Status and Results from the LUX-ZEPLIN Experiment

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XeSAT 2023 Nantes - 2023/06/06

LZ (LUX-ZEPLIN) Collaboration,

37 Institutions - 250 scientists, engineers, and technical staff

- 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

US UK Portugal Korea Australia

Science and Technology Facilities Council

Sanford Underground Research Facility
South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

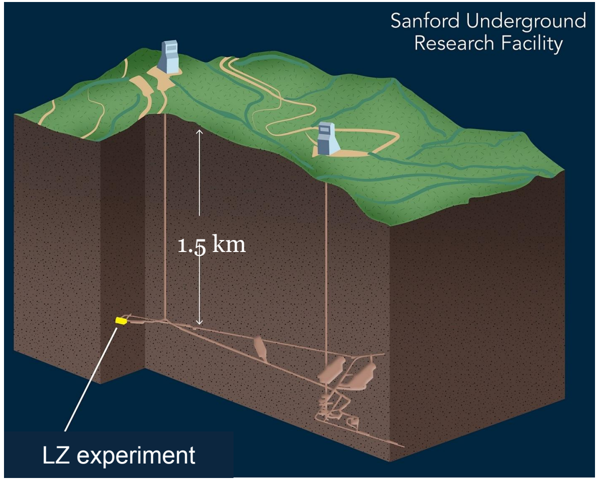
ibs Institute for Basic Science

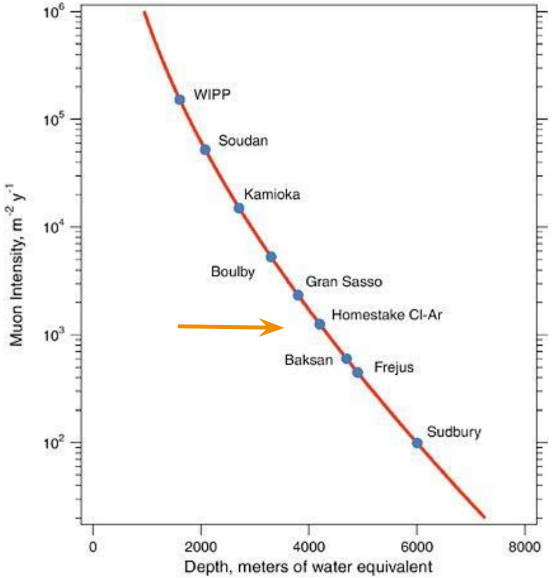
Thanks to our sponsors and participating institutions!

SURF Underground Lab

LZ is installed at SURF (SD, USA) in the Homestake gold mine at a depth of 4850 ft (1.5 km)

- 4300 m.w.e overburden
- ~10^6 muon flux reduction





The LUX-ZEPLIN (LZ) Experiment

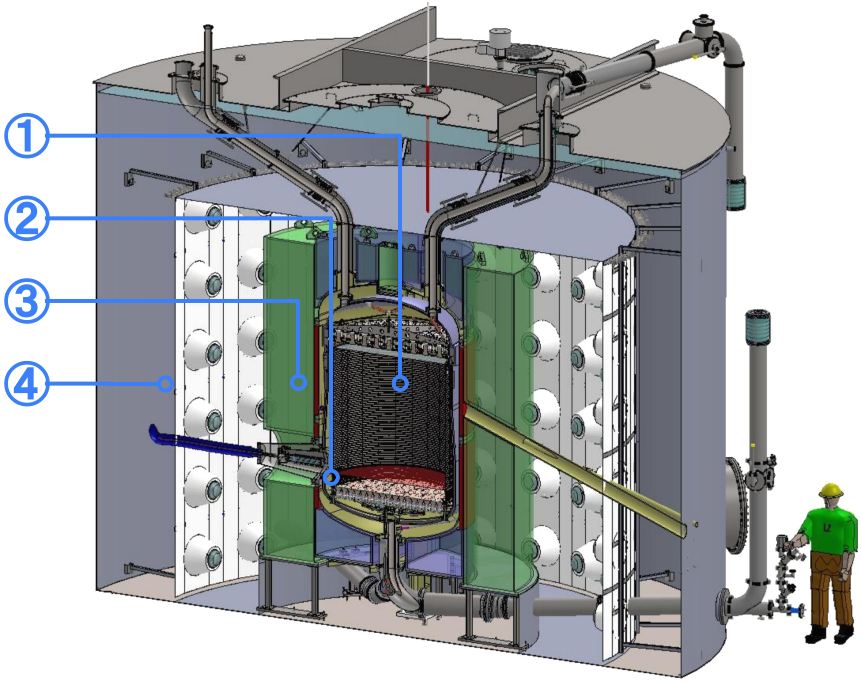
7 tonne dual-phase Xe ultra-low background TPC designed for dark matter searches ①

- ➢ Observed by two arrays of 253 (top) and 241 PMTs (bottom).
- ➢ 1.5 m diameter and height
- ➢ 4-high voltage wire mesh electrodes:
  - ○ Drift field (193 V/cm)
  - ○ Extraction region (7.3 kV/cm)
- ➢ PTFE Field cage for increased light collection
  - ○ >0.971 reflectivity (95% CL)

Two additional detectors for background modeling and mitigation: "Skin" detector ② and Outer Detector (OD) ③

All instrumented volumes submerged in a 228 t water shield ④ also working as a muon veto (>99% eff.)

LZ is primarily a **dark matter** search experiment, but has a broad science program: rare xenon decays, neutrino interactions, axions, etc.

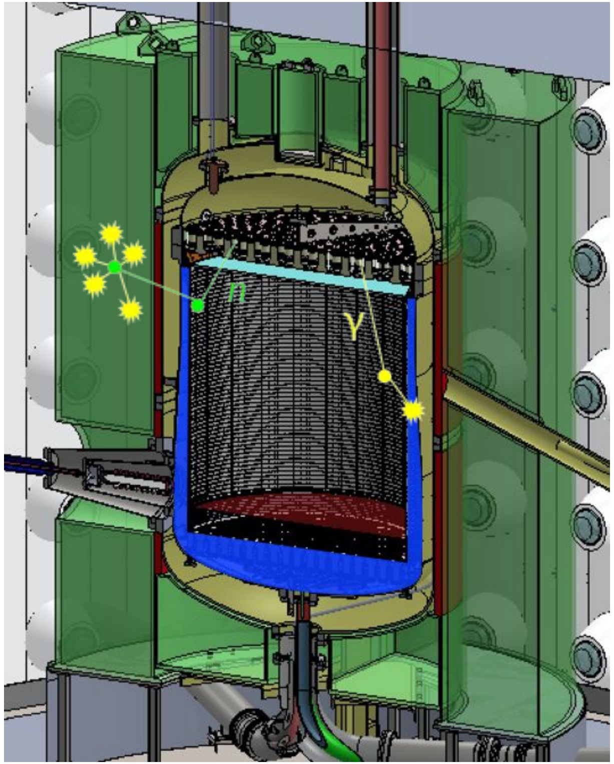


Skin and Outer Detectors

Gamma and Neutron Vetoes: in situ characterization, tagging and reduction of neutron and gamma backgrounds to improve sensitivity.

The Skin detector:

- 2 tonnes of LXe surrounding the TPC
- 131 1'' and 2'' PMTs on top, side and bottom
- Lined with PTFE to maximize light collection (100 keV threshold in >95% volume)
- Anti-coincidence detector for γ-rays

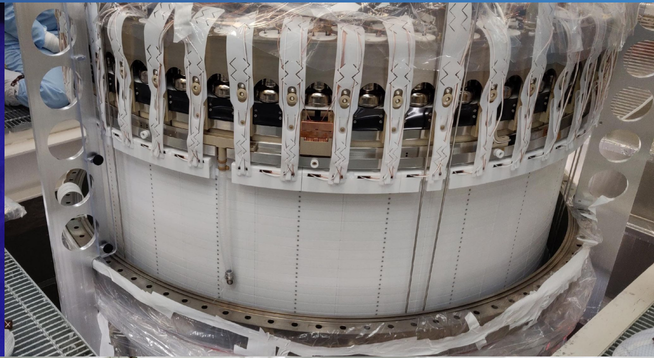


The Outer Detector (OD):

- 17.3 t Gd-loaded liquid scintillator in acrylic vessels
- 120 8" PMTs mounted in the water tank
- Anti-coincidence detector for γ-rays and neutrons
- 8 MeV γ-rays from thermal neutron capture on Gd, 2.2 MeV γ-ray from H capture.
- **89% neutron tagging efficiency.**

Construction, Deployment and Commissioning






LZ Science Run 1 (SR1)

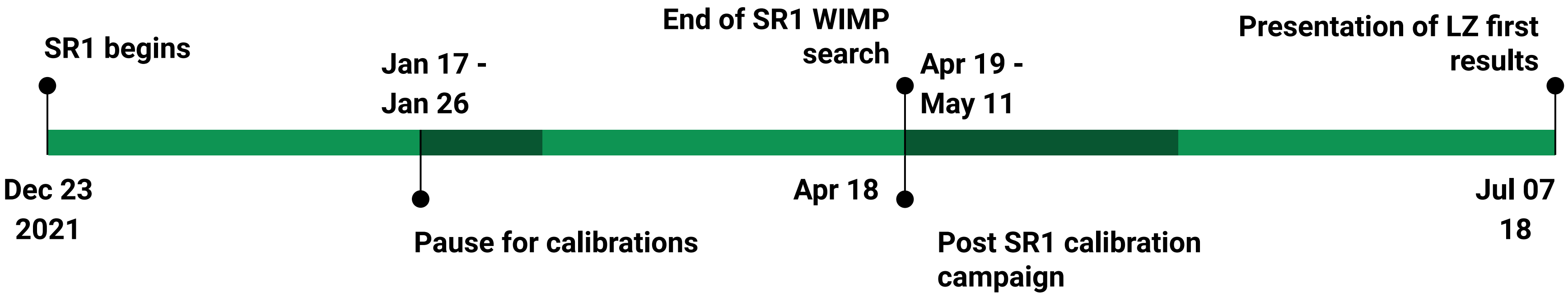
Planned to collect <u>60 live-days</u> after completing extensive commissioning and testing campaigns across all detector systems.

