First Results from the LZ Dark Matter Experiment

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On Behalf of LZ Collaboration

WIN2023, Zhuhai, China
July 7th 2023

These projects are partially supported by US DOE

LZ (LUX-ZEPLIN) Collaboration,

@lzdarkmatter

https://lz.lbl.gov/

37 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
- 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 Texas at Austin
- University of Wisconsin, Madison

US UK Portugal Korea Australia

Thanks to our sponsors and participating institutions!

U.S. Department of Energy

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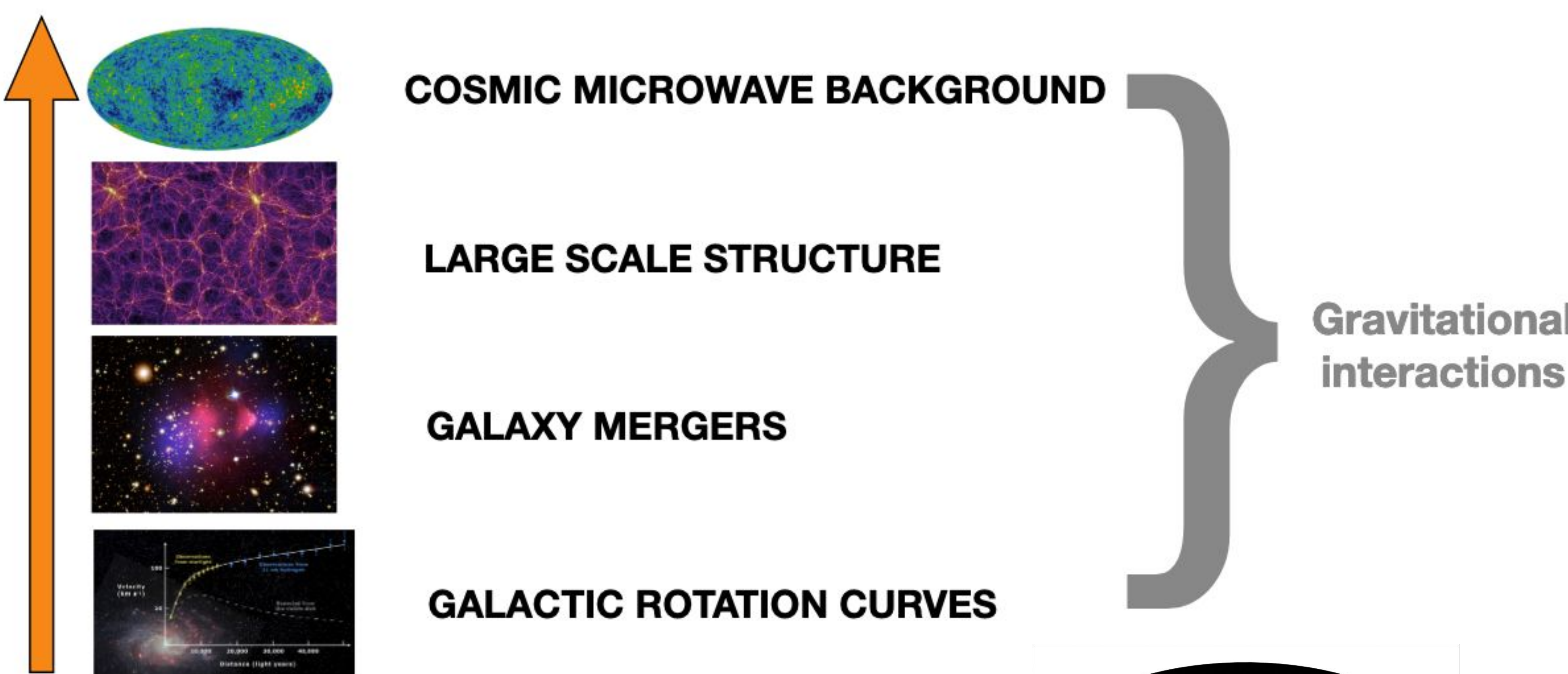
Sanford Underground Research Facility
South Dakota Science and Technology Authority

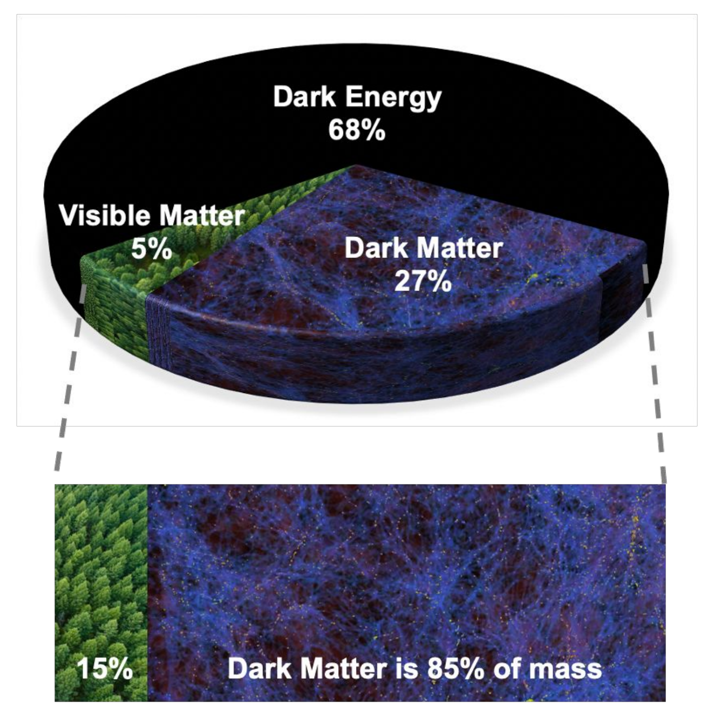
FCT Fundação para a Ciência e a Tecnologia

Institute for Basic Science

Dark Matter

Tien-Tien Yu - Hot Topics on the Cosmic Frontier Colloquium, June 10

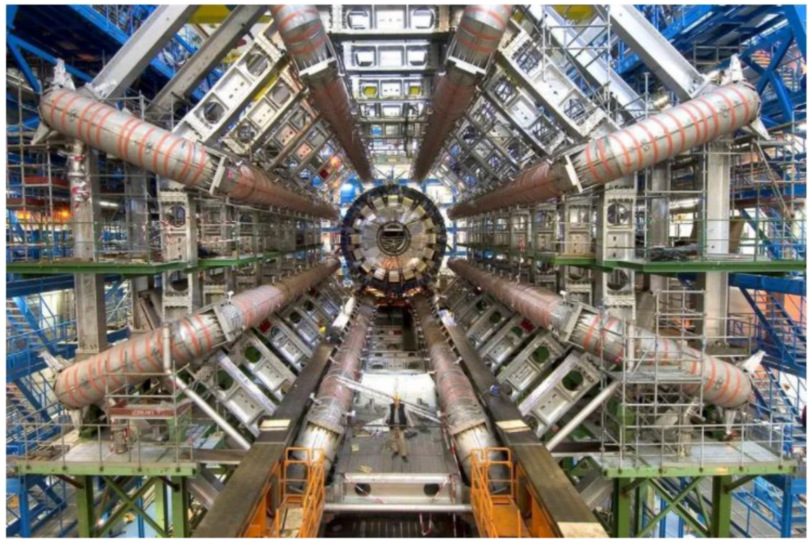




- There is strong consensus regarding how much stuff there is in the universe

Detection Techniques of Dark Matter

Figure Link



LHC

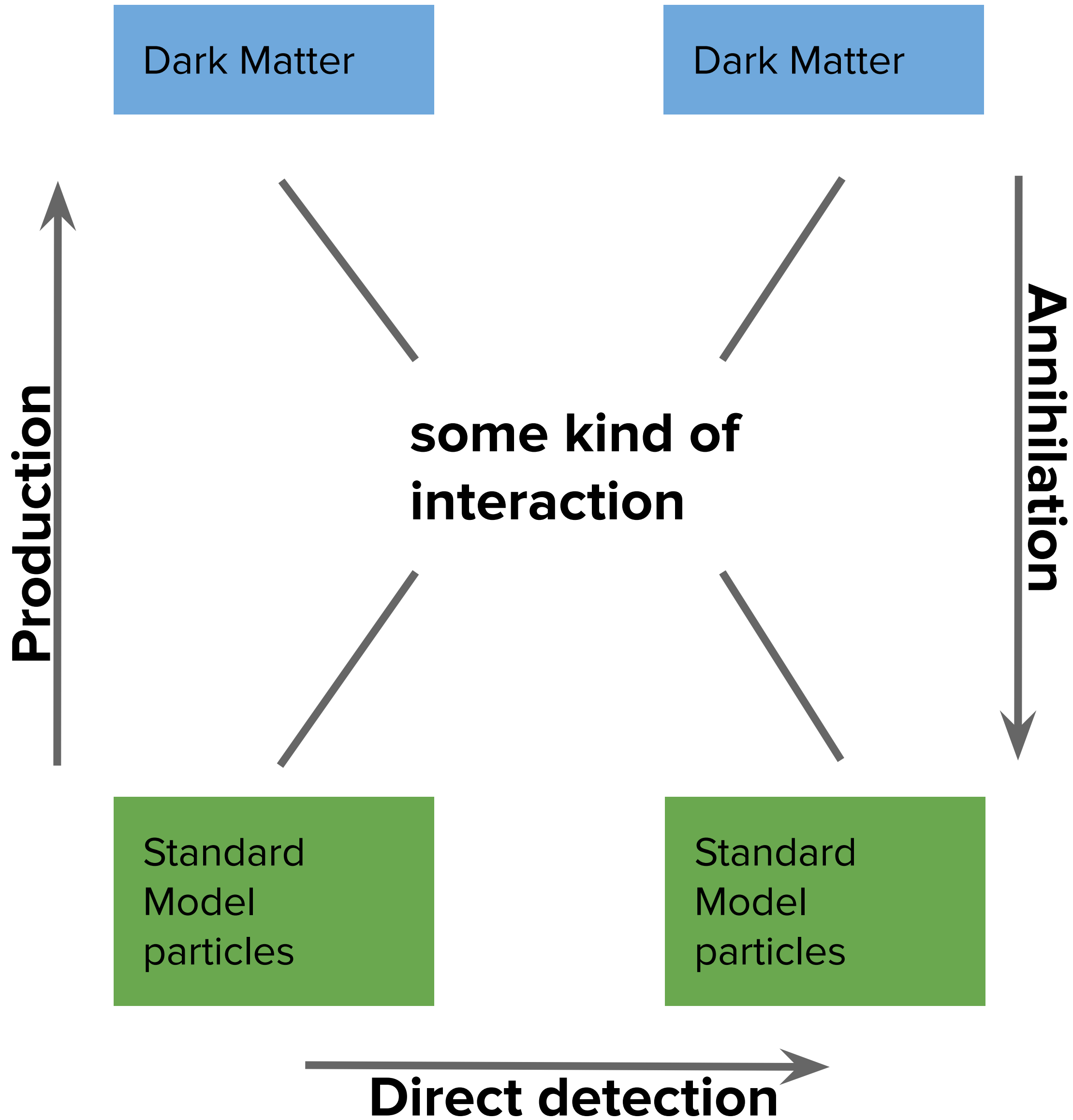
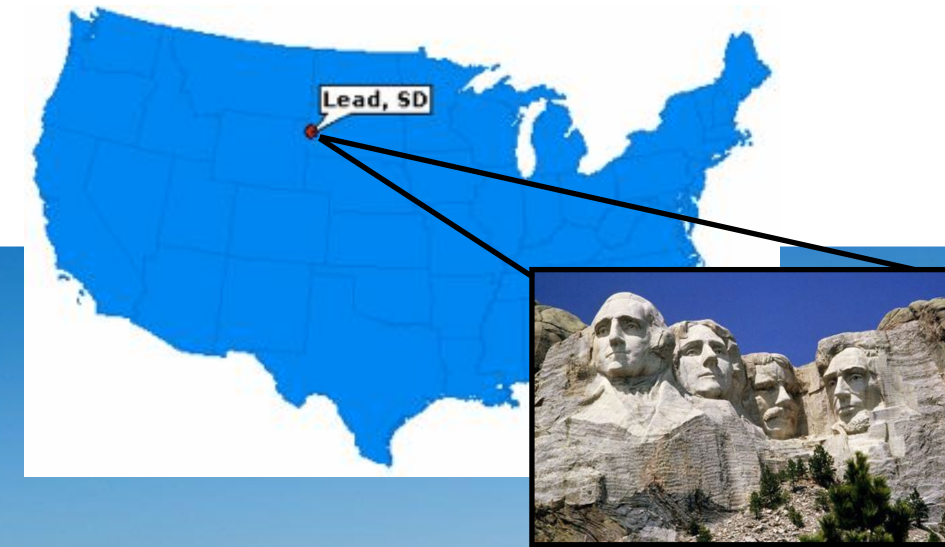


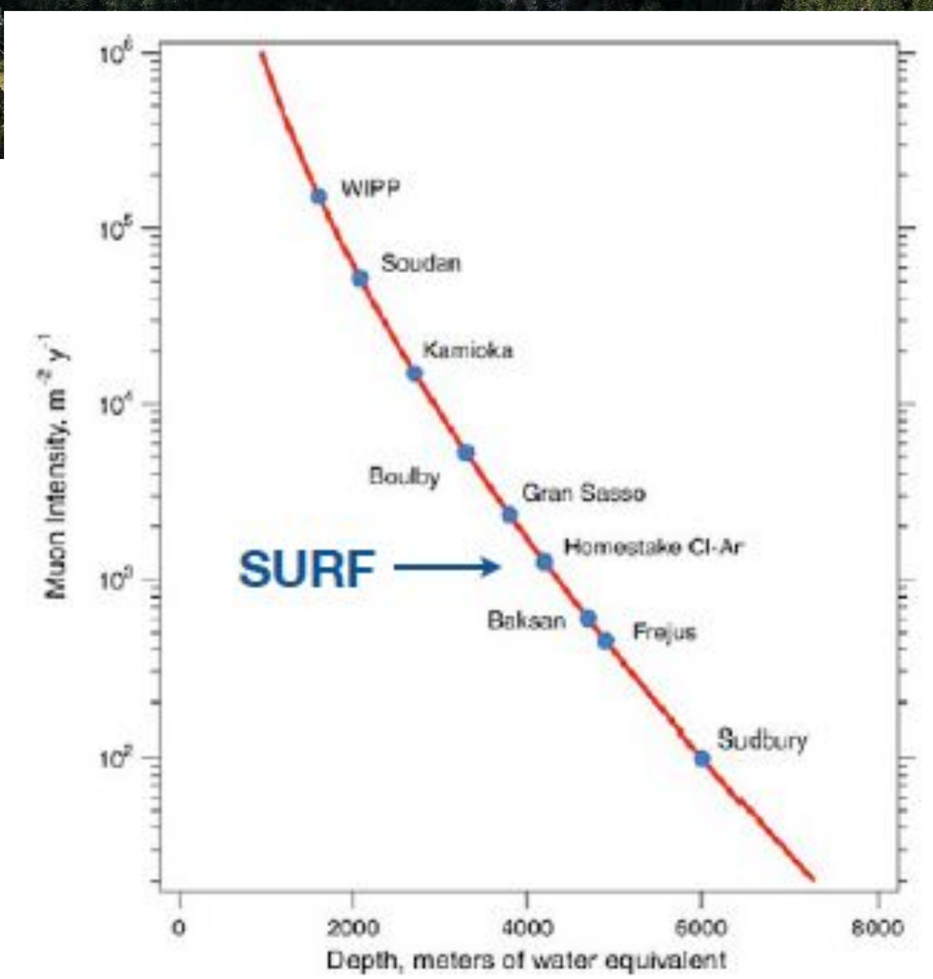
Figure link

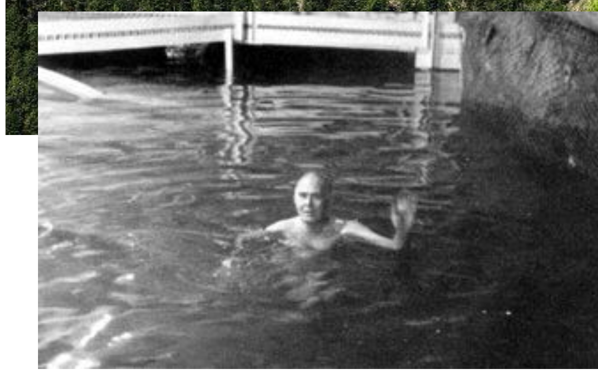
Fermi gamma-ray space telescope

LZ Experiment

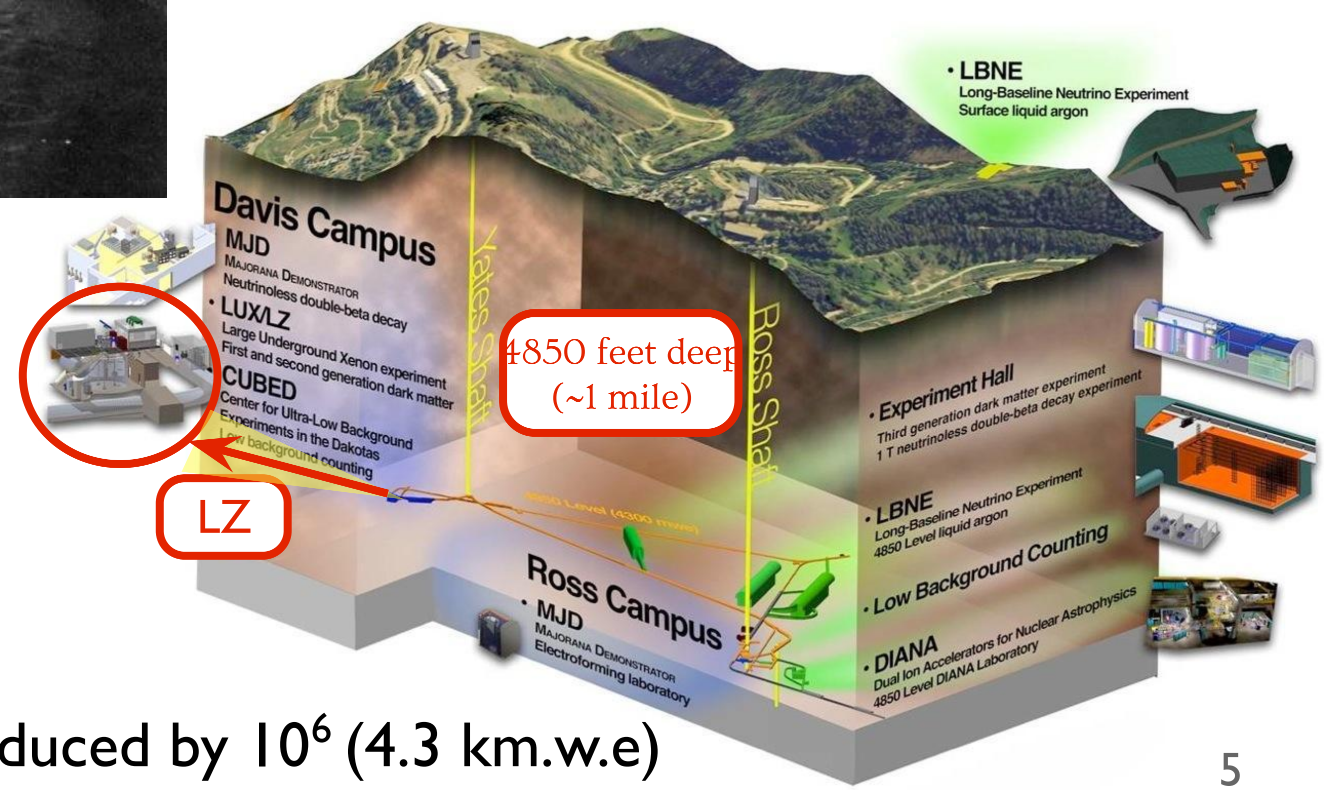
Sanford Underground Research Facility (SURF) in Lead, SD







