Current results and outlook for the LUX-ZEPLIN (LZ) experiment

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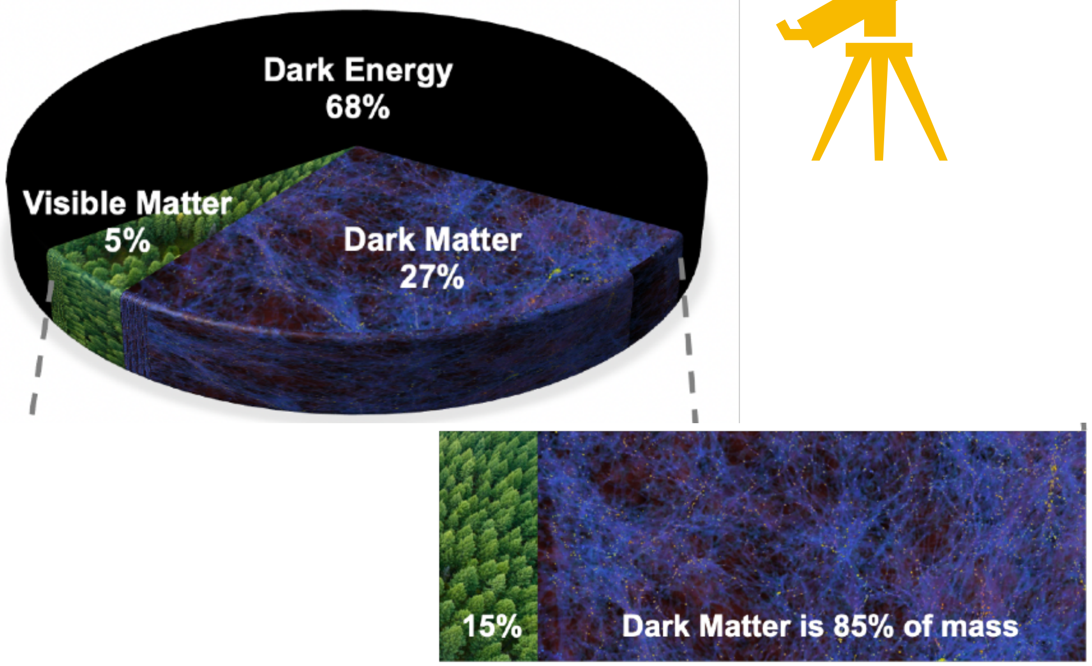
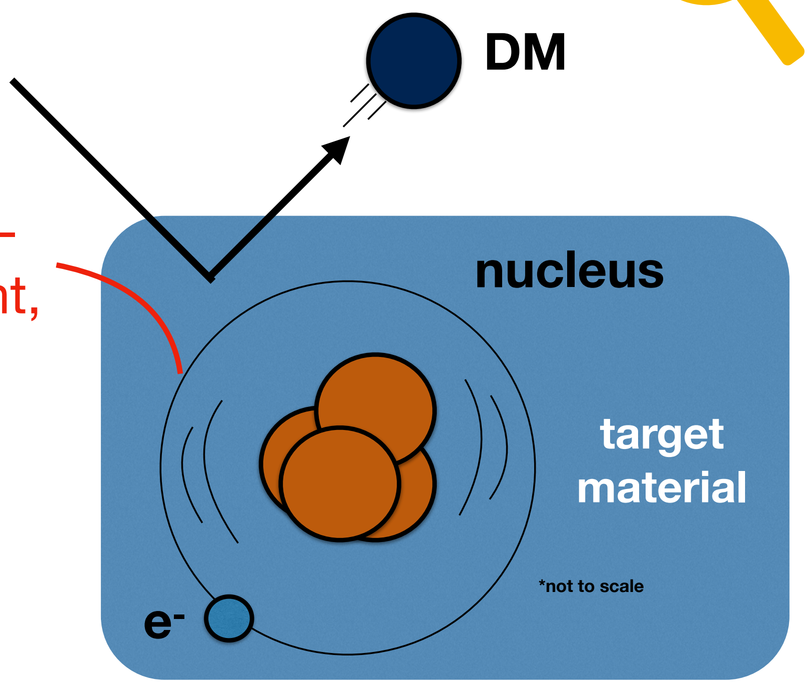
APS/JPS 2023
International Workshop on Double Beta Decay and Underground Science
Waikaloa, HI (USA)

Introduction

What are we searching for?



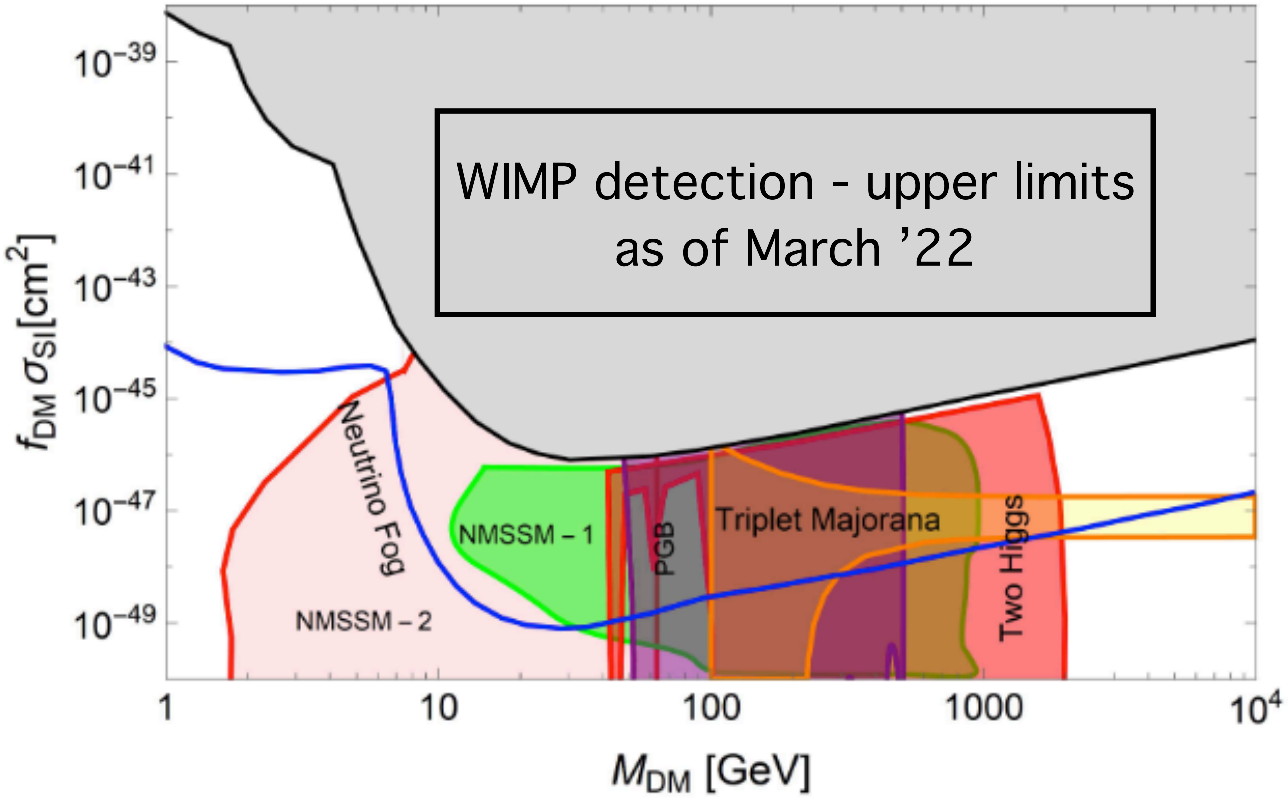
How can we search?



Graphic by Tien-Tien Yu (COSSURF 2022)

How are we doing?

