First results of the LZ dark matter experiment

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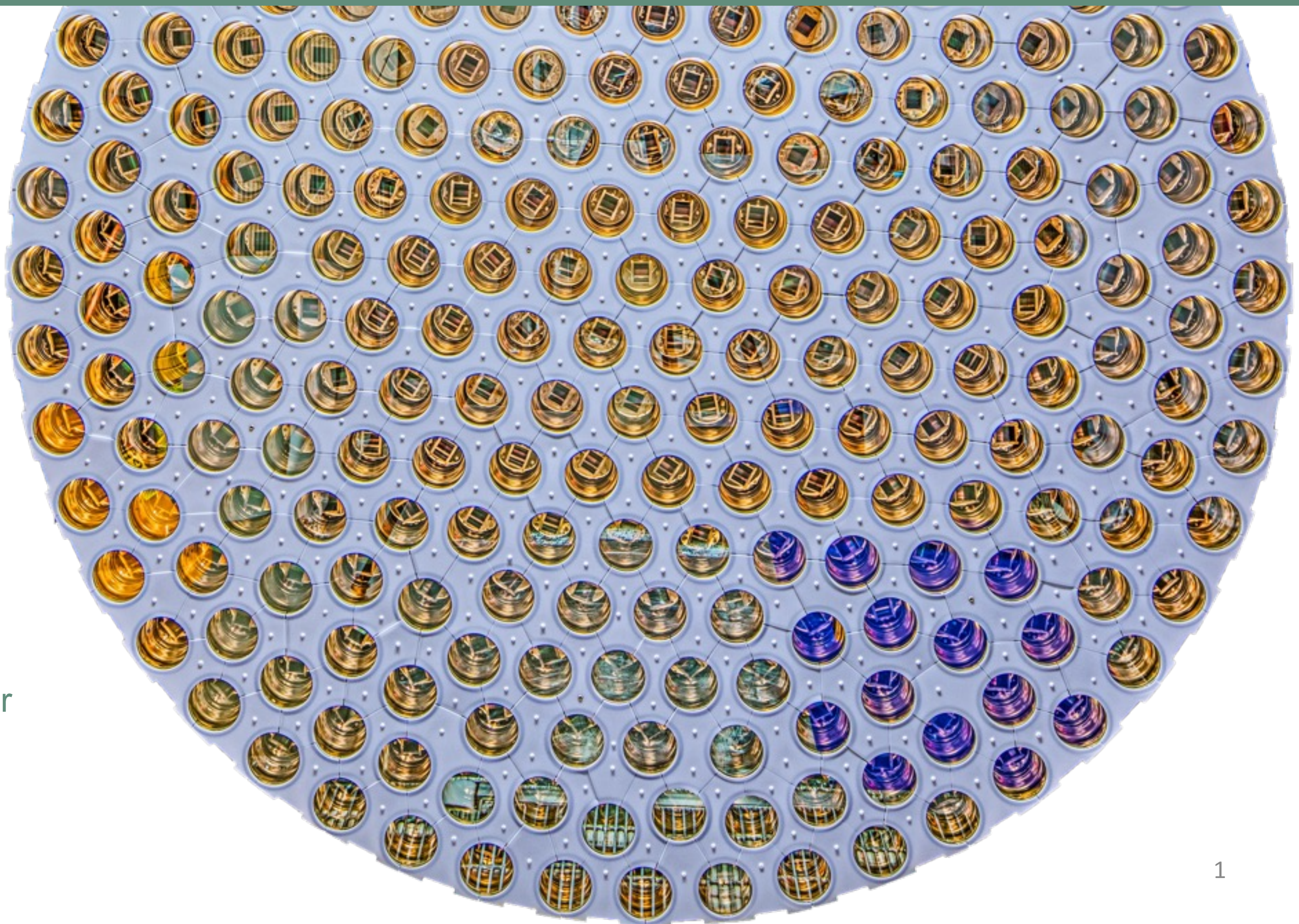
ARC Centre of Excellence for Dark Matter Particle Physics Annual Meeting,
23 Nov 2022



LZ collaboration - 35 Institutions: 250 scientists, engineers, and technical staff

Black Hills State University
Brookhaven National Laboratory
Brown University
Center for Underground Physics
Edinburgh University
Fermi National Accelerator Lab.
Imperial College London
Lawrence Berkeley National Lab.
Lawrence Livermore National Lab.
LIP Coimbra
Northwestern University
Pennsylvania State University
Royal Holloway University of London
SLAC National Accelerator Lab.
South Dakota School of Mines & Tech
South Dakota Science & Technology Authority
STFC Rutherford Appleton Lab.
Texas A&M University
University of Albany, SUNY
University of Alabama
University of Bristol
University College London
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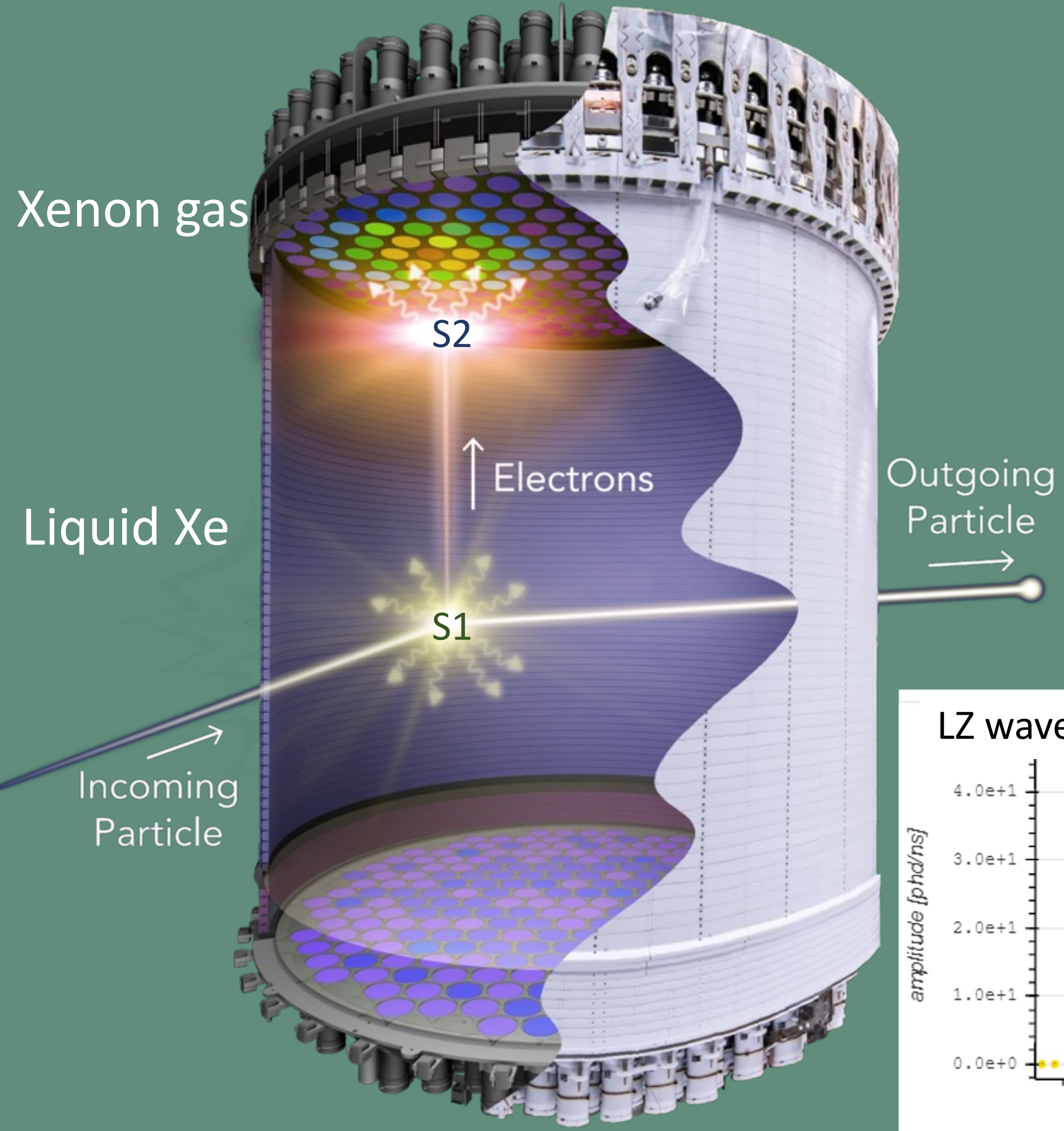
Institute for Basic Science

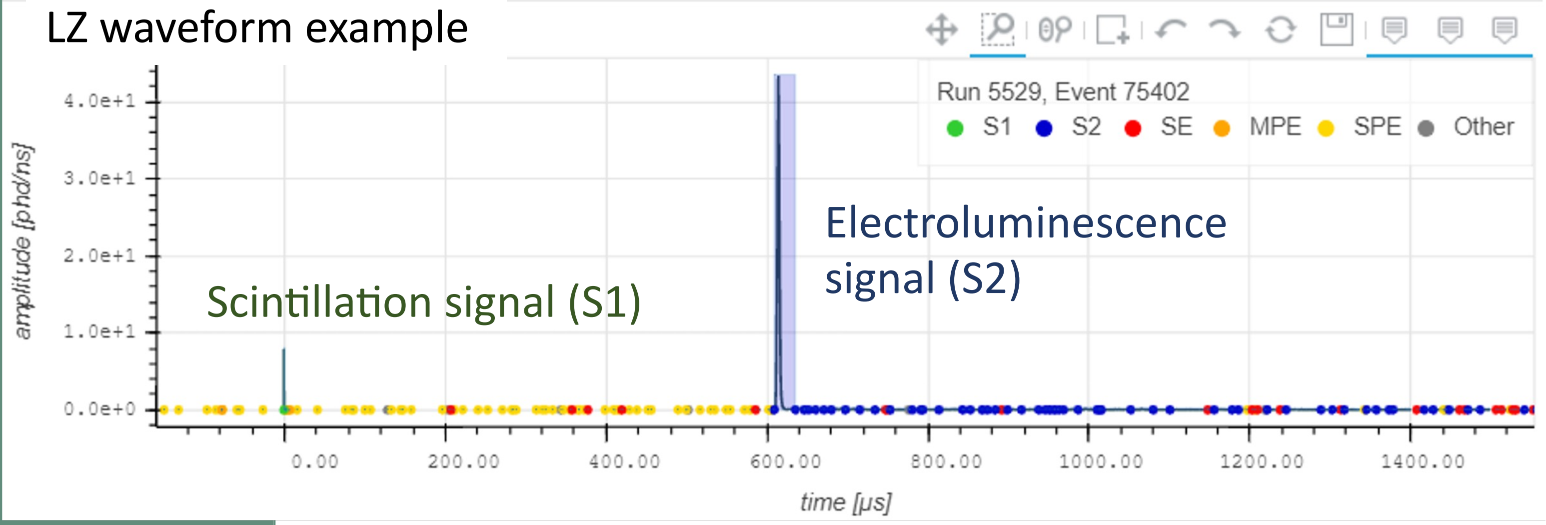
|LUX-ZEPLIN

Overview

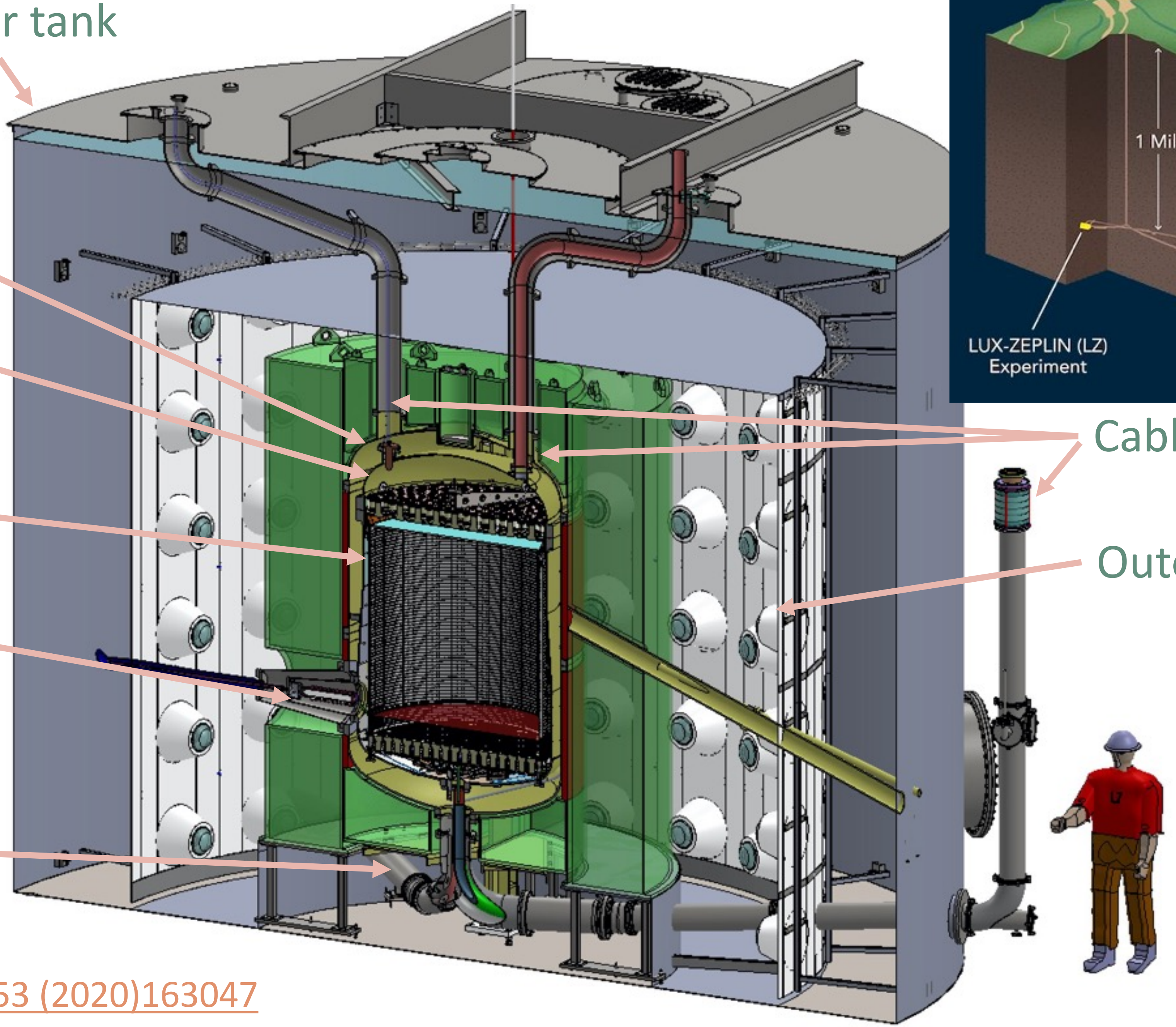
- Principal goal: the direct detection of dark matter via nuclear recoils
- Scintillation & charge (via electroluminescence) signals
- 3D event reconstruction

