EDSU 4th Conference
La Reunion Island
November 7-11, 2022

LUX-ZEPLIN (LZ) First Science Results & Outlook

Prof. Alvine Kamaha

University of California, Los Angeles

LUX-ZEPLIN (LZ) Collaboration

35 Institutions: 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
- 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 Wisconsin, Madison

US UK Portugal Korea Australia

Thanks to our sponsors and participating institutions!

U.S. Department of Energy Office of Science

UKRI Science and Technology Facilities Council

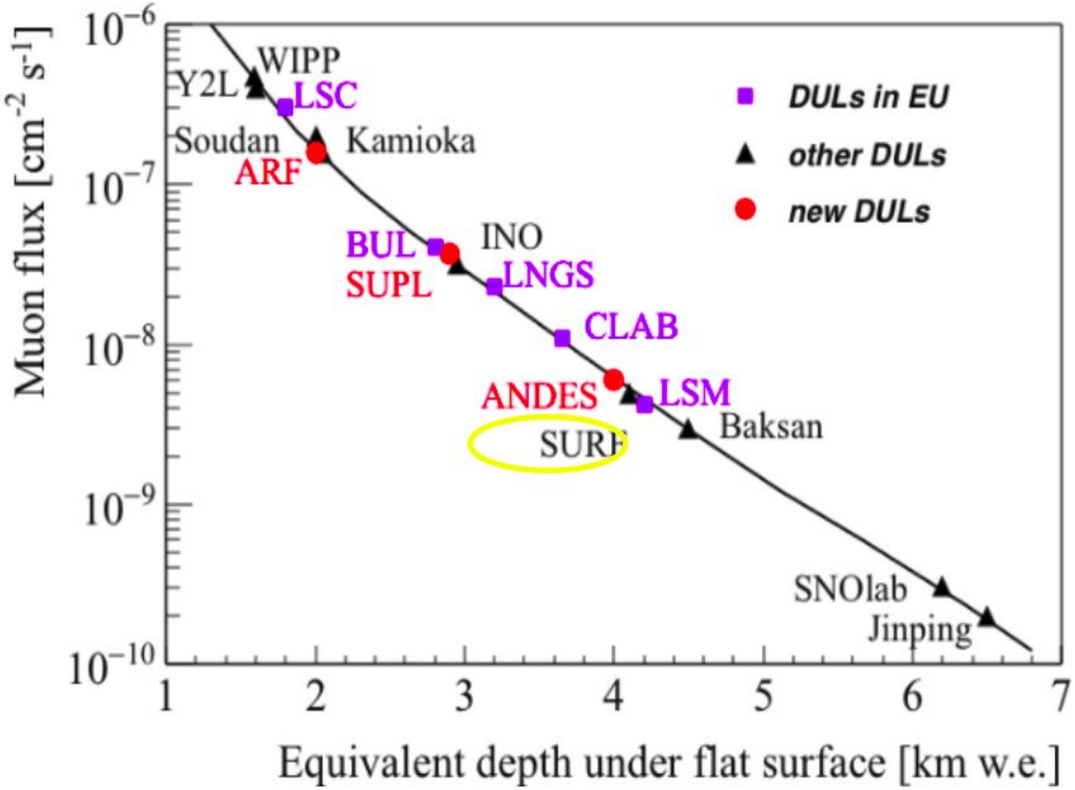
FCT Fundação para a Ciência e a Tecnologia

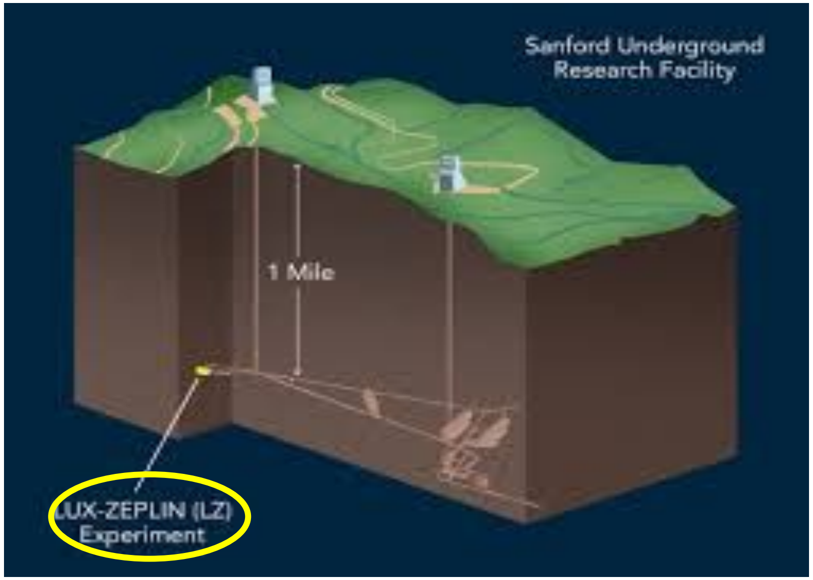
Sanford Underground Research Facility
South Dakota Science and Technology Authority

ibs Institute for Basic Science

LZ Experiment

- Located at the Sanford Underground Research Facility (SURF) in South Dakota in USA
- ~1 mile of rock overburden to reduce muon flux contributing to experiment background

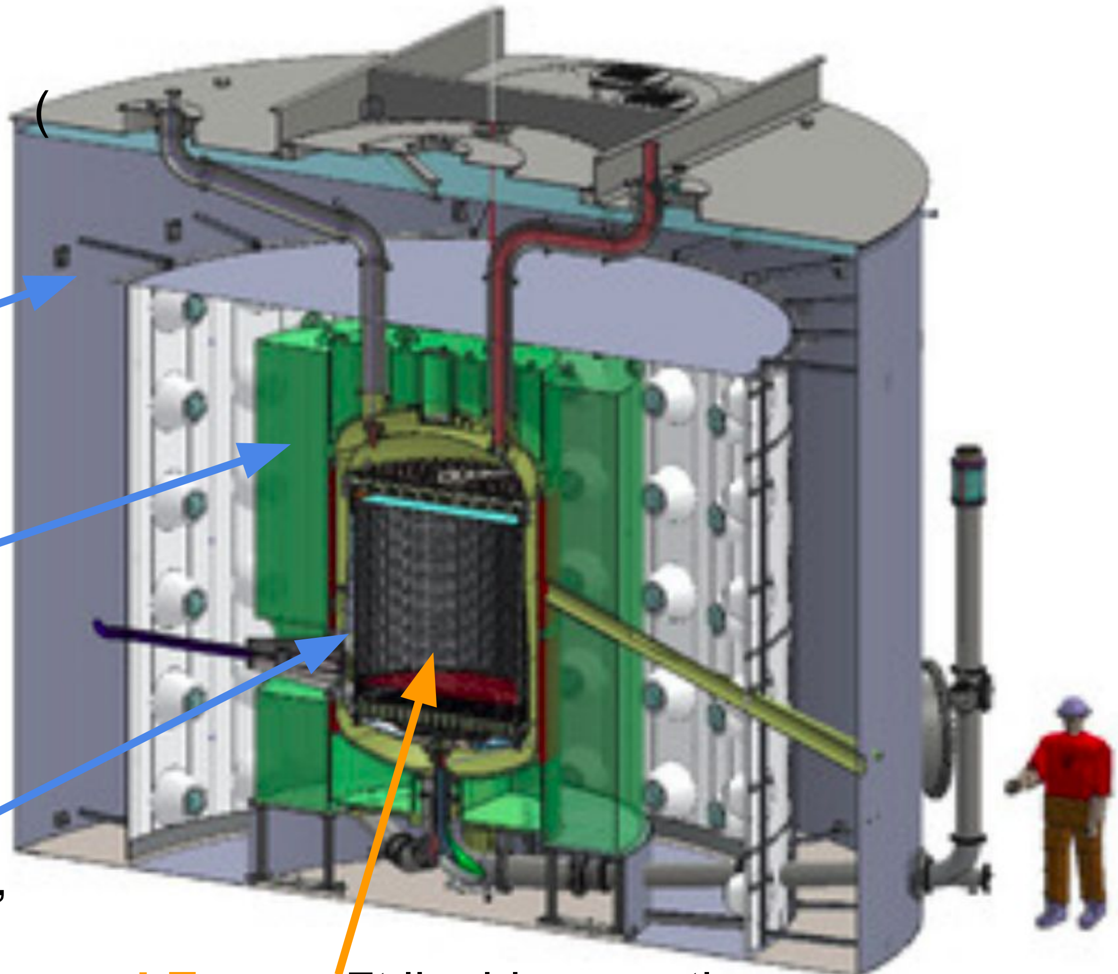




- Muon flux reduced by O(10^7)
- Radiogenic backgrounds become the dominant ones

LZ Detector Overview

Nested detector system made of ultrapure materials selected from ~5years of screening campaign (ref. Eur.Phys.J.C 80 (2020) 11, 1044)



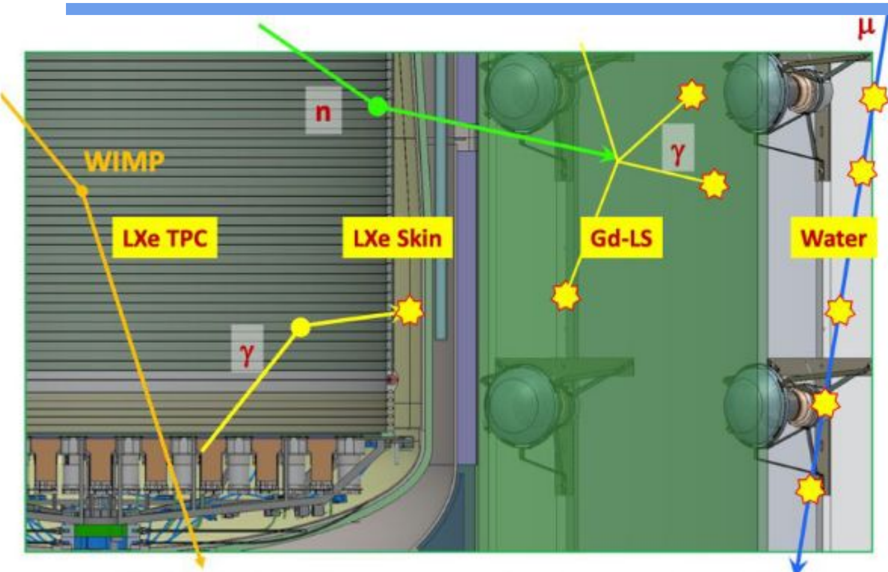
LZ vetoes

- 120t High purity water tank with 120 8" PMTs
- 17t Gd-loaded liquid scintillator, outer detector
- 2t liquid xenon "skin" region instrumented with 1" & 2" PMTs

LZ core: 7t liquid xenon time projection chamber (TPC)

[LZ Technical Design Report: NIM 2019, 163047]

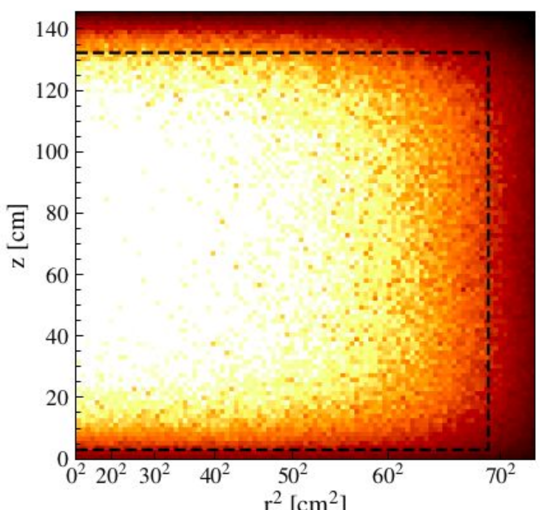
LZ vetoes: Outer Detector and Skin Region

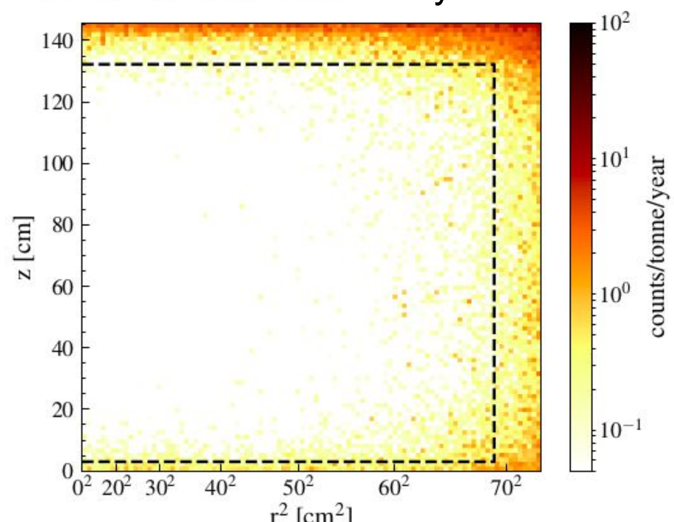


Purpose:

- Characterization, tagging and rejection of background (n,γ) events to enhance discovery potential
  - *E.g*, 88.5% OD ***n*** tagging efficiency was measured in situ with AmLi neutrons
- Coupled to LXe self-shielding property, enable to increase fiducial volume & increase sensitivity.

