Backgrounds in the LZ Dark Matter Experiment

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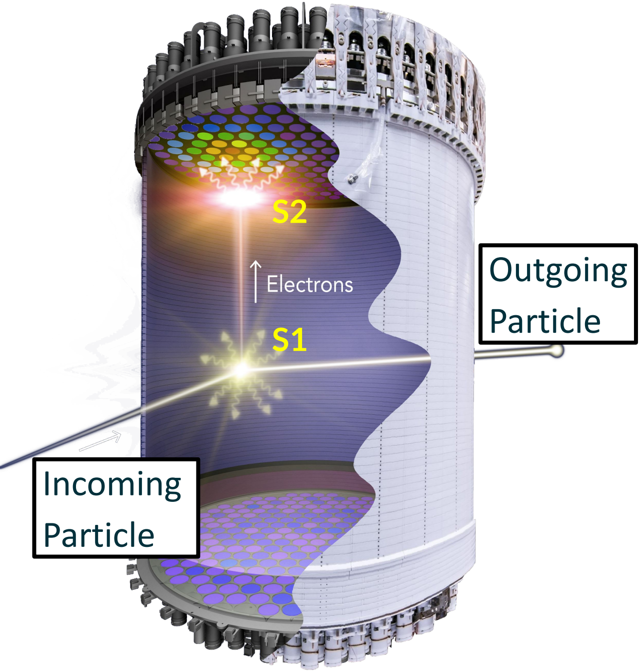
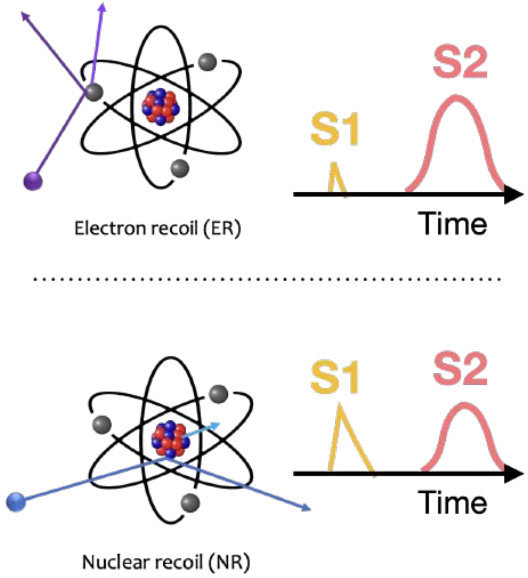
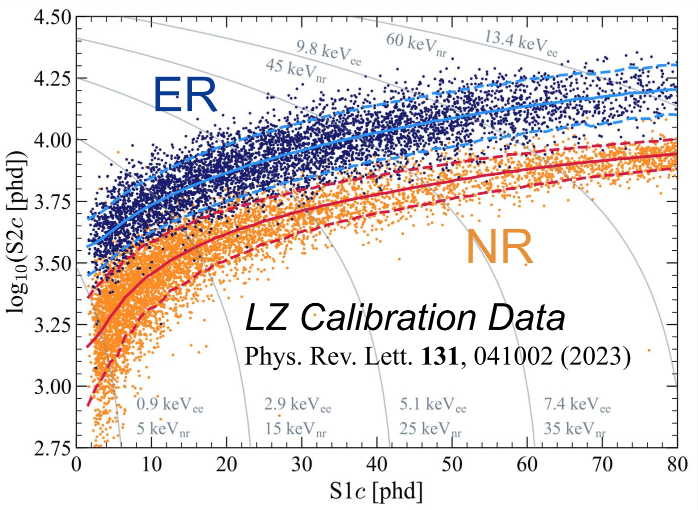
Lawrence Berkeley National Lab
On behalf of the LUX-ZEPLIN (LZ) Collaboration

ICHEP July 18, 2024

Dual-Phase Time Projection Chamber (TPC)







- LZ utilizes 7 tonne active xenon volume → Self-shielding and purifiable ⇒ low background
- S1 and S2 signals → Strong 3D position reconstruction and single vs multiple scatter resolution
- S1-S2 ratio → Particle discrimination between electron recoils (**ER**) and nuclear recoils (**NR**)

Signals and Backgrounds

Signals:

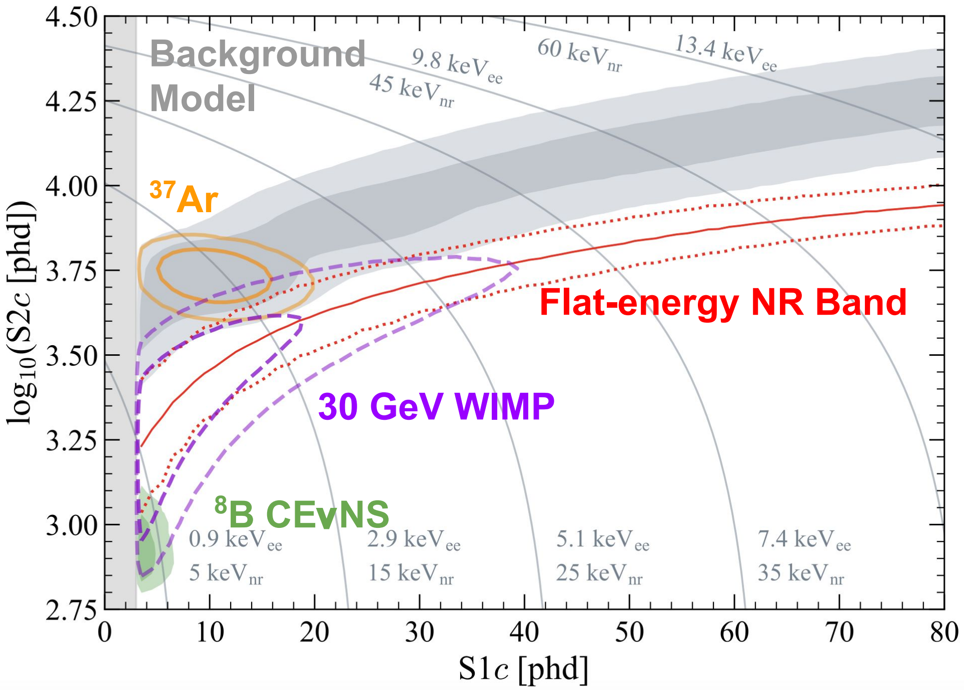
- Single scatter nuclear recoil (NR) of DM candidate (e.g. WIMP)

Backgrounds:

- Single scatter neutrons and CEνNS neutrino recoils
  - ***Neutrons vetoed with (89 ± 3)% efficiency***
- Low energy betas and single scatter gammas
  - ***99.75% ER-NR discrimination***

Why's it matter?

- Need strong control and understanding of backgrounds to claim DM discovery!



Background model from first science results

Backgrounds In The TPC

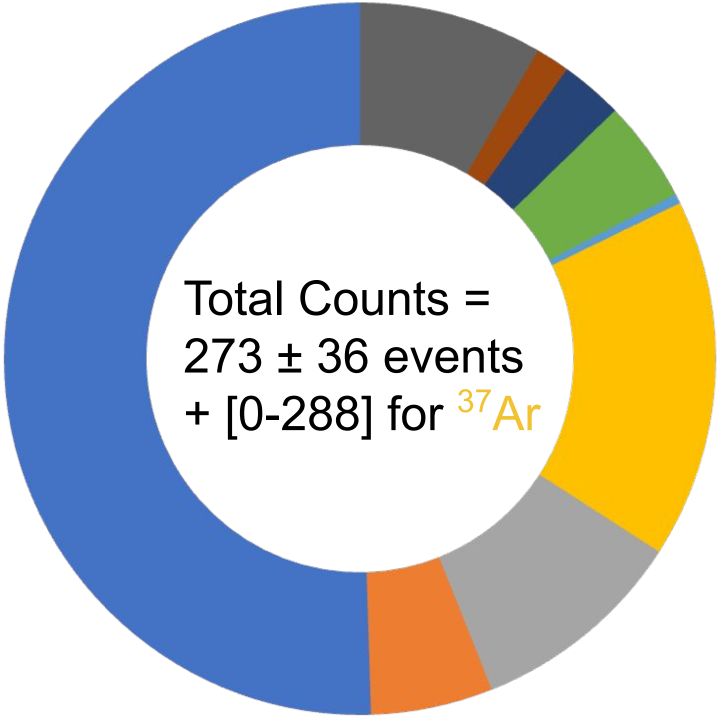
Xenon Contaminants
(ER Backgrounds)

- ^{214}Pb (β in ^{222}Rn chain)
- ^{212}Pb (β in ^{220}Rn chain)
- ^{85}Kr (β)
- ^{124}Xe (2νECEC)
- ^{136}Xe (2$\nu\beta\beta$)
- ^{127}Xe (EC)

Detector Materials

ER Backgrounds
- ^{238}U, ^{232}Th, ^{40}K, ^{60}Co

NR Backgrounds (< 0.2)
- Neutrons from (α,n) and spontaneous fission



Neutrinos

ER Backgrounds (ν-e$^-$)
- Solar-ν: pp + ^{7}Be + CNO

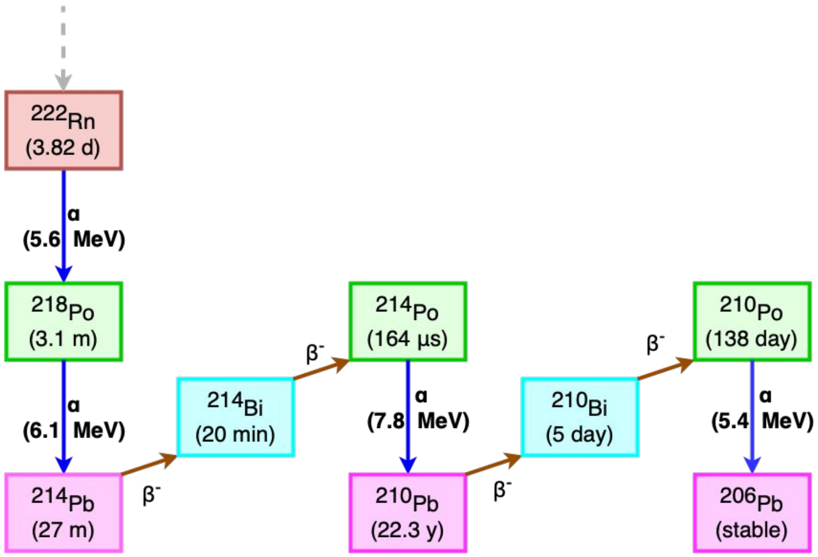
NR Backgrounds (CEνNS)
- Solar-ν: ^{8}B, HEP
- Atmospheric ν
- Diffuse supernova ν

