First Results from the LUX-ZEPLIN (LZ) Experiment

Rencontres du Vietnam Flavour Physics Conference 2022
Quy Nhon, Vietnam

Gregory Blockinger, SUNY at Albany
On behalf of the LZ collaboration
August 2022

LZ (LUX-ZEPLIN) Collaboration

35 institutions; 250 scientists, engineers, and technicians

@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


LZ Collaboration Meeting – September 8–11, 2021

Thanks to our sponsors and participating institutions!

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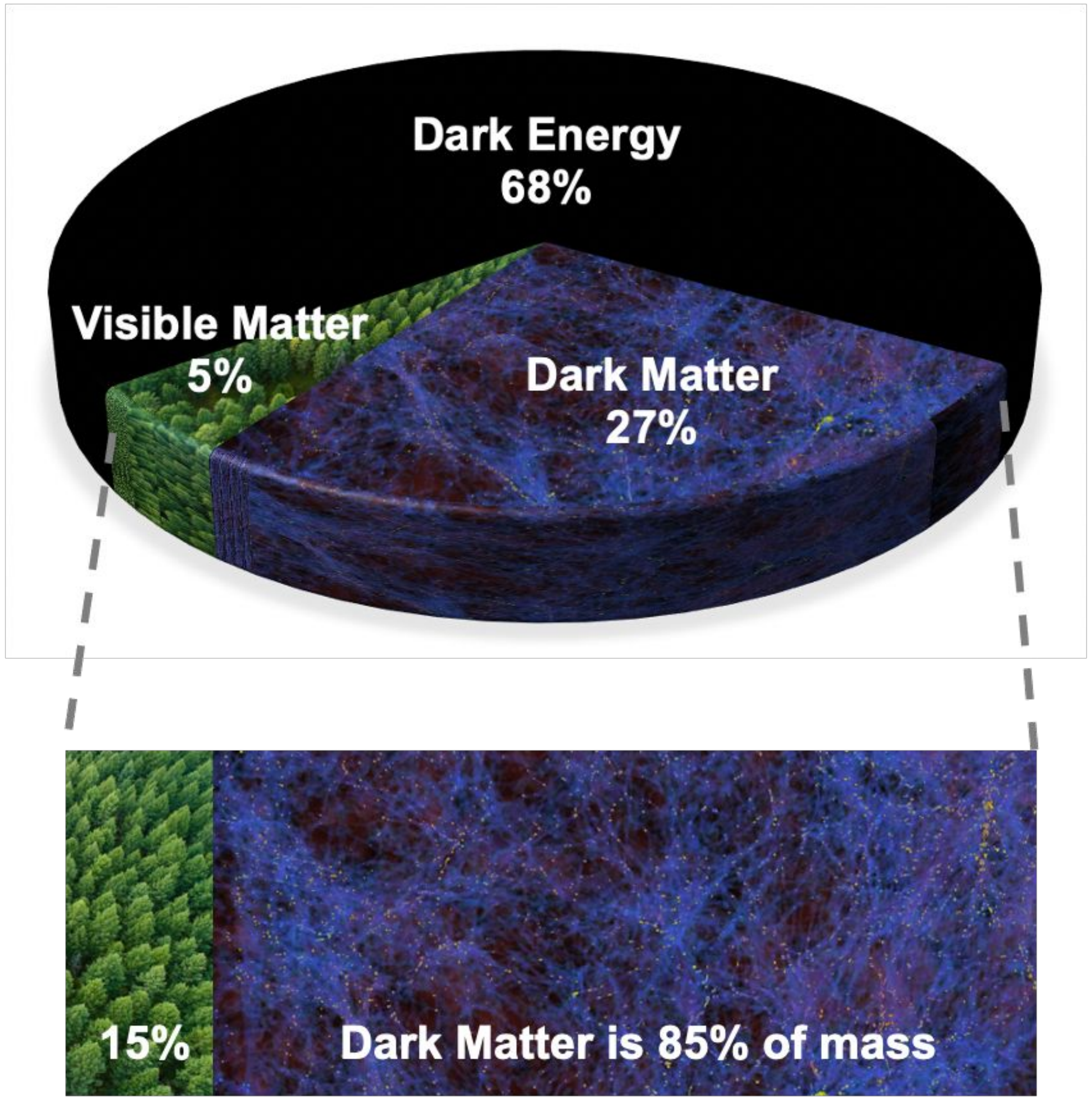
Sanford Underground Research Facility
South Dakota Science and Technology Authority

Institute for Basic Science

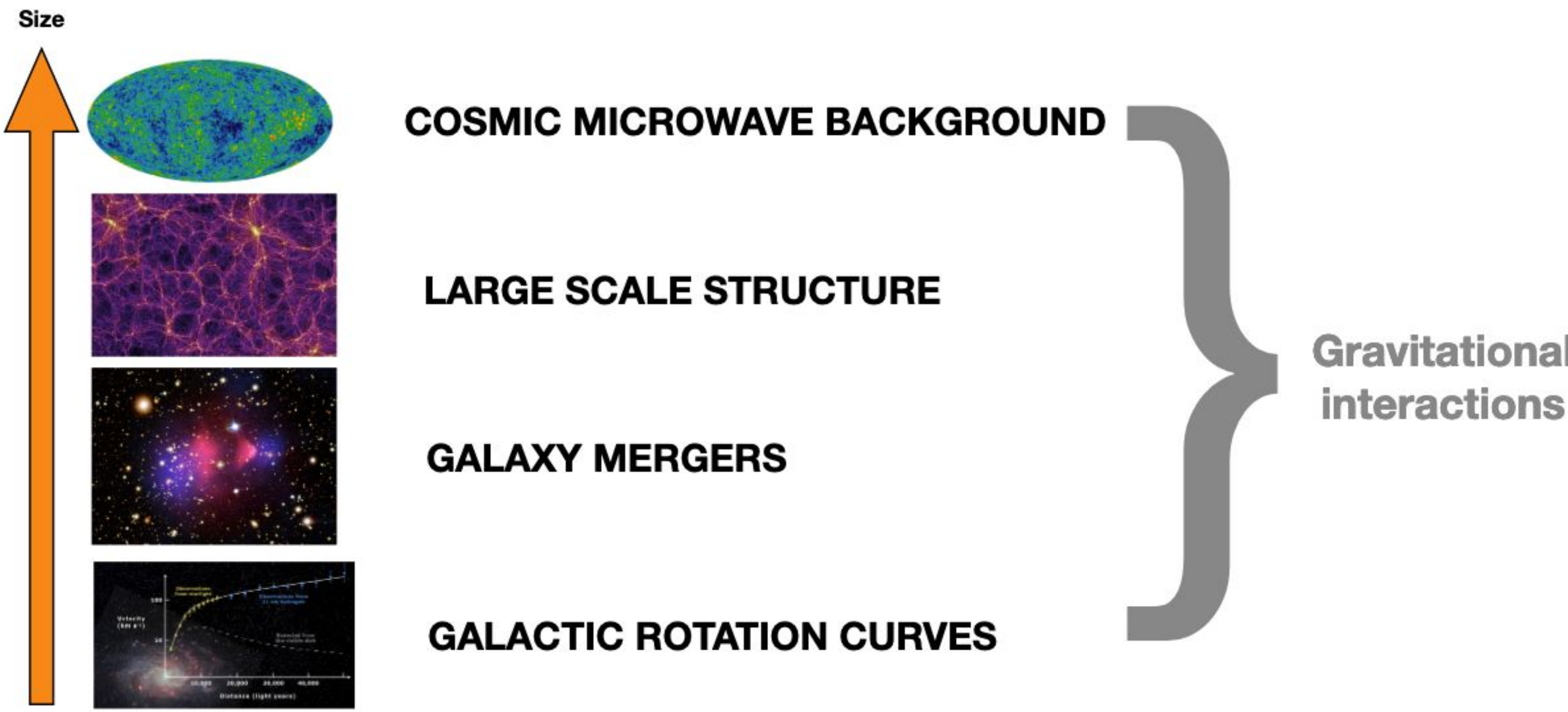
Dark Matter

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



- By that same token, we only understand about 5% of it

Dark Matter



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

Dark Matter

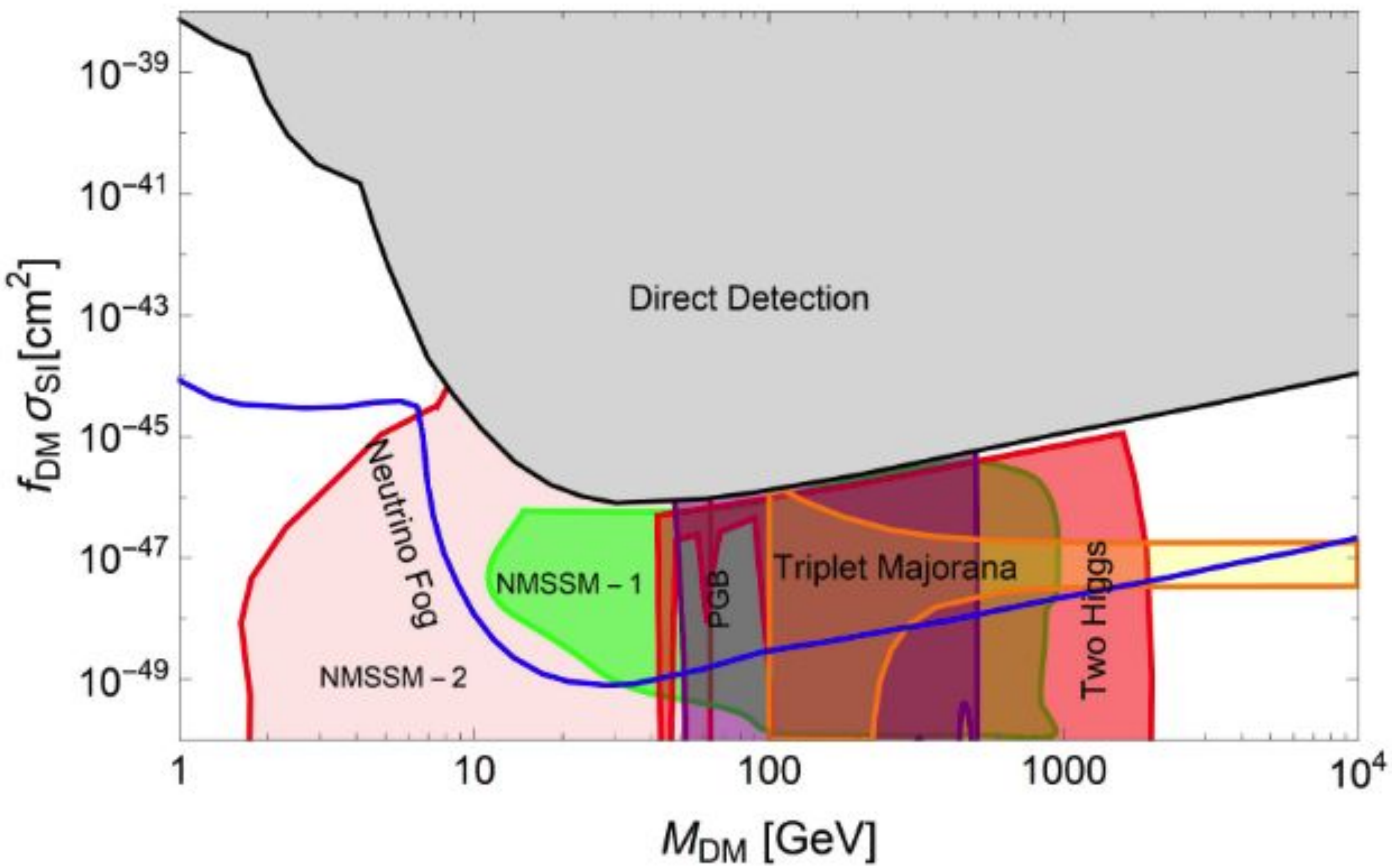
- “Dark” - does not interact with light or electromagnetism
- Interacts gravitationally
- Nearly collisionless
- Stable
- Slow - 0.001c
- Local density 0.3 GeV/cc

Beyond the Standard Model!

Dark Matter

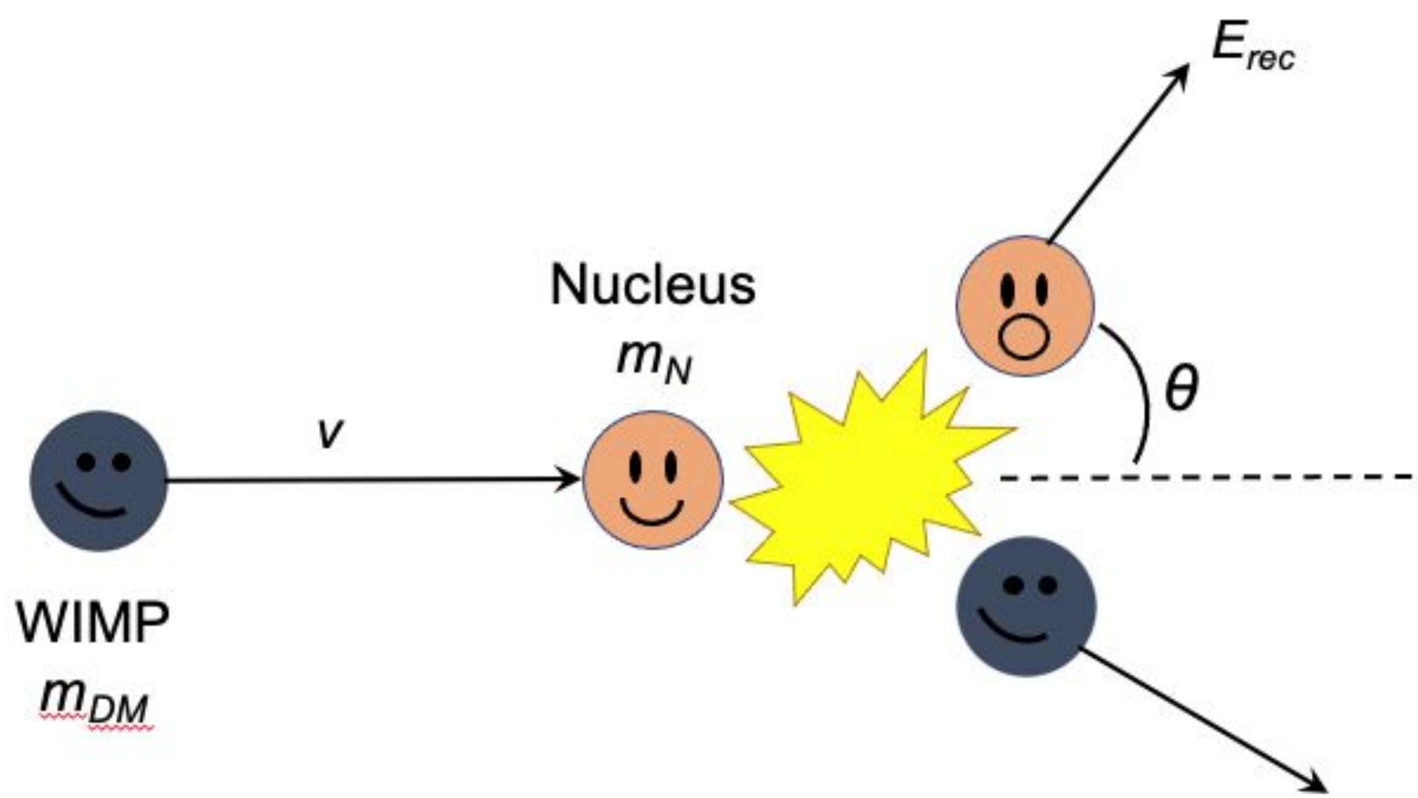
- One of the best motivated candidates is a "WIMPy" thermal relic
  - ✦ MeV - 100 TeV scale particle (cosmological bounds)
  - ✦ Weak scale interactions leads to correct density today
- Highly motivated (with important constraints from DM results)

- e.g. SUSY models, twin Higgs, Triplet Majorana, Hidden Sector
- Recent summary in Snowmass CF1-WP1 - 2203.08084
  - ✦ Many other references therein
- Now probing some of the most interesting models from 20 years ago



Detecting Dark Matter

Fill a detector with your favorite material and wait for WIMPs to scatter off it



Courtesy Alissa Monte

Non-relativistic elastic scattering

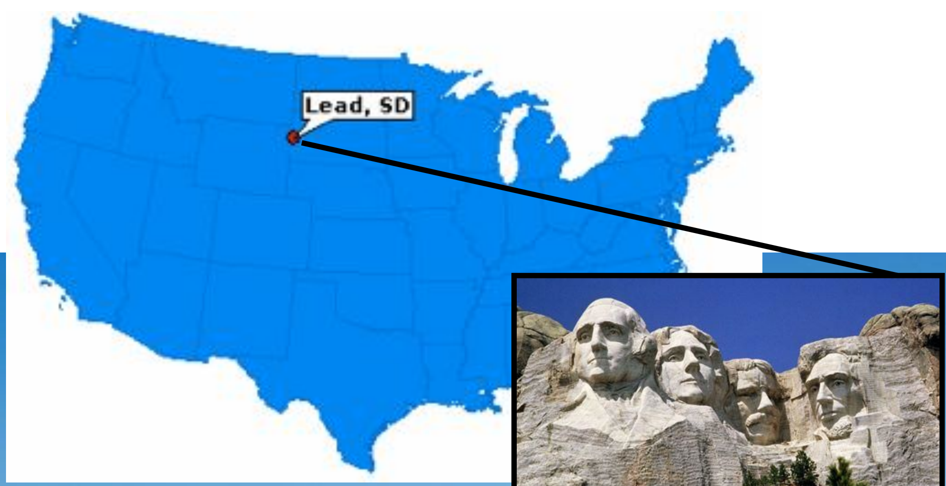
$$\mu = \frac{m_{DM} m_N}{m_{DM} + m_N}$$

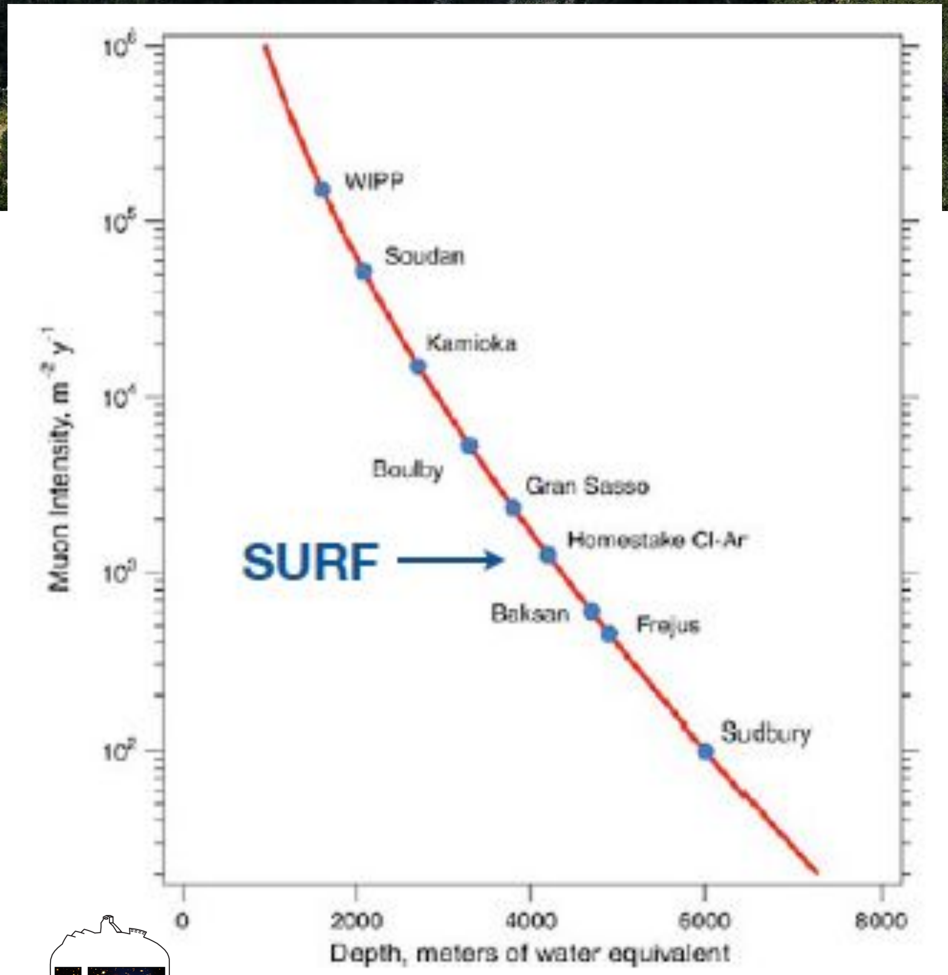
$$E_{rec} = \frac{\mu^2 v^2}{m_N}(1 - cos\theta)$$