	Without veto (3.2t fid.vol)	**With veto (5.6t fid.vol)**
Expected bckg NR:	10.31 cts/1000 days	1.03 cts/1000 days

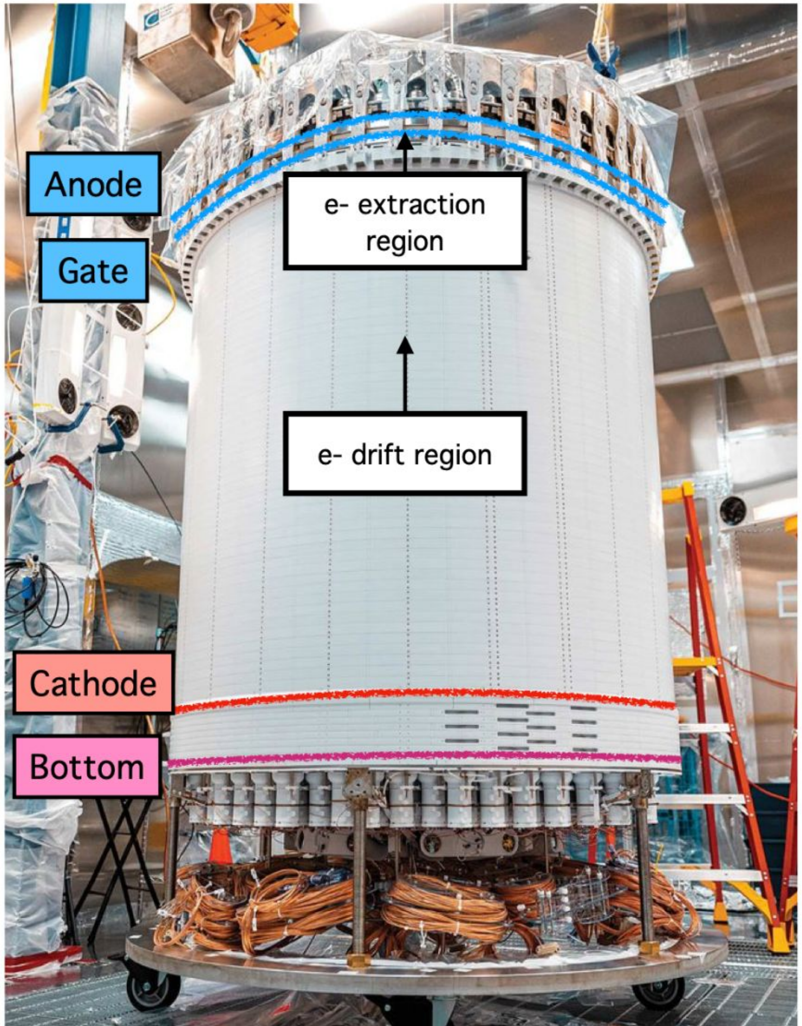




[LZ Projected WIMP sensitivity for 1000 live days, 5.6 tonnes FV,PRD.101.052002]

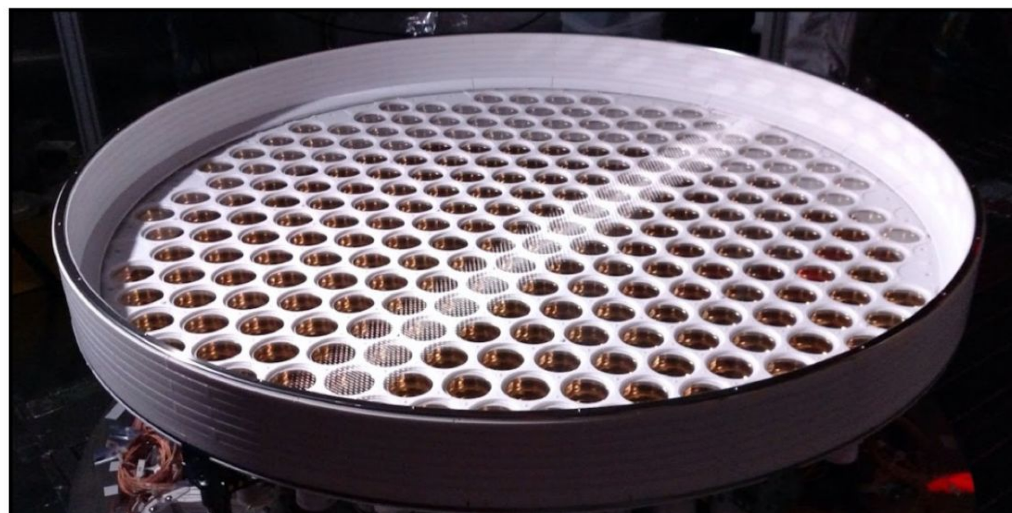
Distributions of single-scatter nuclear recoils in 40GeV WIMP ROI (6-30 keV)

LZ Core: the Xenon TPC



Construction in radon reduced clean room at surface assembly lab completed in 2019

- 1.5 m diameter x 1.5 m height
- 7 t liquid xenon target
- PTFE construction for light collection
- 494 3” PMTs in two arrays on top and bottom
- 4 grids (bottom, cathode, gate, anode)
- Field cage to define TPC
- 3 spill-over weirs to define liquid surface

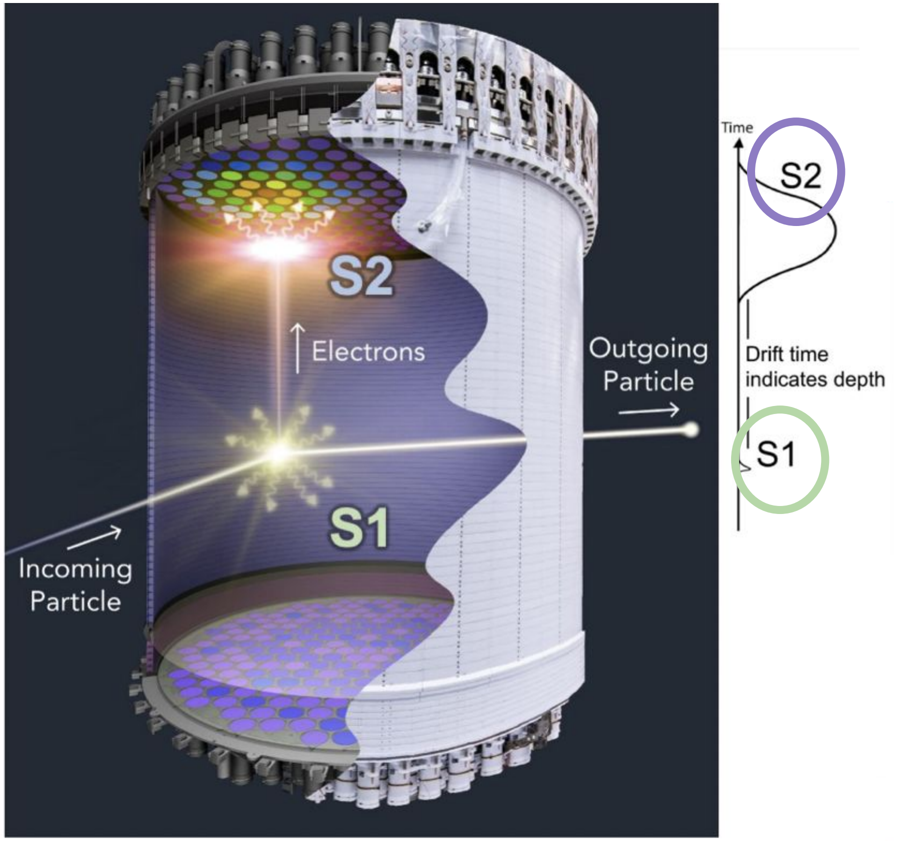


Bottom PMT array and cathode electrode during construction

[LZ Technical Design Report, NIM 2019, 163047]

LZ Detection Principle

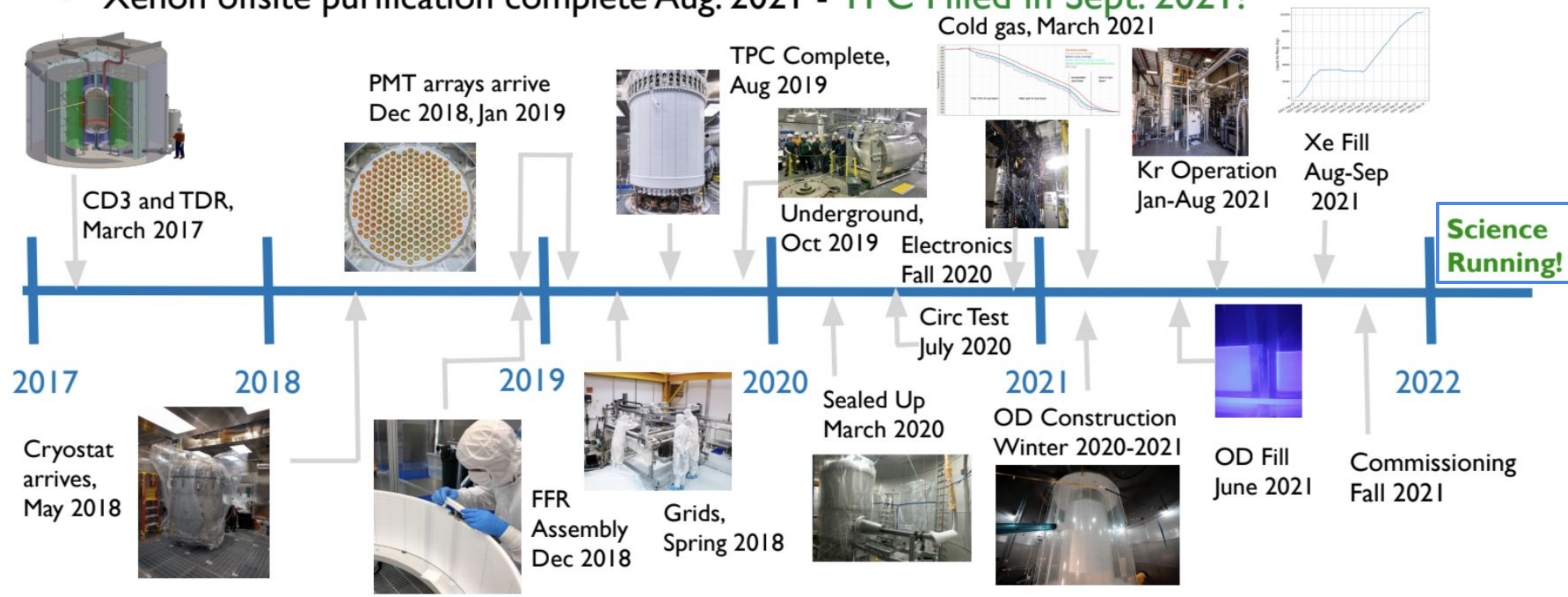
- **Dual phase time projection chamber** primarily searching for WIMPs via low-energy nuclear recoils
- Particle scattering on xenon produces prompt scintillation (S1) and ionization electrons
- Electrons drift up into gas phase to produce electroluminescence **S2**
- Excellent 3D position reconstruction from S1-S2 timing (Z) and PMT hit pattern (XY)
- S2/S1 ratio allows for nuclear recoil (NR) vs electron recoil (ER) discrimination



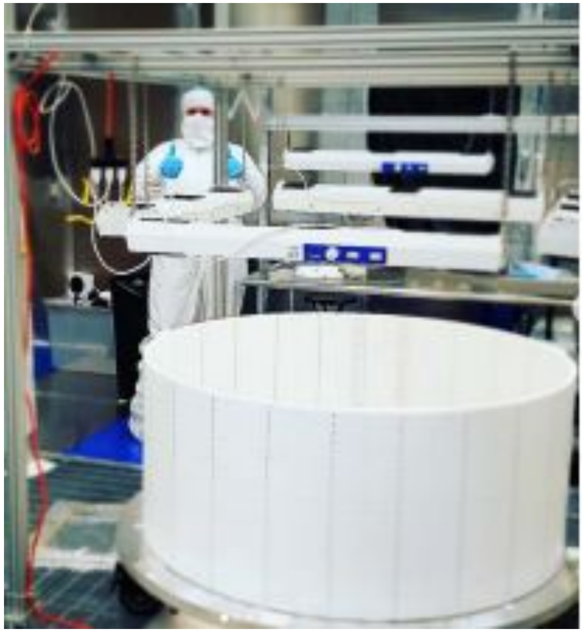
[LZ Technical Design Report, NIM 2019, 163047]

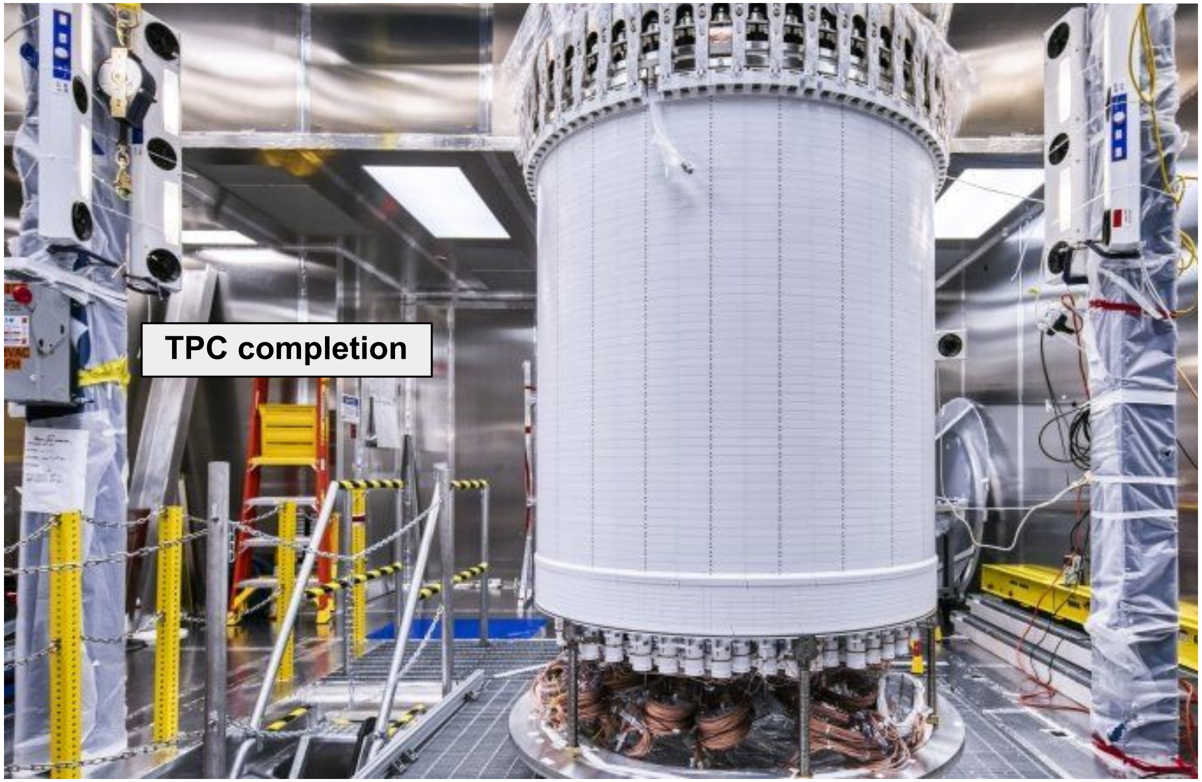
LZ Timeline

- Detector assembly began in earnest in fall, 2018 on surface at SURF
  - ✦ 13,500 working hours in the low radon clean room with tens of thousands of ultra-clean, low background components
- TPC brought underground in October 2019
- Cryostat closed in March 2020, ahead of COVID-19 shutdowns
- OD complete and filled by July 2021
- Xenon offsite purification complete Aug. 2021 - TPC Filled in Sept. 2021!