Accidental Coincidences

- Coincidences of isolated S1 and S2 pulse (largely removed by analysis cuts)

^{214}Pb (β in ^{222}Rn chain)

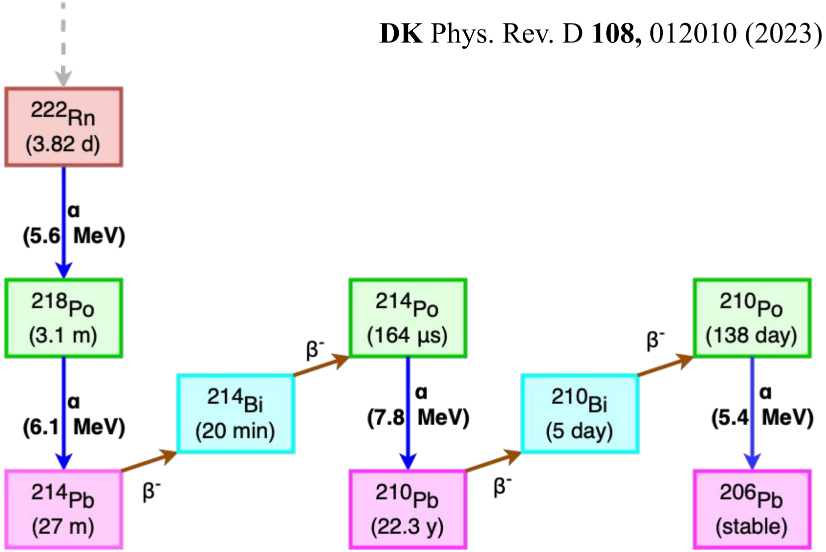
- ^{222}Rn emanates from ^{238}U present in detector materials and diffuses/mixed within the LXe
- Betas from ^{214}Pb is largest low energy background



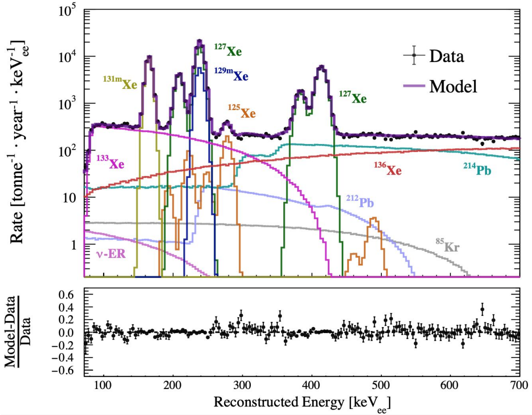
DK Phys. Rev. D 108, 012010 (2023)

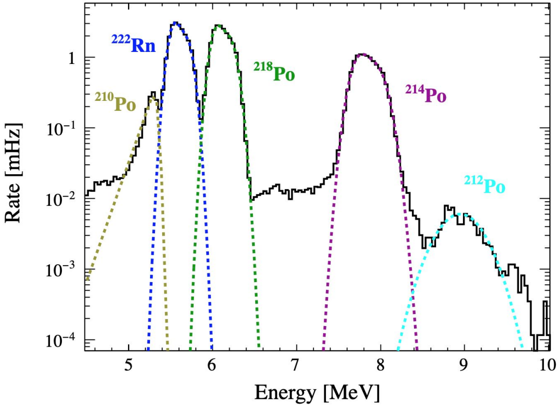
^{214}Pb (β in ^{222}Rn chain)

- ^{222}Rn emanates from ^{238}U present in detector materials and diffuses/mixed within the LXe
- Betas from ^{214}Pb is largest low energy background
- ^{214}Pb can be inferred from measuring alphas or from direct fits to background



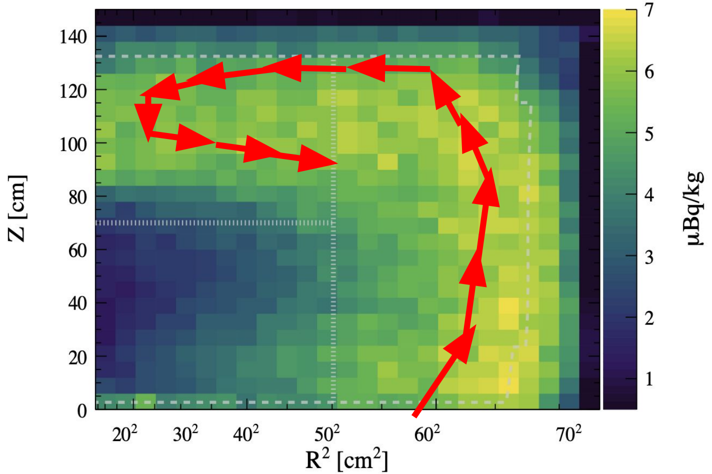
Measured ^{214}Pb rate:
3.26 ± 0.17 μBq/kg
in first science run





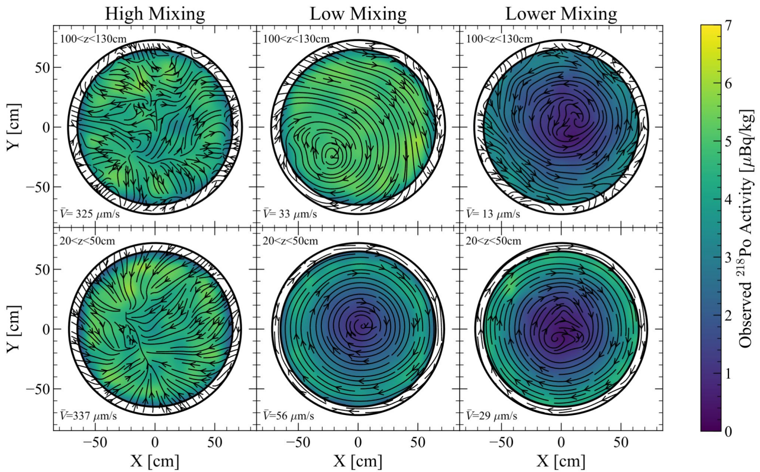
Xenon Flow Modeling

- Observations of $^{222}Rn/^{218}Po$ and calibration injections indicate laminar mixing state within TPC
- Can use ^{222}Rn-^{218}Po pairs to build a map of the xenon flow
- **Demonstrated strong control and understanding of Xe flow and mixing in TPC!**



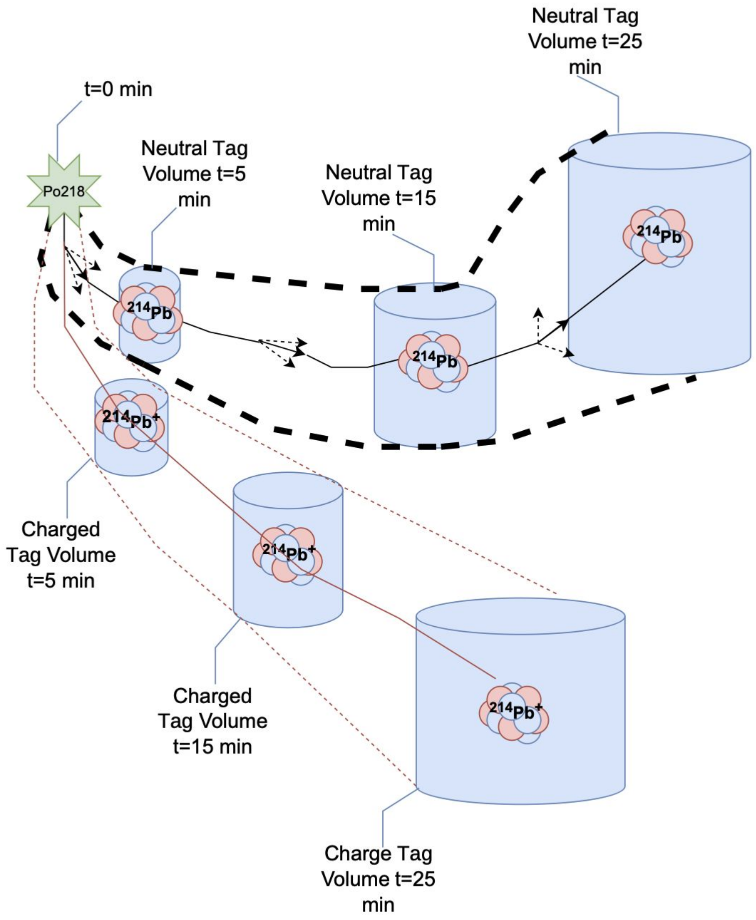
Observed distribution of ^{218}Po and sketch of Xe flow

^{218}Po rate and Xe flow in different Xe mixing states



^{214}Pb Tagging

- Observations of ^{222}Rn/^{218}Po and calibration injections indicate laminar mixing state within TPC
- Can use ^{222}Rn-^{218}Po pairs to build a map of the xenon flow
- Define time-space voxels within TPC following ^{218}Po event to tag ^{214}Pb backgrounds
- Likelihood is split into tagged and untagged data-sets (no data is explicitly removed)
  - Tagged data has reduced ^{214}Pb background!

