The LUX-ZEPLIN Experiment

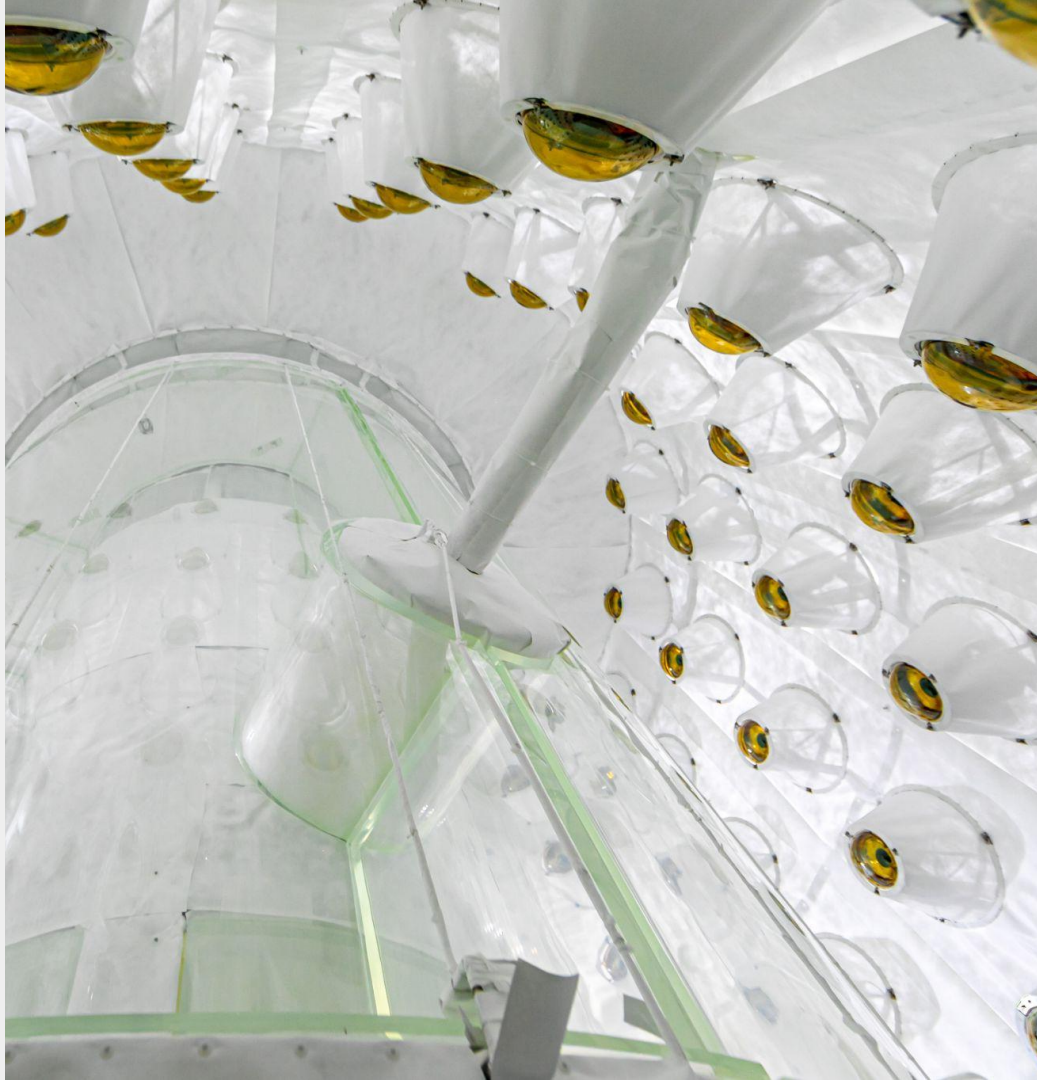
Overview and Key Results

Sam Woodford (sam.woodford@ed.ac.uk)

UC Louvain - Seminar

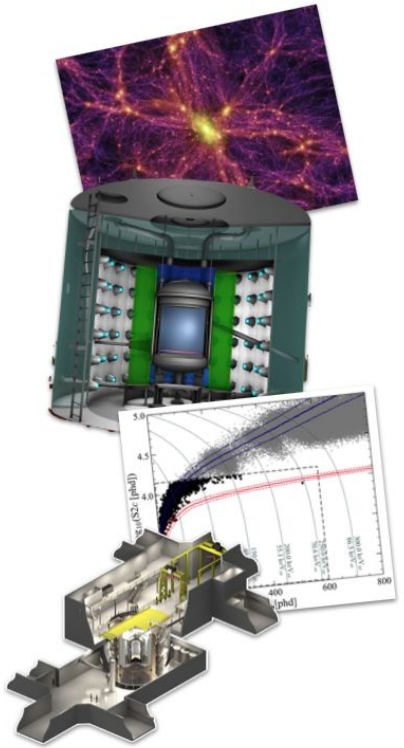
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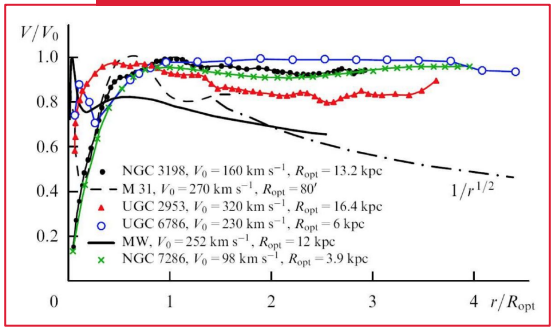
Outline

1. Dark matter, WIMPs, and direct detection
2. The LUX-ZEPLIN experiment
3. Our latest WIMP searches at different regimes:
    a. Lower recoil energies → WS2025
    b. “Standard” recoil energies → WS2024
    c. Higher recoil energies → EFT WS2024
4. Conclusions and future



Dark matter | Indirect evidence

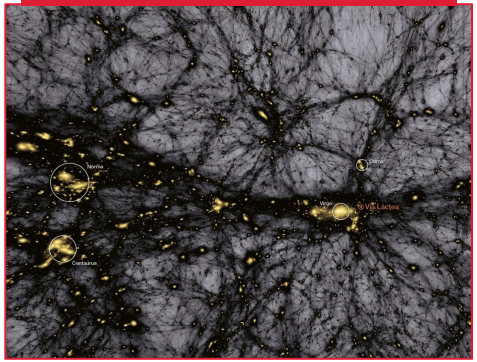
Rotation Curves



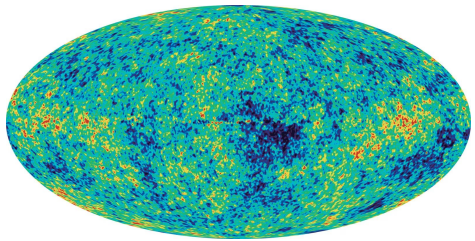
Bullet Cluster

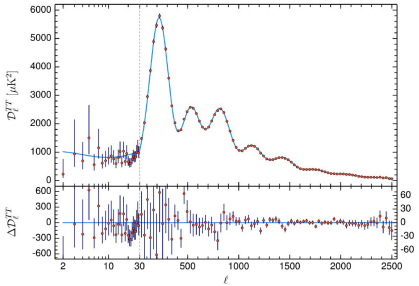


Large Scale Structure



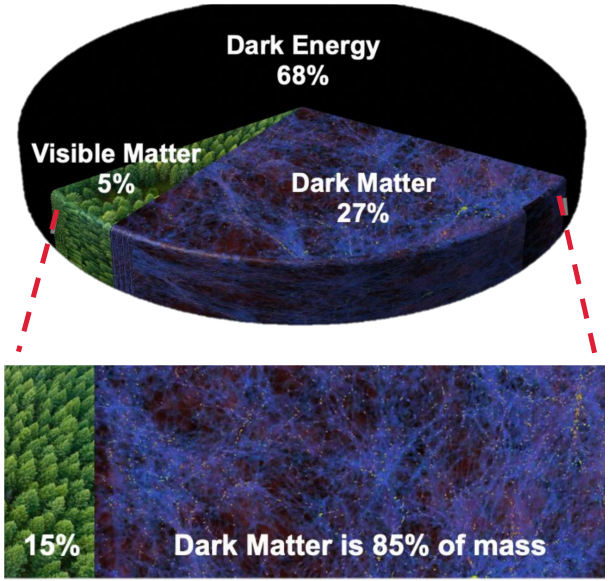
CMBR Anisotropies

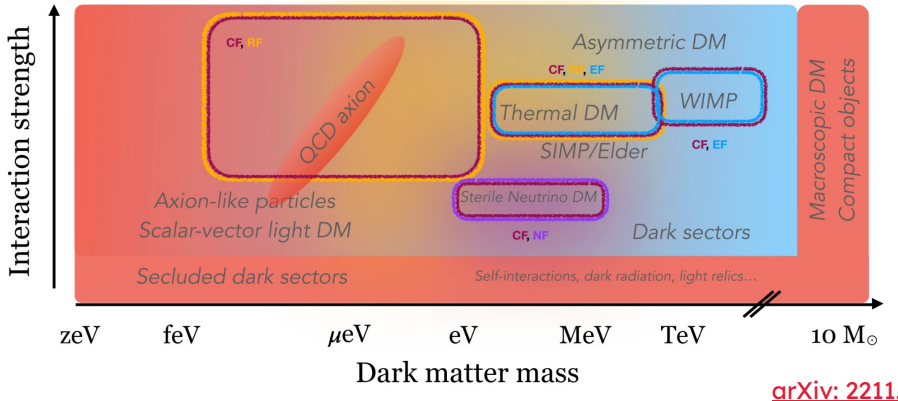




Dark matter

Properties: neutral, non-Baryonic, cold, stable, ~collisionless





arXiv: 2211.07027

‘Maximise Opportunities for Discovery:
Delve Deep, Search Wide’

Weakly Interacting Massive Particles (WIMPs)

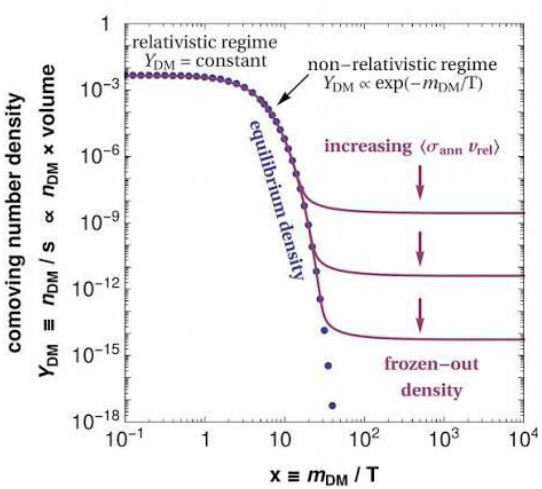
Theoretically well-motivated candidate to explain DM

➔ **Stable** particles with masses around **GeV-TeV** scale

Natural thermal origin ("WIMP miracle"):

1. In early Universe → WIMPs in thermal equilibrium with SM: $\chi\bar{\chi} \leftrightarrow$ SM particles
2. Universe expanded and cooled down → lower annihilation rate → not equilibrium
3. Annihilations freeze-out → relic population of WIMPs

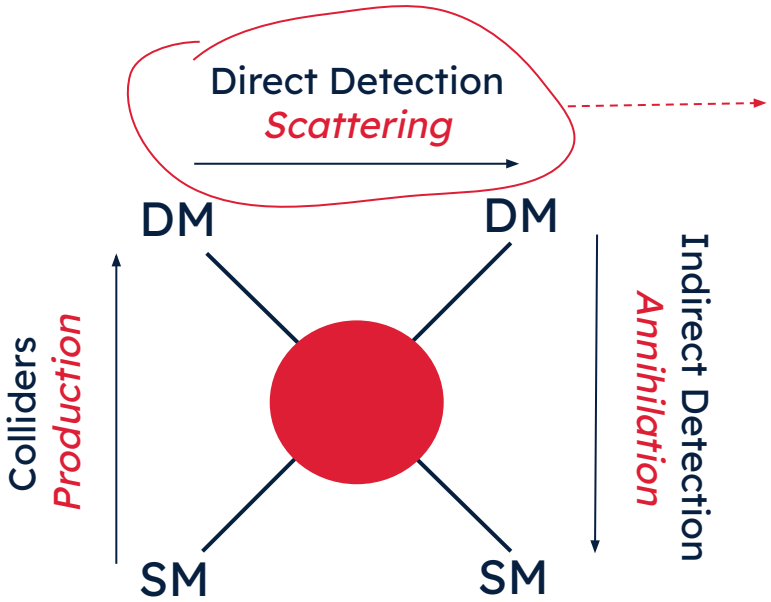
For ~**weak-scale masses** and **interaction** strengths, resulting relic abundance is naturally of the right order to explain DM



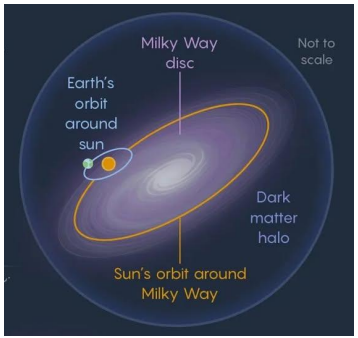
No formal further definition:

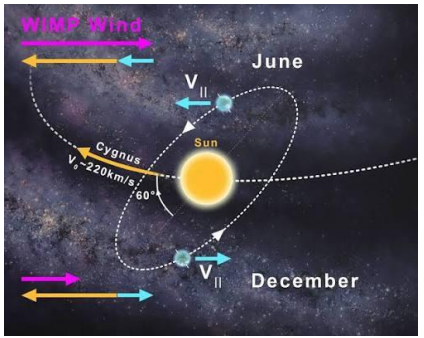
- WIMPs arise naturally in many extensions of the SM
- Lightest supersymmetric particle (LSP) from SUSY models is an ideal candidate (e.g. neutralino)

Dark matter | How do we find it?



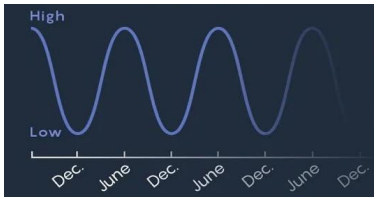
Dark matter confined in a halo that extends far beyond visible boundaries of galaxy



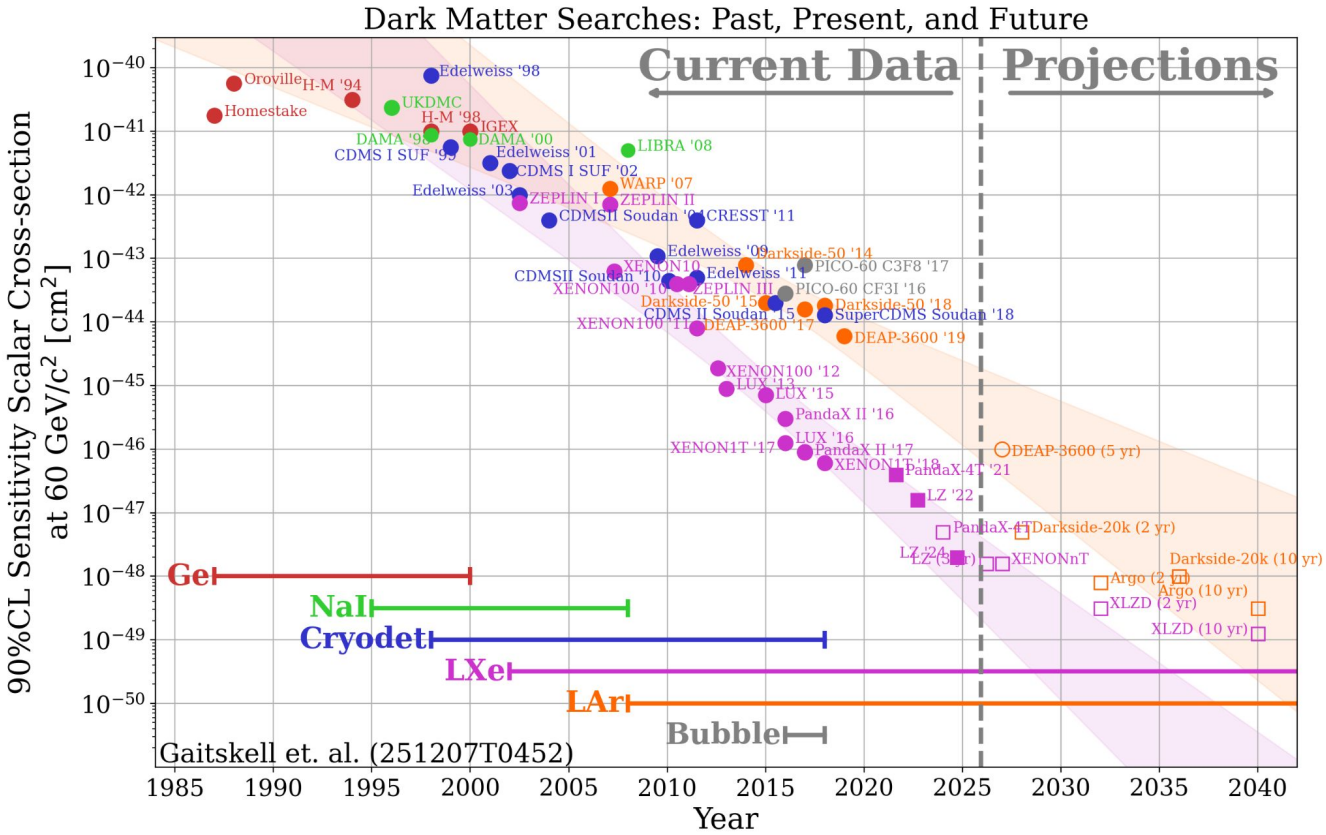


Dark matter follows velocity distribution within the halo (in the Galactic frame) with a maximum velocity of v_{esc}

Earth's relative velocity produces annual modulation:



WIMP-nucleon sensitivity over time



The LUX-ZEPLIN (LZ) collaboration

- 38 institutions
- 250 scientists, engineers, and technical staff



Thanks to our sponsors and participating institutions

Science and Technology Facilities Council

Fundação para a Ciência e a Tecnologia

SANFORD UNDERGROUND RESEARCH FACILITY

Swiss National Science Foundation

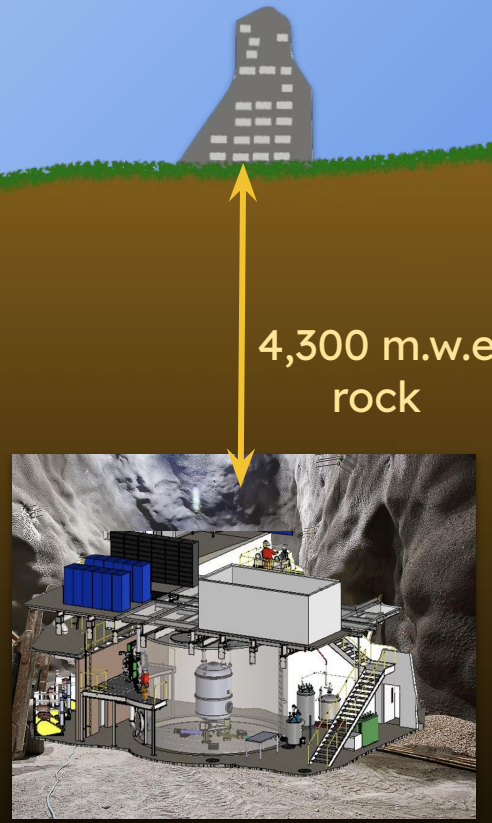
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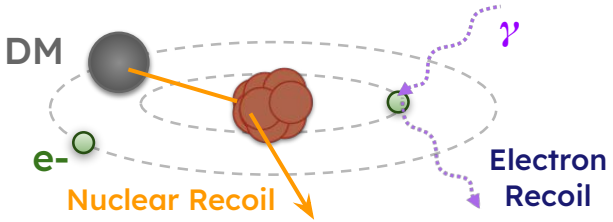
The LUX-ZEPLIN detector

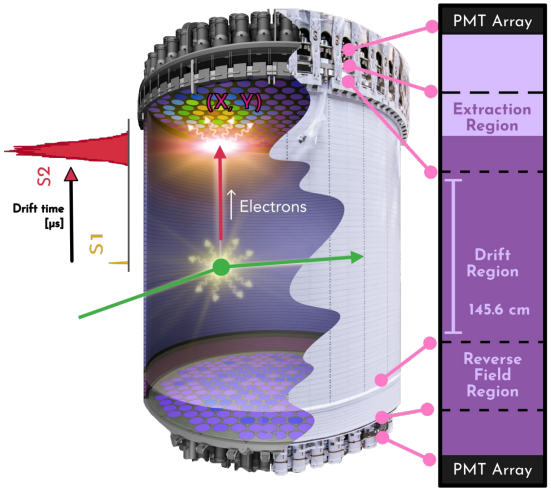
- Optimised for searching WIMPs with masses above ~5 GeV/c^2
- Sensitive to additional processes, including BSM physics: 0v$\beta\beta$, axions, etc
- Located 1.5 km underground at the Sanford Underground Research Facility (SURF), SD (US)
- Comprises:
  - LXe Time Projection Chamber (TPC)
  - Veto system

