Backgrounds for the First LZ WIMP Search Results

Dongqing Huang
University of Michigan
On behalf of the LZ Collaboration

CIPANP 2022, Lake Buena Vista, FL
August 30th 2022

UNIVERSITY OF MICHIGAN

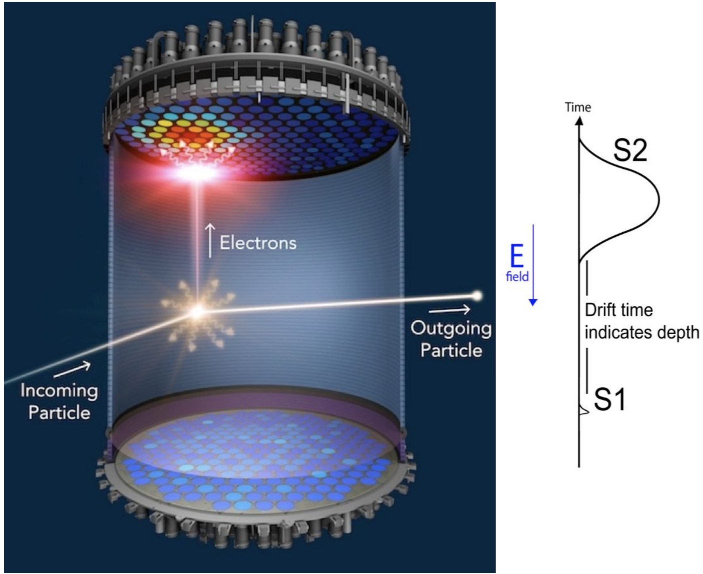
This project is partially supported by DOE

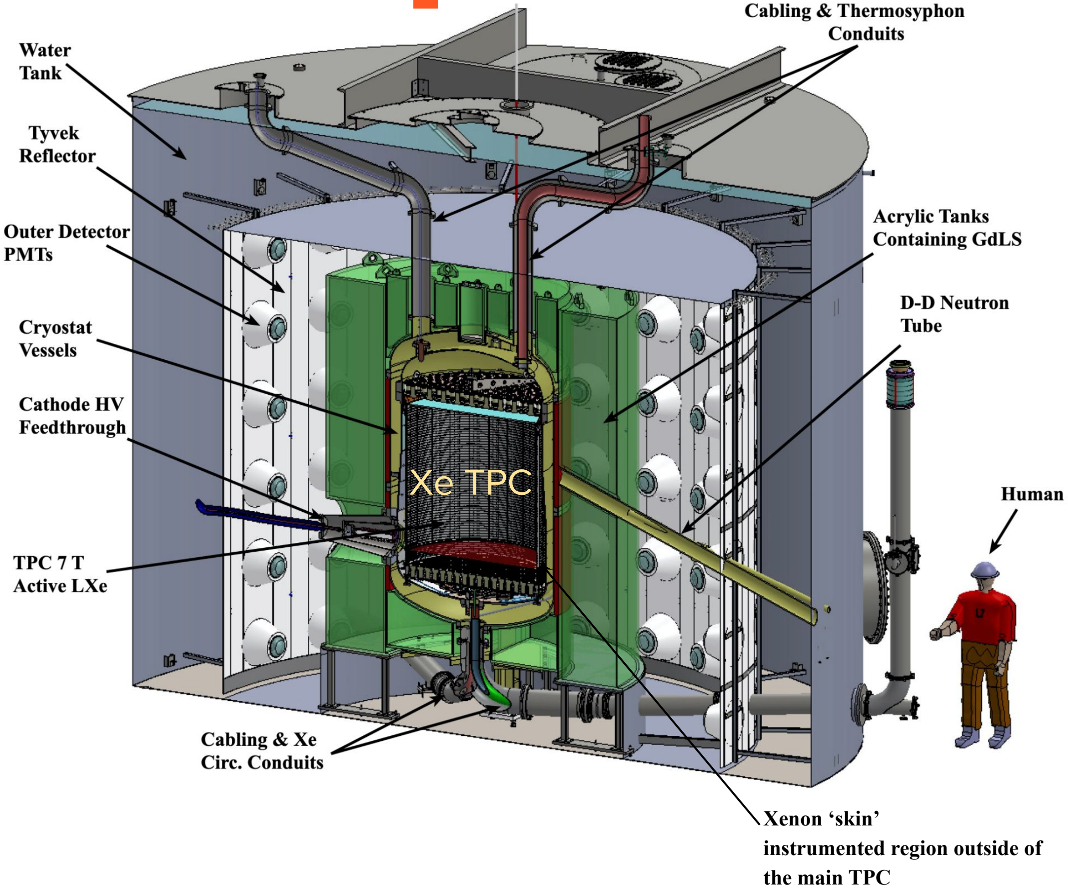
U.S. DEPARTMENT OF ENERGY
Office of Science

Section I:
LZ Background Hardware Mitigation

The LZ Dark Matter Search Experiment

- **Target: WIMP (weakly interacting massive particles)**
- **Dual-phase liquid/gas xenon TPC**
  - 7 t active LXe in TPC
- **494 3'' Hamamatsu R11410-22 TPC PMTs**
  - 253 top and 241 bottom
- **S1 prompt scintillation signal**
- **S2 delayed ionization signal**
- **3-D position reconstruction**
- **LXe self-shielding**
- **NR (Nuclear Recoil) and ER (Electronic Recoil) discrimination**