LZ Detector Assembly Highlights

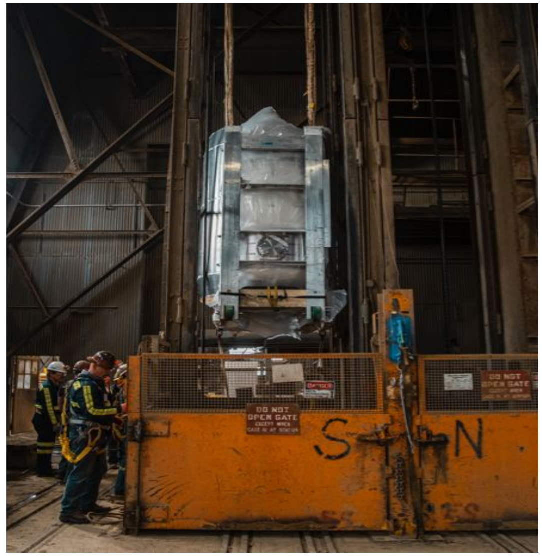


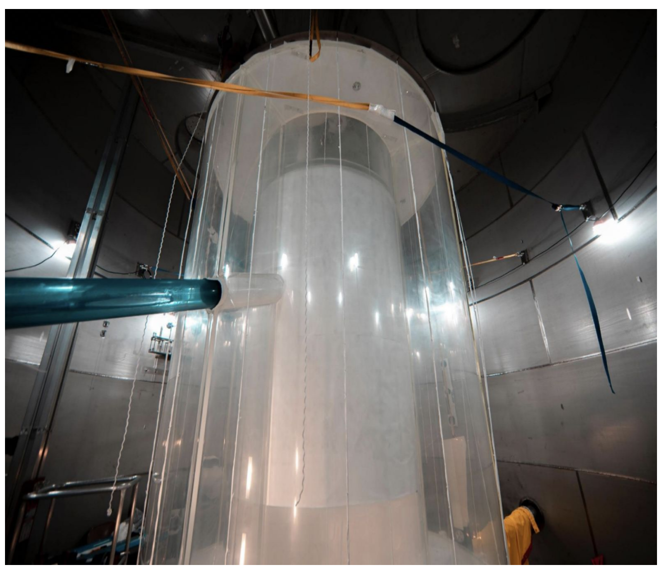


Central TPC assembly under stringent cleanliness protocols in ISO-6 cleanroom

(ref. Eur.Phys.J.C 80 (2020) 11, 1044)

LZ Detector Assembly Highlights

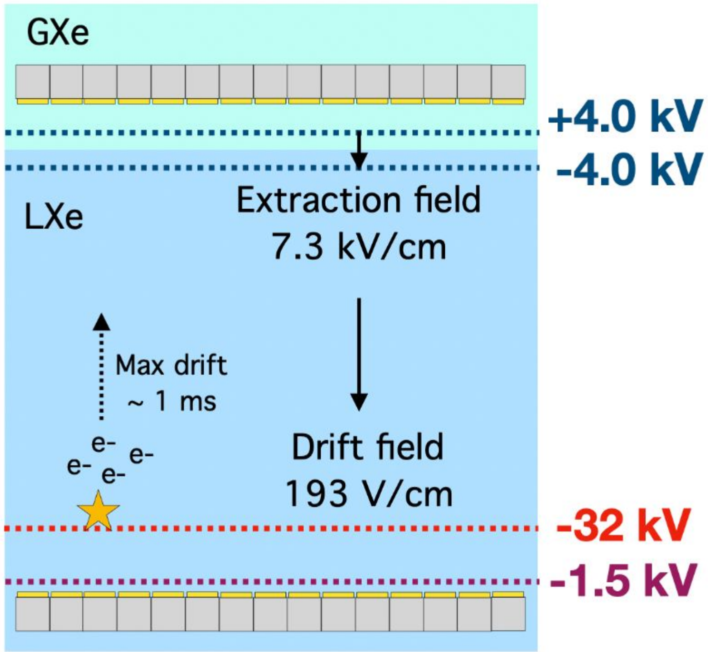


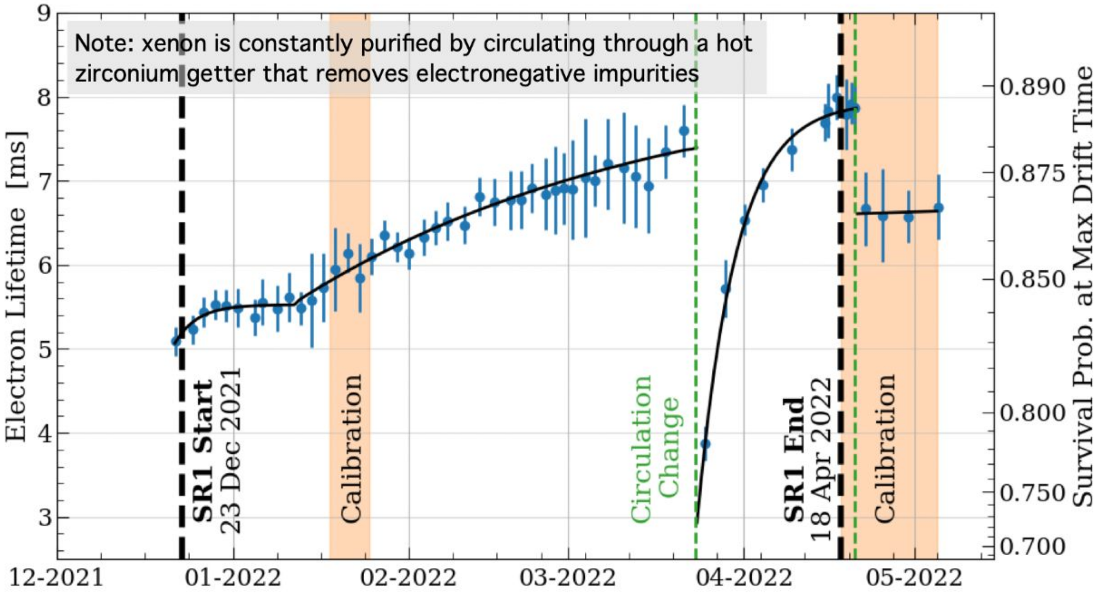


TPC underground transportation & insertion into OD/ water tank

LZ's Science Run 1 (SR1)

- Initial plan for Science Run 1 to collect 60 live days
  - Demonstrate successful detector operation and physics capability of LZ detector





➔ >97% of TPC PMTs operational
➔ Stable liquid temp (0.02% variation), Gas pressure (0.2% variation) & liquid level (10 μm)
➔ Gas Circulation~3.3t/day

➔ Data taken from Dec. 23, 2021 to May 12, 2022
➔ Engineering run → **data not blinded**
➔ Mid-run & post-run calibrations
➔ In SR1, e-lifetime consistently greater than 5ms (above LZ requirement)

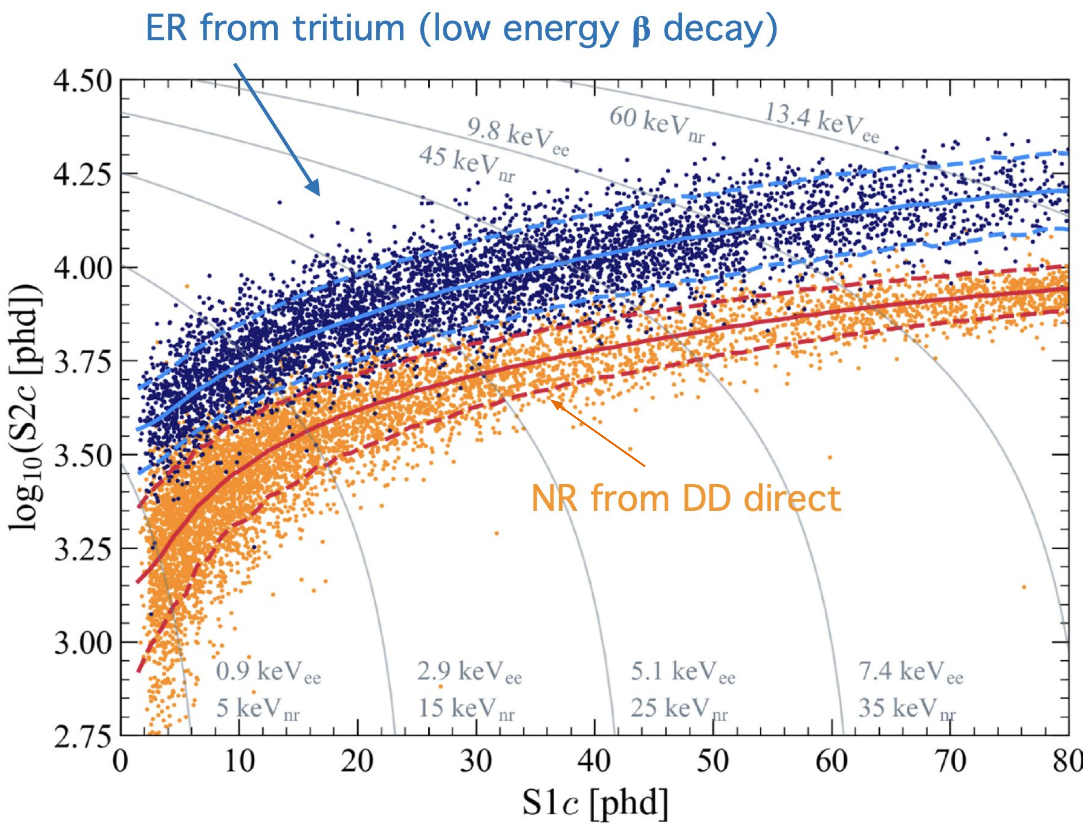
LZ Detector Calibration

LXe response modeled using the Noble Element Simulation Technique (NEST)

Fit data to NEST-based model for detector-performance parameters

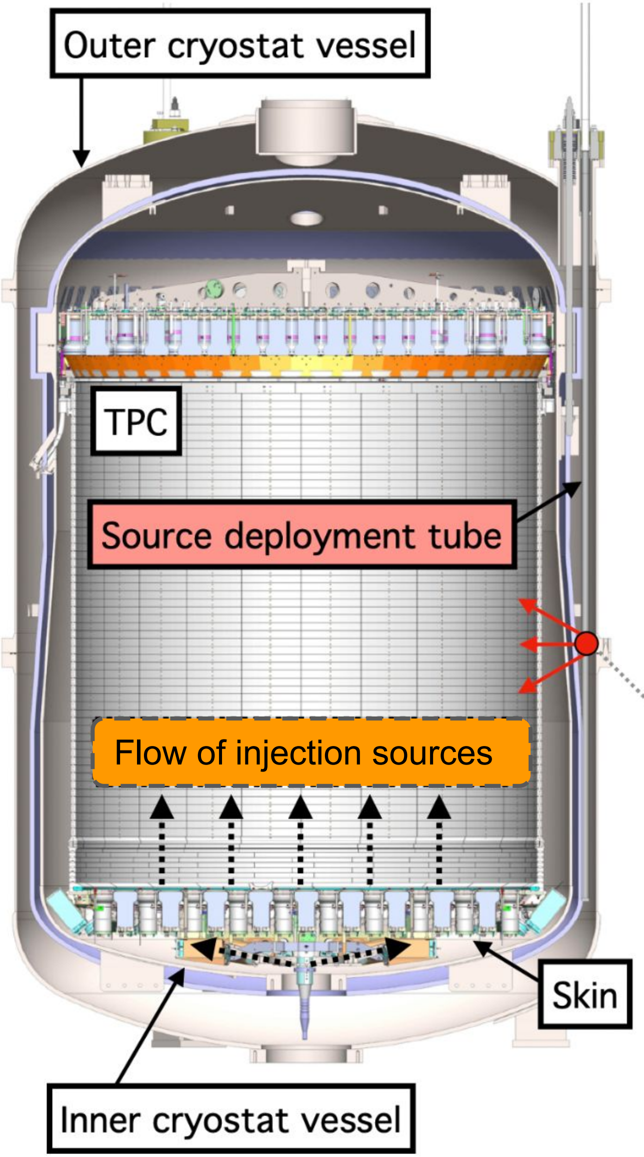
- NEST-based ER model tuned to CH3T data first and then propagated to NR and verified with

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

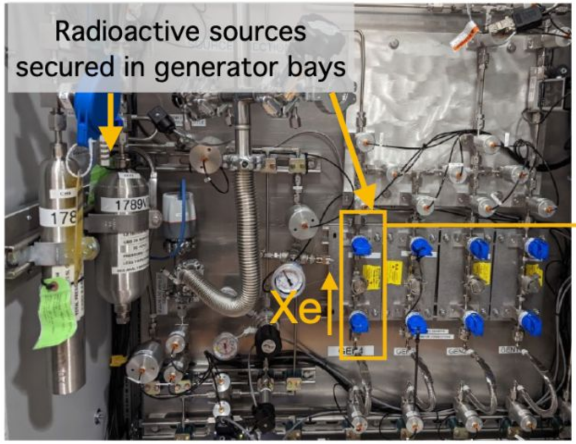


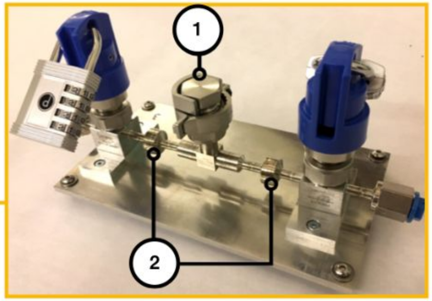
In SR1, electron recoils (ER) vs nuclear recoil (NR) discrimination = 99.9% for 40 GeV WIMP

LZ Detector Calibration: ER



Injection sources (dispersed into LXe)





1: Parent nuclide (producing daughter calibration isotope) enclosed in VCR cap.
2: Filter elements for incoming and outgoing xenon flow

Methane tagged with tritium, CH_3T (β; 18.6 keV endpoint)
Kr83m (e-; 32.1 keV, 9.4 keV)
Rn220 (γ, β, α; various energies)

Sealed γ sources of various energies

- x3 deployment tubes between inner and outer cryostat vessels
- Laser-guided deployment to specific z-positions at 5 mm precision

LZ Detector Calibration: NR

AmLi source

$\alpha + ^{7}\textbf{Li} \rightarrow n + ^{10}\textbf{B}$

- Three AmLi sources deployed in calibration source tubes.
- Allows for a scan of different detector depths.
- Tungsten enclosure to contain low energy γ-rays.