★ To prove successful detector operation and expectation for competitive sensitivity.

★ Data collected from 23 Dec 2021 to 11 May 2022 under stable detector conditions.

★ Engineering run - no salting/blinding.

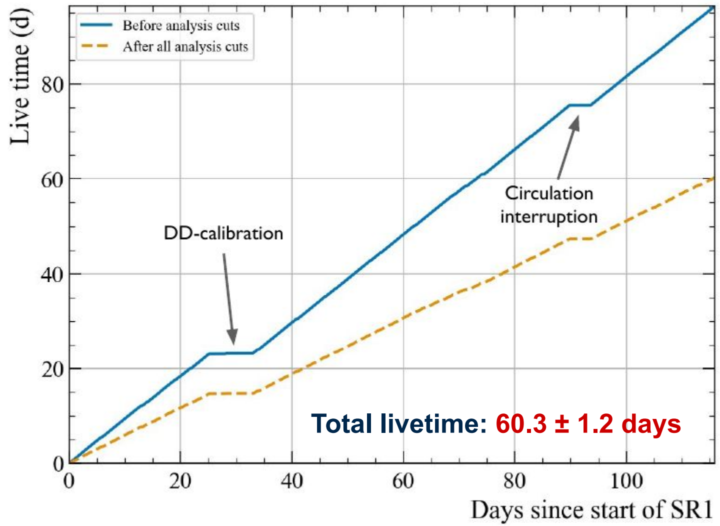
- Goal was to understand the detector and sources of systematic errors.
- **Bias mitigation: all analysis cuts were developed and optimized on sideband selections and calibration data.**



LZ Science Run 1 (SR1)

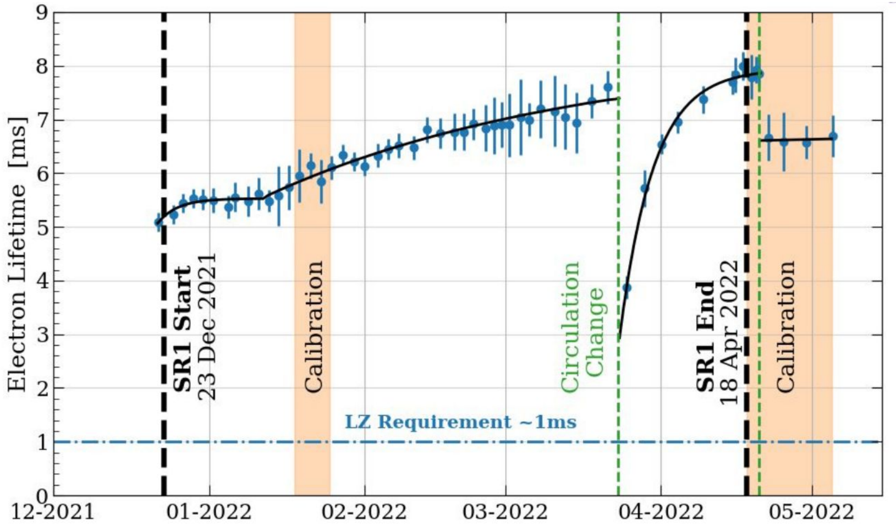
Total livetime: 60.3 ± 0.5 days

- 1 Hz GPS trigger signal used to quantify systematics in livetime estimator.
- Two periods of paused science-data:
  - Mid-run neutron calibration campaign
  - Circulation interruption



Electron lifetime: the mean time a free electron will live before getting captured by impurities.

- LZ requirement: > 1ms (max drift time)
- During SR1, e-lifetime consistently greater than 5ms



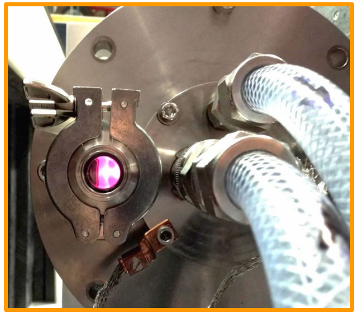
Detector Calibrations

Several **calibration strategies** deployed:

- Internal sources mixed in the xenon
- Vertical source tubes for commercial rod sources
- Photo-neutron source
- DD neutron generator

What we get from calibrations:

- Normalize spatial variations in observed S1 and S2
- Position reconstruction & TPC wall position
- Inter-detector timing calibrations
- Electron Recoil (ER) & Nuclear Recoil (NR) response
- OD light yield
- OD neutron tagging efficiency

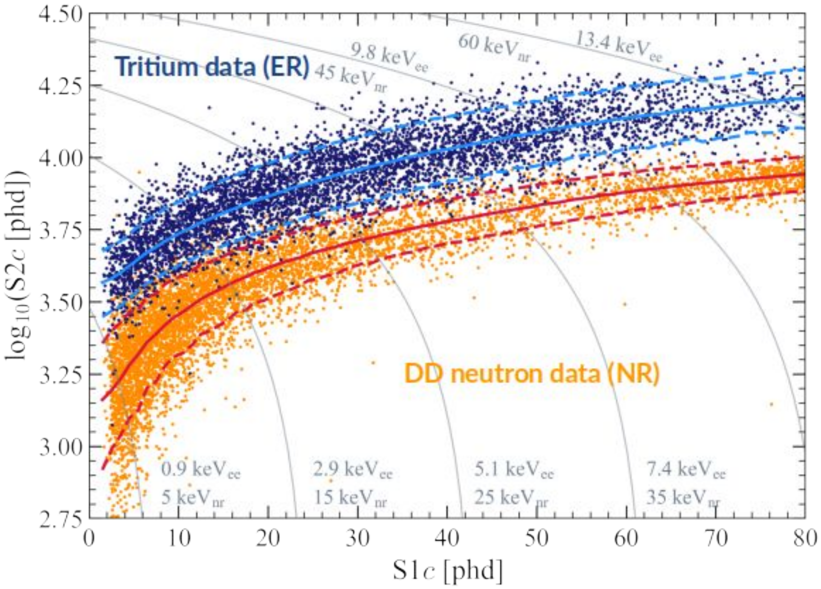


	Nuclide	Type	Energy [keV]	$\tau_{1/2}$
Internal/injected	^{83m}Kr	γ	32.1 , 9.4	1.83 h
	^{131m}Xe	γ	164	11.8 d
	^{220}Rn	α, β, γ	various	10.6 h
	^{3}H	β	18.6 endpoint	12.5 y
	^{14}C	β	156 endpoint	5730 y
External	^{241}AmLi	(α,n)	1500 endpoint $^{(a)}$	432 y
	^{252}Cf	n	Watt spectrum	2.65 y
	^{241}AmBe	(α,n)	11,000 endpoint	432 y
	^{57}Co	γ	122	0.74 y
	^{228}Th	γ	2615	1.91 y
	^{22}Na	γ	511,1275	2.61 y
	^{60}Co	γ	1173 , 1333	5.27 y
	^{133}Ba	γ	356	10.5 y
	^{54}Mn	γ	835	312 d
	^{88}YBe	(γ,n)	152	107 d
	^{124}SbBe	(γ,n)	22.5	60.2 d
	^{205}BiBe	(γ,n)	88.5	15.3 d
	^{206}BiBe	(γ,n)	47	6.24 d
DD generator	DD	n	2450	–
	D Ref.	n	272 $\rightarrow$ 400	–

ER and NR response

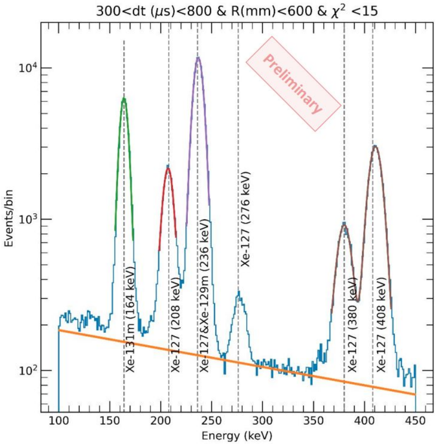
https://nest.physics.ucdavis.edu/

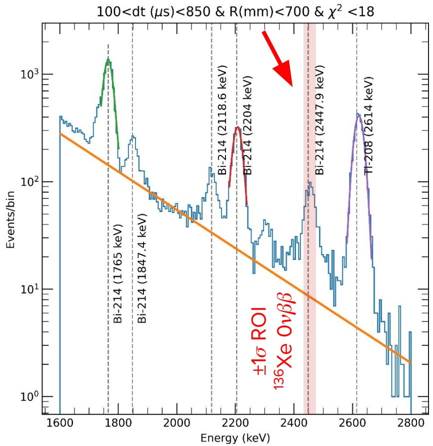
- LXe response and ER/NR band fits obtained using Noble Element Simulation Technique (NEST)
- ER band from CH_3T calibration (blue).
- NR band from DD calibration (orange).
- ER leakage: **99.9% rejection of ERs below NR median**
- Fit data to model for detector-performance parameters:
  - Light collection efficiency g_1= 0.114 ± 0.002 phd/photon
  - Charge gain g_2= 47.1 ± 1.1 phd/electron