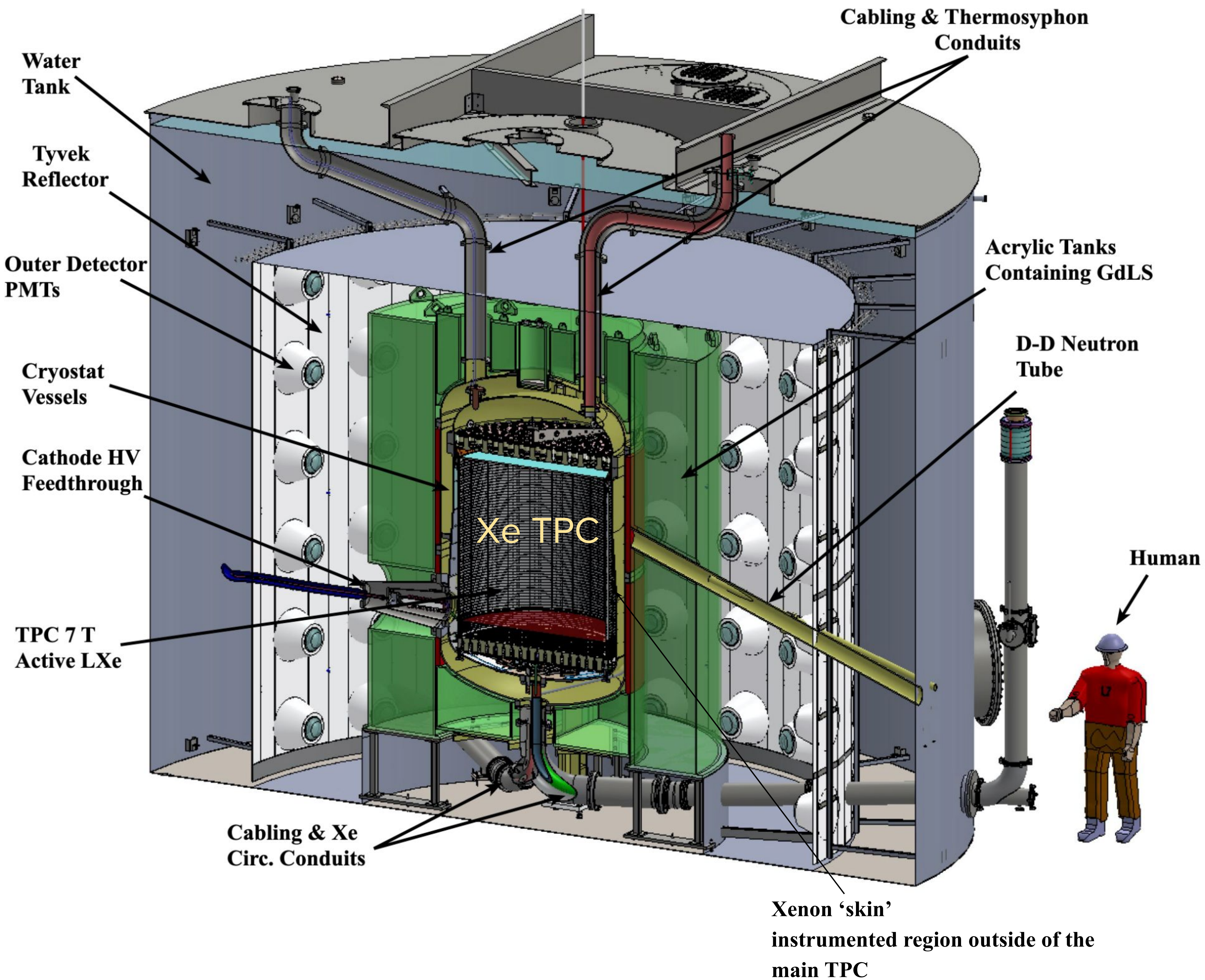
Ray Davis, nobel prize winner



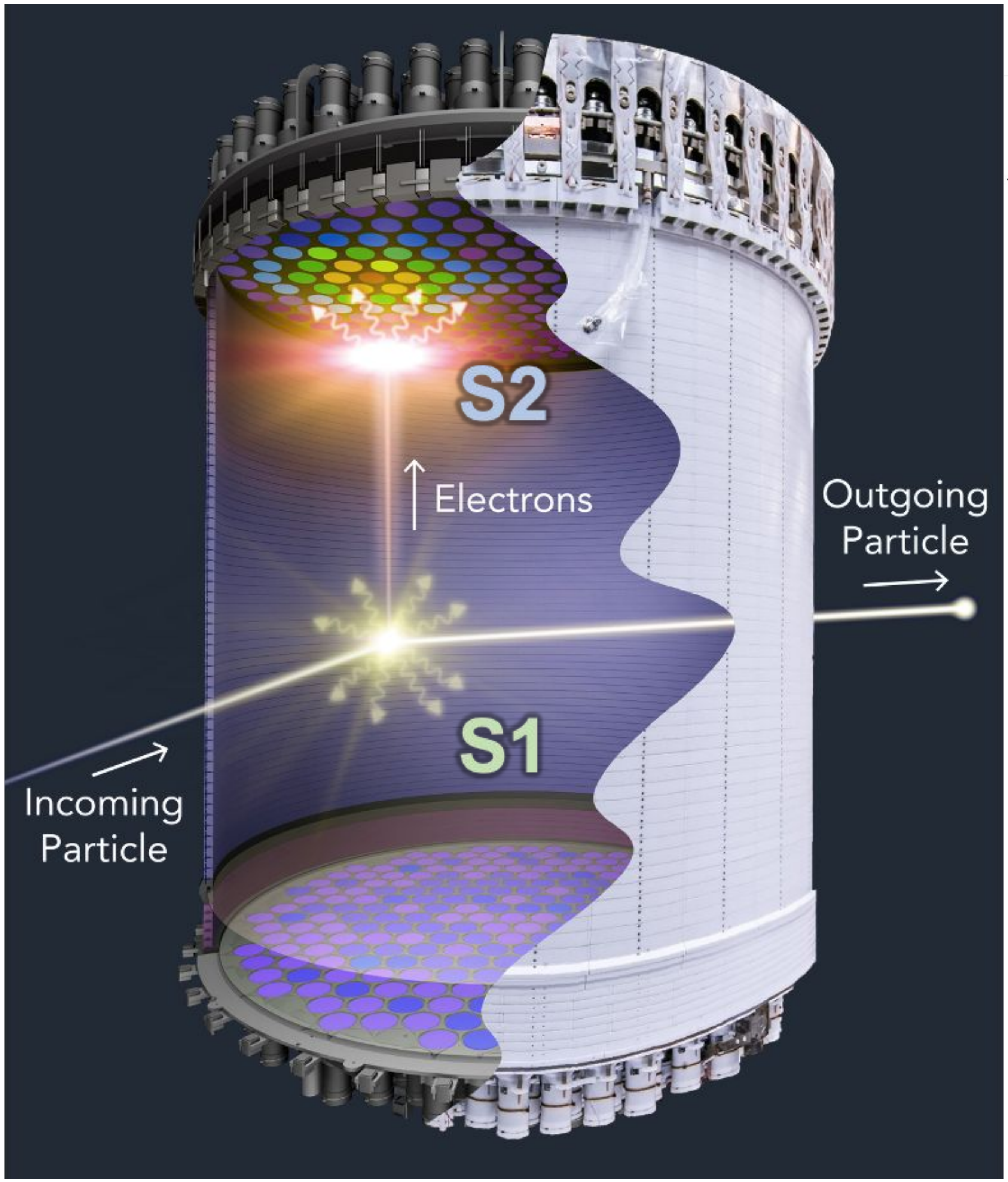
Muon flux reduced by 10^6 (4.3 km.w.e)

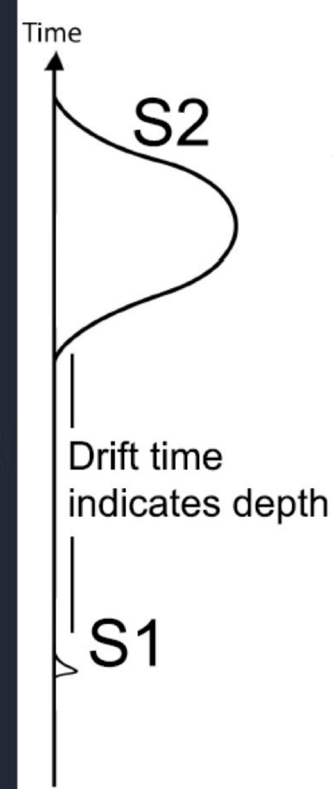
LZ Detector Overview

Three segmented detectors
(details will be discussed later)

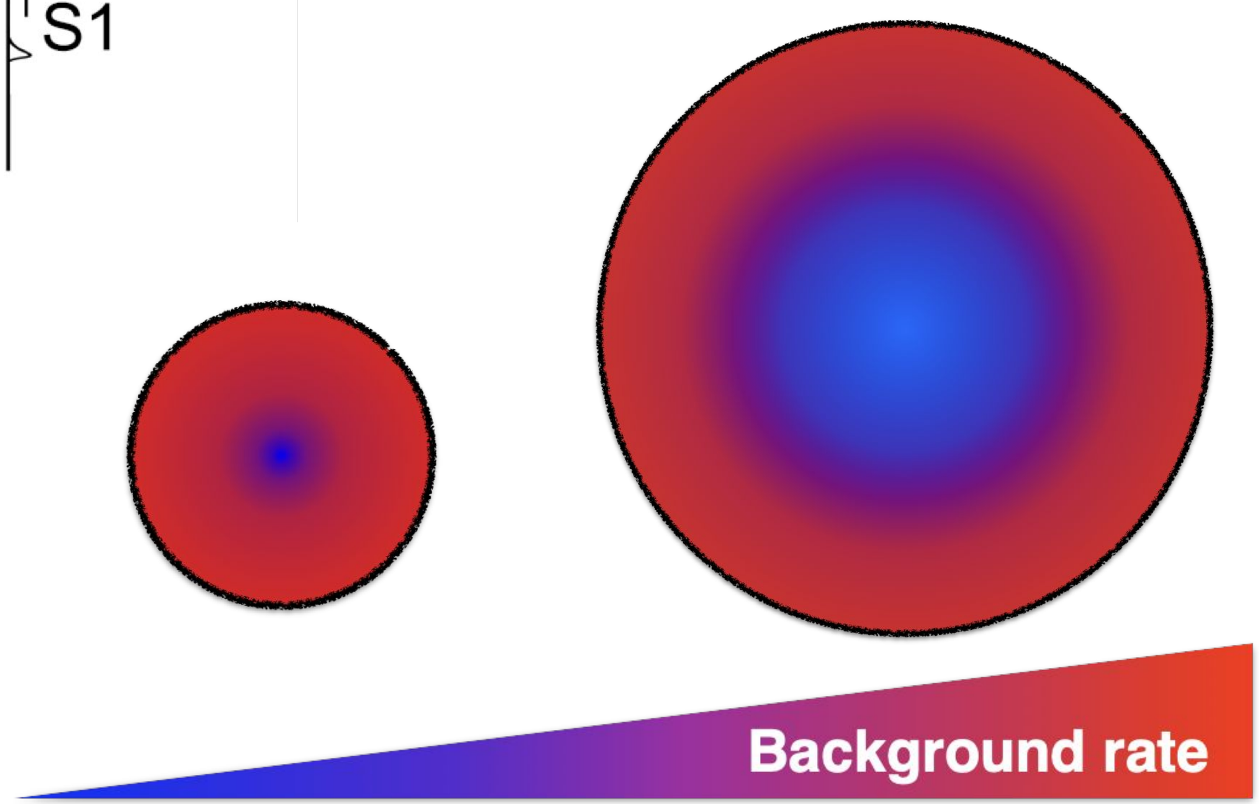


Dual Phase Xenon TPC

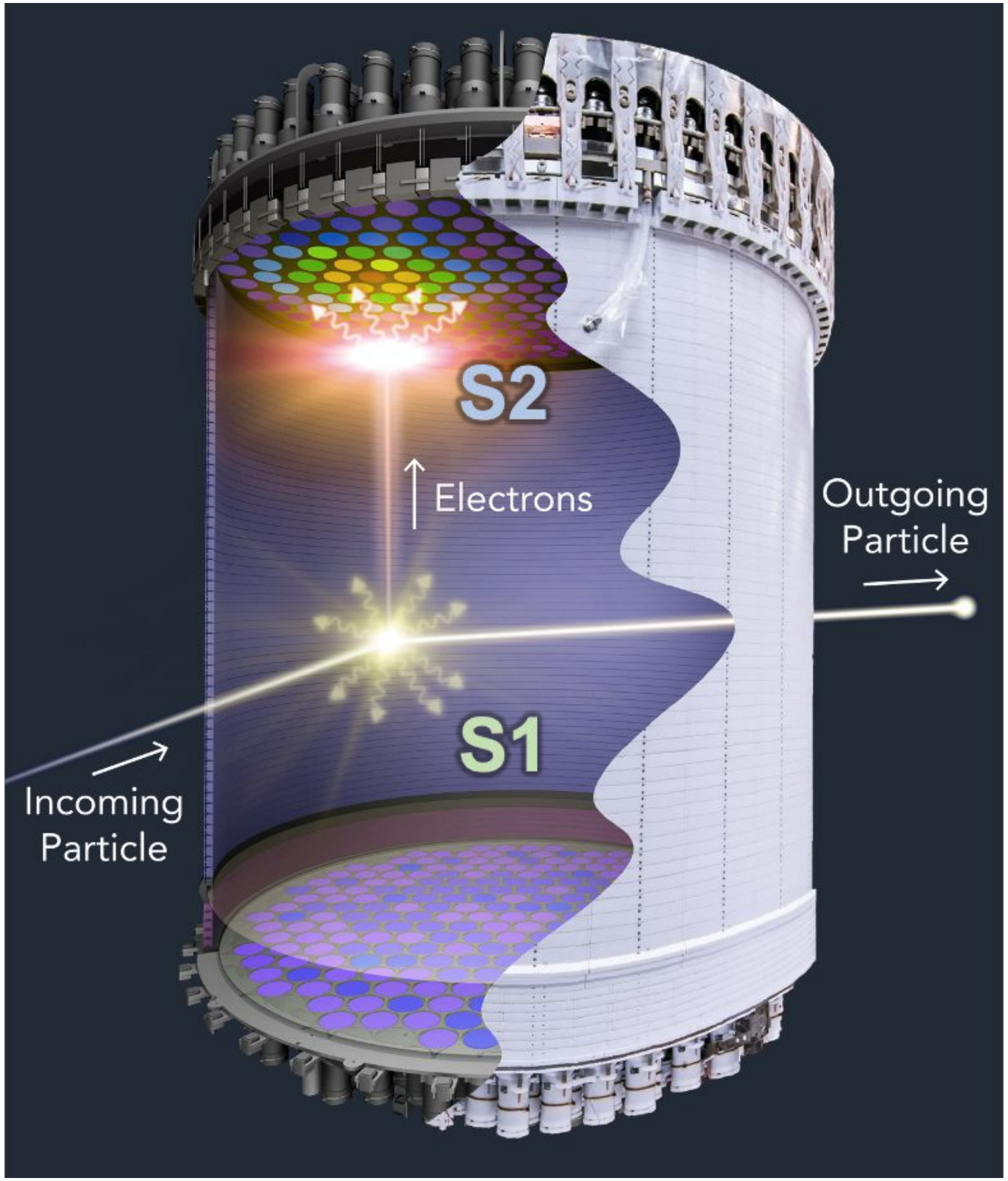




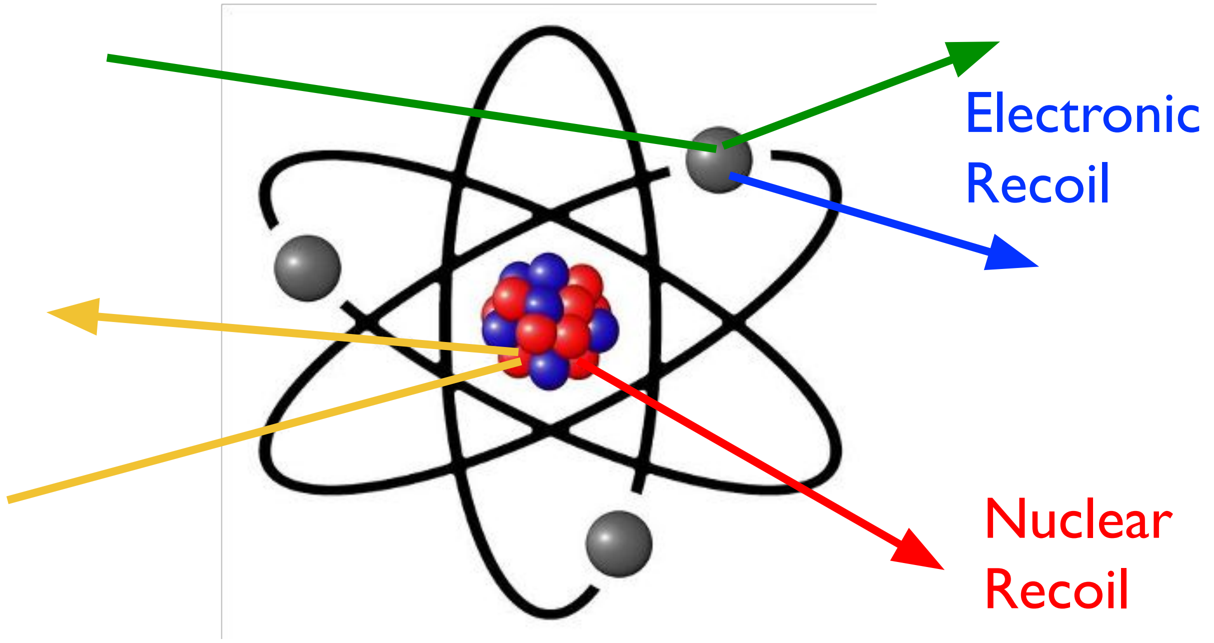
- Excellent 3D imaging capability
  - ✦ Z position from S1 - S2 timing
  - ✦ XY positions from S2 light pattern
- Xenon is easily purified
- Xenon is DENSE!



