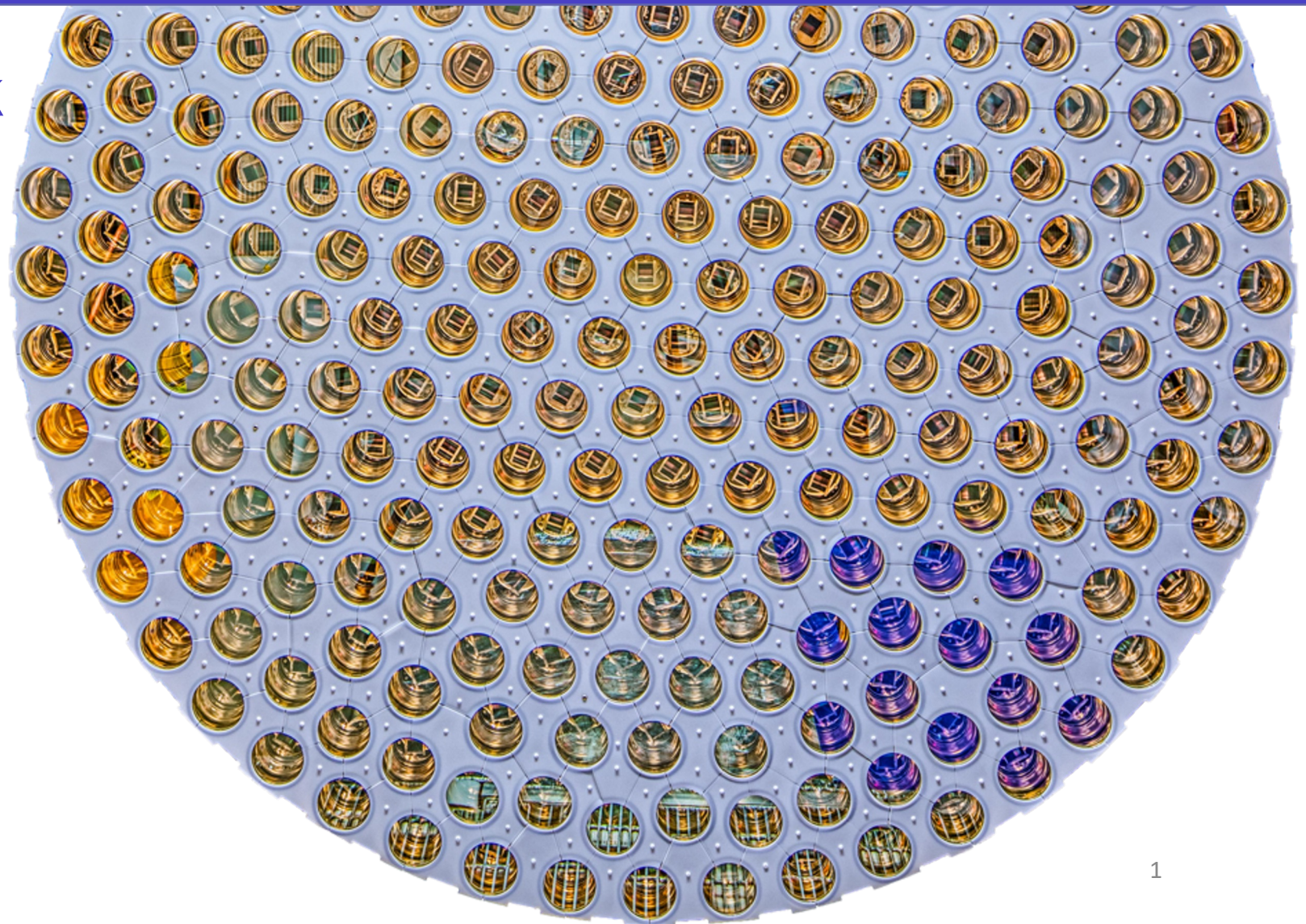
The LUX-ZEPLIN dark matter experiment

Theresa Fruth
On behalf of the LZ collaboration

Symposium on Frontiers of Underground Physics
Chengdu, China
31st October 2023



THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

LZ collaboration - 37 Institutions: more than 250 scientists, engineers, and technical staff

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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.
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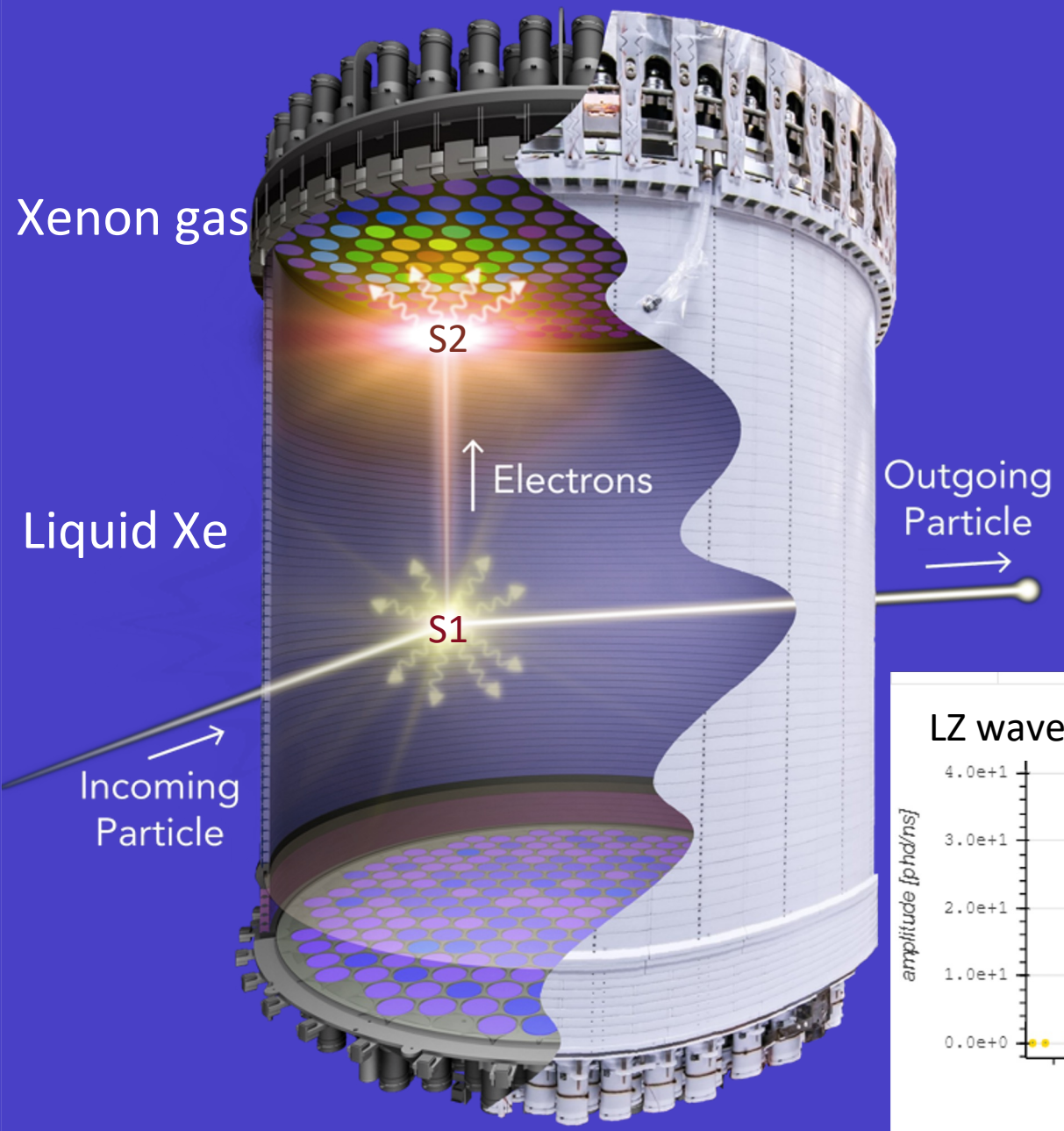
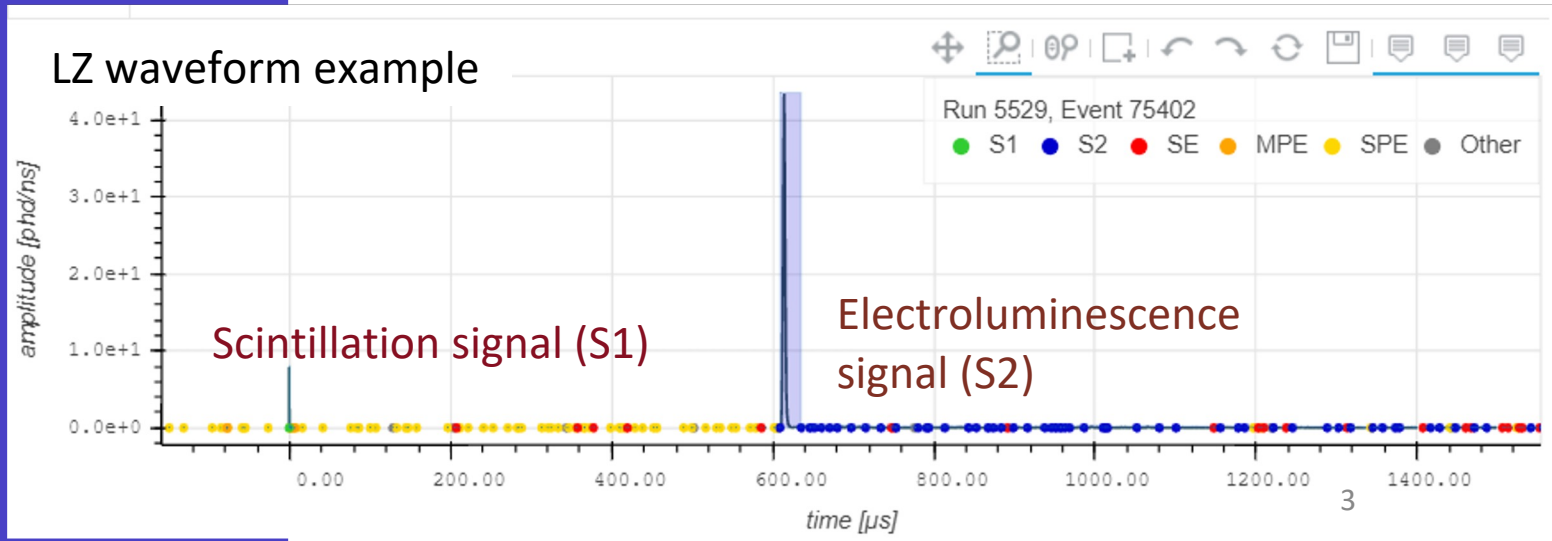
Overview

- Principal goal: the direct detection of dark matter via nuclear recoils
- Scintillation & charge (via electroluminescence) signals
- 3D event reconstruction





|Detector

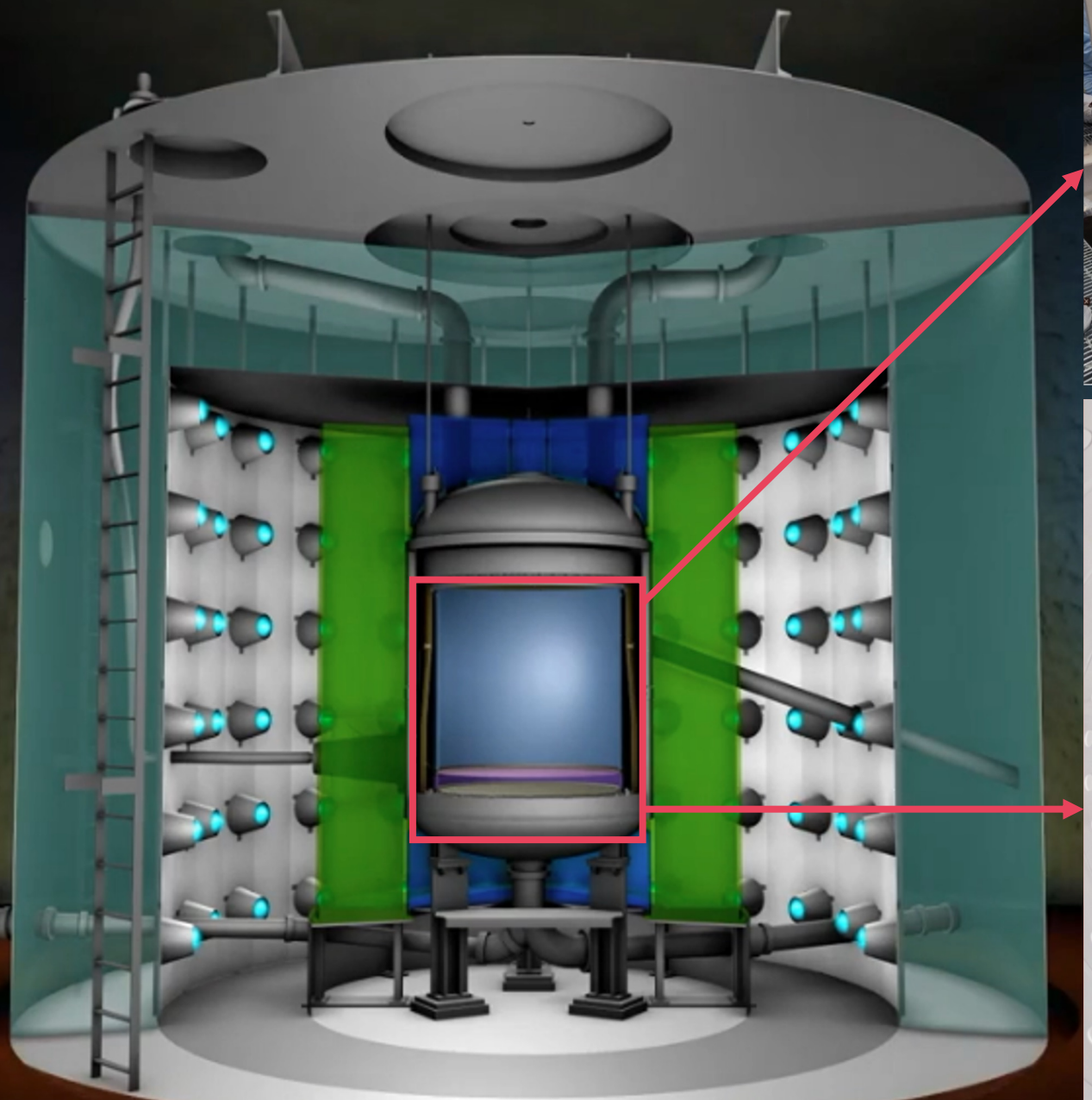
TPC

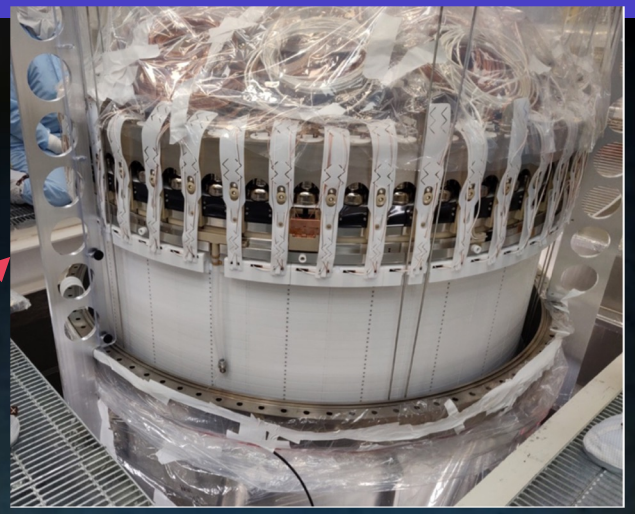
- 494 TPC PMTs (R11410-22)
- PTFE field cage
- 4 HV grids to establish:
  - drift field
  - extraction region

|Detector

Skin

- LXe between TPC & inner cryostat vessel
- Instrumented with 131 PMTs as veto detectors