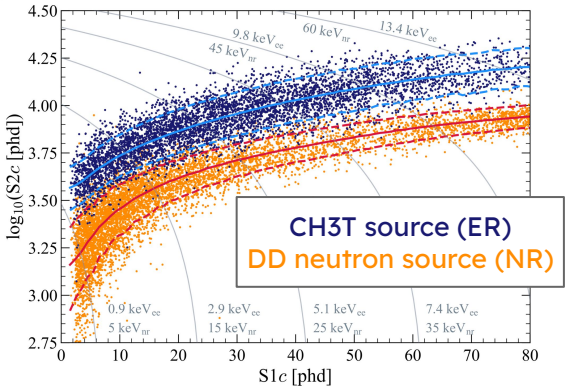


The LZ TPC

- 7t active mass dual-phase xenon TPC
- Events reconstructed combining scintillation (S1) and ionisation (S2)
- Light measured by 494 PMT arranged in two arrays at top and bottom
- Excellent 3D position reconstruction (~mm)
- Single Scatter (SS) vs Multiple Scatter (MS) interactions discrimination
- S2/S1 signal size ratio allows nuclear (NR) vs electron (ER) recoil discrimination







Phys. Rev. Lett. 131, 041002 (2023)

LZ Veto System

Two subsystems:

Outer detector

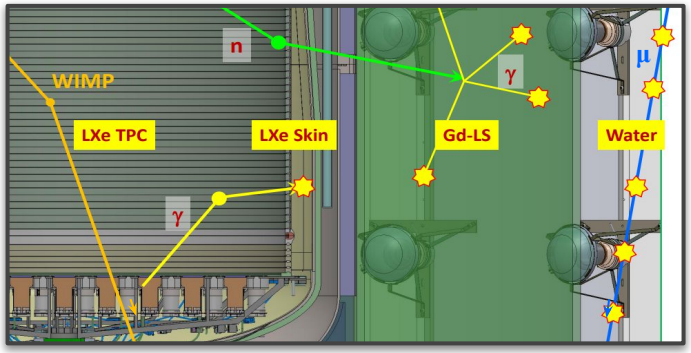
Purpose:

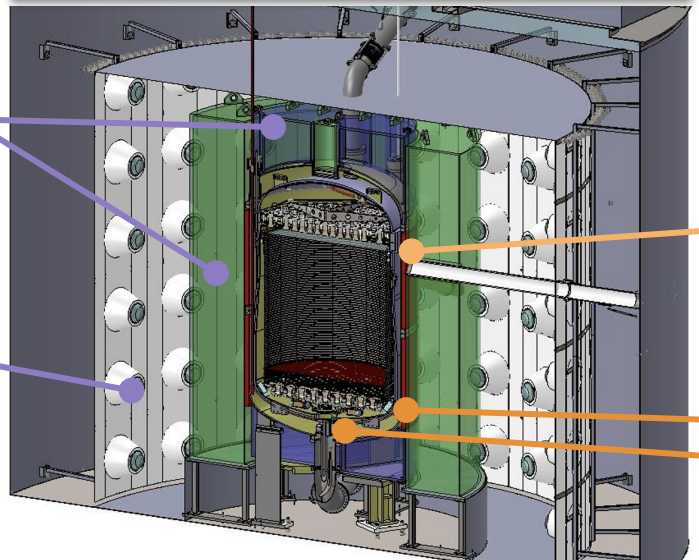
- active muon and internal neutrons veto
- passive external neutron veto

Comprises:

1. 10 UV-transparent acrylic tanks with 17t of Gd-loaded (0.1% by mass) liquid scintillator
2. 238t ultra-pure water tank with 120 8-inch PMTs

Neutron tagging efficiency of 92±4%



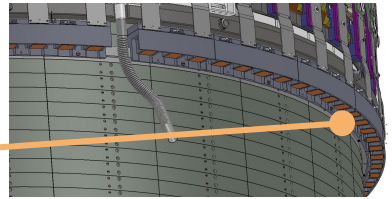


LXe *Skin* detector

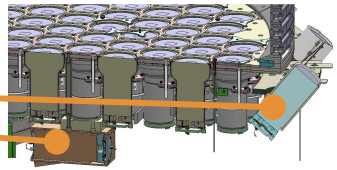
Purpose: veto Compton recoils from ~MeV radiogenic γ-rays

2t-LXe region between TPC outer walls and inner cryostat vessel instrumented with:

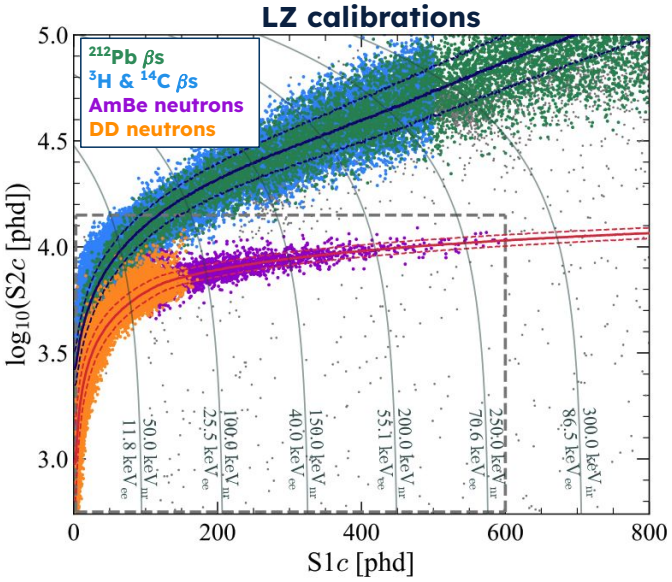
- 93 PMTs at the top



- 38 PMTs at the bottom



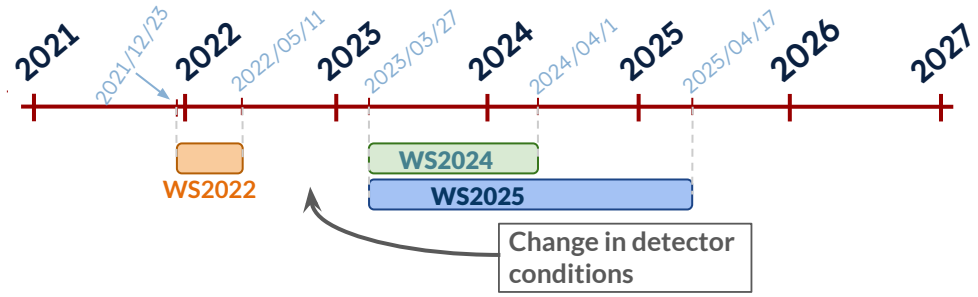
Latest WIMP searches



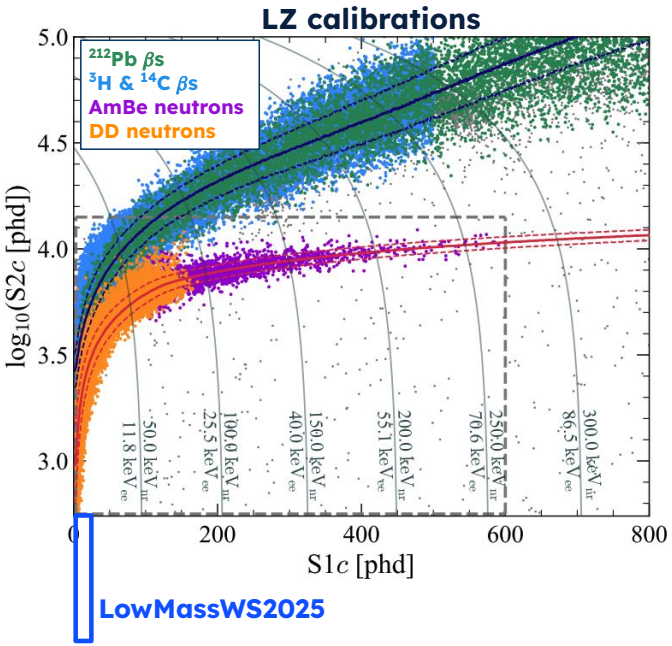
Analyses discussed in this seminar:

Name	Recoil energy	Dataset	ROI [phd]	Reference

Datasets summary



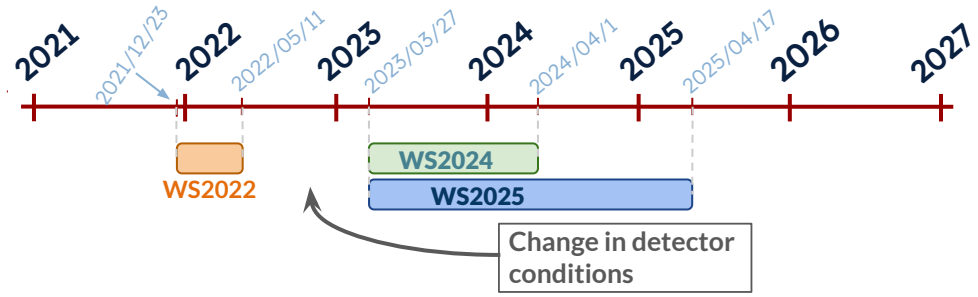
Latest WIMP searches



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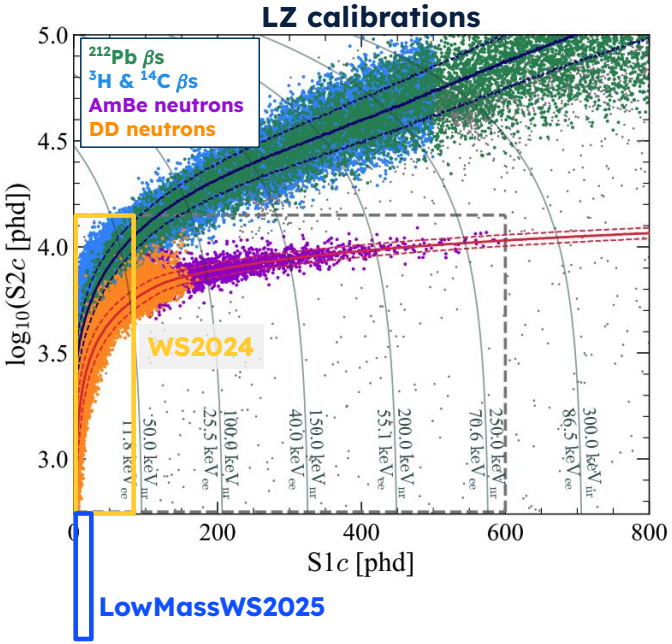
Name	Recoil energy	Dataset	ROI [phd]	Reference
^{8}B / low-mass-WS (LowMassWS2025)	≲ 8 keV	WS2025 (417d)	0 < S1c < 15 155 < S2c < 645	PRL 137, 091806 (2026)

Datasets summary



*WS≡WIMP Search

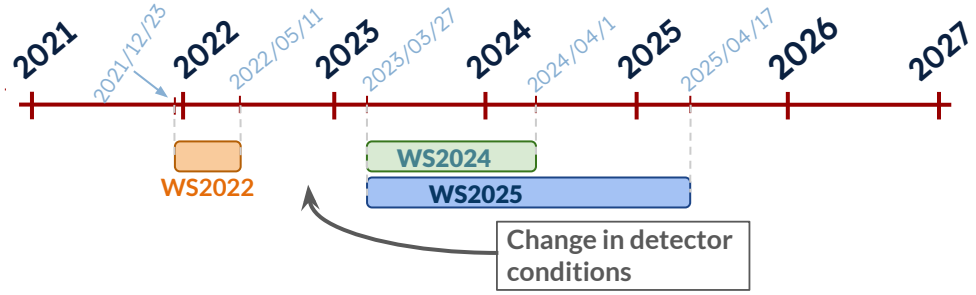
Latest WIMP searches



Analyses discussed in this seminar:

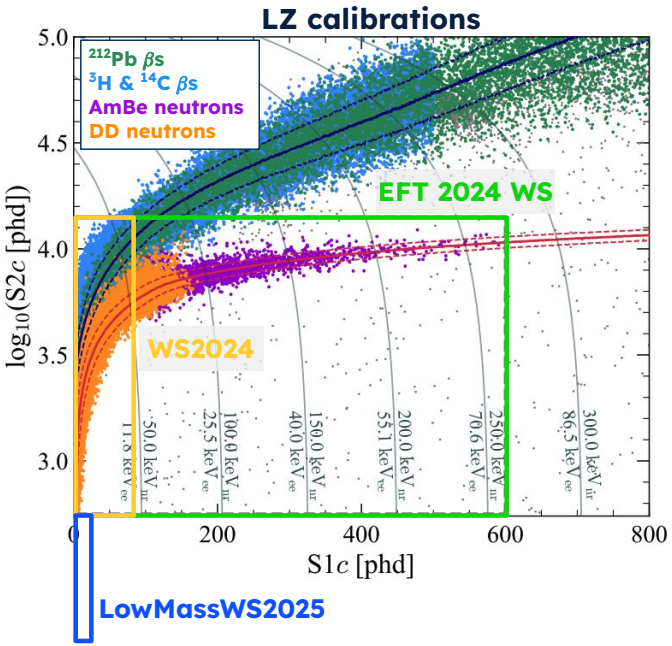
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^{8}B / low-mass-WS (LowMassWS2025)	≲ 8 keV	WS2025 (417d)	0 < S1c < 15 155 < S2c < 645	PRL 137, 091806 (2026)
"Standard" WS (WS2024)	(8, 55) keV	WS2022 (60d) + WS2024 (220d)	0 < S1c < 80 645 < S2c <$10^{4.5}$	PRL **135**, 011802 (2025)

Datasets summary



*WS≡WIMP Search

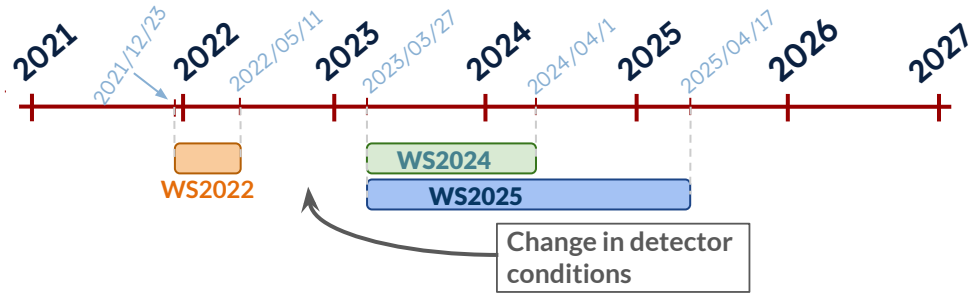
Latest WIMP searches



Analyses discussed in this seminar:

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"Standard" WS (WS2024)	(8, 55) keV	WS2022 (60d) + WS2024 (220d)	0 < S1c < 80 645 < S2c <$10^{4.5}$	PRL **135**, 011802 (2025)
EFT WIMP search (EFT 2024 WS)	(8, 270) keV	WS2024 (220d)	0 < S1c < 600 645 < S2c < $10^{4.5}$	arXiv:2609.02823 [hep-ex]

Datasets summary

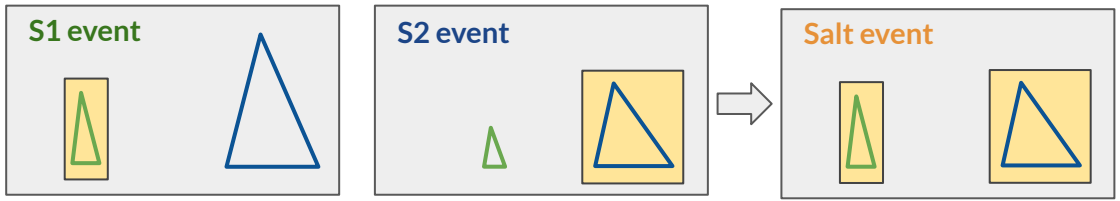


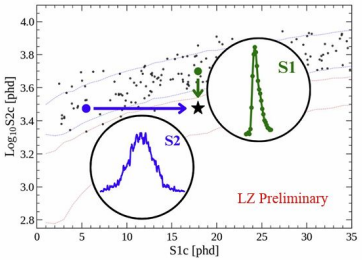
*WS≡WIMP Search

Bias mitigation: salting

"*Salting*": injecting a random number of fake signal events during science data collection

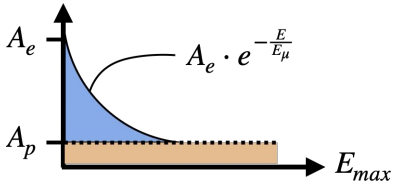
- **How?** Events manufactured by combining S1s & S2s signals from sequestered calibration data at waveform level





- **Which energy?**

  Exponential distribution for WIMP scattering + flat pedestal for higher energies



- **How many?** Enough to obscure any bias, but not so many as to overwhelm any pathological events in the real data. Exact number not known.

Salt only revealed after all analysis selections and decisions are finalised

Main backgrounds

Three main categories, depending on their location in the S1c vs S2c space:

ER backgrounds

- Dissolved β emitters:
  - **^{214}Pb** (^{222}Rn), ^{212}Pb (^{220}Rn), **^{85}Kr**, ^{136}Xe (ββ)
- Dissolved **EC** decays (X-rays/Auger cascades):
  - $^{127/125}$Xe, ^{125}I from neutron calib. activation
  - ^{124}Xe double EC
- Calibration:
  - Injected: ^{83m}Kr, ^{3}H, ^{14}C
- Solar pp and ^{7}Be **neutrinos**
- Long-lived gamma emitters in **detector materials**:
  - ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co

NR backgrounds

- **Neutrons** from spontaneous fission (SF) and (α,n) reactions in detector materials (≡"DetNR")
- Solar ^{8}B and hep **neutrinos** (**CEvNS**)

Instrumental backgrounds

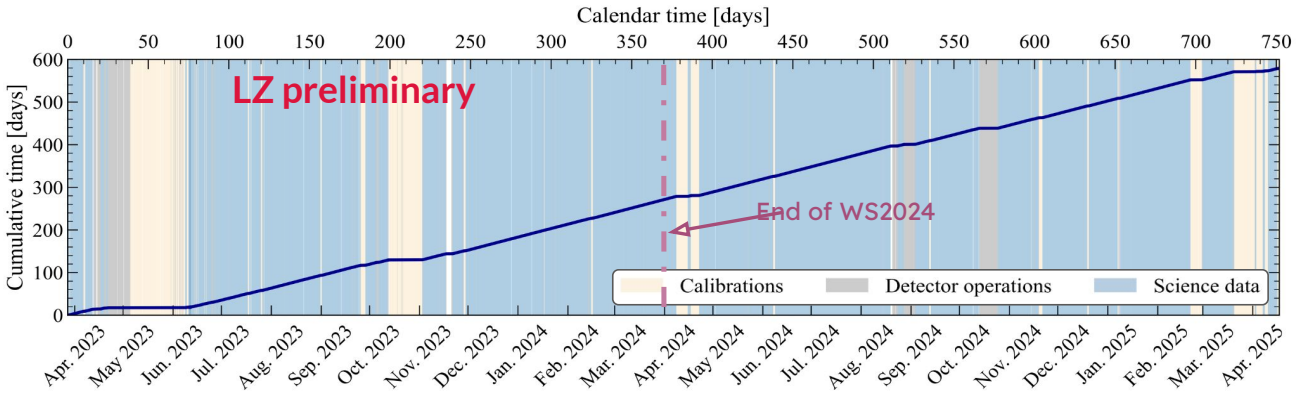
- **Accidental** coincidences from uncorrelated isolated S1 and S2 pulses
- Multiple scatter single ionisation (MSSI)

Low Energy Recoil: solar ^{8}B neutrino measurement and Low-Mass WIMP (3-9 GeV/c^2) Search: “WS2025”

