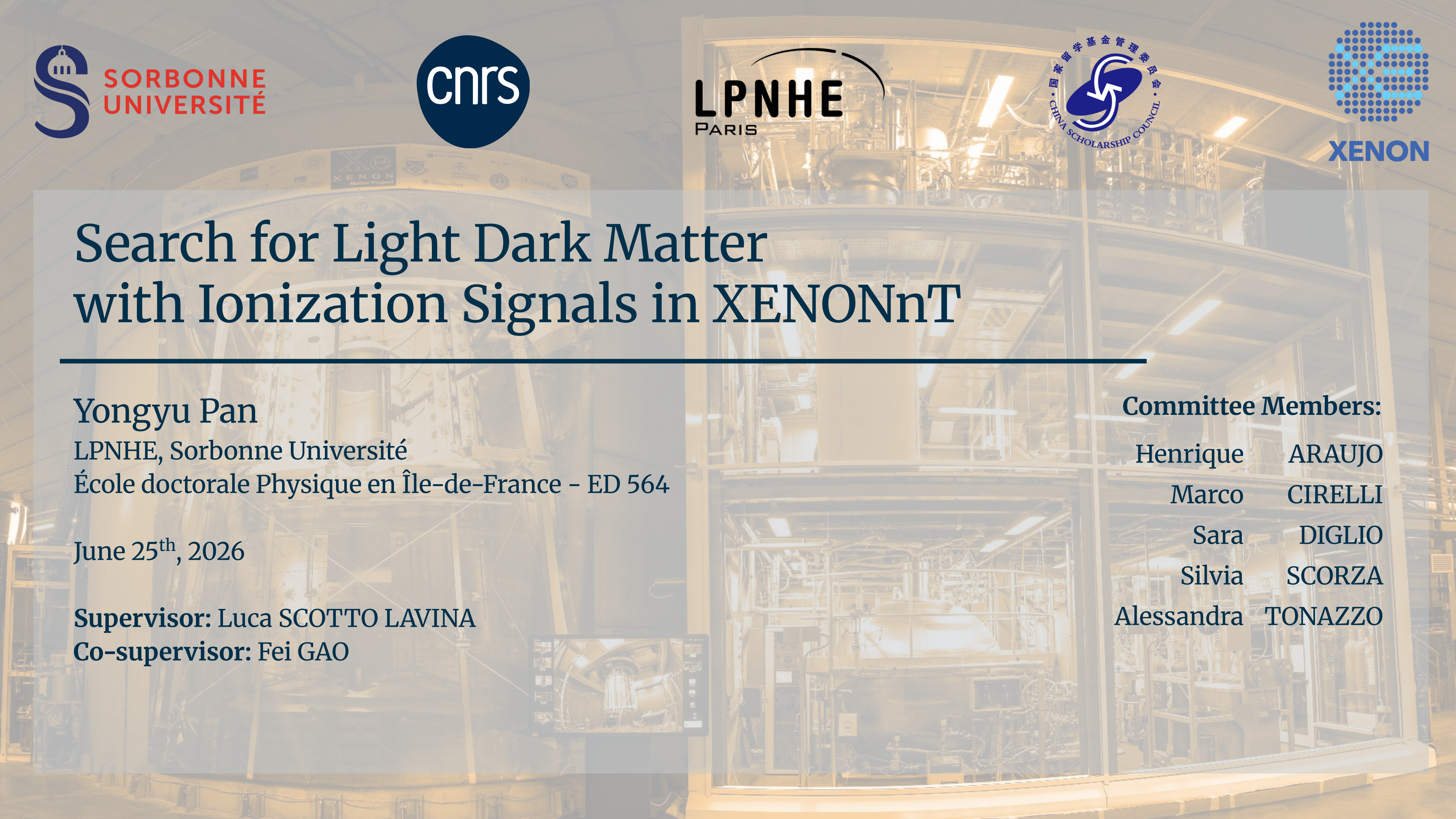

Search for Light Dark Matter with Ionization Signals in XENONnT

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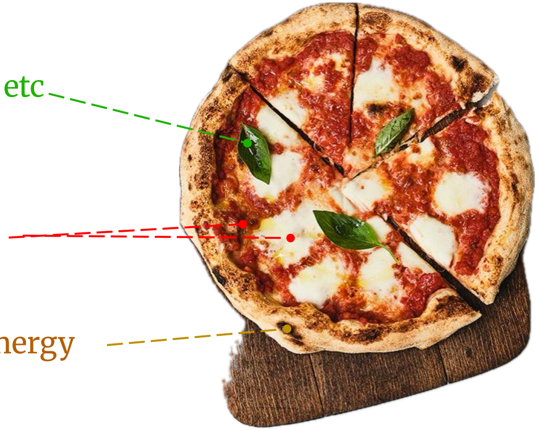
Alessandra TONAZZO

Table of Content

01. The Dark Matter Problem

DM evidence, properties, detections, mass regime

Our Universe



5% Planets, stars, etc

26% Dark Matter

69% Dark Energy

What we can actually see (detect)

🤔 What is the nature of dark matter?

Dark Matter Evidence

Galactic Scale

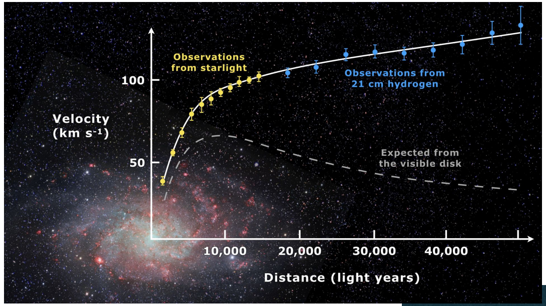
Galaxy rotation curves

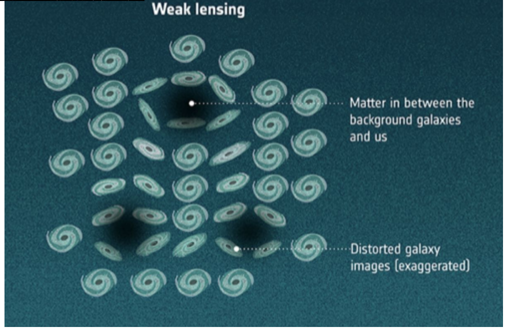
Galaxy Cluster Scale

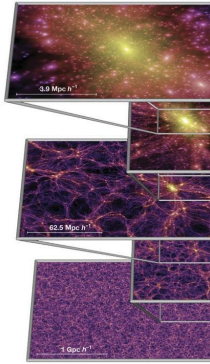
- Bullet cluster
- Weak Gravitational Lensing

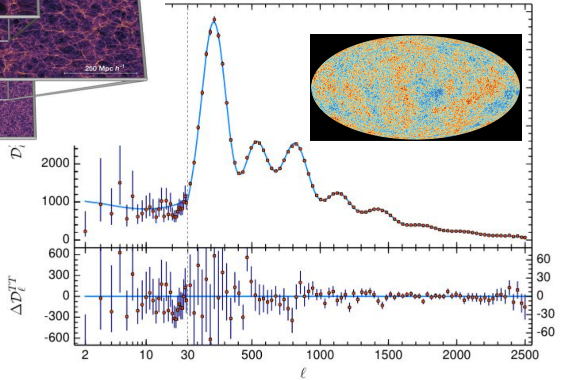
Cosmological Scale

- Galactic Large Scale Structure (LSS)
- Cosmic microwave background (CMB)









Dark Matter Properties

Galactic Scale

Galaxy rotation curves

- Gravitationally active
- Halo-distribution

Galaxy Cluster Scale

- Bullet cluster
- Weak Gravitational Lensing

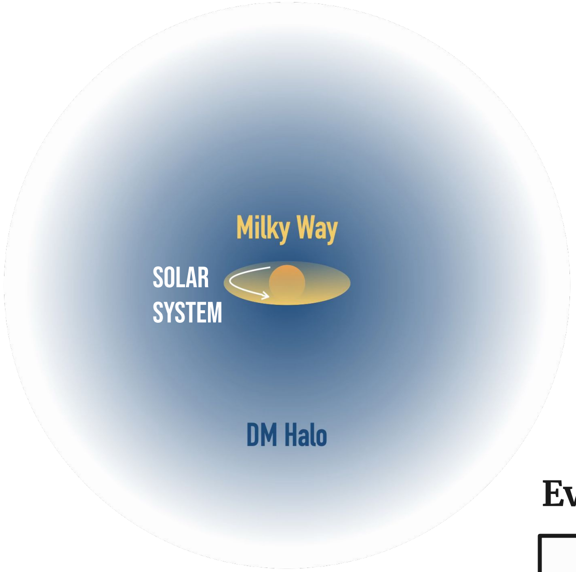
- Collisionless or weakly interacting

Cosmological Scale

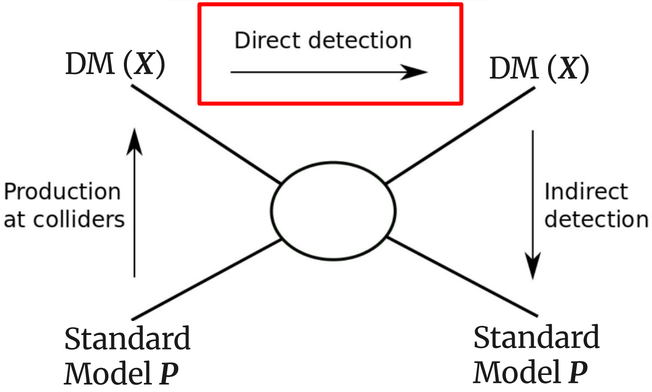
- Galactic Large Scale Structure (LSS)
- Cosmic microwave background (CMB)

1. Long-lived & clustering
2. Electrically neutral & non-baryonic
3. Dark matter: ~ 27% of the Universe and 84% of matter content

Dark Matter Detection



$$\chi + T \to \chi + T$$



Event rate:

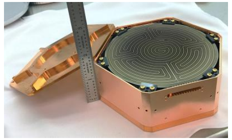
$$\frac{dR}{dE_R} \propto \frac{\rho_0}{m_\chi} \int_{v_{min}} \frac{d\sigma}{dE_R} v \cdot \mathbf{f(v)} d^3\mathbf{v}$$

Local mass density:
~0.3 GeV/cm^3
In an Earth-sized volume:
~0.5 kg

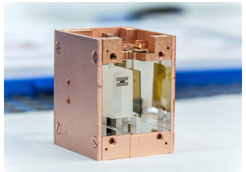
Astrophysics inputs

Velocity distribution:
- Standard Halo Model

Dark Matter Detection



SuperCDMS



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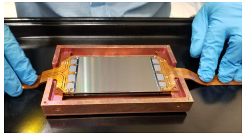


DAMIC, SENSEI

Phonons (Heat)

Charge (Ionization)

Light (Scintillation)

Deposited Energy

XENON, *LZ*, *PandaX* (Xenon-based)
DarkSide (Argon-based)

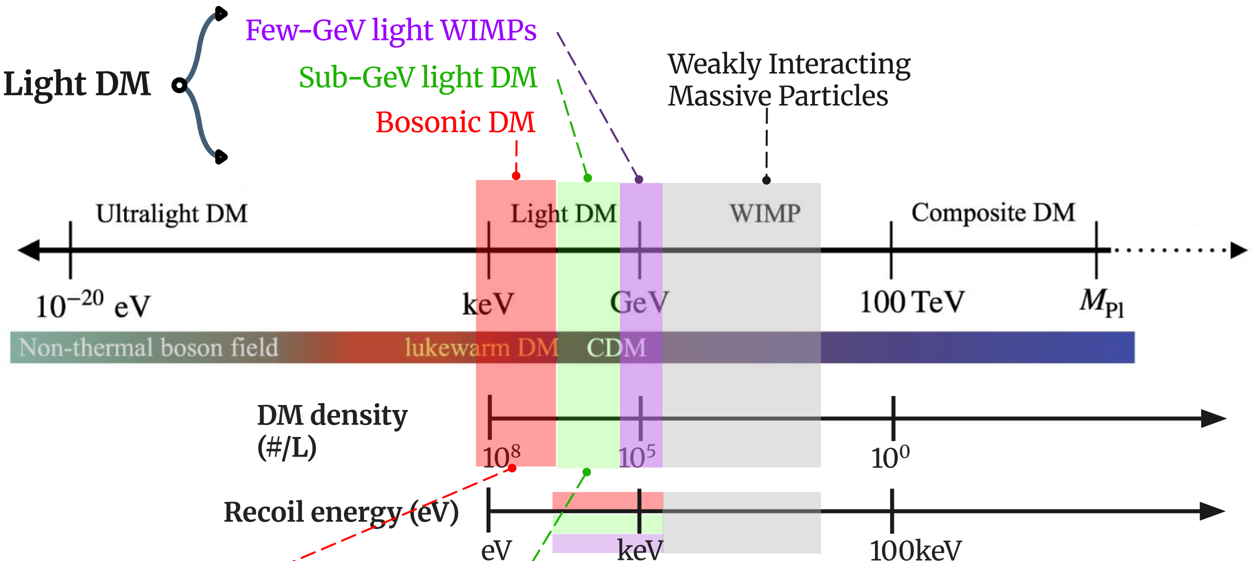
Event rate:

$$\frac{dR}{dE_R} \propto \frac{\rho_0}{m_\chi} \int_{v_{min}} \frac{d\sigma}{dE_R} v \cdot \mathbf{f}(\mathbf{v}) d^3\mathbf{v}$$

Parameters to constrain

DM mass & DM-target cross section

Dark Matter Mass Regime



Event rate:

$$R \propto \sigma_{\mathrm{PE}}$$

Photoelectric cross section

$$\frac{dR}{dE_e} \propto \mathbf{F}_{\mathrm{ion}}$$

Ionization factor

Bosonic DM:

- Axion-like particles
- Dark photon

02.
XENONnT Experiments

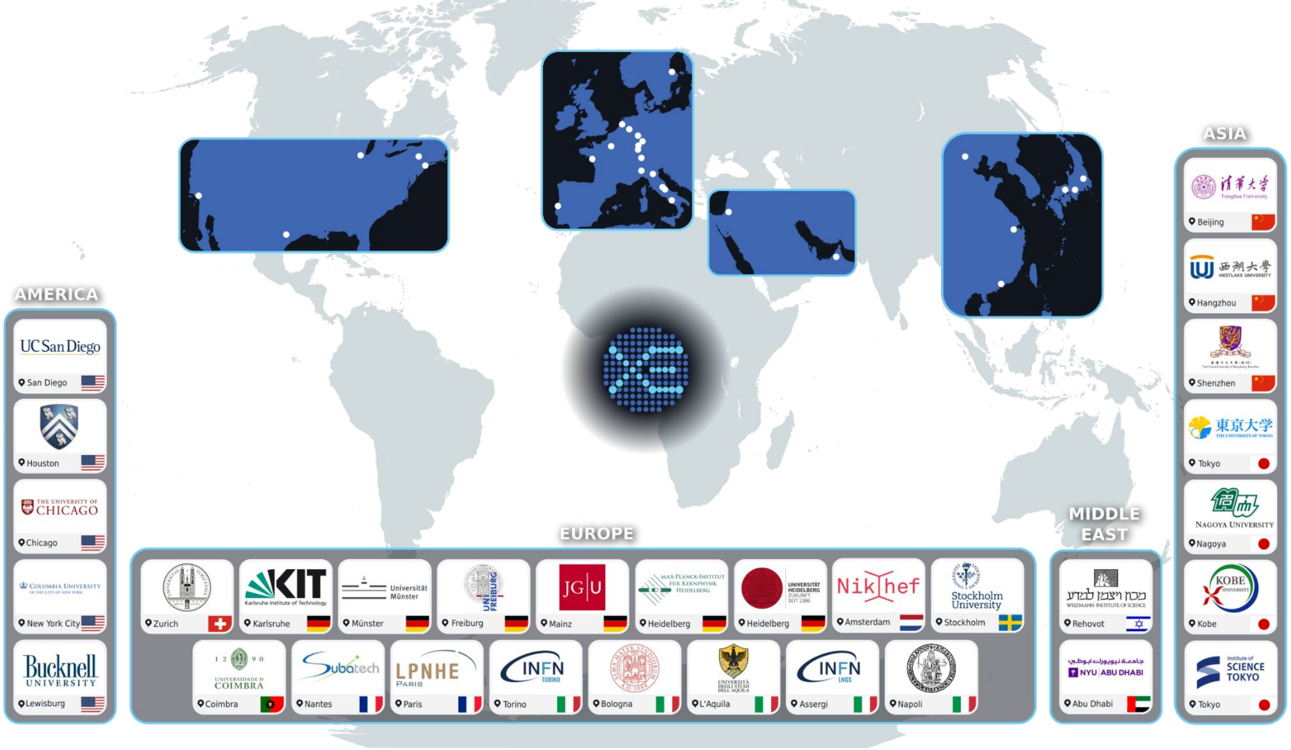
- Detector working principle
- Science data overview

