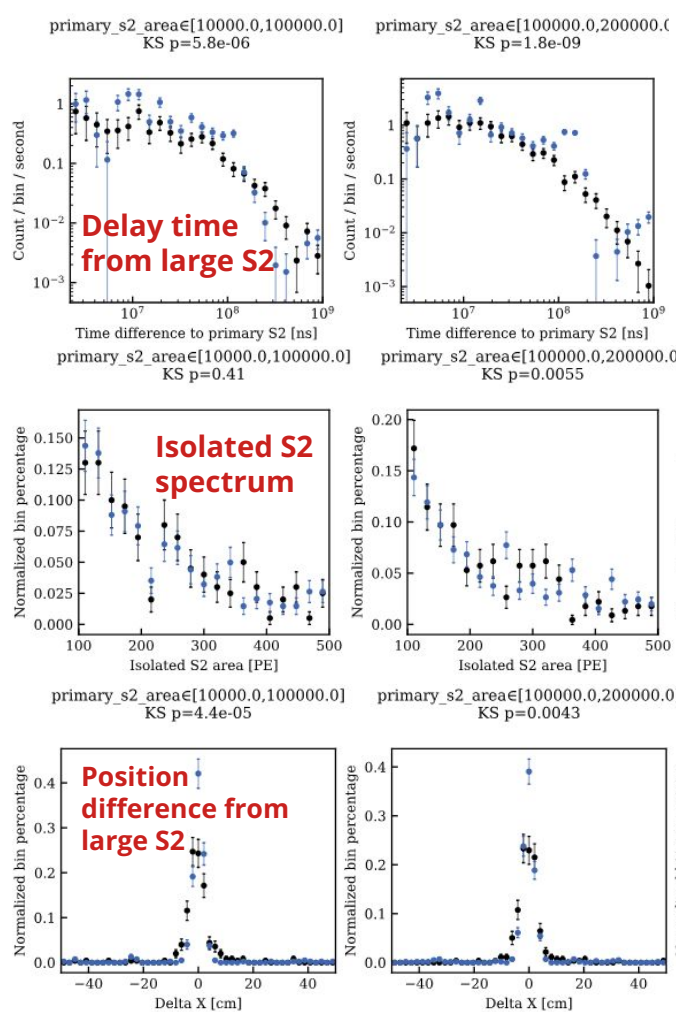
DE Modeling

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

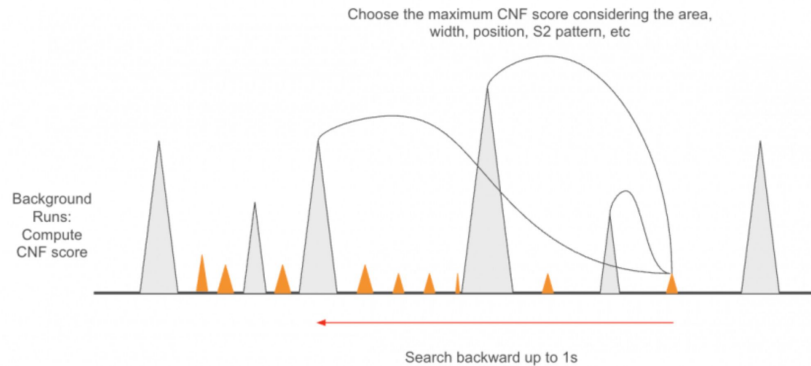
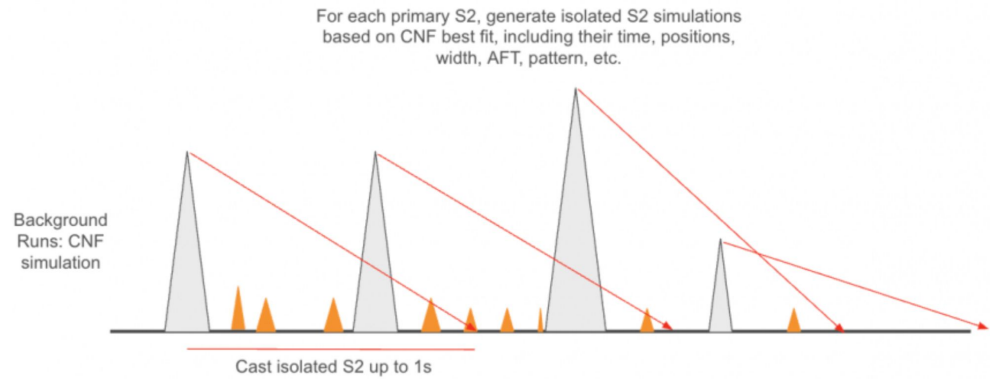
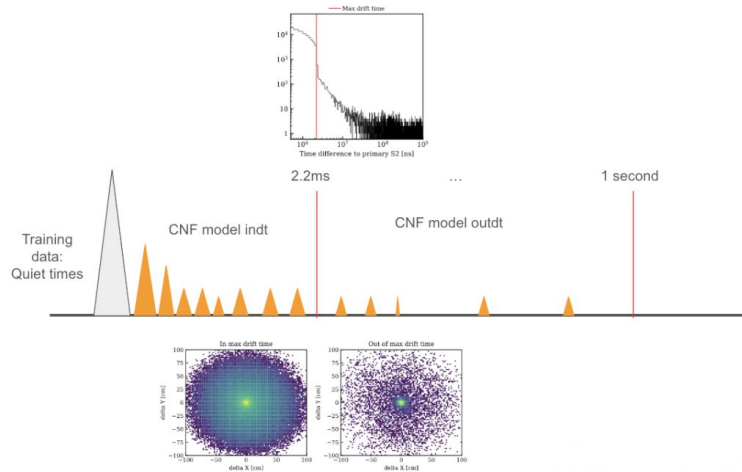
Isolated S2s can be modeled:

- **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.