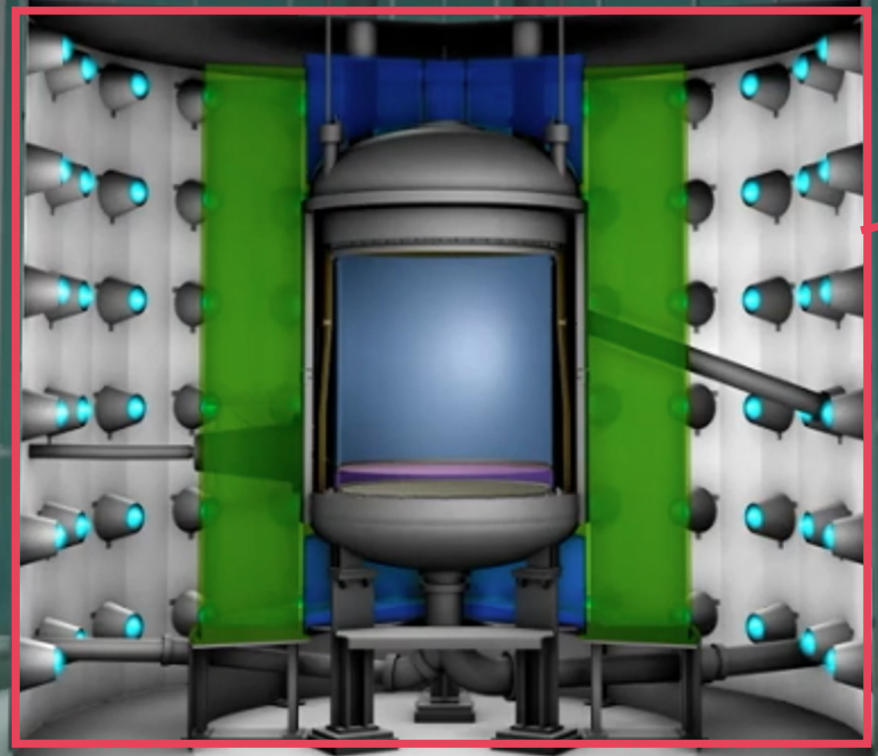


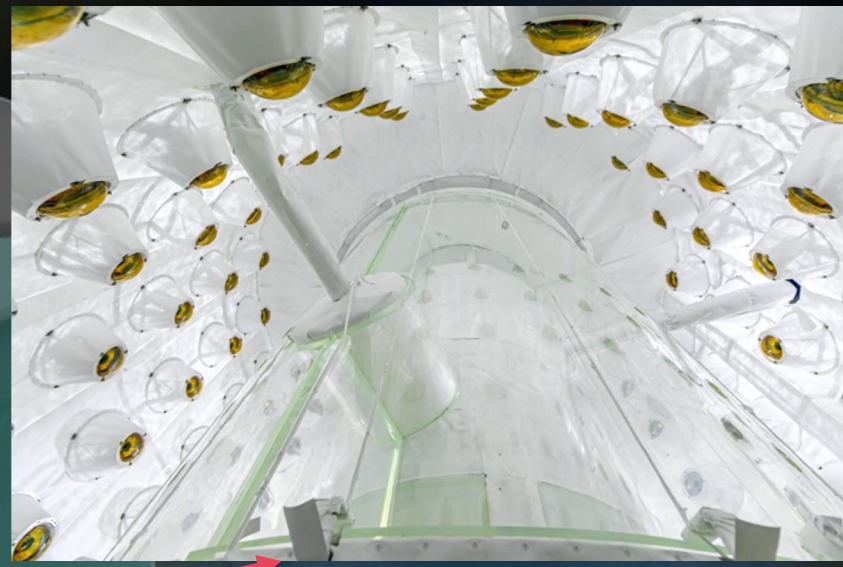


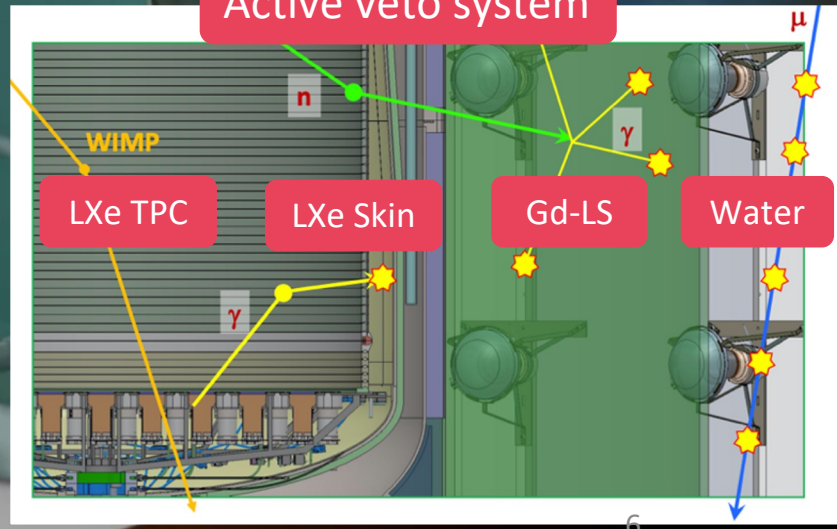
|Detector

Outer Detector

- 17 tonnes Gd-loaded liquid scintillator in acrylic vessels
- 120 8” PMTs (R5912)

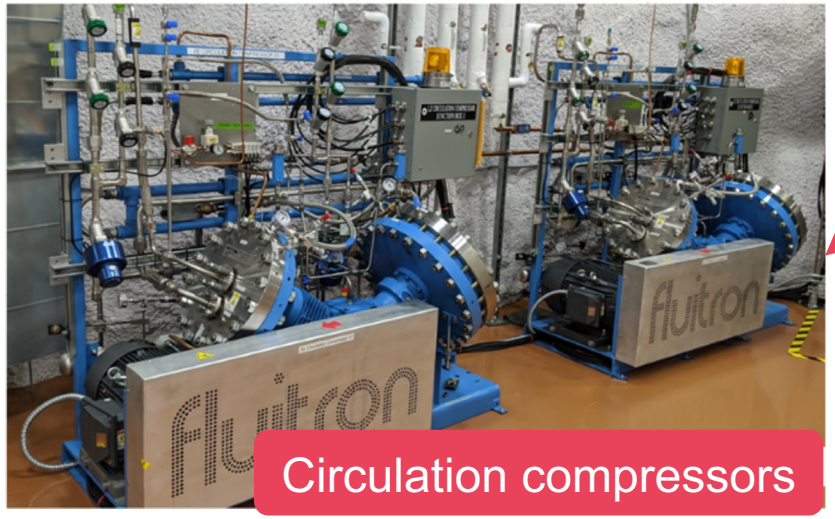






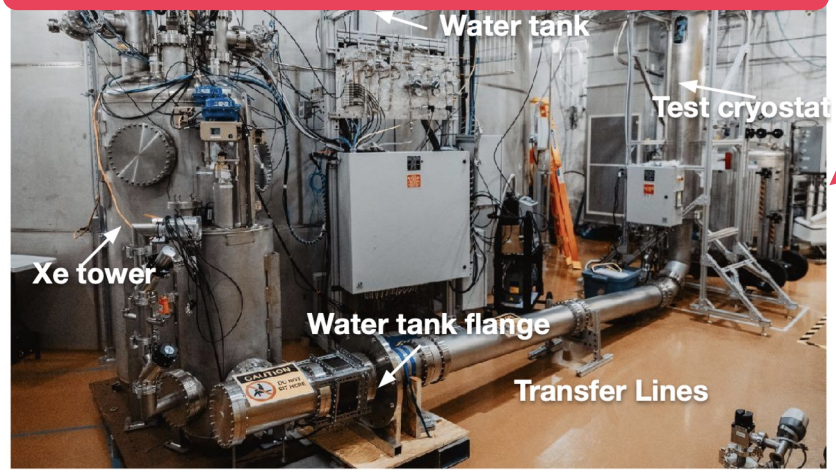
|Detector

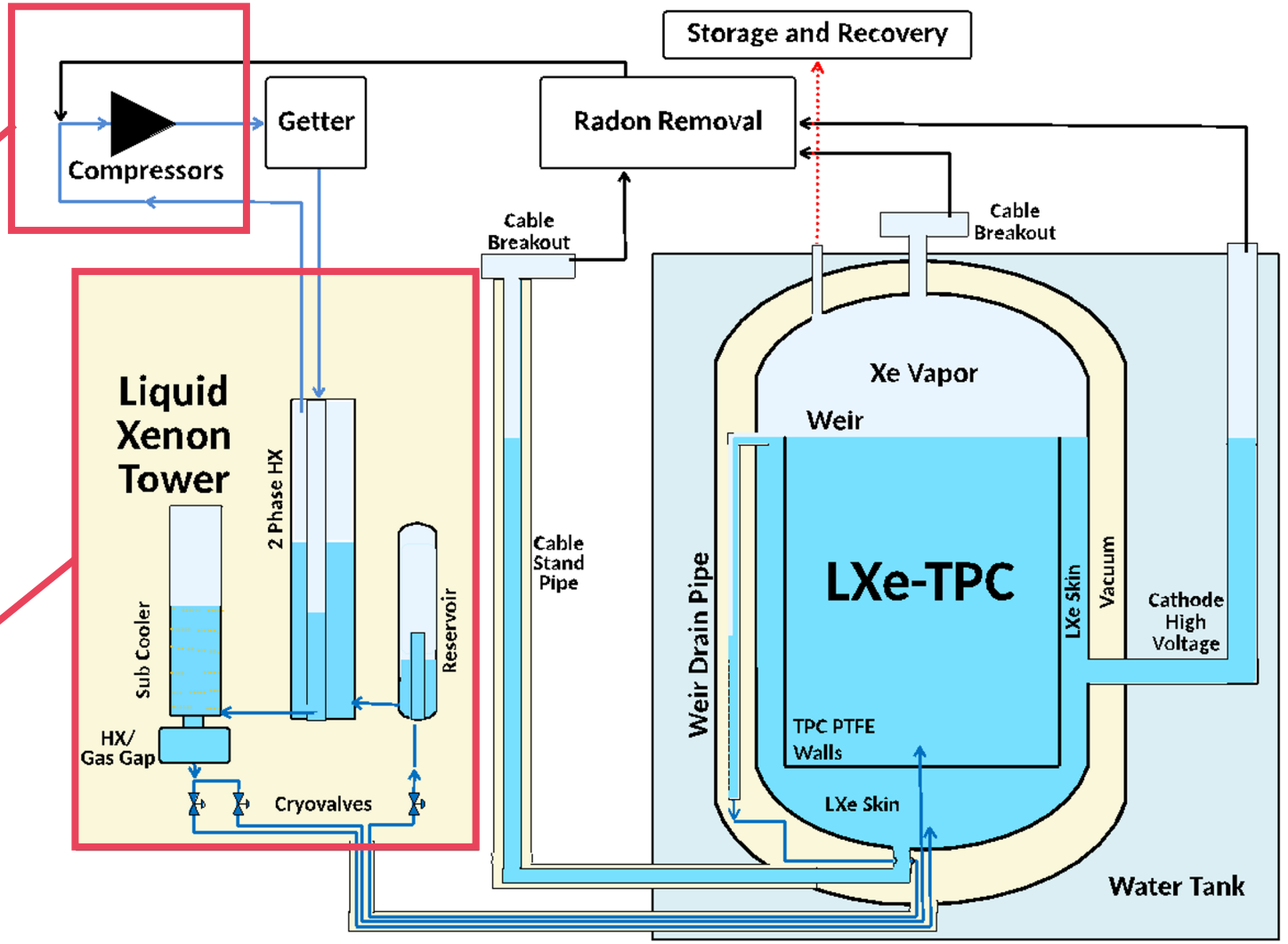
Circulation System



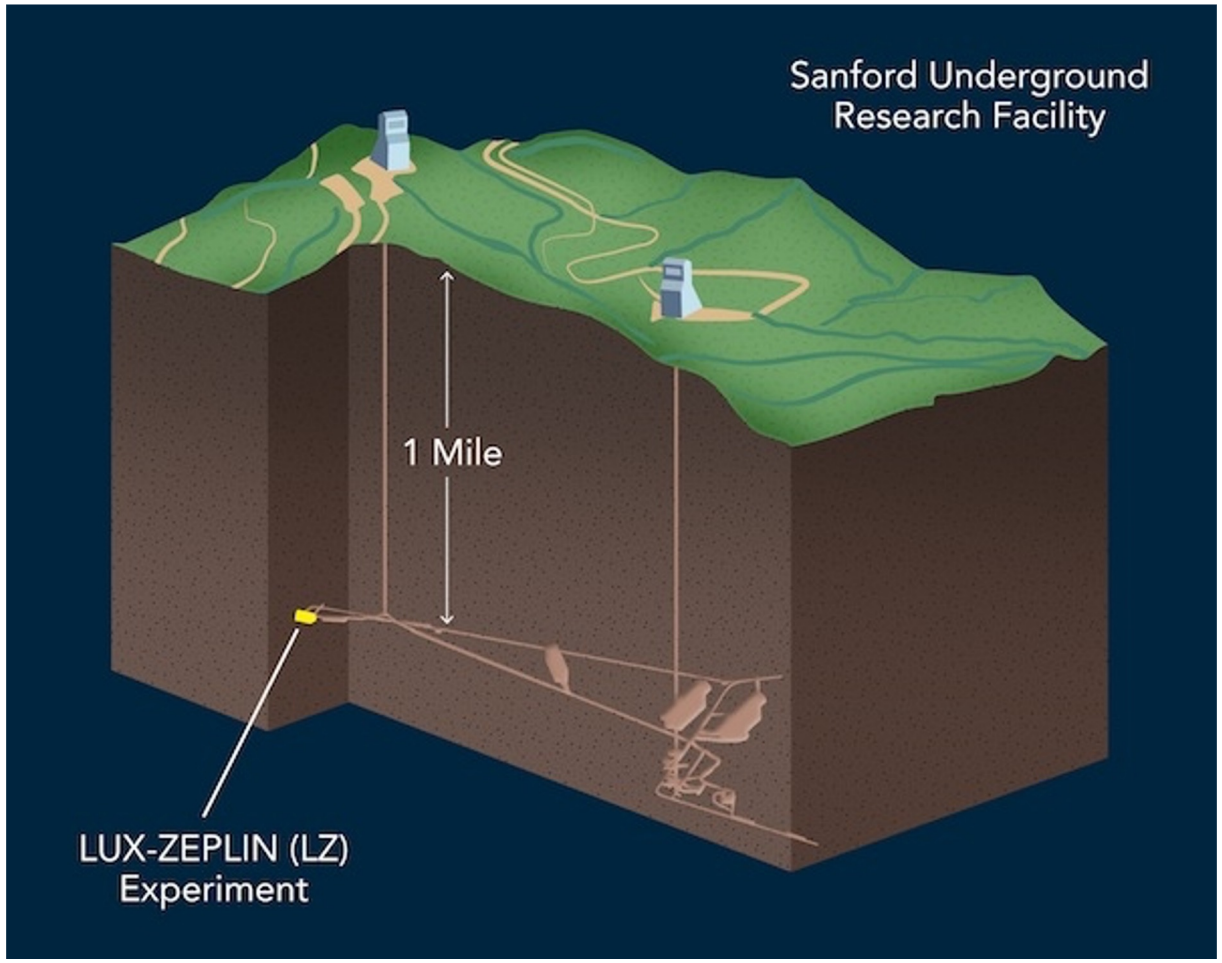
Circulation compressors

Xenon tower during circulation test





Sanford Underground Research Facility



Overview

Stable detector conditions:

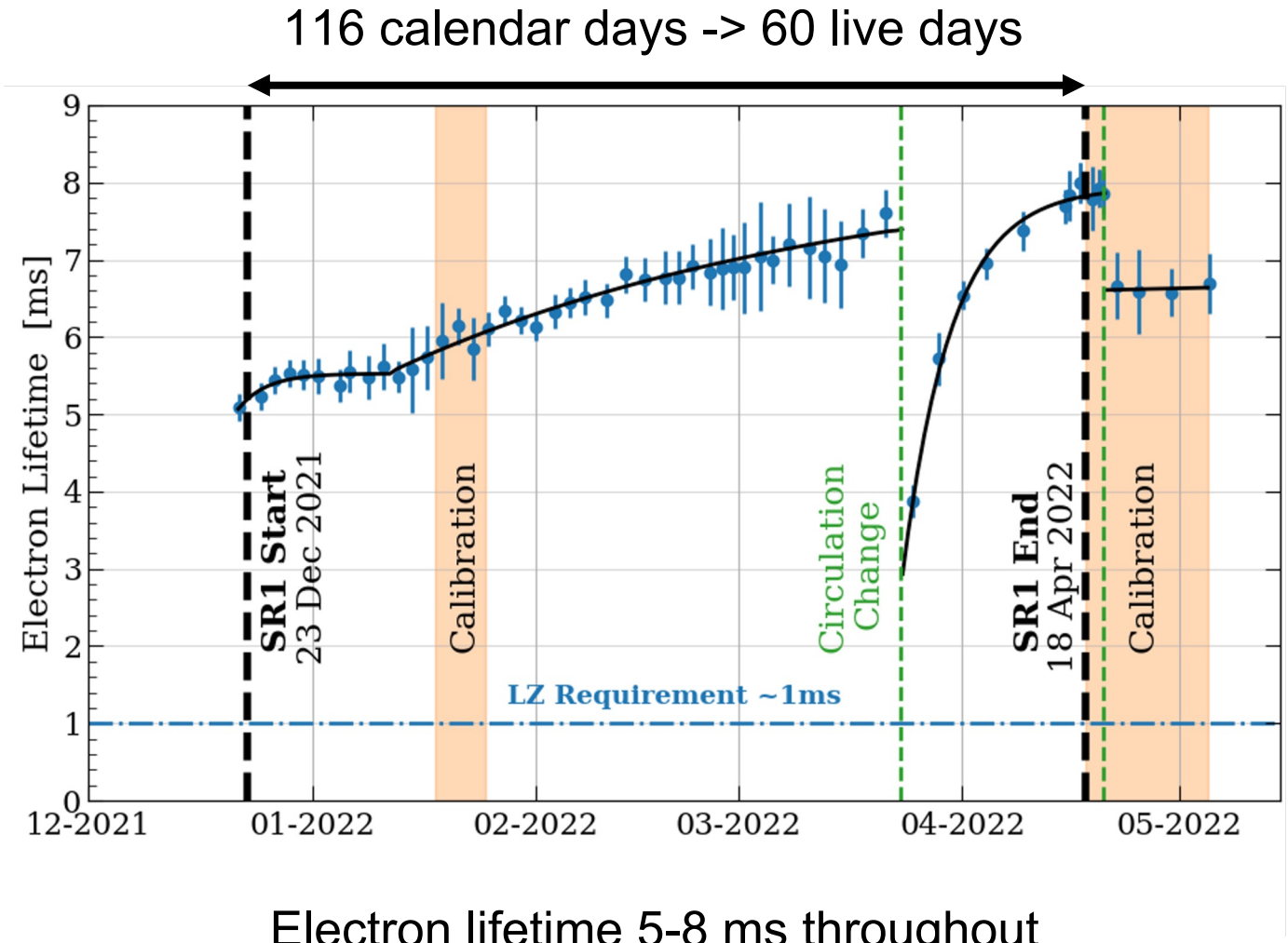
- Temperature = 174.1 K
- Gas pressure = 1.791 bar
- Drift field = 193 V/cm
- Extraction field = 7.3 kV/cm (in gas)
- >97% PMTs operational

Continuous purification:

- 3.3 t/day through hot getter system

Engineering run

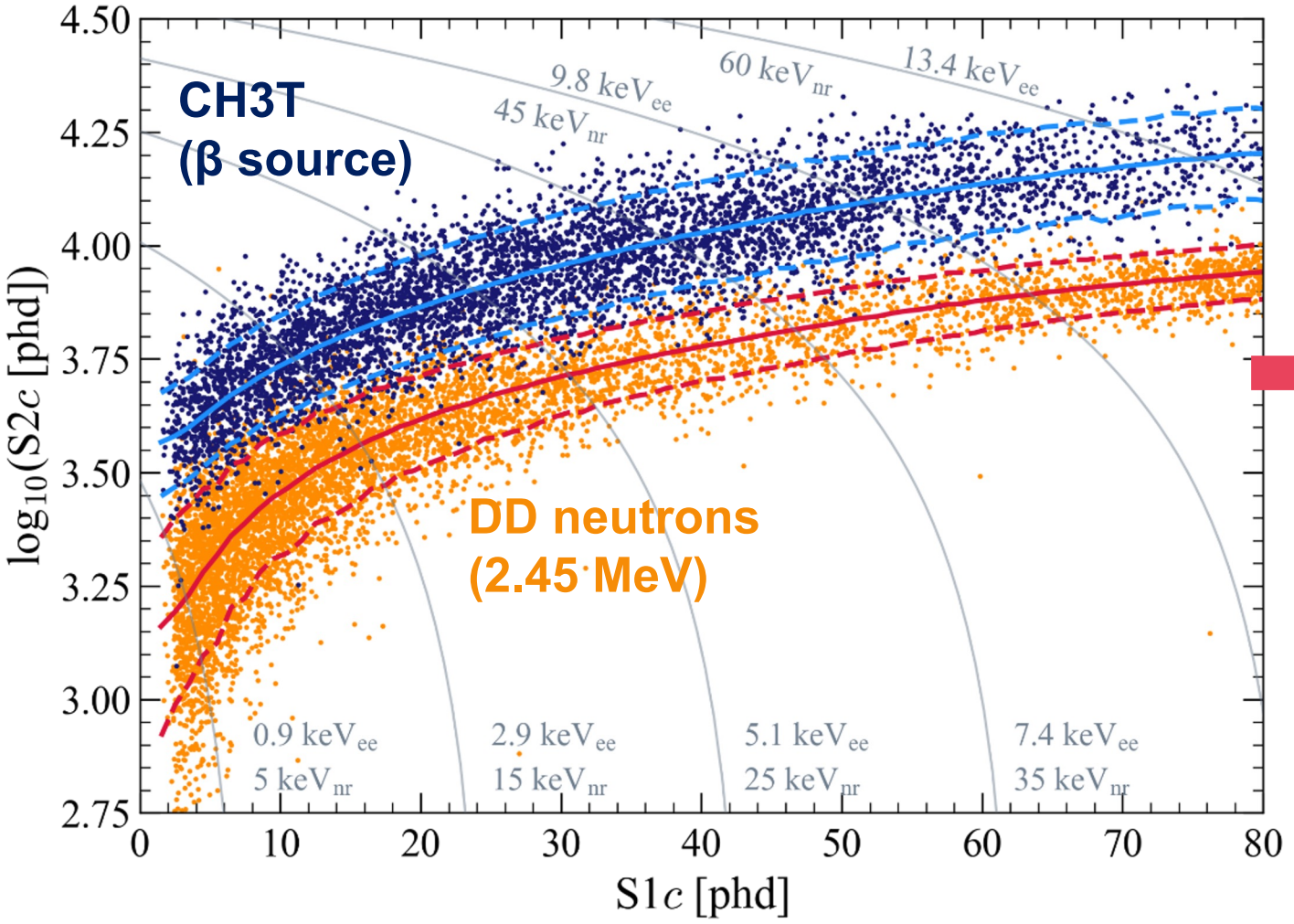
- Bias mitigation: analysis cuts developed on non-WIMP ROI background & calibration data



Electron lifetime 5-8 ms throughout

|First Science Run

TPC Calibrations



Band fits performed with NEST v2.3.7 [1]

Photon detection efficiency:
g1 = 0.114 +/- 0.002 phd/photon

Ionization channel gain:
g2 = 47.1 +/- 1.1 phd/electron

99.9% discrimination of beta backgrounds under NR band median achieved

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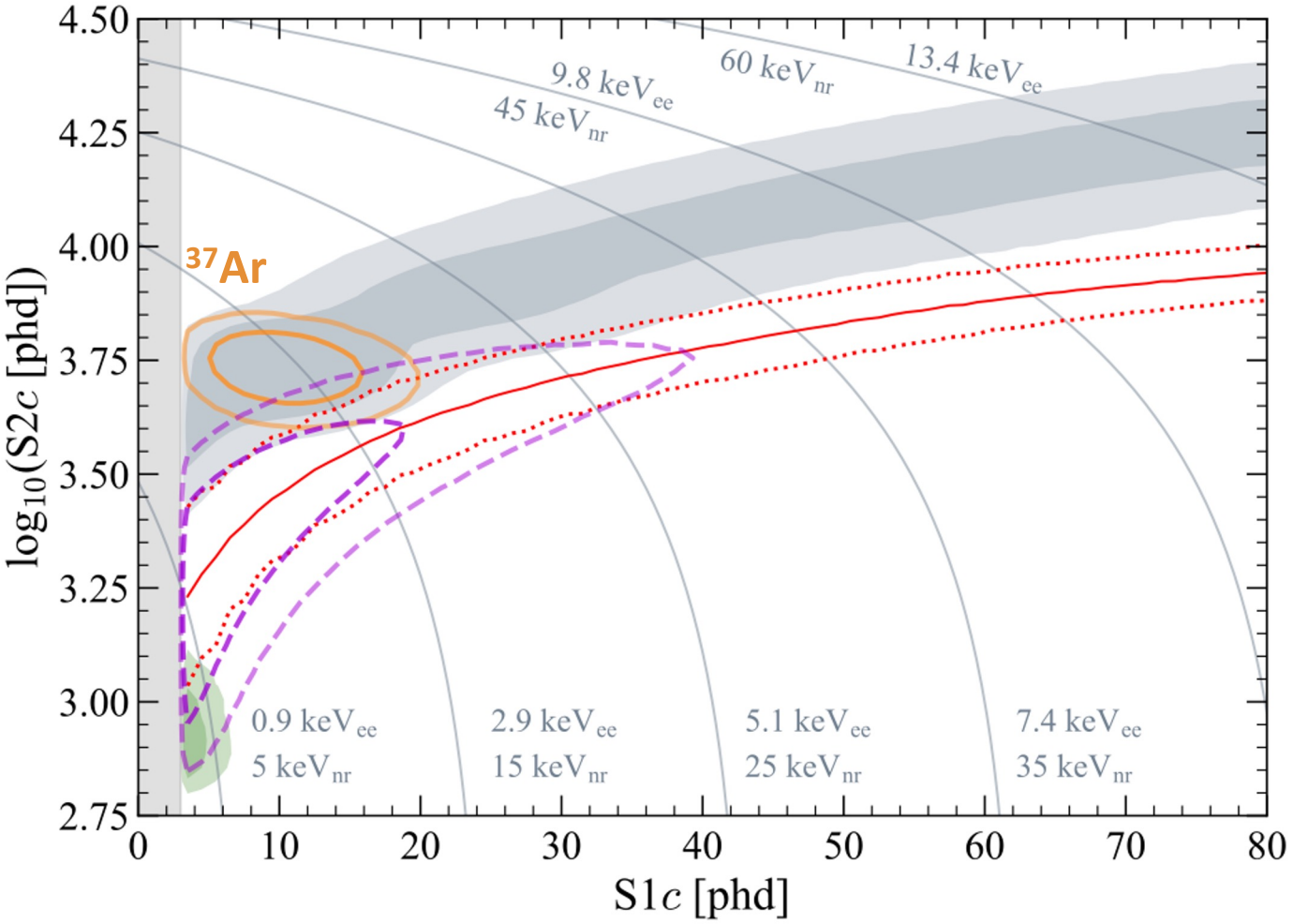
Background model



