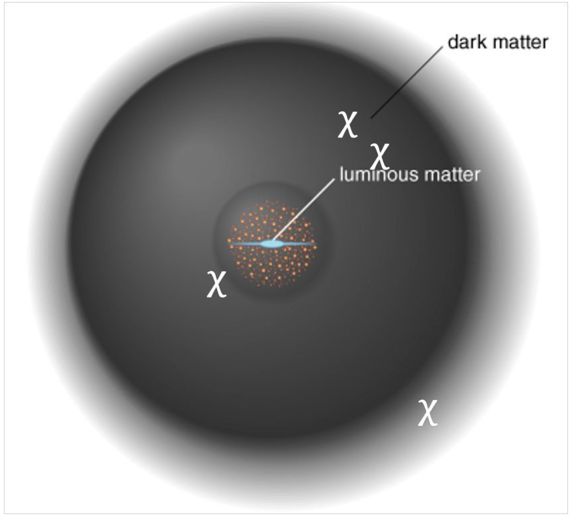
First Results of the LUX-ZEPLIN Experiment

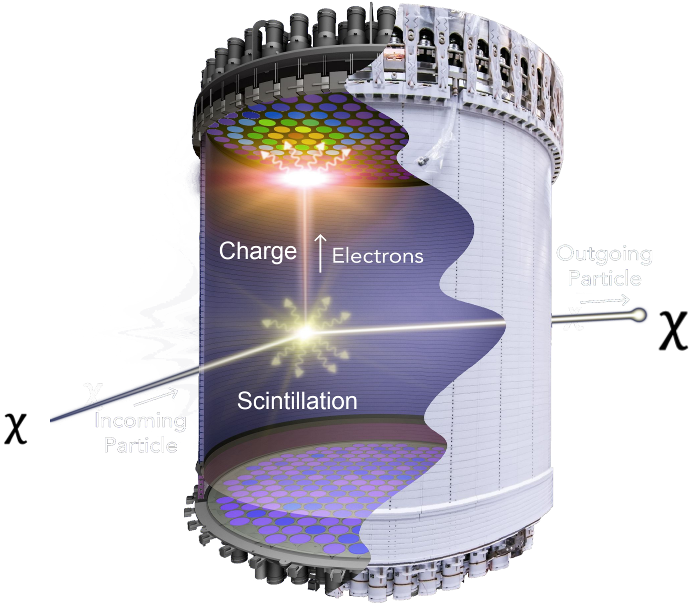
57th Rencontre de Moriond 2023

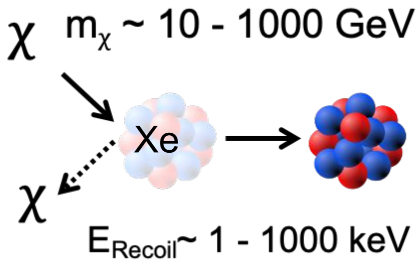
Geertje Heuerman

Direct detection of Dark Matter: The LZ Experiment

Motivation: Direct detection of dark matter particle (WIMP) via elastic scattering off xenon nucleus







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Background Sources

Electronic Recoils (ER):

Radiation from detector components:

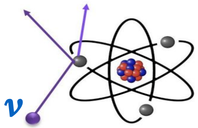
- γ from U, Th chain, K, Co
- Dissolved β: Rn-chain, Kr, Xe
- e- capture: Ar, Xe-isotopes
- Cosmogenically activated xenon

External ambient radiation:

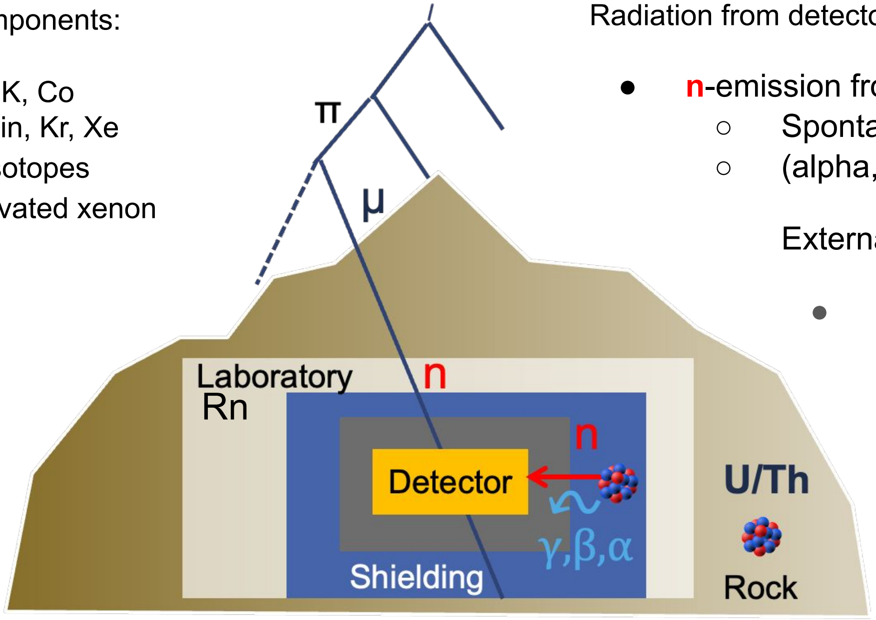
- U, Th, K, Co, Rn

Cosmogenic radiation:

- Solar ν: pp-ν
- μ



γ, β, μ, ν



Nuclear recoils (NR):

Radiation from detector components:

- **n**-emission from U/Th:
  - Spontaneous fission
  - (alpha,n) reaction

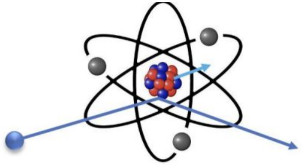
External ambient radiation:

- U/Th

Cosmogenic radiation:

- Solar ν: ^{8}B-ν
- μ-induced **n**

n, ν, □



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The Dual Phase Time Projection Chamber

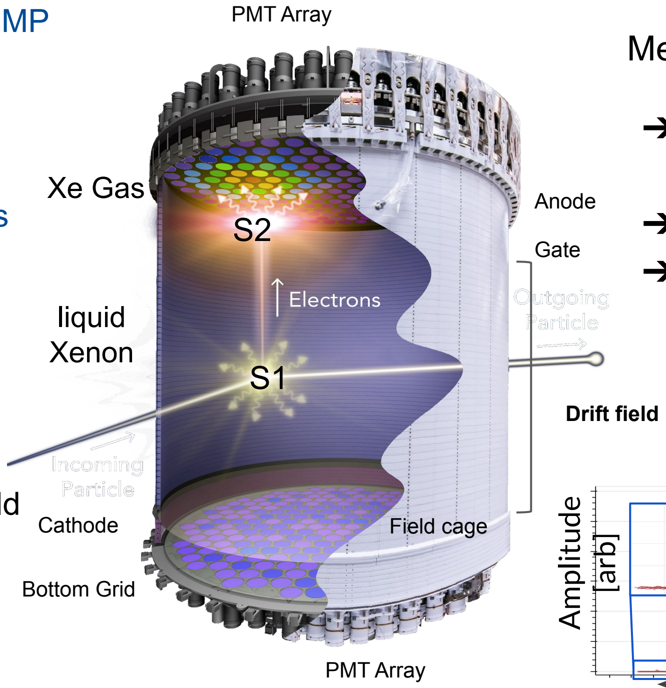
Why Xenon:

1. Xe nucleon is sensitive to “vanilla” WIMP mass
2. It is quiet
3. Allows for particle ID
4. Self shielding
5. Provides numerous additional physics capabilities

Particle detection:

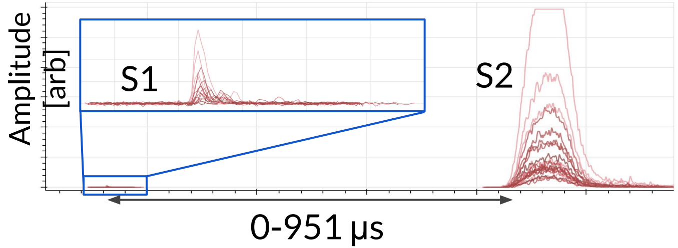
1. **S1**: Prompt scintillation photons
2. **S2**: Delayed scintillation:

   Ionization electrons drift up in drift field and produce electro-luminescence light in the gas region



Measurement of S1 and S2 allows for:

- ➔ Position reconstruction (PMT hit map)
- ➔ Energy reconstruction (S1 + S2)
- ➔ Particle ID (S2/S1):
  - ◆ Electron recoil
  - ◆ Nuclear recoil



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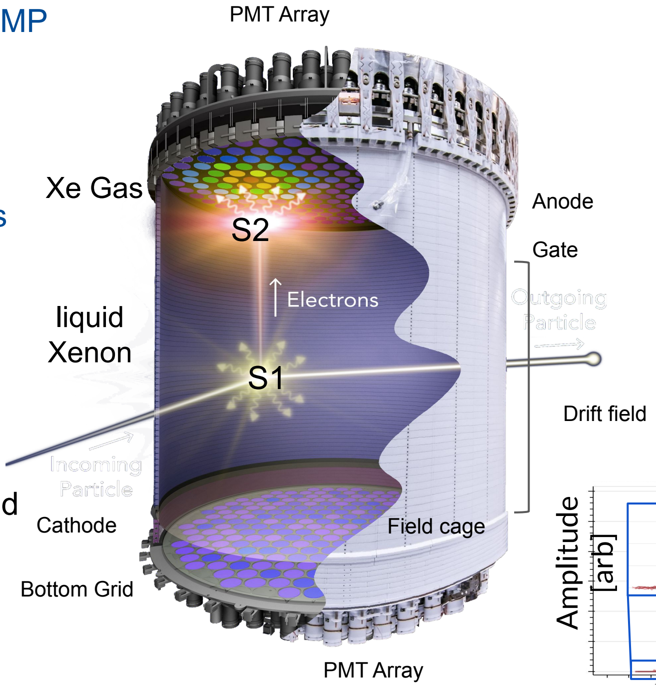
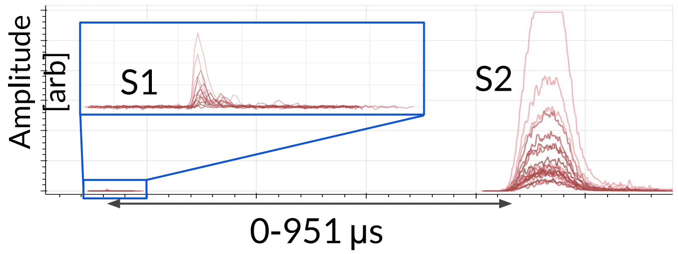