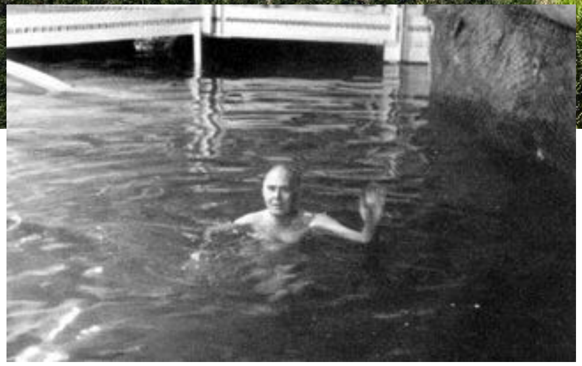
m_{DM} = 100 GeV/c^2
m_N = 131 GeV/c^2
v = 220 km/s
E_{rec} = 3 keV

…but it needs to be someplace very "quiet"

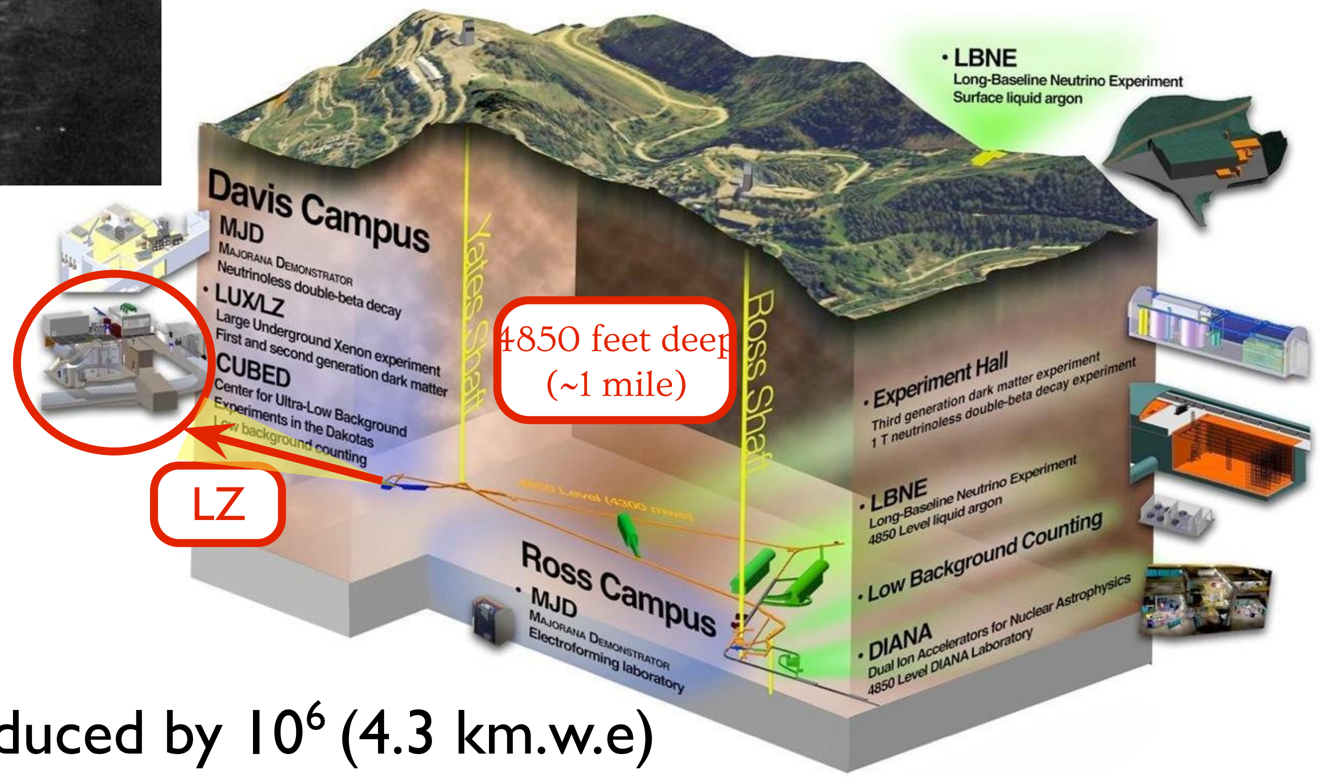
Sanford Underground Research Facility (SURF) in Lead, SD







Ray Davis, nobel prize winner

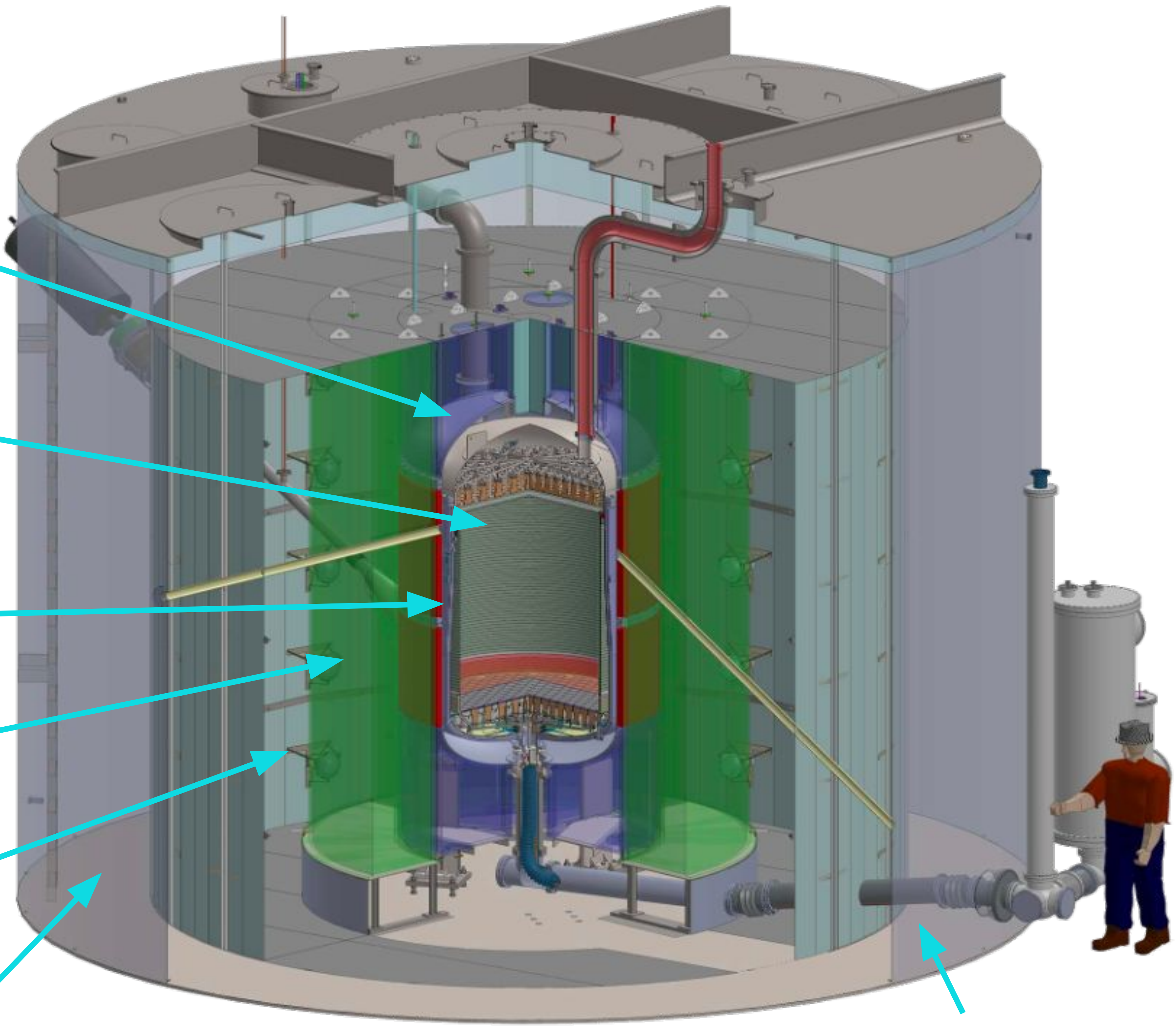


Muon flux reduced by 10^6 (4.3 km.w.e)

G. Blockinger

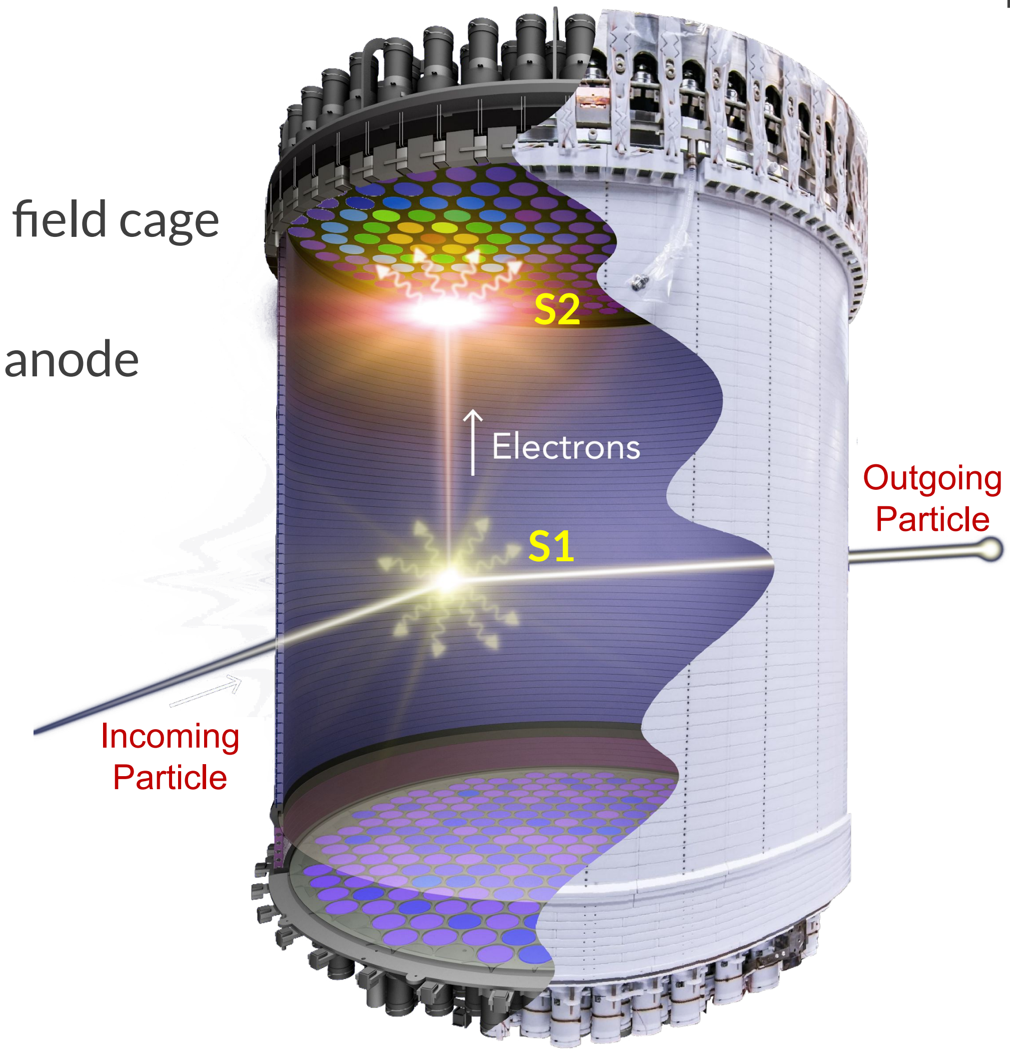
LZ Detector Overview

LZ detector design:
[NIM A, 163047 (2019)](#)

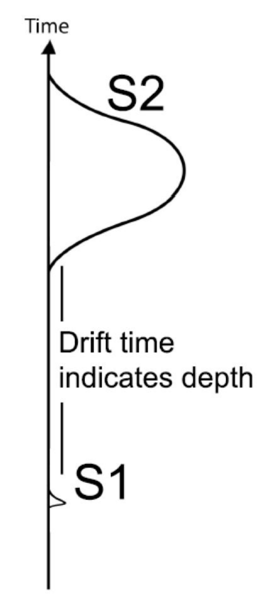


Dual-Phase Xenon TPC

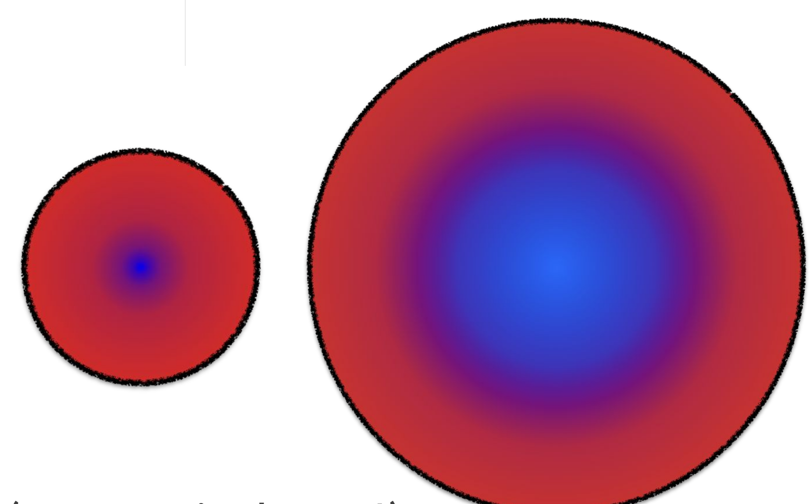
- 1.5 m ∅ x 1.5 m height
- 7 tonne active LXe (5.5 tonne fiducial)
- PTFE everywhere for efficient light collection
- 494x 3” PMTs in two arrays
- 4 wire mesh electrodes + Ti field cage for uniform electric fields
    - Bottom, cathode, gate, anode



- Detection principle:
    - Interactions produce scintillation light (S1) and ionization electrons
    - Electrons drift to gas phase and produce electroluminescence (S2)



Max drift time ~ 950μs

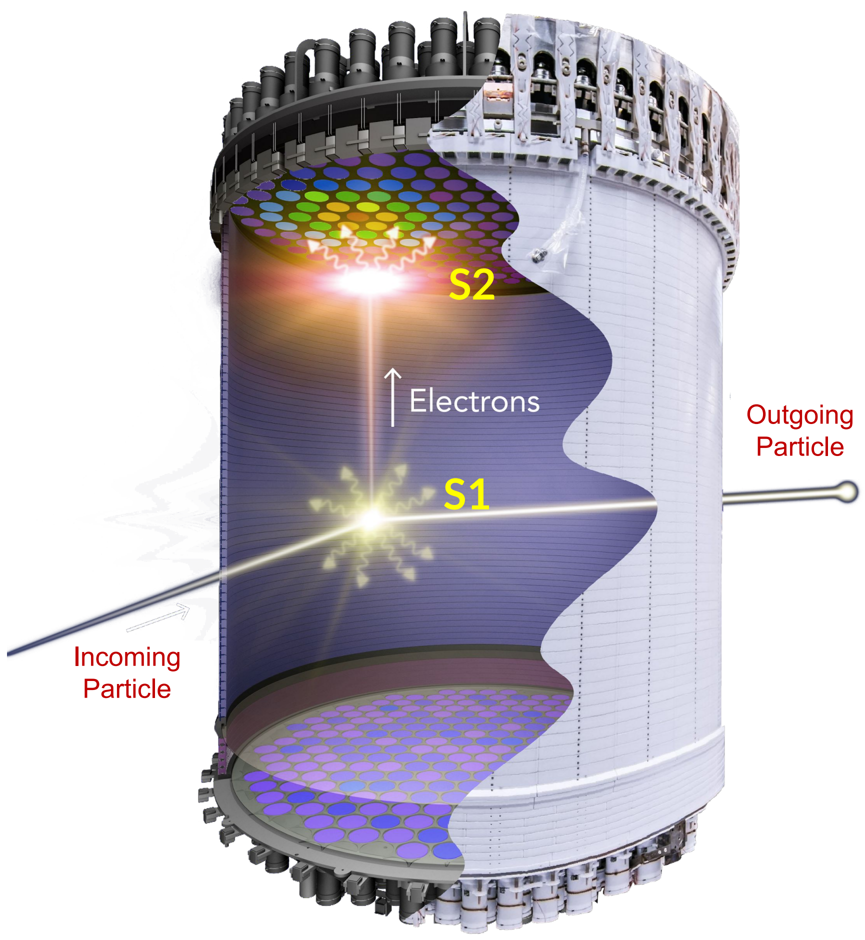


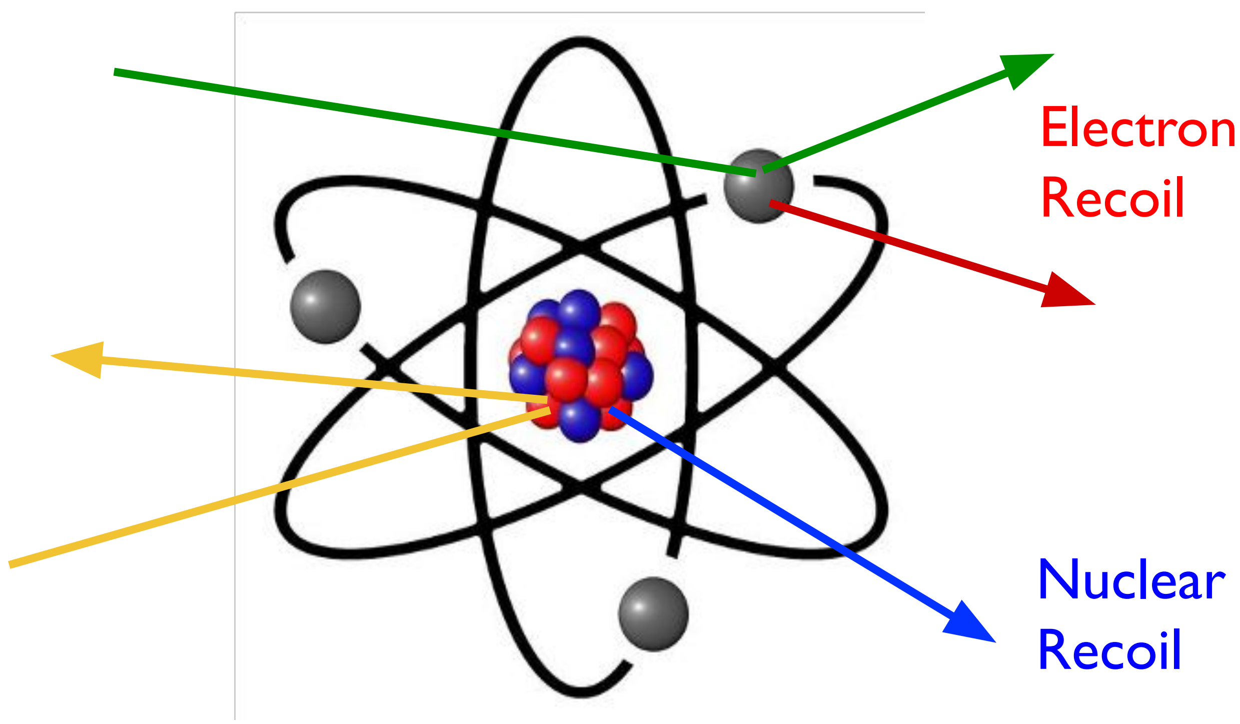
Self-shielding (+xenon is dense!)