Phys. Rev. Lett. ***137****, 091806 (2026)*

^{8}B / Low Mass WIMP (LMW) Search

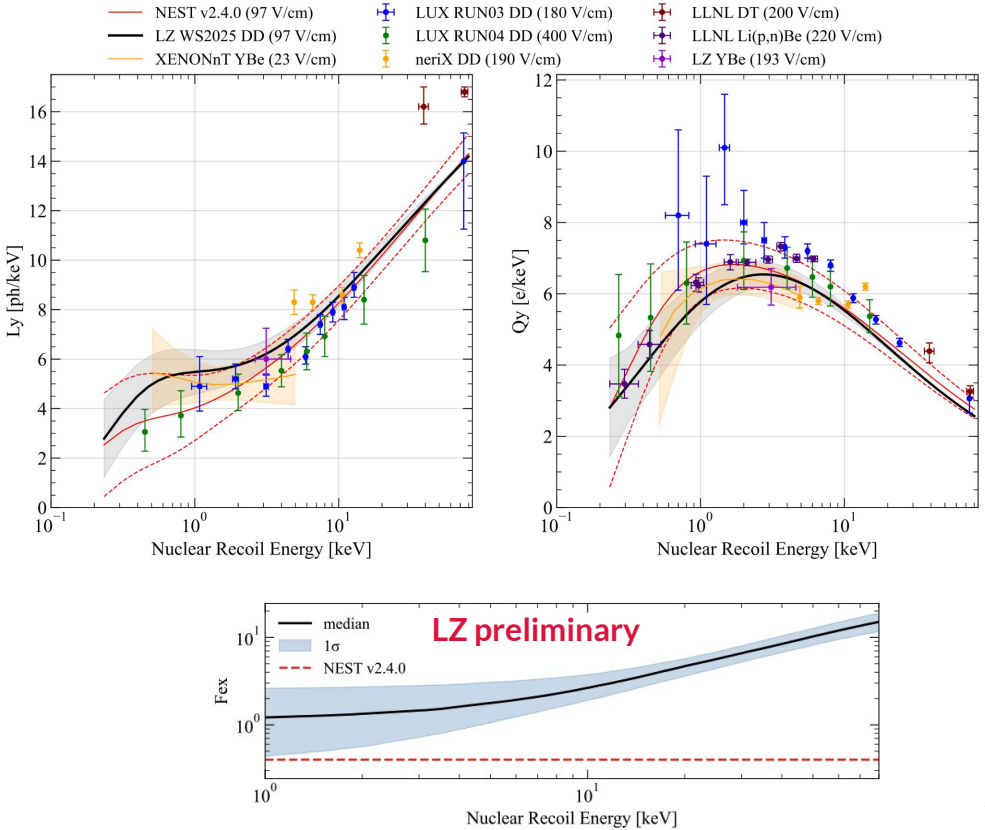
- Target WIMP masses between **3** and **9** GeV/c^2
- Use of whole WS2025 dataset (417 live-days exposure)
- In ROI → simpler background model (no ERs): **^{8}B (CEνNS)**, **DetNR**, and **accidentals**
- **Difficulty:** ROI unexplored → new set of challenges:
  - Refine **NR model** at ROI
  - Refine **instrumental BGs** modelling and suppression, due to their major prominence



- Drift field: 97 V/cm
- Extraction field: 3.4 kV/cm

^{8}B / Low Mass WIMP Search: new NR model

- ^{8}B/LMW signals sit at very edge of LZ's energy sensitivity → precise NR model with accurate systematic uncertainties
- In LZ, the semi-empirical NEST framework is used to model ER and NR responses
- NEST parameters tuned exploiting DD* 2.45 MeV neutron data (up to 74 keV recoils)



*DD (Deuterium-Deuterium) neutron sources produce monoenergetic neutrons of 2.45 MeV via the fusion reaction: $^2H+^2H \rightarrow ^3He + n$

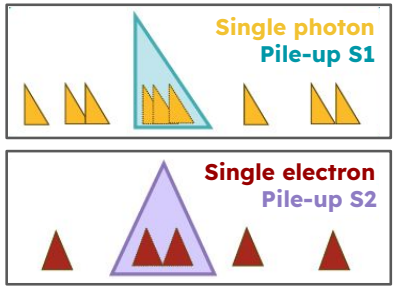
^{8}B / LMW Search: Instrumental Backgrounds

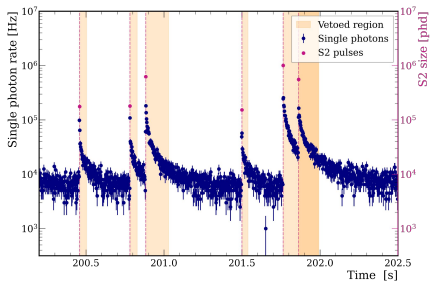
Background dominated by accidental pile-up of unrelated isolated S1 and S2 pulses that mimic expected SS DM events

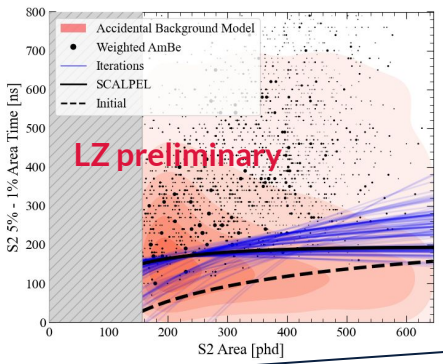
They can come from: PMT dark counts, charge loss near TPC walls, large γ/e- rates after big deposits

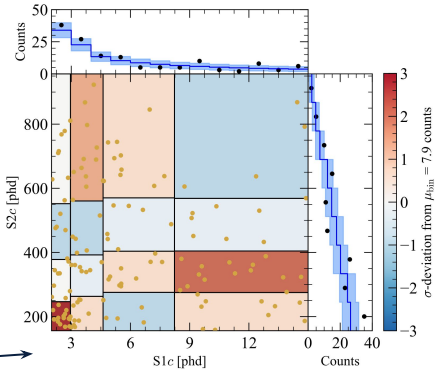
To deal with them:

1. Targeted by simultaneously optimised set of cuts across multiple spaces
2. Modelled by:
   a. Combining iS1s and iS2s from similar γ and e- rate environment
   b. Resulting S1c-S2c spectrum rate normalised to known accidental events (SS with unphysical drift)







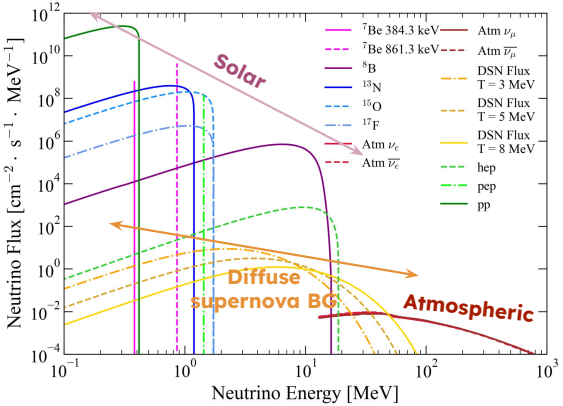


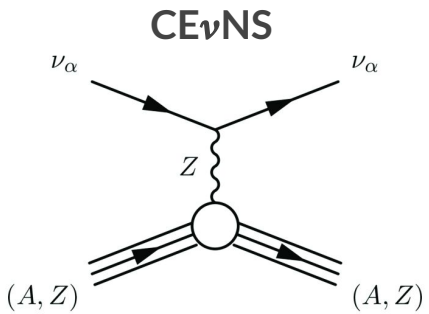
Predict 6.6 ± 0.3 events in full exposure

^{8}B / LMW Search: neutrinos & ^{8}B CEvNS

Several solar neutrino background sources in our regular WIMP searches:

- pp/^{7}Be/CNO undergo electroweak interactions with LXe → **ERs**
- **^{8}B**/hep/DSN/atm can interact via **CEνNS** (Coherent elastic neutrino-nucleus scattering) → NRs





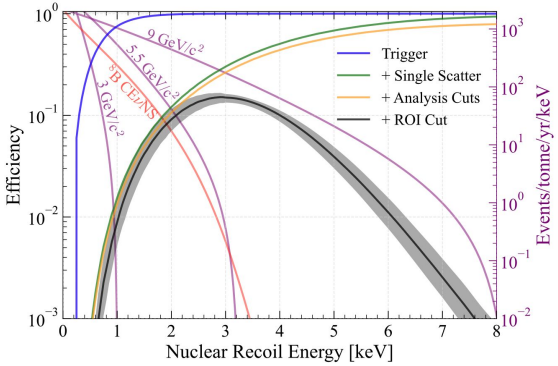
Boron-8

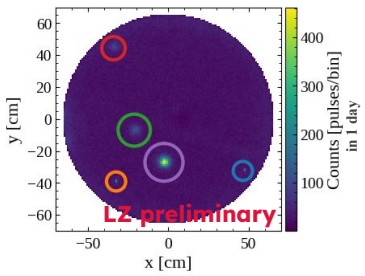
- Similar signal to **5.5 GeV/c^2 DM** candidate
- First CEνNS measured by the COHERENT experiment in 2017 using the Spallation Neutron Source
- Indications (**<3σ**) of solar νs CEνNS in LXe from other experiments
- Assume Standard Model CEνNS cross-section and ^{8}B flux measured by SNO experiment

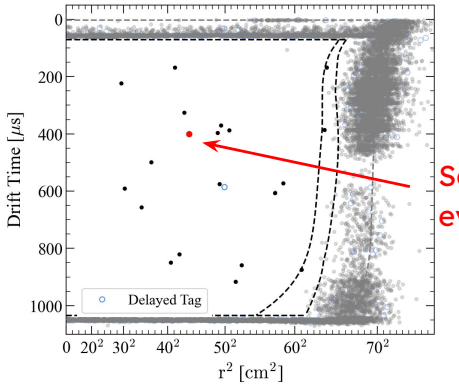
→ Expect **$20.6^{+8.9}_{-6.8}$** events

^{8}B / LMW Search: Final dataset

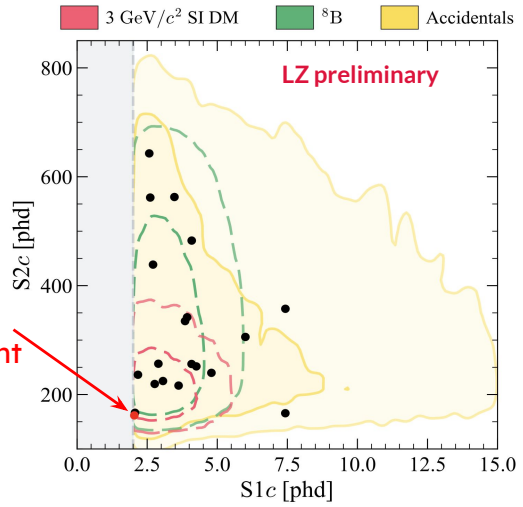
- Cuts applied include **FV (5.09±0.15 t)**, data-quality, punctual e- emission, ACs, neutrons/gammas with vetoes,…
- **20 events** in dataset after all selections → **1** of them revealed to be salt
- No post-unsalting changes to model
- "Neutron-rich" sideband included (i.e. passing all selection but delayed veto) → 1 event
- Statistical analysis in observed S1c vs $\log_{10}$(S2c) space
- Data used in two PLR tests:
  1) 3-9 GeV/c^2 dark matter search
  2) ^{8}B CEνNS search







Salt event

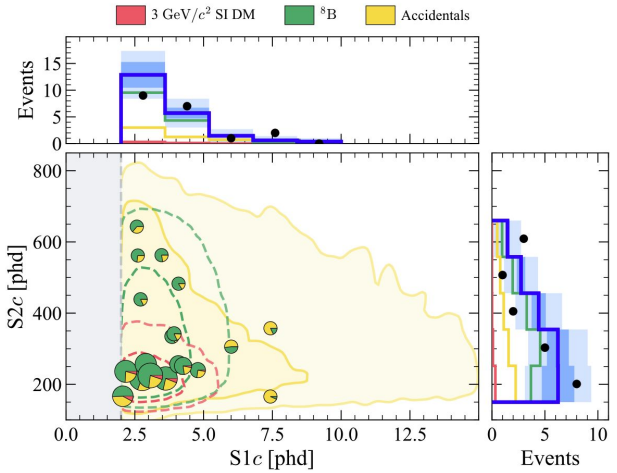


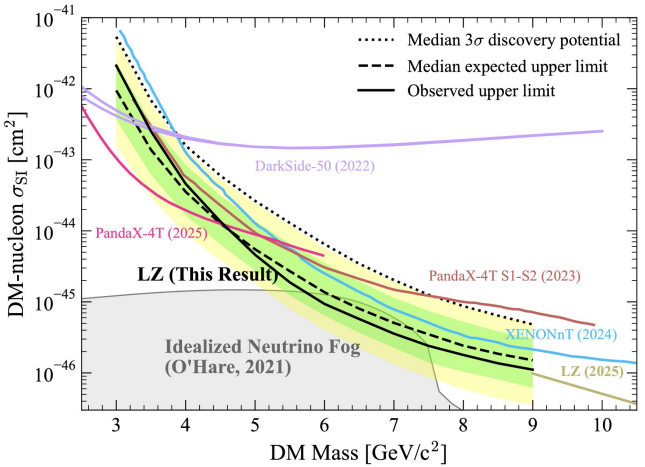
^{8}B / LMW Search: WIMP limits

- ^{8}B CEνNS rate constrained based on predictions using SNO measurement *Phys. Rev. C **88**, 025501*
- Best-fit number of DM events consistent with **0** at all DM masses tested
- Exclusion limit with two-sided test statistic
  - Factor of two improvement in sensitivity over existing limits between 5 and 9 GeV/c^2
  - **World-leading limits > 5 GeV/c^2**

Components	Expectation	Background-Only Fit	3 GeV/c^2 Fit	9 GeV/c^2 Fit
SI DM	-	-	$0.4^{+5.4}_{-0.4}$	$0.0^{+4.0}_{-0.0}$
^{8}B CEνNS	$20.6^{+8.9}_{-6.8}$	$15.0^{+2.9}_{-2.5}$	$14.7^{+3.0}_{-2.8}$	$15.0^{+2.9}_{-2.5}$
Accidental coinc.	6.6 ± 0.3	6.5 ± 0.3	6.5 ± 0.3	6.5 ± 0.3
Detector neutrons	$0.04^{+0.25}_{-0.04}$	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$
Total	$27.2^{+10.1}_{-7.3}$	$21.6^{+4.7}_{-3.8}$	$21.7^{+6.2}_{-2.8}$	$21.6^{+5.0}_{-2.5}$
σ_{eff}	0 ± 1	$-0.81^{+0.59}_{-0.60}$	$-0.86^{+0.63}_{-0.71}$	$-0.81^{+0.58}_{-0.60}$

SD limits in back-up





^{8}B/LMWS: ^{8}B CEνNS measurement

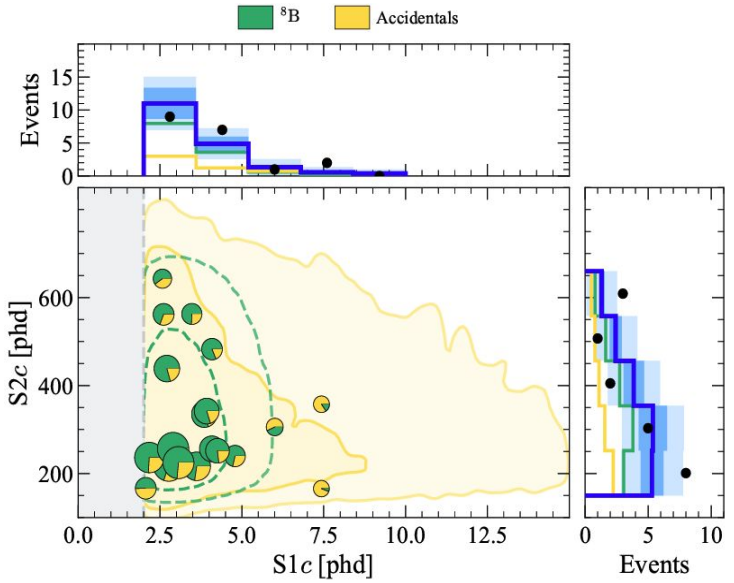
PLR test statistic to reject background-only model

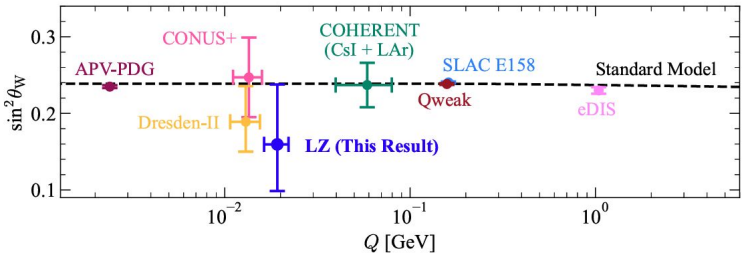
- Assumed no DM events
- Unconstrained ^{8}B CEνNS rate

Components	Expectation	Fit Results
^{8}B CEνNS	-	$12.3^{+7.0}_{-5.4}$
Accidental coincidences	6.6 ± 0.3	6.6 ± 0.3
Detector neutrons	$0.04^{+0.25}_{-0.04}$	$0.1^{+0.2}_{-0.1}$
Total	6.6 ± 0.3	$18.9^{+7.0}_{-5.5}$

➔ Background-only model rejected with **4.5σ** significance

Measure weak-mixing angle ($\sin^2\Theta_W$) at low momentum transfer (Q), consistent with SM



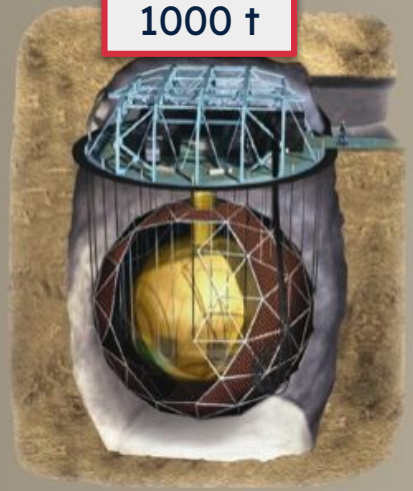


LZ: the smallest solar neutrino detector

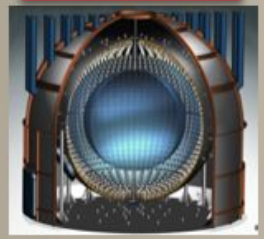
Super-Kamiokande
50 kt

St. Michael &
St. Gudula Cathedral

SNO
1000 t



Borexino
270 t



LZ
7 t !



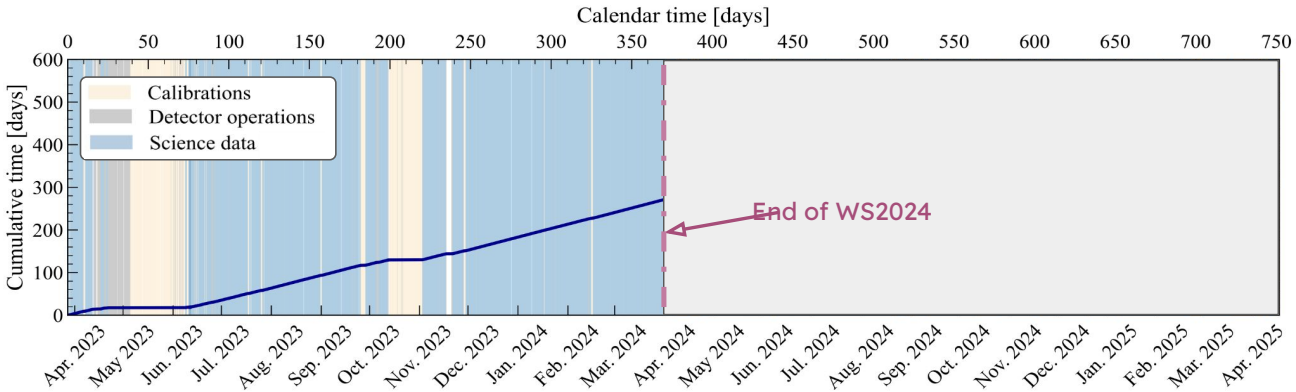
Credit slide: Alberto Usón

Intermediate Energy Recoil: typical WIMP (10 GeV/c^2-10 TeV/c^2) Search: "WS2024"

Phys. Rev. Lett. ***135***, *011802 (2025)*

WS2024: Outline

- ROI targeted “standard” ≥9 GeV/c^2 DM masses
- Chronologically happened before 8B/LMWS → WS2024 dataset
- Update needed wrt to our WS2022 (PRL **131**, 041002 (2023); 60 days) results because:
  a. WS2022 included cosmologically-activated Xe and Ar backgrounds that hadn’t decayed away
  b. More calibration was required
  c. WS2022 analysis didn’t include any **bias mitigation**
  d. New features that upgrade the analysis:
     - Xenon-flow-based **Radon-tag**
     - Charge suppression in EC backgrounds

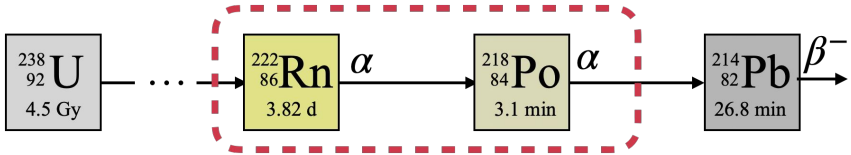


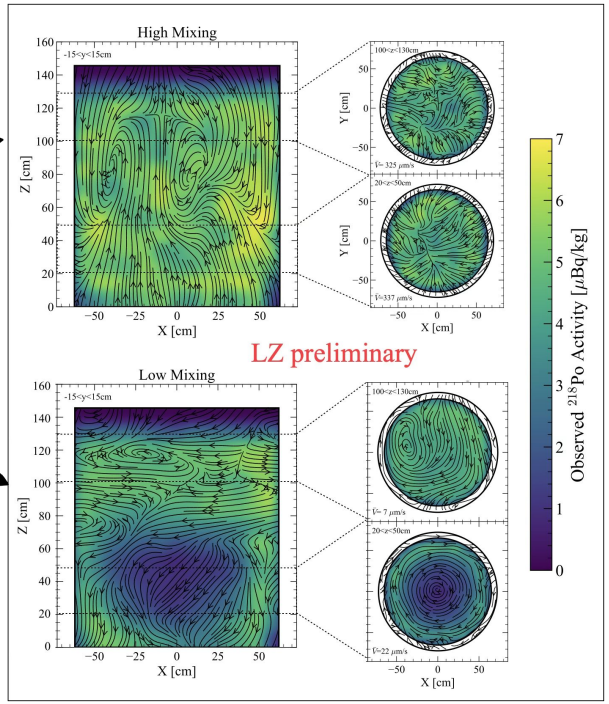
- Drift field: 97 V/cm
- Extraction field: 3.4 kV/cm