CNF machine



DE BDT

Main feature of DE: Temporal + spatial correlation with large S2

Delayed electron BDT cut

Correlation with preceding large S2

CNF Training dataset:

Pairing of large + DE from bkg data

CNF Feature:

- S2 area, position of large S2 and DE



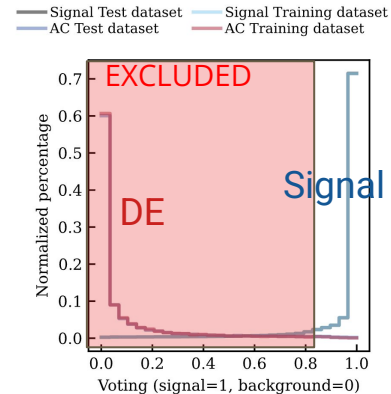
CNF score:
Correlation with preceding large S2

BDT training dataset:

- Simulated signal from FUSE, salted in dataset
- Simulated DE from CNF

BDT features:

- CNF score
- S2 widths
- S2 area



Shadow
+ ambience

As in CEvNS search

DE BDT

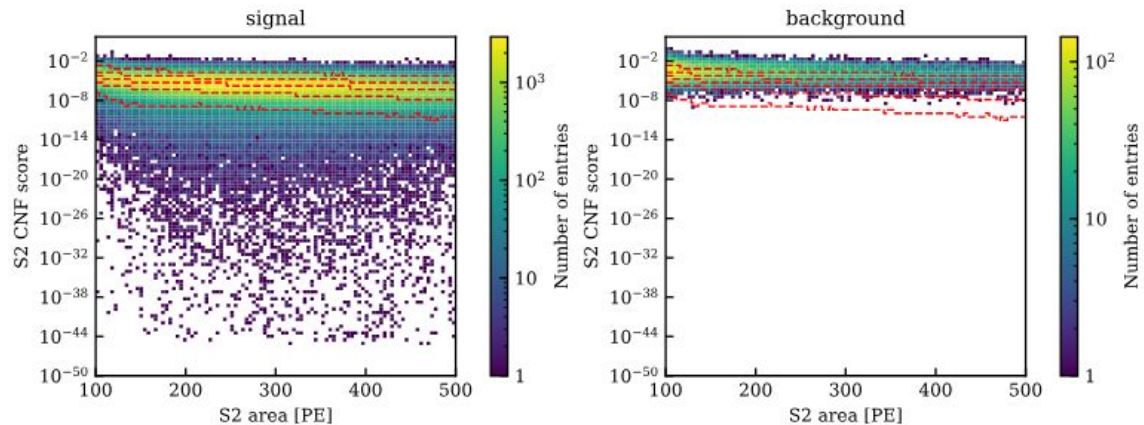
BDT machine learns the features:

- S2 area
- S2 width
- CNF score

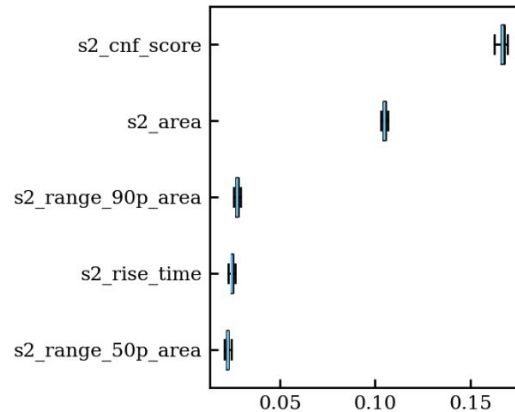
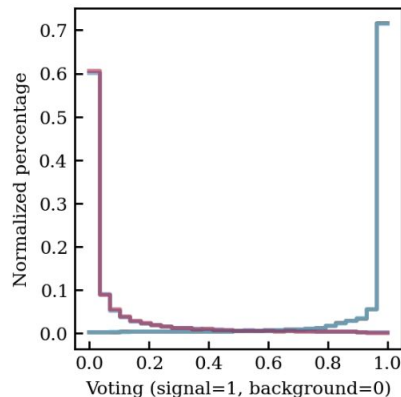
evaluating the correlation to previous primary S2s.

Can suppress the DE background to near negligible level:

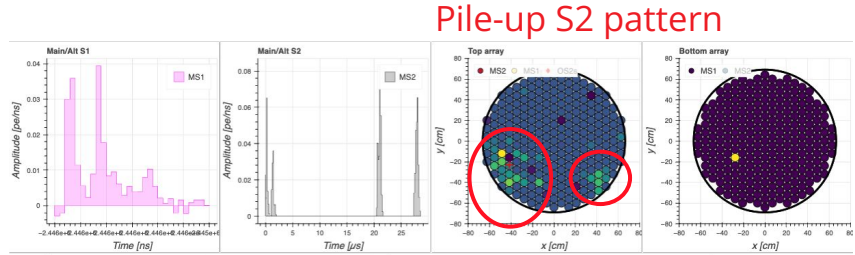
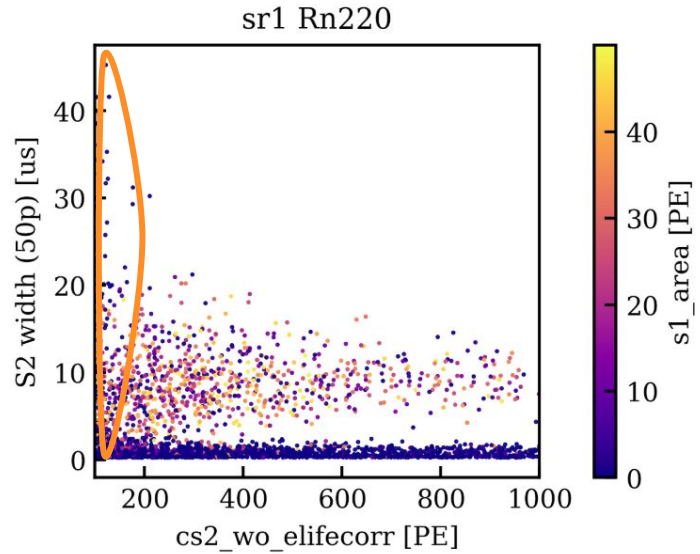
- DE rejection: 97%
- Signal acceptance: 90%