Very small scattering cross-sections!
1 event / ton / year

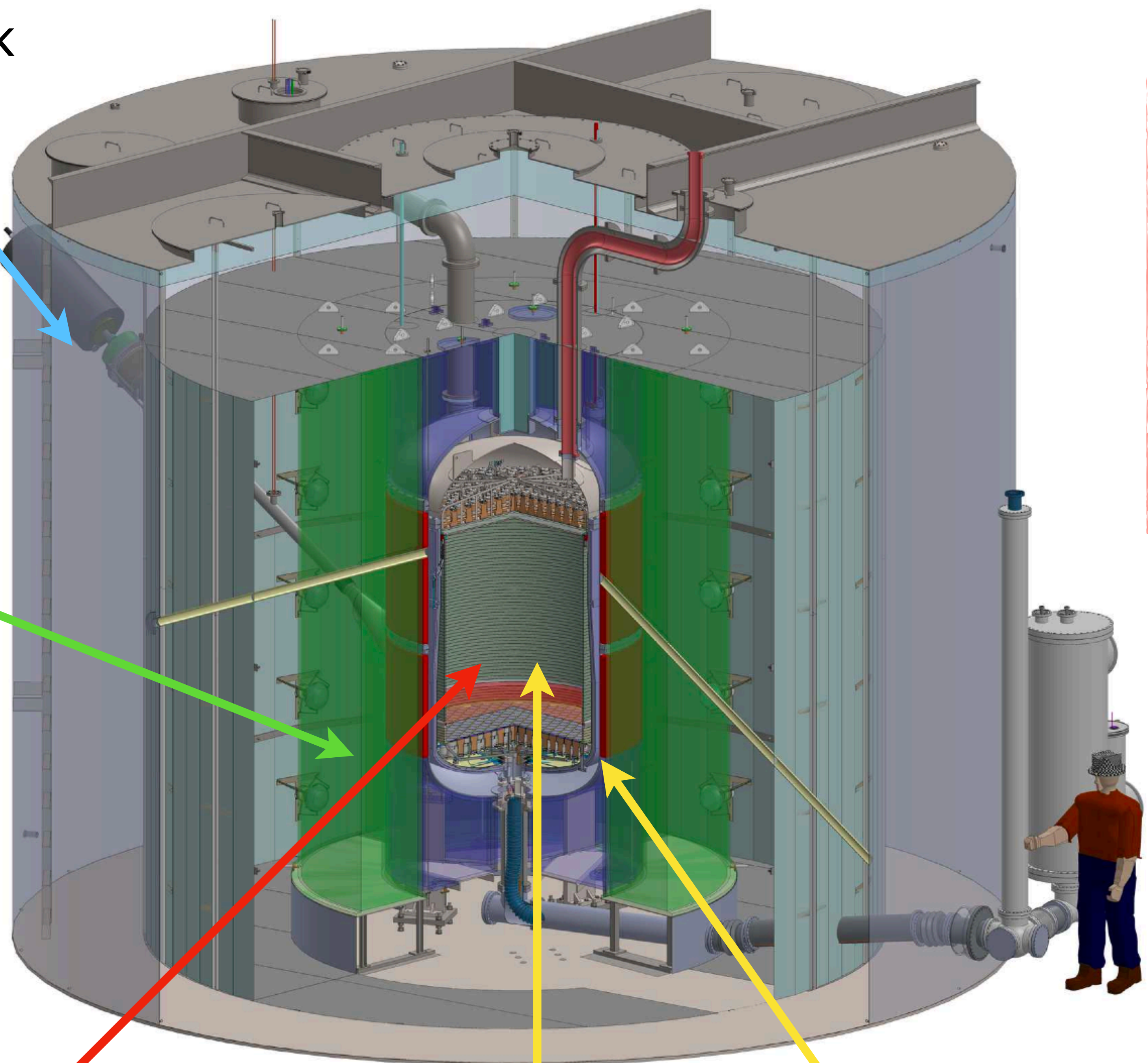


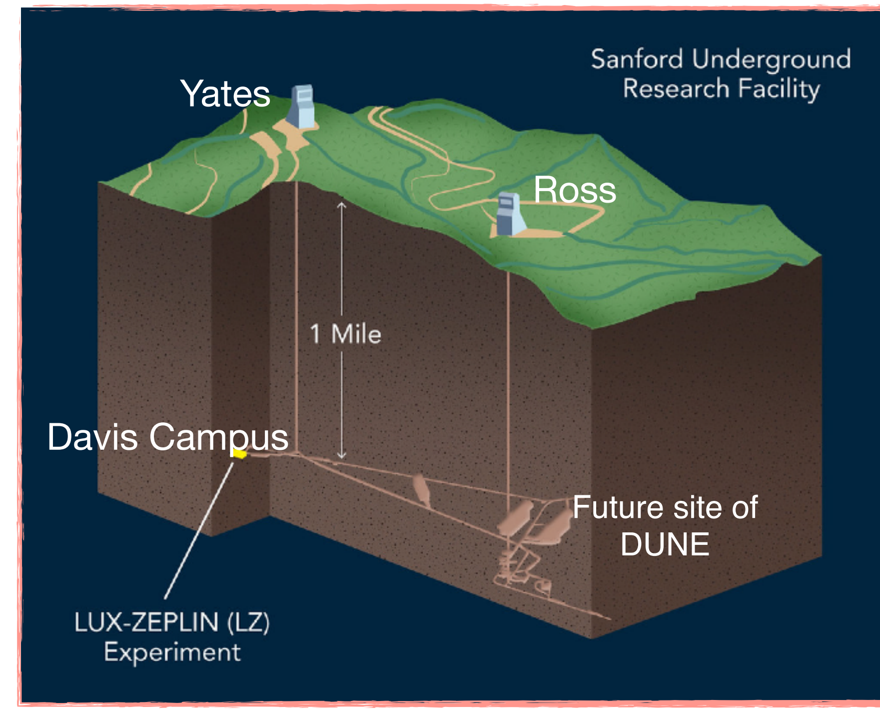
Snowmass CF1-WP1
arXiv:2203.08084


LZ
Part 1: LZ

The LUX-ZEPLIN (LZ) experiment

LZ detector paper:
NIM 953 (2019), 163047

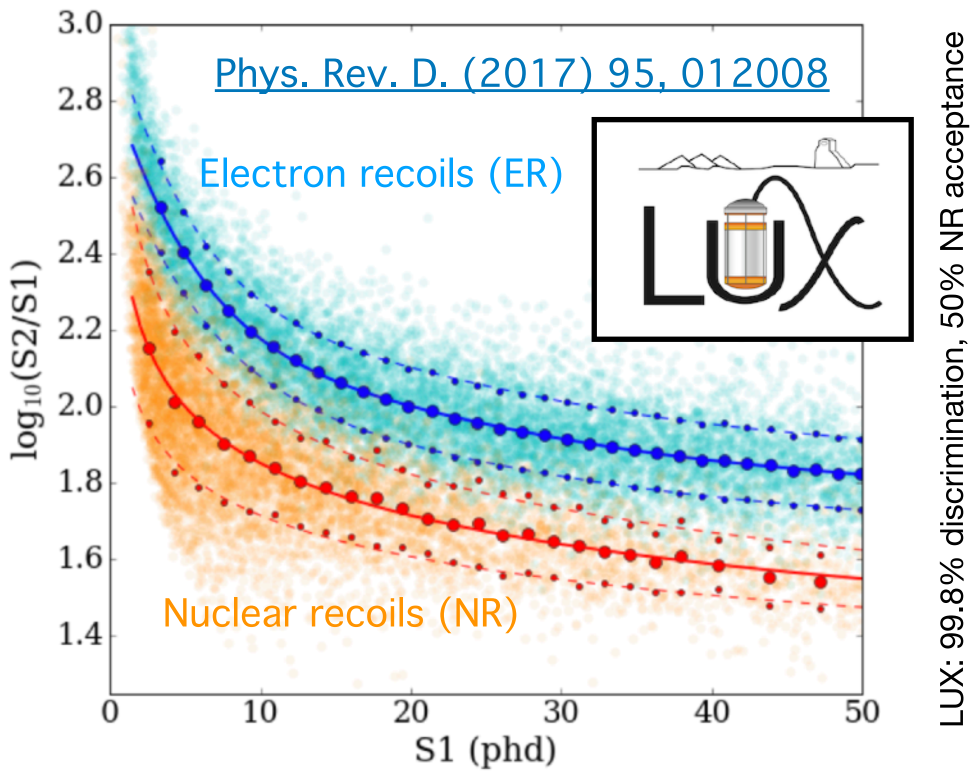




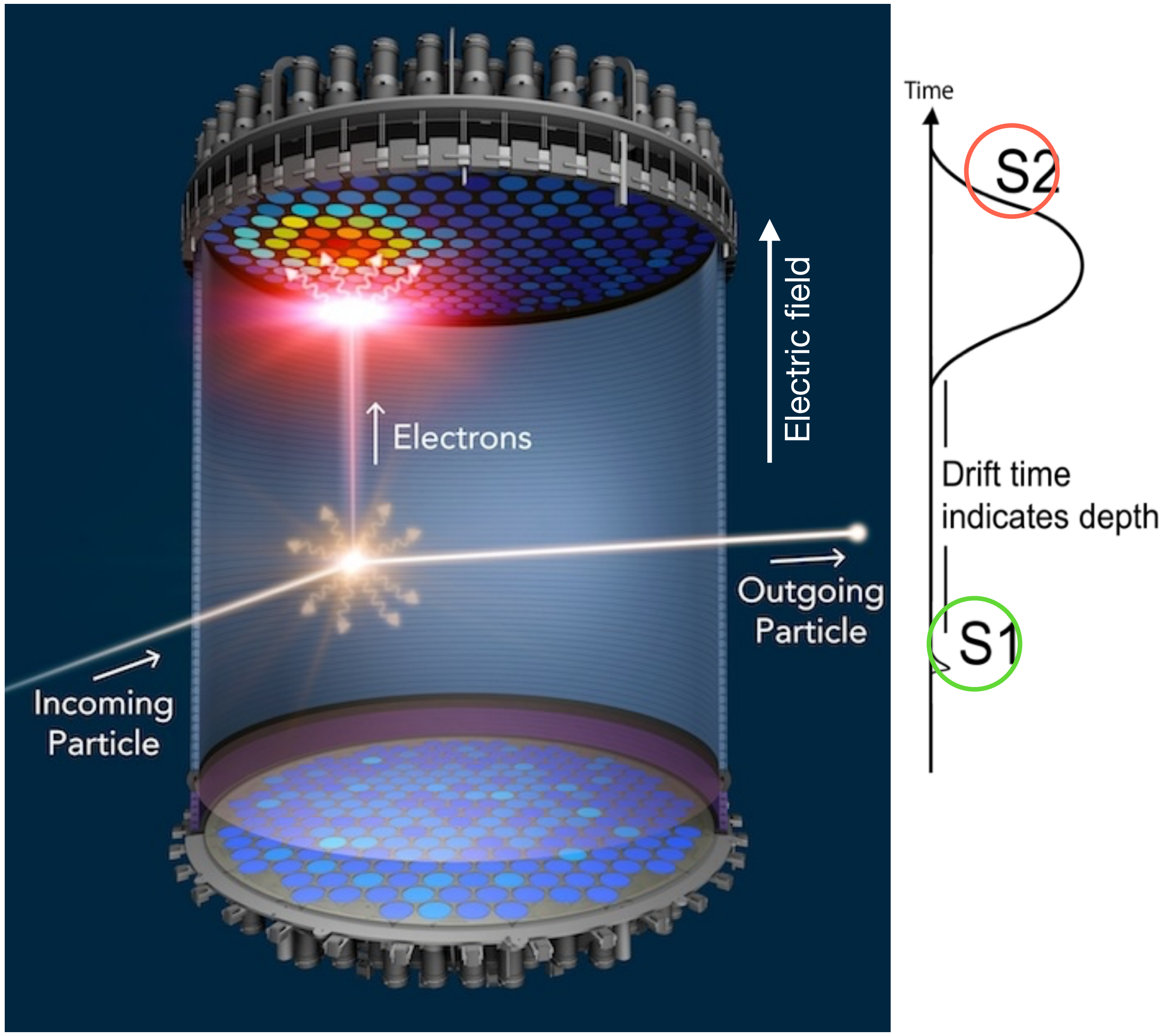
Low-background detector - extensive material screening campaign to select radiopure materials (see Eur.Phys.J.C 80 (2020) 11, 1044)

