Recent results from the LUX-ZEPLIN (LZ) experiment

Aiham Al Musalhi – UCL HEP seminar (Nov. 2024)

Illustration by Sandbox Studio, Chicago with Ana Kova

Content overview

The direct detection landscape

A bit about the LZ detector

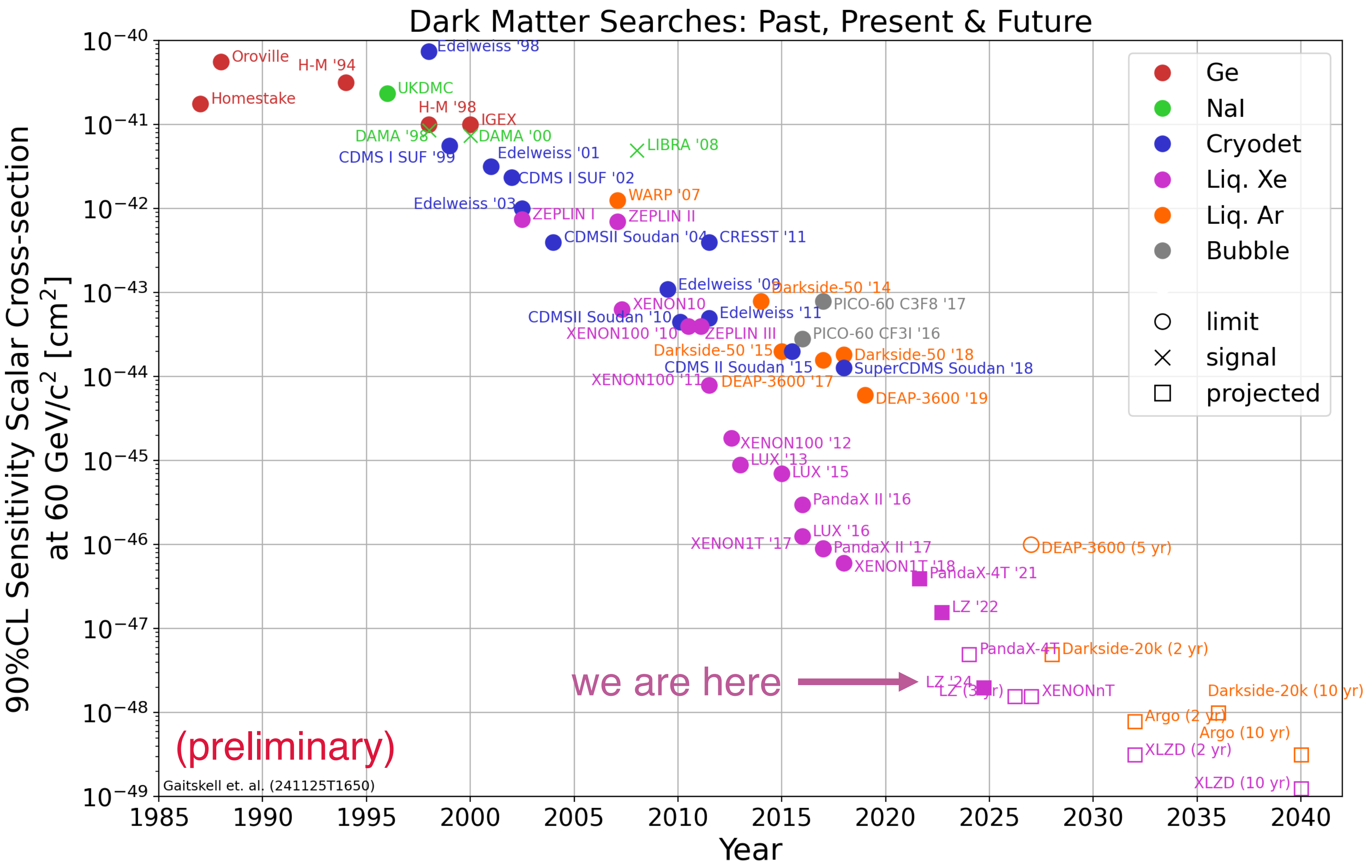
Recap of the first LZ results

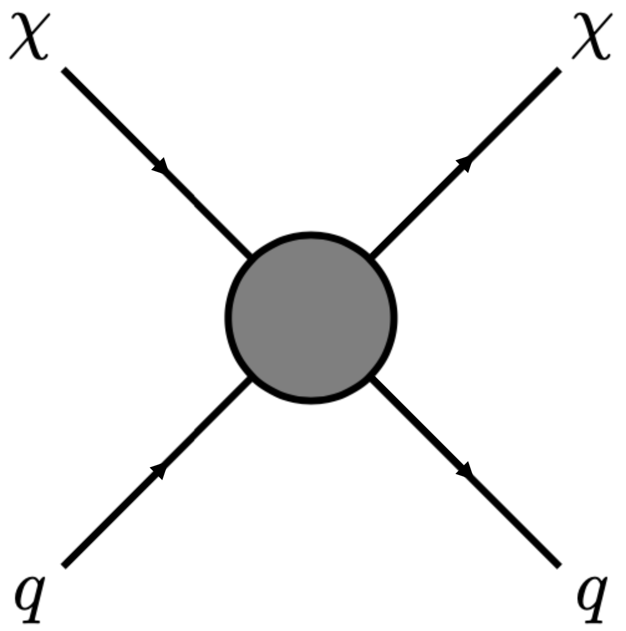
Ingredients of the latest WIMP search

Latest results

Current status and next steps

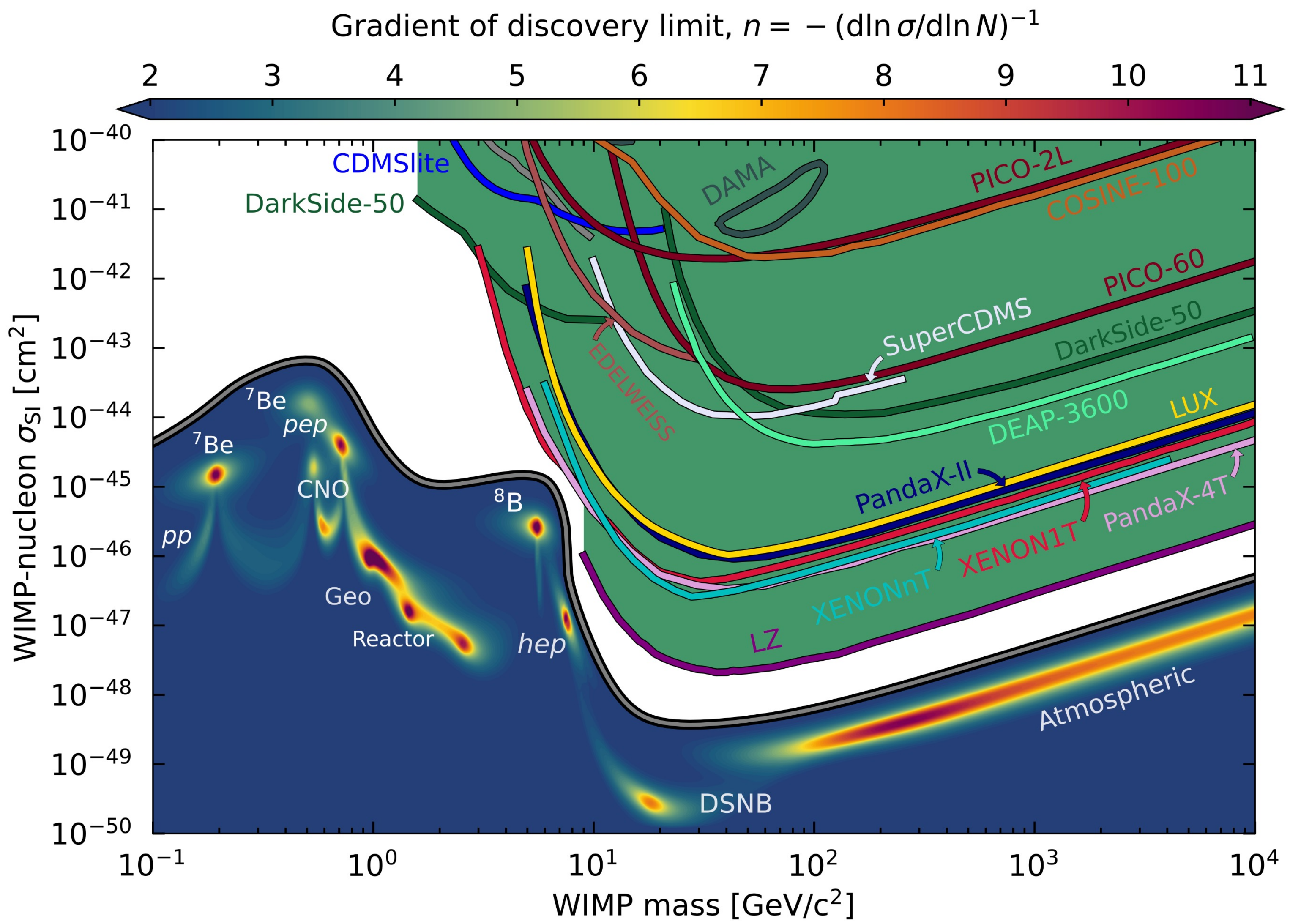
Dark matter direct detection

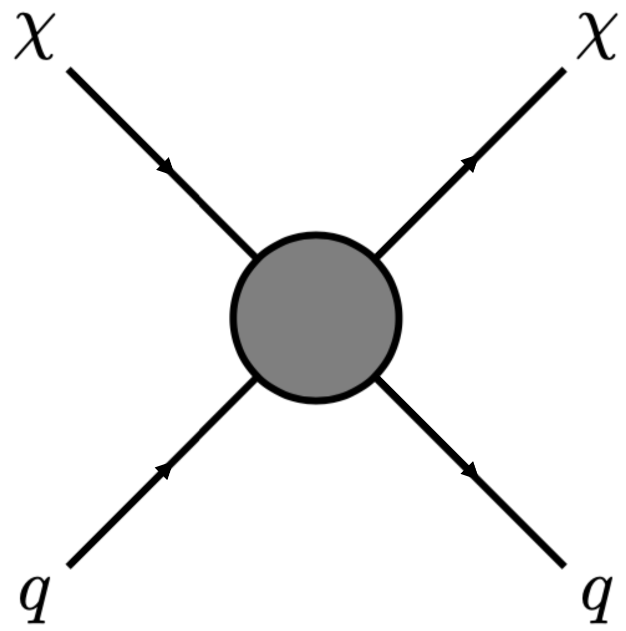




Sensitivity driven by **xenon** experiments for **nearly two decades**

Dark matter direct detection



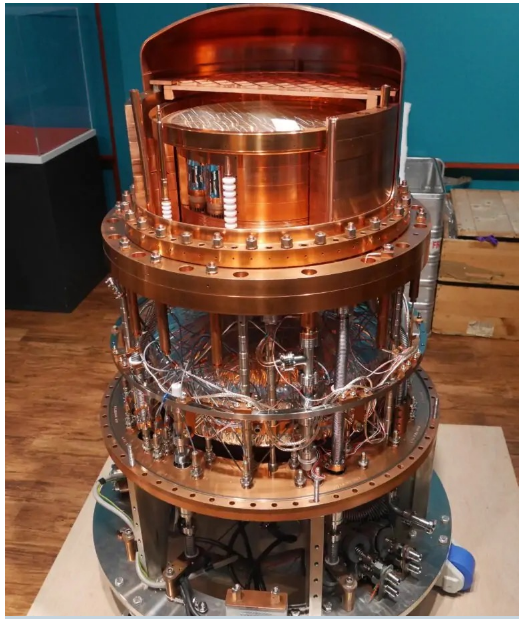


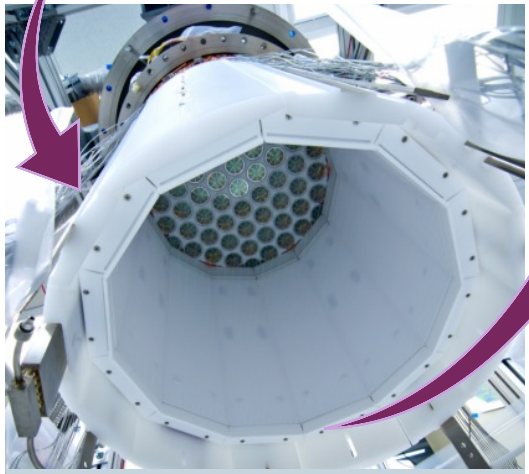
Sensitivity driven by **xenon** experiments for **nearly two decades**

Xenon detectors

Why xenon?

- Coherent nuclear scaling ($\boldsymbol{\sigma \propto A^2}$)
- Greatest **charge & light yield** of all noble elements
- Very dense ⇒ **self-shielding** (short attenuation scale)
- Inert & highly **purifiable**
- Highly scalable ⇒ **large target mass**


ZEPLIN-III – 12 kg (7 kg)


LUX – 250 kg (100 kg)


LZ – 7000 kg (5500 kg)

The LZ collaboration

38 institutions, with over **250** scientists, engineers, and technical staff

@lzdarkmatter

Black Hills State University
Brookhaven National Laboratory
Brown University
Center for Underground Physics
Edinburgh University
Fermi National Accelerator Lab.
Imperial College London
King's College London
Lawrence Berkeley National Lab.
Lawrence Livermore National Lab.
LIP Coimbra
Northwestern University
Pennsylvania State University
Royal Holloway University of London
SLAC National Accelerator Lab.
South Dakota School of Mines & Tech
South Dakota Science & Technology Authority
STFC Rutherford Appleton Lab.
Texas A&M University

University of Albany, SUNY
University of Alabama
University of Bristol
University College London
University of California Berkeley
University of California Davis
University of California Los Angeles
University of California Santa Barbara
University of Liverpool
University of Maryland
University of Massachusetts, Amherst
University of Michigan
University of Oxford
University of Rochester
University of Sheffield
University of Sydney
University of Texas at Austin
University of Wisconsin, Madison
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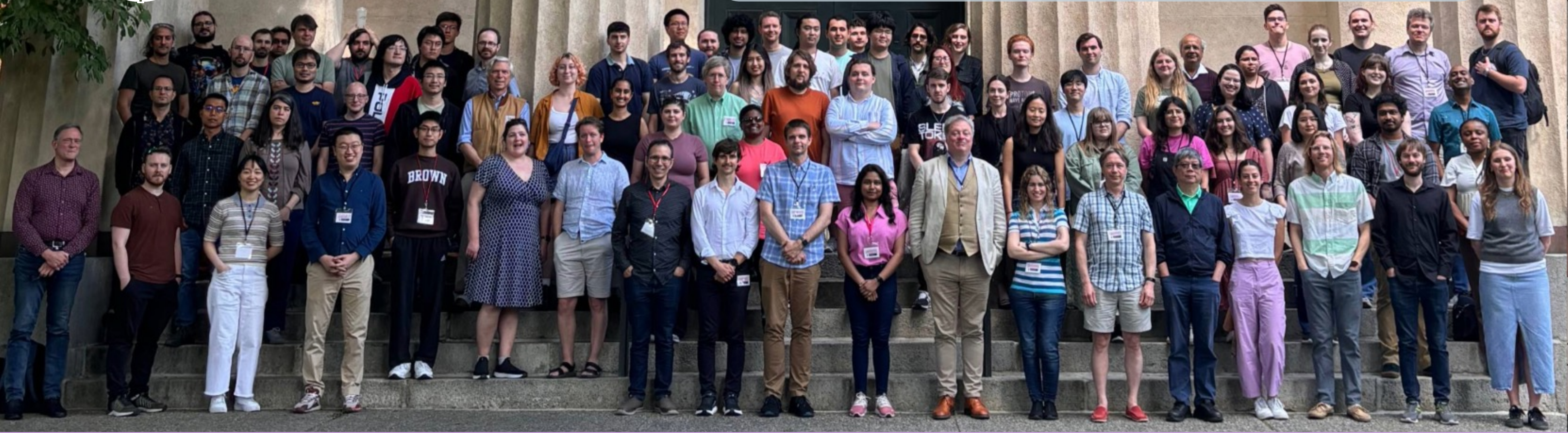
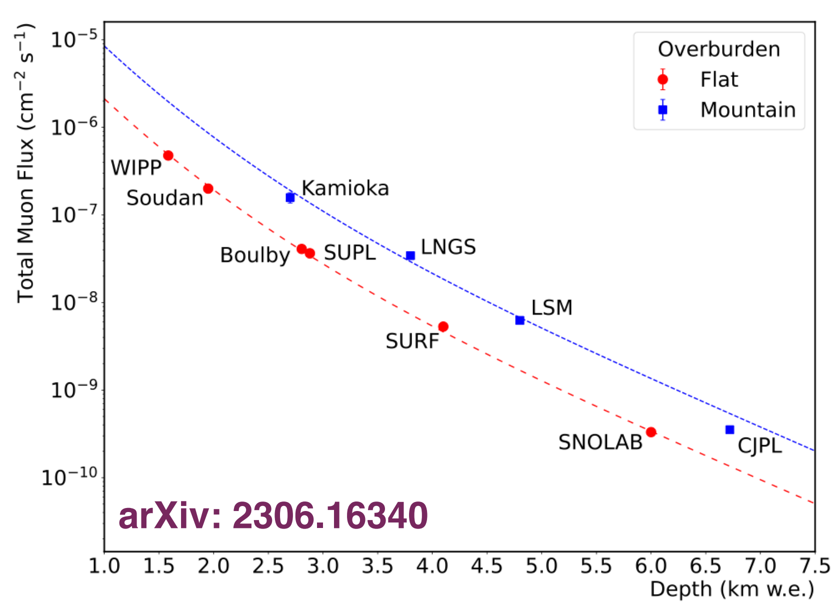
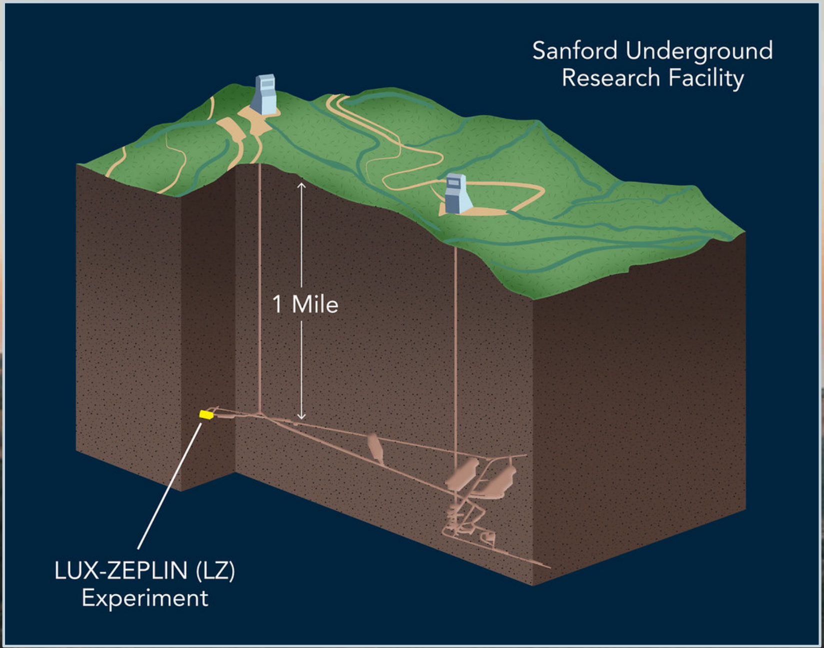


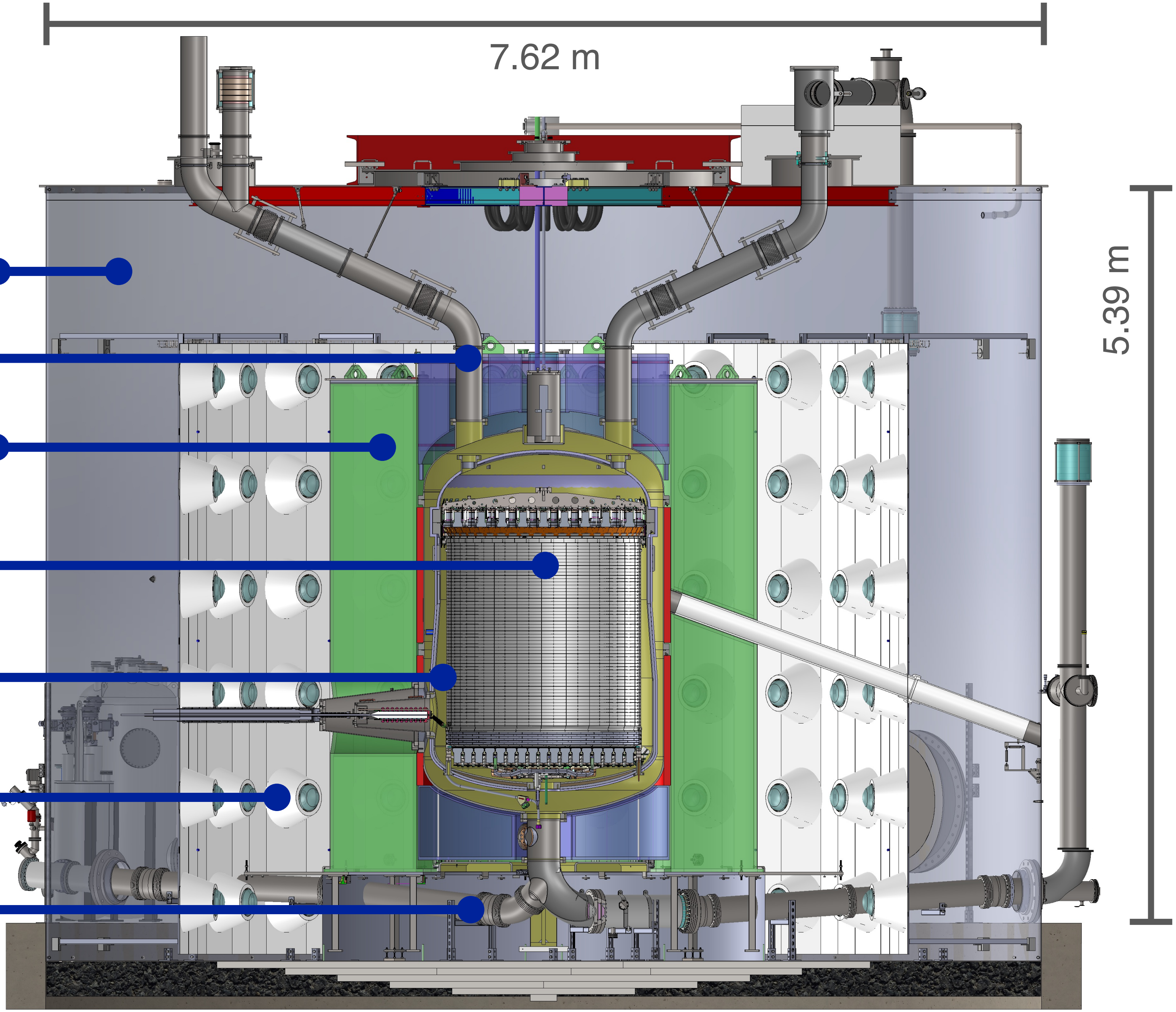
The LZ experiment

- Situated in Davis Cavern, **1480 m underground** in Lead, South Dakota
- 1100 m (4300 m.w.e) rock overburden
  ⇒ muon flux attenuated by a factor of **3×10^6**



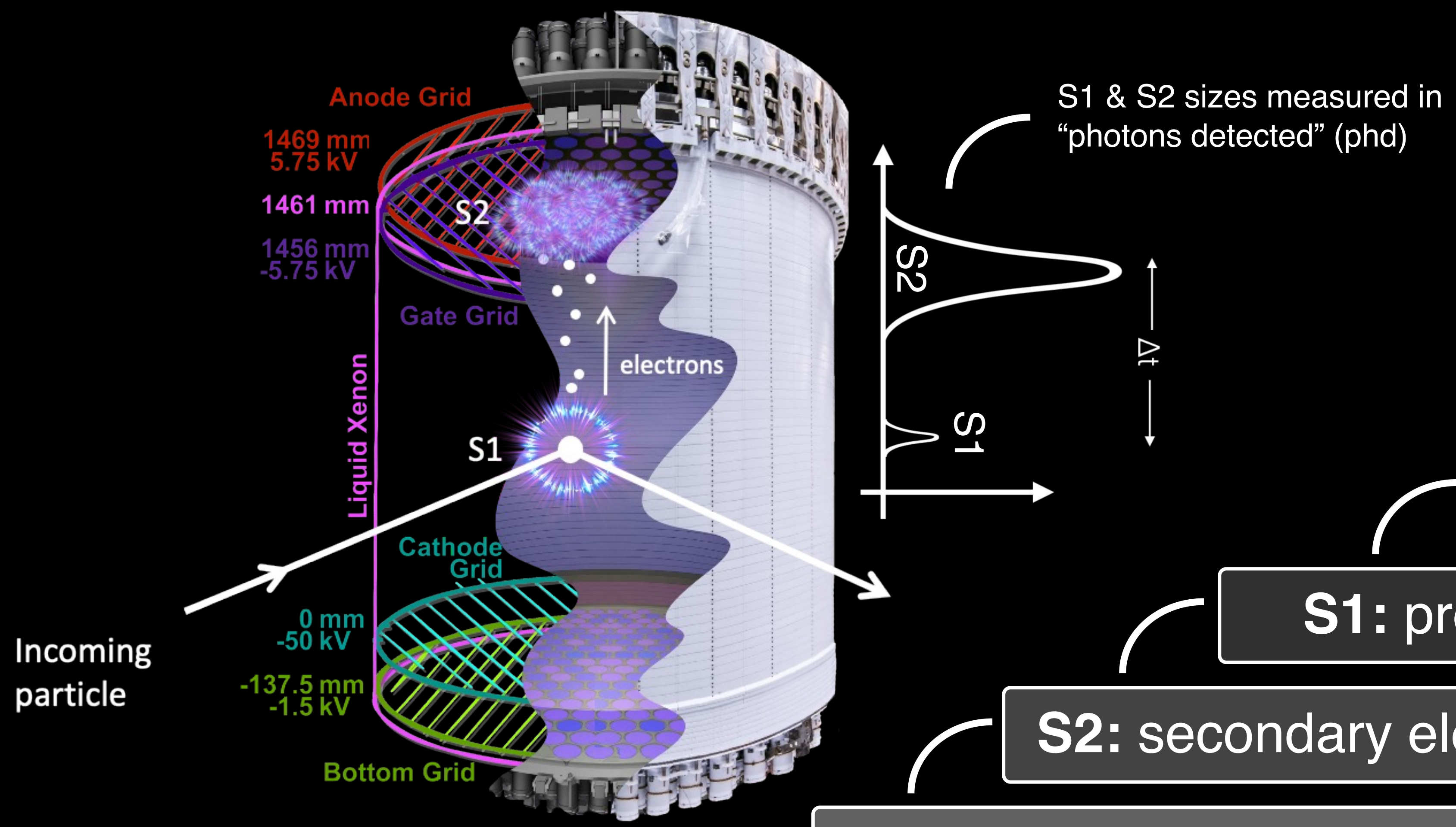


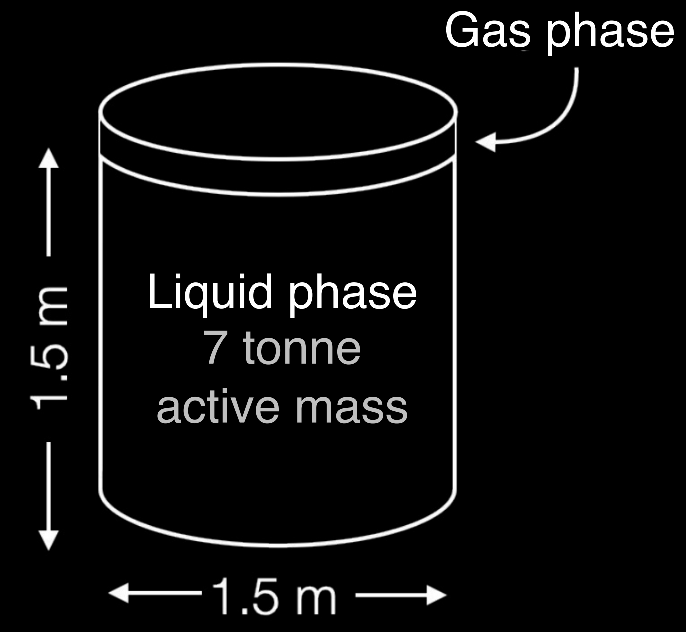
The LZ detector



J. NIM A953, 163047 (2019)

The time projection chamber (TPC)