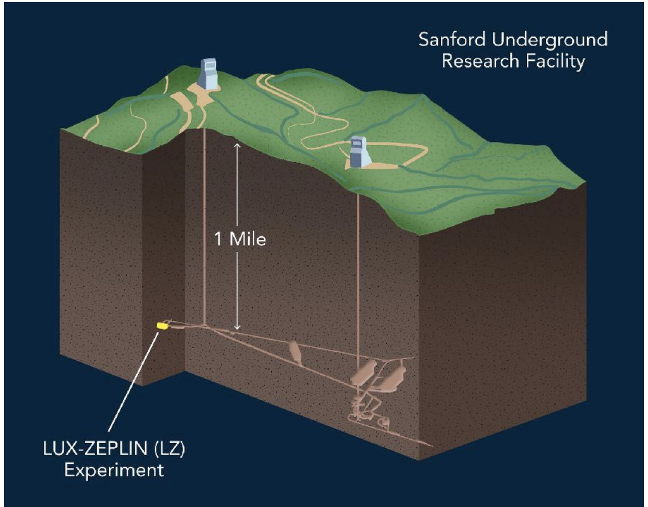




External BG Mitigation

- **Experiment located at Sanford Underground Research Facility (SURF) in Lead, SD (USA)**
- **LZ detector at the 4850 level (1492 m underground) in the Davis Cavern**
    - 4300 m water equiv.
    - Reduce muon flux by $O(10^6)$

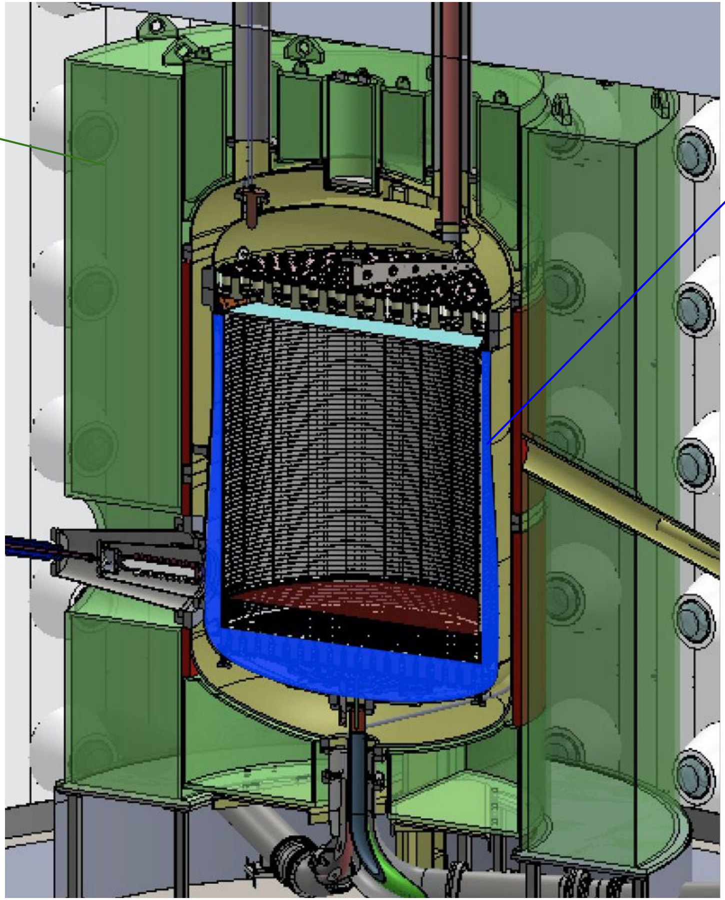
- **LZ detector is surrounded by a 7.6 m diameter water shield**
    - Shield neutron and gamma background originated from cavern rocks



BG Mitigation
- The Outer Detector and Xenon Skin

The Outer Detector

- 17 tonnes gadolinium loaded liquid scintillator in acrylic vessels
- 120 8'' Veto PMTs mounted in the water tank
- Anti-coincidence detector for gamma-rays and neutrons
- Observe ~8 MeV gamma-rays from thermal neutron capture on Gd



The Xenon Skin

- 2 tonnes of LXe surrounding the main TPC
- Instrumented with 1'' and 2'' PMTs at the top and bottom of the skin region
- Lined with PTFE to maximize light collection efficiency
- Anti-coincidence detector for gamma-rays

Detector Component BG Control

- Every detector component down to solder and welding tips are screened for their radiopurity to ensure they all meet LZ background control requirements.
- Contamination in Detector Components
  - < 10% irreducible / physics backgrounds (^{136}Xe double beta decay, solar neutrinos) in 5.5 tonne fiducial volume
- 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

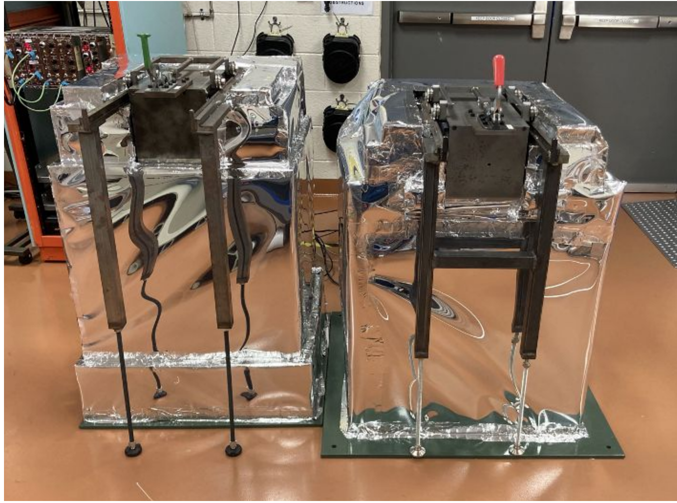
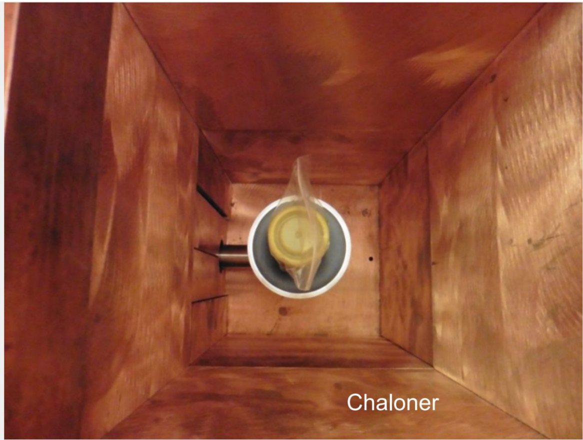