Two-phase xenon time projection chamber

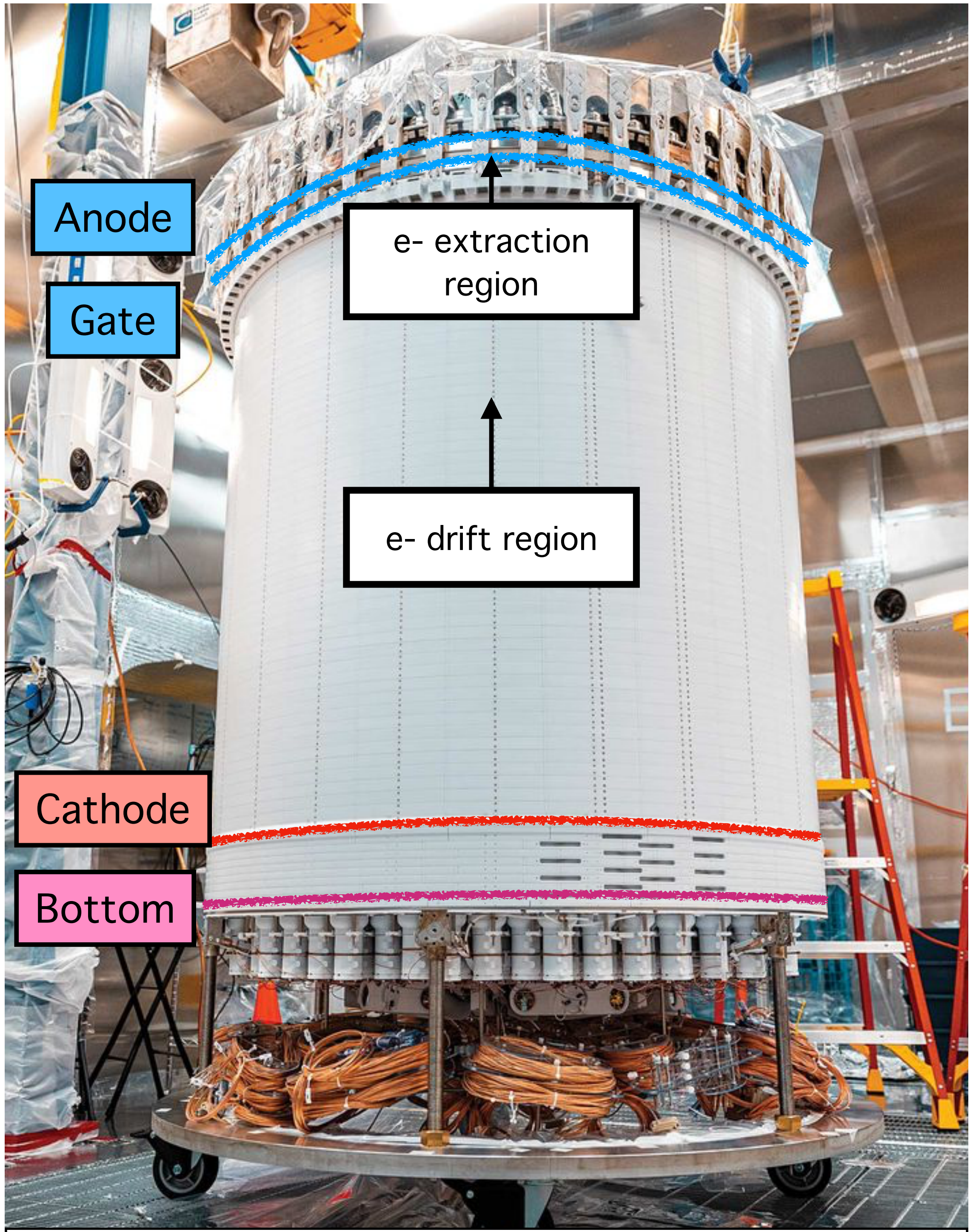
- S1 prompt scintillation
- S2 delayed scintillation after ionization electrons are drifted and extracted in gas phase
- For each event in the detector with an S1 and S2 signal, we can determine:
  - Position
  - Energy (threshold ~ few keV)
  - Recoil identification