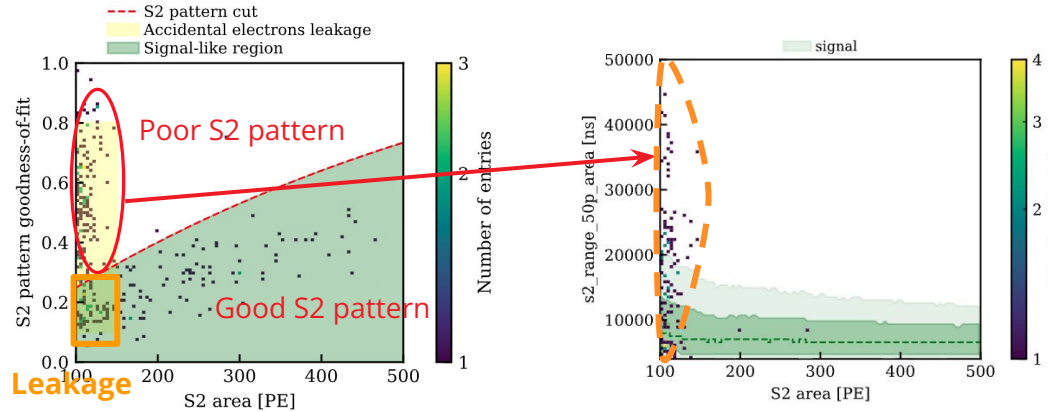
— Signal Test dataset — Signal Training dataset
— AC Test dataset — AC Training dataset



Accidental electrons (AE) Model



Pile-up S2 pattern

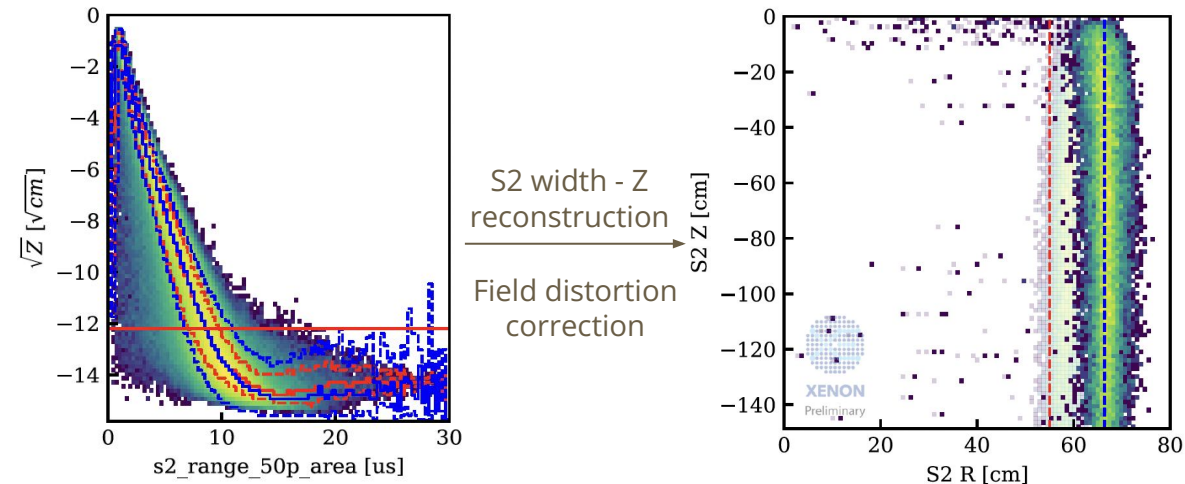


Poor S2 pattern (due to the pile-up) + **Large range of width** (merging in peak reconstruction)

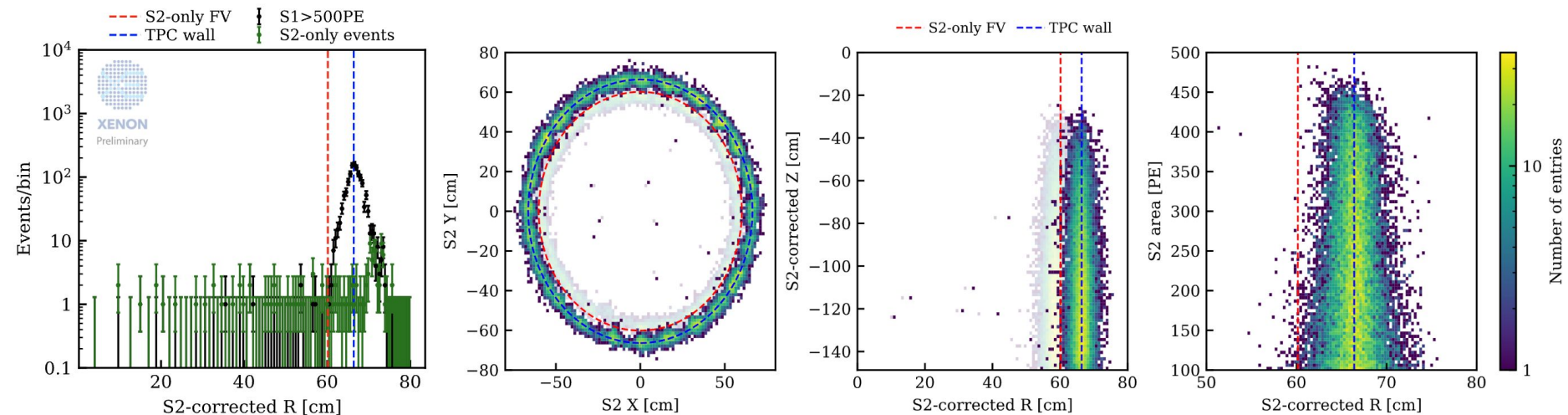
- AE can be modeled on cS2 - S2 width with a data driven approach