WS2024: Xenon flow and Radon Tag

- "Naked" ^{214}Pb β decay is the biggest ER background
- We have excellent control of temperature and xenon flow
- WS2024 data acquired in two different flow states:
  a. **High-mixing**: turbulent flow → uniform distribution of injected calibration sources
  b. **Low-mixing**: distinct regions of laminar flow → possibility to map the fluid velocity field

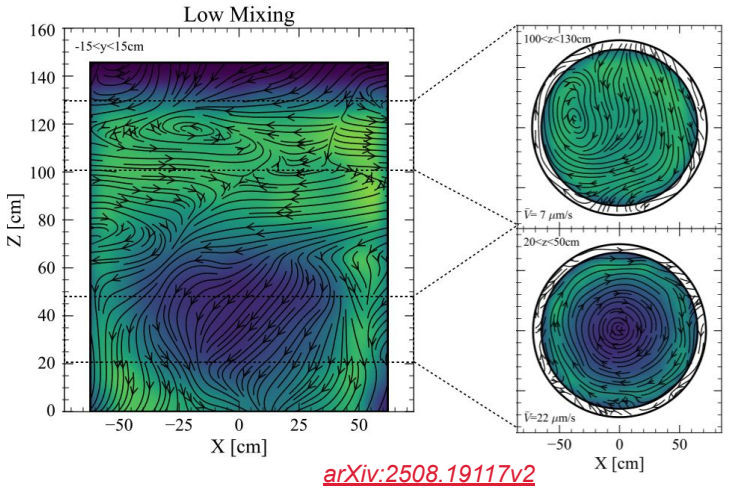
Coincident ^{222}Rn(^{238}U chain)-^{218}Po α decays (^{218}Po = 3.1 min) to map the fluid velocity field



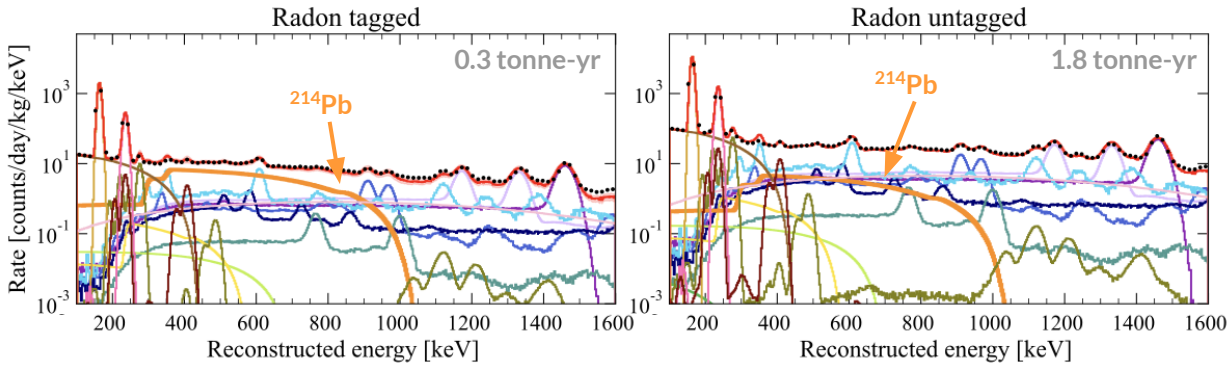


WS2024: Xenon flow and Radon Tag

- Identify events with high likelihood of being ^{214}Pb decays
- Based on simulations of neutral and charged progenies using velocity fields during low-mixing state
  - Tag volume defined for each identified ^{218}Po α decay along streamlines for 3× (^{214}Pb)
- ^{214}Pb in untagged subsample 1.8±0.3 μBq/kg (3.9 ±0.6 μBq/kg in total exposure → ~60% reduction)
- Both tagged and untagged data included in WIMP analysis → no “loss of exposure”

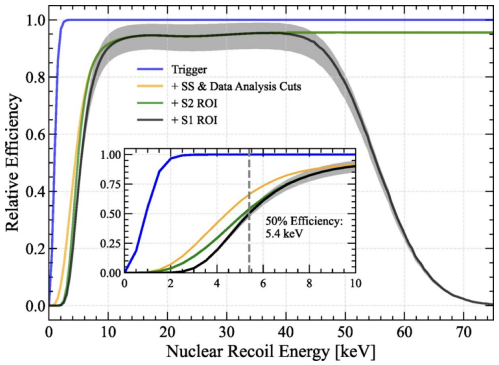


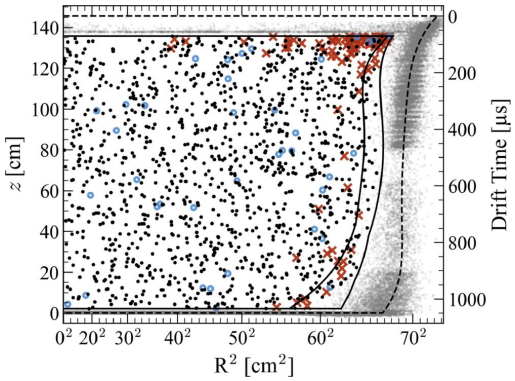
arXiv:2508.19117v2

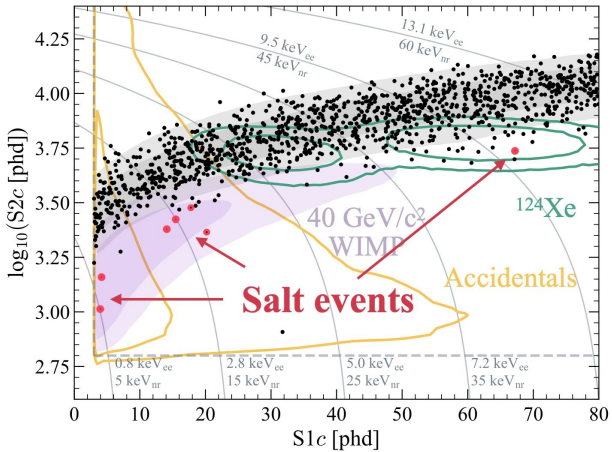


WS2024: Final dataset

- Cuts applied include **FV (5.5±0.2 t)**, data-quality, ACs, neutrons/gammas with vetoes with Skin (**x**) and OD (**o**),...
- **1227 events** in dataset after all selections → **7** of them revealed to be salt
- No post-unsalting changes to model
- Statistical analysis in observed S1c vs $\log_{10}$(S2c) space
- Likelihood fed with 6 subsamples: WS2024 (with 4 Rn-tag configurations), Skin/OD veto sideband, WS2022





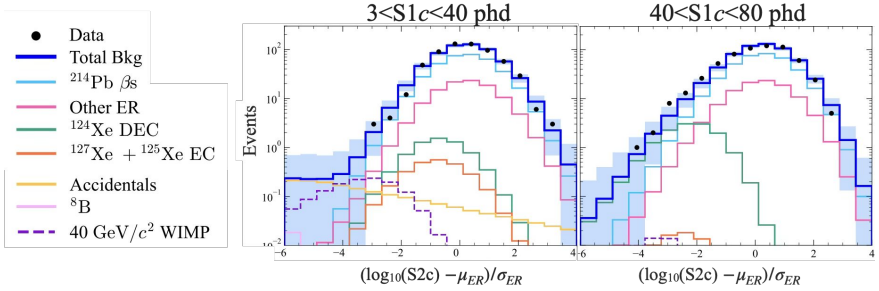


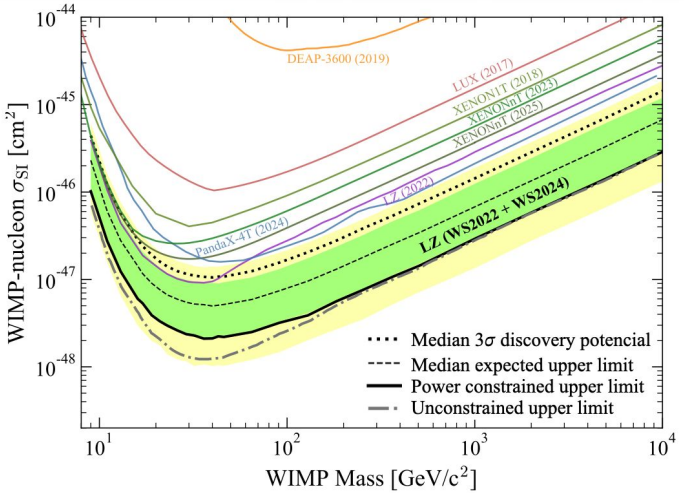
WS2024: Fit and results

- Good data/model agreement in all spaces
- Best fit of **zero WIMPs** at all tested masses (9 GeV/c^2 - 100 TeV/c^2)
- Upper limit power constrained at -1σ sensitivity band (as DM conventions EPJC 81 907 (2021))
- Under fluctuations from distribution of accidental events in WIMP region (in WS2024) + ER under fluctuation in WS2022

WS2024+WS2022 combined minimum limit: **2.2 x 10^{-48} cm^2 at 43 GeV/cm^2**

SD WSs also considered (back up)





Extended Energy Recoil: momentum-dep. & Inelastic WIMP Search: “EFT WS2024”

arXiv:2609.02823 ***[hep-ex]***

EFT WS: Why extend the energy window?

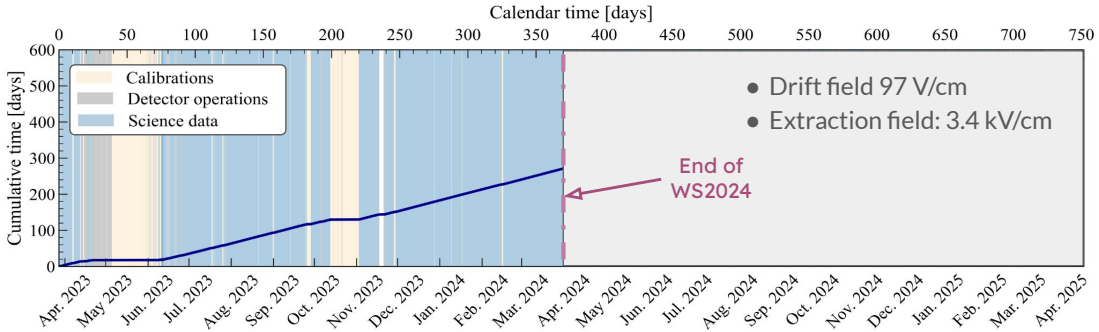
DM scattering can include contributions at HE recoil spectra if:

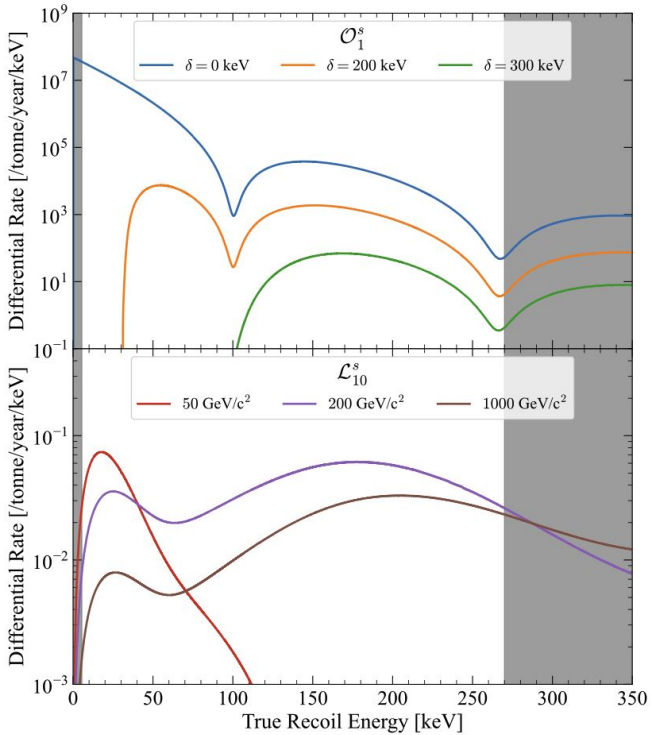
- ➔ **Momentum-dep.** WIMP-nucleon coupling (standard SD/SI WS assume no dependence) [1,2], **or**
- ➔ DM candidate has two states separated by energy δ and **inelastically** scatters [3]

$$v_{min} = \frac{1}{\sqrt{2E_R m_N}} \left(\frac{E_R m_N}{\mu} + \delta \right)$$

Benefits:

- Larger separation between ER and NR band
- ROI: Most of BGs same as in WS2024 (+ ^{83m}Kr & ^{125}I) → very similar analysis to WS2024 (same dataset used: 220 days, up to April 2024)





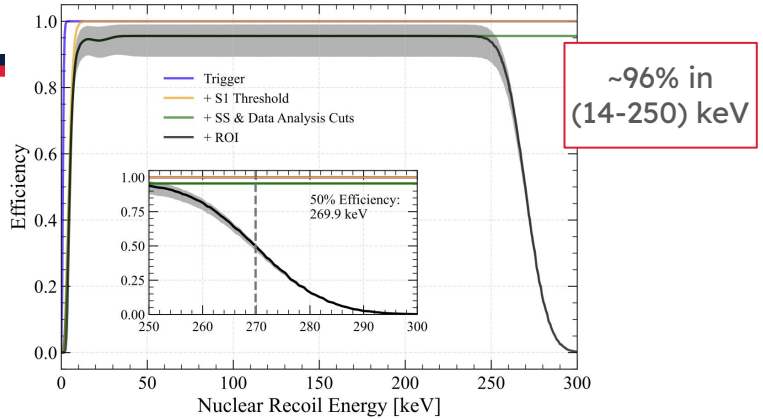
[1] Chang *et al* JCAP01(2010)006
[2] Feldstein *et al* JCAP01(2010)020
[3] Barello et al. Phys. Rev. D 90, 094027 (2014)

EFT WS: Analysis cuts

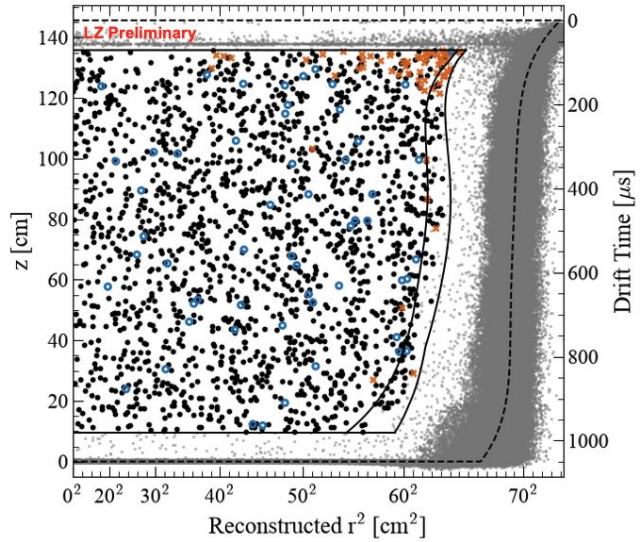
Cuts developed on non-WIMP ROI data:

- Single Scatter (**SS**) events
- **ROI:**
  - S1*c* in [3,600] phd
  - S2 > 645 phd
  - $\log_{10}$(S2*c*) in [2.75, 4.15]
- **Data quality**, including:
  - exclusion of high-rate periods
  - hold-offs after large energy depositions

  as a result: 81.5% livetime retention
- **Fiducial volume** → **4.71 ± 0.08 t** (14.5% reduction wrt WS2024)
- **S1**- and **S2**-based cuts for accidentals reduction
- External **vetoes**: prompt (x) + delayed (o) Skin or/and OD → **92 ± 4 %** neutron-tag efficiency



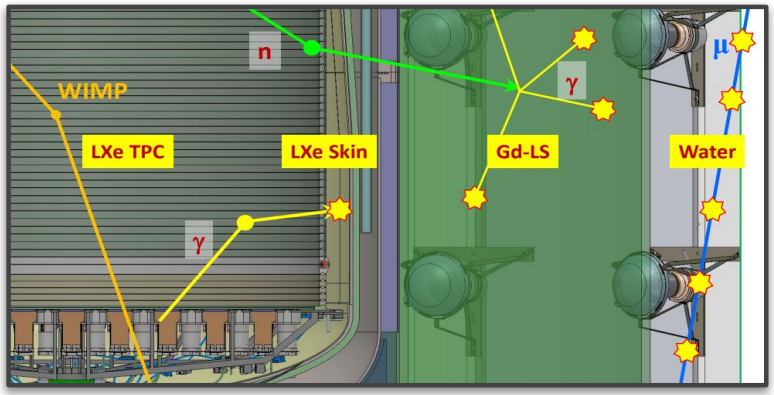
~96% in (14-250) keV

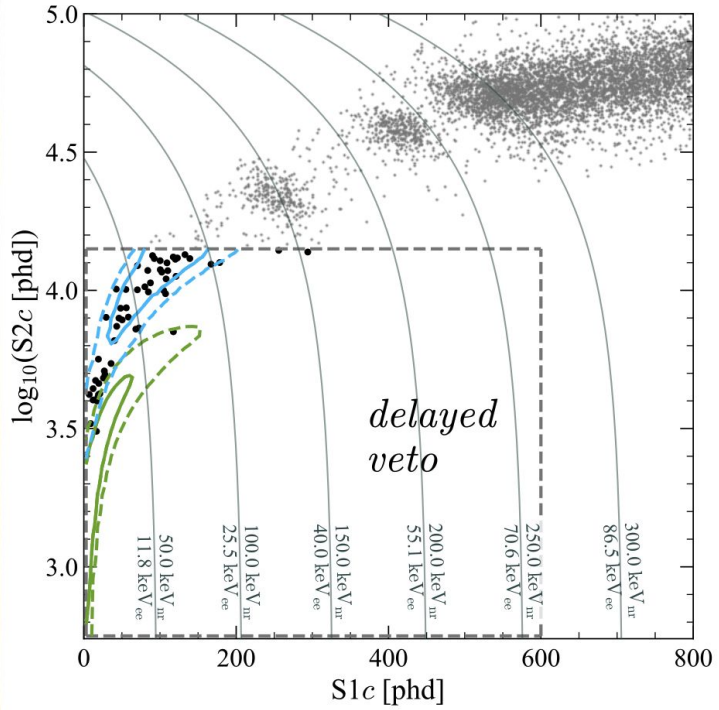


EFT WS: Datasets

Data separated into 3 samples based on Skin/OD tag:

- **Delayed veto:**
  - Skin signal > 300 keV or OD signal > 200 keV
  - Within 600 μs of S1
  - Tags and constrains neutrons



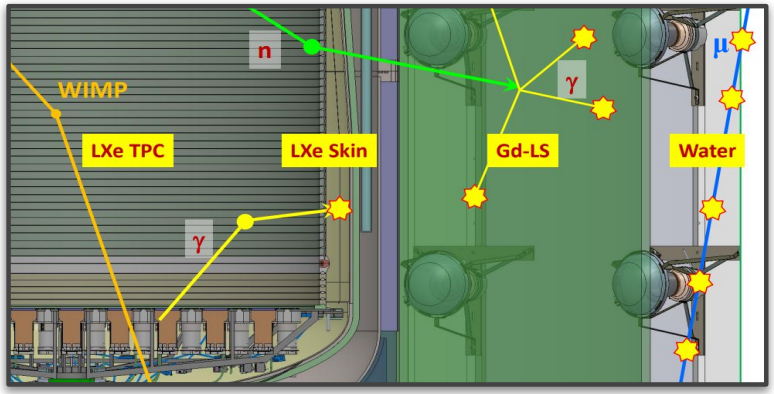


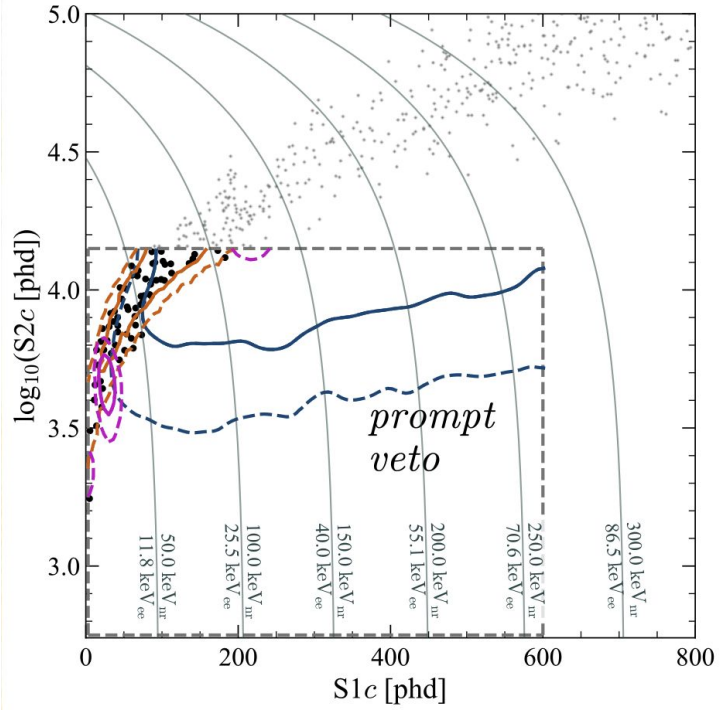
Contours: Neutrons
ER Backgrounds

EFT WS: Datasets

Data separated into 3 samples based on Skin/OD tag:

- **Prompt veto**:
  - Skin signal > 2.5 phd and within ±0.25 μs of S1
  - OD signal > 4.5 phd and within ±0.3 μs of S1
  - Tags and constrains ^{127}Xe, Detector γ-rays, MSSI, and neutrons



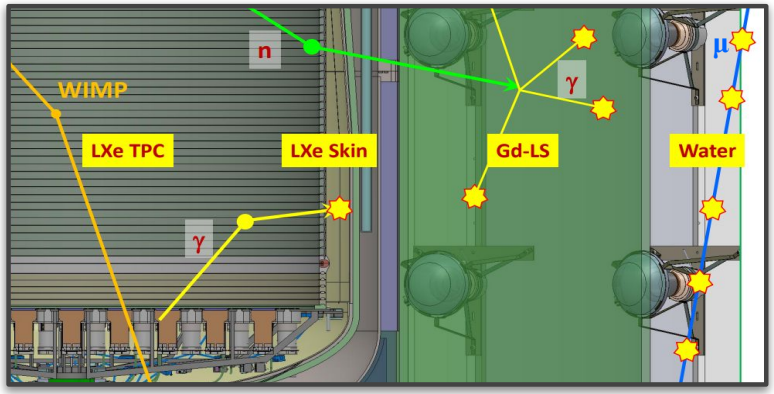


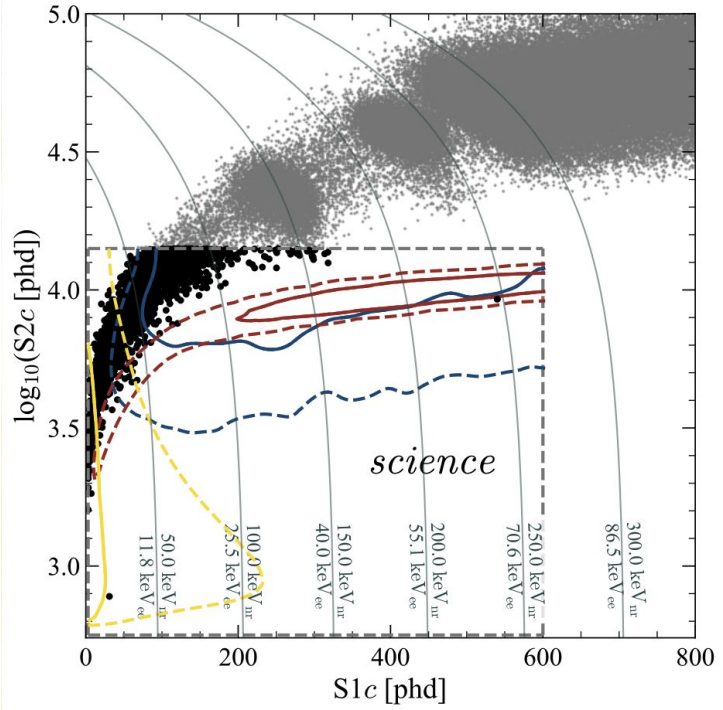
Contours: Detector ER
^{127}Xe MSSI

EFT WS: Datasets

Data separated into 3 samples based on Skin/OD tag:

- **Science**:
  - No tag in veto system





Contours: L10s 1000 GeV/c^2
Accidental Coincidences MSSI

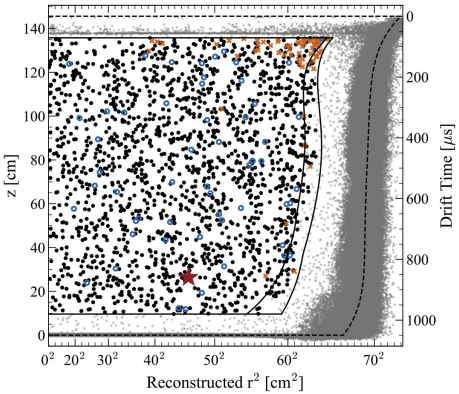
Event of interest: LZ230616

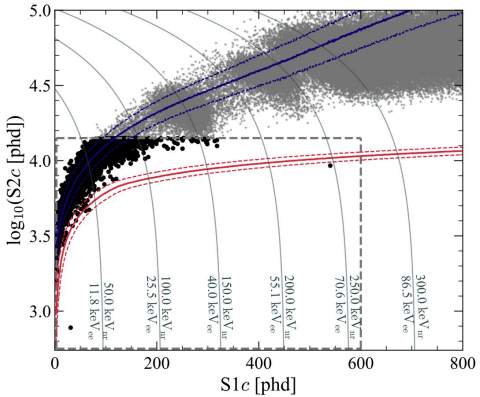
Data separated into 3 samples based on Skin/OD tag:

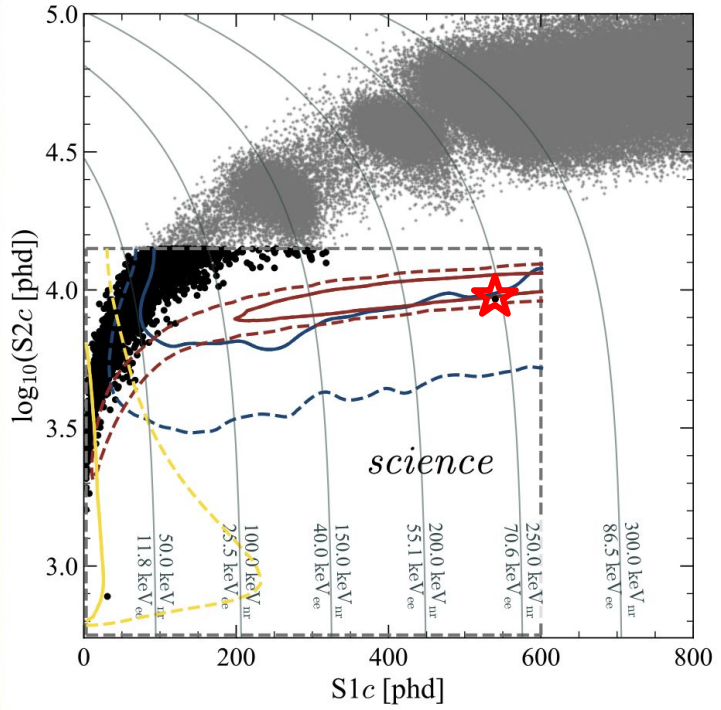
- **Science:**
  - No tag in veto system

One high energy signal-like event remains

- S1*c* = 540.1 phd
- S2*c* = 9268 phd
- On 16 June 2023 (**LZ230616**)
- **248 ± 23$_{stat}$ ± 23$_{sys}$ keV**
- 26.4 cm from cathode
- 26.9 from TPC wall

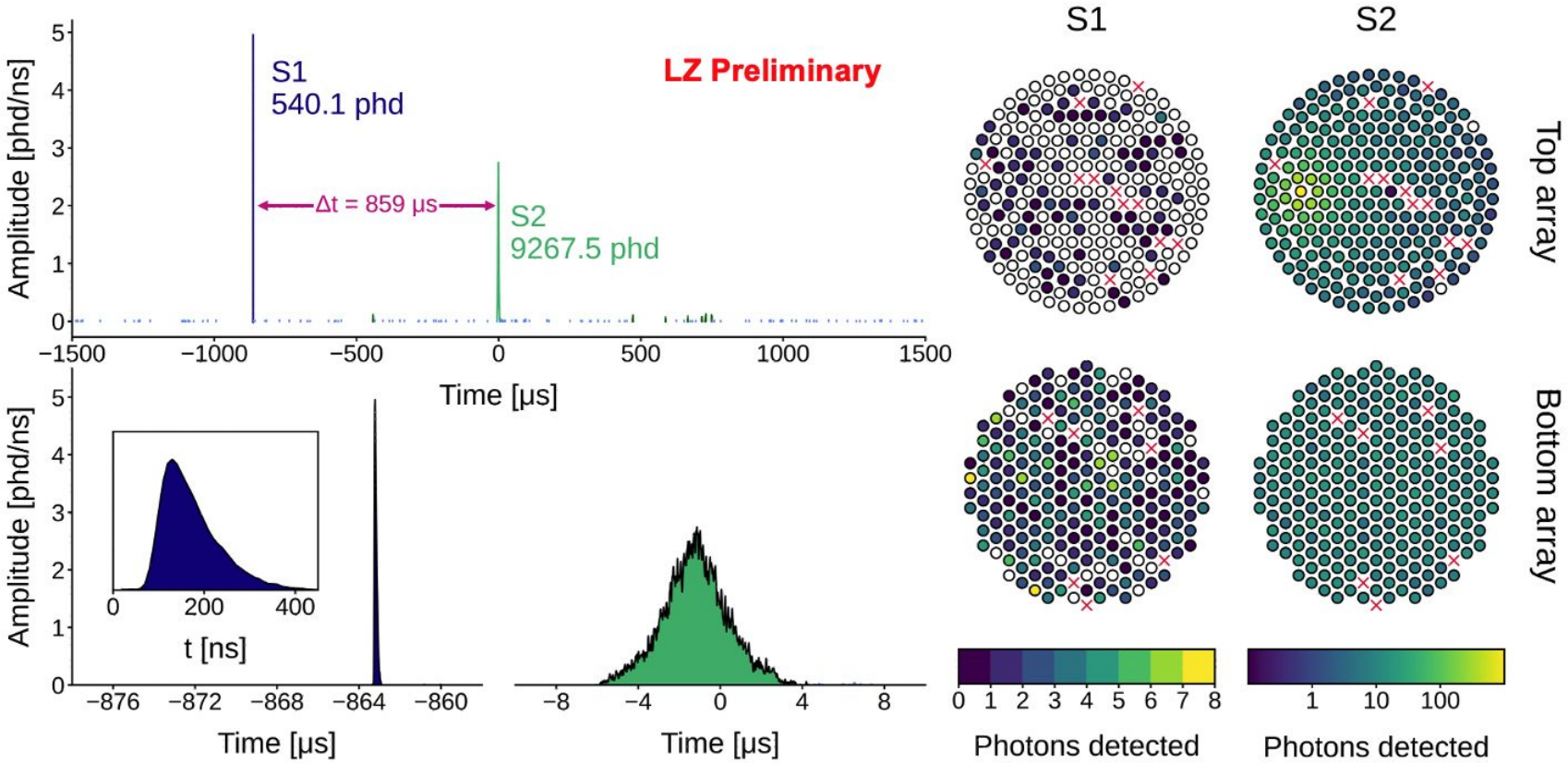






Contours: L10s 1000 GeV/c^2
Accidental Coincidences MSSI

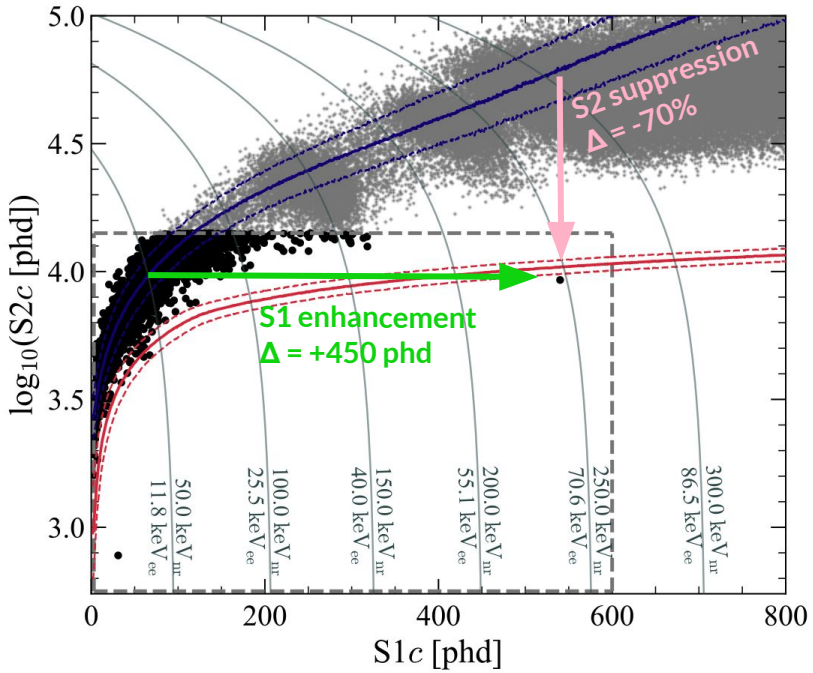
Event of interest: LZ230616 waveform



Topologies that can cause NR-like events

Several source of backgrounds could populate the NR band:

1. Intrinsic NR backgrounds
   a. Neutrons
   b. Neutrinos via CEvNS
2. Accidental coincidences
3. S1 enhancement
   a. **MSSI** (Multiple scatter single ionisation): double scatters where the charge from one is not collected
4. S2 suppression
   a. SS events where not all the charge is collected. E.g.
      i. blocked grid cell
      ii. surface emission
      iii. s2 gain sagging

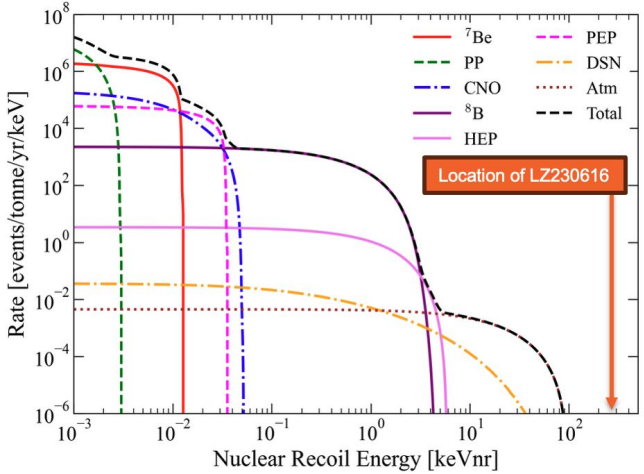


NR backgrounds: neutrinos and neutrons

Neutrinos

As seen, CEvNS produce NR signals

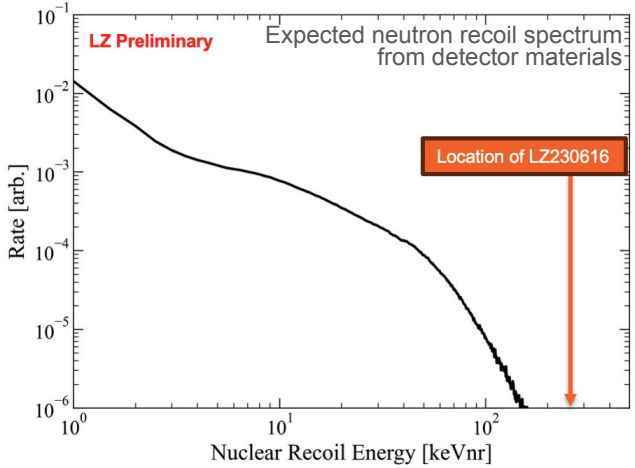
- Large momentum transfer require to produce LZ230616
- CEvNS cross section suppressed in this region



Highly unlikely to see high energy neutrino scatter and no low energy scatters

Neutrons

- >8 MeV neutrons can produce 250 keV elastic scatters
- They can come from (α,n), SF, muon cascades
- Elastic scattering highly forward peaked
- Skin+OD tagging efficiency: 92 ± 4 %



Highly unlikely to see HE neutron scatter and no low energy scatters, and no hint in vetoes

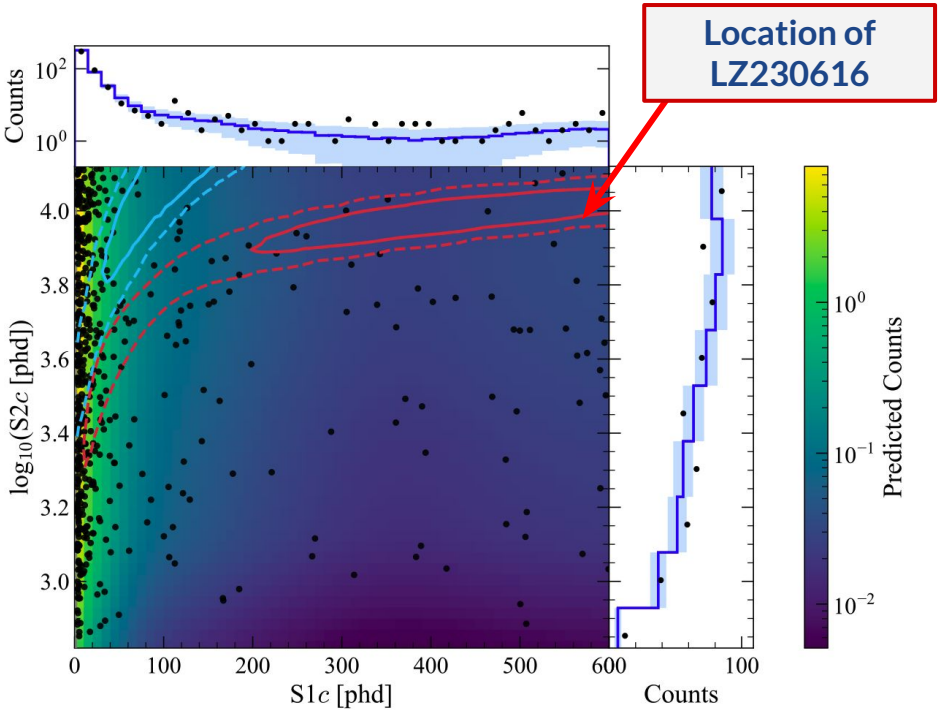
Accidental coincidences

Origin: accidental coincidence of uncorrelated S1 and S2 pulses

- Suppressed with dedicated S1- and S2- based cuts (**99.5 % rejection power**)
- Accidental model:
  - **Shape**: pair isolated S1 and S2 events (at waveform level) to create artificial SS-like event. Then apply analysis cut efficiencies
  - **Rate**: from rate of unphysical drift time SS events.