- 1.5 diameter x 1.5 m height
- 7 tonne of liquid xenon
- 494x 3” PMTs in two arrays
- 4-high voltage wire mesh electrodes:
  - Drift field
  - Extraction region
- PTFE Field cage
- PTFE coverage for increased light collection



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The LZ Detector

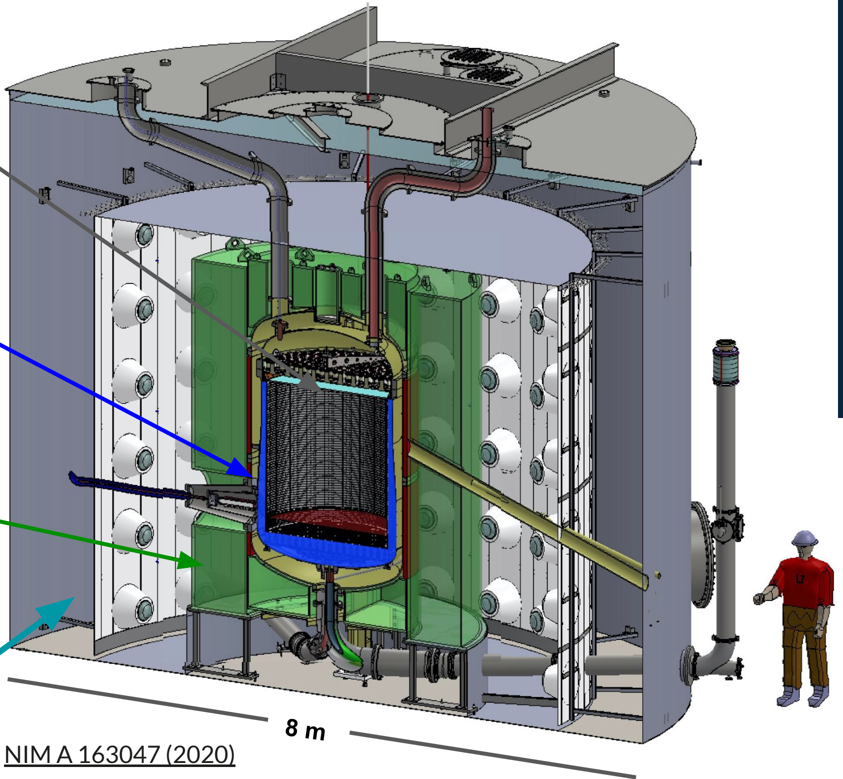
Located 4850 ft underground at
Sanford Underground Research Facility (SURF)
in South Dakota, USA

7t dual-phase xenon Time Projection Chamber (TPC)

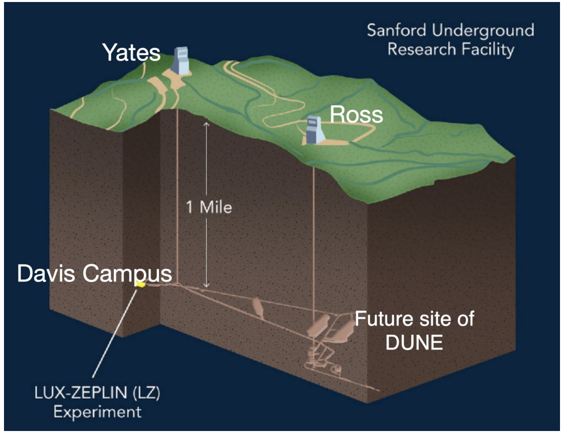
2t liquid xenon “Skin” detector

17t gadolinium-loaded liquid scintillator outer detector

120t high-purity water



NIM A 163047 (2020)



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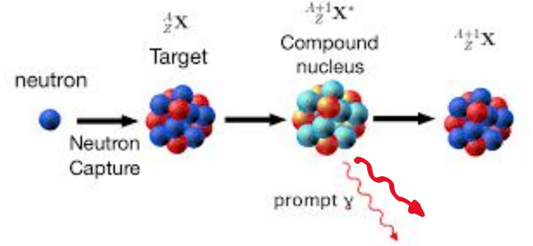
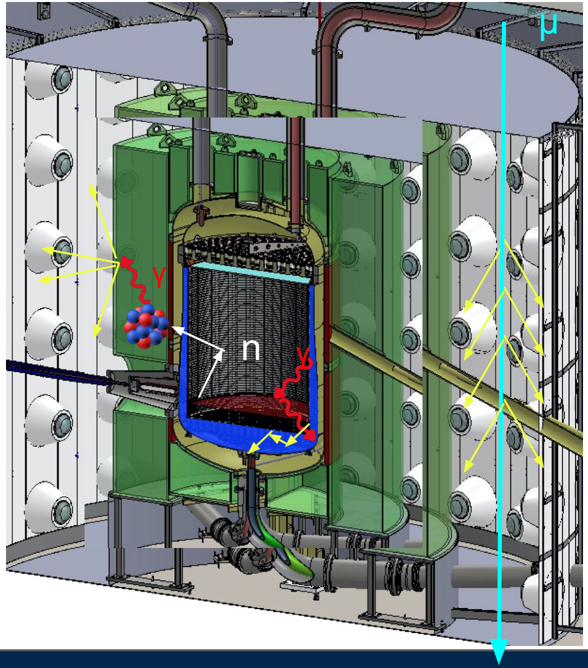
Gamma and Neutron Veto: Skin and Outer Detector (OD)

Motivation: tagging and subsequent reduction of neutron and gamma background to achieve projected WIMP sensitivity

Neutron Detection:



$$^{157}\text{Gd} + \text{n}_{\text{thermal}} \rightarrow {}^{158}\text{Gd} + \boxed{\gamma(7.88\,\text{MeV})}$$



Skin: The gamma-ray veto

- 2 t of Liquid Xenon surrounding TPC instrumented with 131 1” & 2” PMTs

Outer Detector: The neutron veto

- 17 t Gd loaded liquid scintillator embedded in 120 t water, read out by 120 8” PMTs
- **Neutron tagging efficiency: 88 %**

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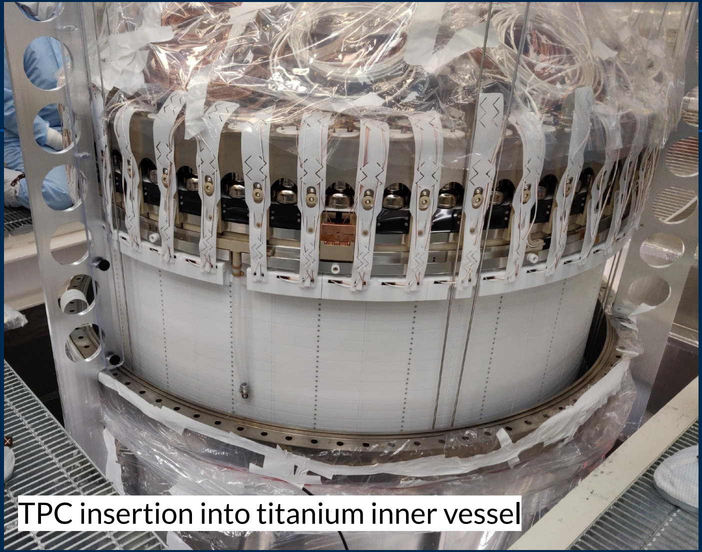
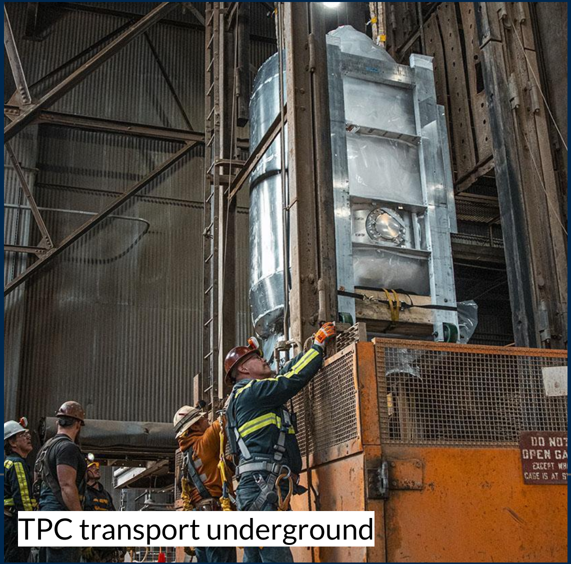
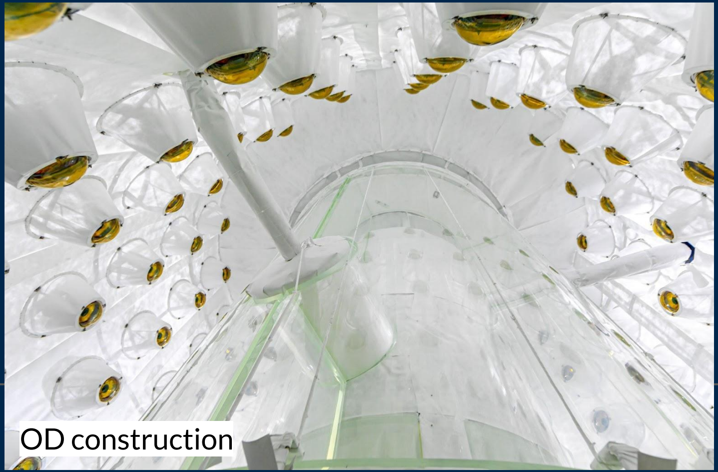
PMT arrays + cabling


