LUX-ZEPLIN (LZ) Status and Results

Lake Louise Winter Institute 2023

Lake Louise, Canada

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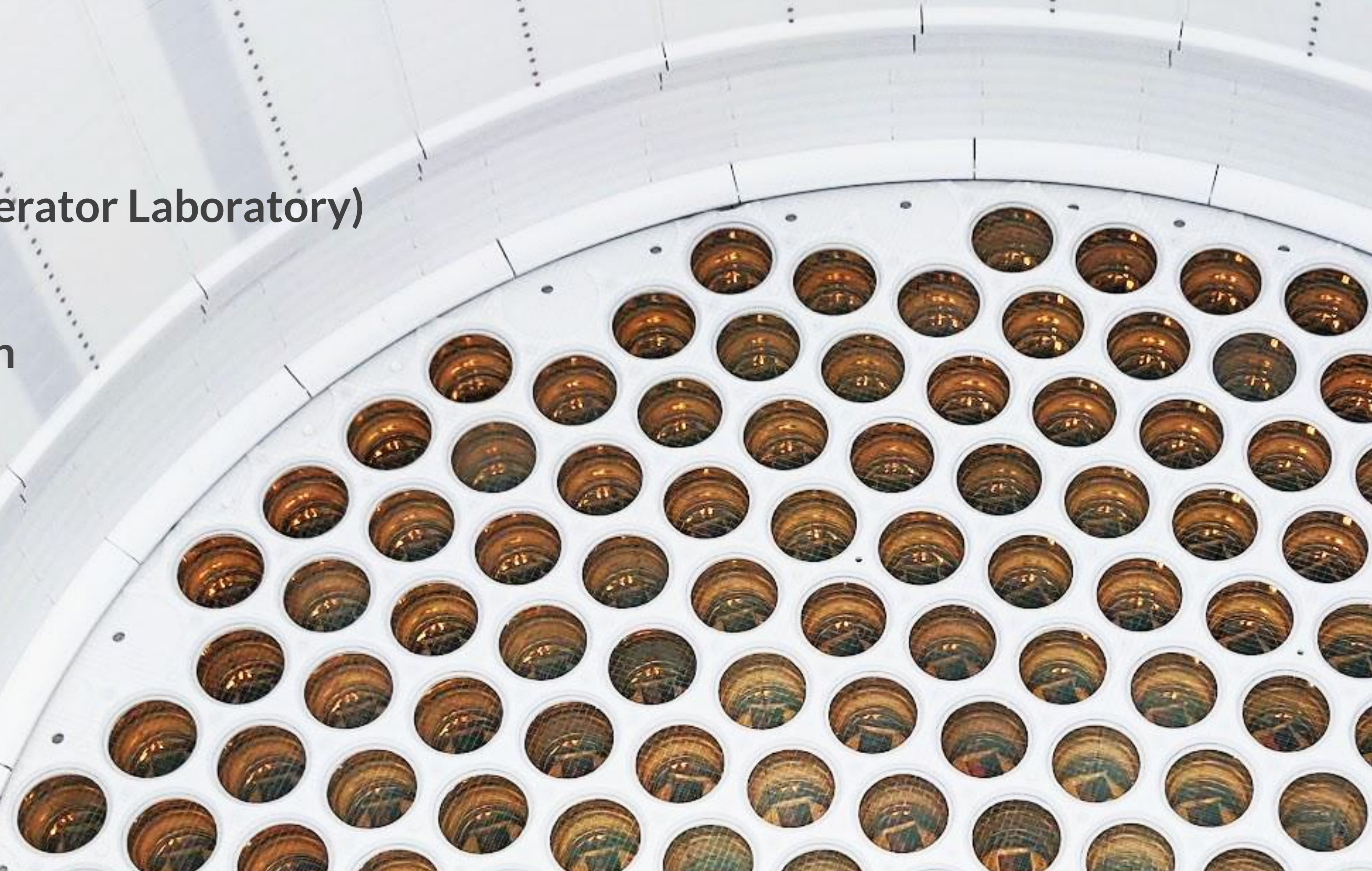
On behalf of the LZ collaboration

21 Feb 2023



SLAC NATIONAL ACCELERATOR LABORATORY

LUX-ZEPLIN (LZ) collaboration

- 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 Wisconsin, Madison

US UK Portugal Korea Australia

A. Fan

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

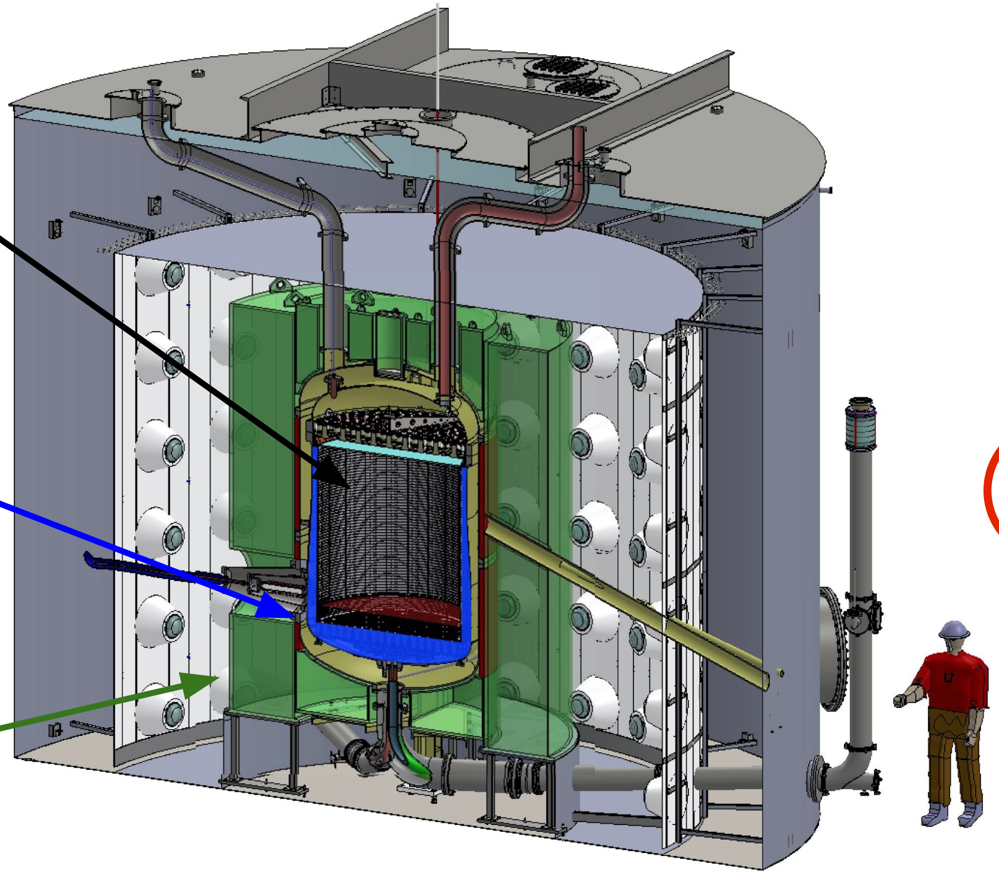
LZ

Dark matter detector

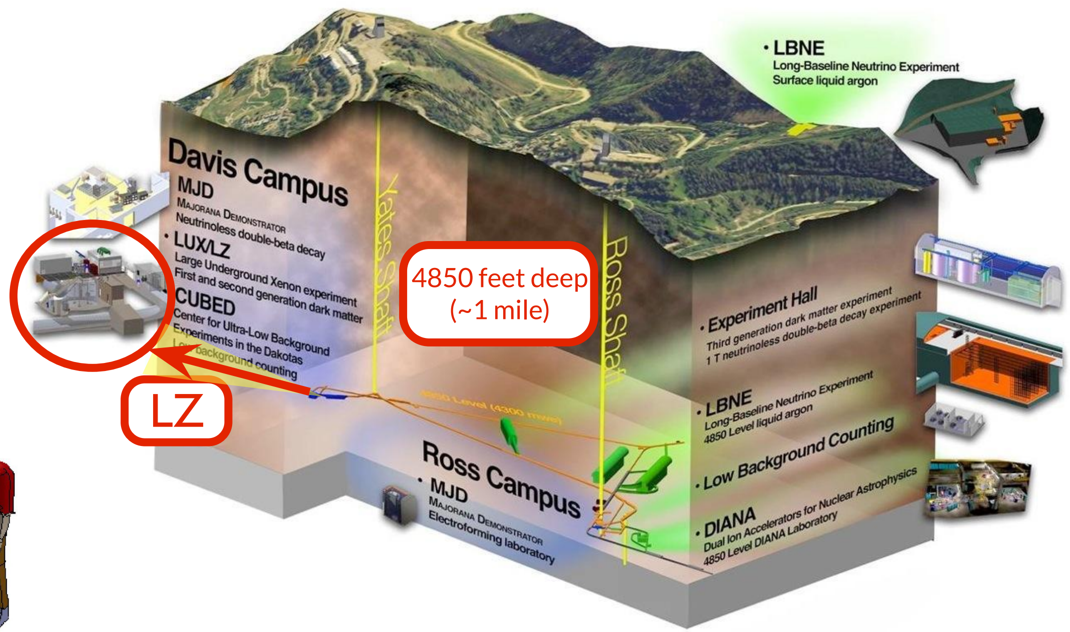
Dual-phase xenon Time Projection Chamber (TPC)

Liquid xenon "Skin" detector

Gadolinium-loaded liquid scintillator outer detector



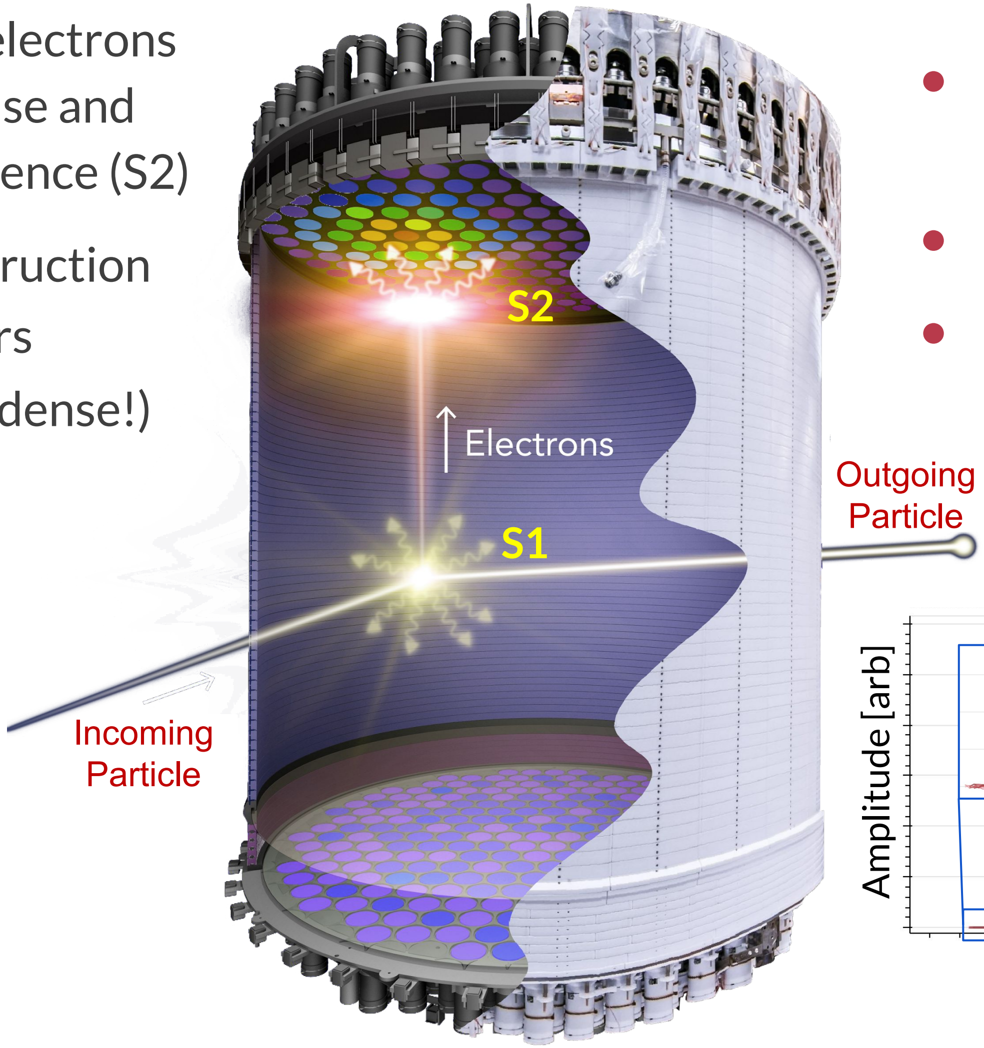
Located 4850 ft underground at Sanford Underground Research Facility (SURF) in South Dakota, USA



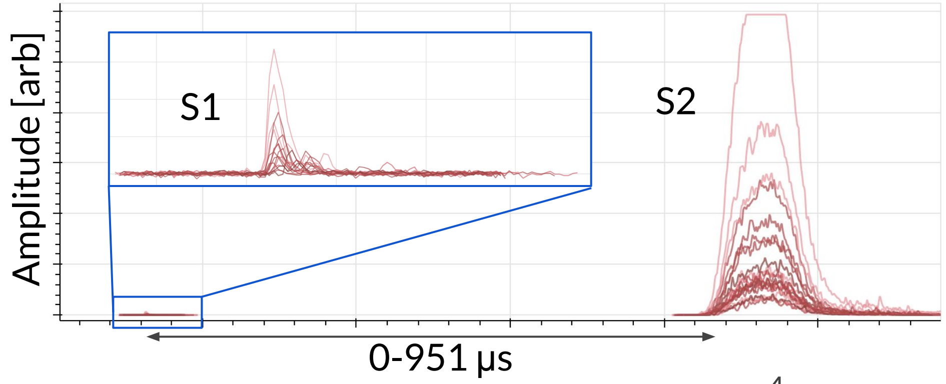
NIM A 163047 (2020)

Dual-phase xenon TPC

- Detection principle:
  - Interactions produce scintillation light (S1) and ionization electrons
  - Electrons drift to gas phase and produce electroluminescence (S2)
- Excellent 3D position reconstruction
  - Single vs. multiple scatters
  - Self-shielding (+xenon is dense!)
- Energy reconstruction
- Particle ID from S2/S1 ratio
  - Dominant BGs produce electron recoils (ER)
  - WIMPs produce nuclear recoils (NR)



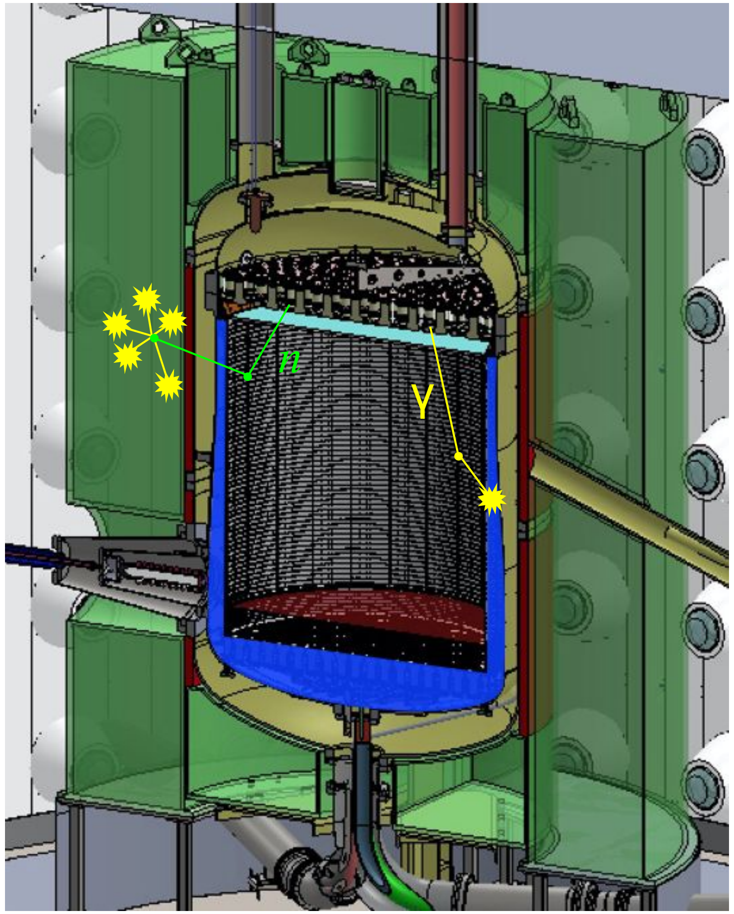
- 1.5 m ∅ x 1.5 m height
- 7 tonne active LXe (5.5 tonne fiducial)
- PTFE everywhere for efficient light collection
- 494x 3” PMTs in two arrays
- 4 wire mesh electrodes + Ti field cage for uniform electric fields
  - Bottom, cathode, gate, anode