Dual-Phase Xenon TPC

- Excellent 3D position reconstruction
  - Single vs. multiple scatters
- Energy reconstruction

- Particle ID from S2/S1 ratio
  - Electrons and gammas interact with atomic electrons, producing electron recoils (ER)
  - WIMPs (and neutrons) interact with Xe nuclei, producing nuclear recoils (NR)



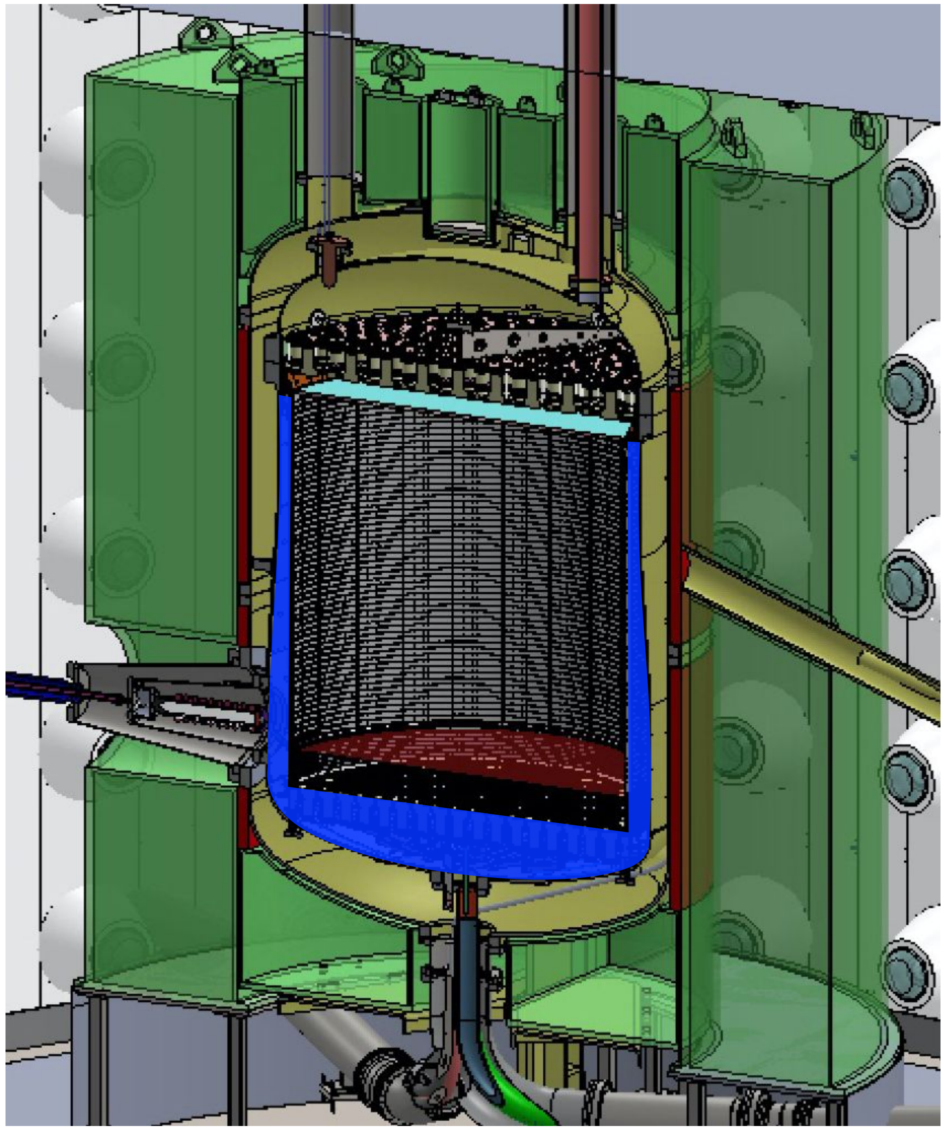


LXe Skin and Outer Detector - Vetoes

- WIMPs will only scatter once
  - Backgrounds can 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

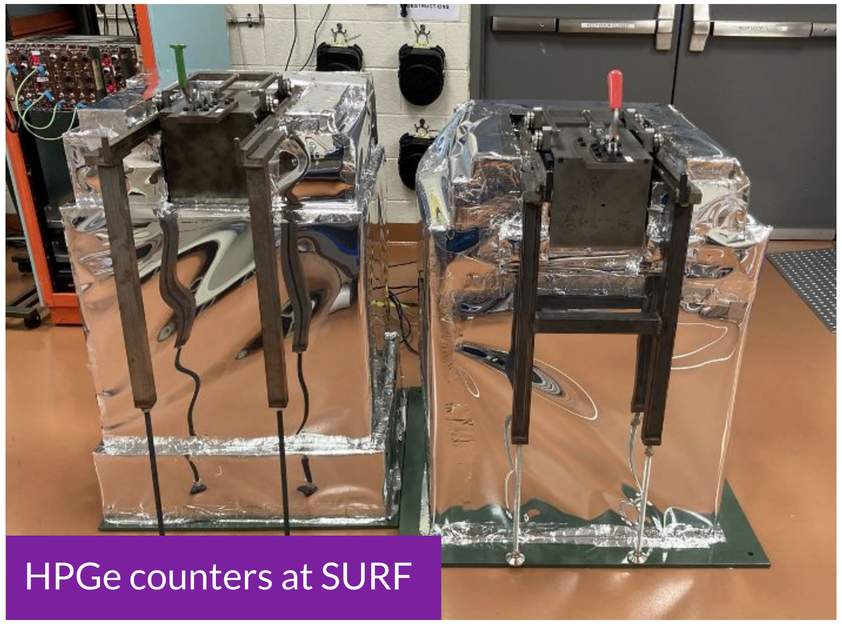
→ **Veto enables discovery potential**

Background Sources and Mitigation

Many sources of BG

Many methods for BG mitigation

- Detector materials
  - Nothing went into the detector without screening
  - Radio-assay campaign with 13 HPGe detectors, ICPMS, neutron activation analysis, and radon emanation
    - For example, cryostat made of most radiopure titanium in the world (Astropart. Phys. 96, 1 2017)
- 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
- Xenon contaminants
  - Charcoal chromatography at SLAC
  - Continuous purification underground



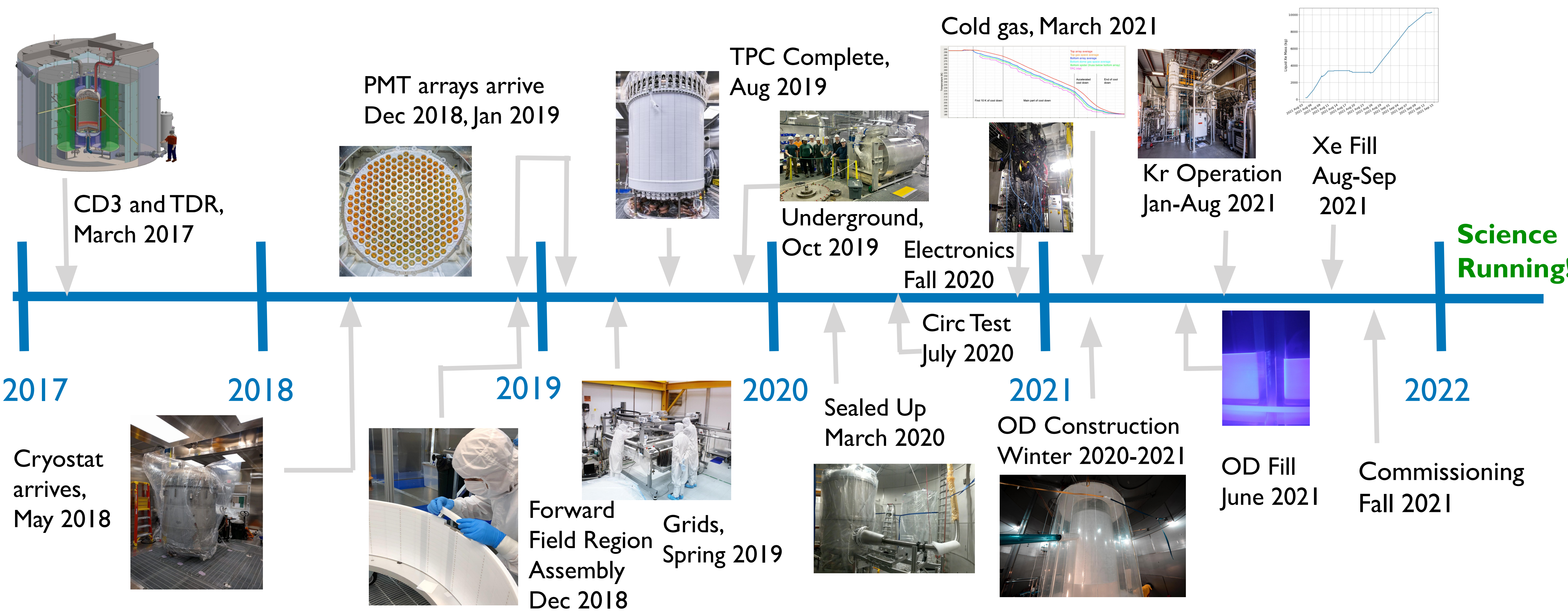
HPGe counters at SURF

Kr-removal at SLAC

Eur. Phys. J. C, 80: 1044 (2020)

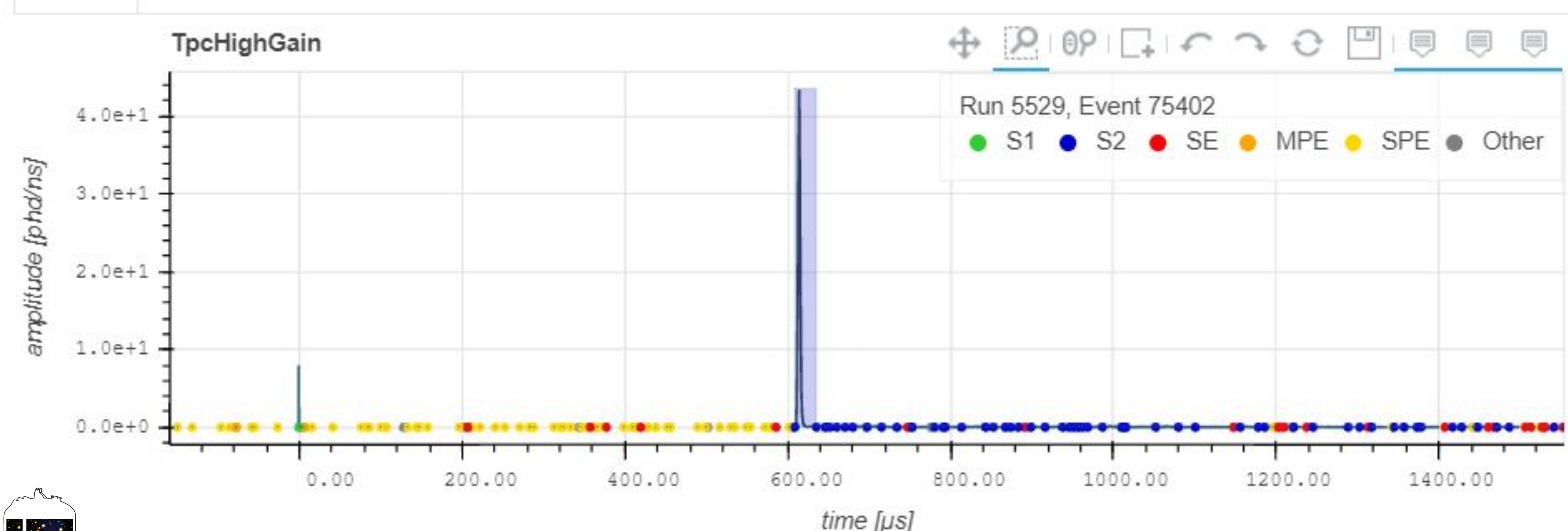
LZ Timeline

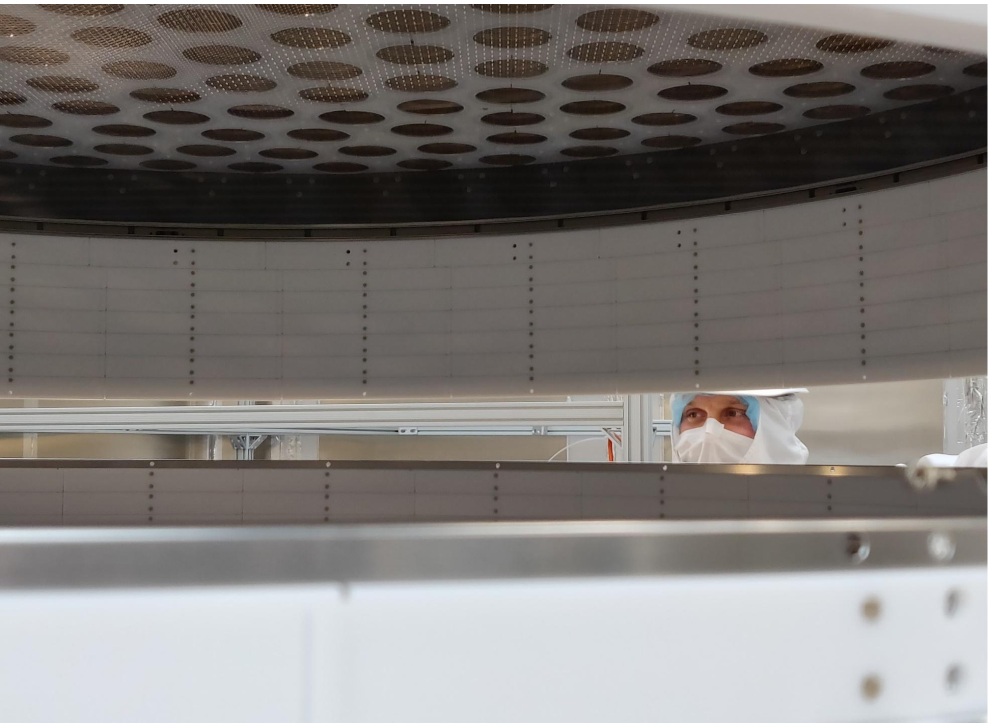
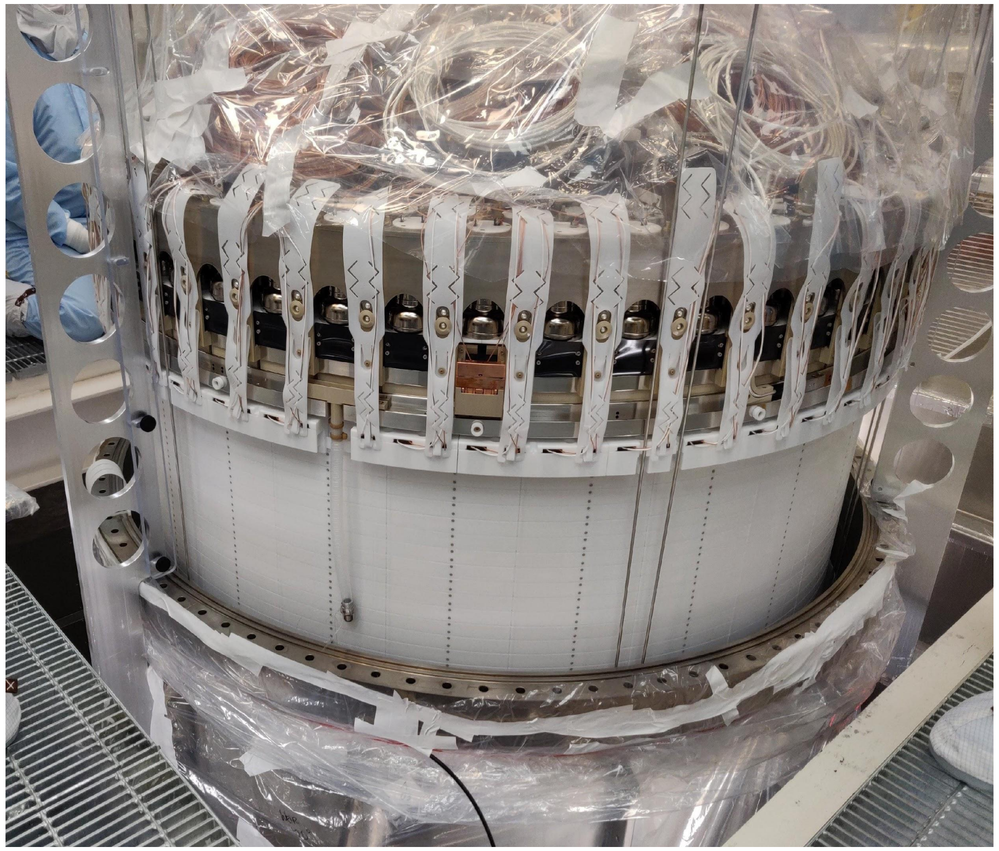
- Detector assembly began in earnest in Fall-2018 at surface lab at SURF
- TPC brought underground in October 2019
- Cryostat closed in March 2020, ahead of COVID-19 shutdowns
- OD complete and filled by July 2021
- Xenon offsite purification complete Aug. 2021 - TPC Filled in Sept. 2021!