Dual Phase Xenon TPC



- Charge (S2) / light (S1) ratio
  => Signal vs Background discrimination

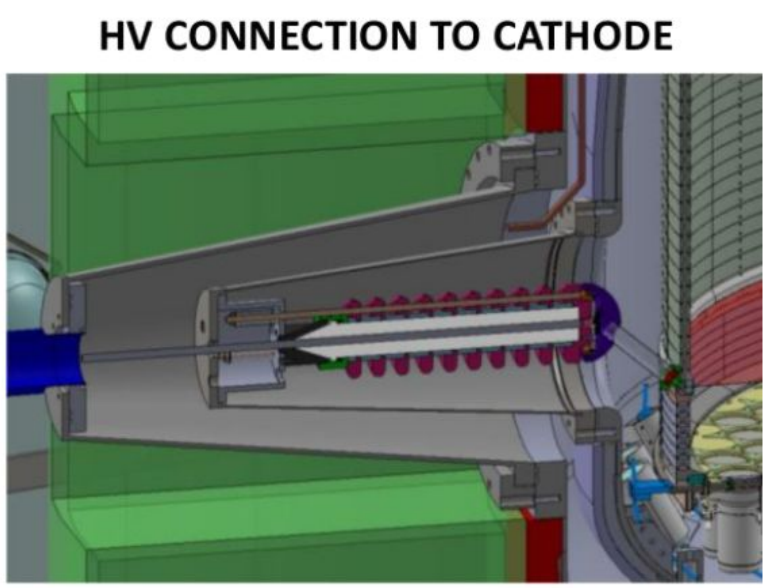


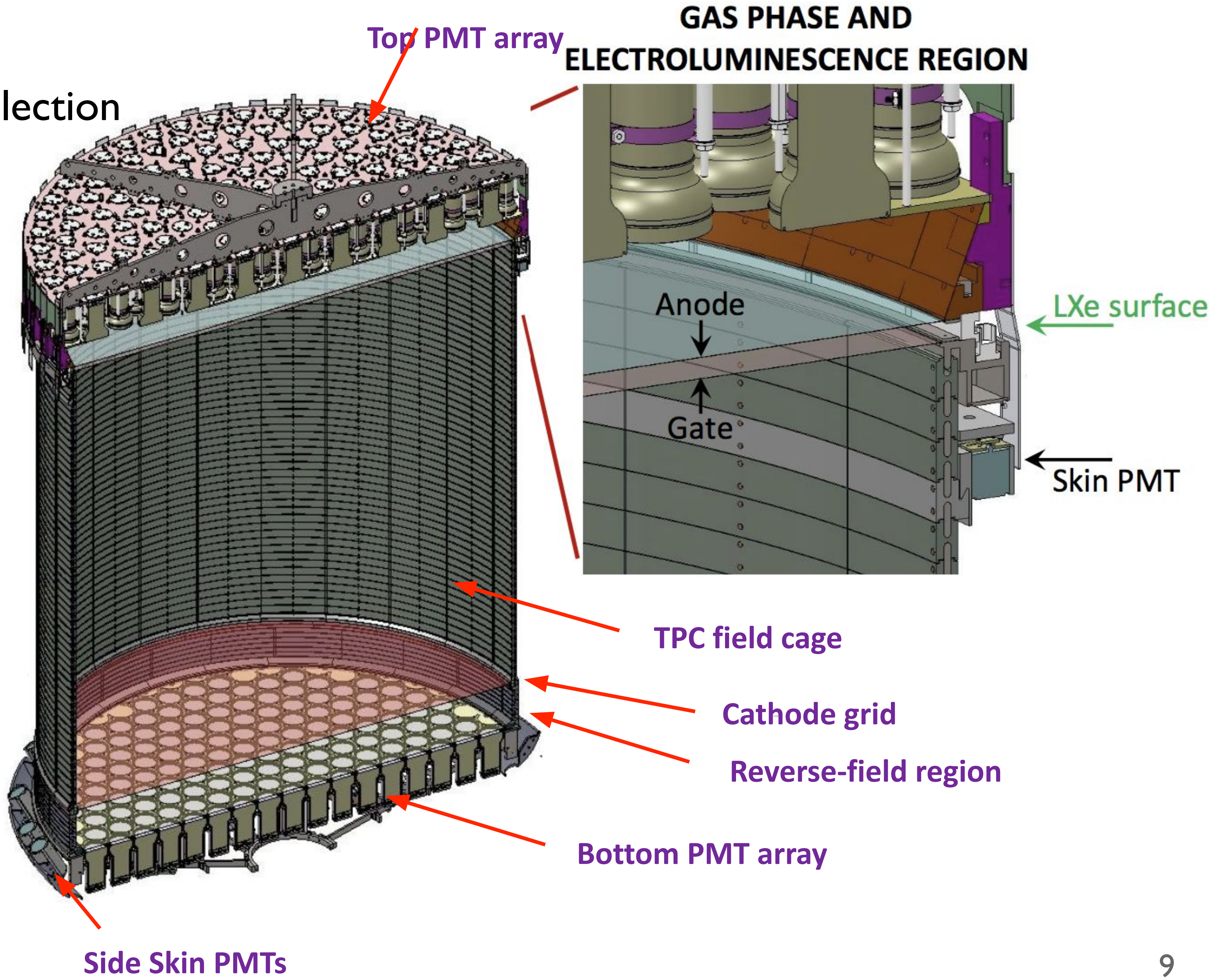
- ✦ Electrons and gammas interact with atomic electrons, produce electronic recoils (ER)
- ✦ WIMPs (and neutrons) interact with Xe nuclei, produce nuclear recoils (NR)

LZ TPC Design Notes

NIM A, 163047 (2019)

- 1.5 m diameter x 1.5 m height
- 7T active LXe (5.6T fiducial)
- PTFE everywhere for light collection
- 494x 3" PMTs
- 4 grids (bottom, cathode, gate, anode) plus field cage define TPC



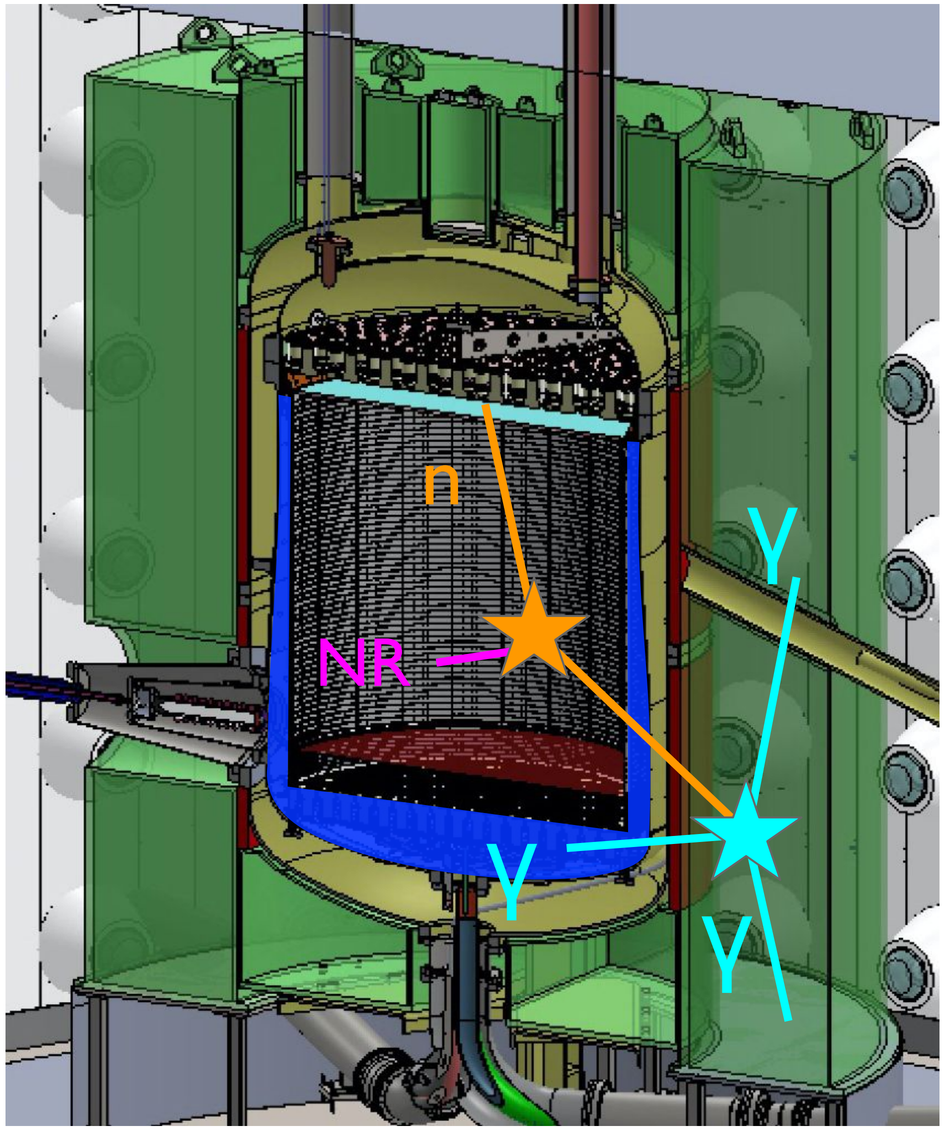


The LZ Vetoes

- WIMPs will only scatter once (10 million light years of lead…)
  - ✦ Backgrounds can and will scatter multiple times - can be vetoed!

The Skin

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



The Outer Detector (OD)

- 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 ~8 MeV of γ-rays from thermal neutron capture

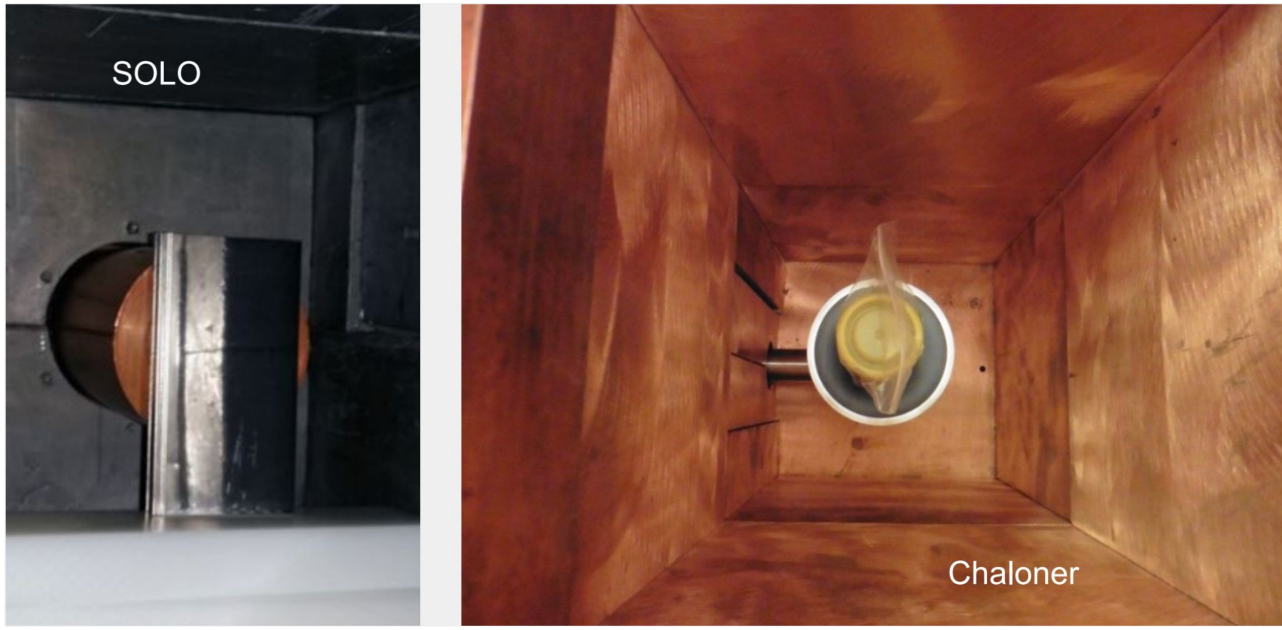
- Neutrons particularly important
- Characterize BGs in situ

→ **Veto enables discovery potential**

BG Mitigation
- Material Screening

- 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 5.6 tonne fiducial volume
- Techniques:
    - Gamma ray spectroscope with ultralow-background HPGe
    - NAA (Neutron activation analysis)
    - ICP-MS (inductively coupled mass spectroscopy)
    - Alpha spectroscopy (for surface contamination)
    - Silicon PIN (Rn emanation)
- Main facilities housing 13 HPGe:
    - Black Hills Underground Campus (BHUC)
    - Boulby Underground Germanium Suite (BUGS)
    - LBNL
    - Alabama

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

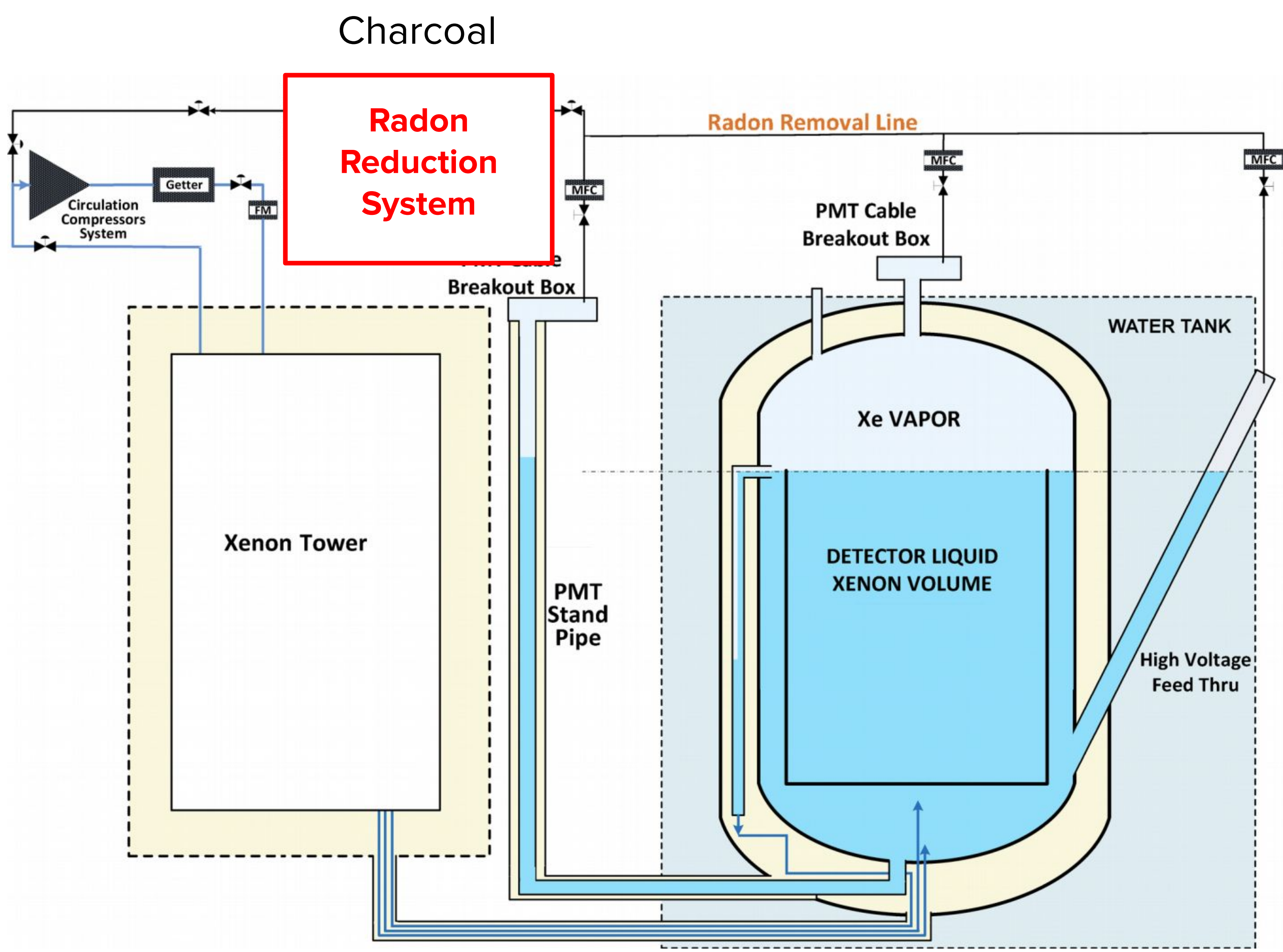


The European Physical Journal C, Volume 80, Article number: 1044 (2020) (arXiv:2006:02506)

Internal BG Mitigation
- Inline Radon Removal System (iRRS)

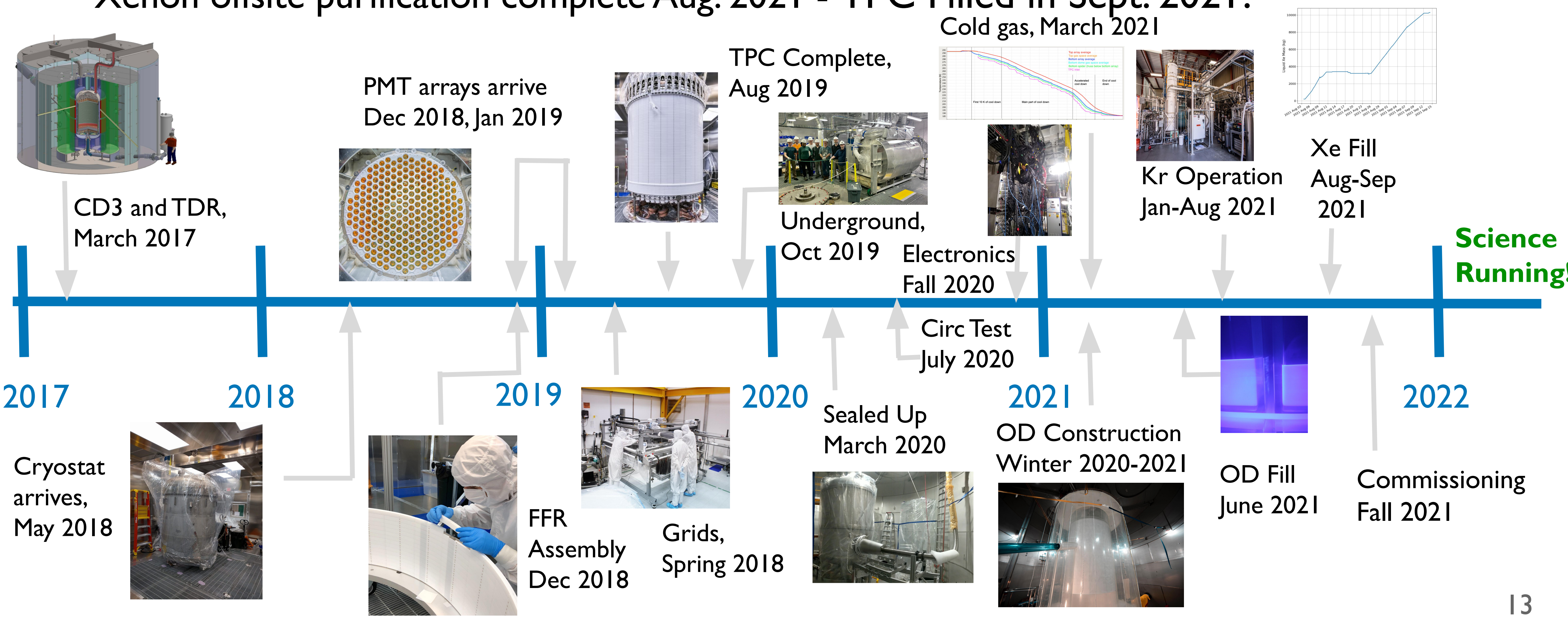
Built by University of Michigan

- ^{222}Rn is a product of ^{238}U decay
  - Decay lifetime: 5.516 days
- ^{222}Rn are constantly emanated from detector components
- It dissolves in liquid xenon
  - Cannot be removed by hot purifying getters
- β-decay of daughter ^{214}Pb mimics WIMP signals
  - potentially leaks into WIMP region
- Reduce ^{222}Rn background of warm sections (cables and feedthroughs) by at least one order of magnitude with iRRS