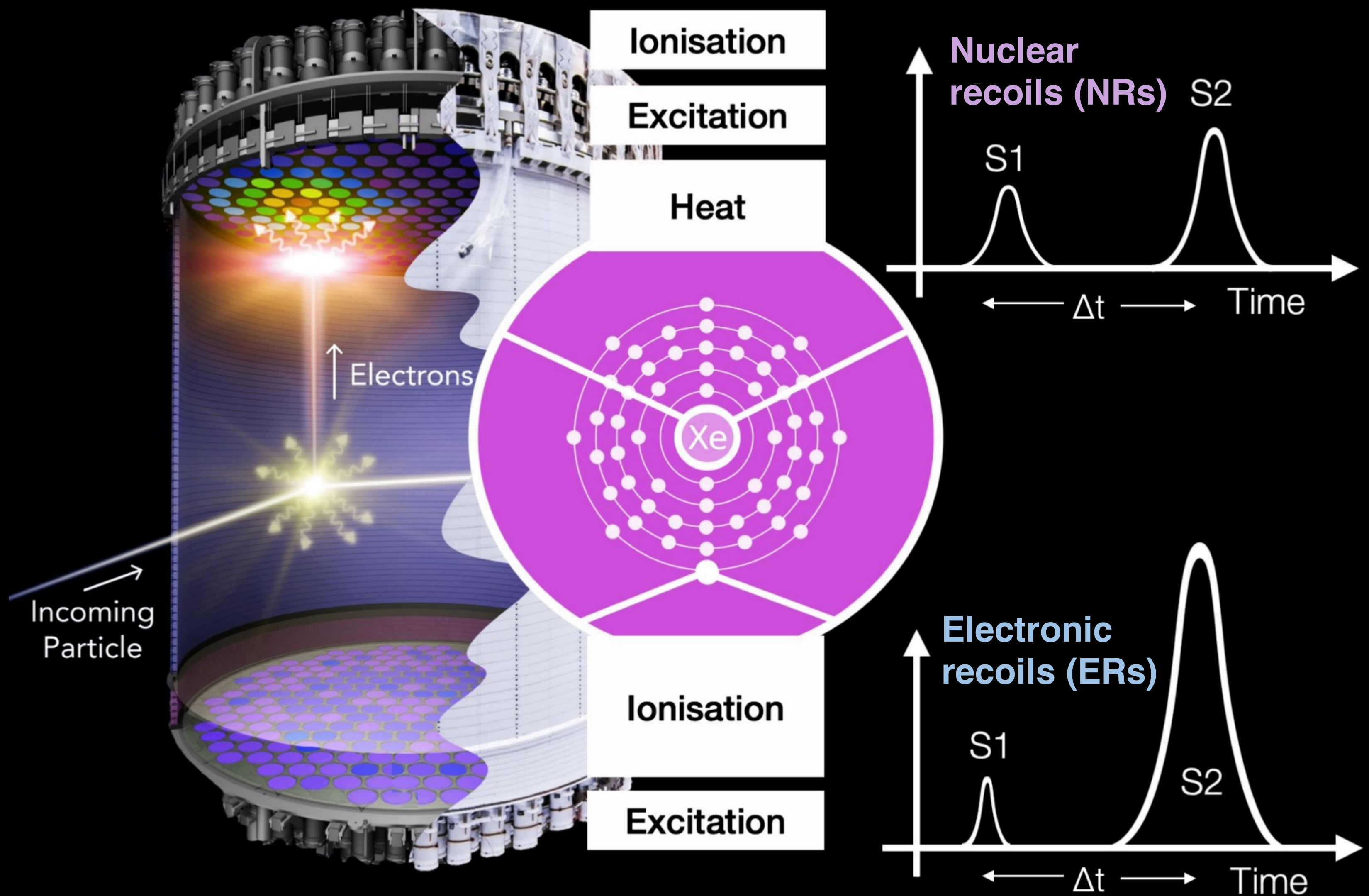
Scatter in liquid xenon

S1: prompt scintillation signal

S2: secondary electroluminescence signal

Light detected by photomultiplier tube (**PMT**) arrays

The time projection chamber (TPC)



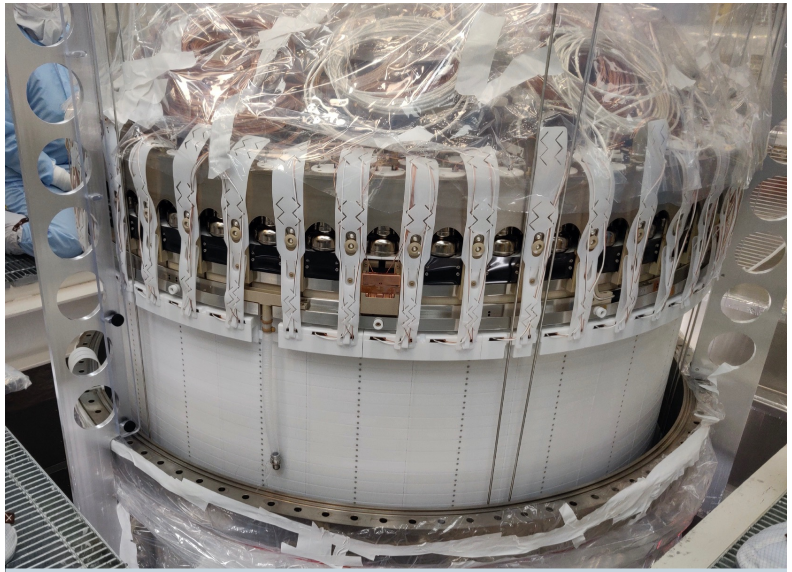
Position reconstruction from top-array hit map (x, y) and drift time (z)

Discrimination between signal-like NRs and background-like ERs via ratio of observables (S1, S2)

Veto detector subsystems

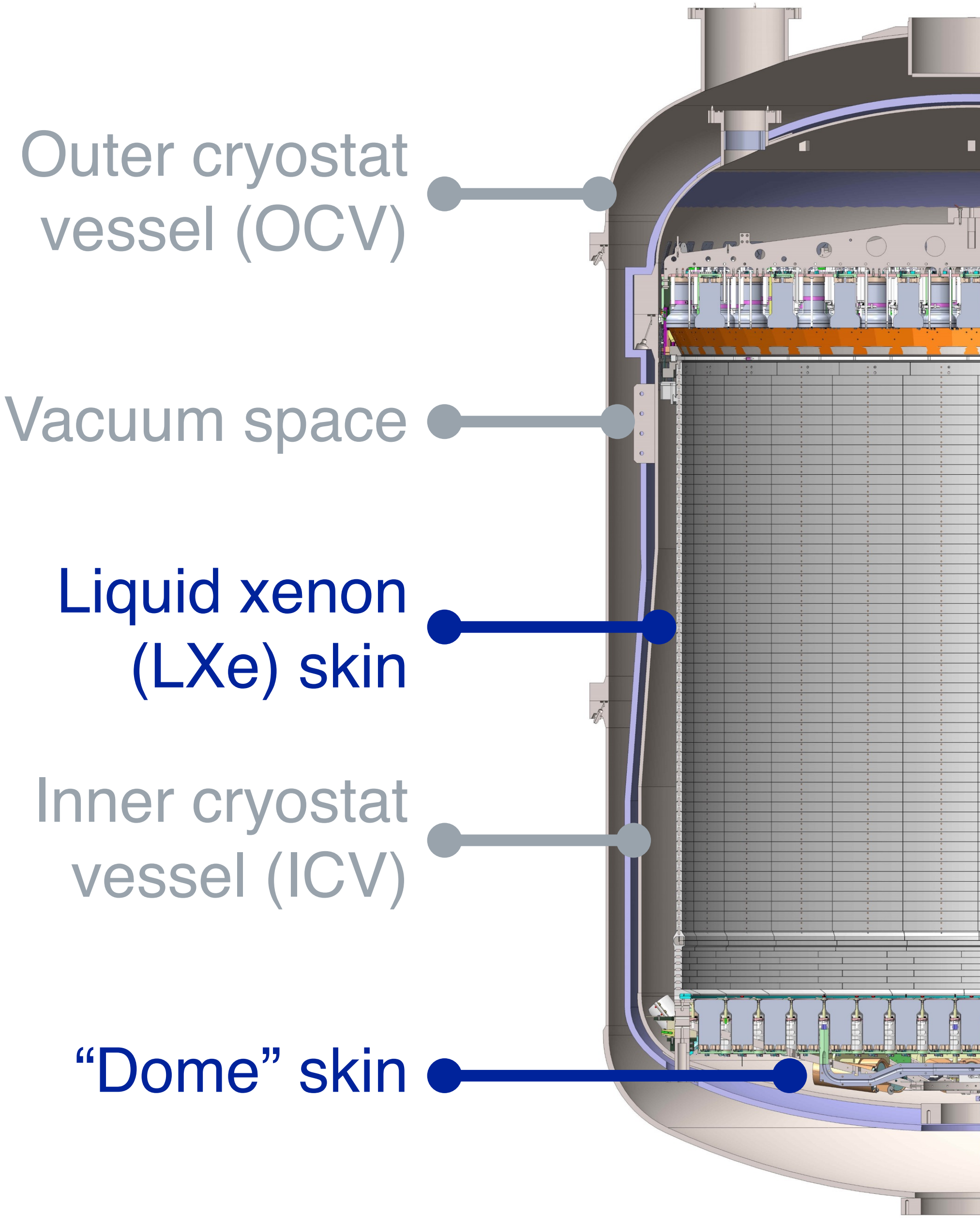
Instrumented LXe skin

- Positioned between TPC and ICV
- Contains approximately **2 tonnes** of xenon
- Mainly tags **γ-ray energy deposits**



Insertion of TPC into ICV

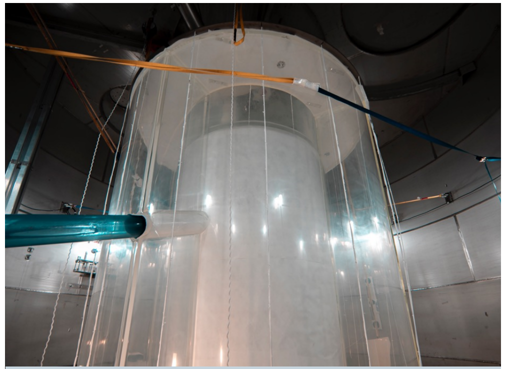
Installation of top skin PMTs

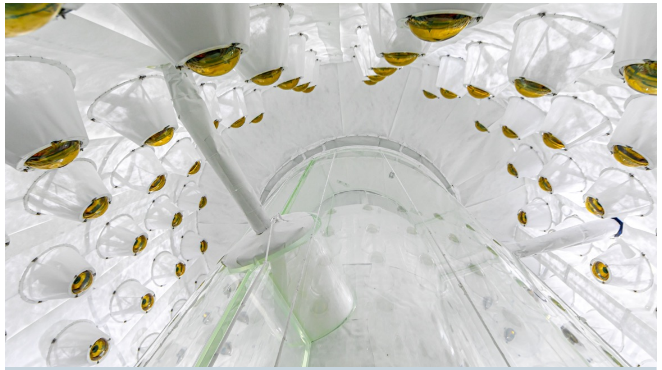


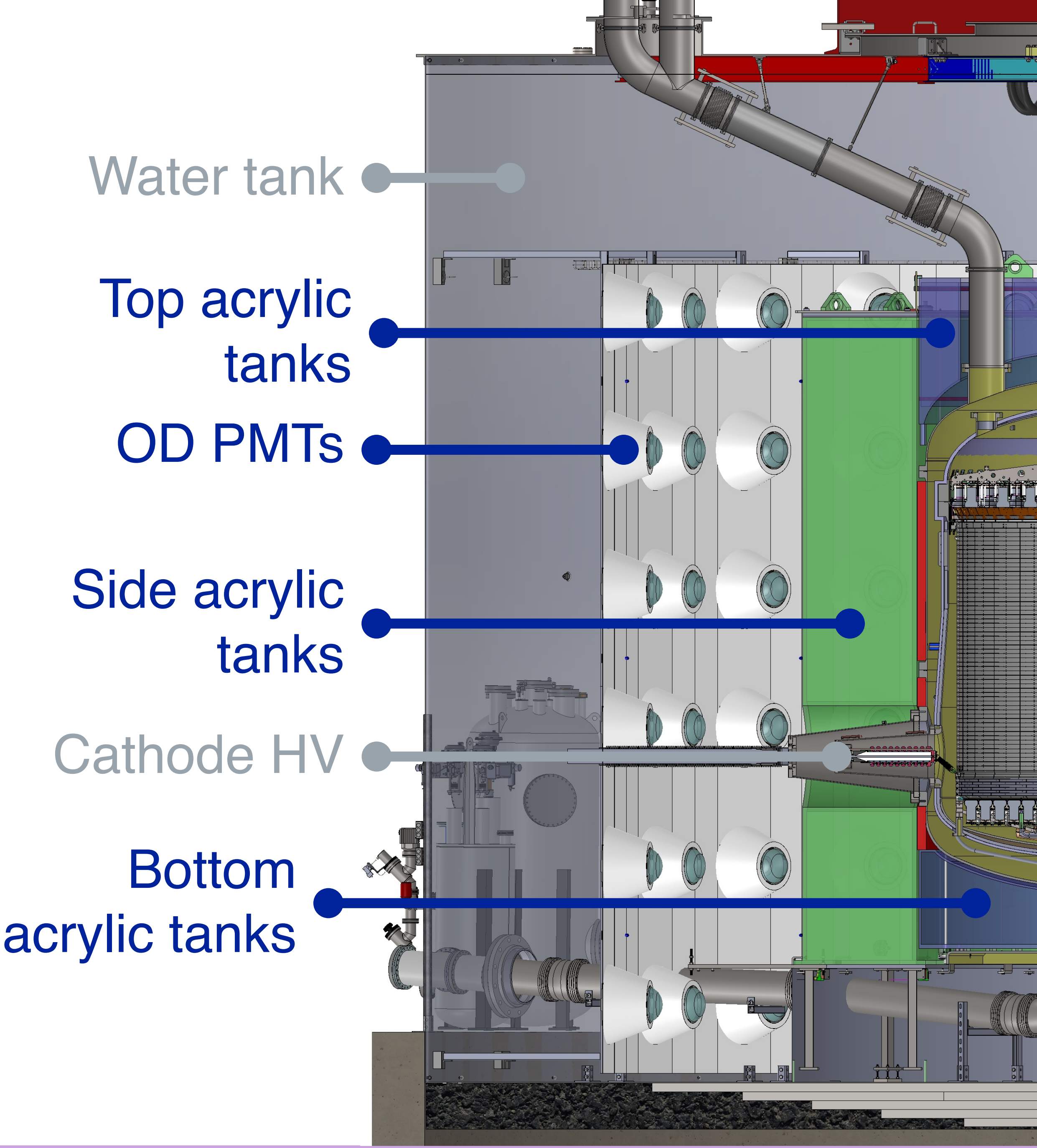
Veto detector subsystems

Outer detector (OD)

- Acrylic tanks containing 17.3 tonnes of Gd-doped liquid scintillator (**GdLS**)
- Primarily tags γ-ray cascades from **neutrons** capturing on Gd (or H)
- All **shielded** within water tank containing 238 tonnes of ultra-pure water


OD installation


Assembled OD



LZ operation timeline

Installation

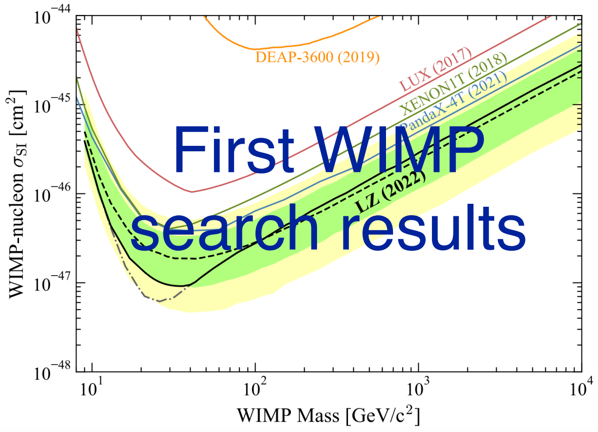
2020 2021 2022 2023 2024

Commissioning begins

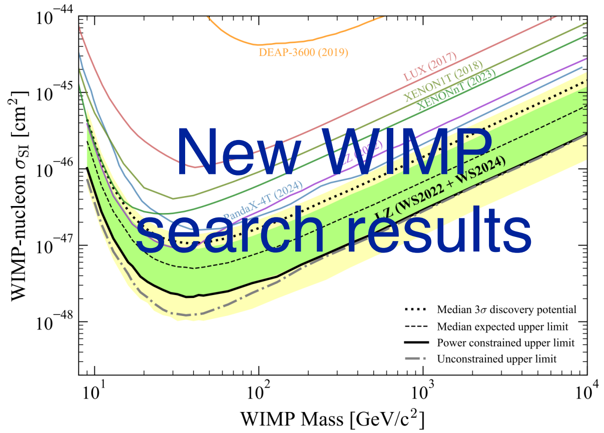
WS2024 starts

TPC underground

WS2022 starts



First WIMP search results



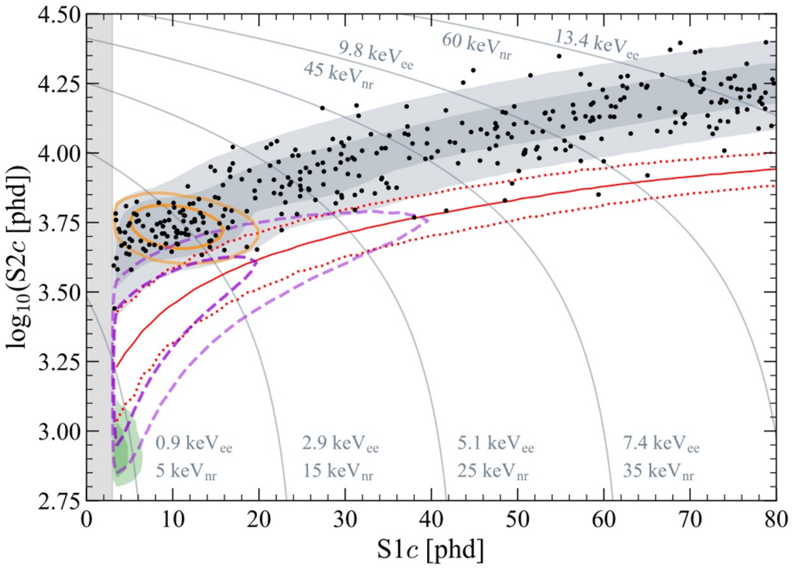
New WIMP search results

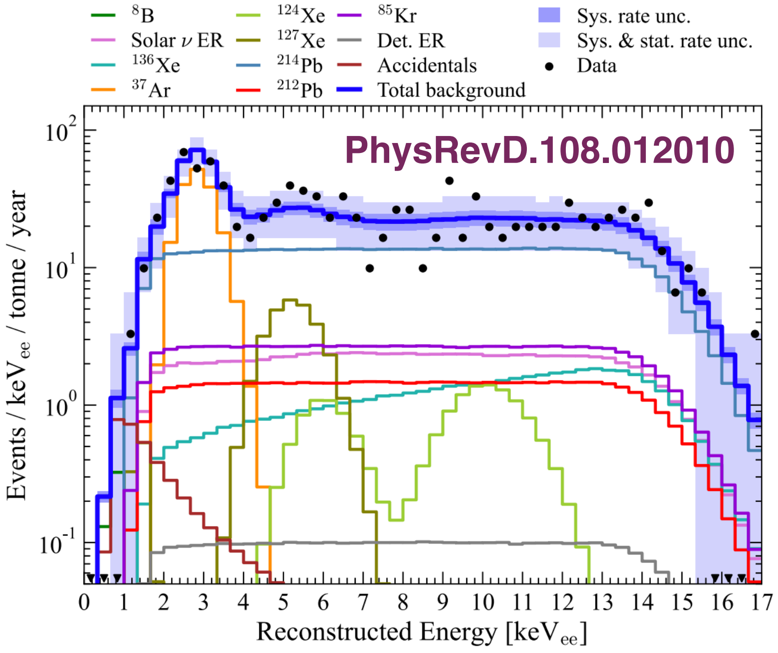
Recap of first WIMP search (WS2022)

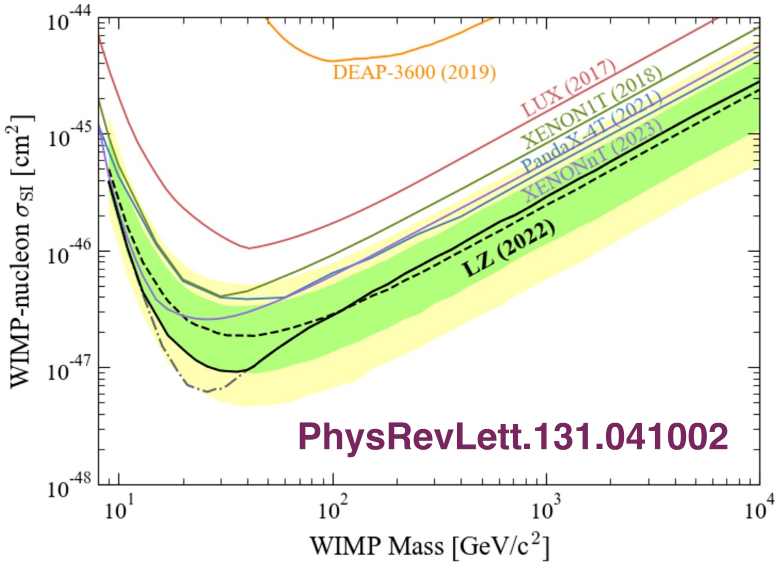
60 live day analysis; first "engineering" run (**not blinded**)

Extensive background modelling (enough for a companion paper)

Minimum cross section of $\sigma_{SI} = 9.2 \times 10^{-48}$ cm^2 for 36 GeV/c^2 WIMPs







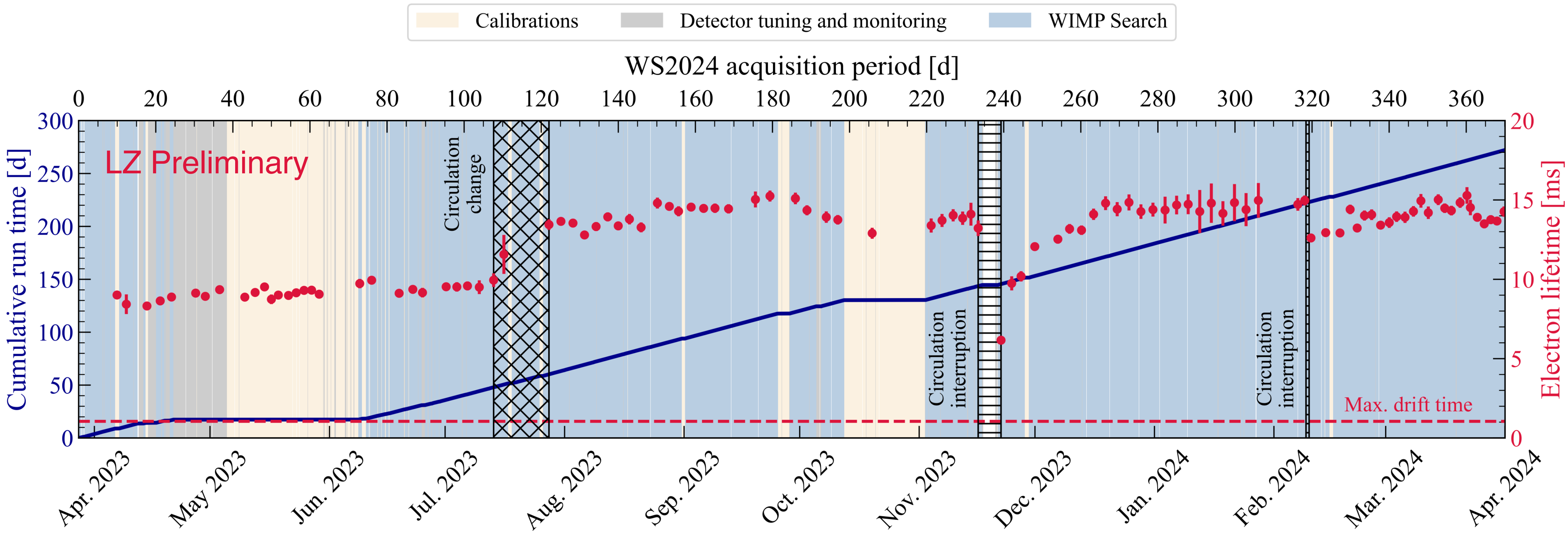
Latest WIMP search (WS2024)

Dark Matter Search Results from 4.2 Tonne-Years of Exposure of the LUX-ZEPLIN (LZ) Experiment

J. Aalbers,[1,2] D.S. Akerib,[1,2] A.K. Al Musalhi,[3] F. Alder,[3] C.S. Amarasinghe,[4] A. Ames,[1,2] T.J. Anderson,[1,2]
N. Angelides,[5] H.M. Araújo,[5] J.E. Armstrong,[6] M. Arthurs,[1,2] A. Baker,[7] S. Balashov,[8] J. Bang,[9]
J.W. Bargemann,[4] E.E. Barillier,[10,11] D. Bauer,[5] K. Beattie,[12] T. Benson,[13] A. Bhatti,[6] A. Biekert,[12,14]

We report results of a search for nuclear recoils induced by weakly interacting massive particle (WIMP) dark matter using the LUX-ZEPLIN (LZ) two-phase xenon time projection chamber. This analysis uses a total exposure of 4.2 ± 0.1 tonne-years from 280 live days of LZ operation, of which 3.3 ± 0.1 tonne-years and 220 live days are new. A technique to actively tag background electronic recoils from ^{214}Pb β decays is featured for the first time. Enhanced electron-ion recombination is observed in two-neutrino double electron capture decays of ^{124}Xe, representing a noteworthy new background. After removal of artificial signal-like events injected into the data set to mitigate analyzer bias, we find no evidence for an excess over expected backgrounds. World-leading constraints are placed on spin-independent (SI) and spin-dependent WIMP-nucleon cross sections for masses $\geq$9 GeV/c^2. The strongest SI exclusion set is 2.1×10^{-48} cm^2 at the 90% confidence level at a mass of 36 GeV/c^2, and the best SI median sensitivity achieved is 5.0×10^{-48} cm^2 for a mass of 40 GeV/c^2.

Latest WIMP search (WS2024)



~370 days of data
⇒ **220 live days**

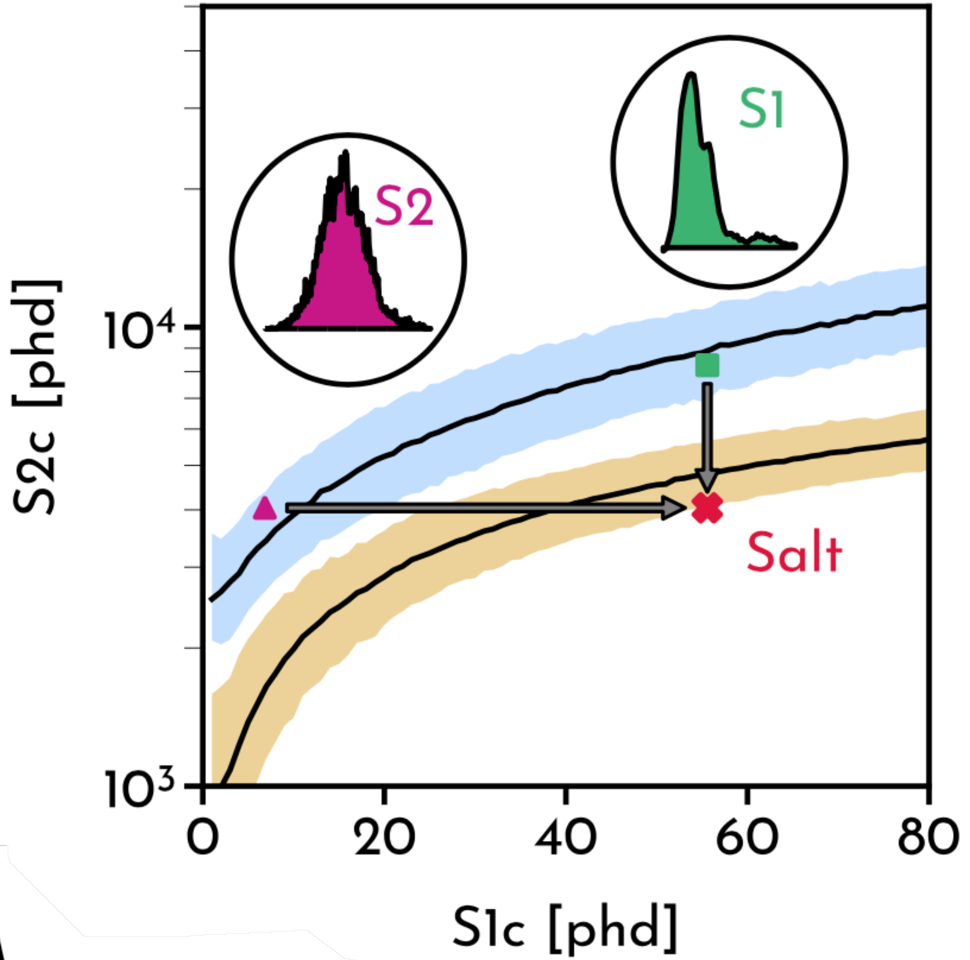
High target **purity**
(3.3 t/day circulation)

Salted for bias
mitigation

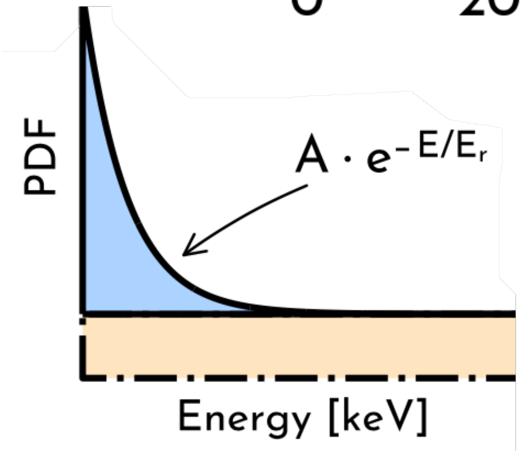
Bias mitigation

Usual approach is to **blind** the region of interest (ROI), but LZ uses **salting**

- **Fake signal events** (salt) created using S1s and S2s from calibration data
- These are **randomly injected** into the data stream during acquisitions
- **Unknown WIMP rate** below WS2022 limit
- Recoil spectrum for WIMP of unknown mass; ⇒ parameters are **all unknown** to analysers



Unsalting happens happens *after* fit inputs are frozen ⇒ enables **unbiased** analysis



Exponential plus flat pedestal

Calibrations

Detector response calibrated* with various sources:

- **ERs:** radiolabelled methane CH_3T, ^{83m}Kr, ^{131m}Xe
- **NRs:** DD neutrons, AmLi, AmBe

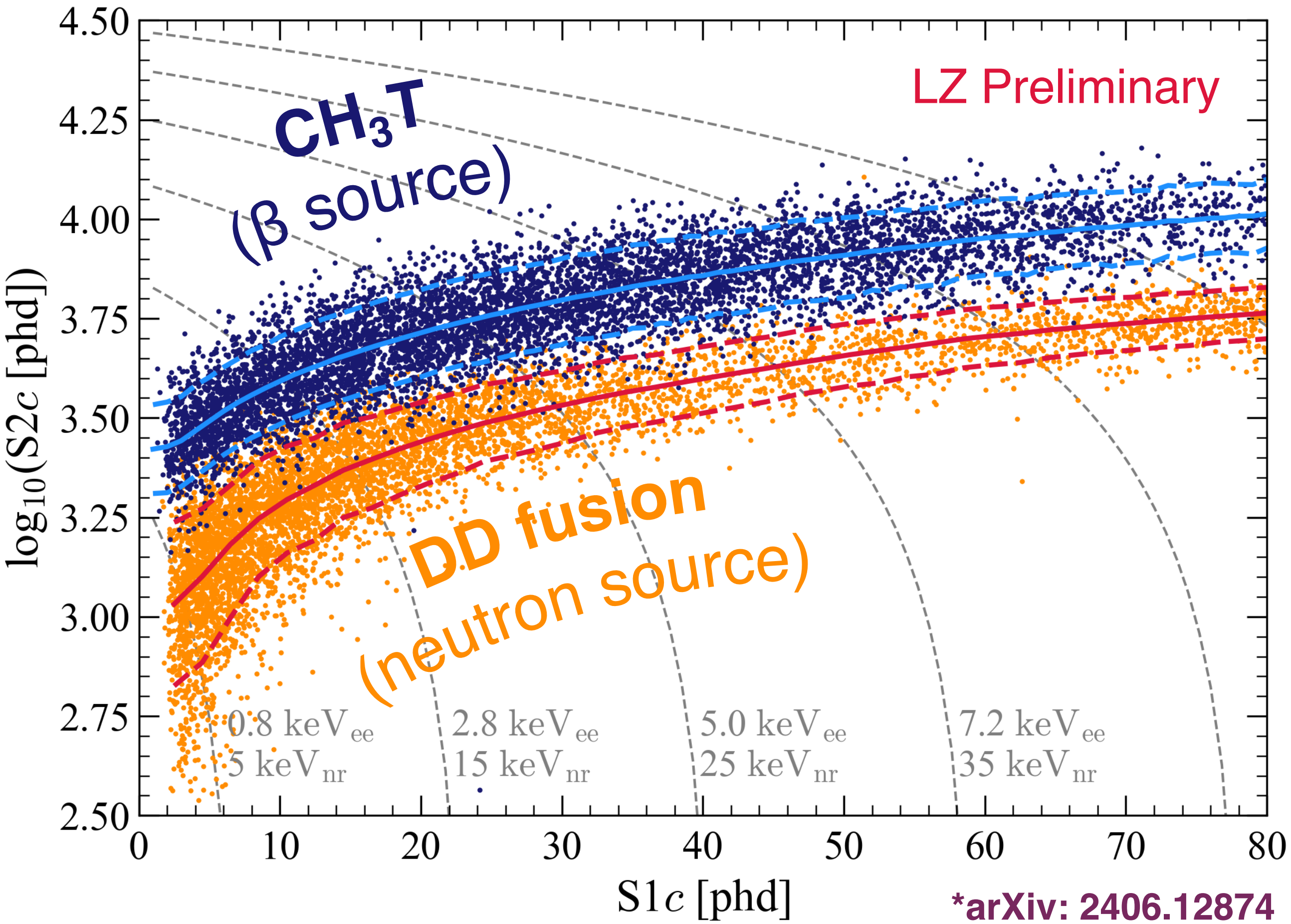
⇒ **99.8% discrimination** achieved

Operating at lower fields w.r.t. WS2022 has *not* affected **discrimination power**

	C/G/A voltage [kV]	Drift field [V/cm]	Extraction field [kV/cm]
WS2022	-32/-4/+4	193	7.3
WS2024	-18/-4/+3.5	97	3.4

Light gain (g_1) = (0.112 ± 0.002) phd/photon

Charge gain (g_2) = (34.0+ 0.9) phd/electron



*arXiv: 2406.12874

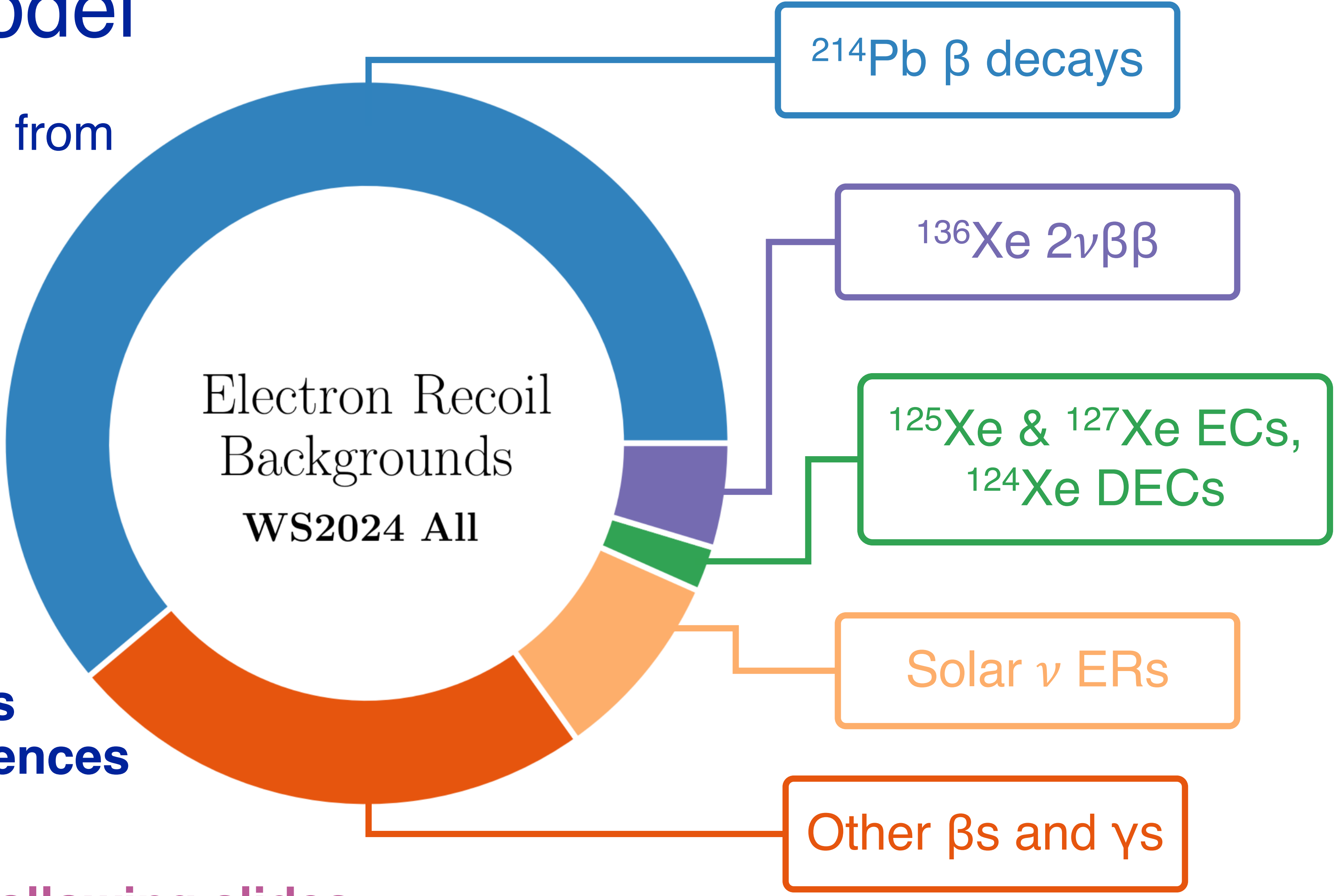
Background model

Understand backgrounds from **sideband** analyses, **assays**, and ***in situ*** **measurements**

Expect **0.18 NR** events from CEνNS (**0 from neutrons**)

Predict **(2.8 ± 0.6) counts** from **accidental coincidences** of S1s and S2s

⇒ more on these **in the following slides**



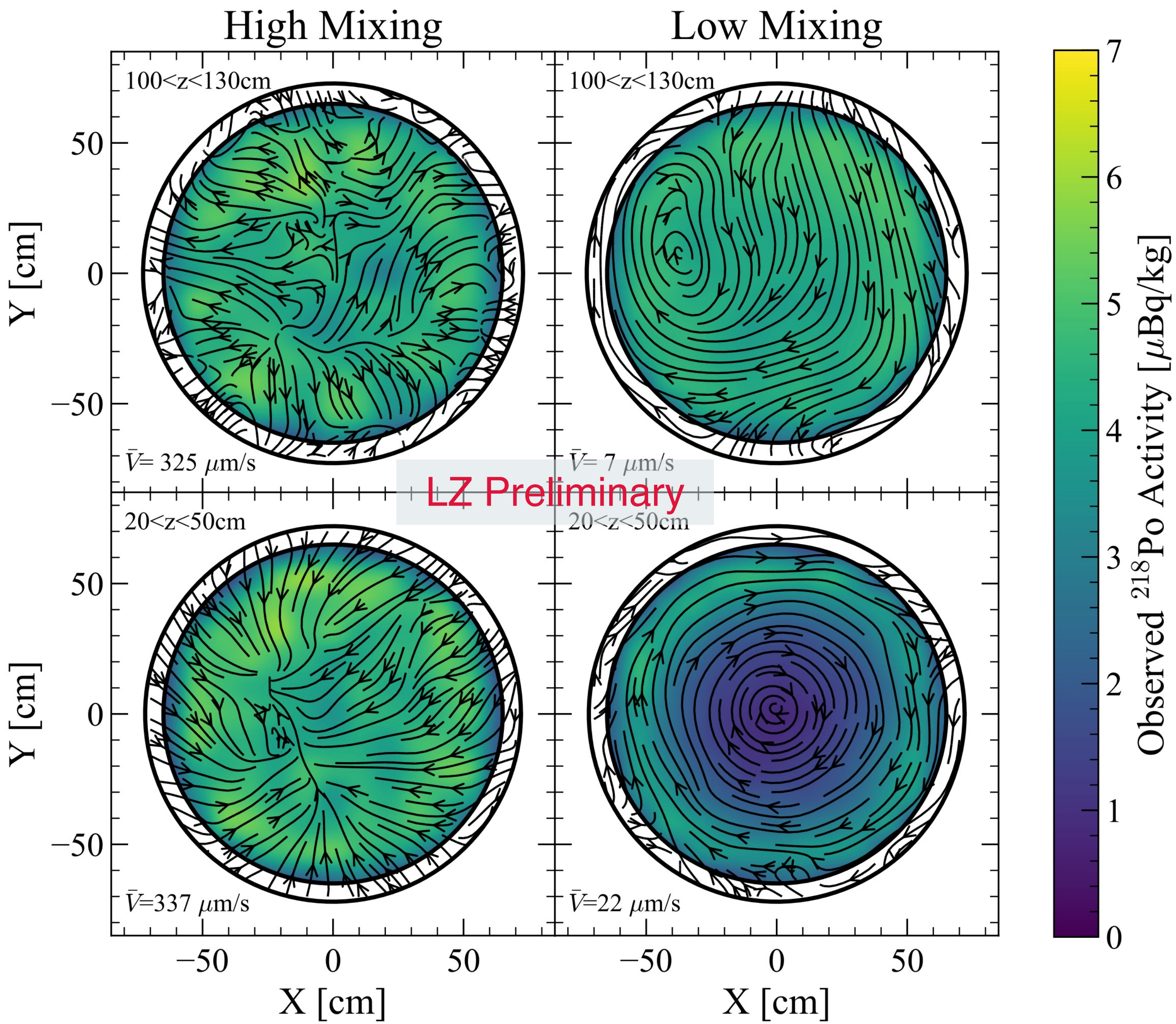
Radon tagging

"Naked" ^{214}Pb β decays (~10%)
⇒ *worst* ER background

Liquid xenon flow

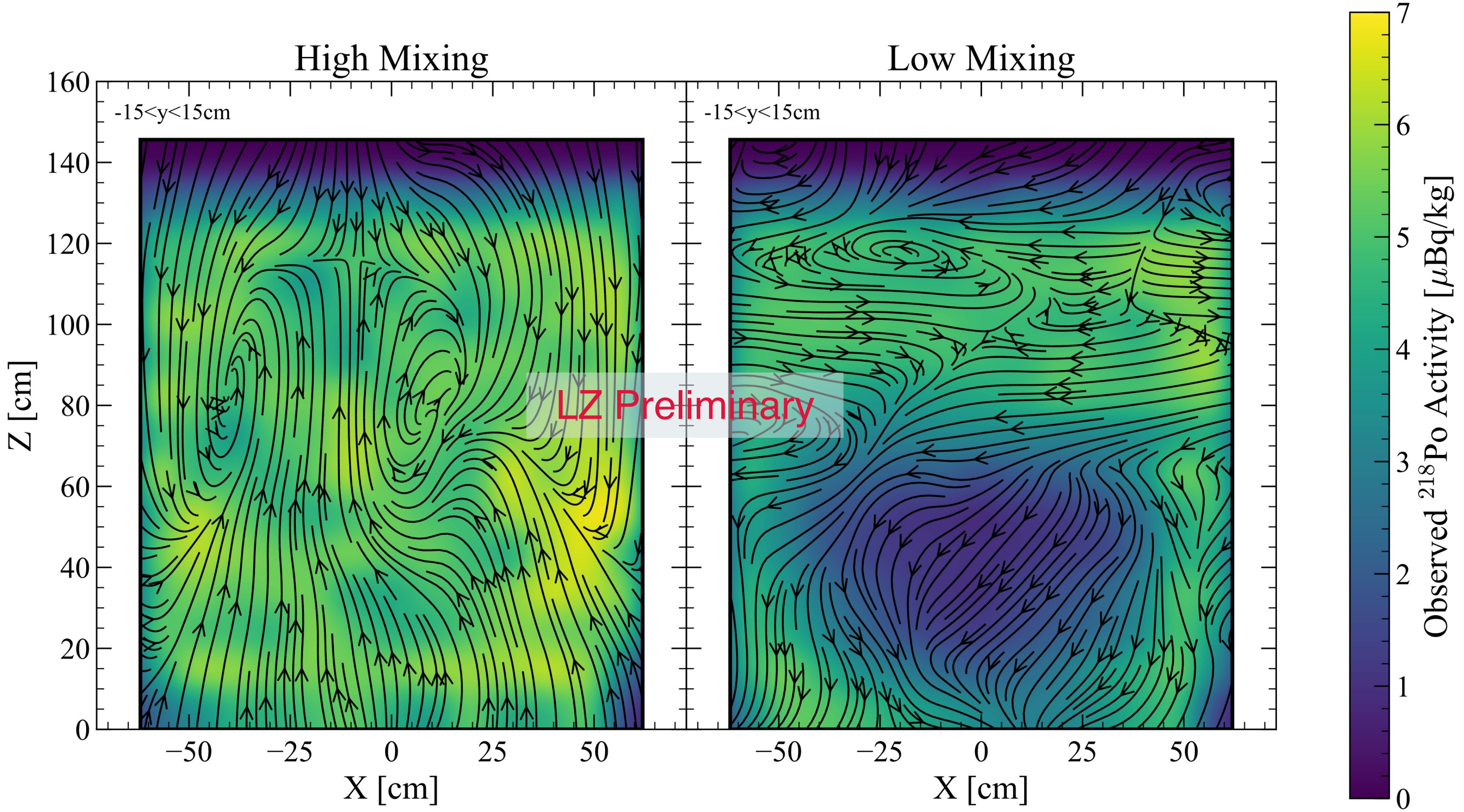
- Flow of xenon can be controlled with circulation and cooling systems
- **High mixing state** ⇒ turbulent
- **Low mixing state** ⇒ laminar

With low mixing, **flow can be mapped for radon tagging**



Radon tagging

Low mixing state establishes an "**isolated region**" with lower rates towards the bottom

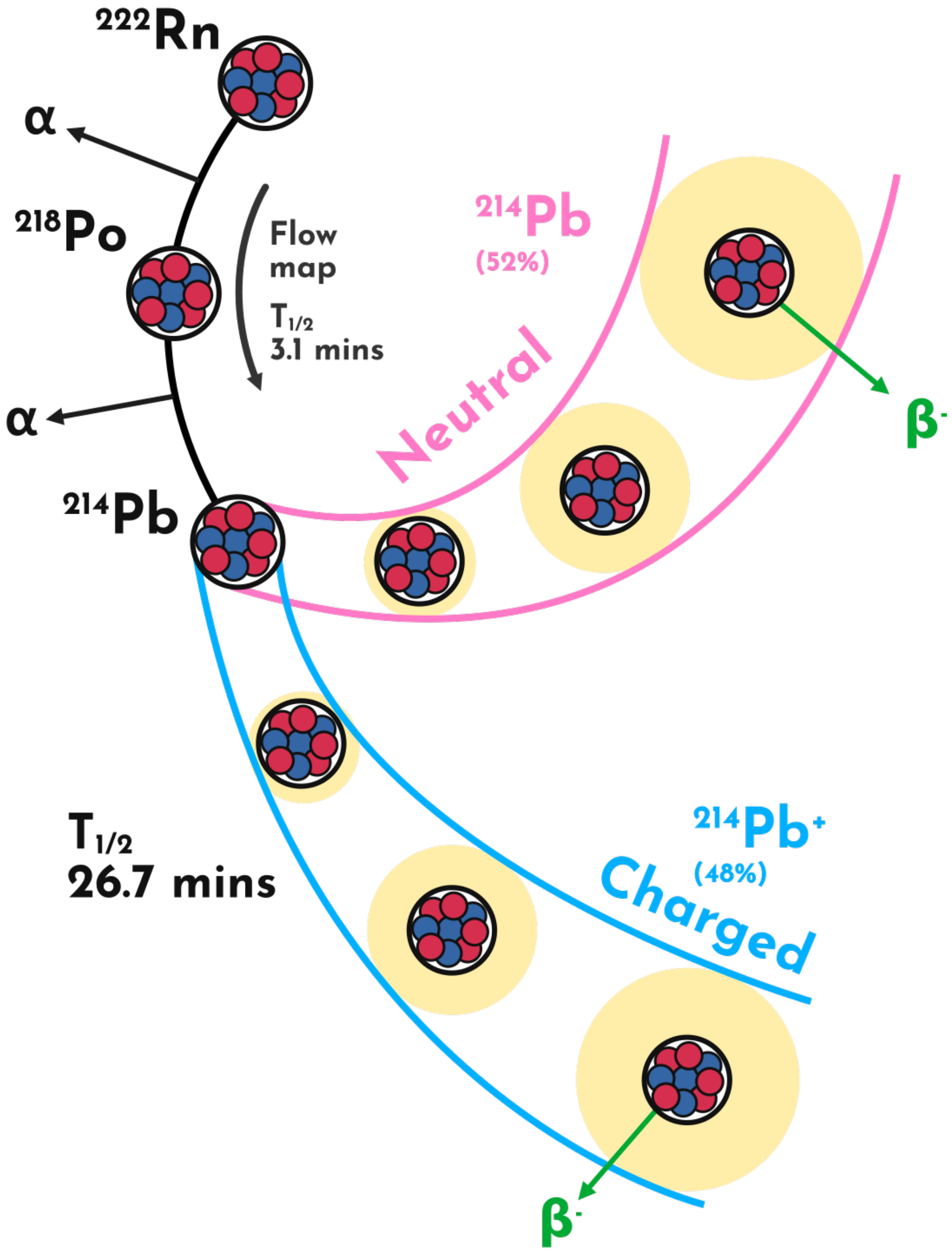


Radon tagging

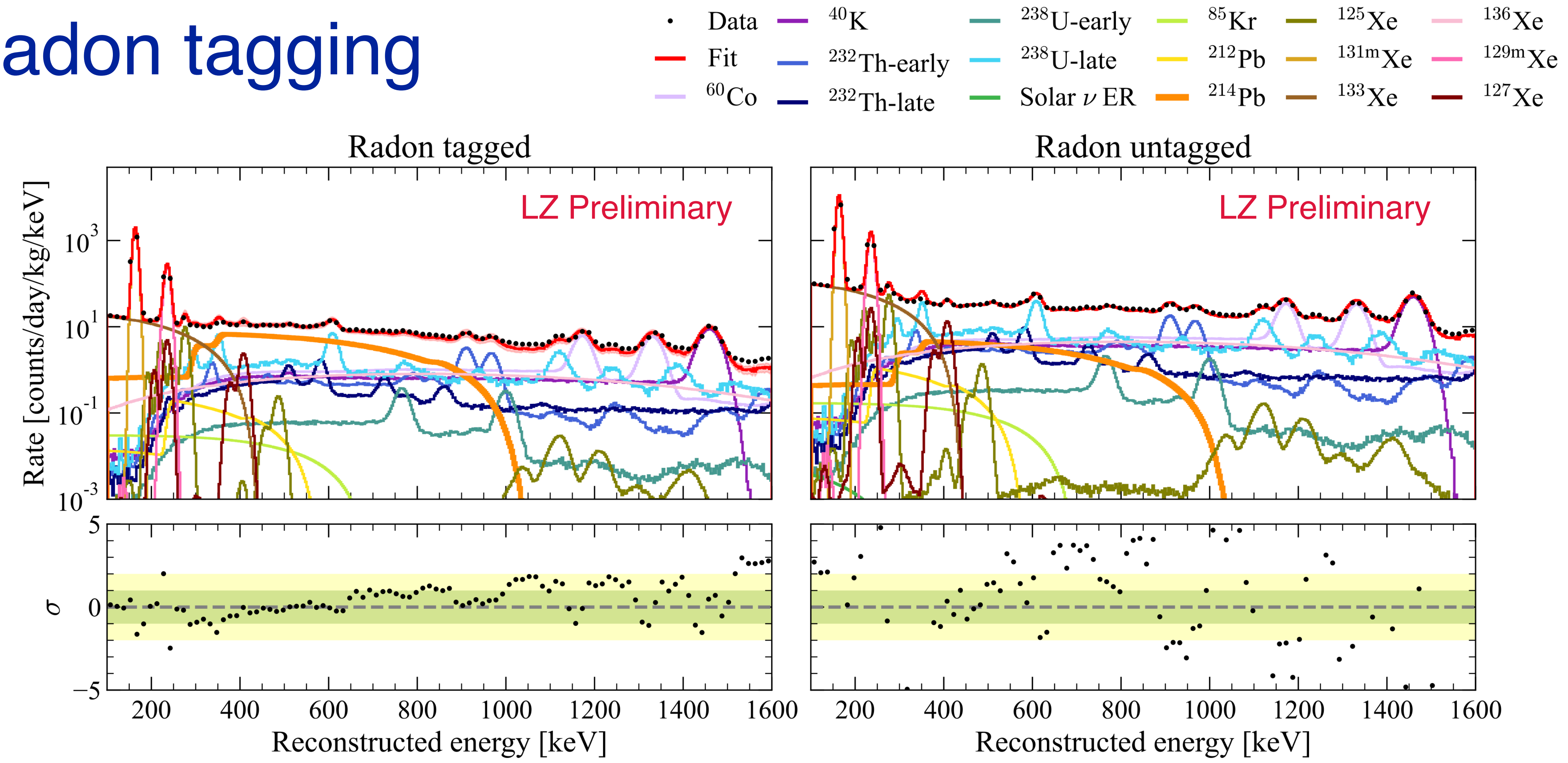
Background mitigation with an **active radon tag***

- **Flow vectors mapped** using α decays of ^{222}Rn-^{218}Po pairs ($t^{1/2}$ = 3.1 min)
- Track co-moving volumes around **streamlines where ^{214}Pb is likely to decay**
- Volumes are active for **81 mins** (~3 × $t_{1/2}$)
- Measured **tagging efficiency** of (60 ± 4)%
- Tagged dataset included in statistical inference, *not removed*

*publication in preparation



Radon tagging

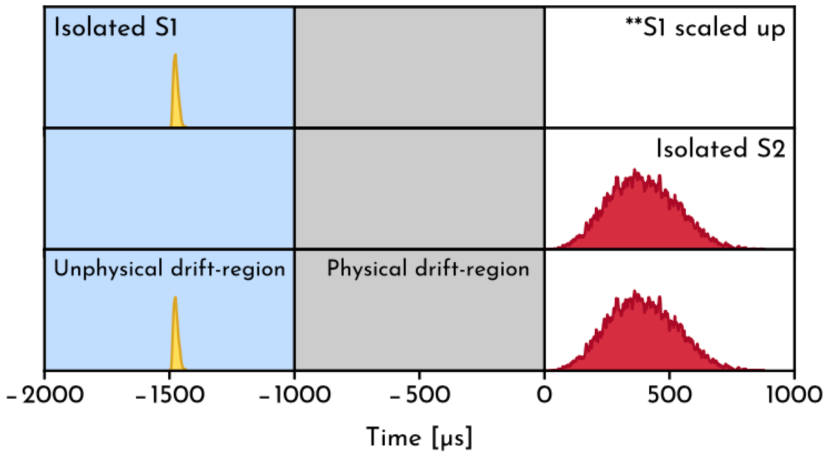


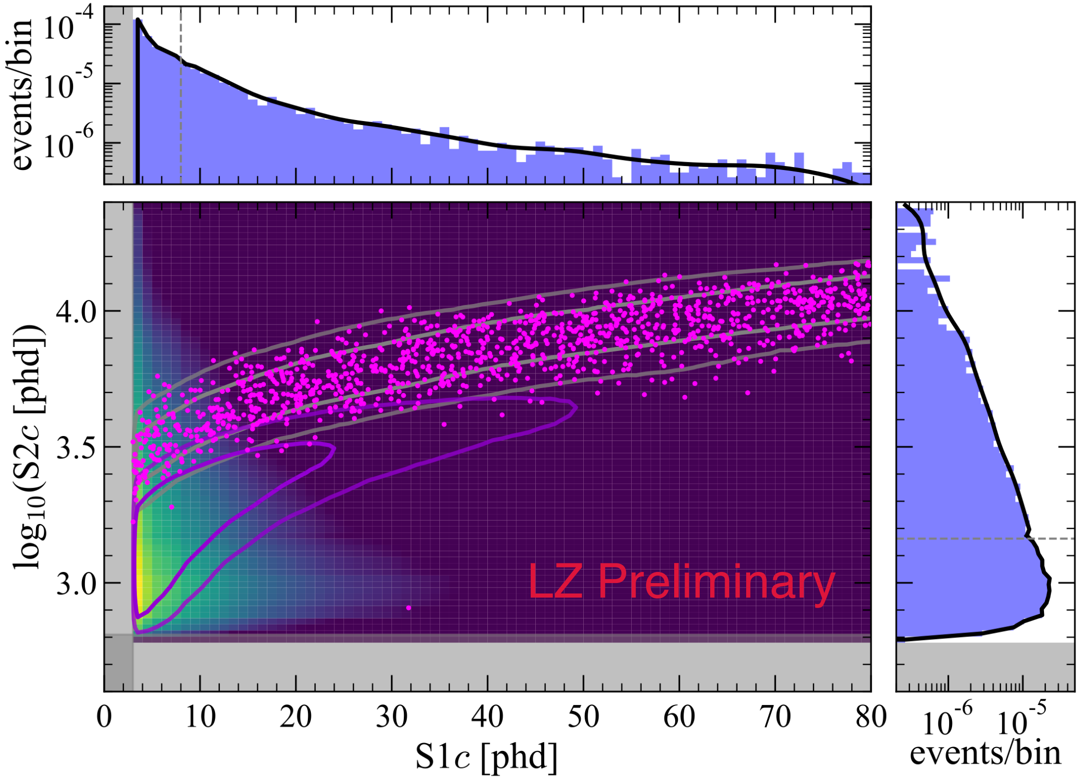
^{214}Pb rate *reduced* from (3.9 ± 0.6) μBq/kg (total) to (1.8 ± 0.3) μBq/kg (untagged)

Accidental coincidences

Coincident pile-up of **isolated S1s and S2s**
⇒ these can look like single scatters and even **mimic WIMPs**

- **Rate** measured using accidentals with *unphysical drift times*
- Distributions **modelled with fake events** constructed from lone S1s and S2s
- Whole suite of **analysis cuts** developed to combat observed pulse & event pathologies
  ⇒ **> 99.5% rejection efficiency,** (**2.8 ± 0.6 counts** in WS2024)





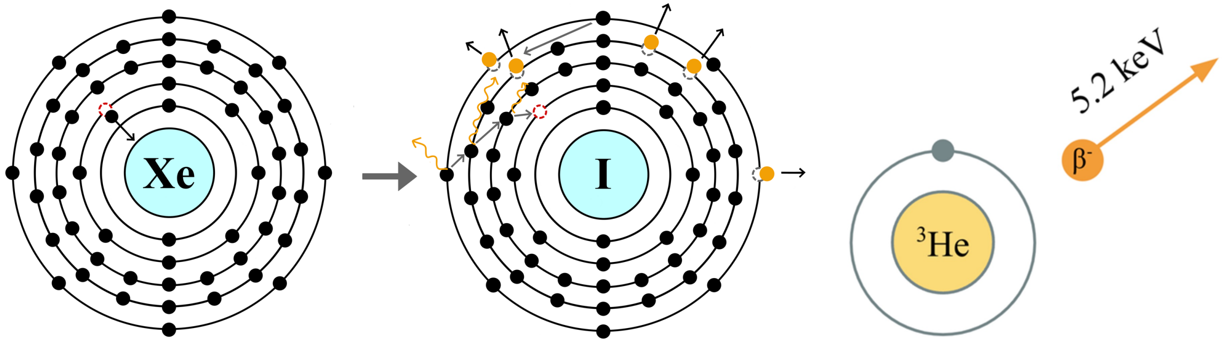
Electron captures (ECs)