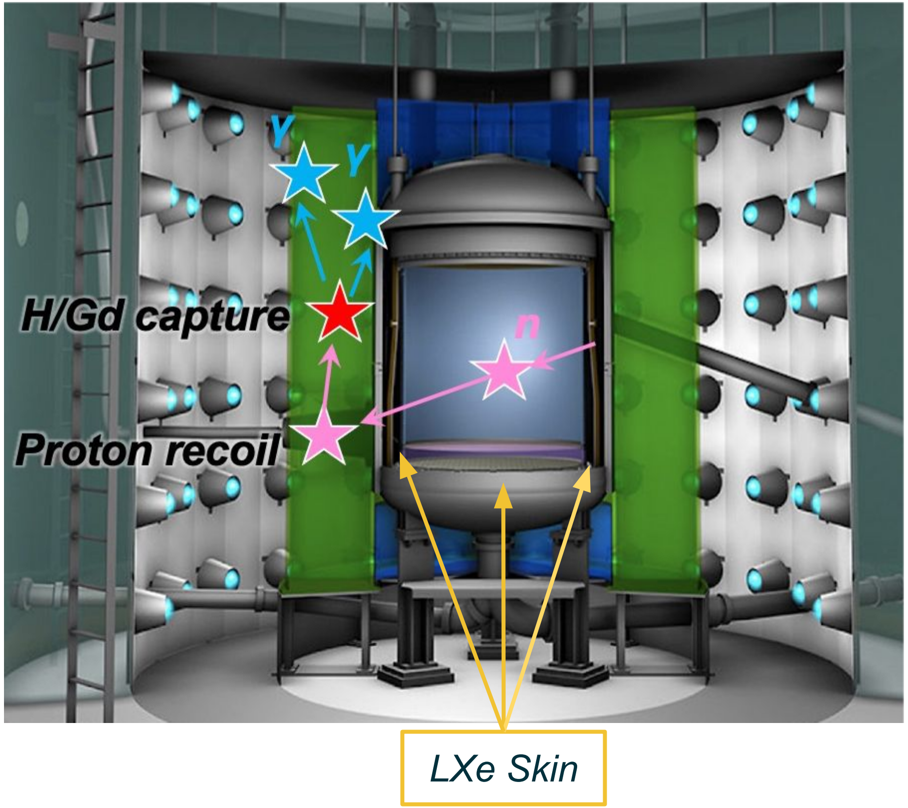


Preliminary performance: ~68% of ^{214}Pb events tagged within ~9% of total exposure

Neutron Backgrounds

- LZ utilizes a two-component active veto system:
  - 2 tonne optically-isolated LXe Skin
  - 17 tonnes liquid scintillator outer detector (OD) doped with 0.1% Gd by mass
- Ultra-pure water tank equipped with 120 PMTs and tyvek reflector

Acrylic tanks containing Gd-LS in green and blue



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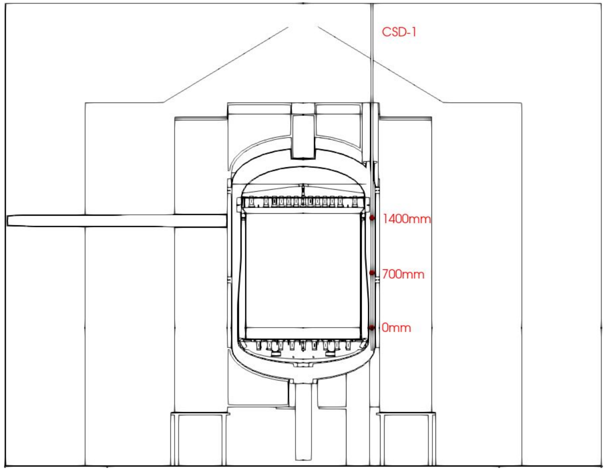
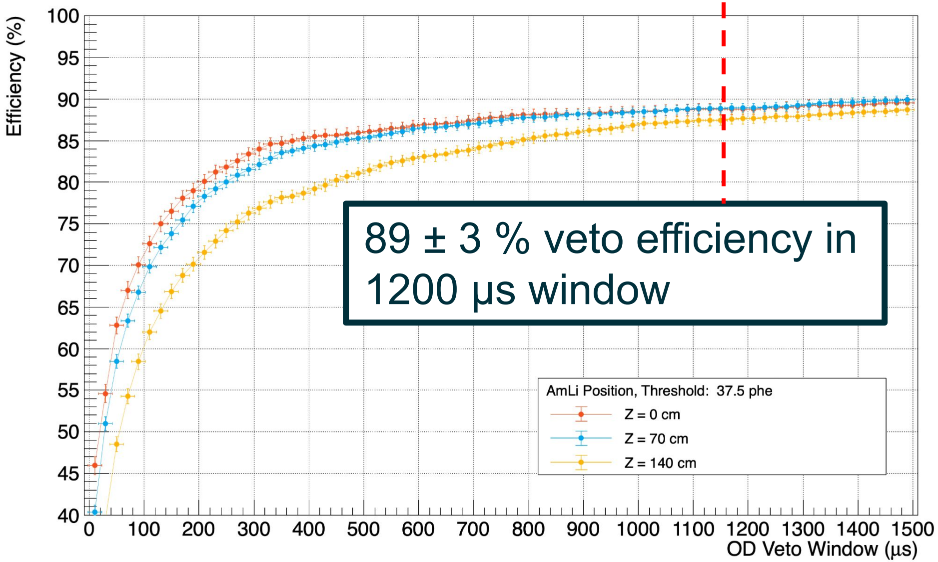
  - 2 tonne optically-isolated LXe Skin
  - 17 tonnes liquid scintillator outer detector (OD) doped with 0.1% Gd by mass
- Ultra-pure water tank equipped with 120 PMTs and tyvek reflector
- Neutron veto efficiency quantified using AmLi deployed at different Z-heights spanning full TPC

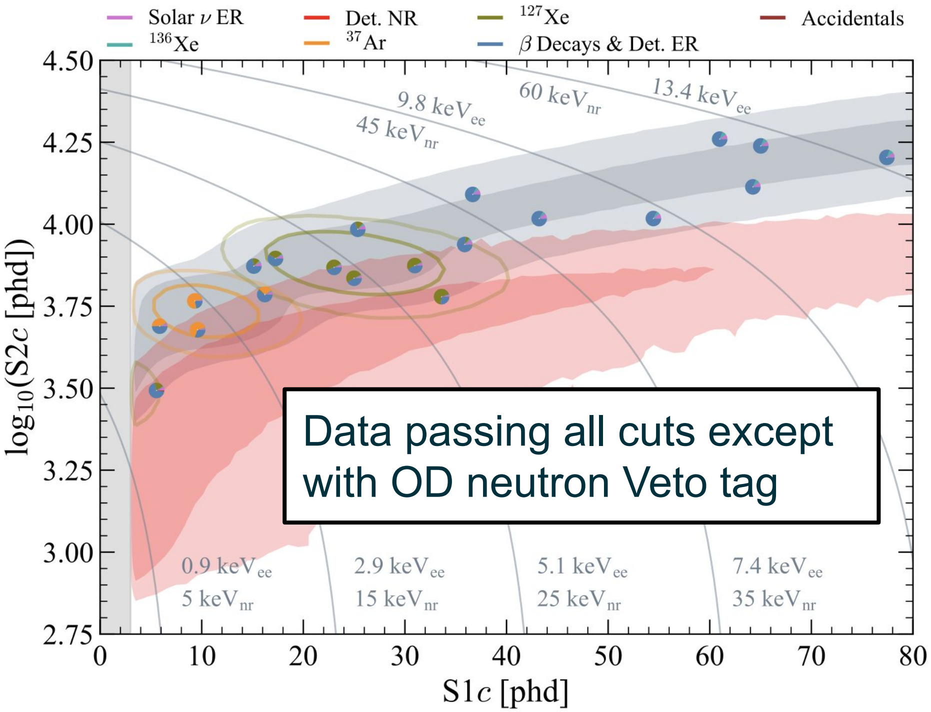




DK Phys. Rev. D **108,** 012010 (2023)

Neutron Backgrounds

- Neutron constraint in background model determined by performing simultaneous fit to OD-tagged data-set
- Data-driven constraint on the rate of Detector neutrons: **<u>< 0.2 events</u> in 60 livedays and 5.5 tonnes LXe**
- In agreement with simulation-driven prediction!



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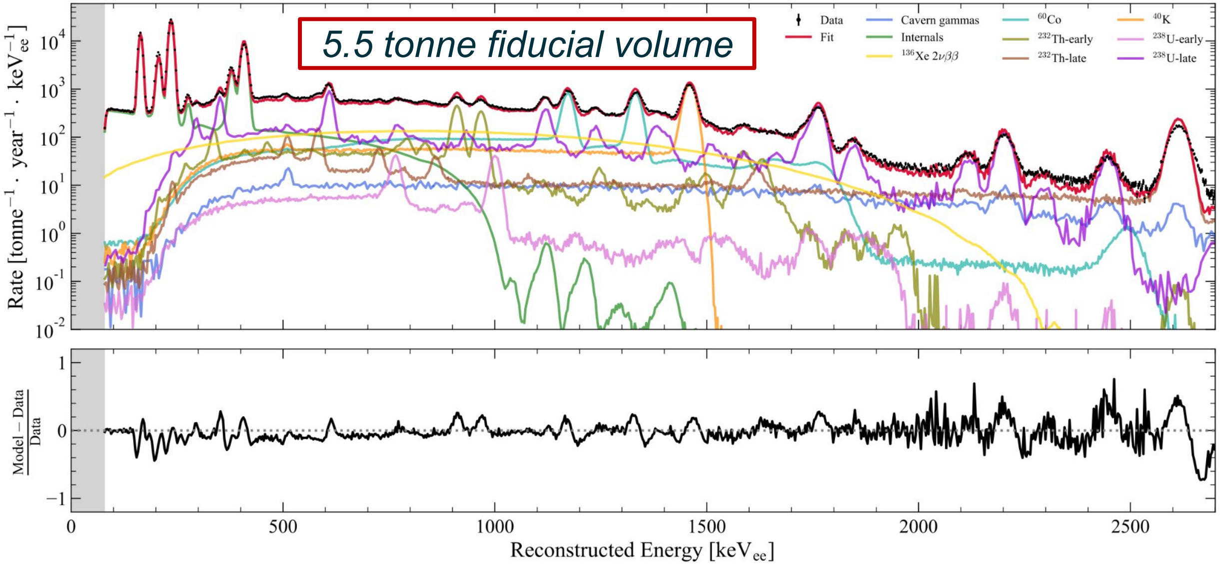
High Energy Fits