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



Wall background



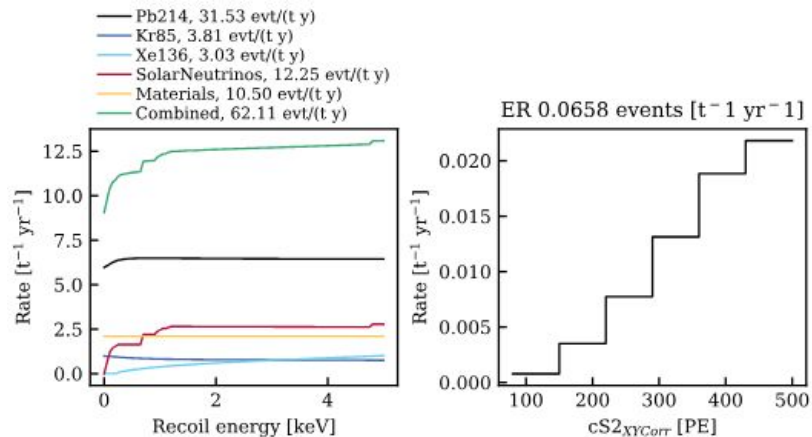
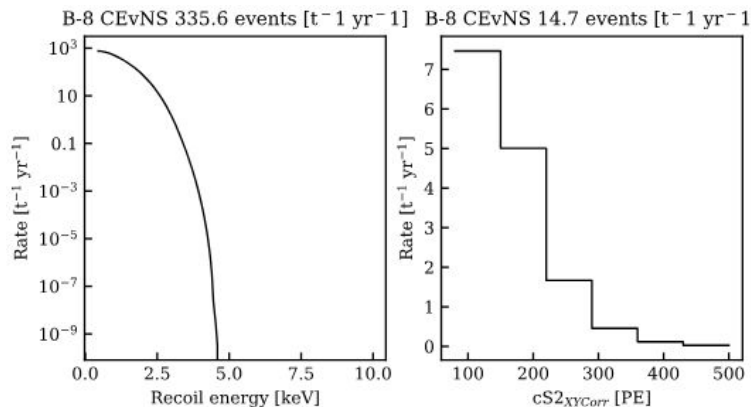
A S2-only position reconstruction algorithm is developed using S2 waveform, allowing **Z reconstruction** and **field distortion correction**.

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.



Summary of Backgrounds: Cuts

1. Background suppression

- a. Reduce **cathode + AE + DE** to lower level
- b. Reduce **gas + wall** to negligible level

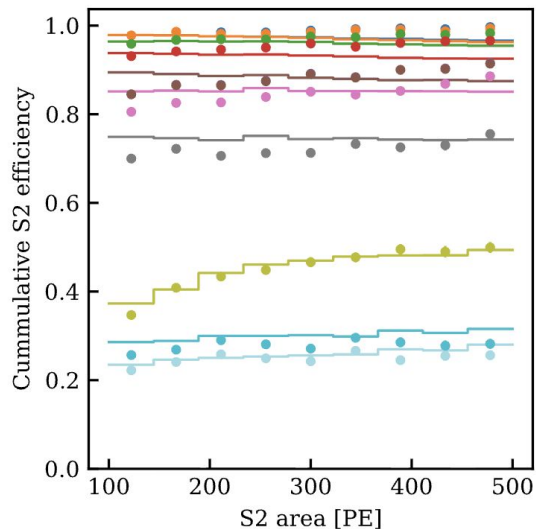
2. Background modeling

- a. Model **cathode + AE + DE** passing the cuts
- b. Unable to model the background from first-principle given our current knowledge!

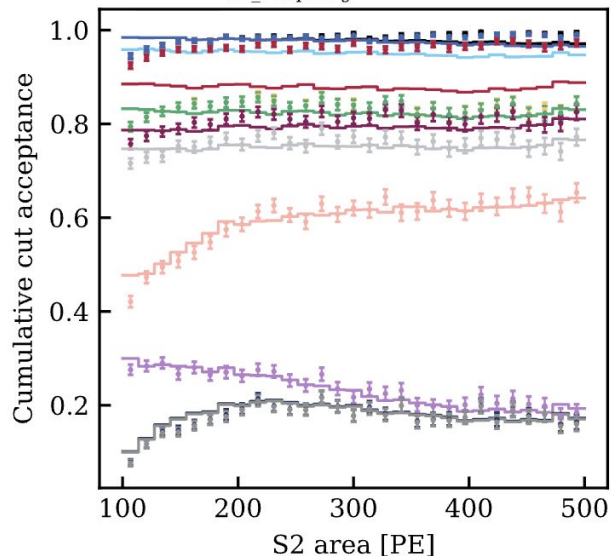
Background	Targeting cuts (Importance from high to low)
Cathode	Cathode BDT cut, S0 drift time cut
DE (Delayed electron)	DE BDT cut, Shadow + Ambience cut, S2 width cut
AE (Accidental electron)	S2 pattern cut, Shadow + Ambience cut, S2 width cut
Gas	S2 width cut, S2 AFT cut, S0 drift time cut
Wall	FV cut on R

Summary of Backgrounds: Cuts

- cut_s2_pattern_s2_only
- cut_s2_single_scatter_s2_only
- cut_cs2_area_fraction_top_s2_only
- cut_hotspot_veto_s2_only
- cut_ambience_s2_only
- cut_time_veto_s2_only
- cut_position_shadow_s2_only
- cut_time_shadow_s2_only
- cut_width_roi_s2_only
- cut_bdt_cathode
- cut_bdt_de



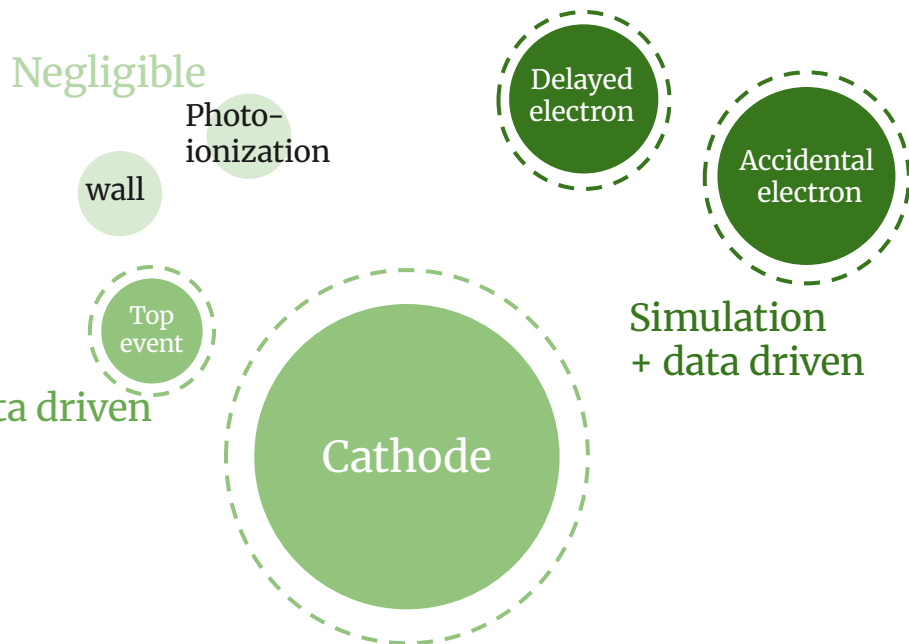
- cut_s2_pattern_s2_only
- cut_s2_single_scatter_s2_only
- cut_cs2_area_fraction_top_s2_only
- cut_hotspot_veto_s2_only
- cut_ambience_s2_only
- cut_time_veto_s2_only
- cut_position_shadow_s2_only
- cut_time_shadow_s2_only
- cut_width_roi_s2_only
- cut_bdt_cathode
- cut_bdt_de
- cut_competing