PMT hit map gives x, y position

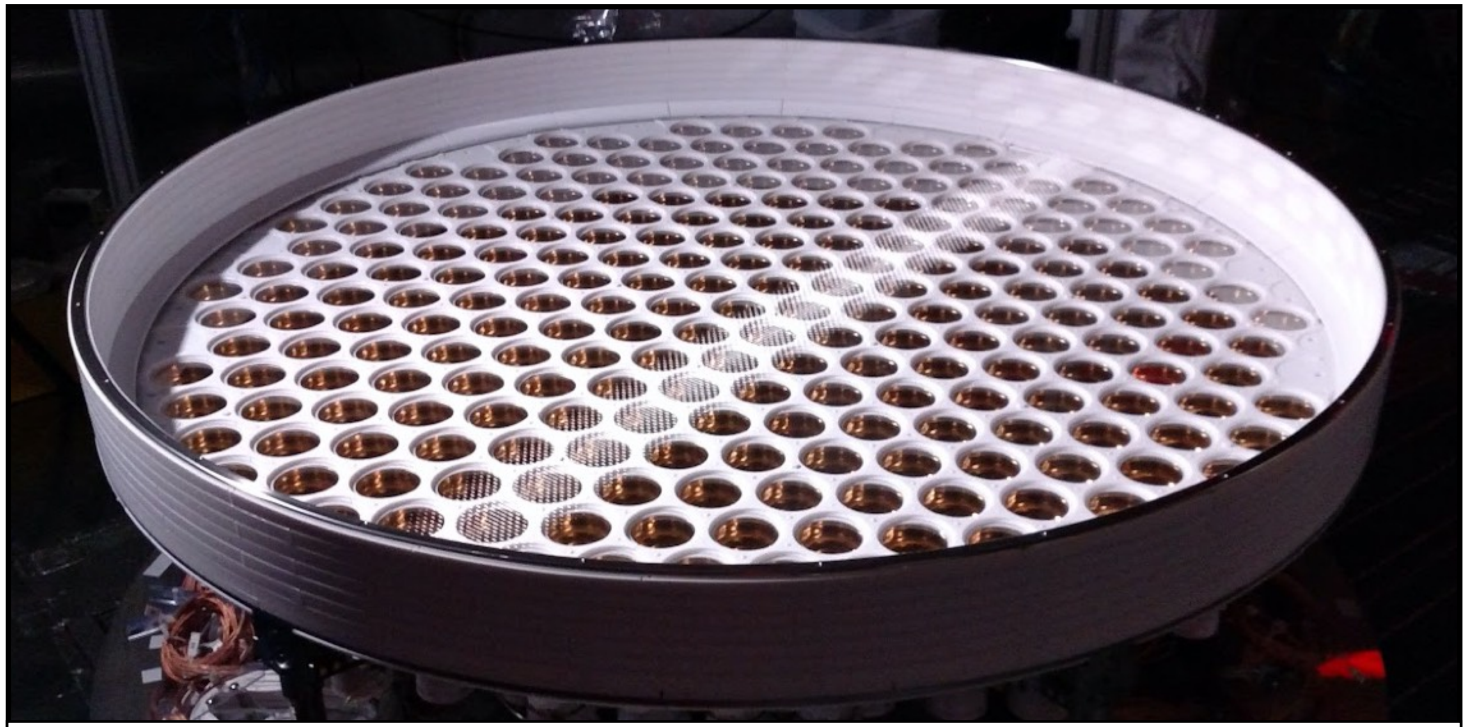


The LZ TPC



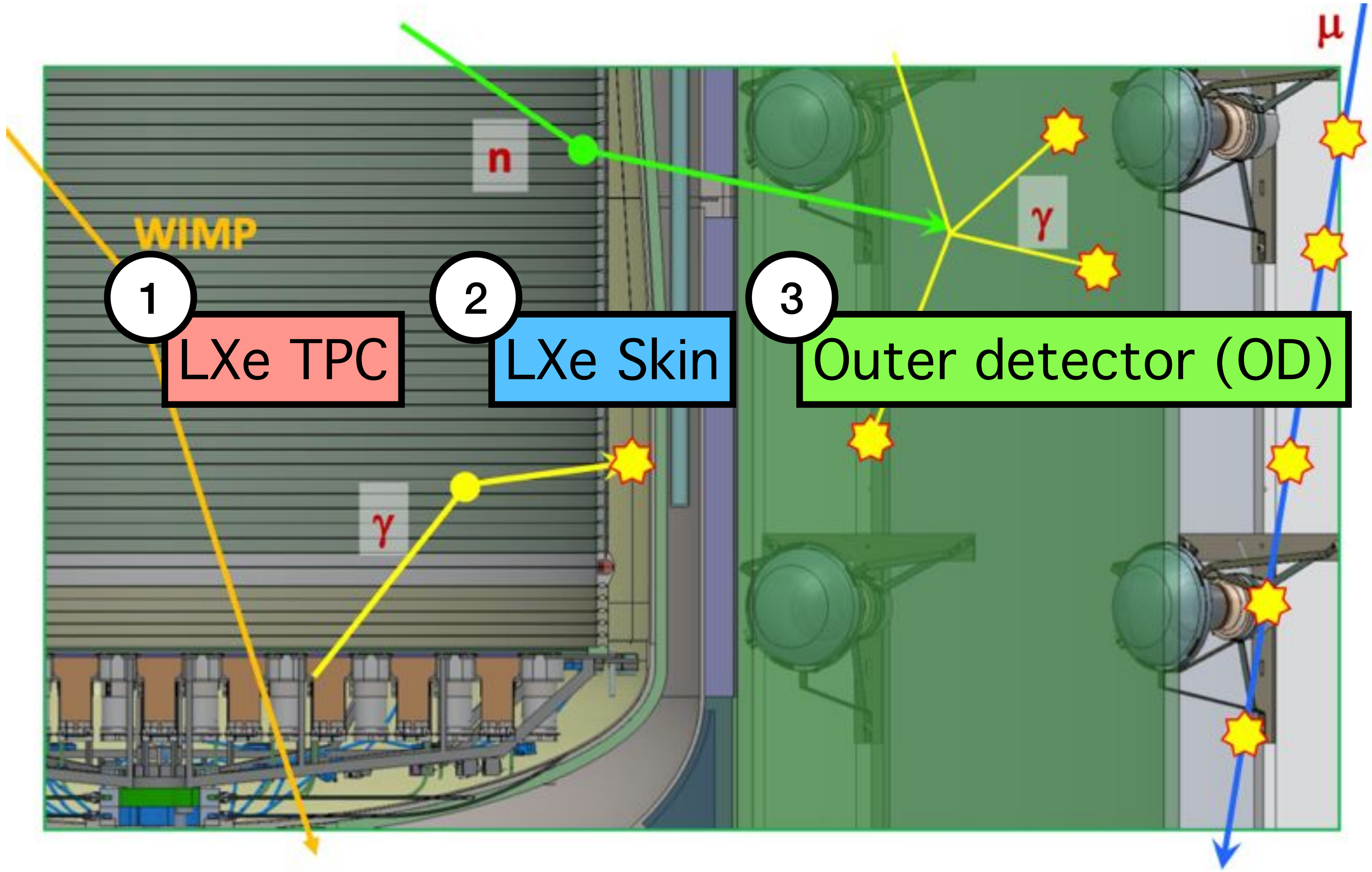
Construction in radon reduced clean room at surface assembly lab completed in 2019

- 1.5 m diameter x 1.5 m height
- 7 t liquid xenon target
- PTFE construction for light collection
- 494 3” PMTs in two arrays on top and bottom
- 4 grids (bottom, cathode, gate, anode)
- Field cage to define TPC
- 3 spill-over weirs to define liquid surface



Bottom PMT array and cathode electrode during construction

3-in-1 integrated detector system



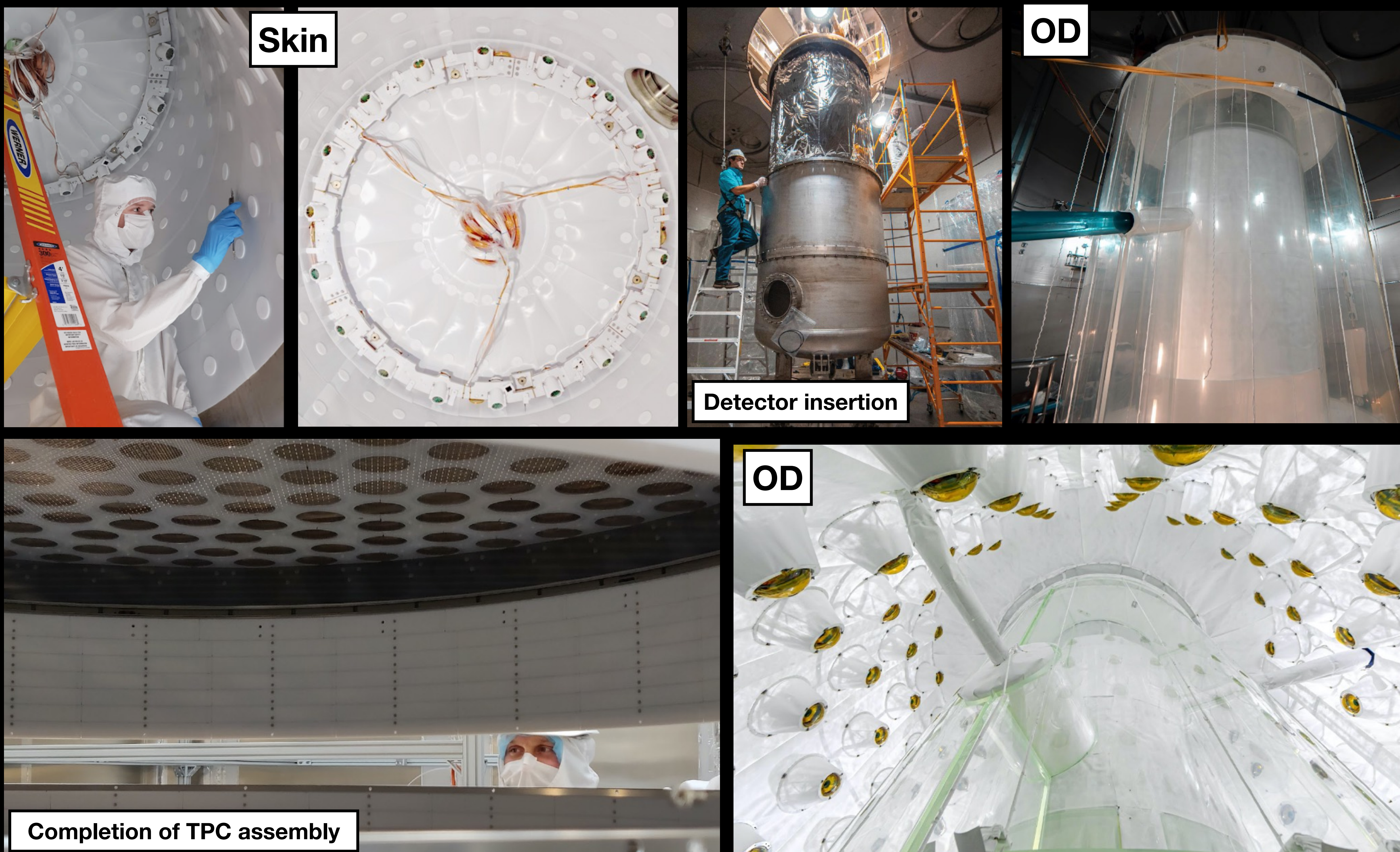
LXe Skin

- 2 t 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 t of Gd-loaded liquid scintillator in acrylic vessels
- 120 8” PMTs mounted in the water tank
- Anti-coincidence detector for γ-rays and neutrons (89% tagging efficiency, measured in situ with AmLi neutrons)

Picture round!



The LZ timeline

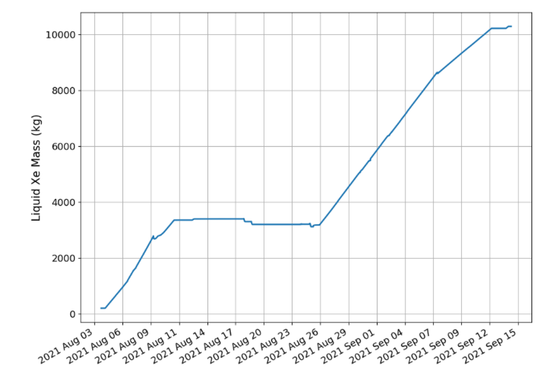
TPC assembled
Aug 2019

Circulation Test
July 2020

Electronics installation
Fall 2020

Kr Reduction
Jan-Aug 2021

Xenon Fill
Aug-Sep 2021



Commissioning
Fall 2021

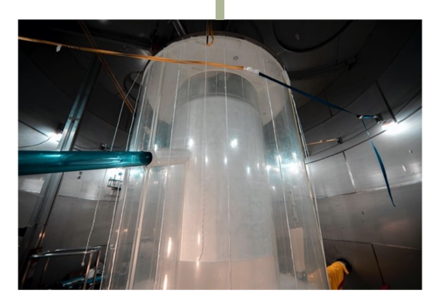
2019 **2020** **2021** **2022**

First science

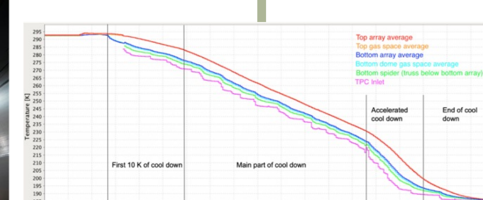
Detector construction at surface lab
Aug 2018 – Aug 2019