- Spectral fits performed *in situ* to measure rate of external detector backgrounds
- Fit results agree with radioassays performed during detector construction

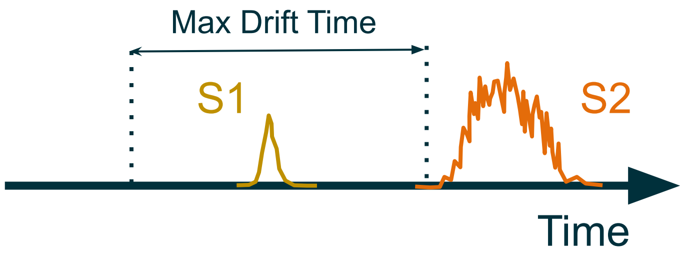


Isotope/ Chain	Region	Screening estimate [Bq]	Best fit [Bq]
^{60}Co	Top	1.13 ± 0.11	1.05 ± 0.11
	Side	1.18 ± 0.12	1.12 ± 1.02
	Bottom	0.81 ± 0.08	1.53 ± 0.19
	Total	3.11 ± 0.18	3.71 ± 1.04
^{40}K	Top	7.63 ± 0.76	2.94 ± 1.66
	Side	2.56 ± 0.26	6.32 ± 0.61
	Bottom	6.54 ± 0.65	5.58 ± 2.19
	Total	16.73 ± 1.04	14.85 ± 2.81
^{232}Th-early	Top	0.28 ± 0.03	0.33 ± 0.29
	Side	0.66 ± 0.07	0.66 ± 0.49
	Bottom	0.22 ± 0.02	0.23 ± 0.17
	Total	1.16 ± 0.07	1.22 ± 0.59
^{232}Th-late	Top	0.25 ± 0.02	0.11 ± 0.16
	Side	1.05 ± 0.10	2.57 ± 1.75
	Bottom	0.30 ± 0.03	0.32 ± 0.27
	Total	1.59 ± 0.11	3.00 ± 1.78
^{238}U-early	Top	2.37 ± 0.24	3.70 ± 1.80
	Side	1.99 ± 0.20	3.92 ± 1.53
	Bottom	1.86 ± 0.19	2.72 ± 1.40
	Total	6.21 ± 0.36	10.34 ± 2.75
^{238}U-late	Top	0.84 ± 0.08	0.63 ± 0.30
	Side	0.54 ± 0.05	3.01 ± 0.61
	Bottom	0.95 ± 0.09	1.28 ± 0.73
	Total	2.32 ± 0.14	4.92 ± 1.00

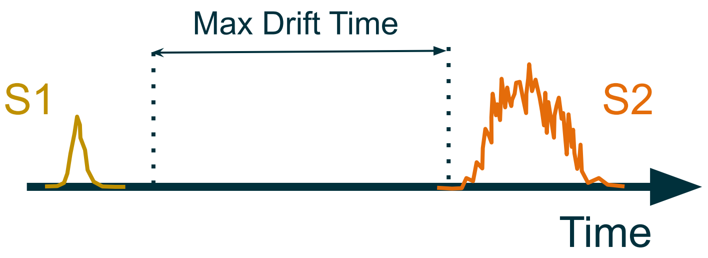
Accidental Coincidences

- Uncorrelated, isolated S1s and S2s can occur within an event window and mimic a real single-scatter event
- Marker of accidental events are those with drift time > length of active volume (*unphysical drift time*)
  - **Rate** determined using this sideband of events
- **Shape** of spectra determined by randomly pairing lone S1s and lone S2s
- Analysis cuts utilized to target specific event/pulse topologies
  - **99.6% rejection!**

Possible Physical Event



Definite Accidental Event

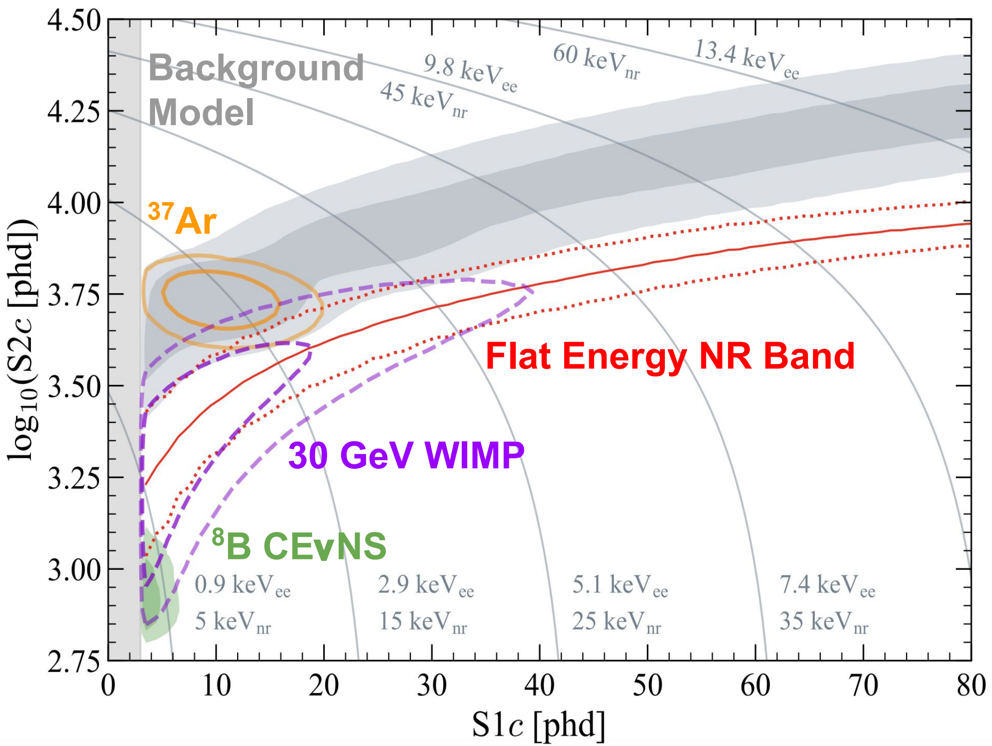


1.2 ± 0.3 events in 60 live-days

Phys. Rev. Lett. **131**, 041002 (2023)
DK Phys. Rev. D **108,** 012010 (2023)

First Science Run BG Model

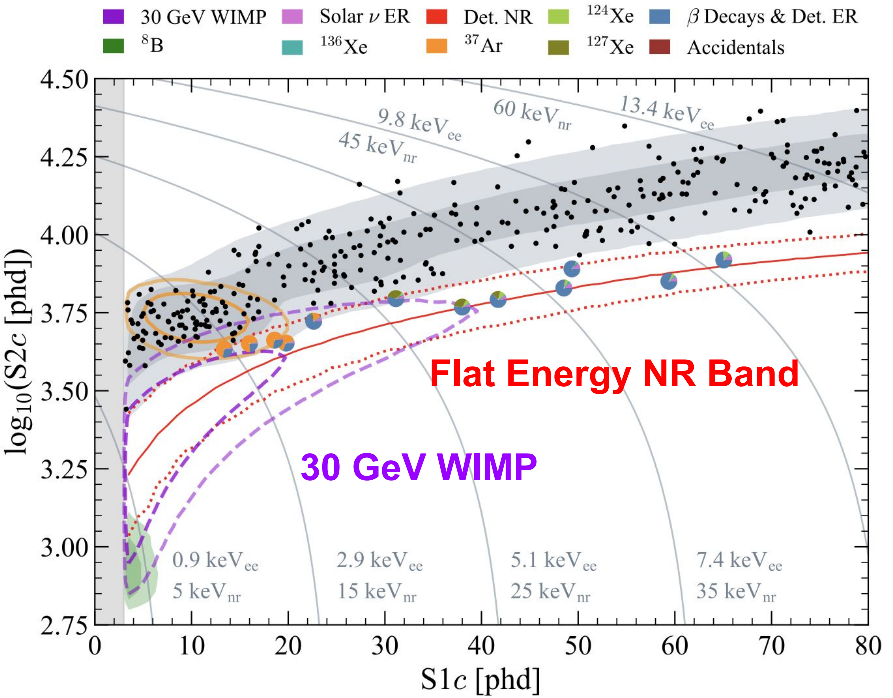
Source	Expected Events
^{214}Pb	164 ± 35
^{212}Pb	18 ± 5
^{85}Kr	32 ± 5
Det. ER	1.2 ± 0.4
β decays + Det. ER	215 ± 36
ν ER	27.1 ± 1.6
^{127}Xe	9.2 ± 0.8
^{124}Xe	5.0 ± 1.4
^{136}Xe	15.1 ± 2.4
^{8}B CEνNS	0.14 ± 0.01
Accidentals	1.2 ± 0.3
Subtotal	273 ± 36
^{37}Ar	[0, 288]
Detector neutrons	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–
Total	–



Phys. Rev. Lett. **131**, 041002 (2023)
DK Phys. Rev. D **108,** 012010 (2023)

First Science Run BG Model

Source	Expected Events	Fit Result
^{214}Pb	164 ± 35	-
^{212}Pb	18 ± 5	-
^{85}Kr	32 ± 5	-
Det. ER	1.2 ± 0.4	-
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17



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

BG Model Going Forward

Source	Expected Events
^{214}Pb	164 ± 35
^{212}Pb	18 ± 5
^{85}Kr	32 ± 5
Det. ER	1.2 ± 0.4
β decays + Det. ER	215 ± 36
ν ER	27.1 ± 1.6
^{127}Xe	9.2 ± 0.8
^{124}Xe	5.0 ± 1.4
^{136}Xe	15.1 ± 2.4
^{8}B CEνNS	0.14 ± 0.01
Accidentals	1.2 ± 0.3
Subtotal	273 ± 36
^{37}Ar	[0, 288]
Detector neutrons	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–
Total	–

Expect to tag >60% of these in future analyses and runs!