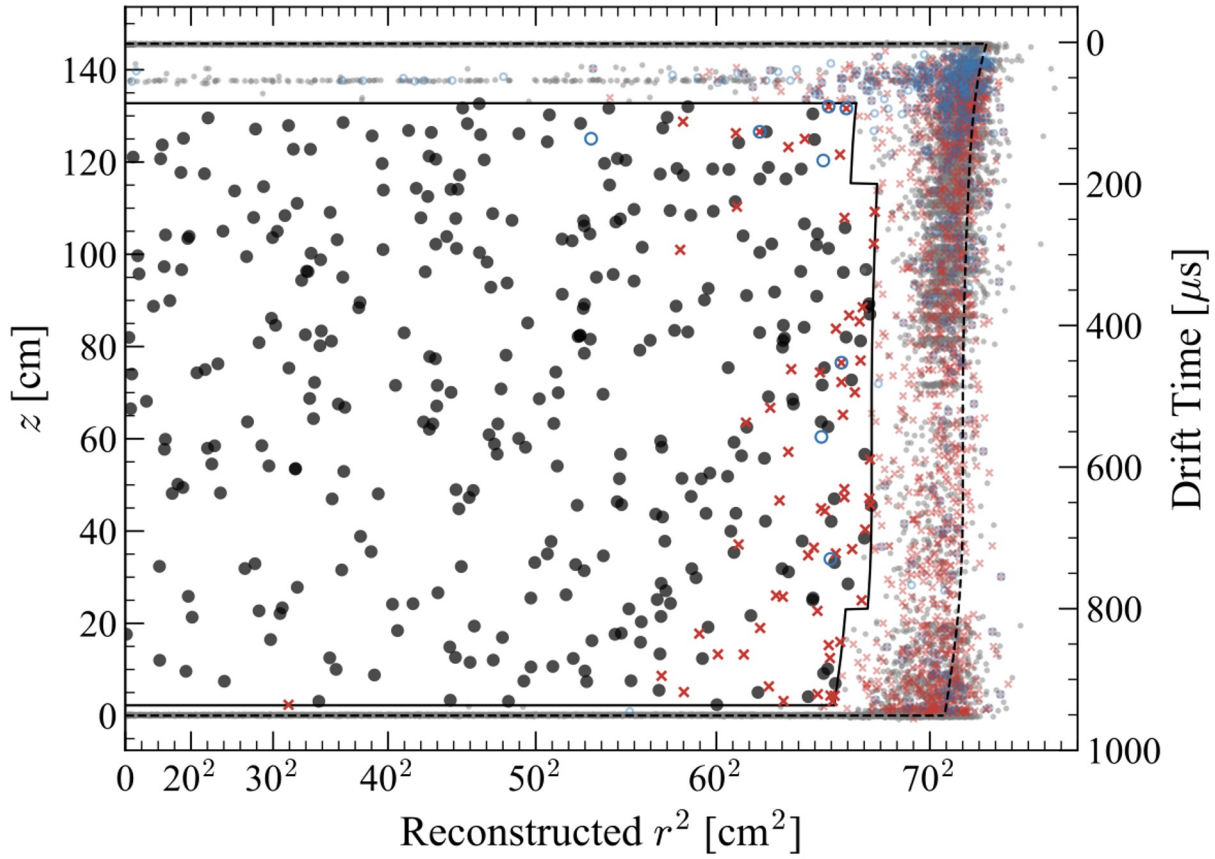
Source	Expected Events
β decays + det ER	218 ± 36
ν ER	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8
^{124}Xe	5.0 ± 1.4
^{136}Xe	15.2 ± 2.4
^{8}B CEνNS	0.15 ± 0.01
Accidentals	1.2 ± 0.3
Subtotal	276 ± 36
^{37}Ar	[0, 291]
Detector neutrons	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–
Total	–

Backgrounds are modelled using energy deposit + detector response simulations [1]

Data selection cuts

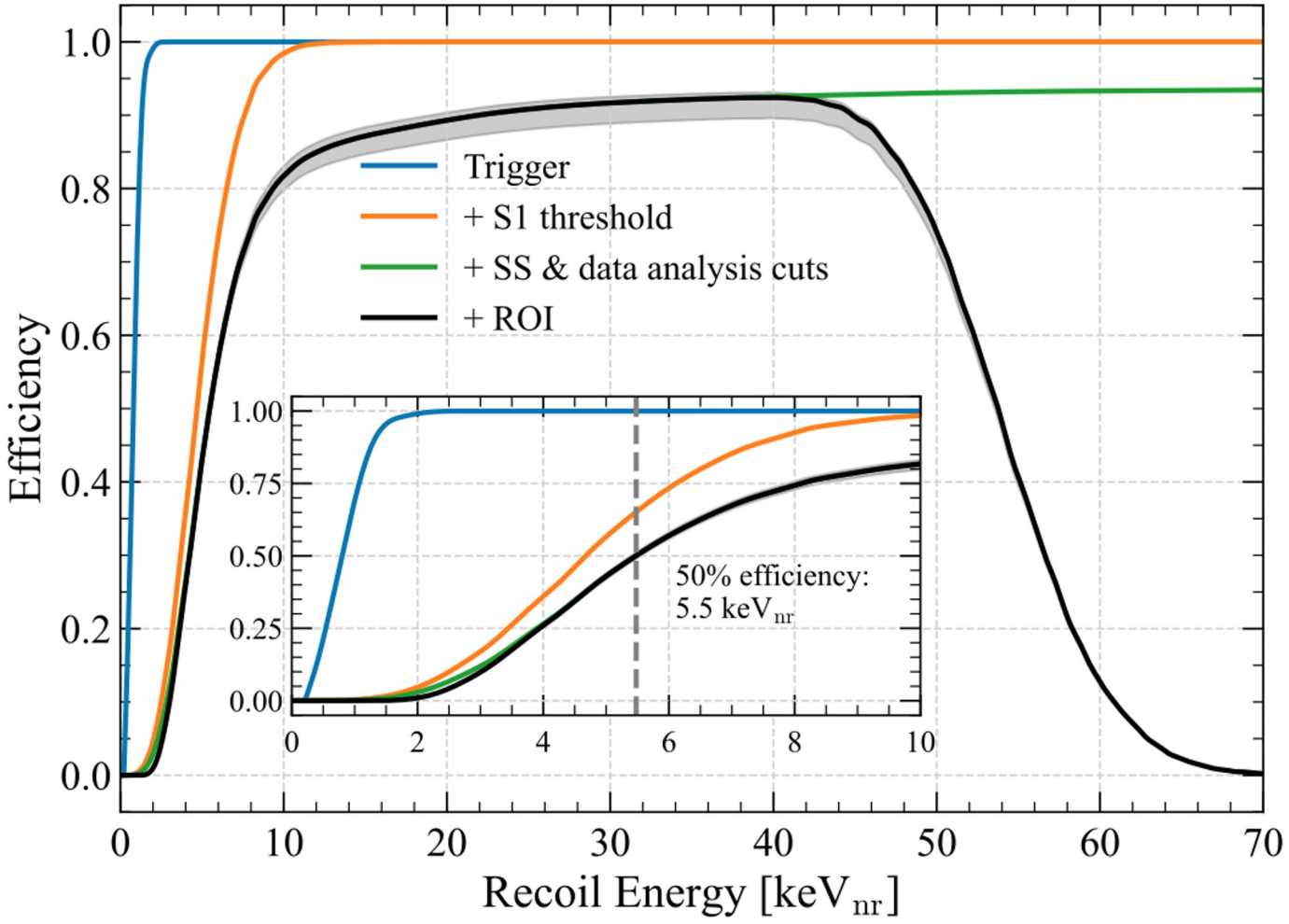
- events passing all cuts
- events outside of fiducial volume
- events vetoed by skin (mostly ^{127}Xe)
- events vetoed by OD

60 live-days, 5.5 t fiducial volume



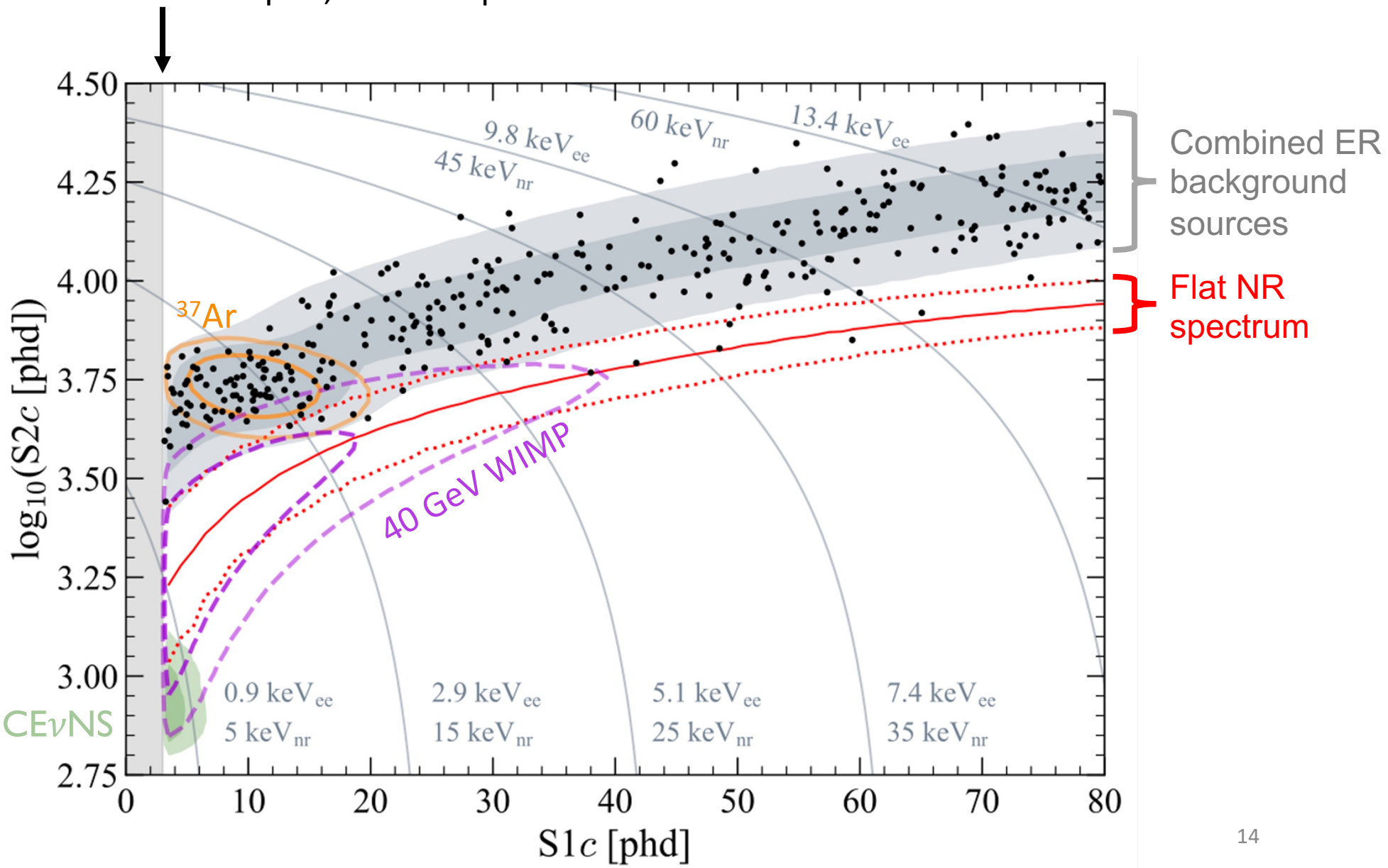
Cuts developed using calibration data and sideband regions outside the WIMP ROI

Signal acceptance



Final data set

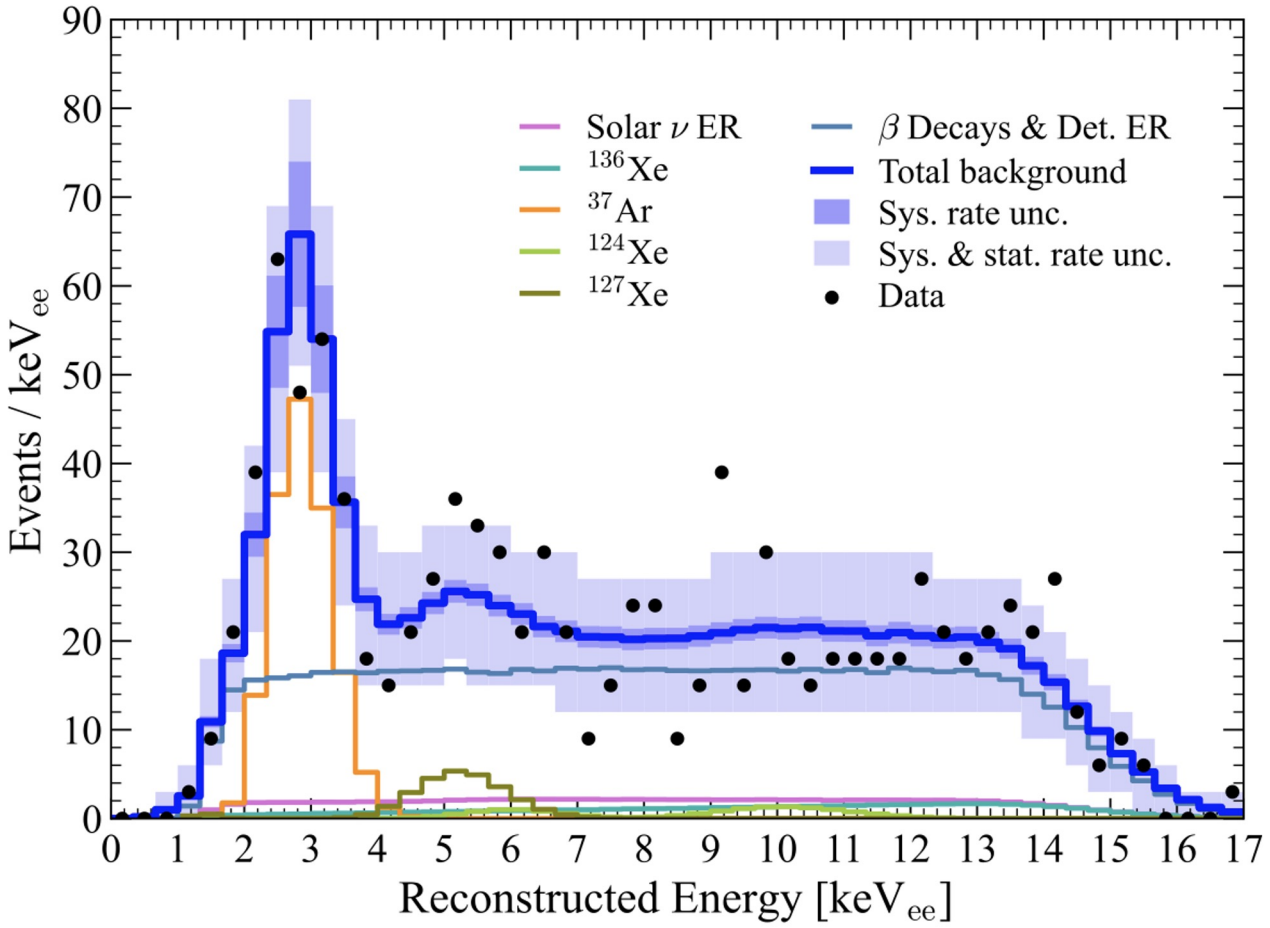
- 335 events observed
- 60.3 ± 1.2 live days
- 5.5 ± 0.2 tonnes



|First Science Run

PLR fits

Source	Expected Events	Fit Result
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