LXe Skin and Outer Detector

The Skin

- 2 tonnes of LXe surrounding the TPC
- 1” and 2” PMTs at the top and bottom of the skin region
- Lined with PTFE to maximize light collection efficiency
- Optically isolated from TPC
- Anti-coincidence detector for γ-rays



The OD

- 17 tonnes Gd-loaded liquid scintillator in acrylic vessels
- 120 8” PMTs mounted in the water tank
- Anti-coincidence detector for γ-rays and neutrons
- Observe ~8 MeV of γ-rays from thermal neutron capture on Gd, 2.2 MeV γ-ray from capture on H

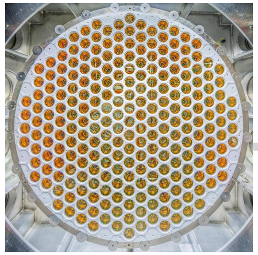
- Tag individual neutrons with ~89% efficiency
- Characterize backgrounds *in situ*

→ **Enables discovery potential!**

Phys. Rev. D 101, 052002 (2020)

Timeline

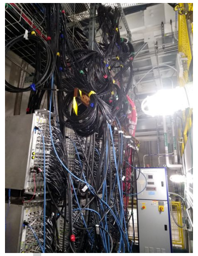
PMT arrays arrive
Dec 2018, Jan 2019



TPC complete
Aug 2019

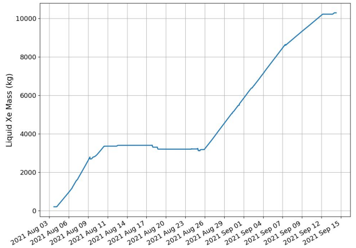
TPC underground
Oct 2019

Electronics
Fall 2020



Kr removal
Jan-Aug 2021

LXe fill
Aug-Sep 2021

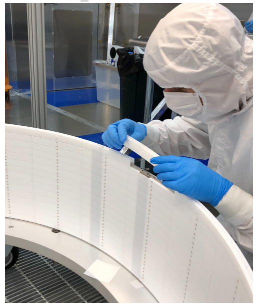


First Results!
Jul 2022

2018 2019 2020 2021 2022 2023

Science
Running!

Cryostat arrives
May 2018



FFR assembly
Dec 2018

Grids complete
Spring 2019

Sealed up
March 2020

OD construction
Winter 2020-2021

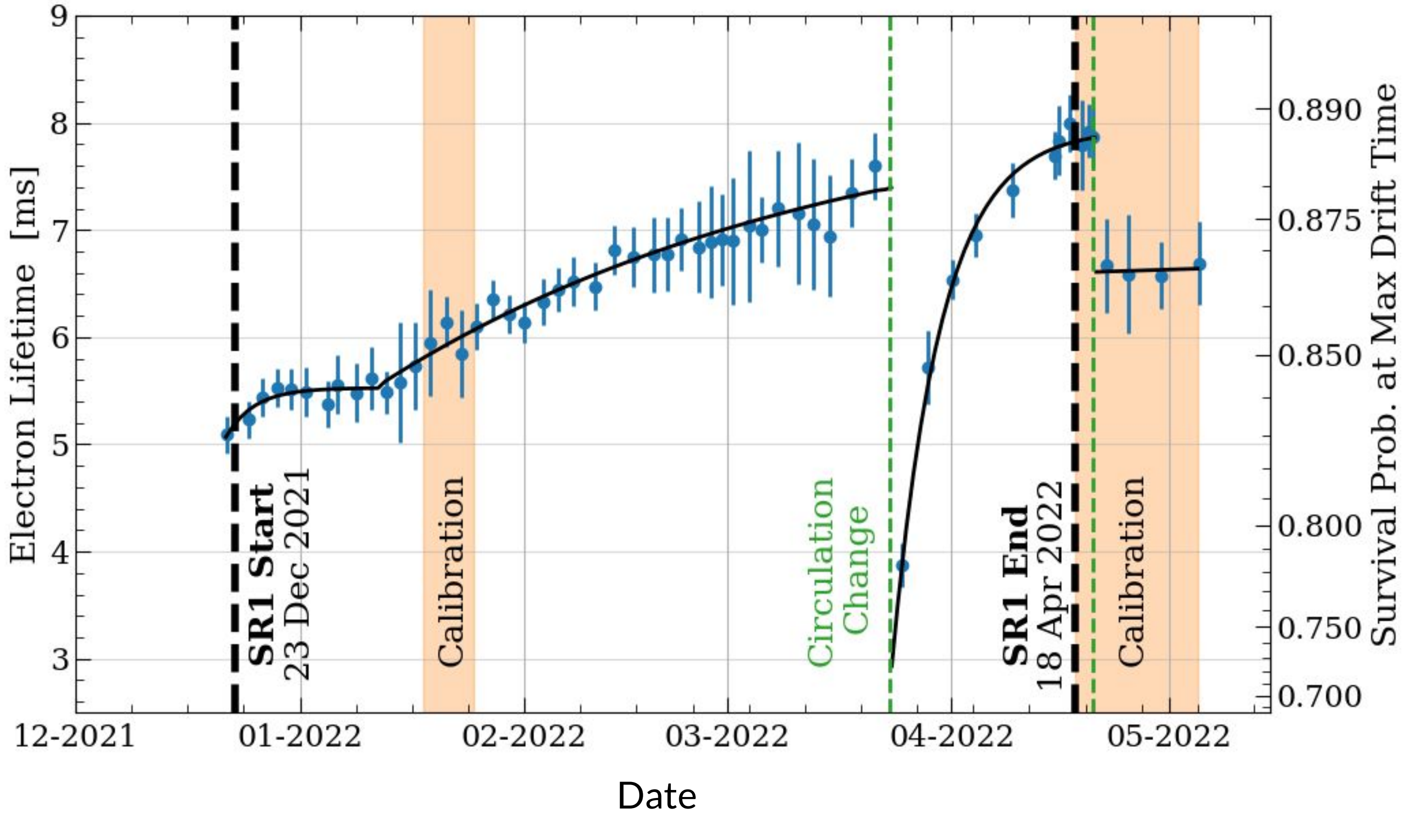
OD fill
June 2021

Commissioning
Fall 2021

First science run

Goal: Demonstrate **physics capability** of the LZ detector, with expectation of **competitive sensitivity**

- Data taken Dec 2021 to May 2022 → WIMP search with **60 live days**
- Electron drift lifetime of **5-8 ms** during search
- Stable detector conditions:
  - PMTs: **>97%** operational throughout run
  - Gas circulation: **3.3t/day**
  - Drift field: **193 V/cm** (32 kV cathode, uniform to 4% in fiducial volume)
  - Extraction field: **7.3 kV/cm** in gas (8 kV gate-anode ΔV)
- Engineering run → data not blinded or salted



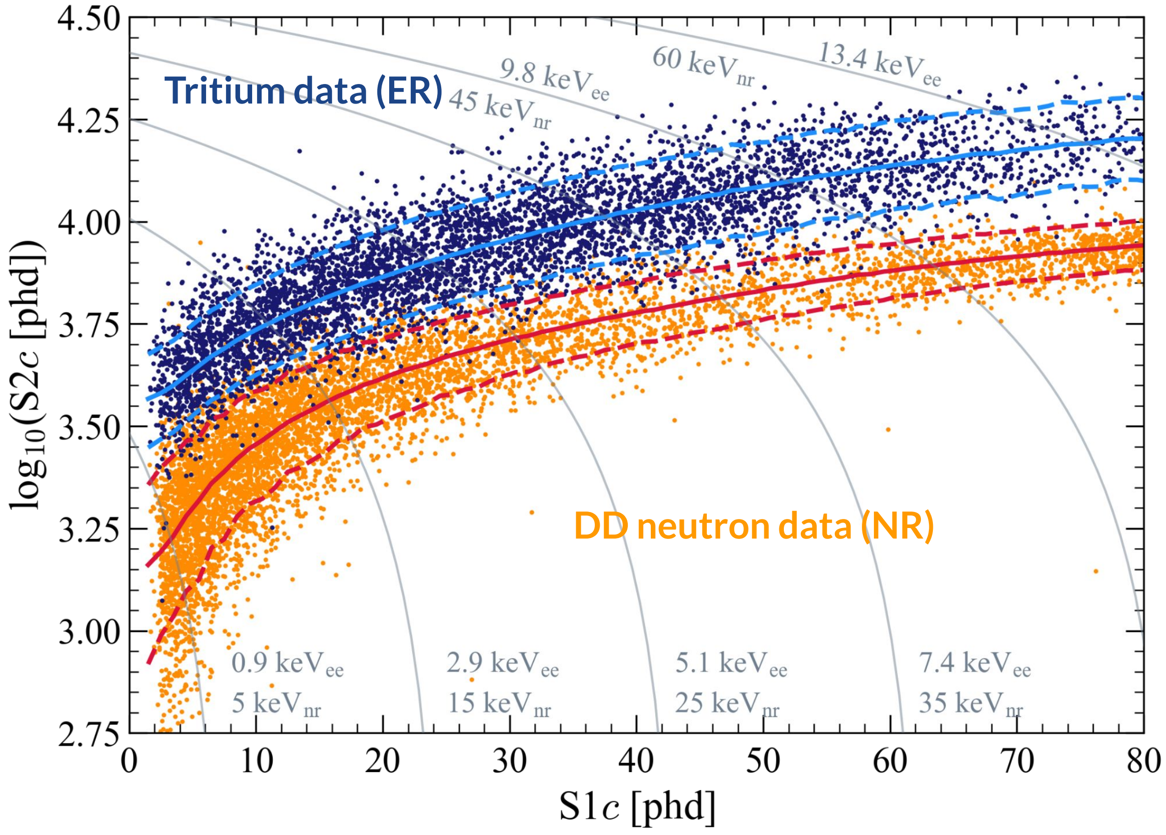
Calibrations

phd = photons detected at each PMT

Comprehensive set of dispersed and external radioactive sources to calibrate detector response of TPC, skin, and OD

Tritium, DD, ^{83m}Kr, ^{131m}Xe, ^{220}Rn, ^{252}Cf, activation lines + more

- Normalize spatial variations in observed S1 and S2
- Light collection efficiency **g1: 0.114** ± 0.002 phd/photon
- Charge gain **g2: 47.1** ± 1.1 phd/electron
- Single electron size: **58.5 phd/e**
- **99.9%** rejection of ERs below the NR median
- OD light yield
- OD neutron tagging efficiency



(*) https://nest.physics.ucdavis.edu/

arXiv:2211.17120

Background model

Total expected **ER** counts in ROI in first run: **276** + [0, 291] from ^{37}Ar

Total expected **NR** counts in ROI in first run: **0.15**

~Flat energy spectra

within ROI

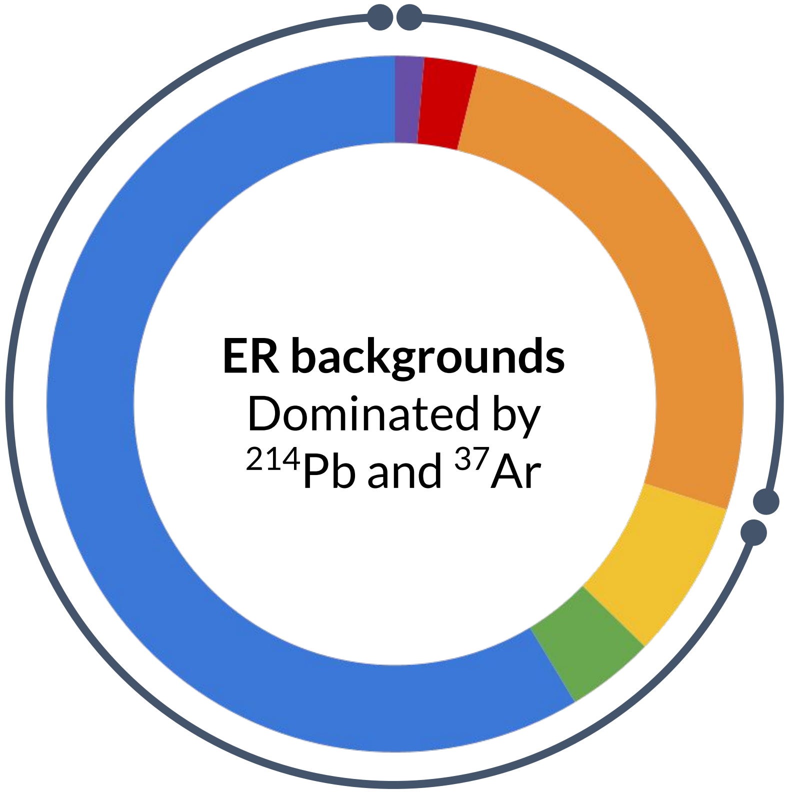
Dissolved radiogenic contaminants

- ^{214}Pb (^{222}Rn daughter)
- ^{212}Pb (^{220}Rn daughter)
- ^{85}Kr

^{136}Xe ($2\nu\beta\beta$)

Solar neutrinos (ER)

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



Mono-energetic spectra

dissolved electron captures

- ^{37}Ar
- ^{127}Xe
- ^{124}Xe (double e-capture)

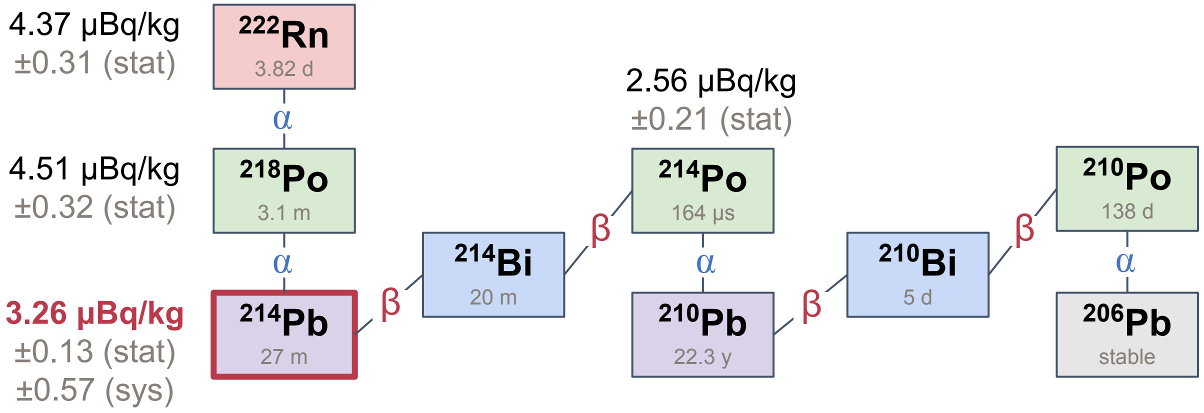
NR backgrounds:

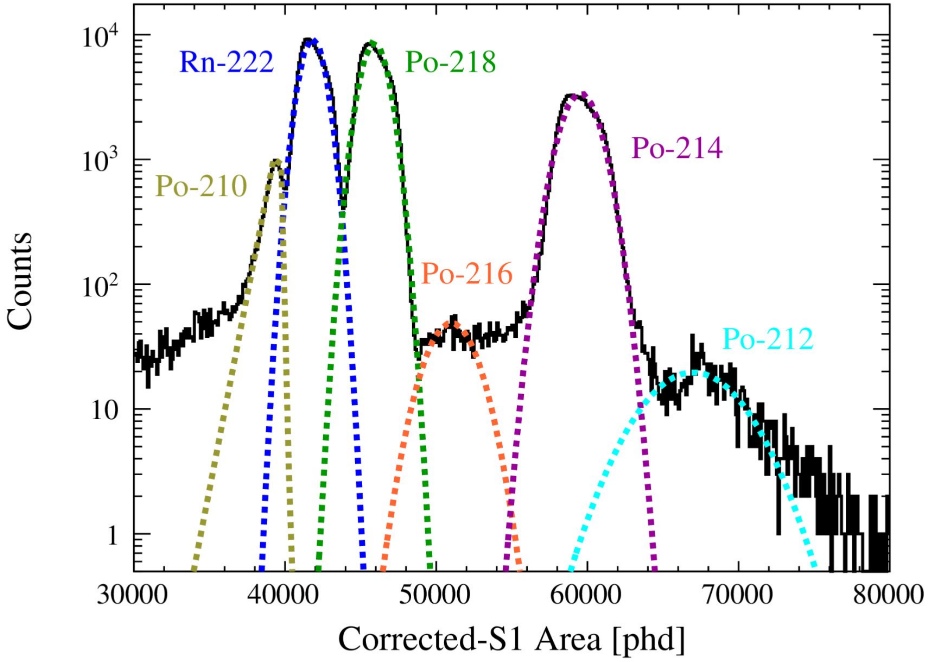
- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar neutrinos

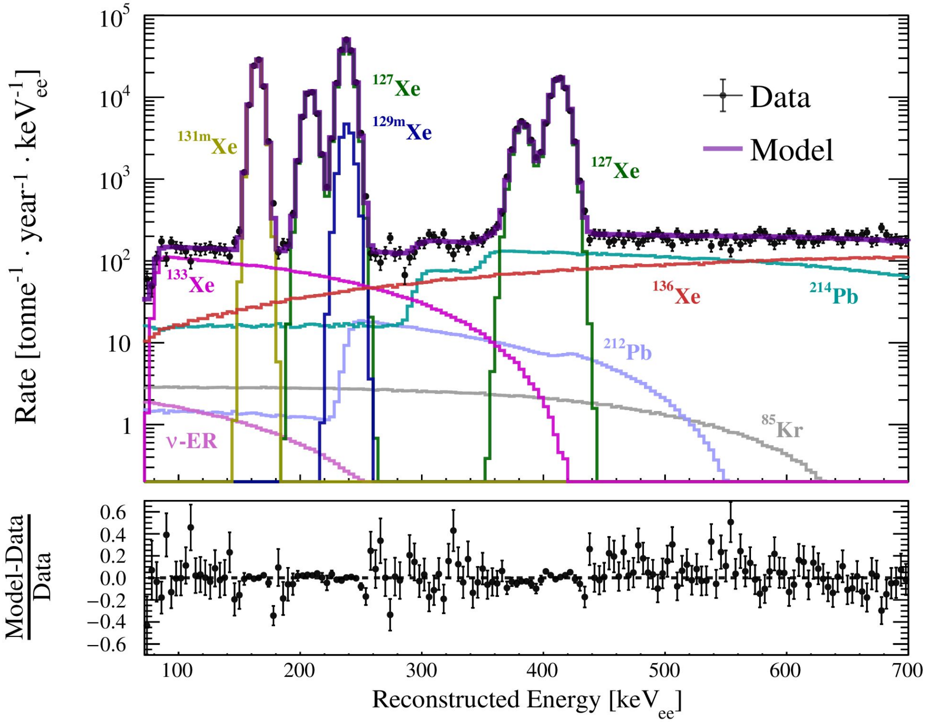
Accidental coincidence of S1 + S2

Background: Radon

- Naked ^{214}Pb β-decays are the main source of background in the WIMP search
- Produced from ^{222}Rn emanated in xenon
- Constrain β-decay rate with multiple methods:
  - Bracket with Rn-chain α tagging
  - Spectral fit of all internal BGs outside of energy ROI
- ^{222}Rn activity within assay expectations

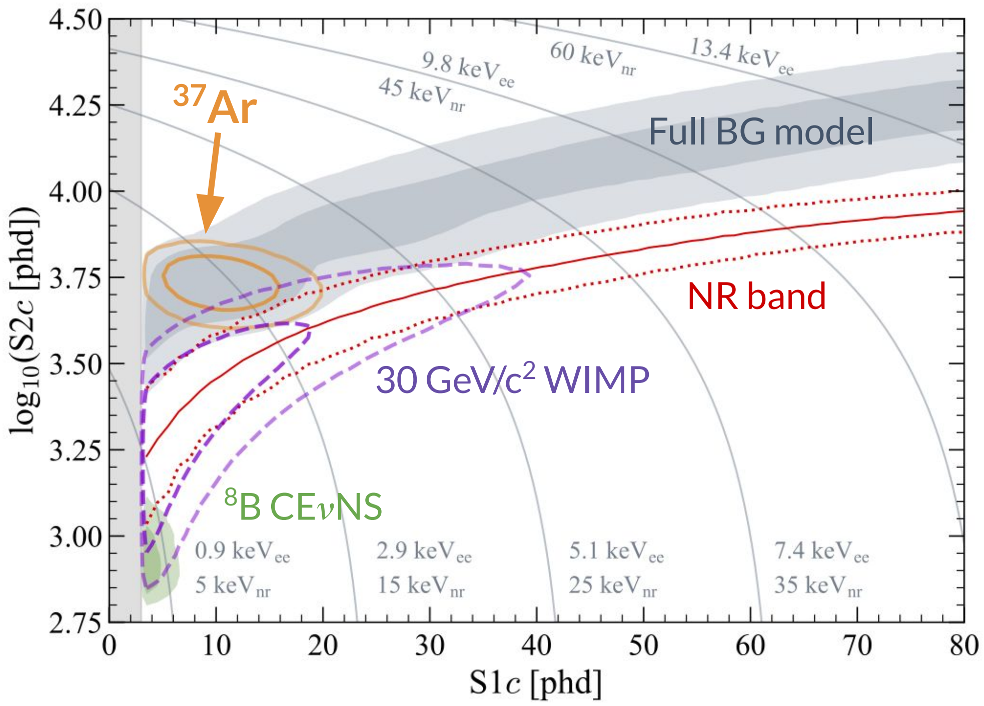


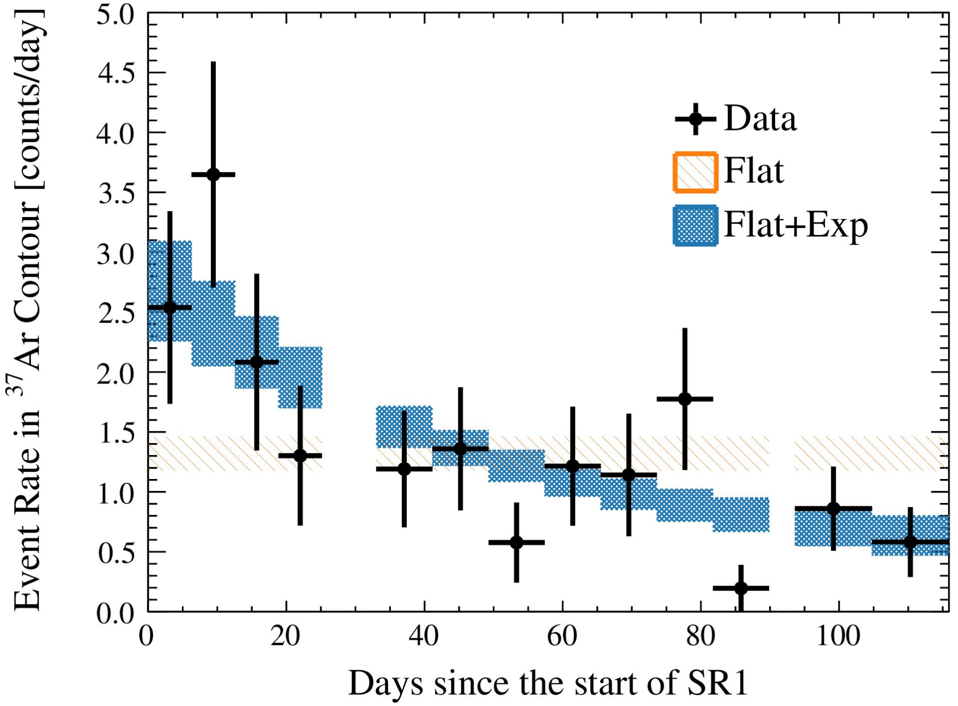




Background: ^{37}Ar

- Electron capture, $t_{1/2}$ = 35 d, monoenergetic 2.8 keV ER deposition
- Occurs naturally in atmosphere via e.g. ^{40}Ca(n,α)^{37}Ar (*), but suppressed during Xe purification by charcoal chromatography
- Also produced by cosmic spallation of natural xenon
- Constrained ^{37}Ar activity based on Xe delivery schedule to SURF (**)
- Expect **~100 decays of ^{37}Ar** in first science run, with a large uncertainty

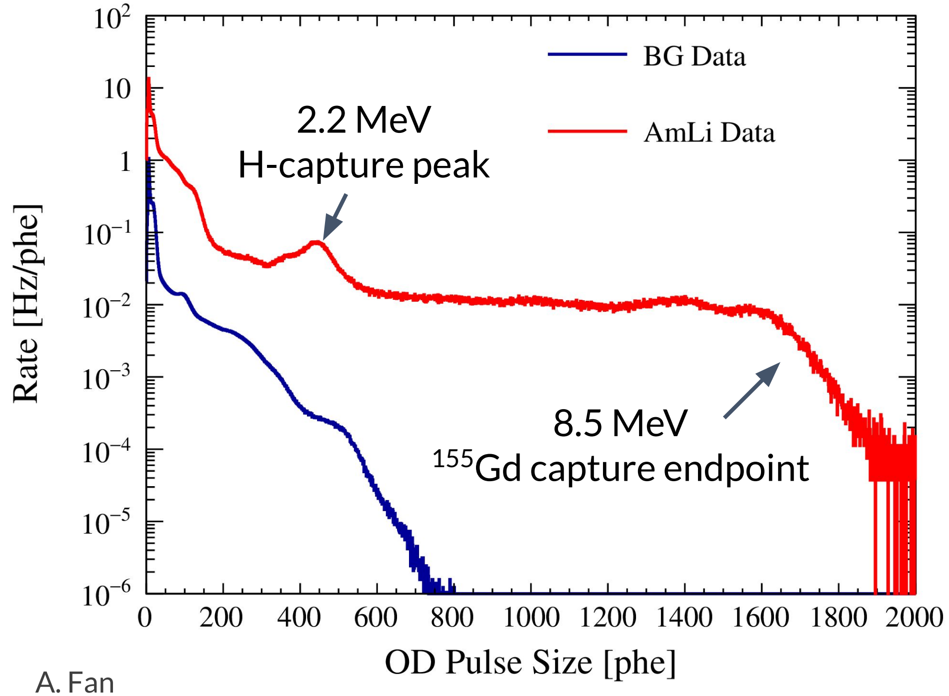


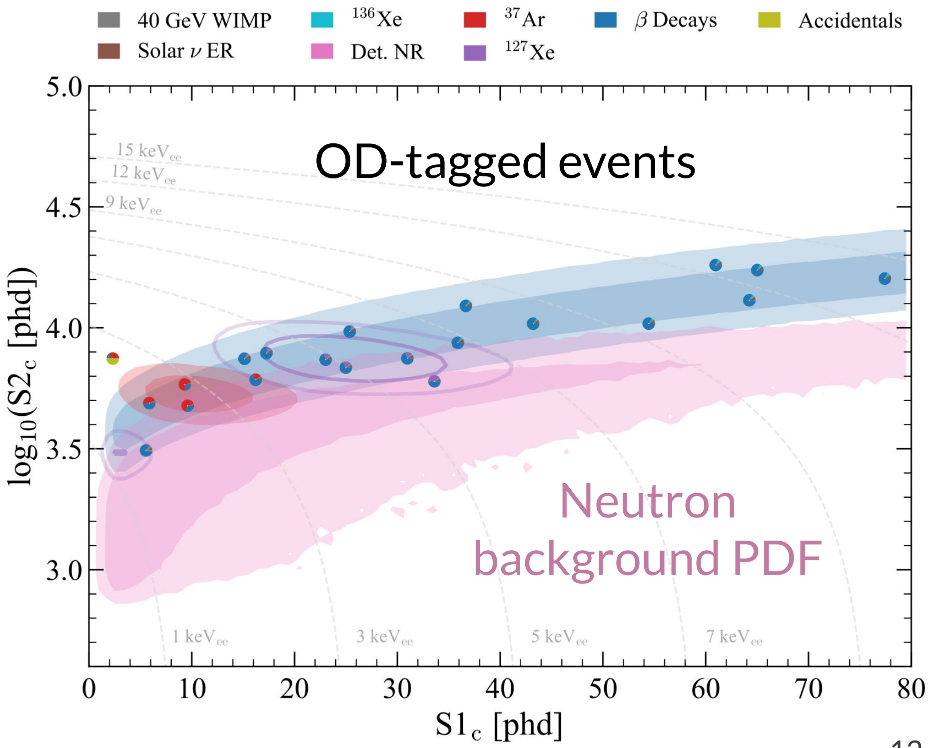


(*) R.A. Riedmann, R. Purtschert, Environ. Sci. Technol. (2011) 45(20), 8656-8664
(**) LZ Collaboration, Phys. Rev. D 105, 082004 (2022), 2201.02858

Background: Neutrons

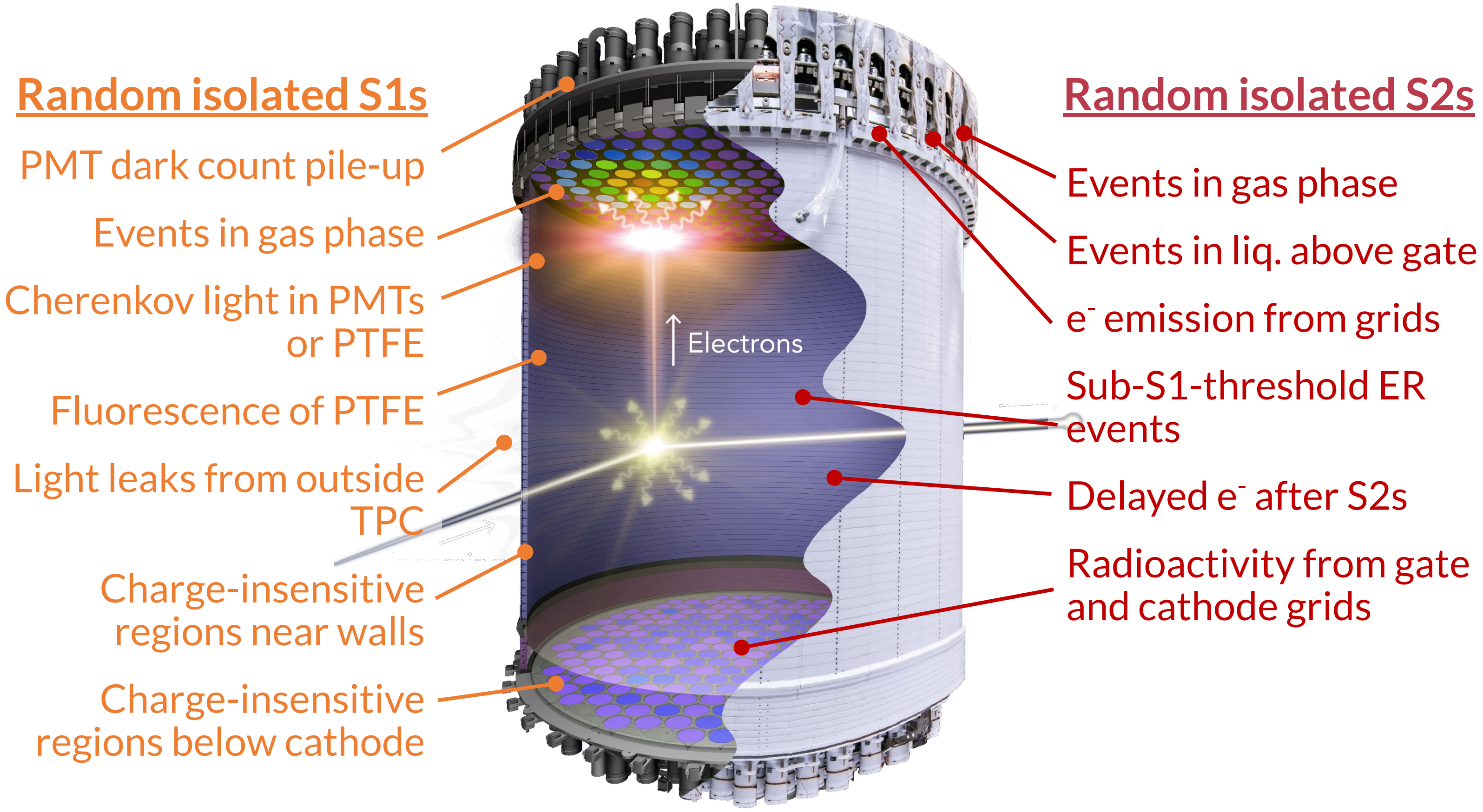
- Neutron captures in the OD produce γ-ray up to 8.5 MeV
- Neutron capture time on Gd: 30 μs
- Measured neutron tagging efficiency: **89±3%**
- *in situ* constraint on neutron background: **$0^{+0.2}$ neutron events**





