BERKELEY LAB

Status of the LUX-ZEPLIN (LZ) Experiment's Search for WIMP Dark Matter

Scott Haselschwardt (LBNL)
On behalf of the LZ Collaboration

IPA 2022, Vienna
September 9, 2022

The LUX-ZEPLIN (LZ) Collaboration

Black Hills State University
Brandeis 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
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University College London
University of California Berkeley
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University of California Los Angeles
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University of Michigan
University of Oxford
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Thanks to our sponsors and participating institutions!

Science and Technology Facilities Council

Sanford Underground Research Facility
South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia

Institute for Basic Science

Direct Detection Principle

Relative Earth-DM halo motion provides a flux of WIMPs:

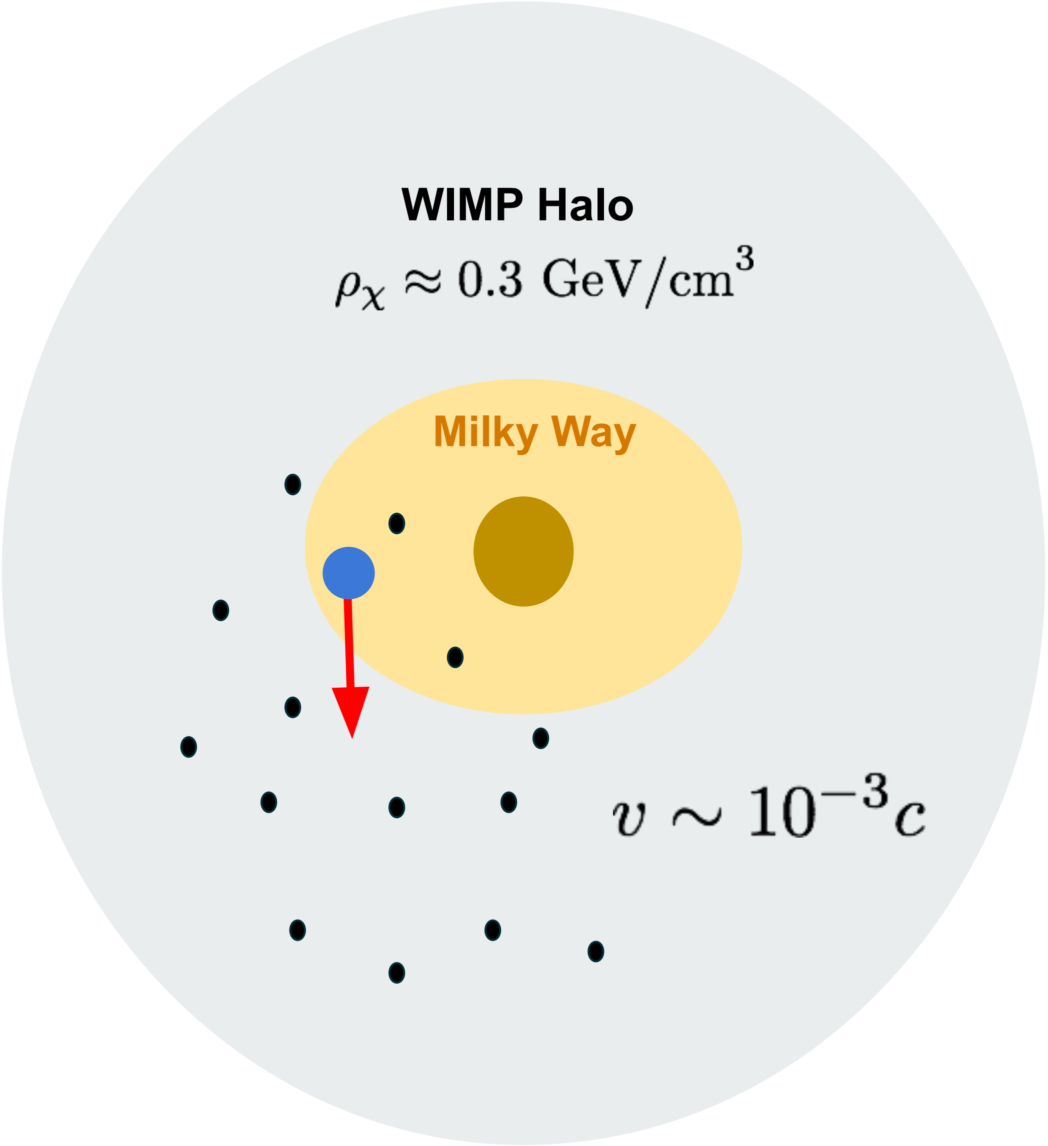
$$\Phi = n_\chi v = \frac{\rho_\chi}{m_\chi} v$$

Recoiling target receives kick:

$$E_R \approx \frac{1}{2} m_T v^2$$

$$E_R \approx \frac{1}{2} (120\ \mathrm{GeV}) 10^{-6}$$

$$E_R \approx 60\ \mathrm{keV}$$



Assuming xenon, A = 131

Liquid Xenon TPC Operational Principle

High voltage grids provide electron drift to liquid surface

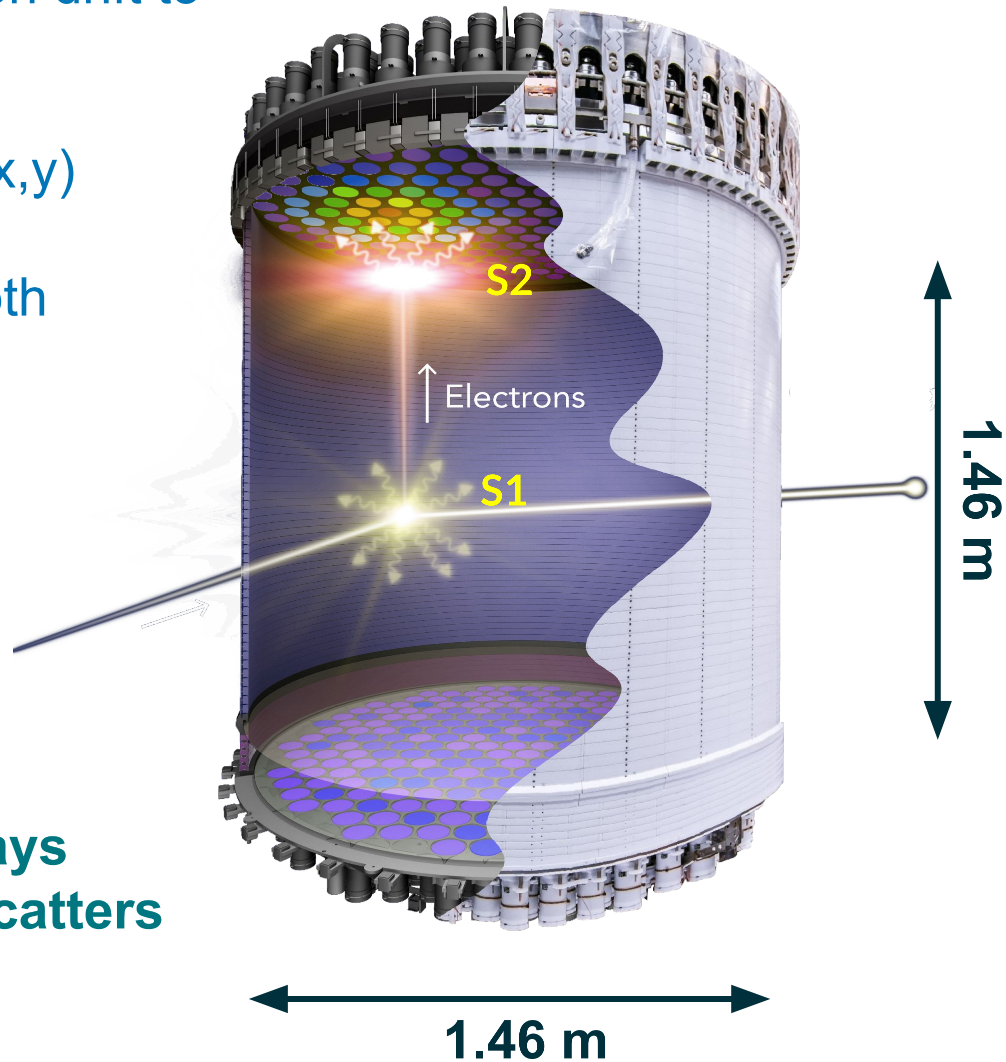
Top PMT array hit pattern gives (x,y)

Time between S1 & S2 gives depth

S2/S1 ratio gives **particle ID** between:

Nuclear Recoils - **neutrons** **WIMPs**

Electron Recoils - **β & EC decays** **Compton Scatters**



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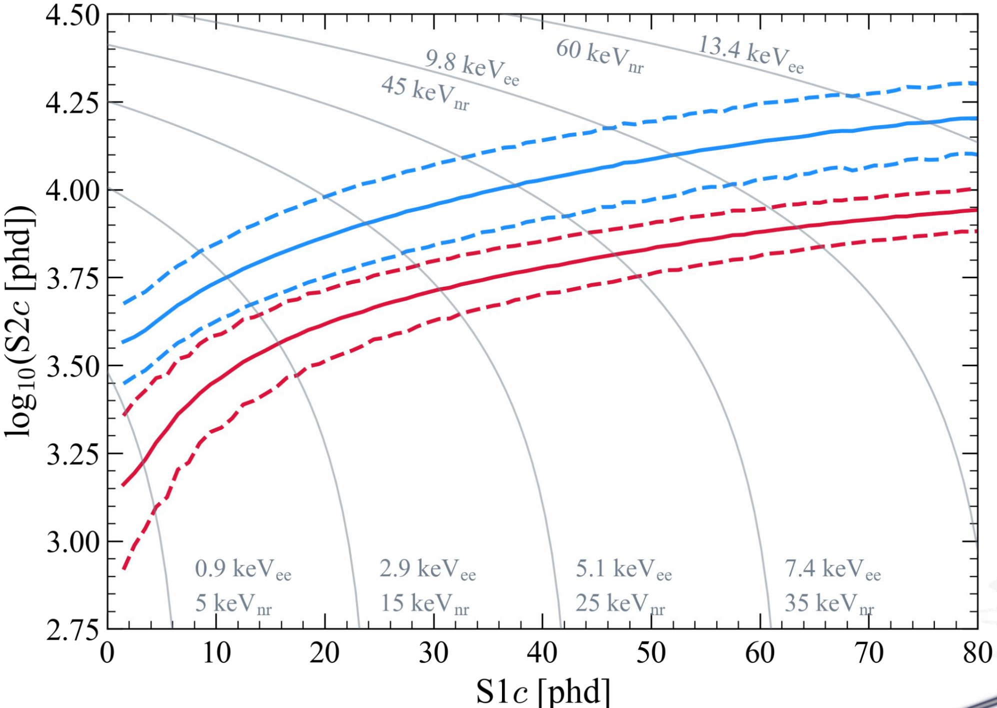