TPC moves underground
Oct 2019

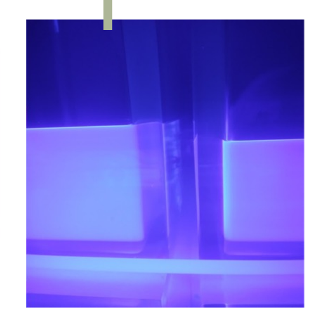
Detector sealed up
March 2020



OD Construction
Winter 2020-2021



Cold Xe gas,
March 2021

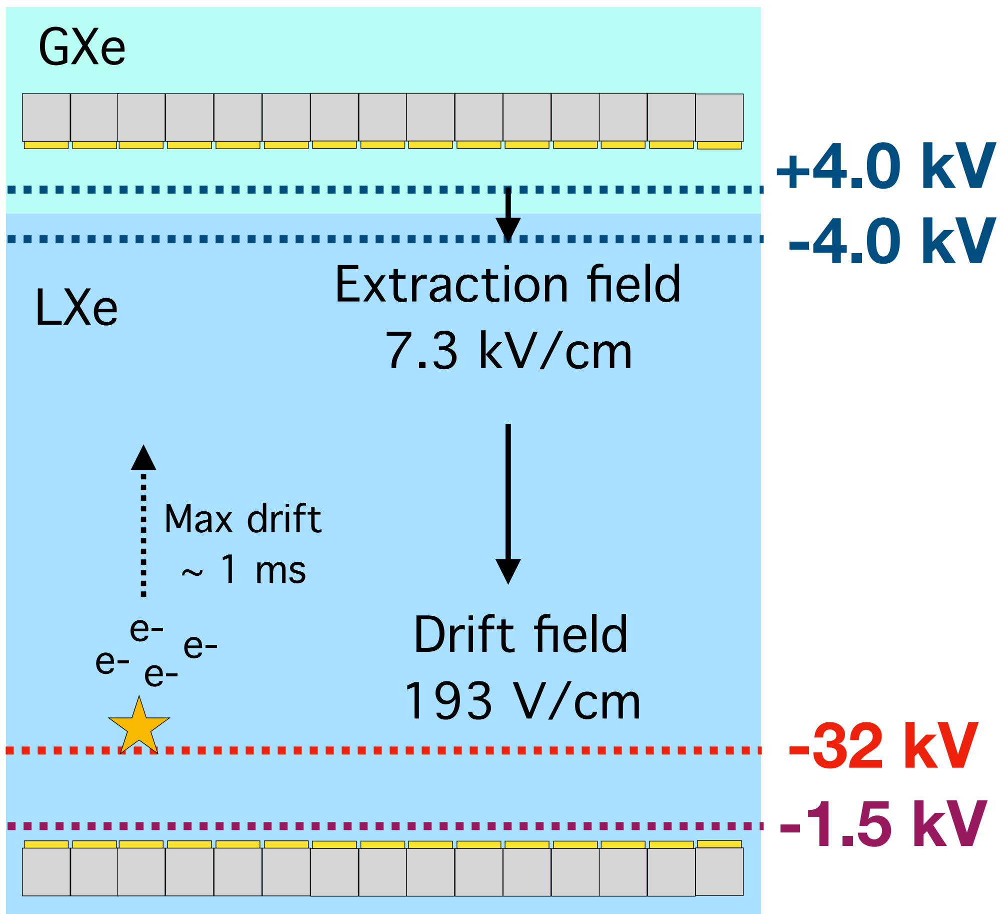


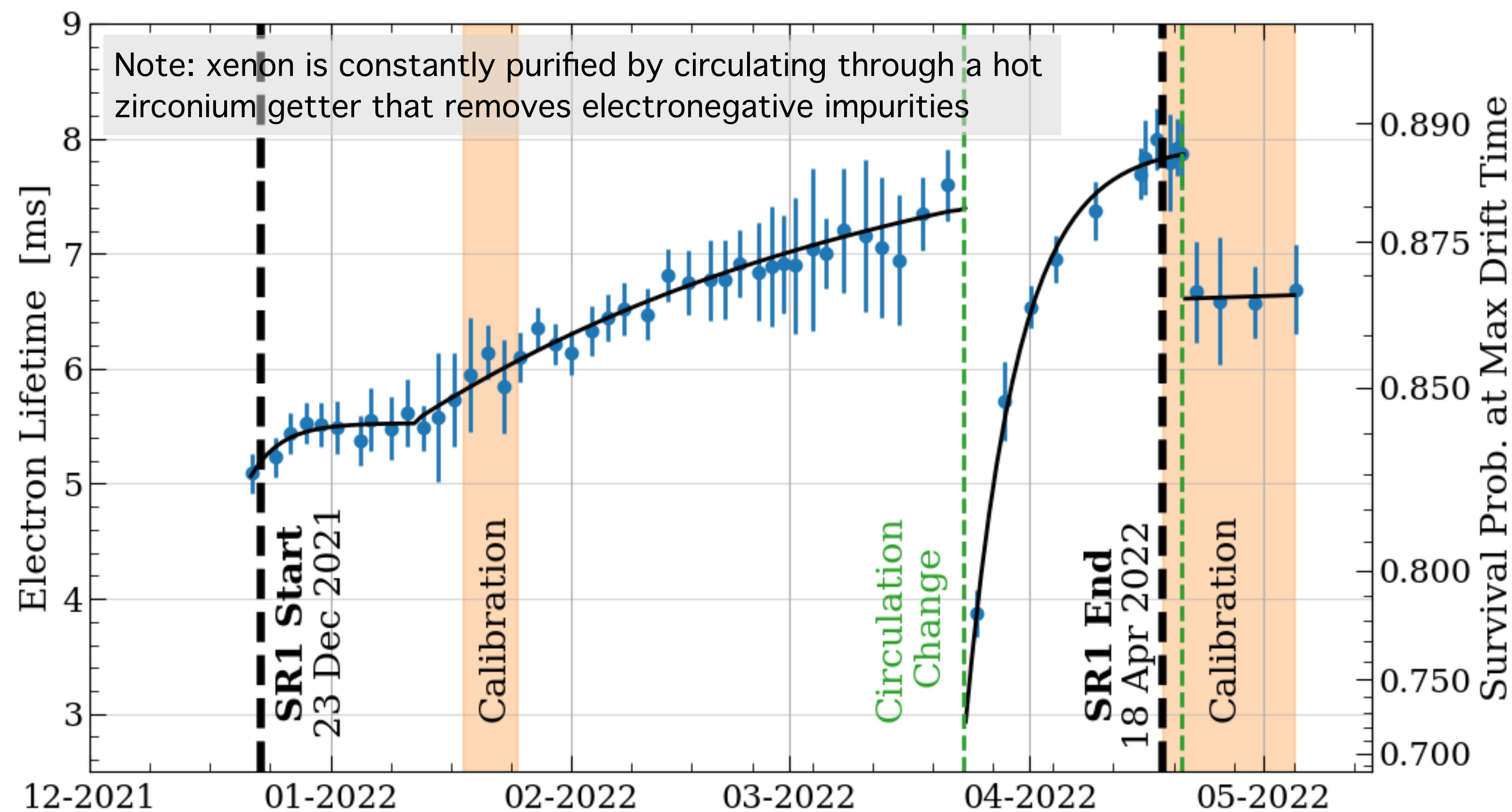
OD Fill
June 2021

Part 2: First Science Run (SR1)

Run conditions

Goal: Demonstrate physics capability of the LZ detector





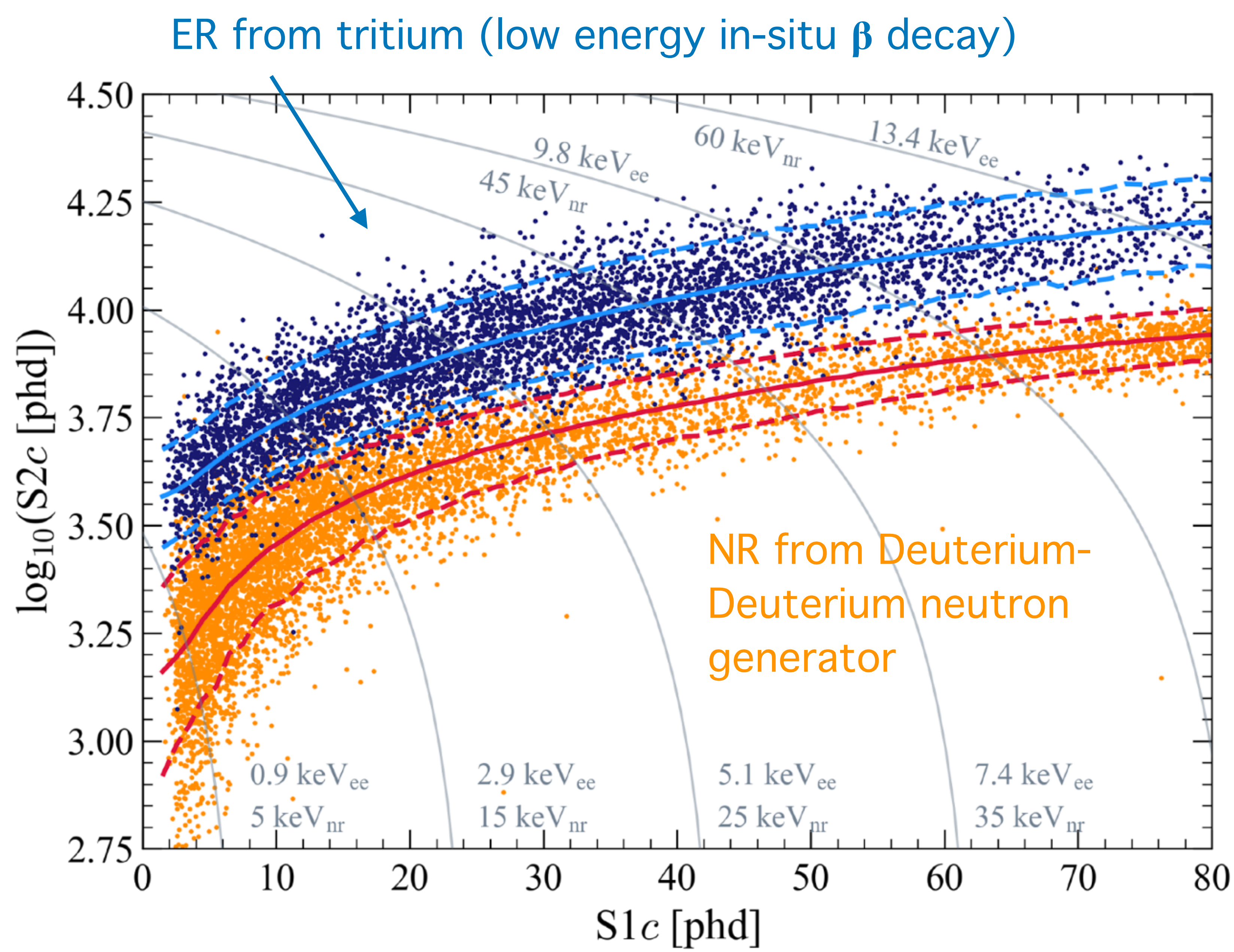
- Data from Dec 23rd ’21 to May 12th ’22
- Mid-run and post-run calibrations
- <u>WIMP search live time = 60 days</u>
- Data not blinded, but analysis developed in side bands and/or calibration data
- > 97% of PMTs operational
- Liquid T = 174.1 K (0.02% variation)
- Gas P = 1.791 bar(a) (0.2% variation)
- Liquid level stable within 10 microns
- Gas Circulation ~ 3.3 t/day

A comprehensive detector model

- NEST(*)-based electron recoil model tuned to tritium data, then propagated to nuclear recoil model and verified with DD data.
- GEANT4-based simulation framework allows us to model backgrounds and signals (Astro Part Phys 102480).