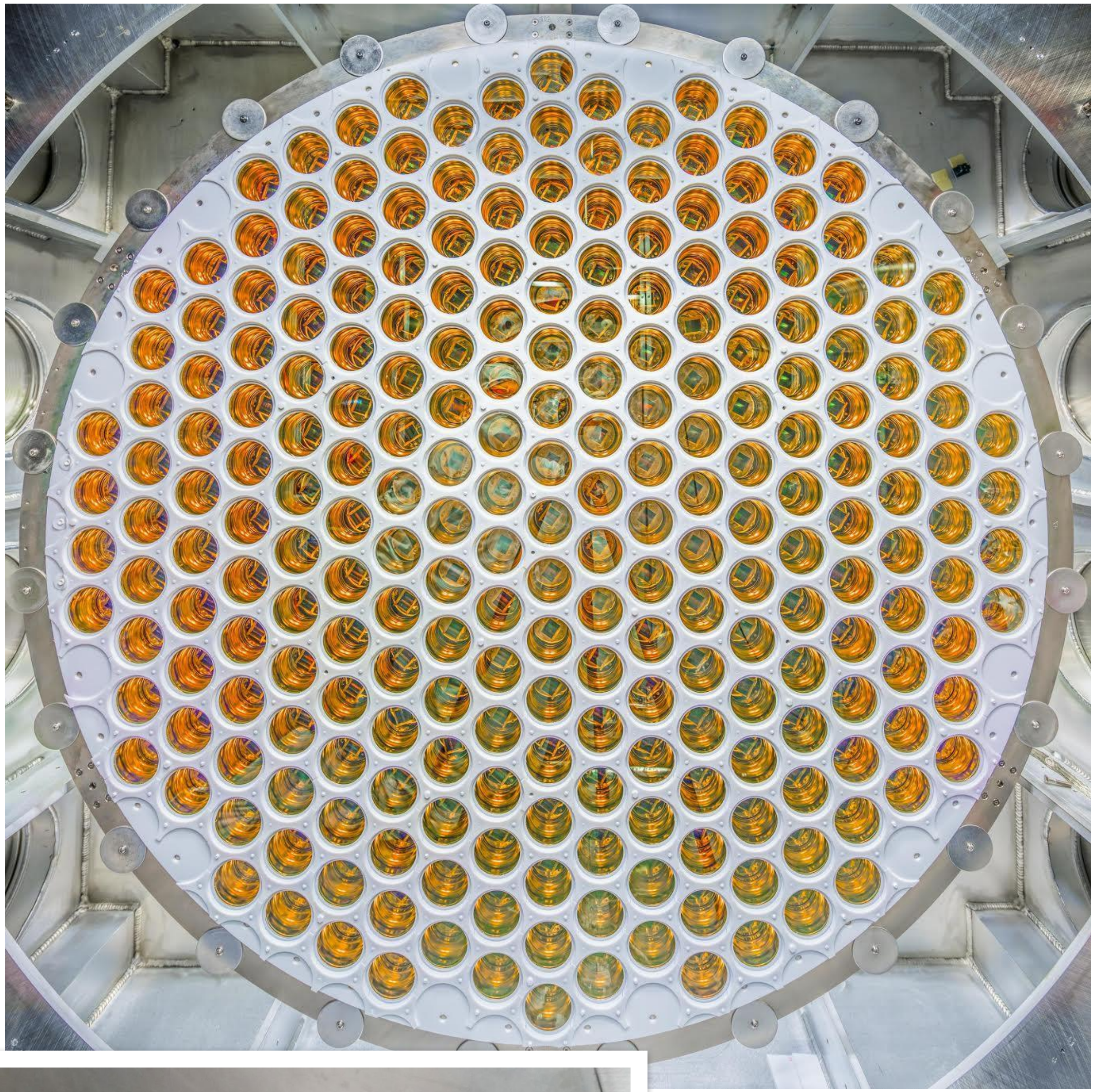


Detector Assembly (The Picture Round)

- Detector assembly began in earnest in fall, 2018 on surface at SURF
    - ✦ 13,500 working hours in the low radon clean room with tens of thousands of ultra-clean, low background components
- TPC brought underground in October 2019
- Cryostat closed in March 2020, ahead of COVID-19 shutdowns
- OD complete and filled by July 2021
- Xenon offsite purification complete Aug. 2021 - TPC Filled in Sept. 2021!



PMT arrays and cabling



11.6 miles of (low background, dust free!) cabling

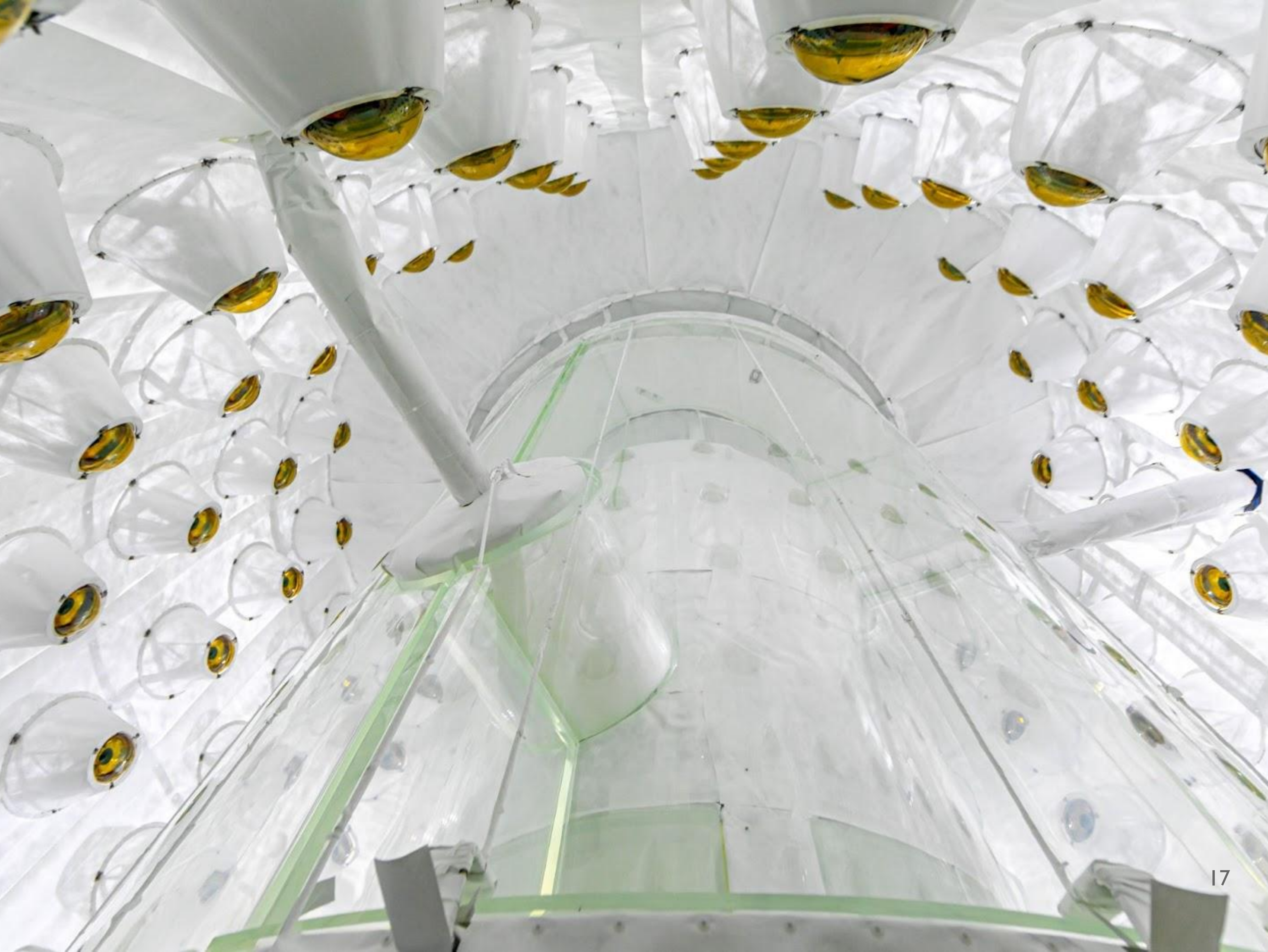
Closing Up

Lower inner cryostat vessel into outer cryostat vessel

Making up cathode connections (under N2 purge)

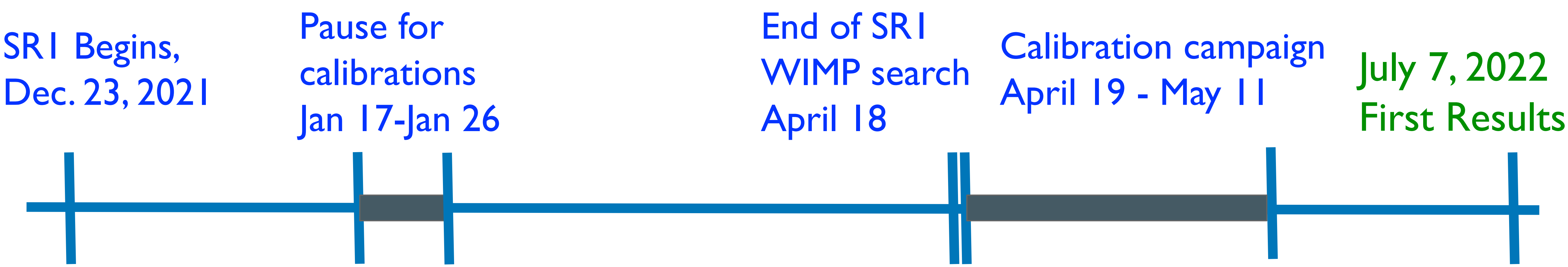
The Outer Detector

Construction leb by the
University of Michigan



LZ's Science Run 1 (SR1)

- Initial plan for Science Run 1 to collect 60 live days
  - Prove successful detector operation and expectation for competitive sensitivity to existing results
- Data taken from Dec. 23 (2021) to May 12 2022, with a break for calibrations in middle and at end

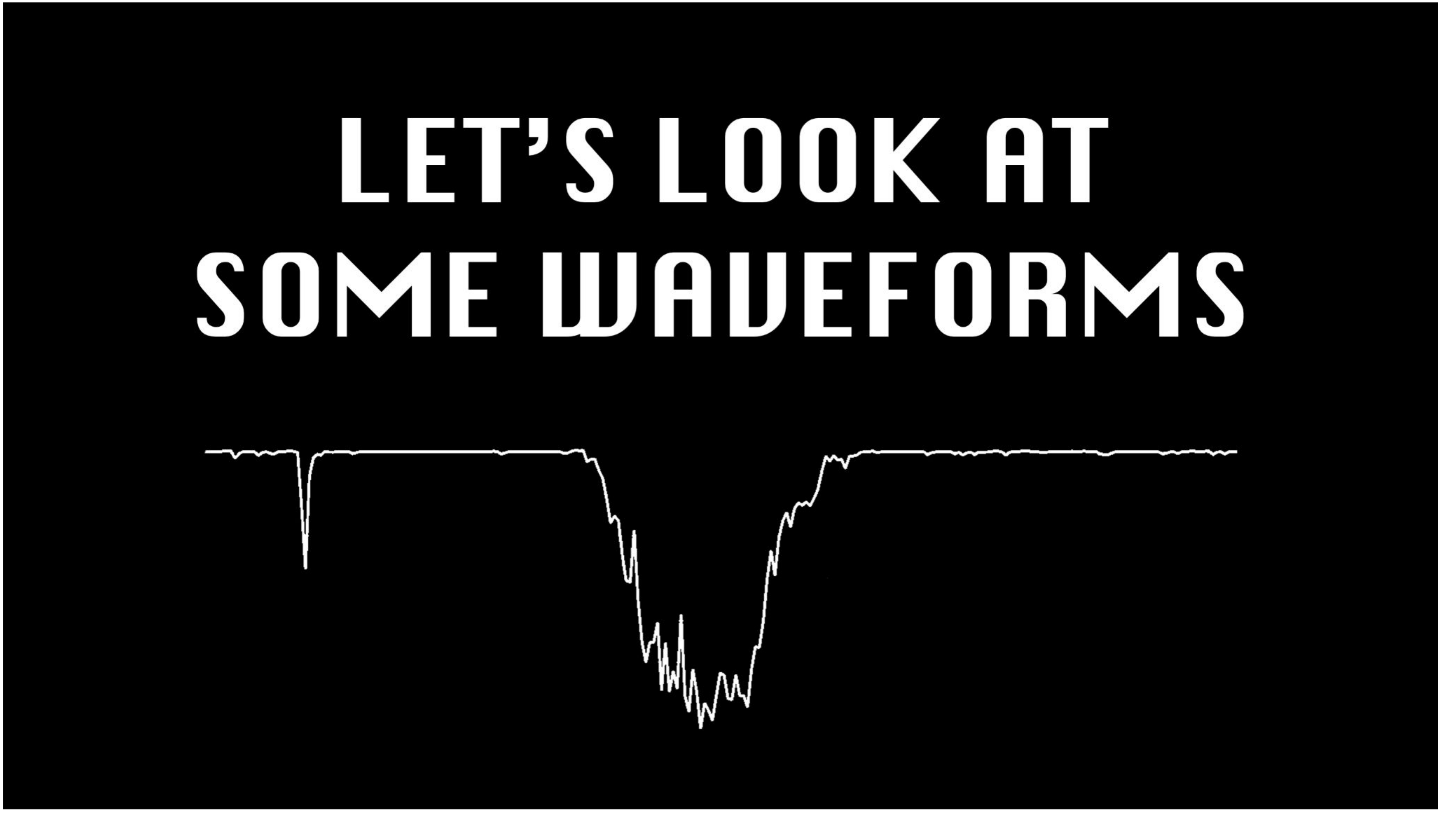


Christmas and
New Years

Easter

July 4

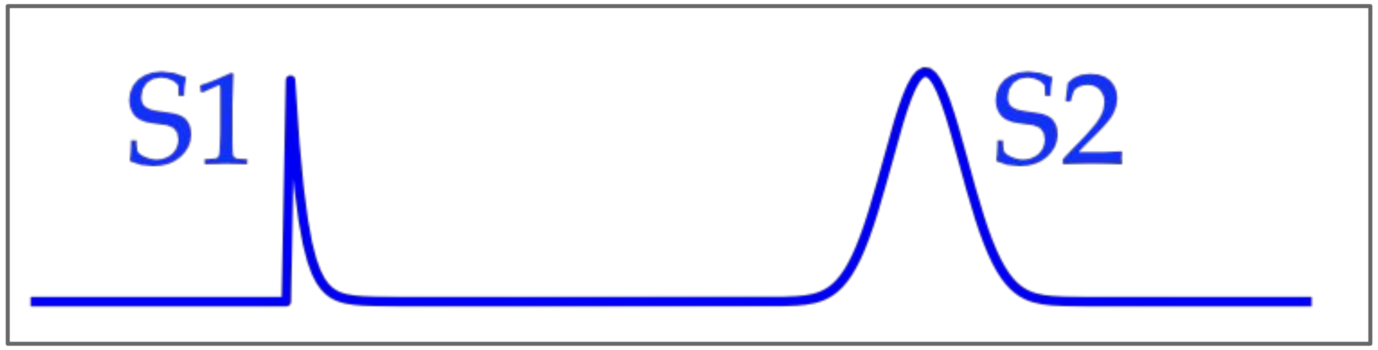
Data Analysis



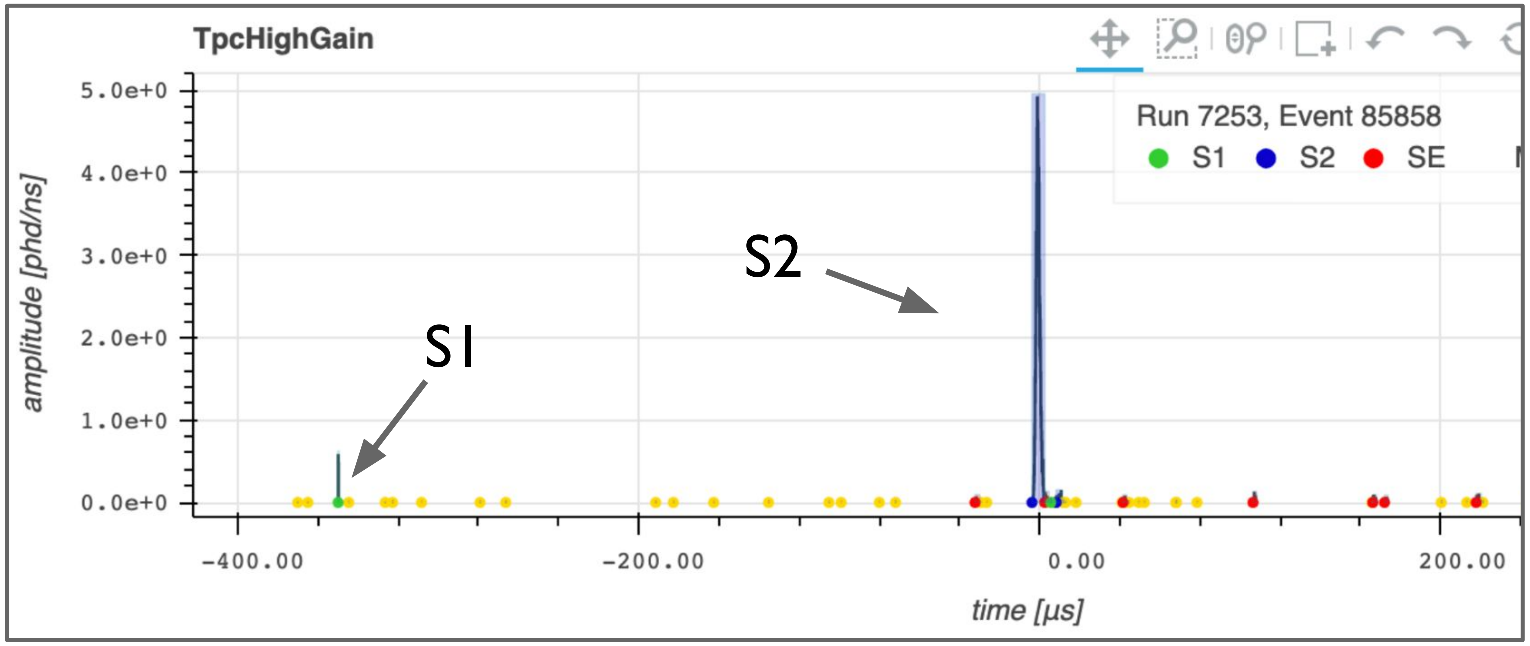
Courtesy Alissa Monte. You can get this on a t-shirt, along with other LZ-related gear at our store (https://alissas-store-3.creator-spring.com/)