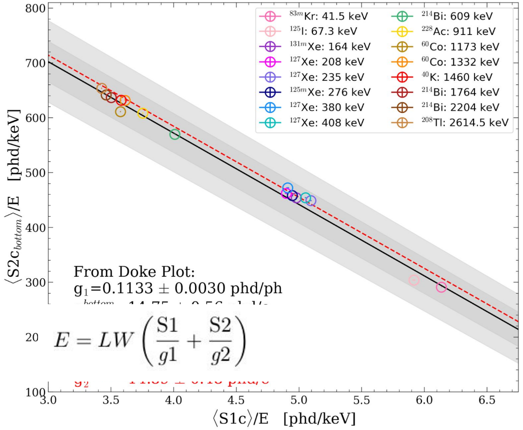


Mono-energetic ER peaks also used to determine detector gains (g_1 & g_2)

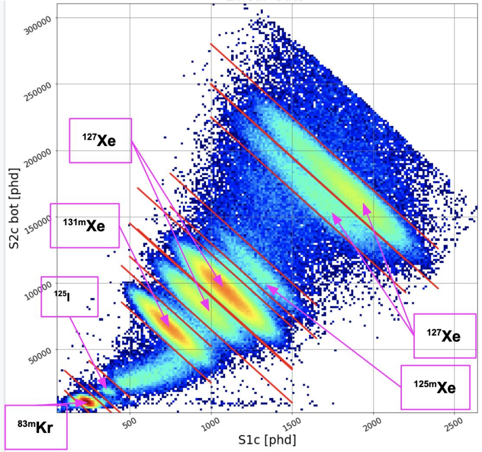
Parameter	Value
g_1^{gas}	0.0921 phd/photon
g_1	0.1136 phd/photon
Effective gas extraction field	8.42 kV/cm
Single electron	58.5 phd
Extraction Efficiency	80.5 %
g_2	47.07 phd/electron







$$E = LW\left(\frac{S1}{g1} + \frac{S2}{g2}\right)$$



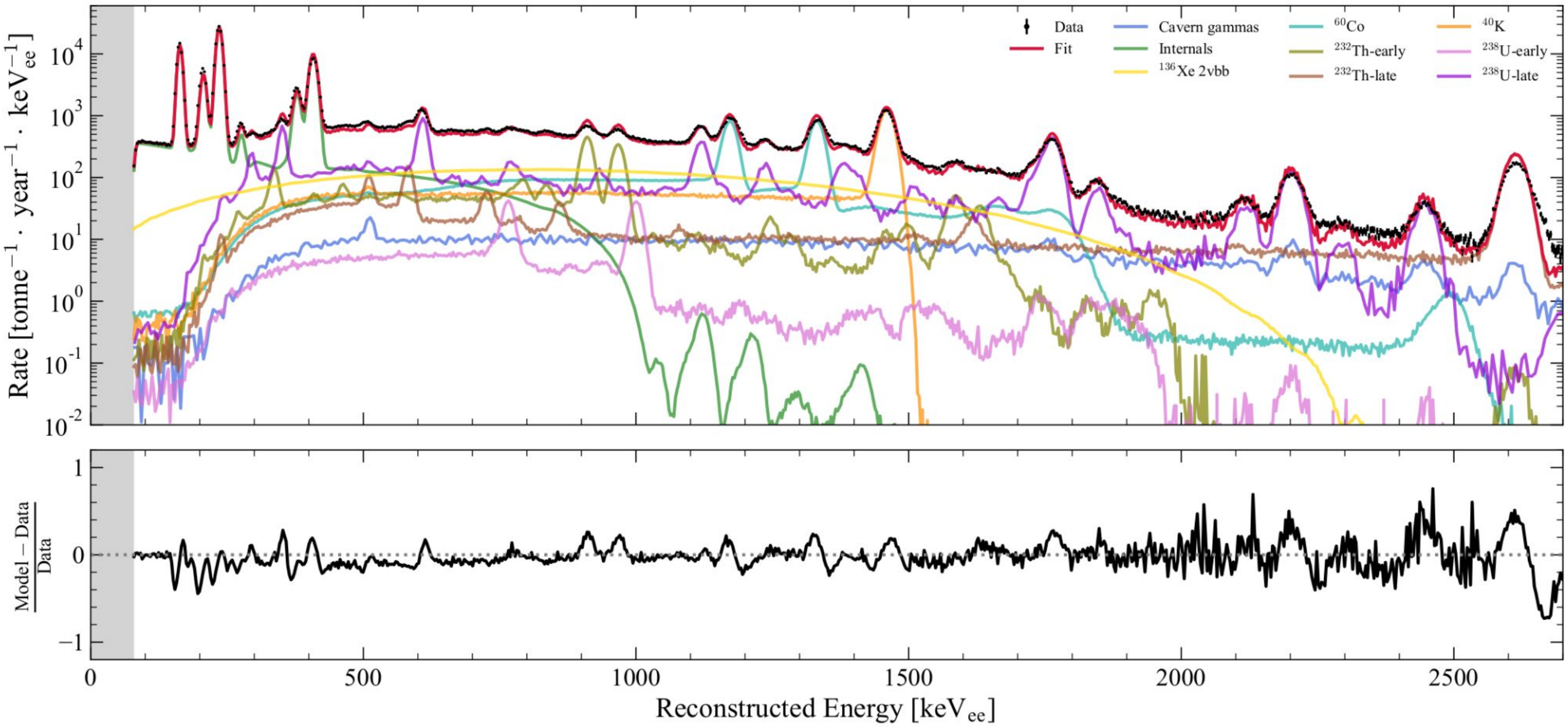
LZ obtained an unprecedented energy resolution for liquid xenon at high energies:

0.64 ± 0.02 % (σ/E) for ^{208}Tl 2614 keV

★ Only using the bottom PMT array to reconstruct energy.

Characterization of all backgrounds across all energies.

- Simulations and extensive assays campaign provide a full BG model:

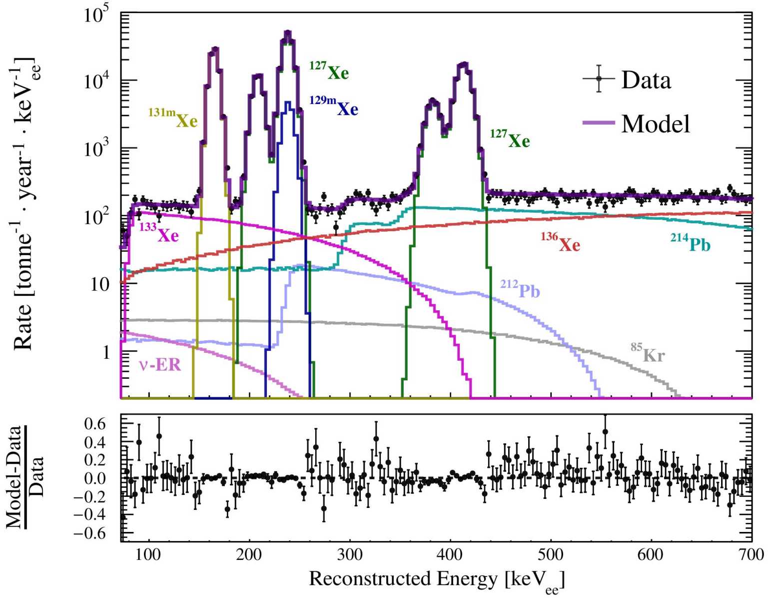


Backgrounds

(e-print 2211.17120)

Backgrounds relevant for WIMP search:

- Dissolved beta emitters:
  - ^{214}Pb (^{222}Rn daughter), ^{212}Pb (^{220}Rn daughter), ^{85}Kr, ^{136}Xe (2 beta)
- Dissolved e-captures (monoenergetic x-ray/Auger cascades):
  - ^{127}Xe, ^{124}Xe (2 e-capture), **^{37}Ar**
- Long-lived gamma emitters in detector materials:
  - ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co
- Neutron emission from spontaneous fission and (α,n)
- Solar neutrinos from ^{8}B (NR) and pp (ER) chains
- **Accidental coincidences**.

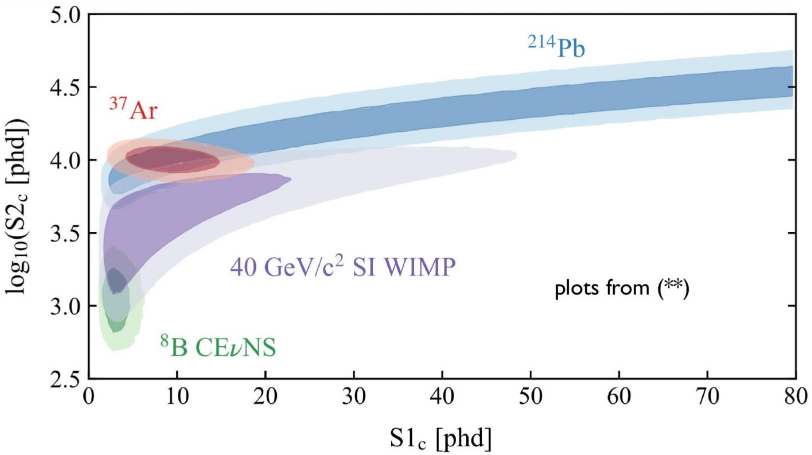


Backgrounds

(e-print 2211.17120)