Detector parameters

- Light gain, g1 = 0.114 ± 0.002 phd/photon
- Charge gain, g2 = 47.1 ± 1.1 phd/electron
- Single electron size = 58.5 phd
- ER / NR discrimination = 99.9% for 40 GeV/c² WIMP



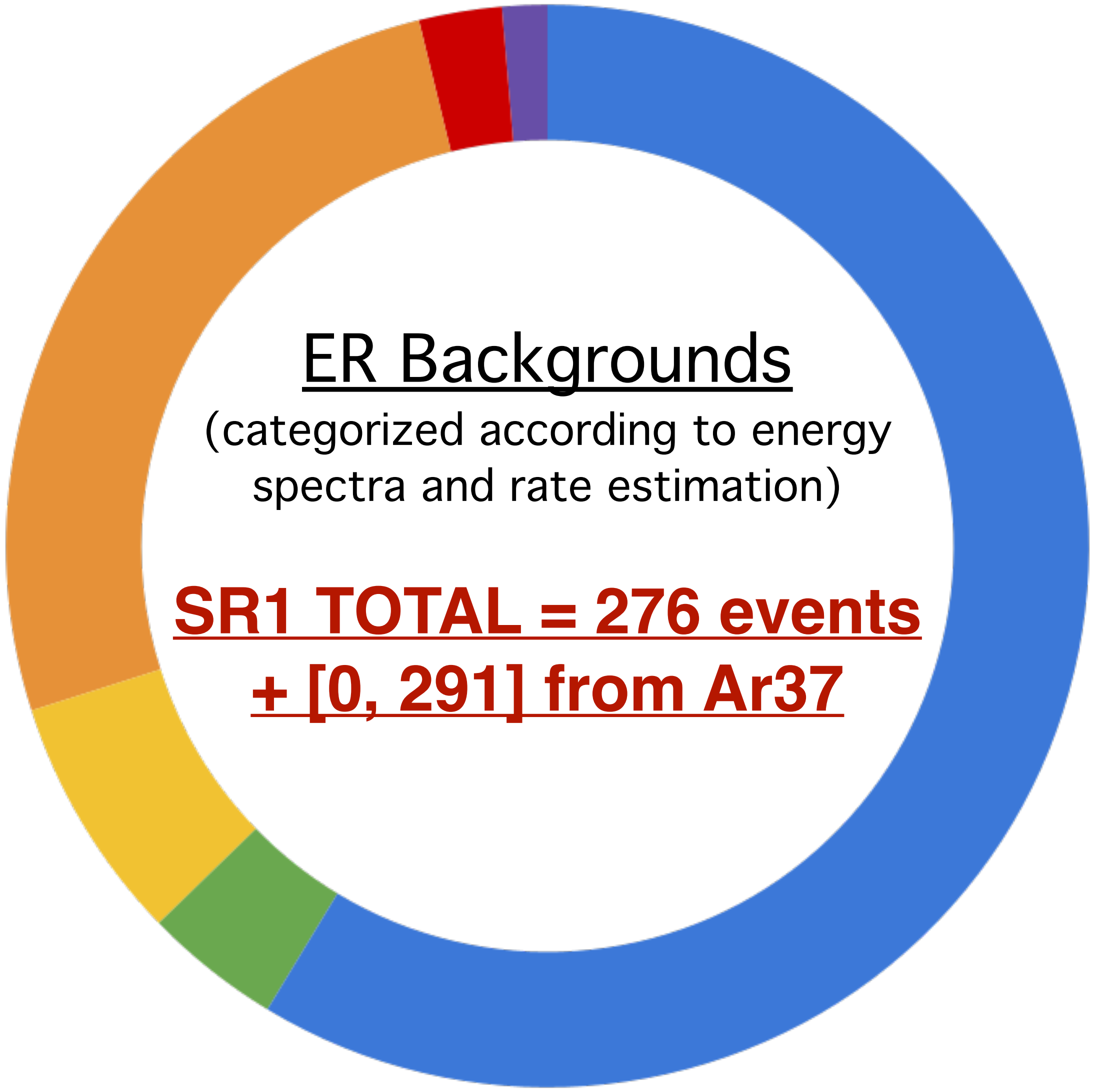
(*) https://nest.physics.ucdavis.edu/

Background model

LZ backgrounds: Phys. Rev. D 108, 012010

Xenon contaminants

- Pb214 (Rn222)
- Pb212 (Rn220)
- Kr85
- Xe136 ($2\nu\beta\beta$)
- Ar37
- Xe127
- Xe124 (double e-capture)



Solar neutrinos (ER)

- pp + Be7 + N13

Detector materials (ER)

- γ-rays from U238, Th232, K40, Co60 contamination

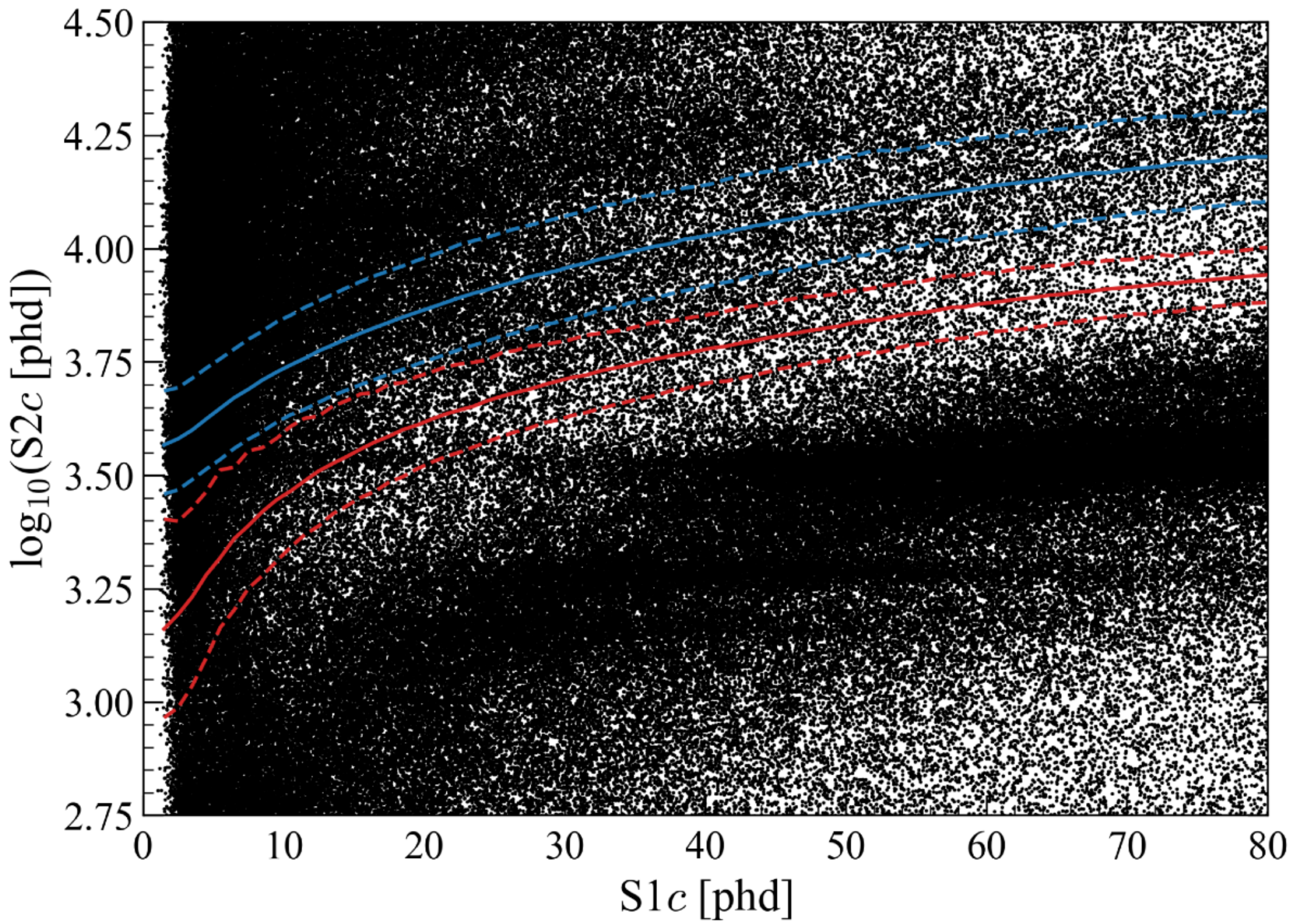
NR Backgrounds

- B8 Solar Neutrinos
- Neutrons from detector materials - (α, n) or spontaneous fission.
- **SR1 TOTAL = 0.15 events**

Accidental coincidences of isolated S1 and S2 pulses - effectively eliminated after analysis selections

Data analysis

- Right: all single scatter interactions in the TPC - no other selections. Can you see the WIMPs?
- Put differently: need to distill O(10^8) events captured throughout SR1.