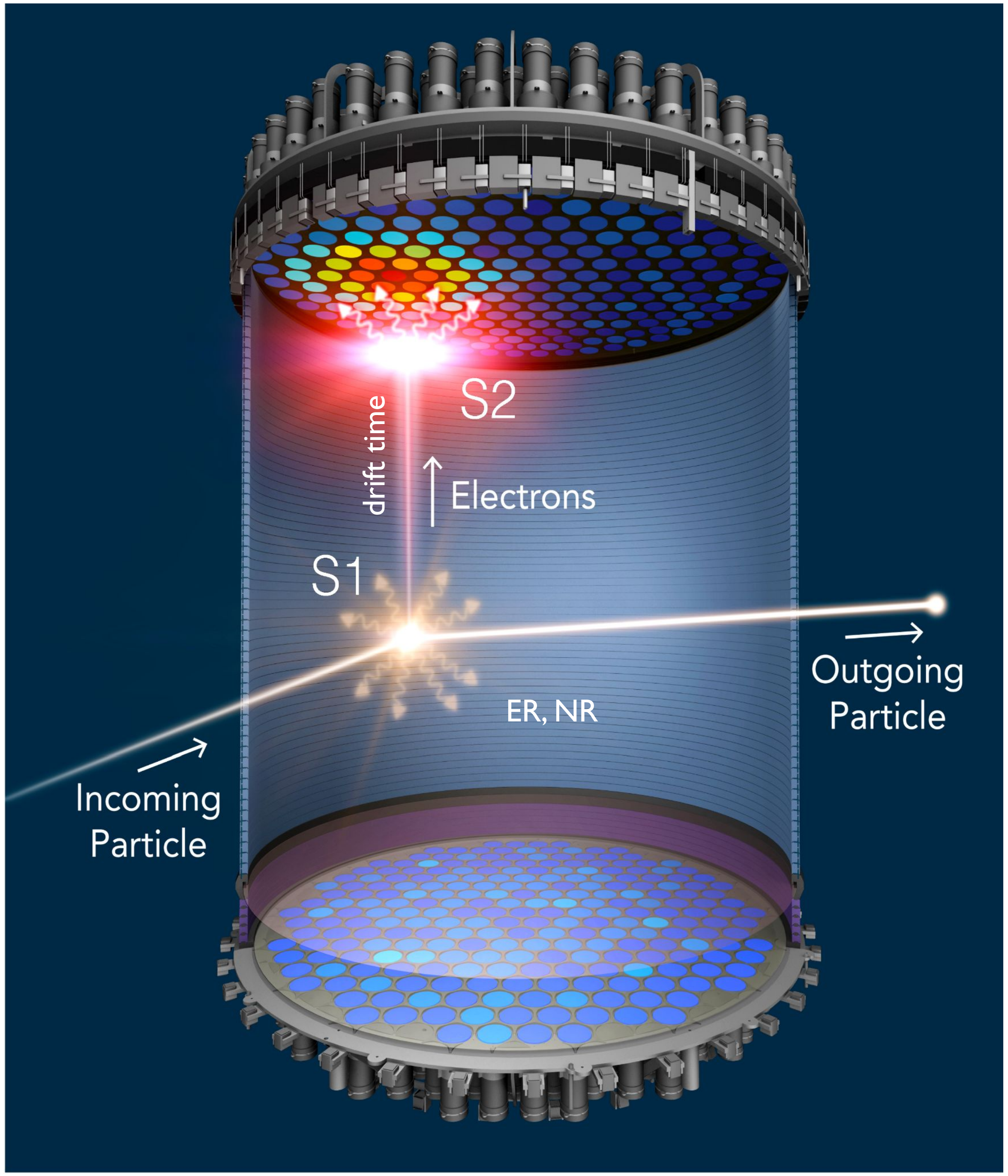
Anatomy of an event

- Cartoon waveform:



- Actual waveform:



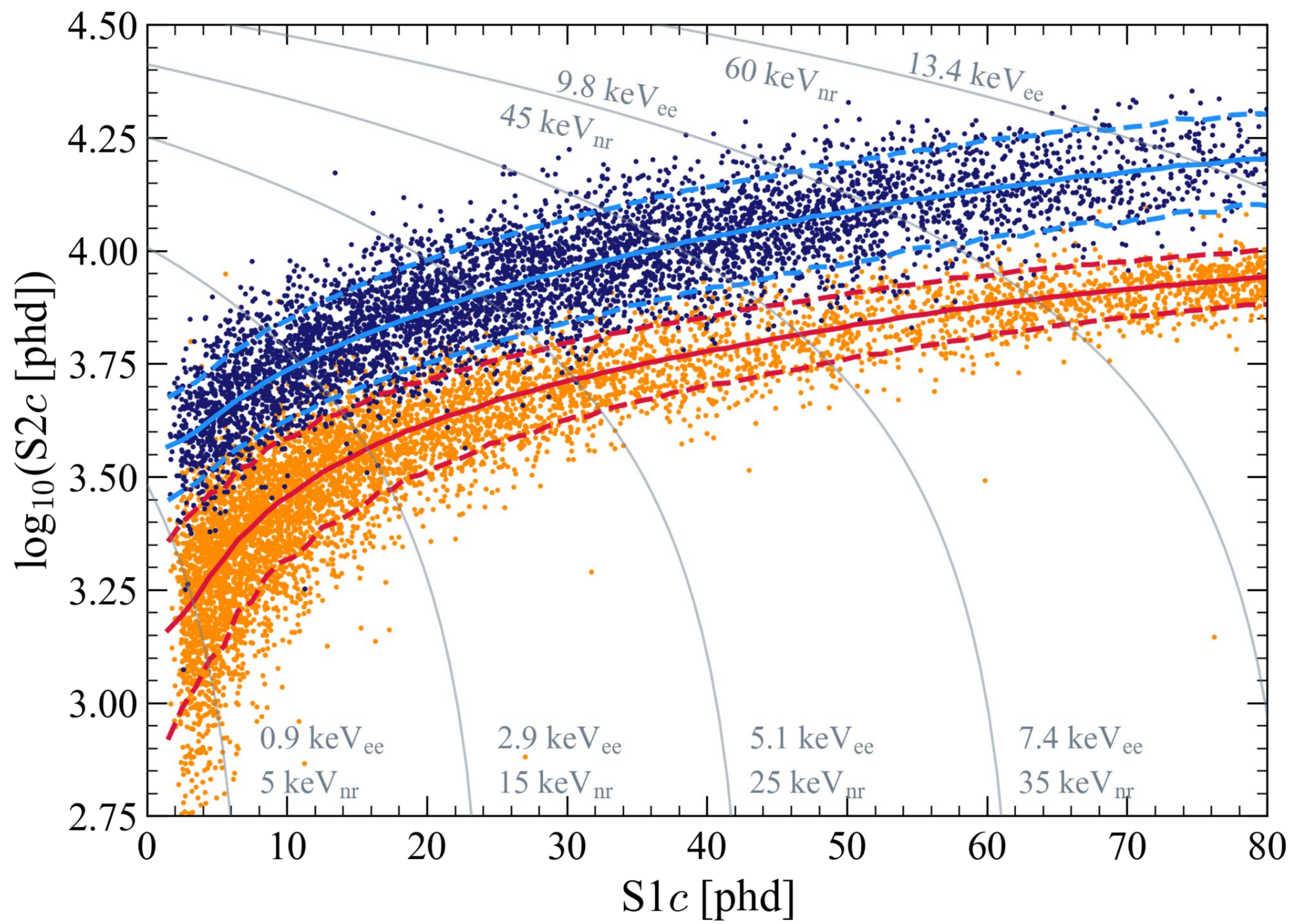


Calibrations

- We use the Noble Element Simulation Technique (NEST)* to model LXe response
- At right:
  - Blue pts: CH_3T data
  - Orange pts: DD (neutron) data
- Fit data to model for detector-performance parameters

Parameter	Value
g_1^{gas}	0.0921 phd/photon
g_1	0.1136 phd/photon
Effective gas extraction field	8.42 kV/cm
Single electron	58.5 phd
Extraction Efficiency	80.5 %
g_2	47.07 phd/electron

- In SR1, we have 99.9% rejection of ER leakage below the median quantile of a 40 GeV WIMP.



(*) https://nest.physics.ucdavis.edu/

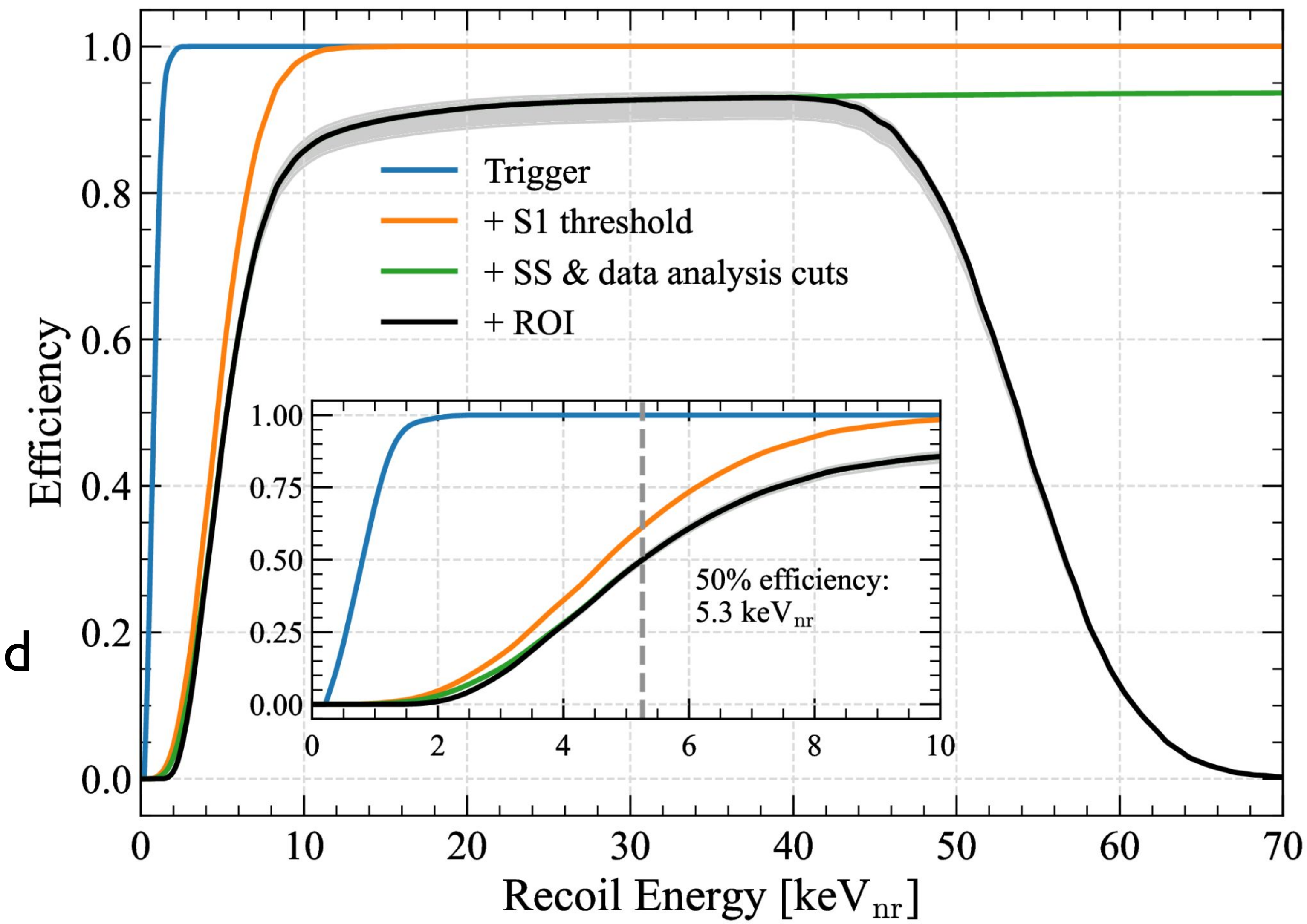
Data Quality - Livetime cuts

- The detector is not continuously in a stable state capable of search for low-energy, rare signals. Identifying (and removing) periods of heightened detector activity is a vital component to data selection.
- Removal of e/ph trains represents the largest single hit to our livetime, removing nearly 30%. Optimizations are possible.

<table>
<tr><th colspan="3">Livetime (LT) impact cuts</th></tr>
<tr><th>Cut name</th><th>Targeted effect</th><th>Impact</th></tr>
<tr><td>Hot spot exclusions</td><td>Grid electron emission</td><td>3.1% LT removed</td></tr>
<tr><td>Muon holdoff</td><td>Glow from TPC-crossing muons</td><td>0.2% LT removed</td></tr>
<tr><td>E/ph-train holdoff</td><td>Glow from S2s</td><td>29.8% LT removed</td></tr>
<tr><td>High S1 rate exclusions</td><td>PMT/HV(?) misbehavior</td><td>0.2% LT removed</td></tr>
<tr><td>Bad buffer cuts</td><td>DAQ issue, caused by glow from muons & S2s</td><td rowspan="3">Deadtime hit, 0.5% LT removed, confirmed with GPS triggers and simple calculation from S2/muon rate</td></tr>
<tr><td>Excess Area cut</td><td>Glow from ghost muons/S2s</td></tr>
<tr><td>Sustained rate cut</td><td>Glow from ghost muons/S2s</td></tr>
<tr><td>Burst noise cut</td><td>Electronics noise</td><td>Deadtime hit, < 0.001% LT removed</td></tr>
</table>

Signal acceptance

- S2 trigger acceptance measured by
  - Use of random triggers
  - DD data, using pulsed plasma trigger
- S1 acceptance dominated by 3-fold coincidence requirement
- Cut acceptance measured from calibration sources.
- Event classification efficiency measured by visual inspection of O(1000) neutron-calibration events
- SR1 measured:
  50% acceptance above 5.3 keVnr
  - Uncertainty band (gray) from differences in cut acceptances as measured with different calibrations, and statistical uncertainties.



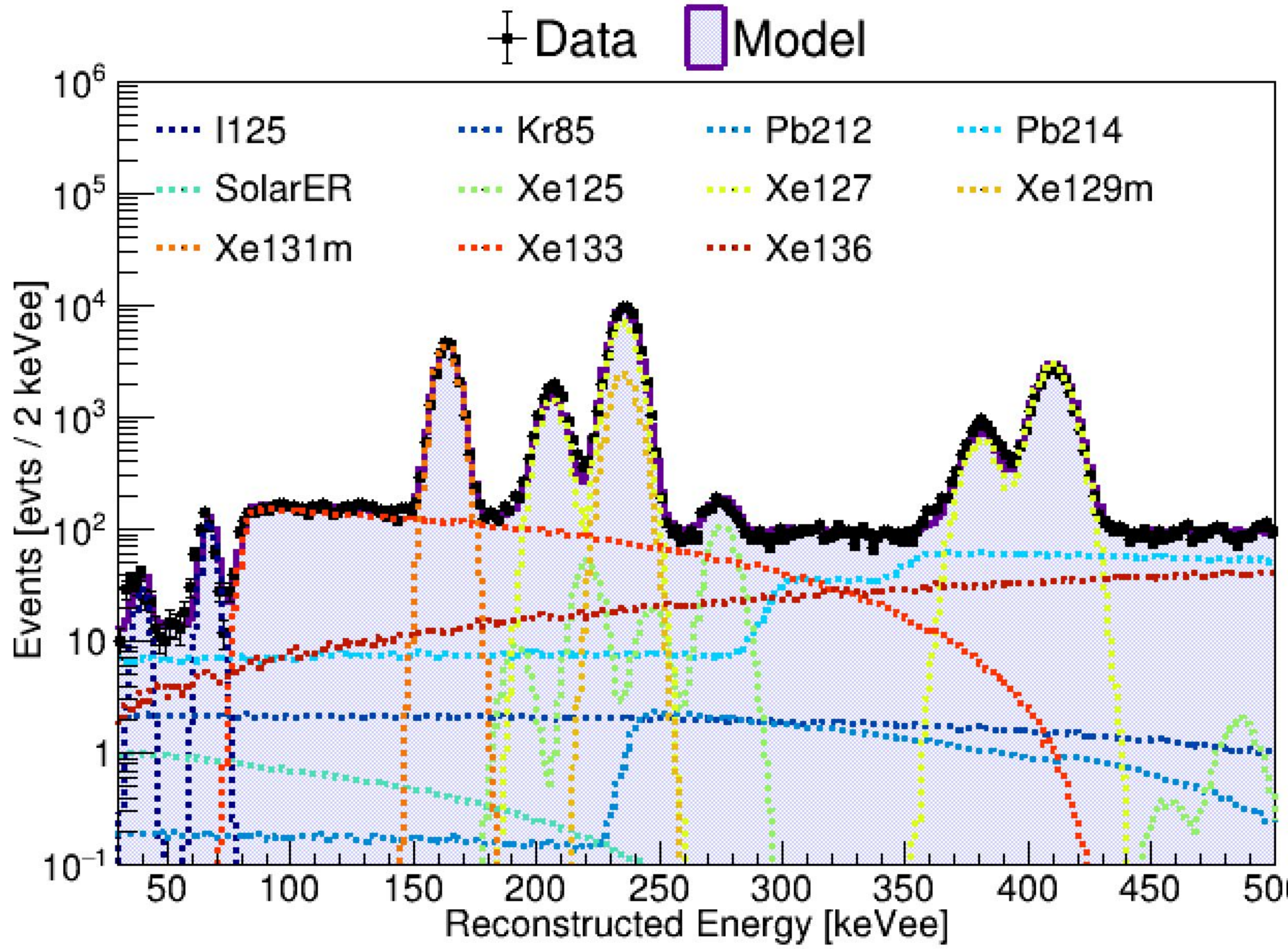
Backgrounds

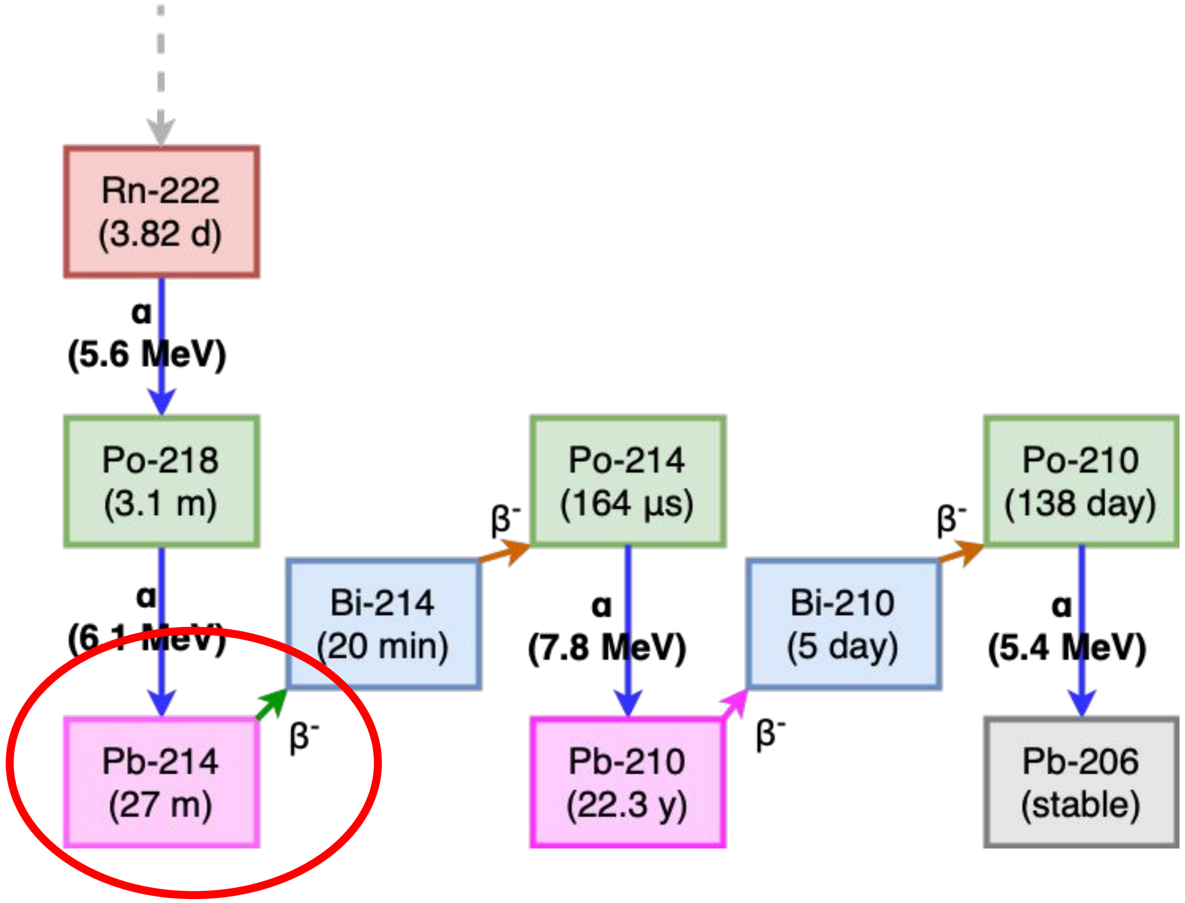
There are many sources of background in our experiment, though not all contribute the same. Listed here are the major contributors to the WIMP-search

- Dissolved beta emitters:
  - ^{214}Pb (^{222}Rn daughter), ^{212}Pb (^{220}Rn daughter), ^{85}Kr, ^{136}Xe (2 beta)
- Dissolved e-captures (monenergetic 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.