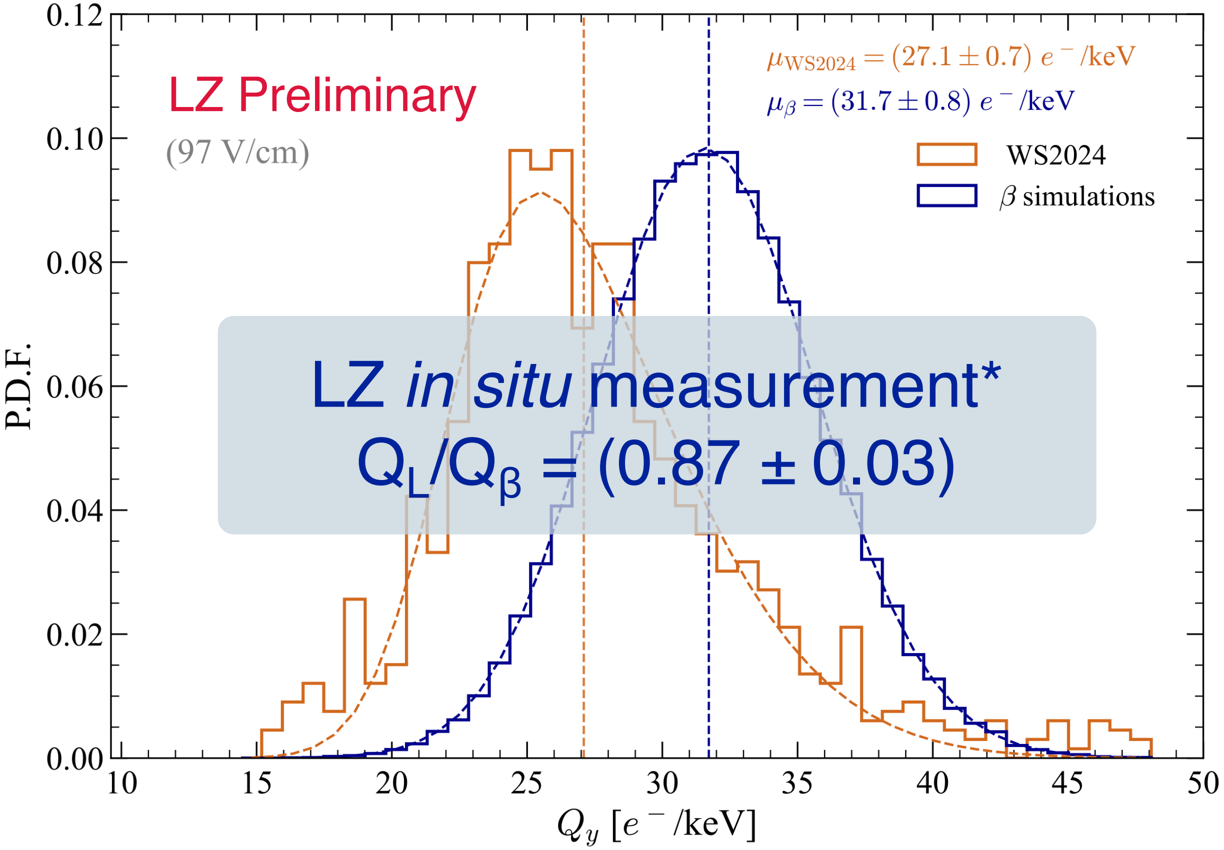
^{125}Xe & ^{127}Xe decays via **electron capture** also introduce backgrounds

- Generated cosmogenically & through neutron activation during calibrations
- Substantially *lower* activity in WS2024

L-shell captures (5.2 keV) most relevant

- Energy depositions from X-ray/Auger cascades are more nucleated than βs ⇒ results in **charge yield suppression** (i.e. appears more NR-like)
- First measured in XELDA and LUX



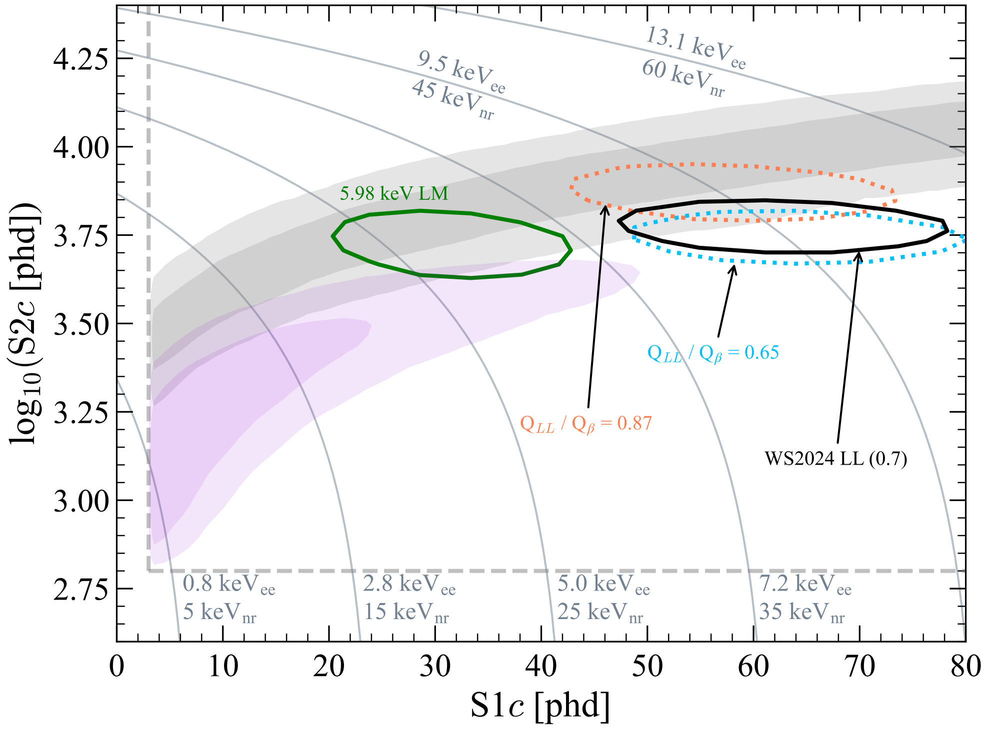


*publication in preparation

Double electron captures (DECs)

*publication in preparation

^{124}Xe DEC is the *rarest* decay measured, at
$T_{1/2} = (1.09 \pm 0.14_{stat} \pm 0.05_{sys}) \times 10^{22}$ yr
⇒ LZ measurement recently published



Despite this, LL (10.0 keV) and LM (5.2 keV) captures form **backgrounds** to the WIMP search

- LM charge suppression modelled the same as single L-shell EC
- Further suppression expected for LL due to higher ionisation density (ID)
  ⇒ **this is floated in the background model**

(2x L-shell ID) **[$0.65 < (Q_{LL}/Q_\beta) < 0.87$]** ($Q_L/Q_\beta$)

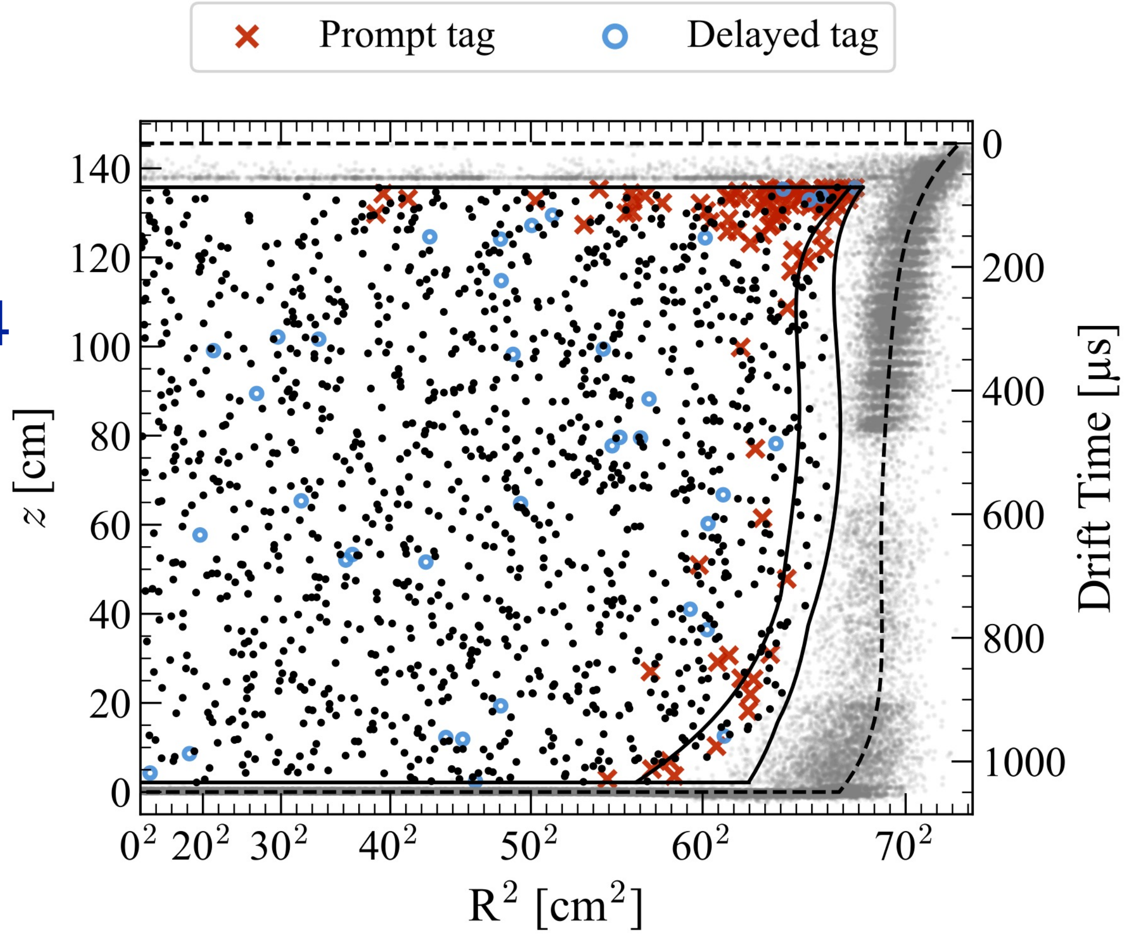
Best-fit value:
$Q_{LL}/Q_\beta = (0.70 \pm 0.04)$

Fiducial volume (FV)

Majority of backgrounds are peripheral;
self-shielding leveraged to reduce this

Fiducial cut excludes outer volumes

- **Azimuthal dependence** added in WS2024
- ~4 cm wall stand-off on average
- ~10 cm from gate, 2.2 cm from cathode
- Designed to allow **< 0.01 wall events**
- Calculated fiducial mass of **(5.5 ± 0.2) t**



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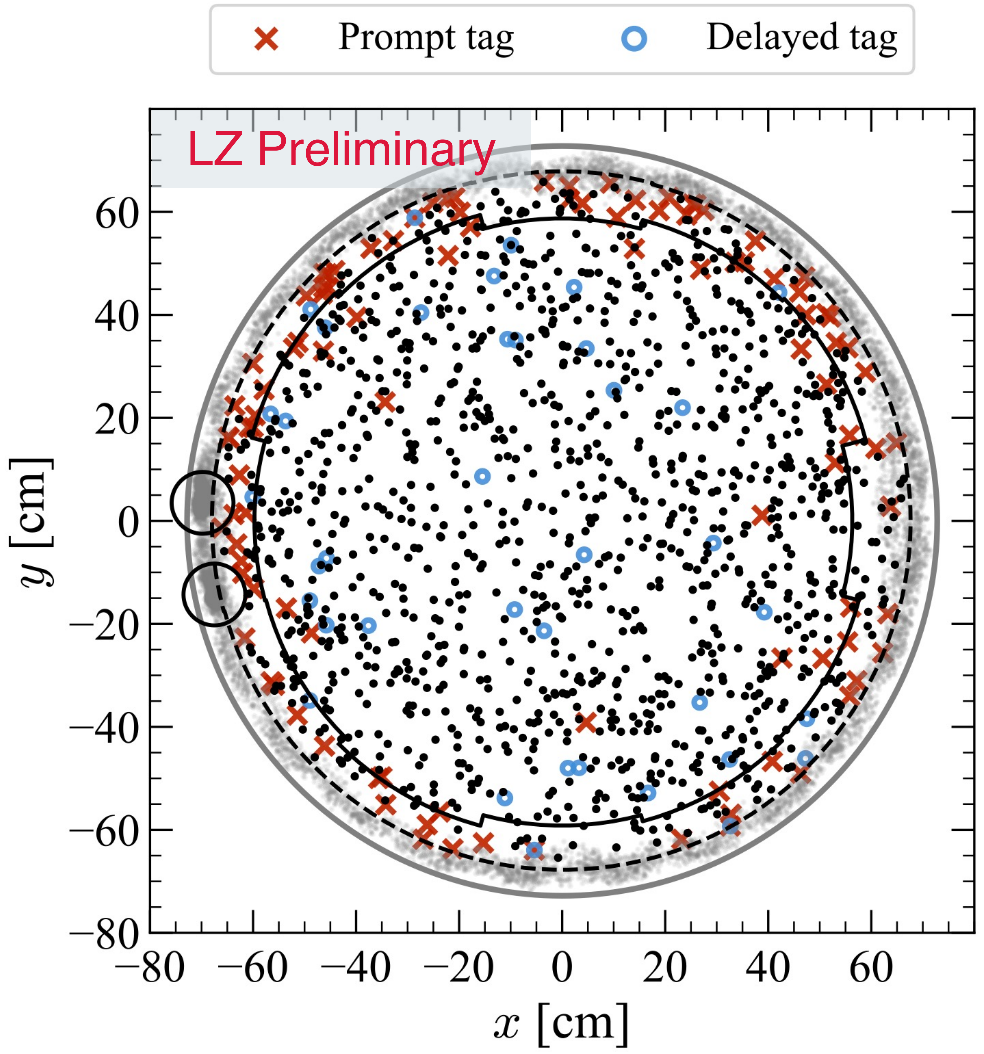


Signal acceptance

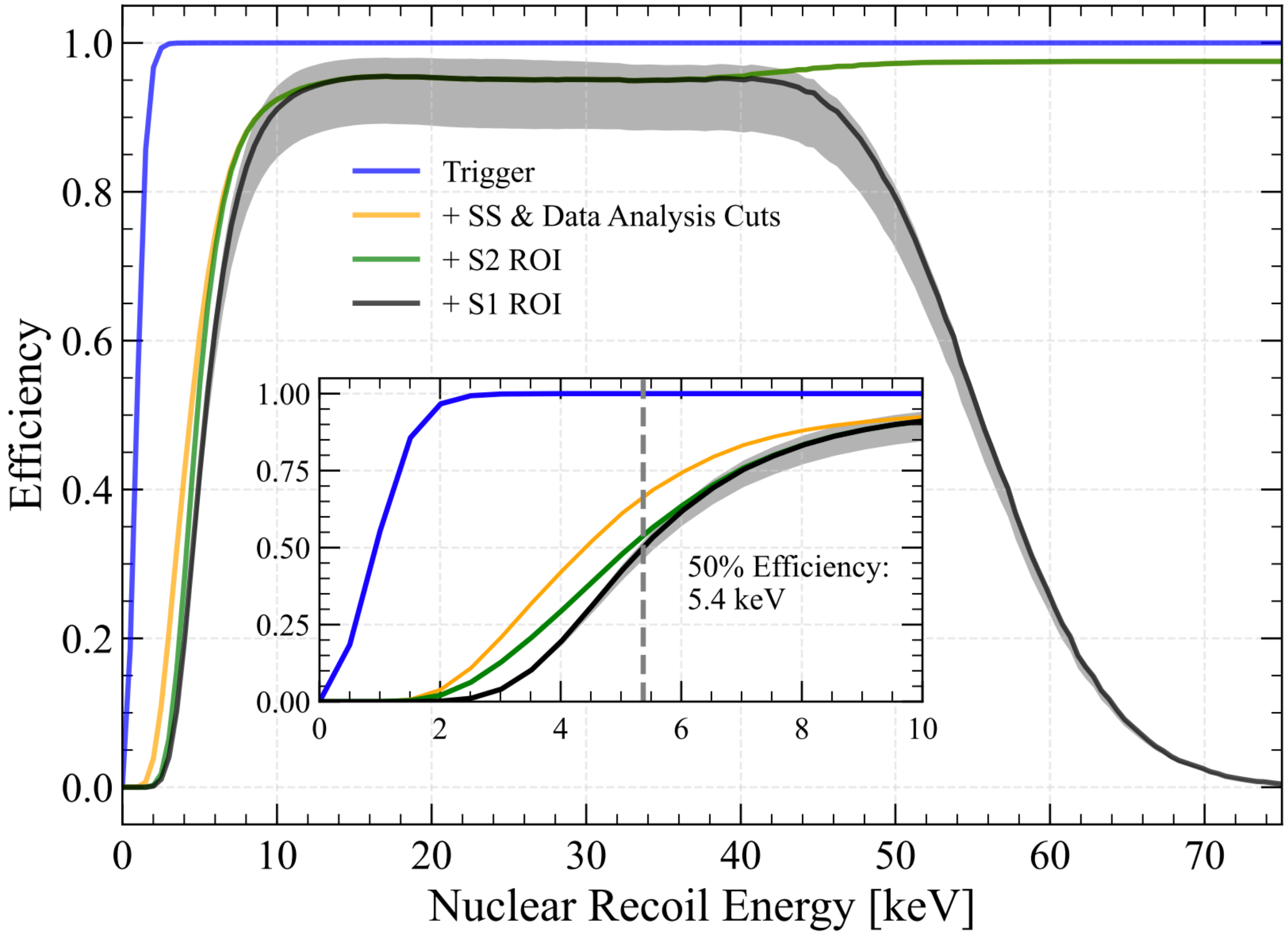
Region of interest (ROI)

- (3 < S1c [phd] < 80);
  three-fold PMT coincidence
- S2 > 645 phd (14.5 e^-)

Event selection criteria

- SS + ROI + FV + veto cuts
- S1- & S2-based cuts

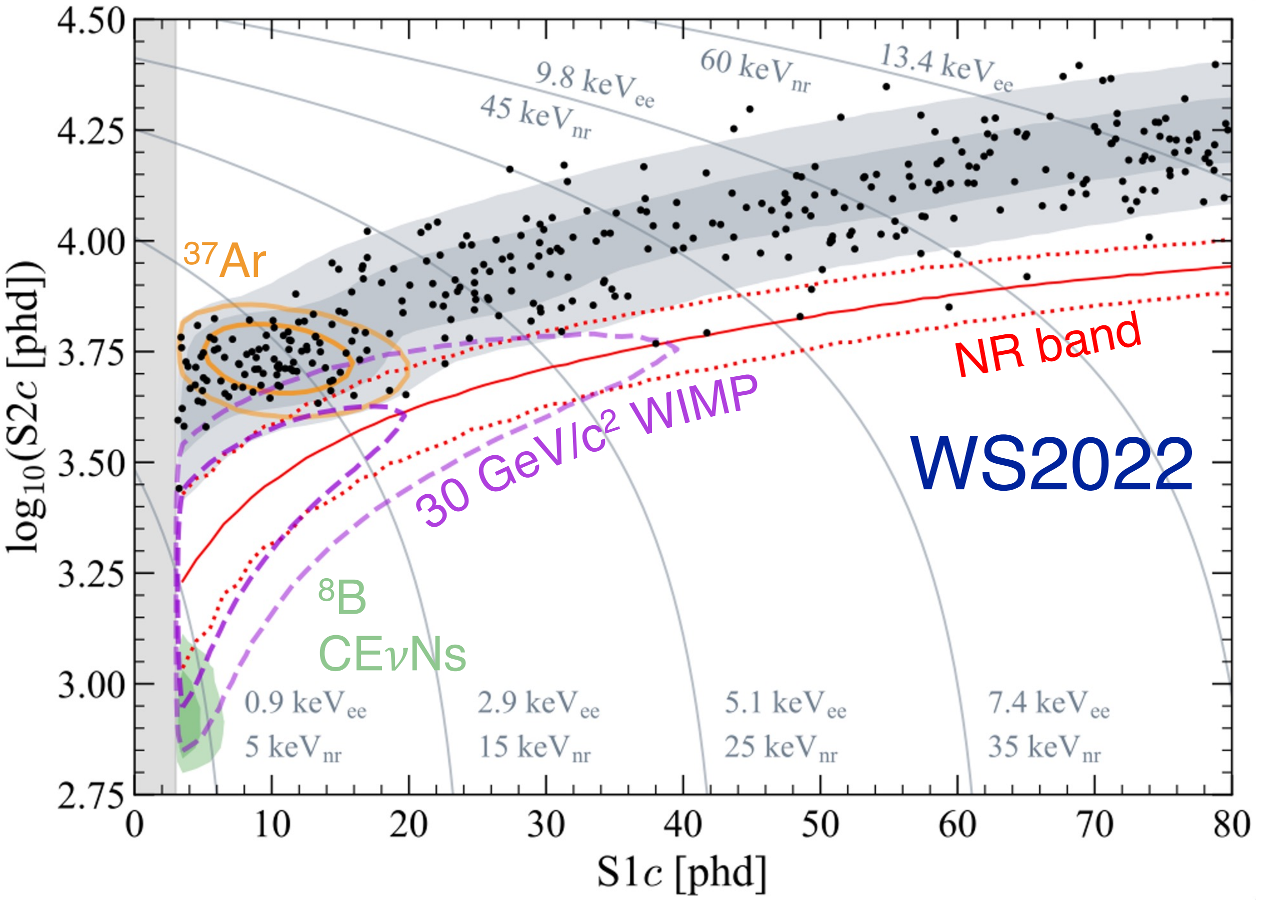
Cuts developed on **sidebands** and **non-WIMP ROI data**

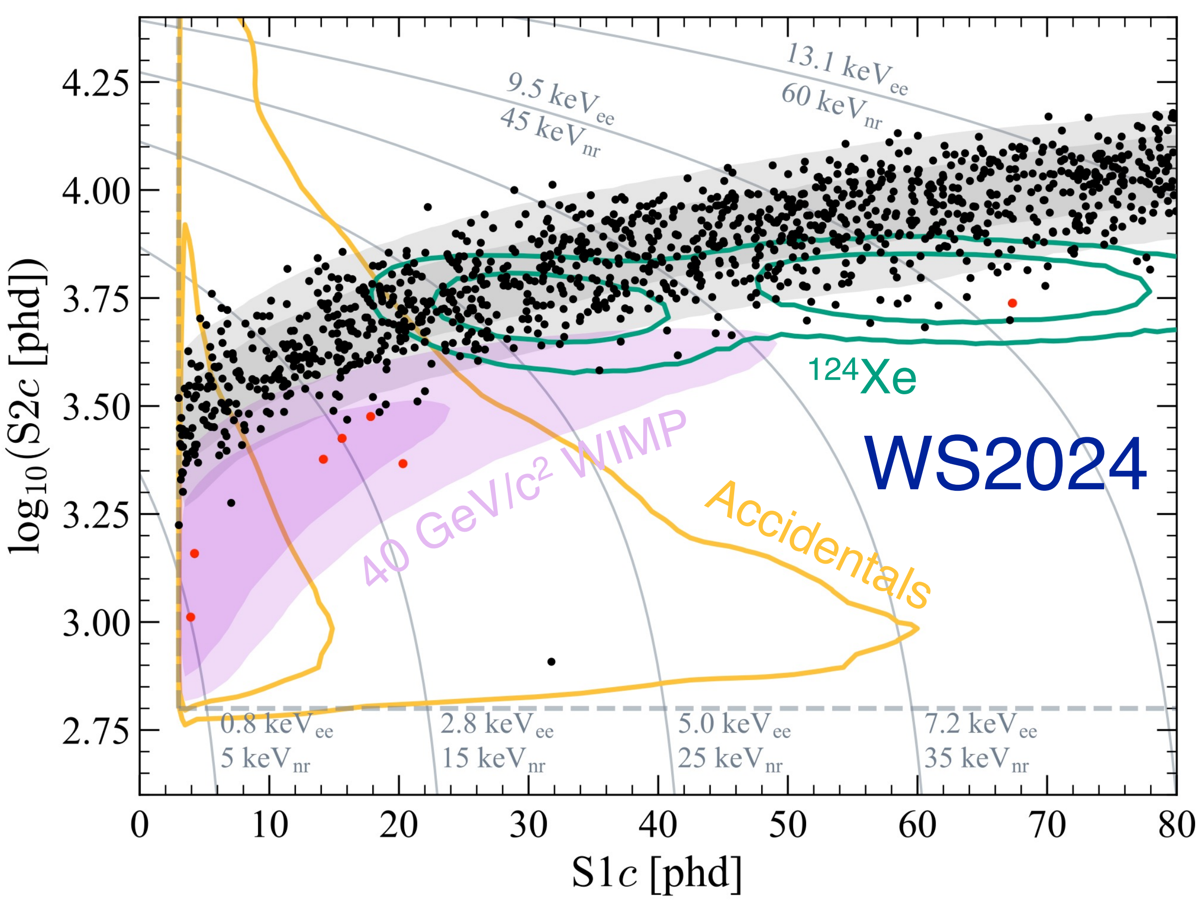


(${}^{8}B$ excluded for dedicated analysis)

Search space

Total of (335 + 1220 + 7 salt) events in combined exposure of (0.9 + 3.3) t × yr





Statistical inference

Fits performed using frequentist **profile likelihood ratio** (PLR) in (S1c, $\log_{10}$S2c);

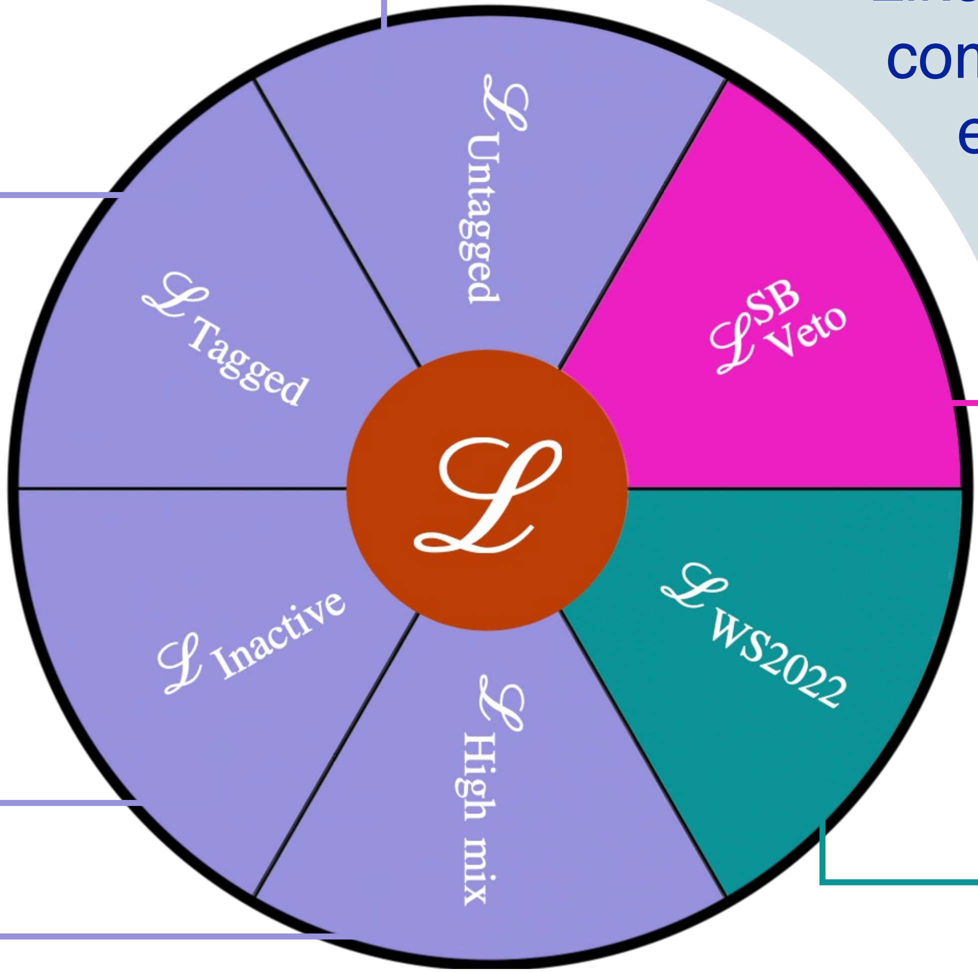
Likelihood function combines **6** sub-likelihoods each describing unique data samples

Passes radon veto
(1.8 t × yr)

Tagged by radon veto
(0.3 t × yr)

Inactive radon veto
(0.6 t × yr)

High-mixing period
(0.6 t × yr)