The XENON Program

~ 200 Scientists

30 Institutions

12 Countries



Timeline

XENON10
2005
14 kg

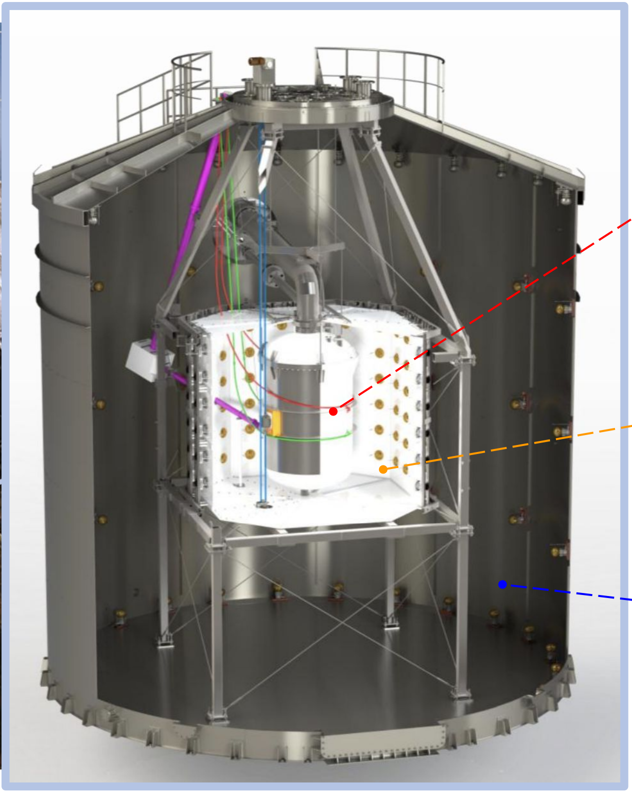
XENON100
2008
62 kg

XENON1T
2016
2 t

XENONnT
2020
6 t

XENONnT Experiment

INFN Laboratori Nazionali del Gran Sasso (**LNGS**)
Italy



Time Projection Chamber

- **5.9 t** active target
- **8.6 t** total mass
- **1.5 m** drift length
- **1.3 m** diameter
- **494** 3” PMTs

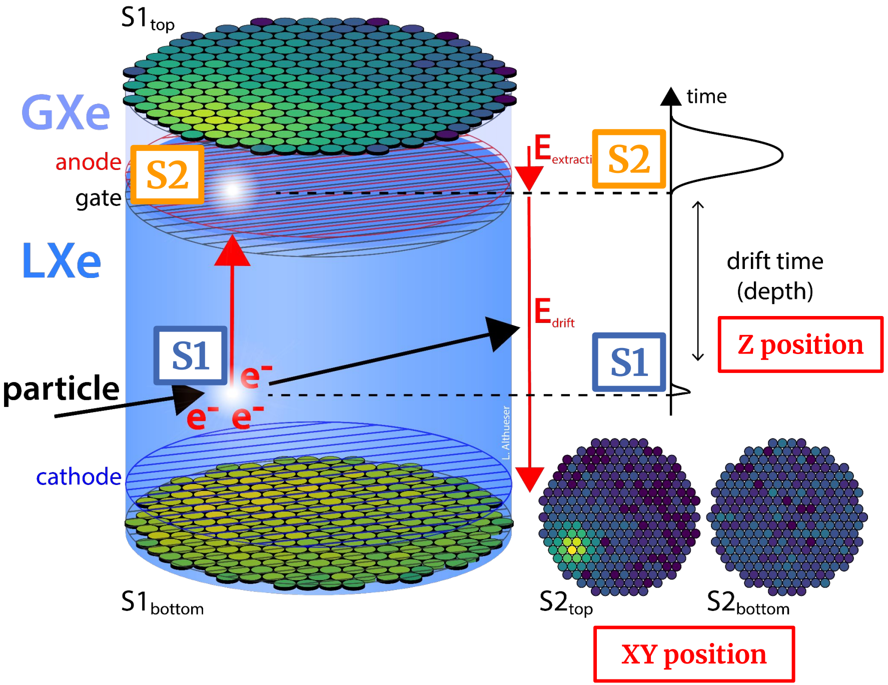
Neutron Veto

- Active Gd-water Cherenkov veto (120 8”PMTs)

Muon Veto

- Active Gd-water Cherenkov veto (84 8”PMTs)

XENONnT Experiment



Dual phase Xe TPC (Time projection chamber)

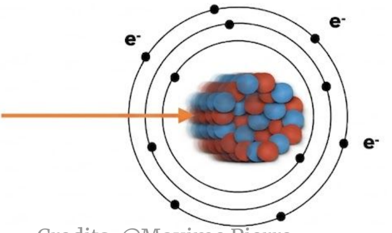
- **S1:** Prompt scintillation light
- **S2:** Secondary scintillation light by ionized electrons
- **3D Position reconstruction:** Drift time + PMT pattern
- **Energy reconstruction:**

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

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)

Event discrimination | Calibrations

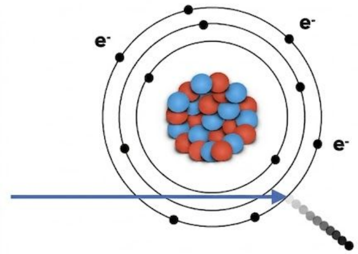
Nuclear Recoil (NR)



Credits: @Maxime Pierre

- **WIMPs**
- Neutrons
- Neutrino (CEvNS)

Electronic Recoil (ER)

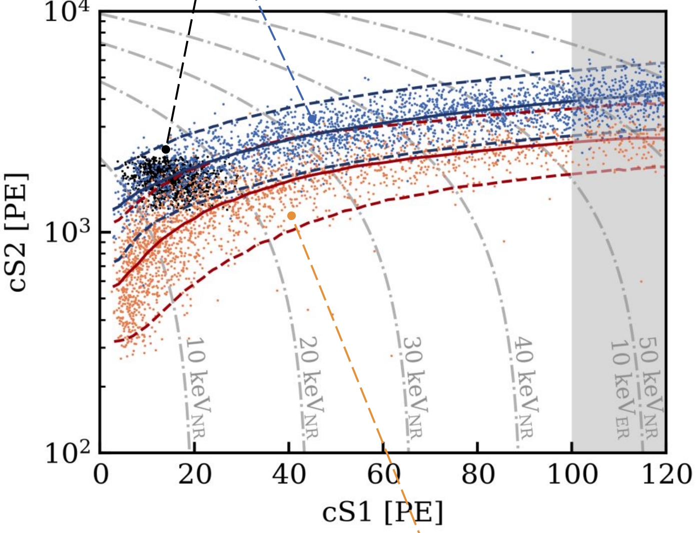


- **Bosonic DM**
- Gamma
- Beta
- Neutrino elastic scattering

$$\left(\frac{S2}{S1}\right)_{NR} < \left(\frac{S2}{S1}\right)_{ER}$$

ER calibrations:

- ^{37}Ar
- ^{220}Rn



NR calibrations:

- ^{241}AmBe neutron source

Science Data Overview

Upgrades and Status

SR0->SR1:

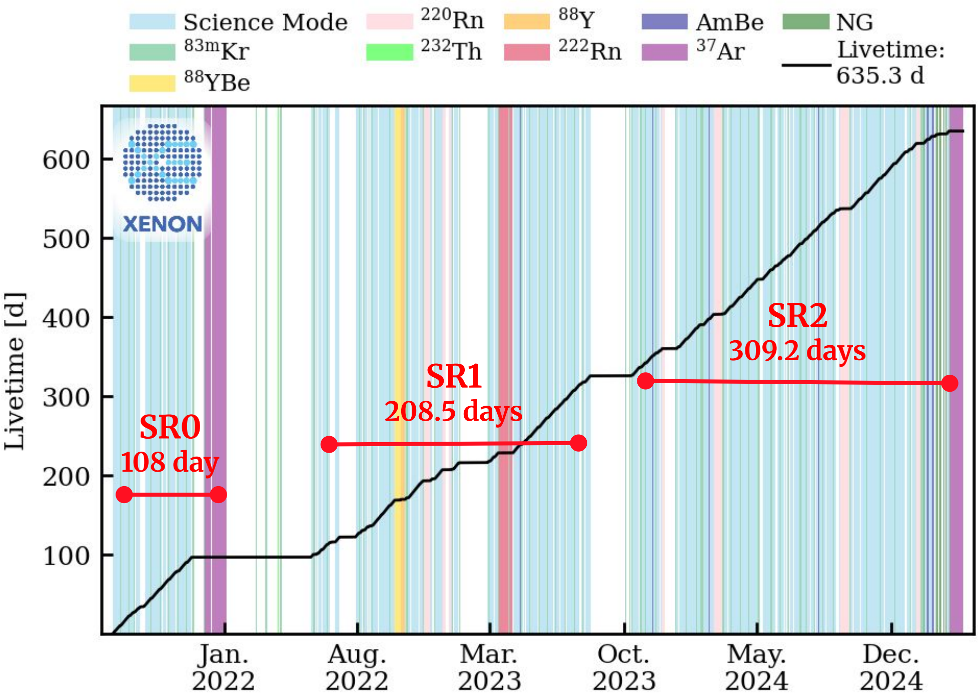
Liquid radon distillation, 1.8→0.9 μBq/kg

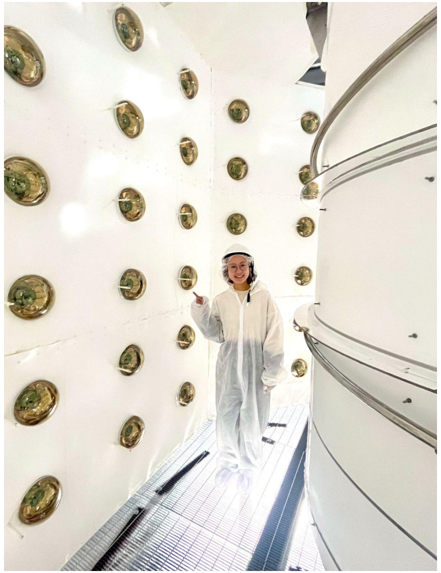
SR1->SR2:

Injected Gd into the neutron Cherenkov veto

SR2-> SR3:

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



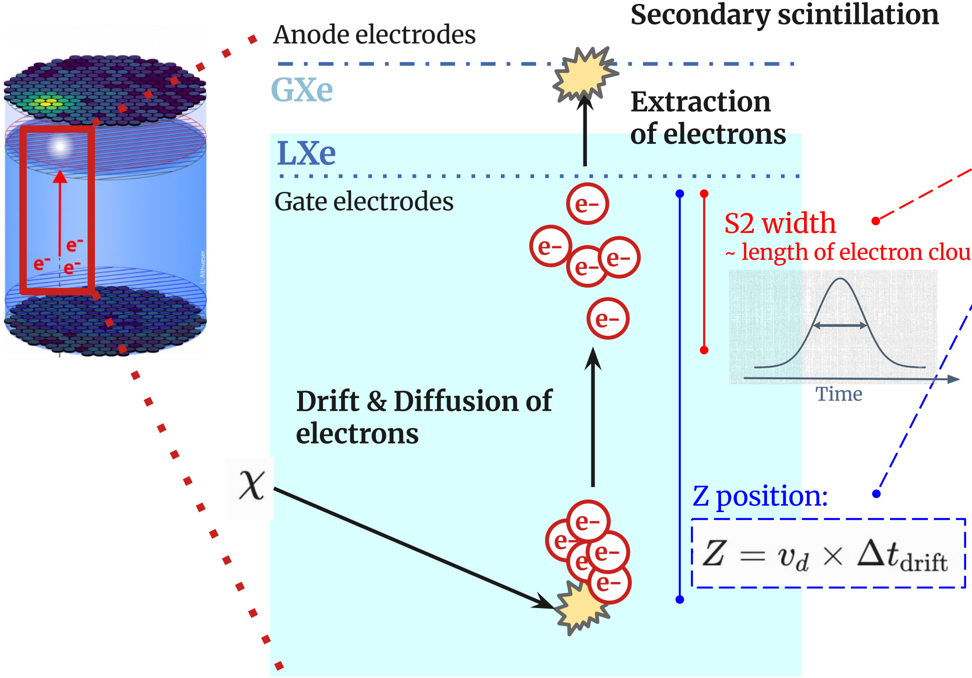


Me inside the neutron veto

03.
Analysis of S2 Pulse Shape

- General purpose analysis
- Electron drift & diffusion
- S2 width simulations
- S2 width cuts

Motivation & Outline



Anode electrodes

Secondary scintillation

Extraction of electrons

Gate electrodes

S2 width
~ length of electron cloud

Drift & Diffusion of electrons

Z position:

$$Z = v_d \times \Delta t_{\text{drift}}$$

01. **Parameters calibration:**
- Drift velocity v_{drift}
- Diffusion constant D_l

Input

02. **S2 width simulation**

Input

03. **S2 width cuts**

General analysis:
Detector dynamics tracking & Background rejection

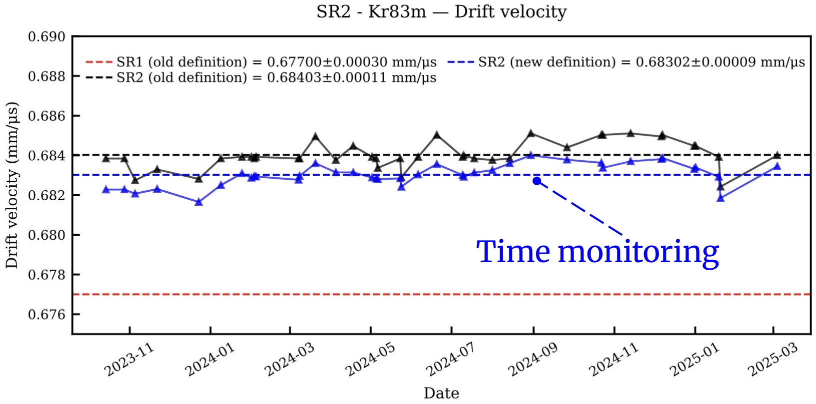
S2-only analysis:
Main discriminator for signal vs. background