YBe source

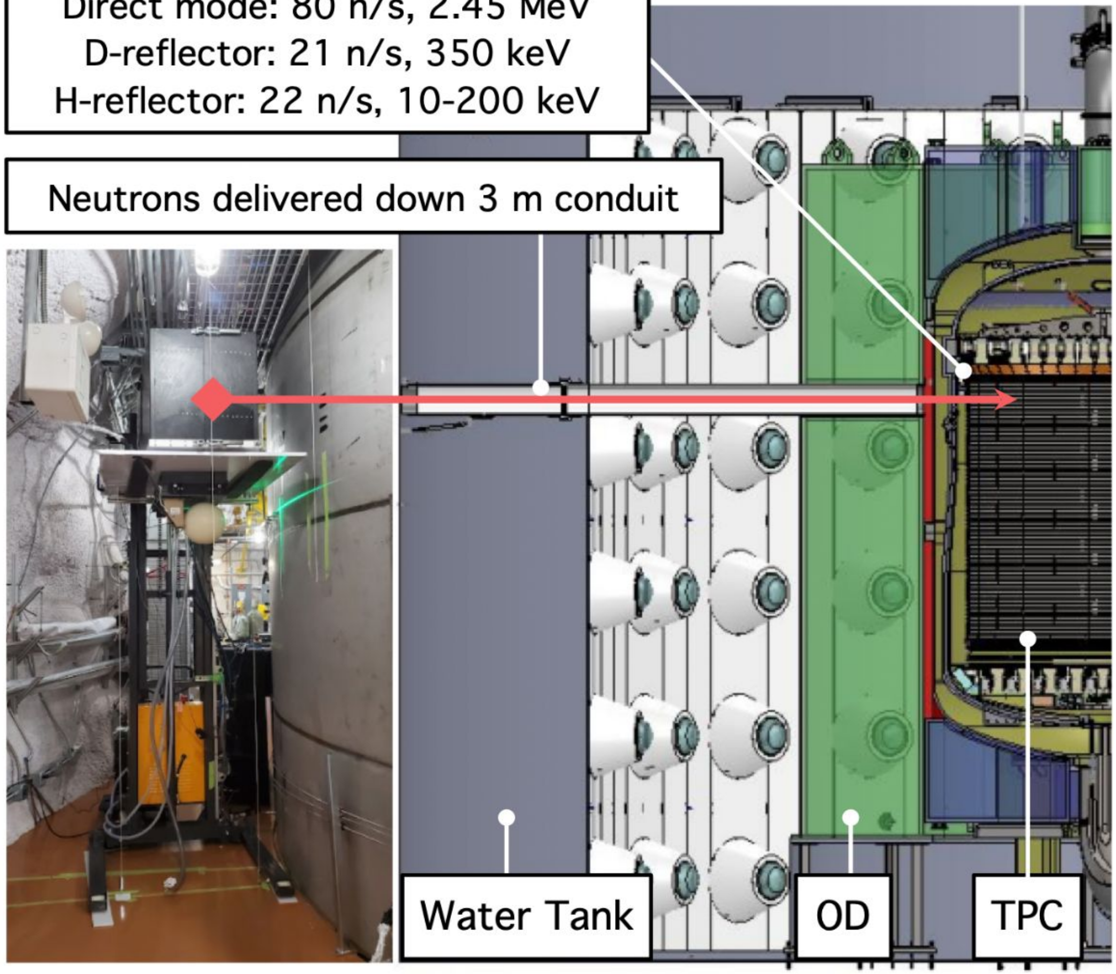
$\gamma + ^{9}\textbf{Be} \rightarrow n + ^{8}\textbf{Be}$

- Photoneutron source for low energy nuclear recoil calibration at threshold.
- Deployment to top of cryostat vessel (between OD top tanks).
- Demonstrated during commissioning at different fields to the final WIMP-search.

DD neutron generator

Direct mode: 80 n/s, 2.45 MeV
D-reflector: 21 n/s, 350 keV
H-reflector: 22 n/s, 10-200 keV

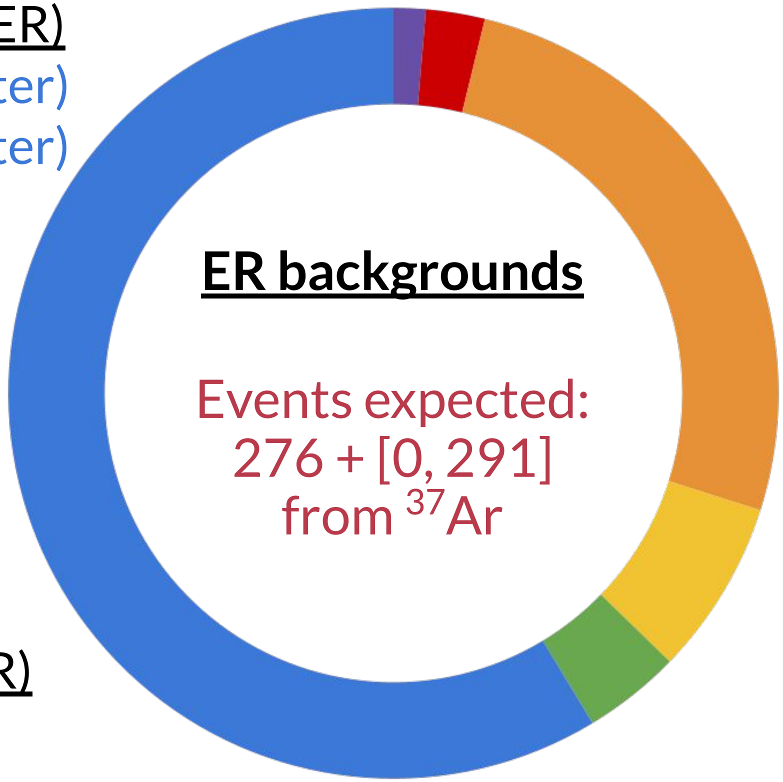
Neutrons delivered down 3 m conduit



Background Origins & Sources in SR1

<u>Xenon contaminants (ER)</u>

- ^{214}Pb (^{222}Rn daughter)
- ^{212}Pb (^{220}Rn daughter)
- ^{85}Kr
- ^{37}Ar
- ^{127}Xe
- ^{136}Xe ($2\nu\beta\beta$)
- ^{124}Xe (double e-capture)



<u>**NR backgrounds**</u>
(0.15 events expected)

- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar neutrinos

<u>**Non-physics sources**</u>
(1.2 events expected)

- Accidental coincidences of isolated S1 and S2 pulses.

<u>Detector materials (ER)</u>

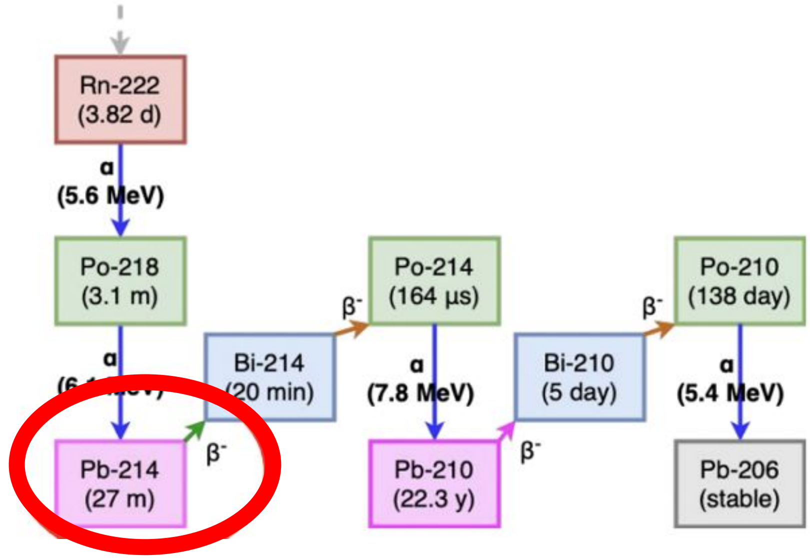
- γ-emitters in ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co

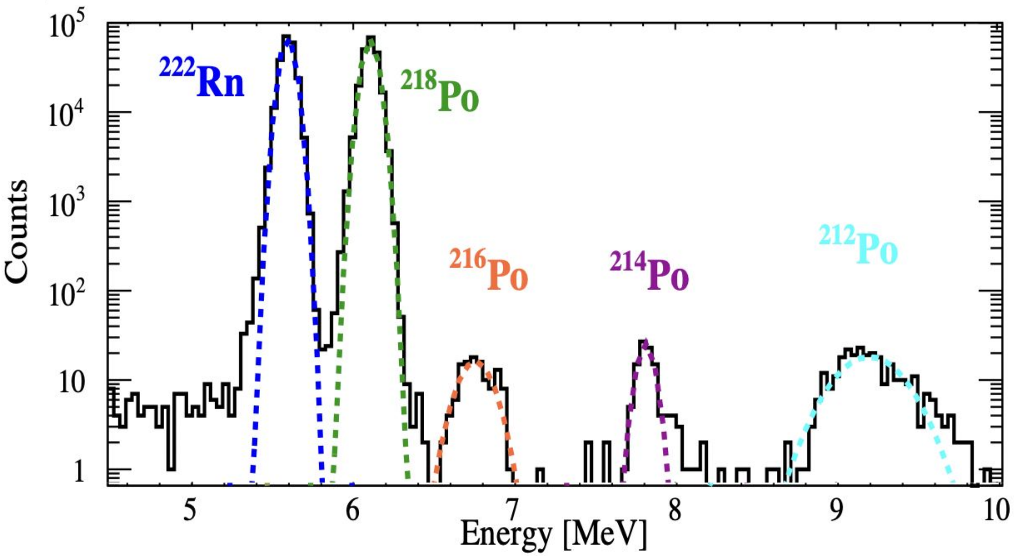
<u>Solar neutrinos (ER)</u>

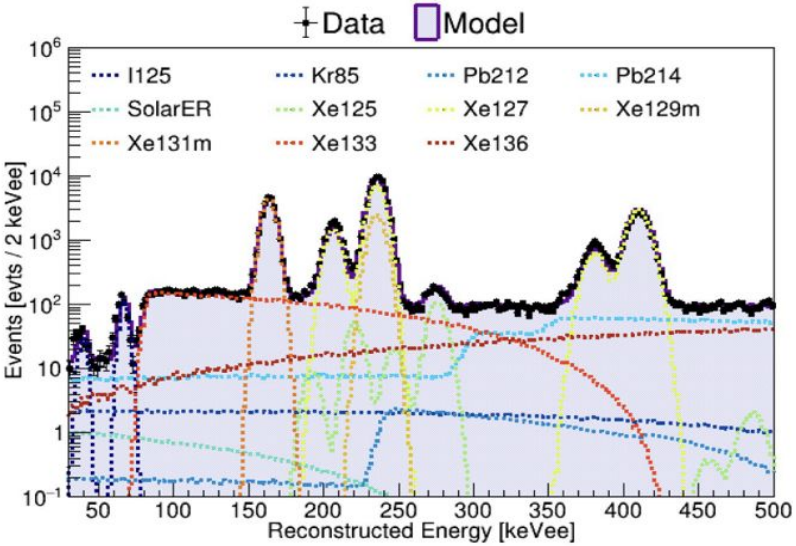
- pp + ^{7}Be + ^{13}N

Radon Progeny Background

- Alphas from ^{222}Rn decay are identified by S1 spectrum.
- Naked ^{214}Pb from ^{222}Rn is the main source of background in the WIMP search
  - ^{214}Pb rate determined using side bands to WIMP ROI in search data and must be ≤ rate of ^{222}Rn decays.