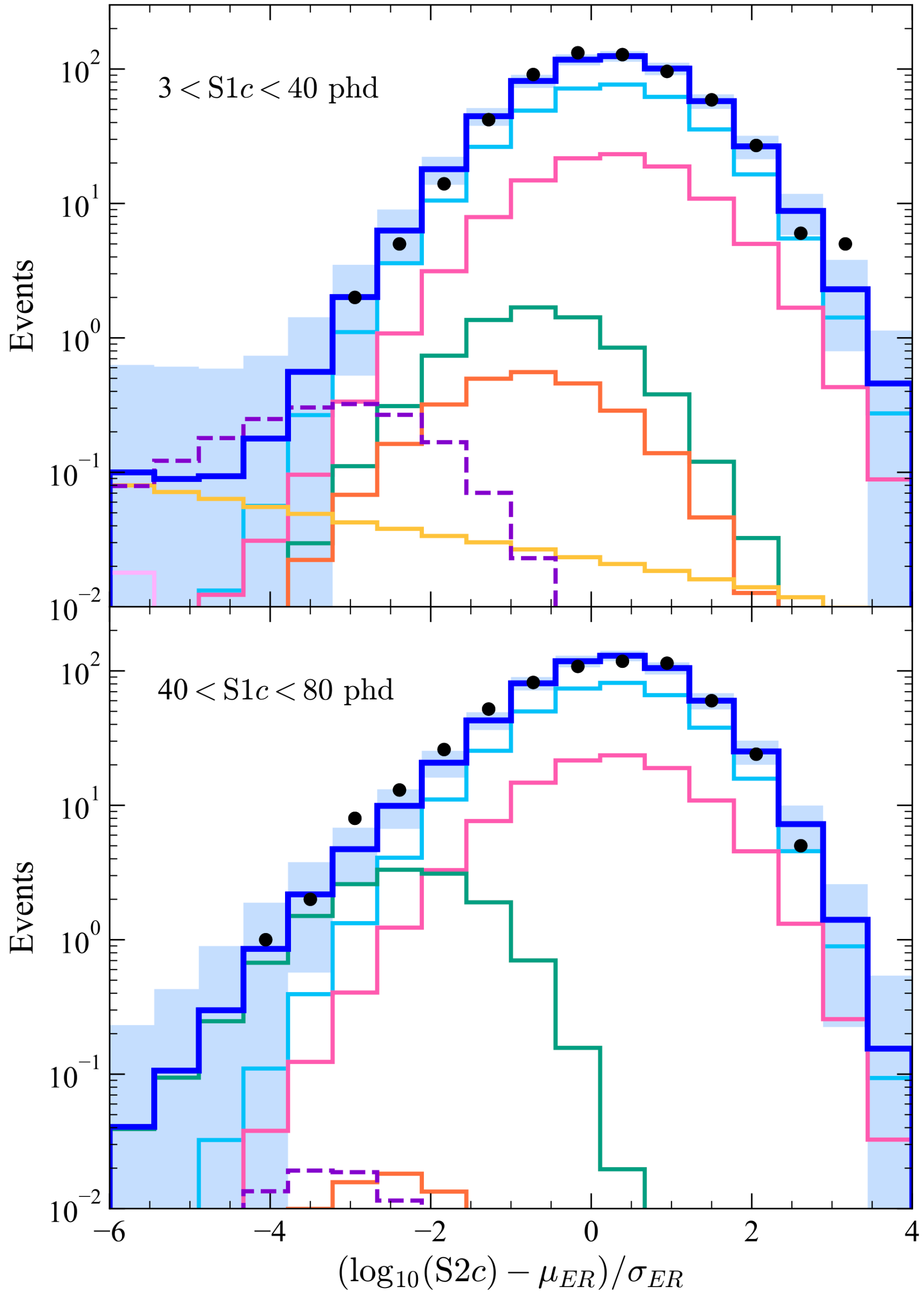
Veto sideband (N/A)
Provides direct constraint on neutron rate

WS2022 sample
(0.9 t × yr)
Unchanged; included to maximise exposure

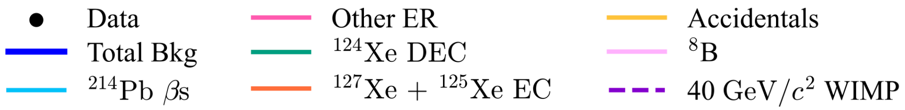
Fit results

Zero WIMPs between 9 GeV/c² and 100 TeV/c²

Source	Pre-fit Expectation	Fit Result
^{214}Pb βs	743 ± 88	733 ± 34
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22	161 ± 21
Solar ν ER	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po βs	62.7 ± 7.5	63.7 ± 7.4
Tritium+ ^{14}C βs	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe $2\nu\beta\beta$	55.6 ± 8.3	55.8 ± 8.2
^{124}Xe DEC	19.4 ± 3.9	21.4 ± 3.6
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
Accidental coincidences	2.8 ± 0.6	2.6 ± 0.6
Atm. ν NR	0.12 ± 0.02	0.12 ± 0.02
^{8}B+*hep* ν NR	0.06 ± 0.01	0.06 ± 0.01
Detector neutrons	[a] $0.0^{+0.2}$	$0.0^{+0.2}$
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1203 ± 42



Fit results



Zero WIMPs between 9 GeV/c^2 and 100 TeV/c^2

Source	Pre-fit Expectation	Fit Result
^{214}Pb βs	743 ± 88	733 ± 34
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22	161 ± 21
Solar ν ER	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po βs	62.7 ± 7.5	63.7 ± 7.4
Tritium+ ^{14}C βs	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe $2\nu\beta\beta$	55.6 ± 8.3	55.8 ± 8.2
^{124}Xe DEC	19.4 ± 3.9	21.4 ± 3.6
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
Accidental coincidences	2.8 ± 0.6	2.6 ± 0.6
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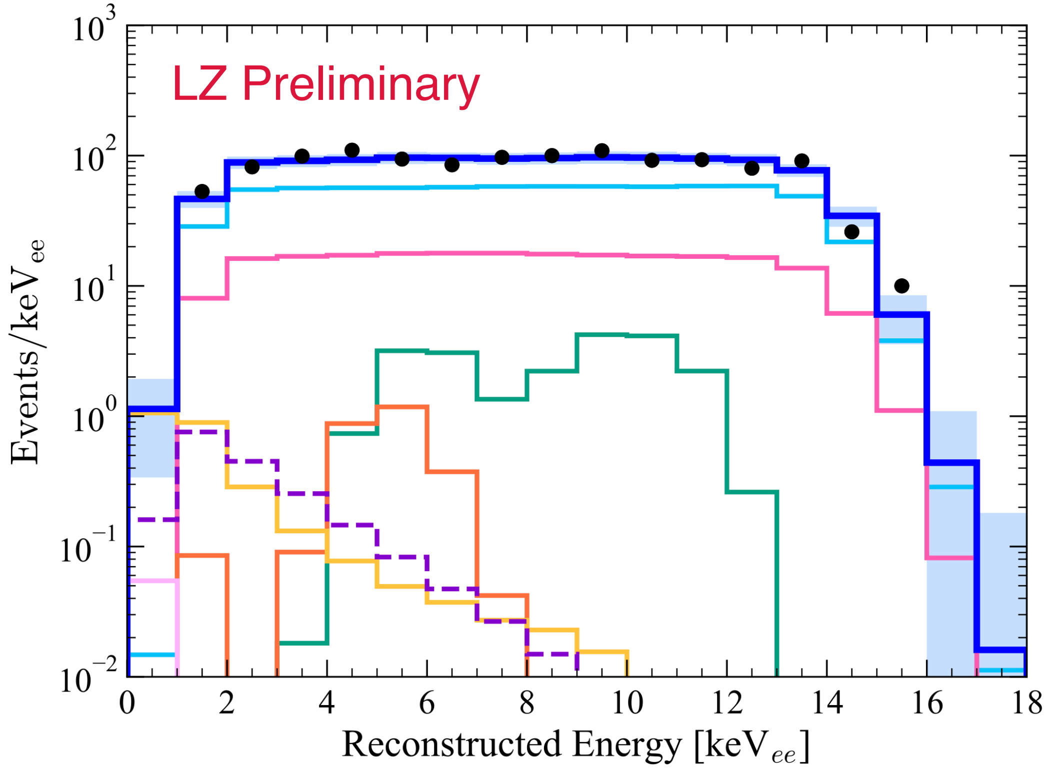
Detector neutrons	[a] $0.0^{+0.2}$	$0.0^{+0.2}$
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1203 ± 42

Good agreement with **background-only** hypothesis



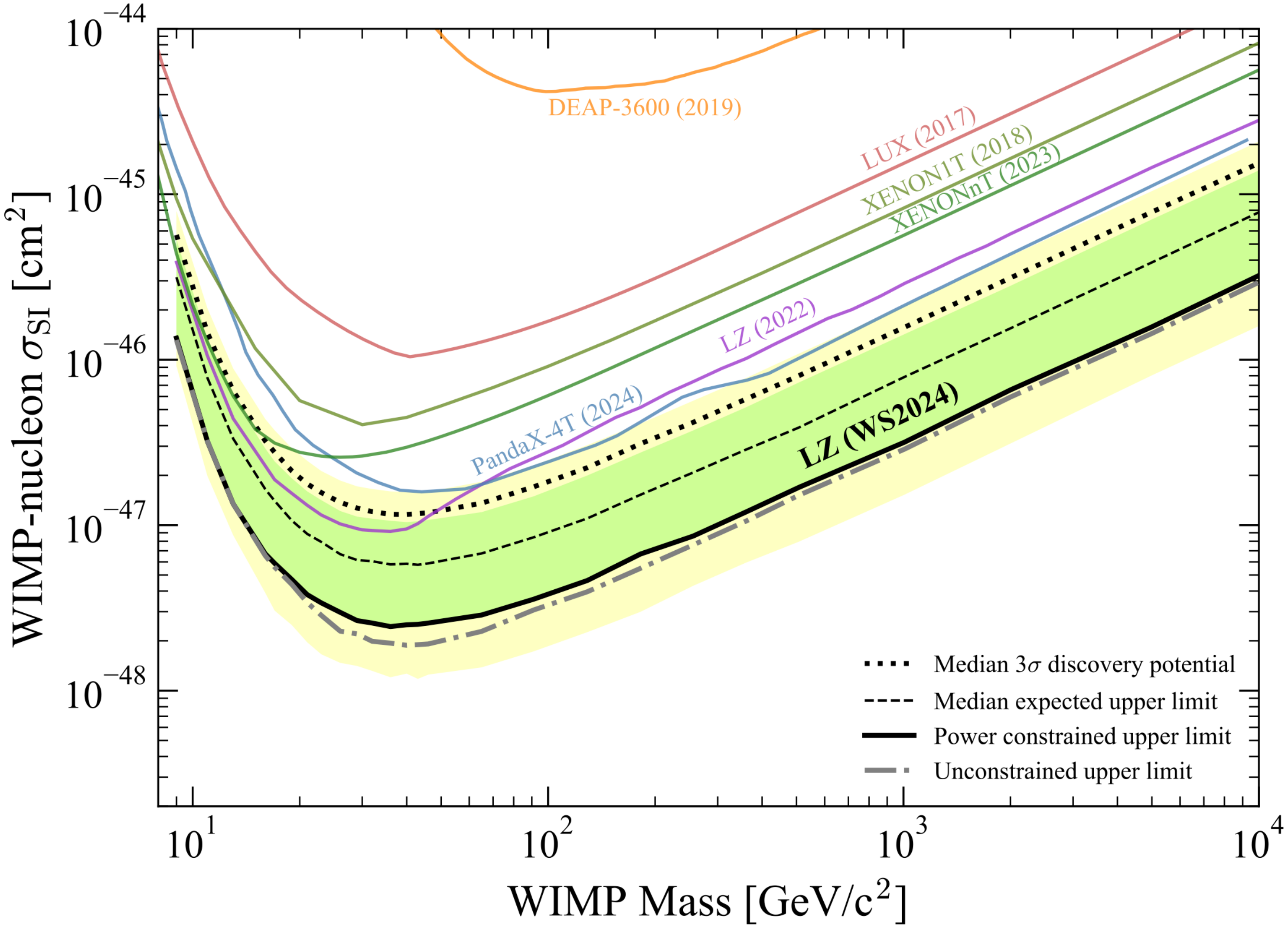
*EPJ C 81 907 (2021)

WS2024-only **spin-independent** limit

Power-constrained* at -1σ, as per recommended conventions

Under-fluctuation in accidentals, which overlap heavily with most WIMP signal distributions

WS2024-only best limit of $\sigma_{SI} = 2.4 \times 10^{-48}$ cm^2 at 43 GeV/c^2

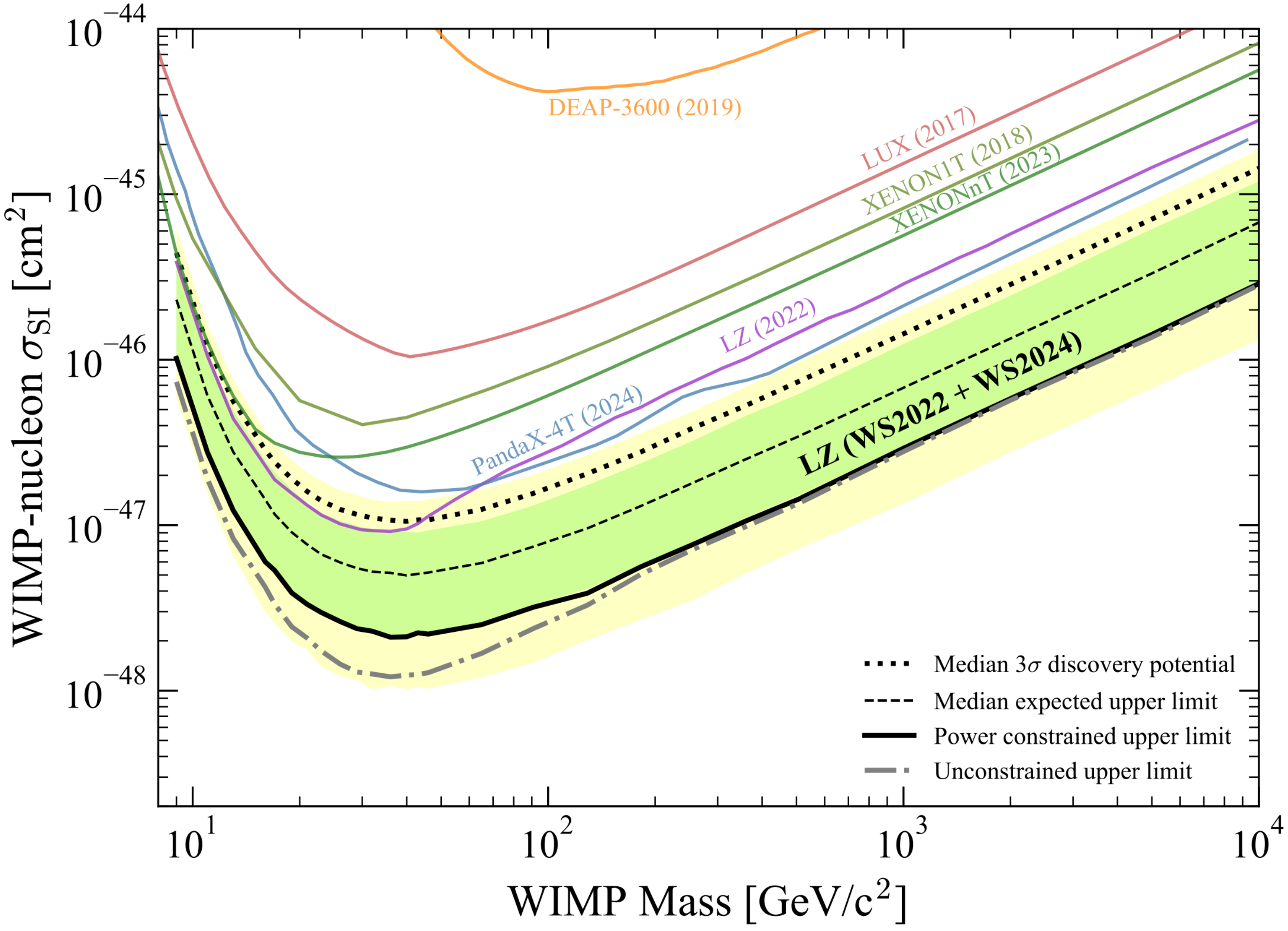


WS2022+WS2024 **spin-independent** limit

Extra under-fluctuation from **WS2022** result, originally around ^{37}Ar population

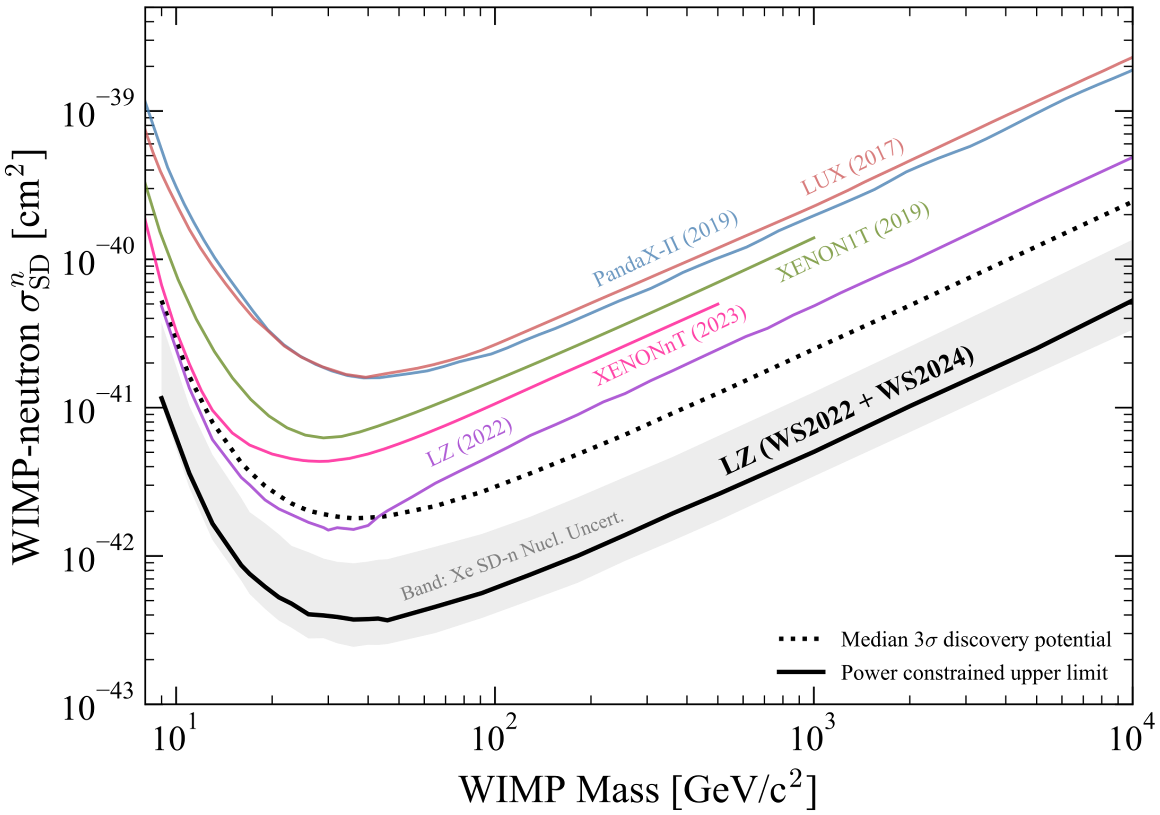
Combined best limit of $\boldsymbol{\sigma_{SI} = 2.1 \times 10^{-48}\ cm^2}$ at 43 GeV/c^2

Factor of **4** improvement in sensitivity overall

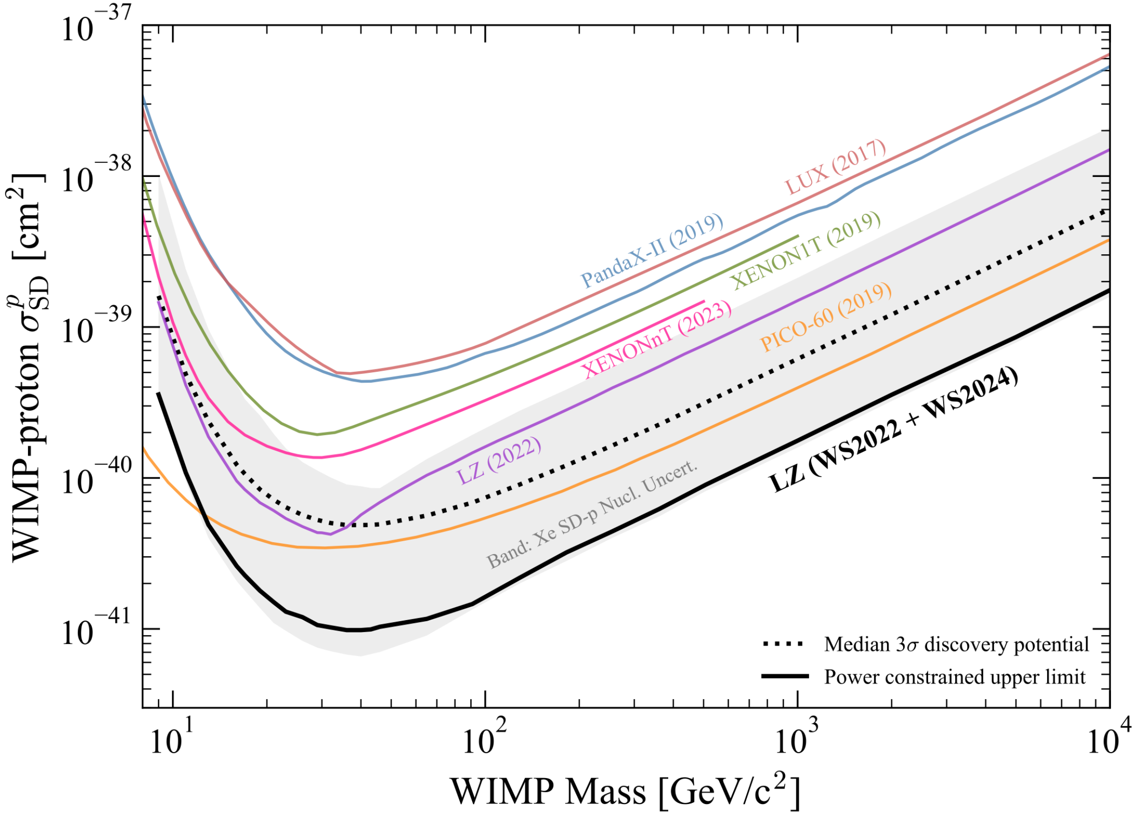


WS2022+WS2024 **spin-dependent** limits

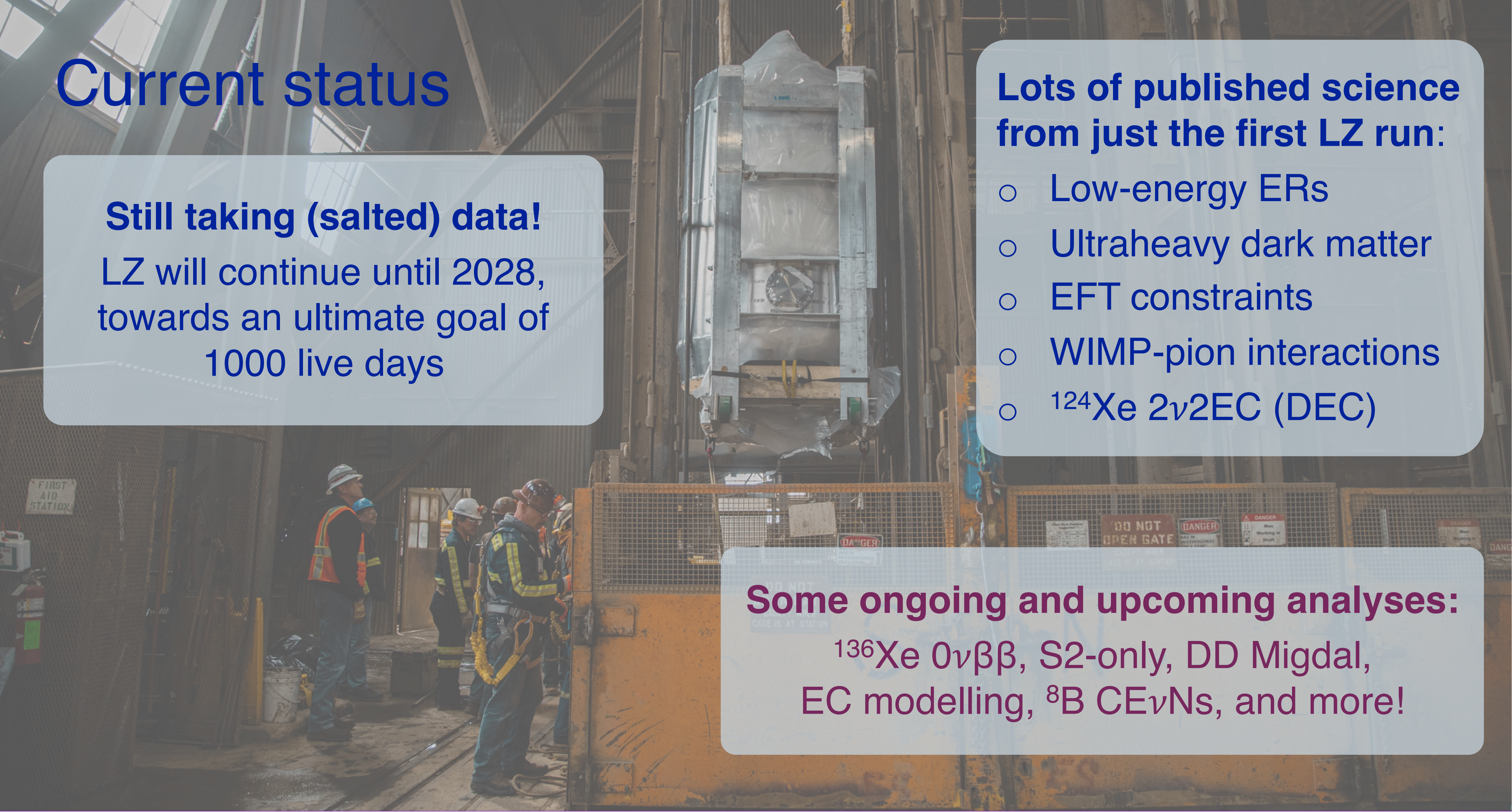
WIMP-*neutron* scattering



WIMP-*proton* scattering



(uncertainty bands represent theoretical uncertainty on Xe nuclear structure factor)



Current status

Still taking (salted) data!

LZ will continue until 2028, towards an ultimate goal of 1000 live days

Lots of published science from just the first LZ run:

- Low-energy ERs
- Ultraheavy dark matter
- EFT constraints
- WIMP-pion interactions
- ^{124}Xe 2ν2EC (DEC)

Some ongoing and upcoming analyses:

^{136}Xe 0$\nu\beta\beta$, S2-only, DD Migdal, EC modelling, ^{8}B CEνNs, and more!

Summary

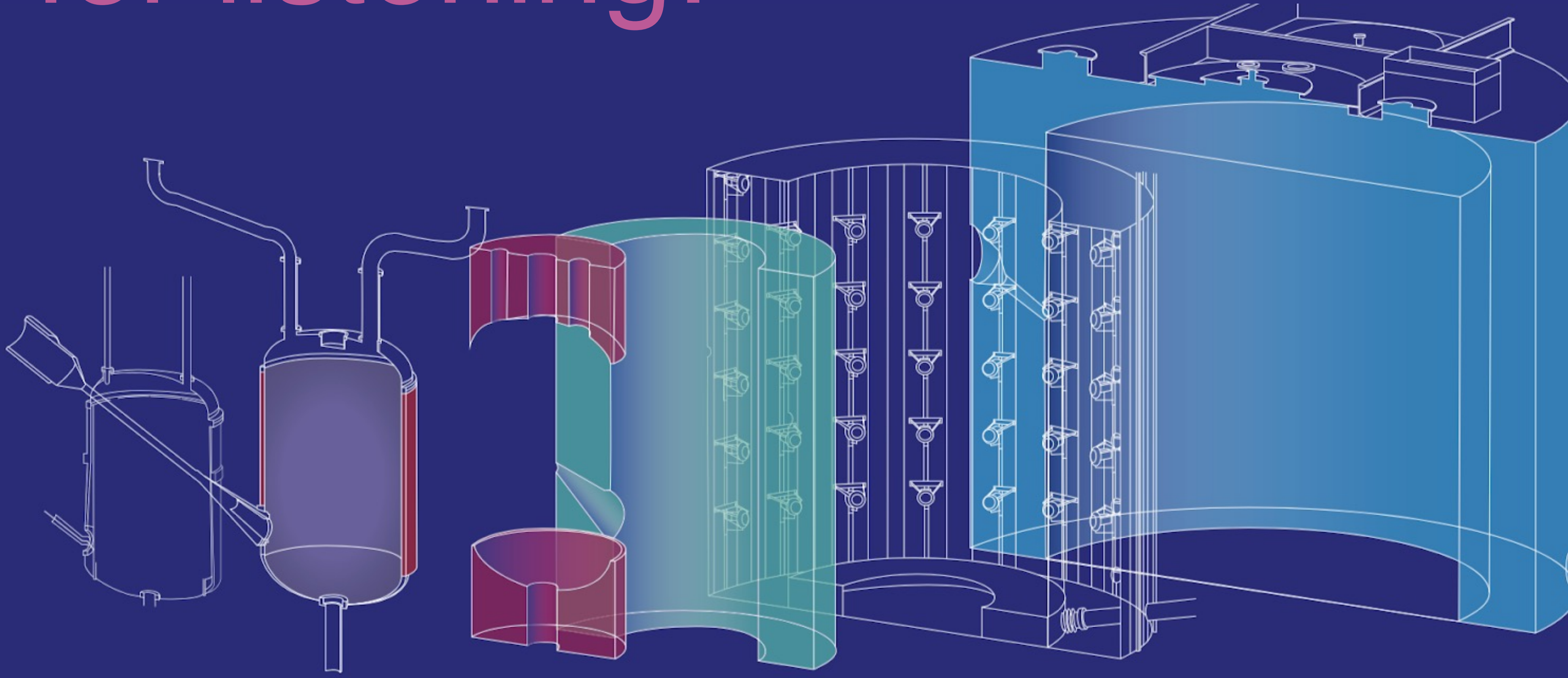
New **world-leading** LZ WIMP limits from **combined 4.2 t × yr exposure**

Radon tag developed for the first time (60% reduction of main ER background)

First observation of charge-suppressed ^{124}Xe DECs

LZ is **discovery-ready** for WIMPS, plus various other new phenomena!