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; rate must be ≤ rate of ^{222}Rn decays.
- Likewise, rate of alphas from ^{214}Po must be ≤ rate of ^{214}Pb

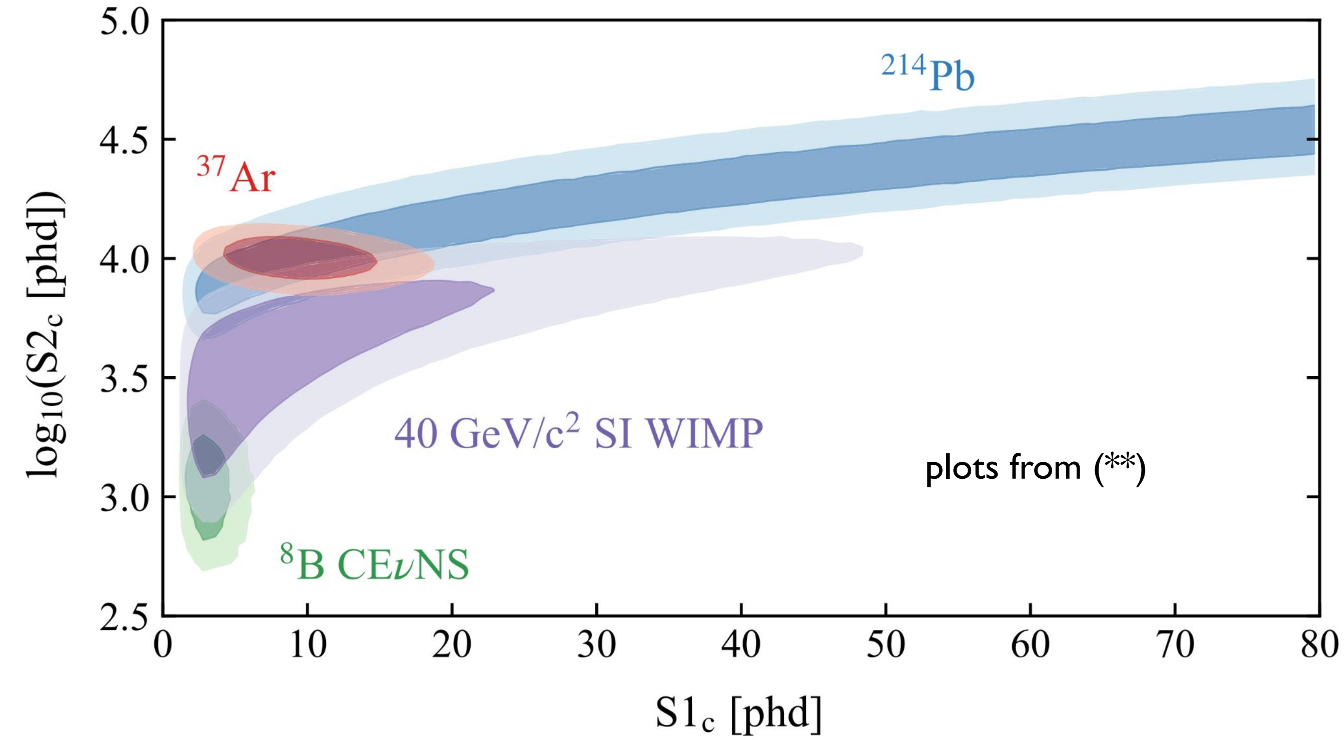


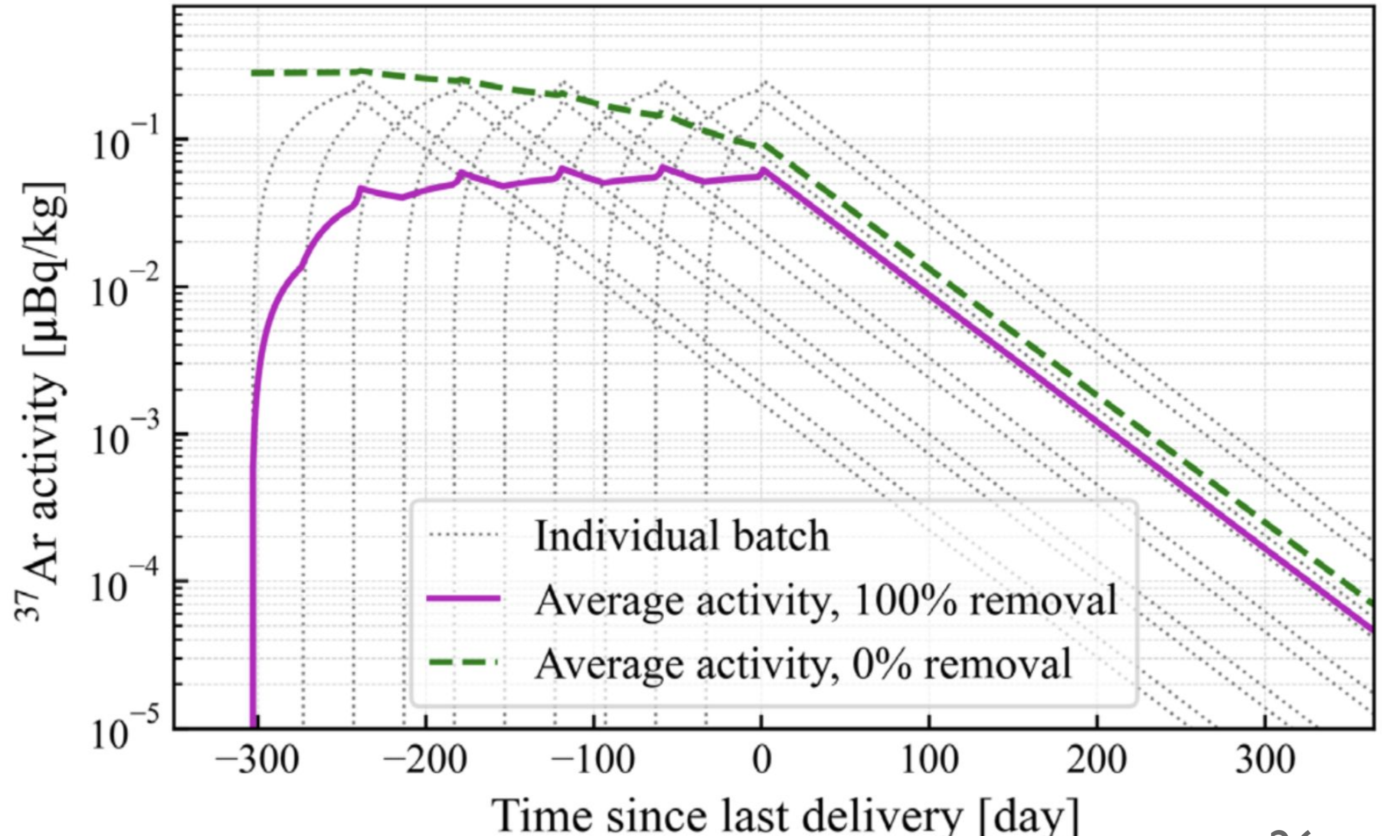


Rn222 (μBq/kg)	Pb214 (μBq/kg)	Po214 (μBq/kg)
4.37 ± 0.31 (stat)	**3.26 ± 0.13(stat) ± 0.57(sys)**	2.56 ± 0.21 (stat)

^{37}Ar

- Electron capture, $t_{1/2}$ = 35 d, monoenergetic 2.8 keV ER deposition
- Occurs naturally in atmosphere via e.g. $^{40}Ca(n,\alpha)^{37}Ar$ (*)
    - 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.

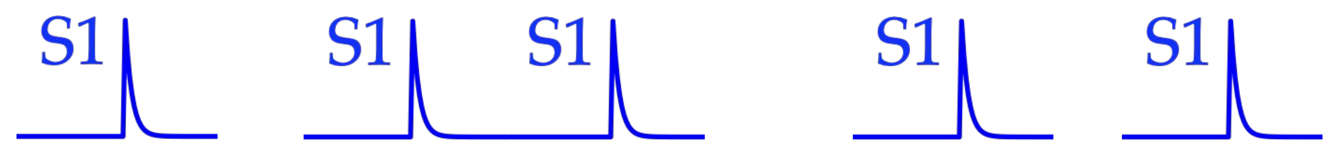




(*) R.A. Riedmann, R. Purtschert, Environ. Sci. Technol. (2011) 45(20), 8656-8664
(**) LZ Collaboration, Phys. Rev. D 105, 082004 (2022), 2201.02858

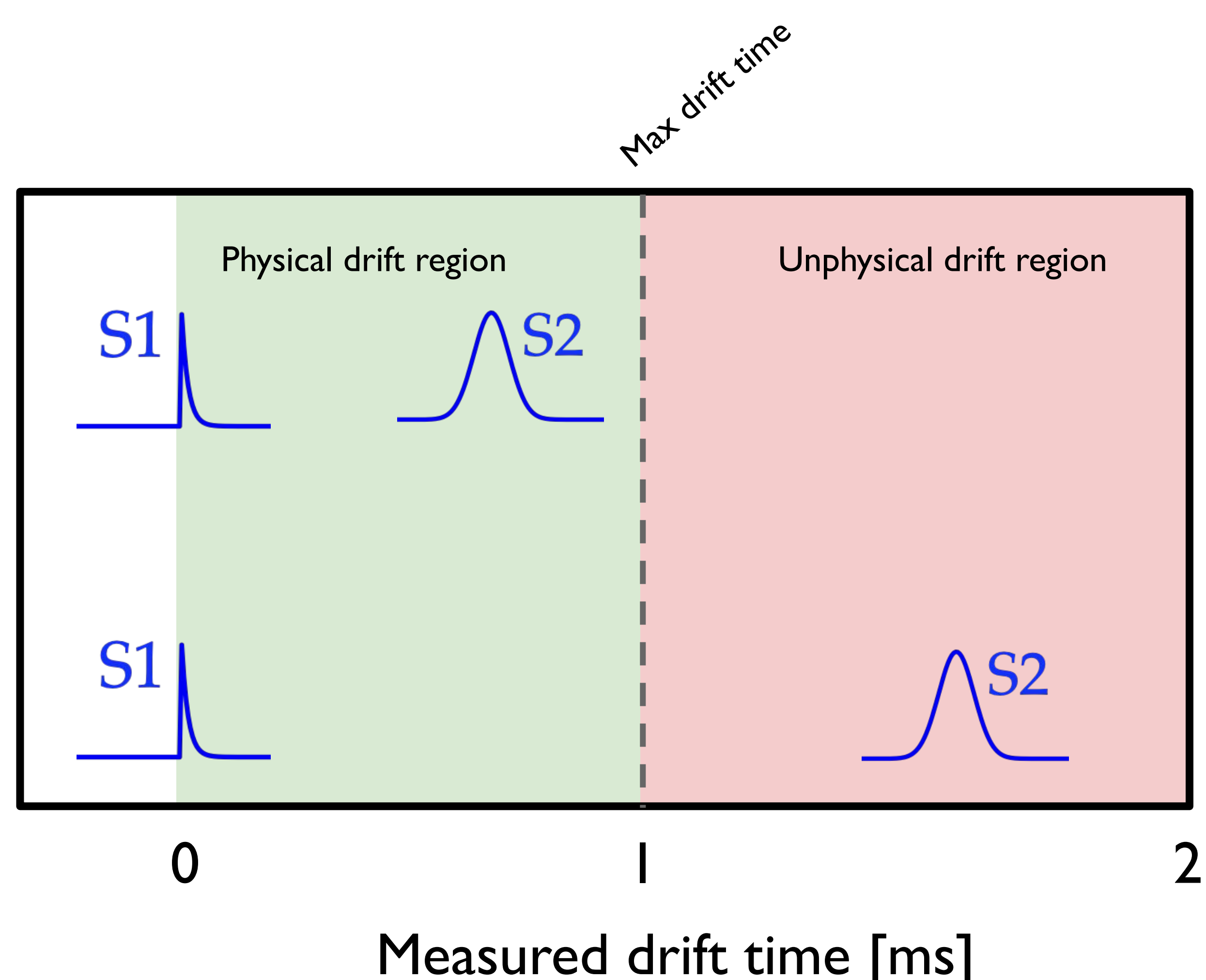
Accidentals Background

- Isolated S1 pulses occur at O(1 Hz)



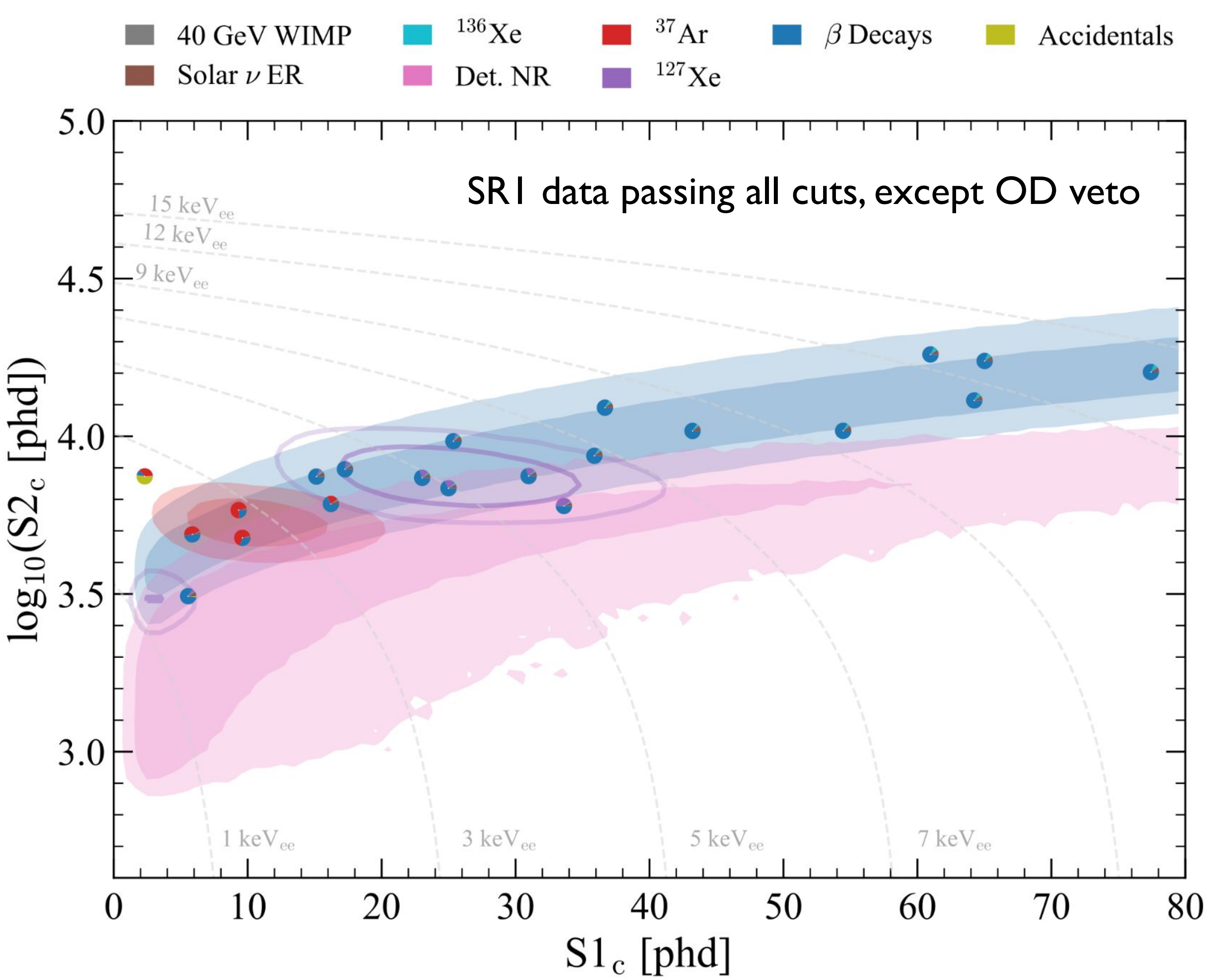
- Isolated S2 pulses occur at O(10^{-3} Hz) (above threshold)

- 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.
- 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**