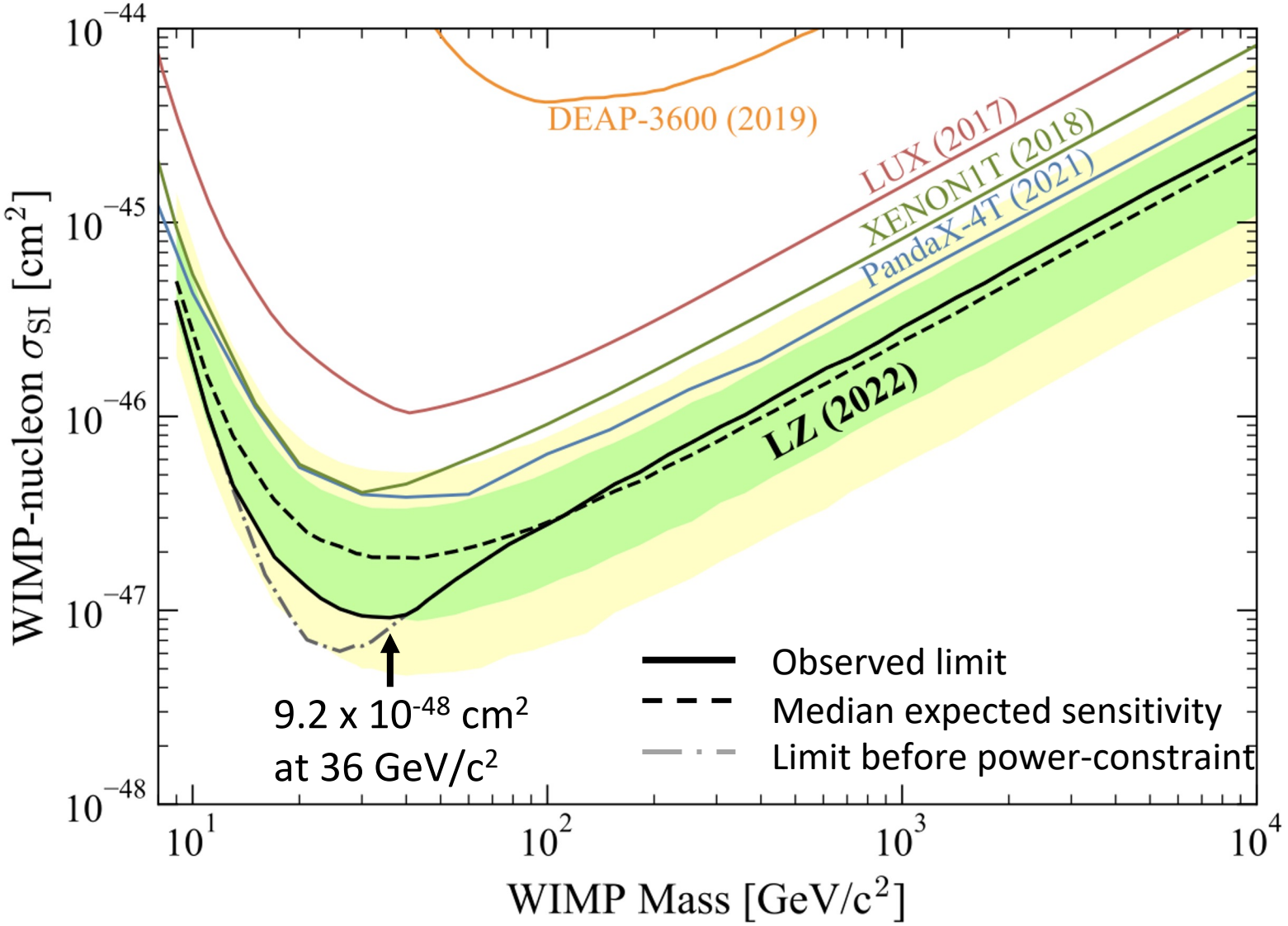
Backgrounds within expectations
~25 counts/keV$_{ee}$/tonne/year

keV$_{ee}$ = Electron-equivalent reconstructed energy

|First Science Run

WIMP search

- Consistent with background-only hypothesis
- Two-sided PLR
  EPJC 81, 907 (2021)
- Power constraint (-1σ)
  G. Cowan et al. arxiv/1105.3166

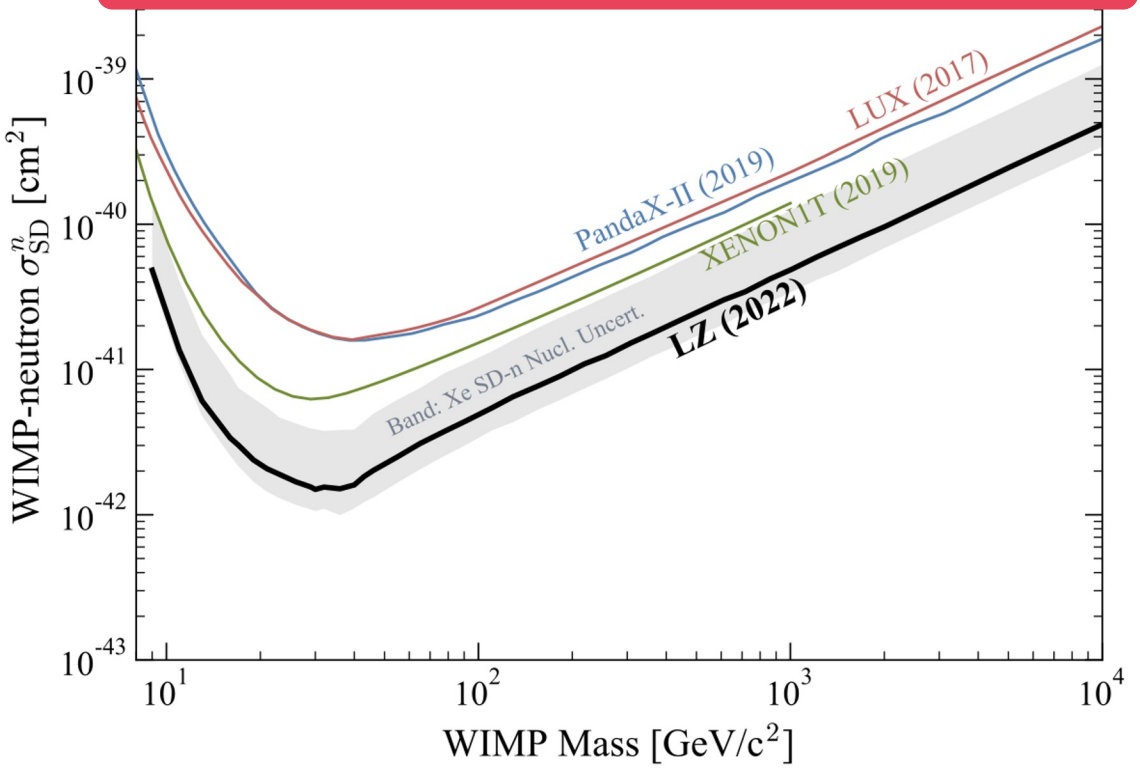


http://link.aps.org/supplemental/10.1103/PhysRevLett.131.041002

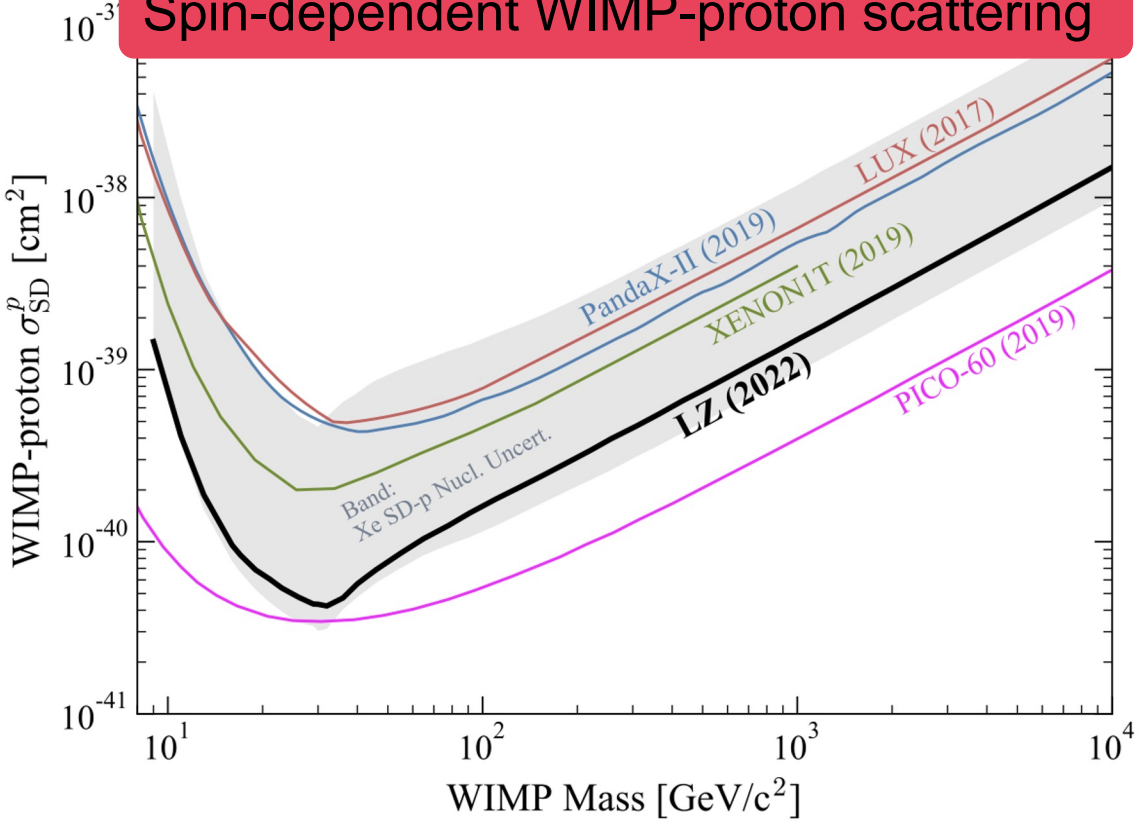
[1] P. Klos, J. Menéndez, D. Gazit, and A. Schwenk Phys. Rev. D 88, 083516 (2013)
[2] First dark matter search result from the LZ Experiment, Phys. Rev. Lett. **131**, 041002 (2023)

WIMP search (spin-dependent)

Spin-dependent WIMP-neutron scattering



Spin-dependent WIMP-proton scattering

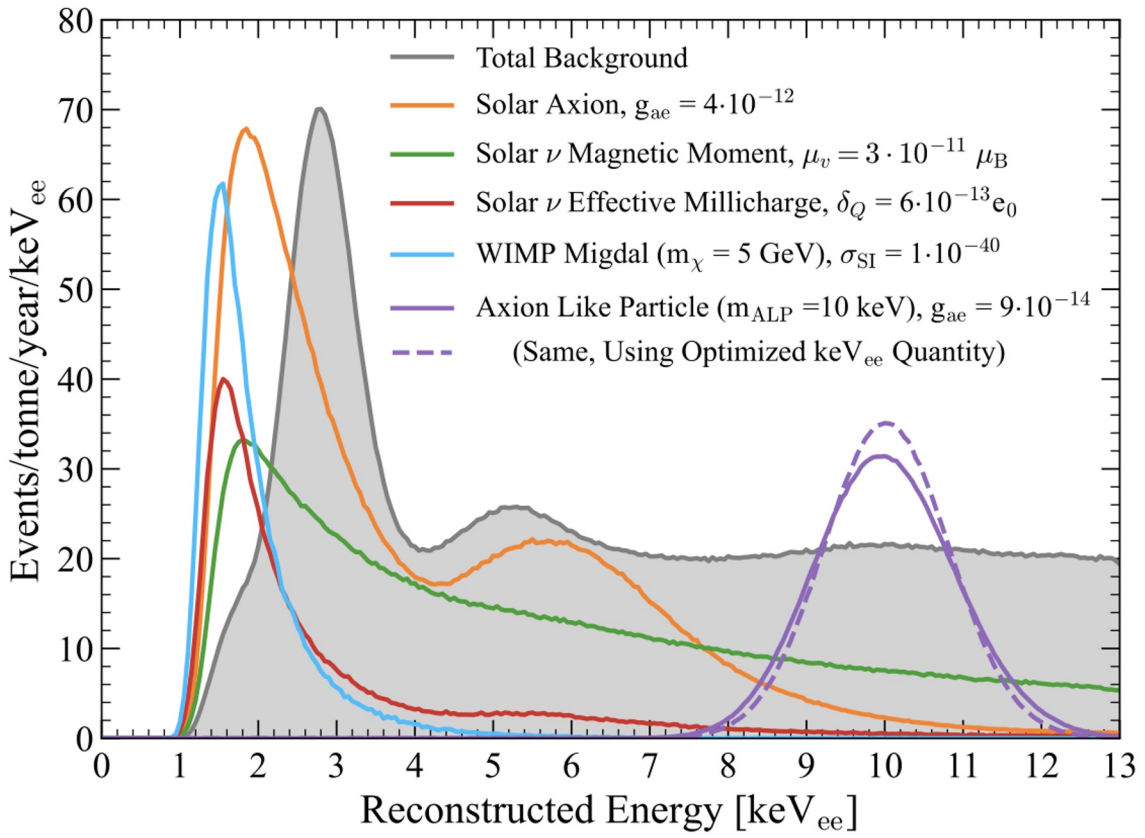


Grey uncertainty band represents uncertainty on Xe form factor [1]

|First Science Run

Searches in the low energy ER band

- Same SR1 data set as WIMP search
- Same cuts & background simulations
- Time dependence added to fit for ^{37}Ar and ^{127}Xe