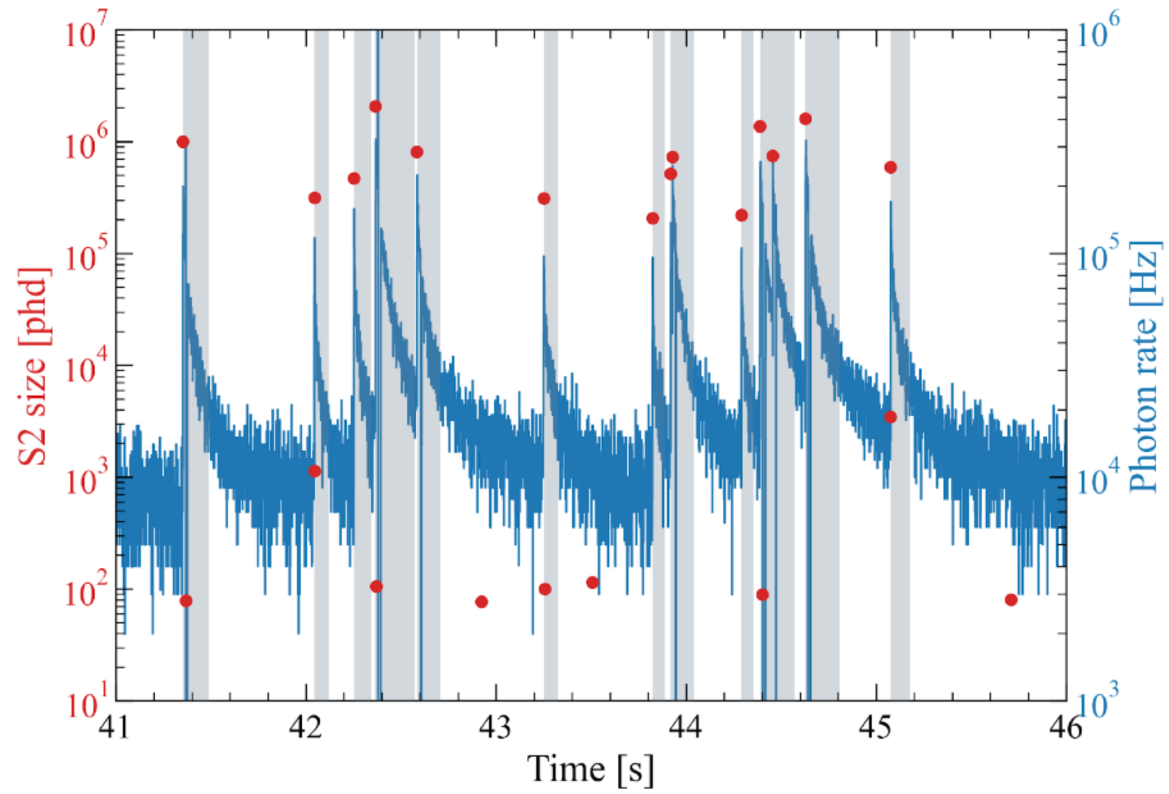
Data quality analysis

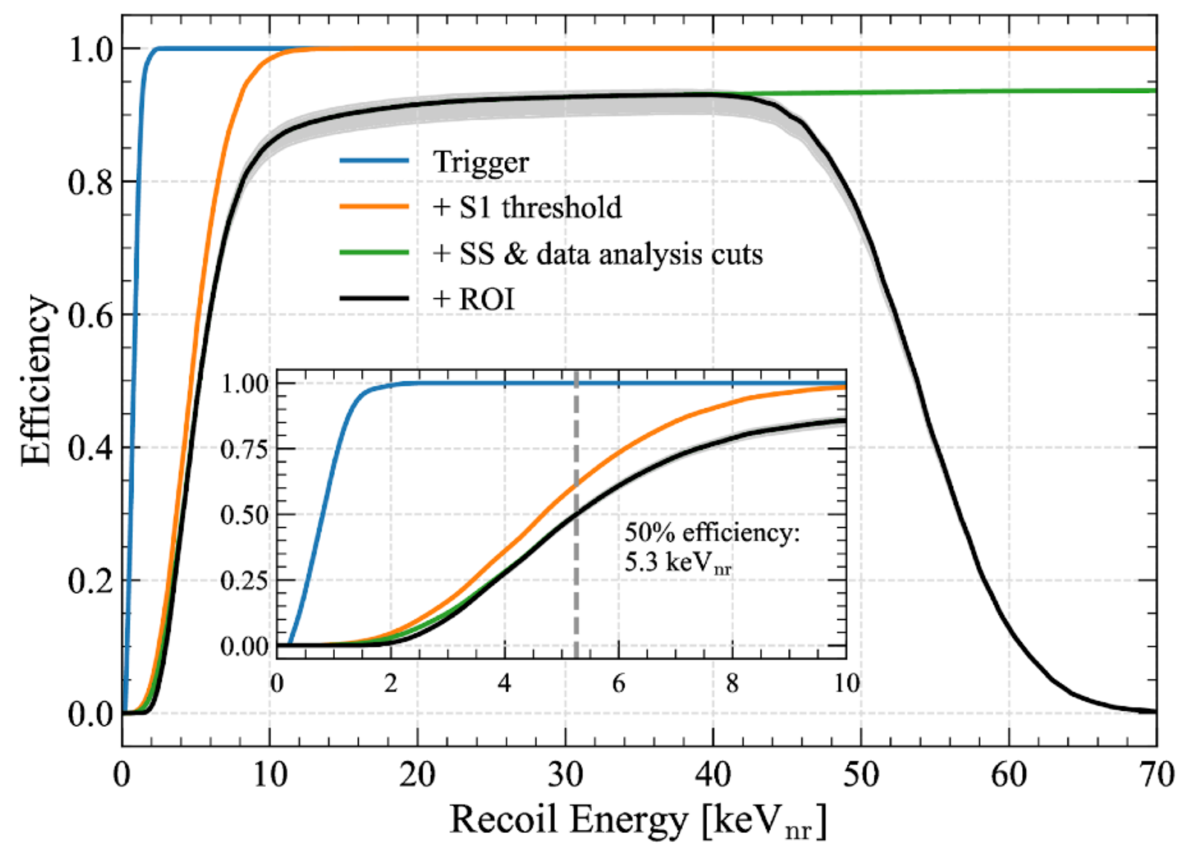
- Two broad categories of data selections allow us to remove data based on bad quality:

  1. Time-based:
  - Exclude periods with high rates of spurious activity (e.g. electron and photon emission)

  2. Pulse-based:
  - Exclude events based on outlier pulse characteristics
  - Impacts signal acceptance - studied using tritium and AmLi calibration data
  - 50% efficiency at 5.3 keV nuclear recoil energy

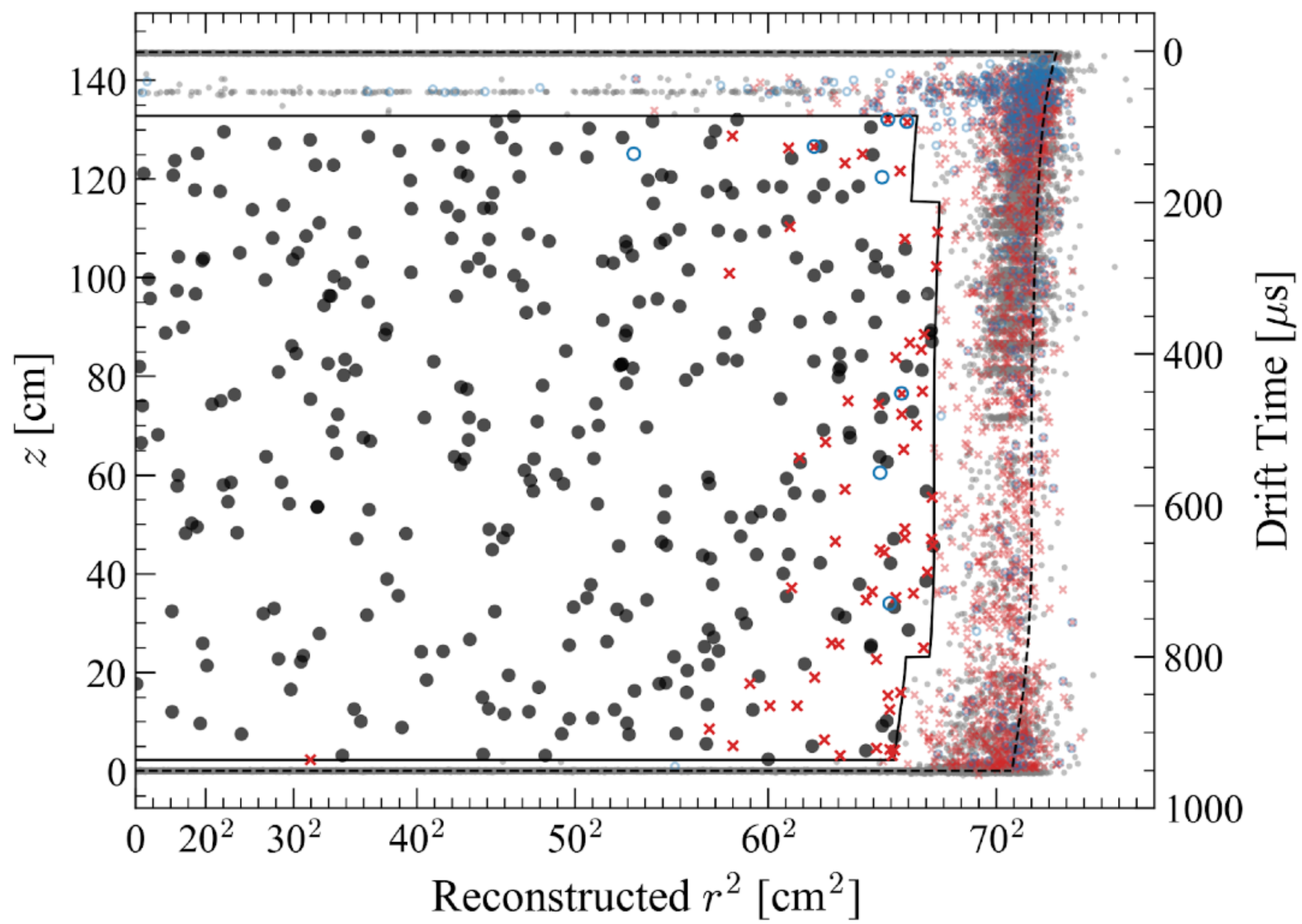
<u>All cuts developed on calibration data or search data outside the WIMP search region of interest</u>