Well characterized and rejected via in analysis

Decaying and won't be present in future runs

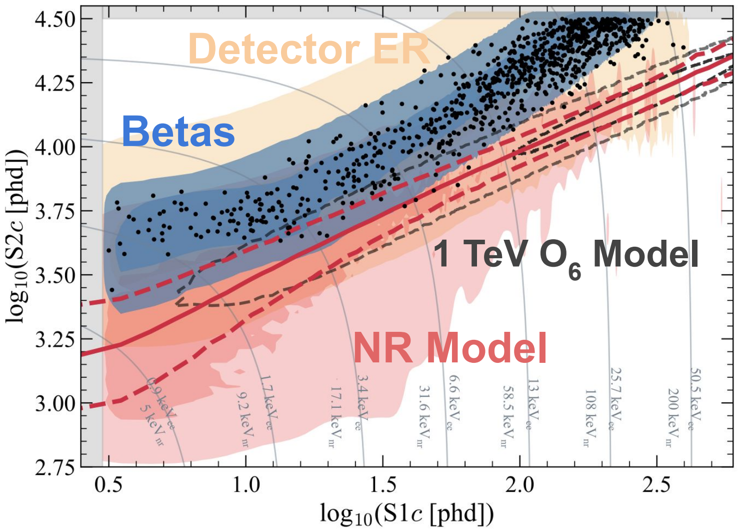
Strongly vetoed by Gd liquid scintillator and consistent with sims-driven prediction

Phys. Rev. D **109**, 092003 (2024)
arXiv:2404.17666

Higher Energy Background Model

- Backgrounds also well characterized and modeled at higher energies
- Allows for probing suite of effective field theory (EFT) operators describing DM interactions with higher recoil energies
  - Probing many of these interactions only possible using isotopes with nuclear spin e.g. ^{129}Xe (spin 1/2, 26.4% abund.) and ^{131}Xe (spin 3/2, 21.2% abund.)

Source	Expected Events	Fit Result
Flat ER	517.4 ± 82.8	574.7 ± 30.2
Detector ER	18.4 ± 9.2	22.3 ± 8.1
ν ER	55.3 ± 5.5	55.5 ± 5.5
^{124}Xe	8.2 ± 2.0	8.7 ± 2.0
^{127}Xe	20.5 ± 1.8	20.8 ± 1.8
^{136}Xe	55.1 ± 11.6	58.2 ± 11.2
^{125}I	30.1 ± 15.6	34.2 ± 8.9
^{8}B CEνNS	0.14 ± 0.01	0.14 ± 0.01
Accidentals	1.3 ± 0.3	1.3 ± 0.03
Subtotal	706 ± 86	775 ± 34
^{37}Ar	[0, 288]	49.5 ± 9.4
Detector neutrons	$0.0^{+0.5}$	$0.0^{+1.8}$
Total	-	825 ± 36



Parting Thoughts

- Strong control/understanding of backgrounds across multiple energy regimes allows for world-leading limits and discovery potential to NR-producing DM candidates
  - Many physics results already out with first data-set
- Strong control of thermodynamics + laminar flow allows for tagging ^{214}Pb
  - Can tag ~68% of ^{214}Pb!
  - ^{214}Pb tagging and flow mapping will be exploited in future analyses and science runs (see upcoming paper!)
- Stay tuned for future results coming soon…

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

250 scientists, engineers, and technical staff

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
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- University of Michigan
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- University of Rochester
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- University of Texas at Austin
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Backup

Phys. Rev. Lett. **131**, 041002 (2023)
DK Phys. Rev. D **108,** 012010 (2023)

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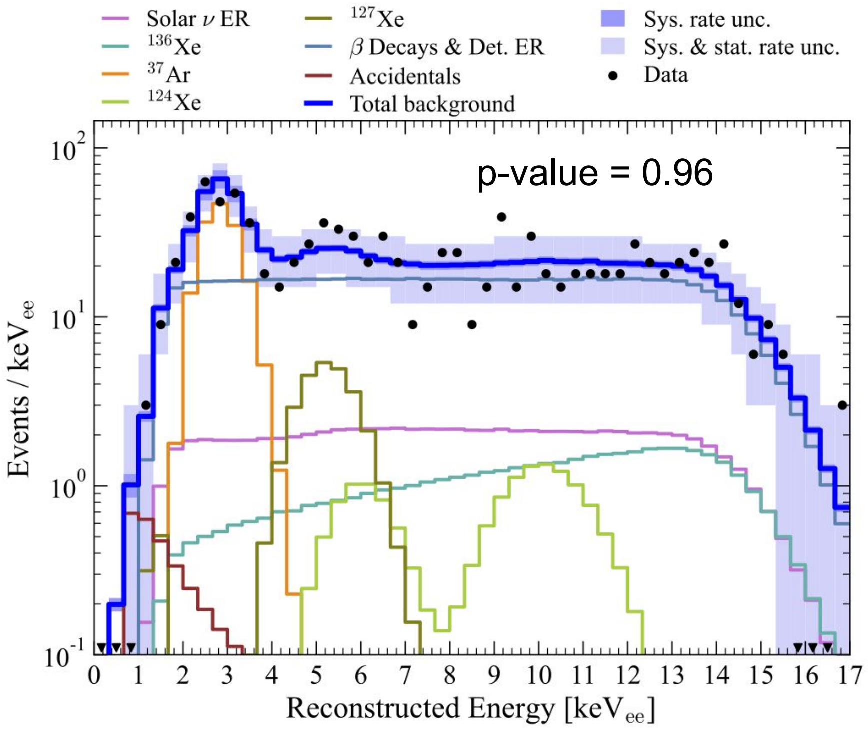
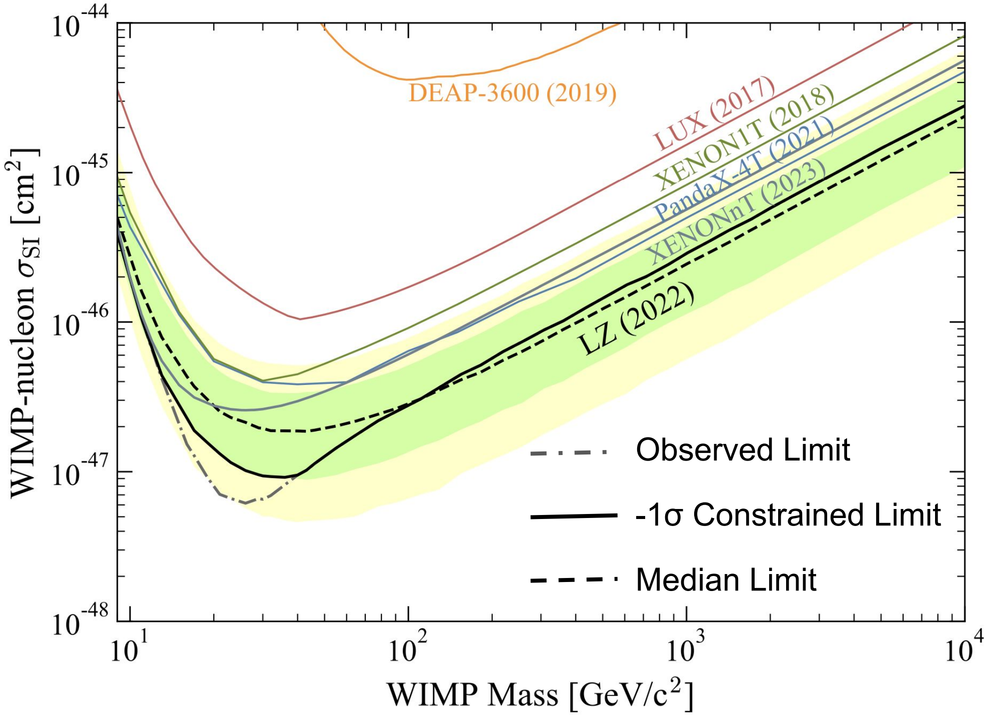


Best-fit number of WIMPs is **zero** across all masses.