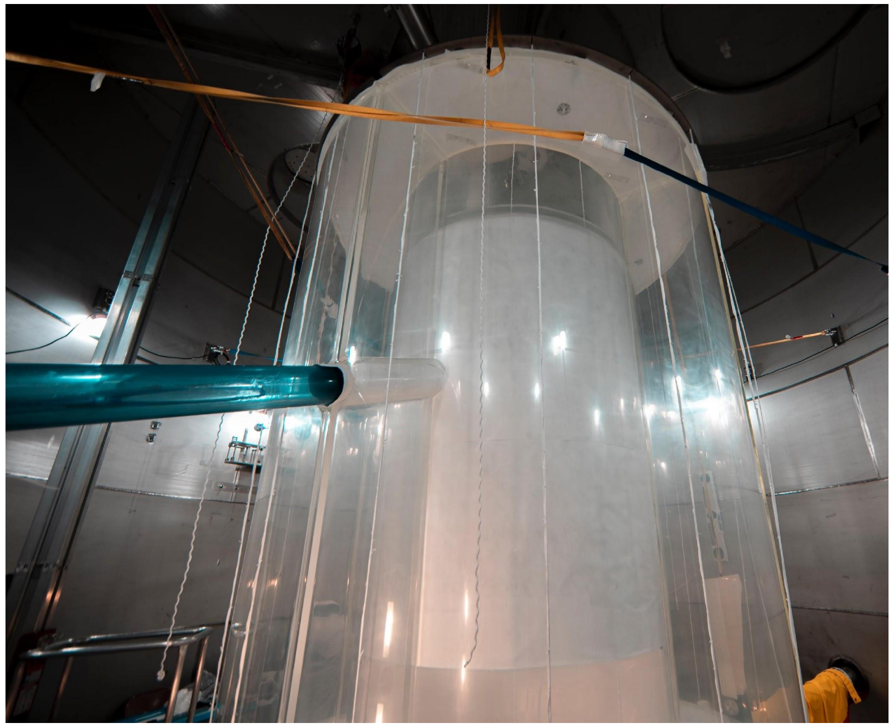
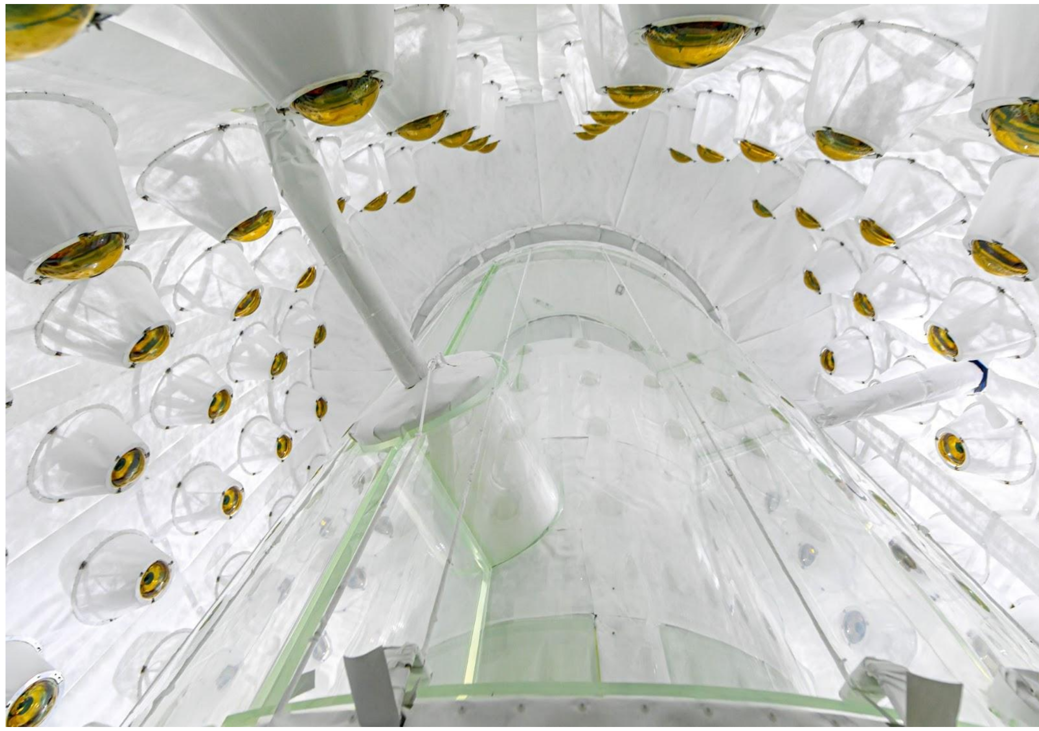


LZ Commissioning

- TPC detector filled and leveled from August through September
- Grids biassed: extraction & drift fields established in October and December
  - First light (and charge) on October 6!
  - Established drift field ~190 V/cm (32 kV on cathode)
  - Established extraction field ~7.3 kV/cm gas (8 kV between gate and anode)



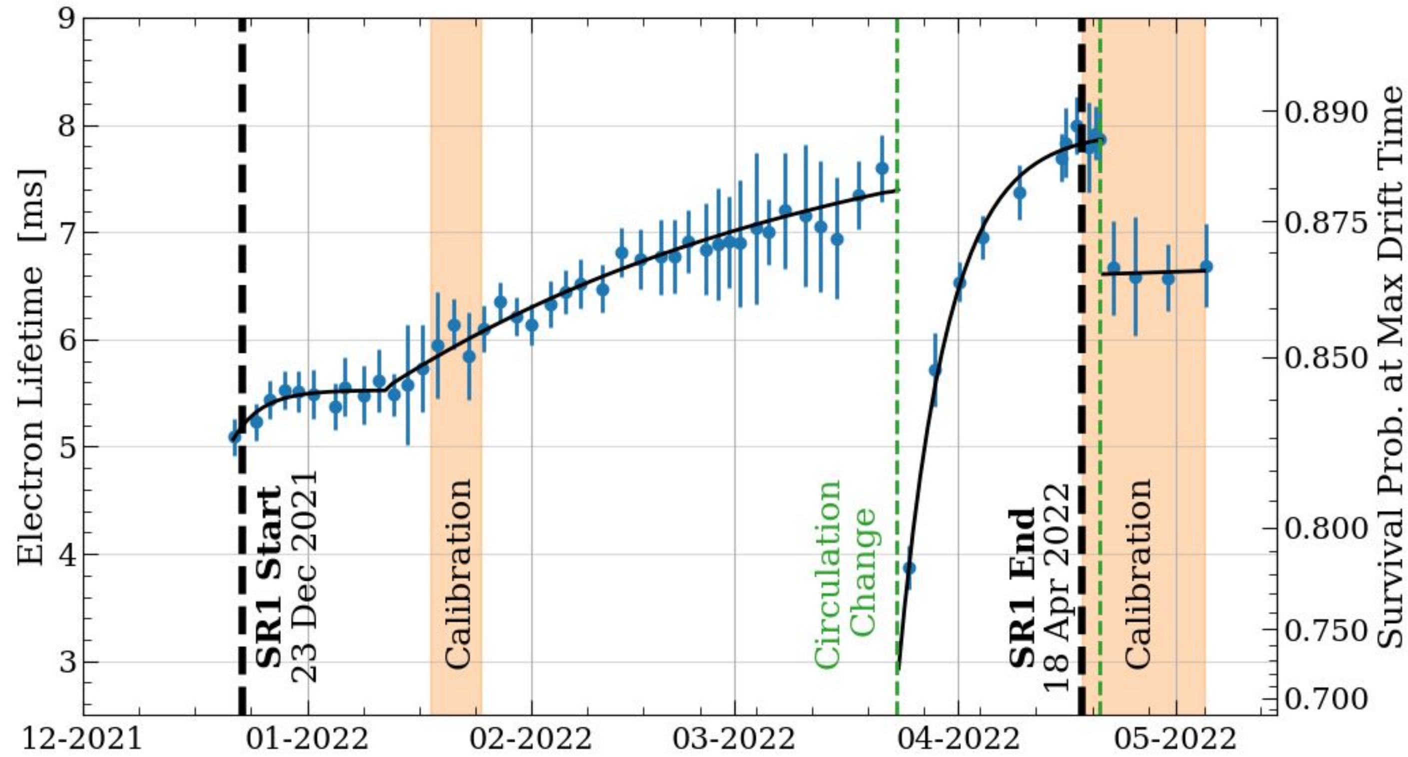



LZ's Science Run 1 (SR1)

Goal: (1) Demonstrate physics capability of the LZ detector, with (2) expectation of competitive sensitivity

- Data taken 23 Dec '21 to 12 May '22, with breaks for calibrations in middle and at end
- WIMP search live time of **60 days**
- Electron drift lifetime of **5-8 ms** during search
- Stable detector conditions:
  - PMTs: **>97%** operational throughout run
  - Liquid temperature: 174.1 K (0.02%)
  - Gas pressure: 1.791 bar(a) (0.2%)
  - Gas circulation: **3.3t/day**
  - Drift field: **193 V/cm** (32 kV cathode, uniform to 4% in fiducial volume)
  - Extraction field: **7.3 kV/cm** in gas (8 kV gate-anode ΔV)



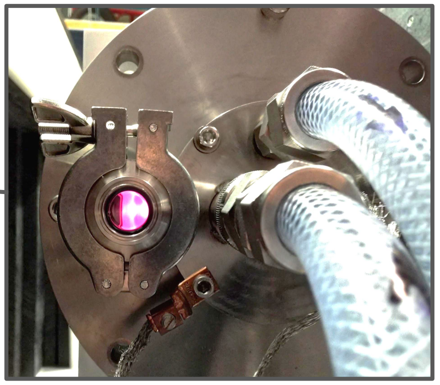
LZ Requirement ~1ms

- Engineering run → data not blinded or salted. Future science runs will be salted.

Calibrations

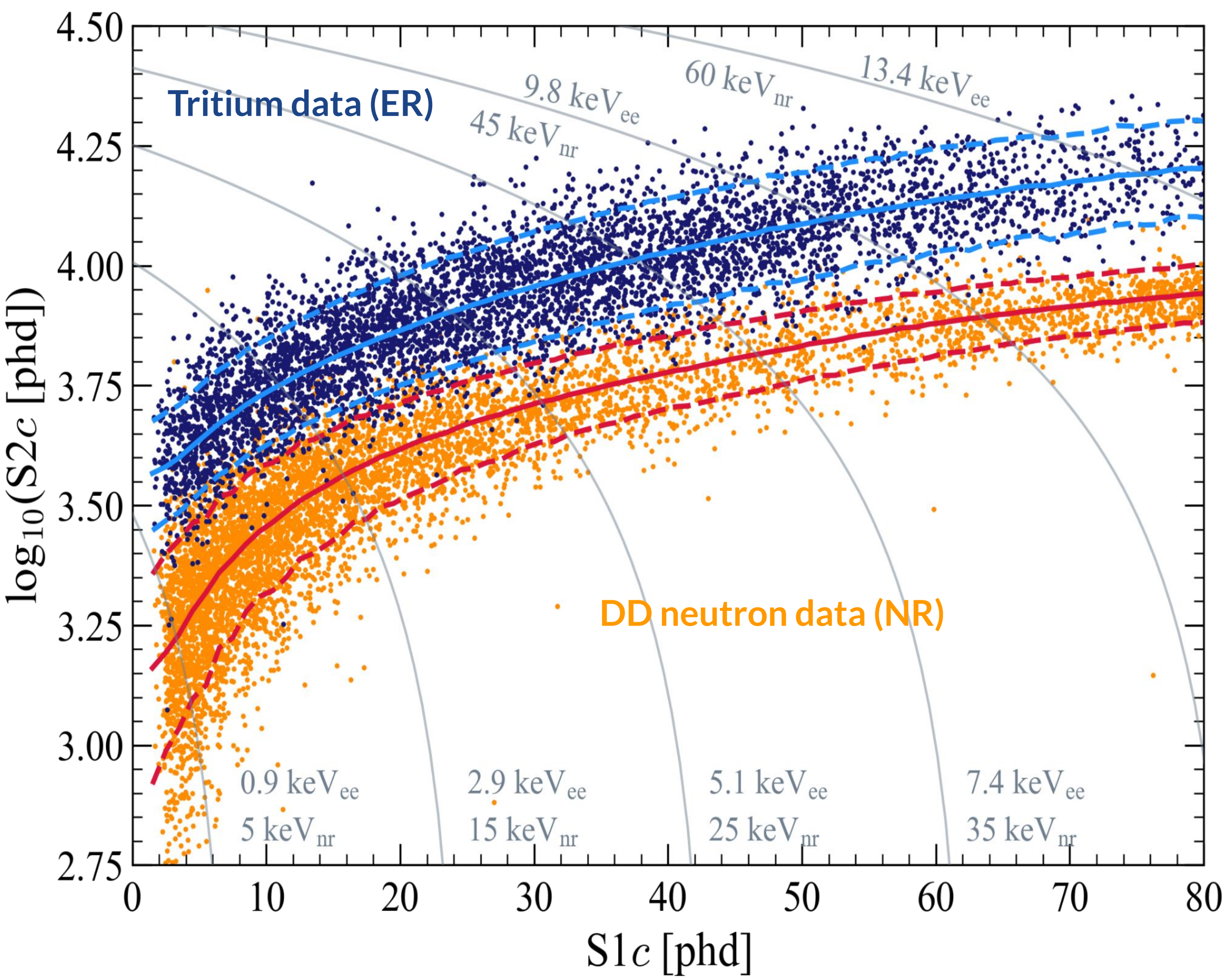
We utilize a variety of calibration sources in LZ. Our main ones include:

- DD neutron generator: 2.45 MeV neutrons, collimated
  - Used for: NR band, trigger efficiency, S1 cut acceptance
- Am-Li: continuum neutrons, isotropic
  - Used for: Outer Detector (OD), neutron-tagging efficiency, S2 cut acceptance
- CH_3T: continuum betas up to 18.6 keV
  - Used for: ER band, fiducial volume, S1 cut acceptance
- ^{83m}Kr: monoenergetic ERs, 32.1 and 9.4 keV
  - Used for: energy scale, xy spatial corrections
- ^{131m}Xe: monoenergetic ER, 164 keV
  - Used for: energy scale, electron lifetime
- Additional background sources (e.g. alphas and cosmics)
  - Used for: energy scale, electron lifetime



Calibrations

- Normalize spatial variations in observed S1 and S2 (light collection efficiency, e-lifetime, etc)
- Tune XY position reconstruction algorithm
- Light gain **g1: 0.114** ± 0.002 phd/photon
- Charge gain **g2: 47.1** ± 1.1 phd/electron
- Single electron size: **58.5 phd**
- NEST(*)-based ER model tuned to tritium data, propagated to NR model, validated with DD data
  - NEST (Noble Element Simulation Technique) is an comprehensive, accurate, and precise simulation of the excitation, ionization, and corresponding scintillation and electroluminescence processes in liquid noble elements
- **99.9%** rejection of ERs below the NR median

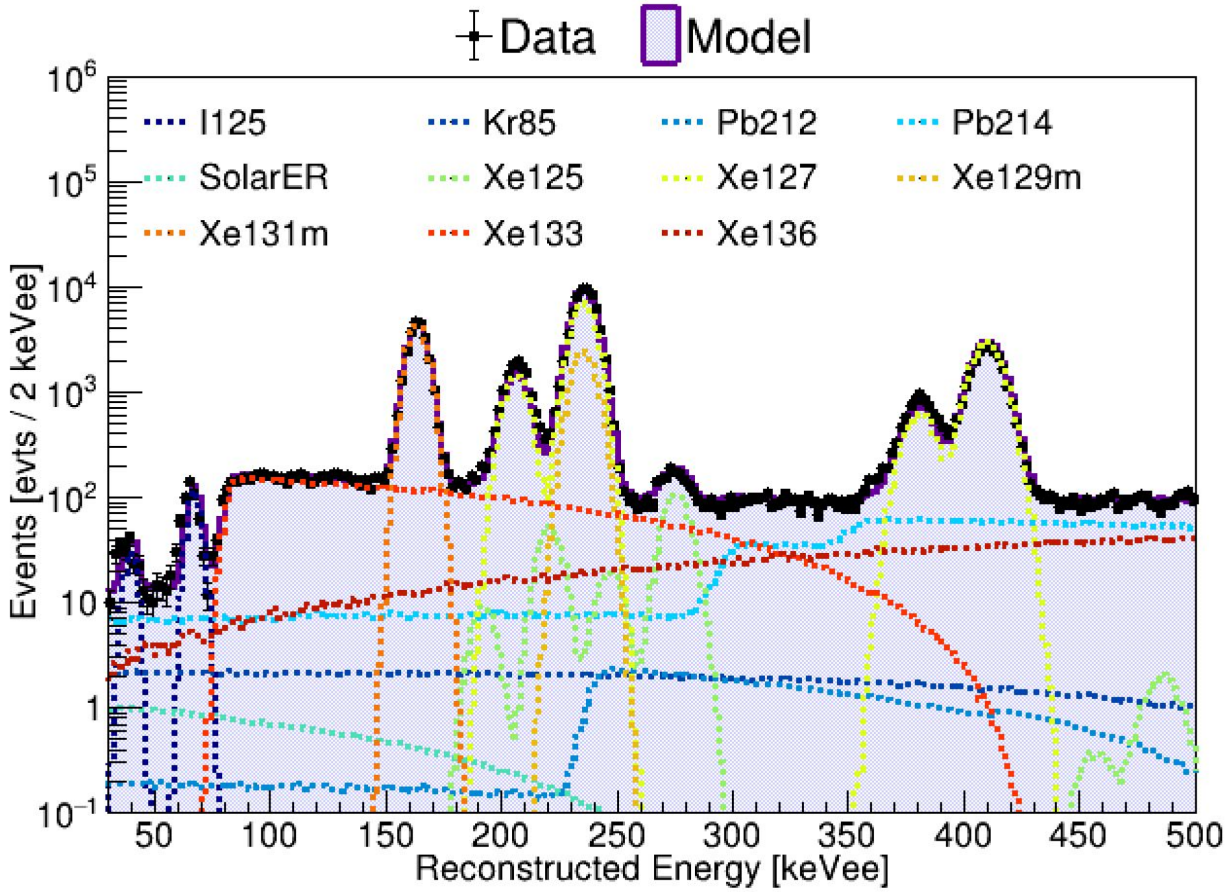


(*) https://nest.physics.ucdavis.edu/
https://github.com/NESTCollaboration/nest

Backgrounds

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

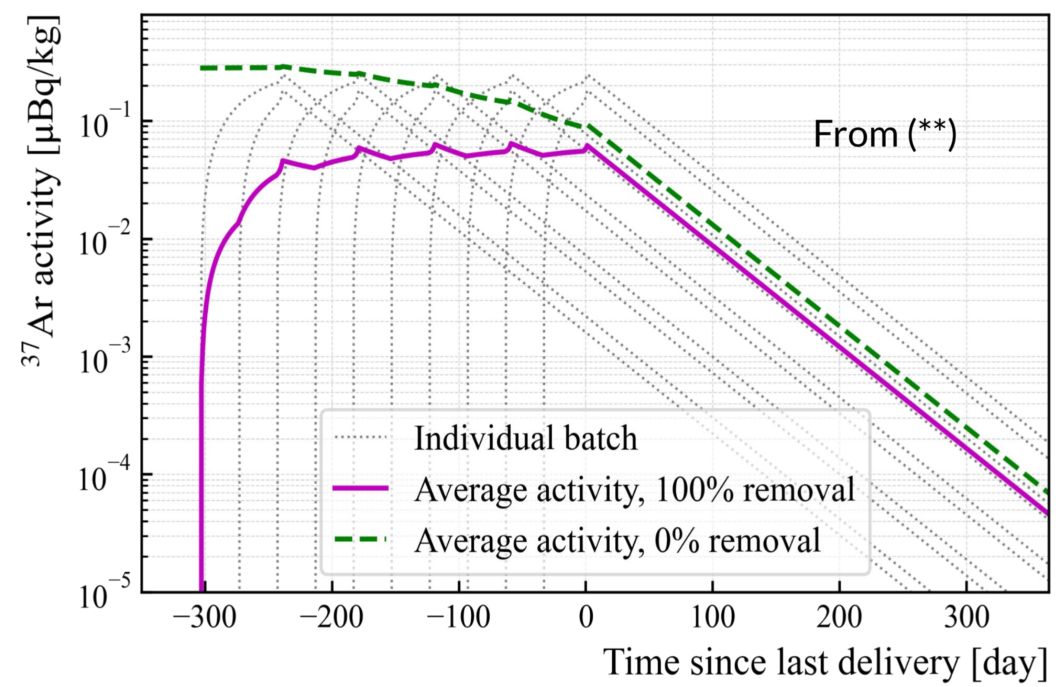
- Dissolved beta emitters:
  - ^{214}Pb (^{222}Rn daughter), ^{212}Pb (^{220}Rn daughter), ^{85}Kr, ^{136}Xe (2 beta)
- Dissolved e-captures (monoenergetic x-ray/Auger cascades):
  - ^{127}Xe, ^{124}Xe (2 e-capture), ^{37}Ar
- Gamma emitters in detector materials:
  - ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co
- Solar neutrinos

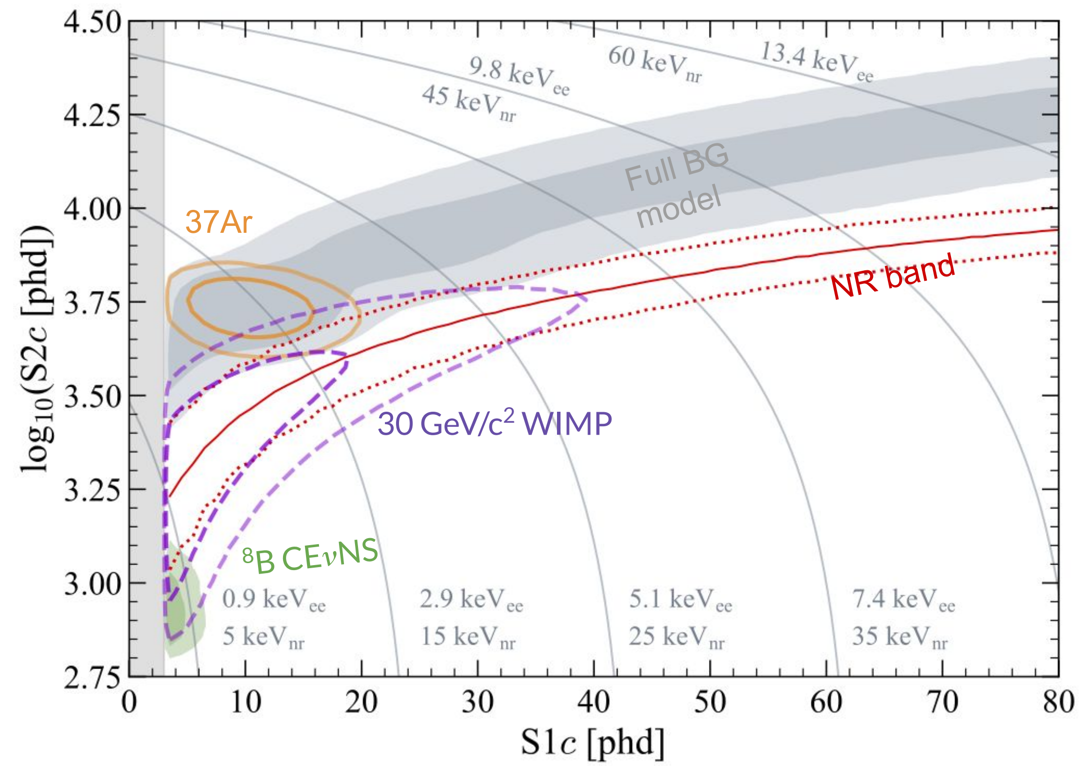


- We had several robust simulation campaigns leading up to science data taking.