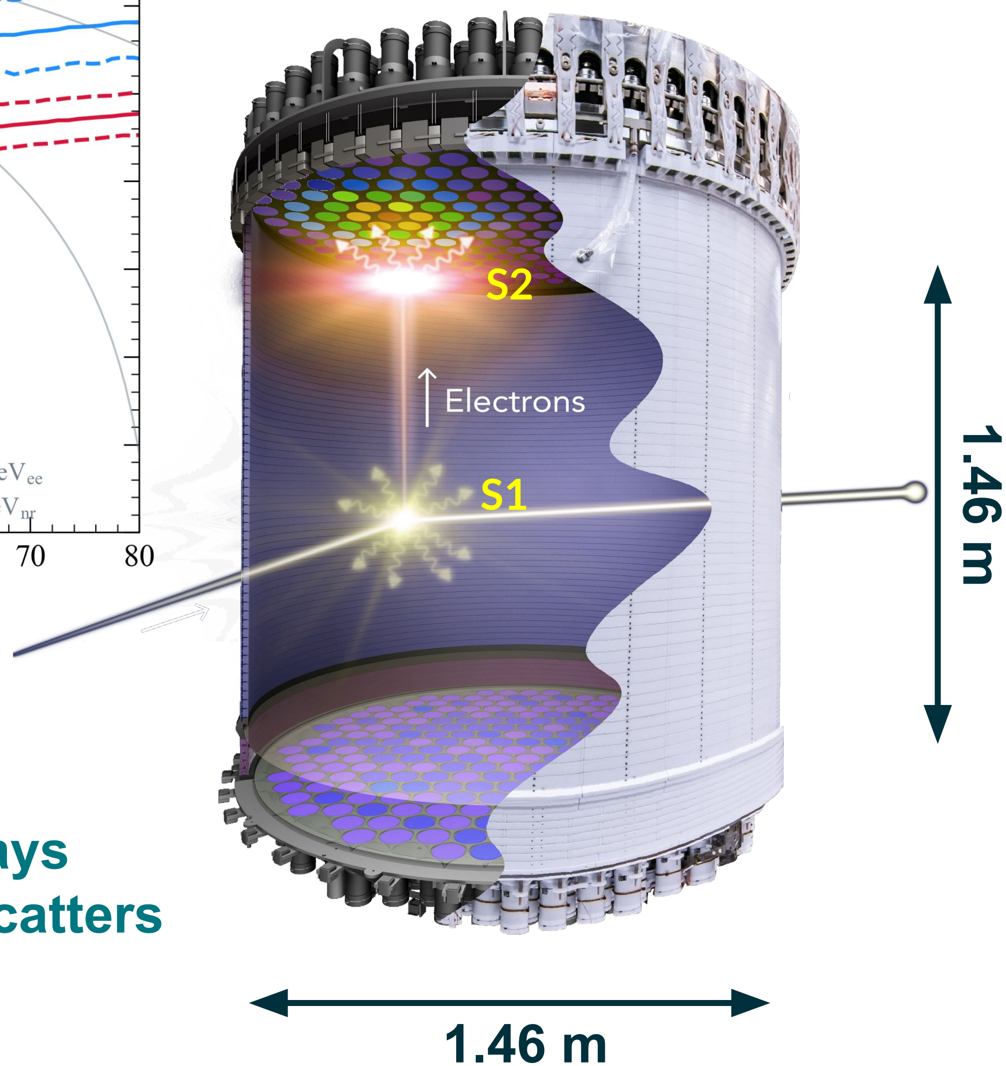

Nuclear Recoils - **neutrons**
WIMPs

Electron Recoils - **β & EC decays**
Compton Scatters

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The LZ Detector

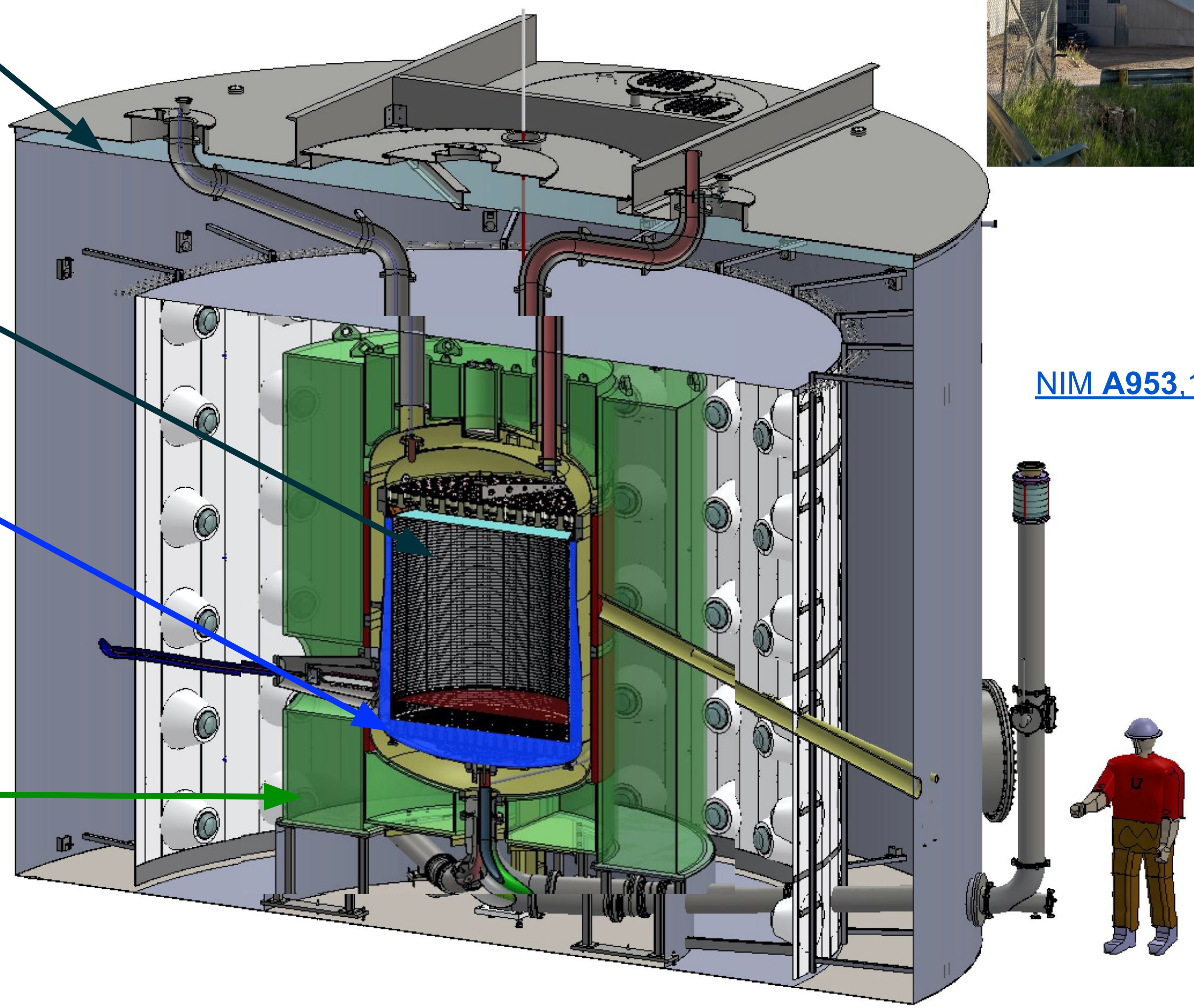
Located underground at
Sanford Underground Research Facility