Spin-Independent Limits

- World-leading limits on Spin-independent, elastic nuclear scattering of WIMP-nucleon
- Frequentist, 2-sided profile-likelihood ratio (PLR) test statistic, reporting 90% confidence levels
- Power constrained to -1σ
- Green and yellow are the 1σ and 2σ sensitivity bands

Phys. Rev. Lett. **131**, 041002 (2023)

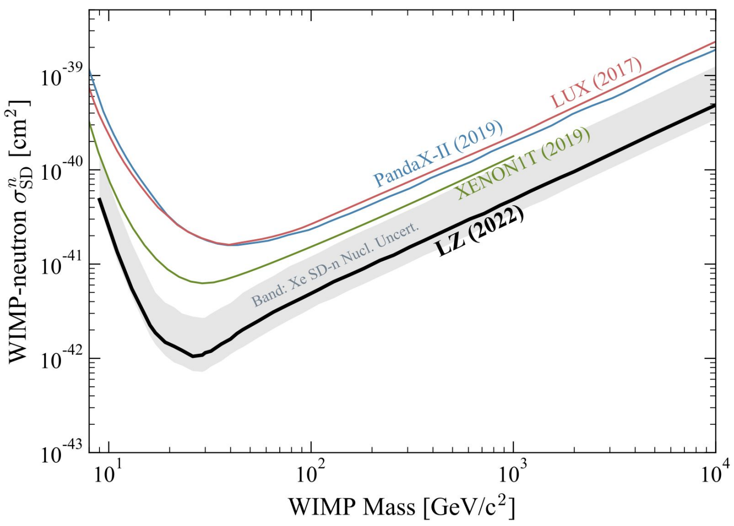


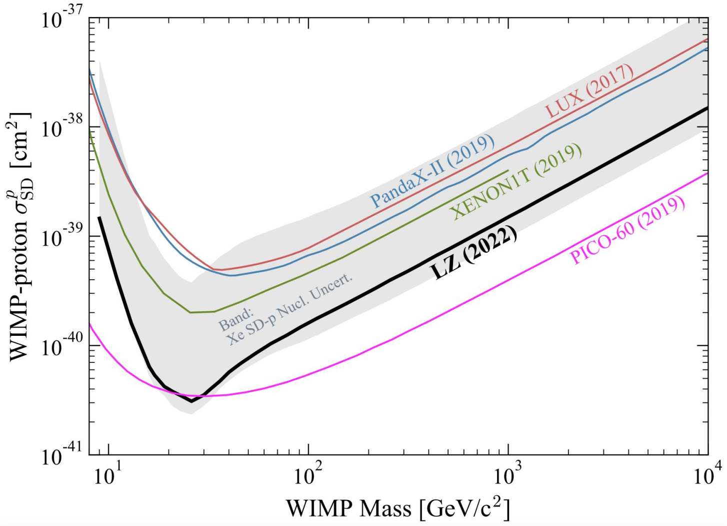
Reporting of limits consistent with Eur. Phys. J. C **71**, 1554 (2011), Eur. Phys. J. C **81**, 907 (2021), and arXiv:1105.3166

Phys. Rev. Lett. **131**, 041002 (2023)

Spin-Dependent Limits

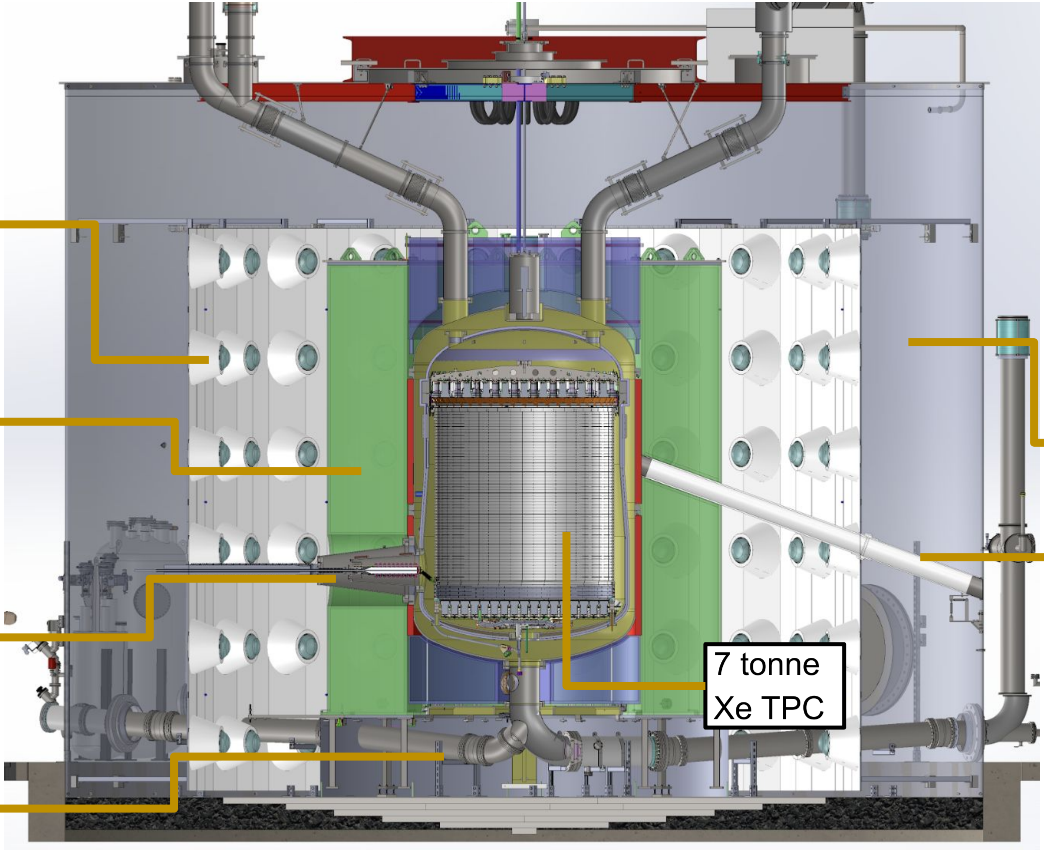
- WIMP interactions with non-zero nuclear spin of ^{129}Xe and ^{131}Xe
- Gray uncertainty bands correspond to theoretical uncertainty on nuclear structure functions (applies to all xenon detectors)
- Mean curve using structure functions from Phys. Rev. D **102**, 074018 (2020)

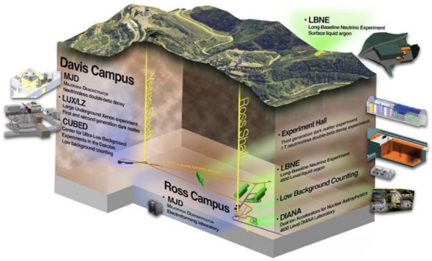




The LZ Detector: located at 4850-ft level underground at SURF in the same cavern as the Ray Davis solar neutrino experiment

Sanford Underground Research Facility
South Dakota Science and Technology Authority





NIM A **953**, 163047 (2020)

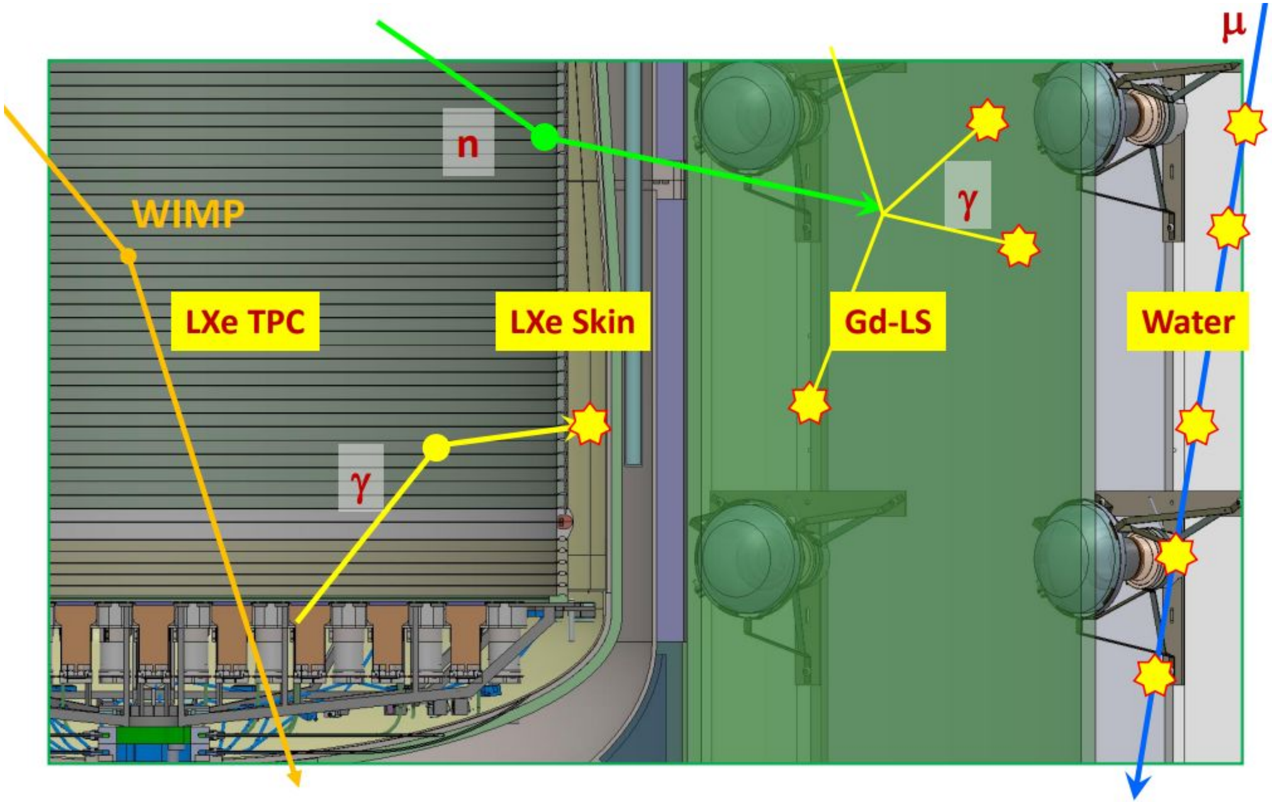
Backgrounds and Mitigations

Eur. Phys. J. C 80, 1044 (2020)
Phys.Rev.D 108 (2023), 012010

Origin	Background	Mitigation/Reduction
Detector Materials	• ERs from ^{238}U, ^{232}Th, ^{60}Co, ^{40}K • NRs from ^{238}U USF and U/Th (α,n) • ERs from ^{222}Rn/^{220}Rn chain	• Radio-assay campaign with gamma screening • Radon emanation • Inline radon reduction system
Cleanliness during Construction	• Radon progeny plate-out on TPC walls • Dust on LXe wetted surfaces	• TPC constructed and assembled in Radon reduced cleanroom
Internal Xenon Contaminants	• ERs from ^{136}Xe ($2\nu\beta\beta$), ^{124}Xe (2νECEC), ^{85}Kr, ^{39}Ar	• Charcoal chromatography at SLAC • Inline gas purification
Cosmogenic/ External	• Gammas from cavern walls • Muon induced neutrons • Activated xenon • Solar neutrinos	• 4300 m.w.e overburden at SURF • Gd-LS OD and LXe Skin • High purity water shield