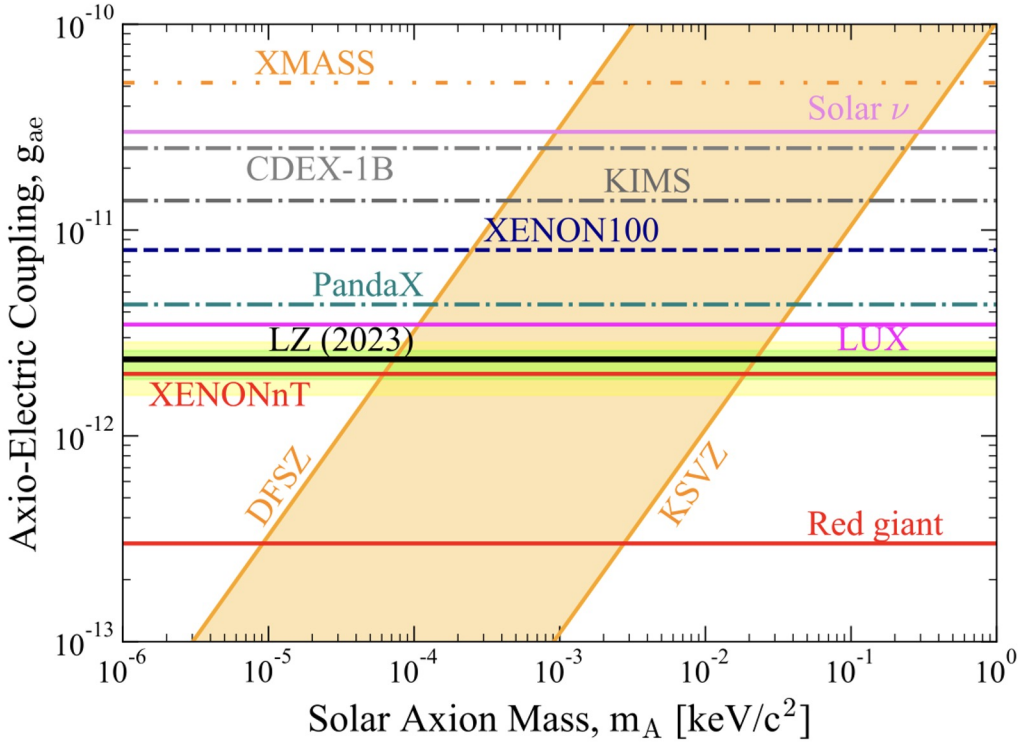


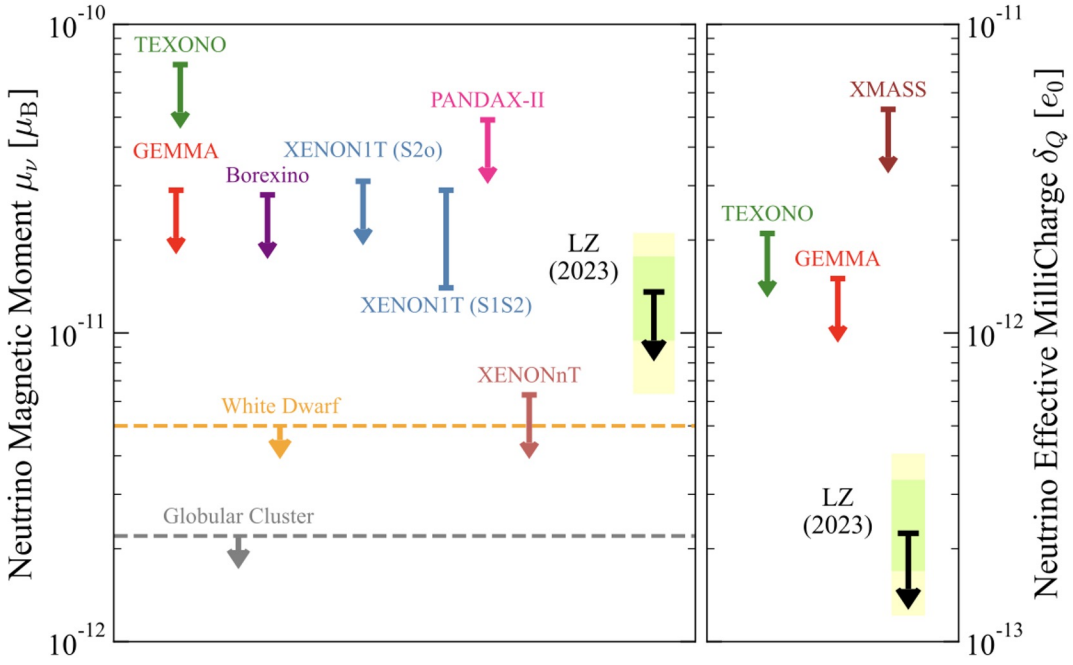
Signal strengths scaled for ease of viewing on same plot

https://tinyurl.com/LZDataReleaseRun1ER

|First Science Run

Searches in the low energy ER band



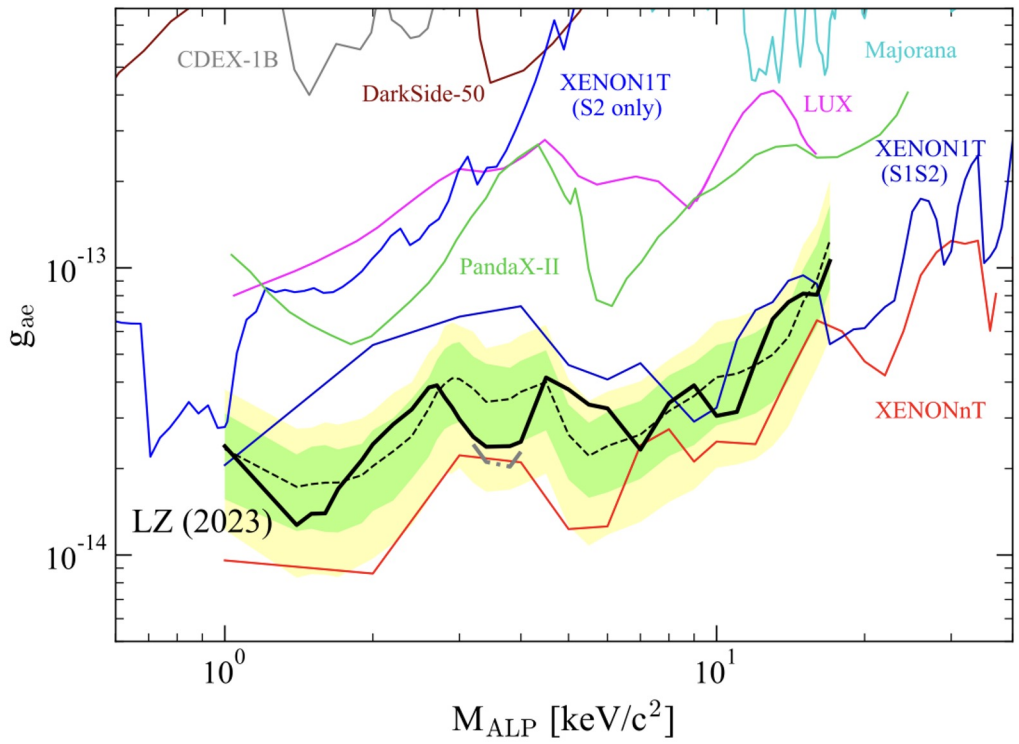


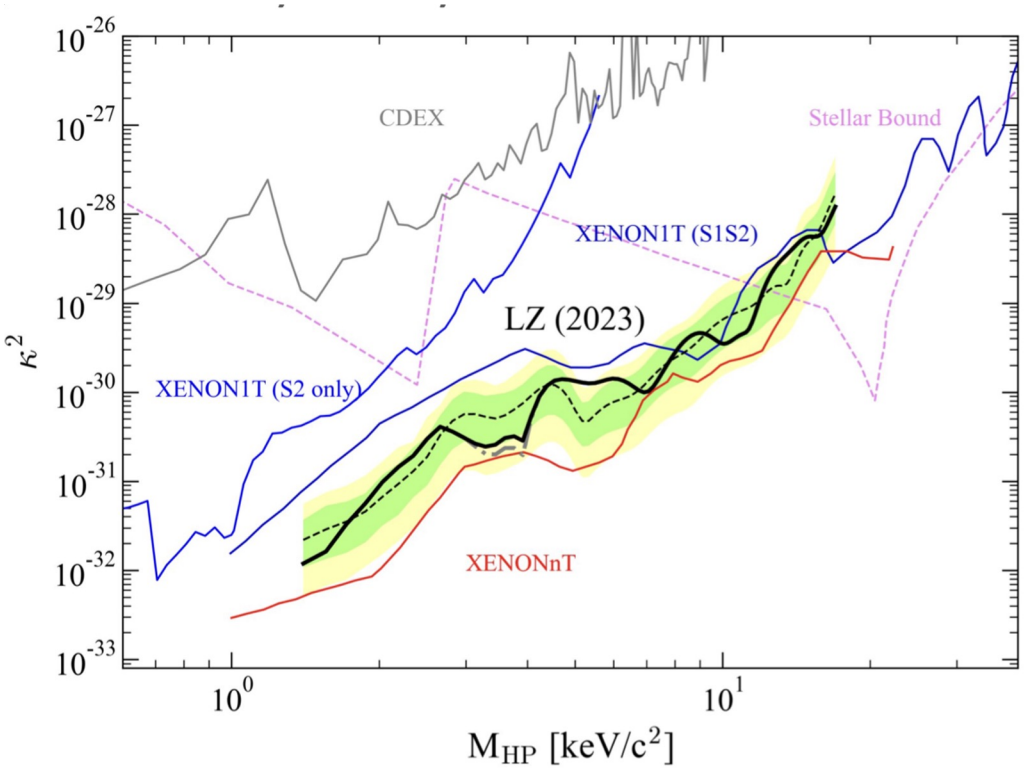
Solar axions
- Production in the sun
- Interaction in Xe via axio-electric effect

Neutrino magnetic moment
- A non-zero neutrino magnetic moment or effective millicharge would increase the rate of solar neutrino ER interactions

|First Science Run

Searches in the low energy ER band





Axion Like Particles (ALPs)
- Gauge pseudo-scalar boson from BSM global symmetry breaking
- Monoenergetic peak in ER spectrum

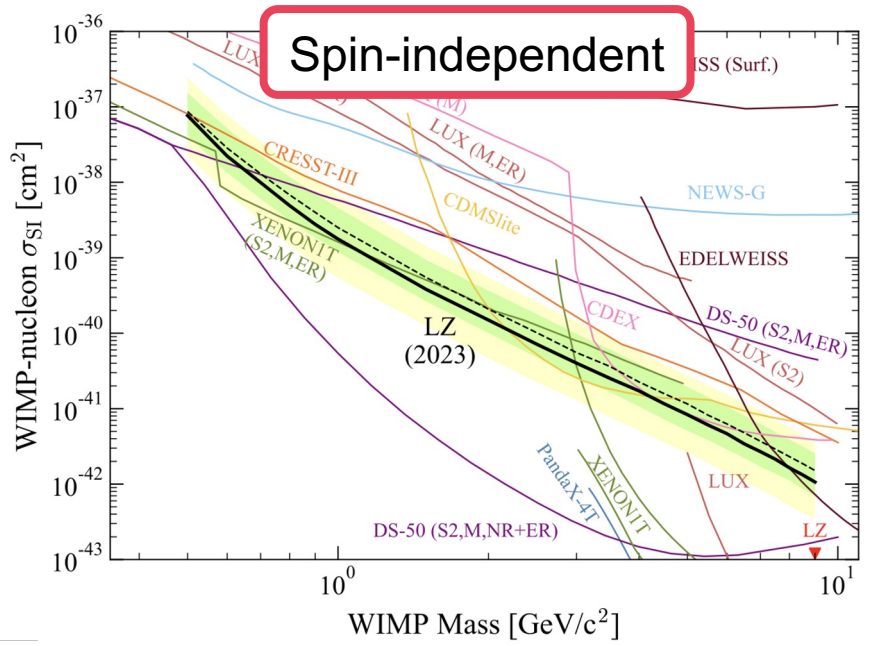
Hidden Photons (HPs)
- Gauge boson of new ‘dark’ U(1) symmetry
- Monoenergetic peak in ER spectrum

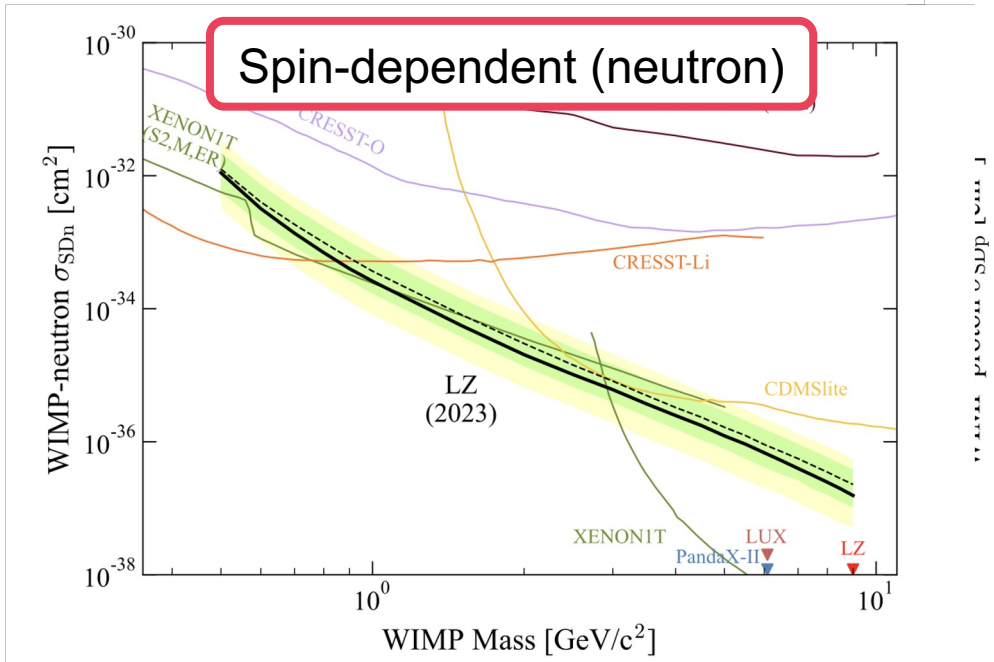
|First Science Run

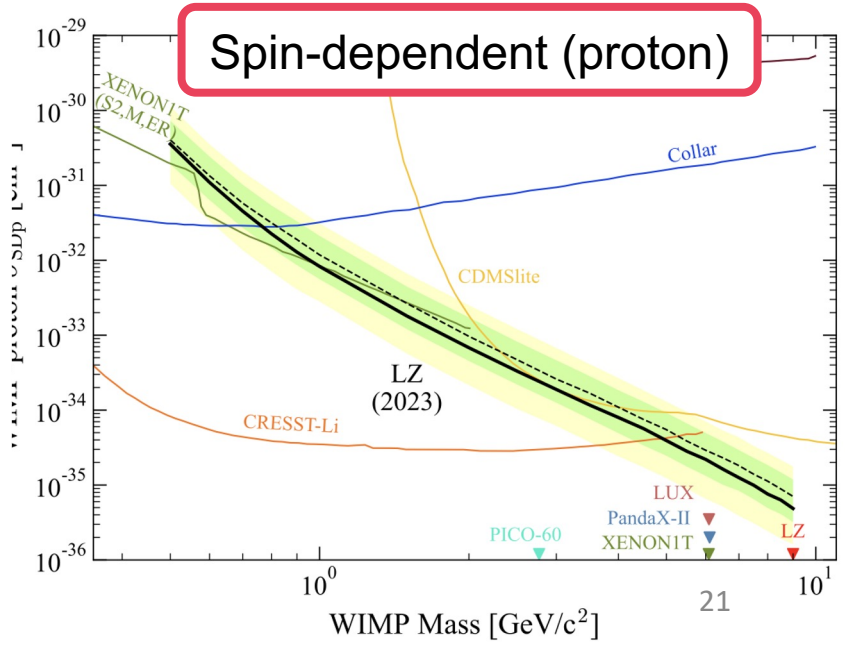
WIMP Search with Migdal Effect

Searching for WIMPs in ER band via Migdal effect

- Electronic excitation and ionization following nuclear recoil
- Sub-dominant to pure NR rate except near threshold