Thanks for listening!



SANFORD UNDERGROUND RESEARCH FACILITY

fct Fundação para a Ciência e a Tecnologia

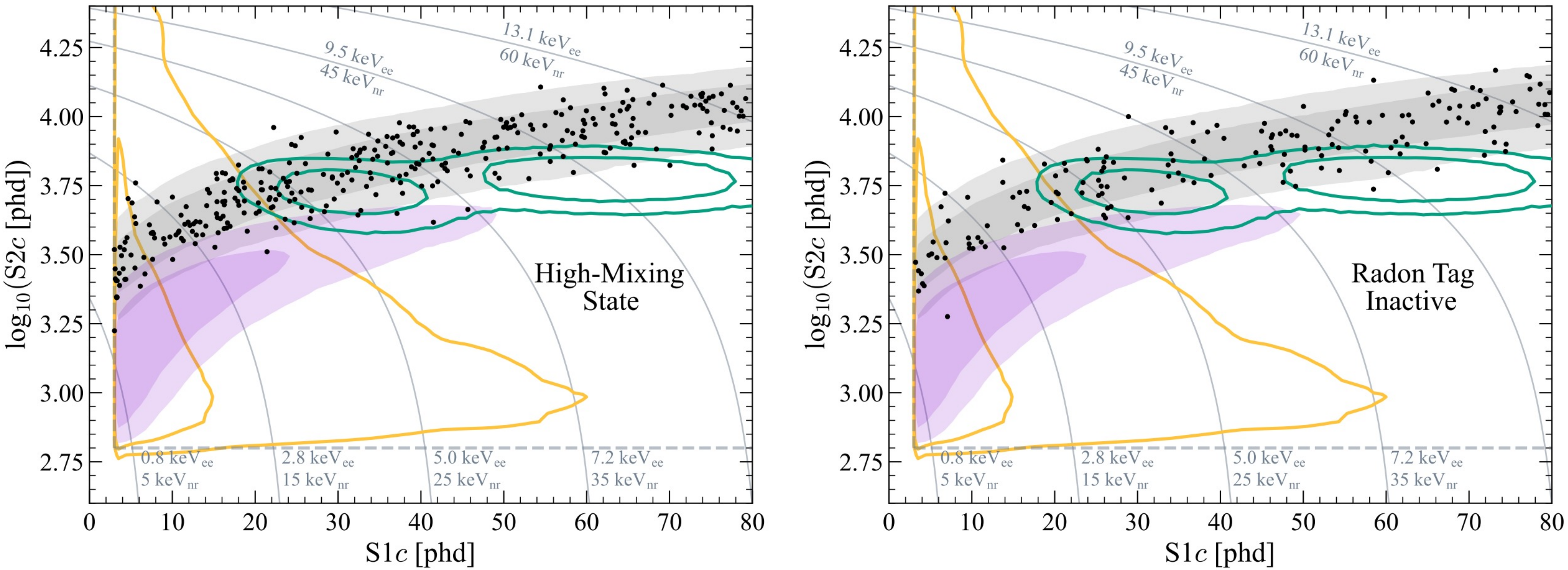
ibs Institute for Basic Science

UKRI Science and Technology Facilities Council

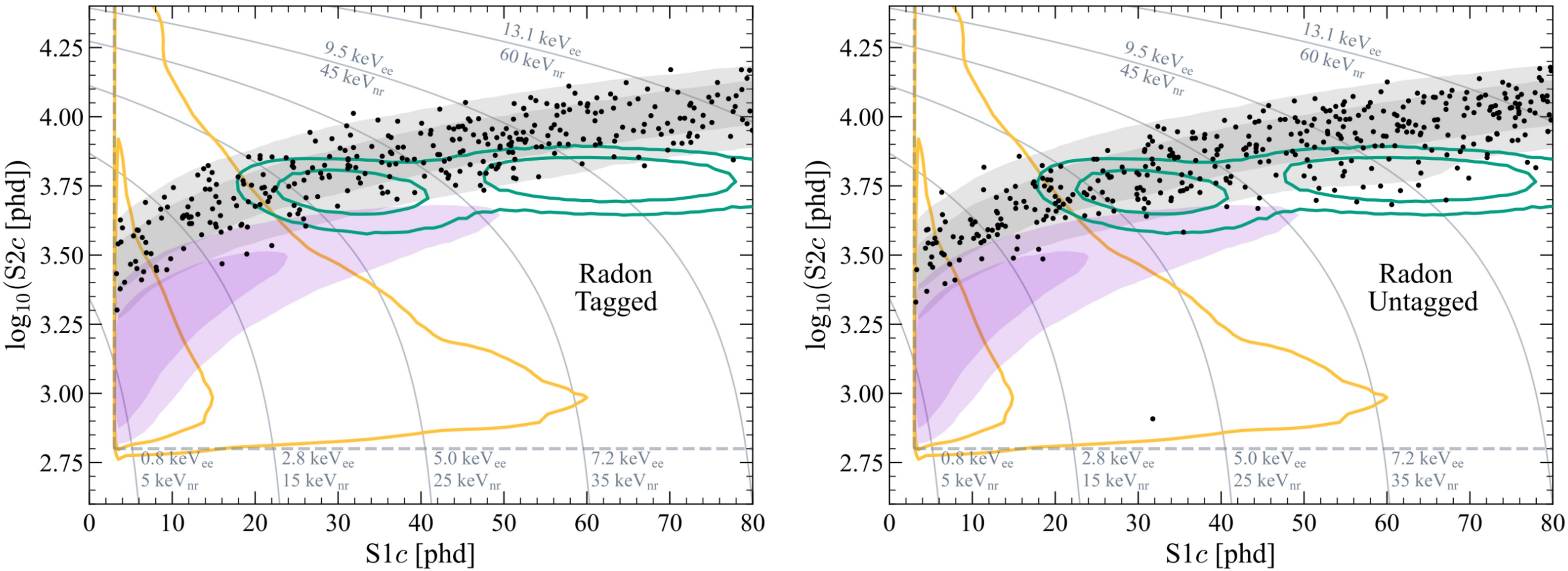
Supplementary slides

LUX - ZEPLIN

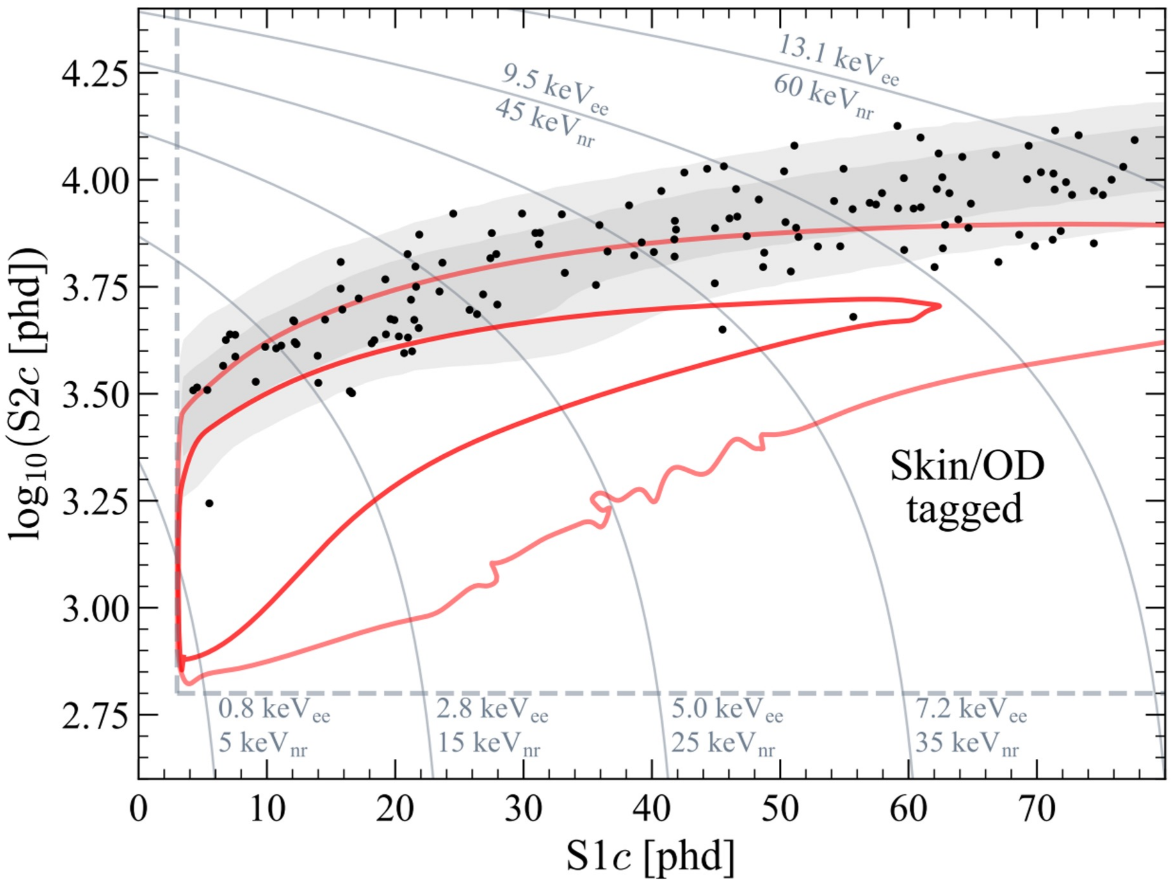
Sub-sample spaces

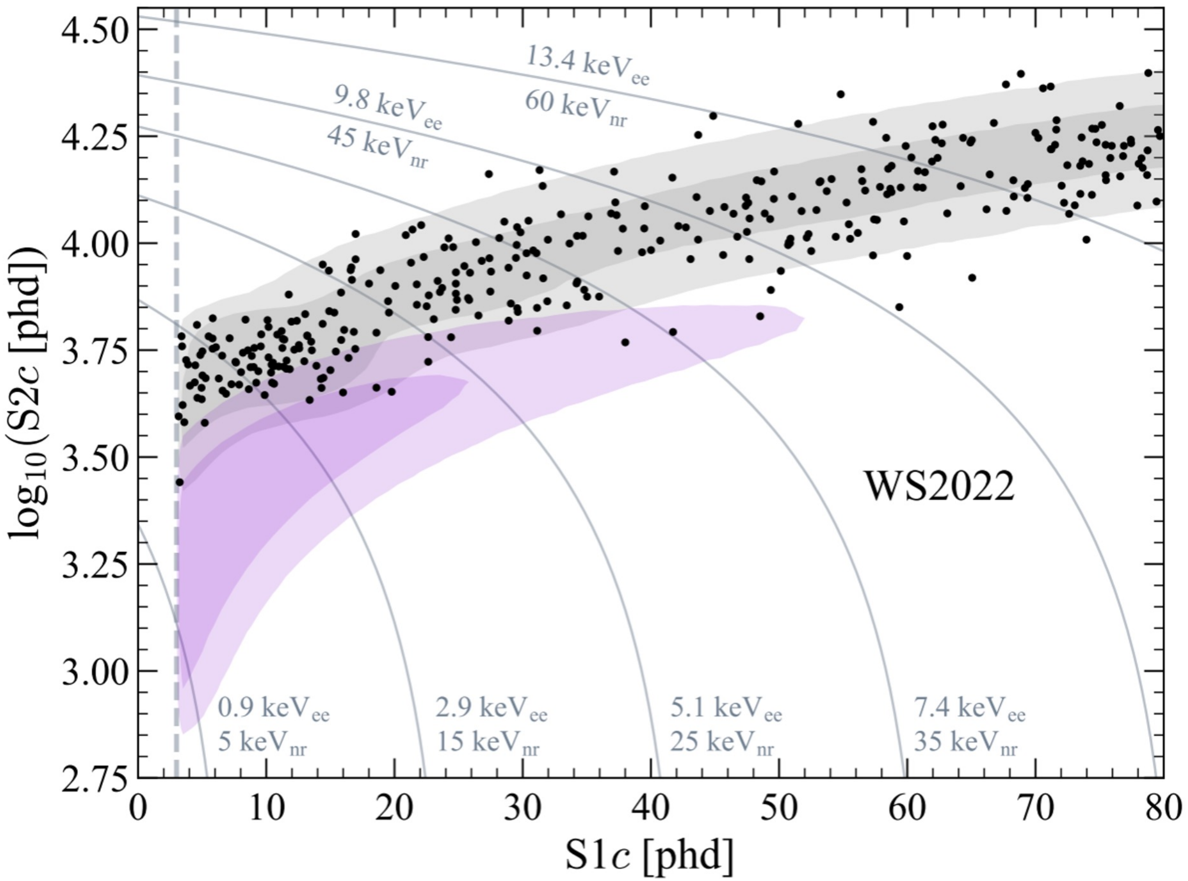


Sub-sample spaces



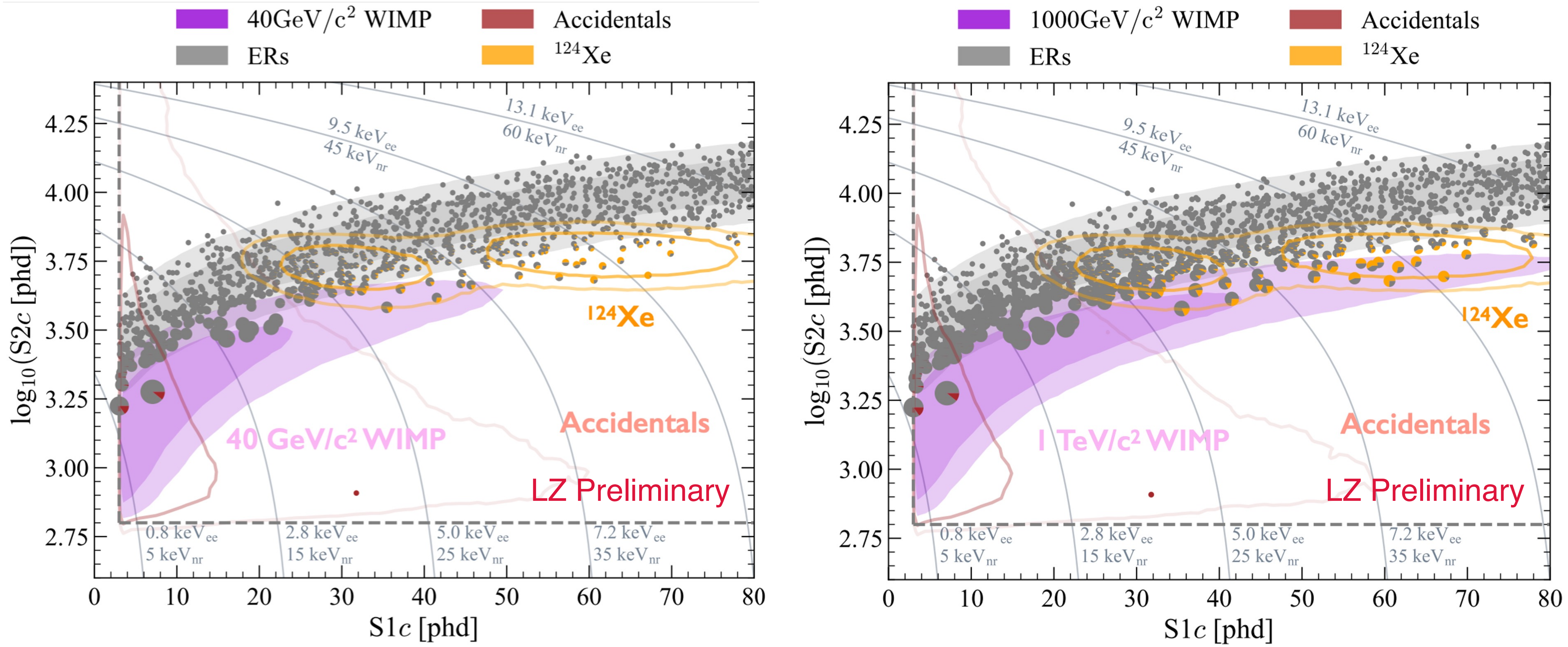
Sub-sample spaces





WS2024 pie plots

Pie fraction: ratio of differential rate at that point
Pie size: proportional to rate sum over WIMPs and NRs

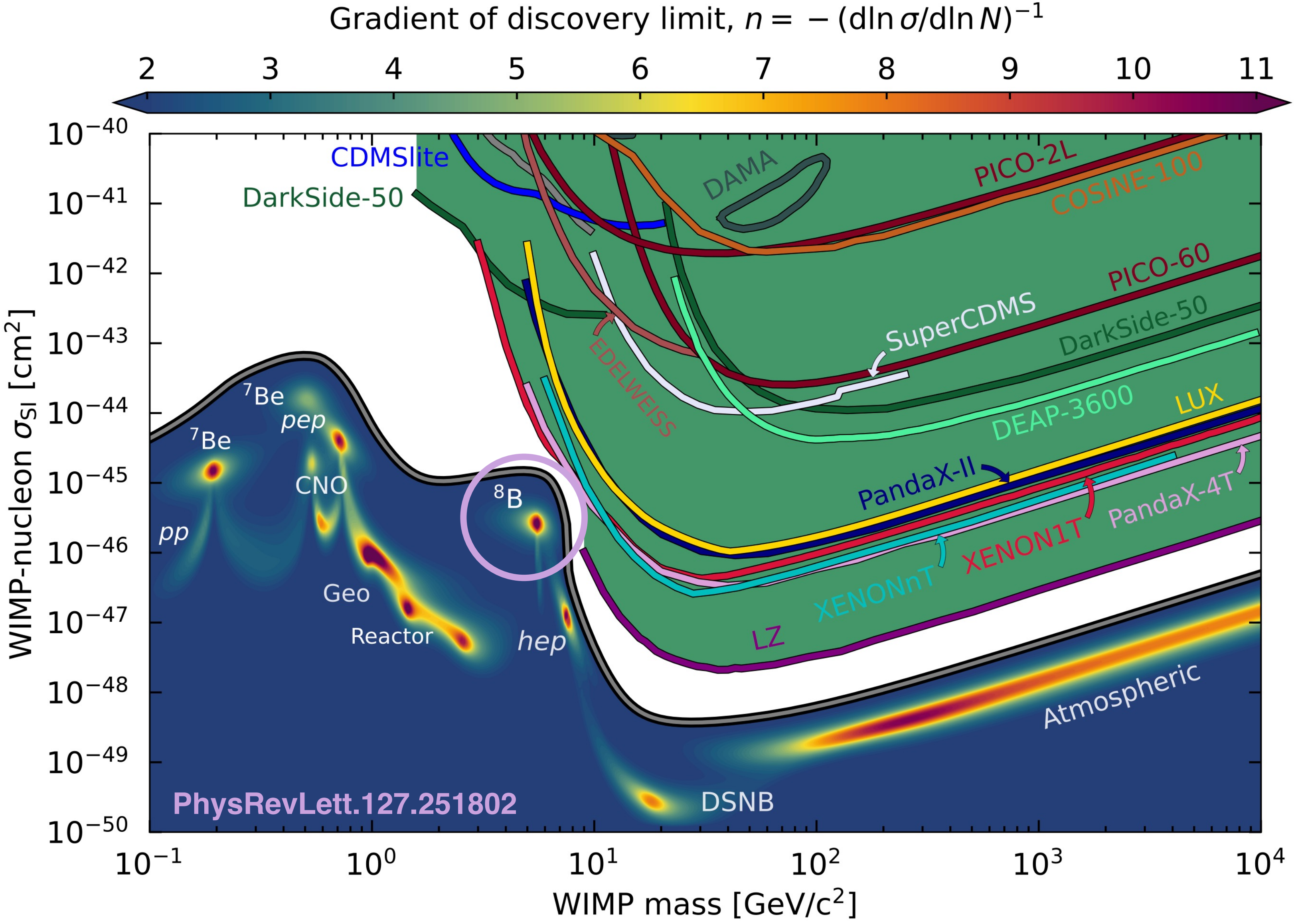


^{8}B CEνNS in LZ

On the horizon, **first > 3σ ^{8}B CEνNS measurement** to be expected from LZ

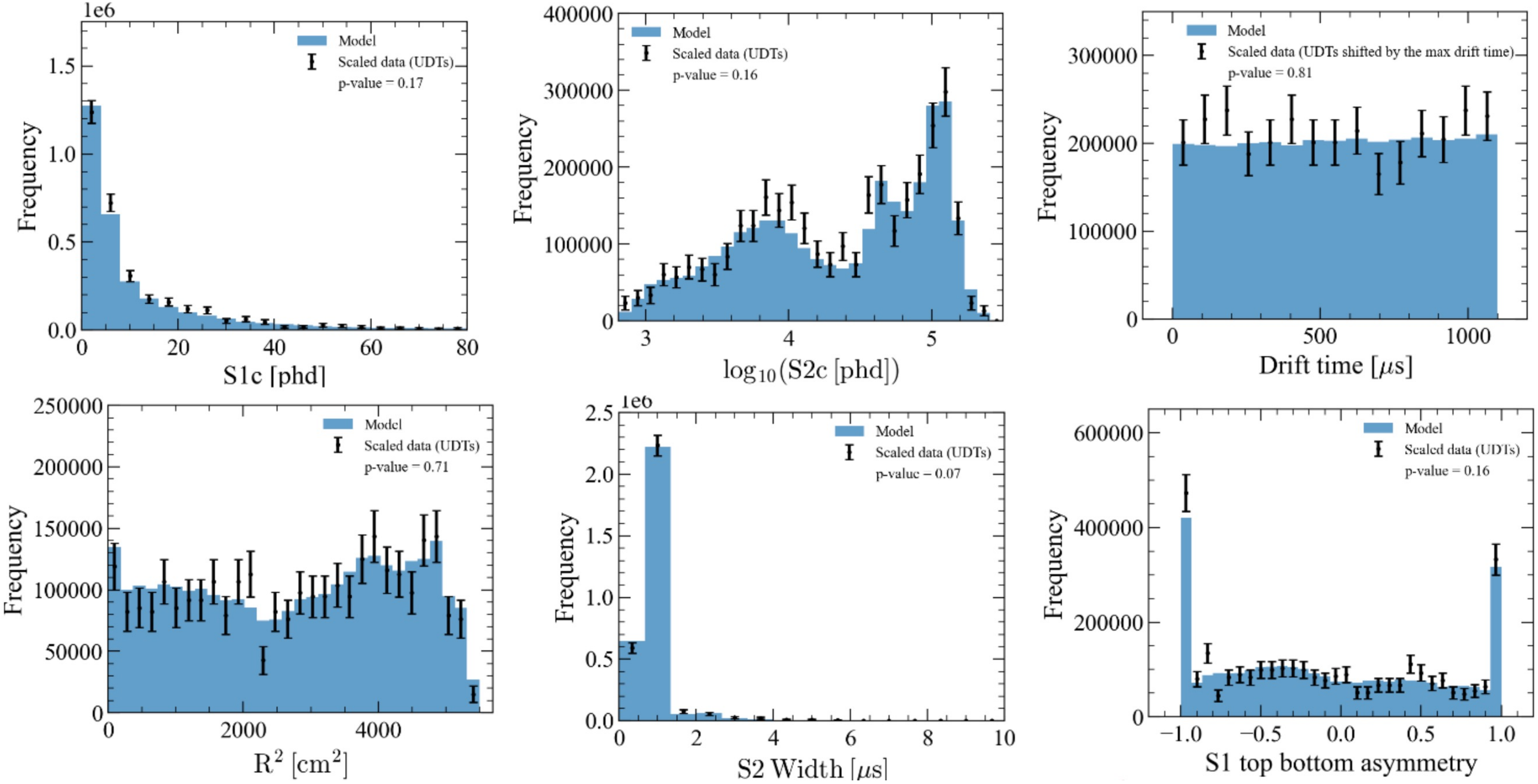
XENONnT: 2.73σ

PandaX-4T: 2.64σ

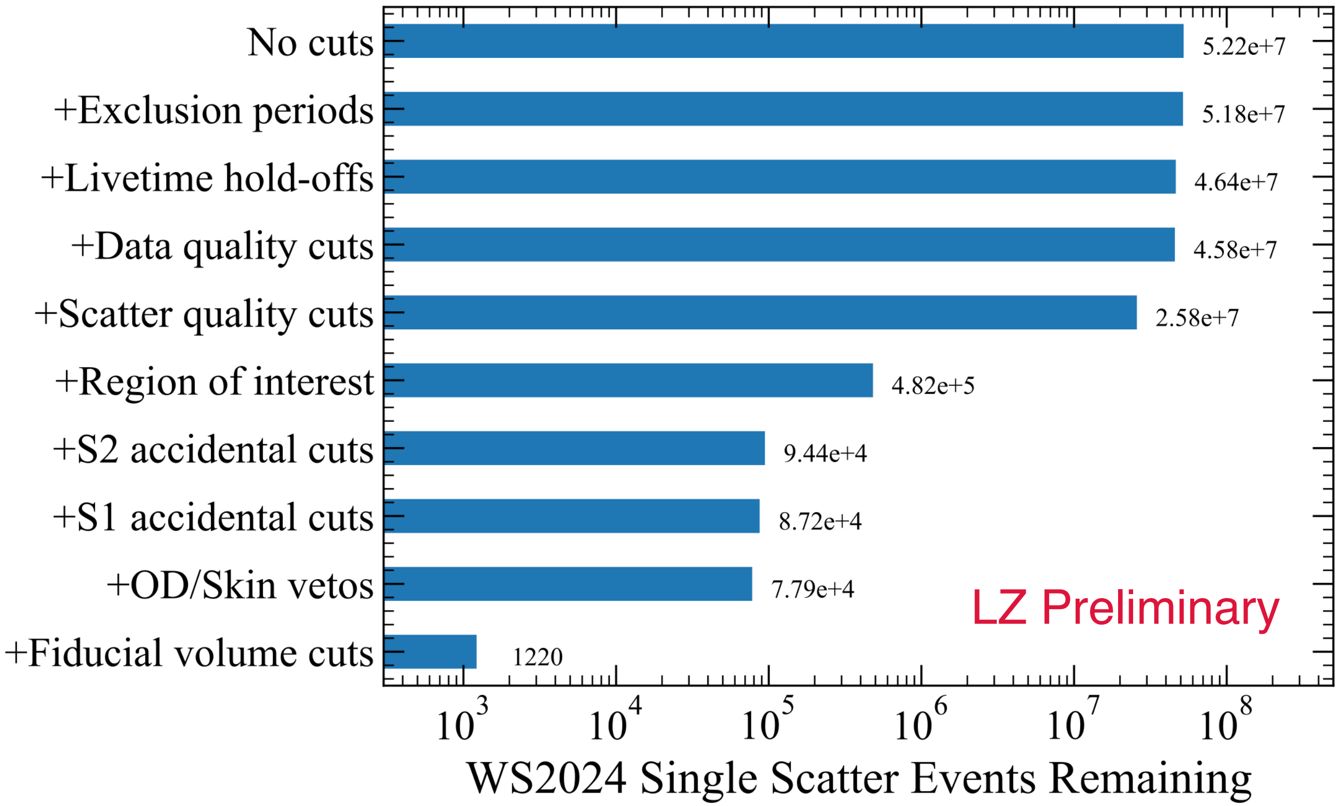


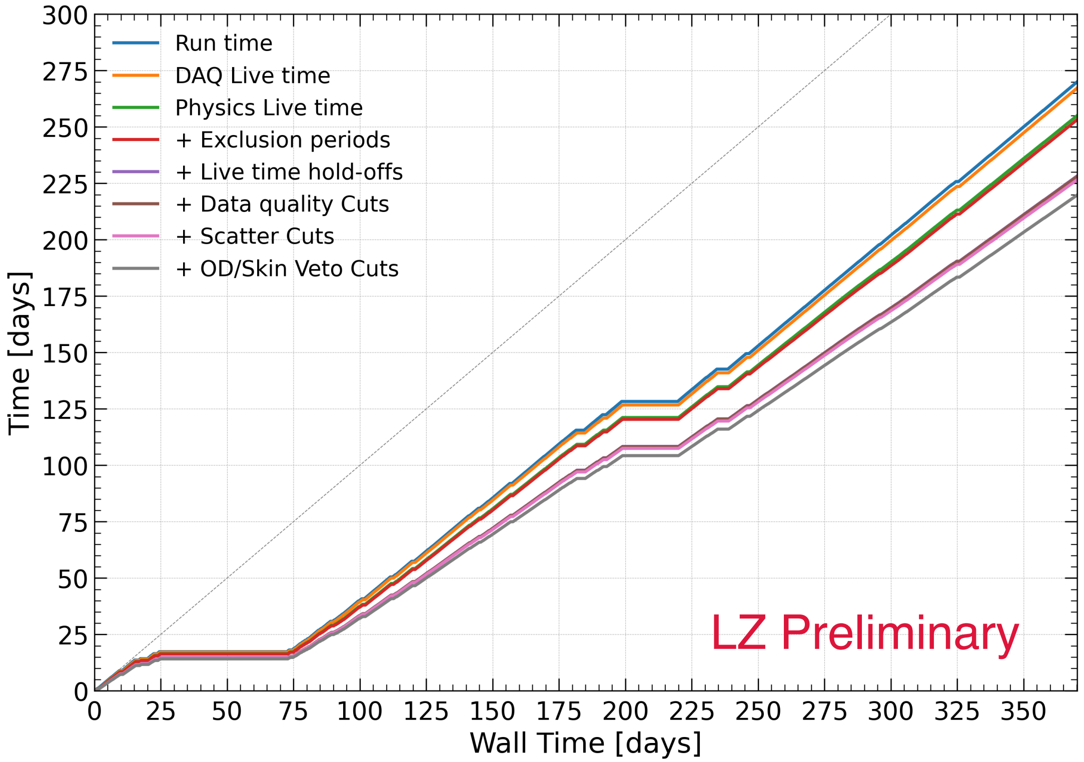
Accidentals checks

LZ Preliminary



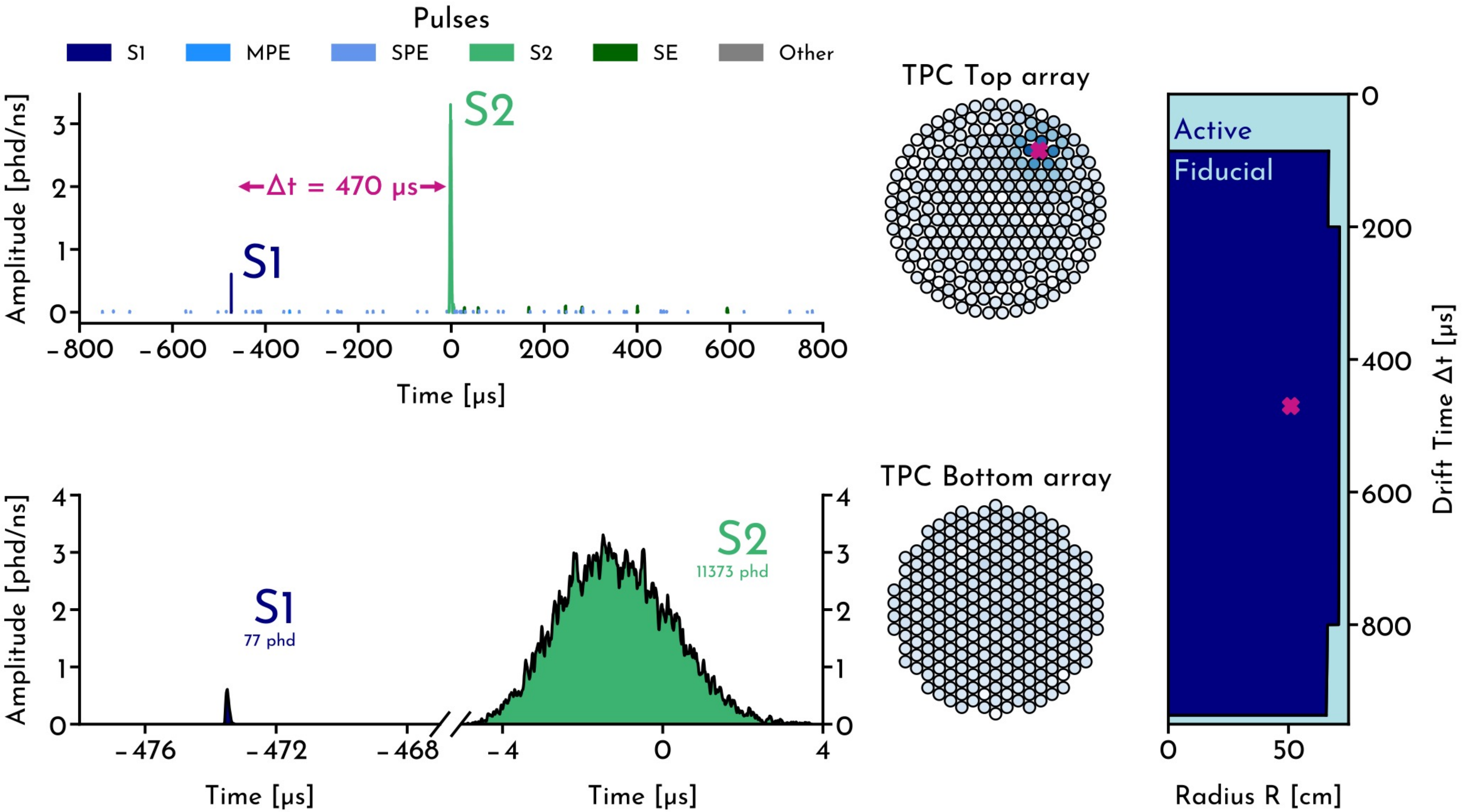
WS2024 live time





86% of live time remaining after all exclusion cuts (improved since WS2022)