- The proximity of the PMT and TPC systems makes them the main contributors to detector gamma background
- ^{136}Xe ($2\nu\beta\beta$), ^{124}Xe (2νECEC), and solar neutrinos are irreducible backgrounds and not subject to the mitigations outlined

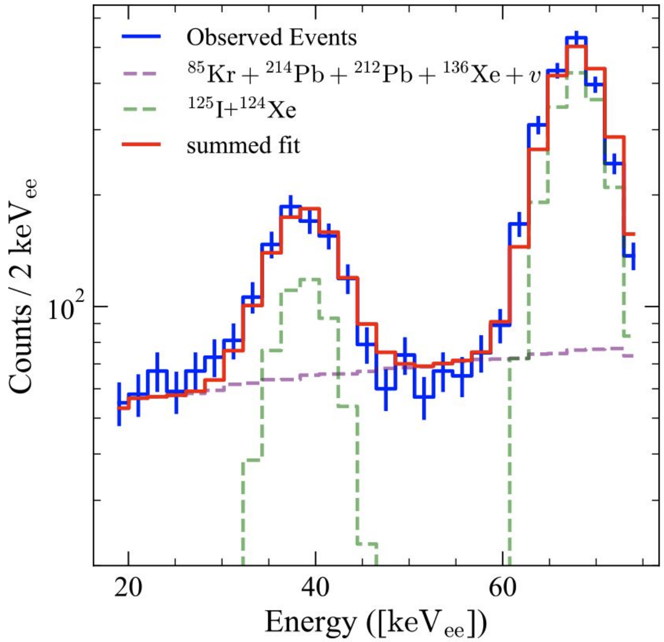
Veto Systems



^{214}Pb Tag Validation

- 68% reduction in ^{214}Pb!

Before flow-based ^{214}Pb selection+ removal



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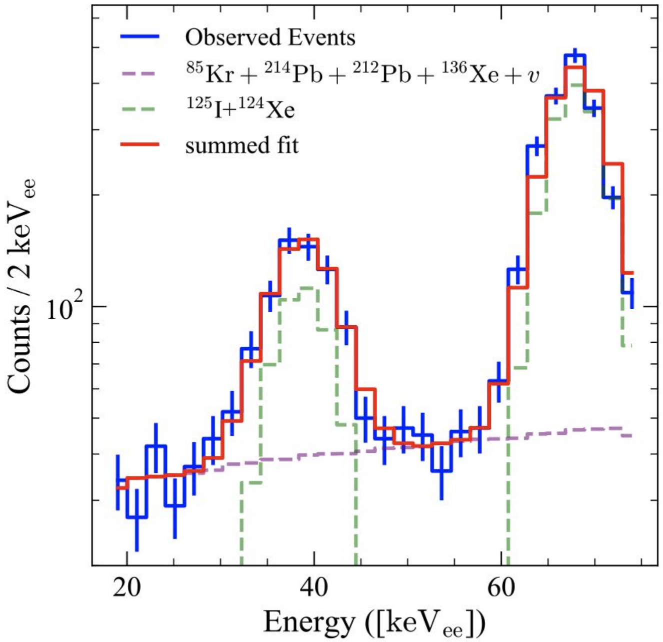
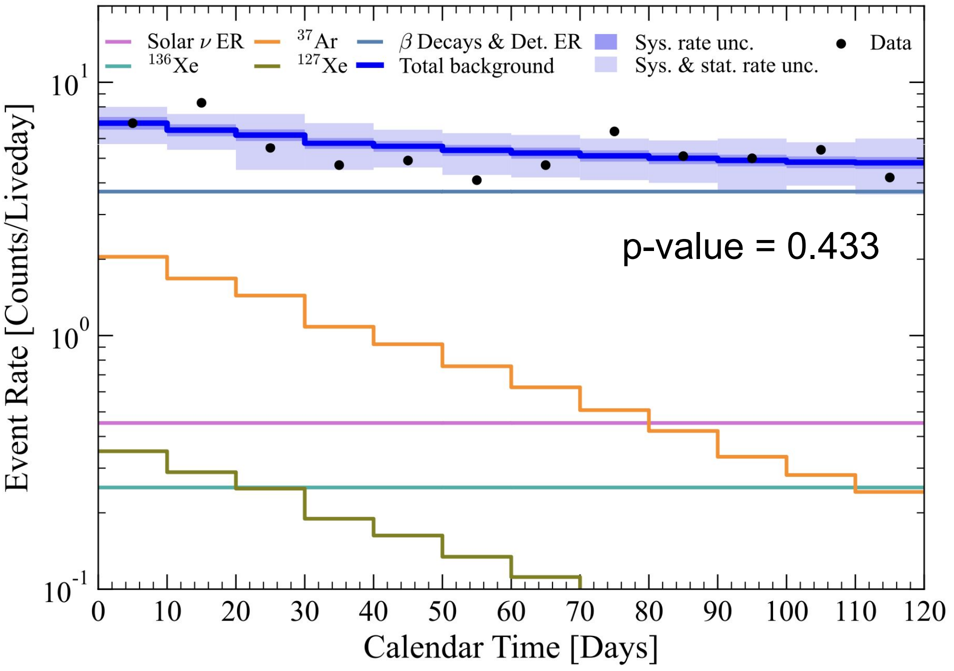


Time Dependent Background Model

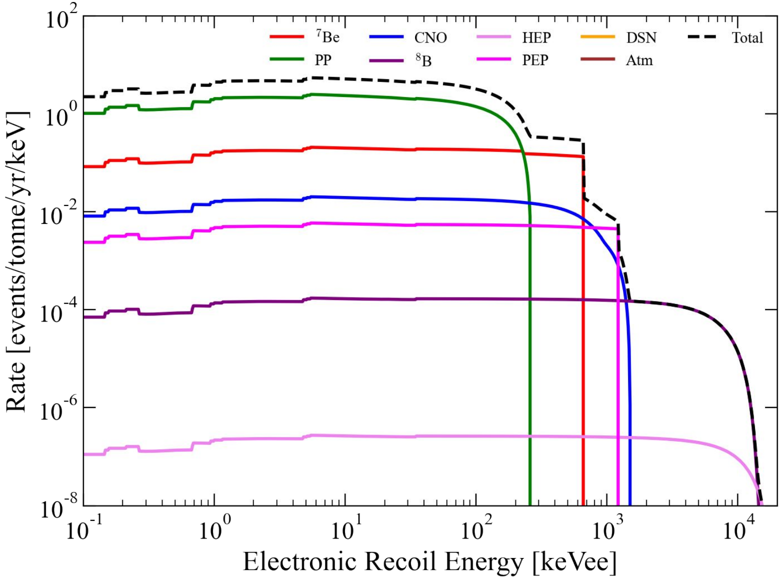
DK Phys.Rev.D **108**, 072006 (2023)

- Time profile of backgrounds introduced as additional variable into background model in {S1c, logS2c} space.
- ^{127}Xe decays with 36.4 d half-life.
- ^{37}Ar decays with 35 d half-life.
- ^{214}Pb time dep. studied by looking at radon alpha rates → constant in time