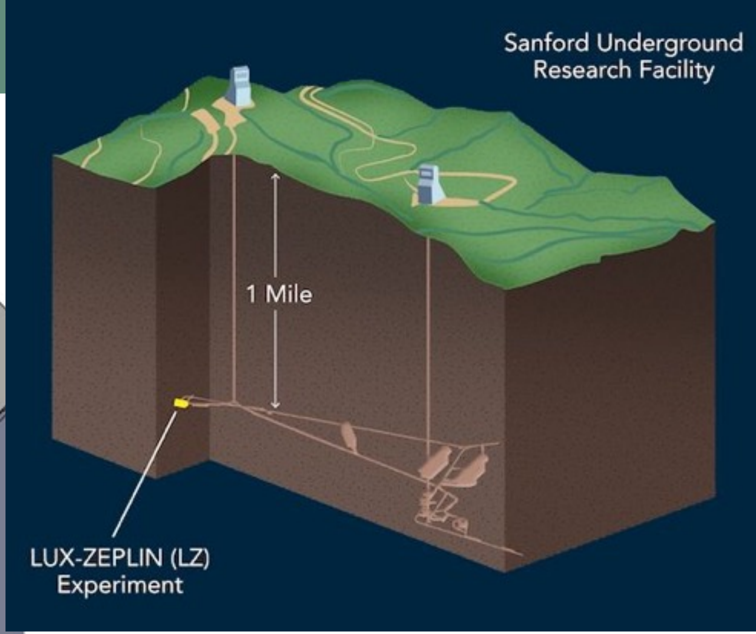


LZ waveform example



Overview





The LZ experiment, NIM A953 (2020)163047

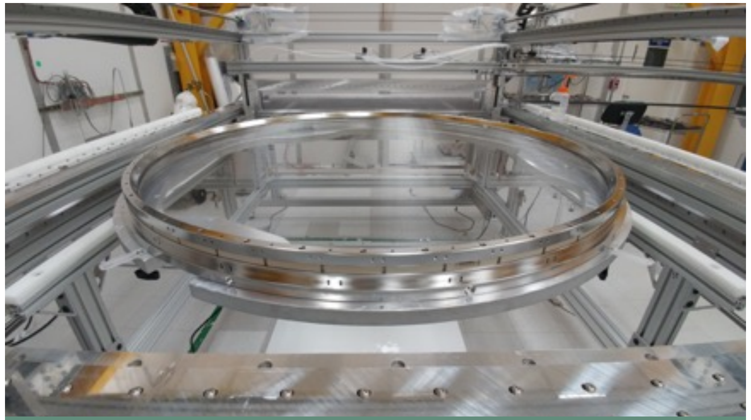
|Detector

TPC

- PTFE field cage
  - 7 tonnes of xenon
  - Optimised for high light collection efficiency
- 4 high-voltage grids for
  - drift field
  - extraction region

Assembled TPC

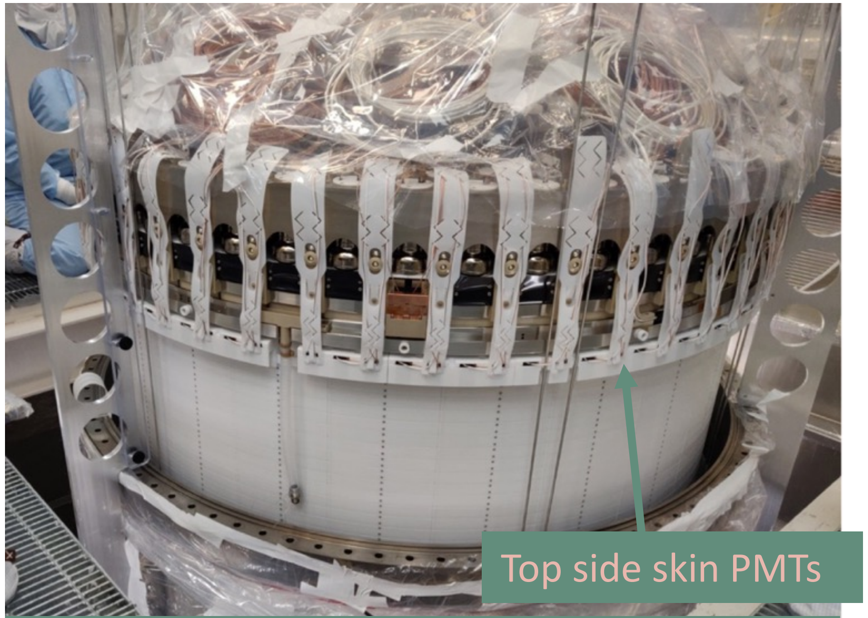
494 TPC PMTs (Hamamatsu R11410-22)
Photo: bottom array + field cage



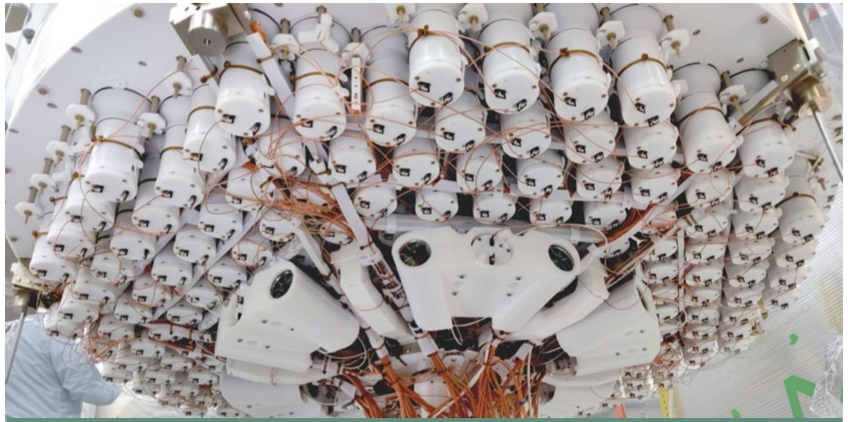
HV grids were
woven on a custom-built loom at SLAC

Skin Veto

- Liquid xenon between TPC and inner cryostat vessel
- Instrumented with 131 PMTs as veto detector
- γ-coincidence veto



TPC insertion into inner cryostat vessel

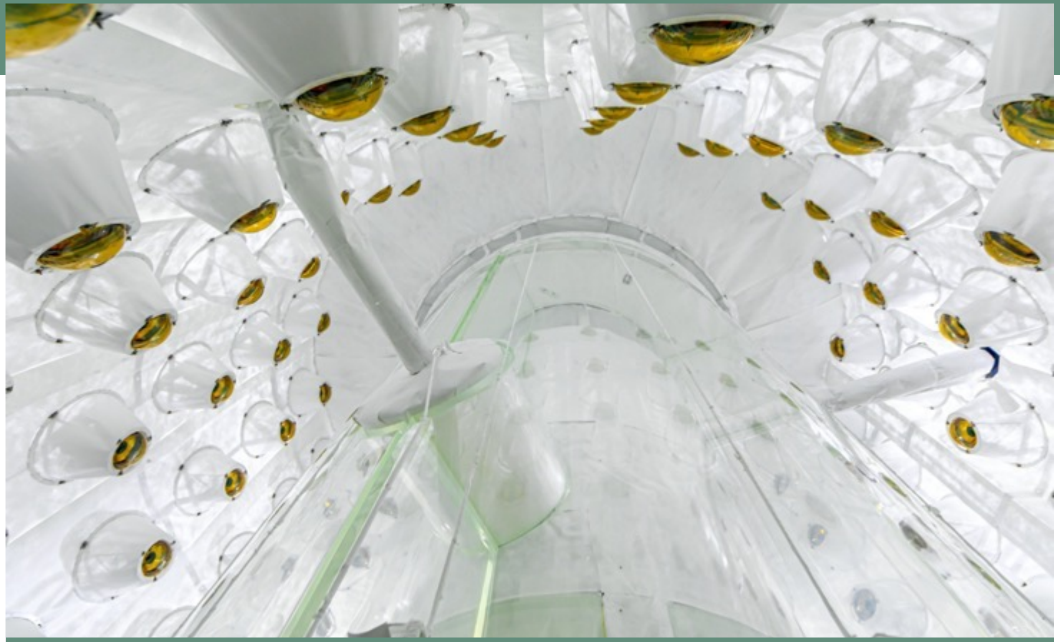


Dome PMTs below bottom array

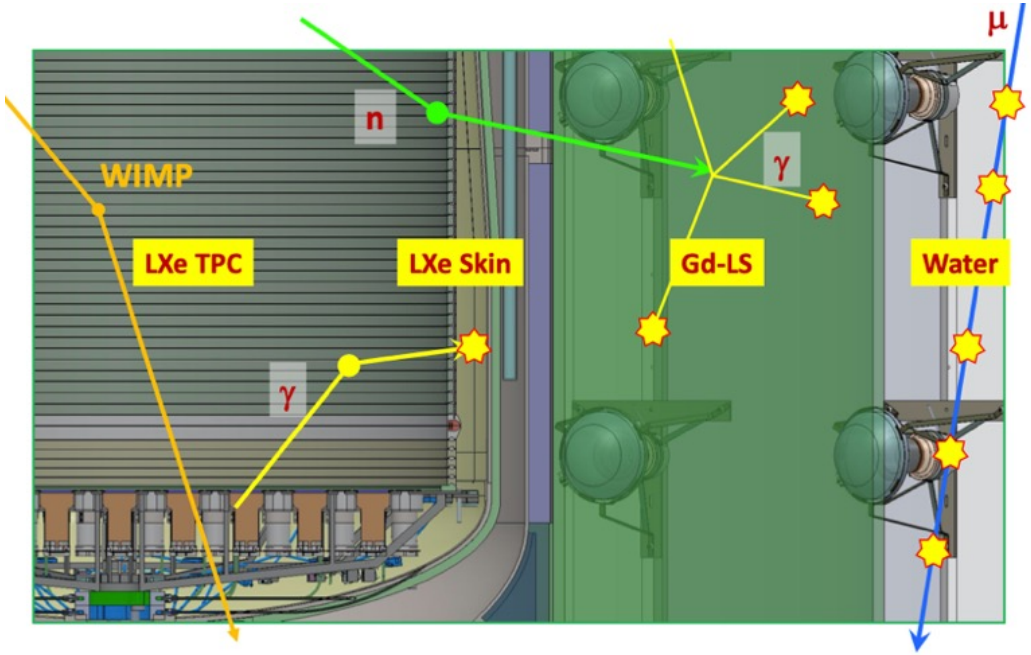
Bottom side skin array & PTFE tiling on cryostat

Outer Detector Veto

- 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 γ-rays from thermal neutron capture with total energy of up to 8.5 MeV