Expectation in exposure: **2.7 ± 0.6**

LZ230616 in **low probability** region of accidentals



Contours: L10s 1000 GeV/c^2
ER Backgrounds

MSSI (multiple scatter single ionisation)

Multiple scatter events where at least one vertex is in a region of incomplete charge collection:

- Reverse field region
- Near the TPC walls

As result → **S1 enhancement**

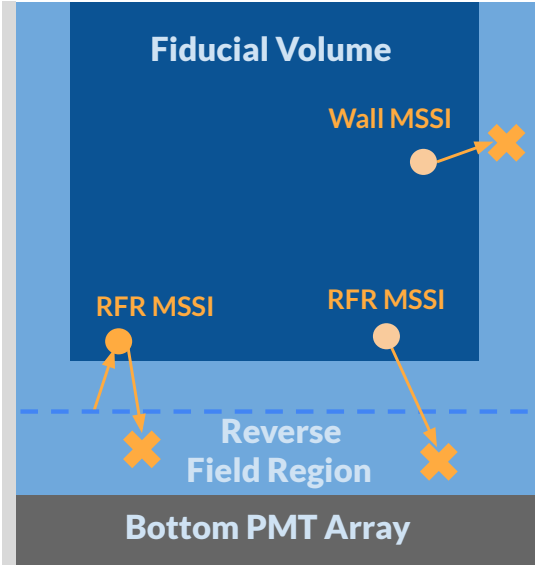
Dominant sources are:

- γ-rays from detector components
- Internal $^{214}Pb \rightarrow {}^{214}Bi + e^{-} + \nu_e$ where ^{214}Bi is not in the ground state

FV aggressively reduced to target these

Prompt tagging efficiency: 94 ± 2 %

Expectation in exposure: **0.005 ± 0.005**



To be caused by MSSI, the γ-ray must:

1. Travel ~25 cm
2. Scatter an additional time that doesn't produce an S2
3. Not be seen in veto detectors

Each of these scenarios are **unlikely**

Signal models: NREFT

High-energy WIMP-nucleon interactions described using a non-relativistic effective field theory (NREFT) [1]

$\longrightarrow$ 15 independent and dimensionless operators, $\mathcal{O}_i$, mapped onto Lagrangians $\mathcal{L}_i$ to allow for more complex interactions

Here, we consider HENR from:

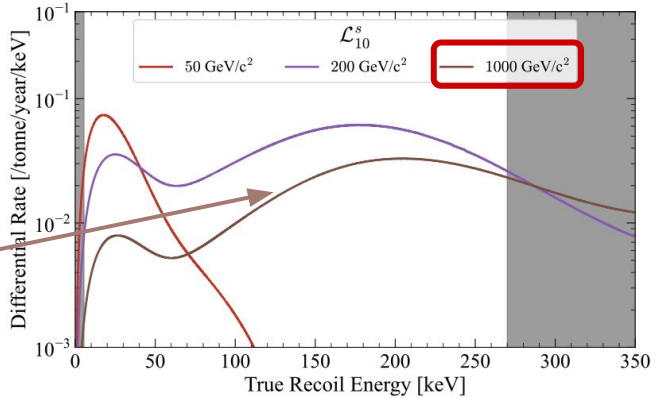
- $\mathcal{L}_1$–$\mathcal{L}_{20}$ Using 13 DM masses from 10 to 4000 GeV/c^2, and
- inelastics from $\mathcal{O}_1$ (isoscalar, SI), and $\mathcal{O}_4$ (isovector, SD) for 3 DM masses and 8 mass splittings δ

As a result, **616 models in total** (293 in the end, due to degeneracies and similar energy spectra)

From here on, we take **1000 GeV/c^2 $\mathcal{L}^s_{10}$ WIMP** model (magnetic moment interaction) as example

$$\mathcal{L}^j_{\text{int}} = d_j \bar{\chi} \mathcal{O}^j_\chi \chi \bar{N} \mathcal{O}^j_N N \quad [2]$$

$$\mathcal{O}_1 = 1_\chi 1_N, \quad \mathcal{O}_2 = \left(v^\perp\right)^2,$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right), \quad [3]$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \quad \mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$



[1] Fitzpatrick *et al.* J. Cosmol. Astropart. Phys. 02, 004 (2013)
[2] LZ Collaboration. Phys. Rev. Lett. 133, 221801 (2025)
[3] LZ Collaboration. Phys. Rev. D 109, 092003 (2024)

Background fit

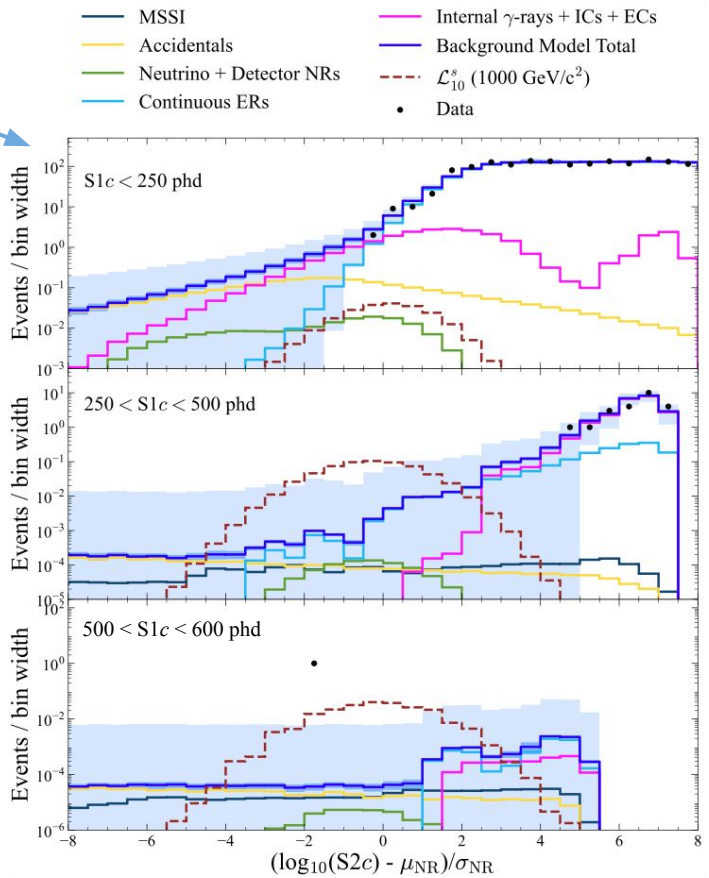
Data and BG model vs NR band mean:

- Lower BG rate at S1c > 250 phd
- In 500 < S1c < 600: BG = 0.0108 ± 0.0008$_{sys}$

3 samples fitted simultaneously in S1c vs S2c space using Profile Likelihood Ratio with two-sided test-statistic

Source	Expected Events	Fit Result
Internal β decays	1341 ± 160	1340 ± 43
ν ER	140.6 ± 8.4	140.3 ± 8.4
^{136}Xe	110.0 ± 16.5	114.2 ± 16.1
CH_3T & ^{14}C	55.3 ± 3.1	55.2 ± 3.1
^{124}Xe	21.0 ± 6.3	22.6 ± 5.0
^{83m}Kr	17.1 ± 5.1	$17.0^{+3.5}_{-3.3}$
^{125}I	8.9 ± 2.7	9.8 ± 2.3
Detector ERs	8.5 ± 3.4	$9.4^{+1.7}_{-1.6}$
Accidental coincs.	2.7 ± 0.6	2.6 ± 0.6
^{127}Xe + ^{125}Xe	1.5 ± 0.3	1.2 ± 0.3
Atmospheric ν	$(1.1 \pm 0.2) \times 10^{-1}$	$(1.1 \pm 0.2) \times 10^{-1}$
^{8}B+*hep* ν	$(5.7 \pm 0.6) \times 10^{-2}$	$(5.7 \pm 0.6) \times 10^{-2}$
MSSI	$(4.9 \pm 4.9) \times 10^{-3}$	$(4.6^{+4.8}_{-4.6}) \times 10^{-3}$
Detector NRs	–	$[0, 0.118]$
$\mathcal{L}^s_{10}$ (1000 GeV/c^2)	–	$1.0^{+1.4}_{-0.7}$
Total counts	–	1713 ± 39
Observed counts	–	1710

➔ Best fit # WIMP: **1**



Fit result and limits

Scan over DM mass or mass splitting for particular Lagrangian or operator:

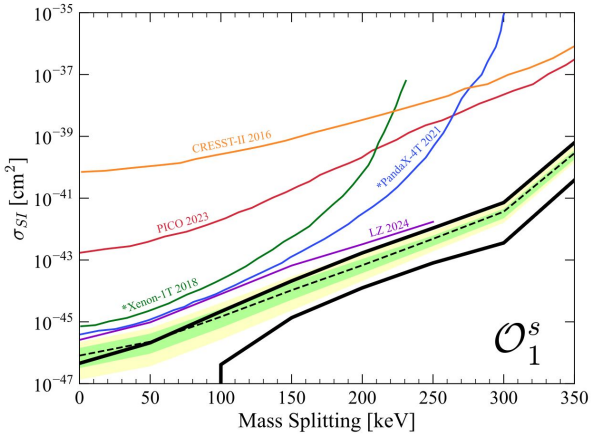
For most of >100 GeV/c^2 tested models:
- ➔ Best fit # WIMP: **1**
- ➔ p-value to reject BG-only <1.3x10^{-3} → local significance **>3σ**

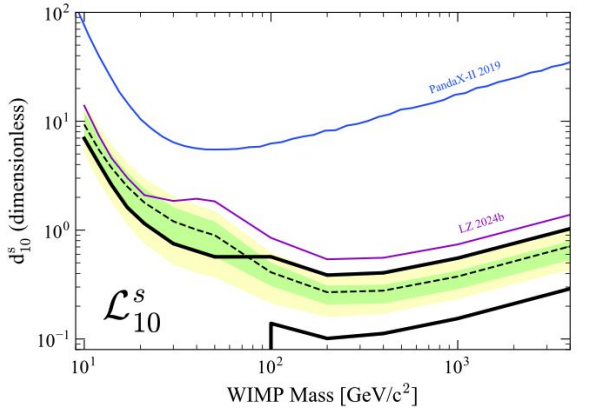
Need to account for large number of models evaluated → look elsewhere effect (LEE) correction **[1]**:

➔ Global significance: **2.6σ**

(local significance of all models in data release)

90% confidence-level intervals set on all models probed:
- ➔ Non-zero lower limit for some masses
- ➔ World-leading constraints on all models for upper limits





[1] Baxter et al. Eur. Phys. J. C 81, 907 (2021)

Proposed interpretations

Our significance increases monotonically with δ (up to 350 keV tested)

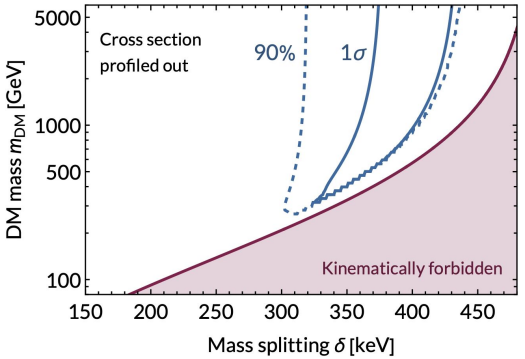
Influx of theory papers (141 at last count) to try and explain event. One example:

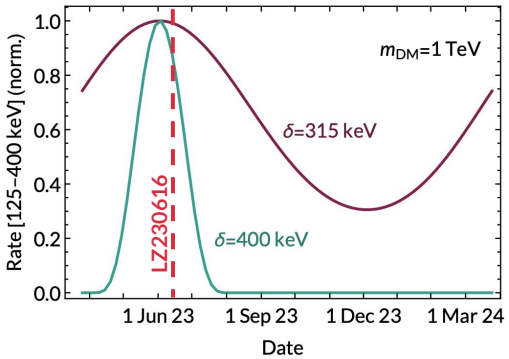
Inelastic DM:

- Lots of interest in (nearly pure) Higgsino DM with two neutral Majorana states:
  - Correct thermal relic abundance for m_{χ} ~1.1 TeV
  - Favours δ within 350 keV - 400 keV
  - Annual modulation strength would depend on δ
- Some caveats, e.g. more events expected at high energies, δ > 566 keV from IceCube (Pospelov, Ramani. arXiv:2609.02775)

Many other alternative candidates proposed

McCabe. arXiv:2609.04181

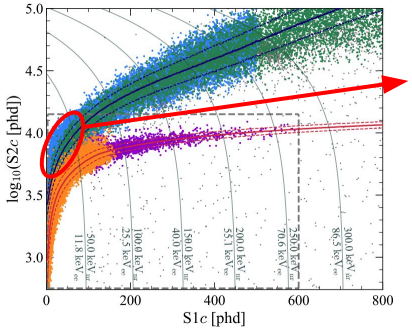


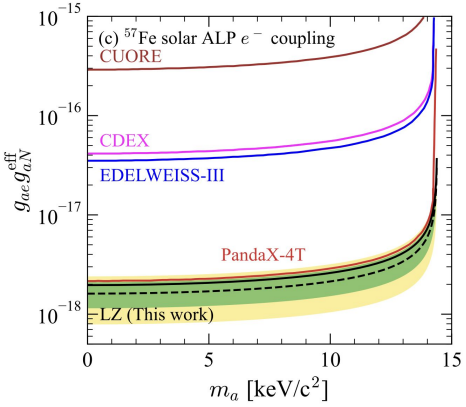


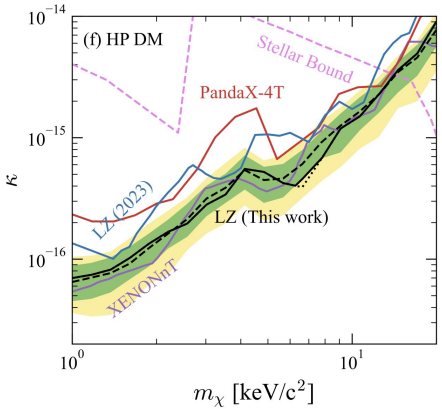
What's next? Near future

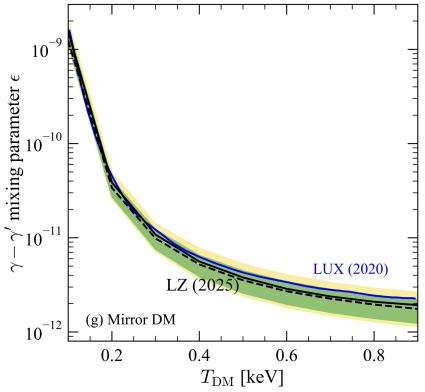
- We have **more data** in the bag, stay tuned for future updates!
- On top of the existing data, LZ plans to take data until 2028 → **1000 live days** goal
- We are **not limited** to the searches presented here, e.g. check out our latest results searching for new physics at low-energy **Electron Recoils**, setting world-leading constraints for multiple ER models, like ^{57}Fe solar ALPs, bosonic dark matter, mirror dark matter, and neutrino millicharge

  → Phys. Rev. Lett. 137, 101803 (2026)









- Multiple other physics searches on the horizon: neutrinoless double beta decay, ionisation-only analyses targeting lower masses, and more!

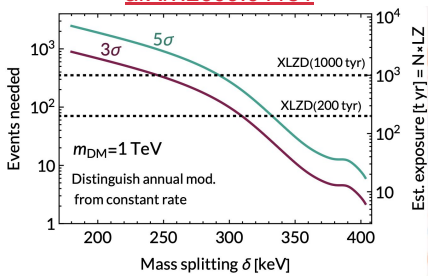
What's next? Further future

- Combination of LZ+XENONnT+DARWIN

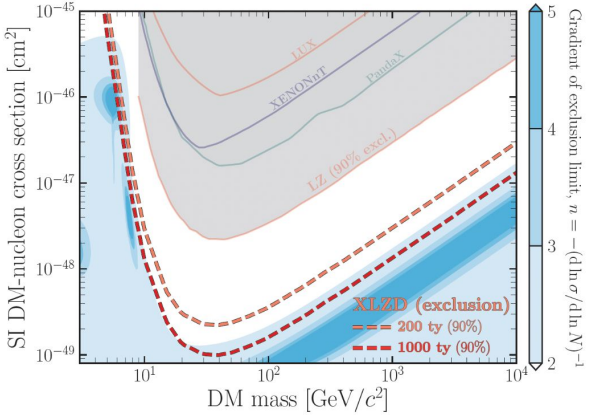
  → **XLZD**
- Formal collaboration since Sept 2024
- 500+ members from 80 institutions and 17 countries
- Next-generation rare-event observatory, with **60t-80t of LXe**
- Could easily confirm this signal if inelastic DM with the favoured values of δ
- Pre CDR stage: significant ongoing work for design and R&D
- Location still not decided (Boulby / LNGS/ SURF/ SNOLAB)
- Fully exclude WIMP parameter space down to neutrino fog after 1000 t·yr
- Broader physics scope: competitive sensitivity to ^{136}Xe $0\nu\beta\beta$ and astrophysical neutrinos



arXiv:2609.04181



arXiv:2410.17137



Conclusions

- We try to remain cautious about **one event**, with **2.6σ** global significance
- Significantly **more livetime** taken, with plans of continuing taking data until 2028
- Increasing our exposure will be fundamental to see whether:
  - More signal-like events appear → increasing significance, or
  - More non-NR events appear → potential background missed
- Looking for community input on backgrounds, have we missed a rare pathology?
- Lots of activity on arXiv from theorists to try and explain this case:
  - Most popular: Higgsino inelastic model (with some caveats)
  - Clear that the halo matters - uncertainty in the tail





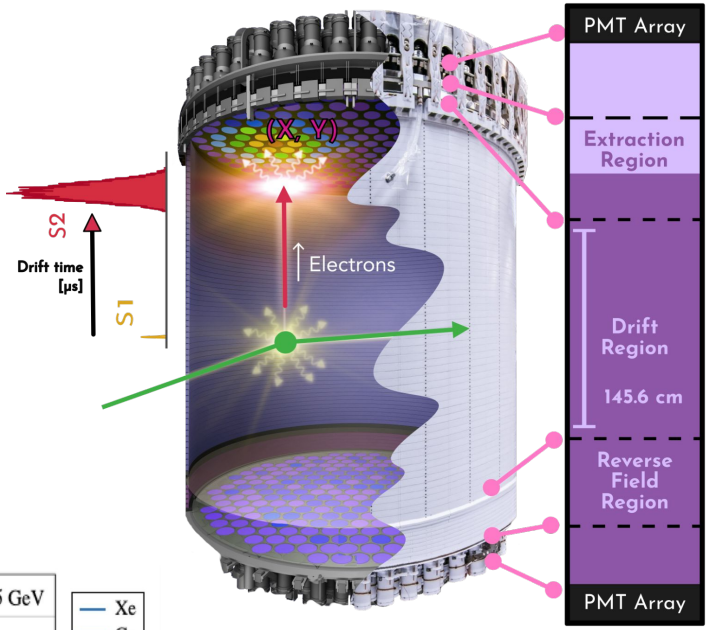
Thanks for listening!

Back-up

LXe-based detectors

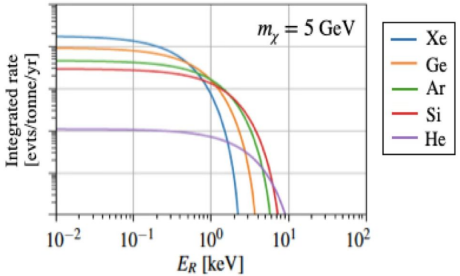
Noble gas detectors:

- Most promising in wide mass range (1 GeV/c^2 - 100 TeV/c^2)
- Excellent media for large, homogeneous, compact, self-shielding
- LXe & LAr excellent scintillators and good ionisers
- Large tradition and good understanding of detector capabilities

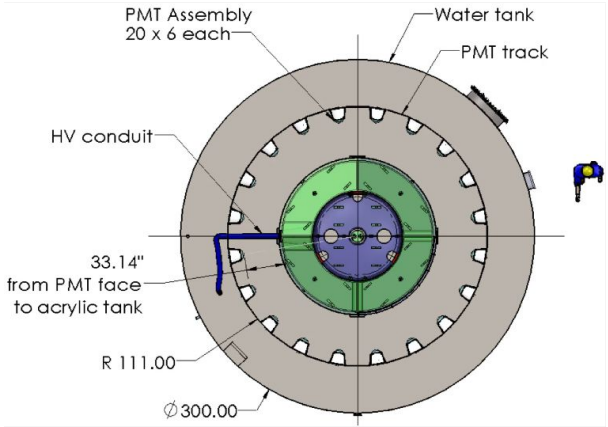


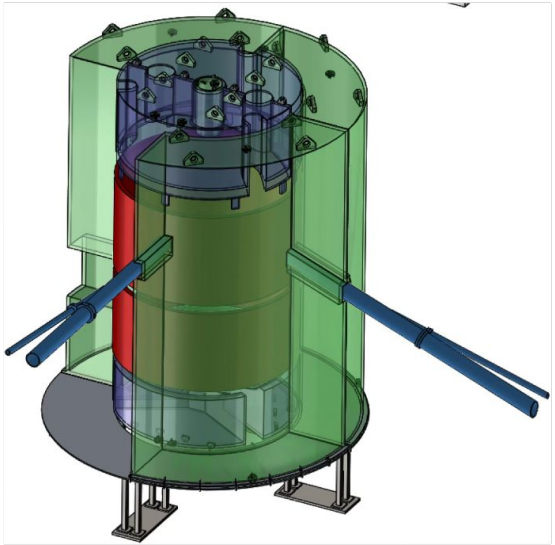
Why xenon?