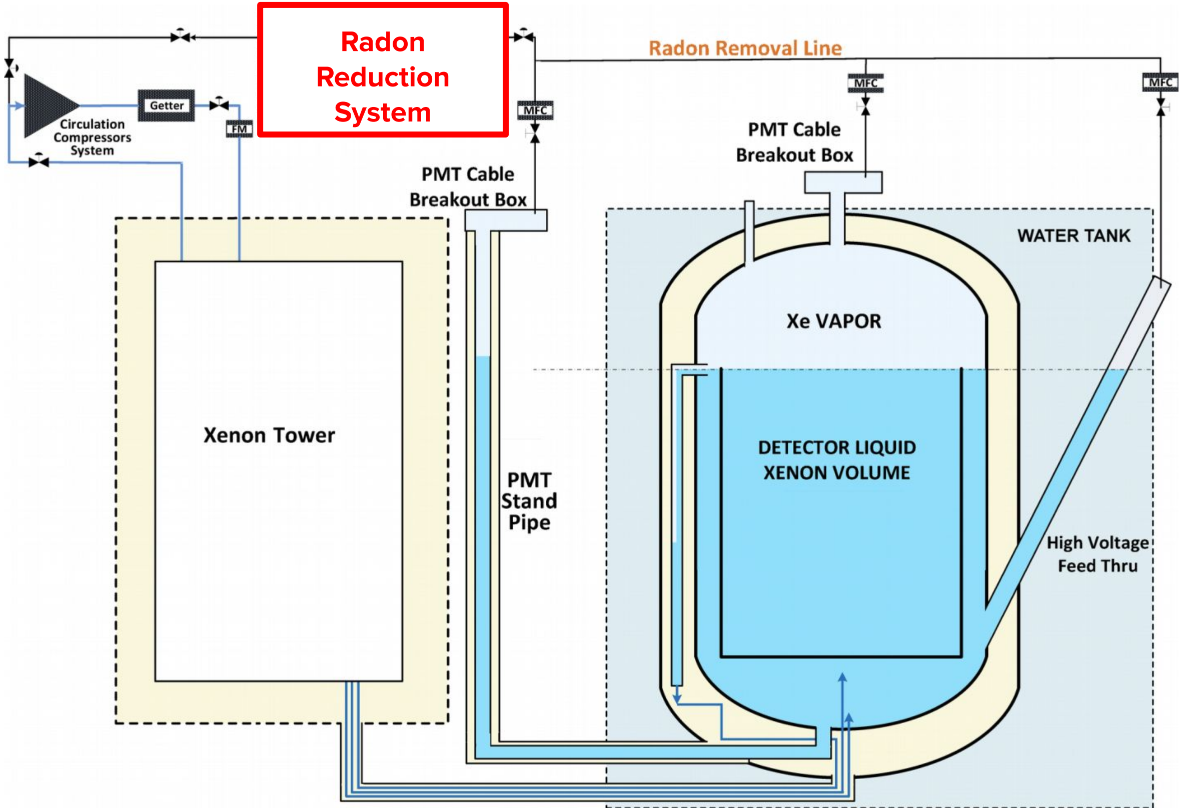
Image shows PMT raw materials are screened by HPGe detectors before they are used for PMT manufacturing



The European Physical Journal C, Volume 80, Article number: 1044 (2020) (arXiv:2006:02506)

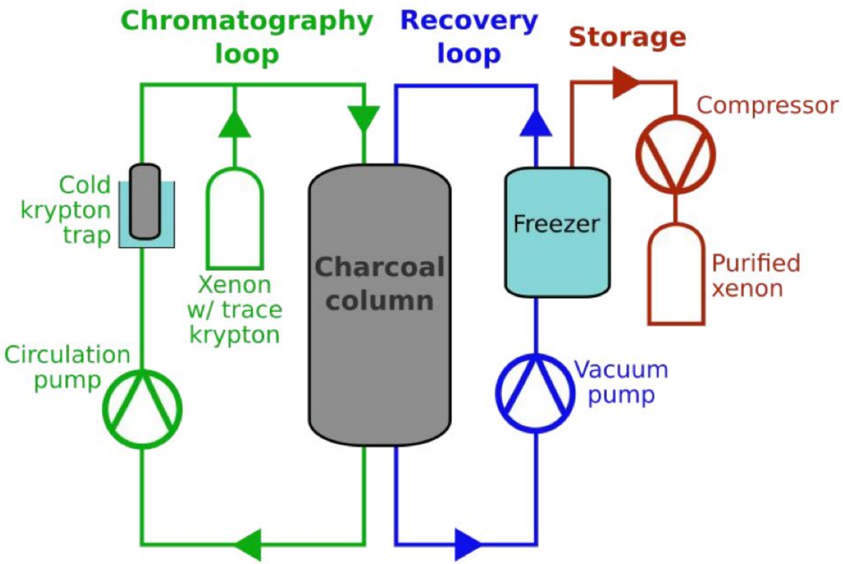
Internal BG Mitigation
- Inline Radon Reduction System (iRRS) Built by UM

- ^{222}Rn is a product of ^{238}U decay
  - Decay half-life: 3.8 days
- ^{222}Rn is constantly emanated from detector components
- It dissolves in liquid xenon
  - Cannot be removed by hot purifying getters
- β-decay of daughter ^{214}Pb presents dominant background for WIMP search
- Reduce ^{222}Rn background of warm sections (cables and feedthroughs) with iRRS



Internal BG Mitigation
- Kr Removal

- Kr-85 is a beta emitter
  - Dissolved in LXe and can not be removed by purifying getter
- Gas chromatography to remove Kr from Xe
  - ^{nat}Kr reduced to 0.1 ppt g/g ^{nat}Kr/Xe and ^{nat}Ar to a negligible level