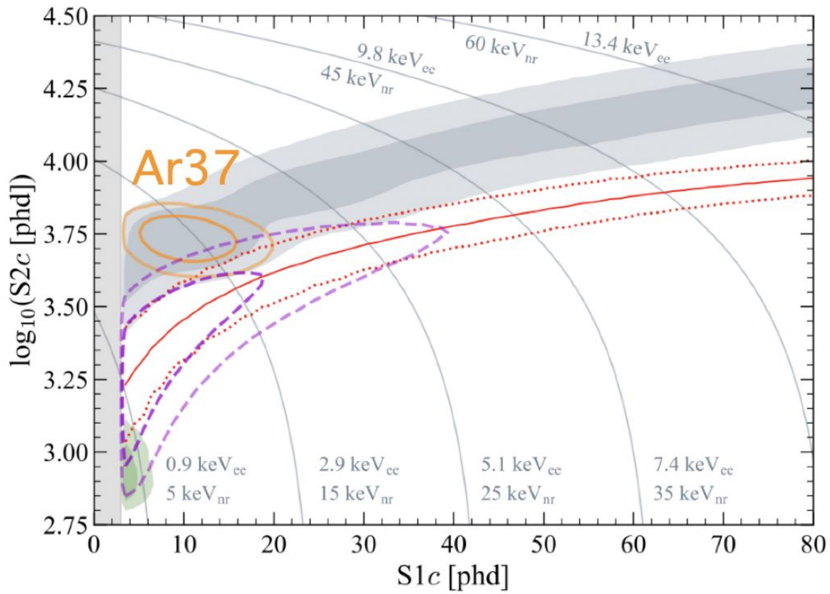


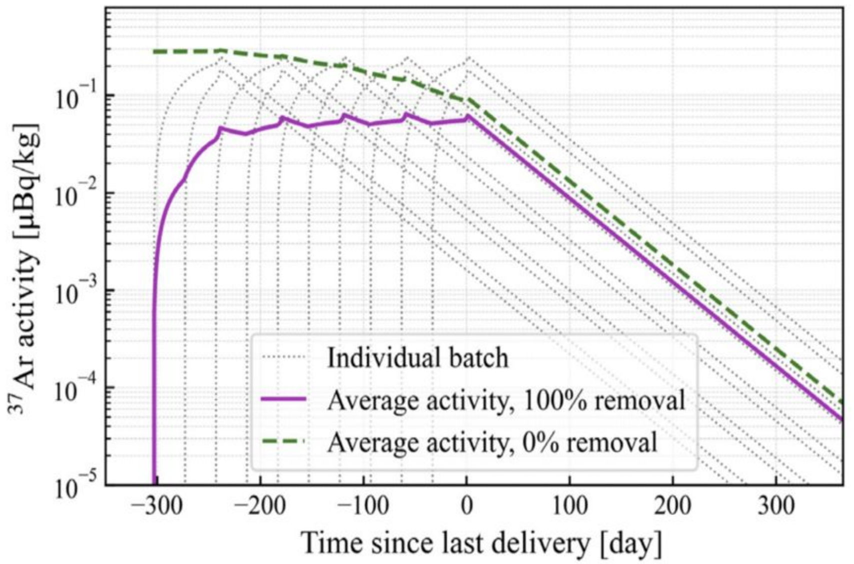




Ar37 Background

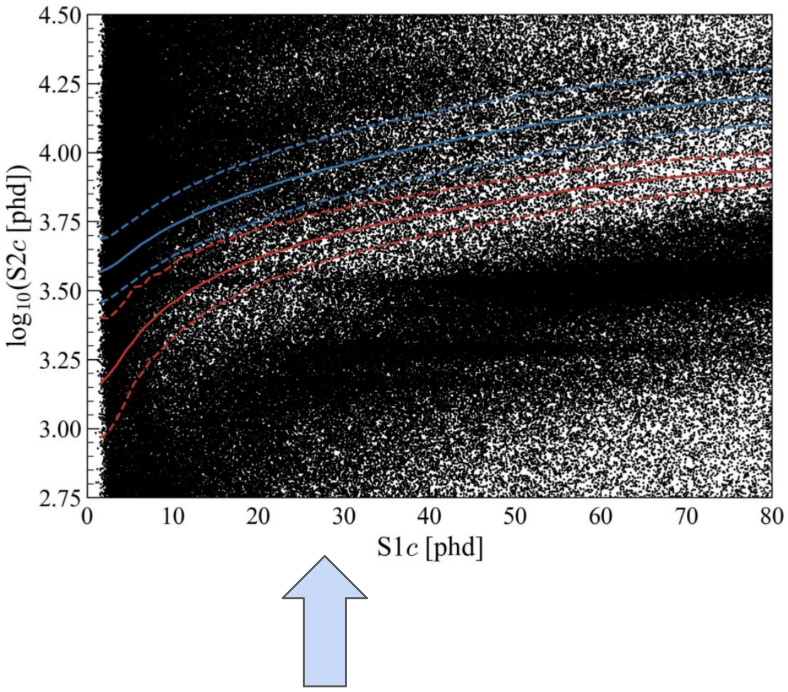
- Ar-37 produced by atmospheric activation and cosmic spallation of xenon.
- Electron capture decay, $t_{1/2}$ = 35 days
  - Mono-energetic 2.8keV ER deposition
- Prediction of ~100 decays in SR1, accounting for surface exposure of LZ xenon
  - Large uncertainty from production models.
- Explicitly included as a component in background model.





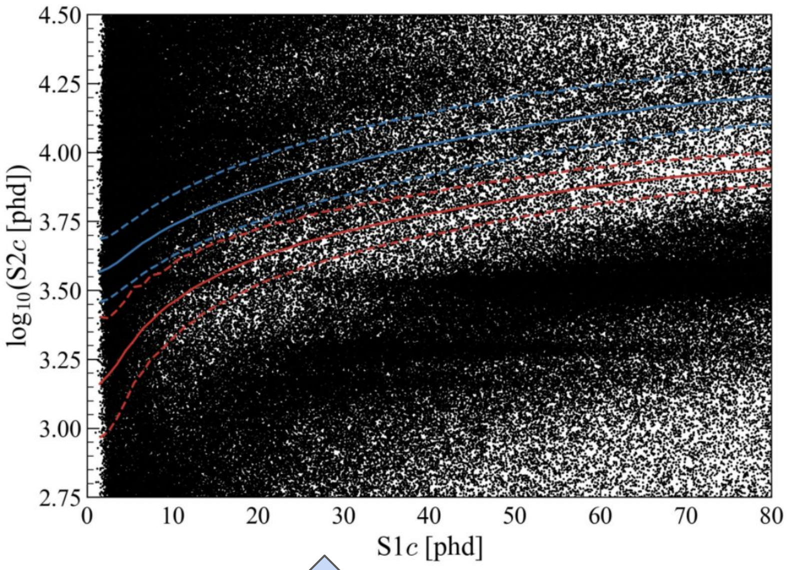
[LZ Collaboration, Phys. Rev. D 105, 082004 (2022), 2201.02858]

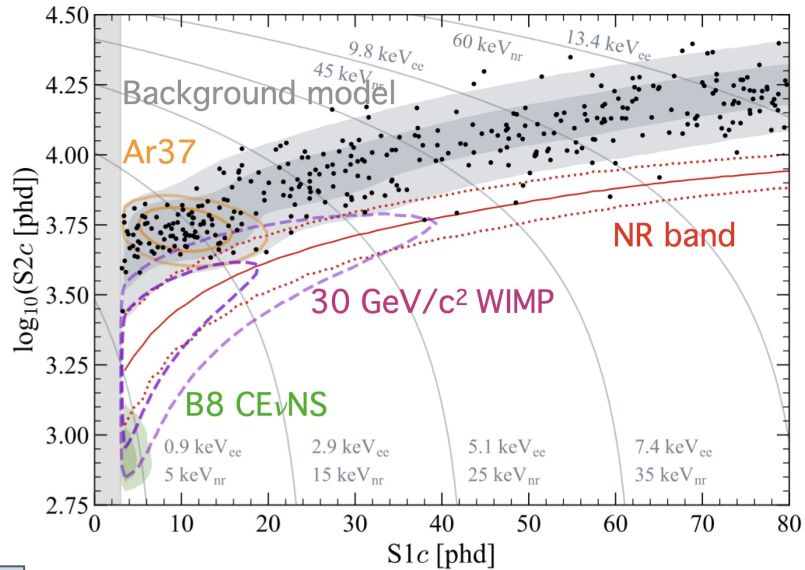
Full Single Scatter dataset from SR1



- All single-scatter data
- No cut of any kind applied
- *Are there WIMP in there?*

Data Analysis Strategy





- All single-scatter data
- No cut of any kind applied
- *Are there WIMP in there?*

1 Apply fiducial cuts to maximize Signal-to-Background

2 Model backgrounds

3 Compare data to test background-only or background + signal hypotheses (Profile Likelihood Test)

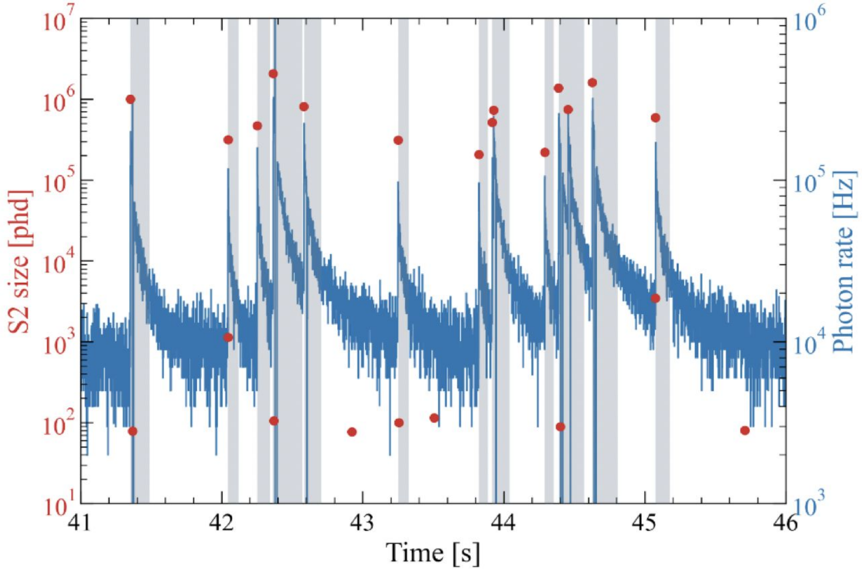
Data Quality Selections

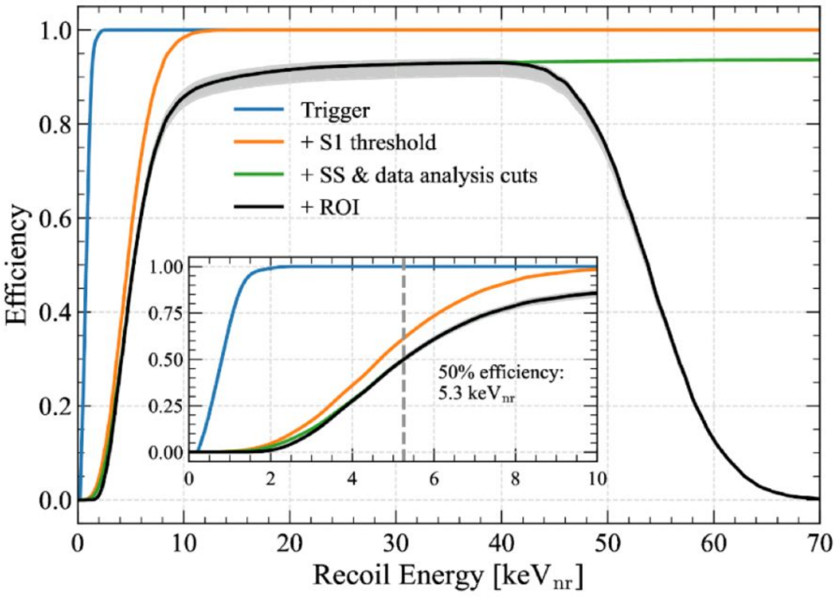
- Two broad categories of data selections allow us to remove data based on bad quality:

  1. Time-based:
     - Exclude periods with high rates of spurious activity (e.g. electron and photon emission)

  2. Pulse-based:
     - Exclude events based on outlier pulse characteristics
     - Impacts signal acceptance - studied using tritium and AmLi data
     - 50% efficiency at 5.3 keV nuclear recoil energy

<u>All cuts developed on calibration data or search data outside the WIMP search region of interest</u>

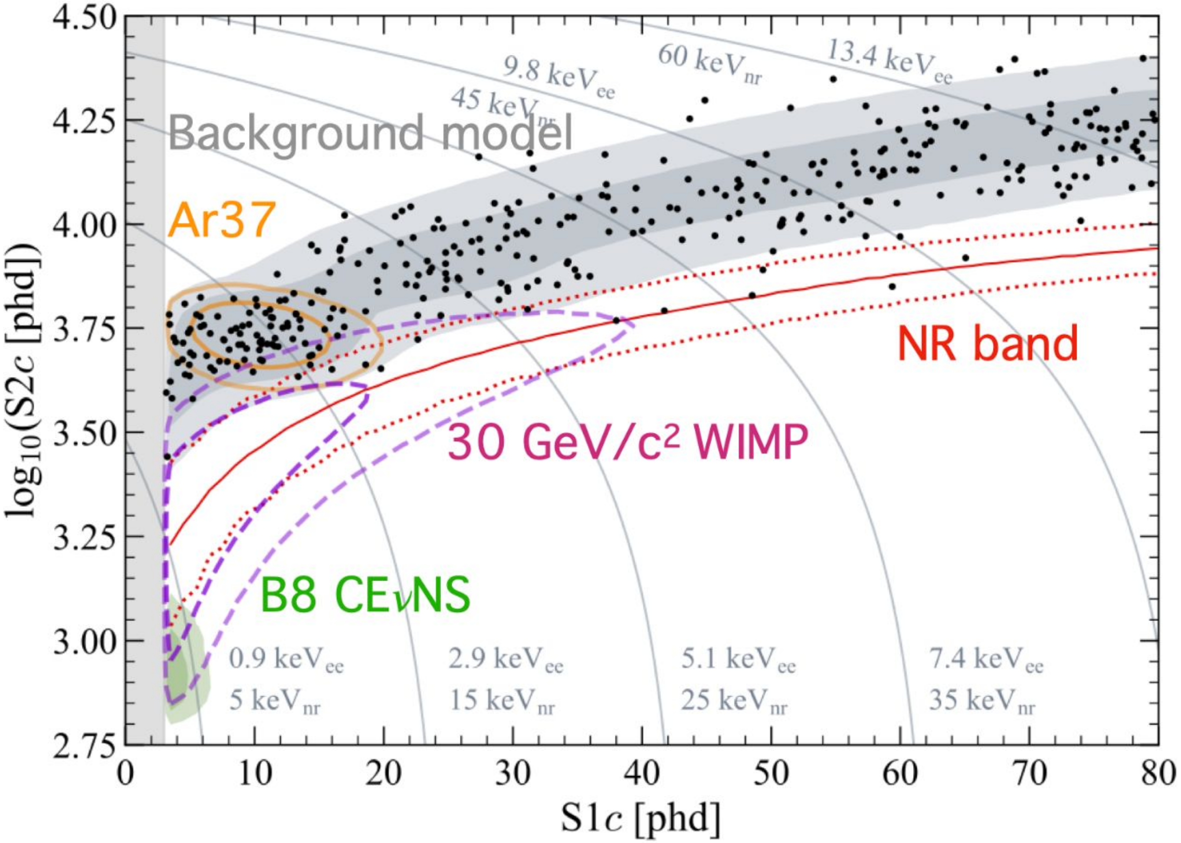




Candidate Events: Final SR1 Data

- 335 events in final dataset
- Define a WIMP search 'region-of-interest' for a Profile Likelihood Ratio (PLR) analysis:
  - 3 phd < S1c < 80 phd
  - S2 > 600 phd (~ 10 extracted electrons)
  - S2c < 10^5 phd