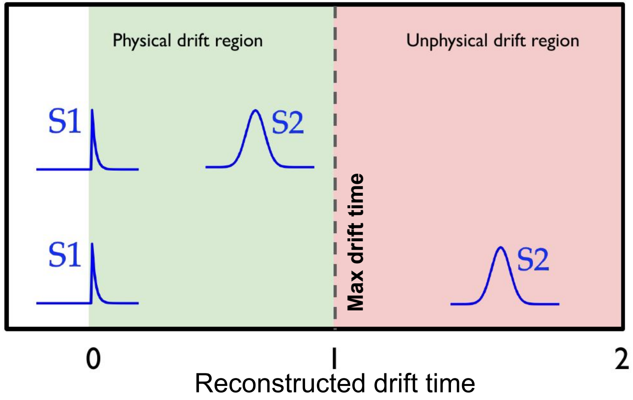
Argon-37 electron capture with $T_{1/2}$ = 35 d and monoenergetic 2.8 keV ER deposition:

- Naturally occurring in the atmosphere via $^{40}Ca(n,\alpha)^{37}Ar^*$, or cosmic spallation of ^{nat}Xe
- Equilibrium values range from 1-100 mBq/m^3
- Expecting O(100) ^{37}Ar events in SR1 [2201.02858]

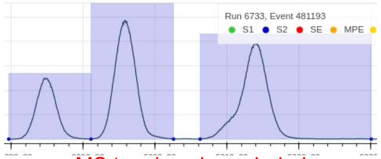


"**Accidentals**": Pairing of random isolated S1s and S2s that mimic real single scatters:

- Isolated S1s (~1 Hz), isolated S2s (~10^{-3} Hz)
- Events with unphysical drift time used to constrain the accidentals rates
- Efficiency of data quality cuts to remove accidentals: >99.5%
- Data-driven accidentals BG: 1.2 ± 0.3 events



Data Quality Cuts

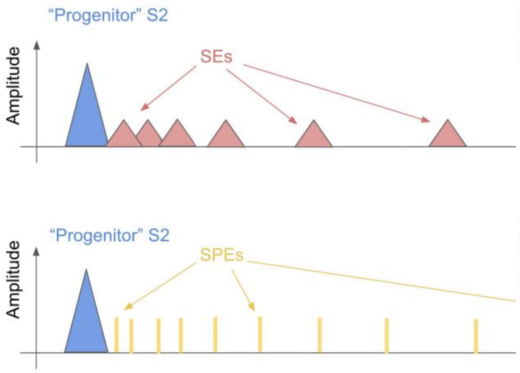


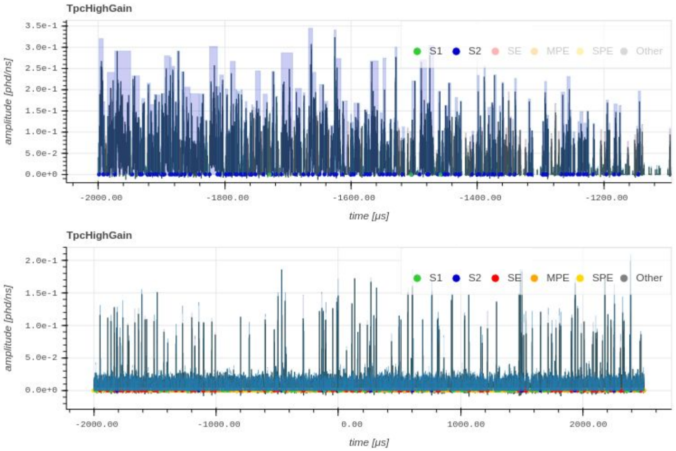
MS topology is excluded

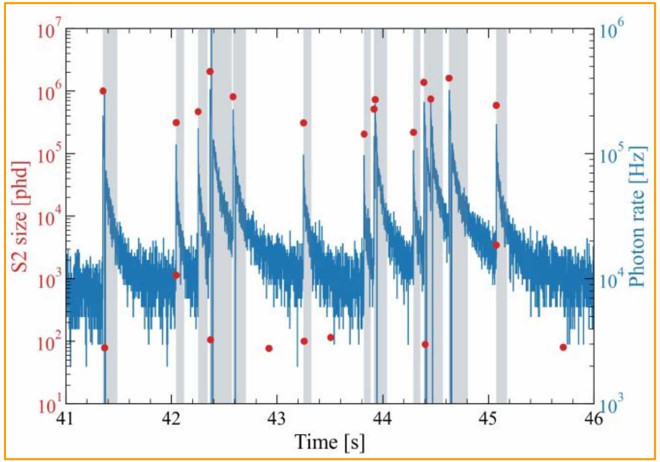
1. Selection of single scatters within a optimized fiducial volume.
2. Identify spurious signals:
   a. Pulse-based cuts: S1 and S2 shape - **signal acceptance loss**
   b. Time-period cuts: exclude periods of detector instability - **small livetime impact**

3. Pulse trains cuts: Large S2s induce delayed emission of pulses lasting O(100ms)

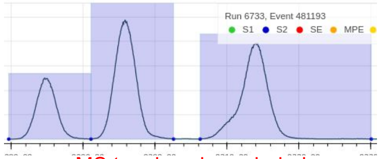
Periods after a large S2 are also excluded - **large livetime impact**







Data Quality Cuts



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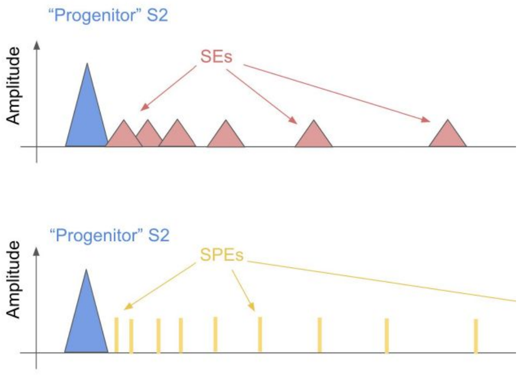


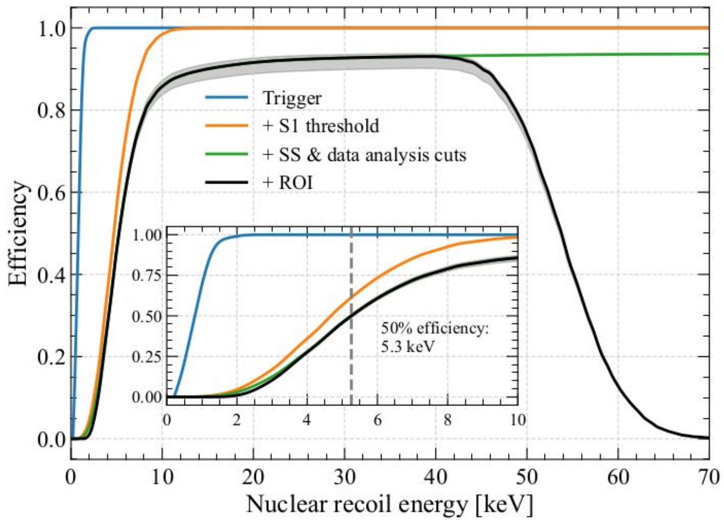
Total livetime: 60.3 ± 0.5 days

Livetime (LT) impact cuts		
Cut name	**Targeted effect**	**Impact**
Hot spot exclusions	Grid electron emission	3.1% LT removed
Muon holdoff	Glow from TPC-crossing muons	0.2% LT removed
E/ph-train holdoff	**Glow from S2s**	**29.8% LT removed**
High S1 rate exclusions	PMT/HV(?) misbehavior	0.2% LT removed
Bad buffer cuts	DAQ issue, caused by glow from muons & S2s	Deadtime hit, 0.5% LT removed, confirmed with GPS triggers and simple calculation from S2/muon rate
Excess Area cut	Glow from ghost muons/S2s	
Sustained rate cut	Glow from ghost muons/S2s	
Burst noise cut	Electronics noise	Deadtime hit, < 0.001% LT removed

Signal Acceptance

- S2 trigger acceptance measured using:
  - Random triggers
  - DD generator data with pulsed plasma trigger
- S1 acceptance dominated by 3-fold coincidence requirement.
- Data selection acceptance measured with calibration sources
- Event classification efficiency measured by blind visual inspection of +1k neutron calibration events

50% acceptance above 5.3 keVnr



Uncertainty band (gray) from differences in cut acceptances as measured with different calibrations, and statistical uncertainties.

LZ SR1 WIMP-search Results

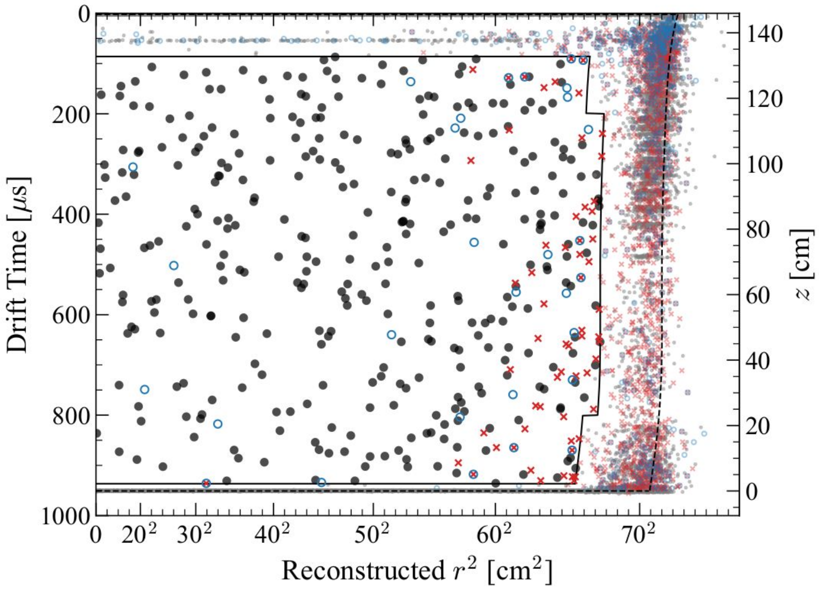
335 events passed the data quality cuts:

- Black dots: events passing all cuts.
- Gray dots: events passing all cuts except for fiducial volume.
- Red ×: events vetoed by the LXe Skin detector (mostly ^{127}Xe)
- Blue circle: events vetoed by the OD.