Parameters Calibrations

01. Parameters calibration:

- Drift velocity v_{drift}
- Diffusion constant D_l

Internal ^{83m}Kr calibration dataset (uniformly distributed in detector)



Time monitoring

Drift Velocity

$$v_d = \frac{z_{\text{gate}} - z_{\text{cathode}}}{t_{\text{cathode}} - t_{\text{gate}}}$$

Maximum drift length

Maximum drift time

Diffusion constant

$$\mathrm{r}_{50}^{\mathrm{mod}}(t) = 1.349\sigma = 1.349\sqrt{\frac{2D\cdot(t - t_{\text{gate}})}{v^2} + scw^2}$$

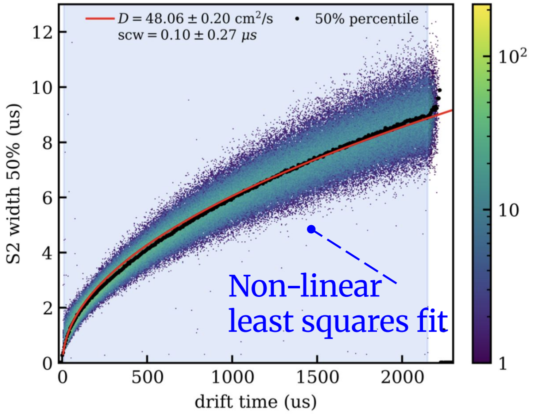
Drift time

Gate drift time

S2 width

Drift velocity

Single electron width



Non-linear least squares fit

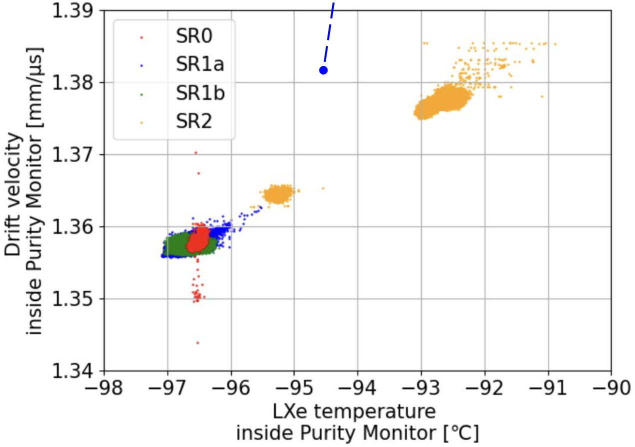
Parameters Calibrations

01. **Parameters calibration:**

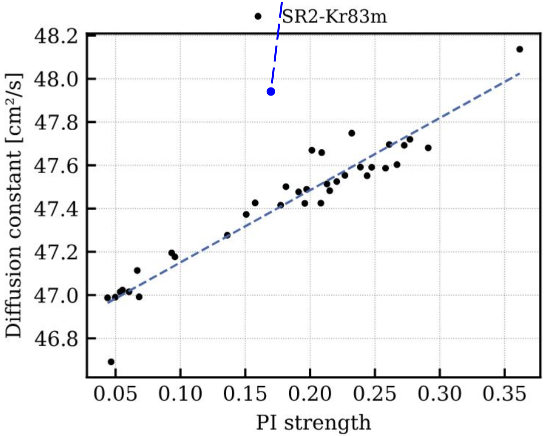
- Drift velocity v_{drift}
- Diffusion constant D_l

Key dependences:

1. The primary dependency ***drift field*** is constant during the data taking period
2. The ***temperature*** increase can explain the macroscopic increase in drift velocity



3. ***Photoionization (PI)*** of impurities introduces single electrons that merge into the S2 waveform ⇒ larger fitted diffusion constant

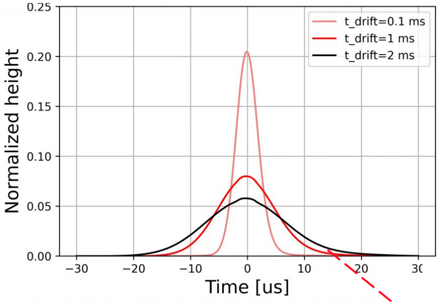


S2 Width Simulations

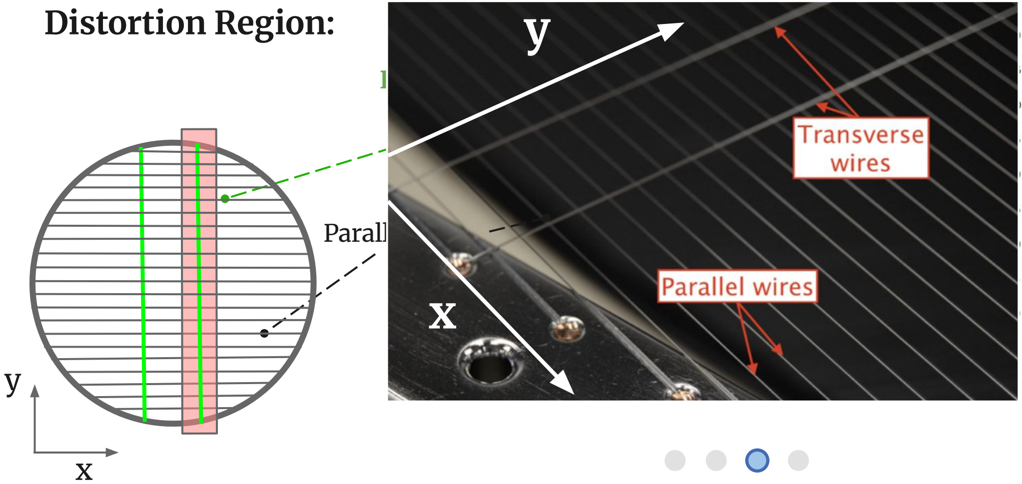
02. **S2 width simulation:**
- Standard S2 width modeling
- Dealing with wire field distortions

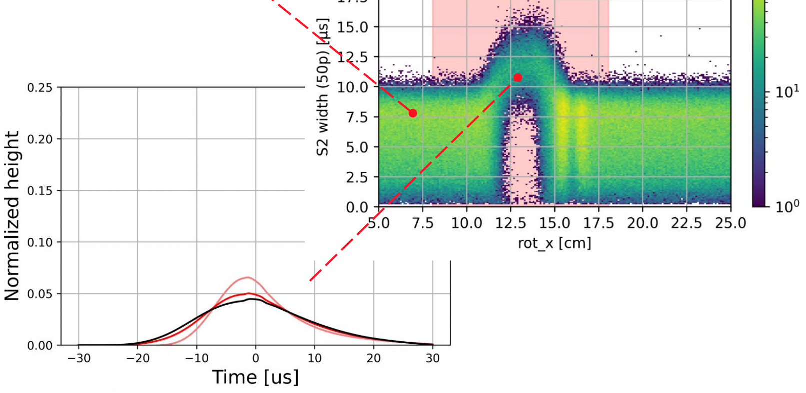
Standard Region:
Electrons undergo longitudinal diffusion in a uniform field.
Arrival times follow a normal distribution:

$$t_{\mathrm{drift},i} \sim \mathcal{N}(\mu_{\mathrm{drift}}, D_l)$$



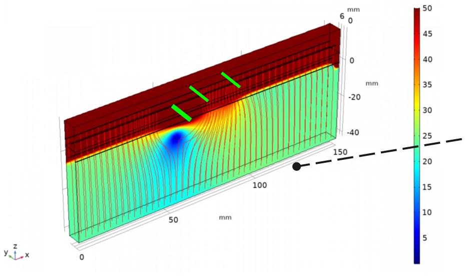
Distortion Region:

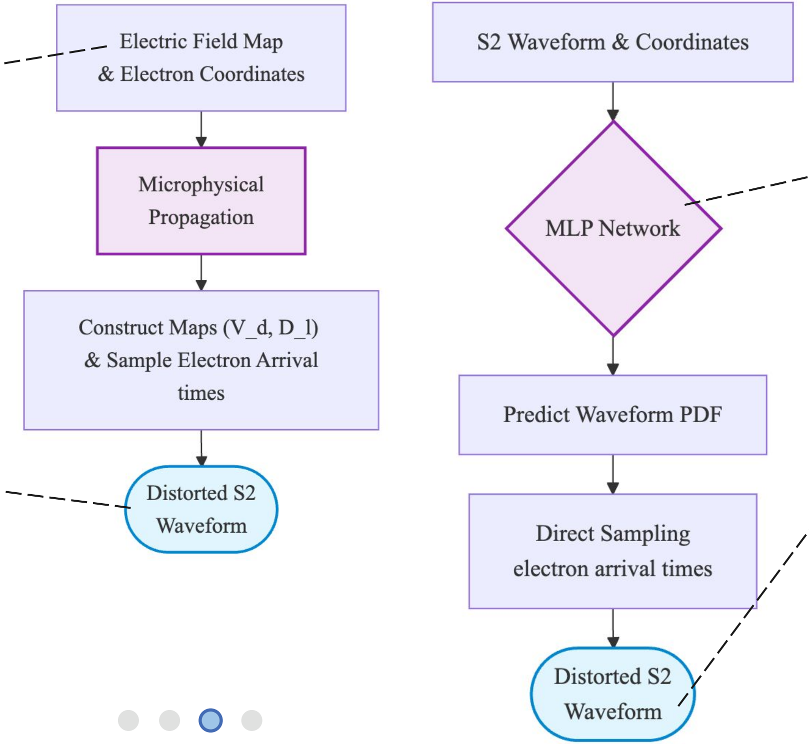




S2 Width Simulations

02. **S2 width simulation:**
- Standard S2 width modeling
- **Dealing with wire field distortions**





Microphysics & simulation driven

Electric Field Map & Electron Coordinates

Microphysical Propagation

Construct Maps (V_d, D_l) & Sample Electron Arrival times

Distorted S2 Waveform

Machine Learning & data driven

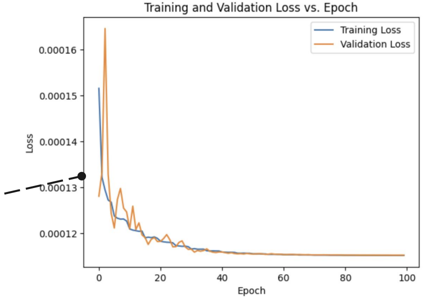
S2 Waveform & Coordinates

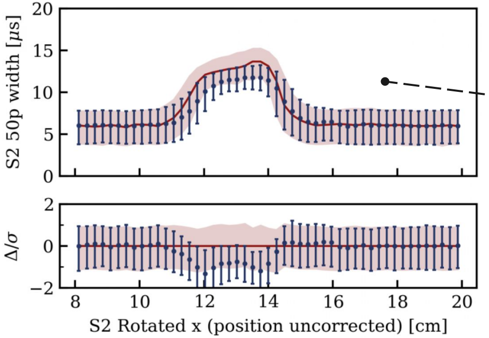
MLP Network

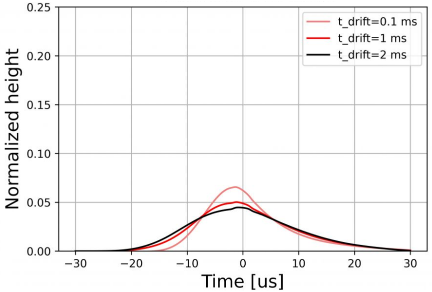
Predict Waveform PDF

Direct Sampling electron arrival times

Distorted S2 Waveform







S2 Width Simulations

02. S2 width simulation:
- Standard S2 width modeling
- **Dealing with wire field distortions**

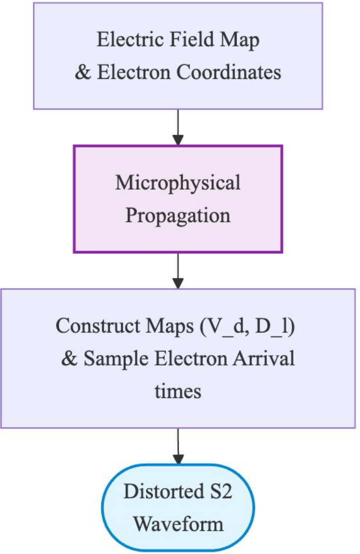
✅

- Built on first principles.
- Compatible with simulation framework.
- Parameters can be tuned for varying detector conditions.

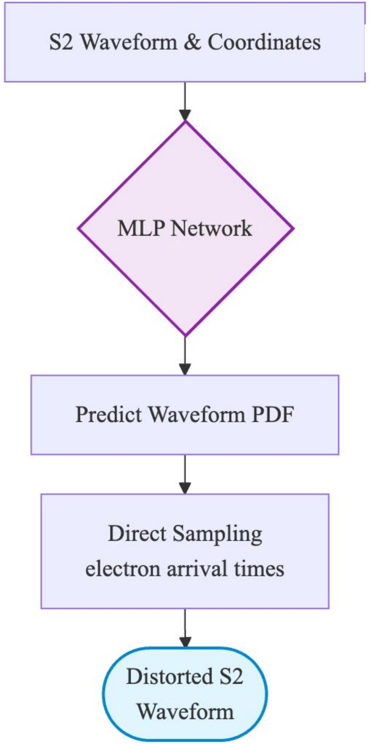
❌

- Mismatch of field models with real world (e.g., wire sagging).
- Uses v_d and D_l in uncalibrated high-field regions.

Microphysics & simulation driven



Machine Learning & data driven



✅

- Bypasses complex diffusion models.
- Naturally matches data.

❌

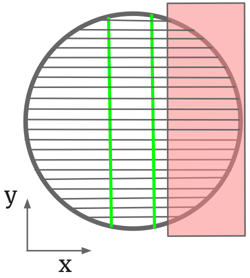
- Black-box
- Systematic Bias: Trained on observed features rather than true features.