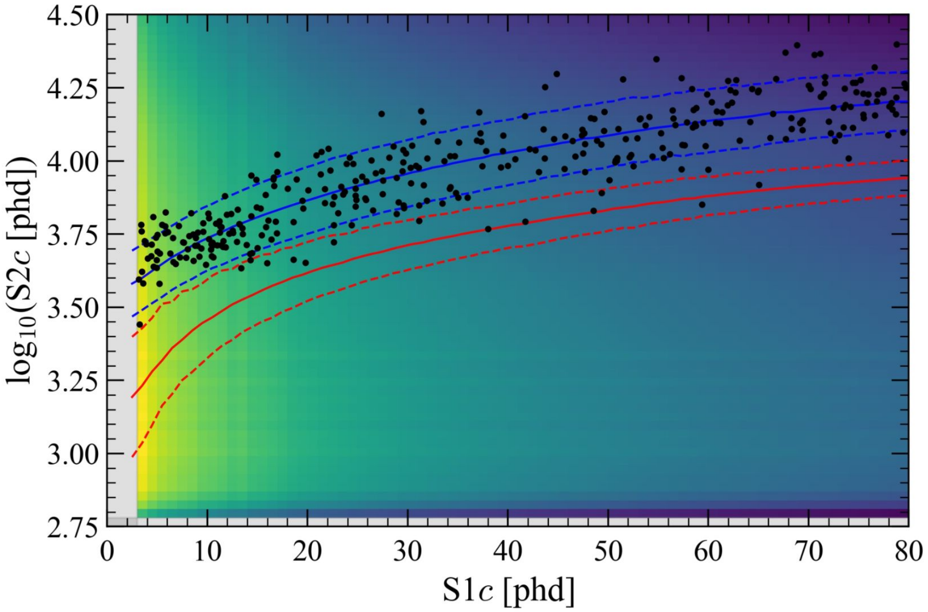
Background: Accidental coincidence events

Accidental pairing of random isolated S1s and S2s mimic real single scatters



Accidentals PDF

derived from bootstrap simulation

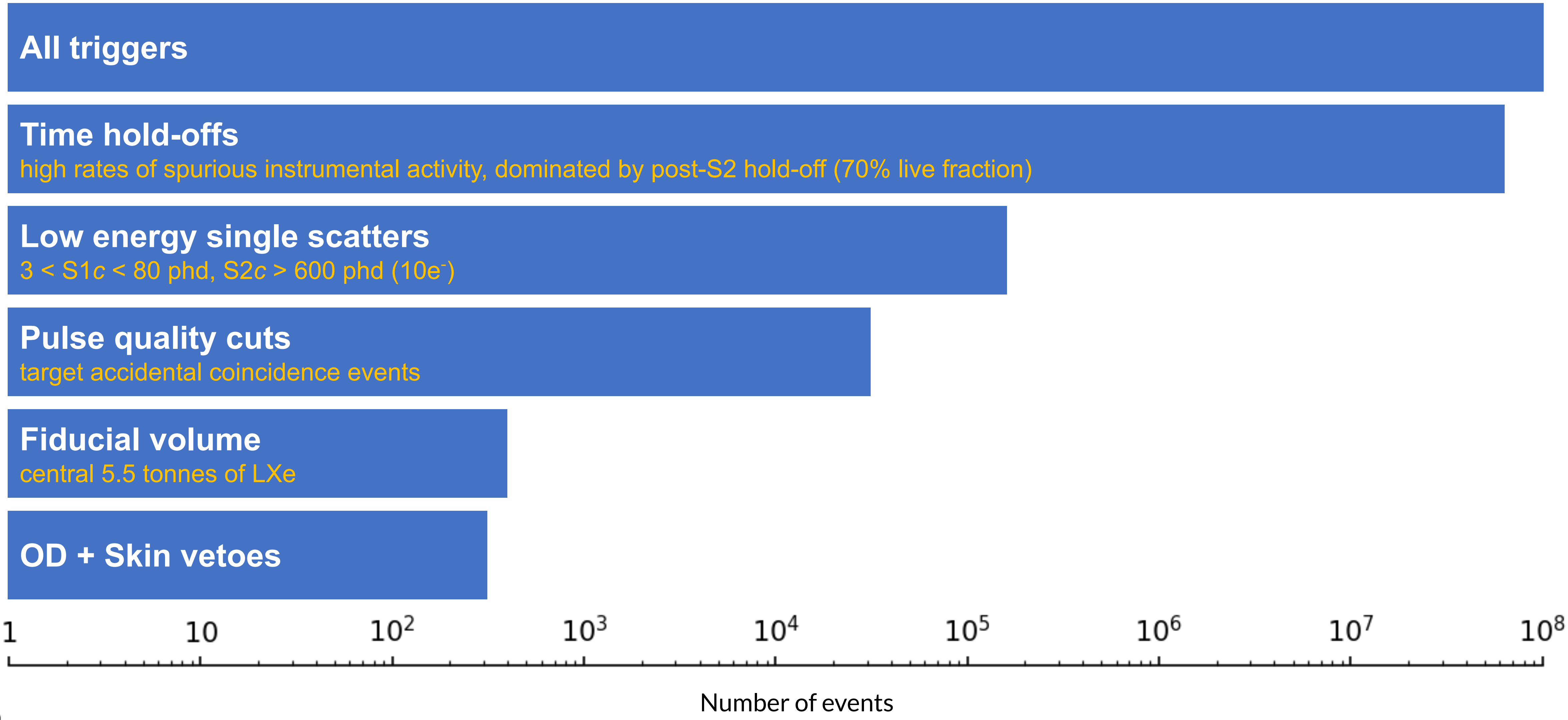


“Remove as much as possible. Model the rest.”

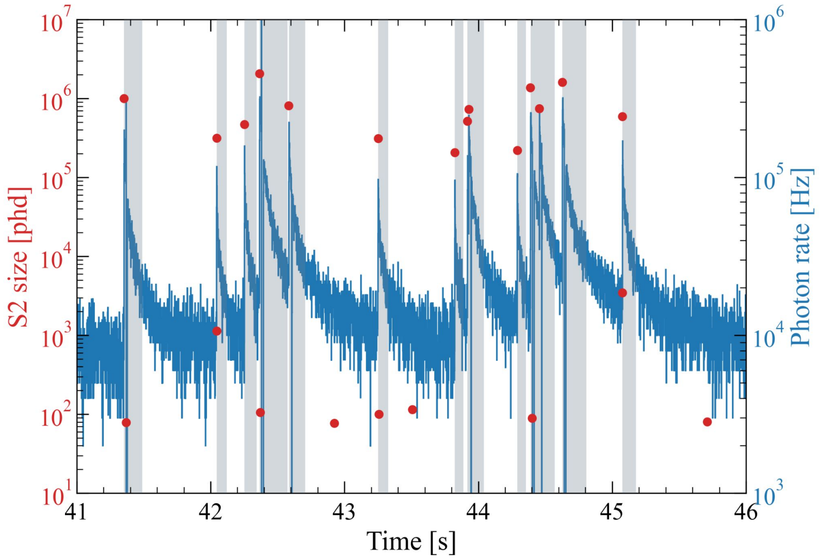
Efficiency of data quality cuts to remove accidentals: **>99.5%**

Data-driven accidentals background: **1.2 ± 0.3 events**

Data selection



Data quality cuts

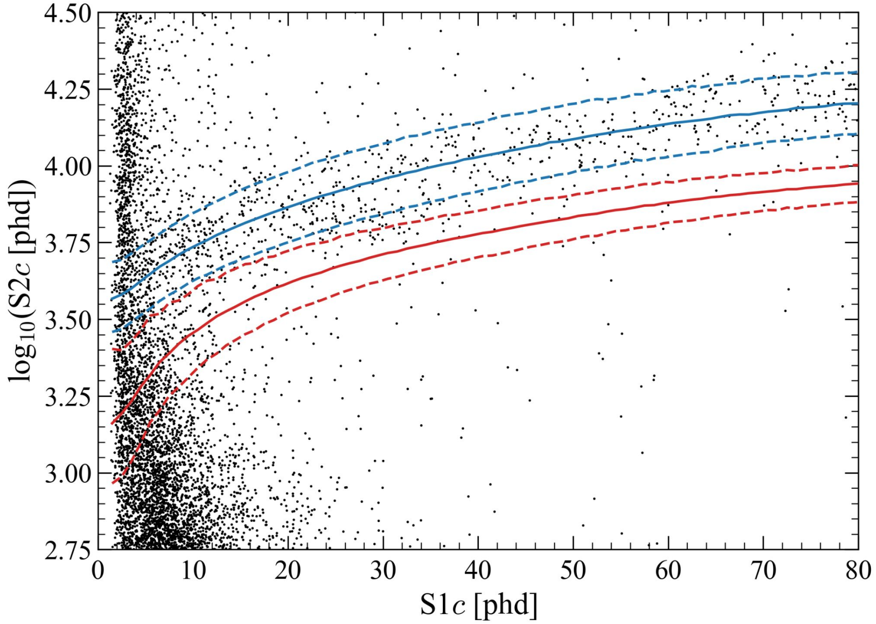


Spurious electrons and photons follow each high energy event (*)

Post-S2 hold-off induces 30% live time loss

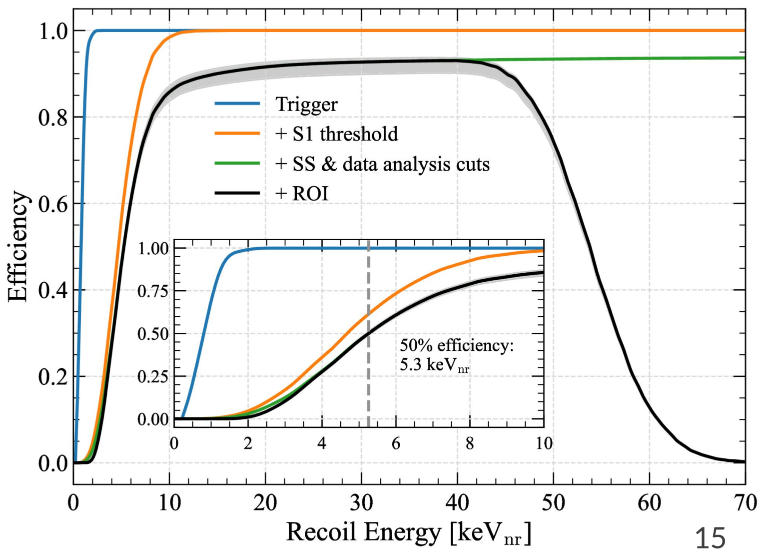
(*) LUX [Phys.Rev.D 102 (2020) 9, 092004]

Events in fiducial volume before pulse-based cuts dominated by accidentals

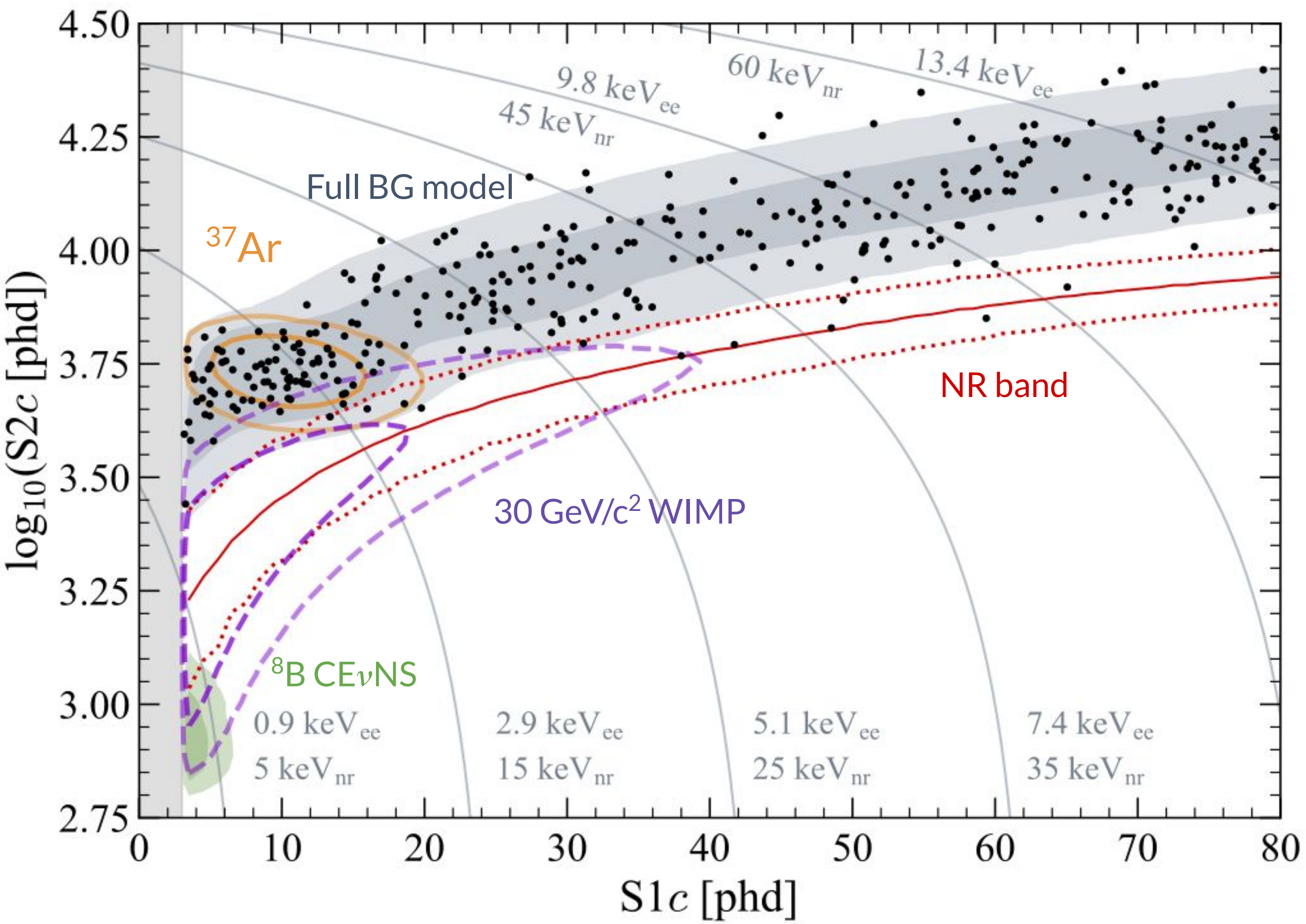


Cut events based on S1, S2 pulse shape and hit pattern

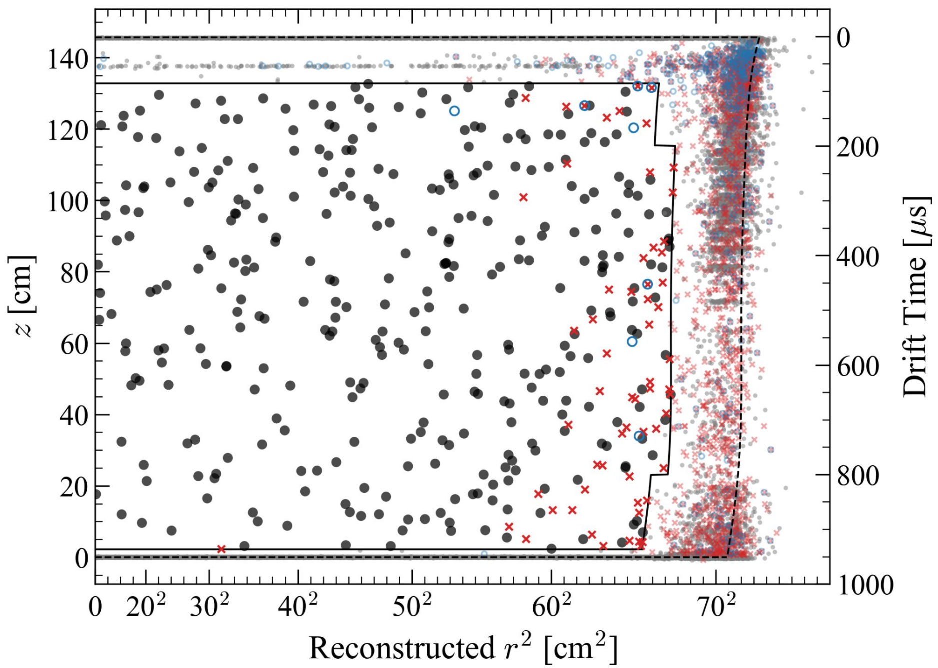
Signal efficiency evaluated using tritium and AmLi calibration data