60 live days, 5.5 t fiducial volume, 0.9 t years exposure

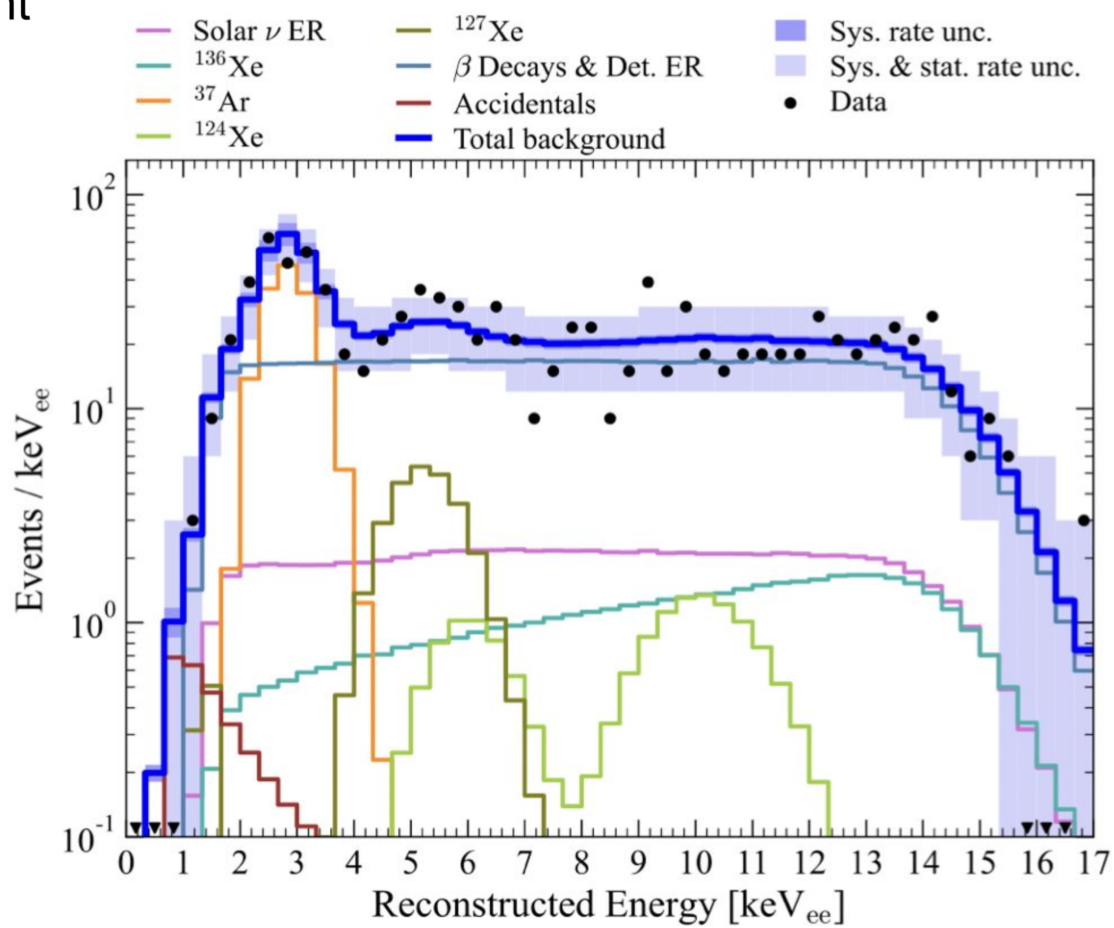


Results - Best fits

Projecting onto electronic-equivalent reconstructed energy ("keVee")

Best fit with **zero** WIMP events at all masses yields p-value =0.96

Source	Expected Events	Best Fit
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17



Background model

Combined fit to data with background model as prior

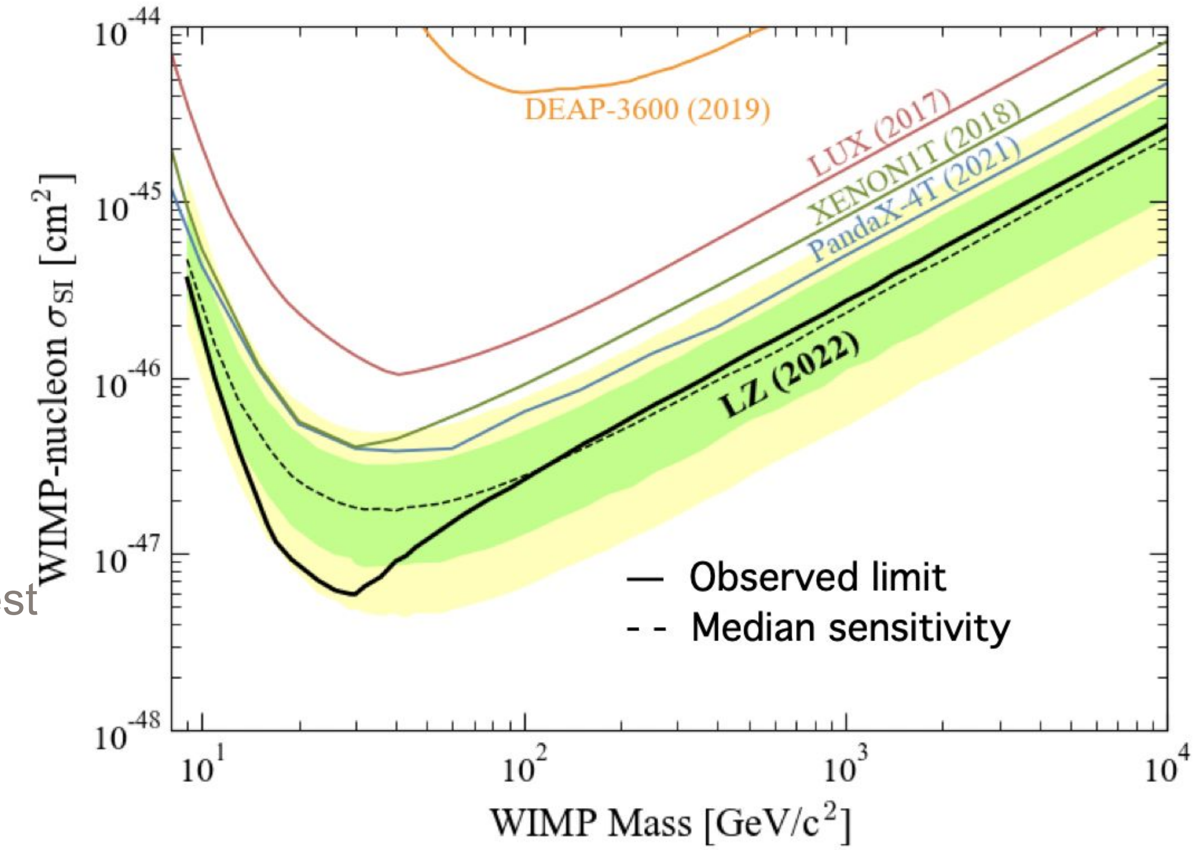
Results - spin independent interactions

New limit @ 90% CL of WIMP-nucleon $\sigma_{SI} = 5.9 \times 10^{-48}$ cm^2 at 30 GeV/c^2 WIMP mass

Green and yellow are the 1σ and 2σ sensitivity bands.

In line with Phystat recommendations:

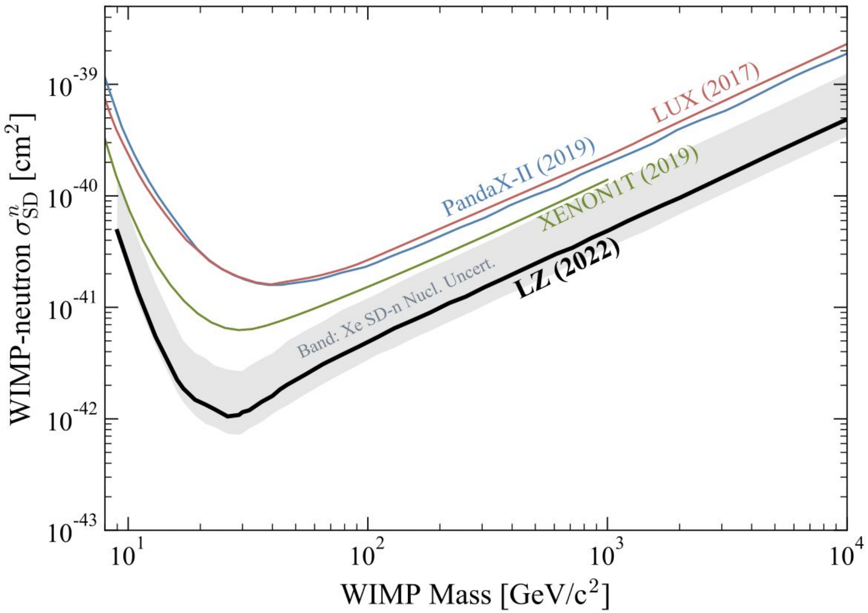
- Frequentist, two-sided profile-likelihood-ratio (PLR) test statistic
- Signal rate must be non-negative
- 90% confidence bands
- Power constrain at $\pi_{crit} = 0.32$



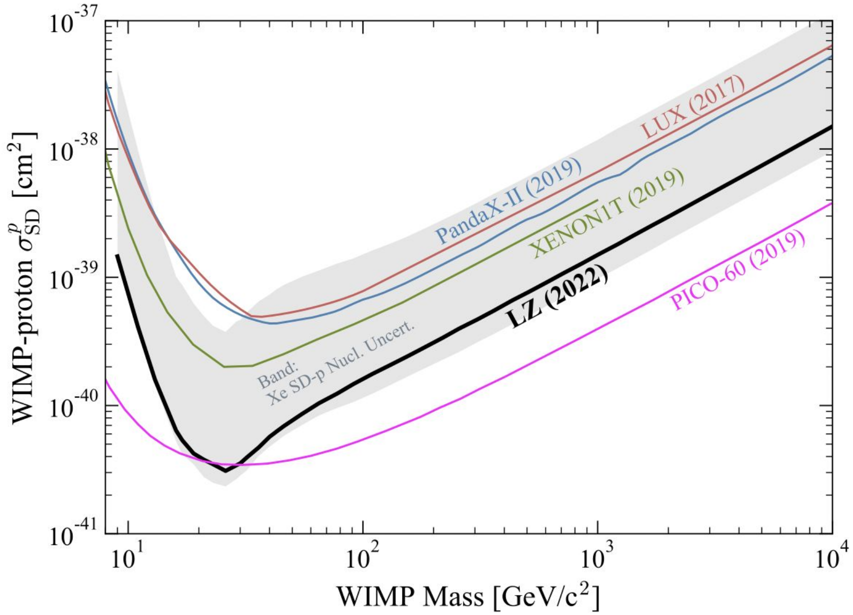
[LZ Collaboration first science results, arXiv:2207.03764]

Results - spin dependent interactions

Spin-dependent WIMP-neutron scattering



Spin-dependent WIMP-protron scattering



Using the two Xe isotopes with non-zero nuclear spin, a spin dependent limit was also set.

Grey band represents theoretical uncertainty on nuclear form factor for Xe (*)

"Brazil" band not shown for clarity

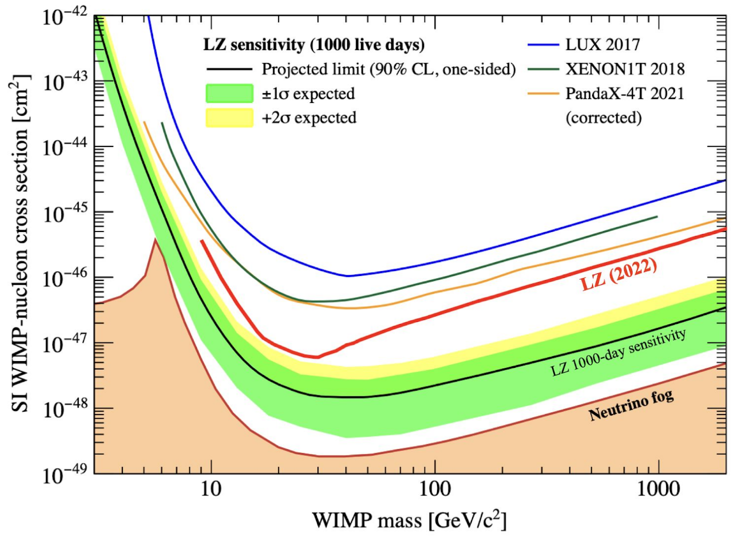
(*) P. Klos, J. Menéndez, D. Gazit, and A. Schwenk Phys. Rev. D 88, 083516 (2013)

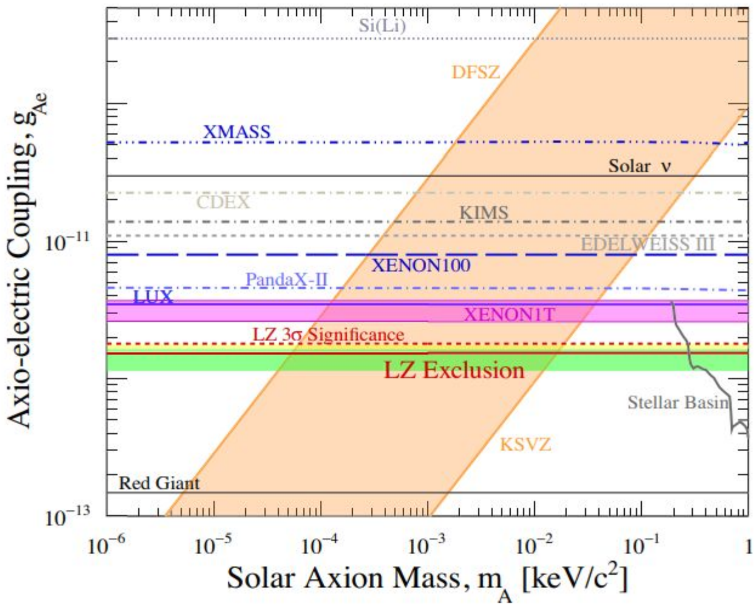
[LZ Collaboration first science results, arXiv:2207.03764]

LZ -What's next?