TPC construction


TPC insertion into titanium inner vessel


TPC transport underground


TPC insertion into outer titanium vessel

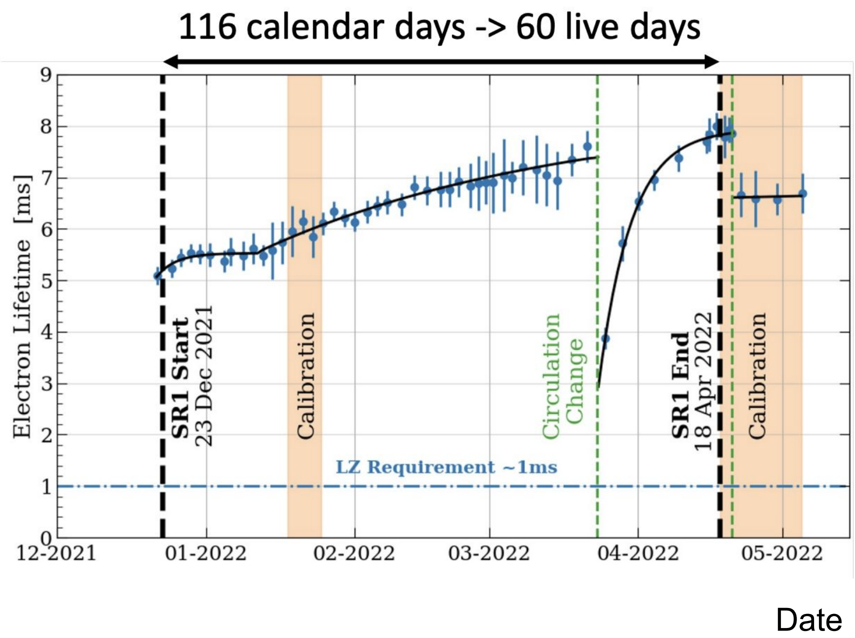

OD construction

LZ's First Science Run

Motivation: Demonstration of detector readiness and competitive measurement of WIMP exclusion

Engineering run (unblinded):

- Stable detector conditions
  - Drift field: 193 V/cm
  - Extraction field: 7.3 kV/cm in gas
  - > 97 % of PMTs operational
  - Liquid temperature (174.1 K)
  - Gas Pressure (1.791 bar)
  - Liquid level stable within 10 microns
- Continuous purification of Xe
  - 3.3 t / day through hot getter system
- Electron lifetime: 5 - 8 ms



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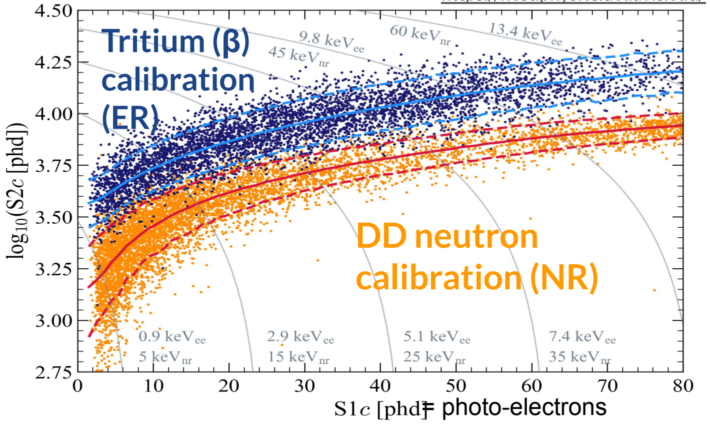
Detector Calibration

Motivation: Determination of Detector response to neutrons, electrons and gammas in TPC, OD & Skin using dispersed and externally deployed sources

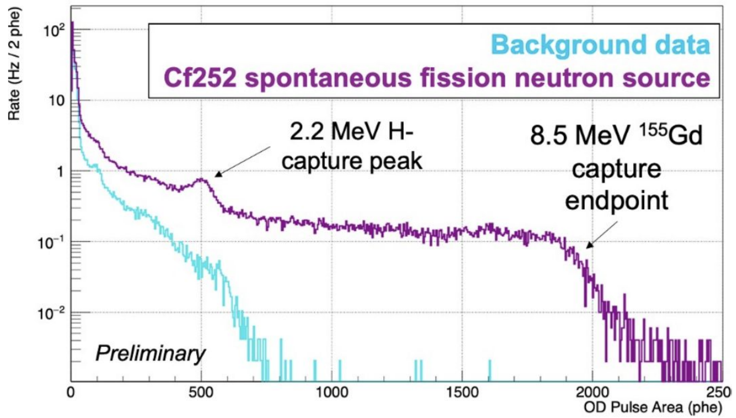
TPC

Band fits performed with NEST(*:)
https://nest.physics.ucdavis.edu/



- Photon collection efficiency: **g1 = 0.114** ± 0.002 phd/photon
- Charge gain: **g2 = 47.1** ± 1.1 phd/electron
- **99.9% rejection of ERs below the NR median**

OD



- Light collection efficiency: 230 phd/MeV

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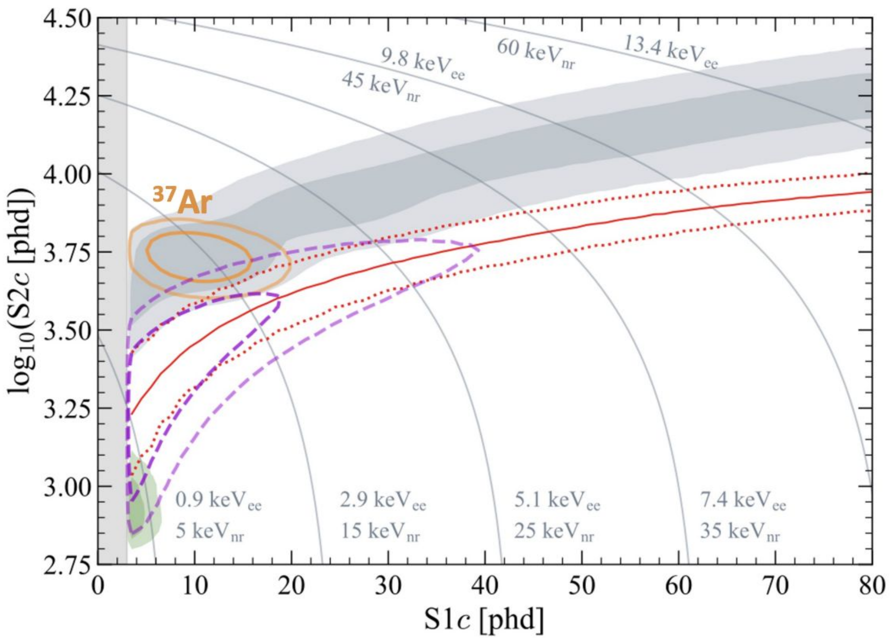
Background Model

arXiv:2211.17120

Motivation: Assess likelihood of excess WIMP signal



Backgrounds simulation: energy deposit + detector response

ER-backgrounds expected in ROI: 276 events (+ [0, 291] from ^{37}Ar)

- **Dissolved β-emitter**: ^{214}Pb (^{222}Rn daughter), ^{85}Kr, ^{136}Xe ($2\nu\beta\beta$)
- **Dissolved e-capture**: ^{37}Ar, ^{127}Xe, ^{24}Xe (double e-capture)
- **γ emitter:** ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co
- **Solar ν:** pp + ^{7}Be + ^{13}N

NR-backgrounds expected in ROI : 0.15 events

- **Neutrons from spontaneous fission and (α,n) reactions**
- **^{8}B solar neutrinos**

Non-physics sources in ROI: 1.2 events

- Accidental coincidences

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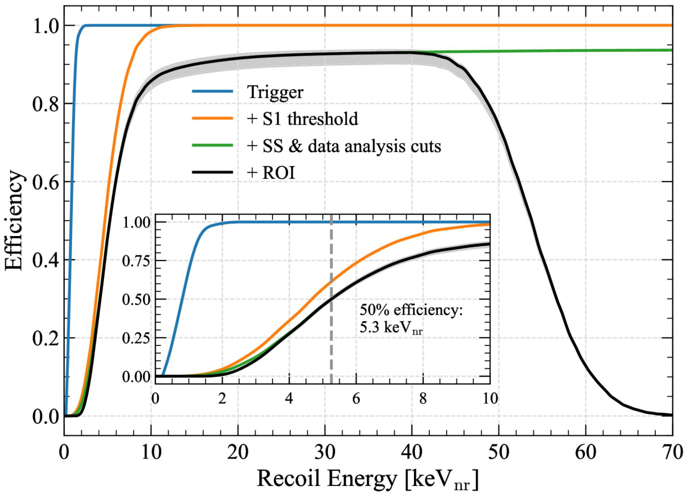
First Science Run