Completed Outer Detector



Construction & commissioning overview

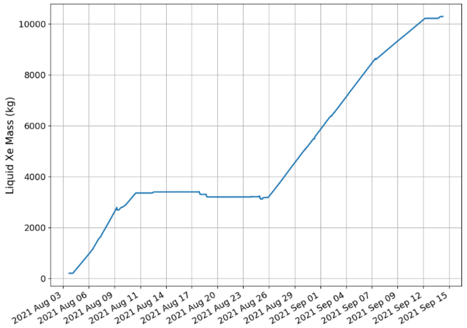
TPC assembled
Aug 2019

Circulation Test
July 2020

Electronics installation
Fall 2020

Kr Reduction
Jan-Aug 2021

Xenon Fill
Aug-Sep 2021



Commissioning
Fall 2021

2019

2020

2021

2022

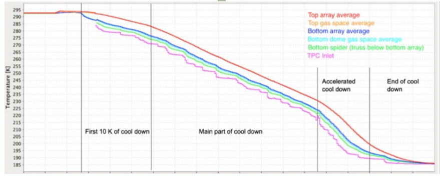
First science

Detector construction at surface lab
Aug 2018 – Aug 2019

TPC moves underground
Oct 2019

Detector sealed up
March 2020

OD Construction
Winter 2020-2021



Cold Xe gas,
March 2021

OD Fill
June 2021

Overview

Stable detector conditions:

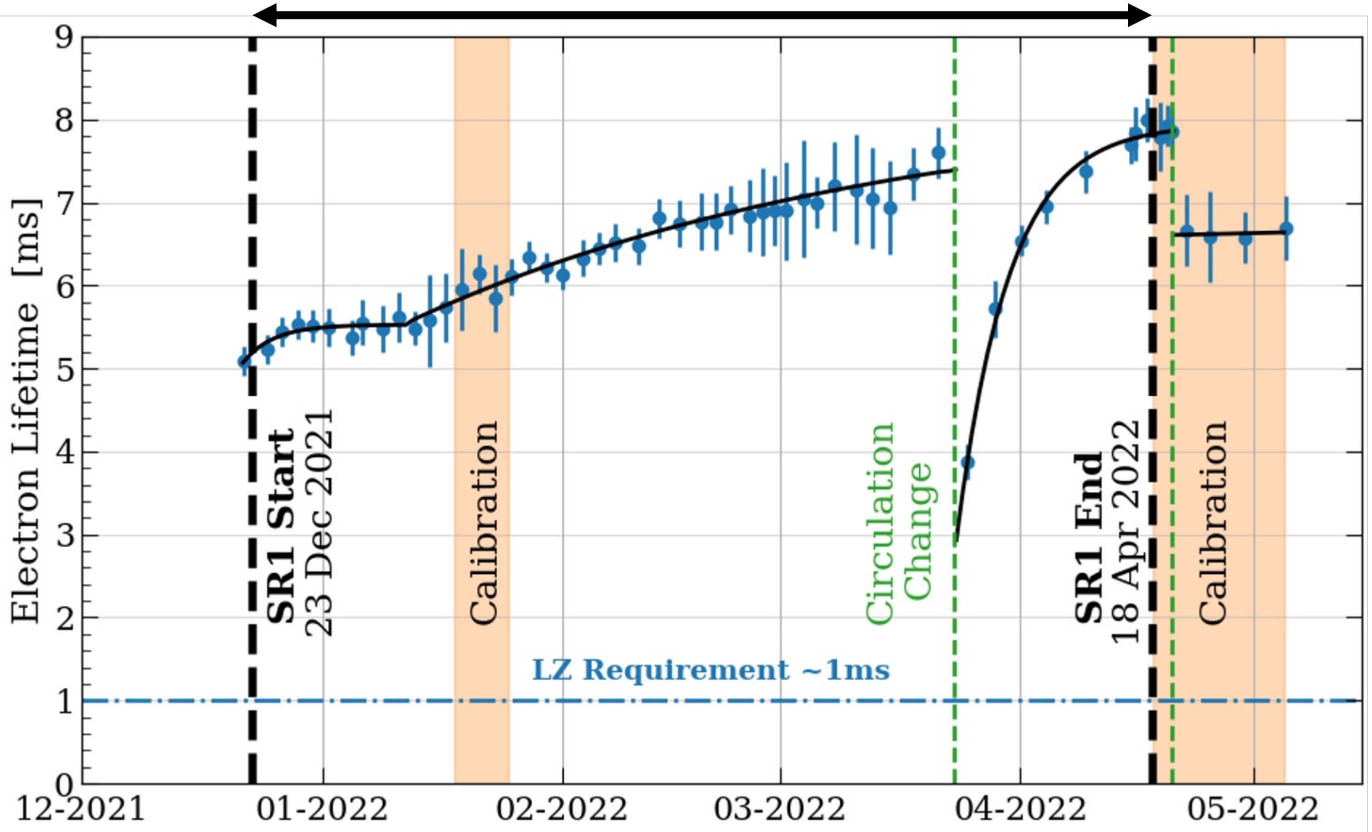
- Temperature = 174.1 K
- Gas pressure = 1.791 bar
- Drift field = 193 V/cm
- Extraction field = 7.3 kV/cm (in gas)
- >97% PMTs operational

Continuous purification:

- 3.3 t/day through hot getter system

Engineering run (data unblinded)

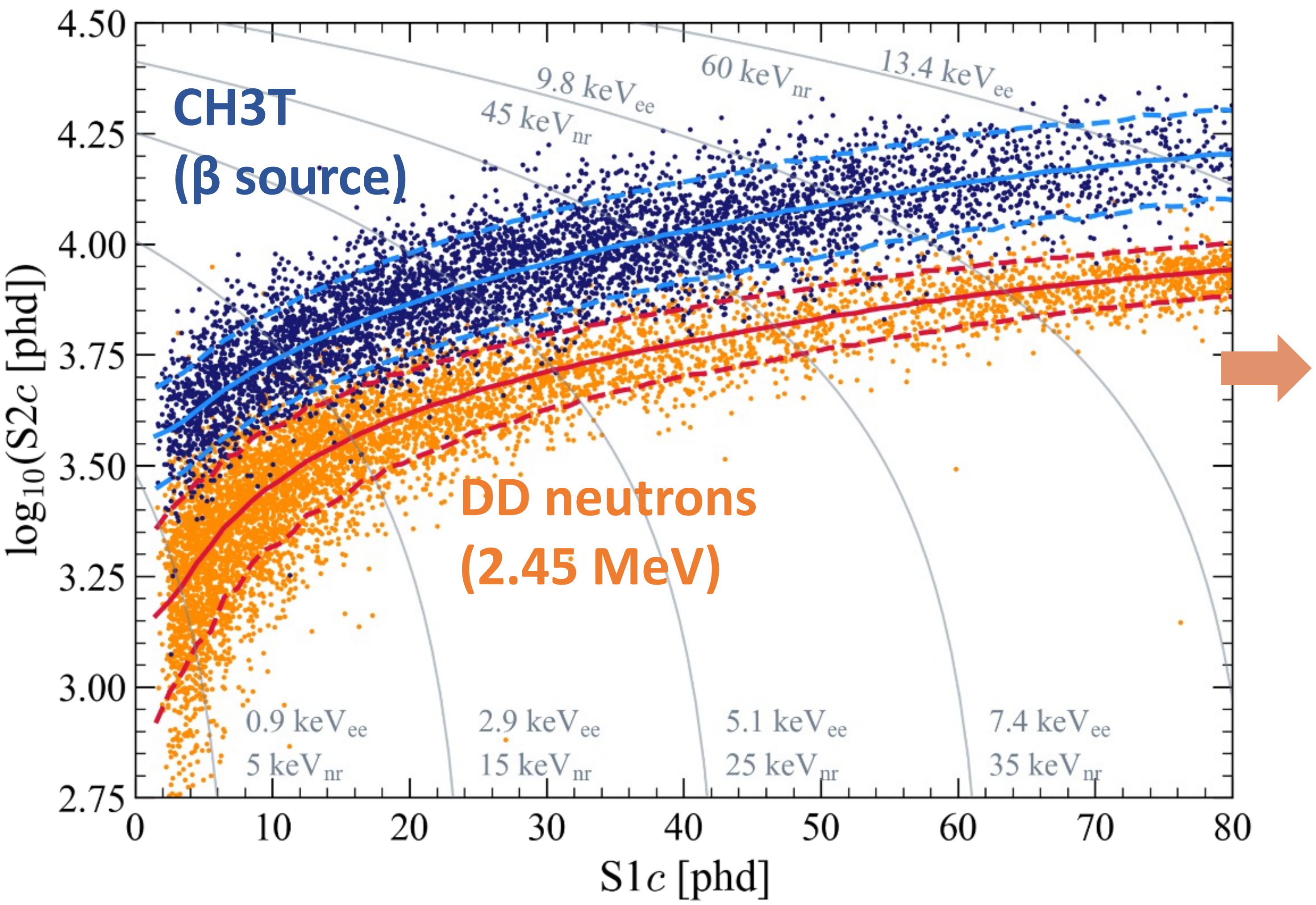
116 calendar days -> 60 live days



Electron lifetime 5-8 ms throughout

|First Science Run

TPC Calibrations



Band fits performed with NEST v2.3.7 [1]

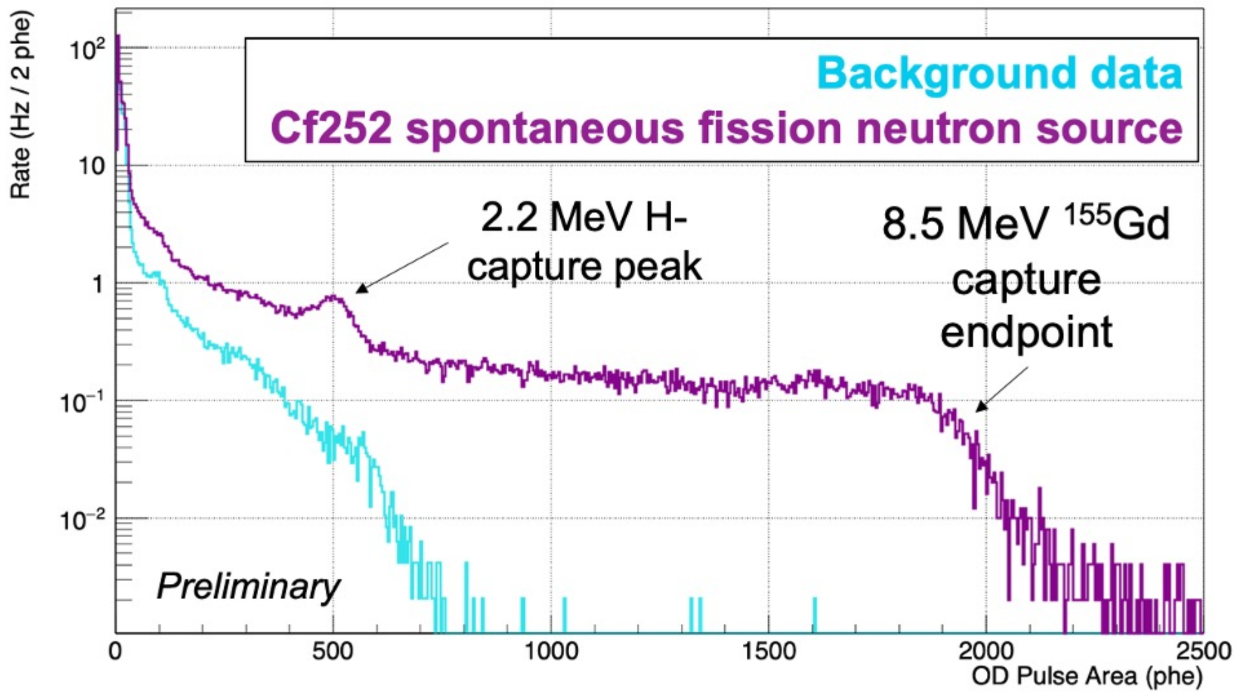
Photon detection efficiency:
g1 = 0.114 +/- 0.002 phd/photon

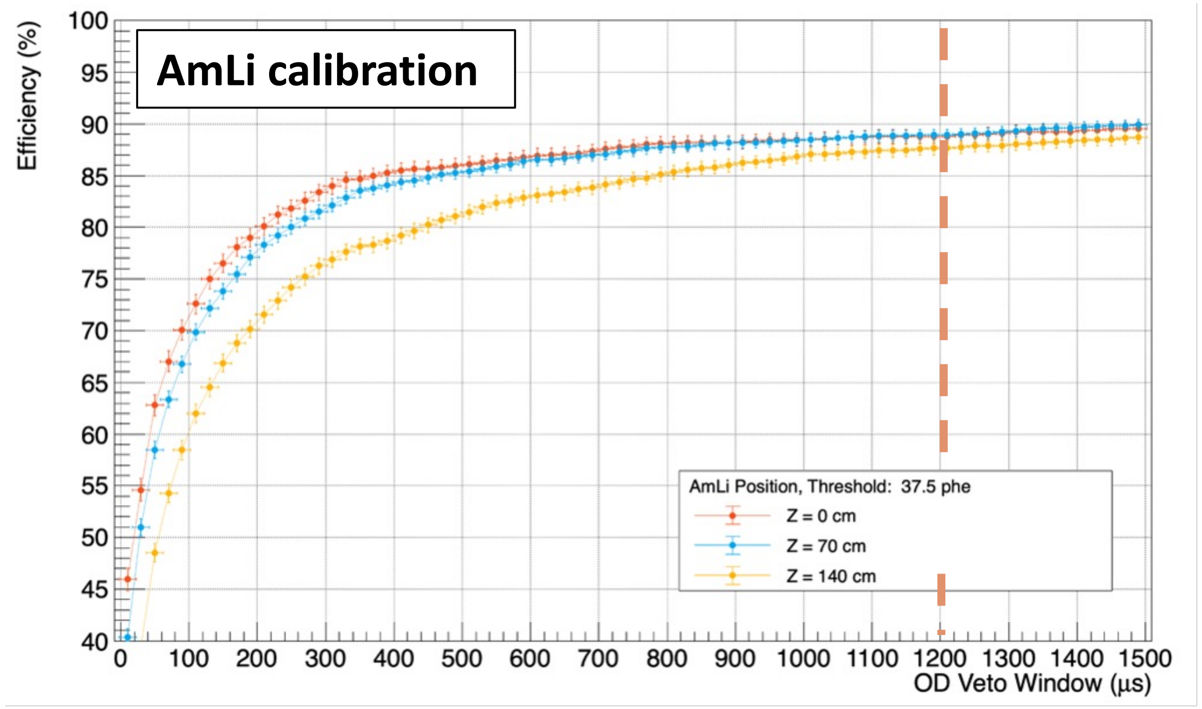
Ionization channel gain:
g2 = 47.1 +/- 1.1 phd/electron