Water tank

7 tonne LXe TPC

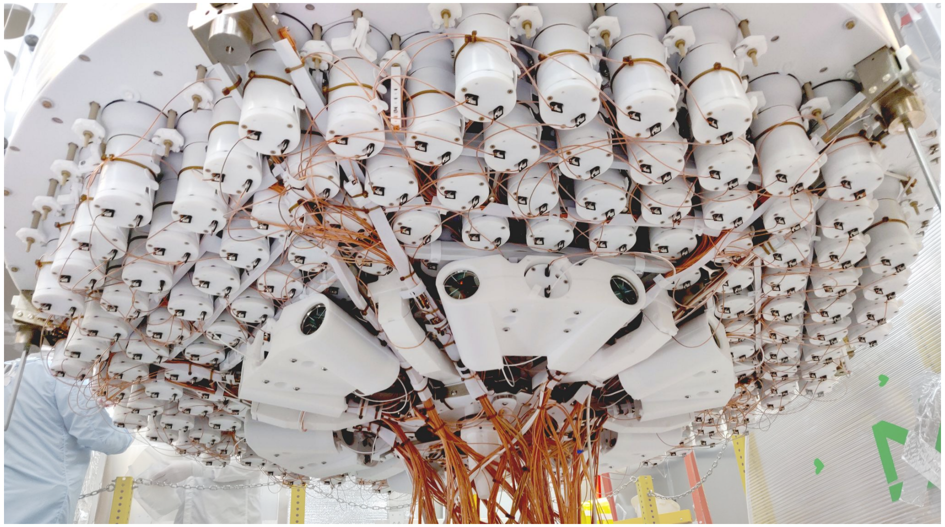
LXe “skin” veto

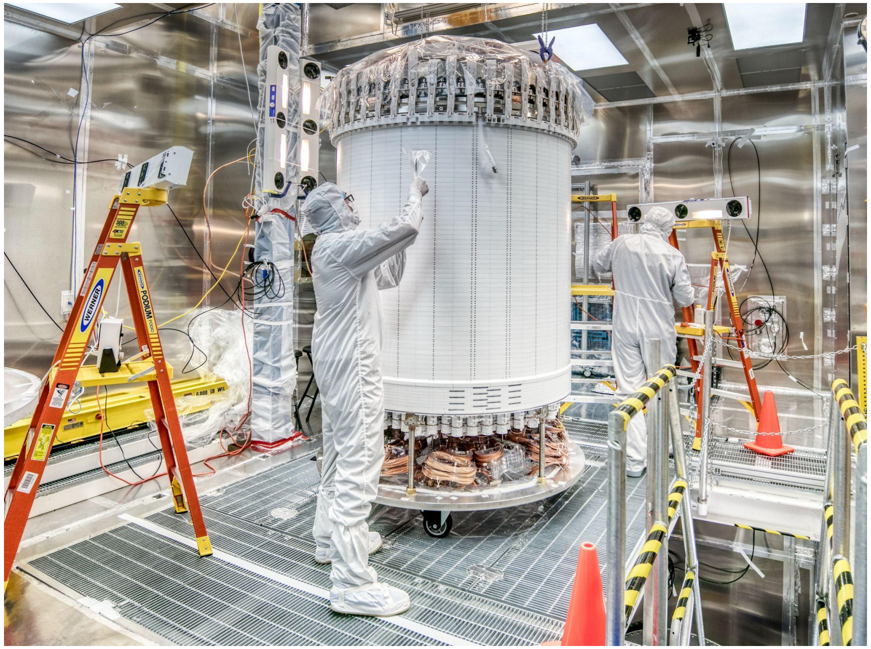
Outer Detector - Gd-loaded liquid scintillator



NIM **A953**,163047 (2020)

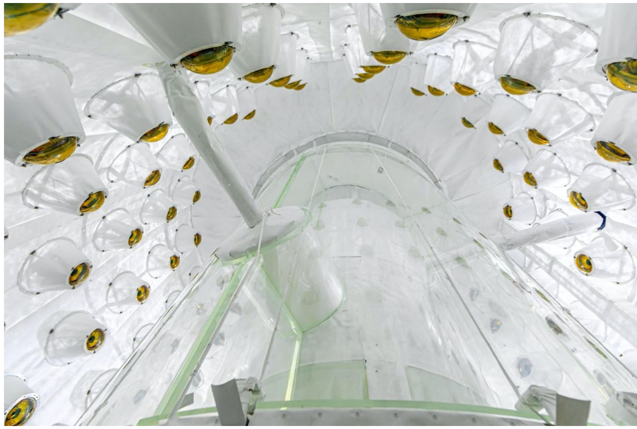
LZ in the Flesh

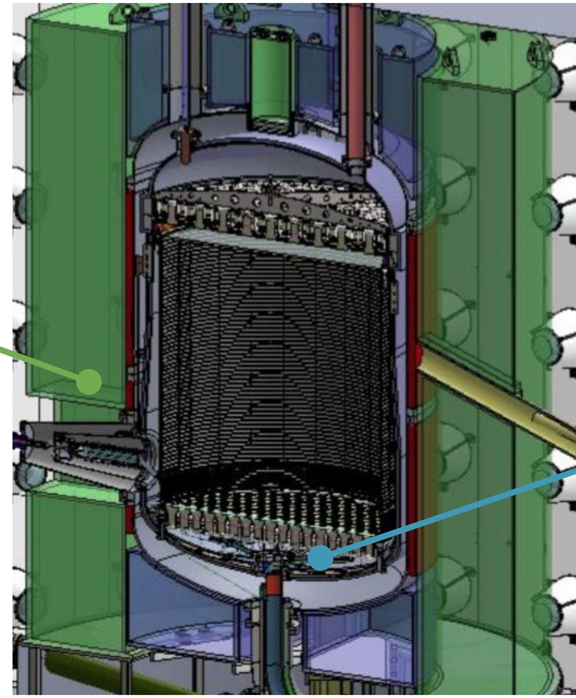


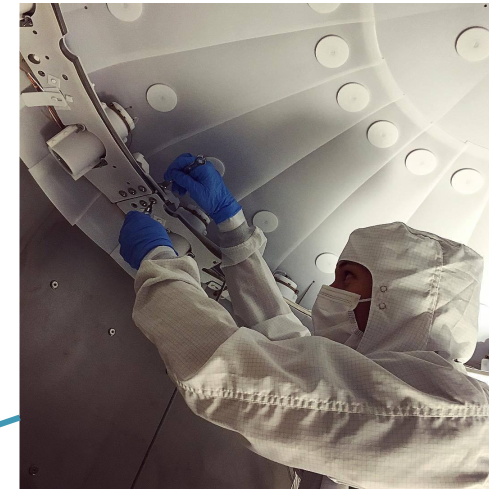


Outer Detector (OD)

Xenon Skin







17t Gd-loaded liquid scintillator

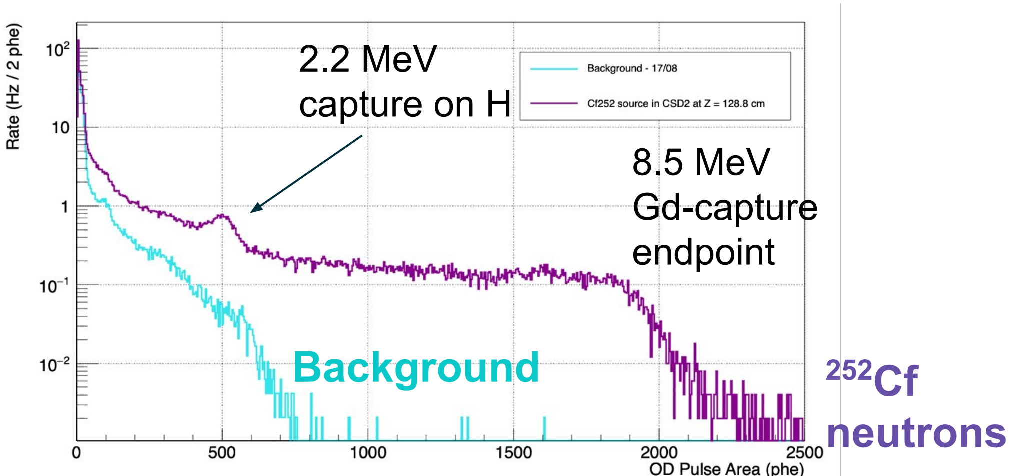
Viewed by 120 8” PMTs

Gd n-capture gives ~8 MeV for clear neutron signal

2t of liquid xenon between TPC and cryostat walls

93 1” and 38 2” PMTs

Efficiently tags γ-rays from detector materials and decays in the TPC xenon



Together, the Skin and OD reject & characterize the background!

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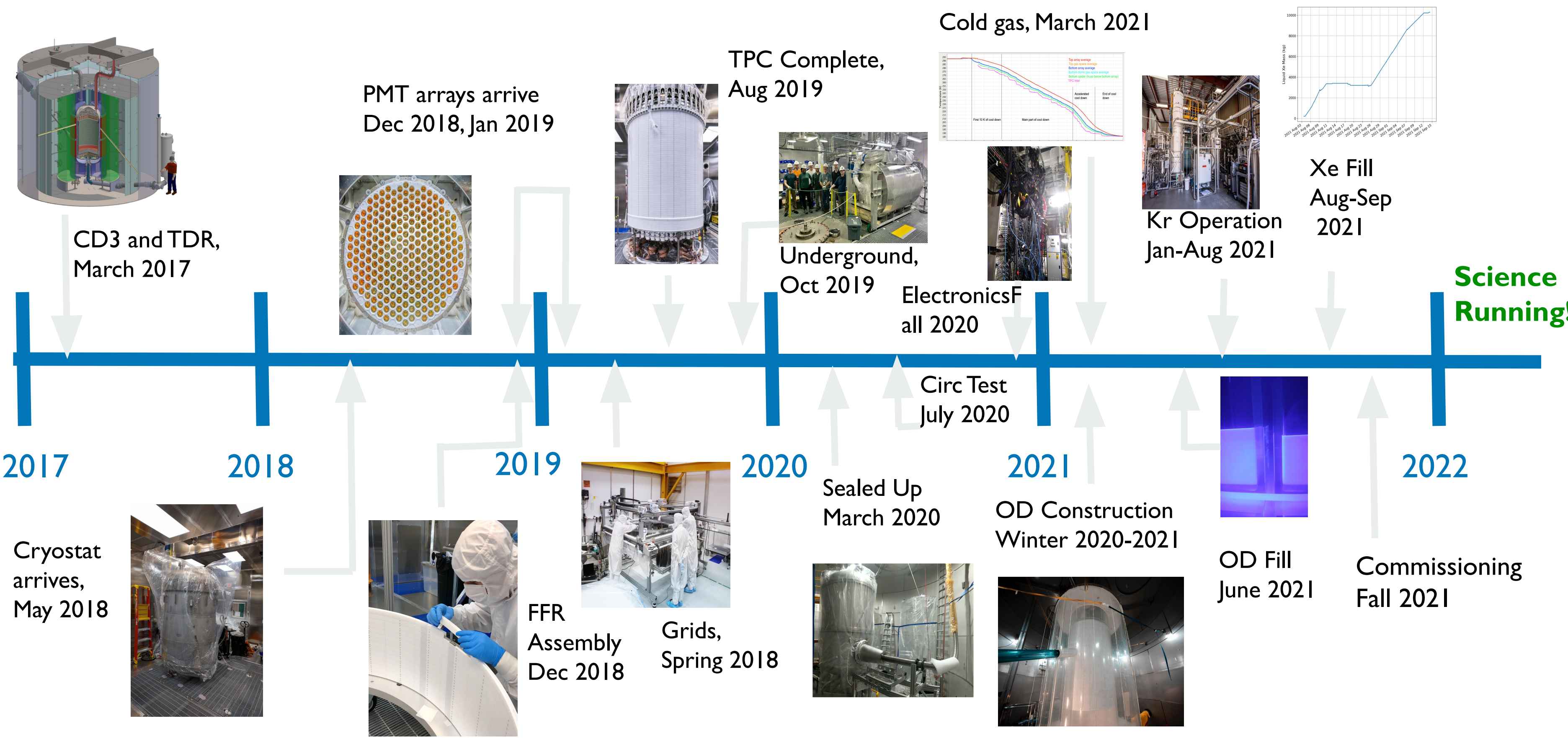
LZ Timeline