^{37}Ar

- Electron capture, $t_{1/2}$ = 35 d, monoenergetic 2.8 keV ER deposition
- Occurs naturally in atmosphere via e.g. $^{40}Ca(n, \alpha)^{37}Ar$ (*), but suppressed during Xe purification by charcoal chromatography
- Also produced by cosmic spallation of natural xenon
- Constrained ^{37}Ar activity based on Xe delivery schedule to SURF (**)
- Expect **~100 decays of ^{37}Ar** in first science run, 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

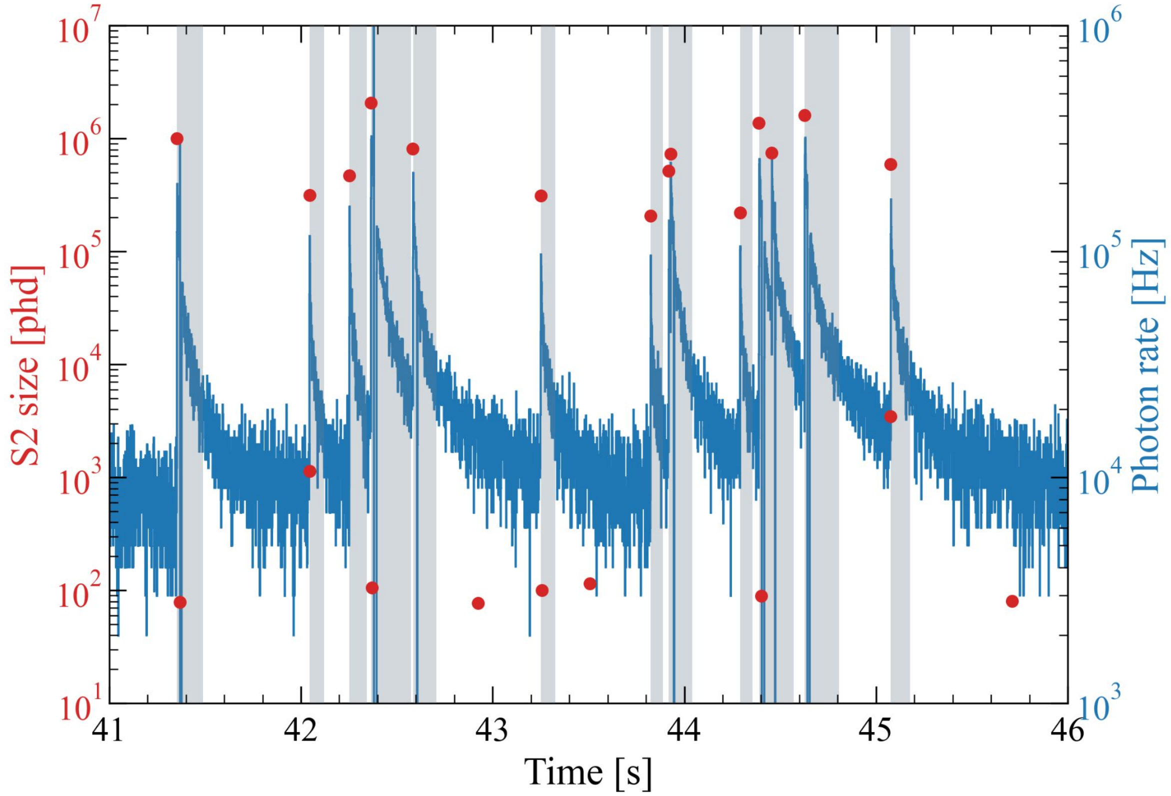
Data Quality

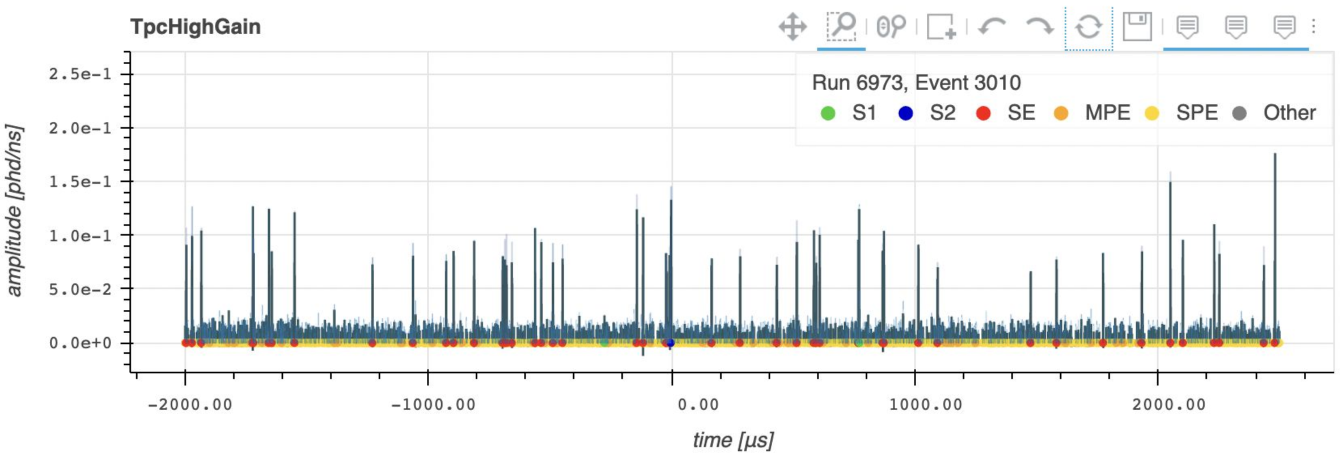
Instrumental effects give rise to many spurious signals

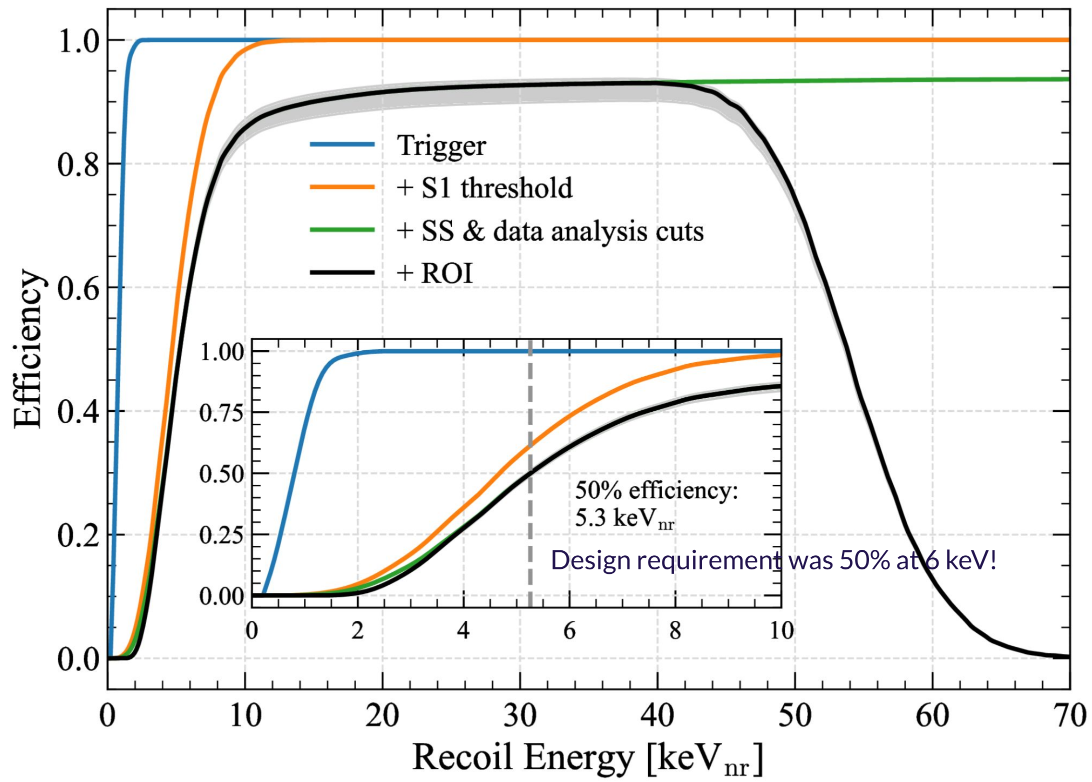
- High rate of single photons and electrons after large S2s
- Interactions in charge- or light-insensitive regions
- Interactions in the liquid and gas above the gate grid

Address with two suites of cuts:

1. **Time-based cuts**
2. **Pulse-based cuts**

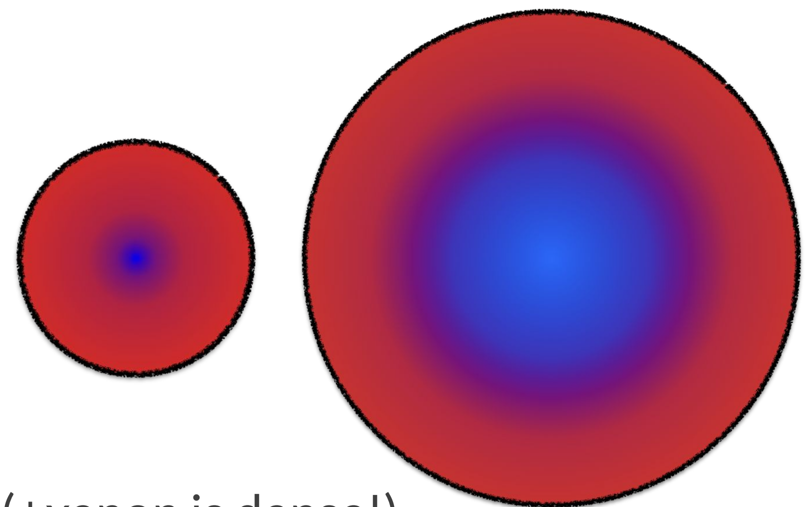




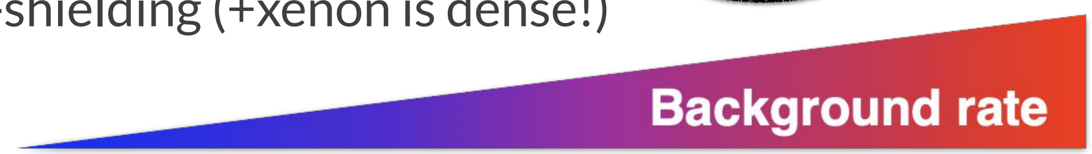


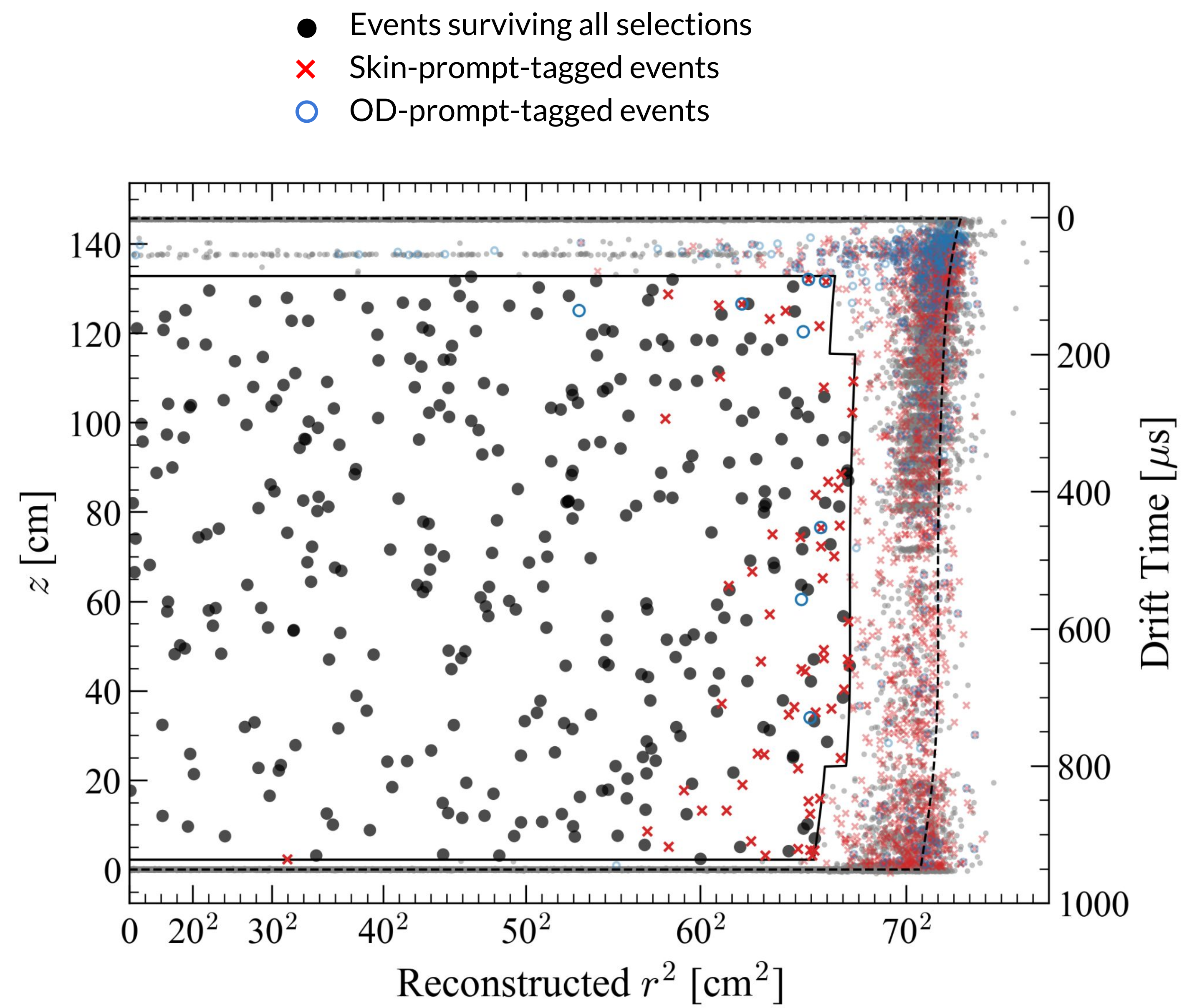
Fiducial Volume and OD/Skin Tags

- Inner **5.5 tonne fiducial volume** (FV) is lowest background and uniform.



Self-shielding (+xenon is dense!)

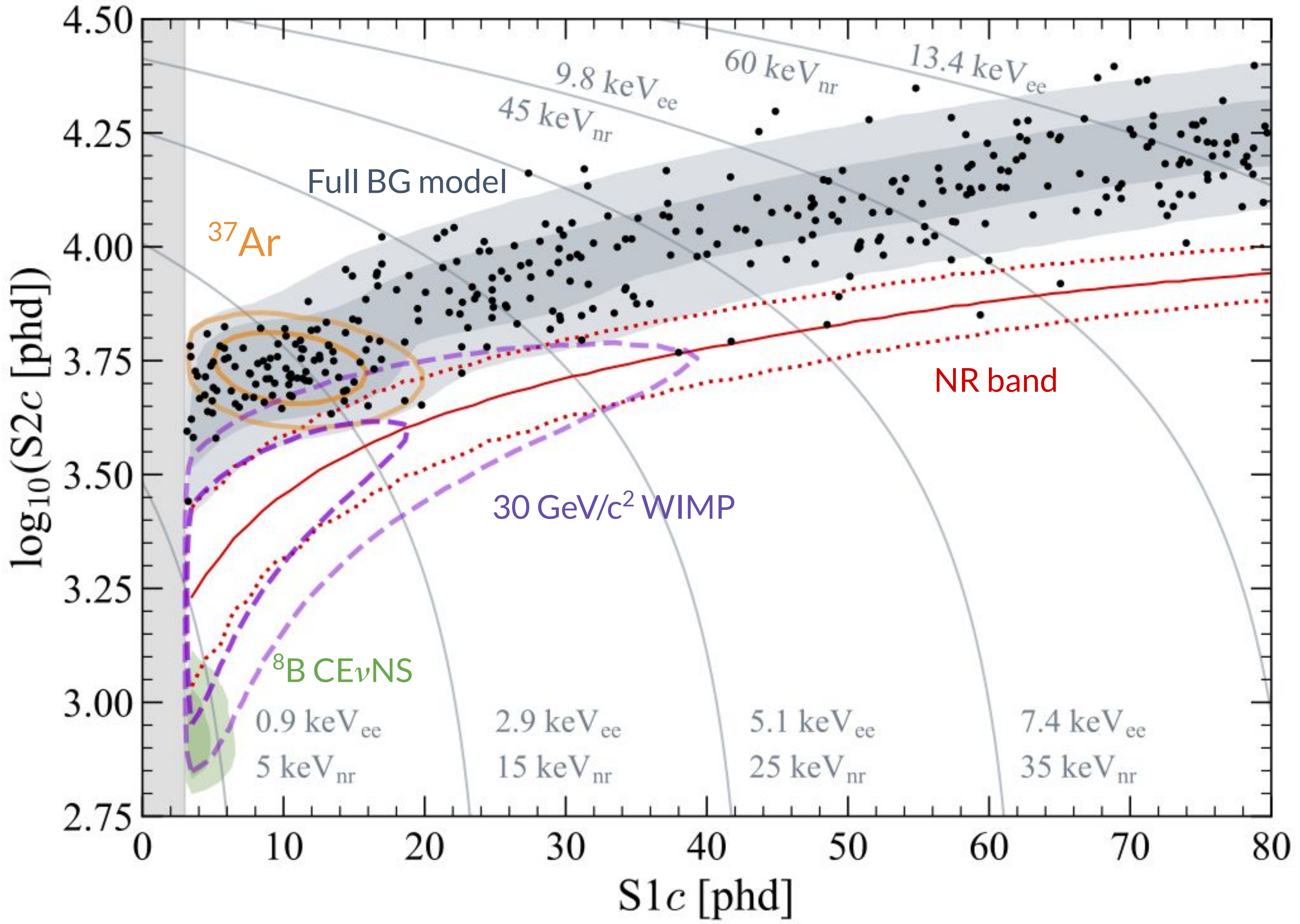




- **Vetoes:**
  - Removes gammas
  - Skin reduces bare L,M-shell ^{127}Xe background 5x
  - 1200 μs capture window, ~200 keV threshold
  - Tag neutron capture
  - Provides *in situ* constraint on neutron BG: **$0^{+0.2}$ neutron events** in first science run