99.9% discrimination of beta backgrounds under NR band median achieved

Outer detector efficiency

Single -scatter neutron tagging efficiency: 88.5±0.7%





- 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)

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

[1] https://doi.org/10.1016/j.astropartphys.2020.102480

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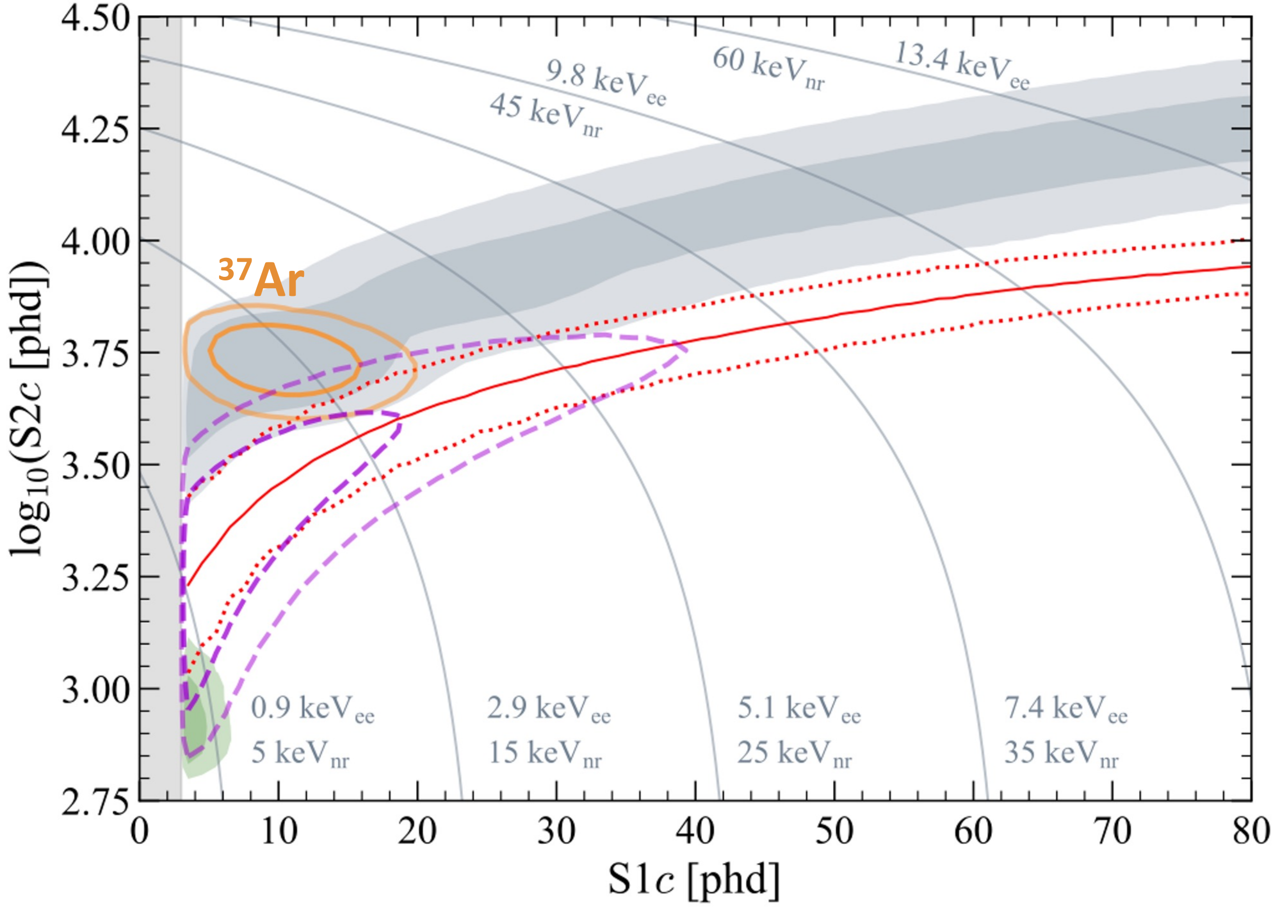
Background model



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

ER backgrounds in ROI:

- Dissolved β-emitters
  - ^{222}Rn daughters, ^{85}Kr
  - ^{136}Xe ($2\nu\beta\beta$)
- Dissolved e-captures (mono-energetic x-ray, Auger cascades):
  - ^{37}Ar, ^{127}Xe, ^{124}Xe
- γ-emitters in detector materials
  - ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co
- Solar neutrinos (ER)
  - pp + 7Be + 13N

NR backgrounds in ROI:

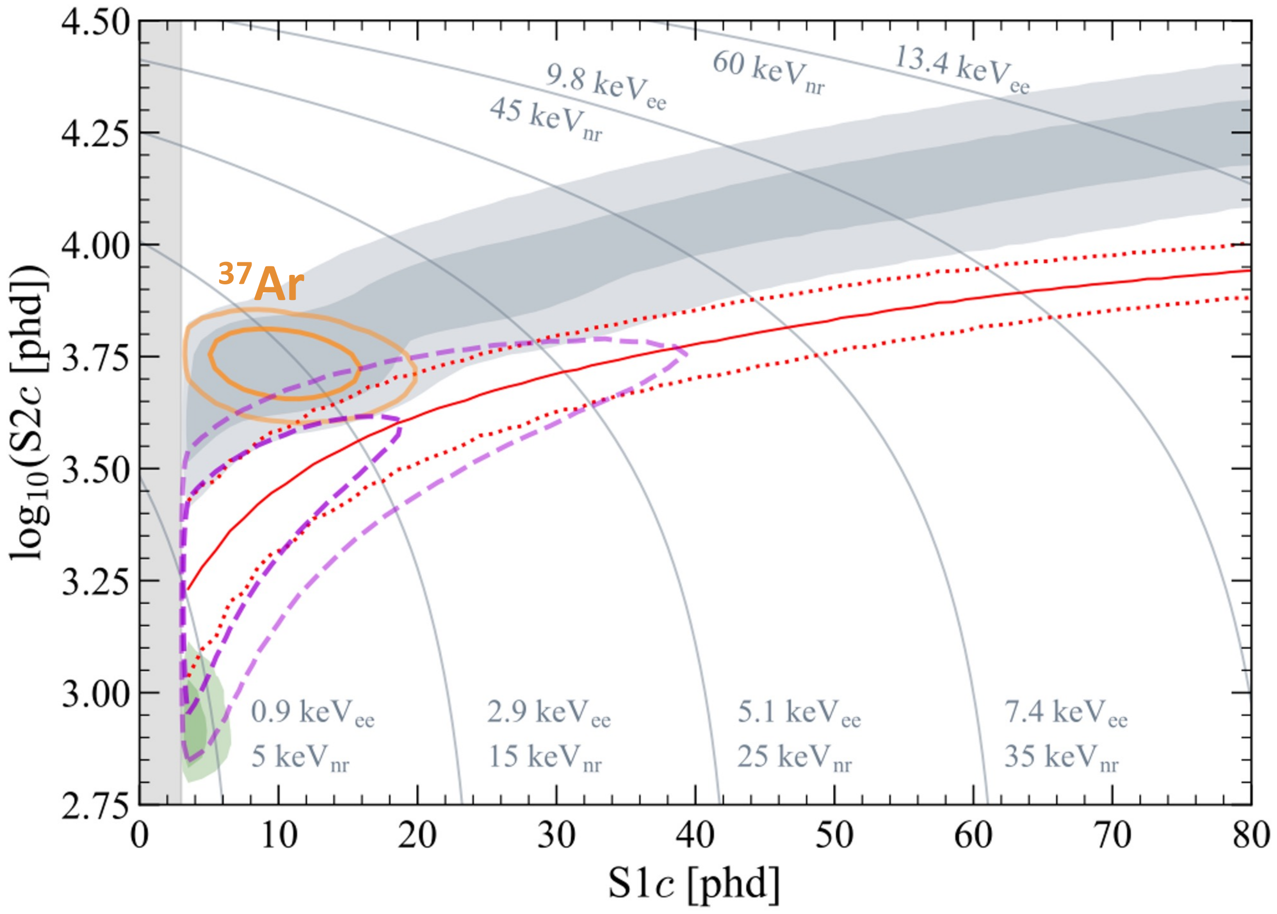
- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar CEνNS

Expected accidental coincidences in ROI:

- Coincidence of lone S1 and lone S2 pulses

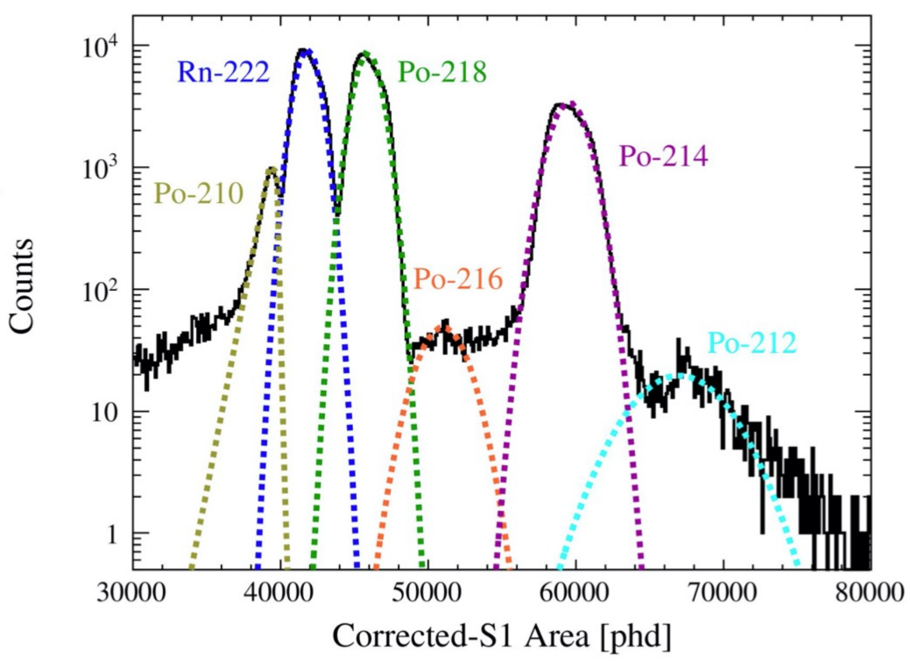
|First Science Run

Background model

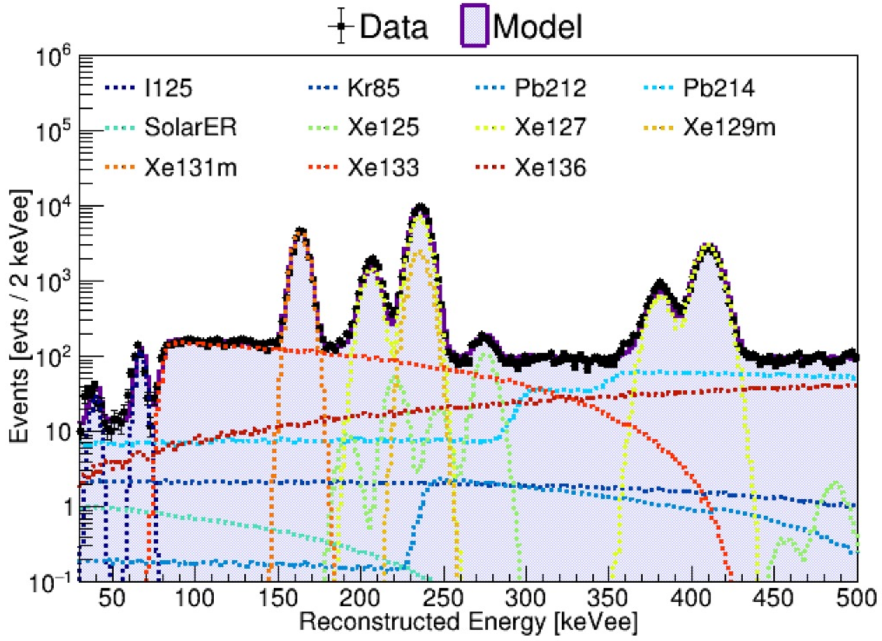


Source	Expected Events
β decays + det ER	218 ± 36
ν ER	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8
^{124}Xe	5.0 ± 1.4
^{136}Xe	15.2 ± 2.4
^{8}B CEνNS	0.15 ± 0.01
Accidentals	1.2 ± 0.3
Subtotal	276 ± 36
^{37}Ar	[0, 291]
Detector neutrons	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–
Total	–