S2 Width Cuts

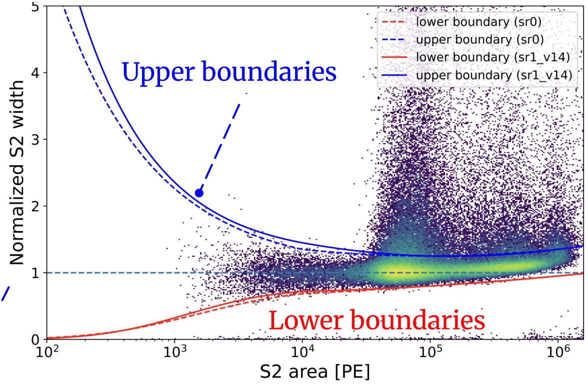
03. S2 width cuts:

- Simulation & machine learning based cuts
- Background rejection

To remove gas event, accidental coincidence event



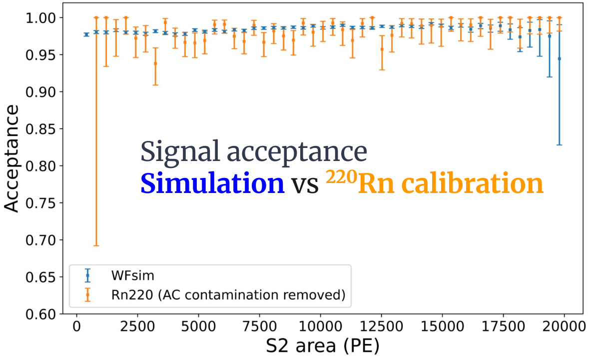
Standard Region
(Far wire)



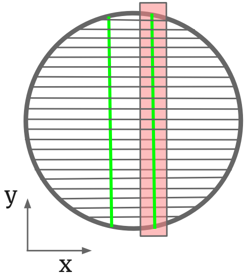
Upper boundaries

Lower boundaries

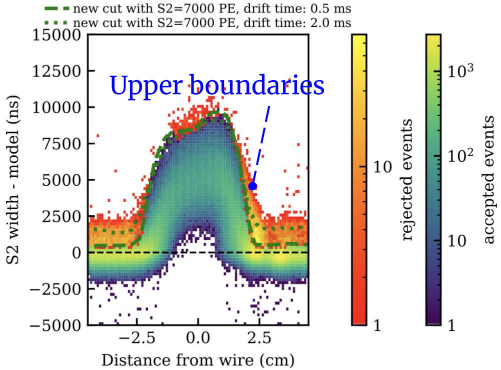
$$\frac{\text{Observation}}{\text{Model}}$$



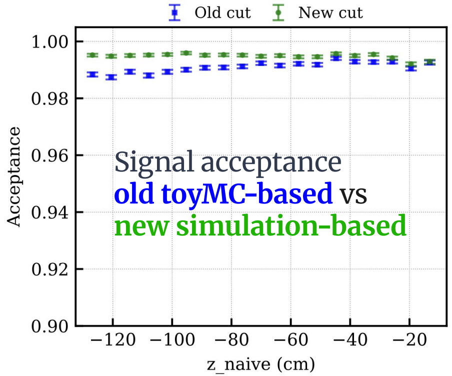
Signal acceptance
Simulation vs **^{220}Rn calibration**



Distortion Region
(Near wire)



Upper boundaries



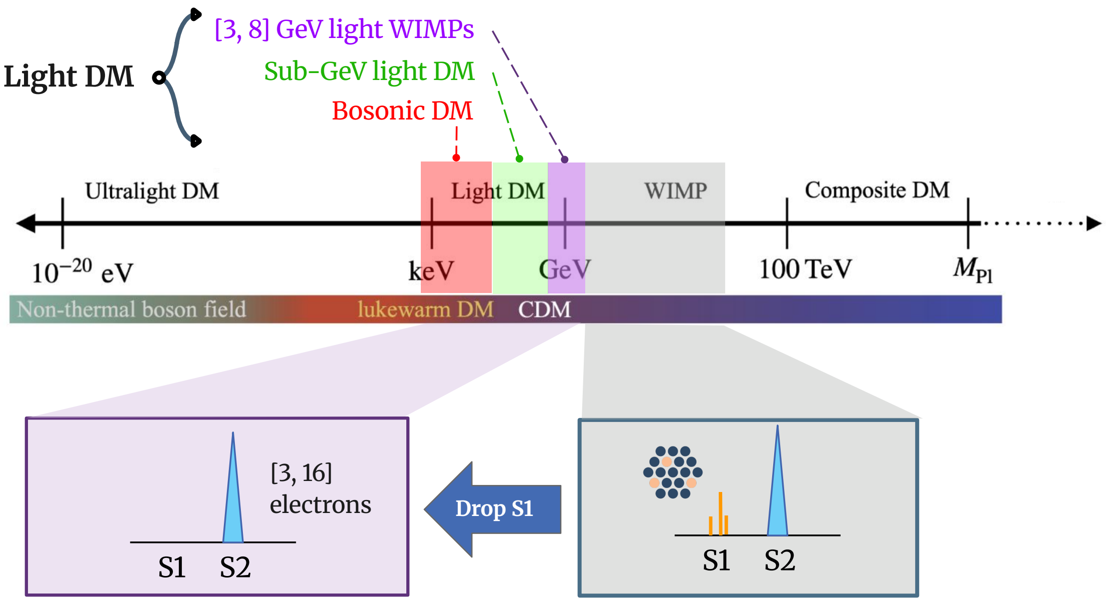
Signal acceptance
old toyMC-based vs
new simulation-based

04.

Search for Light Dark Matter using S2-only Data

- Motivation & Challenges
- Background Model
- Signal Model
- Limits on light dark matter model

Motivation of S2-only analysis



S2-only analysis

S1 + S2 analysis

Sensitive to > 8 GeV/c^2 DM

S1 fails for Light Dark Matter

Photon generation

Light yield suppression L_y

↓

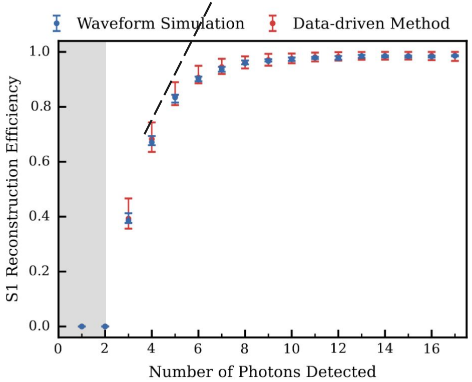
Photon detection

Low efficiency g_1

↓

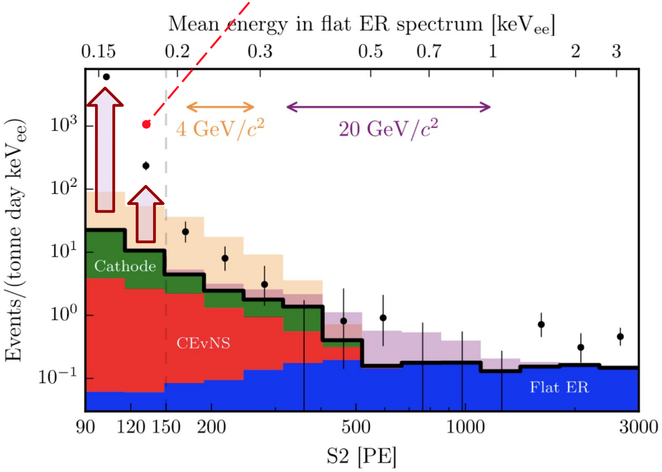
S1 reconstruction

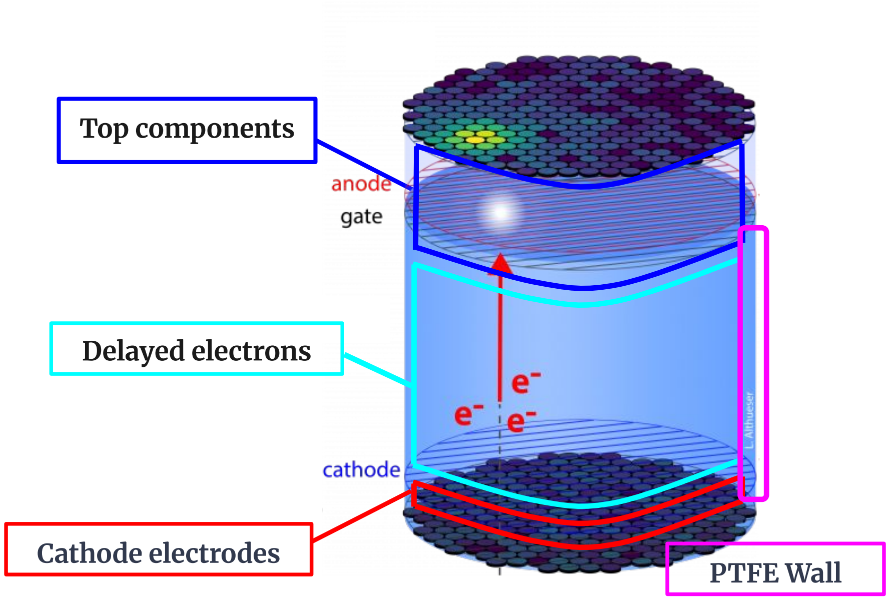
3-fold PMT coincidence



Challenges of S2-only analysis

- Losing S1 to reconstruct the depth (Z-coordinate)
- Losing ER/NR discrimination using the S2/S1 ratio
- Unmodeled instrumental backgrounds at low energies





Top components

Delayed electrons

Cathode electrodes

PTFE Wall

The S2-only recipe 🥘 🧑‍🍳

Stage 1:

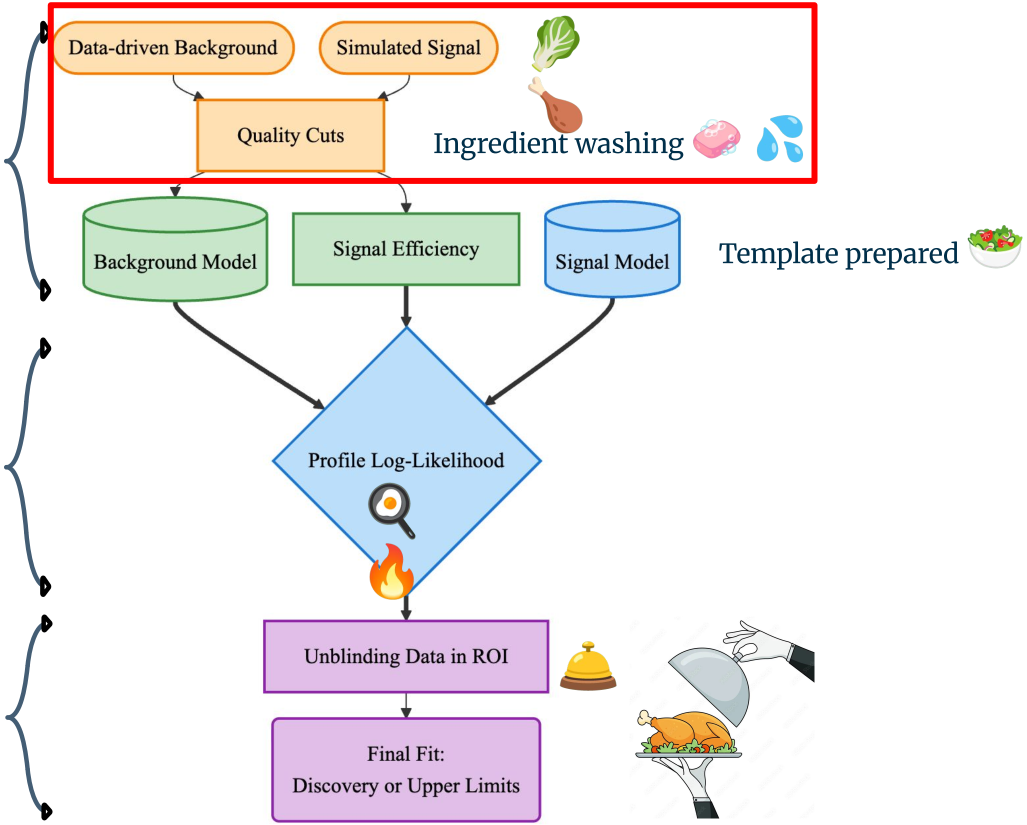
Ingredient Preparation

Stage 2:

Statistical cooking

Stage 3:

Food serving



Data-driven Background

Simulated Signal

Quality Cuts

Ingredient washing

Background Model

Signal Efficiency

Signal Model

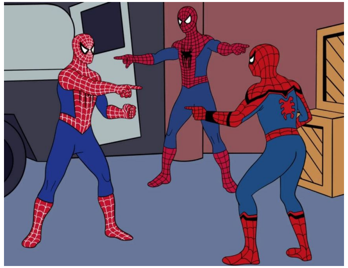
Template prepared

Profile Log-Likelihood

Unblinding Data in ROI

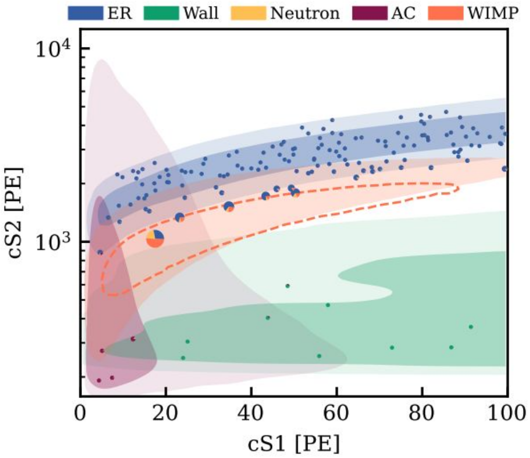
Final Fit:
Discovery or Upper Limits

Backgrounds | Discrimination Space

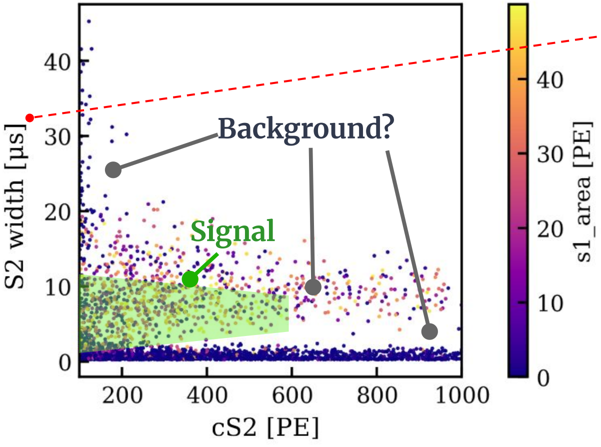


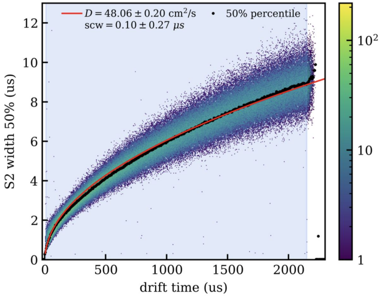
Losing the S2/S1 discrimination space
⇒ novel background discrimination space

S1+S2 analysis

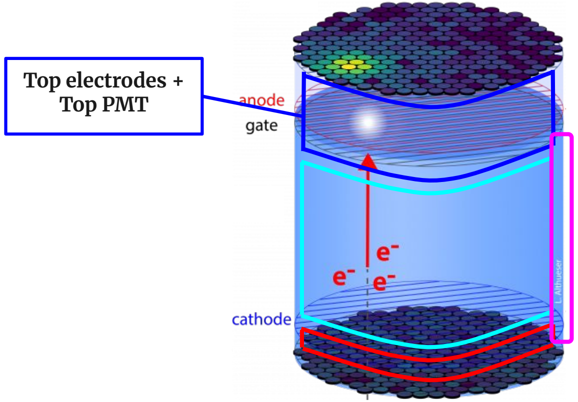


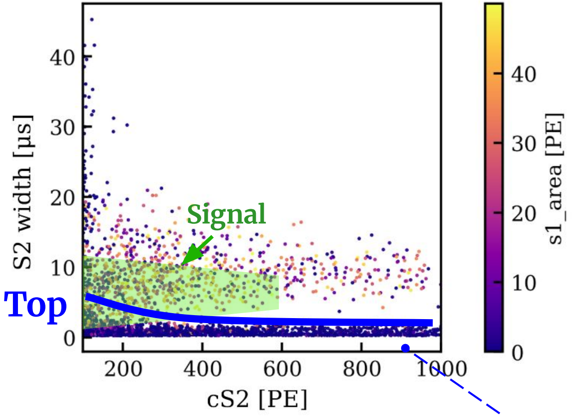
S2-only analysis

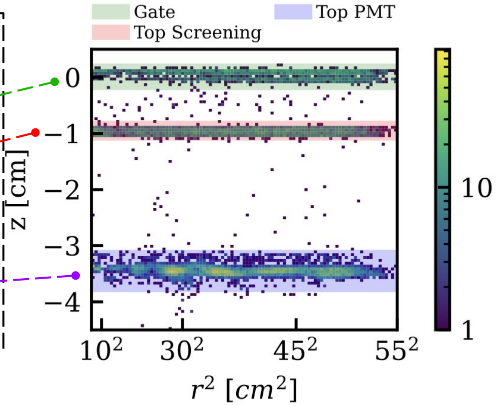




Backgrounds | 01. Top regions





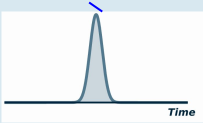


Background origin:

Top electrodes (Plated out radioactivity from ^{222}Rn decay chain)

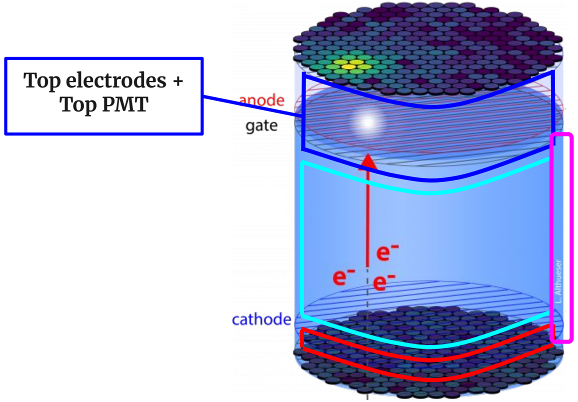
- Gate
- Top screening

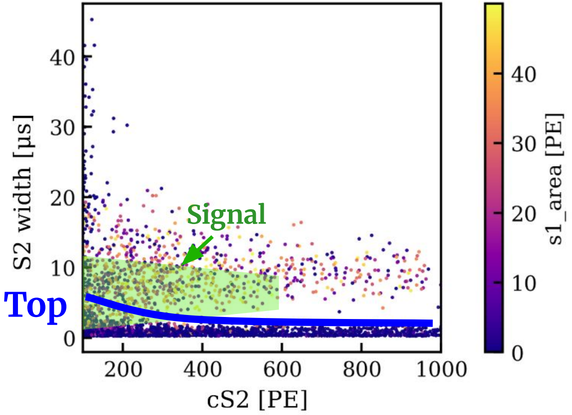
Top PMTs (Radioactivity from Photocathode & Kovar flanges)



S2 width < 3 us due to smaller diffusion

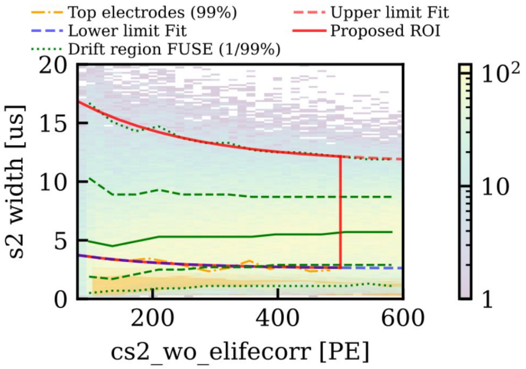
Backgrounds | 01. Top regions

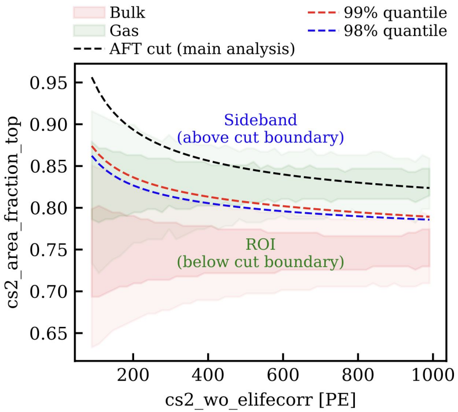




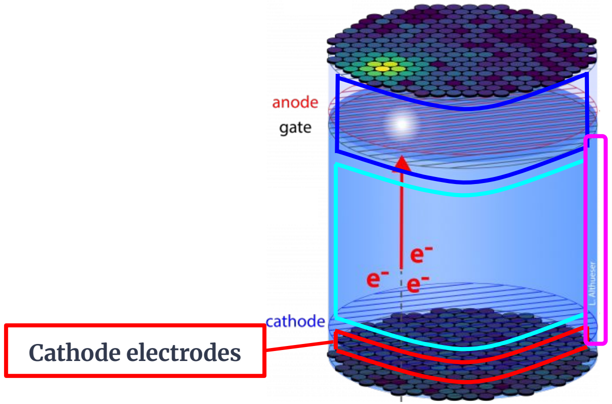
Background rejection:

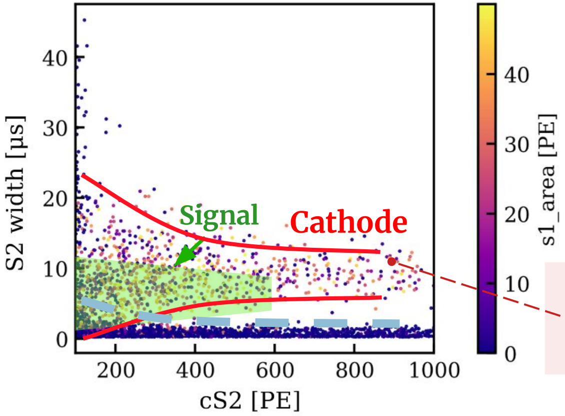
- **S2 width**: reject narrow pulses
- **S2 light distribution:** Selects events with liquid-like top/bottom ratios
    - ~99% signal acceptance.
- Temporal veto
- At **negligible** level after cuts

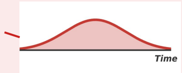




Backgrounds | 02. Cathode







S2 width ~ 10 us
large overlap with signal region

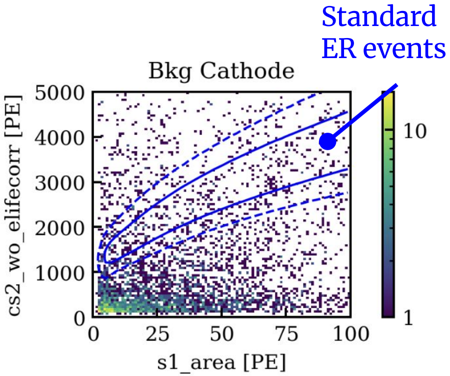
Background origin:

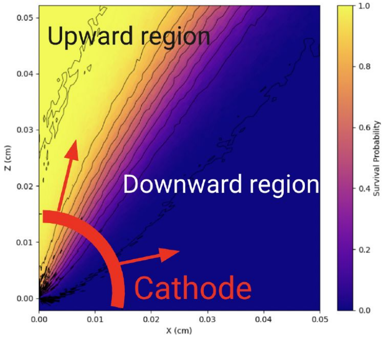
Plated out radioactivity from ^{222}Rn decay chain onto the cathode

- beta decay from ^{210}Pb (Q=63.5 keV) and daughters

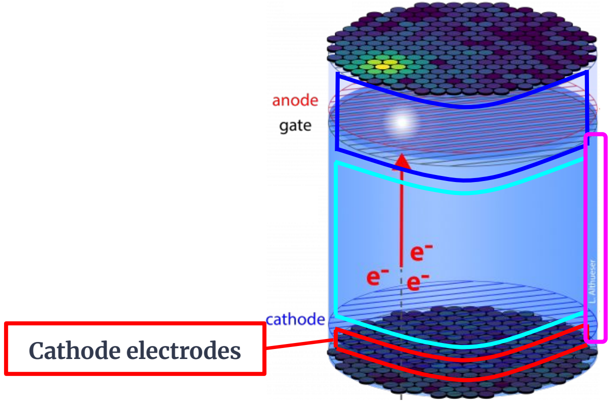
Cathode events suffer strong **photon and charge loss**:

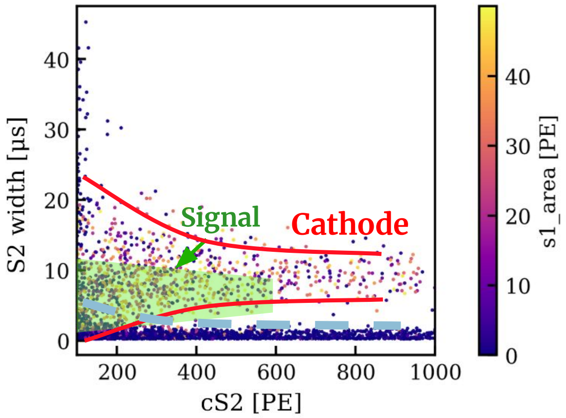
- S1: Strong field ⇒ Suppression of electron-ion recombination + optical effect
- S2: Electrons drifting following downward electric fields lines

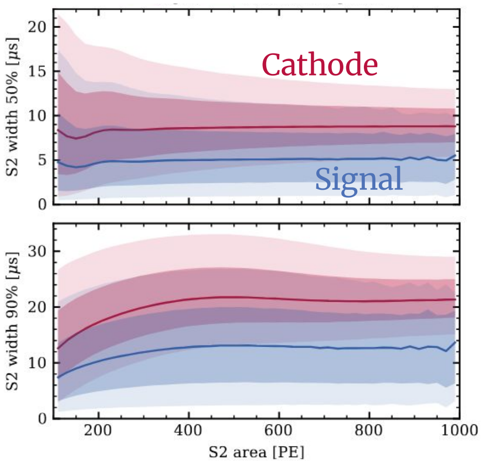




Backgrounds | 02. Cathode

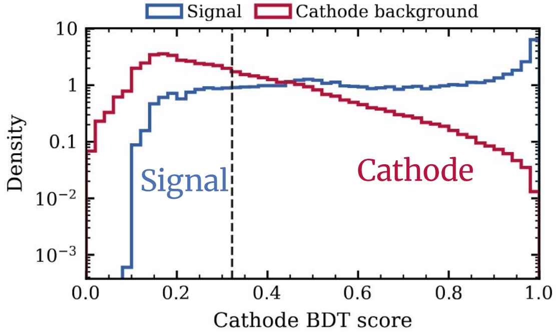




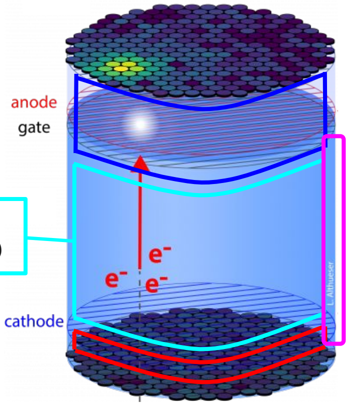


Background rejection:

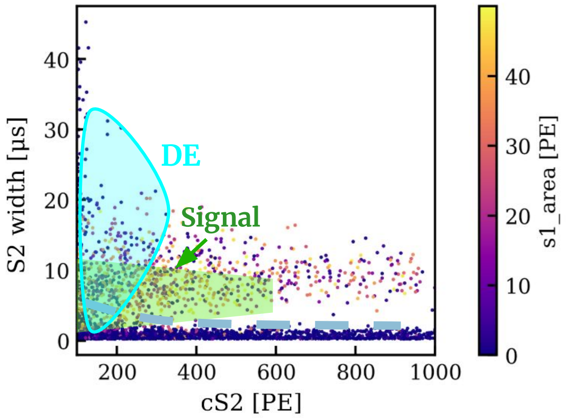
- S2 width (upper boundary)
- **Boosted Decision Tree (BDT) classifier**
  - S2 pulse features (width 50%, 90% etc)
  - Cathode rejection: ~50%, signal acceptance: ~80%
- Temporal veto
  - Cathode rejection: ~14%, signal acceptance: 99.5%

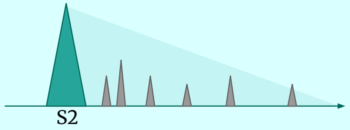


Backgrounds | 03. Delayed Electrons (DE)



Delayed electrons (DE)
Accidental electrons (AE)



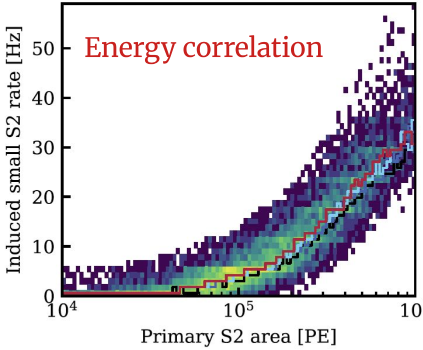


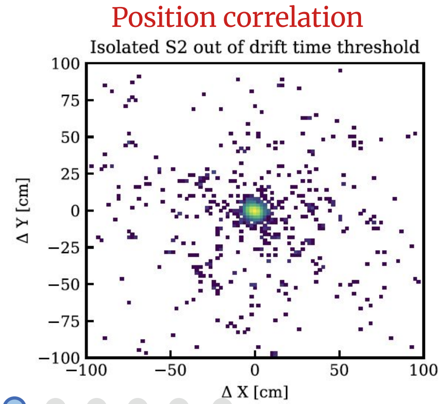
DE:
Large S2 width due to the peak merging

Background origin:

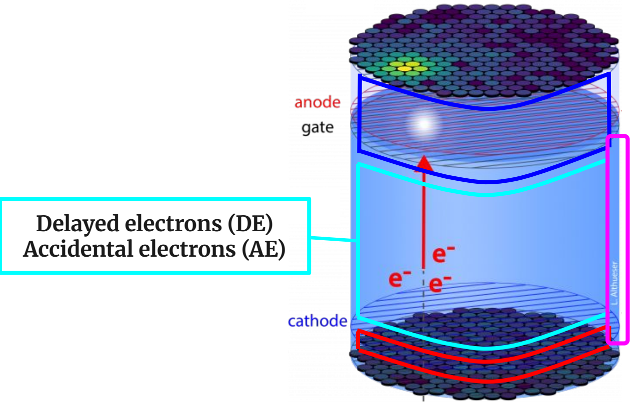
Electrons of high-energy event captured by impurities in LXe, and emitted afterwards up to 1s

Position and time correlated with primary S2

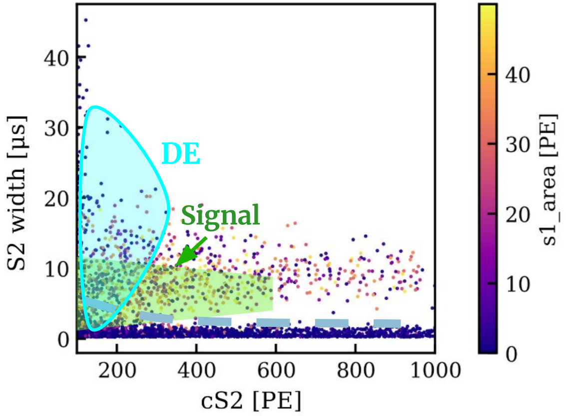


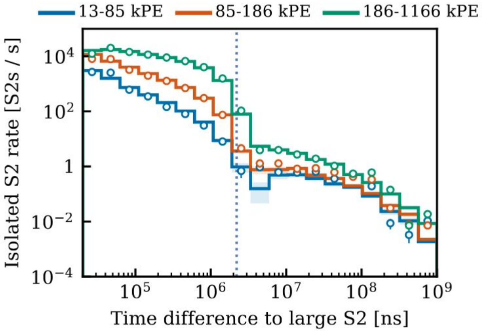


Backgrounds | 03. Delayed Electrons (DE)



Delayed electrons (DE)
Accidental electrons (AE)