Result

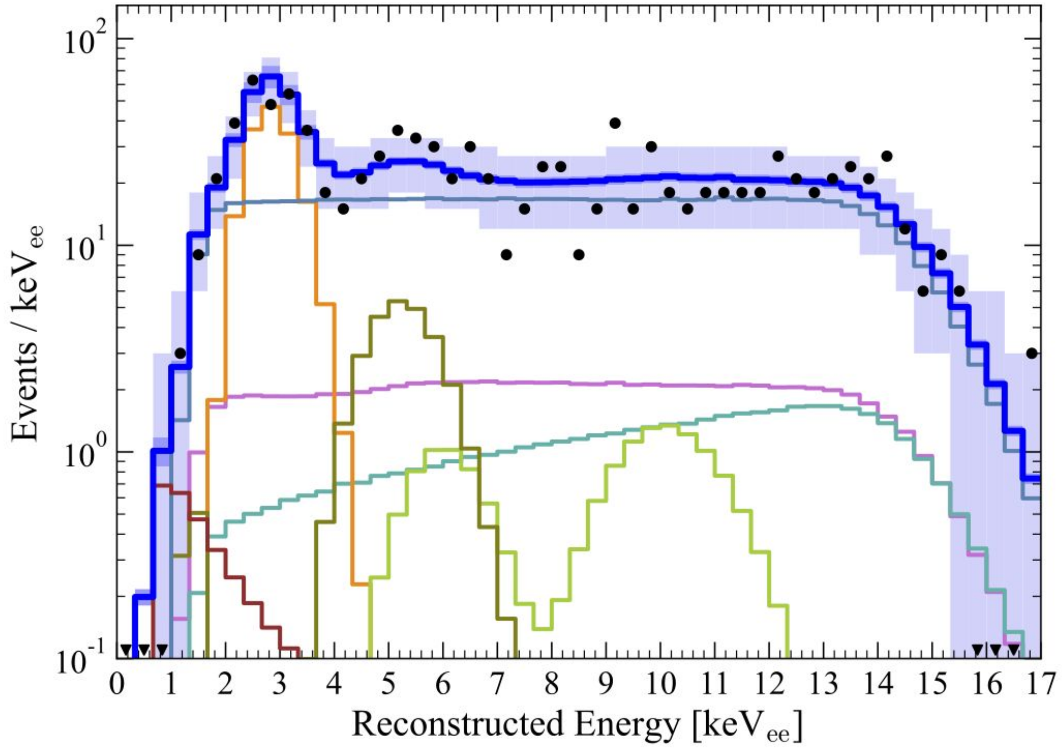
- Region-of-interest:
  - 3 phd < S1c < 80 phd
    Also require S1 coincidence ≥3
  - S2 > 600 phd ($10e^-$)
  - S2c < 10^5 phd
- 335 events in final dataset
- 60 ± 1 live days
- 5.5 ± 0.2 tonne FV

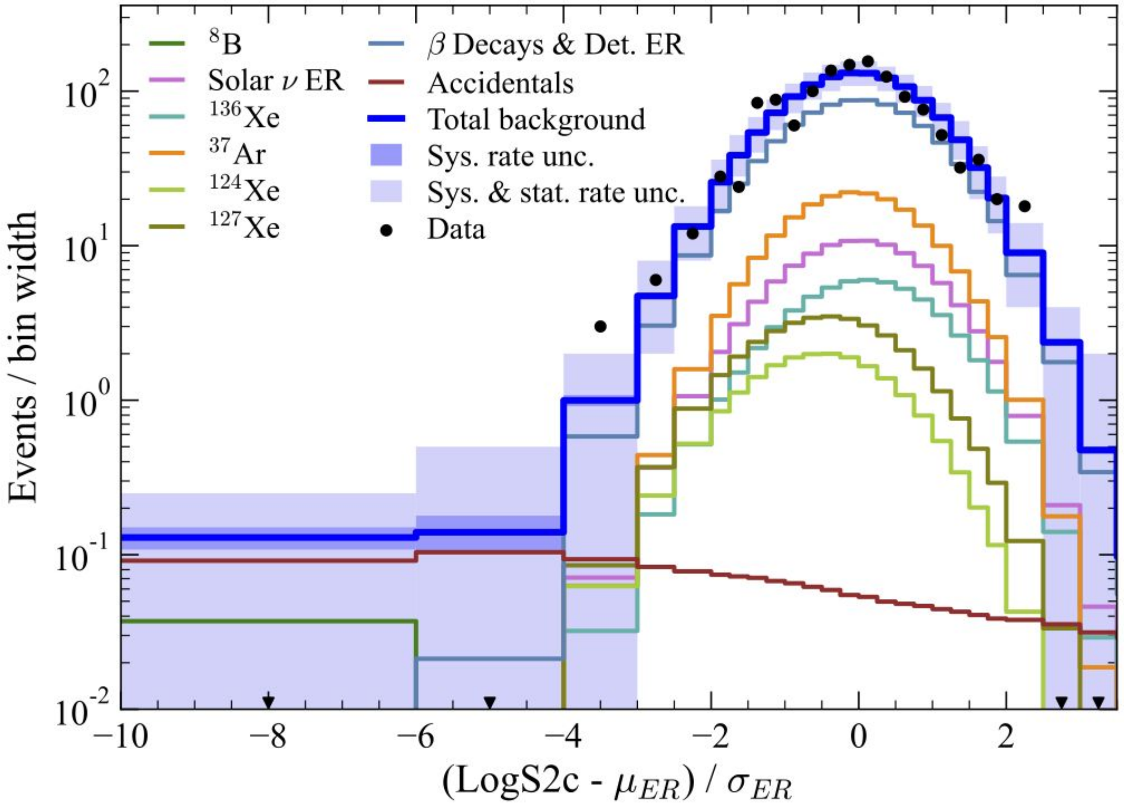


Result - Fit

Best fit with zero WIMP events at all masses

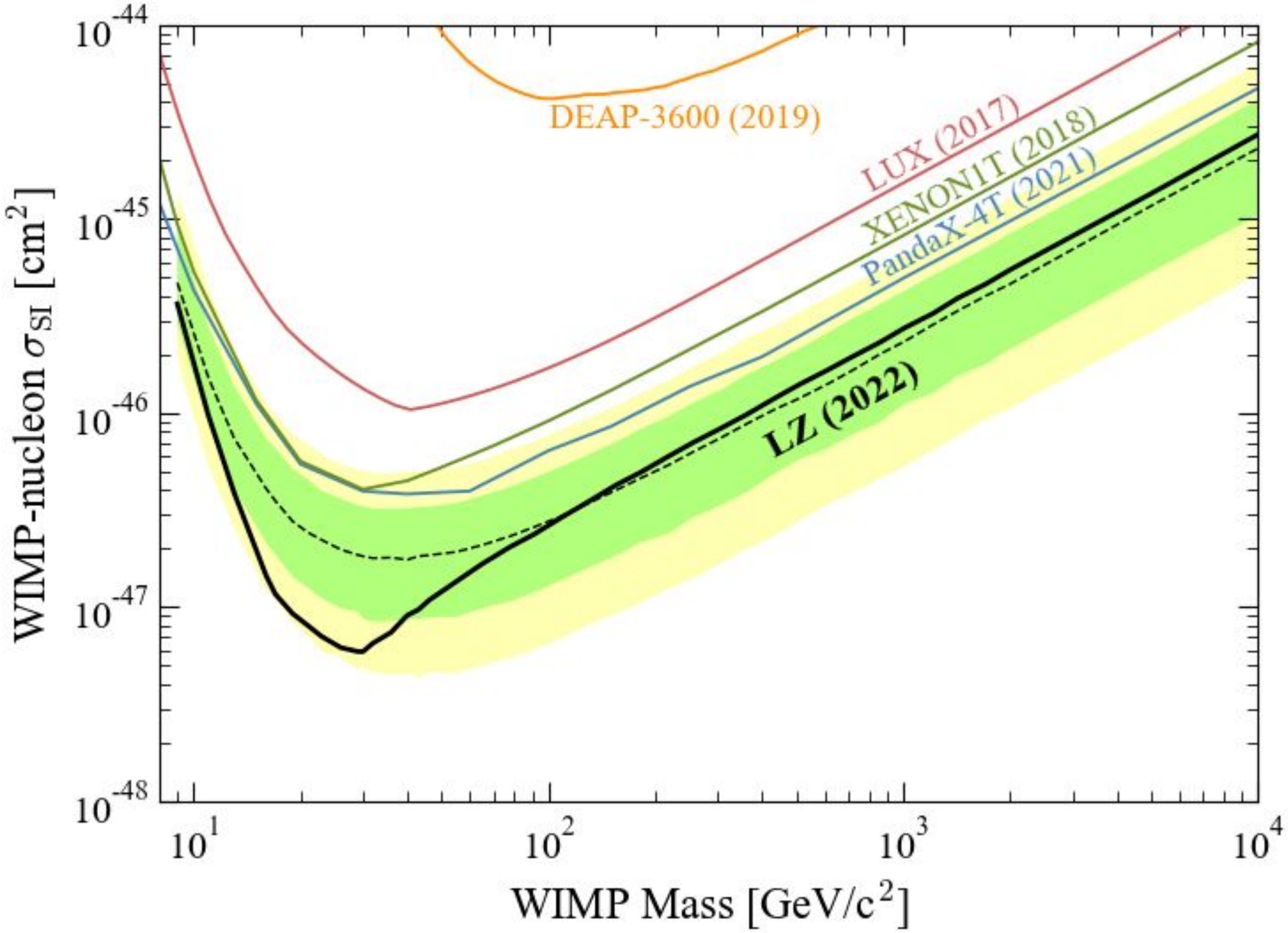
Source	Expected Events	Best Fit
β decays + Det. ER	218 ± 36	222 ± 16
ν ER	27.3 ± 1.6	27.3 ± 1.6
^{127}Xe	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.2 ± 2.4	15.3 ± 2.4
^{8}B CEνNS	0.15 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	276 ± 36	281 ± 16
^{37}Ar	[0, 291]	$52.1^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
30 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17





Result

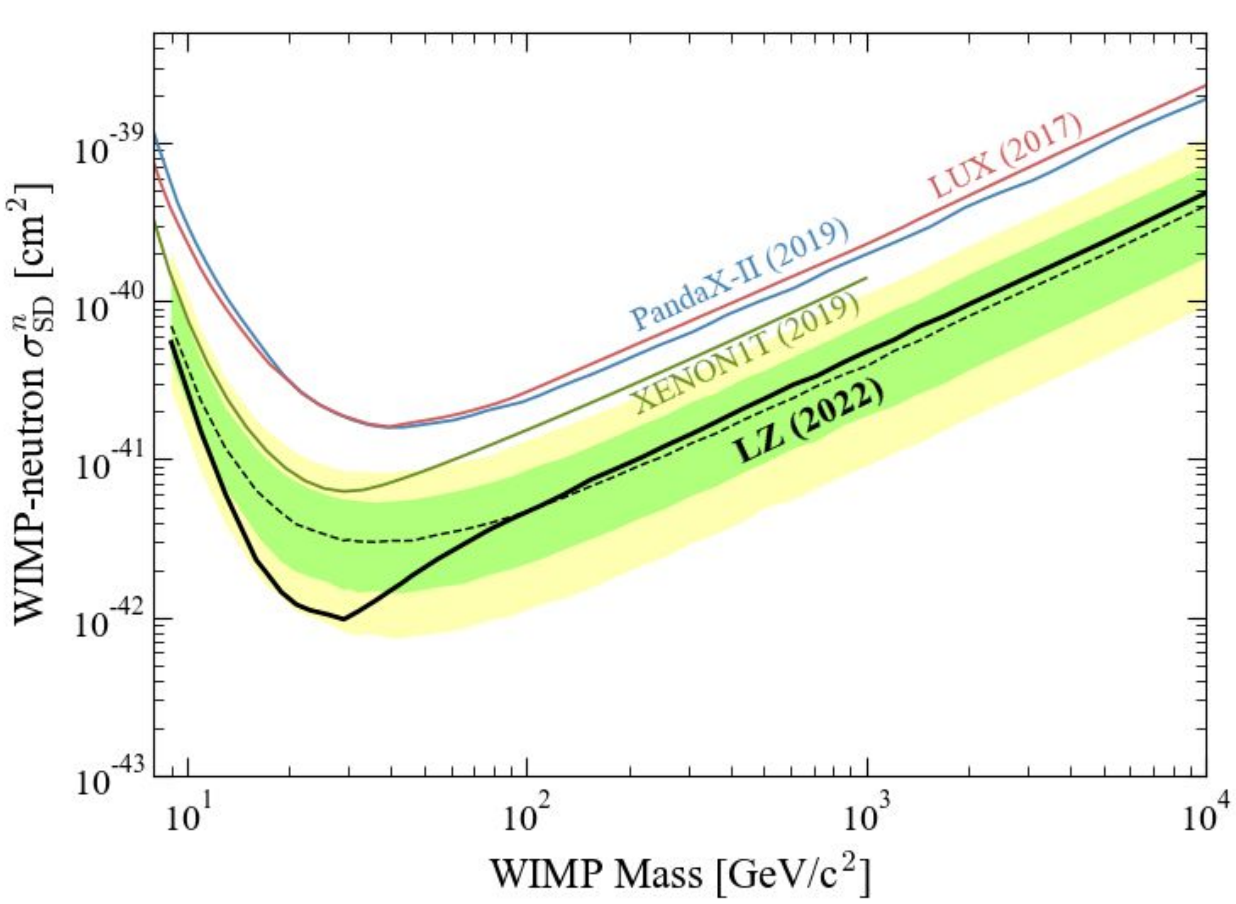
arXiv:2207.03764



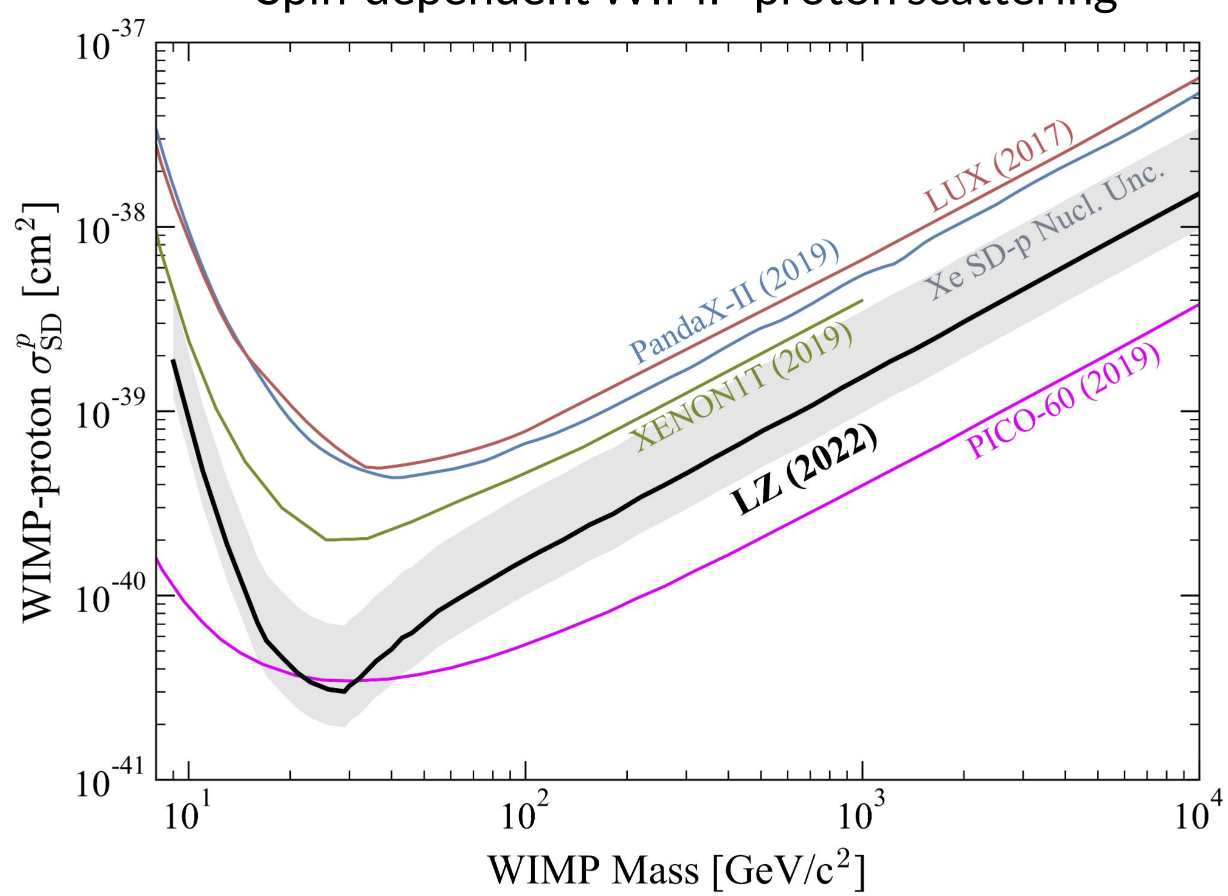
- Curves:
  - Solid black: observed limit
  - Dashed-black: median expected sensitivity
- No evidence of WIMPs at any mass
- Minimum exclusion on WIMP-nucleon cross section (SI) of 6×10^{-48} cm^2 at 30 GeV
- Comparing to existing strongest upper limit:
  - x6.7 improvement at 30 GeV
  - x1.7 improvement above 1 TeV

Result - New

Spin-dependent WIMP-neutron scattering



Spin-dependent WIMP-proton scattering



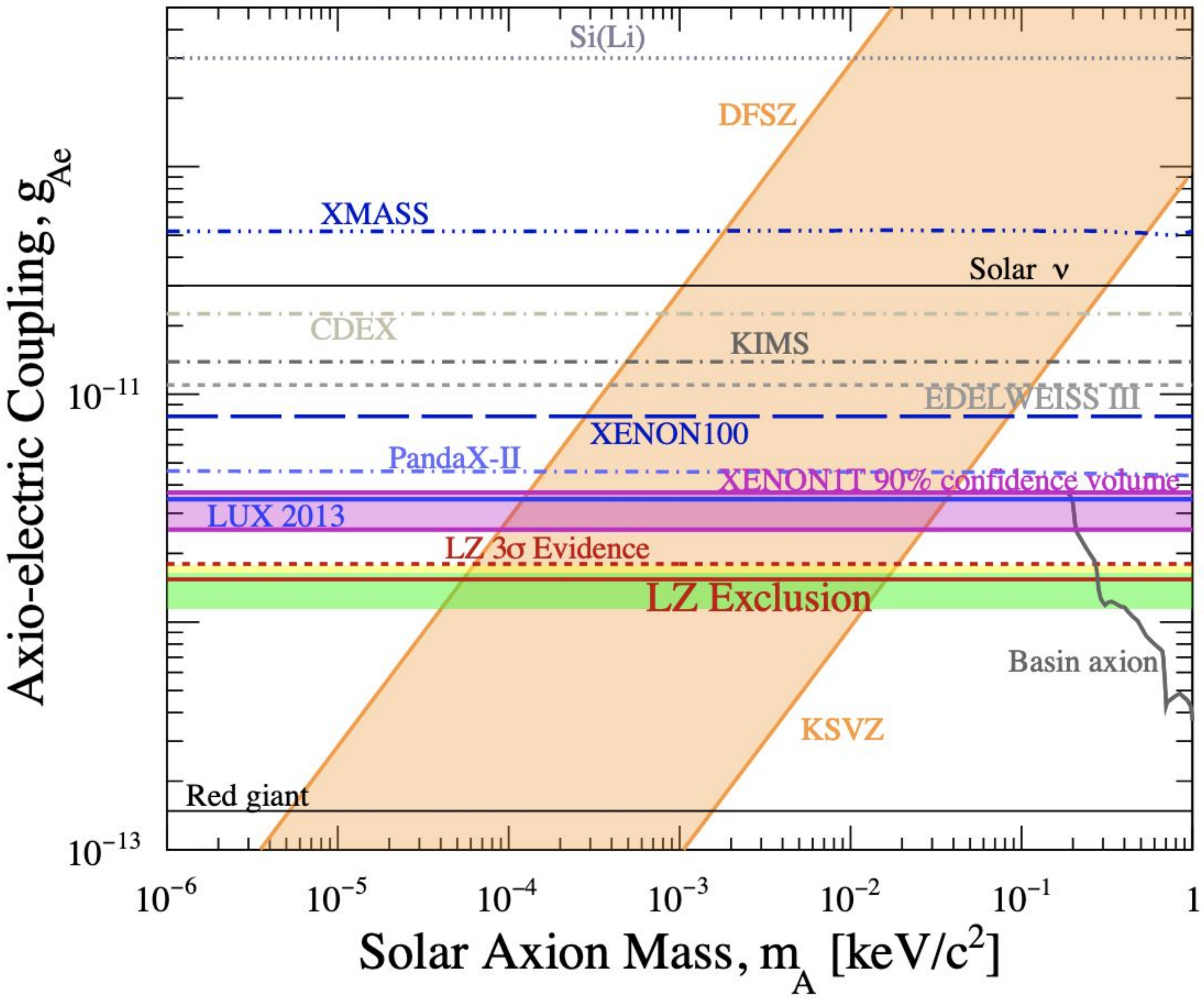
Uncertainty band represents theoretical uncertainty on nuclear form factor for Xe (*)

"Brazil" band elided for clarity

Next Steps for LZ

- LZ plans to take 1000 live days of data (x17 more exposure)
- Lots of science to do in addition to primary DM search!
  - Effective field theory couplings for dark matter
  - Solar axions, ALPs, neutrino magnetic moment
  - Low mass dark matter searches (S2 only, Migdal effect)
  - Leptophilic dark matter
  - Mirror dark matter
  - Neutrinoless double beta decay
  - Rare decays of other xenon isotopes
  - And more!