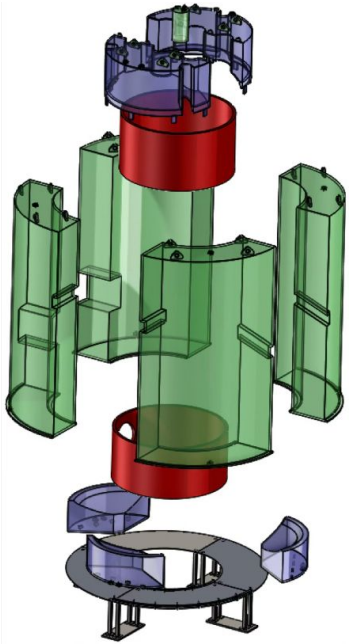
- Coherent scalar WIMP-nucleus scattering: $\sigma \propto A^2$
- More effective self-shielding
- Allows both SD and SI searches
- Relatively high boiling point
- Leasing detectors:
  - LZ, XENONnT, PandaX-4t



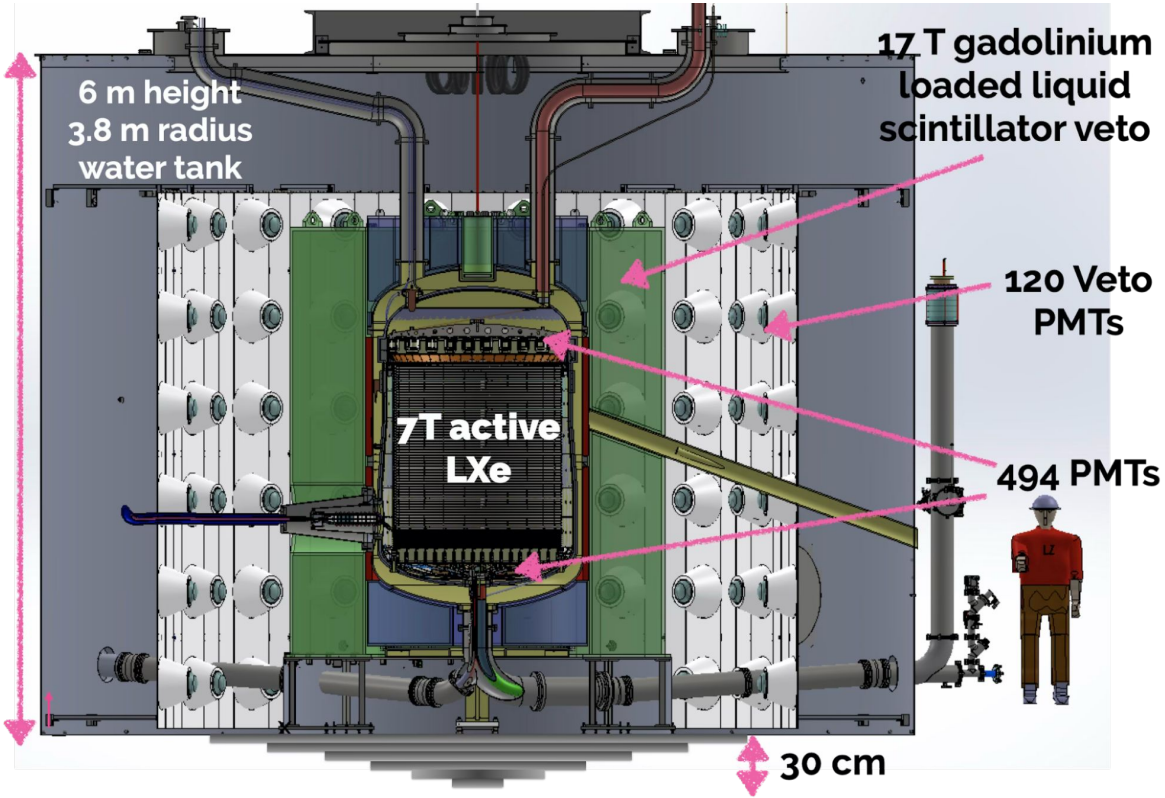
Outer Detector







Outer Detector



Accidental coincidences

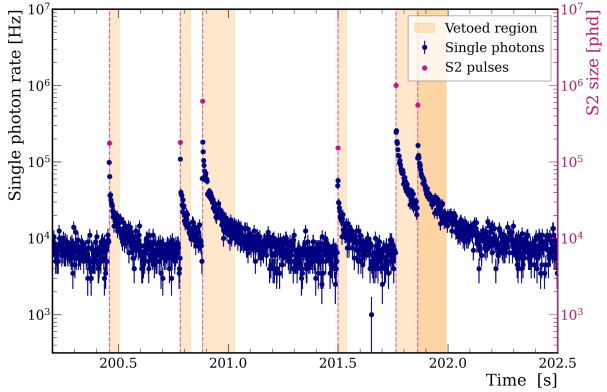
Isolated S1s and S2s appear from a wide variety of instrumental effects, e.g.:

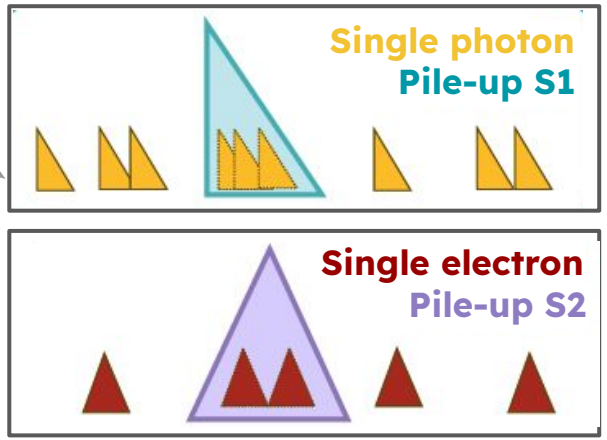
- PMT dark counts
- Insensitive regions (e.g. charge loss near the TPC walls)
- Large photon/electron rates after big energy depositions → single photons/e- can pile up to form isolated S1s and S2s respectively

They can pile-up to **fake single scatters**, especially forming small pulses…

Main contribution to backgrounds in this search, given the small size of S2s considered

⇨ Need to <u>mitigate</u> & <u>model</u> them!



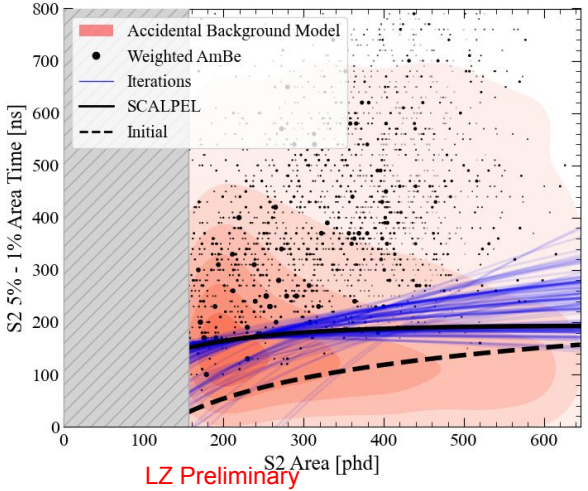


Accidental coincidence mitigation

Target accidental coincidences with selections targeting anomalous S1 and S2 characteristics (pulse shape, PMT hit map)

- Selections are designed and optimized using neutron (AmBe) calibration and fabricated background datasets
- Covariance Matrix Adaptation Evolution Strategy (CMA-ES) optimization technique used to simultaneously tune several selections across multiple parameter spaces

→ Powerful, and not a black box!



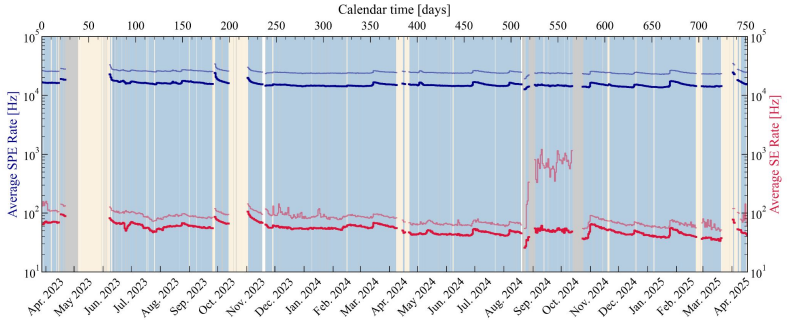
Additional 90% rejection of accidental coincidences

Accidental coincidence model

Step 1: Create data-driven synthetic accidental-like dataset

⇨ **Idea**: pair iS1 and iS2 events to create artificial SS-like event

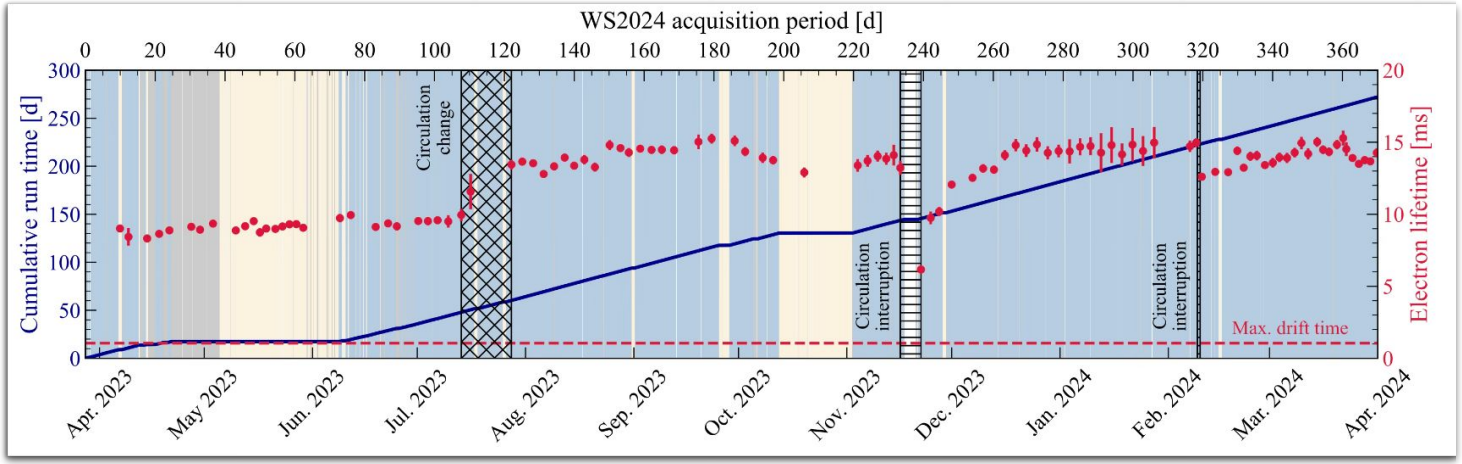




However, pile-up S1 more likely to be accidentally paired with pile-up S2

To consider that → isolated pulses from same single-photon and single-electron rate environment are stitched

WS2024 dataset

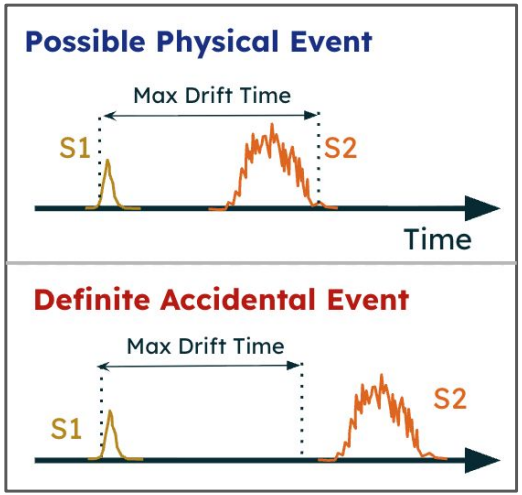


Accidental coincidence model

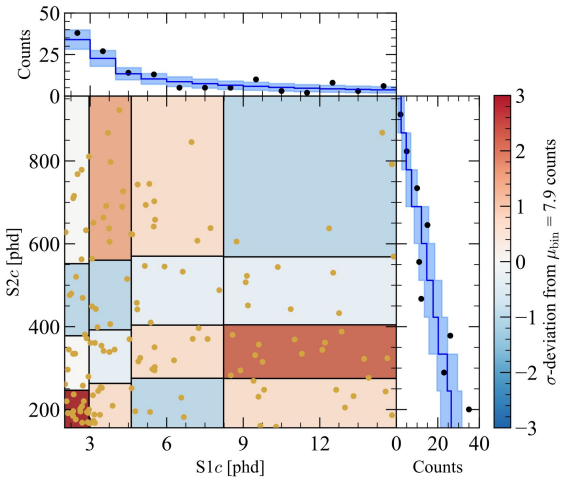
Step 2: Normalise rate of artificial dataset

⇨ **Idea**: use SS with unphysically long drift times

Prediction: **6.6 ± 0.3** events in full exposure



Step 3: Validate model with multiple datasets



Observe excellent agreement across datasets with a variety of detector conditions

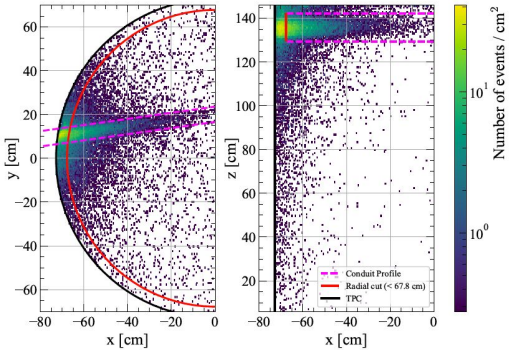
NR calibration

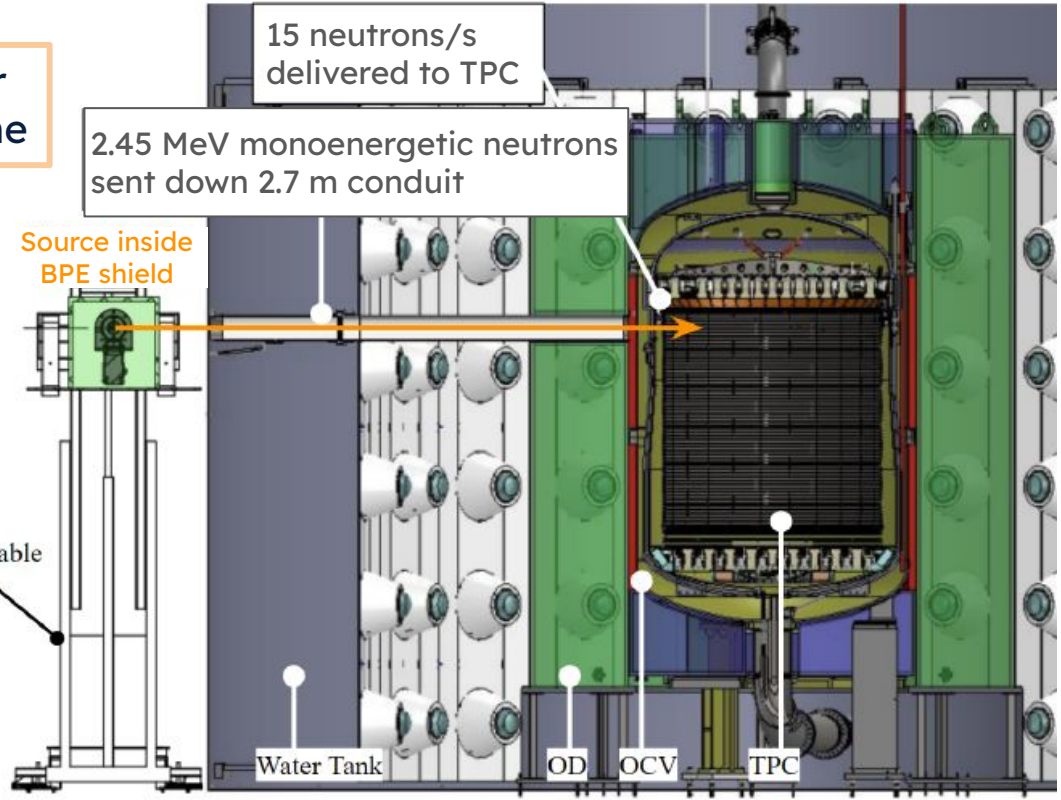
We need to understand/model our detector response in this new regime

- Neutrons with 2.45 MeV produced from Deuterium-Deuterium (DD) fusion:

$$^{2}H + ^{2}H \rightarrow ^{3}He + n$$

- Triggered using plasma ignition

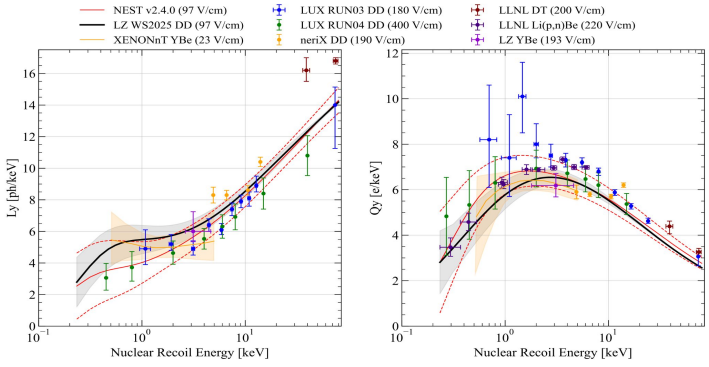


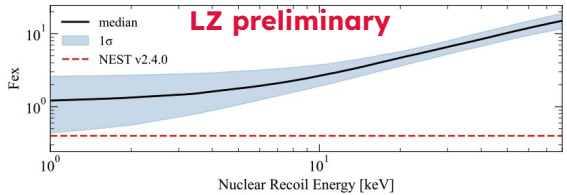


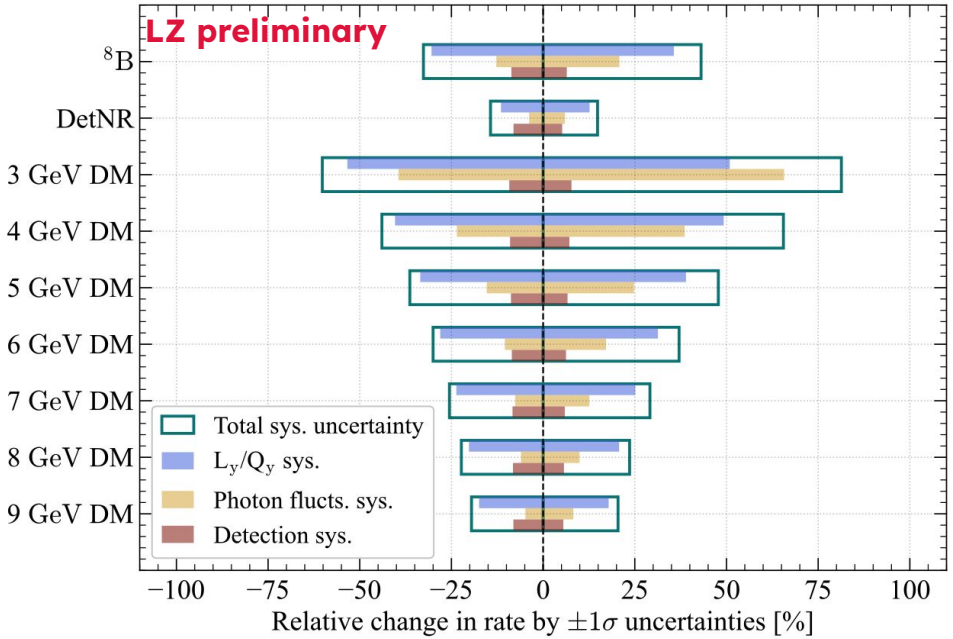
Systematic Uncertainties

Total uncertainty combined the one coming from the updated DD-based NR model (from both yields and fluctuations) and detector response

The former dominates:



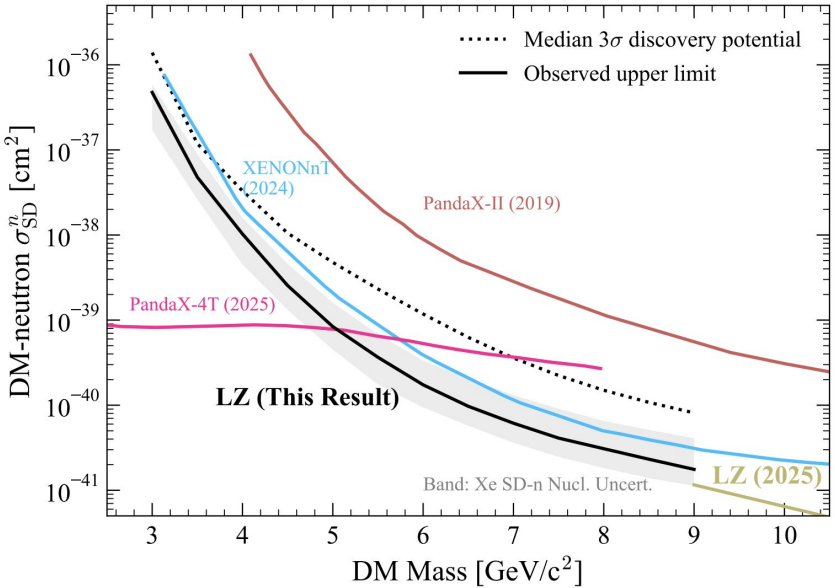


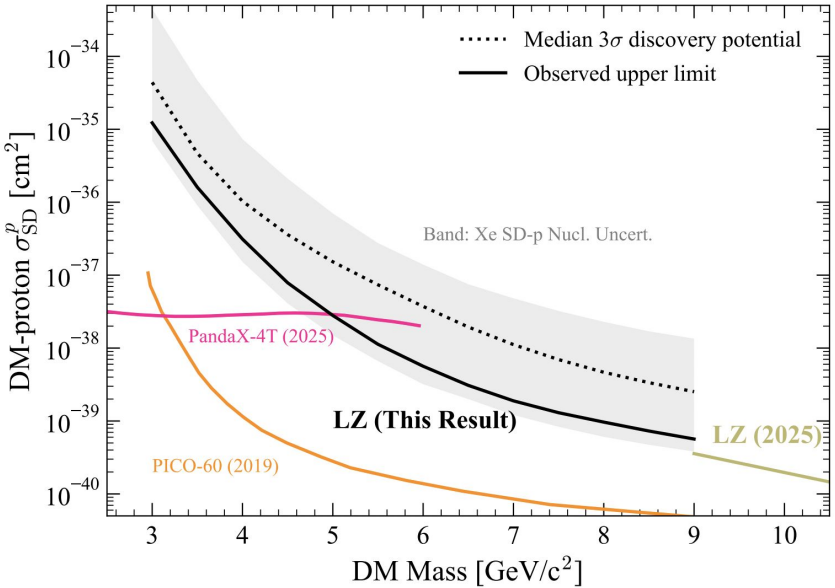


Phys. Rev. Lett. 137, 093006 (2026)