CD3 and TDR, March 2017
PMT arrays arrive Dec 2018, Jan 2019
TPC Complete, Aug 2019
Underground, Oct 2019
Cold gas, March 2021
ElectronicsFall 2020
Kr Operation Jan-Aug 2021
Xe Fill Aug-Sep 2021
Science Running!
2017
2018
2019
2020
2021
2022
Circ Test July 2020
Cryostat arrives, May 2018
FFR Assembly Dec 2018
Grids, Spring 2018
Sealed Up March 2020
OD Construction Winter 2020-2021
OD Fill June 2021
Commissioning Fall 2021

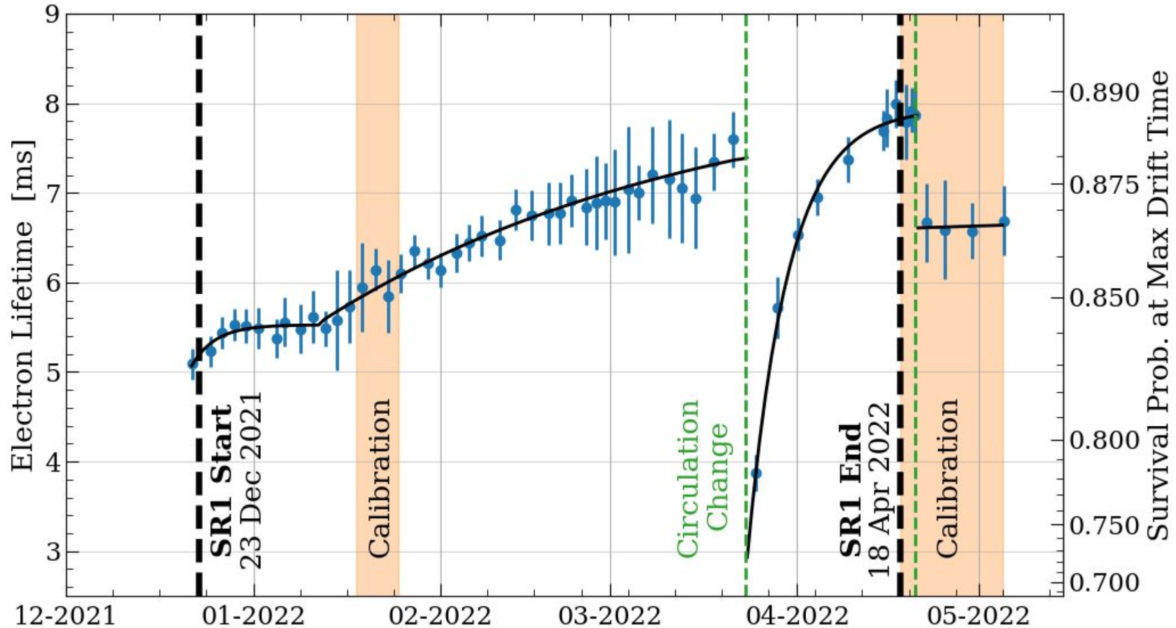
LZ’s First Science Run - “SR1”

Demonstrate LZ’s **physics readiness** and expect **world leading sensitivity**

New detector → SR1 unblinded/salted

Run/detector configuration:

- WIMP search **livetime 60 days** acquired 23 Dec 21 - 12 May 22
- Electron lifetime **5-8 ms**
- Drift field **193 V/cm** (32 kV on cathode), uniform within 4% in fiducial volume
- Extraction field **7.3 kV/cm**, 8 kV between gate-anode
- **>97%** PMTs operational



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Calibration and Detector Response

Both **internal** and **external** sources calibrate response:

ERs: ^{83m}Kr, ^{131m}Xe, Activation lines, Rn-chain α's, CH_3T (tritium), ^{220}Rn, + more

NRs: AmLi, deuterium-deuterium (DD) neutrons, YBe

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light collection efficiency, $\mathbf{g_1 = 0.114 \pm 0.002}$ **phd/photon**

charge gain, $\mathbf{g_2 = 47.1 \pm 1.1}$ **phd/electron** w/ **1 electron = 58.5 phd**

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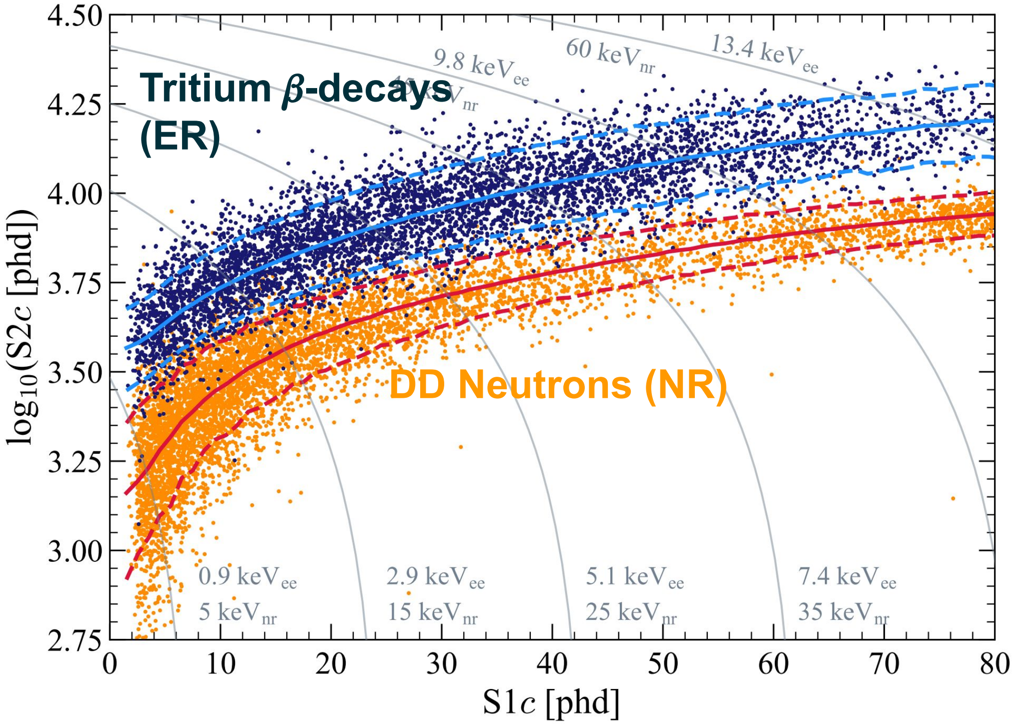
Signal & background models informed by

CH_3T injection (ER)

DD neutrons (NR)

NEST-based response model tuned to tritium data & validated against DD data



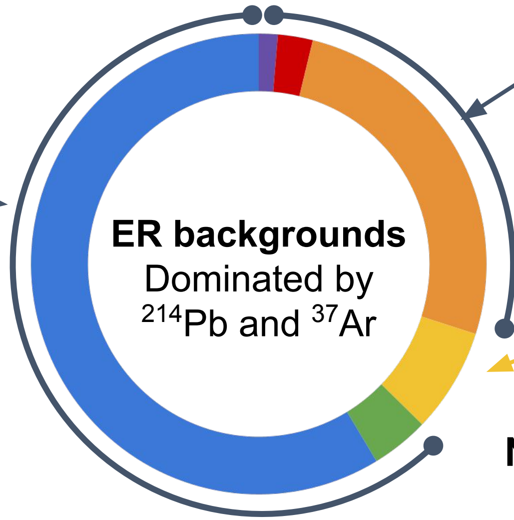
Background Model

Total expected **ER** background in WIMP ROI: **276 + [0,291] ^{37}Ar**

Total expected **NR** background in WIMP ROI: **0.15**

Dissolved β-emitters
- ^{214}Pb (^{222}Rn daughter)
- ^{212}Pb (^{220}Rn daughter)
- ^{85}Kr
- ^{136}Xe ($2\nu\beta\beta$)

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



Dissolved e-captures (mono-energetic x-ray/Auger cascades):
- ^{37}Ar
- ^{127}Xe
- ^{124}Xe (double e-capture)

Solar neutrinos (ER)
- pp + ^{7}Be + CNO

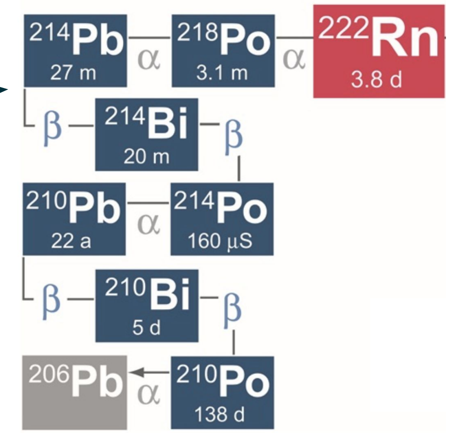
NR backgrounds:
- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar neutrinos

Accidental coincidence backgrounds
- Pile up of isolated S1 and S2 pulses

Radon / ^{214}Pb Background

^{222}Rn emanates out of detector materials into liquid xenon

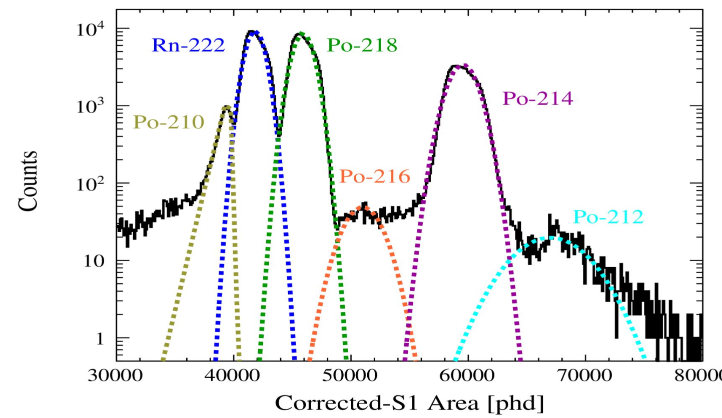
Ground state ^{214}Pb β-decays form dominant WIMP search background