Phys. Rev. C 102, 014602 (2020)
Phys. Rev. D 104, 092009 (2021)
Phys. Rev. C 104, 065501 (2021)



XLZD Consortium

Leading Xenon Researchers unite to build next-generation Dark Matter Detector

SURF is distributing this press release on behalf of the DARWIN and LZ collaborations

July 20, 2021

Successful joint XLZD meeting June 27-29 at KIT

https://xlzd.org/

[White paper (2203.02309)](https://arxiv.org/abs/2203.02309)

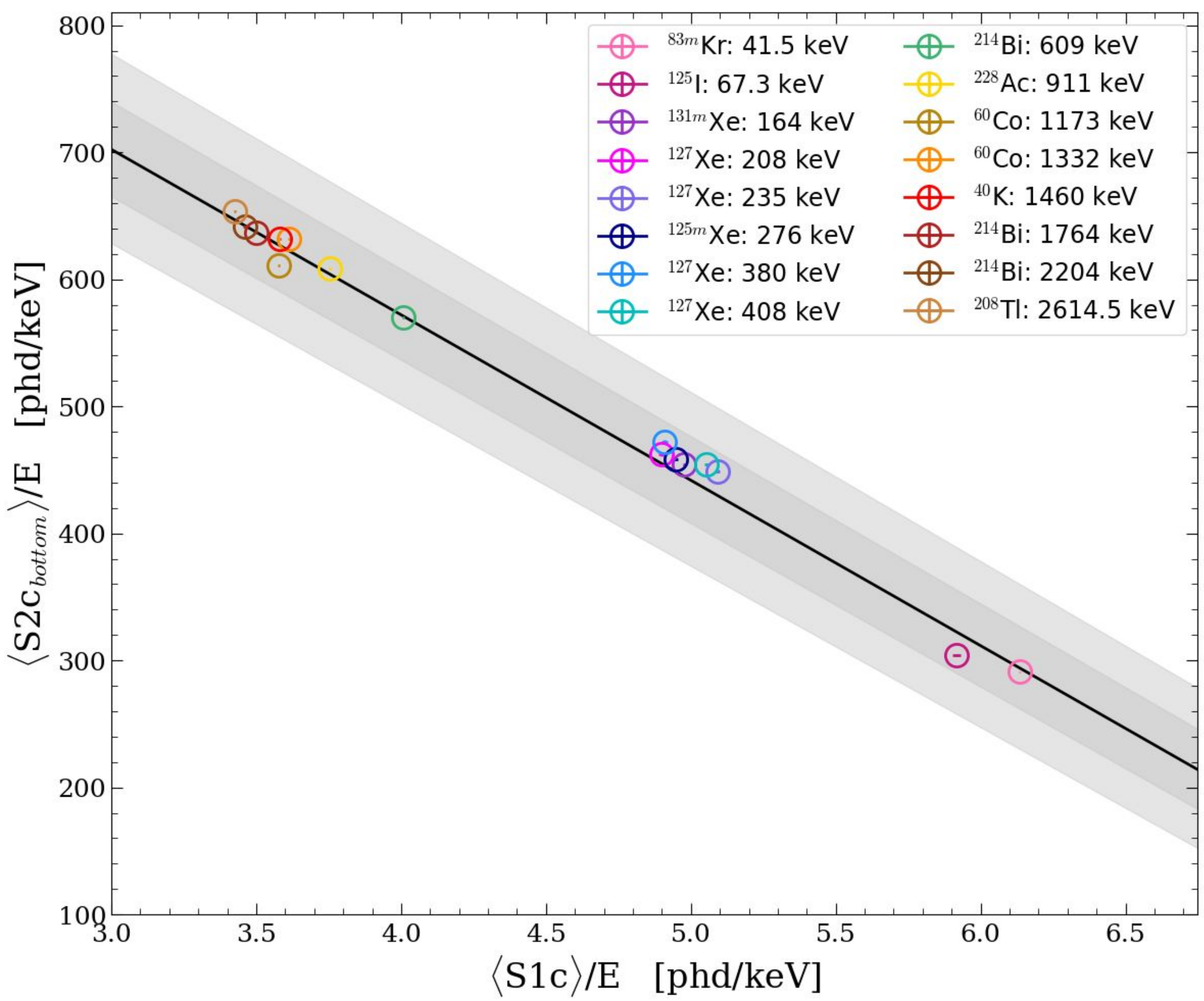
Summary

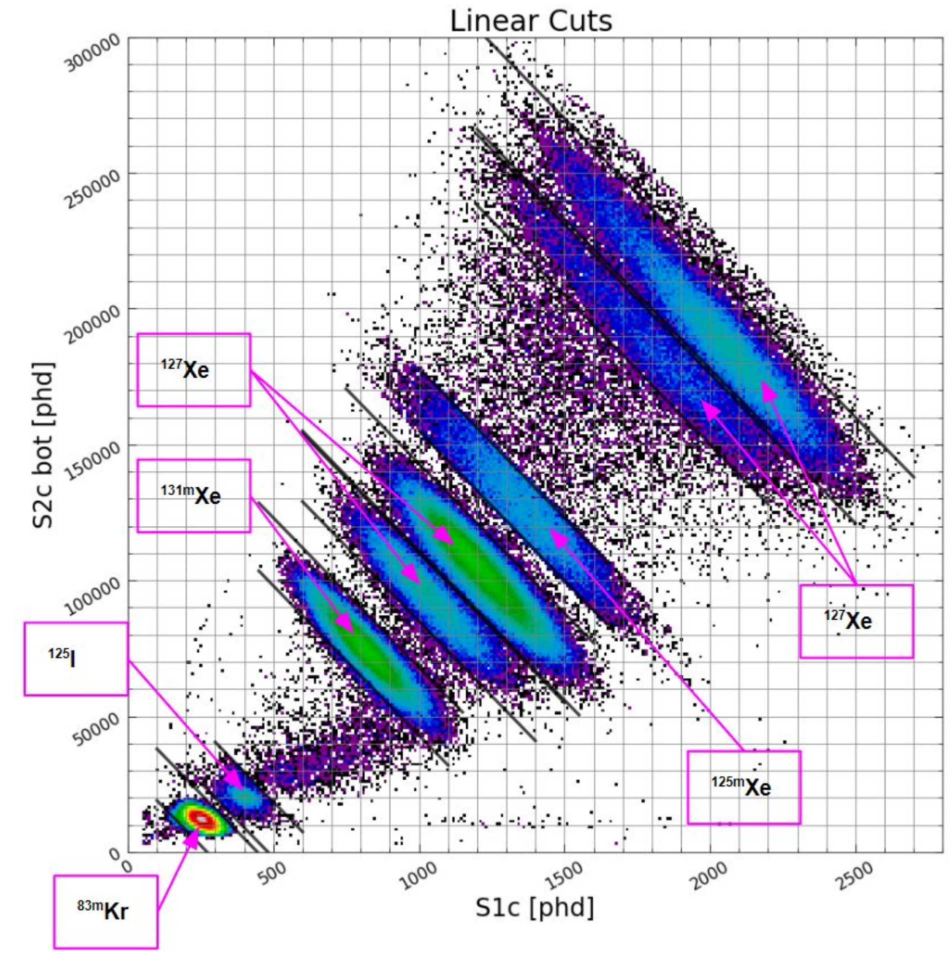
- LZ is online and taking high quality physics data
  - All detectors performing well
  - Backgrounds within expectation
- After 60 live days, LZ is the most sensitive dark matter detector in the world above 9 GeV
  - Paper: arXiv:2207.03764, submitted to PRL
- Xenon community uniting into the XLZD Consortium to build one xenon experiment to rule them all
  - Multi-purpose observatory with huge physics potential!

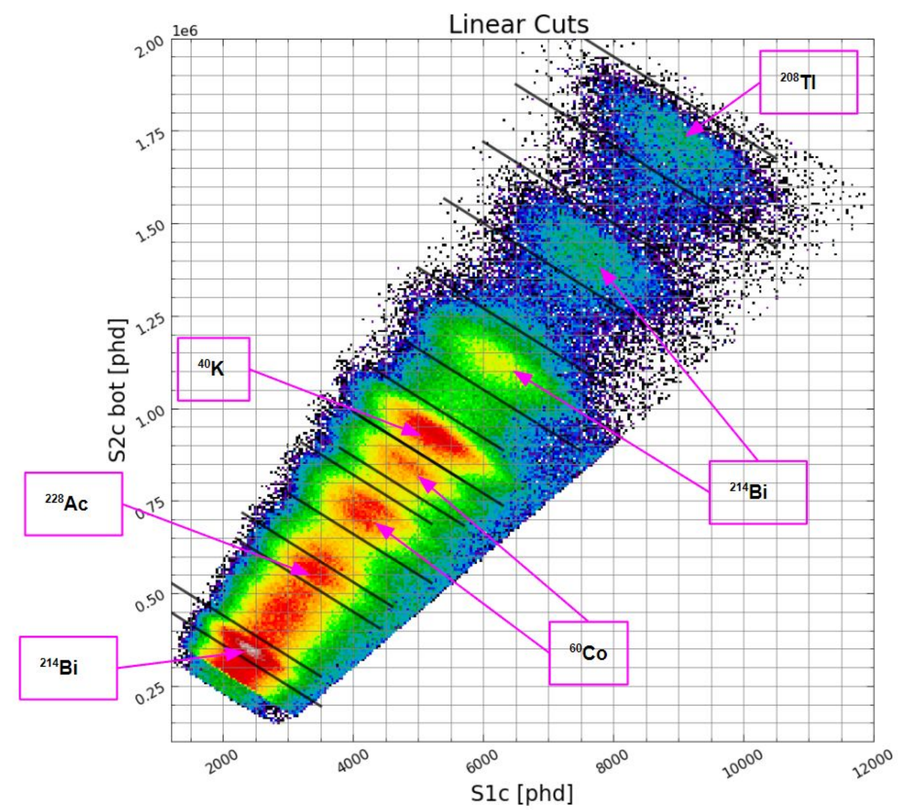
Backup

Detector Response Characterization

- Monoenergetic ER peaks used to determine
  - g1: photon detection efficiency
  - g2: amplification factor of an ionization electron







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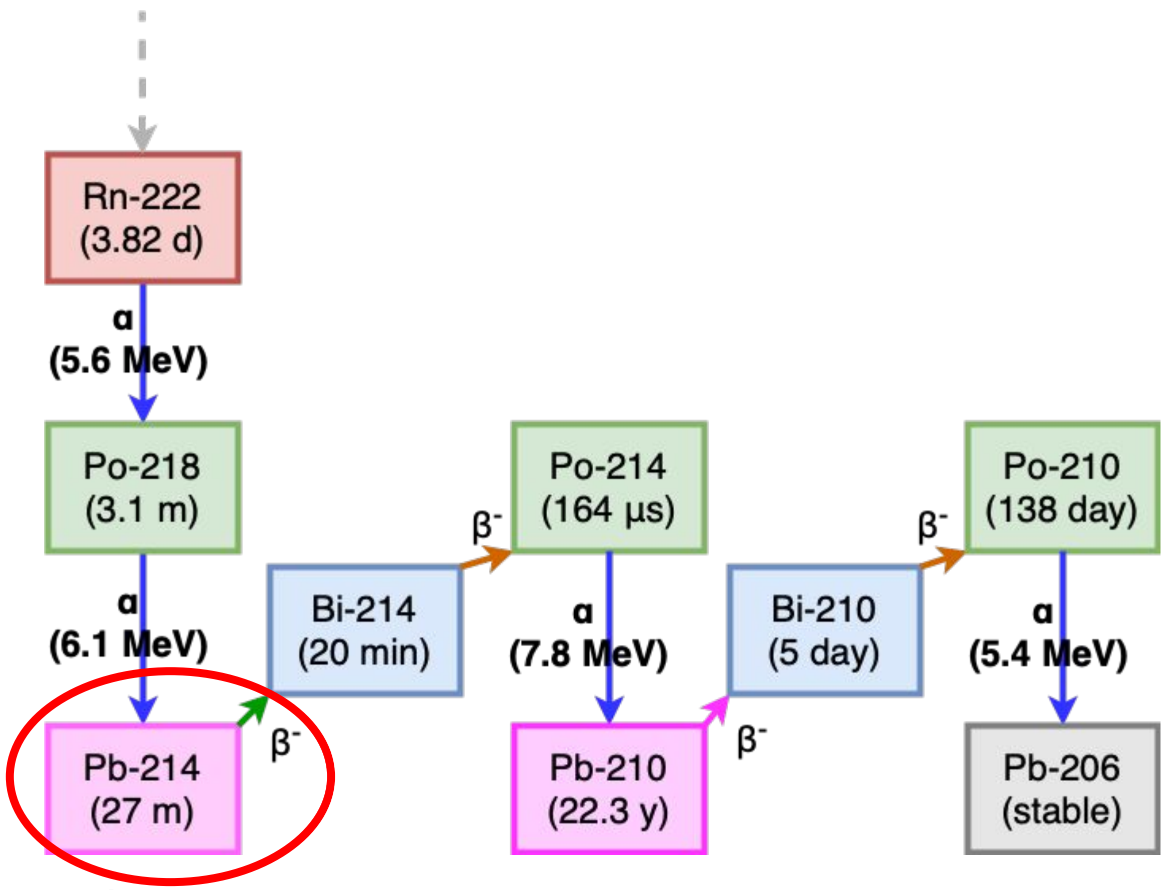
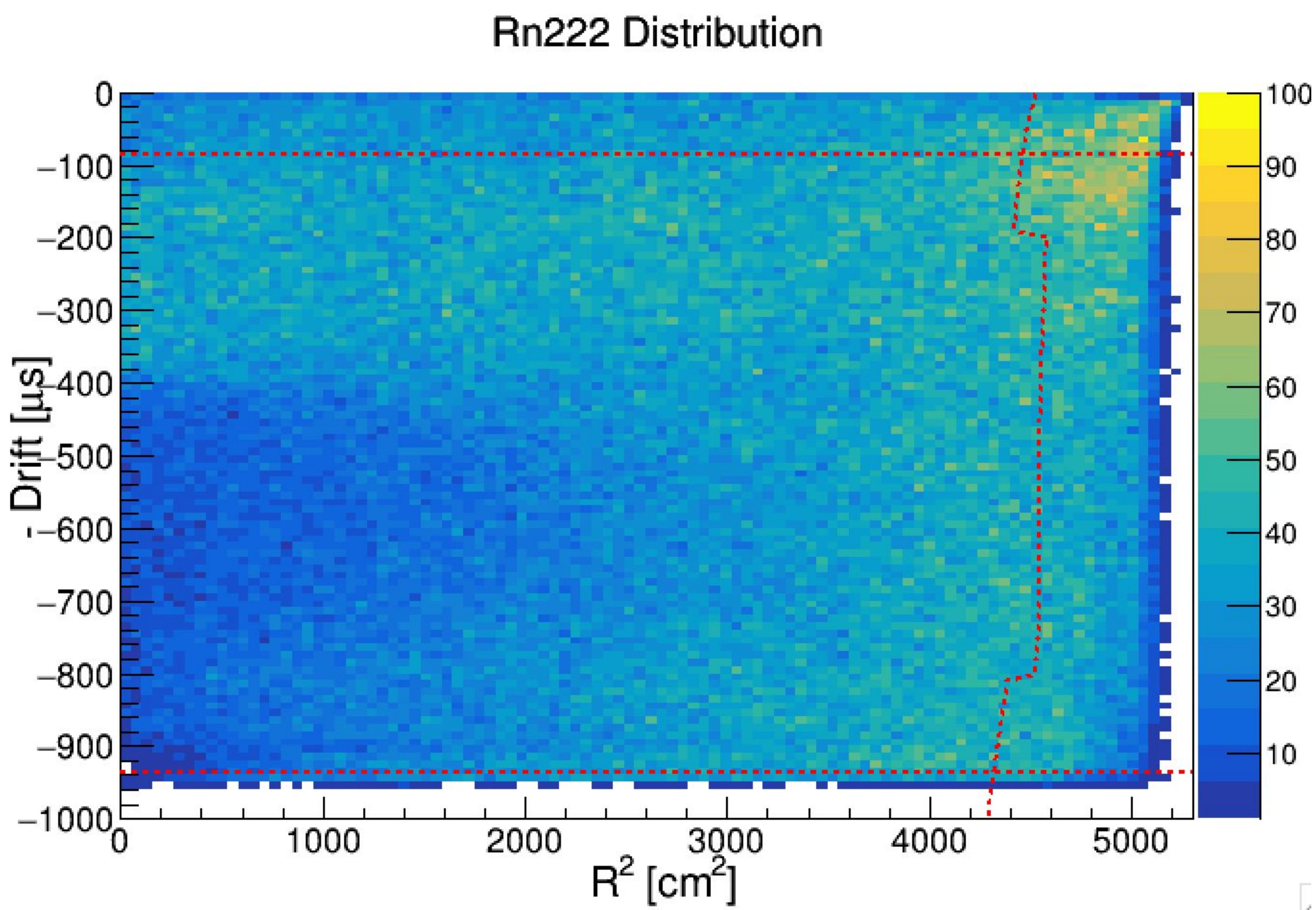
Rn-chain Backgrounds

- Alphas from ^{222}Rn easily identified by S1 spectrum.
- ^{222}Rn not uniformly distributed
  - Stratification in LXe flow is a possible tool to reject ^{214}Pb in future