5.5 ± 0.2 tonnes fiducial volume (FV):

★ Total SR1 exposure of 330 tonne·days

★ Skin veto improved radial acceptance significantly.

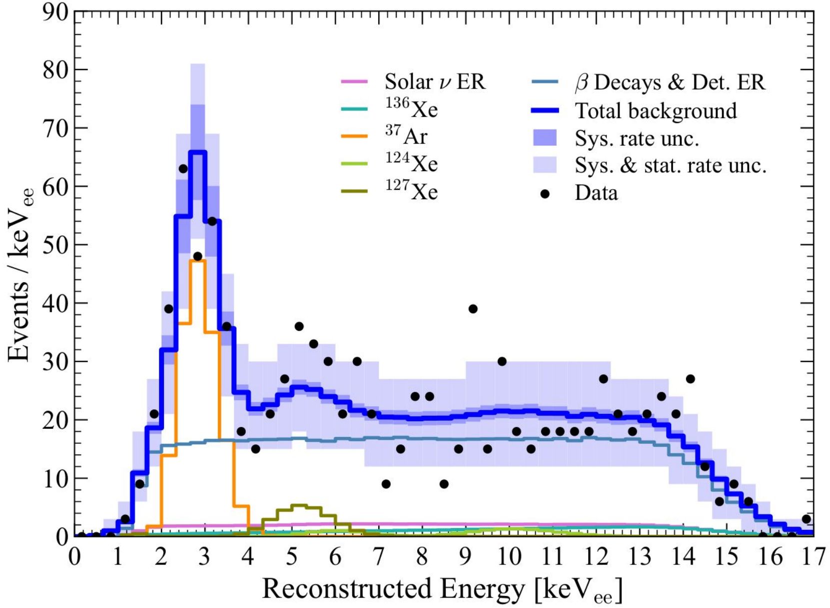


LZ SR1 WIMP-search Results

All backgrounds are within expectations.

- ★ Data agrees with the background-only model (p-value of 0.96).
- ★ Data is shown as black dots. Expected range of stat fluctuations for best fit in blue.
- ★ ^{37}Ar excess observed at 2.7 keV, consistent with projected rate and decay time.

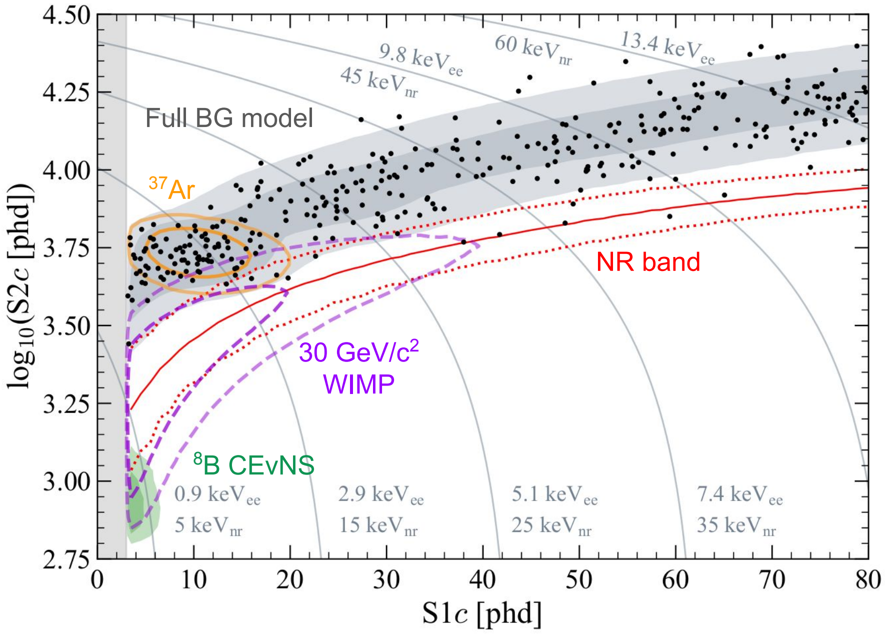
Source	Expected Events	Fit Result
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17



LZ SR1 WIMP-search Results

Observed 335 events for an exposure of 331.65 tonne · day.

- ★ S1 threshold: 3 phd +3-fold coincidence
- ★ S2 threshold: 600 phd (>10 e^- extracted)
- ★ Shaded gray bands: 1σ and 2σ contours of the combined ER background sources
- ★ Red solid and dashed lines: NR median and 10% - 90% contours
- ★ Dashed purple lines: 1σ and 2σ contours for an expected 30 GeV WIMP signal
- ★ Orange contours: ^{37}Ar component
- ★ Green band is ^{8}B CEvNS signal region

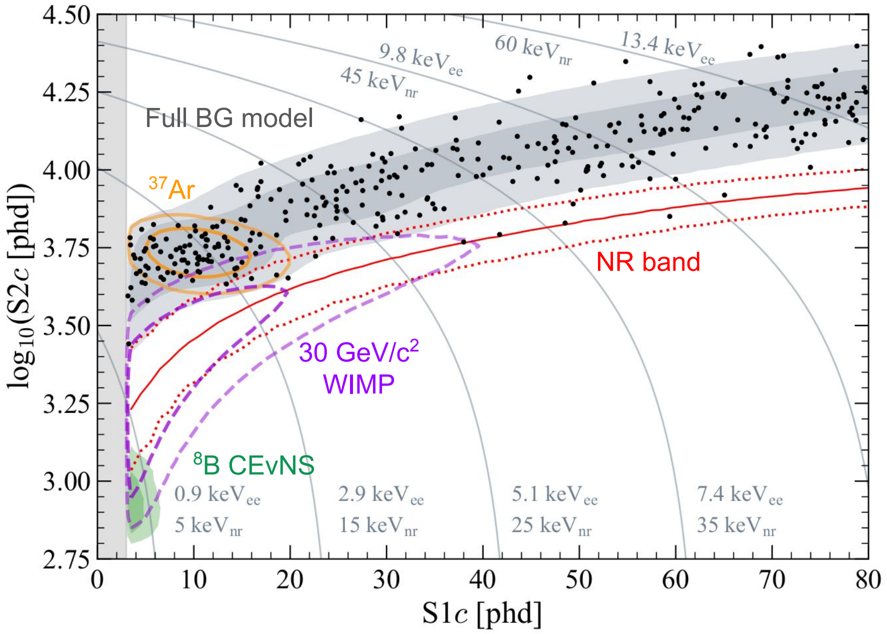


LZ SR1 WIMP-search Results

Using the Phystat recommendations for statistical and astrophysical conventions (Eur Phys J C (2021) 81:907)

- ★ Frequentist, 2-sided profile likelihood ratio (PLR) test statistic, 90% confidence bounds
- ★ Signal rate must be non-negative
- ★ Local density of DM: 0.3 GeV/cm^2
- ★ v_0 = 238 km/s; v_{esc} = 544 km/s
- ★ Power constraint* at π_{crit} = 0.16

Extended unbinned profile likelihood statistic in the $\log_{10}$(S2c)-S1c observable space.

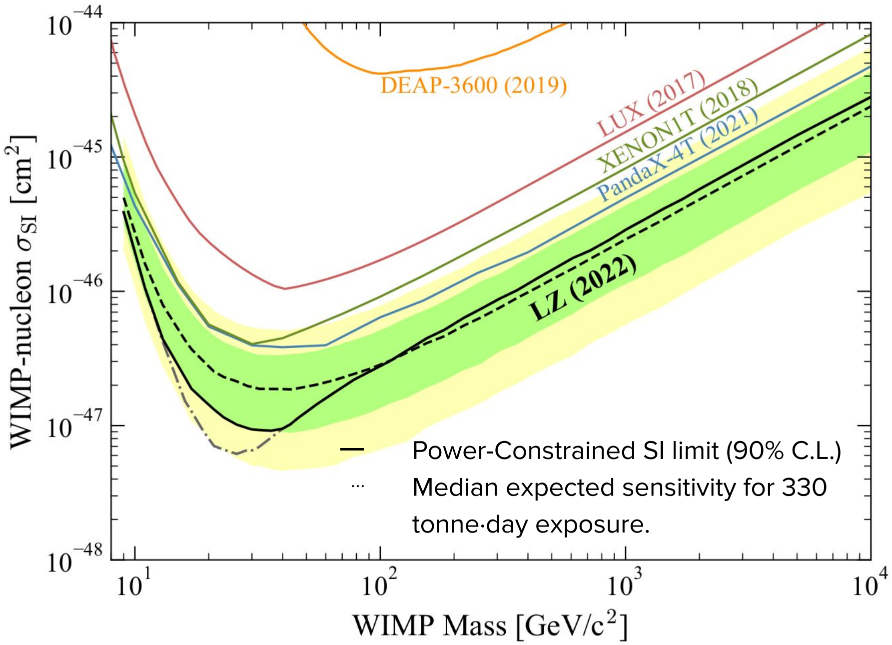


*Power-Constrained Limit redefined using "rejection power" (arxiv:1105.3166)

LZ SR1 WIMP-search Results

No evidence for WIMPs at any mass.