Radon



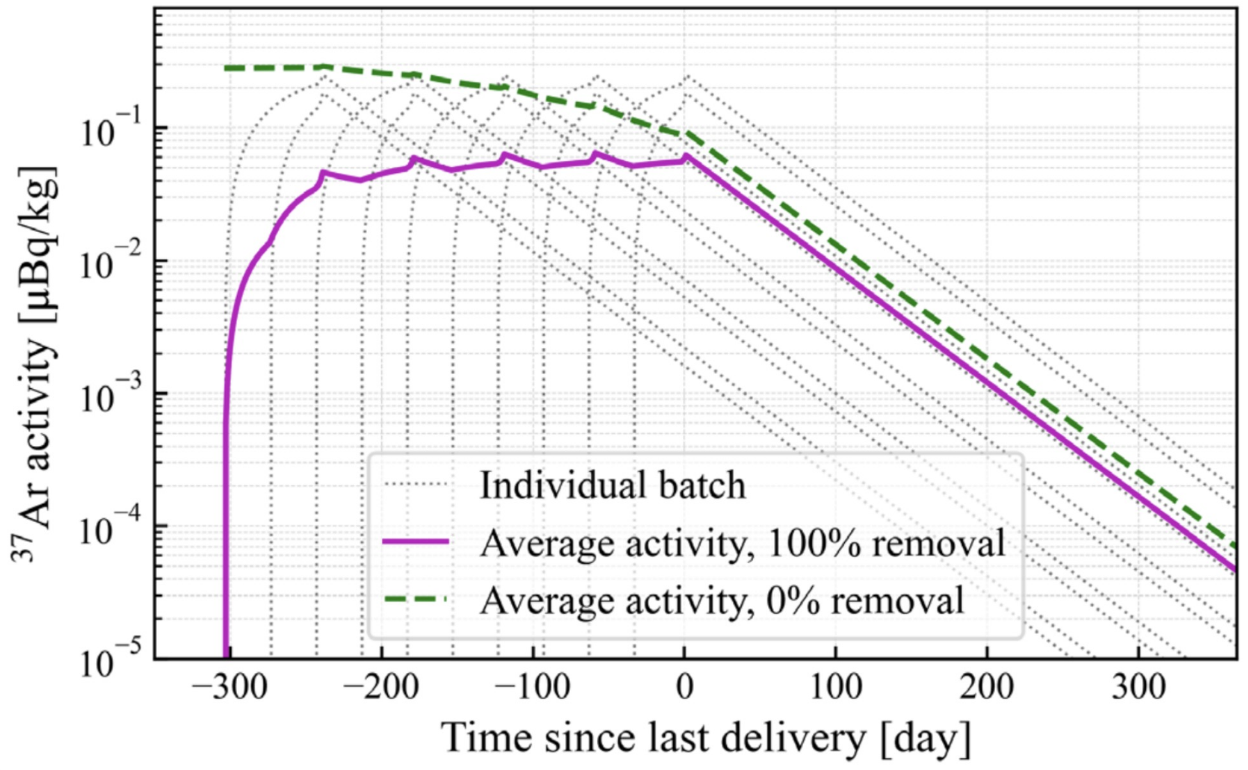
- Naked ^{214}Pb β-decays are the **main** WIMP background
- Rn emanating from detector materials into TPC xenon
- Constrain β-decay rate with two methods:
  - Rn-chain α tagging
  - Spectral fit of all internal BGs outside of energy ROI



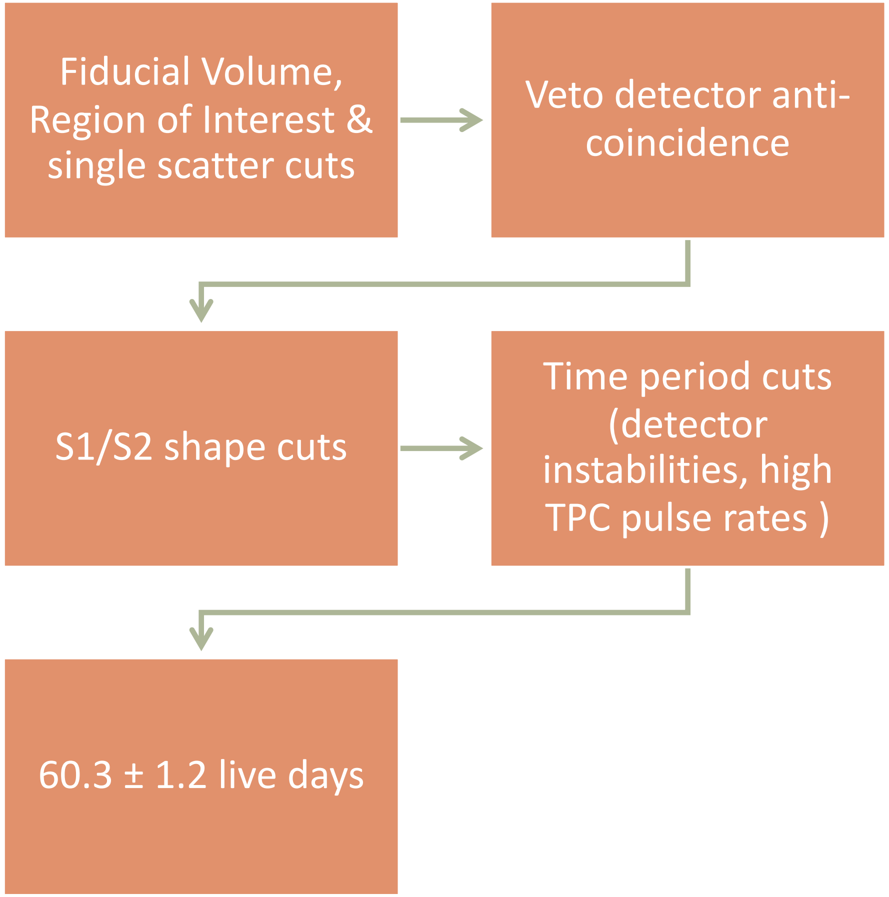
^{222}Rn (μBq/kg)	^{214}Pb (μBq/kg)	^{214}Po (μBq/kg)
4.37 ± 0.31 (stat)	3.26 ± 0.13(stat) ± 0.57(sys)	2.56 ± 0.21 (stat)

^{37}Ar

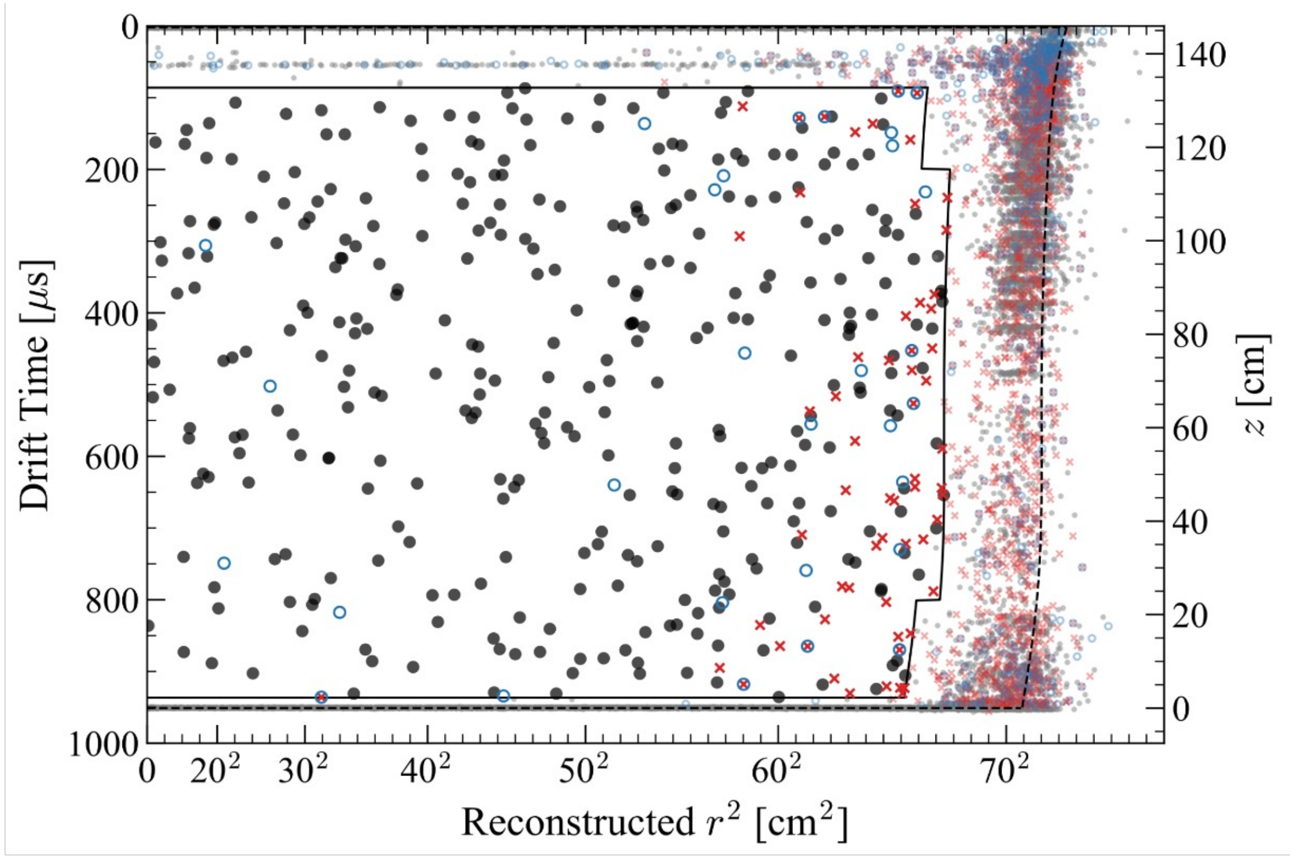
- ^{37}Ar is a significant background in early LZ data ($t_{1/2}$ = 35 d)
- Occurs naturally in atmosphere via e.g. Ca(n,α)Ar[1], but suppressed during Xe purification by charcoal chromatography
- Produced by cosmic spallation of natural xenon
- Estimating exposure during transport allows calculation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



Data selection cuts



- ● events passing all cuts.
- ● events passing all cuts except for fiducial volume.
- x events failing LXe skin veto cut (mostly ^{127}Xe)
- ○ events failing OD tag veto.



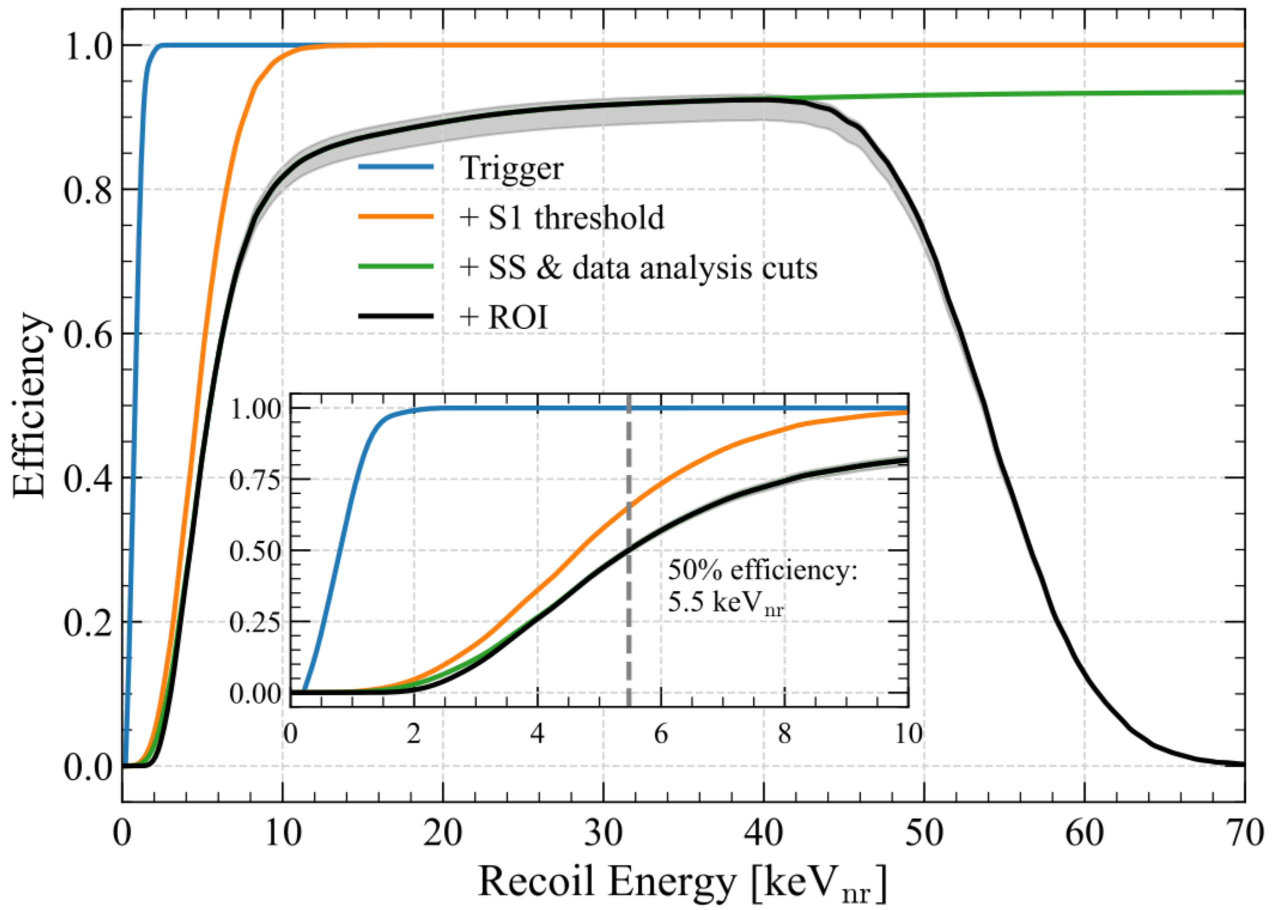
Cuts were developed on non-WIMP ROI background & calibration data