Outer Detector Neutron Tagging

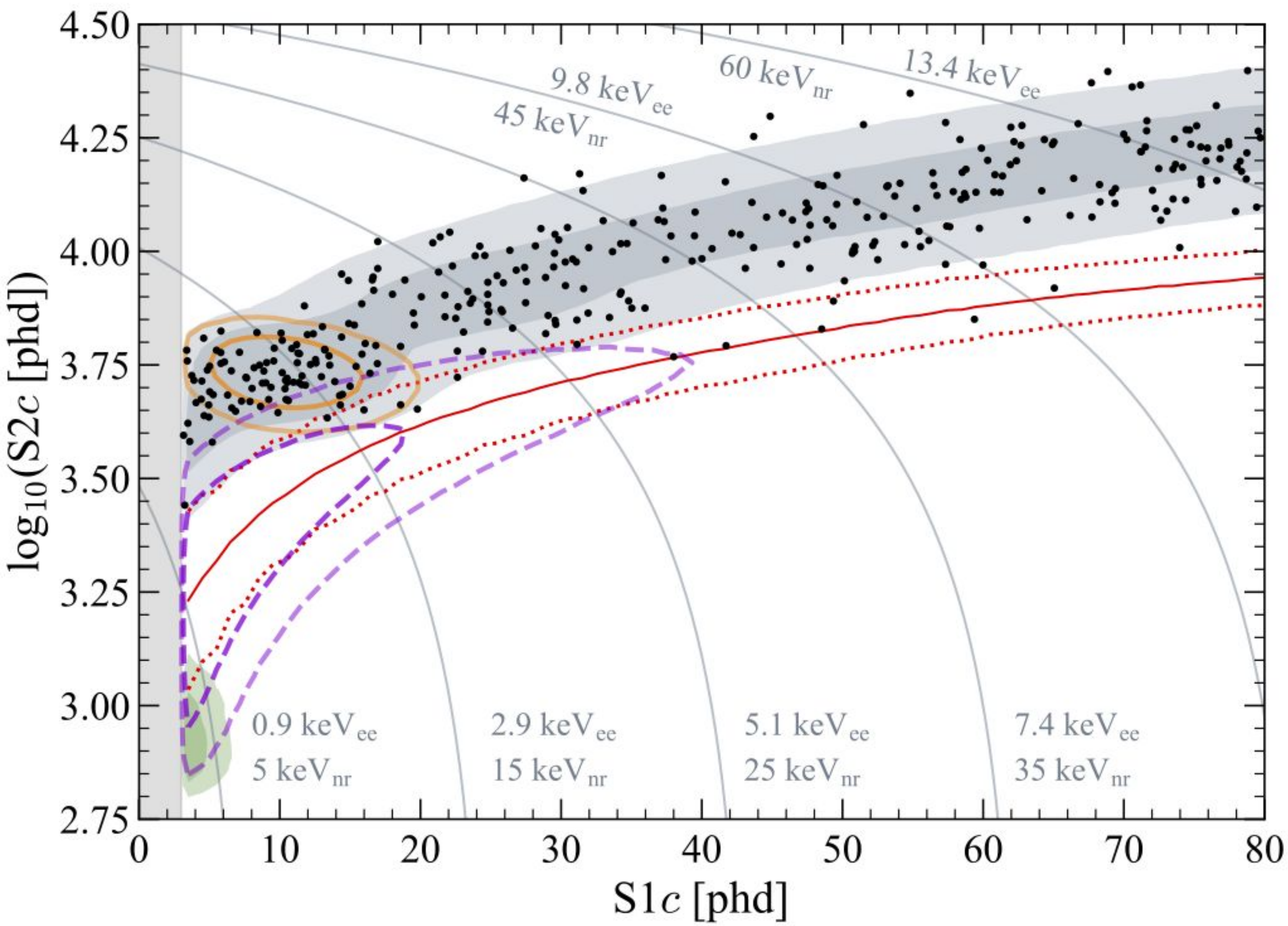
- Neutron backgrounds ("Det. NR") with OD tag are 7.75 times larger than without (because the tagging efficiency is 88.5%).
  - 5% of non-neutron backgrounds have accidental OD tag
- We use OD-tagged data to find a data-driven constraint on the rate of Det. NR
- Result: **Number of Det. NR in SR1 WIMP search is <0.2 events (2-sided constraint).**
  - Consistent with simulation-derived estimate of 0.06 events in 60 live days.



Above: each data point is a pie chart showing the post-fit likelihood contribution of each component in the fit.

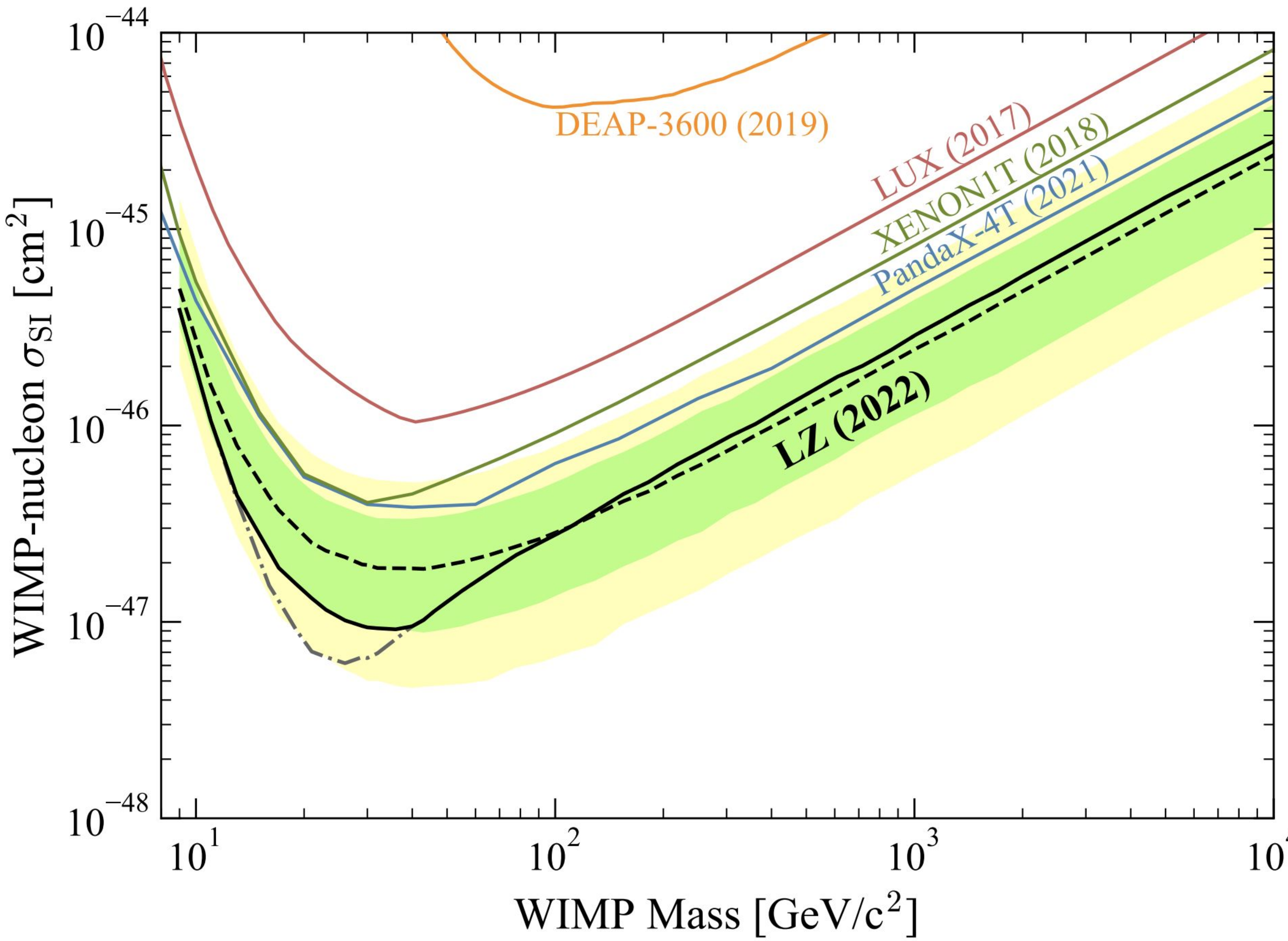
SR1 Data

- S1 threshold: 3 phd
- S2 threshold: 600 phd
- Gray bands are combined ER background sources
- Dashed-purple curves indicate 1- and 2-sigma contours of a 40 GeV WIMP
  - Red curves - flat NR spectrum
- Green band: ^{8}B CEνNS
- Orange curves: contours for Ar-37
- **335** events observed
- **276 ± 36** events expected, not including ^{37}Ar.
- We bound the ^{37}Ar with a uniform constraint between **0 and 291** events
- 60.3 ± 1.2 live days
- 5.5 ± 0.2 tonnes



SR1 WIMP-search

- Curves:
  - Solid black: observed limit
  - Dashed-black: median expected sensitivity
  - Gary dot-dash: limit before applying the power constraint**
- No evidence of WIMPs at any mass
- Minimum exclusion on WIMP-nucleon cross section (SI) of $9.2\text{x}10^{-48}$ cm^2 at 36 GeV



** the limit is constrained to cross section such that the power of the alternative hypothesis is 0.16 [G. Cowan, etc.]

https://doi.org/10.48550/arXiv.2207.03764

(paper recently accepted by PRL)

Summary & Outlooks

- LZ detectors are performing well and backgrounds are within expectations.
- With its first science run, LZ has achieved world-leading WIMP sensitivity, and been demonstrated to be the most sensitive dark matter detector ever built.
- LZ plans to take 1000 live days of data (x17 more exposure)
- Broad physics programs ahead of LZ
  - Effective field theory couplings for dark matter
  - Solar axion, ALPs, neutrino magnetic moment
  - Low-mass WIMP searches
  - Solar 8B CEvNS searches
  - Neutrinoless double beta decay
  - And more!

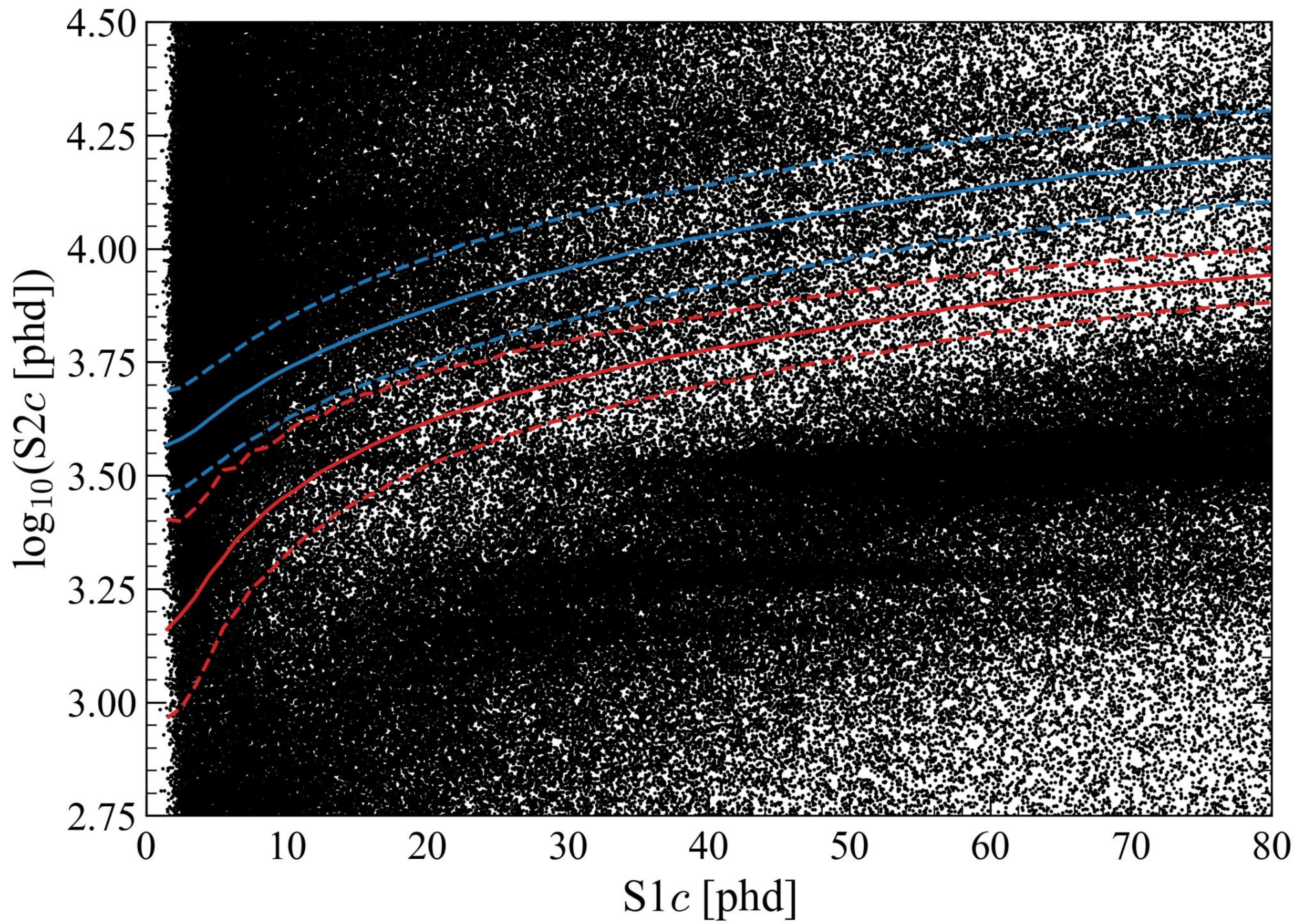
https://doi.org/10.48550/arXiv.2207.03764
(paper recently accepted by PRL)

Thanks for Your Attention

Backup Slides

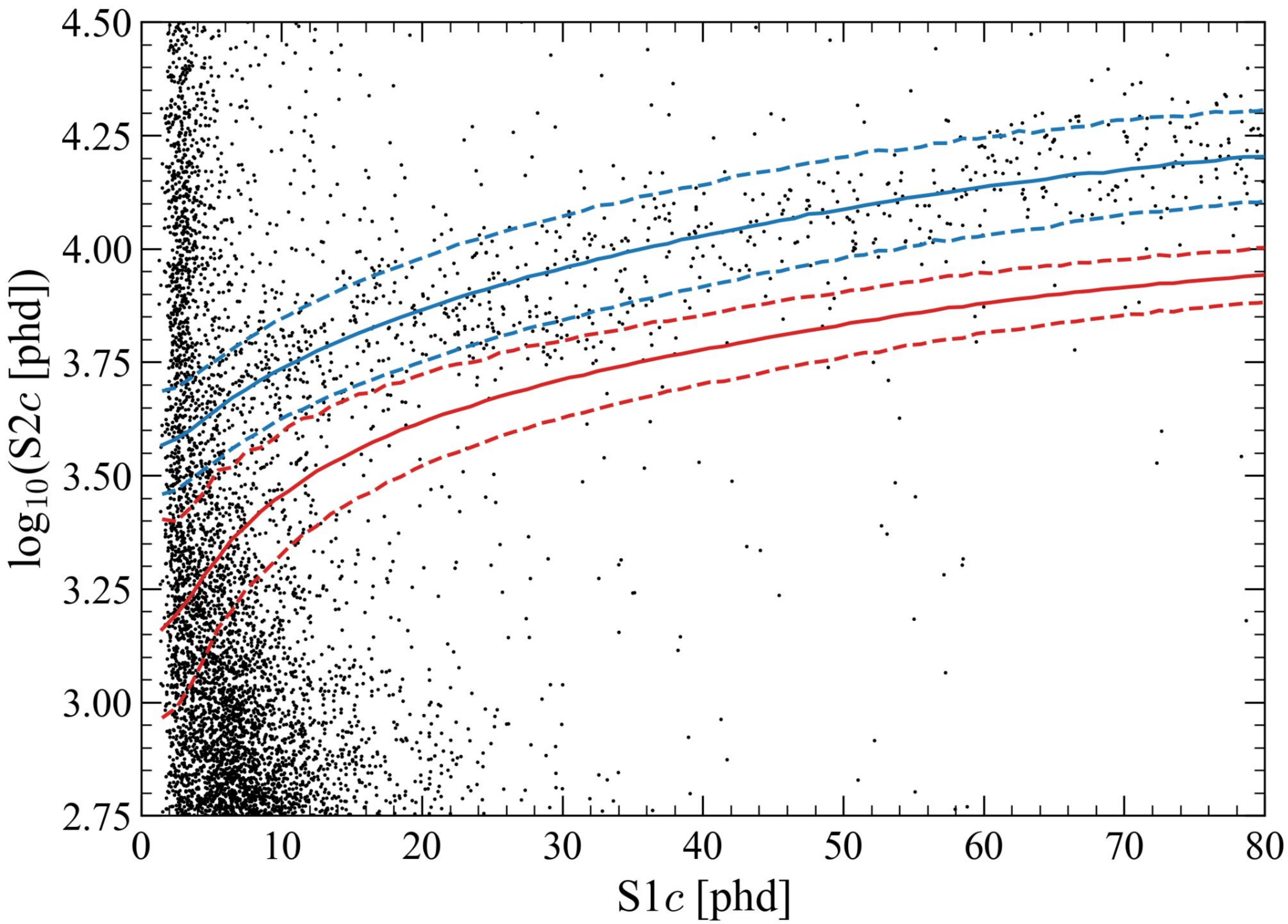
Data Quality

- All single-scatter data
- No cuts of any kind
- Are there WIMPs in there?



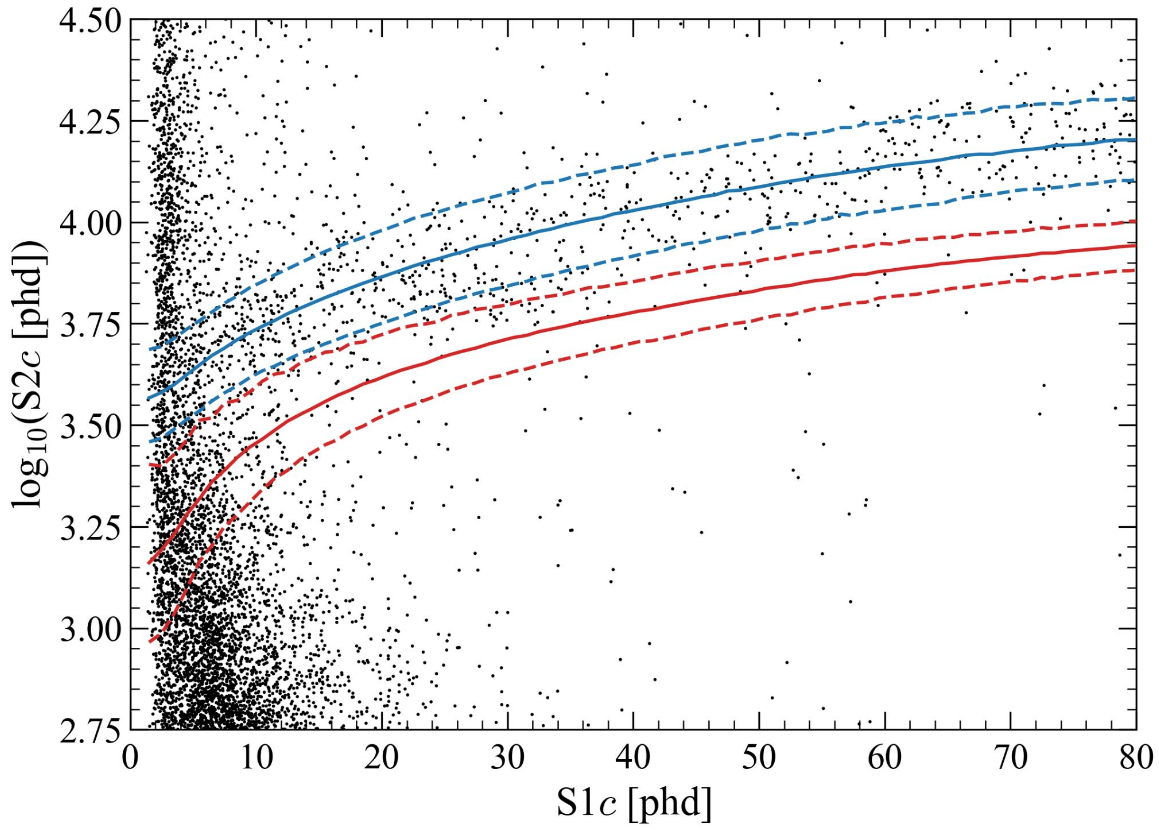
Data Quality

- All single-scatter data
- Only fiducial-volume cuts applied here.
- Fiducial mass: 5.5 ± 0.2 tonnes
- Still quite difficult to look for WIMPs.