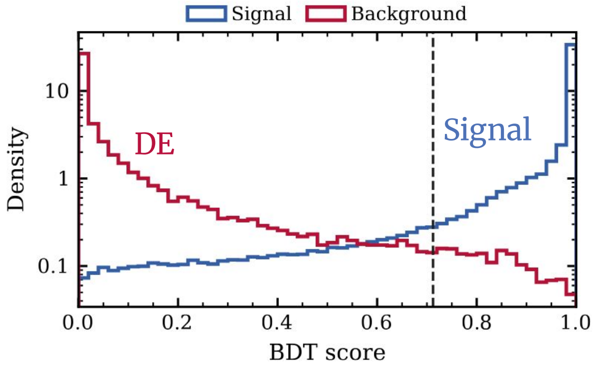




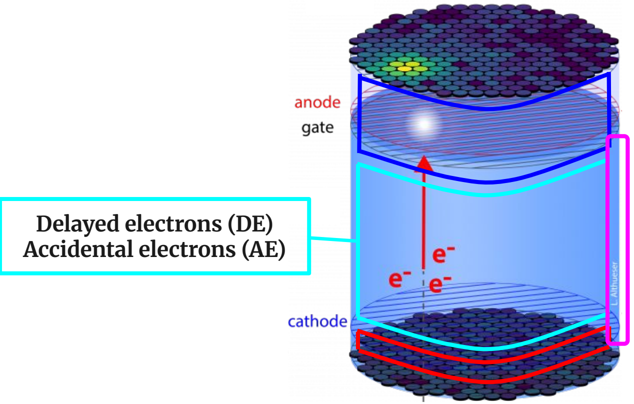
Background rejection:

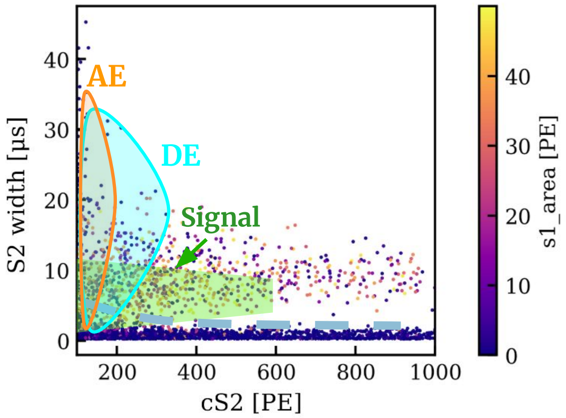
Generative ML model Conditional Normalizing Flow (CNF)
- Learns high-dimensional PDF of delayed trains
- Calculates CNF Score for observed isolated S2s

BDT classifier based on waveform features + CNF score
- DE rejection: 98%, signal acceptance: 80%



Backgrounds | 04. Accidental Electrons (AE)



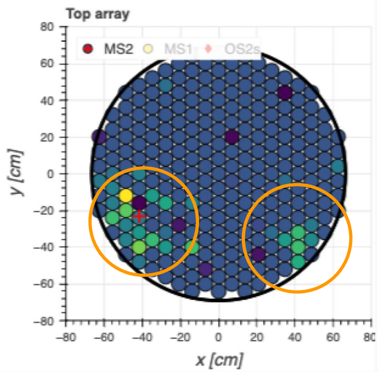


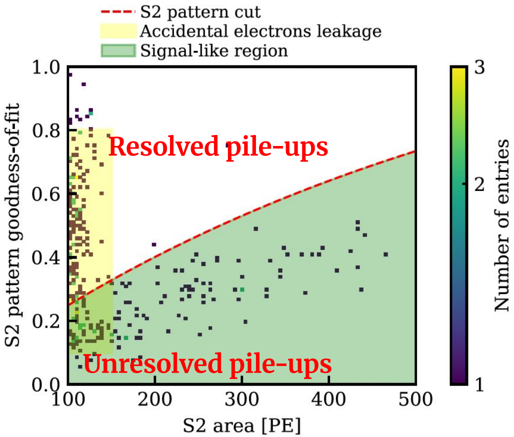
Background origin:

Random temporal pile-up of delayed single electrons (SE)

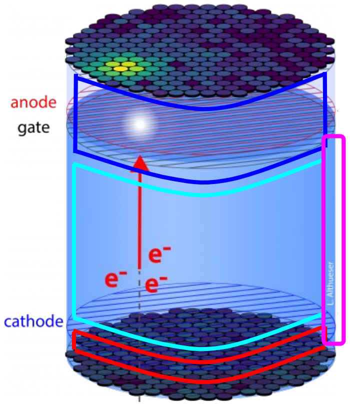
Background rejection:

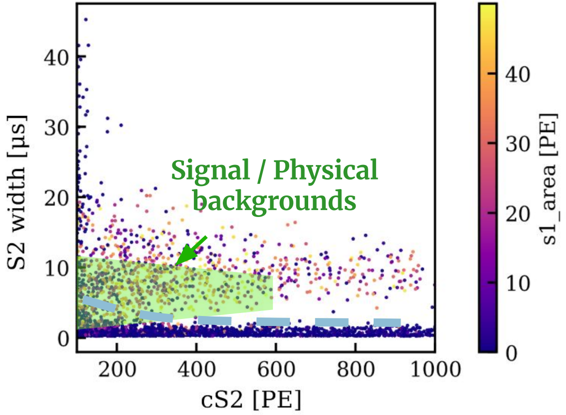
Comparison of observed **hit patterns** against neural-network optical maps, >98% acceptance

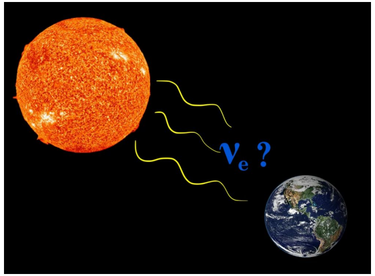




Backgrounds | 05. Physical background



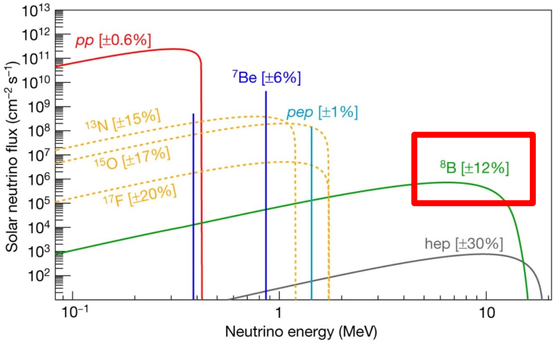




1. **^{8}B solar neutrino**
Coherent Elastic Neutrino-Nucleus Scattering (**CEvNS**) signal

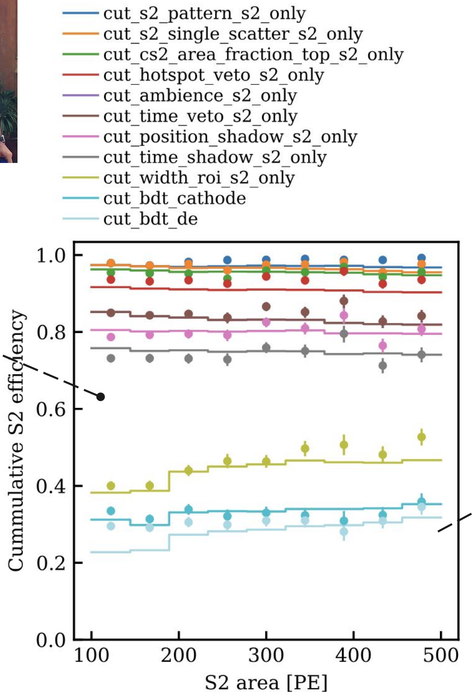
- Neutrino Flux from the SNO (Sudbury Neutrino Observatory) experiment.
- Energy distribution from standard ^{8}B nuclear decay spectrum.
- Cross-Section from Standard Model interaction.

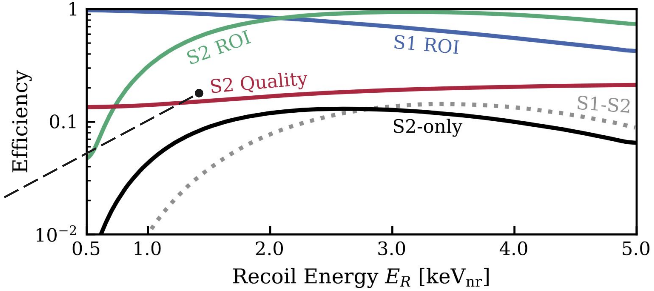
2. NR from neutron
3. ER from radioactivity



Cut efficiency

1. **Salting:** Simulate DM-like S2 peaks and inject these peaks into real science data.
2. Calculate **survival fraction** as total efficiency.
3. **Efficiency gain** (up to 5x) below 3 keV_{nr} compared to traditional S1+S2 searches.
4. **Energy Reach** [0.5, 5.0] keV_{nr} and [0.04, 0.7] keV_{ee}





The S2-only recipe 🥘 👨‍🍳

Stage 1:

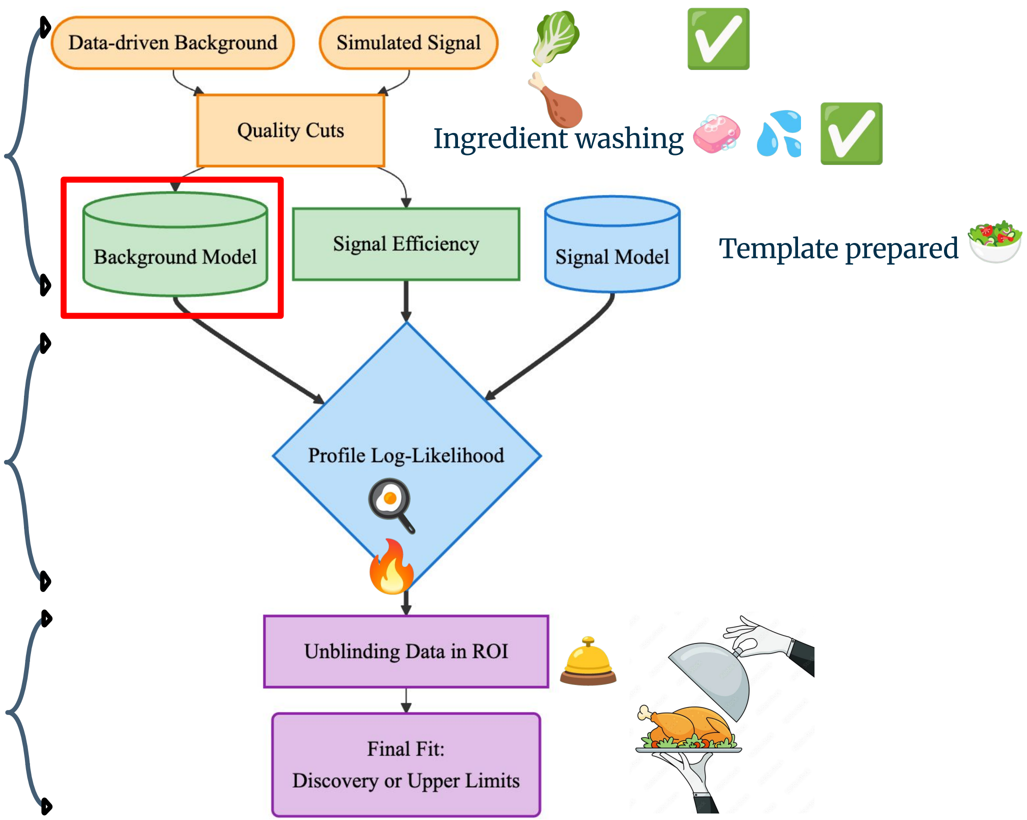
Ingredient Preparation

Stage 2:

Statistical cooking

Stage 3:

Food serving



✅

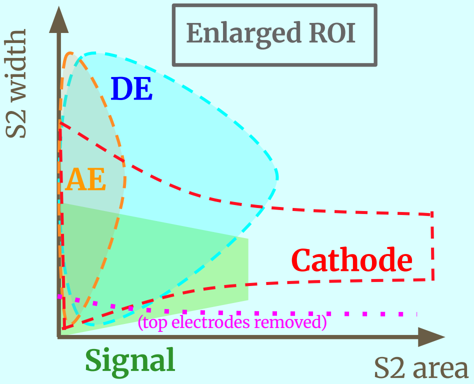
Ingredient washing 🧼 💦 ✅

Template prepared 🥗

Background Modeling | Blinded Analysis

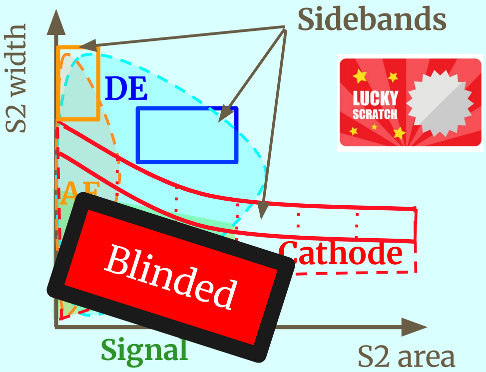
Data-driven modeling:

DE, AE, cathode background modeling in full space



Sideband technique:

Unblind science data in sideband region, extrapolate the background modeling to Signal ROI.

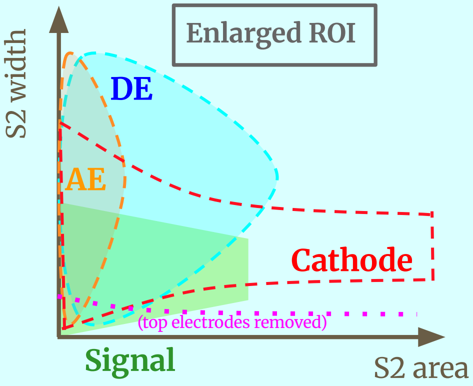


Backgrounds	**Modeling**	**Sideband**	σ
Cathode	BDT Sideband	Main selection on background discrimination space	7-15 %
Delayed Electron (DE)	ML Generative		13-40 %
Accidental Electron (AE)	Data-driven		8-17 %
CEvNS (Physics)	First Principles	-	~4%

Background Modeling

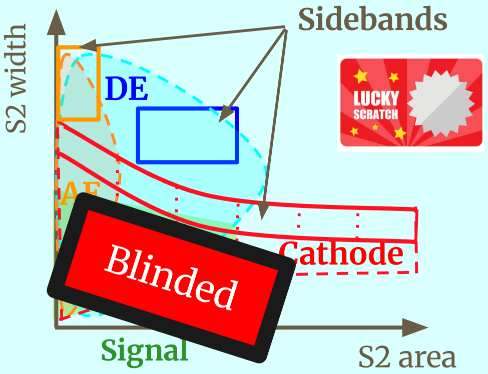
Data-driven modeling:

DE, AE, cathode background modeling in full space



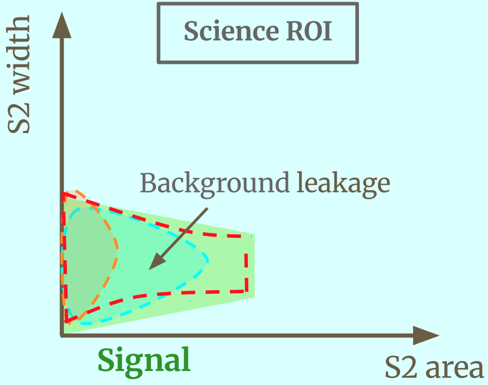
Sideband technique:

Unblind science data in sideband region, extrapolate the background modeling to Signal ROI.