- Power-Constrained critical threshold set to ~1 sigma*
- 90% CL upper limit on WIMP-nucleon cross section
  - **σ_{SI} < 9.2×10^{-48} cm^2 @ 36 GeV/c^2**
- World-leading sensitivity to WIMPs
  - ~3× improvement at 30 GeV/c^2
  - ~1.7× improvement at 1 TeV/c^2



*Power-Constrained Limit initially defined using "discovery power" as per Phystat recommendation. Updated to use "rejection power" (arxiv:1105.3166).

What’s Next?

Phys. Rev. D 101, 052002 (2020)

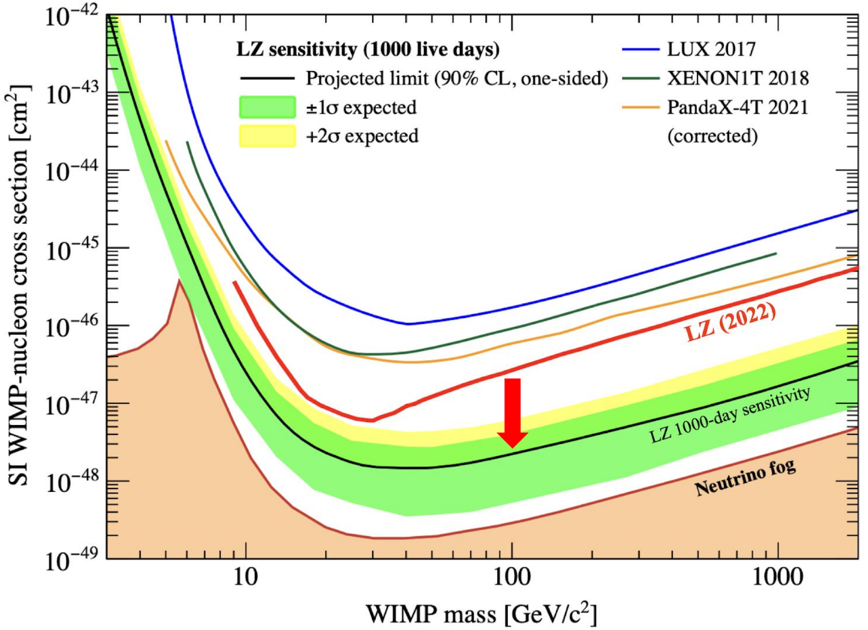
LZ plans to take 1000 live days of data (17× more exposure)

Probing the 10^{-48} cm^2 σ_{SI} range for the first time with only 6% of planned exposure,

➔ Next science runs will cover unexplored WIMP parameter space!

Projected sensitivity 90% CL minimum (one sided) to σ_{SI}

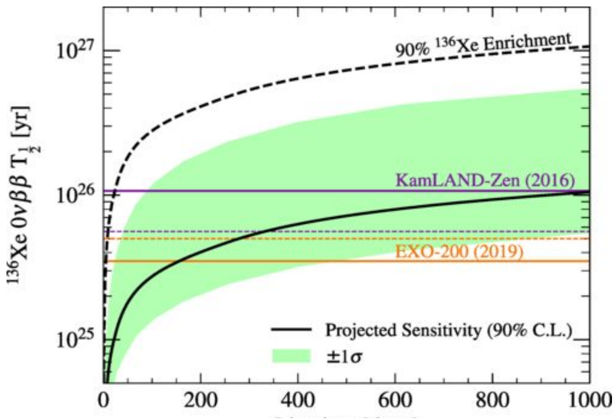
➔ 1.4×10^{-48} cm^2 at 40 GeV/c^2 for 1000 live-days and 5.6 t exposure.

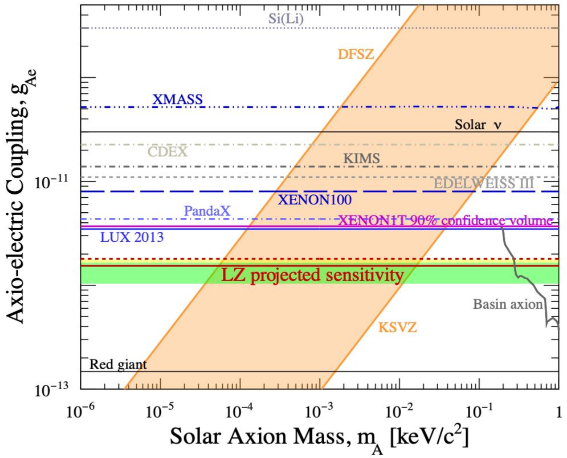


LZ plans to take 1000 live days of data (17× more exposure)

Lots of science to do in addition to primary DM search:

- Neutrinoless double beta decay in ^{136}Xe (PRC.102.014602) and ^{134}Xe (PRC.104.065501)
- Rare decays of other xenon isotopes
- Effective field theory couplings for dark matter
- Solar axions, ALPs, neutrino magnetic moment (PRD.104.092009)
- Low mass dark matter searches (S2-only, Migdal effect)
- Leptophilic dark matter
- Mirror dark matter





XENON, LZ and DARWIN collaborations took the first steps for a joint 3rd generation experimental effort to probe WIMP DM down to the neutrino fog with a hundred-tonnes scale xenon detector.

Very productive XLZD meetings:

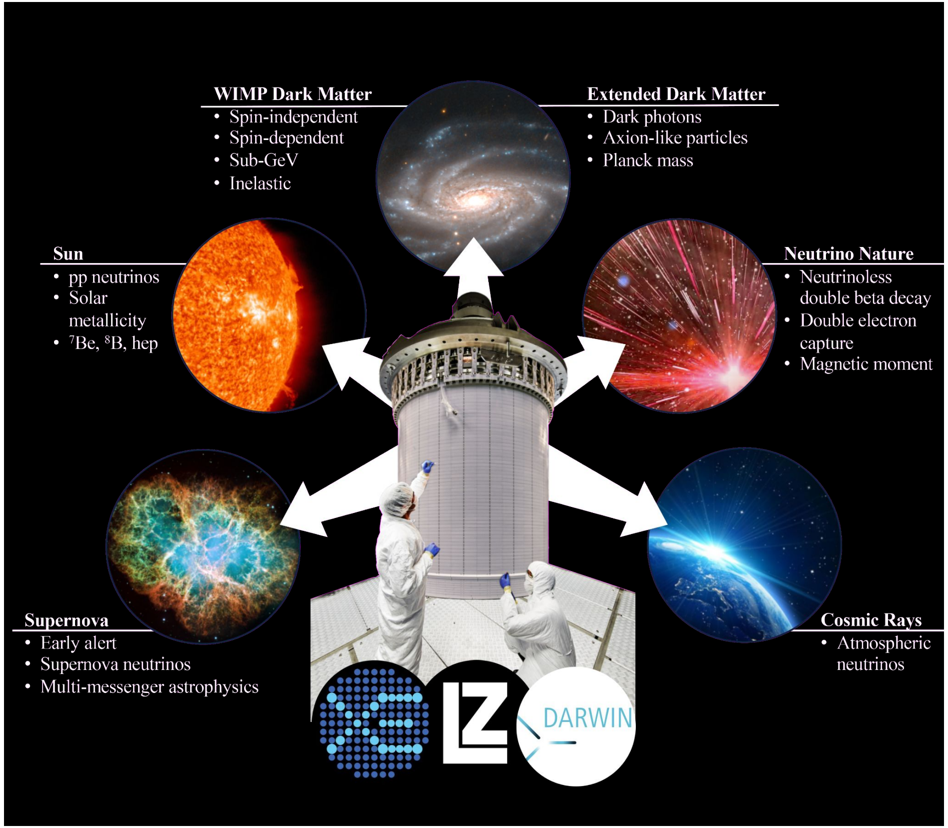
➔ First meeting Summer 2022 at KIT;

➔ Second meeting Spring 2023 at UCLA.

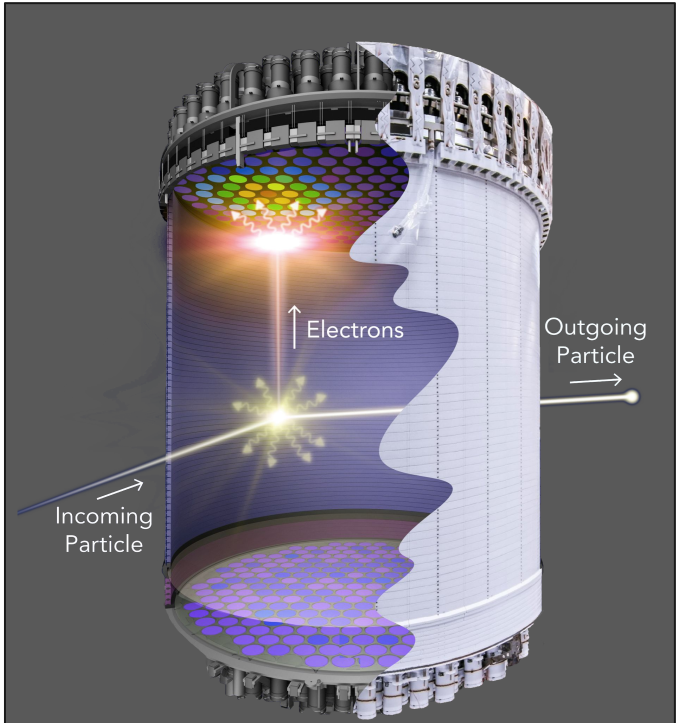
White paper (2203.02309)

Broad science reach ⟶

See talk by Alex Lindote tomorrow at 10:20 am



Thank you!