Result



- 335 events in final dataset
- 60 ± 1 live days
- 5.5 ± 0.2 tonne FV

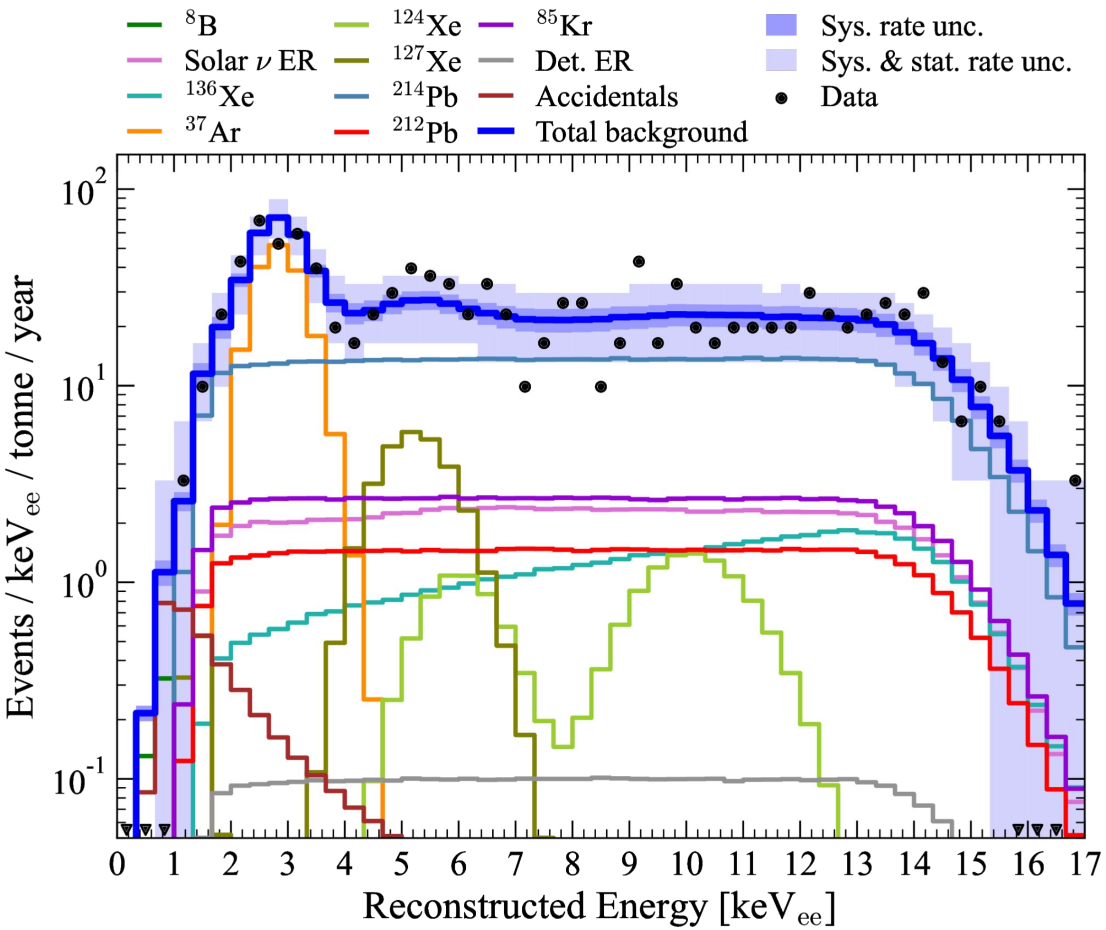


- ● Events surviving all selections
- × Skin-prompt-tagged events
- ○ OD-prompt-tagged events

Result

Best fit with zero WIMP events at all masses

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



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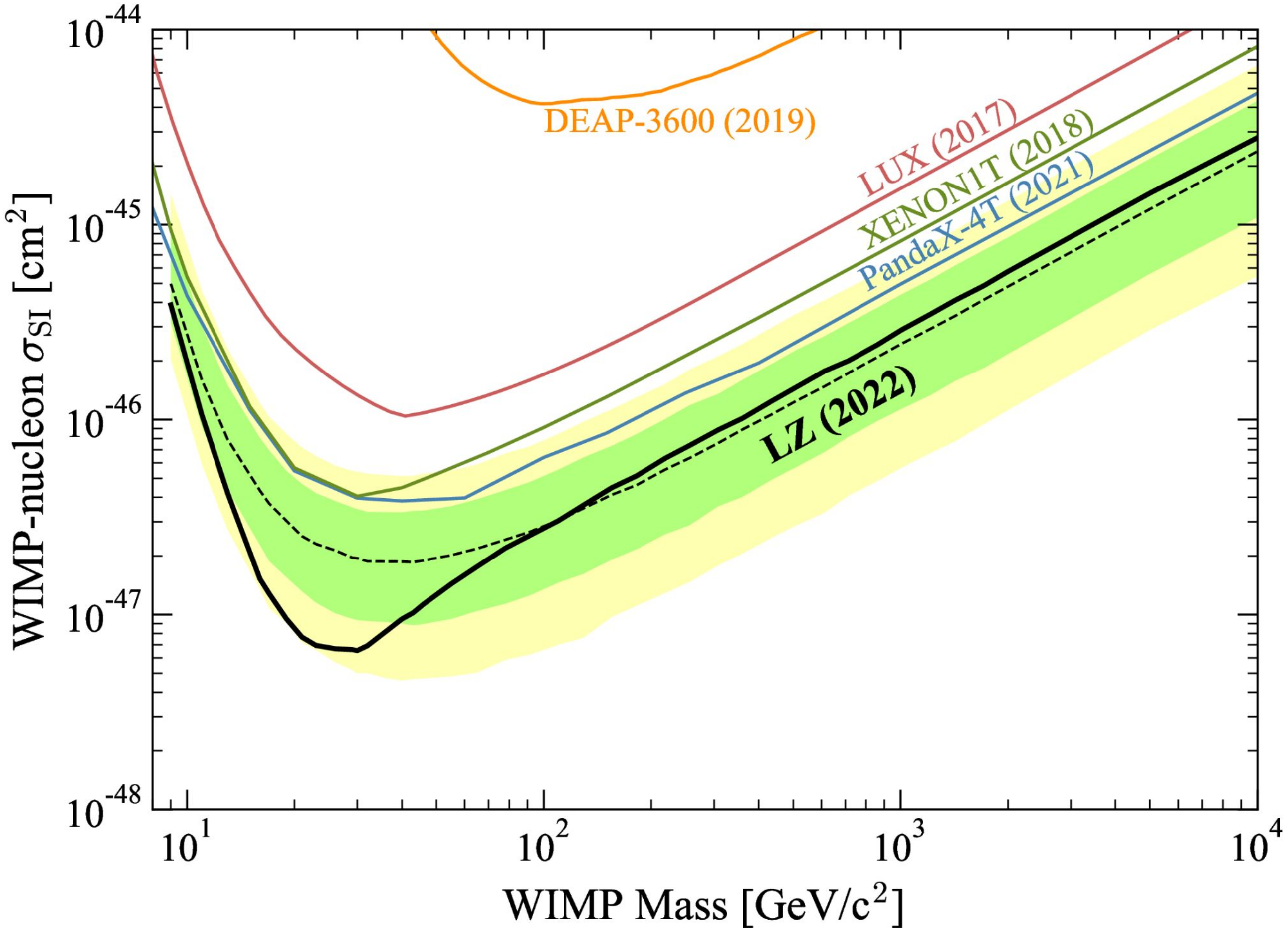


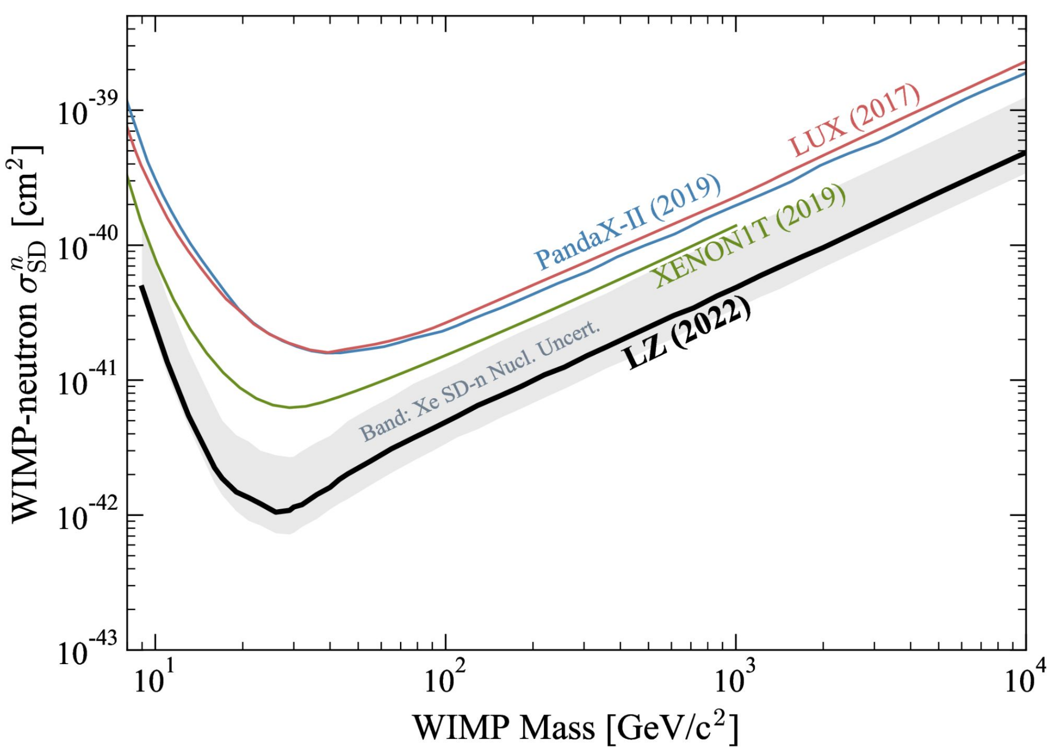
World leading sensitivity!

90% CL upper limit on WIMP-nucleon σ_{SI} is 6.5 x 10^{-48} cm^2 at 30 GeV/c^2 WIMP mass

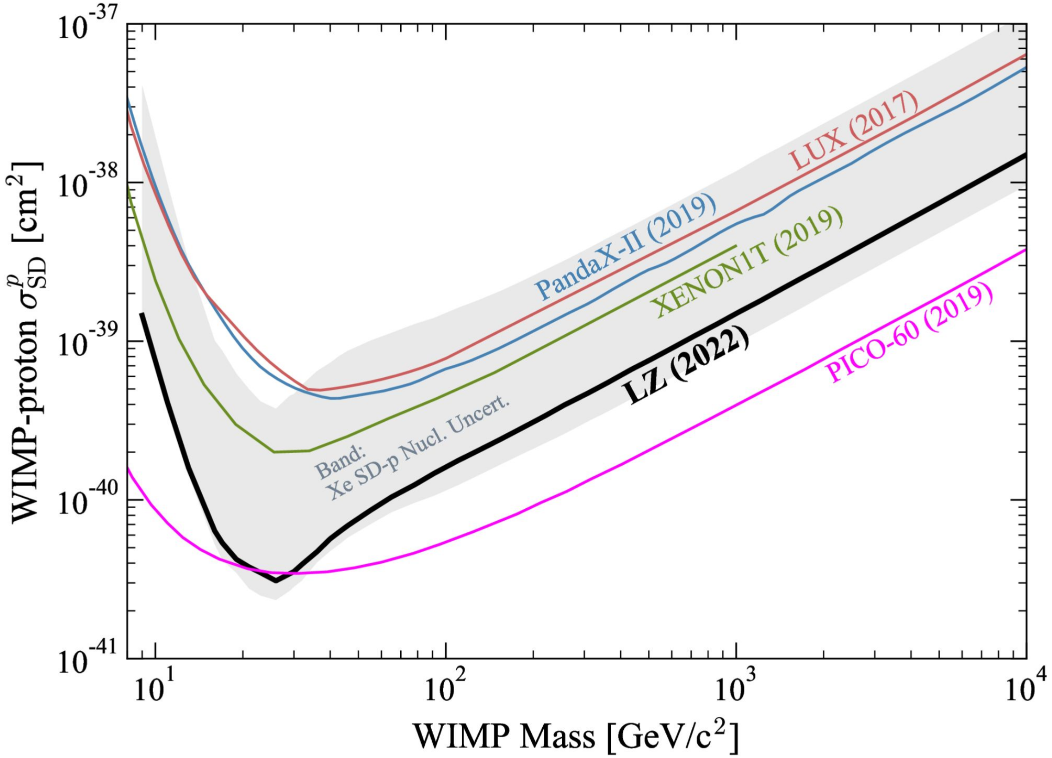
- Frequentist, two-sided profile-likelihood-ratio (PLR) test statistic
- Power constrained
- Followed conventions of Eur.Phys.J.C 81 (2021) 10, 907

Result

Spin-dependent WIMP-neutron scattering



Spin-dependent WIMP-proton scattering



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

"Brazil" band elided for clarity

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

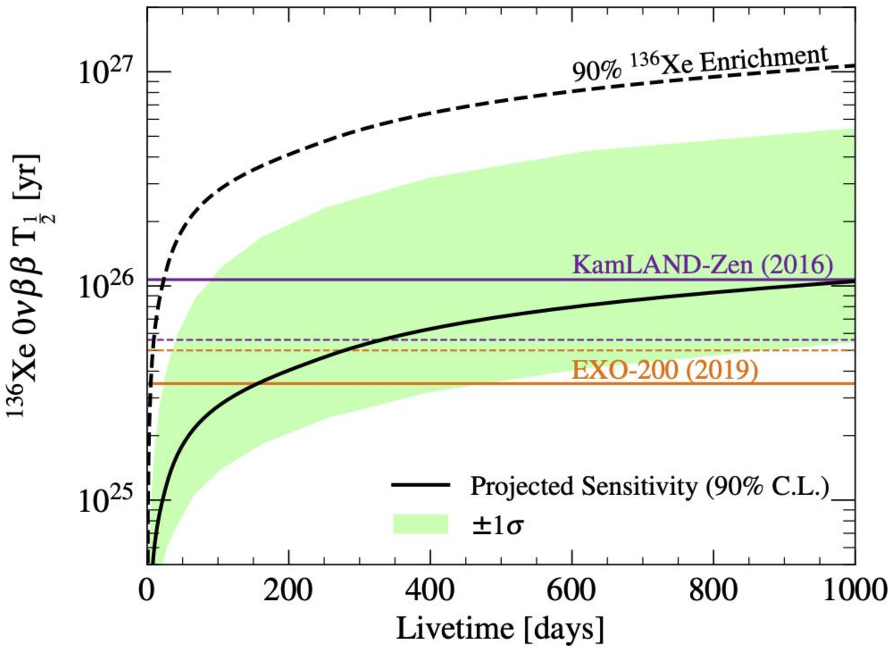
Next for LZ

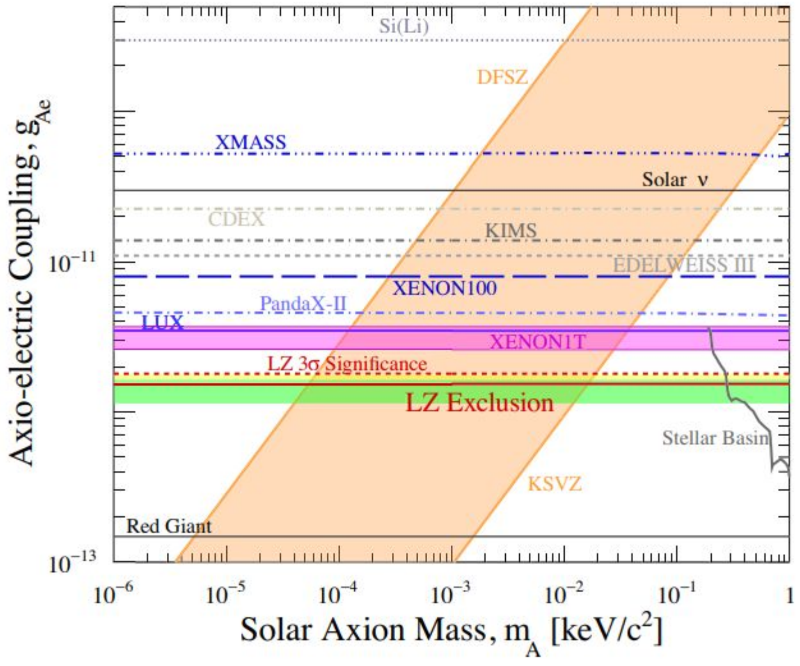
Phys. Rev. C 102, 014602 (2020)
Phys. Rev. D 104, 092009 (2021)
Phys. Rev. C 104, 065501 (2021)