LZ plans to take 1000 live days of data (x17 more exposure)

- **Increase sensitivity to WIMP** (projection: 1.4 x 10^{-48} cm^2 at 40 GeV/c^2 (90% CL one-sided)
- **Other science channels**
  - **Extending the reach**: S2-only, Migdal effect, EFT
  - **Non-WIMP DM candidates**: Axions, ALPs, hidden photons, mirror dark matter, leptophilic DM, and more
  - **Astrophysical neutrinos**: ^{8}B CEvNS, solar-pp, supernova, and more
  - **Rare decays**: 0v$\beta\beta$ of ^{136}Xe, 2v$\beta\beta$ and 0v$\beta\beta$ of ^{134}Xe, and more





Phys. Rev. D 101, 052002 (2020)
Phys. Rev. C 102, 014602 (2020)
Phys. Rev. D 104, 092009 (2021)
Phys. Rev. C 104, 065501 (2021)

XLZD Consortium

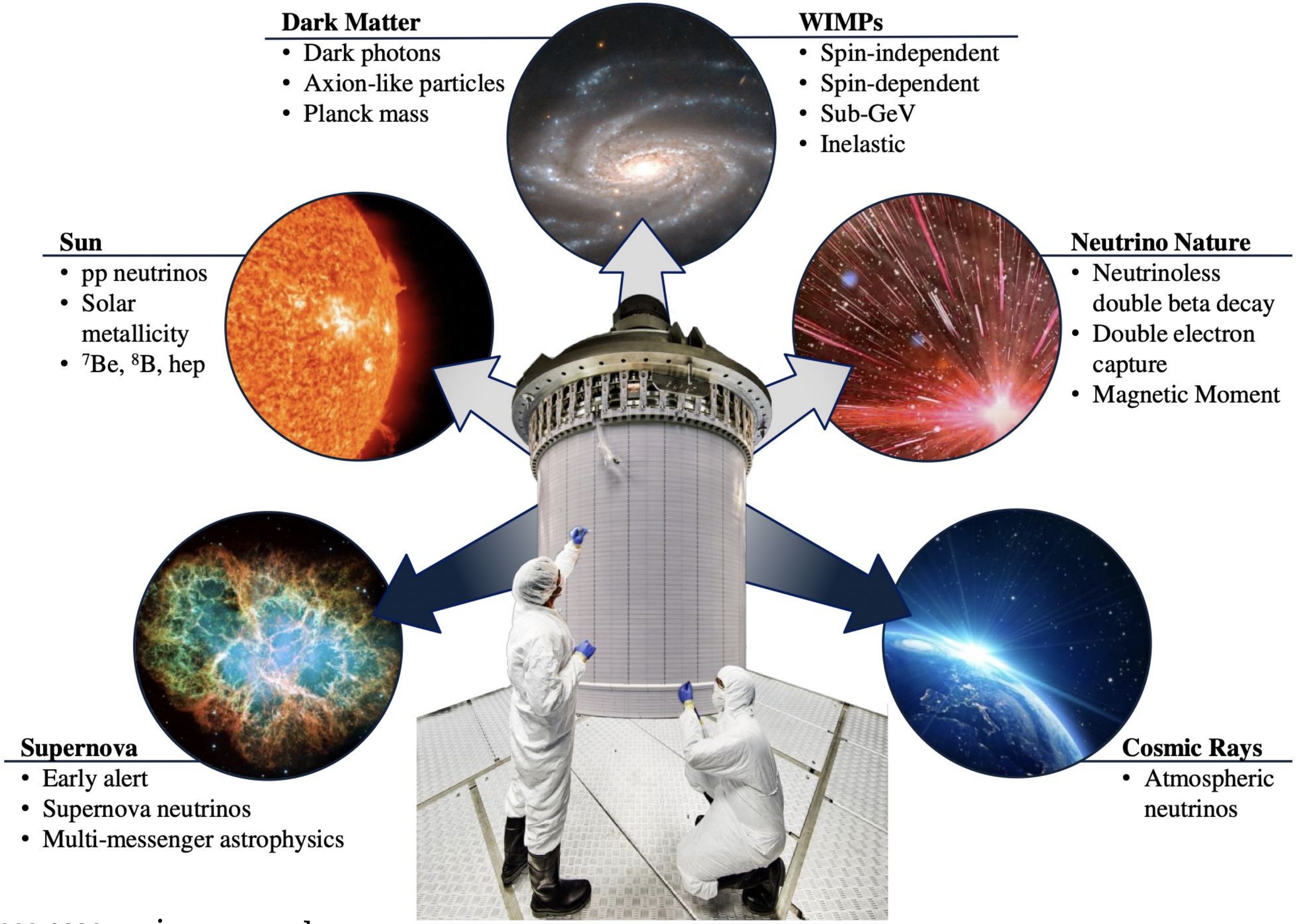
- LZ, XENON and DARWIN collaborations have joined forces to work toward the next generation of LXe dark matter detector
  - See https://xlzd.org and white paper (arXiv:2203.02309)
- First meeting Summer 2022 at KIT in Germany
- Second meeting Spring 2023 in USA
- Ongoing R&D works in various institutions

Leading Xenon Researchers unite to build next-generation Dark Matter Detector

SURF is distributing this press release on behalf of the DARWIN and LZ collaborations

XLZD Meeting in Karlrushe, Germany (June 2022)

XLZD: A Rare Event Observatory



[XLZD science case, arxiv 2203.02309]

Summary

- LZ is online and taking high quality physics data
  - All detectors (OD, Skin, TPC) performing well
  - Backgrounds within expectation

- After 60 live days, LZ has set new limit on WIMP interactions for masses >30 GeV/c^2

- With its planned 1000 livedays, an increased in WIMP sensitivity is expected and a broad physics program lies ahead for LZ!

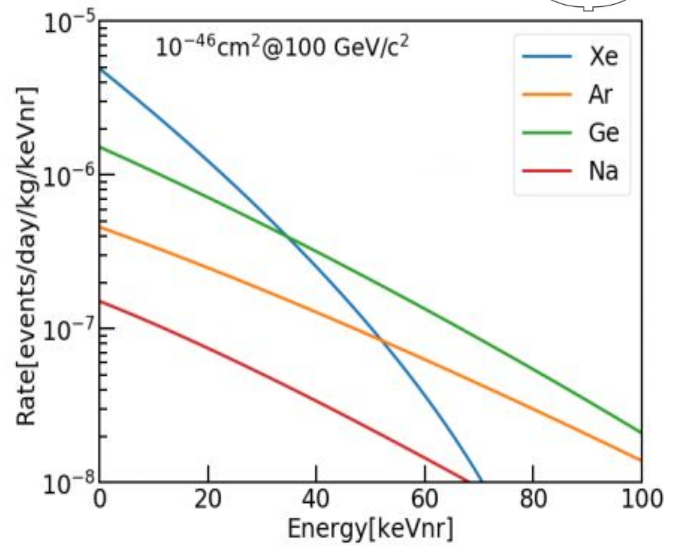
- The xenon community (LZ, XENONnT & Darwin) have unified into the XLZD consortium to build one big xenon experiment to rule them all!
  - This new experiment will address numerous scientific questions in addition to probing dark matter nature.

Backup slides

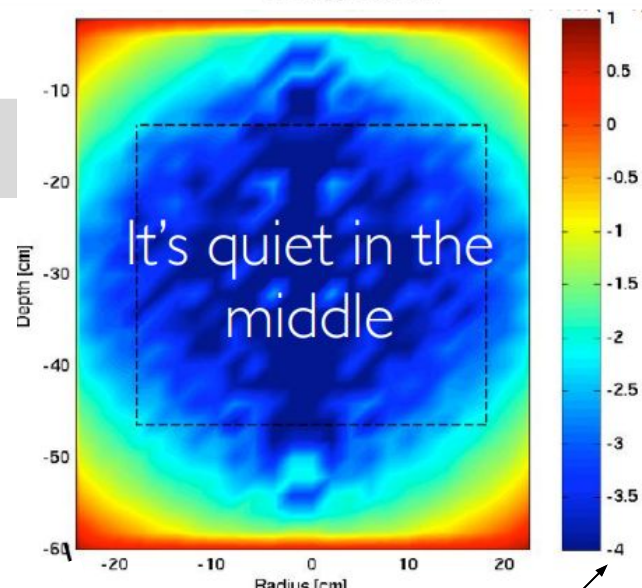
Using Xenon as target material

- High density (>3 g/cm³)
- High atomic mass (A=131g/mol)
  ⇒ Large signal rate via coherent nuclear scattering
- 50% odd isotopes in natural Xenon
  ⇒ spin-dependent sensitivity as well
- Self-shielding
  ⇒ Ultra-low background inner region (using 3D position recons)
- No long-lived radioactive Xe isotopes
- Large light output and fast response
- Long electron drift lengths (~1 m)

Large signal rate



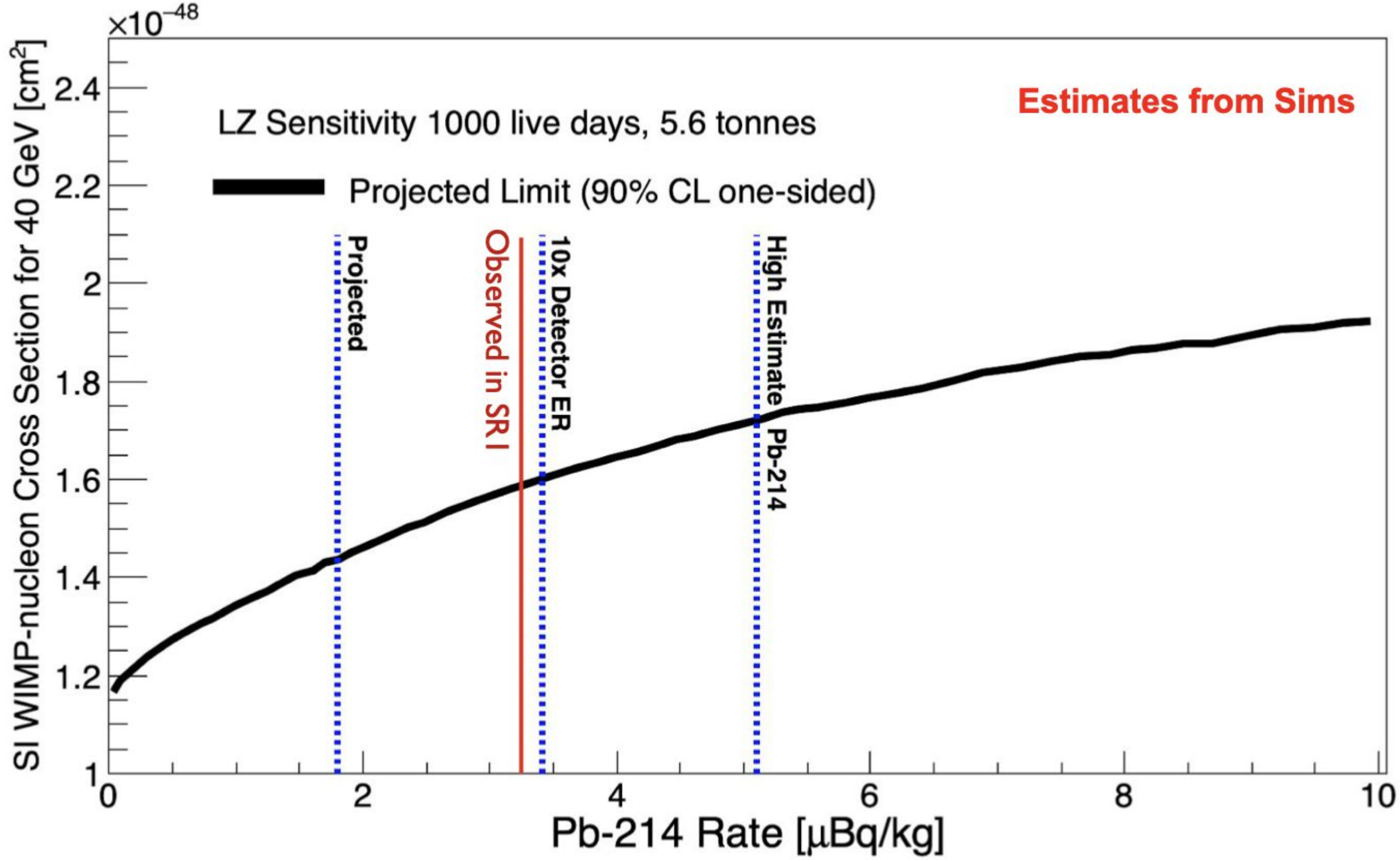
Self shielding



Event rate in cts/keVee/kg/day

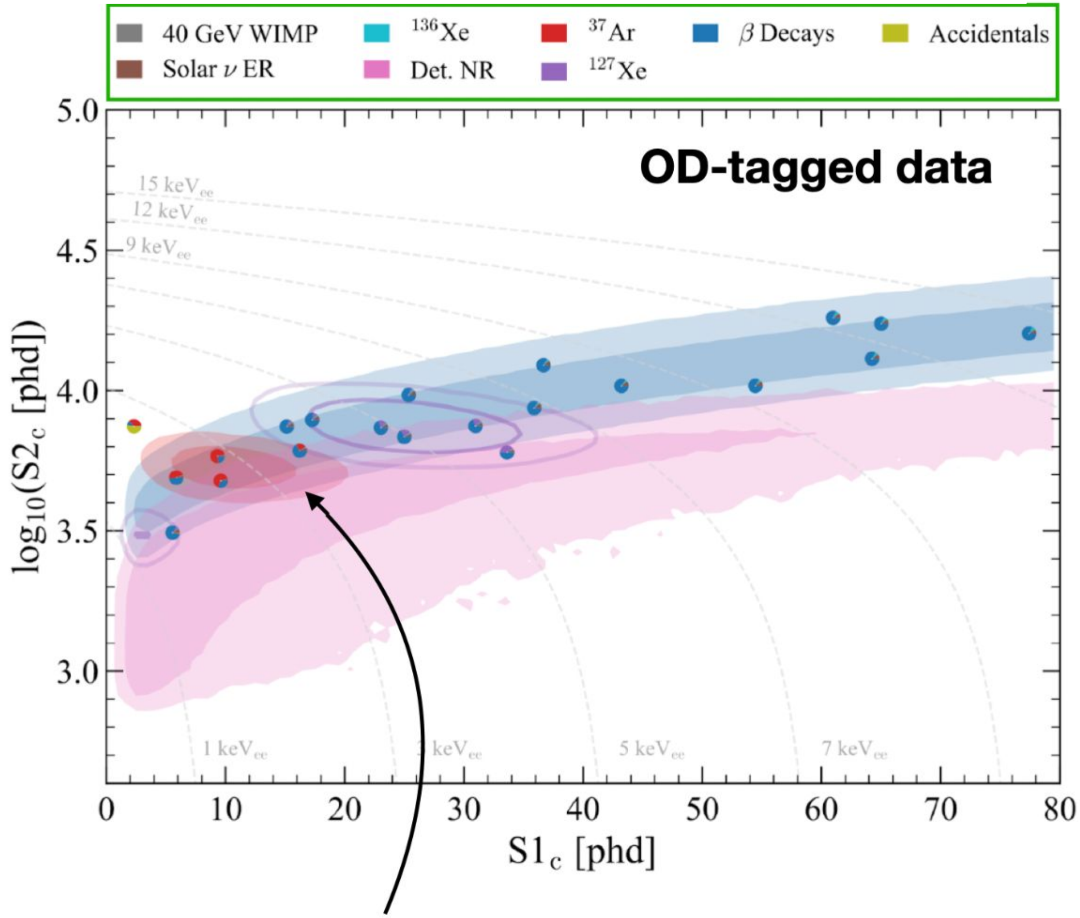
Sensitivity Reach vs Pb-214 rate

Impact on 40 GeV WIMP sensitivity with increasing Pb-214 rate, as a proxy for increasing flat ER backgrounds



Neutron Background

- Use OD-tagged SR1 data as a ‘neutron enhanced’ dataset.
- 5% of non-neutron backgrounds have accidental OD tag.
- Multi-component fit on OD-tagged single scatter events to constrain neutron contribution.
- Result: Number of neutrons in SR1 exposure with OD veto applied is $0^{+0.2}$
    - 88.5% tagging efficiency, measured by AmLi source at multiple positions
    - Neutron background simulations: 0.06 events in 60 live days.