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Find more graphics here or directly contact Nicolas (UCL)

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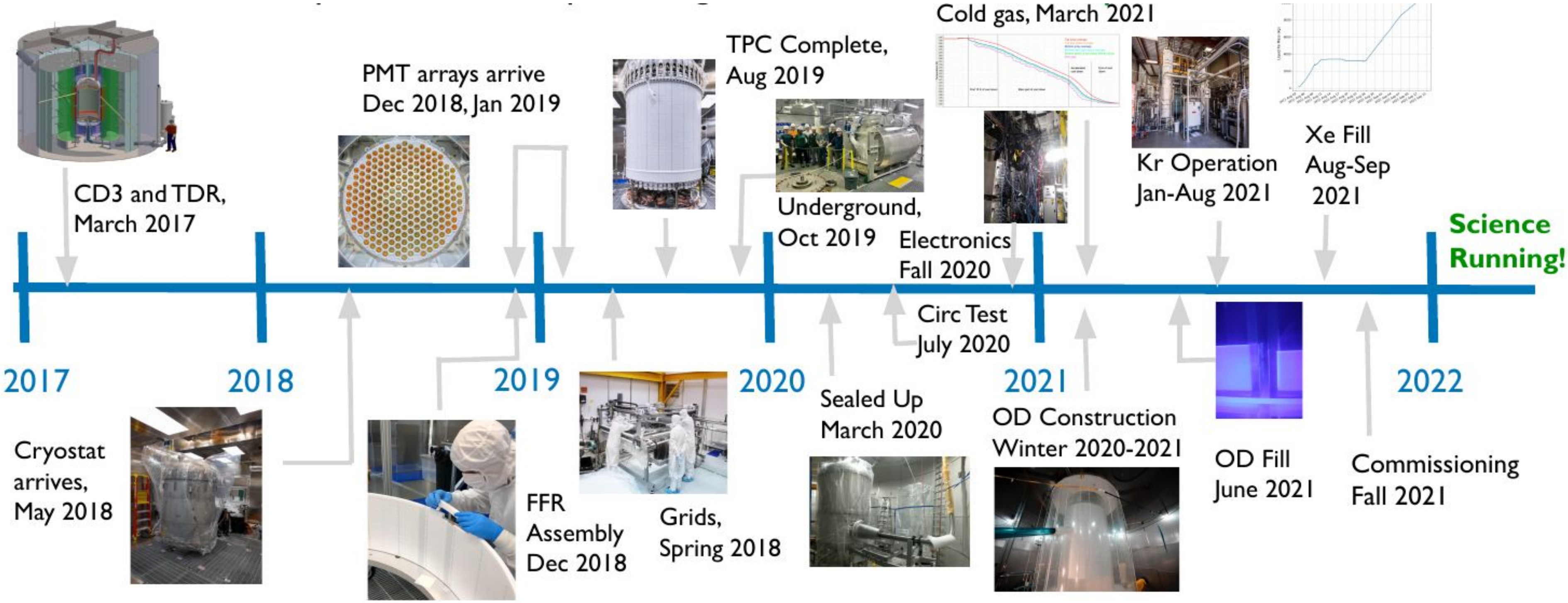
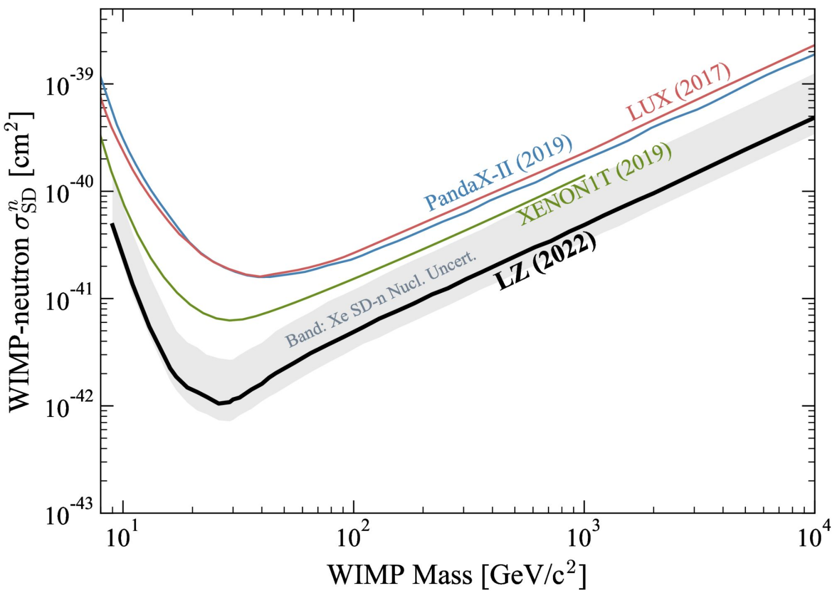
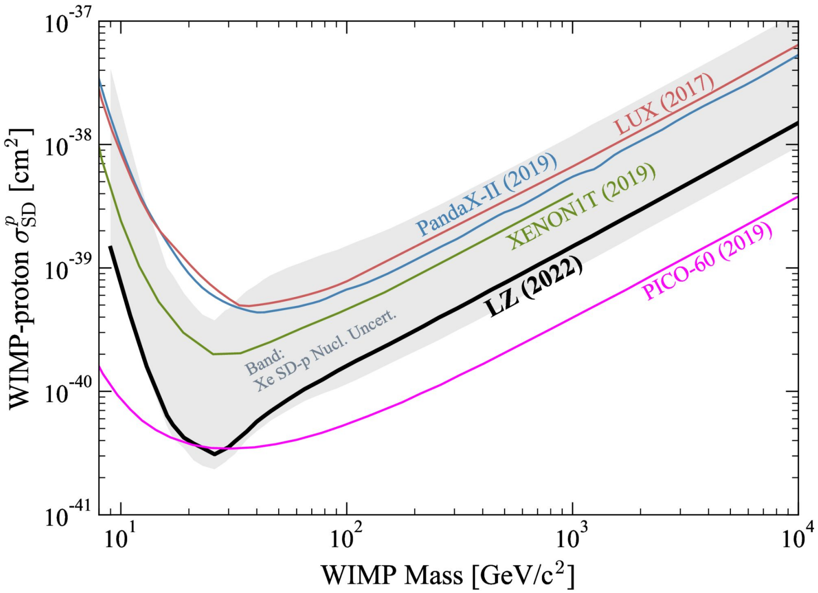


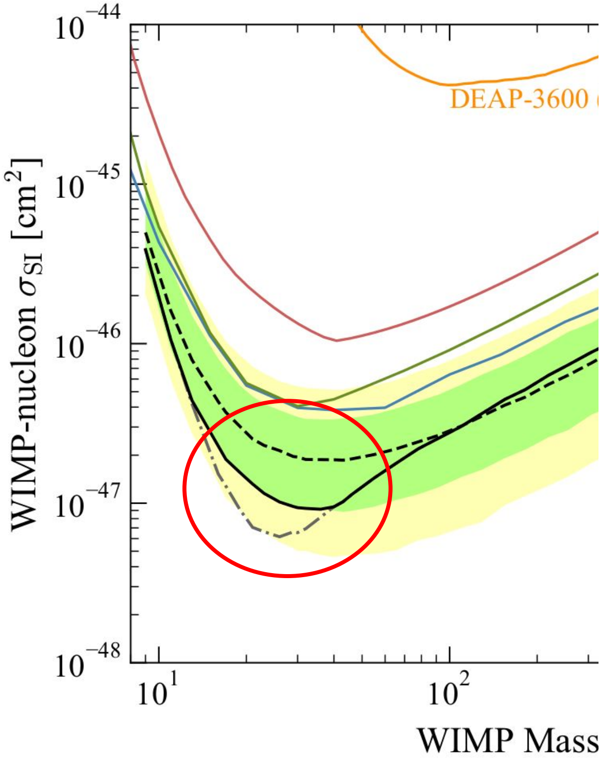
Spin-dependent WIMP-neutron scattering and spin-dependent WIMP-proton scattering

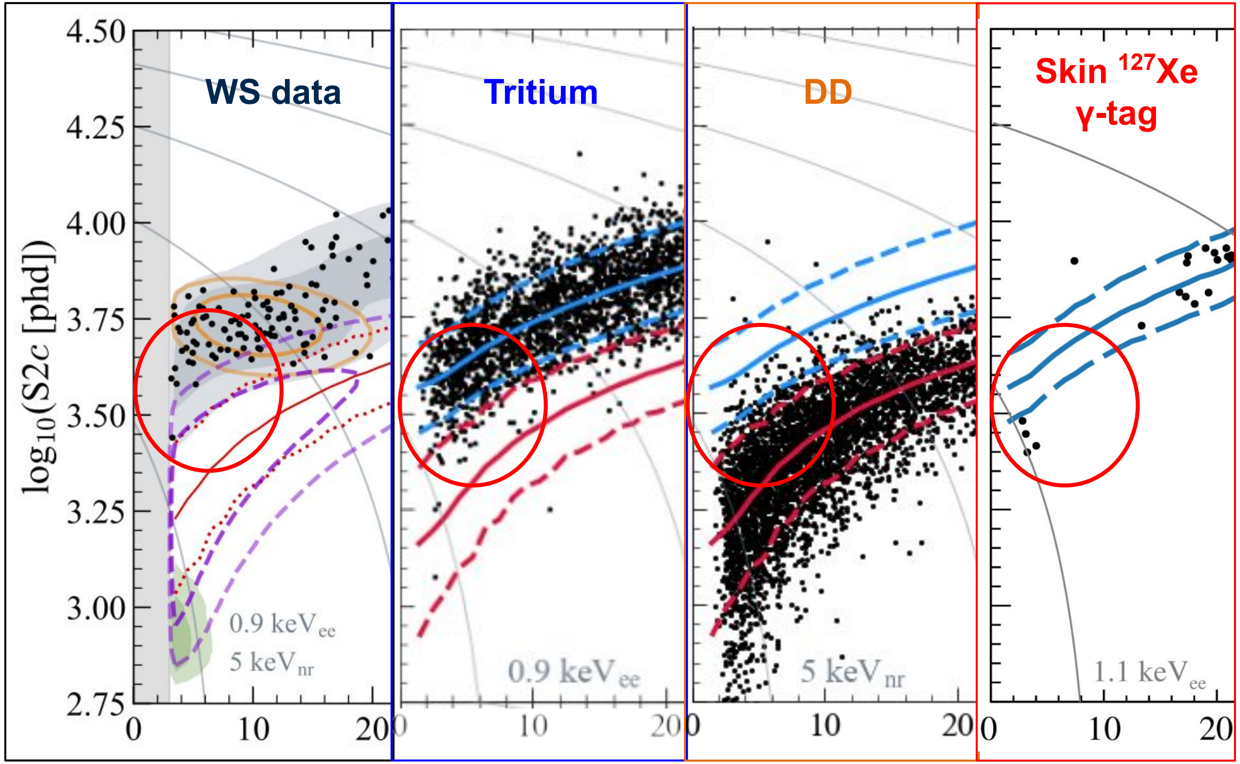
- Uncertainty band represents theoretical uncertainty on nuclear form factor for Xe