Detector and analysis optimization and continued science running, with salting

LZ plans to take 1000 live days of data (x17 more exposure) to enable a broad physics program:

- **Extending the reach**: S2-only, Migdal effect, EFT
- **Non-WIMP DM candidates**: Mirror dark matter, leptophilic DM, hidden photons, UHDM, 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





XLZD Consortium

- LZ, XENON and DARWIN collaborations have joined forces to work toward a G3 xenon observatory
- https://xlzd.org/
- White paper (2203.02309)

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

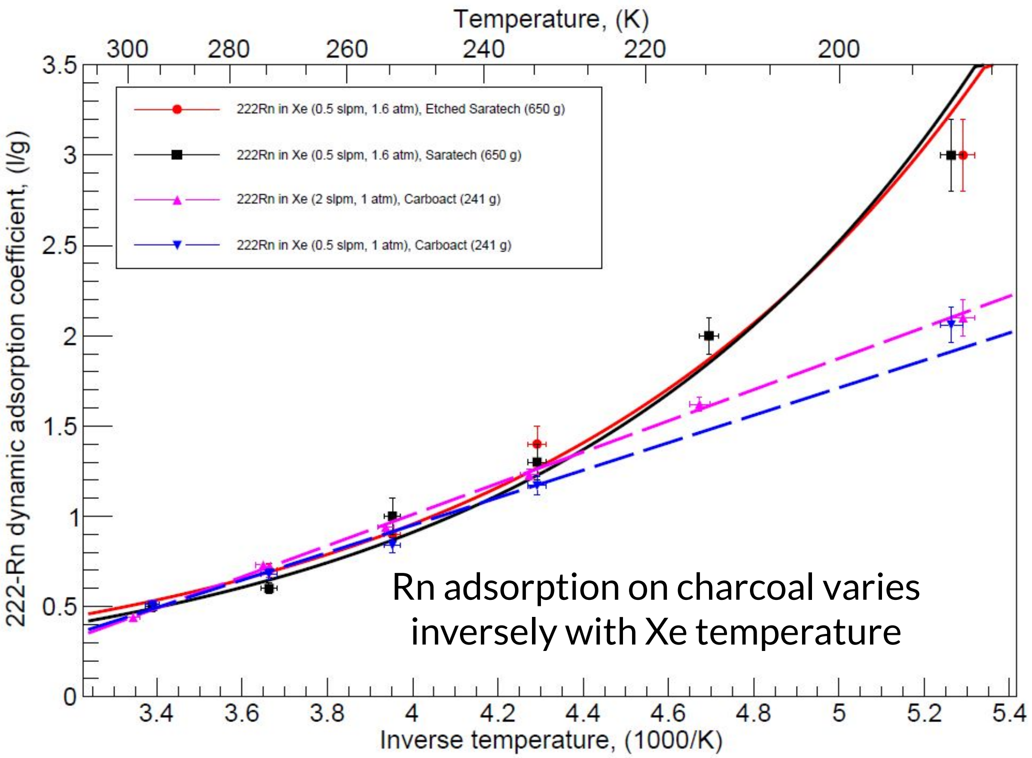
SURF is distributing this press release on behalf of the DARWIN and LZ collaborations

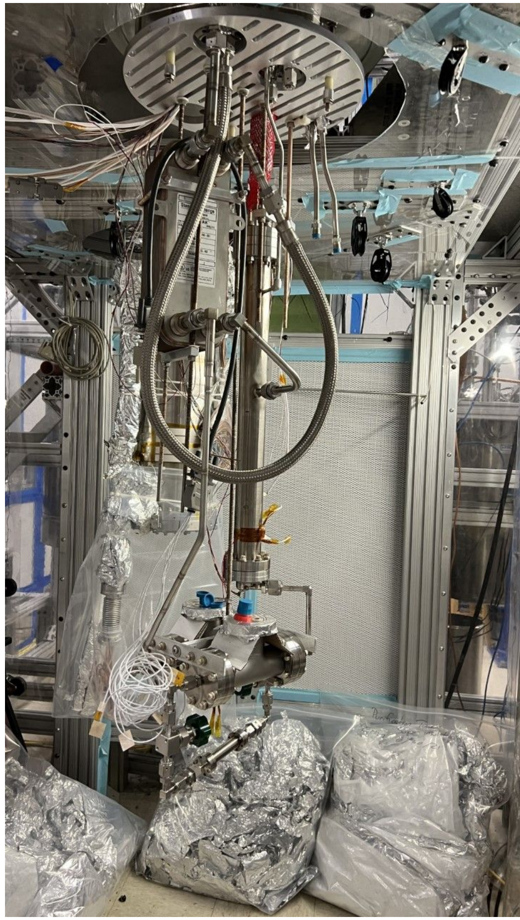
A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

J. Aalbers,[1,2] K. Abe,[3,4] V. Aerne,[5] F. Agostini,[6] S. Ahmed Maouloud,[7] D.S. Akerib,[1,2] D.Yu. Akimov,[8] J. Akshat,[9] A.K. Al Musalhi,[10] F. Alder,[11] S.K. Alsum,[12] L. Althueser,[13] C.S. Amarasinghe,[14] F.D. Amaro,[15] A. Ames,[1,2] T.J. Anderson,[1,2] B. Andrieu,[7] N. Angelides,[16] E. Angelino,[17] J. Angevaare,[18] V.C. Antochi,[19] D. Antón Martin,[20] B. Antunovic,[21,22] E. Aprile,[23] H.M. Araújo,[16] J.E. Armstrong,[24] F. Arneodo,[25] M. Arthurs,[14] P. Asadi,[26] S. Baek,[27] X. Bai,[28] D. Bajpai,[29] A. Baker,[16] J. Balajthy,[30] S. Balashov,[31] M. Balzer,[32] A. Bandyopadhyay,[33] J. Bang,[34] E. Barberio,[35] J.W. Bargemann,[36] L. Baudis,[5] D. Bauer,[16] D. Baur,[37] A. Baxter,[38] A.L. Baxter,[9] M. Bazyk,[39] K. Beattie,[40] J. Behrens,[41] N.F. Bell,[35] L. Bellagamba,[6] P. Beltrame,[42] M. Benabderrahmane,[25] E.P. Bernard,[43,40] G.F. Bertone,[18] P. Bhattacharjee,[44] A. Bhatti,[24] A. Biekert,[43,40] T.P. Biesiadzinski,[1,2] A.R. Binau,[9] R. Biondi,[45] Y. Biondi,[5] H.J. Birch,[14] F. Bishara,[46] A. Bismark,[5] C. Blanco,[47,19] G.M. Blockinger,[48]

R&D for possible upgrade or next gen - **Improved Rn removal**

- Rn is the dominant background in current generation of LXe dark matter experiments (LZ, XENONnT, PandaX)
- Improve sensitivity with novel methods to remove Rn
- Charcoal is effective Rn absorber, demonstrated and used with Xe in gas phase
- But charcoal is also a Rn emitter
- Going to liquid Xe phase helps:
  - Increase Rn adsorption
  - Reduce required charcoal mass
- Investigating feasibility at SLAC

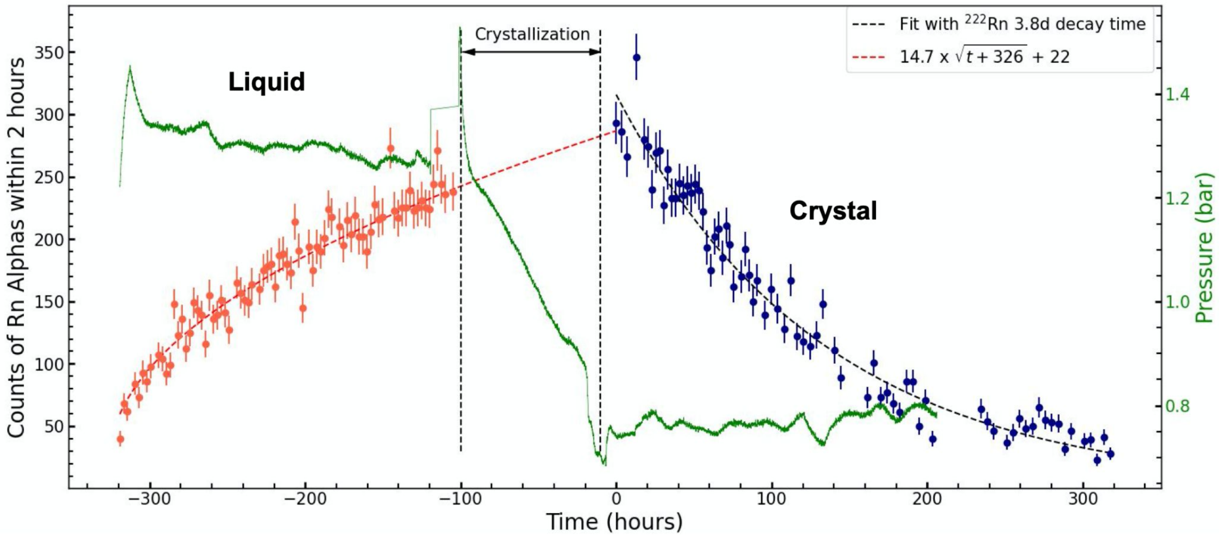


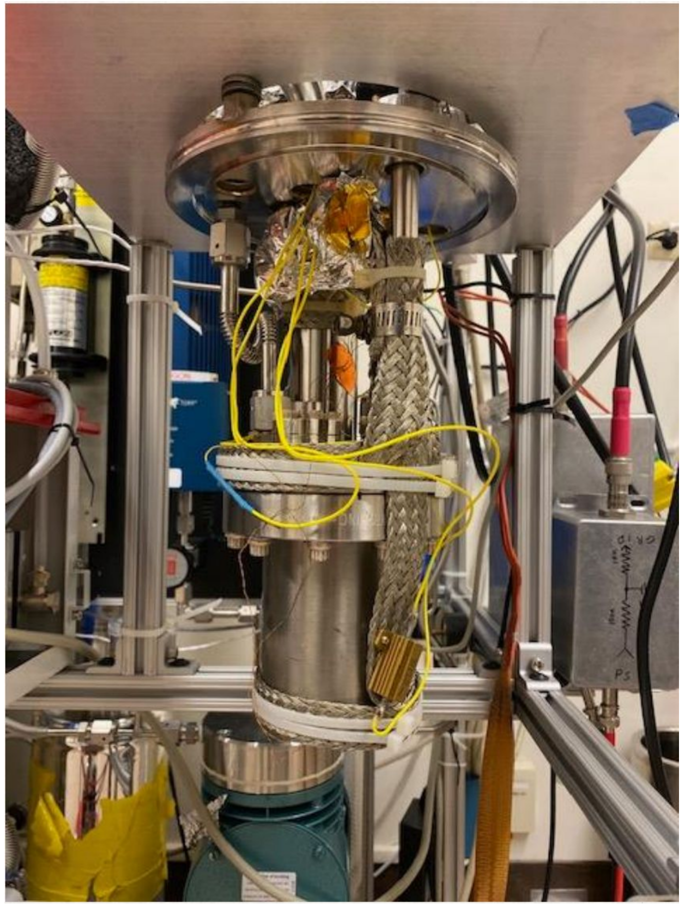


Pushkin et al. Nucl.Instrum.Meth.A 903 (2018) 267-276

R&D for possible upgrade or next gen - **Crystalline xenon**

- Another potential method to mitigate Rn: freeze the xenon
- In liquid xenon: Rn emanated anywhere migrates everywhere
- In solid xenon:
  - Rn emanated from surfaces do not migrate → excluded from the bulk Xe
  - Rn in the bulk decay in place and Rn chain decays can be fully tagged
- Crystalline/vapor Xe TPC operation has been demonstrated at LBNL (*)