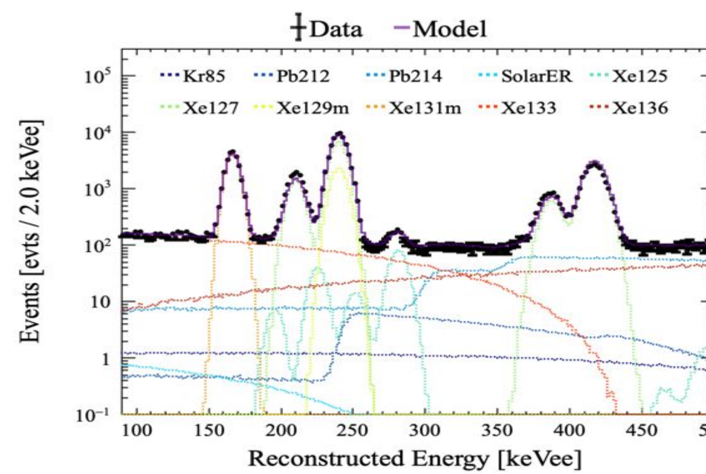


We use two methods to constrain the amount of ^{214}Pb background:

1. High-energy α-decays before & after ^{214}Pb
2. Spectral fit at energies above WIMP ROI

Isotope	Activity [μBq/kg]
^{222}Rn (α)	4.37 ± 0.31 (stat)
^{218}Po (α)	4.51 ± 0.32 (stat)
^{214}Pb (β)	**3.26 ± 0.13(stat) ± 0.57(sys)**
^{214}Po (α)	2.56 ± 0.21 (stat)





Extrapolating these numbers to the WIMP ROI requires knowledge of β **shape*** and **branching ratio**

* **SJH**, Kostensalo, Mougeot, Suhonen, Phys. Rev. C **102**, 065501

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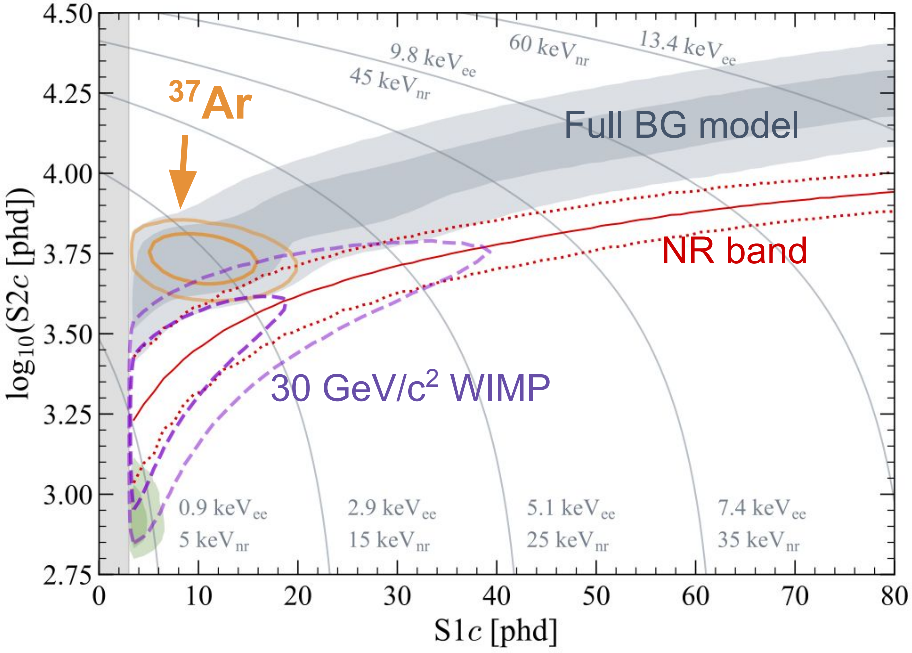
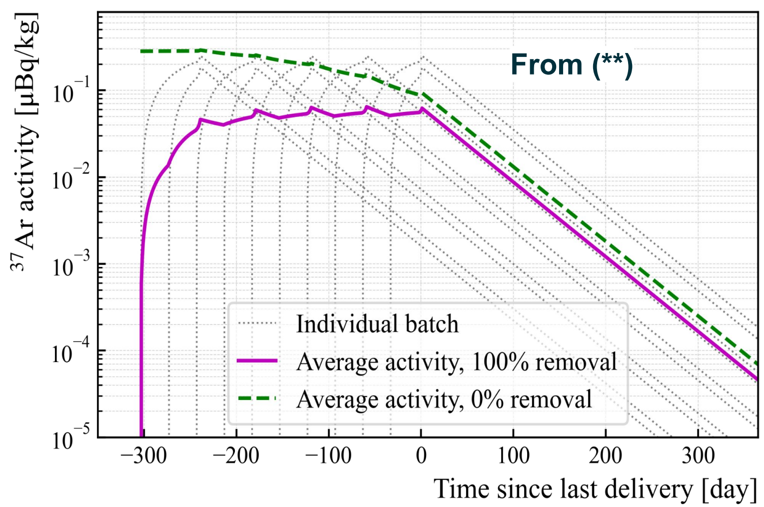
^{37}Ar Background





Electron capture, **$T_{1/2}$ = 35 days**

Capture from **K-shell** releases **2.8 keV**

Component in raw xenon stock purified away by chromatography BUT:

Cosmic-ray spallation on xenon produces ^{37}Ar continuously**…

Decay begins once xenon moves underground

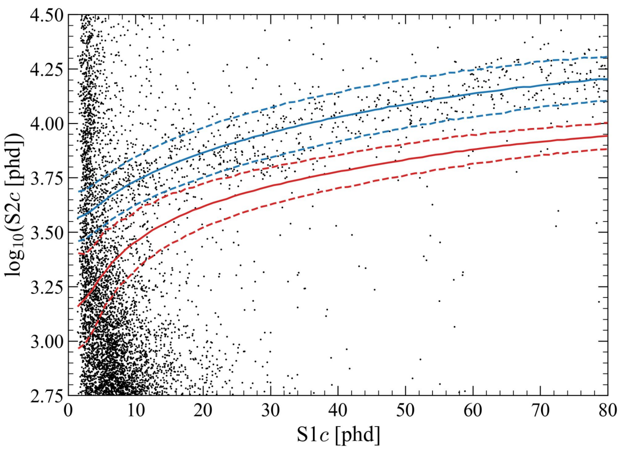
Predict 100 ^{37}Ar events in SR1 using spallation model & Xe transport schedule

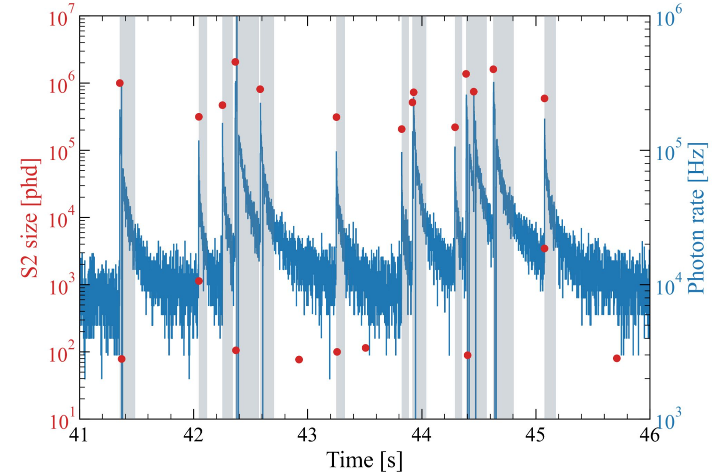
Large theoretical uncertainties

** LZ Collaboration, Phys. Rev. D **105**, 082004

Data Quality

Events in the fiducial volume before pulse-based cuts





Time-based cuts

remove periods of high rate from instrumental effects

impacts **total livetime** in search

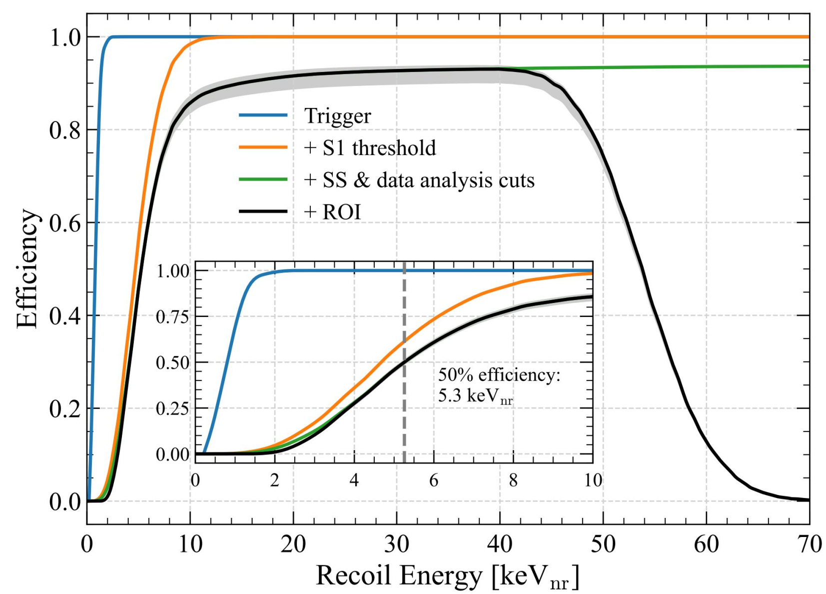
largest contributor from post-S2 hold off, 70% live fraction

Pulse-based cuts

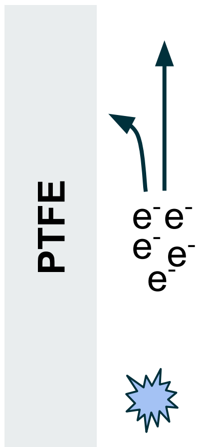
Target coincident pile-up of S1s and S2s