Data-quality cuts

- Spurious signals contaminate the data
- Two categories of cuts target data quality
  a. Pulse-based cuts:
     - Cuts events based on S1 and S2 shape, hit patterns.
     - Impacts signal acceptance, measured with calibration data sets.
  b. Time-period cuts:
     - Cuts time periods based on detector behavior.
     - Impacts cumulative livetime.

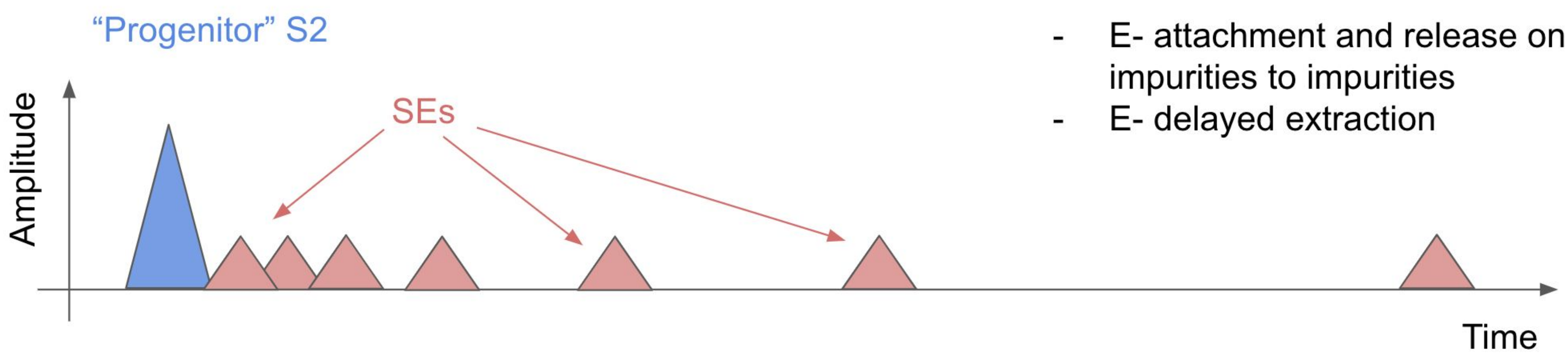


Data Quality - pulse trains

- Large S2 pulses induce "trains" of pulses that last much longer than the event window (100s of ms)
- Elevated rates can contribute to accidental-coincidence backgrounds
- [rare] muons produce a similar effect, but on a much longer timescale (10s of s)

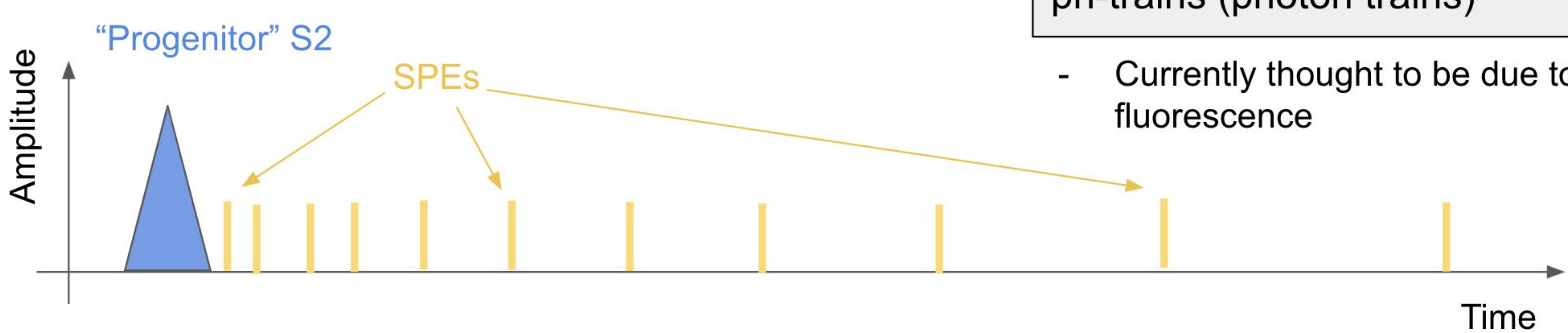
E-trains (electron trains)

- E- attachment and release on impurities to impurities
- E- delayed extraction



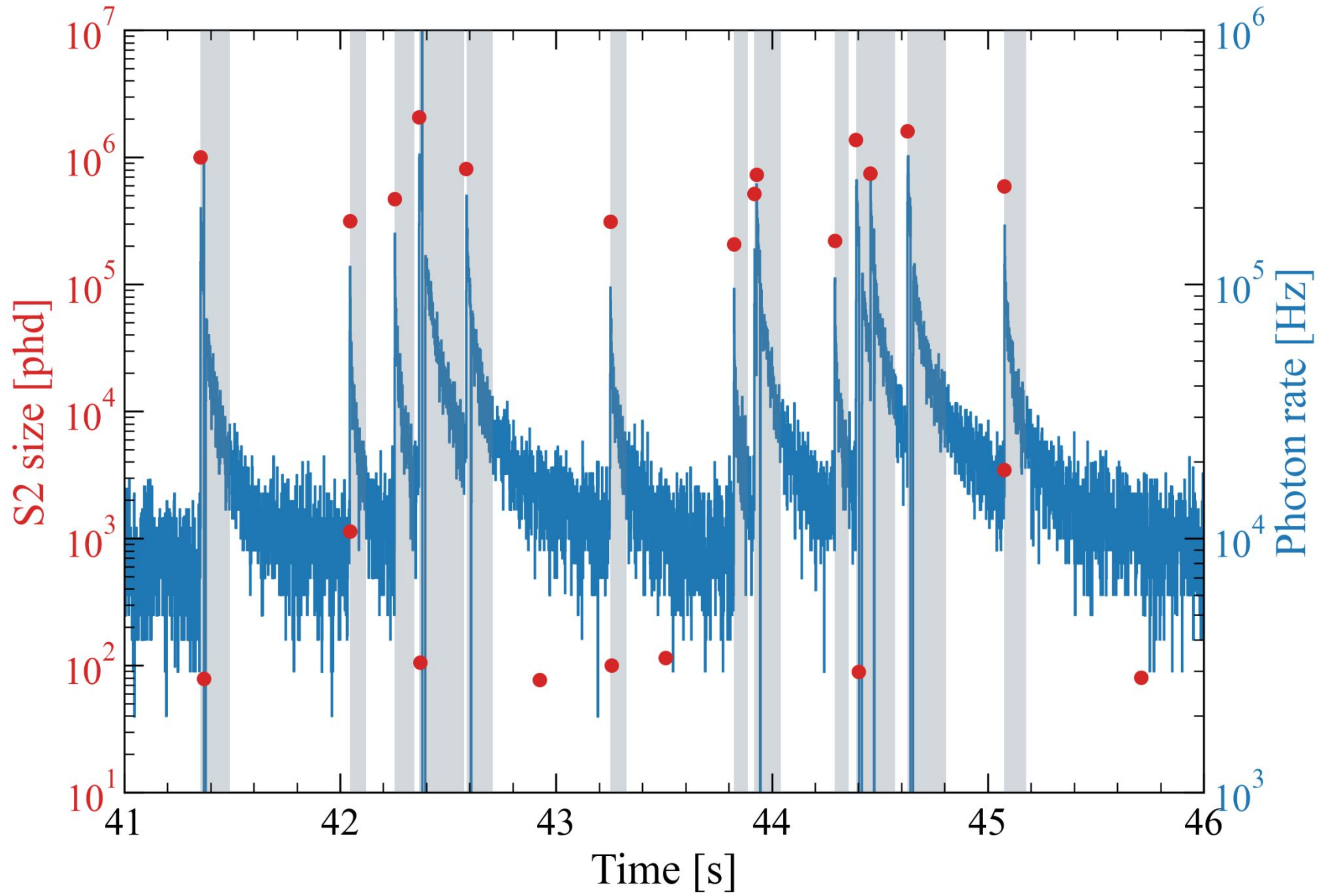
ph-trains (photon trains)

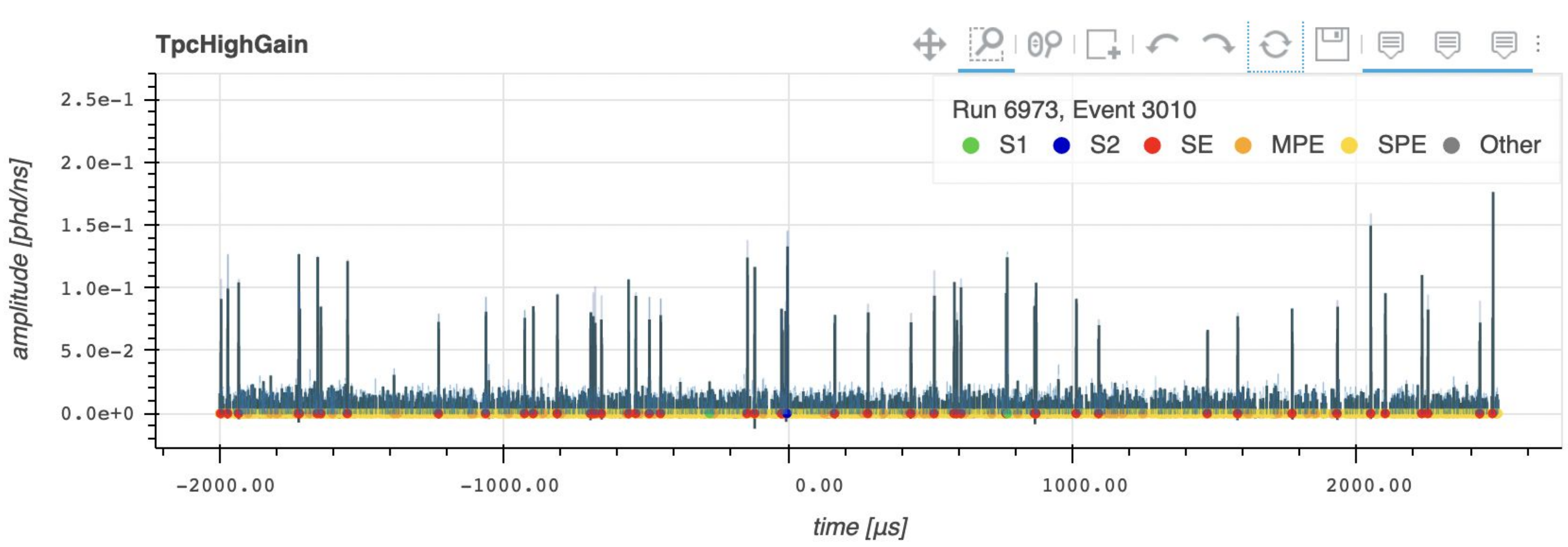
- Currently thought to be due to fluorescence



Data Quality - pulse trains

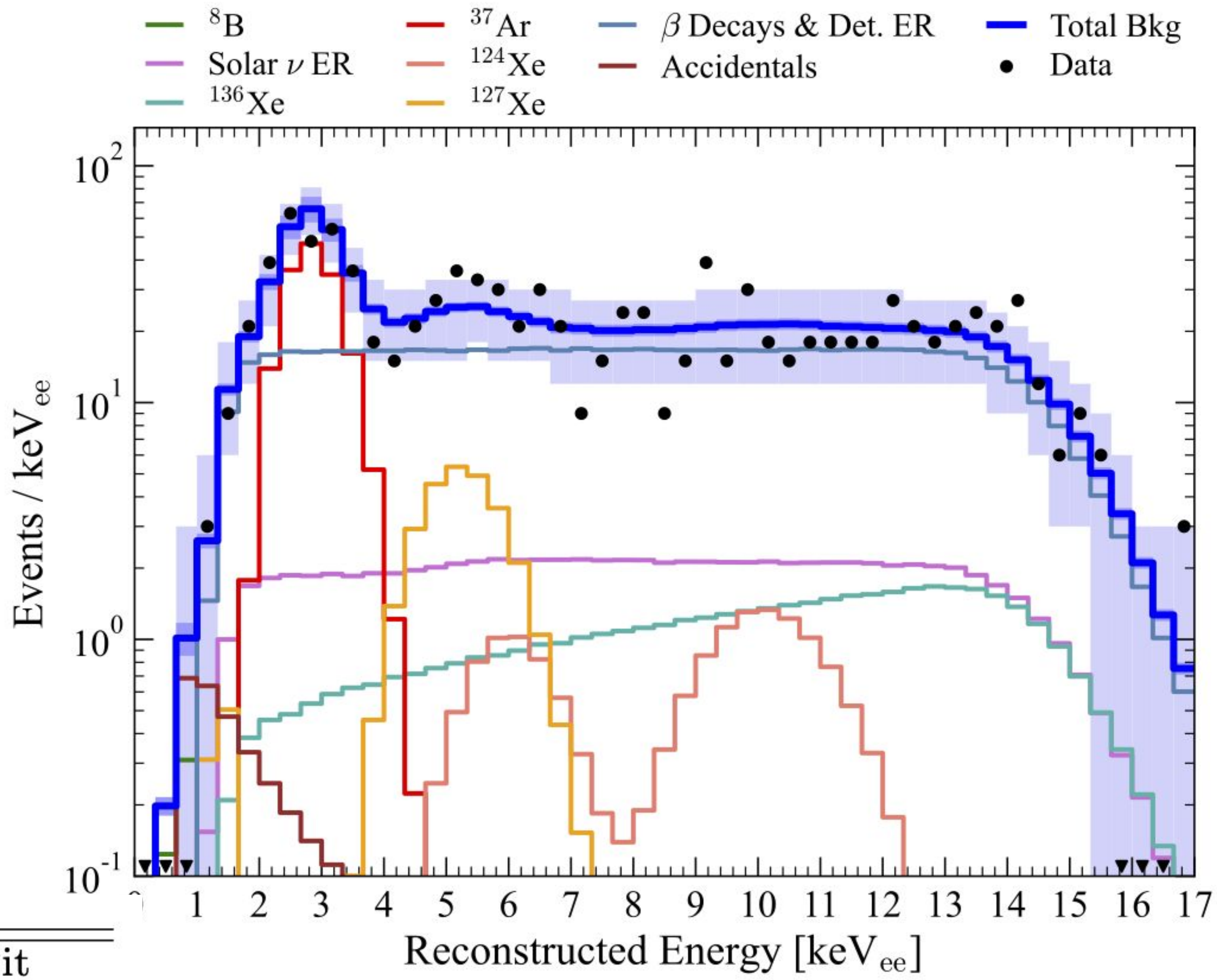
- The rate of single photons and single electrons in a train depends on the size of the progenitor S2 pulse.
- We veto live time (gray bands) following large S2s (red dots)





Final SR1 Data

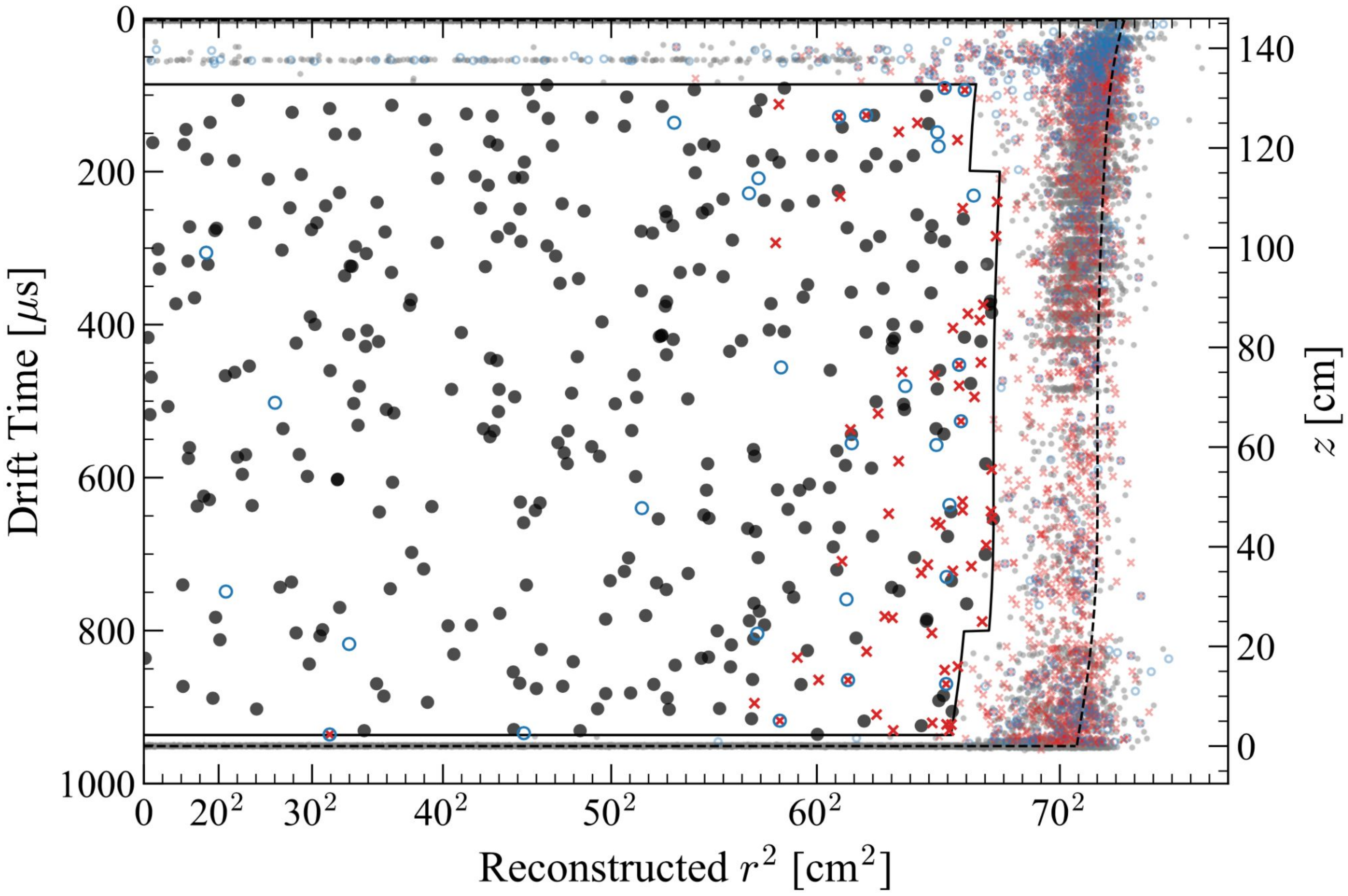
- Projecting onto electronic-equivalent reconstructed energy ("keVee")
- Data histogram shown as black points
- Best fit with *no* WIMP signal yields p-value of 0.96
- Expected range of statistical fluctuations for best-fit: light-blue boxes



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

SR1 Data

- 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.



Background-only expectation of data

- Gray regions: 1- and 2-sigma extent of expected backgrounds in the WIMP search (not including ^{8}B neutrinos, green)
- 276 ± 36 events expected, not including ^{37}Ar.
- We bound the ^{37}Ar 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	–