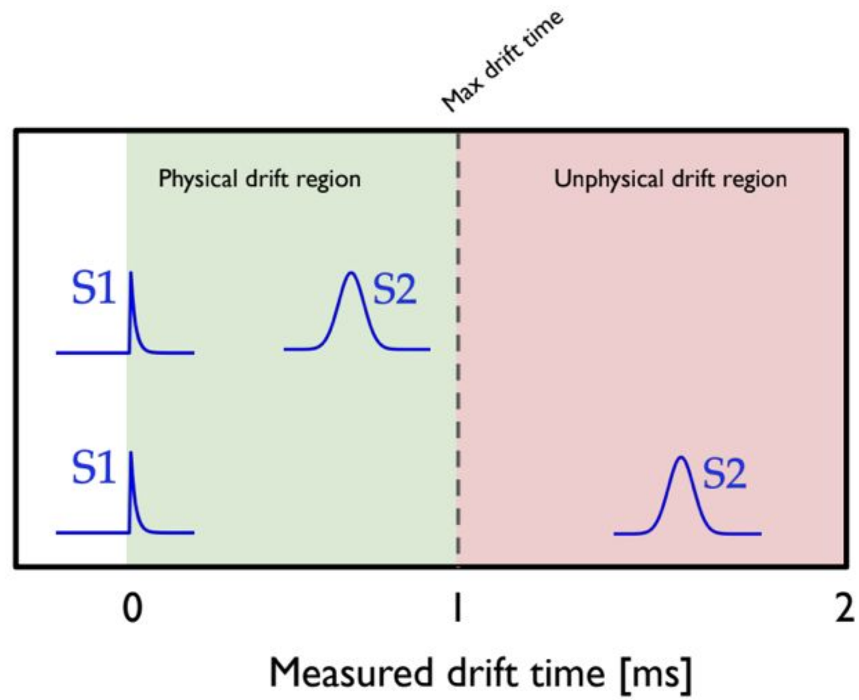
Pie charts show likelihood contribution of each background component

Accidentals Background

- Isolated S1 pulses occur at O(1 Hz)

- Isolated S2 pulses occur at O(10^{-3} Hz) (above threshold)

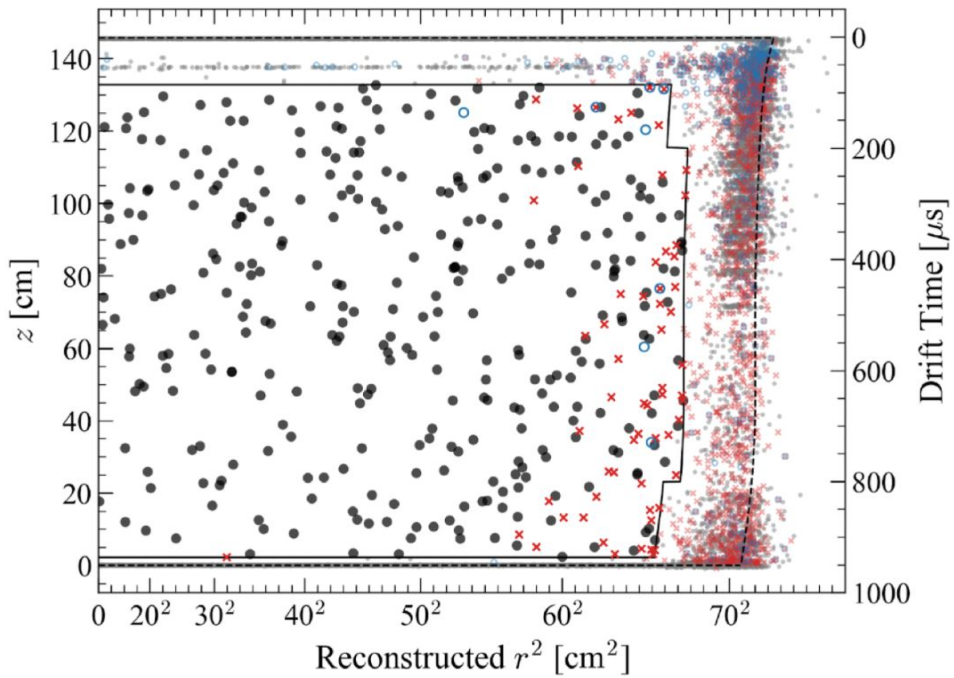
- Occasionally, a lone S1 will accidentally come within 1ms of an unrelated, lone S2, and will look like a valid single scatter in the TPC.
- Events with measured drift > 1ms are caused by accidental coincidences and are used to constrain our rate of this background.



- **Estimated number of accidentals in SR1 is 1.2 ± 0.3 events**

Fiducial Volumes & Vetoes

- S2 charge-loss close to TPC wall leads to poor position resolution at radial boundary
  - Choose a central fiducial volume simultaneously with S2 threshold to make wall background leakage negligible for this analysis
  - 5.5 t fiducial mass (measured by uniformly dispersed tritium source)

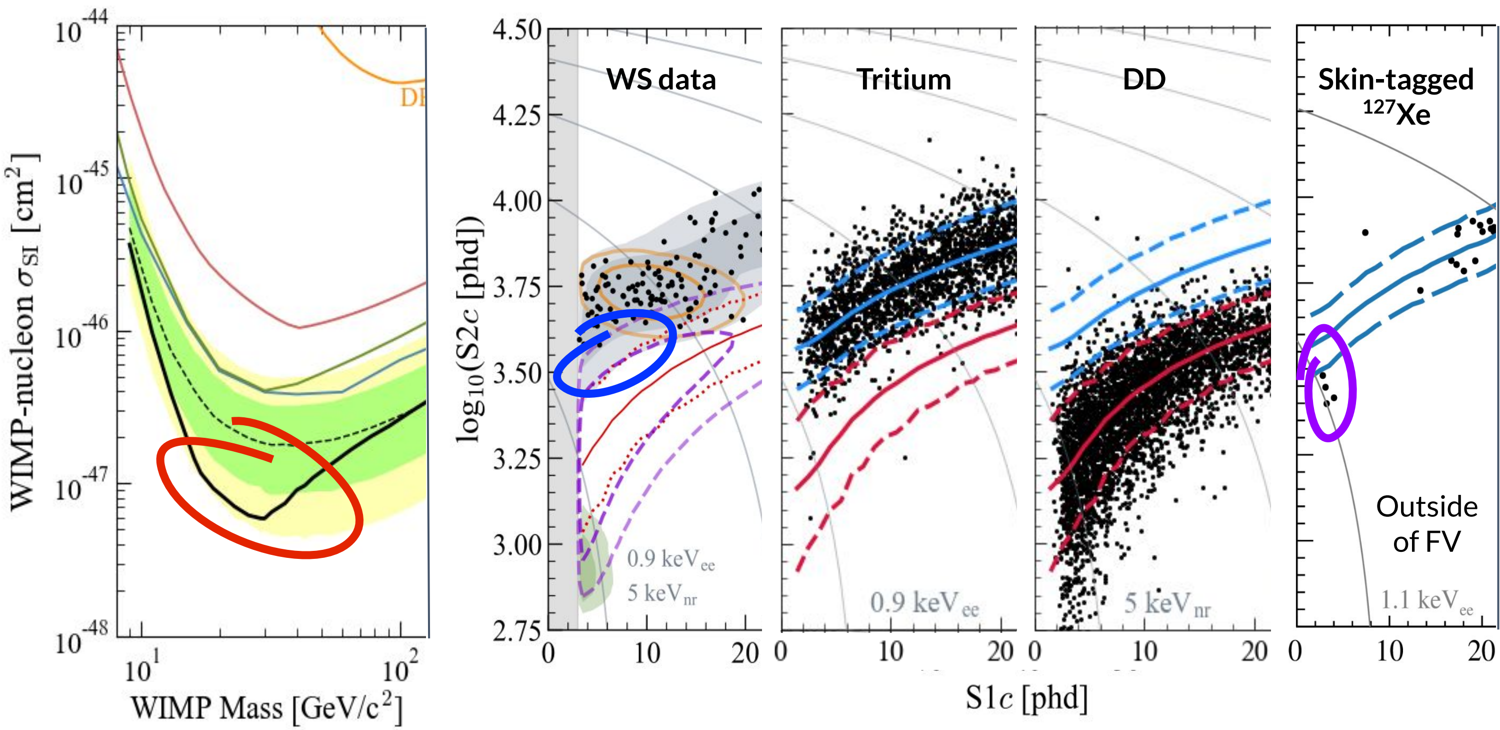


● = pass all selections (candidates), ● = pass all sections outside fiducial volume, X = skin tagged, ◯ = OD tagged

- Prompt (< 0.5 μs) Skin and OD tag:
  - Reduces naked L-, M-shell Xe127 background by x5 by tagging γ-ray that escapes the TPC

- Delayed OD (and skin) tag:
  - 1200 μs window, ~ 200 keV threshold for n-capture tag - 5% false veto rate
  - OD helps constrain neutron background: $0^{+0.2}$ for this analysis

Downward Fluctuation



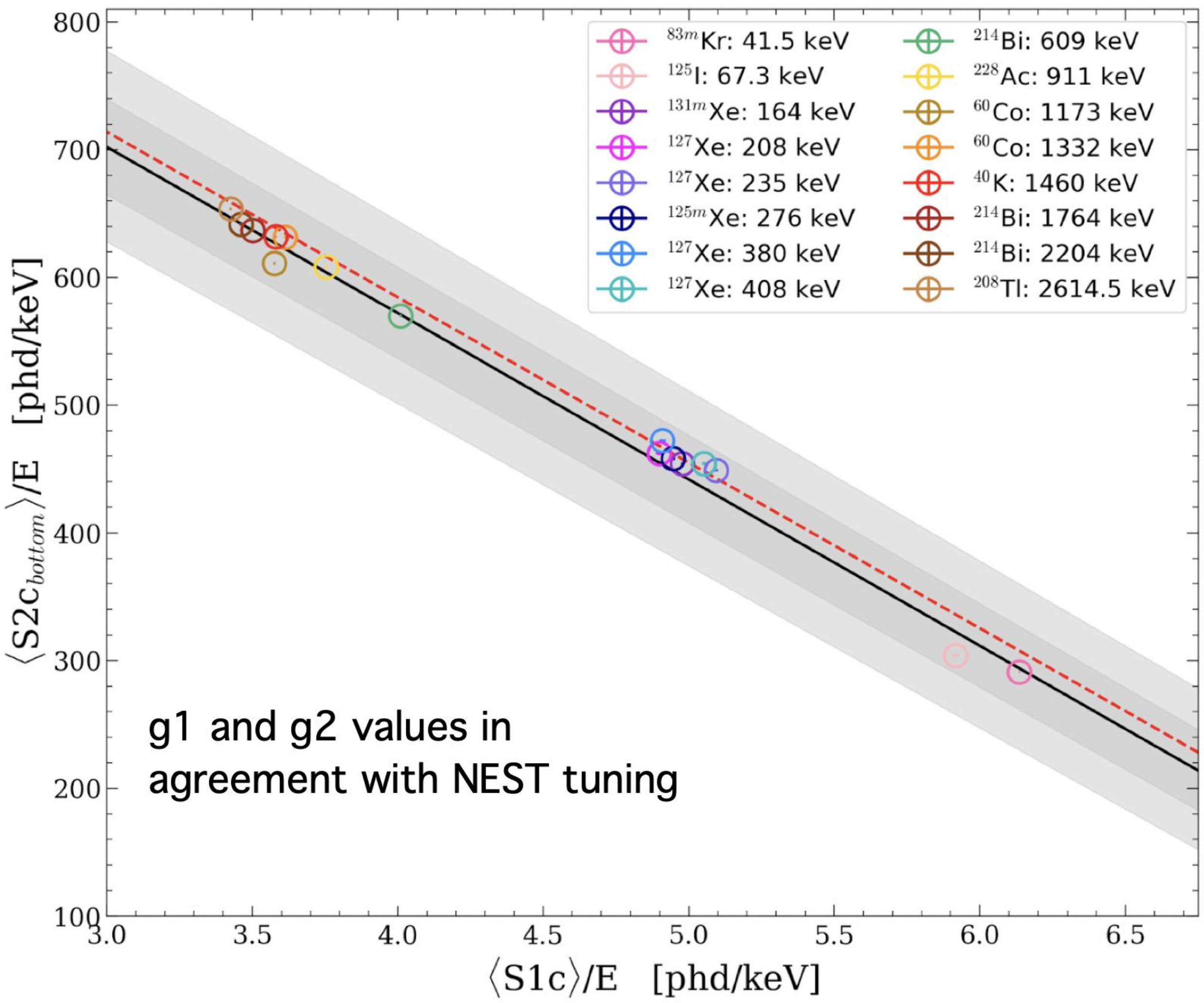
4. Bare M-shell decays of ^{127}Xe populate near deficit region. Observed rate of M-shell decays with coincident γ-ray tagged by the skin is consistent with expectation, given signal efficiencies.
5. Deficit appears consistent with under-fluctuation of background.

1. Downward fluctuation in the observed upper limit near 30 GeV/c^2 is a result of the deficit of events under the ^{37}Ar population.
   Due to background under-fluctuation or unaccounted for signal inefficiency? Probe the latter.
2. **Tritium** data analyzed identically to WS data. Deficit region is well-covered.
3. **DD** data also shows deficit region is well-covered.
   (Not shown here) AmLi neutron calibration data also shows deficit region well-covered.

Data Selection Summary

Selection description	Events after selection
All triggers	1.1×10^8
Analysis time hold-offs	6.0×10^7
Single scatter	1.0×10^7
Region-of-interest	1.8×10^5
Analysis cuts for accidentals	3.1×10^4
Fiducial volume	416
OD and Skin vetoes	335

Doke Plot (Detector response characterization)



$$E = W \cdot \left(\frac{S1_c}{g1} + \frac{S2_c}{g2}\right)$$

$$\longrightarrow \frac{S2_c}{E} = -\left(\frac{g2}{g1}\right) \cdot \left(\frac{S1_c}{E}\right) + \frac{g2}{W}$$

LZ Commissioning Highlights

- TPC detector filled and leveled from August through September
- Grids biassed: extraction & drift fields established in October and December
- First light (and charge) on October 6 2021!
- Established drift field ~190 V/cm (32 kV on cathode)
- Established extraction field ~7.3 kV/cm gas (8 kV between gate and anode)

An actual waveform!