SD Low Mass WIMP Search

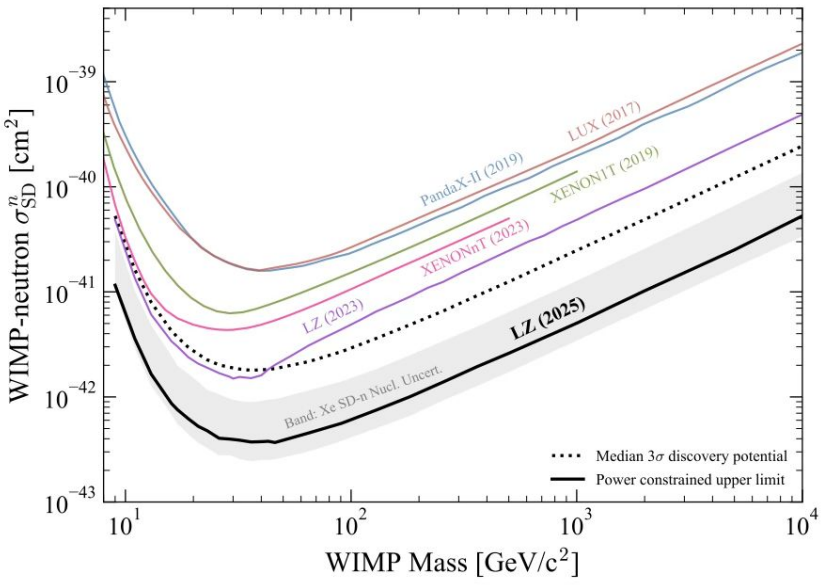
- Limits on SD neutron-only and proton-only:

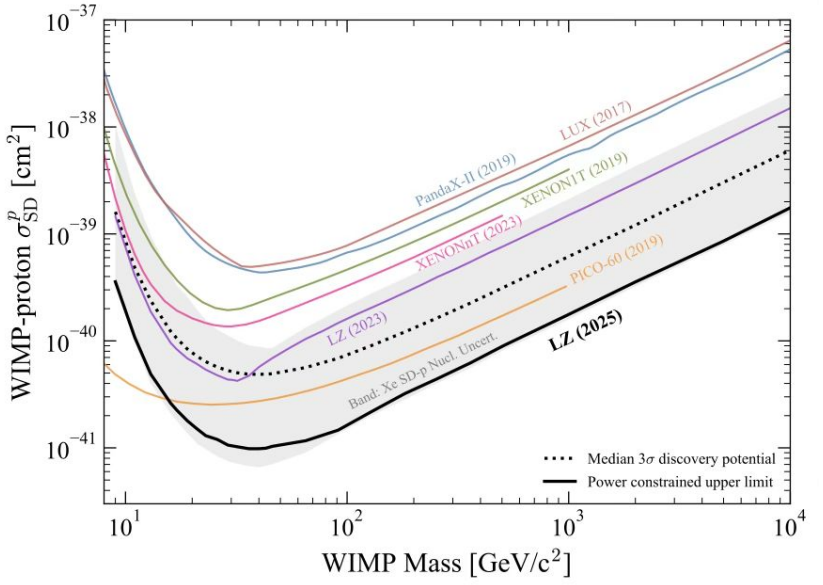




SD WS2024 Limits

Similar analysis to search for Spin-Dependent (SD) WIMP-nucleon interactions. Two limiting cases considered: WIMP-neutron, and WIMP-proton

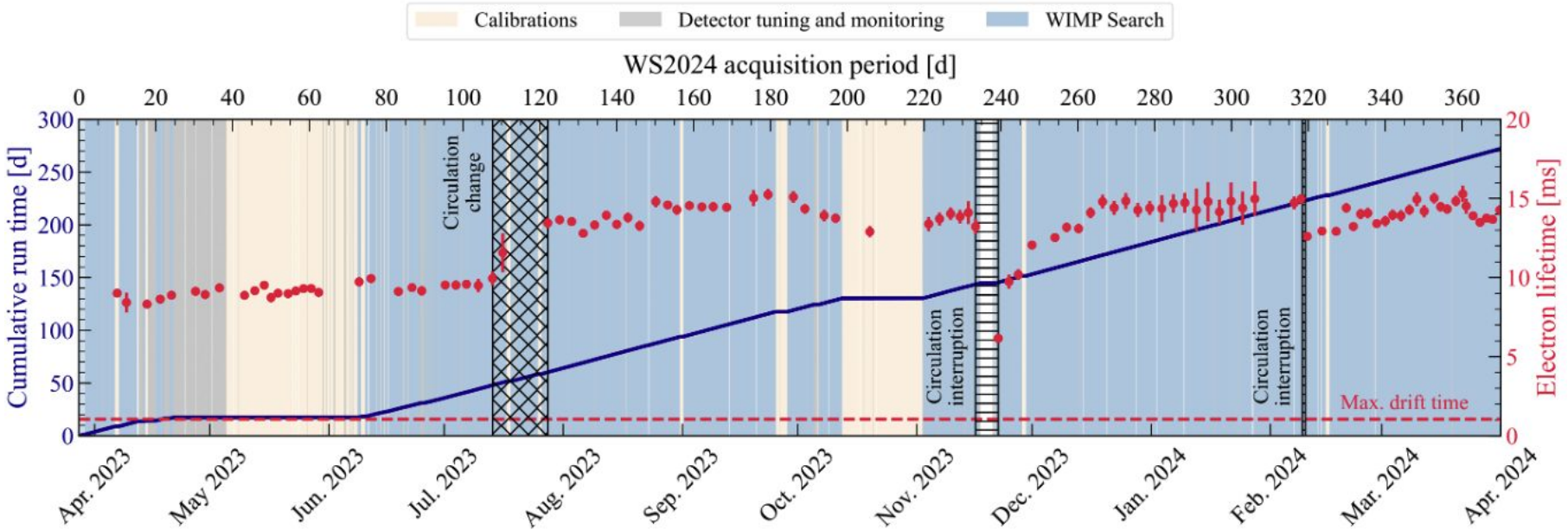




WS2024 Dataset

Acquired data for ~370 days

- 95.2% detector up-time
- 220 live-days of exposure after data quality cuts



EFT WS2024 FV

To limit backgrounds from detector materials, plateout, and abnormalities from non-uniform electric fields near the edges

Wall backgrounds:

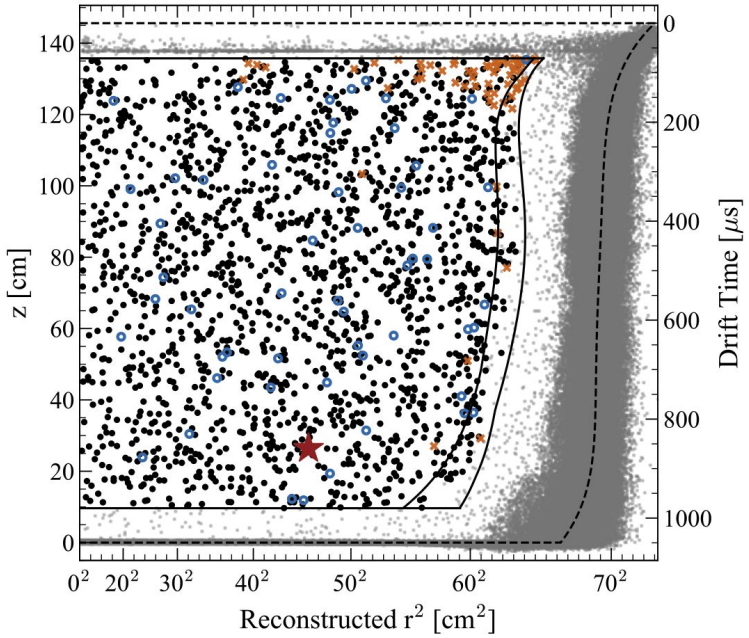
- Limit wall contribution to **<10^{-4}** events in exposure
- At least 4 MFP for *γ*-rays from the dominant MSSI source (352 keV from ^{214}Pb)

Cathode:

- At least 4 MFP for γ-rays from the dominant MSSI source (352 keV from ^{214}Pb)

Analysis volume:

- **4.7 +/- 0.2 tonnes**
- Analysis exposure: **2.8 tonne-years**



MSSI (Multiple scatter single ionisation)

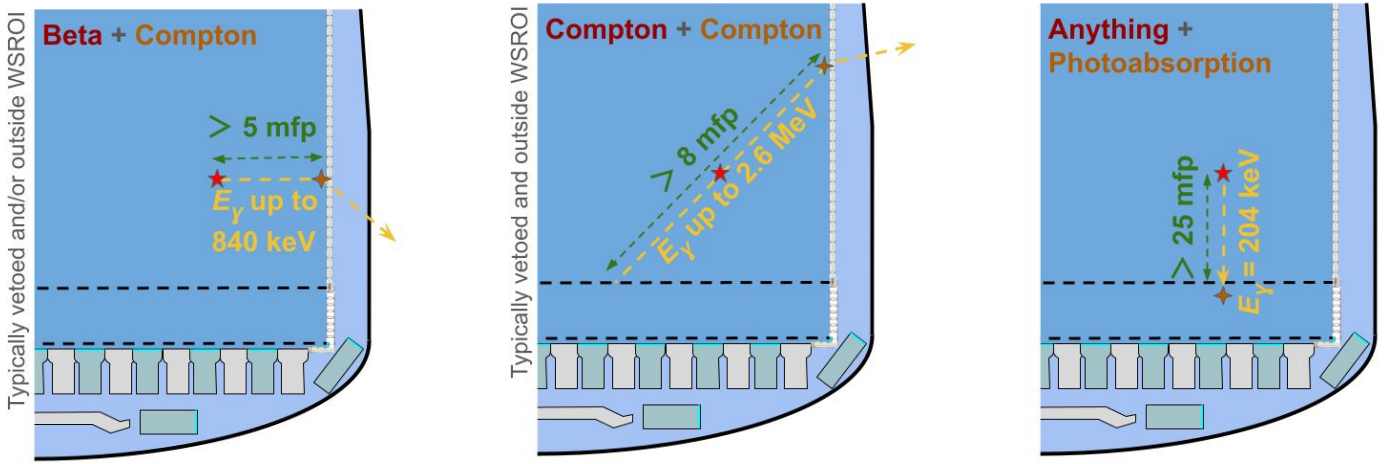
Hypothesis: the event is MSSI from two ER deposits, then:

- S2c of event (9268 phd) corresponds to an expected 12 ± 2 keV recoil energy, and the expected S1c is 69 ± 17 phd

→ Missing 471 phd, for the second S1, two options:

- 204 ± 40 keV in RFR, or
- 77 ± 7 keV by Wall

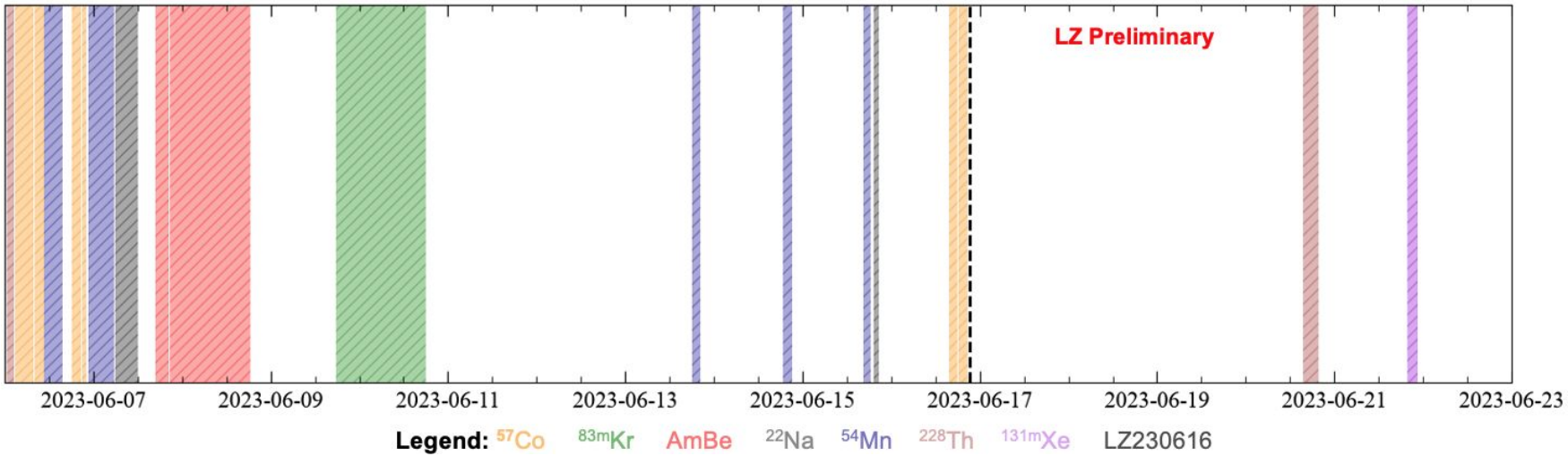
Unlikely, since ~12 keV would require forward scattering, so the gamma-ray would have to travel >60 cm in LXe without second interaction



Detector conditions around LZ230616

Previous calibrations in source deployment tubes:

- ^{57}Co removed 25 mins earlier
  → not a concern as occurred on opposite side of detector
  → ^{57}Co are low energy γ-rays used for calibrating the Skin and OD.
- AmBe on 8 June 2023
  → one week before



EC and DEC Modelling: Charge suppression

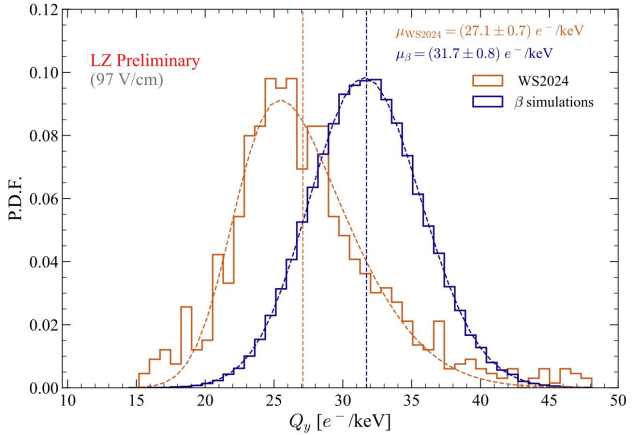
Single Electron Capture (EC) backgrounds:

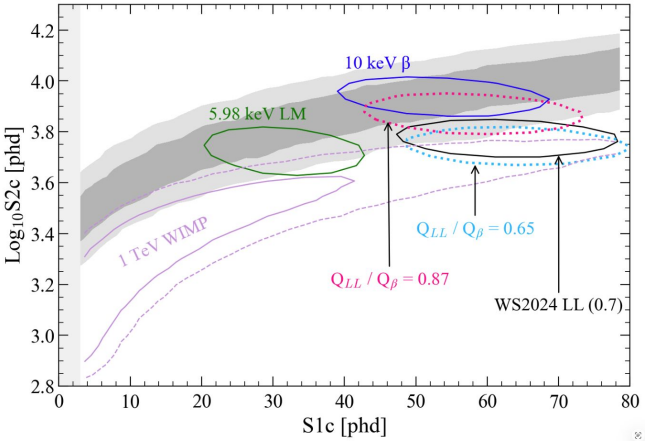
- ^{125}Xe and ^{127}Xe from neutron activation
- Especially relevant xenon L-shell @5.2 keV
- X-ray + Auger emission charge suppressed compared to β due to higher ionisation density → **ER band leakage**
- Measured in-situ with WS2024 data: $\mathbf{Q_L/Q_\beta = 0.87 \pm 0.03}$
- In-situ from skin-tagged and multiple scatter decays

Double Electron Capture (DEC) backgrounds:

- ^{124}Xe 0.095% natural abundance
- LM-shell (5.98 keV) and LL-shell (10 keV)
- Expect LL decays to be further suppressed $0.65 < Q_{LL}/Q_\beta < Q_L/Q_\beta$
- Allowed to float in statistical analysis to 2x ionization density
- Best fit to WS2024 data $\mathbf{Q_{LL}/Q_\beta = 0.70 \pm 0.04}$

More details in dedicated LZ paper on EC charge yields: Phys. Rev. D **112**, 012024





Look Elsewhere Effect

Baxter et al. Eur. Phys. J. C 81, 907 (2021)

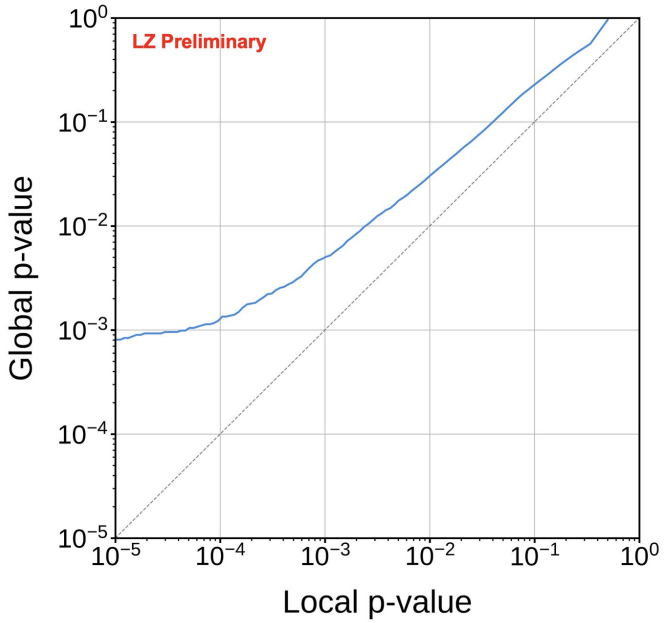
Account for the fact that, when doing many tests to see if a signal exists in excess of backgrounds, the probability to get some test that exceeds a certain threshold increases with the number of tests you do

To correct it:

- Create toy datasets from background-only model
- Perform significance tests on these toy datasets for each all models
- Find the most significant test and record the p-value (local p-value) to get a distribution of most significant p-values

When fitting to real data

- Find the most significant test and compare that to distribution of most significant p-values
- We compare how extreme the observed data is to the other local p-value to get a global p-value.
- This is the probability that we would find a dataset this extreme across all of the model tests that we do



HE Muon-induced neutrons

Muons cascades can produce neutrons, which are:

- Neutrons can be O(GeV) in energy
- Likely aligned with muon direction
- Accompanied by other products

If a muon enters any of the detectors, it is observed, and the event is removed. Only a dangerous background if:

- The neutron is the only particle to enter any detector system
- Simulations of mono-energetic neutrons (50 MeV – 1GeV) indicate 80 ± 4% tagging efficiency.

Still, contribution evaluated through simulation:

- 1200 years of LZ exposure simulated with no signal-like deposits
- Normalised to flux: $5.09 \pm 0.08_{stat.} \pm 0.10_{sys.} \times 10^{-9}$ cm^{-2} s^{-1}

90% confidence level upper limit of 4.6×10^{-4}

Selection	# Particles
μ generated	2.1×10^{9}
+ n in Lxe	5.6×10^{5}
+ SS	230
+ in FV	19
+ in ROI	0

EFT WS2024: Salt

Un-salting occurred after finalising all selections and models

Salt is injected at WF level as data is acquired

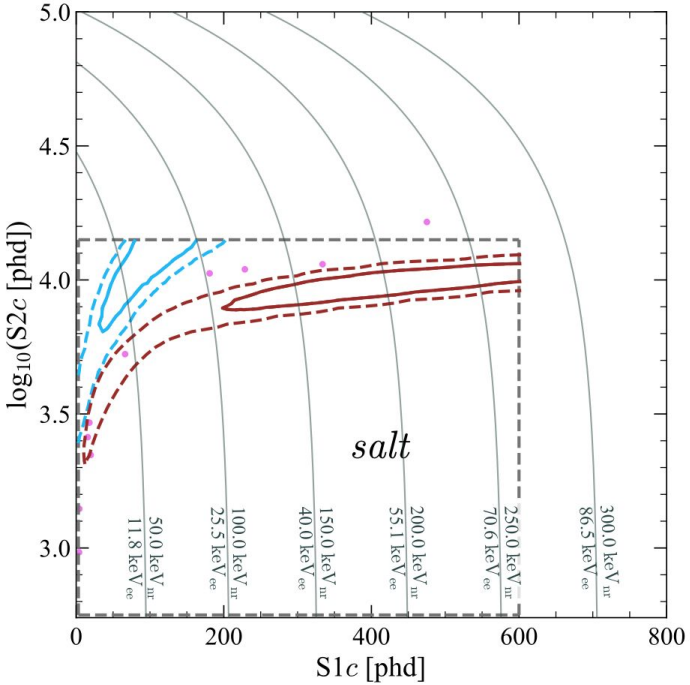
- This occurred prior to AmBe calibrations
- An assumption is made on the NR model

Upon collection of AmBe, the NR model is improved,

- As such consider this analysis **unblind**

Un-salting

- **4 salt events** were revealed
- **7 salt events** from Phys. Rev. Lett. **135**, 011802



PLR

- Likelihood is defined as

$$\mathcal{L}(\theta) = \prod_{i=0}^{2} \left[\text{Pois}(N_i|\mu_{\text{tot},i}) \times \prod_{e=1}^{N_i} \frac{1}{\mu_{\text{tot},i}} \left(\mu_{\text{sig},i}(\vec{\lambda}) f_{\text{sig},i}(\vec{x}_e) + \sum_{b=1}^{N_b} \mu_{b,i}(\vec{\lambda}) f_{b,i}(\vec{x}_e) \right) \right] \times \prod_{b=1}^{N_b} g_b(\mu_b|\vec{\nu}_b)$$

- 127Xe, Detector γ-rays are constrained by the prompt veto sample through a 88 ± 2% tagging efficiency
- MSSI are constrained by the prompt veto sample through a 94 ± 2% tagging efficiency
- Detector neutrons are constrained by the prompt veto sample a 5 ± 1% tagging efficiency and by the delayed veto sample by a 87 ± 2% tagging efficiency