Dongqing Huang - University of Michigan / LZ

Section II:
Background for first LZ WIMP Search

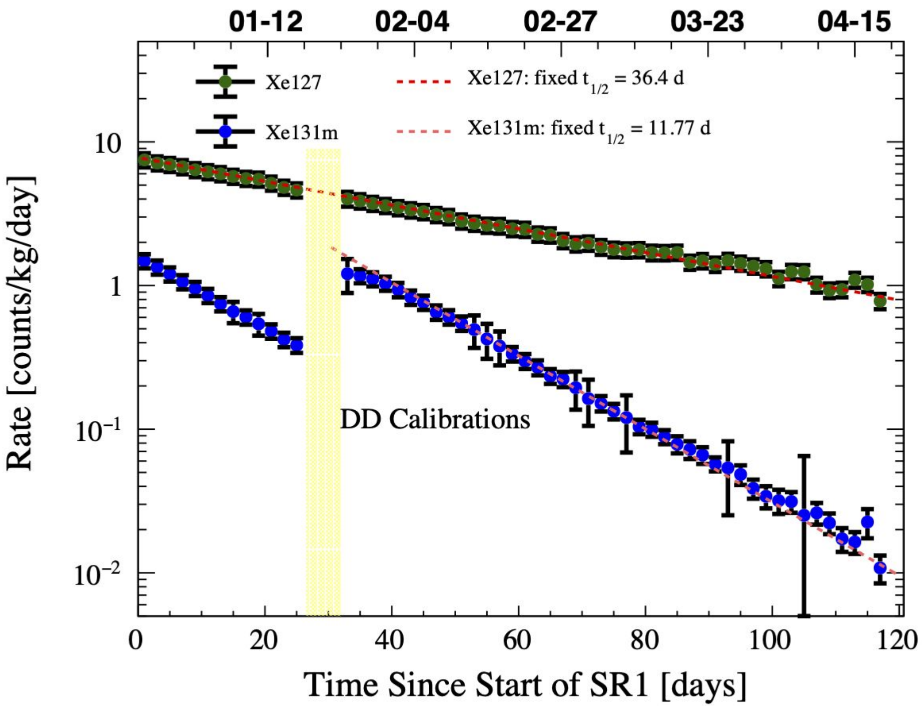
Remaining Backgrounds for WIMP Search

There are many sources of background in our experiment, though not all contribute the same. Listed here are the major contributors to the WIMP-search (1.5 - 15 keVee)

- Dissolved beta emitters:
  - ^{214}Pb (^{222}Rn daughter), ^{212}Pb (^{220}Rn daughter), ^{85}Kr, ^{136}Xe (2 beta)
- Dissolved e-captures (monoenergetic X-ray/Auger cascades):
  - ^{127}Xe, ^{124}Xe (2 e-capture), ^{37}Ar
- Long-lived gamma emitters in detector materials:
  - ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co
- Neutron emission from spontaneous fission and (α,n)
  - NR
- Solar neutrinos
  - ^{8}B (NR), pp (ER)
- Accidental coincidences.

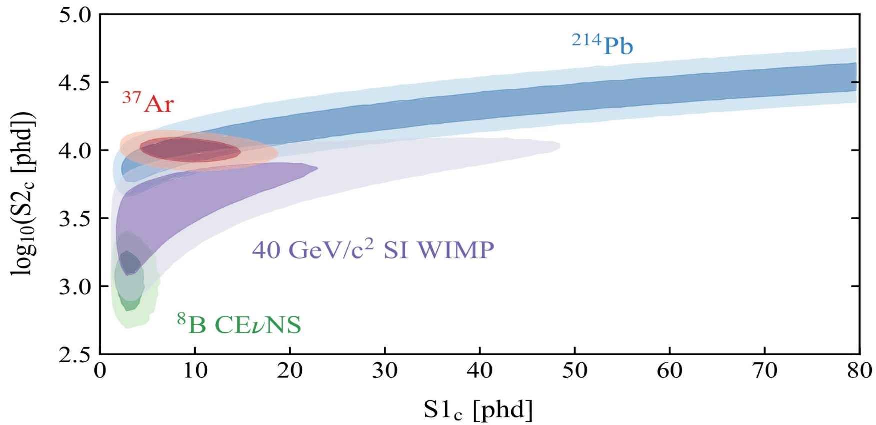
Active Xenon Isotopes

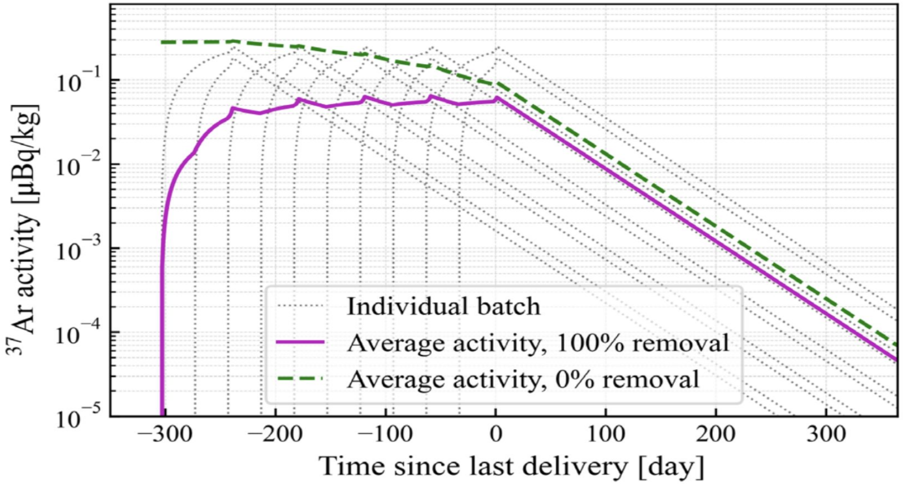
- Cosmogenically activated xenon isotopes during xenon transport
  - Xe-127
    - Includes gamma ray that is usually vetoed by the TPC itself, or the LXe skin
  - Xe-131m
  - Xe-129m
  - Xe-133
- Only Xe-127 is a BG for SR1 WIMP search
  - Low energy X-rays in WIMP ROI
  - $t_{1/2}$ = 36.4 days
  - It decays away during SR1
- The rest:
  - Short half-lives (< 12 days)
  - High energy gamma emission (> 80 keVee)



Ar-37

- Electron capture, $t_{1/2}$ = 35 d, monoenergetic 2.8 keV ER deposition
- Occurs naturally in atmosphere via e.g. $^{40}Ca(n,\alpha)^{37}Ar$ (*)
  - Equilibrium values can range from 1-100 mBq/m^3
- Also produced by cosmic spallation of natural xenon
- We expect ~100 decays of ^{37}Ar in SR1(**) with a large uncertainty.