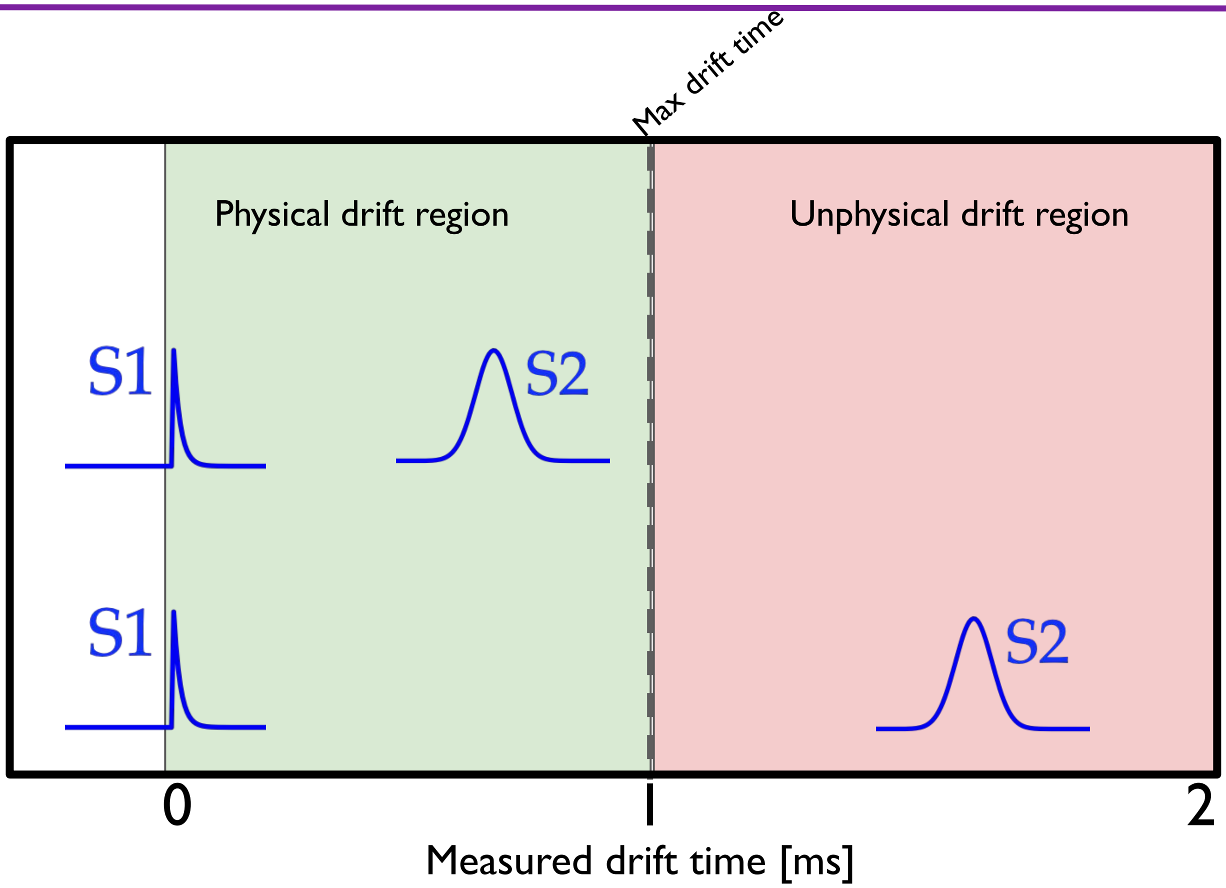




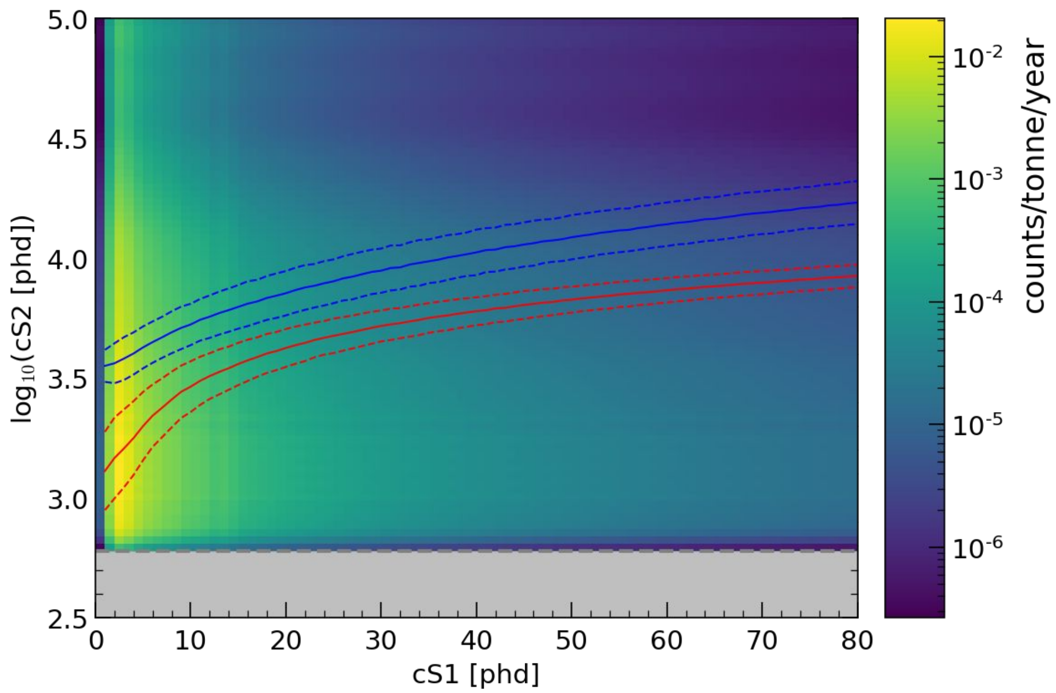
Rn222 (μBq/kg)	Pb214 (μBq/kg)	Po214 (μBq/kg)
4.37 ± 0.31 (stat)	**3.26 ± 0.13(stat) ± 0.57(sys)**	2.56 ± 0.21 (stat)

Accidentals Backgrounds

- 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.

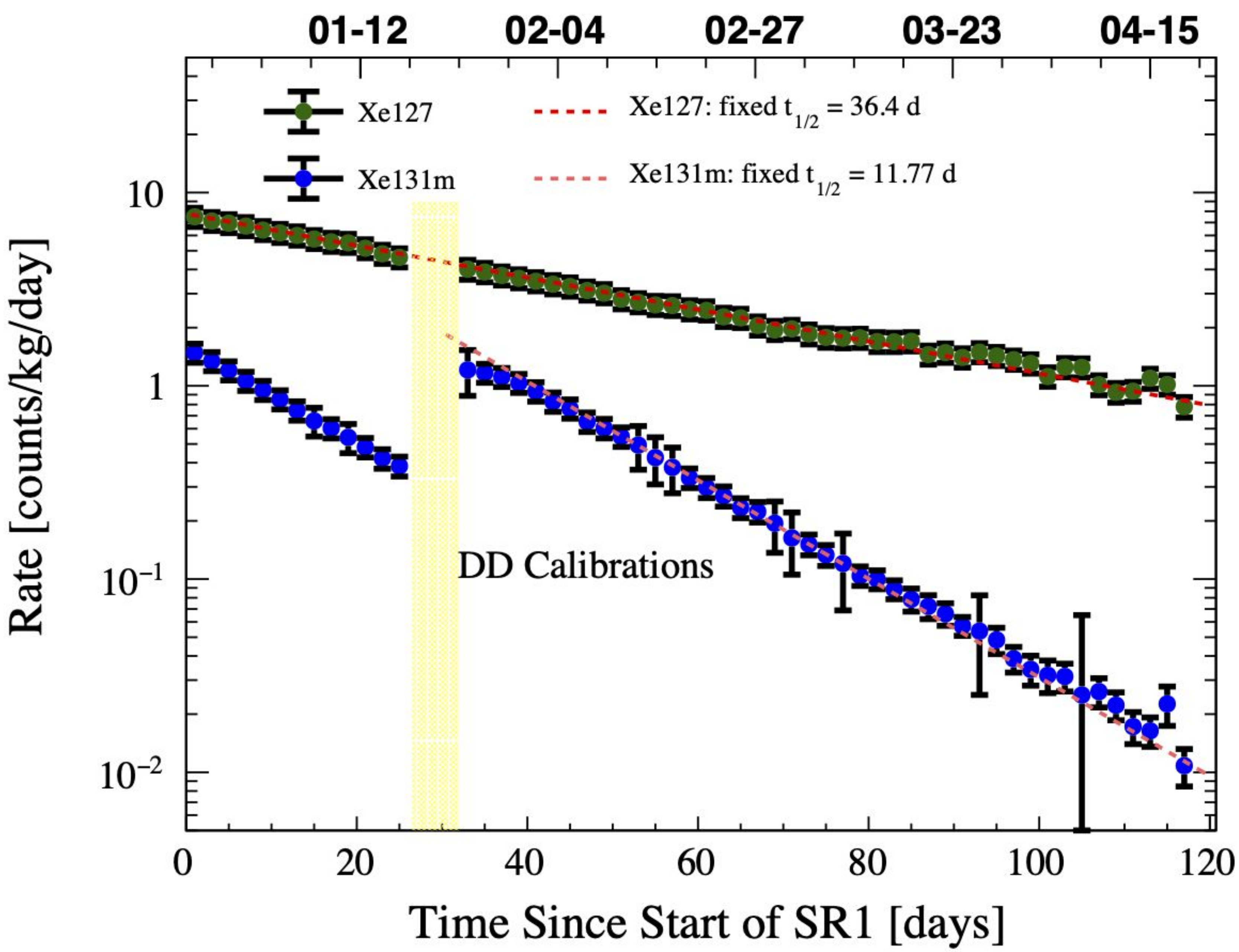


- Data-quality cuts largely address this background
- We build a data set of fake events built from isolated raw pulses and pass them through our processing+analysis frameworks to generate the PDF
- Estimated number of accidentals in SR1 is **1.2 ± 0.3 events**



Active Xenon Isotopes

- Cosmogenically activated xenon isotopes
  - Xe-127
    - Includes gamma ray that is usually vetoed by the TPC itself, or the LXe skin
  - Xe-131m
  - Xe-129m
  - Xe-133



SR1 WIMP conventions

Using the statistical and astrophysical conventions recommended in (*). Highlights:

- Frequentist, 2-sided profile-likelihood-ratio (PLR) test statistic
- 90% confidence bands
- Signal rate must be non-negative
- Power constrain at $\pi_{crit} = 0.32$
- Local density of DM: 0.3 GeV/cm^2
- $v_0 = 238$ km/s
- $v_{esc} = 544$ km/s

(*)

Eur. Phys. J. C (2021) 81:907
https://doi.org/10.1140/epjc/s10052-021-09655-y
THE EUROPEAN PHYSICAL JOURNAL C
Check for updates
Special Article - Tools for Experiment and Theory

Recommended conventions for reporting results from direct dark matter searches

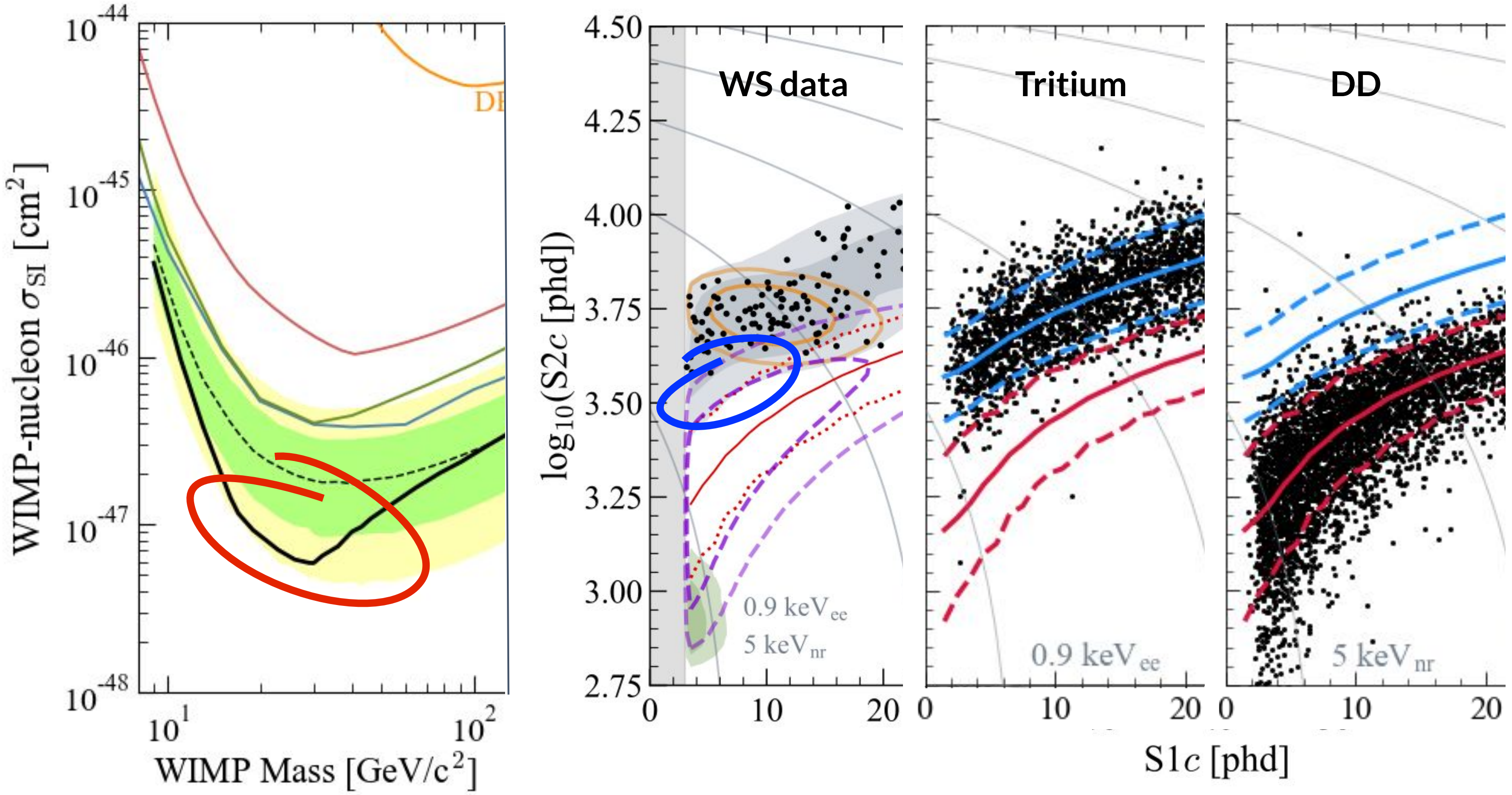
D. Baxter[1], I. M. Bloch[2], E. Bodnia[3], X. Chen[4,5], J. Conrad[6], P. Di Gangi[7], J. E. Y. Dobson[8], D. Durnford[9], S. J. Haselschwardt[10], A. Kaboth[11,12], R. F. Lang[13], Q. Lin[14], W. H. Lippincott[3,a], J. Liu[4,5,15], A. Manalaysay[10], C. McCabe[16], K. D. Morå[17], D. Naim[18], R. Neilson[19], I. Olcina[10,20], M. -C. Piro[9], M. Selvi[7], B. von Krosigk[21], S. Westerdale[22], Y. Yang[4], N. Zhou[4]

SR1 Data

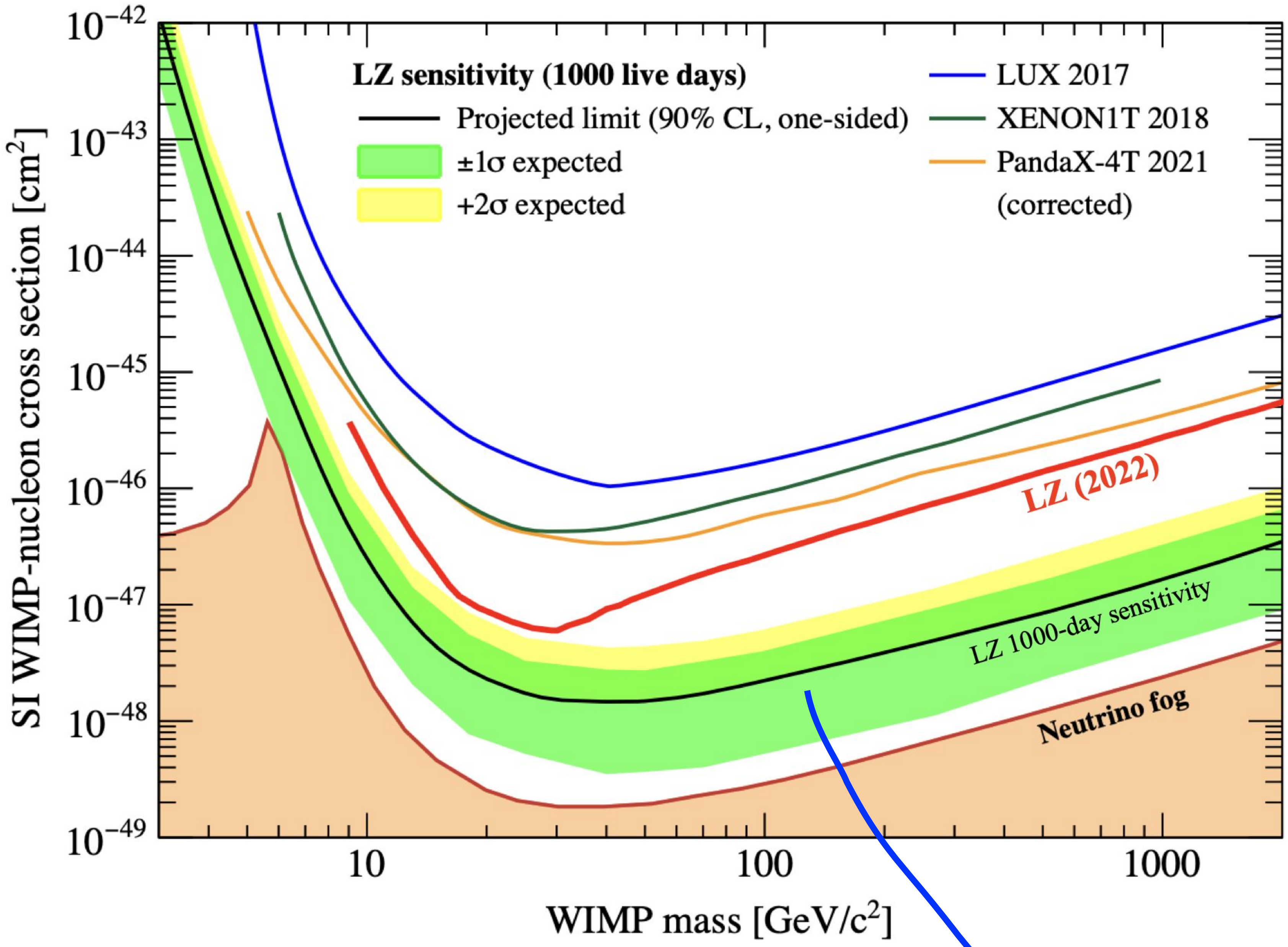
Selection description	Events after selection
All triggers	1.1×10^8
Analysis time hold-offs	6.0×10^7
Single scatter	1.0×10^7
Region-of-interest	1.8×10^5
Analysis cuts for accidentals	3.1×10^4
Fiducial volume	416
OD and Skin vetoes	335

Downward fluctuation at 30 GeV

- Downward fluctuation in the observed upper limit near 30 GeV/c^2 is a result of the deficit of events under the ^{37}Ar population.
  Due to background under-fluctuation or unaccounted for signal inefficiency? Probe the latter.
- **Tritium** data analyzed identically to WS data.
  Deficit region is well-covered.
- **DD** data also shows deficit region is well-covered.
  (Not shown here) AmLi neutron calibration data also shows deficit region well-covered.
- Deficit appears consistent with under-fluctuation of background.



Projected Sensitivity (5.6 t exposure, 1000 live day)



90% CL minimum (one sided) of 1.4×10^{-48} cm^2 at 40 GeV/c^2

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