Data Selection

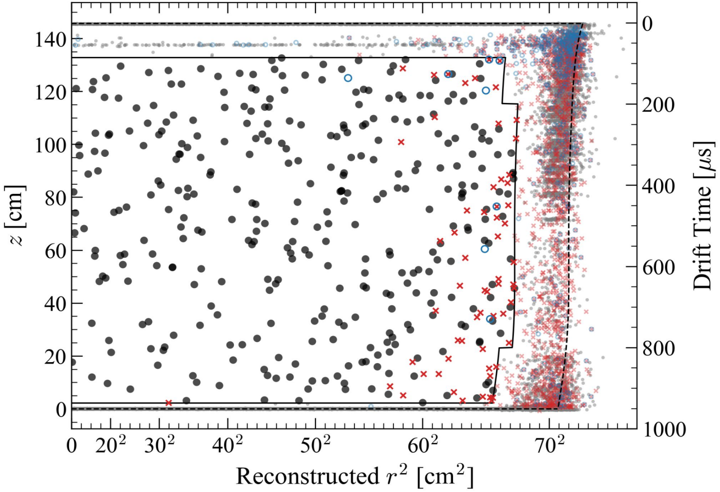
Time based cuts: detector instabilities, high TPC pulse rates → Pulse Shape Cuts → Single Scatter Cut → Fiducial Volume & RoI Cut → OD and Skin Veto Cut

Signal acceptance after all cuts: ~ 90 %



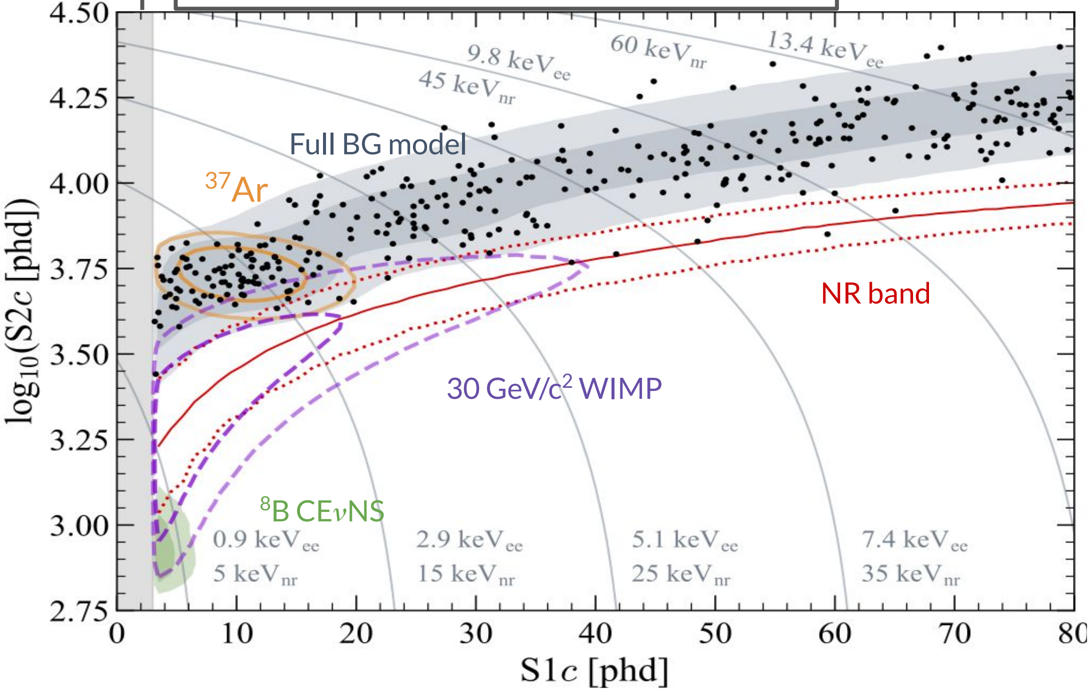
5.5 ± 0.2 tonne Fiducial volume

- Events surviving all selections
- Skin-prompt-tagged events
- OD-prompt-tagged events



Final Data Set

Threshold: S1 > 3 phd, S2 > 600 phd



- 335 events in final dataset
- 60 live days
- 5.5 ± 0.2 tonne Fiducial volume

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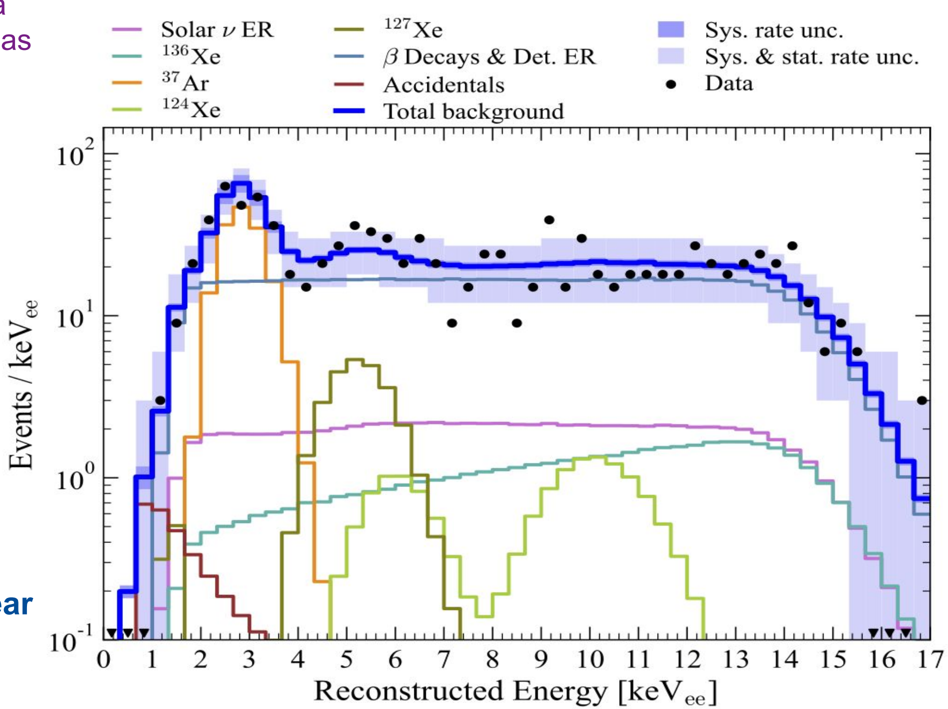
First Science Run

PLR fit to Background Model

Source	Expected Events (From LZ Background model)	Best Fit (Combined fit to data with expected events as priors)
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

25 counts/keV$_{ee}$/ton/year

Best fit with zero WIMP events



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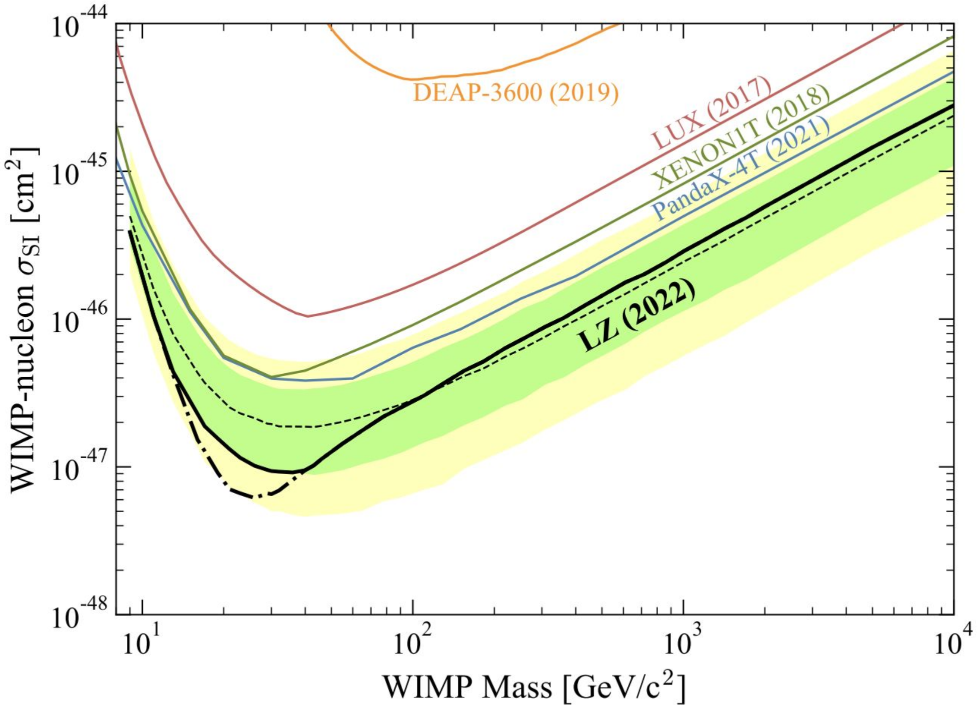
First Science Run

Spin Independent WIMP search



- Frequentist, two sided PLR following Phystat recommendations
- First result released July 7, 2022