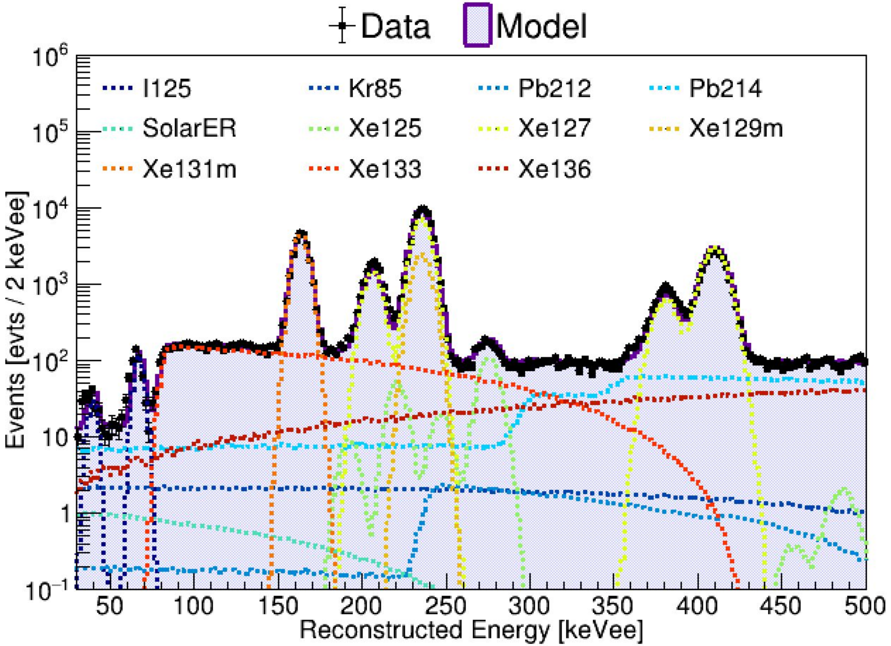


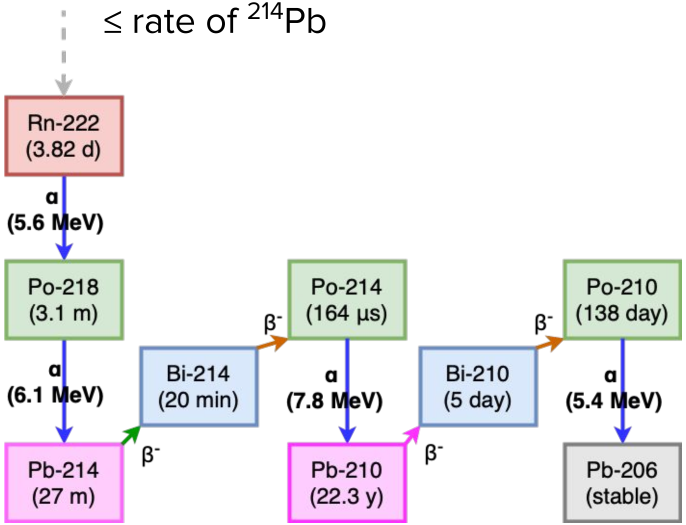


(*) R.A. Riedmann, R. Purtschert, Environ. Sci. Technol. (2011) 45(20), 8656-8664
(**) LZ Collaboration, Phys. Rev. D 105, 082004 (2022), 2201.02858

Rn-chain Backgrounds

- Alphas from ^{222}Rn chain easily identified by S1 spectrum.
- ^{214}Pb is the main source of background in the WIMP search; its naked beta decay could mimic WIMP signal; rate must be ≤ rate of ^{222}Rn decays.
- Likewise, rate of alphas from ^{214}Po must be ≤ rate of ^{214}Pb



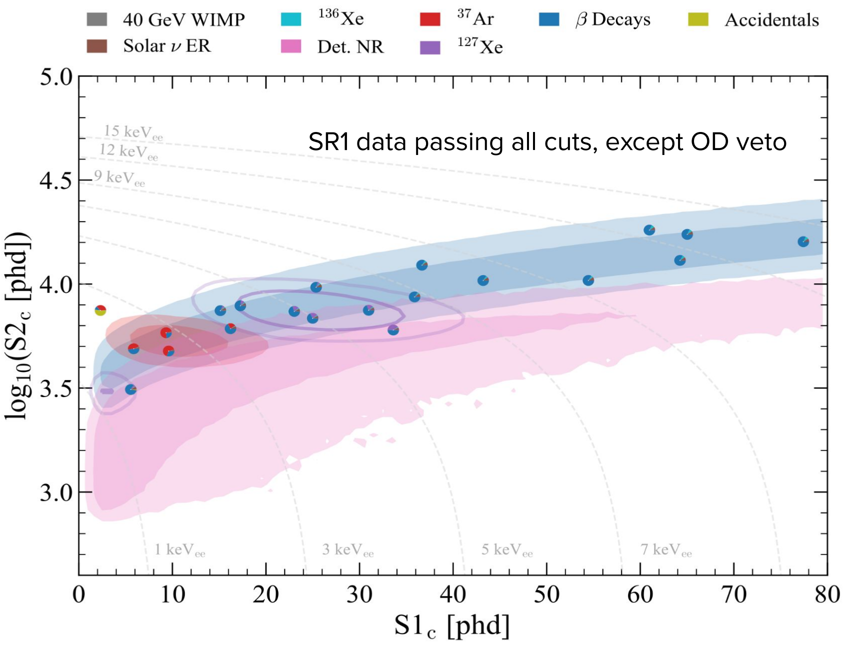


Rn222 (µBq/kg)	Pb214 (µBq/kg)	Po214 (µBq/kg)
4.37 ± 0.31 (stat)	**3.26 ± 0.13(stat) ± 0.57(sys)**	2.56 ± 0.21 (stat)

Neutron Background

- OD has neutron tagging efficiency of 88.5%
  - Neutron NR backgrounds reduced by a factor of ~8
- We use OD-tagged data to find a data-driven constraint on the rate of Det. NR
- Result: Number of Det. NR in SR1 WIMP search is <0.2 events (2-sided constraint).
  - Consistent with simulation-derived estimate of 0.06 events in 60 live days.