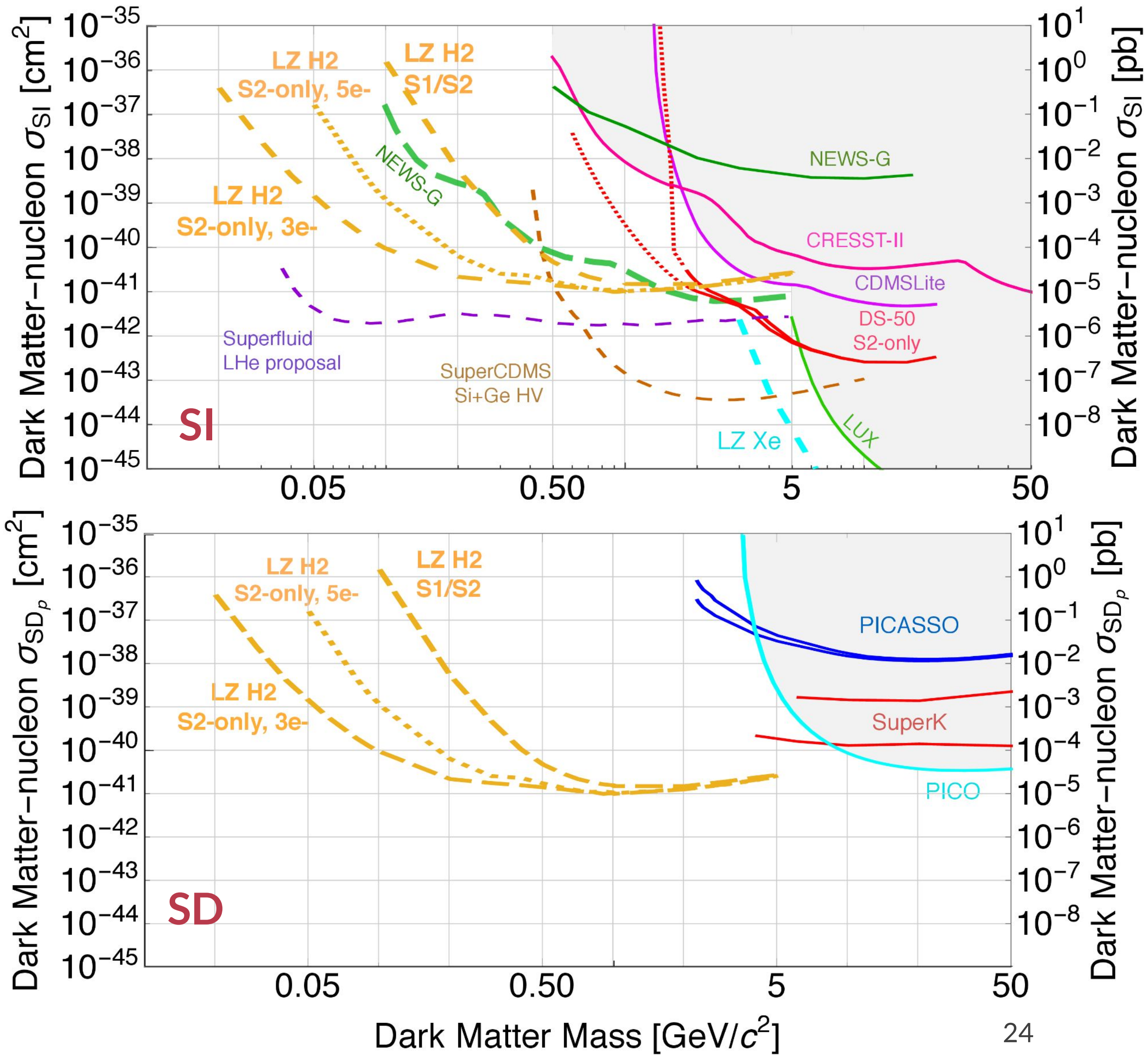




(*) Kravitz et al JINST 17 (2022) 04, P04014

R&D for possible upgrade or next gen - **Hydrogen doping**

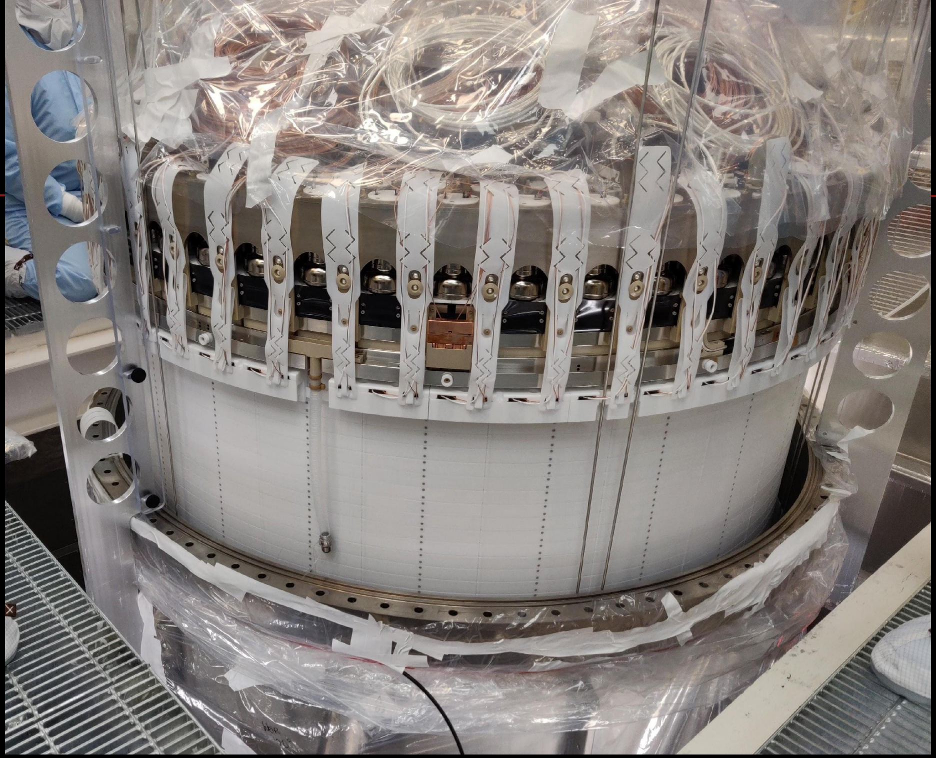
- Idea: Dissolve ~2 kg of hydrogen in LZ's xenon
- Potentially extend sensitivity of LZ to ~100 MeV/c^2 dark matter masses
- Advantages:
  - Kinematic match to sub-GeV dark matter
  - Proton recoils offer increased signal yield over Xe recoils
  - Retain all other background mitigations of LZ (self-shielding, assays, etc)
  - SI and (unique at low mass) SD sensitivity
- Much R&D needed: mixing fraction, signal yields, cryogenics...
  - Investigating at SLAC, UCSB and others

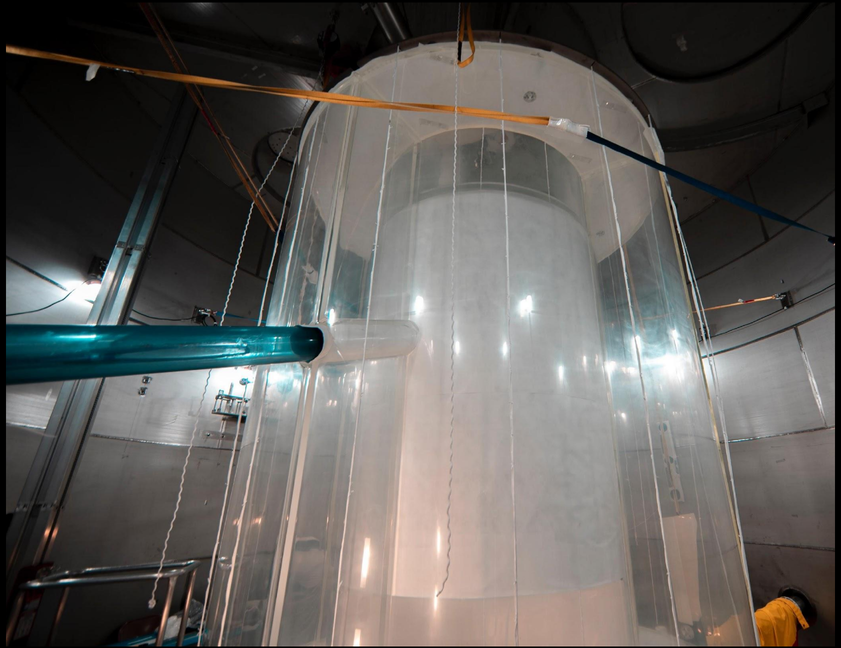
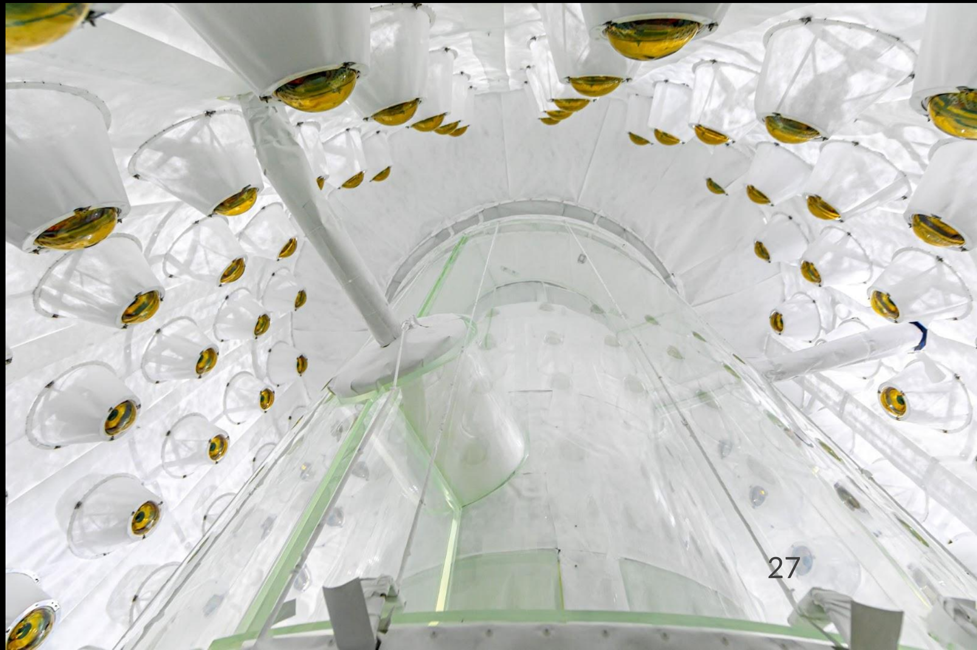


Summary

- LZ is operating and taking high quality physics data
  - All detectors are performing well
  - Backgrounds are within expectation
- With its first run, LZ has achieved world-leading WIMP sensitivity
  - arXiv:2207.03764
- Broad physics program still lies ahead for LZ
- The xenon community is uniting into the XLZD Consortium to build the ultimate xenon rare event observatory
- Exciting R&D underway for improvements to LXe dark matter searches

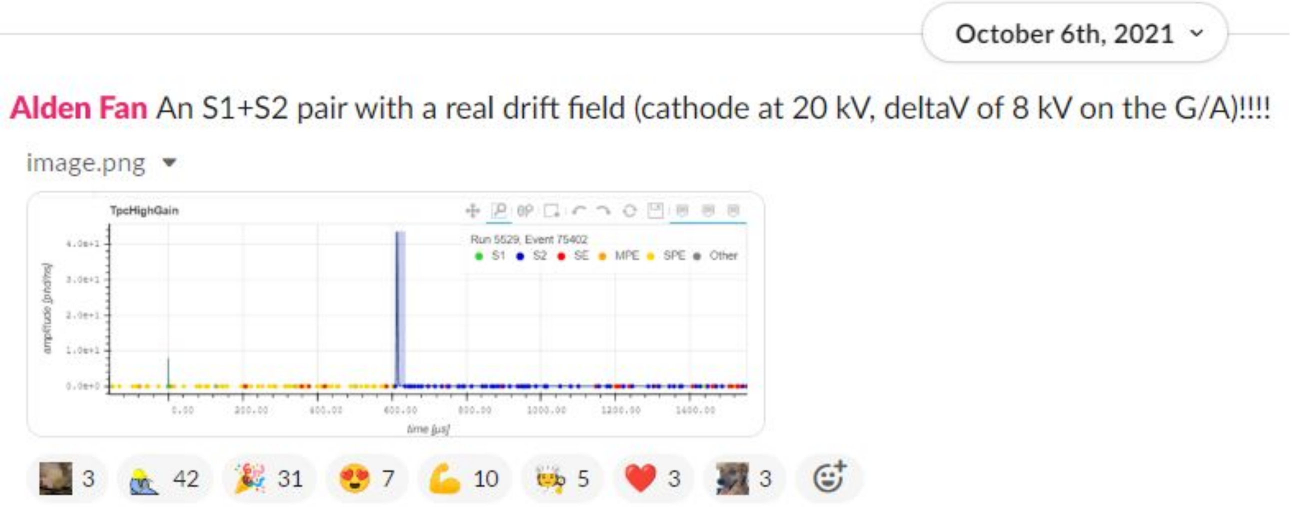
Backup

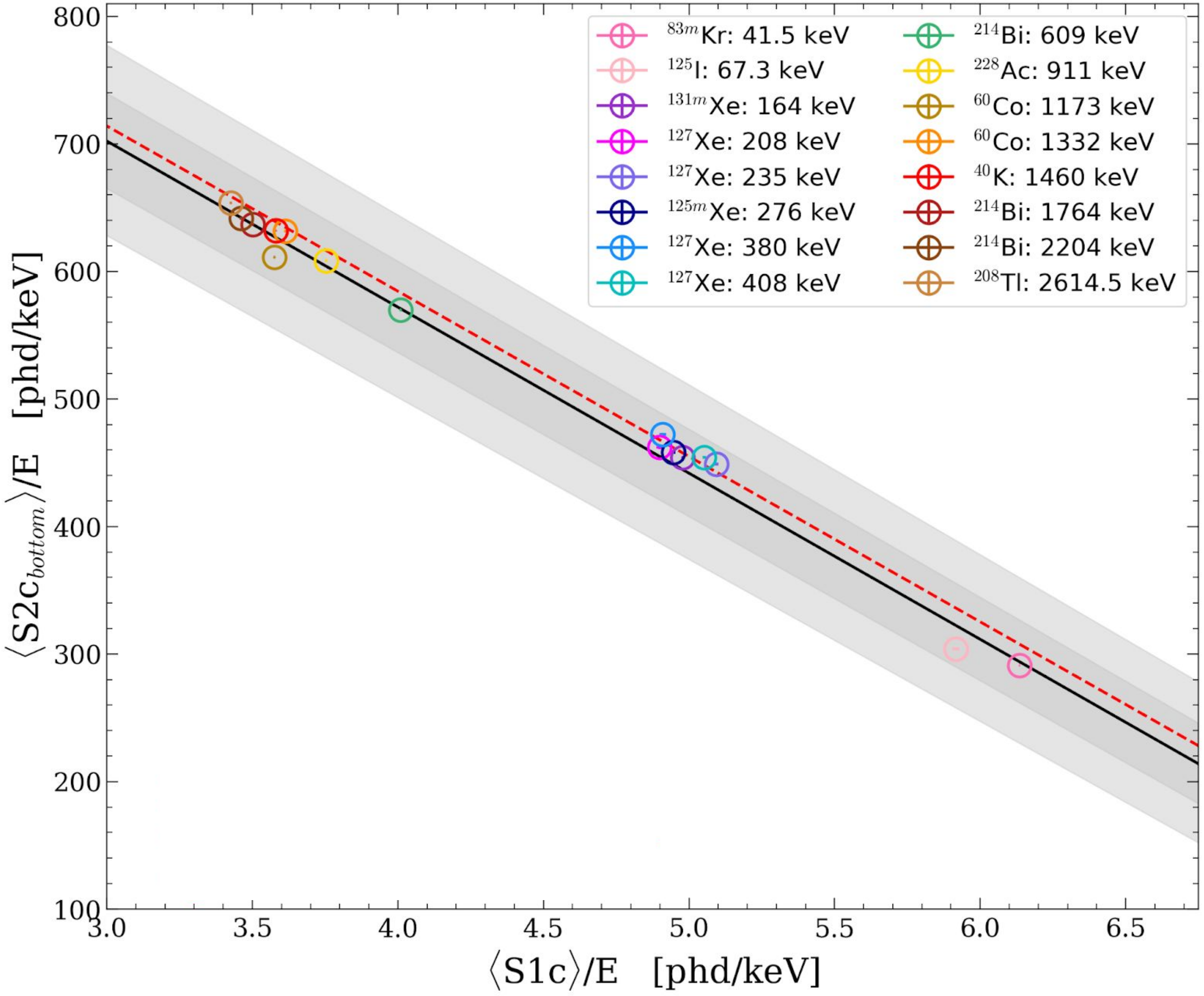
Commissioning

- Grids biased: extraction & drift fields established in October and December 2021
  - Established drift field ~190 V/cm (32 kV on cathode, ~4% variation in fiducial volume)
  - Established extraction field ~7.3 kV/cm gas (8 kV between gate and anode)
- PMT operations & characterization
  - LED measurements for PMT after-pulsing and gain-matching
  - 482/494 TPC PMTs, 129/131 Skin PMTs, 120/120 OD PMTs operational during run (>97%)
- Exercised full data processing chain
- Tuned data acquisition & trigger settings
  - S2 trigger efficiency - fully efficient at 600 phd or 10 electrons
- Initial calibrations complete (primarily in November 2021)