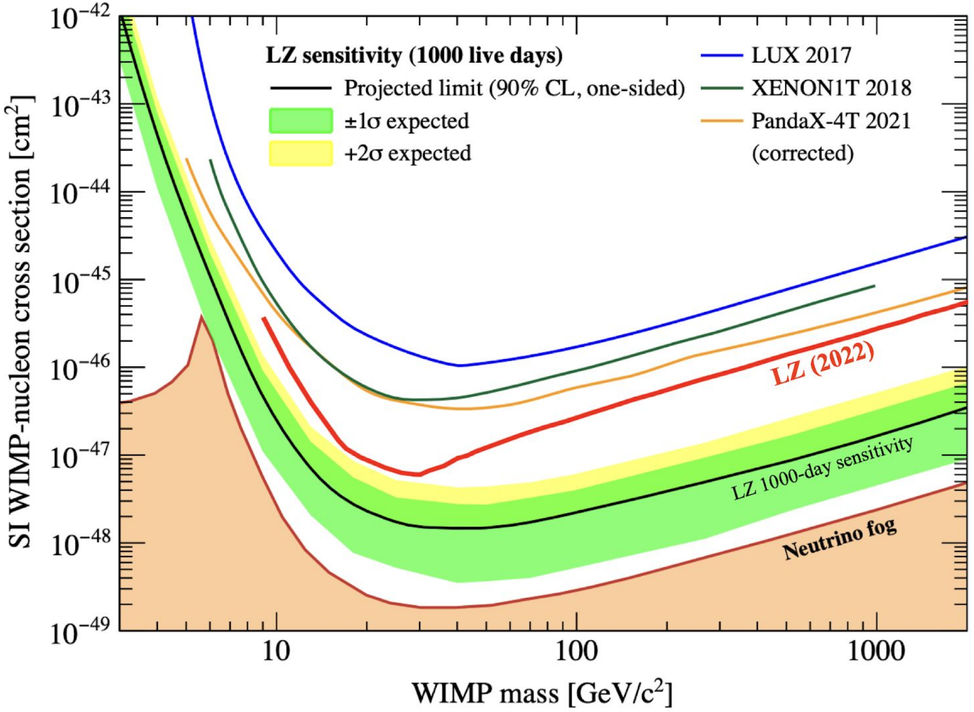
90% CL upper limit on WIMP-nucleon σ_{SI} :
9.2×10^{-48} cm^2 at 36 GeV/c^2 WIMP mass

WIMP sensitivity: Phys. Rev. D 101, 052002 (2020)
$0\nu\beta\beta$ ^{136}Xe: Phys. Rev. C 102, 014602 (2020)
Low energy ER: Phys. Rev. D 104, 092009 (2021)
$0\nu\beta\beta$ ^{134}Xe: Phys. Rev. C 104, 065501 (2021)

What's next?

Planning on **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**: 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



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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**
    - Paper: 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**
    - White paper: arXiv:2203.02309

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

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]

The LZ (LUX-ZEPLIN) Collaboration

@lzdarkmatter

https://lz.lbl.gov/

- 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

LZ Collaboration Meeting

University Of Maryland

5th-7th January 2023

36 Institutions: 250 scientists, engineers, and technical staff

Science and Technology Facilities Council

FCT Fundação para a Ciência e a Tecnologia

Sanford Underground Research Facility
South Dakota Science and Technology Authority

Institute for Basic Science

Thanks to our sponsors and participating institutions!

Backup slides

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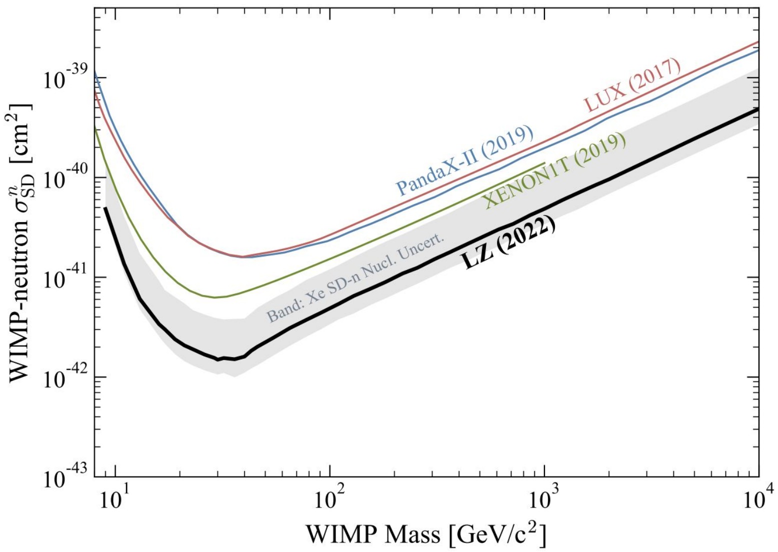
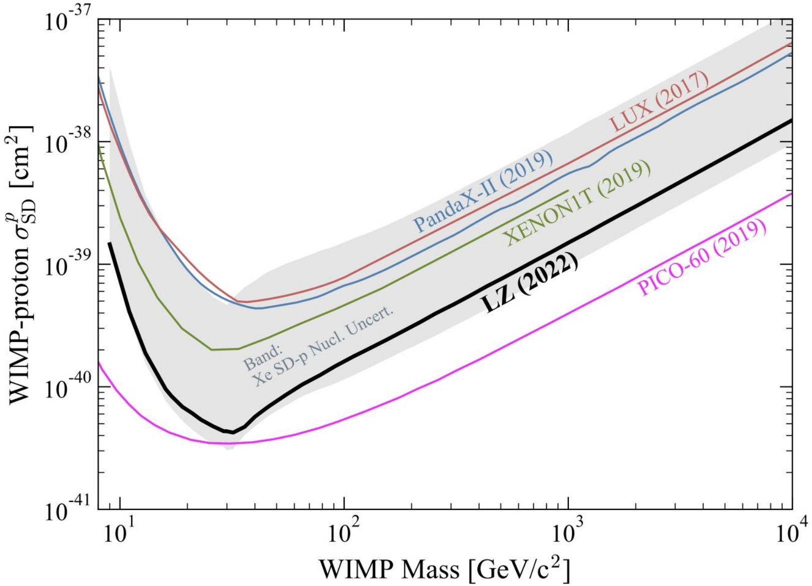
First Science Run

Spin dependent WIMP search

WIMP-neutron Scattering



WIMP-proton Scattering



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

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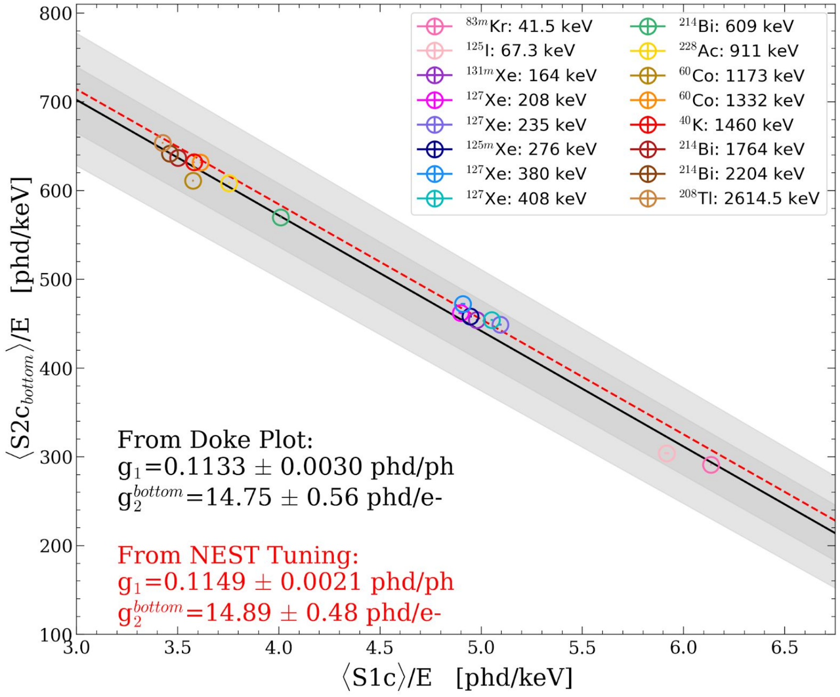
Detector response characterization

"Doke" plot



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

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

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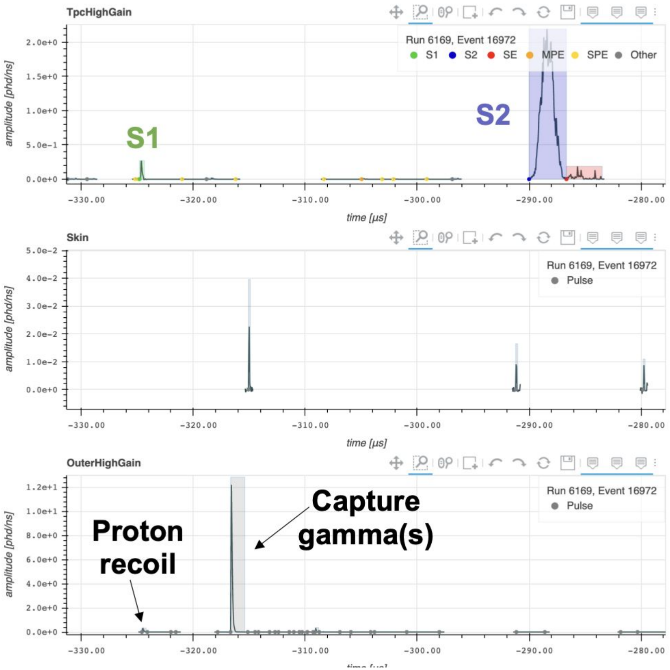
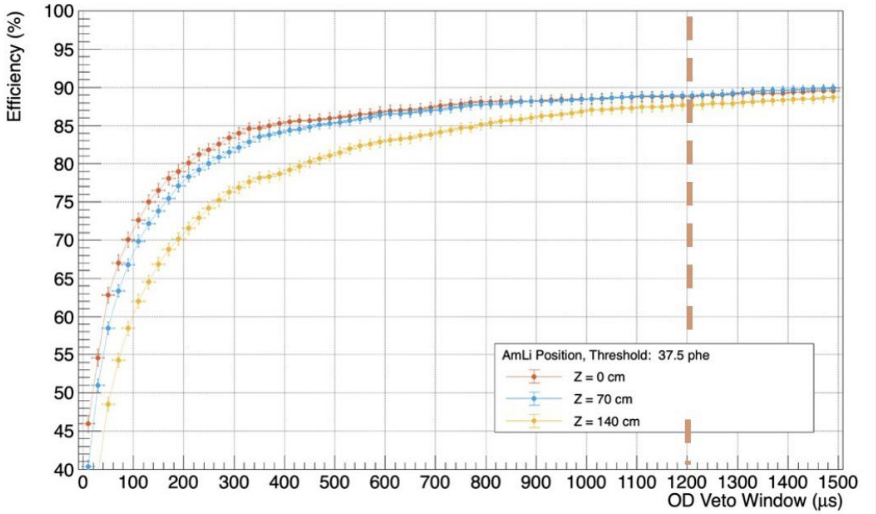
OD: neutron tagging