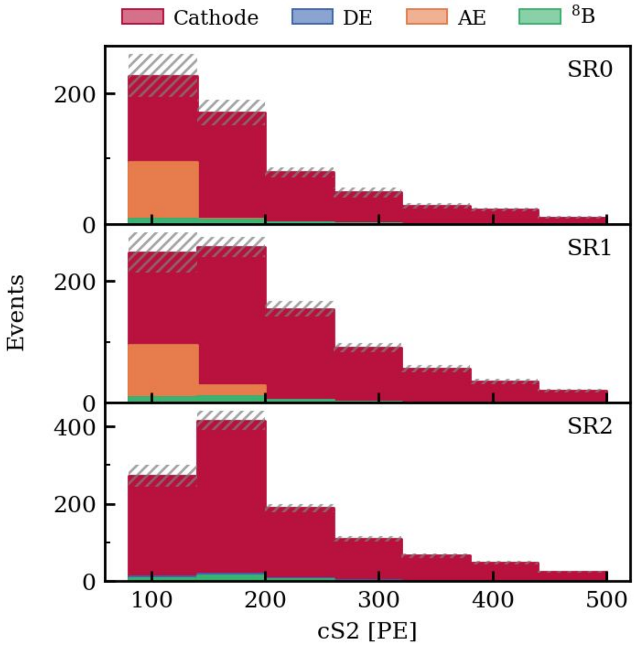


Final Background Model

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

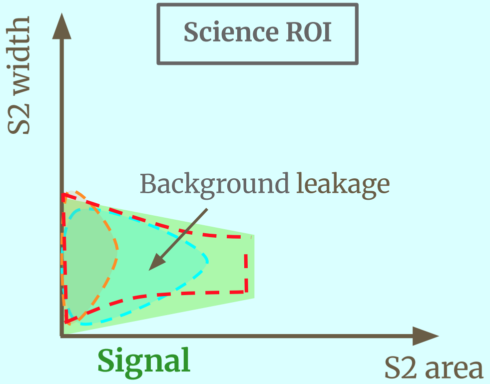


Background Summary



Final Background Model

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



The S2-only recipe 🥘 👨‍🍳

Stage 1:

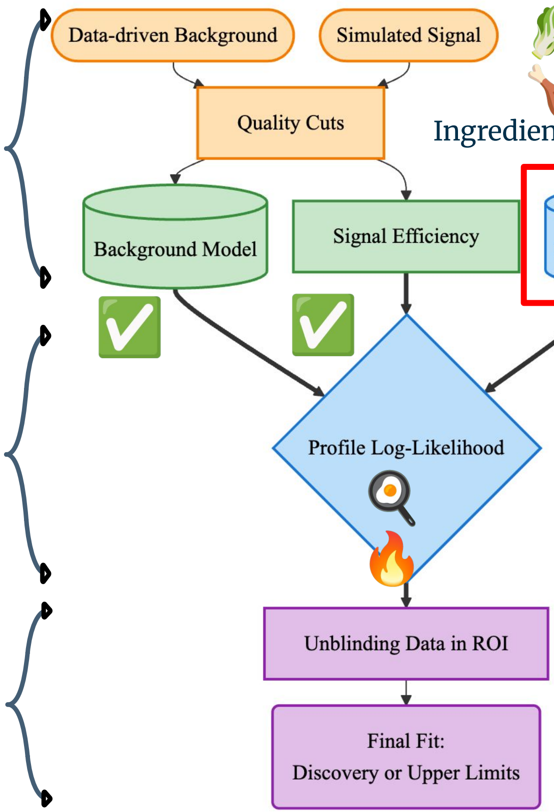
Ingredient Preparation

Stage 2:

Statistical cooking

Stage 3:

Food serving



Data-driven Background

Simulated Signal

Quality Cuts

Background Model ✅

Signal Efficiency ✅

Signal Model

Profile Log-Likelihood 🍳 🔥

Unblinding Data in ROI

Final Fit:
Discovery or Upper Limits

🥬 🍗 ✅

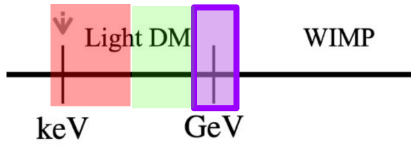
Ingredien washing 🧼 💦 ✅

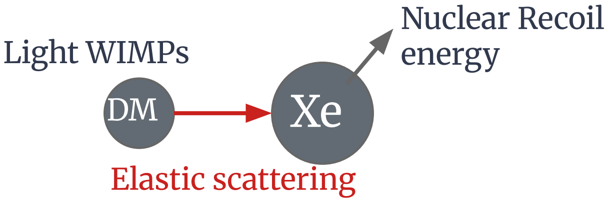
Template prepared 🥗

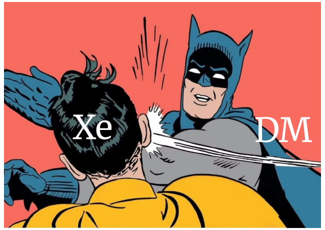
🛎️

Signal Model | Nuclear Recoil

[3, 8] GeV light WIMPs







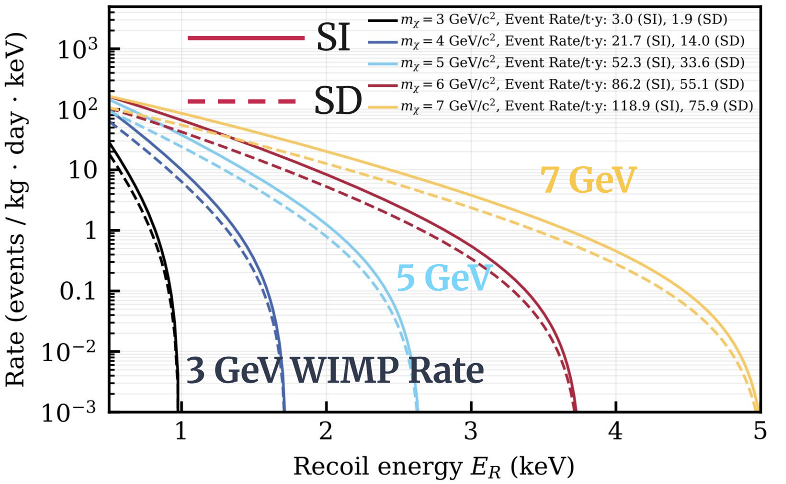
$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_{\mathrm{Xe}}} \int_{v_{\mathrm{min}}}^{v_{\mathrm{max}}} f(v) v \frac{d\sigma_{\chi-\mathrm{Xe}}}{dE_R}(v)\, dv$$

DM & Xe Properties

DM Velocity

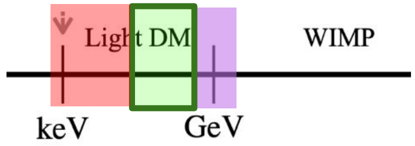
Model Dependent Cross section

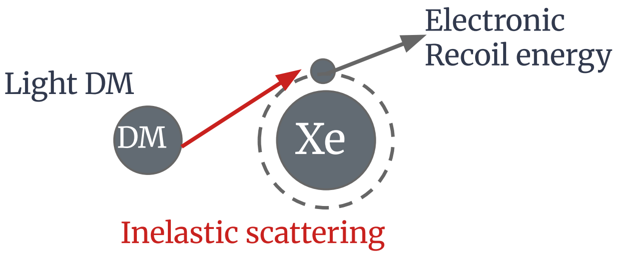
Spin-Independent Spectrum ($\sigma_n = 10^{-45}$ cm^2)
Spin-Dependent (neutron coupling) Spectrum ($\sigma_n = 10^{-40}$ cm^2)



Signal Model | Electronic Recoil

[50, 1000] MeV light DM

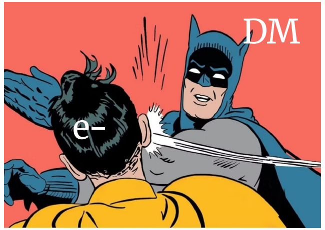


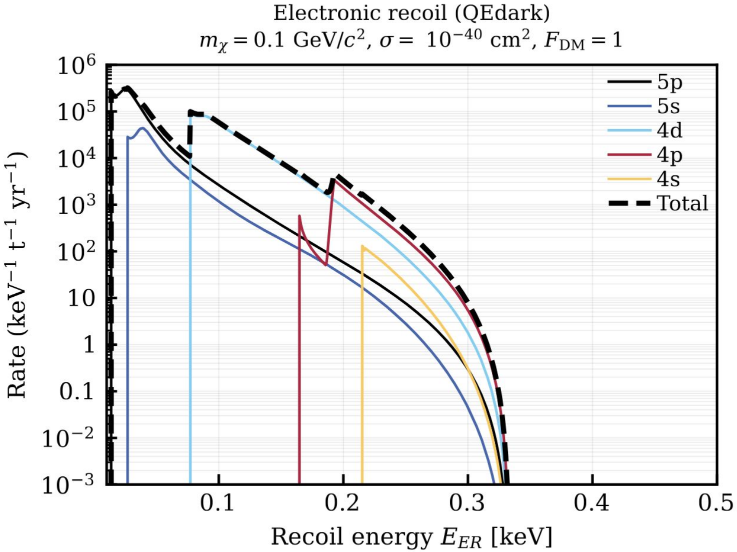


Light DM

Electronic Recoil energy

Inelastic scattering





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

DM & Xe Properties

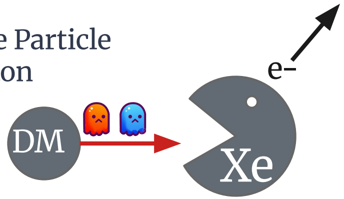
DM Velocity

Form Factor related to mediator

Atomic Response Term

Signal Model | Absorption of bosonic DM

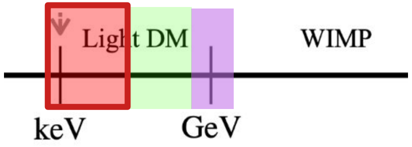
Axion-like Particle
Dark Photon



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

Recoil energy

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



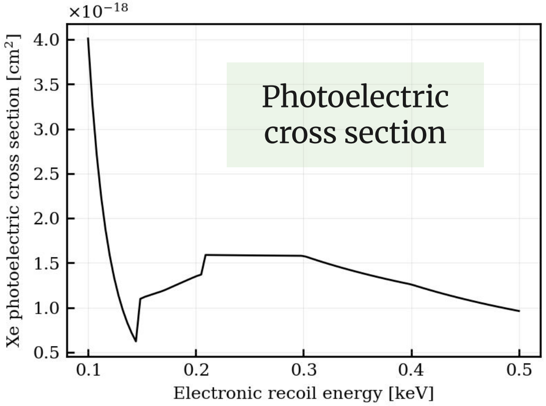
[0.1, 0.5] keV
Bosonic DM

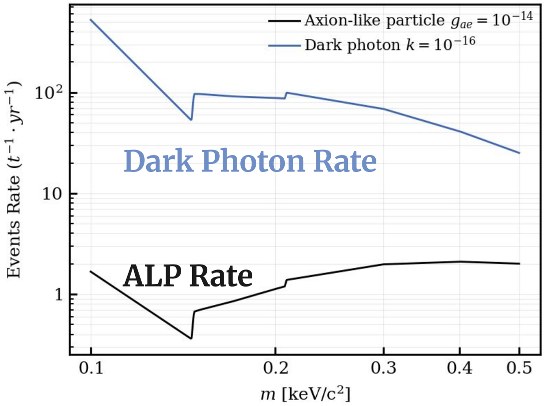
$$R_{\mathrm{DP}} \propto k^2 \cdot \frac{\sigma_{\mathrm{PE}}}{m_{\mathrm{DP}}}$$

Kinetic Mixing constant

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

Axio-electric coupling constant





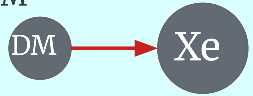
Signal Model | Signal spectrum

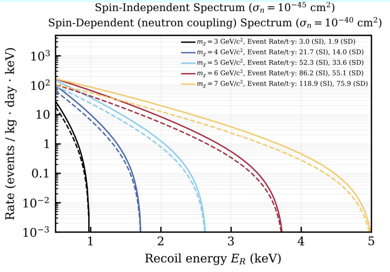
Recoil Energy Spectrum

- Charge Yield
- Signal Efficiency

Signal Prediction

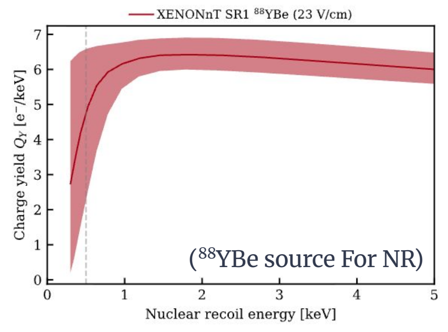
Light DM



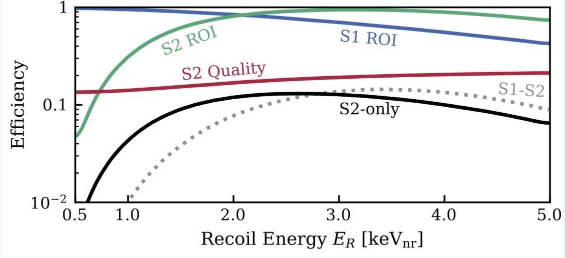


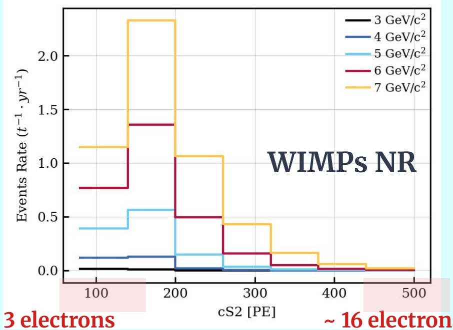
Charge Yield:

E_recoil ⇒ N_electrons



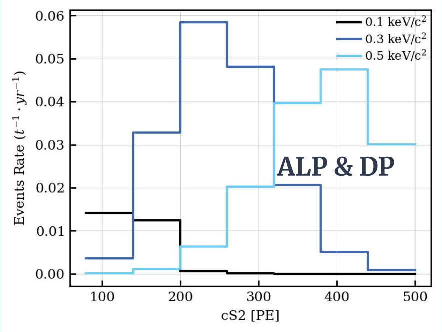
Signal Efficiency





~ 3 electrons

~ 16 electrons



The S2-only recipe 🥘 👨‍🍳

Stage 1:

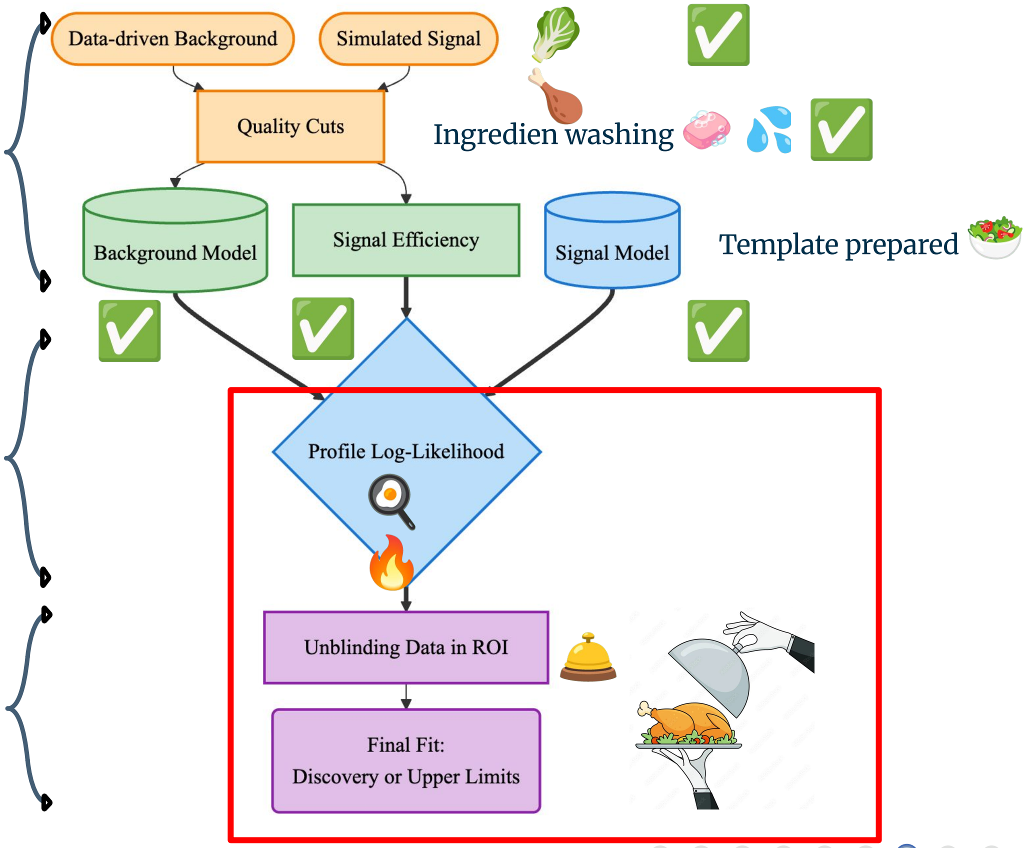
Ingredient Preparation

Stage 2:

Statistical cooking

Stage 3:

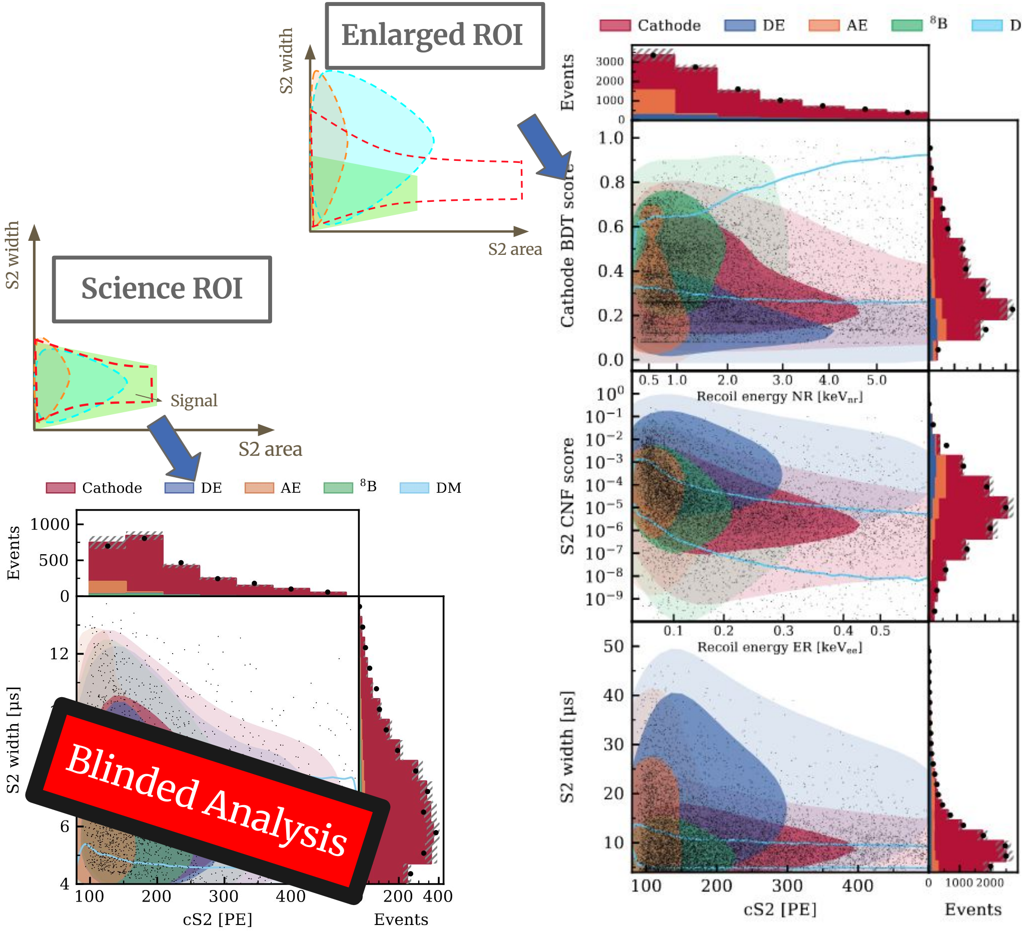
Food serving



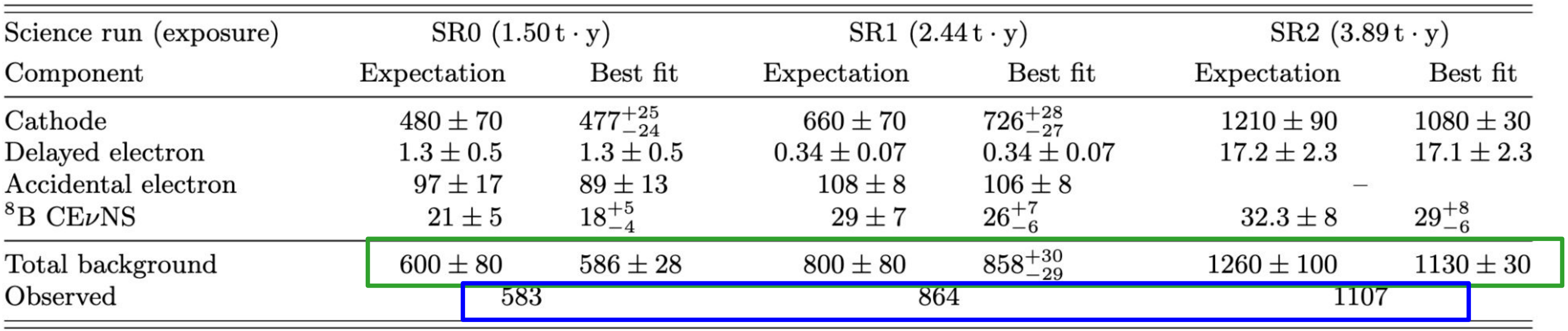
Unblinding

Validation of background model

1. Unblind S2-only data of **7.83 tonne-year** combining SR0, SR1 and SR2
2. **Good agreement** between the observed events and background model
3. First complete S2-only background model, **validated across different dimensions**



Unblinding Events

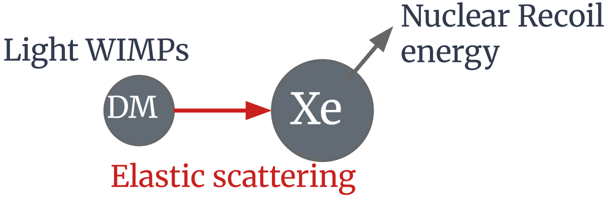


Science run (exposure)	SR0 ($1.50\,\mathrm{t} \cdot \mathrm{y}$)		SR1 ($2.44\,\mathrm{t} \cdot \mathrm{y}$)		SR2 ($3.89\,\mathrm{t} \cdot \mathrm{y}$)	
Component	Expectation	Best fit	Expectation	Best fit	Expectation	Best fit
Cathode	480 ± 70	477^{+25}_{-24}	660 ± 70	726^{+28}_{-27}	1210 ± 90	1080 ± 30
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	–	
^{8}B CEνNS	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
⇒ No signal excess

Limits on light DM (NR channel)

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

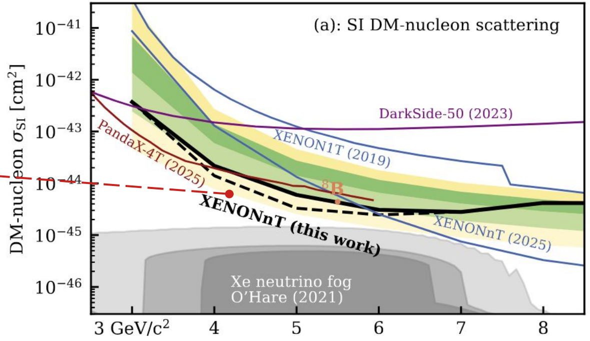


Light WIMPs

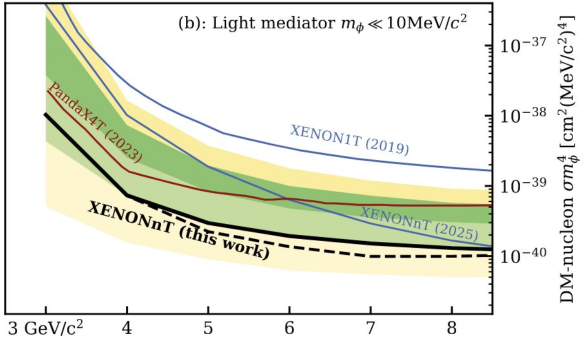
Nuclear Recoil energy

Elastic scattering

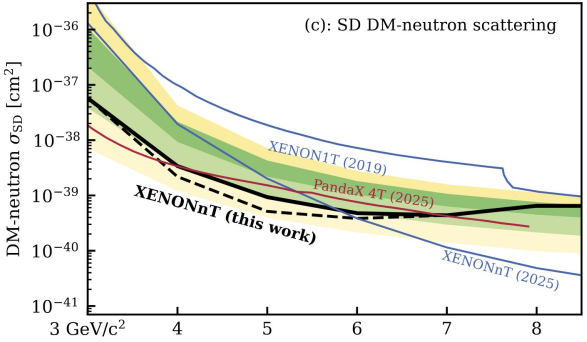
Spin-independent + heavy mediator



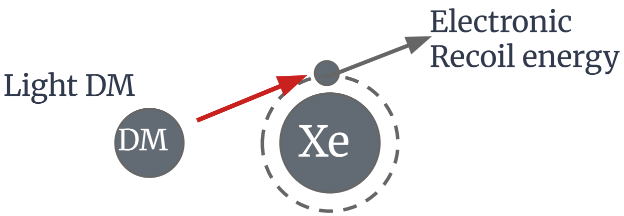
Spin-independent + light mediator



Spin-dependent + heavy mediator

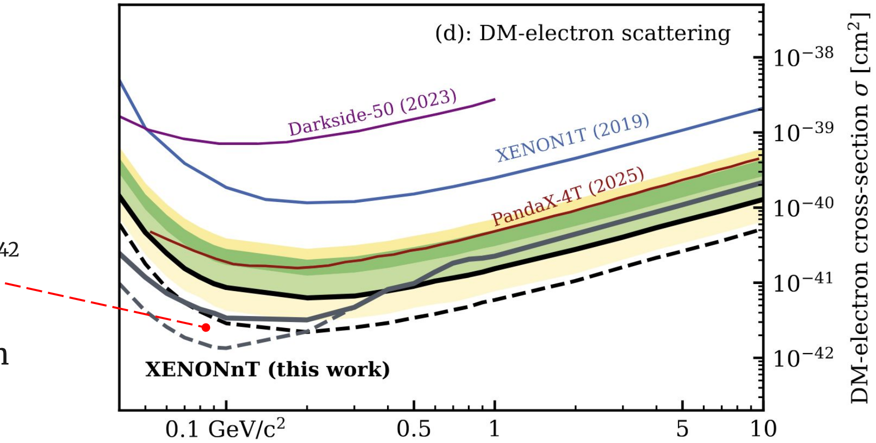


Limits on light DM (ER channel)

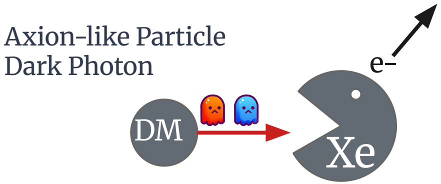


- Excluding DM–electron scattering σ above 6.3 × 10^{-42} cm^2 at m_χ = 0.2 GeV/c^2.
- Two signal models are adopted for comparison with other experiments.

Electronic recoil + heavy mediator



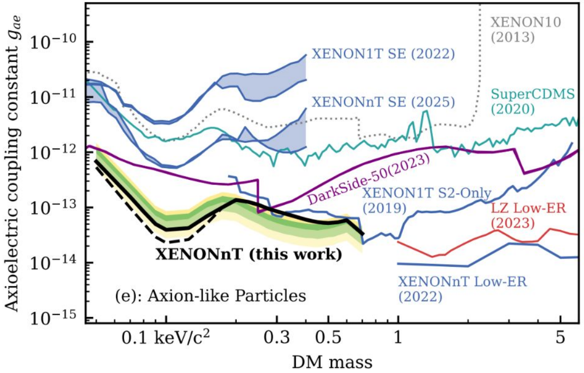
Limits on light DM (ER channel)

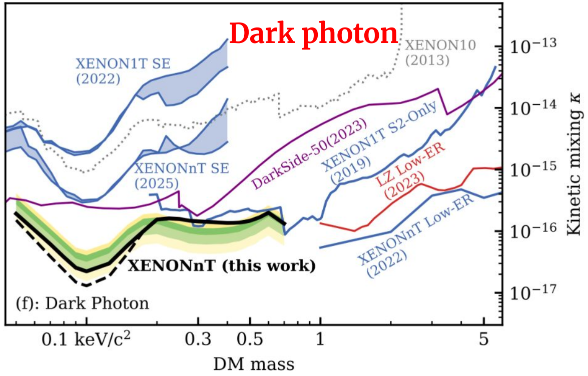


Exclude the parameter spaces for **bosonic DM**:

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

Axion-like particle





Summary

This four-year PhD research was conducted within the XENON collaboration, with the funding support from the China Scholarship Council (CSC):

1. Technical Contributions: **Deepened the understanding of ionization signals (S2)**.

- Characterized electron drift, diffusion, and local field distortions.
- Developed S2 pulse shape models and the data selections based on simulation and ML.
- Benefited not only the S2-only search but also improved the standard S1+S2 analysis.

2. Main Analysis: **Contributed to the comprehensive S2-only framework for Light Dark Matter.**

- Overcame the loss of S1 by developing waveform, topological, and ML-based background suppression strategies.
- Constructed the **first complete, multi-dimensional background model** (Cathode, DE, AE) for S2-only searches.
- Achieved world-leading sensitivities for multiple Light Dark Matter candidates using an 7.8 tonne-year exposure.
- Accepted by *PRL*, *arxiv*: *2601.11296*: Responsible of this analysis, member of writing team, corresponding author.

Outlook

1. **Pushing the energy threshold:** Extend the current analysis methods to the fewer-electron regimes to construct a more comprehensive background model.
2. **Refining background models:** Address cathode background through hardware improvements and advanced software techniques (simulation-driven cross-modeling) to lower prediction uncertainties.

THANK YOU for being part of my PhD journey!!!

Fei's group @Tsinghua

Queen of fève @group meetings 😎👑

XENON & Xelab team @LPNHE

ag-s2-only Analyzing isolated ioniz...

XENON collaboration & S2-only Group

Special thanks to my supervisors, the committee, the funding...

Thank you for your attention !