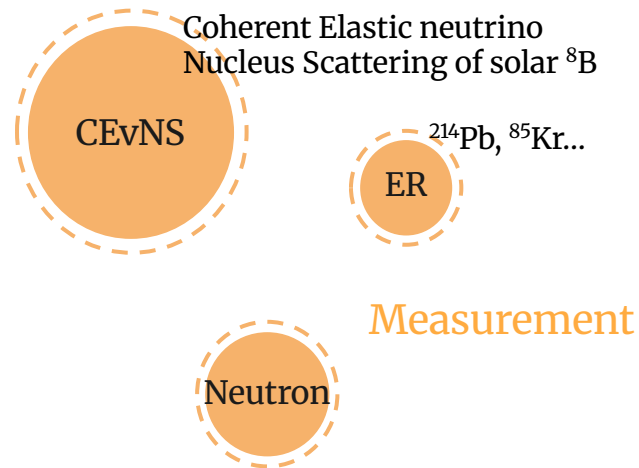
Summary of Backgrounds

Without S1 ⇒ No z-related data selection
Small S2 area ⇒ More sensitive to detector condition

Instrumental background



Physics background



Counts

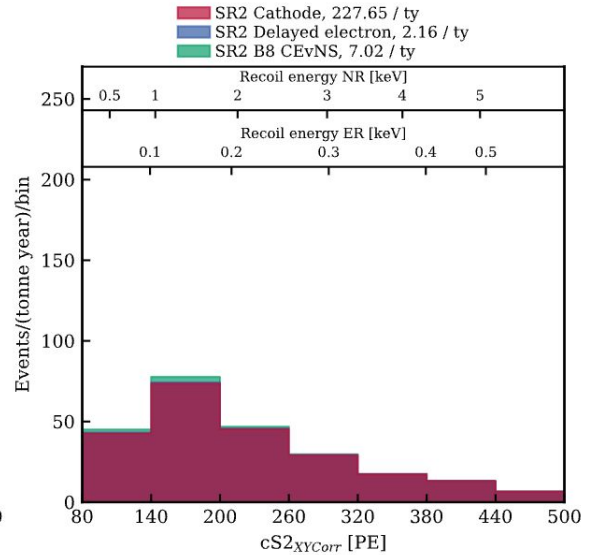
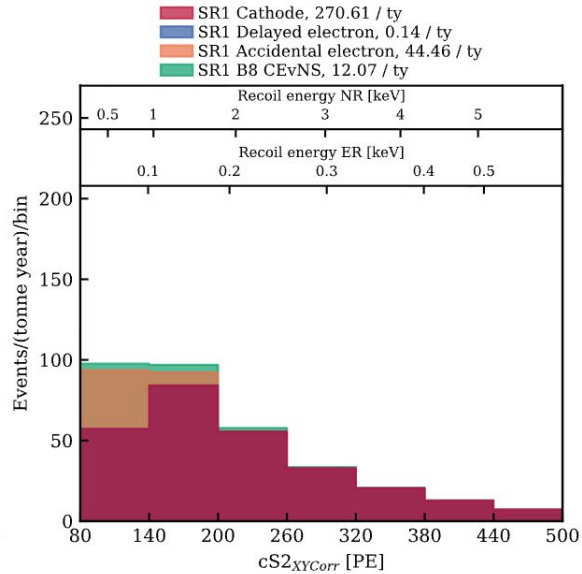
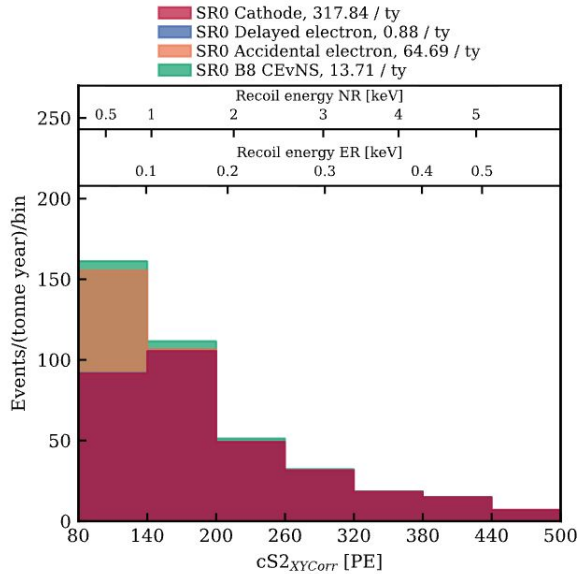


Uncertainties



Summary of Backgrounds

This is what we expect to see after unblinding:

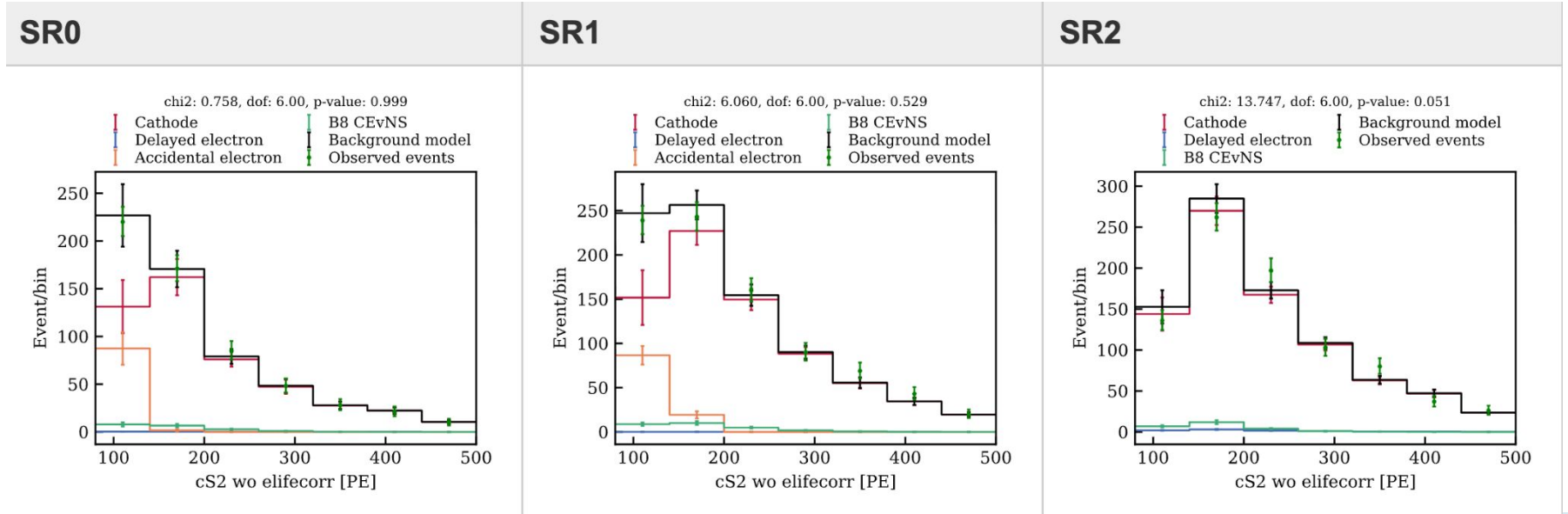


S2-Only Unblinding

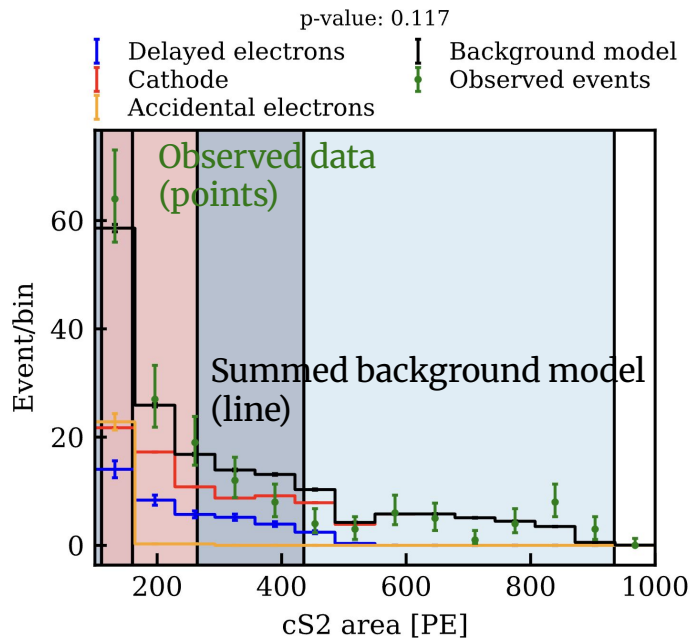
Unblinding scope:

- **S2: s2_area [100, 500] PE**
- **S1: No S1 or S1 < 3 PE**

Science search data: Combined SR0+SR1+SR2 (579.46 live days and 7.83 tonne*year of exposure)



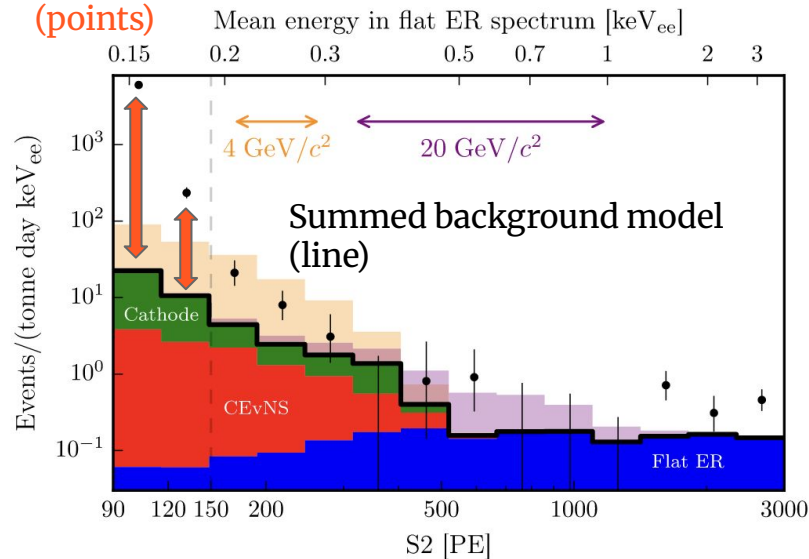
Background Model Challenge



Background validation in XENONnT (SR0 Rn220 calibration)

Current background model can describe better the data compared to XENON1T

Observed data (points)