Real LZ AmLi calibration neutron event





OD neutron tagging settings:

- ≥ 200 keV
- Δt ≤ 1200 μs

Livetime hit: 5%

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Background Mitigation

Detector materials:

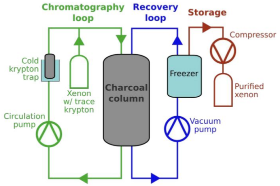
- Radio-assay campaign with 13 HPGe detectors, ICPMS, neutron activation analysis

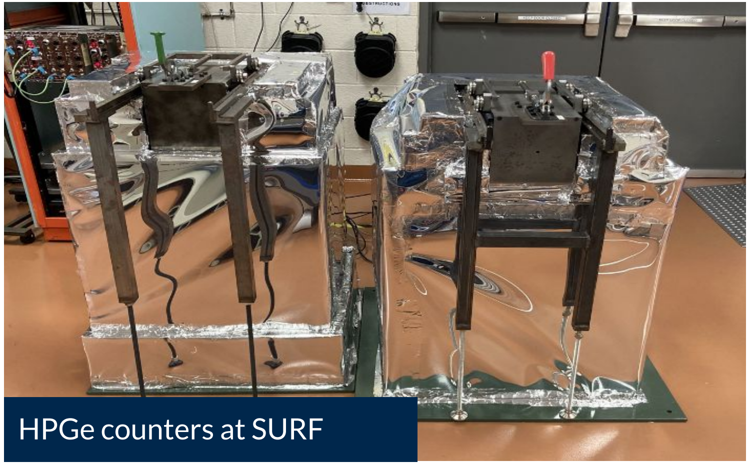
Rn daughters and dust on surfaces:

- TPC assembly in Rn-reduced cleanroom
- Dust <500 ng/cm^2 on all LXe wetted surfaces
- Rn-daughter plate-out on TPC walls <0.5 mBq/m^2

Xenon contaminants:

- Charcoal chromatography at SLAC (remove ^{85}Kr, ^{39}Ar)
- Continuous purification underground





HPGe counters at SURF

Kr-removal at SLAC

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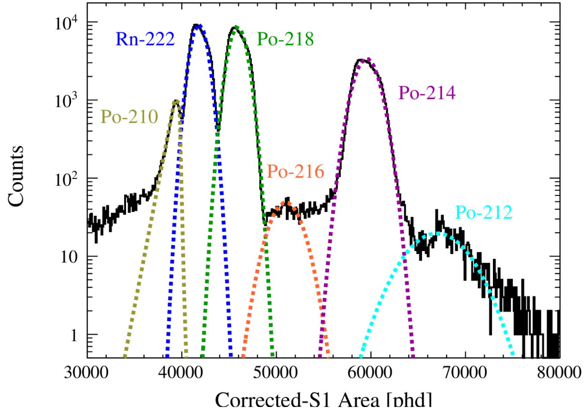
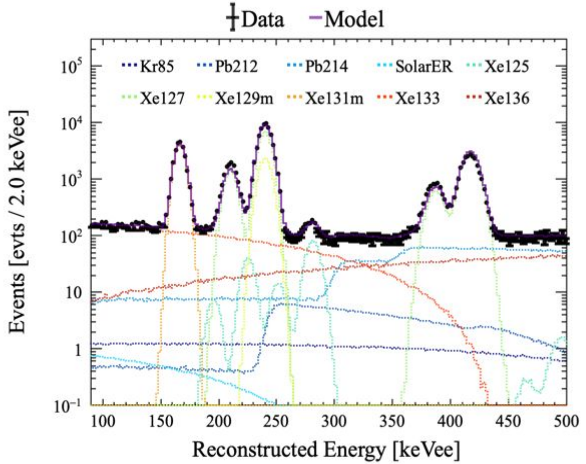
Radon Background

- Naked ^{214}Pb β-decays are the main source of background in the WIMP search
- Produced from 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

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





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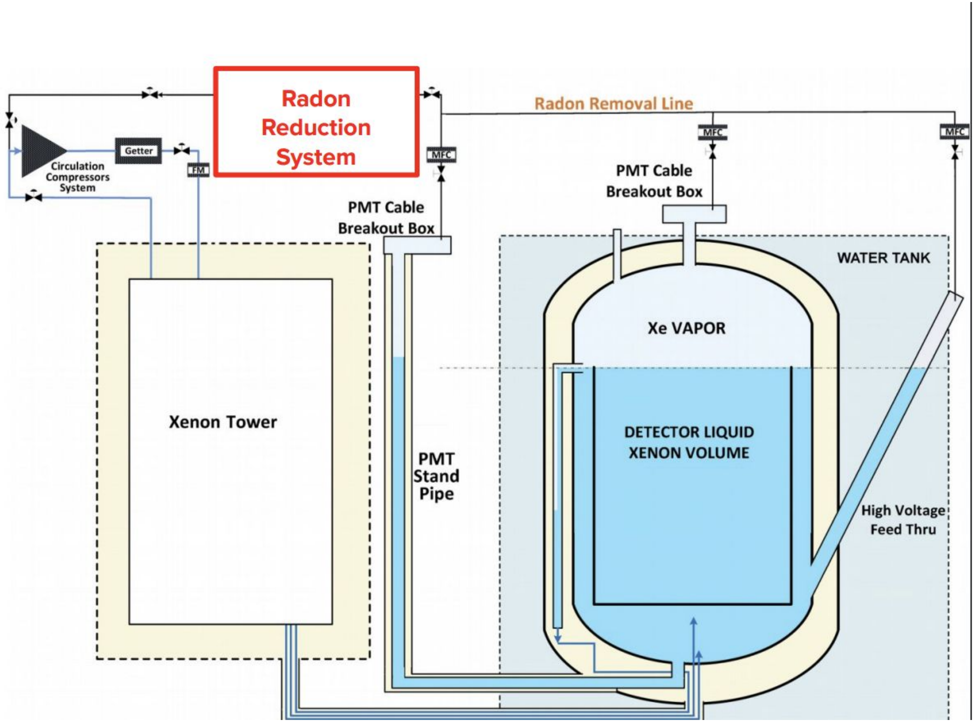
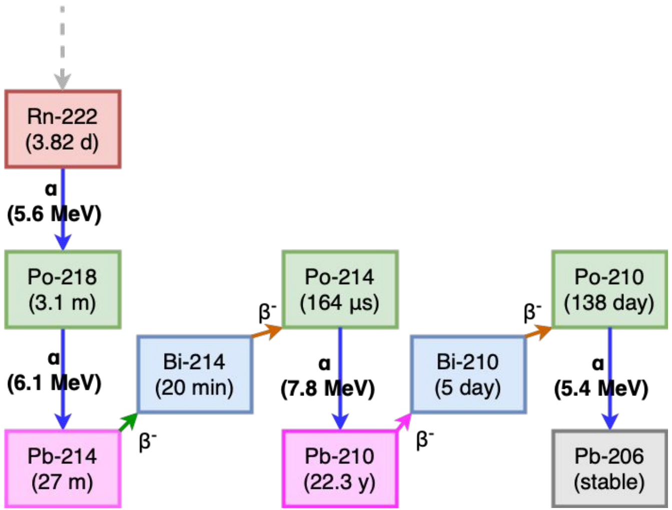
Radon reduction system

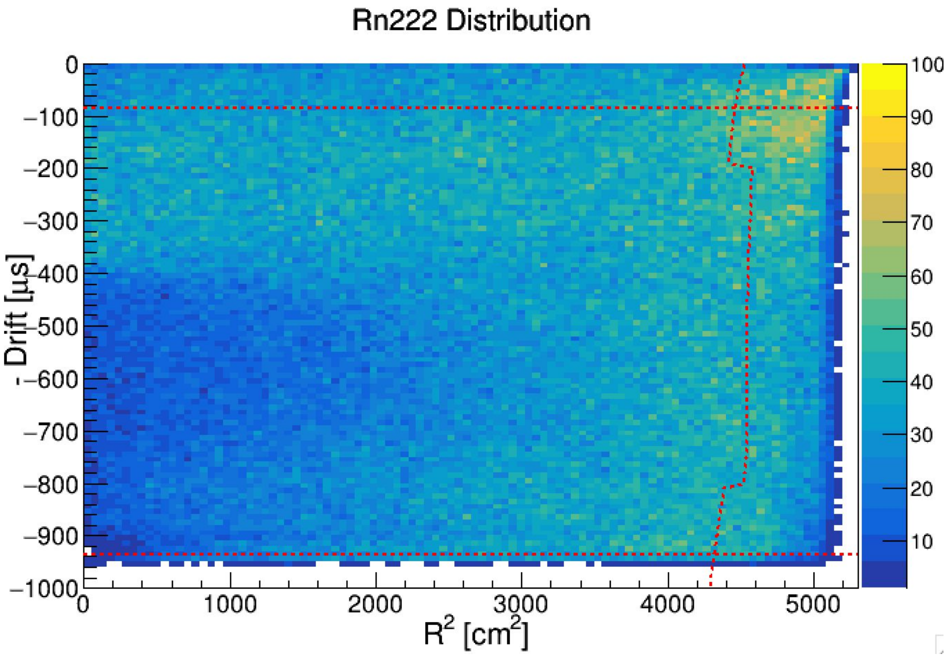


Radon Background

^{222}Rn not uniformly distributed.