Signal acceptance

Fiducial Volume, Region of Interest & single scatter cuts → Veto detector anti-coincidence

→ S1/S2 shape cuts → Time period cuts (detector instabilities, high TPC pulse rates)

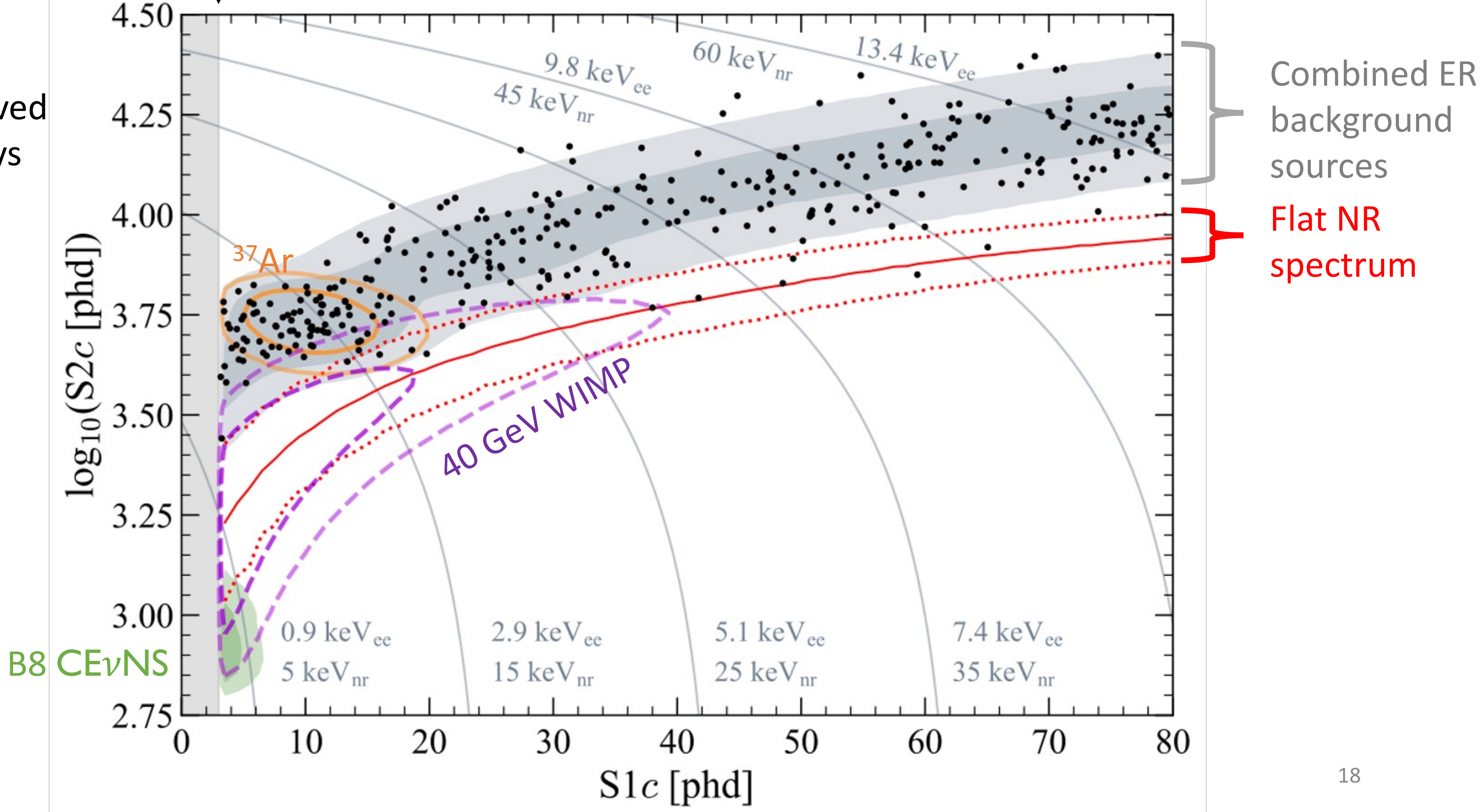
→ 60.3 ± 1.2 live days



Final data set

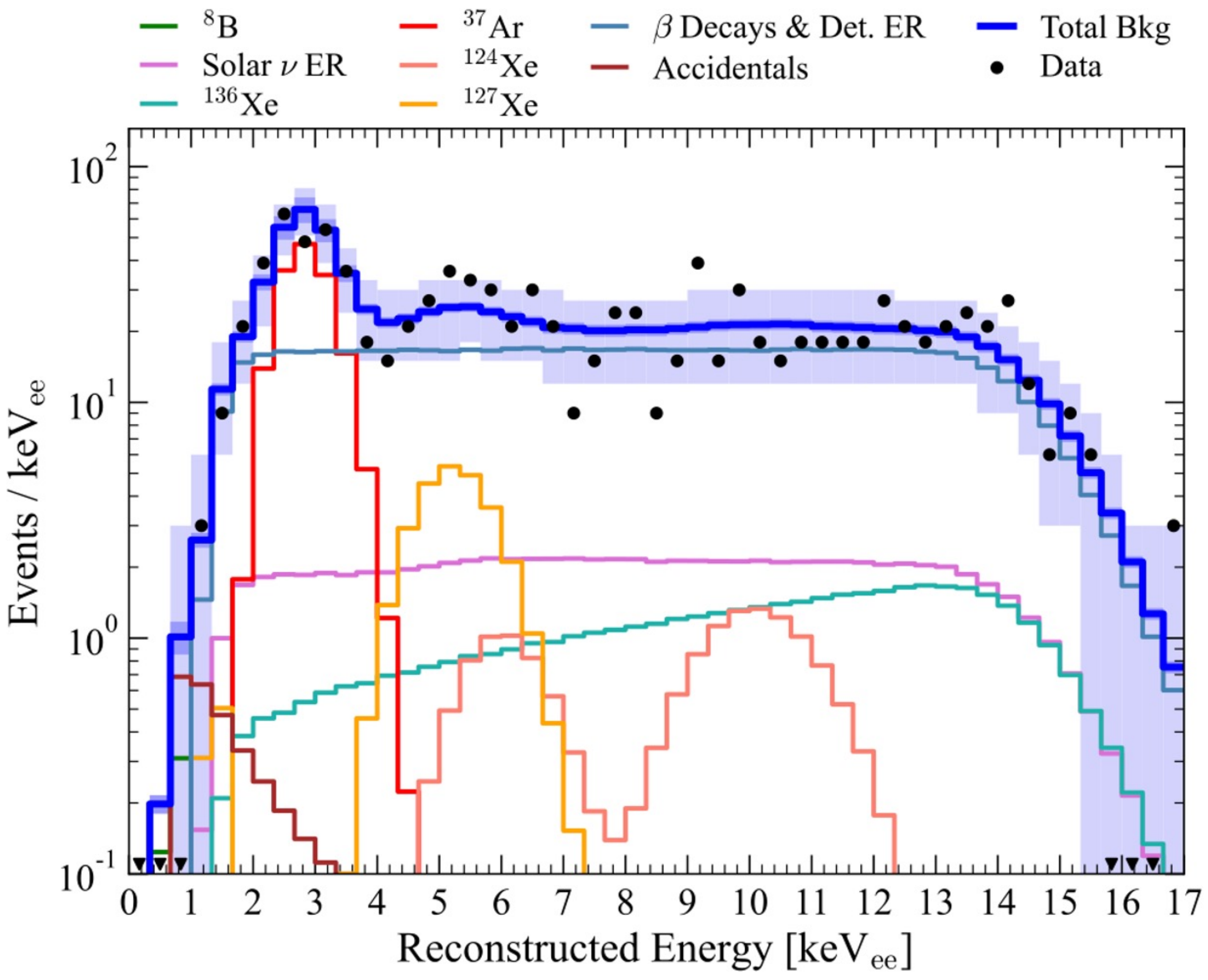
Threshold: S1 – 3phd, S2 – 600 phd

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



PLR fits

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

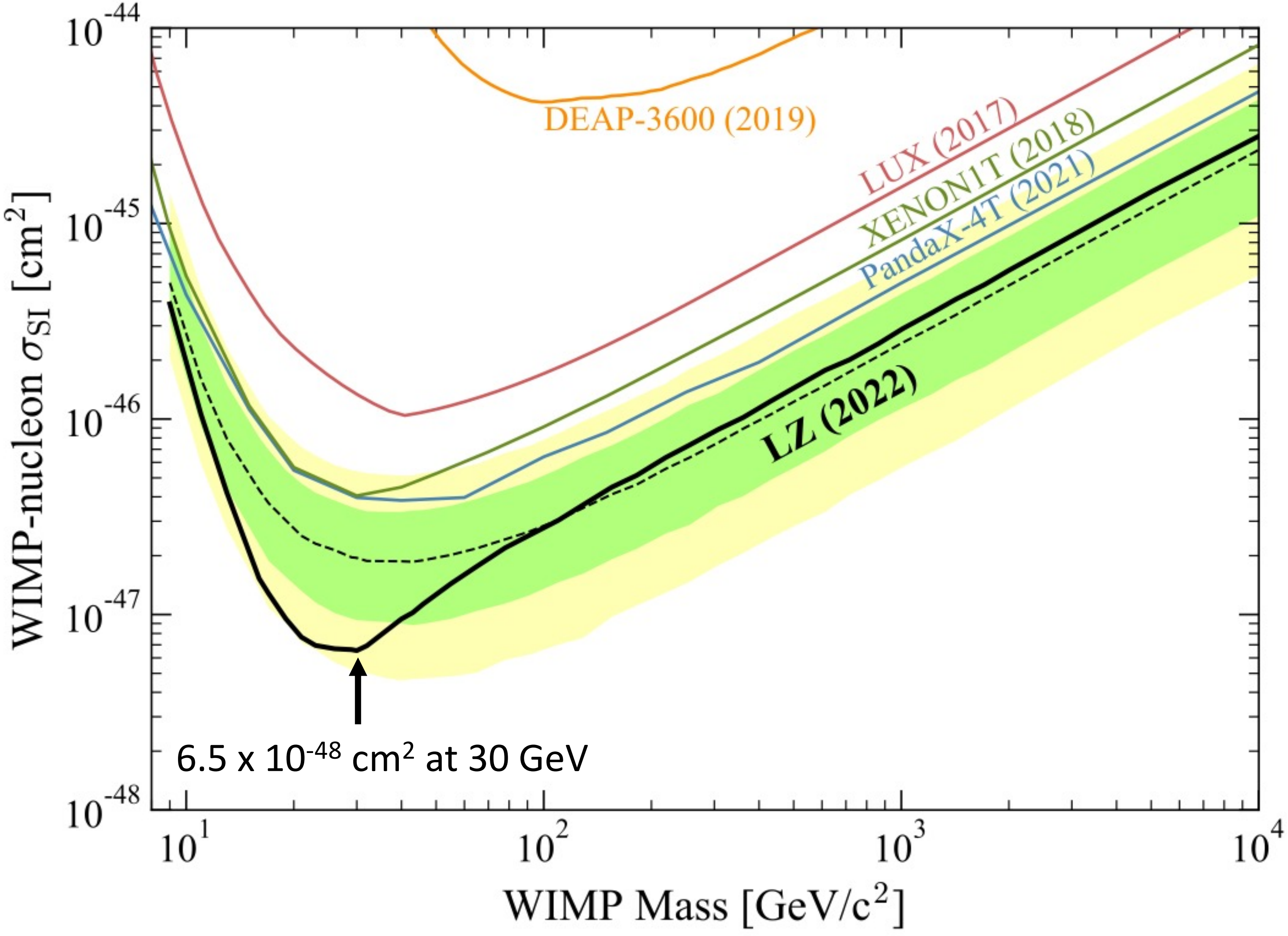


Backgrounds within expectations
~25 counts/keVee/tonne/year

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

|First Science Run

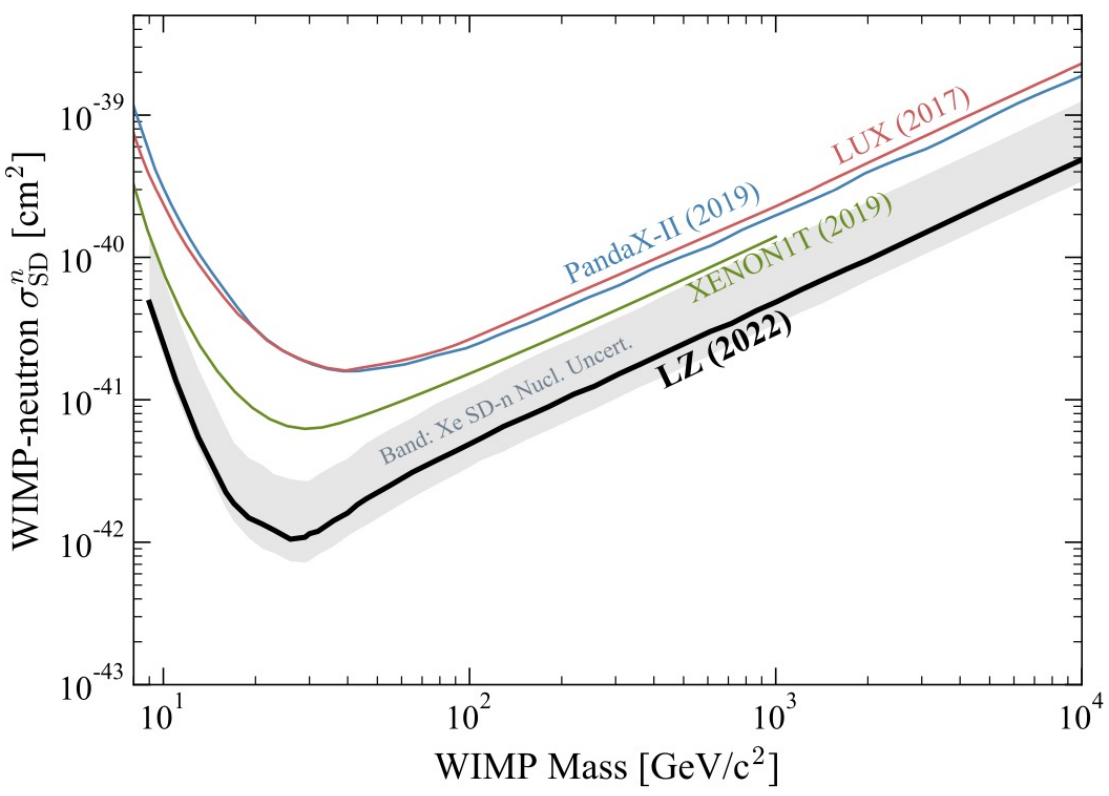
WIMP search



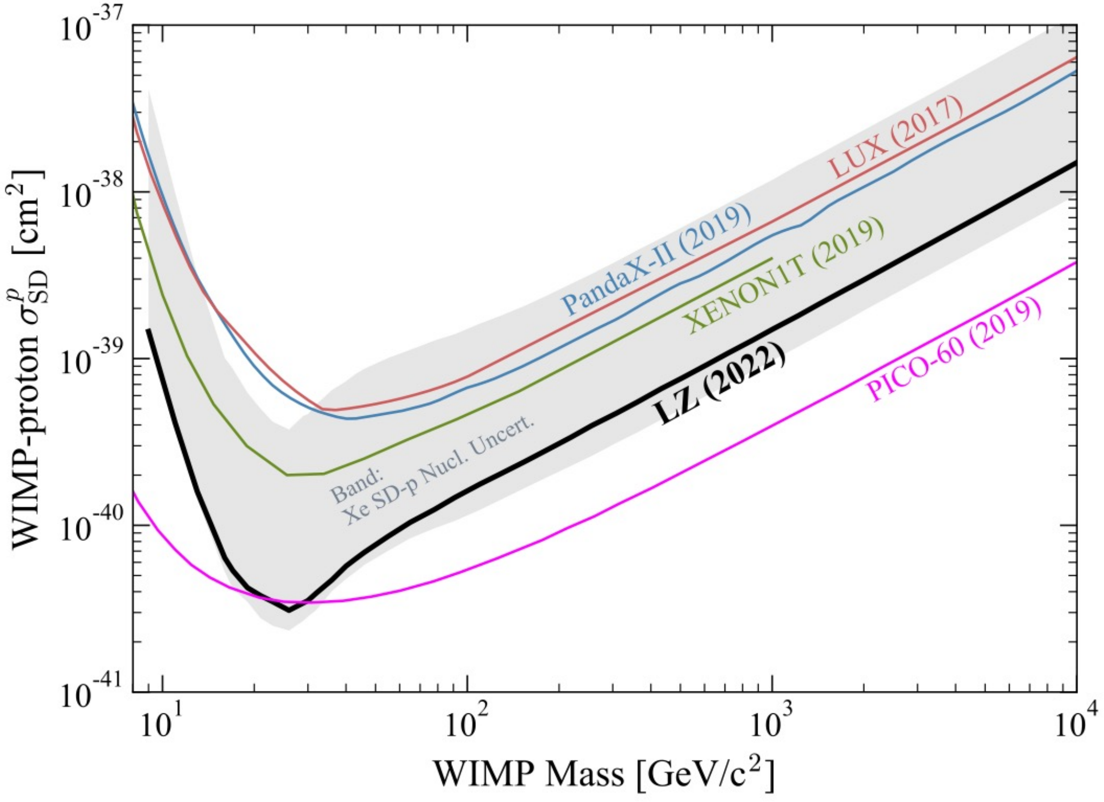
Two sided PLR following conventions: EPJC 81, 907 (2021)

WIMP search (spin-dependent)

Spin-dependent WIMP-neutron scattering



Spin-dependent WIMP-proton scattering



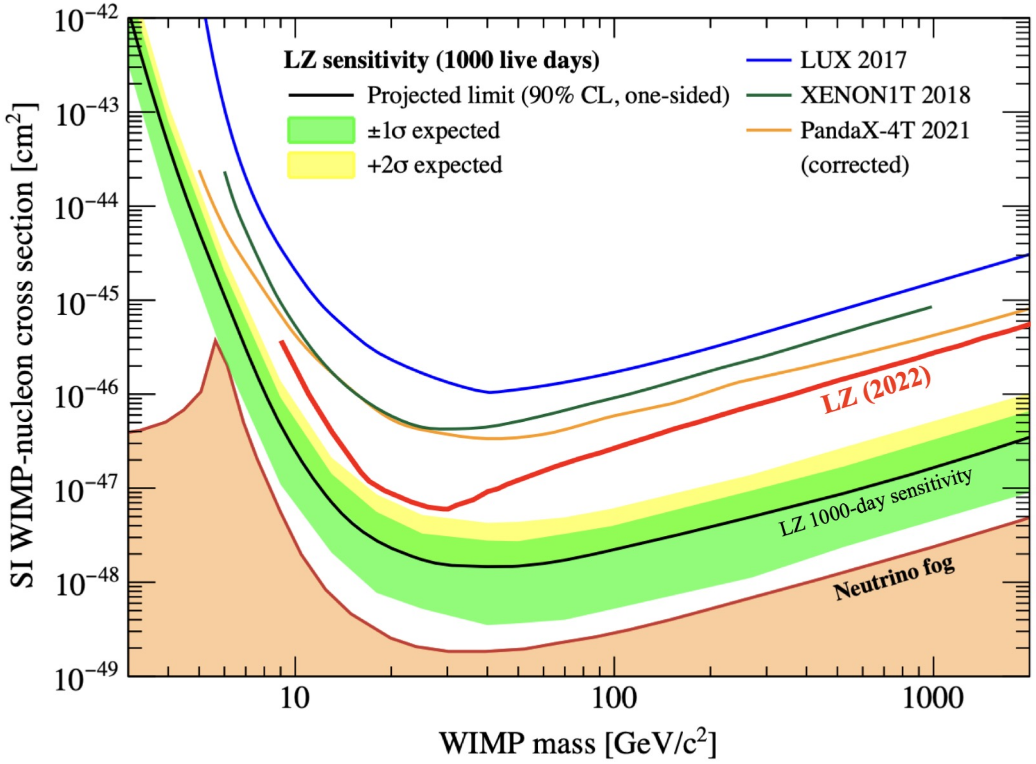
Grey uncertainty band represents uncertainty on Xe form factor [1]

What's next?

[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 low-E ER band searches sensitivity: Phys.Rev.D 104, 092009 (2021)
[4]LZ Xe136 0νββ sensitivity: Phys. Rev. C 102, 014602 (2020)
[5]LZ Xe124 0νββ sensitivity: Phys. Rev. C 104, 065501 (2021)

- 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:
    - Enhanced sensitivity to lower WIMP masses and ^{8}B solar neutrinos (S2-only, Migdal)[2]
    - Low energy electron recoil searches for new physics (ALPs, hidden photons, mirror dark matter & more)[3]
    - Neutrinoless double-beta decay searches with ^{136}Xe & ^{124}Xe [4,5]

Current limit compared to projected sensitivity for 1000-day exposure[1]:



|Next Generation
Towards the ultimate LXe observatory

XENON

DARWIN

- MOU between LZ, XENON, DARWIN
- Successful XLZD meeting 27-29 June 2022 at Karlsruhe Institute of Technology
- https://xlzd.org/
- White paper (2203.02309)