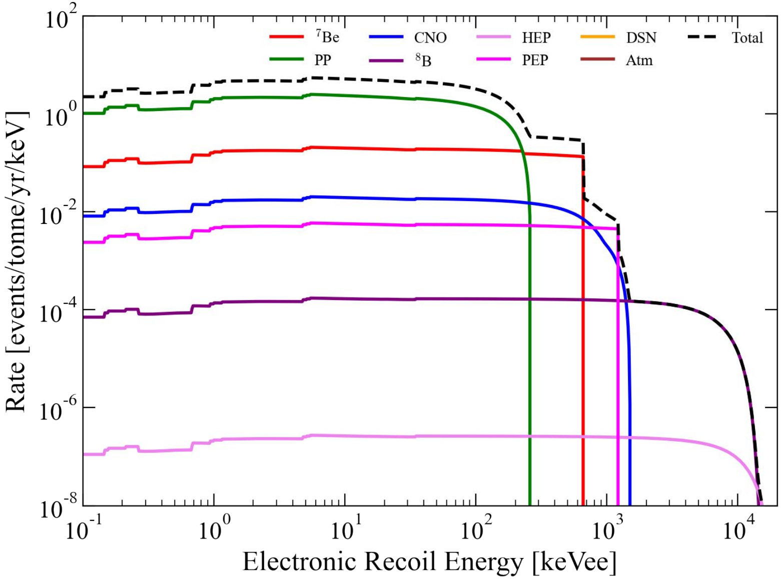


Solar Neutrinos

EW RRPA ν-e Recoil Spectra



CEvNS Recoil Spectra



Activation Backgrounds

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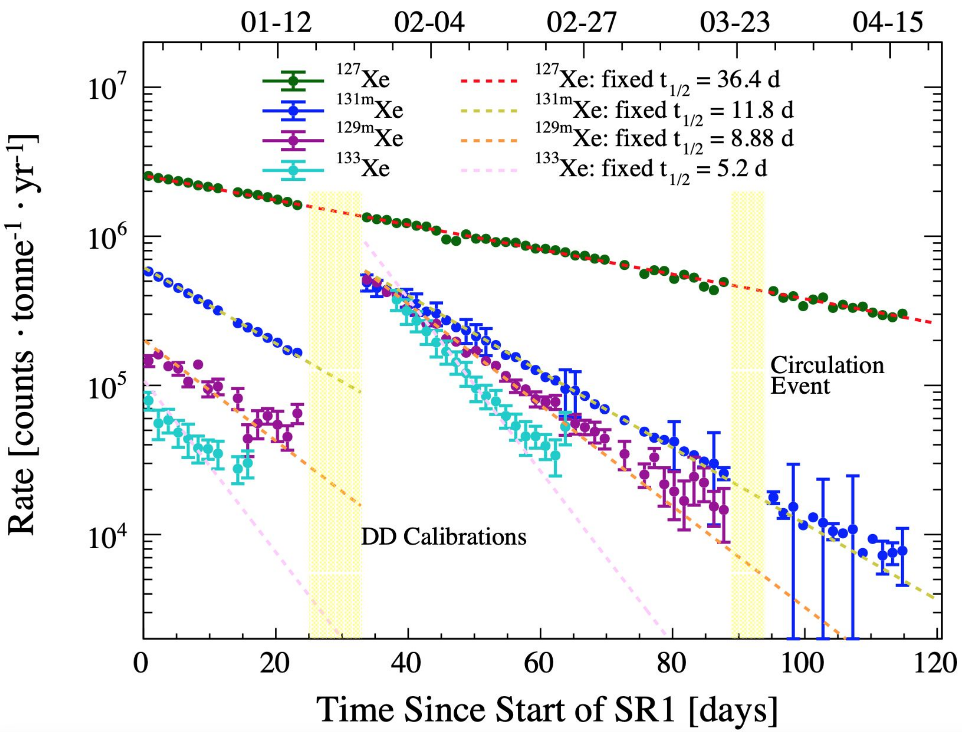
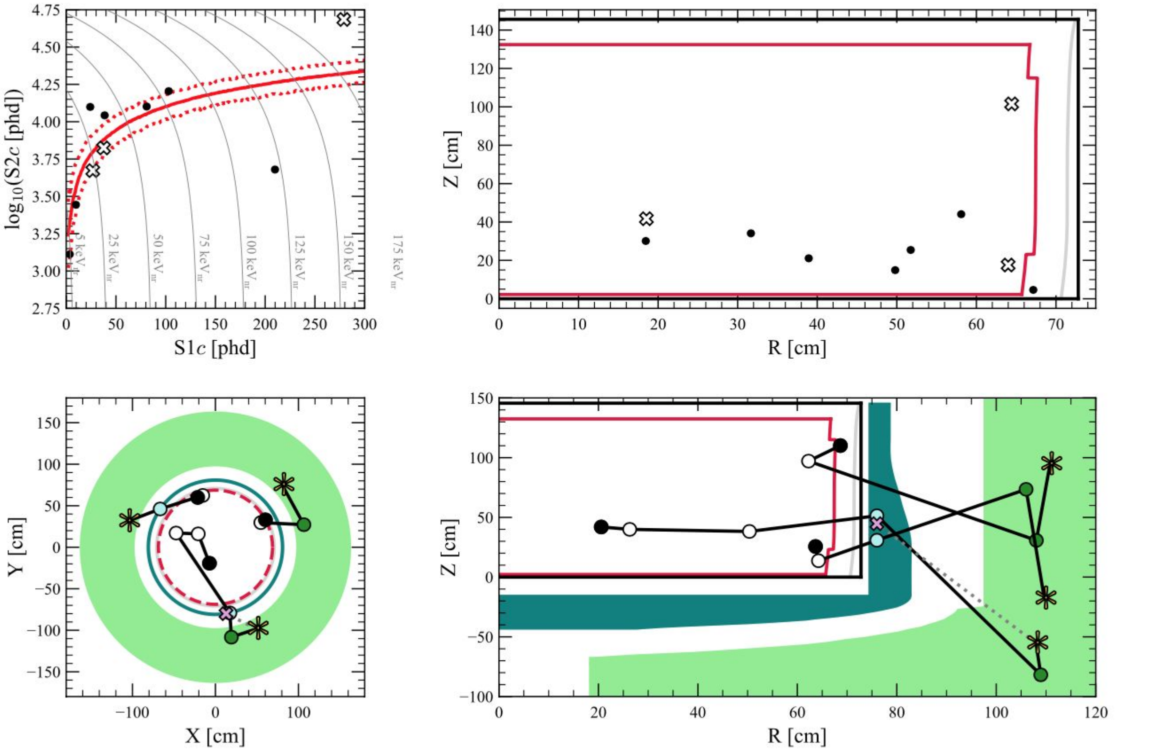
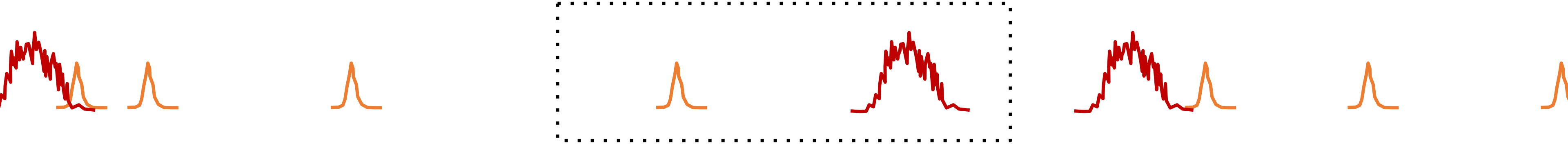
- Xenon can be cosmogenically activated leading to background contributions from ^{127}Xe, ^{129m}Xe, ^{131m}Xe, ^{133}Xe
  - Other Xe activation products are much shorter lived
  - ^{127}Xe forms low energy background
- Neutron calibrations before and during first science run also lead to xenon activation
- Rates measured *in situ* by fitting spectral peaks in reconstructed energy space



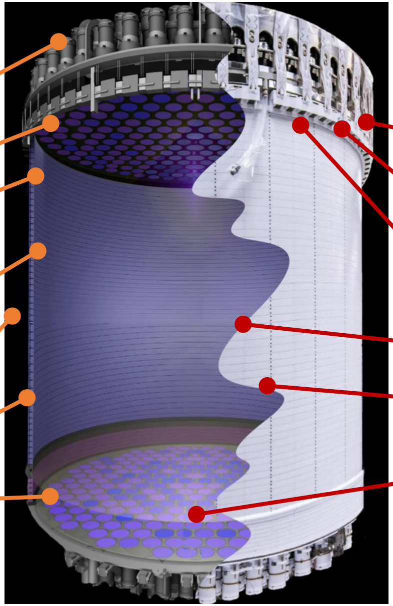
Multiple Scatter Neutrons



Accidentals Origins



Mimics a real scatter



Isolated S1s

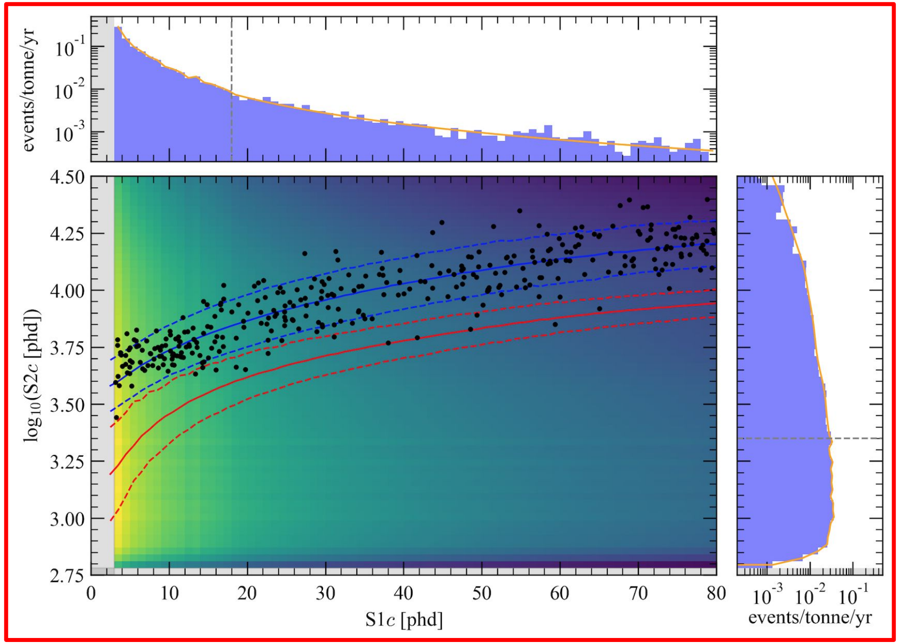
- PMT dark count pile-up
- Events in gas phase
- Cherenkov light in PMTs or PTFE
- Fluorescence of PTFE
- Light leaks from outside TPC
- Charge-insensitive regions near walls
- Charge-insensitive regions below cathode

Isolated S2s

- Events in gas phase
- Events in liquid above gate grid
- Electron emission from grids
- Sub-S1-threshold ER events
- Delayed electrons after S2s
- Radioactivity from gate and cathode grids

Accidental PDF

Source	Expected Events	Fit Result
^{214}Pb	164 ± 35	-
^{212}Pb	18 ± 5	-
^{85}Kr	32 ± 5	-
Det. ER	1.2 ± 0.4	-
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17



EFT Operators

- Build up all possible non-relativistic operators that can occur in the effective Lagrangian that describes the WIMP-nucleus interaction
- These operators depend on (1) the relative velocity between the incoming WIMP and the nucleon, (2) the momentum transfer, (3) in addition to the WIMP spin, and (4) nucleon spin
- Spin-Independent is O_1 operator
- Spin-Dependent is O_4 operator

Fitzpatrick, Haxton, *et al* JCAP **02,** 004 (2013)

$$\mathcal{O}_1 = 1_\chi 1_N$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$
$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

Plot of ^{37}Ar decaying away

- ^{37}Ar decays with 35 d half-life via electron capture with 2.8 keV peak from K-shell.
- Produced as result of cosmogenically induced spallation of Xe (nuclear fragmentation).
  - Predicted 11 nBq/kg rate at start of SR1
- 85 events falling within ^{37}Ar 2.8 keV contour plotted as function of time.
  - Well fit by flat + exponential with 35 d half-life.
- Large theoretical uncertainty on production cross section → let float in model up to x3 predicted rate.

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