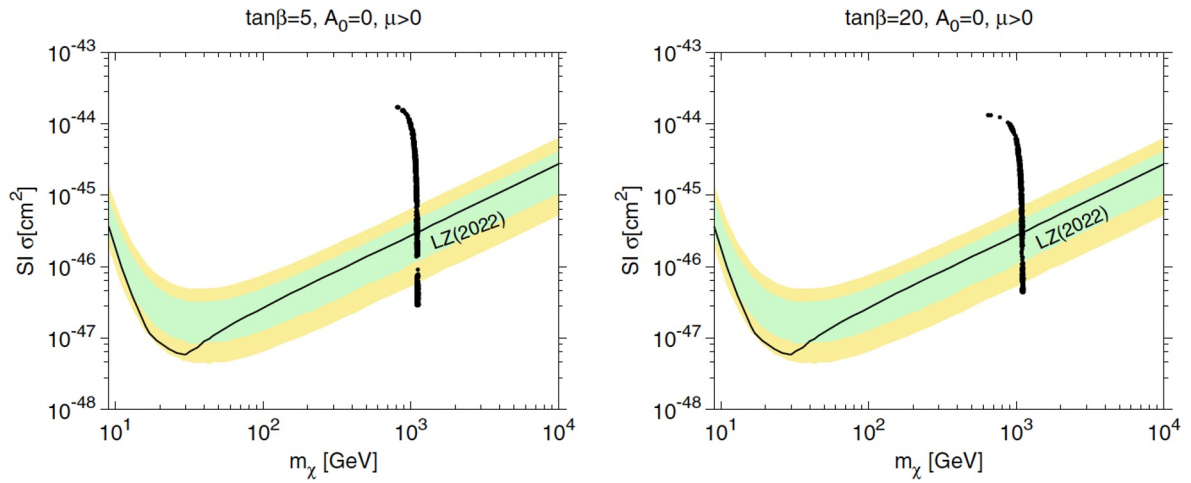




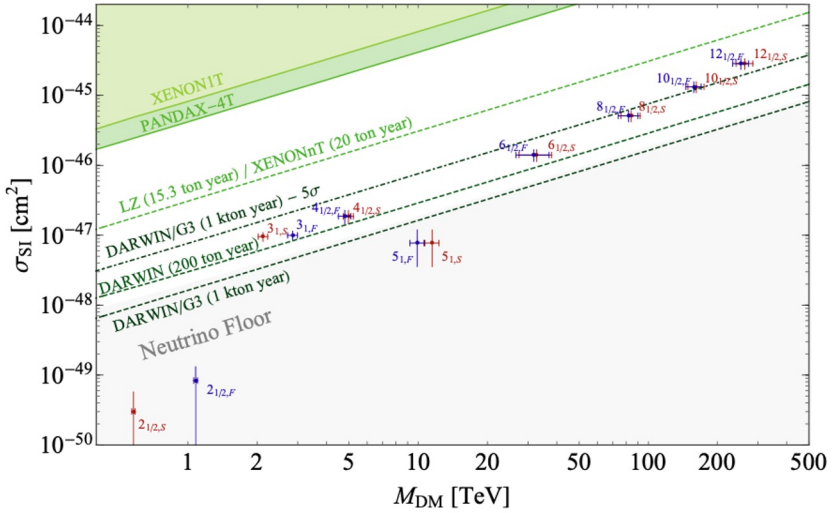
What's next?

- There's much more data to come! Planning for a total 1000 live days (x 17 more exposure than SR1)
- More physics searches to look forward to, among them:
  - ^{8}B solar neutrinos (S2-only)[2]
  - Neutrinoless double-beta decay searches with ^{136}Xe & ^{124}Xe [3,4]
  - High energy EFT searches
  - Ultraheavy/multiply interacting dark matter

[1]LZ WIMP search sensitivity paper: Phys. Rev. D 101, 052002 (2020)
[2]LZ S2-only and Migdal sensitivity: https://arxiv.org/abs/2101.08753 (2021)
[3]LZ Xe136 0νββ sensitivity: Phys. Rev. C 102, 014602 (2020)
[4]LZ Xe124 0νββ sensitivity: Phys. Rev. C 104, 065501 (2021)



Ellis et al., EPJC Vol. 83: 246 (2023)



Bottaro et al., Eur. Phys. J. C**82**, 992 (2022)

Towards the ultimate LXe observatory

- MOU between LZ, XENON, DARWIN
- Two in-person meetings
  - Karlsruhe 2022
  - UCLA 2023
- https://xlzd.org/
- White paper (2203.02309)

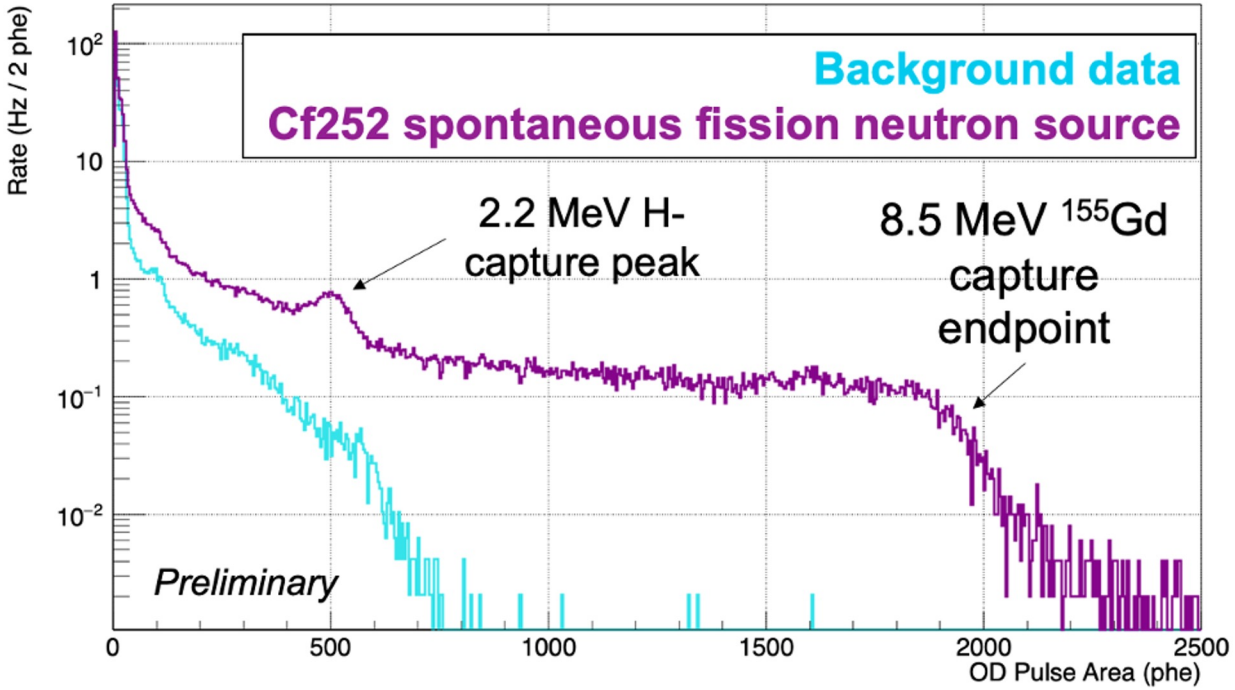
First in-person meeting June 2022

https://lz.lbl.gov/

@lzdarkmatter

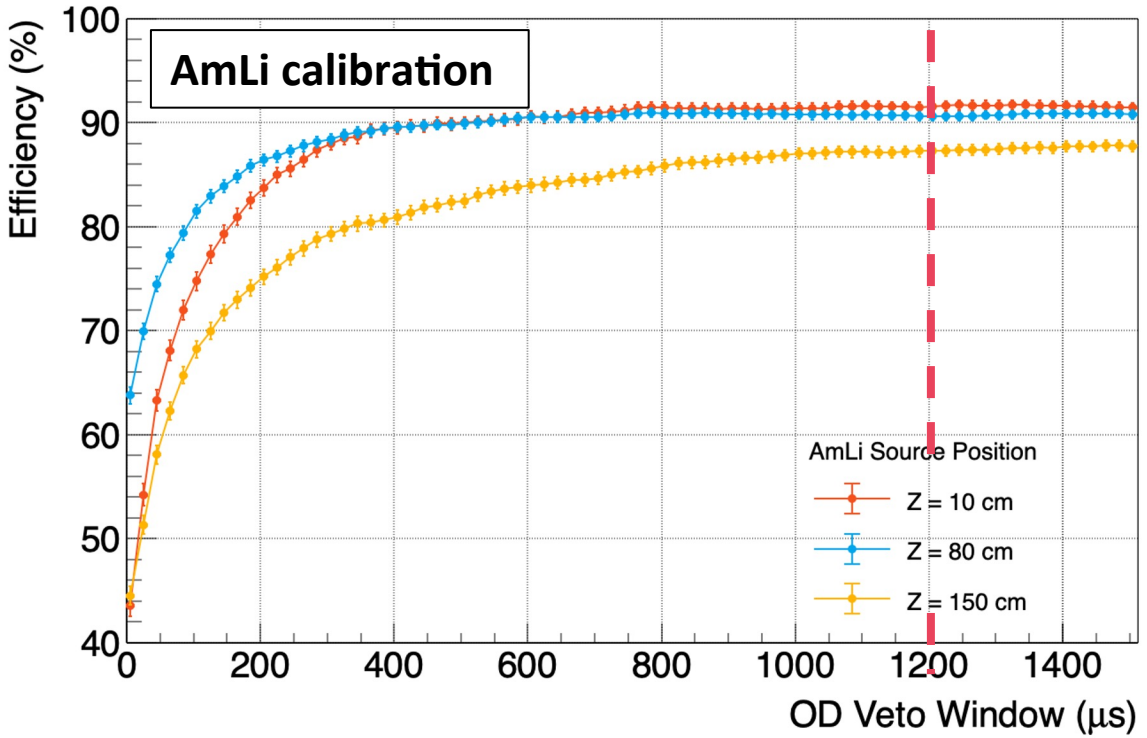
- All LZ systems are performing well and backgrounds are within expectations
- Short engineering run has produced world-leading WIMP limits!
- Much more to come for LZ:
  - Ultimately planning for 1000 live-days
  - Many more physics searches
- Beyond LZ: planning next generation detector with XLZD consortium

Neutron tagging



- Neutron capture on Gd produces gamma emission of up to 8.5 MeV
- Time delay between neutron scatter in LXe and capture is O(0.1-1 ms)
- Skin can detect proton recoil/Gd-capture gammas

Single -scatter neutron tagging efficiency: 89±3%



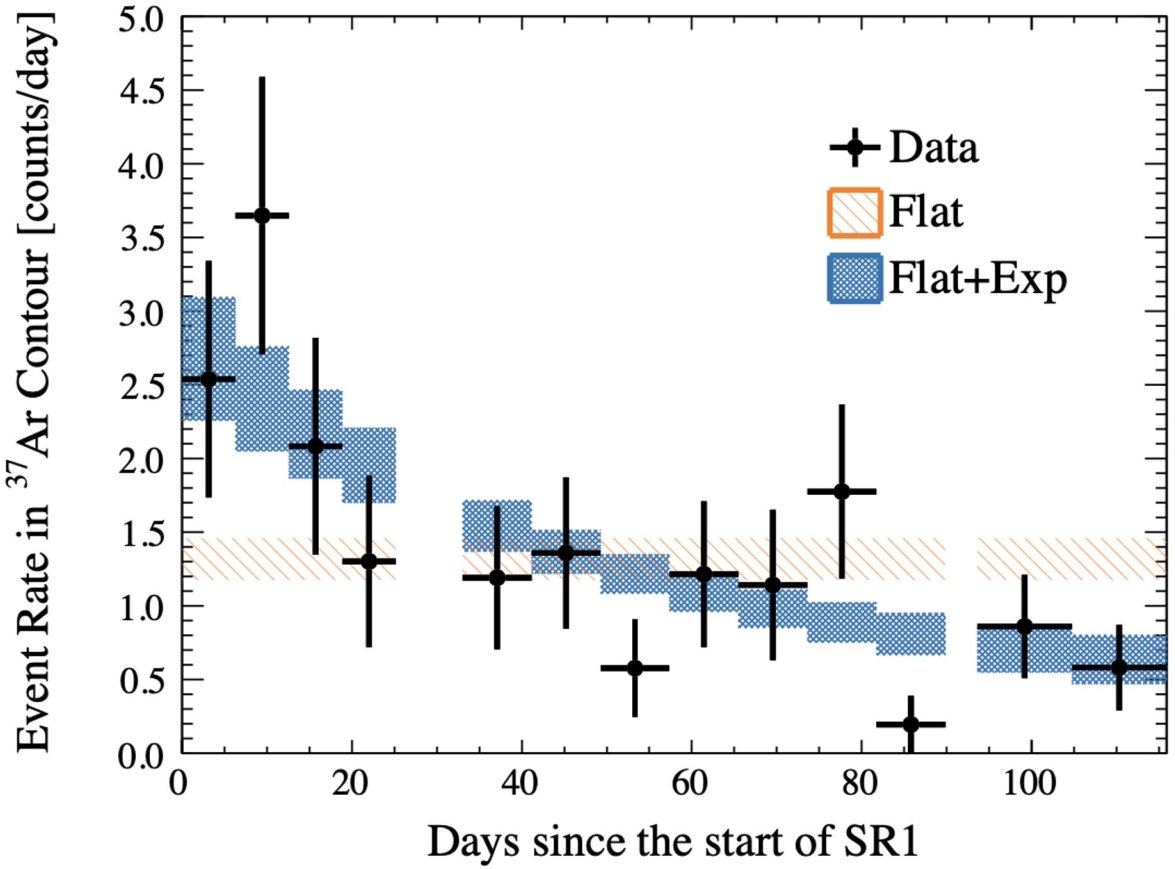
- OD neutron tagging settings
  - ≥ 200 keV
  - Δt ≤ 1200 μs
- Live-time hit: 5%

|Backup

Background Determination for the LUX-ZEPLIN (LZ) Dark Matter Experiment, Phys. Rev. D **108**, 012010 (2023)