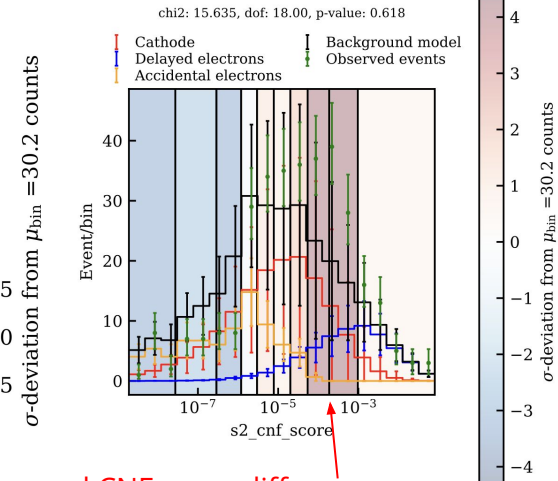
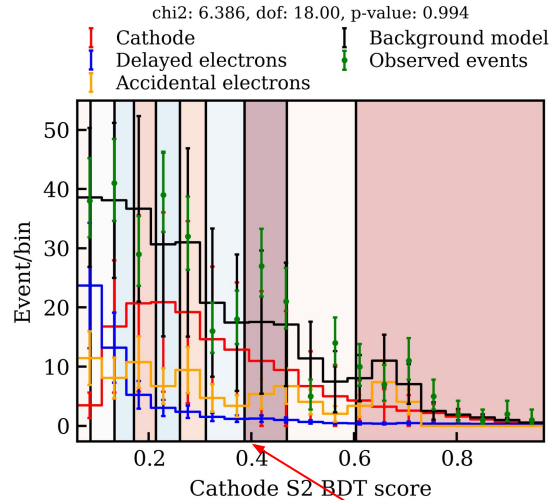
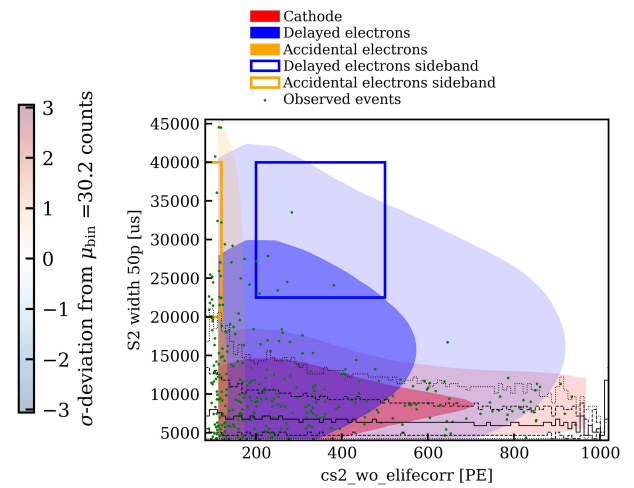
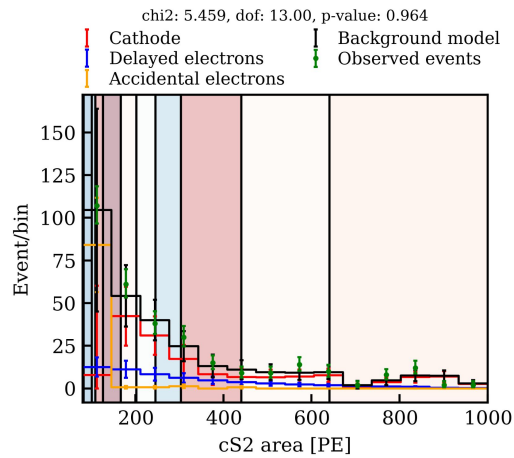
Background validation in XENON1T

Validation

SRO Rn220

We perform a two-step validation:

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

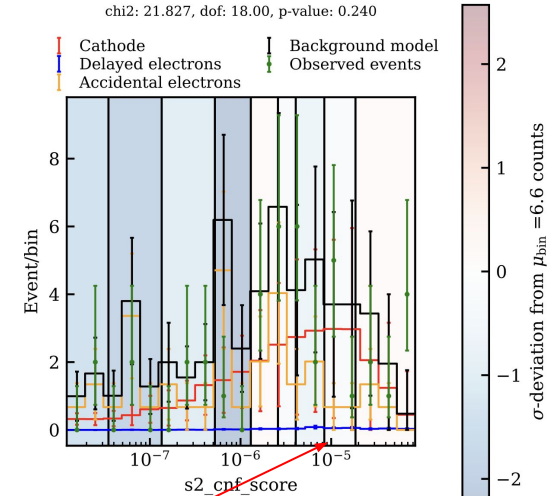
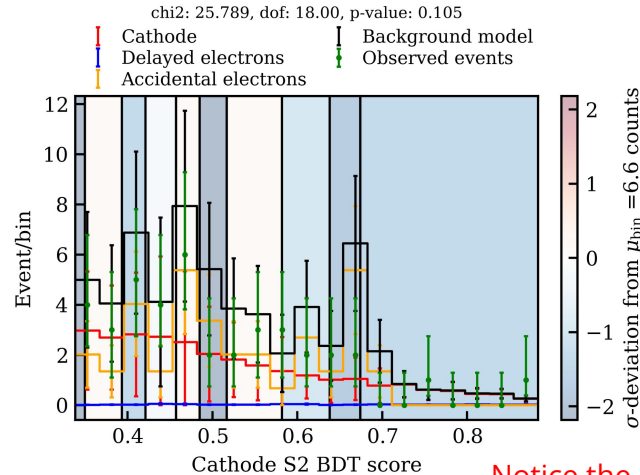
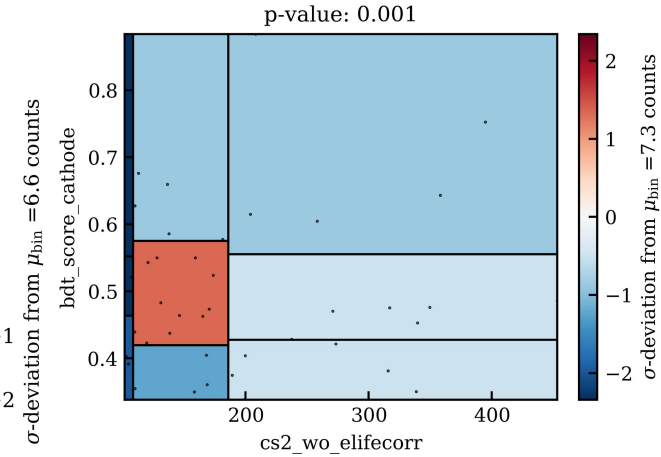
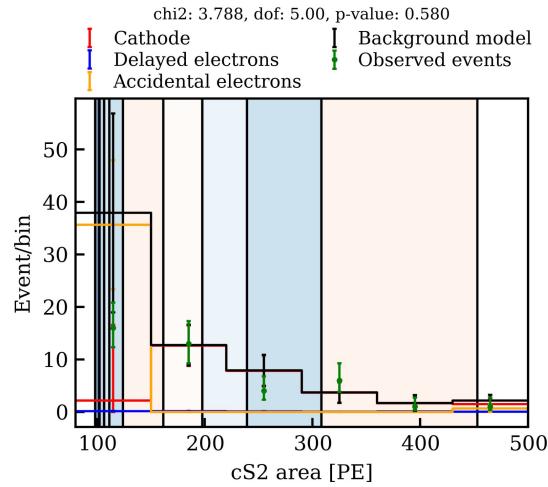