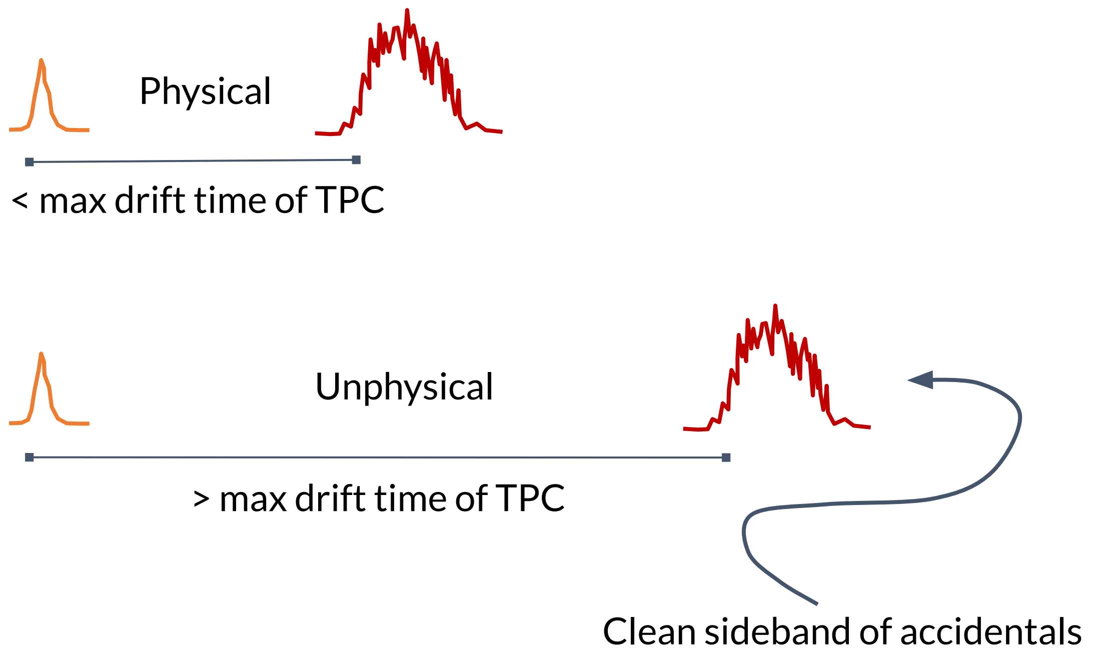
Detector response characterization

"Doke" plot



Accidental coincidence background

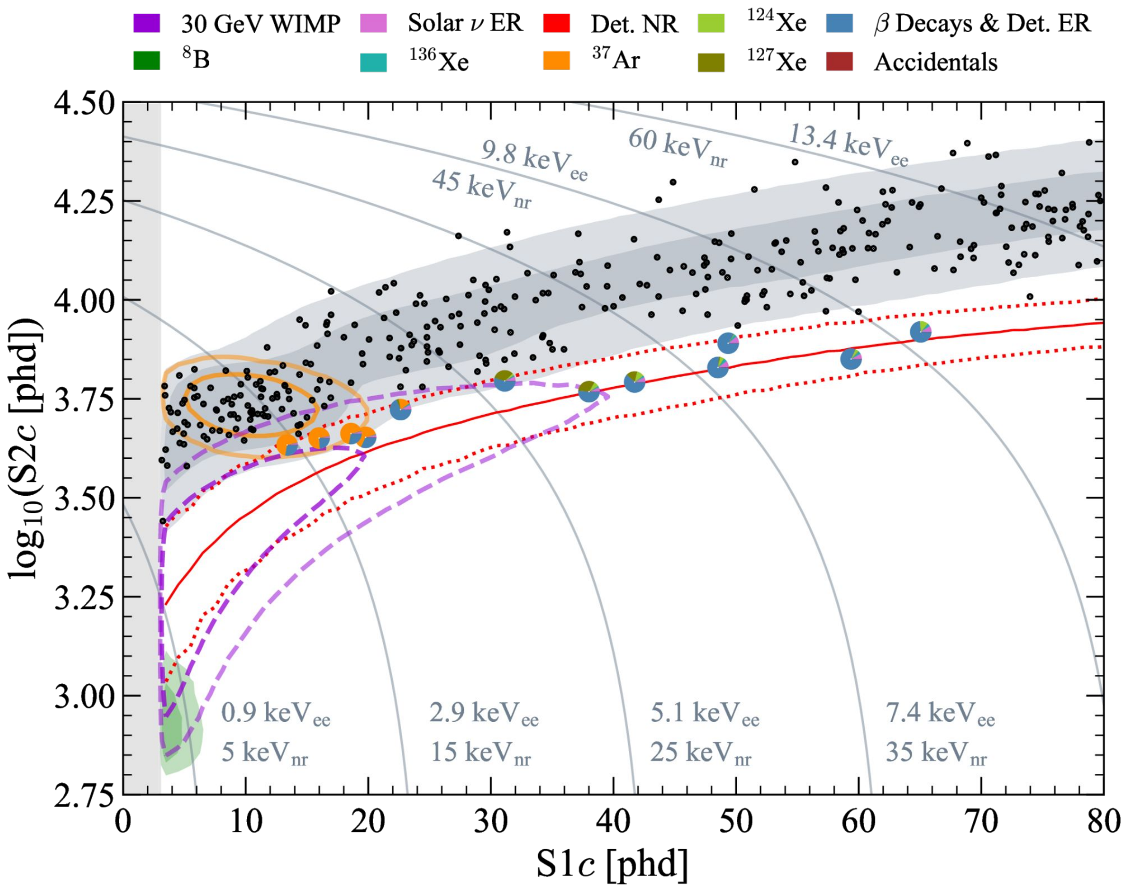
- Accidentals PDF generated from random pairing of isolated S1s and isolated S2s
- Mix pulses at waveform level → allows to apply reconstruction and data analysis identically to WS data
- Normalize PDF to data using UDT sideband:
  - Events with unphysical drift time (UDT) longer than 951 μs are purely from accidentals
- Estimated rate of accidentals in first science run: **1.2 ± 0.3 events**

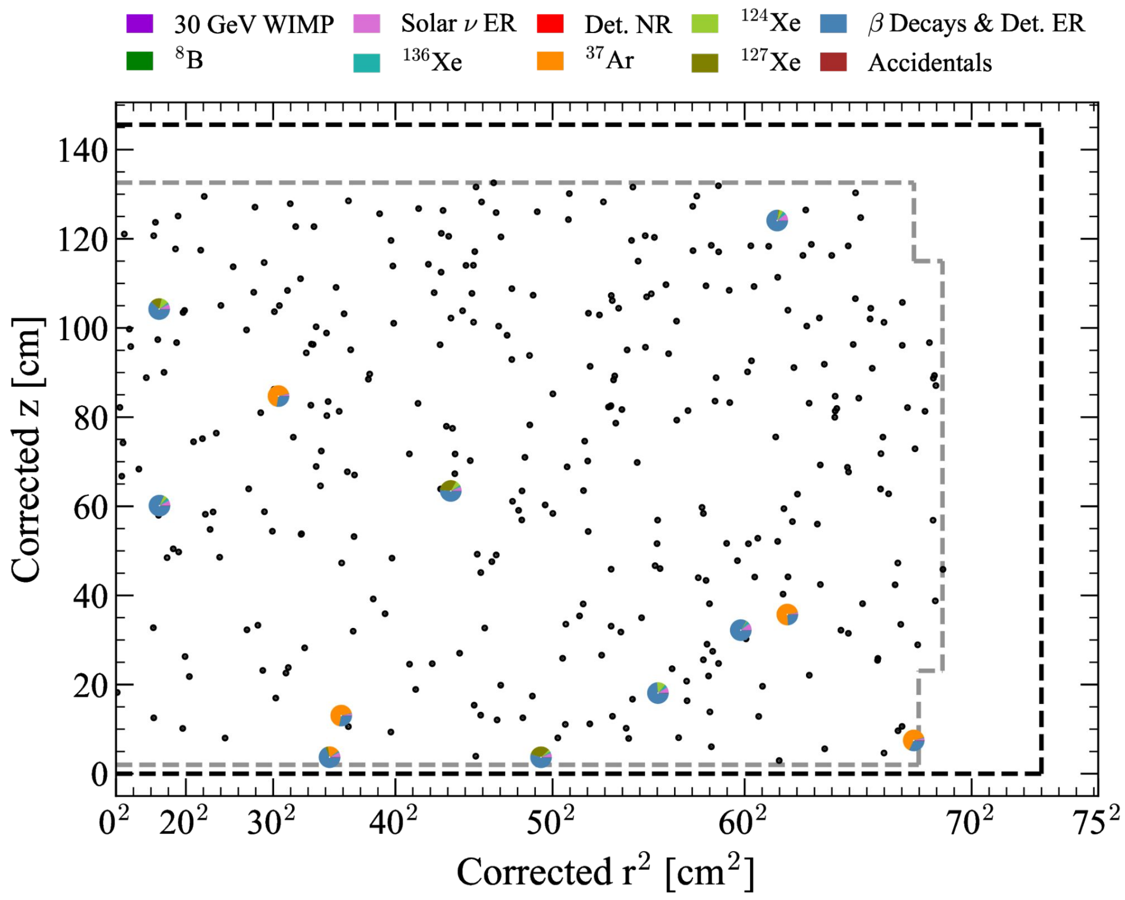


Event counts

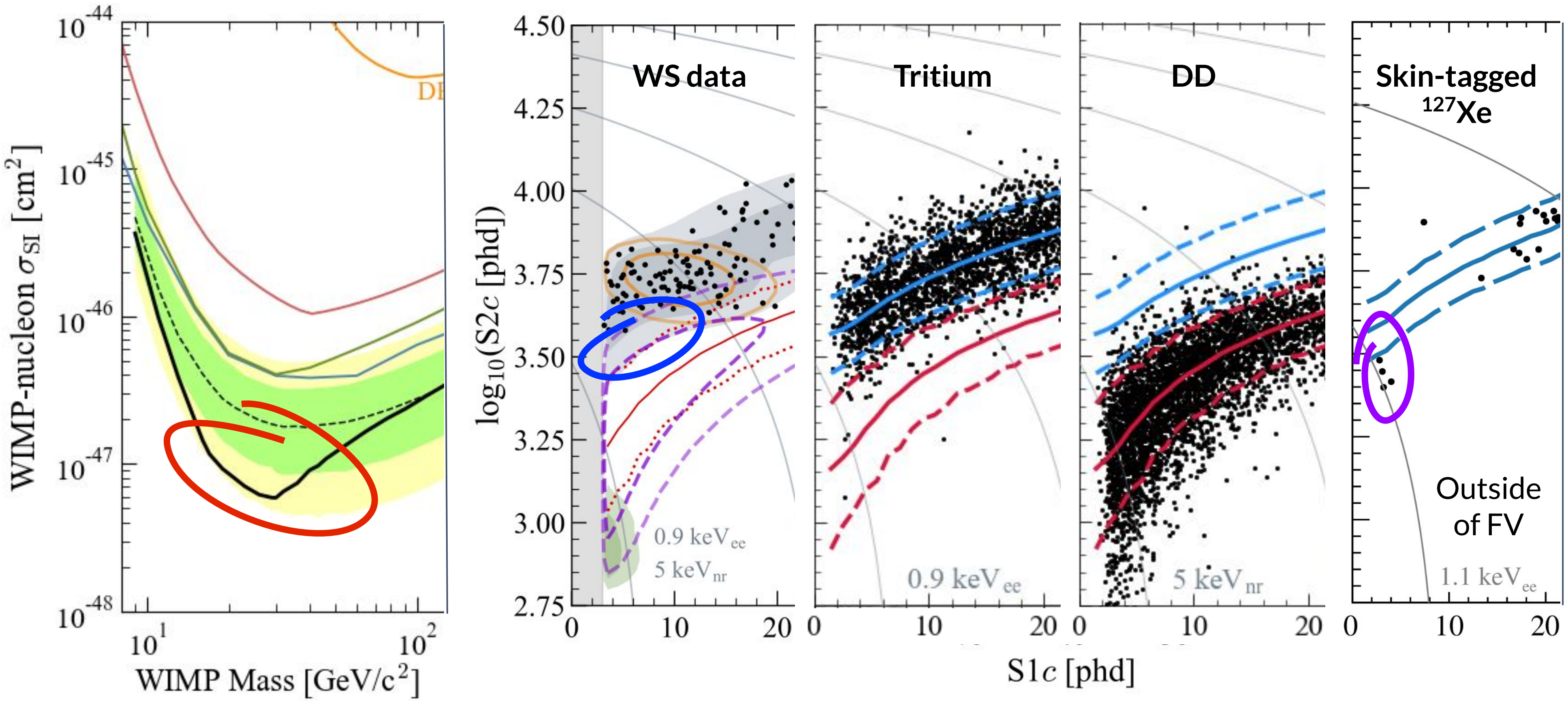
Selection description	Events after selection
All triggers	1.1×10^8
Analysis time hold-offs	6.0×10^7
Single scatter	1.0×10^7
Region-of-interest	1.8×10^5
Analysis cuts for accidentals	3.1×10^4
Fiducial volume	416
OD and Skin vetoes	335

Pie charts


30 GeV WIMP
Solar ν ER
Det. NR
124Xe
β Decays & Det. ER
8B
136Xe
37Ar
127Xe
Accidentals
9.8 keVee
60 keVnr
13.4 keVee
45 keVnr
0.9 keVee
5 keVnr
2.9 keVee
15 keVnr
5.1 keVee
25 keVnr
7.4 keVee
35 keVnr
log10(S2c [phd])
S1c [phd]


30 GeV WIMP
Solar ν ER
Det. NR
124Xe
β Decays & Det. ER
8B
136Xe
37Ar
127Xe
Accidentals
Corrected z [cm]
Corrected r2 [cm2]

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.

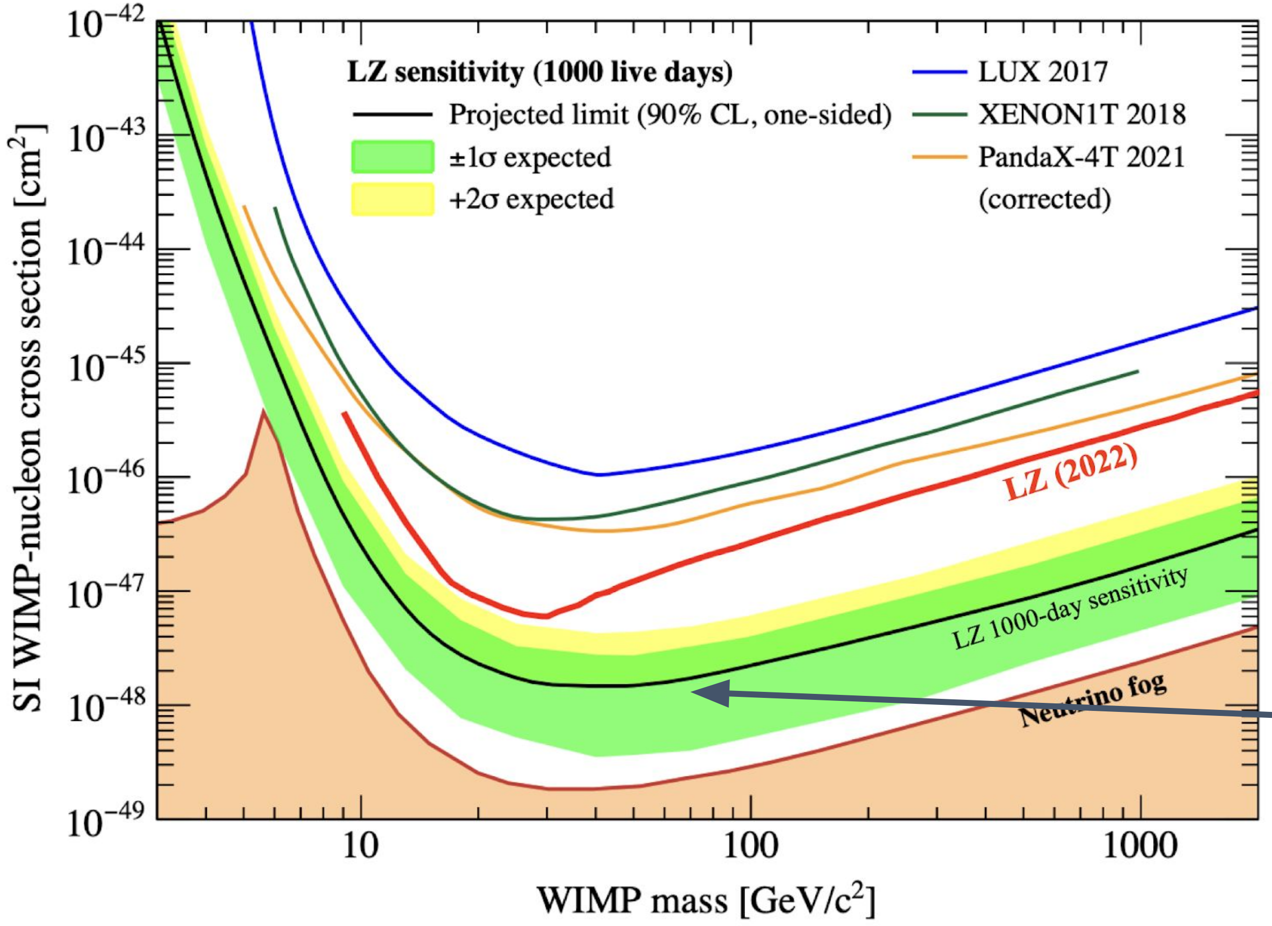
5. Deficit appears consistent with under-fluctuation of background.

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.

Projected Sensitivity (5.6 t exposure, 1000 live days)



90% CL minimum (**one sided**) of
1.4 x 10^{-48} cm^2 at 40 GeV/c^2
from Phys. Rev. D 101, 052002 (2020)