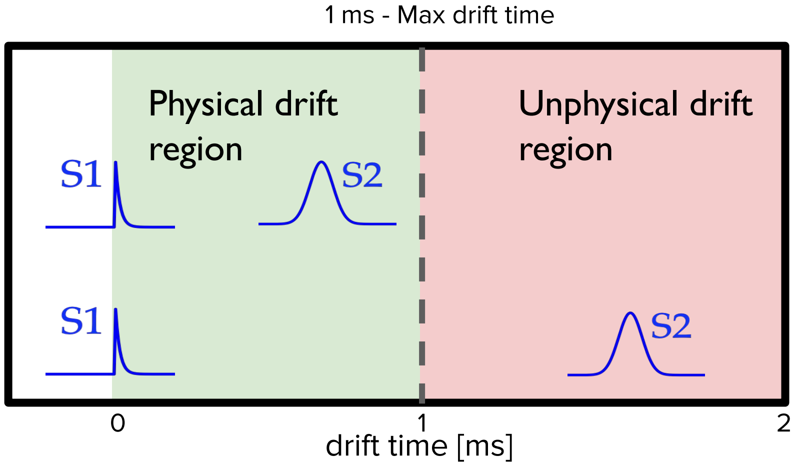
Possible event types:

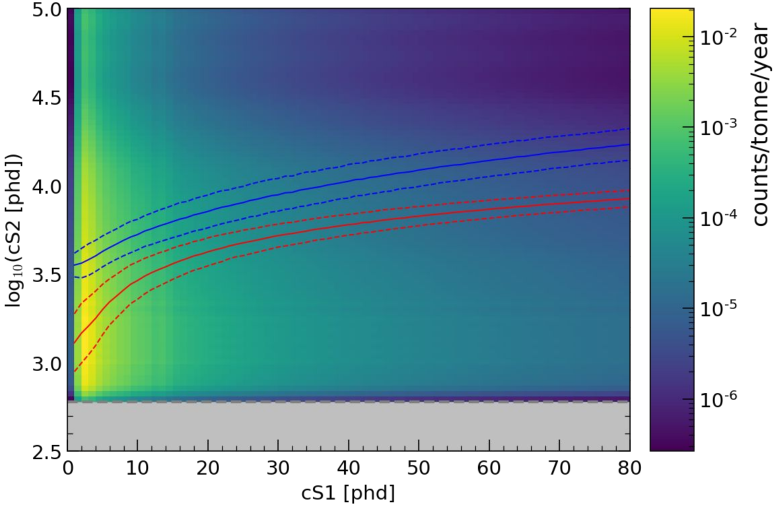


Each data point is a pie chart showing the post-fit likelihood contribution of each of the eight components in the fit.

Accidentals Background

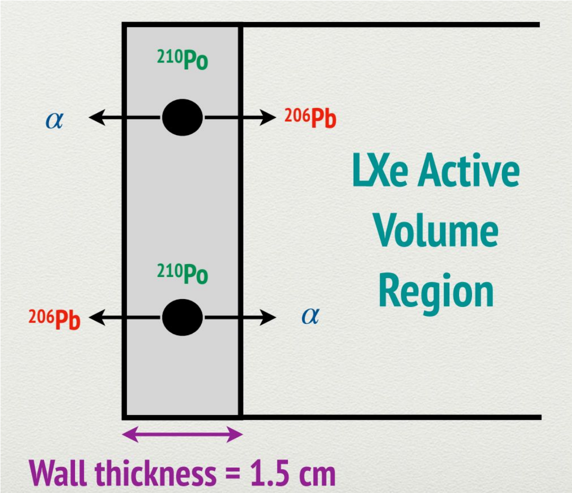
- Isolated S1 pulses occur at O(1 Hz)
- Isolated S2 pulses occur at O(10^{-3} Hz) (above threshold: 600 phd)
- Occasionally, a lone S1 will accidentally come within 1ms of an unrelated, lone S2, and will look like a valid single scatter in the TPC.
- Data-quality cuts addressing S1 and S2 shape to reduce this background
- Events with measured drift > 1ms are caused by accidental coincidences and are used to constrain our rate of this background.
- Estimated number of accidentals in SR1 is **1.2 ± 0.3 events**