Notice the BDT score and CNF score differences

Validation SRO Rn220

We perform a two-step validation:

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



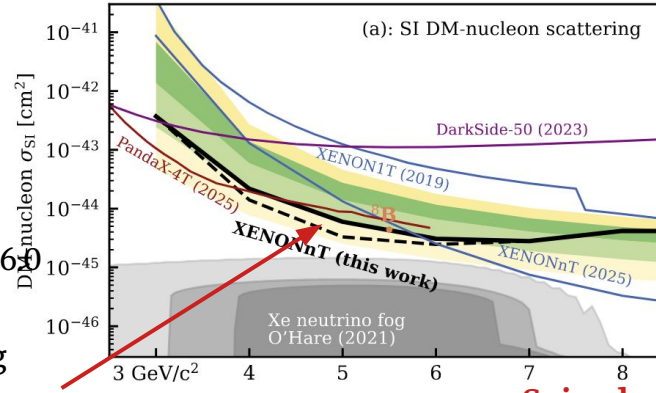
Notice the DE is gone, AE survived

Limits on light DM (NR channel)

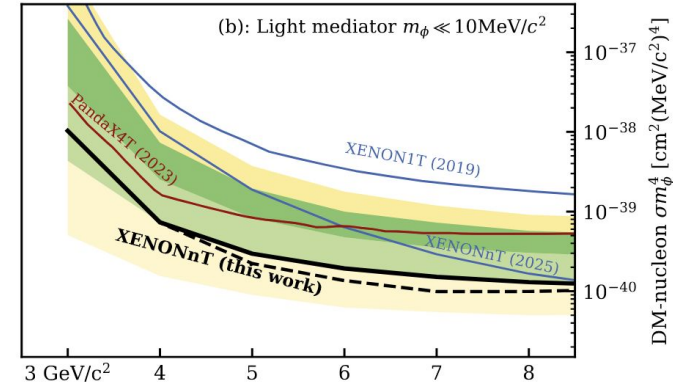


XENON

Spin-independent + heavy mediator

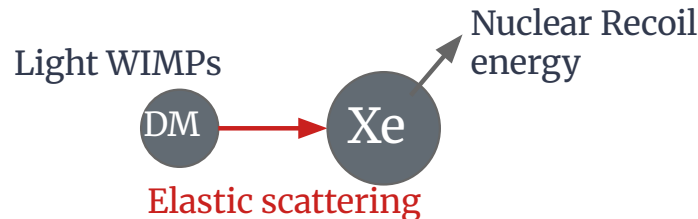
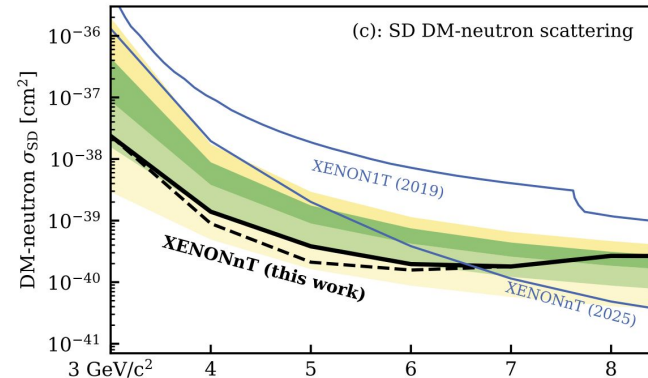


Spin-independent + light mediator



- Exclude cross sections above $6 \times 10^{-45} \text{ cm}^2$ at $m_\chi = 5 \text{ GeV}/c^2$
- Approaching the neutrino fog
- Downward fluctuations at low end
- PCL (Power-Constrained Limit) applied

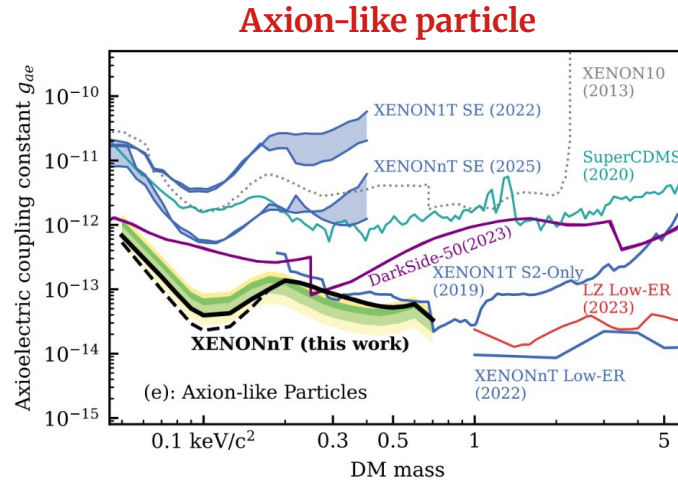
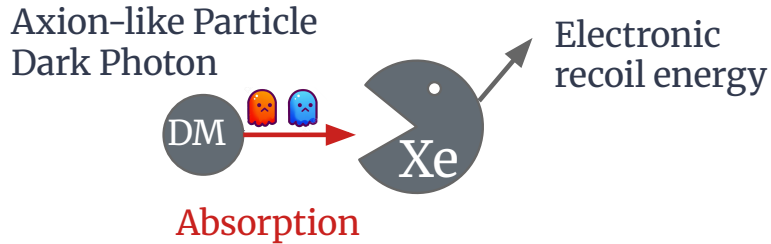
Spin-dependent + heavy mediator



Limits on light DM (ER channel)



XENON



Exclude the parameter spaces for bosonic DM:

- Axion-like particles (axioelectric coupling constant)
 - $g_{ae} = 3.9 \times 10^{-14}$ @ $m_\chi = 0.1 \text{ keV}/c^2$
- Dark photon (kinetic mixing constant)
 - $\kappa = 2.2 \times 10^{-17}$ @ $m_\chi = 0.1 \text{ keV}/c^2$