Cuts on pulse shape, timing, distribution in PMTs, etc

signal acceptance evaluated using **tritium** and **AmLi** calibration data



Fiducial Volume & Veto Cuts



Charge loss near detector wall degrades S2 size → Radial position resolution is degraded & background leaks in

=> S2 (electron) threshold and fiducial volume are chosen together to **expect negligible background** from wall events

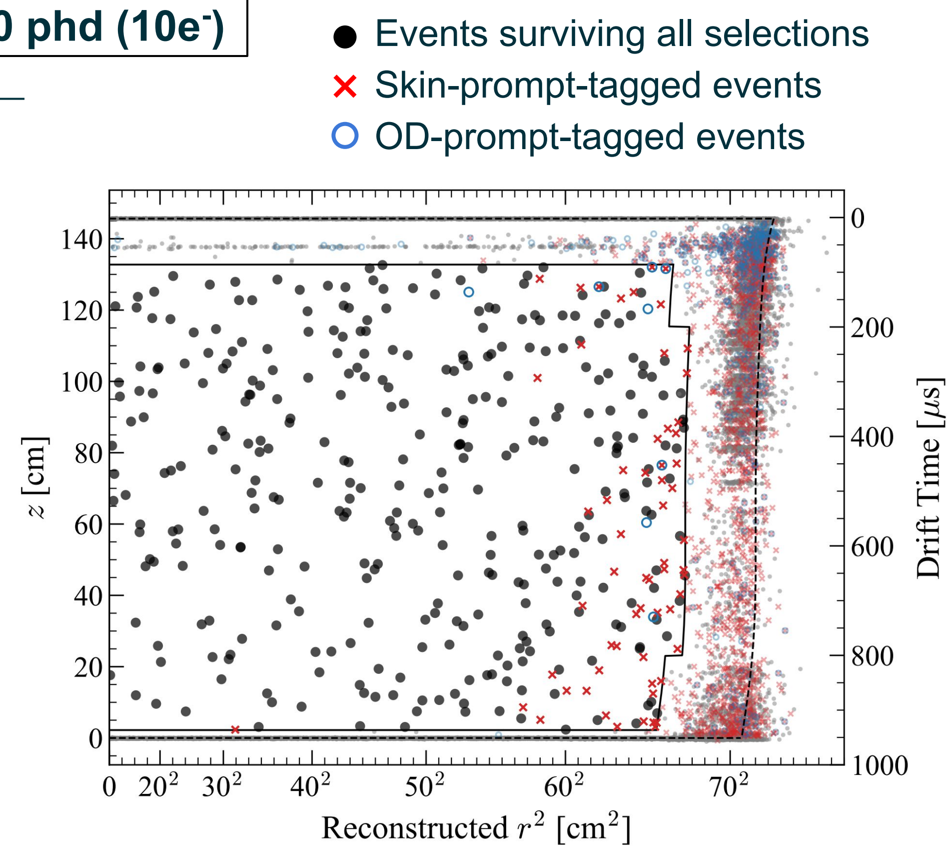
Fiducial mass used here is **5.5 tonnes**

S2 analysis threshold is 600 phd ($10e^-$)

Veto tags with two windows:

1. Prompt - removes gammas and ^{127}Xe EC+gamma events
2. Delayed - tags neutrons capturing in OD: 1200 μs, 200 keV

   → Delayed tagged sample provides *in situ* sideband on neutron background
   - Post fit prediction is **$0.0^{+0.2}$ evts**



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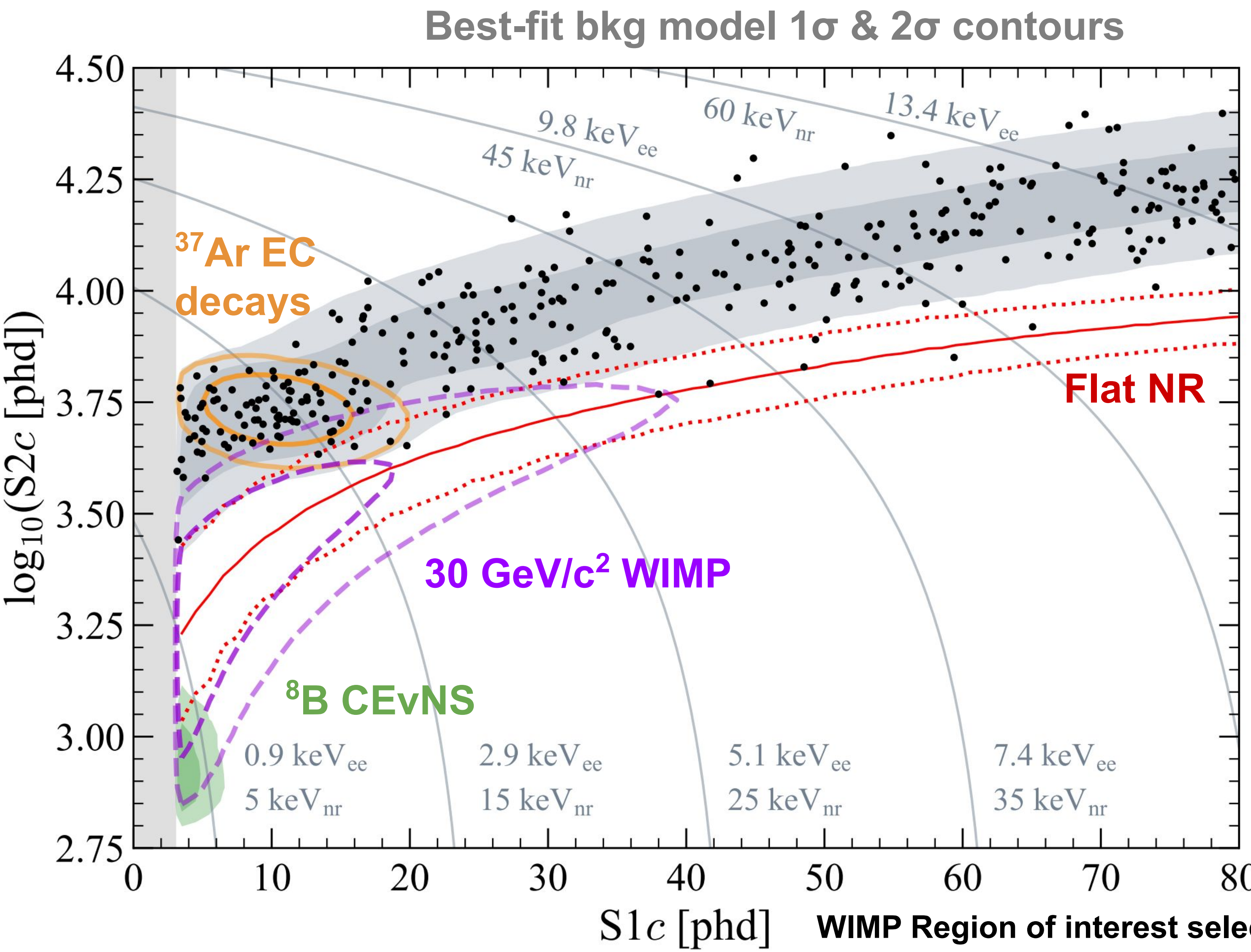
Final Dataset

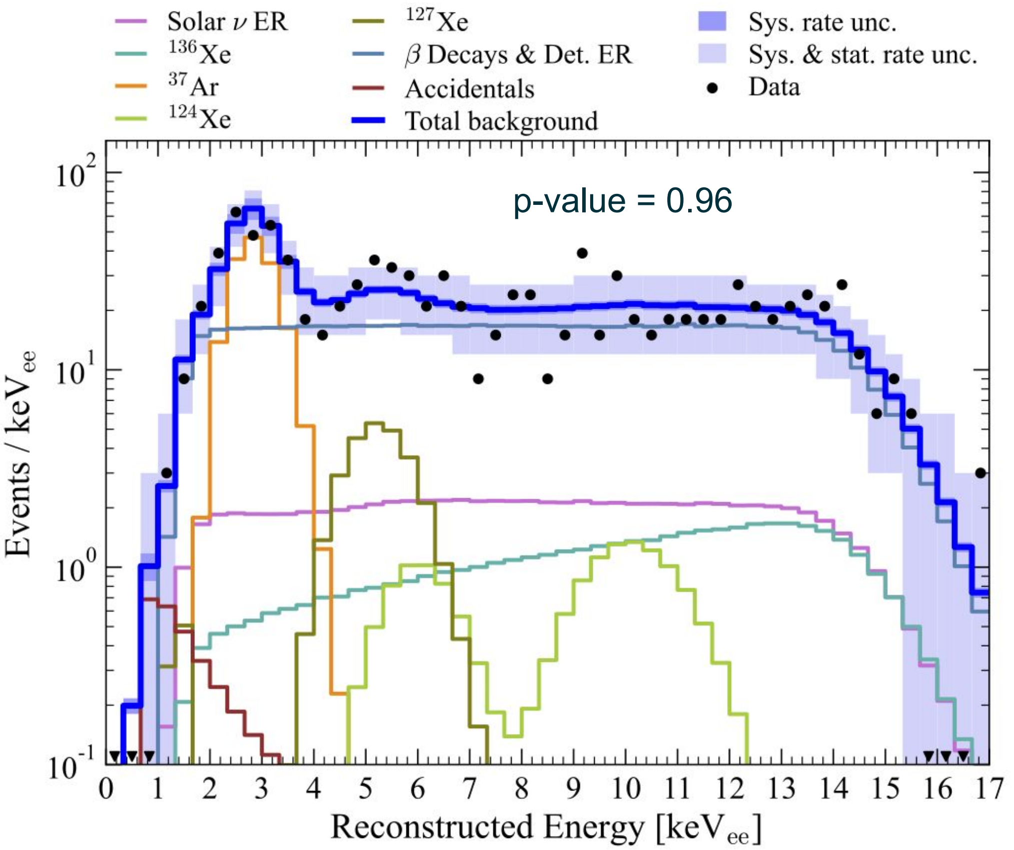
335 events
60 ± 1 live days
5.5 ± 0.2 tonne FV