^{37}Ar

- ^{37}Ar is a significant background in early LZ data ($t_{1/2}$ = 35 d)
- Occurs naturally in atmosphere via e.g. Ca(n,α)Ar[1], but suppressed during Xe purification by charcoal chromatography
- Produced by cosmic spallation of natural xenon
- Estimating exposure during transport allows calculation of expected activity
  - ➢ We expect ~100 decays of ^{37}Ar in SR1 with a large uncertainty.[2]

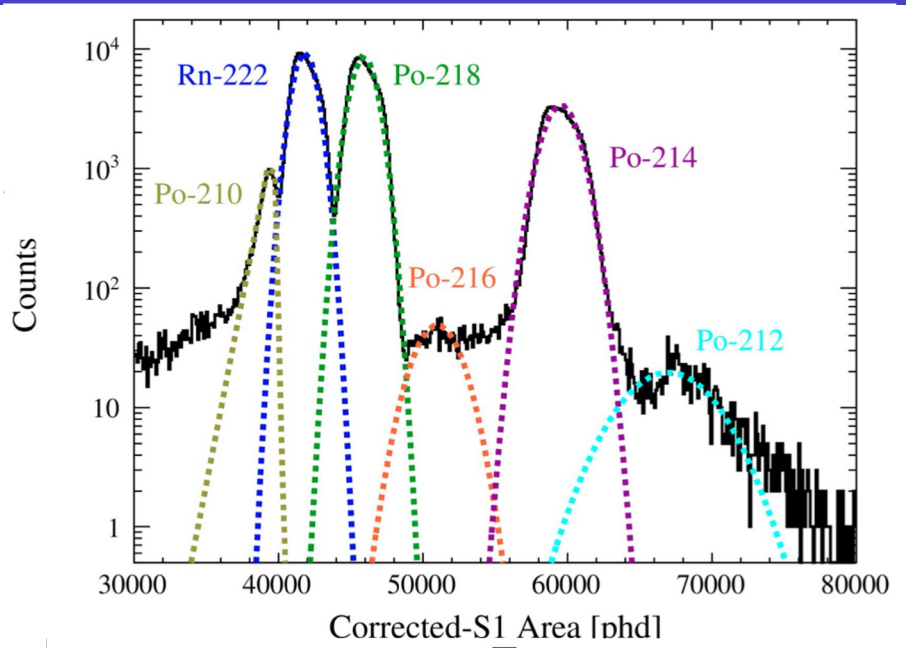


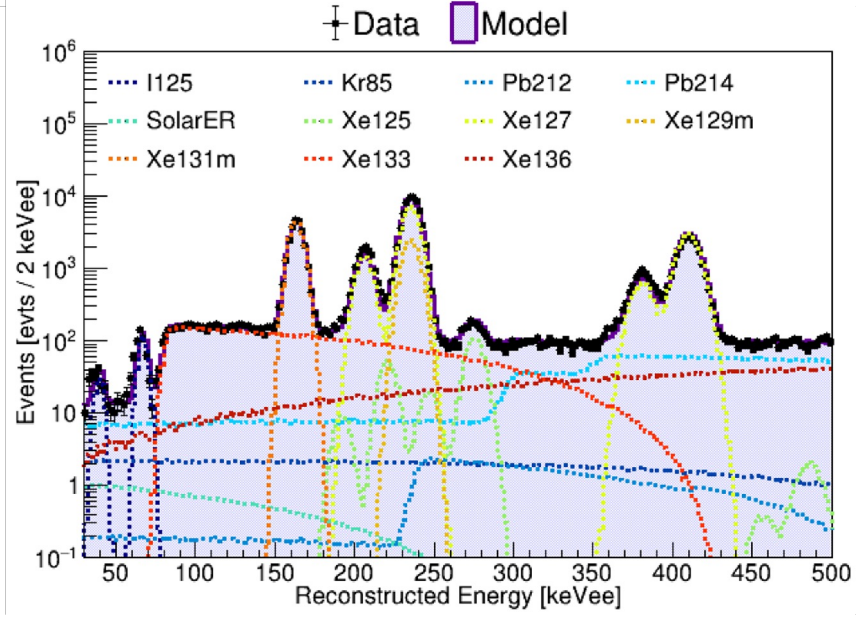
|Backup

Radon

- Naked ^{214}Pb β-decays are the **main** WIMP background
- Rn emanating from detector materials into TPC xenon
- Constrain β-decay rate with two methods:
  - Rn-chain α tagging
  - Spectral fit of all internal BGs outside of energy ROI

^{222}Rn (μBq/kg)	^{214}Pb (μBq/kg)	^{214}Po (μBq/kg)
4.37 ± 0.31 (stat)	**3.26 ± 0.13(stat) ± 0.57(sys)**	2.56 ± 0.21 (stat)

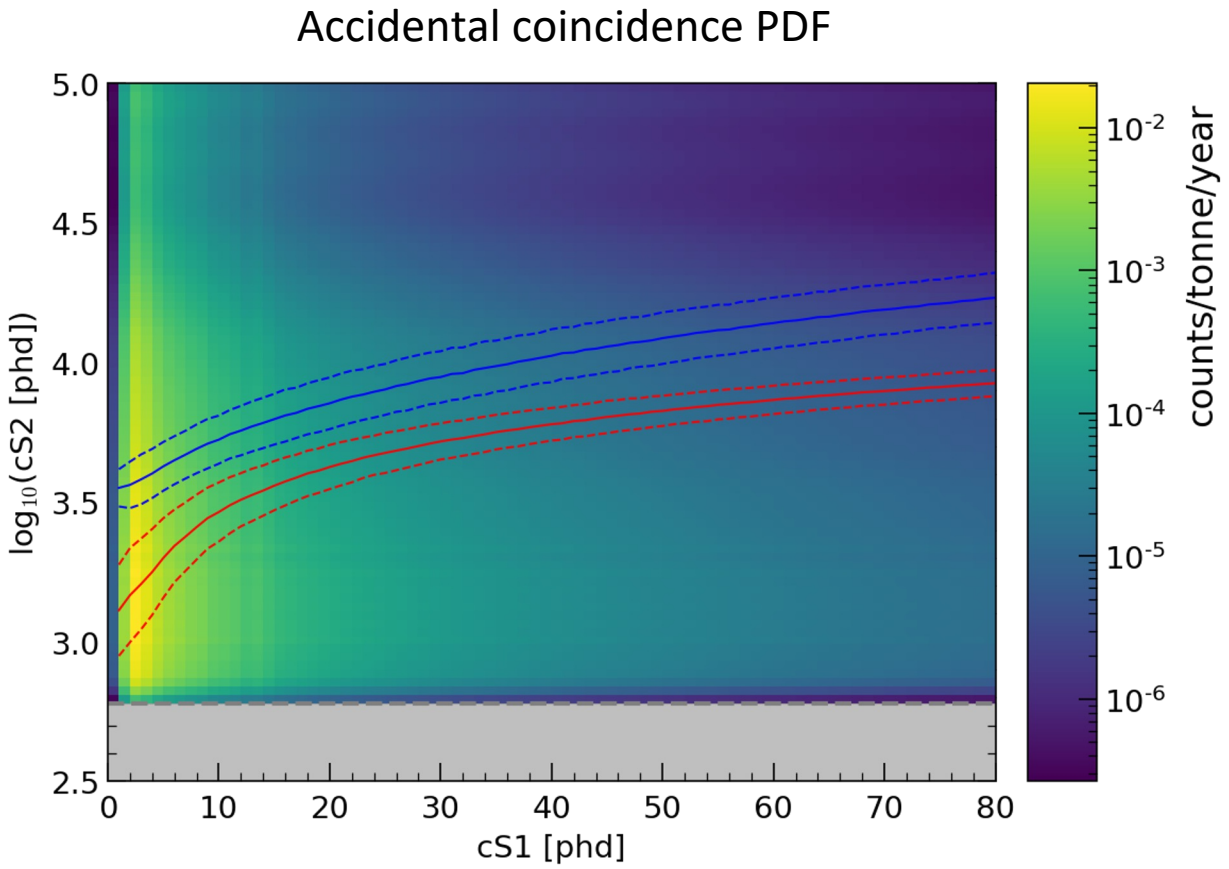




|Backup

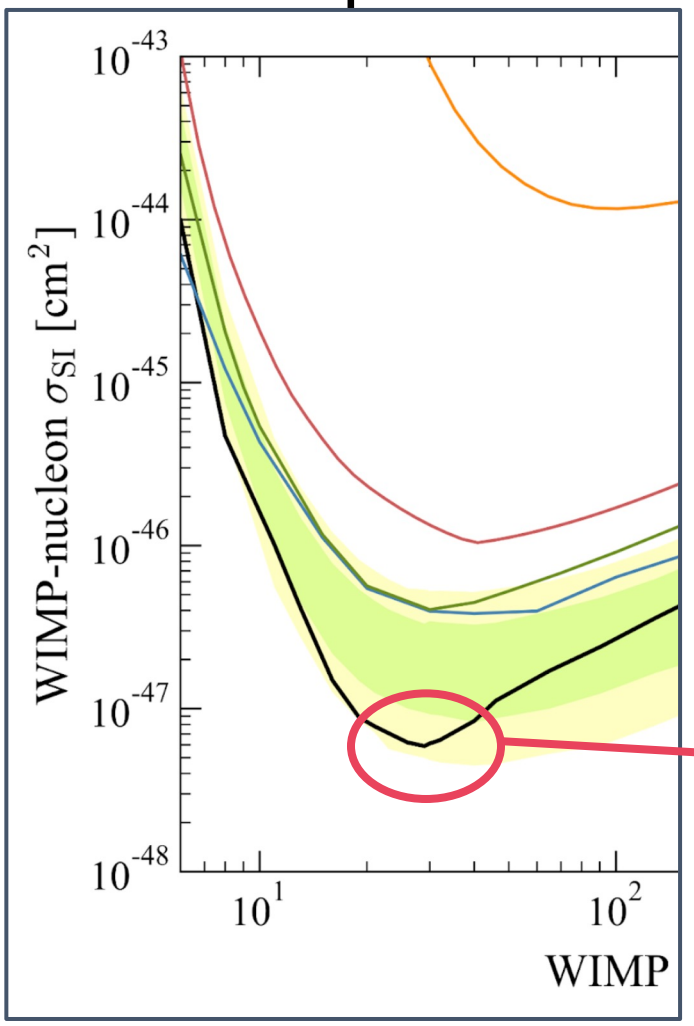
Accidental coincidences

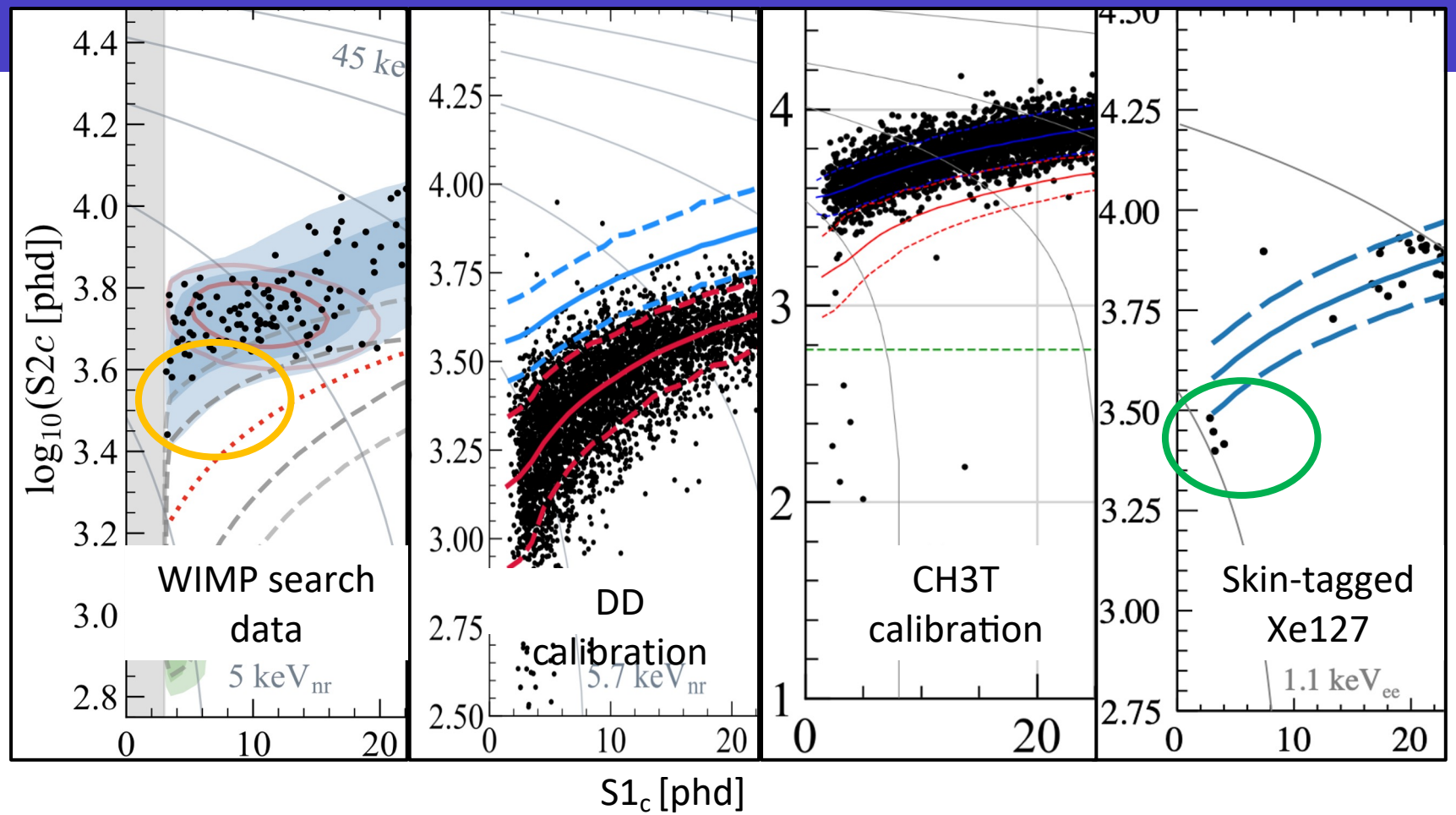
- Isolated S1s & S2s can accidentally combine to form WIMP ROI events
- Data quality cuts successfully developed to address this background
- To construct PDF, stitch isolated raw pulses together for fake events. Normalised using events with unphysical drift time
  (i.e. drift time > TPC height)
- Expect 1.2 ± 0.3 events in SR1



|Backup

Limit shape





Downward fluctuation in the observed upper limit (pink ellipse) is a result of the deficiency of events under the Ar-37 population (yellow ellipse).

Calibration (both DD and CH3T) and Xe127 M-shell counts (green ellipse) in this region are as expected with our signal acceptance model.
=> Deficit in WIMP search data appears consistent with under-fluctuation of background.