Example of a good event



^{124}Xe 2ν2EC (or DEC)

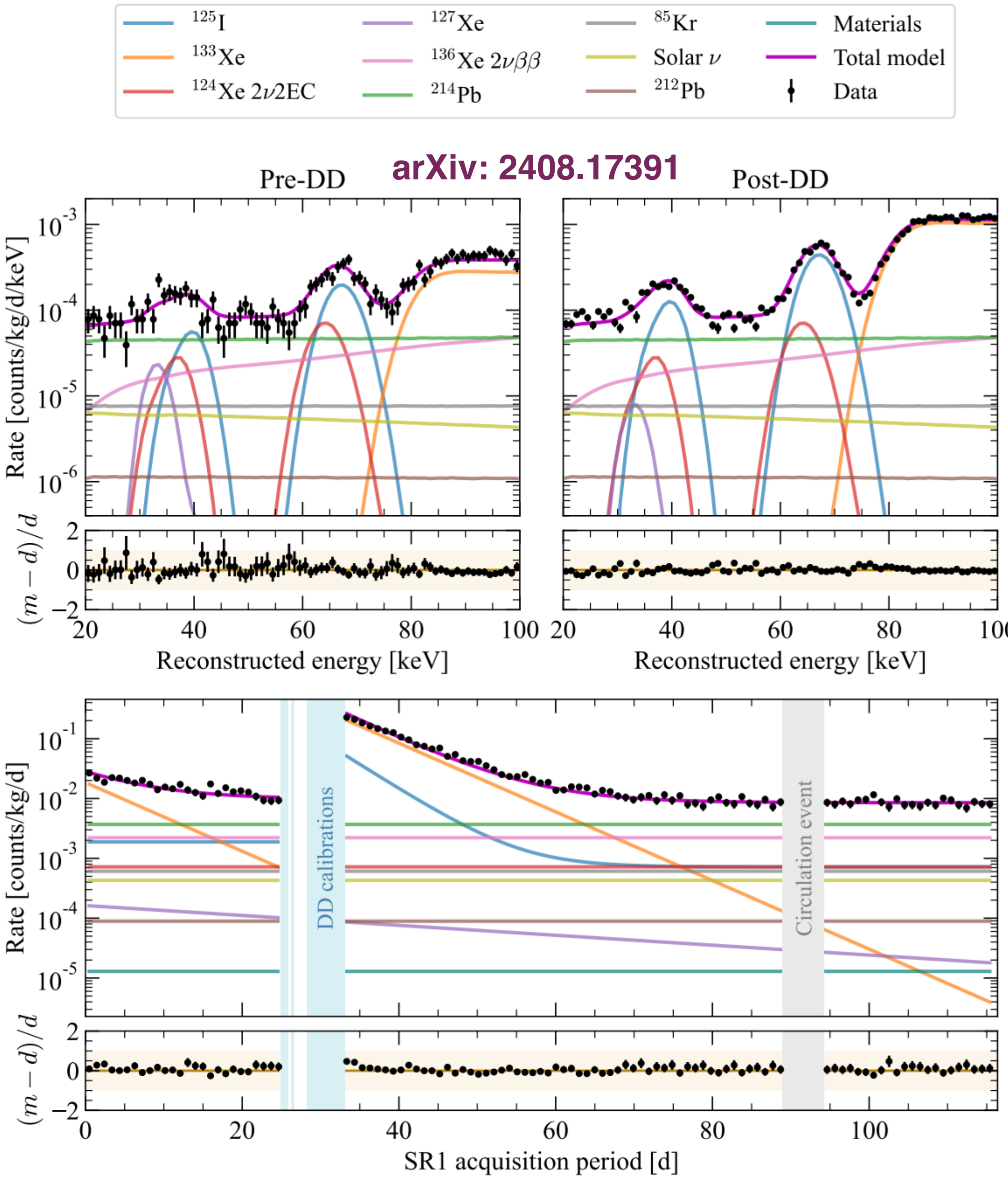
8.3σ measurement using LZ first science run:

$T_{1/2} = (1.09 \pm 0.14_{stat} \pm 0.05_{sys}) \times 10^{22}$ yr

Main background is **^{125}I**, formed from neutron activation during calibrations

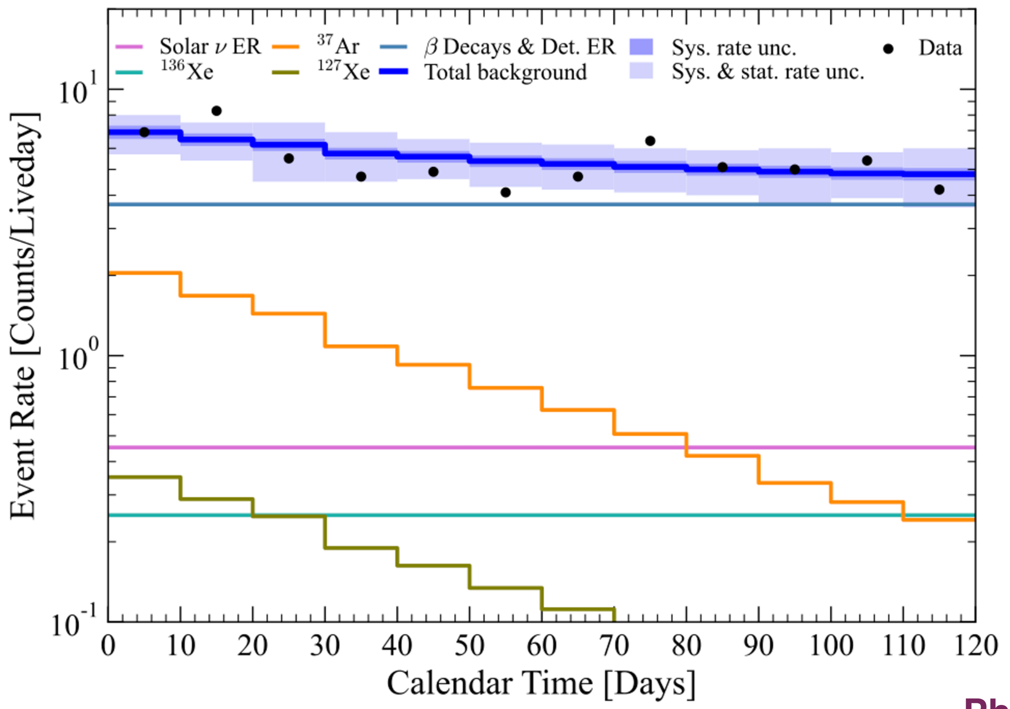
- Constrained using **simultaneous fit** between pre- and post-DD calibration windows
- Modelled in both **energy** and calendar **time**

First attempt at measuring the **relative shell capture fractions** (KK and KX)

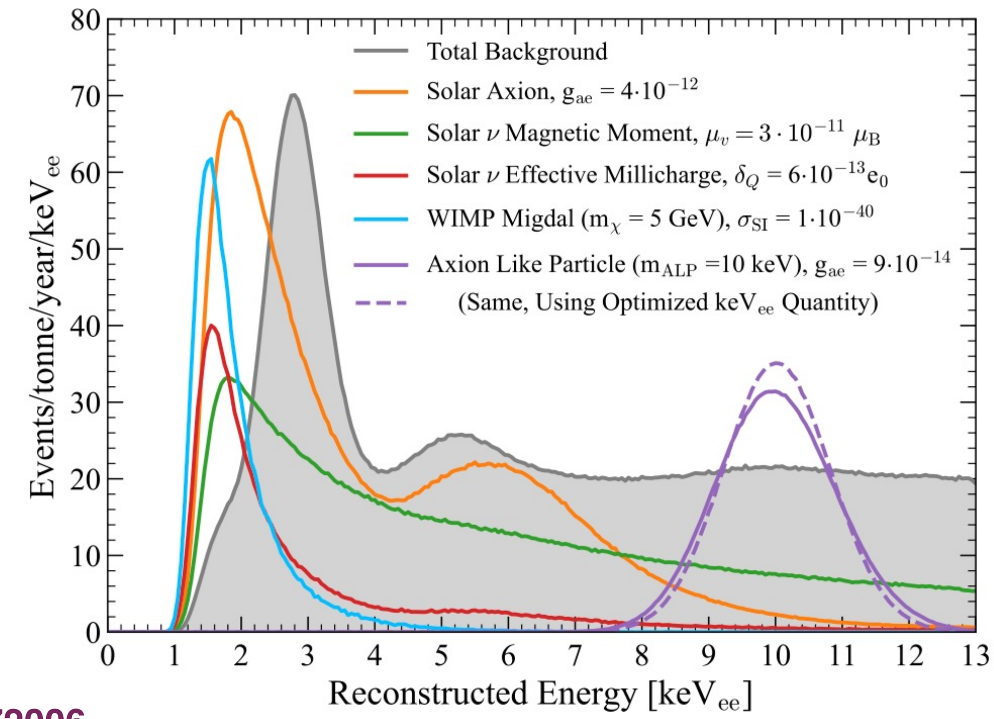


Low-energy ER searches

- **Employs a time-dependent PLR technique** to constrain ^{37}Ar and ^{127}Xe backgrounds



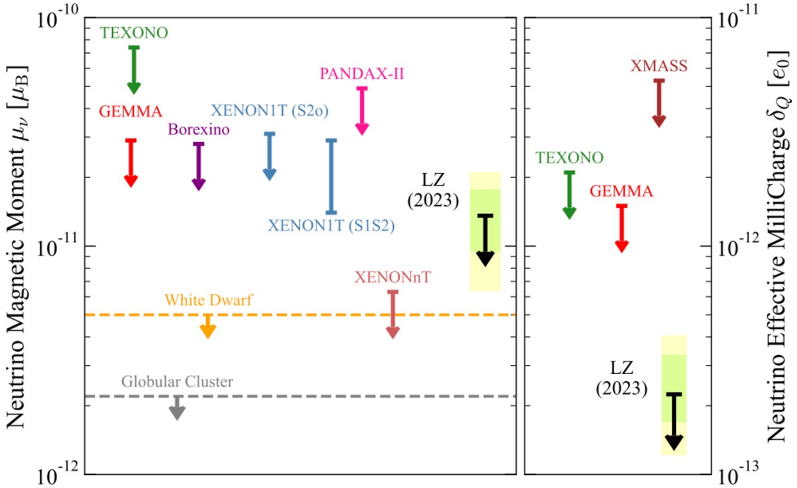
- **Probes for various new phenomena**
  - Solar axions
  - Solar ν magnetic moment and eff. millicharge
  - Axion-like particles (ALPs)
  - Hidden photons (HPs)
  - Low-mass WIMPs via Migdal effect



PhysRevD.108.072006

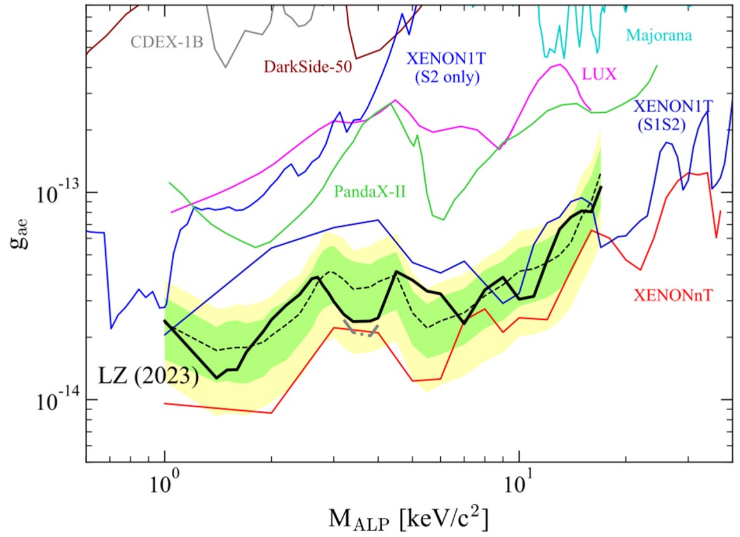
Low-energy ER searches

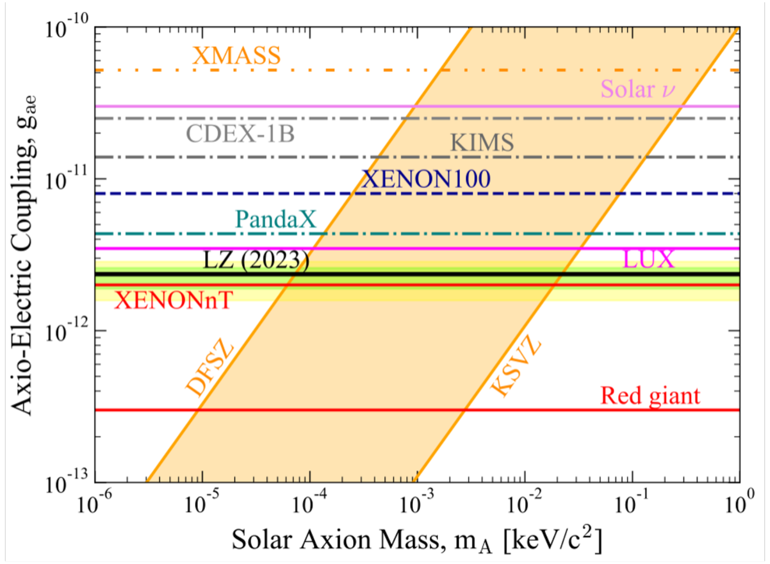
*XENONnT has a **lower ER background**, so there is room for improvement in future iterations



Exotic solar ν properties

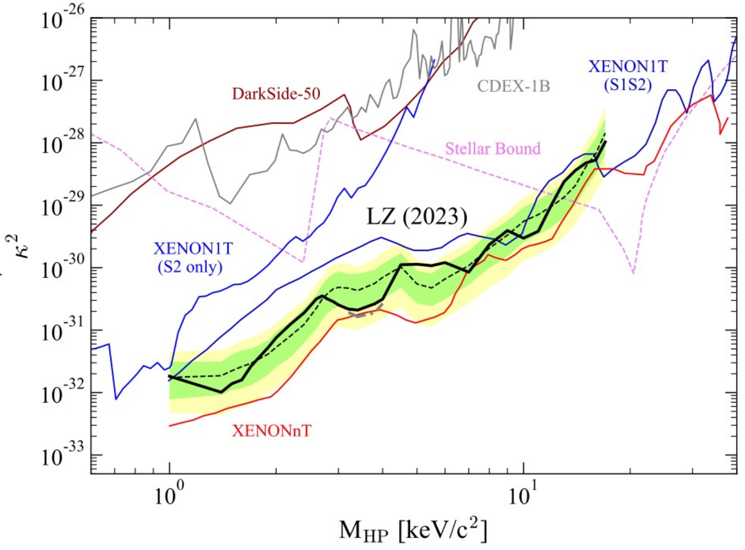
ALP constraints





Solar axion constraints

HP constraints



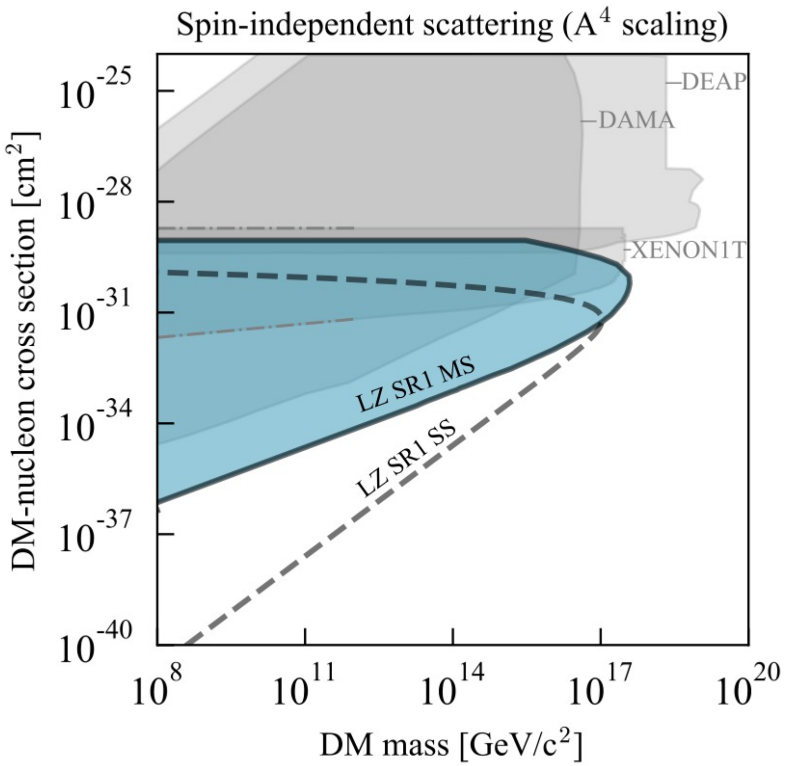
PhysRevD.108.072006

Ultraheavy dark matter searches

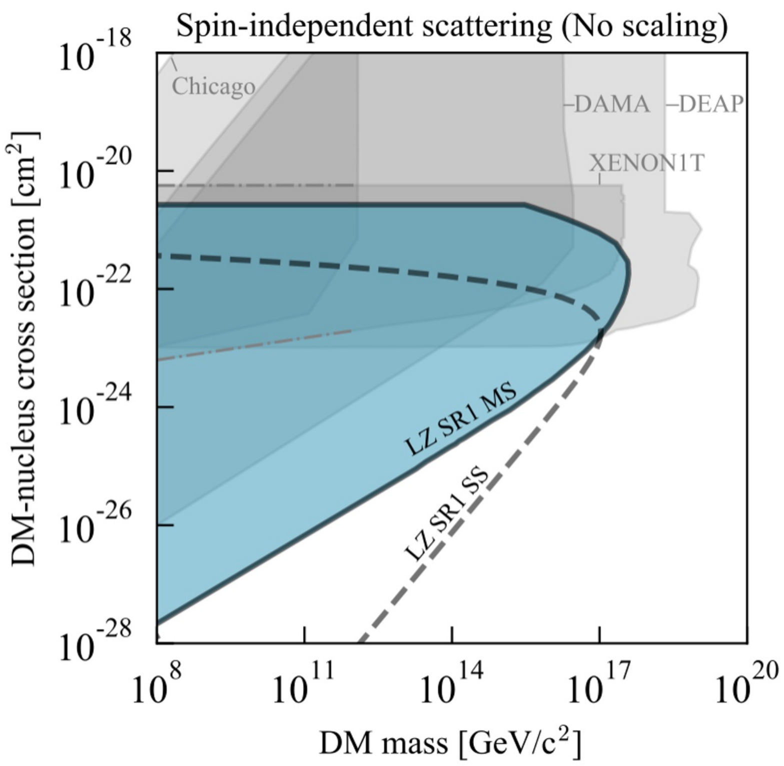
Multiply Interacting Massive Particles (MIMPs)

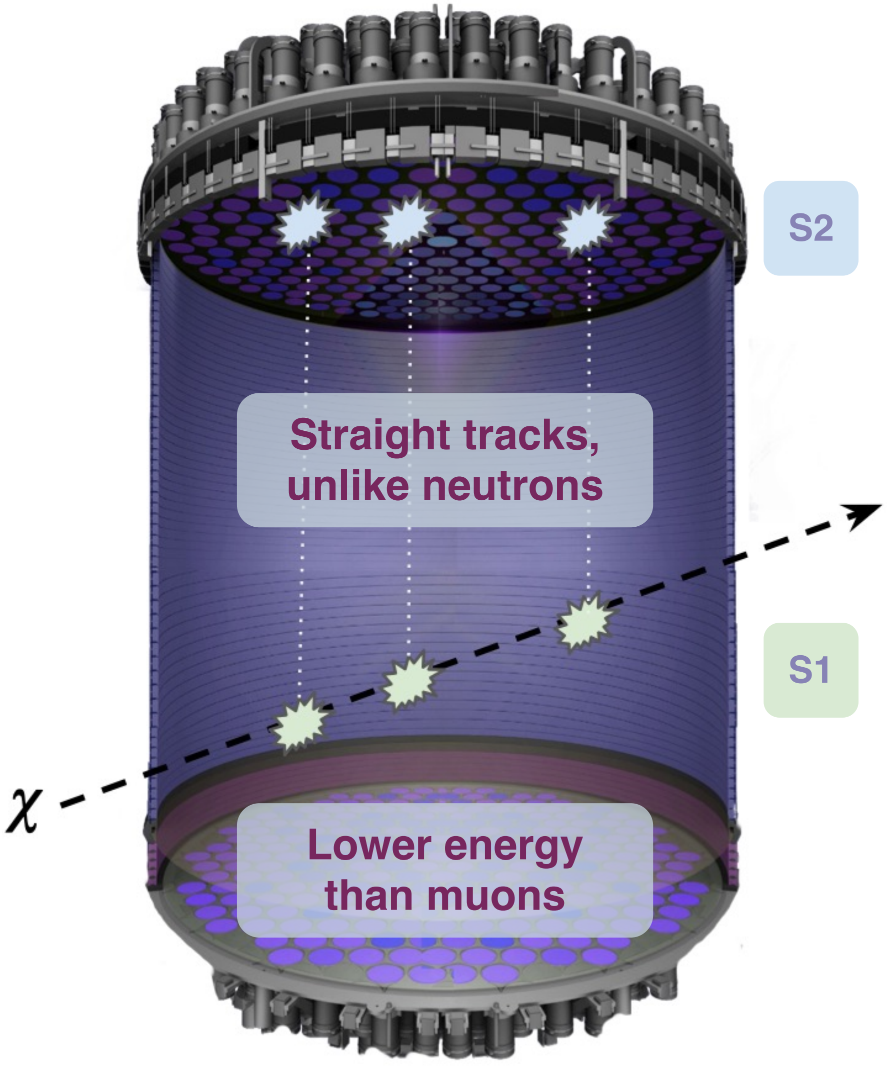
- Higher mass scale (> 10^4 GeV/c^2), unique pathology

(MIMP-**nucleon**)



(MIMP-**nucleus**)

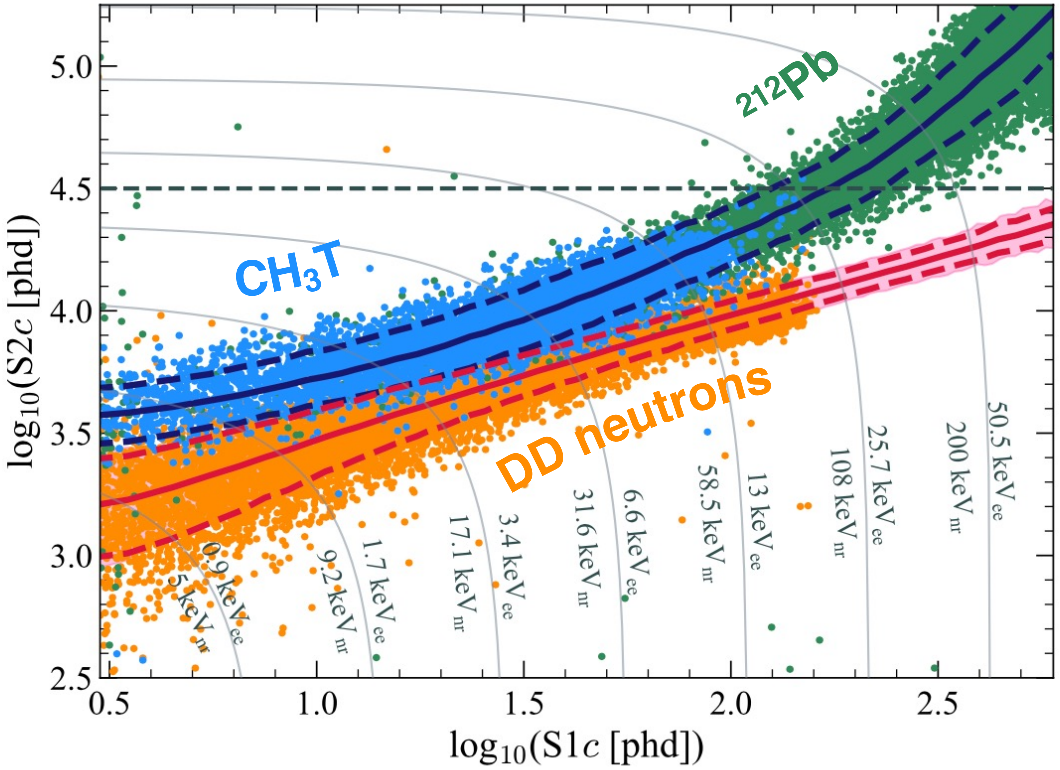


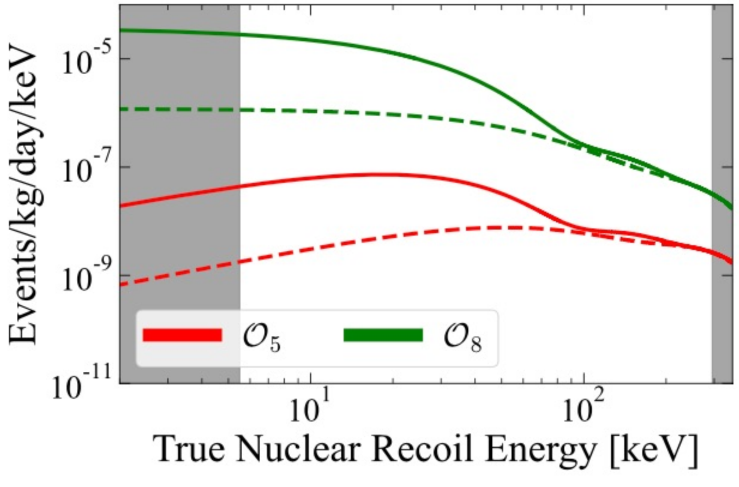


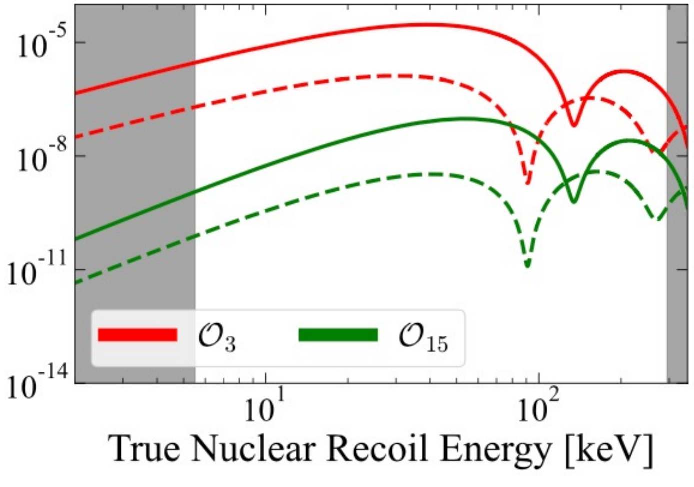
PhysRevD.109.112010

EFT constraints

- Standard SI and SD interactions assume **suppressed momentum dependence**
- **EFT** provides a more generalised (**model independent**) description
- Effective Lagrangian is expanded in terms of dimensionless operators