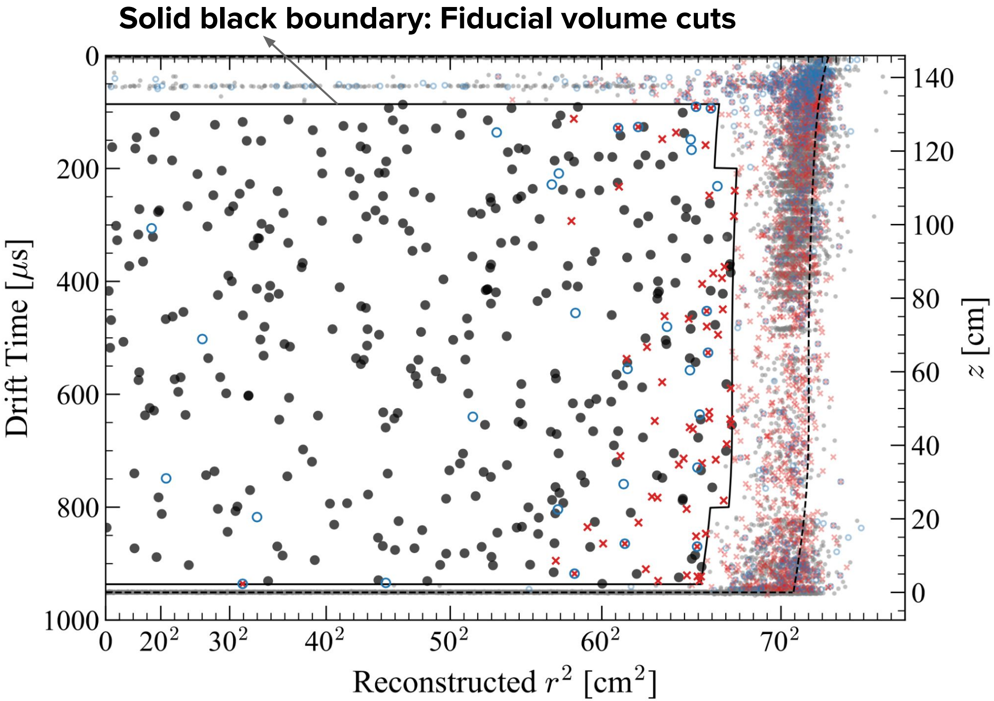


Wall Background

- 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 (negligible level)



- Black points: events passing all cuts.
- Gray points: events passing all cuts except for fiducial volume.
- Red x: events failing LXe skin veto cut (mostly ^{127}Xe)
- Blue circle: events failing OD tag veto.

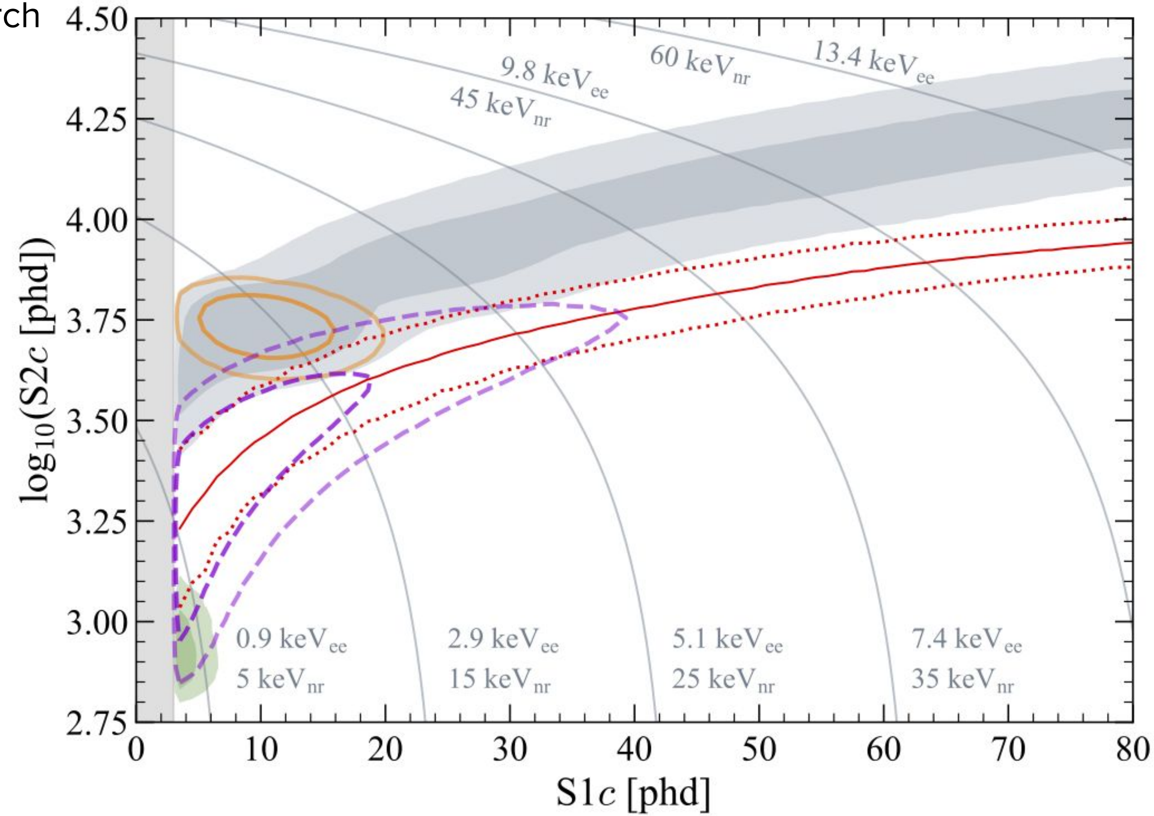


LZ SR1 Background-only Expectation

- Gray regions: 1- and 2-sigma extent of expected backgrounds in the WIMP search (^{8}B neutrinos (green) are separated)
- 276 ± 36 events expected (this does not include ^{37}Ar).
- ^{37}Ar bound with a uniform constraint between 0 and 291 events