Stratification in LXe flow is a possible tool to reject ^{214}Pb in future





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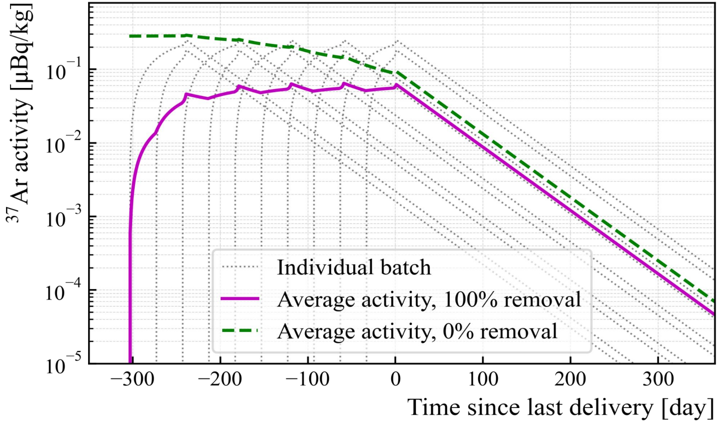
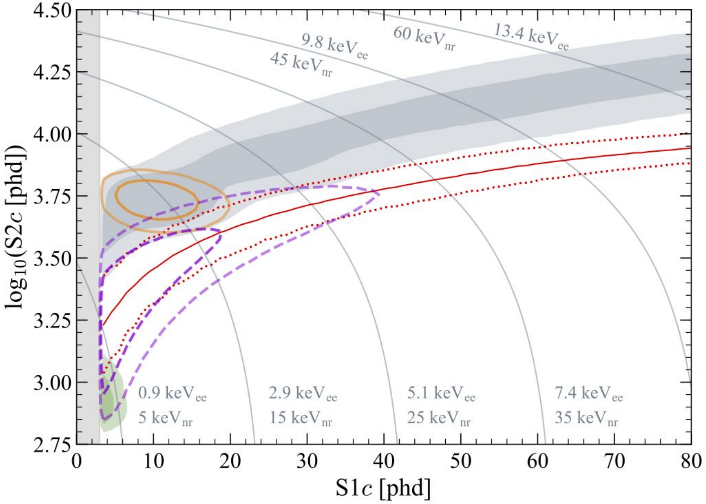
^{37}Ar

- 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





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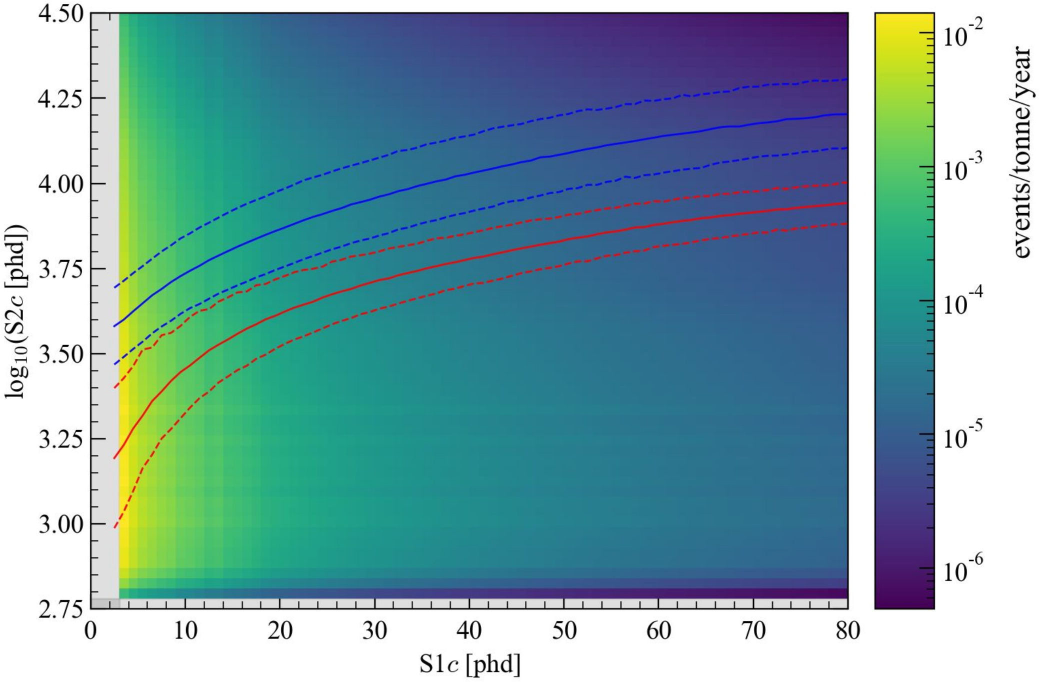
Accidentals

- Isolated S1 & S2 can accidentally combine to form WIMP ROI event
- Accidentals PDF generated from random pairing of isolated S1s and isolated S2s
- Normalize PDF to data using sideband:
  - Events with unphysical drift time (drift time > TPC height)
- Estimated rate of accidentals in first science run: **1.2 ± 0.3 events**



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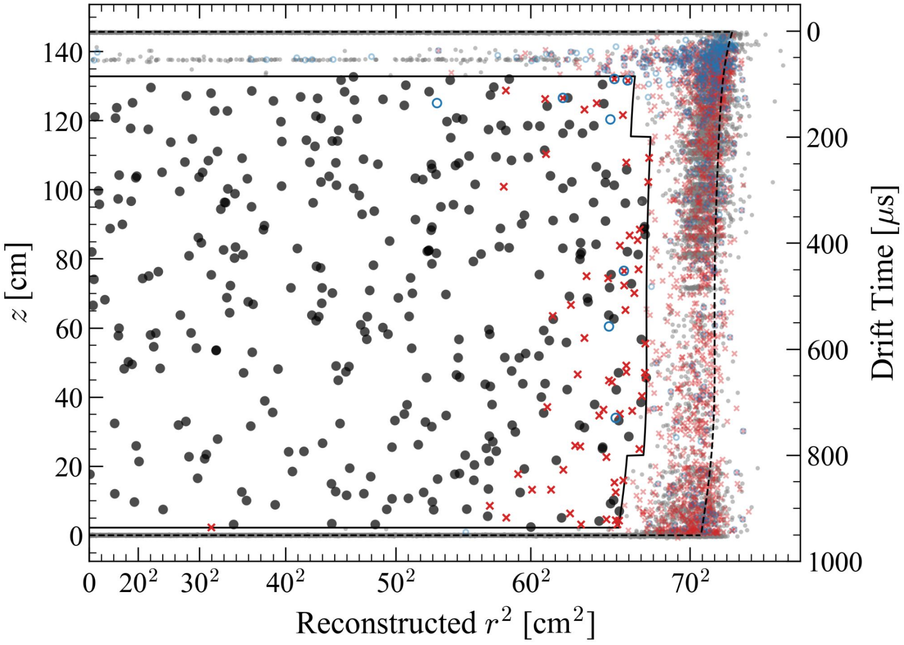
Fiducial Volume

- Inner **5.5 tonne fiducial volume** (FV) is lowest background and uniform
- Degraded S2s due to charge-loss effects (“wall BG”) drive poor position resolution near the wall
  - ➢ Choose S2 threshold and FV simultaneously, such that **wall BG is negligible** in this analysis

- **Skin and OD prompt tag**:
  - Removes gammas
  - Skin reduces bare L,M-shell ^{127}Xe background 5x
- **OD (and skin) delayed tag**:
  - 1200 μs capture window, ~200 keV threshold
  - Tag neutron capture
  - Provides *in situ* constraint on neutron BG: **$0^{+0.2}$ neutron events** in first science run



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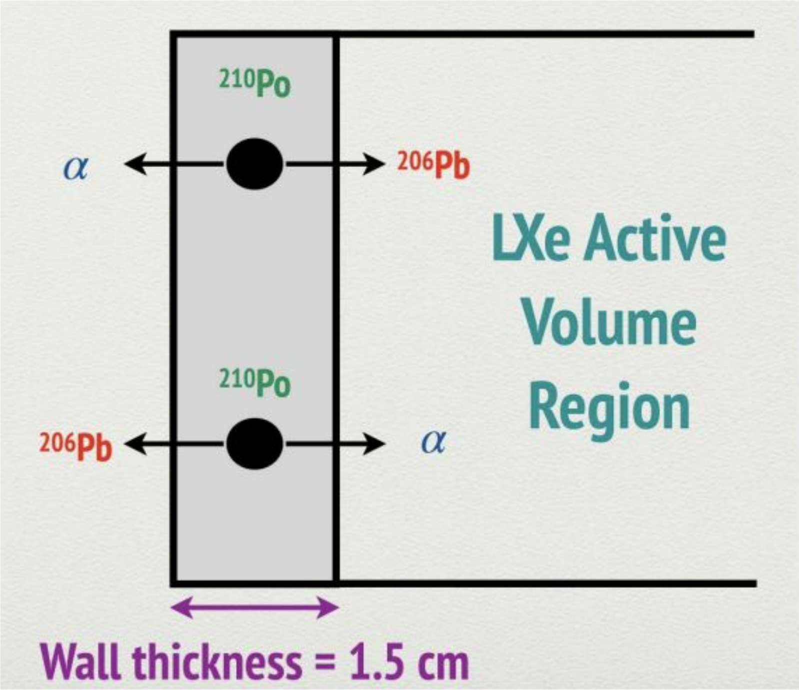
Wall Background