WIMP Region of interest selection:
3 phd < S1c < 80 phd; S1 coincidence ≥3
S2 > 600 phd (10 e^-)
S2c < 10^5 phd

Final Dataset - Fit Results

Source	Expected Events	Fit Result
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



Best-fit number of WIMPs is **zero** across all masses

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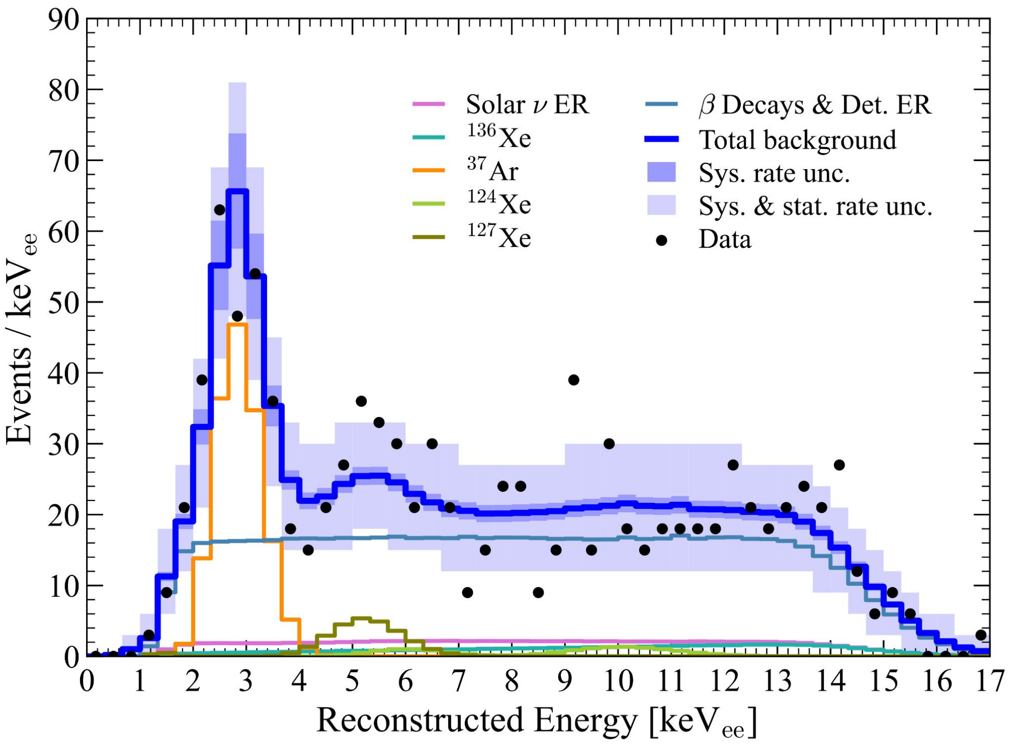


Best-fit number of WIMPs is **zero** across all masses arXiv:2207.03764

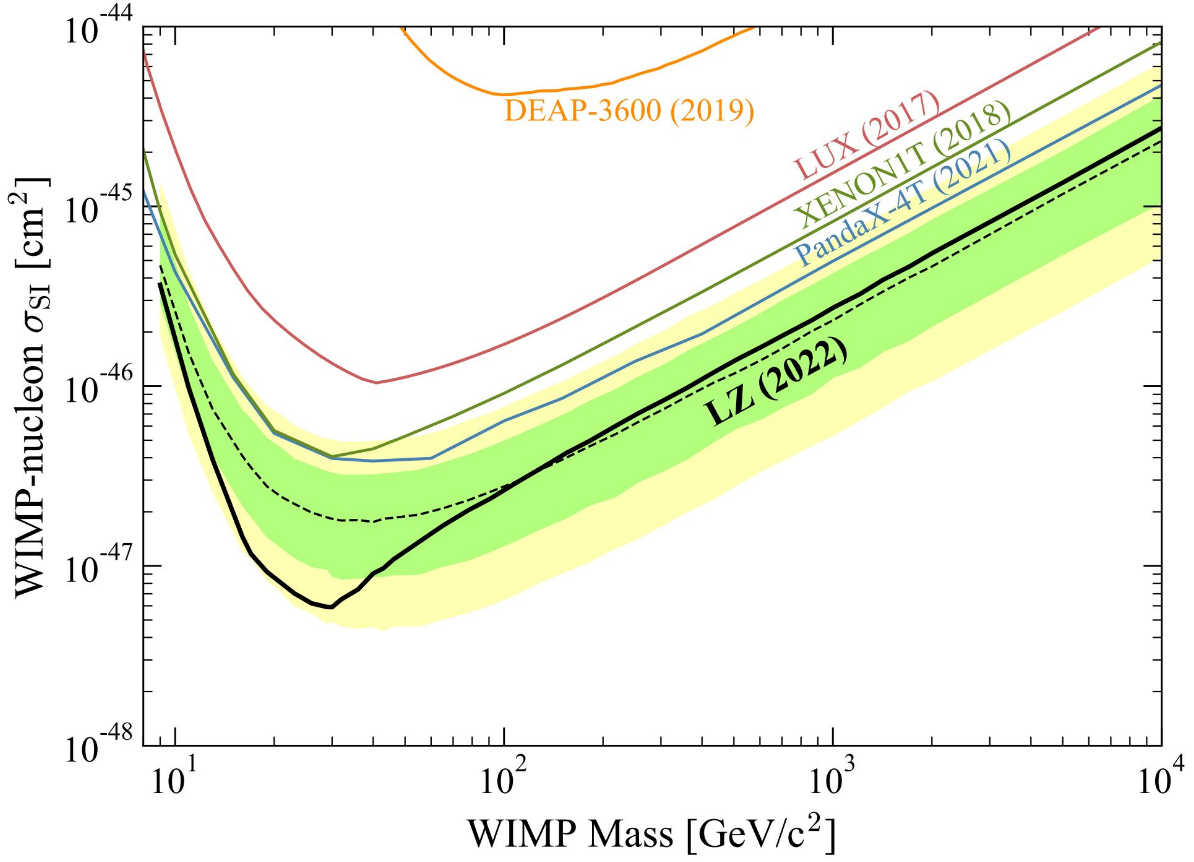
World-leading spin-independent limit

Frequentist, 2-sided profile likelihood ratio test statistic

Toy MC used to construct TS distributions

Limit is power constrained @ discovery power of 0.32 as agreed in

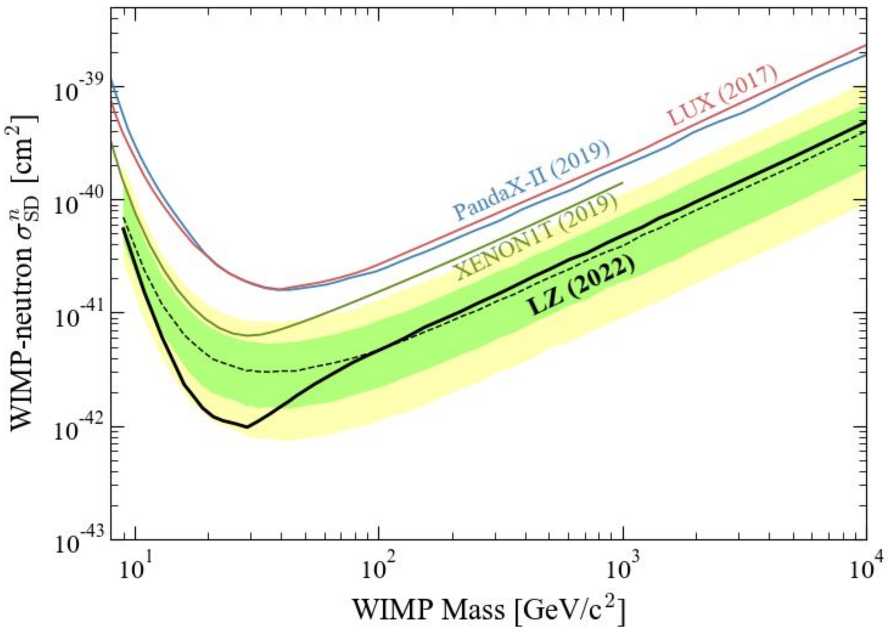
Eur Phys J C (2021) 81:907



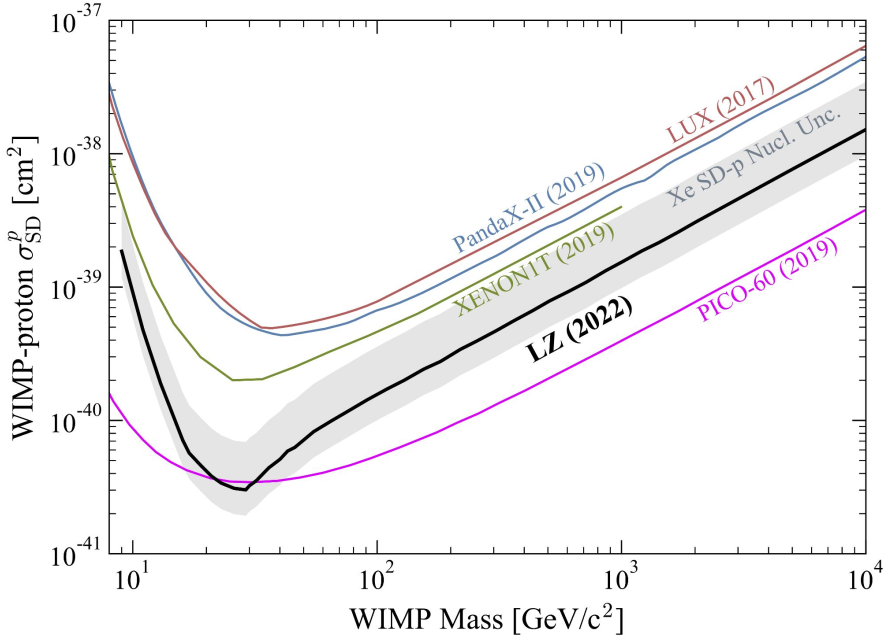
Leading 90% CL UL is **5.9 x 10^{-48} cm^2 @ 30 GeV/c^2 WIMP mass**