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	–

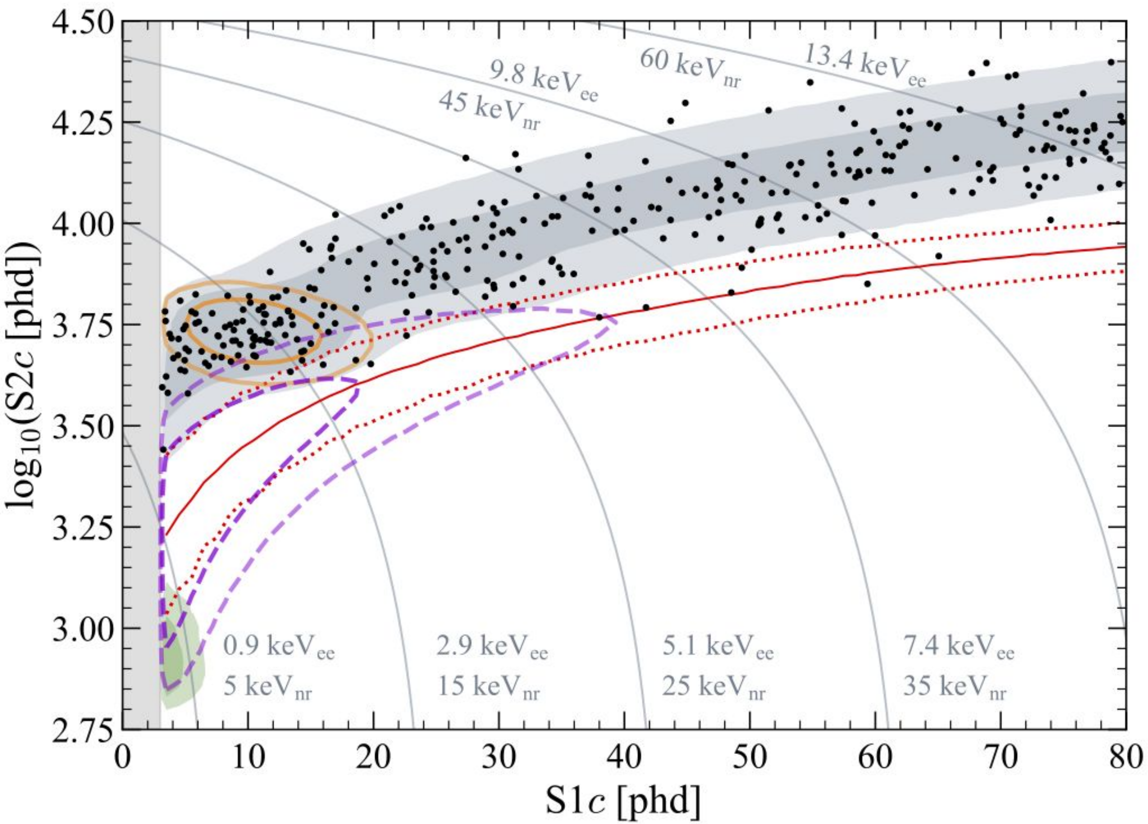
Background only expectation of data



LZ SR1 Data

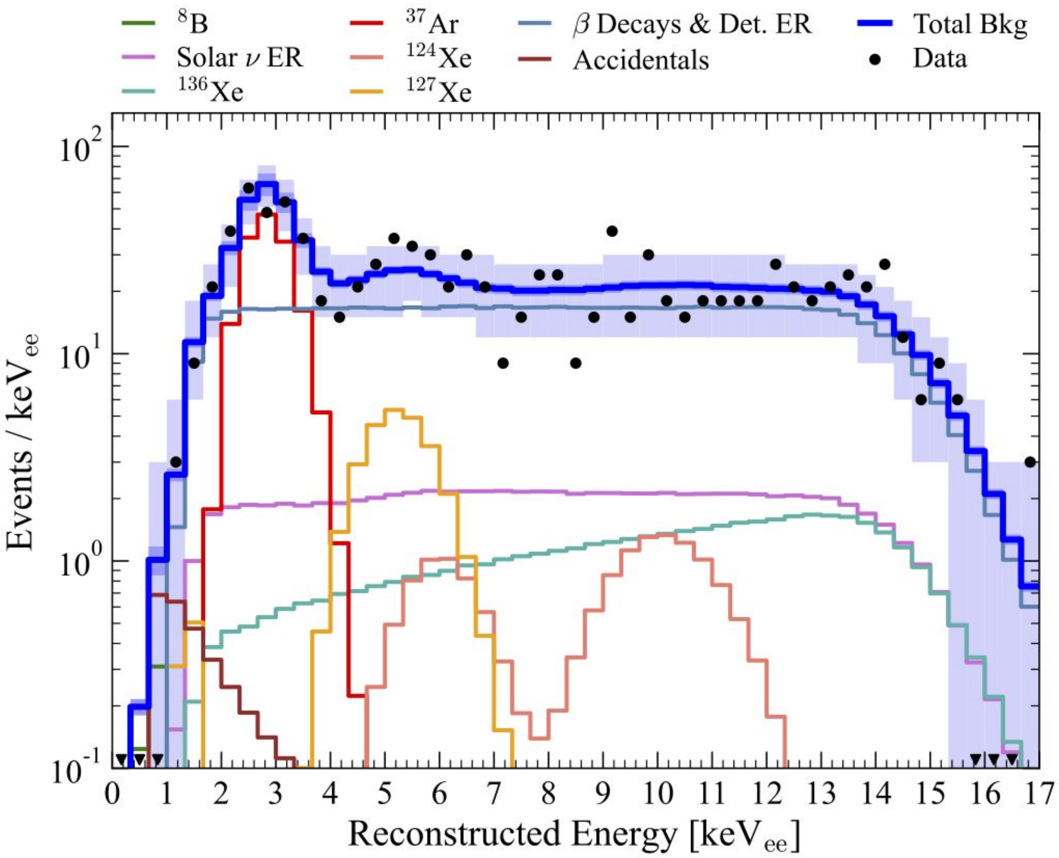
- Gray regions: 1- and 2-sigma extent of expected backgrounds in the WIMP search; ^{8}B neutrinos (green) are separated
- 276 ± 36 events expected (this does not include ^{37}Ar).
- ^{37}Ar bound with a uniform constraint between 0 and 291 events

Source	Expected Events	Fit Result
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



LZ SR1 Data

- Projecting onto electronic-equivalent reconstructed energy ("keVee")
- Data histogram shown as black points
- Best fit with *no* WIMP signal yields p-value of 0.96
- Expected range of statistical fluctuations for best-fit: light-blue boxes



Talk Summary:

- We have demonstrated LZ detector is performing well
- Backgrounds are within expectations
  - ~25 counts/keVee/tonne/year
- LZ is the world's most sensitive dark matter search detector

(Also see David Woodward's talk for LZ first WIMP search results, and Harvey Birth's talk for LZ OD)

LZ (LUX-ZEPLIN) Collaboration

35 Institutions: 250 scientists, engineers, and technical staff

@lzdarkmatter

https://lz.lbl.gov/

- Black Hills State University
- Brandeis 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
- 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 Wisconsin, Madison

US UK Portugal Korea

Thanks to our sponsors and participating institutions!

U.S. Department of Energy
Office of Science

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