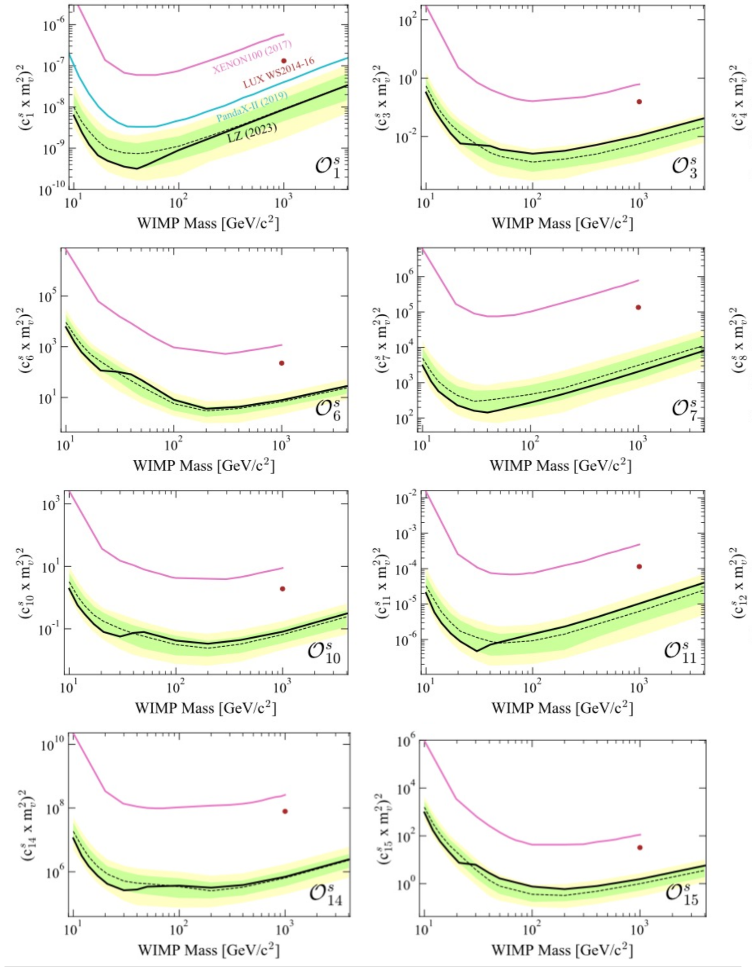
$$\mathcal{O}_1 = 1_\chi 1_N, \quad \mathcal{O}_2 = \left(v^\perp\right)^2, \quad \mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \quad \mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right), \quad \mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp, \quad \mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}, \quad \mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N},$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}^\perp\right), \quad \mathcal{O}_{13} = i\left(\vec{S}_\chi \cdot \vec{v}^\perp\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \vec{v}^\perp\right),$$
$$\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right).$$

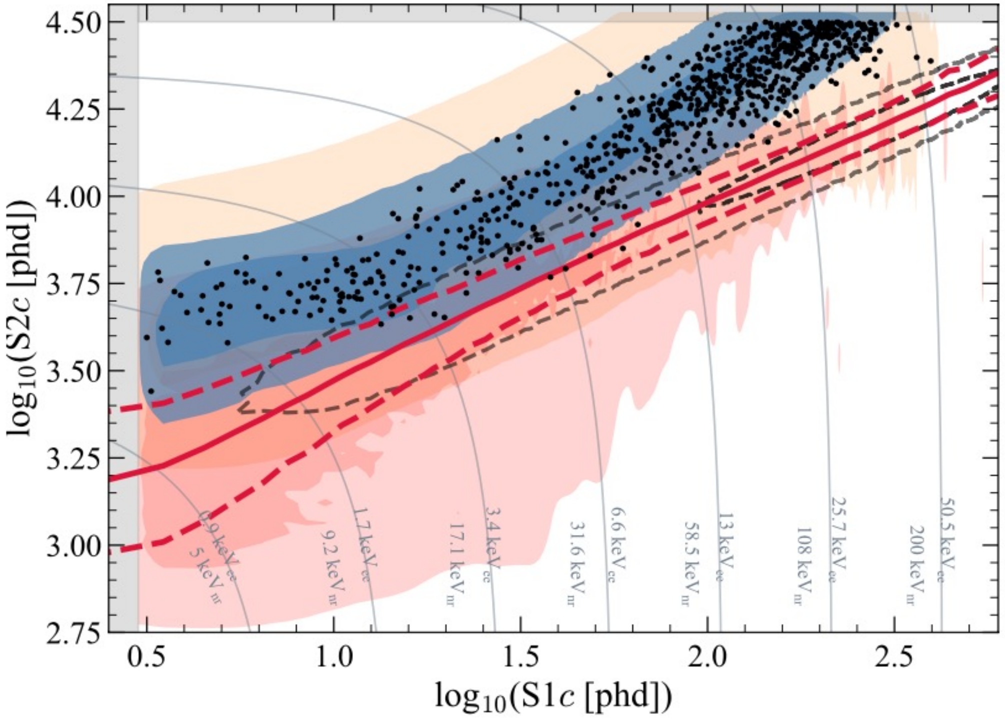
EFT constraints

*Two SR1 EFT publications so far!

PhysRevD.109.092003

arXiv: 2404.17666

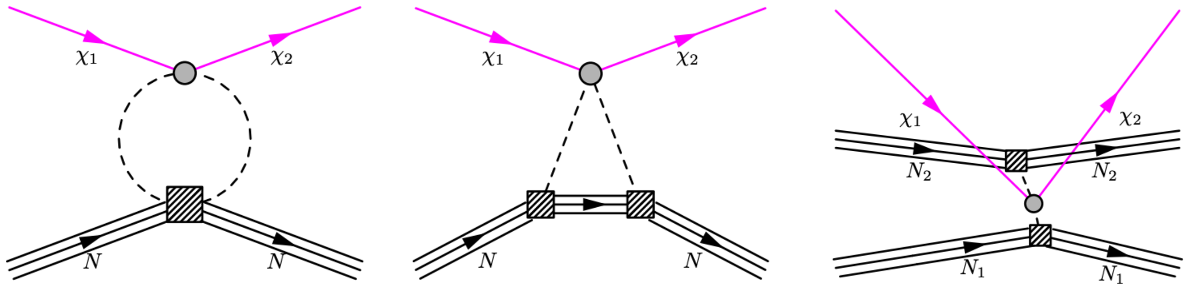


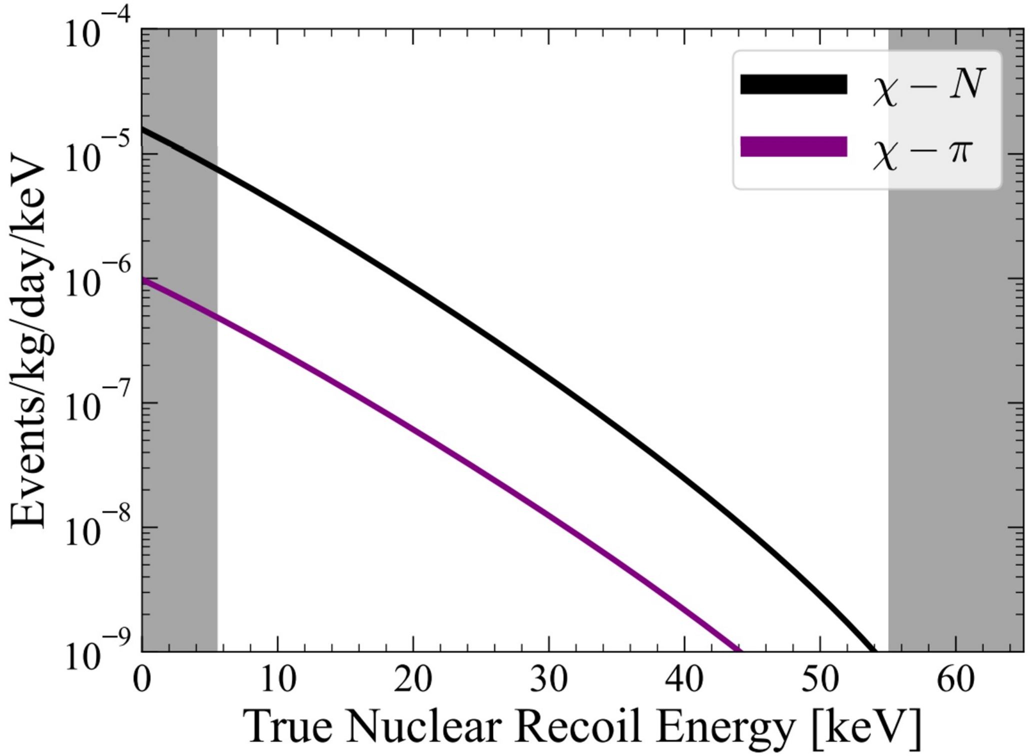


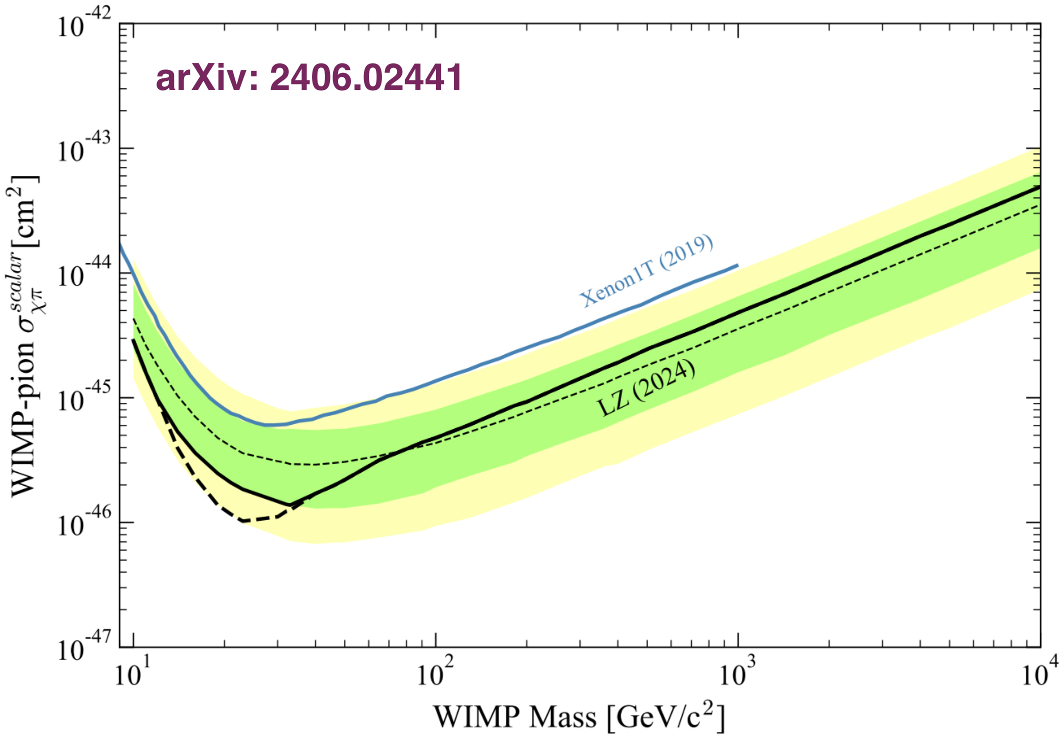
- EFT searches extend up to **higher energies**; new backgrounds are introduced
- **No excesses** observed, but **several world-leading constraints** set on different operator couplings

WIMP-pion interactions

- Probes for interactions between WIMPs and **virtual pions** exchanged between nucleons
- No excess observed; upper limit set at **1.5×10^{-46} cm²** for a 33 GeV/c² WIMP mass



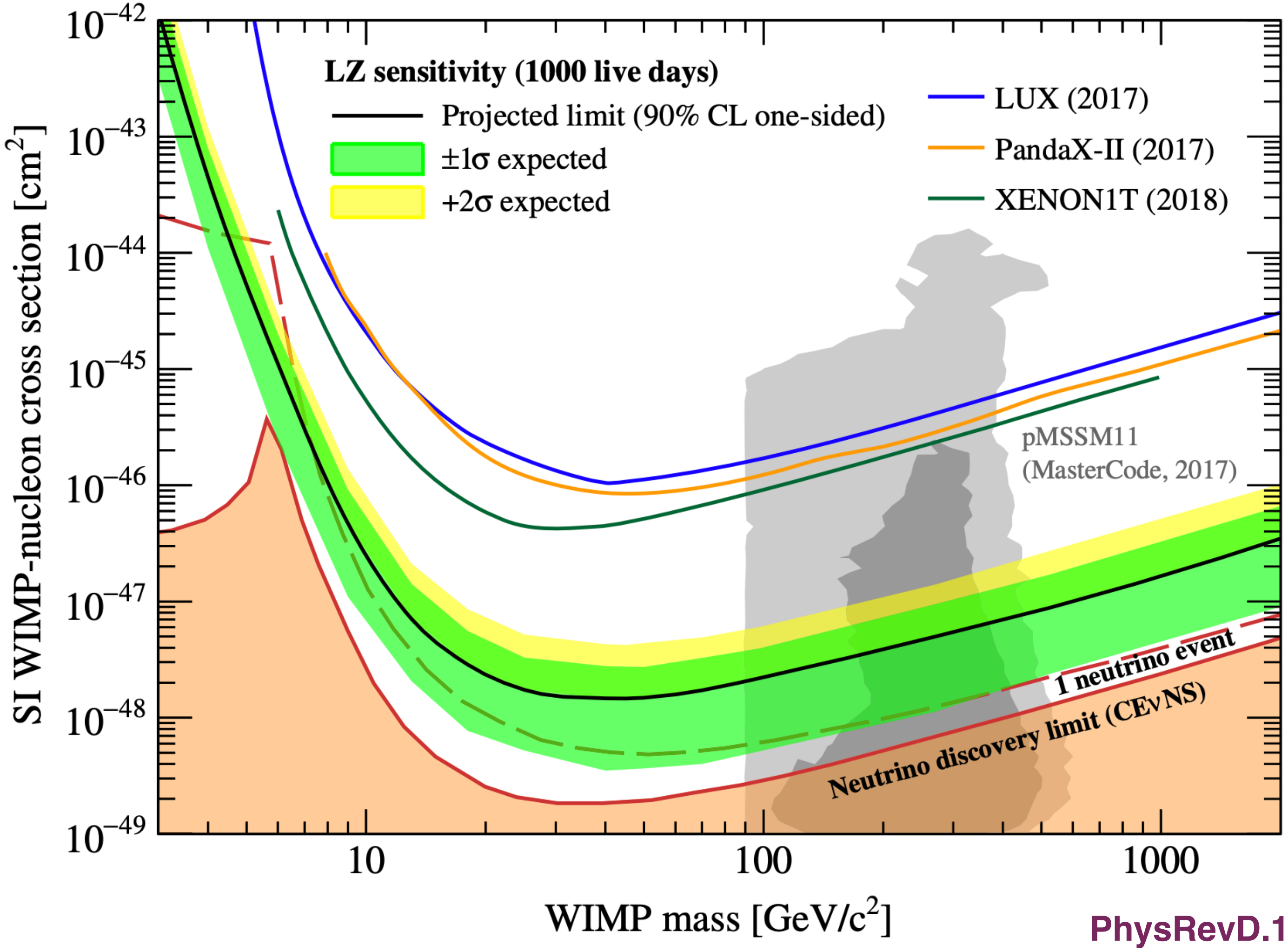


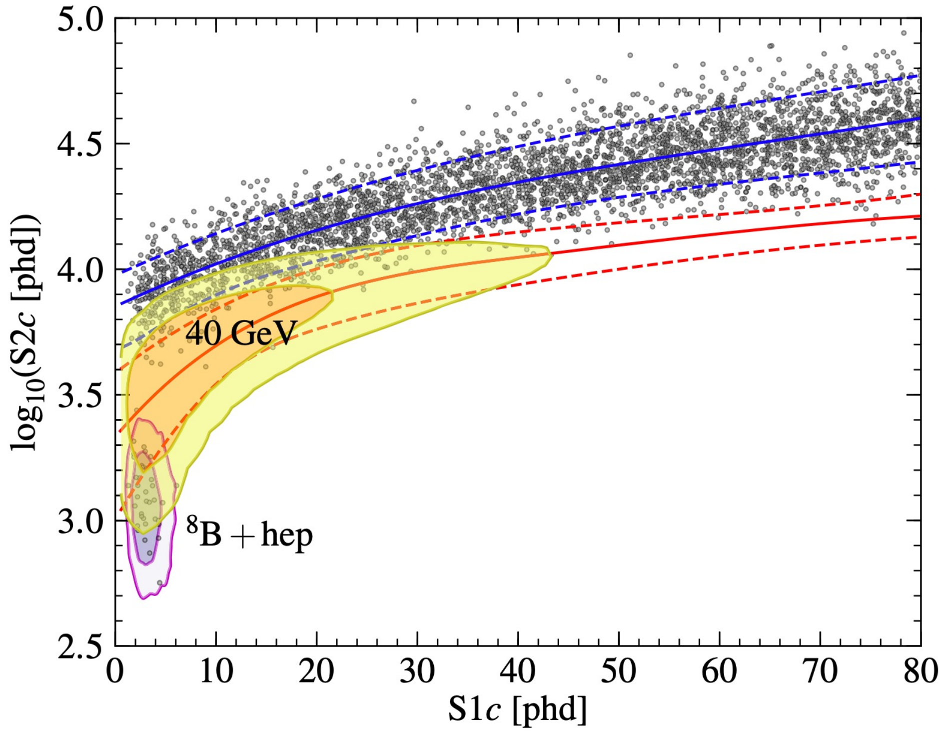


LZ projected sensitivity

SR1 is just **6%** of the planned **1,000 live day exposure**

Expect to achieve **1.4 × 10^{-48} cm^2** for **40 GeV/c^2** WIMPs

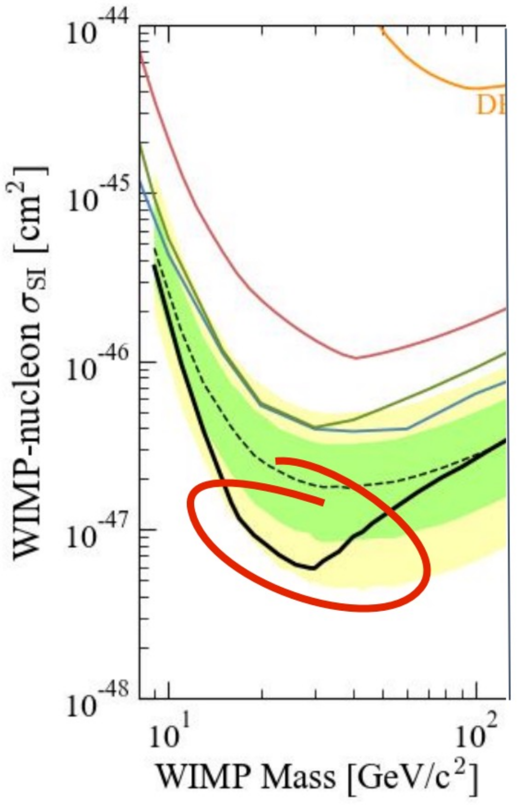


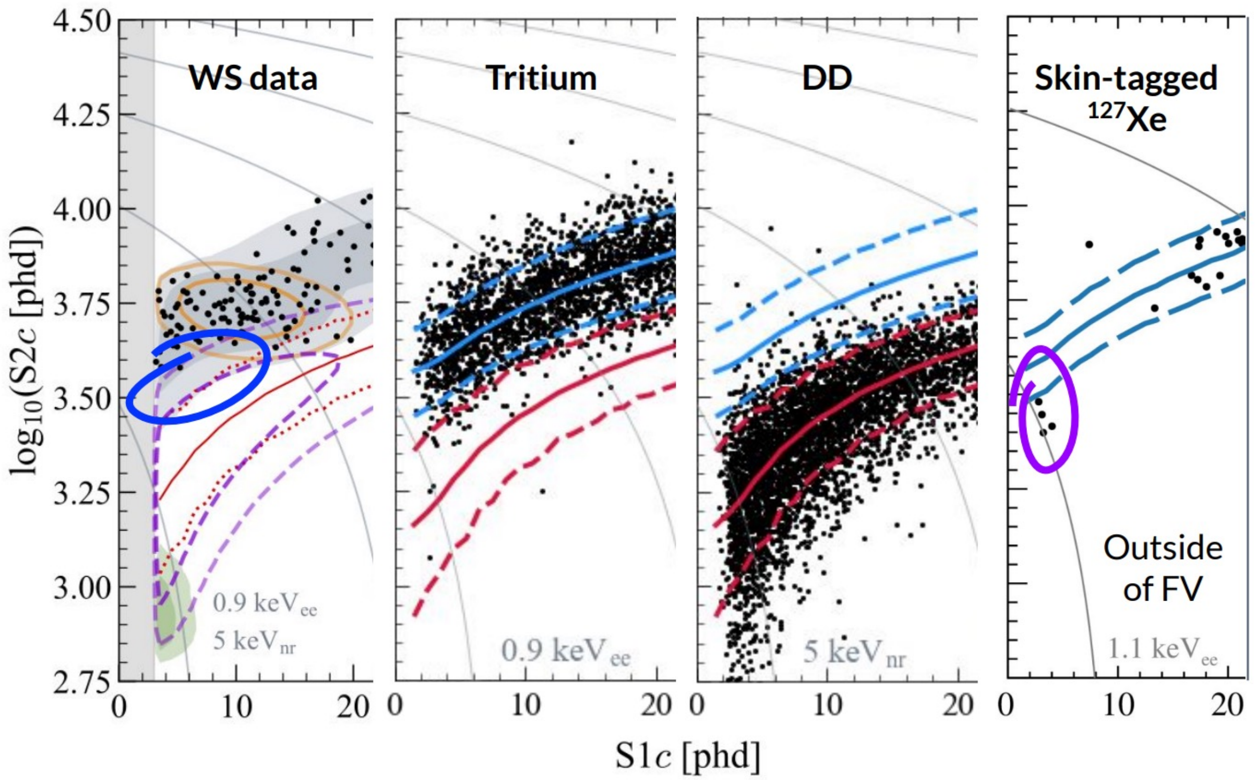


PhysRevD.101.052002

WS2022 limit shape

EPJ C 81 907 (2021)





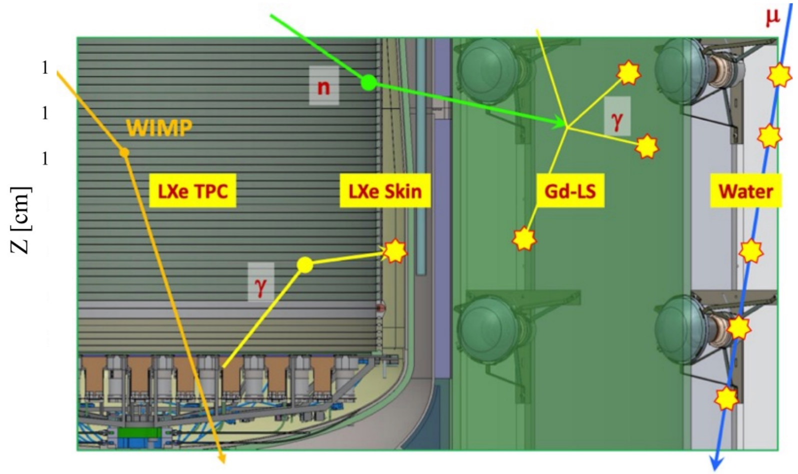
Deficit region is **well-covered by calibration data ⇒ not a signal inefficiency**

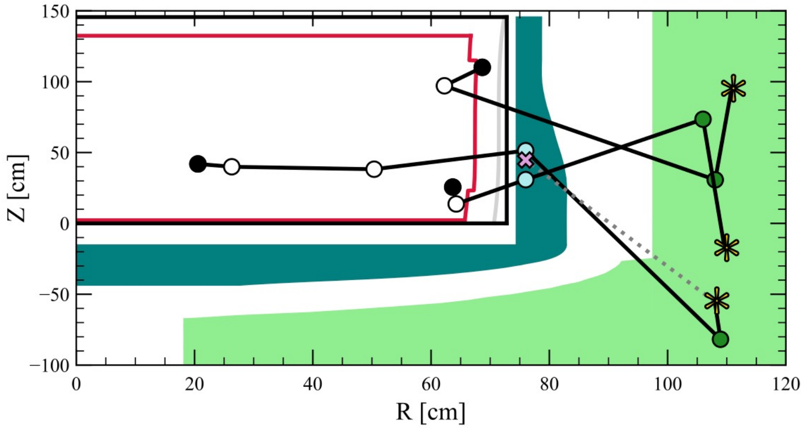
Dip in the limit is due to an **under-fluctuation (deficit) in background events** below the ^{37}Ar population

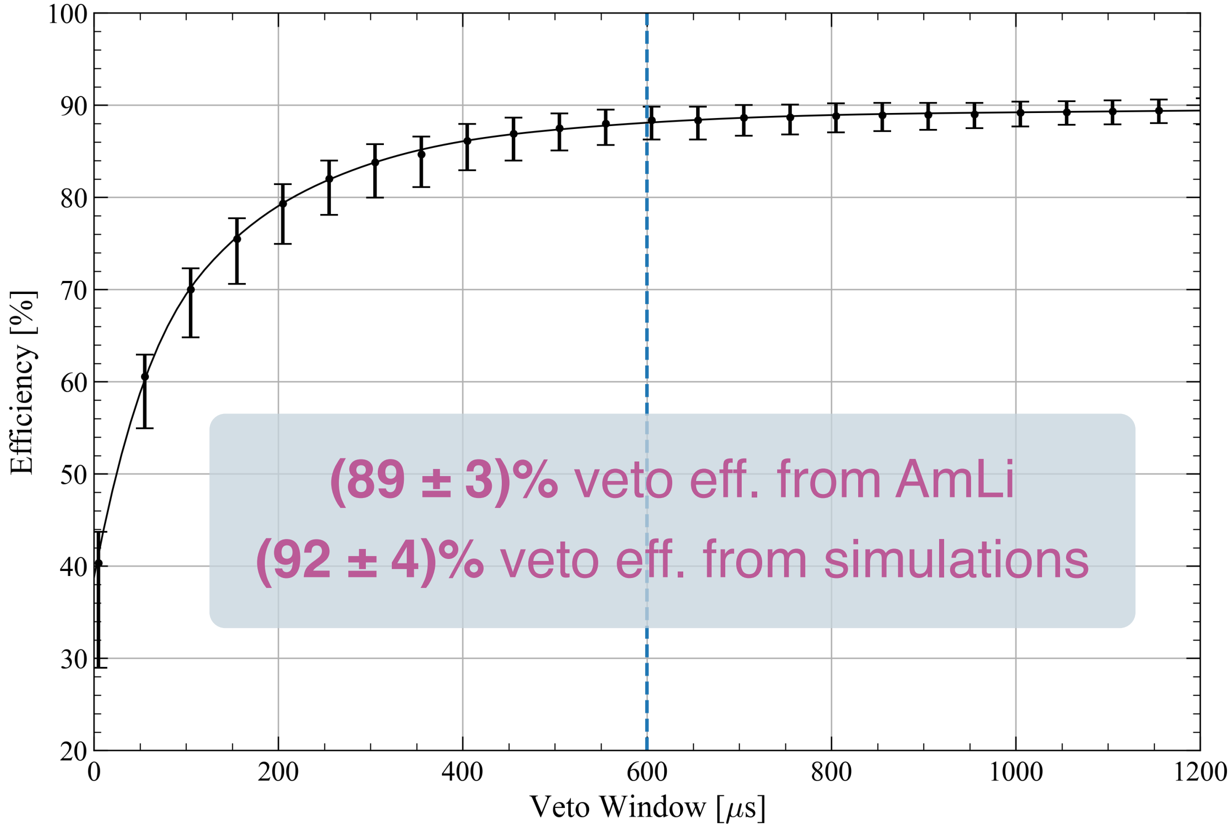
Power constraint is applied to the limit (restricts curve to **-1σ contour**, as per **recommended conventions***

Neutrons

Neutron backgrounds constrained via **OD-tagged sideband** and **multiple scatter (MS) data**; 89% tagging efficiency measured with calibrations and simulations







(89 ± 3)% veto eff. from AmLi

(92 ± 4)% veto eff. from simulations