Background events arising from the internal wall of the TPC:

- S2 charge loss to the wall - reduction of observed S2 signal
  - Reduced S2 size due to field effect near the wall
- Pb-206 recoil from Pb-210 decay (Rn daughter plate-out)
- Fiducial volume cuts are set such that total wall background leakage events into fiducial volume is less than 0.01 count

Likelihood Function

$$\mathcal{L}(\boldsymbol{\theta}) = \left[\text{Pois}(n_0|\mu(\boldsymbol{\theta})) \prod_{e=1}^{n_0} \frac{1}{\mu(\boldsymbol{\theta})} \left(\mu_s f_s(\boldsymbol{x}_e|\boldsymbol{\theta}) + \sum_{b=1}^{N_c} \mu_b f_b(\boldsymbol{x}_e) \right)\right] \prod_{p=1}^{N_c} f_p(\boldsymbol{g}_p|\mu_p)$$

Parameters of interest: signal mean ($\boldsymbol{\mu}_s$)

Observables: (S1, S2)

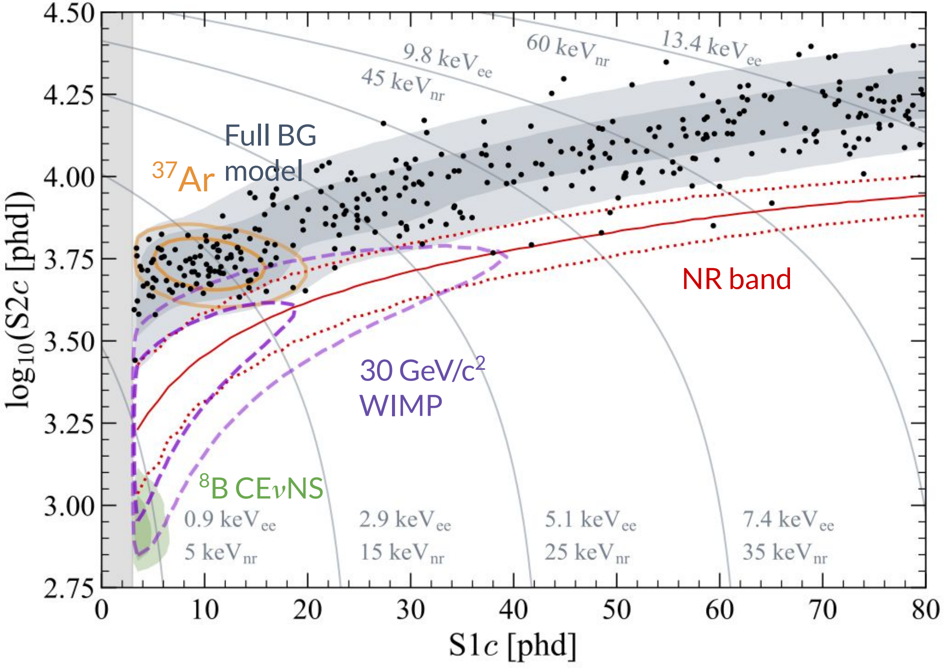
Nuisance parameters: background means

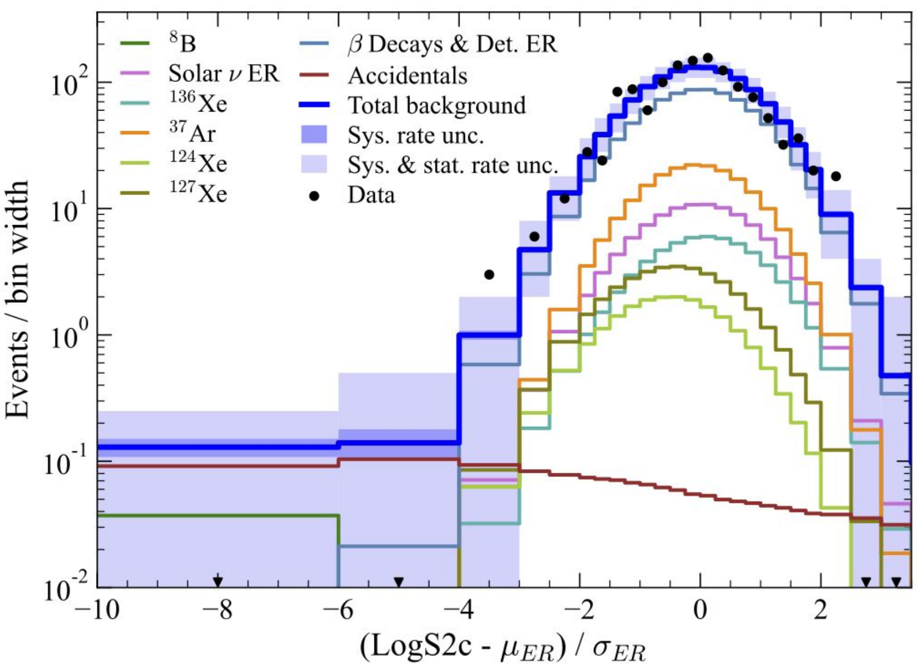
Extended term

Constraint functions

Global observables: expected events

ER-fluctuations within expectations





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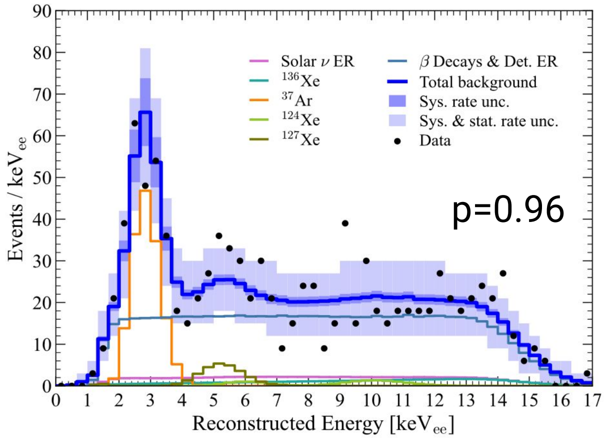
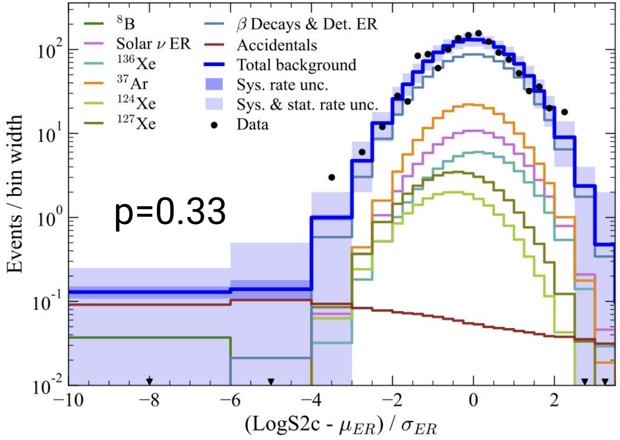
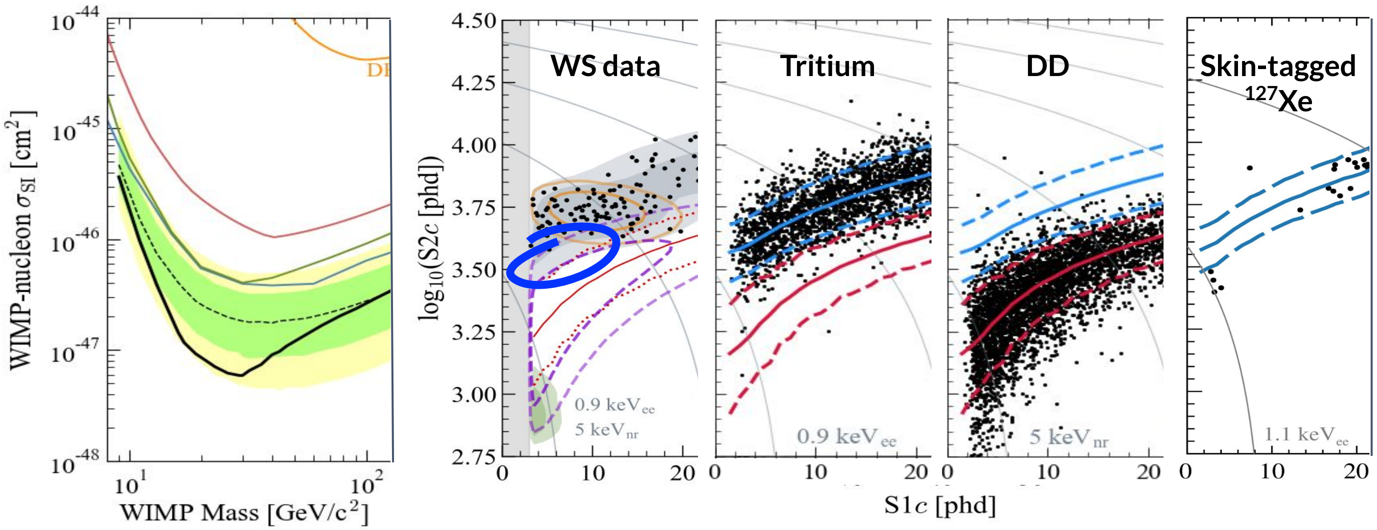
Why is the background only p-value “so good”?

- We chose the binning for the reconstructed energy spectrum to best show the resolution of the 37Ar peak
- If we look at other observables (e.g. reduced ER band) or rebinning in Erec, the p-value returns other values, which show that the data is not inconsistent with the background-only model
- This appears to be a random fluctuation





Downward fluctuations



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.

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