Spin Dependent Limits

Spin-dependent WIMP-neutron scattering



Spin-dependent WIMP-proton scattering



Uncertainty band represents theoretical uncertainty on nuclear form factor for Xe

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Summary & Outlook

- **LZ is currently running and collecting high quality data**
- **LZ has world-leading limits on WIMP-nucleon scattering**
- **More science running to come this year**
- **Many more physics analyses to come with LZ's data**
  ER searches: Solar ν MM, ALPs, Migdal, …

  WIMP EFT

  Lowering S1+S2 thresholds/accidentals: ^{8}B CEνNS

  Double-weak processes (ECEC, $0\nu\beta\beta$)

  …

Paper and data release found at arXiv:2207.03764

XLZD Consortium - Towards the ultimate xenon detector

The **XLZD Consortium:** XENON + LZ + DARWIN

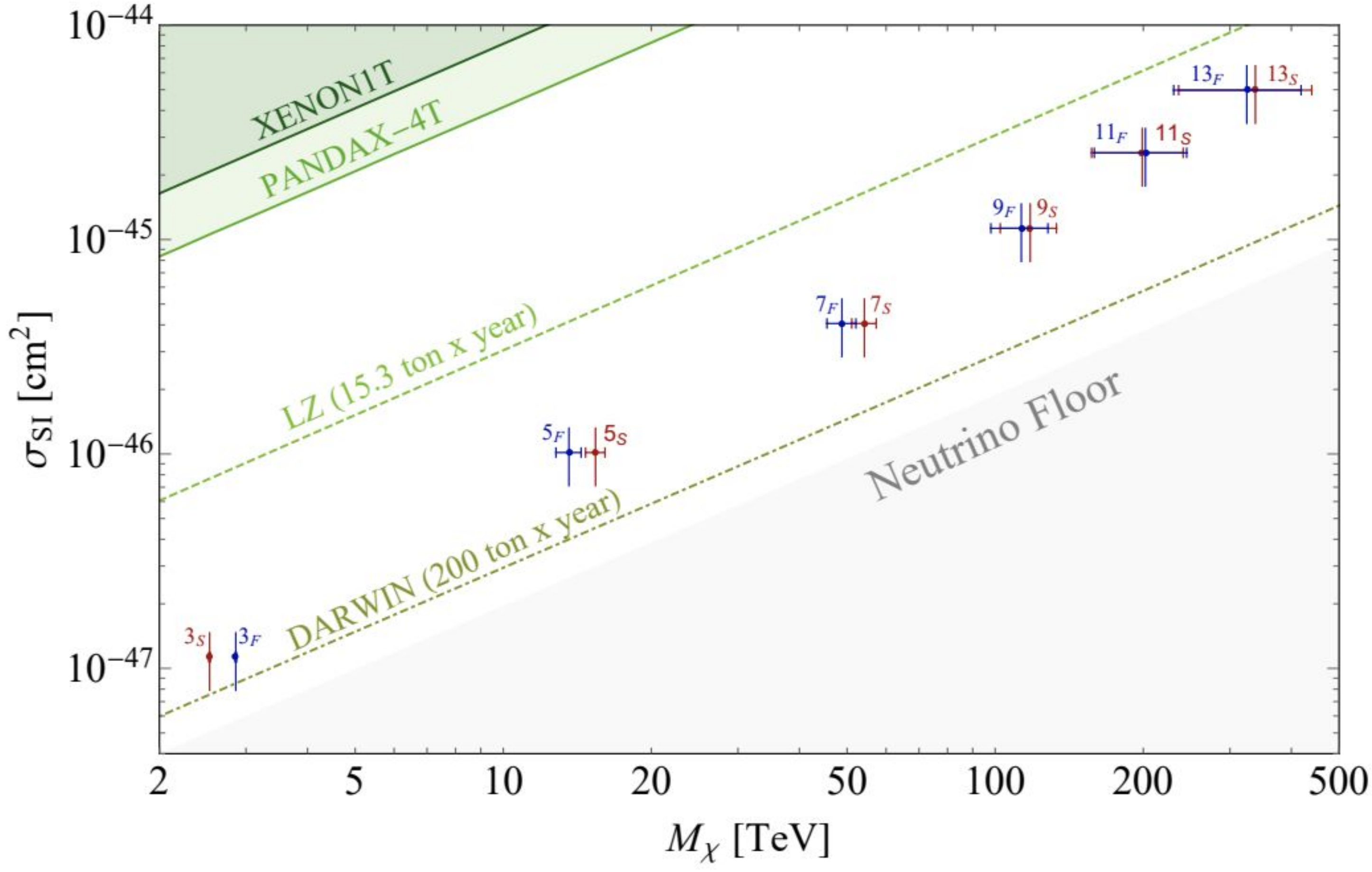
https://xlzd.org/

White Paper: arXiv2203.02309

First meeting June 2022

XLZD Consortium - Towards the ultimate xenon detector

Parameter space down to the neutrino floor is prime WIMP hiding place: arxiv2107.09688



Thank you!

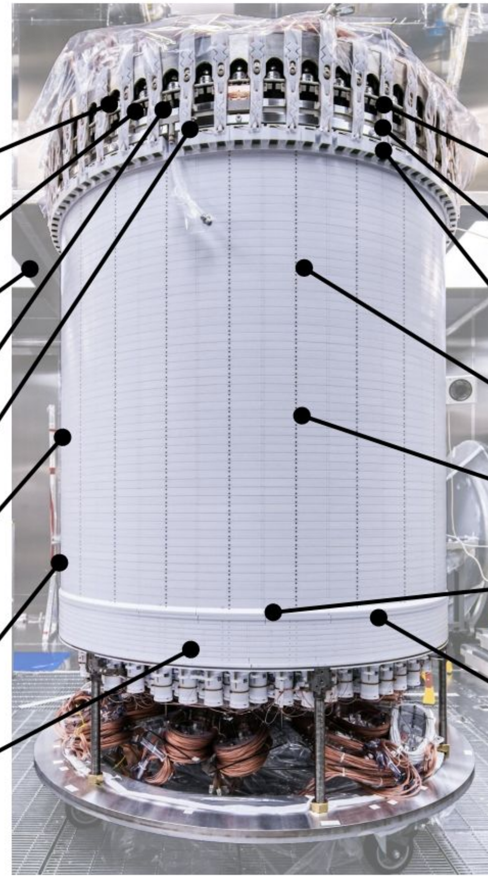
Supporting Slides

S1 and S2 Sources

S1-only sources:

- PMT dark count pile-up
- Above-anode events
- Light leaks from outside TPC
- Radioactivity from grid wires
- Cherenkov from PMT windows
- Fluorescence of PTFE
- Charge loss events near TPC walls
- Reverse Field Region events

Rate of O(1 Hz) after cuts



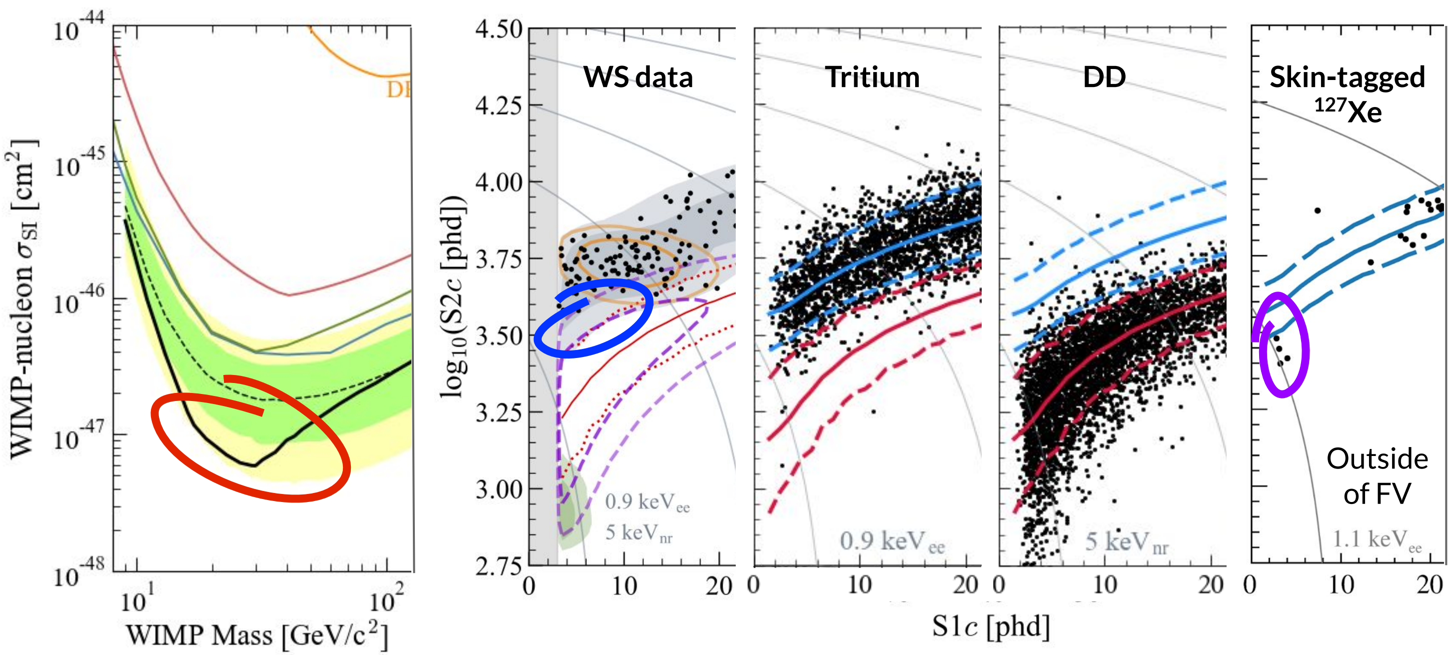
S2-only sources:

- Above-anode events
- Extraction region gas events
- Near liquid surface events
- Sub-S1 threshold ER events
- Electrons in S2 tails
- Radon daughters from cathode
- Electron emission from grids

Rate of O(10^{-3} Hz) after cuts

credit: I. Olcina

Power Constraint at 30 GeV



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.

Best fit model in 'discrimination' projection

p = 0.33