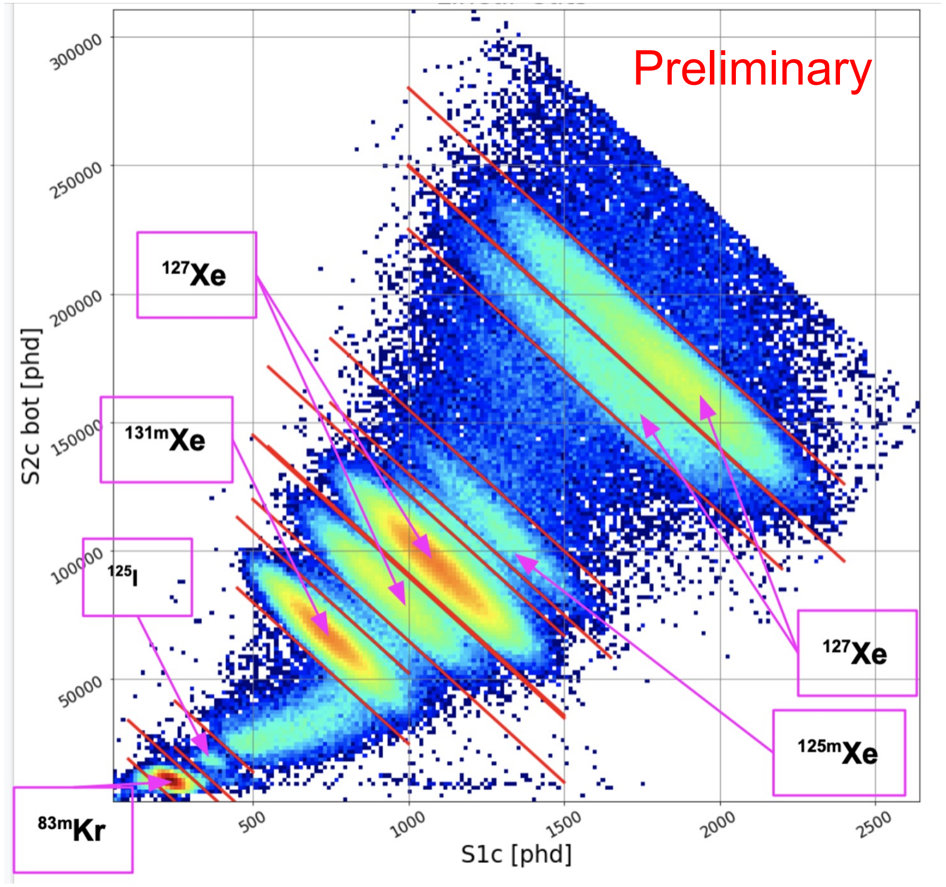
First in-person meeting June 2022

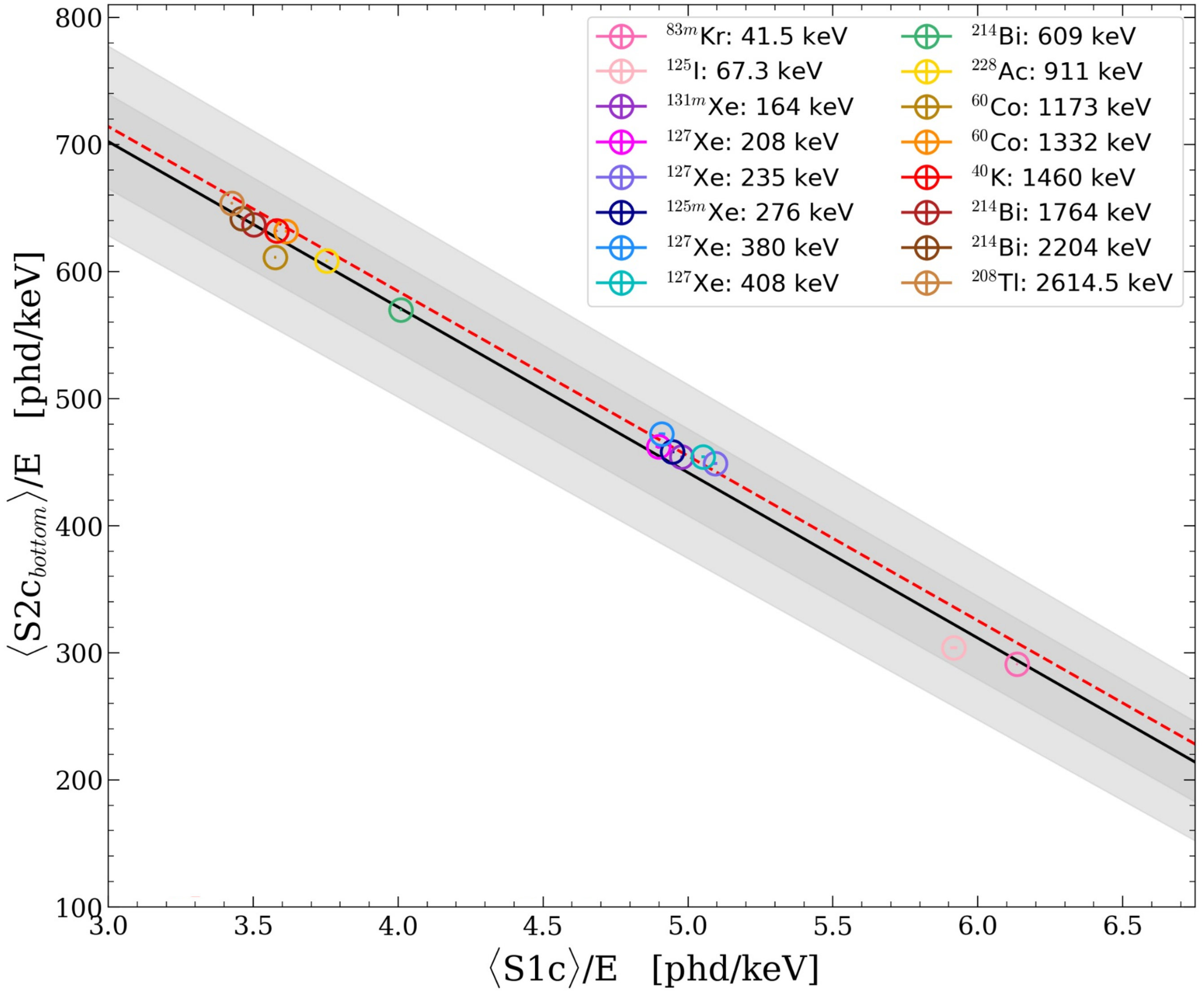
- All LZ systems are performing well and backgrounds are within expectations
- Short engineering run has produced world-leading WIMP limits!
- Much more to come for LZ:
  - Ultimately planning for 1000 live-days
  - Many more physics searches
- Beyond LZ: xenon community is uniting in XLZD consortium

@lzdarkmatter
https://lz.lbl.gov/

Doke plot

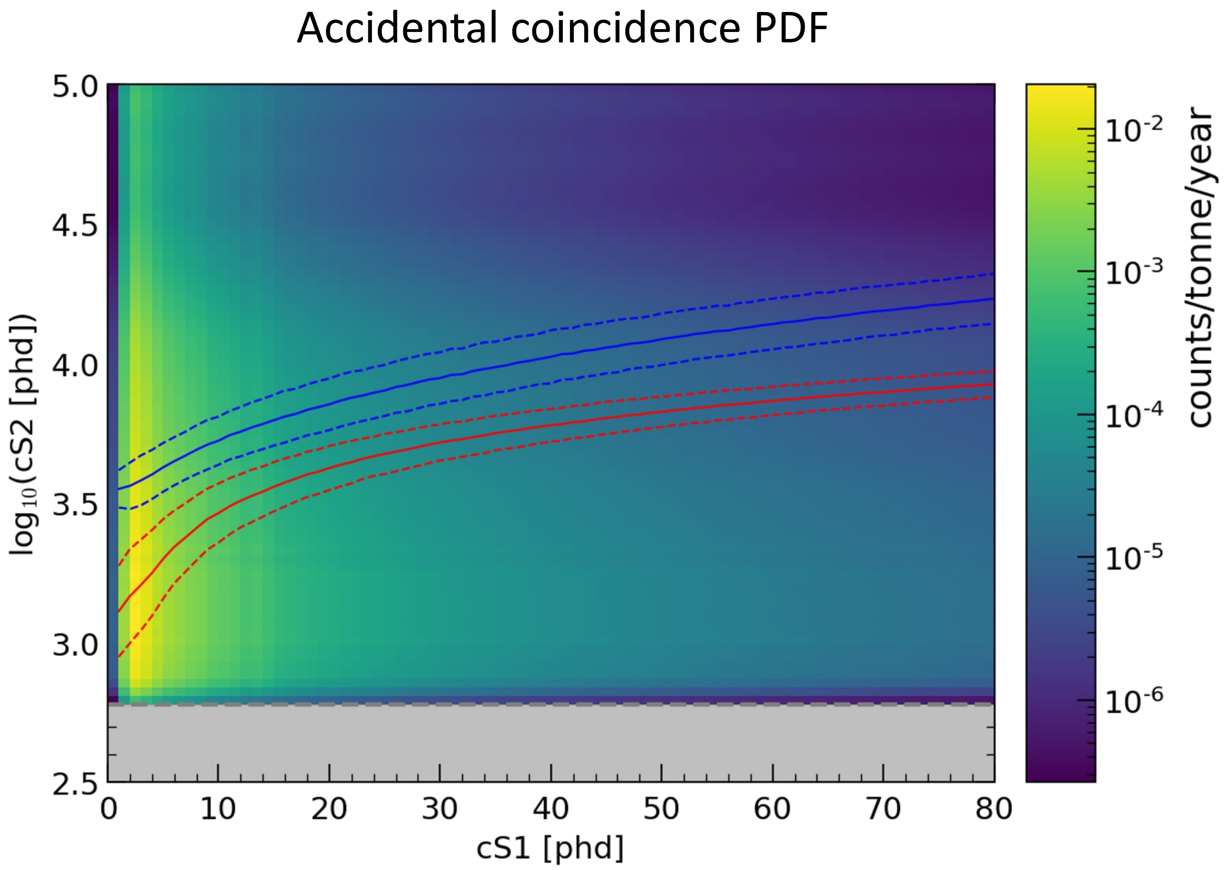
Doke plot constructed with mono-energetic electron recoil peaks





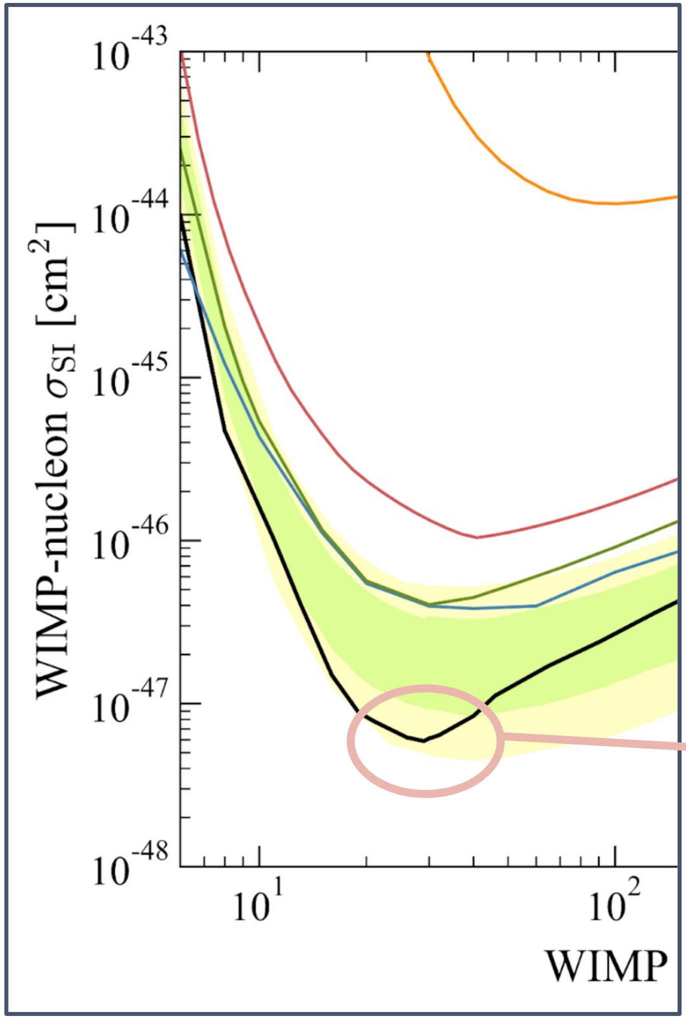
Accidental coincidences

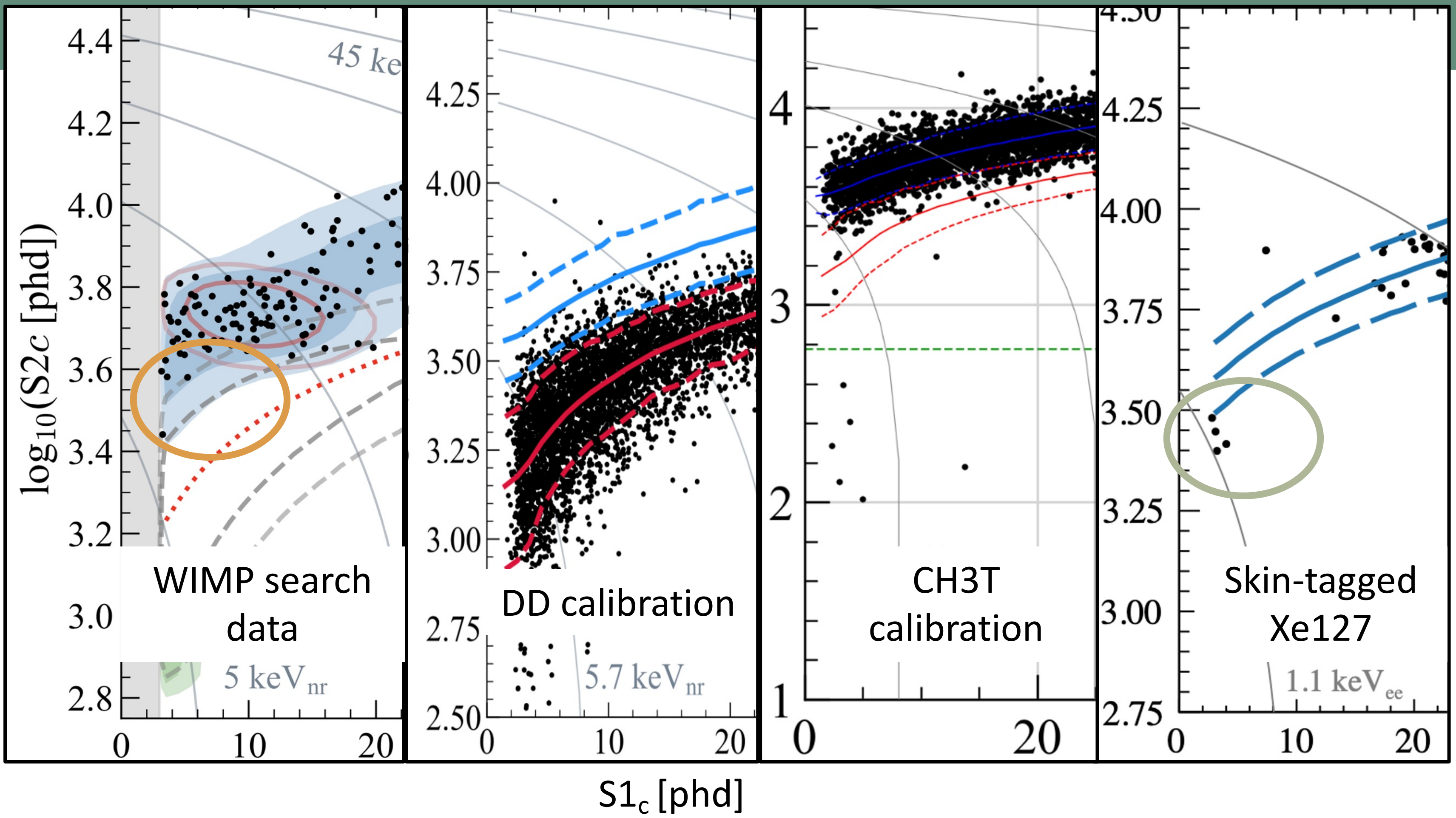
- Isolated S1s & S2s can accidentally combine to form WIMP ROI events
- Data quality cuts successfully developed to address this background
- To construct PDF, stitch isolated raw pulses together for fake events. Normalised using events with unphysical drift time
  (i.e. drift time > TPC height)
- Expect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