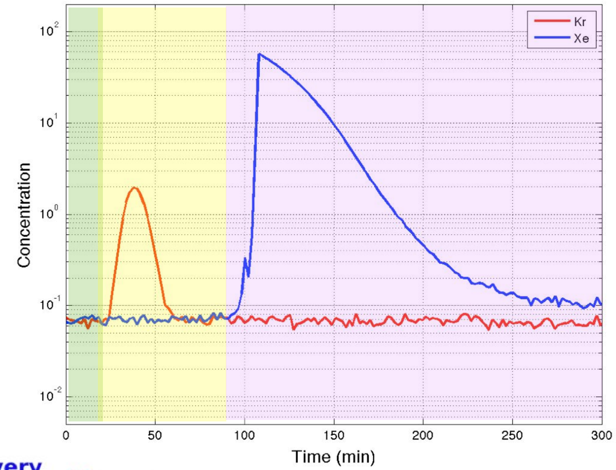
Downward fluctuation in the limit ⟶ under fluctuation of the background.

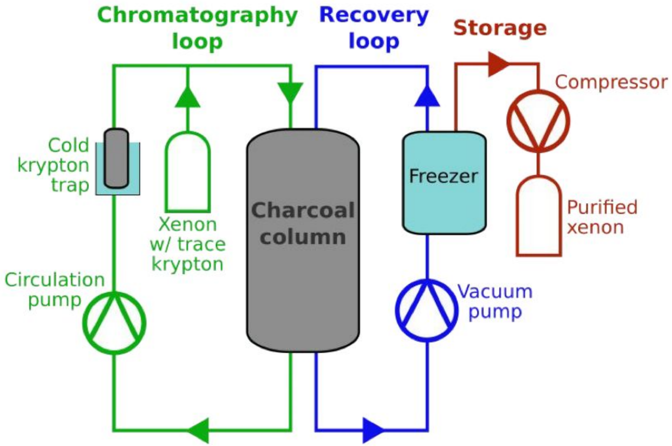




Kr Removal System

- ★ Gas chromatography to remove Kr from Xe
  - ○ in situ mass spectroscopy measurement of 144 ± 22 ppq g/g ^{nat}Kr/Xe
- ★ ^{nat}Ar to a negligible level
- ★ Major operations from January to August 2021
- ★ Continuous purification underground





^{85}Kr is a beta-emitter with 687 keV endpoint

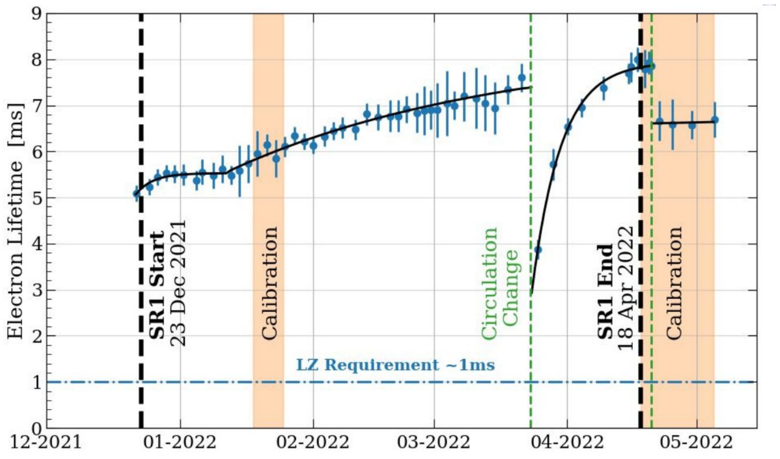
Xenon Circulation System & Cryogenics

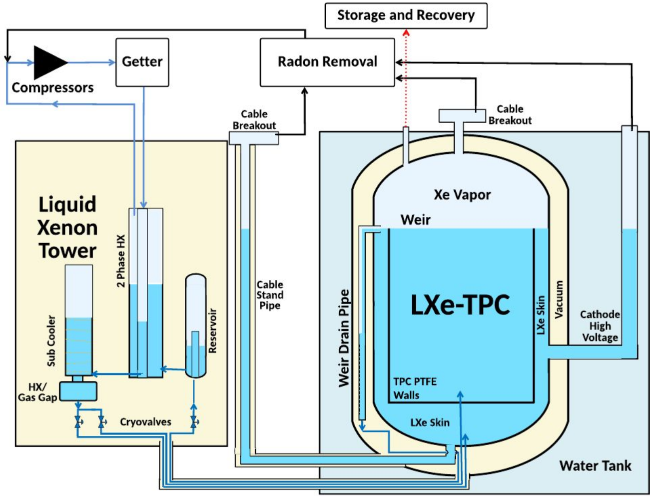
Designed to circulate gas at 500 slpm

- Turnover full Xe mass every 2.4 days
- Up to 600 slpm demonstrated

Purification using hot zirconium getter

- Purity ≡ electron lifetime (ELT)
- LZ requirement ELT> 1ms (maximum drift time)
- During SR1 ELT consistently greater than 5 ms

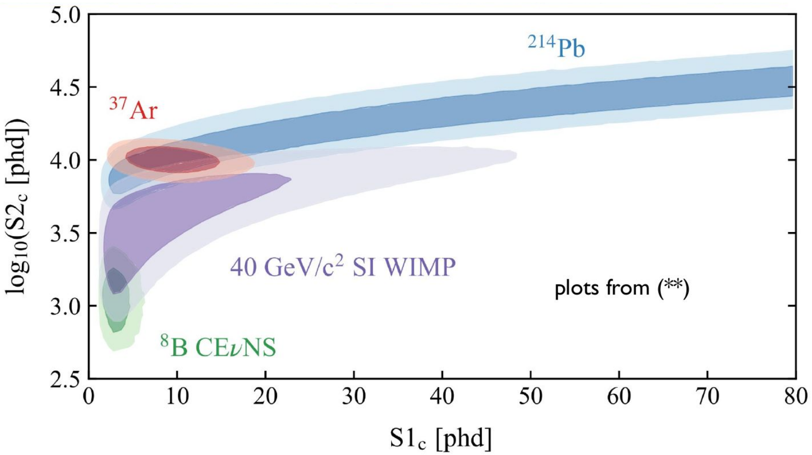




(e-print 2211.17120)

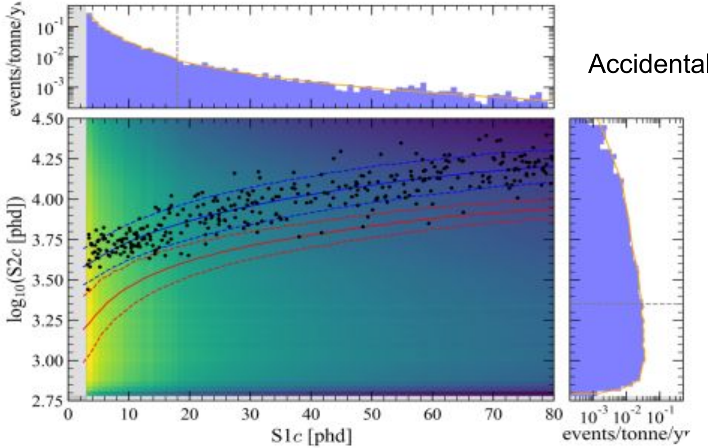
Argon-37 electron capture with $T_{1/2}$ = 35 d and monoenergetic 2.8 keV ER deposition

- Naturally occurring in the atmosphere via $^{40}Ca(n,\alpha)^{37}Ar^*$, or cosmic spallation of ^{nat}Xe
- Equilibrium values range from 1-100 mBq/m^3
- Expecting O(100) ^{37}Ar events in SR1 [2201.02858]



"Accidentals": Pairing of random isolated S1s and S2s that mimic real single scatters

- Isolated S1s (~1 Hz), isolated S2s (~10^{-3} Hz)
- Events with unphysical drift time used to constrain the accidentals rates
- Efficiency of data quality cuts to remove accidentals: >99.5%
- Data-driven accidentals BG: 1.2 ± 0.3 events



Accidentals PDF