Fiducial volume and vetoes

- S2 charge-loss close to TPC wall leads to poor position resolution at radial boundary
  - Choose a central fiducial volume simultaneously with S2 threshold to make 'wall backgrounds' negligible for this analysis
  - 5.5 t fiducial mass (measured by uniformly dispersed tritium source)



● = pass all selections (candidates), ● = pass all sections outside fiducial volume, X = skin tagged, ◯ = OD tagged

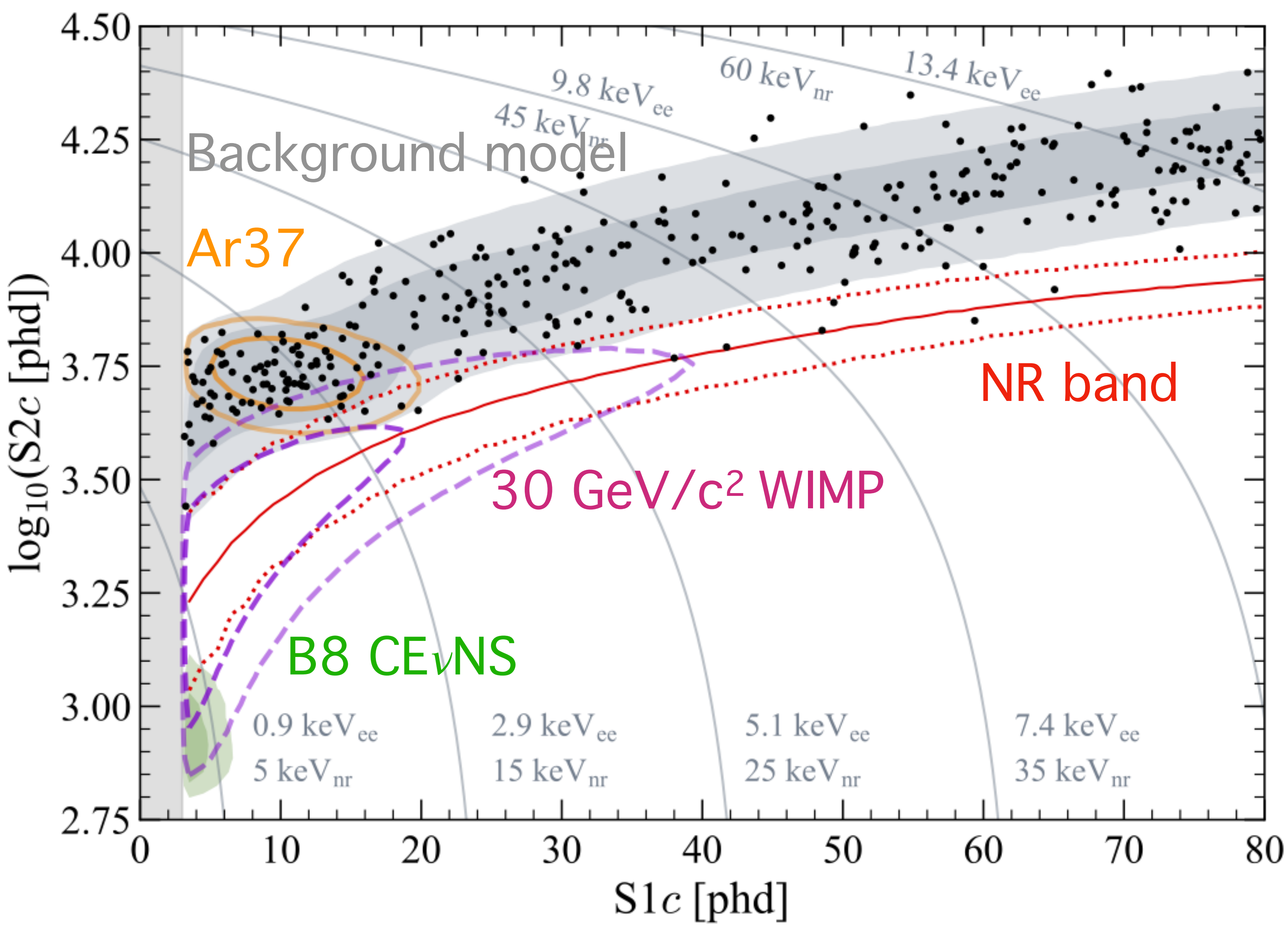
- Prompt (< 0.5 μs) Skin and OD tag:
  - Reduces naked L-, M-shell Xe127 background by x5 by tagging γ-rays that escape the TPC

- Delayed OD (and skin) tag:
  - 1200 μs window, ~ 200 keV threshold for n-capture tag - 5% false veto rate
  - Constraint on neutron background $0^{+0.2}$ for this analysis

The final dataset

- 335 events in the final dataset
- Define a WIMP search 'region-of-interest' for a Profile Likelihood Ratio (PLR) analysis:
  - 3 phd < S1c < 80 phd
  - S2 > 600 phd (~ 10 extracted electrons)
  - S2c < 10^5 phd

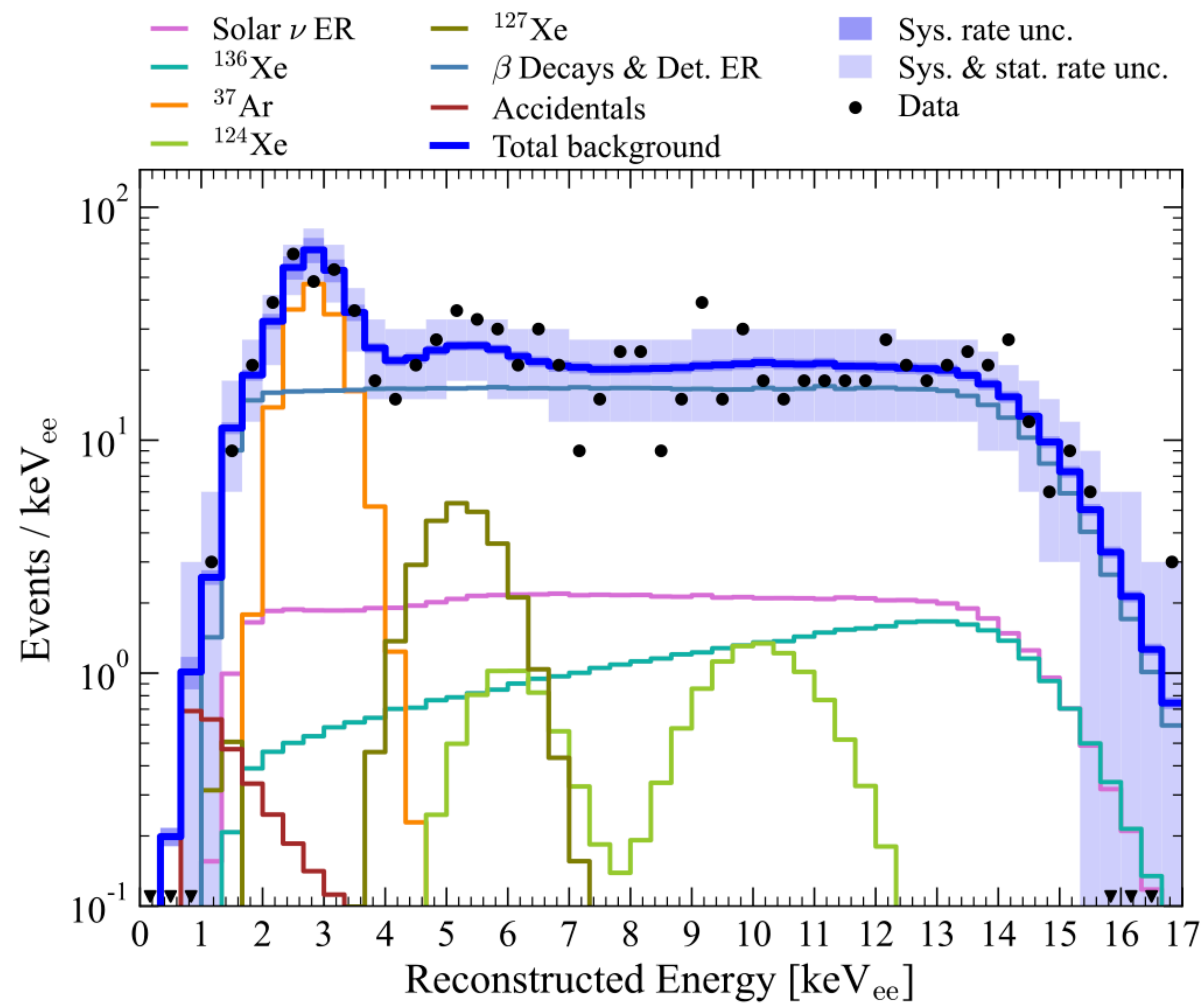
60 live days, 5.5 t fiducial volume, 0.9 t years exposure



Results - best fits

Best fit of <u>zero</u> WIMP events at all masses, p-value = 0.96

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



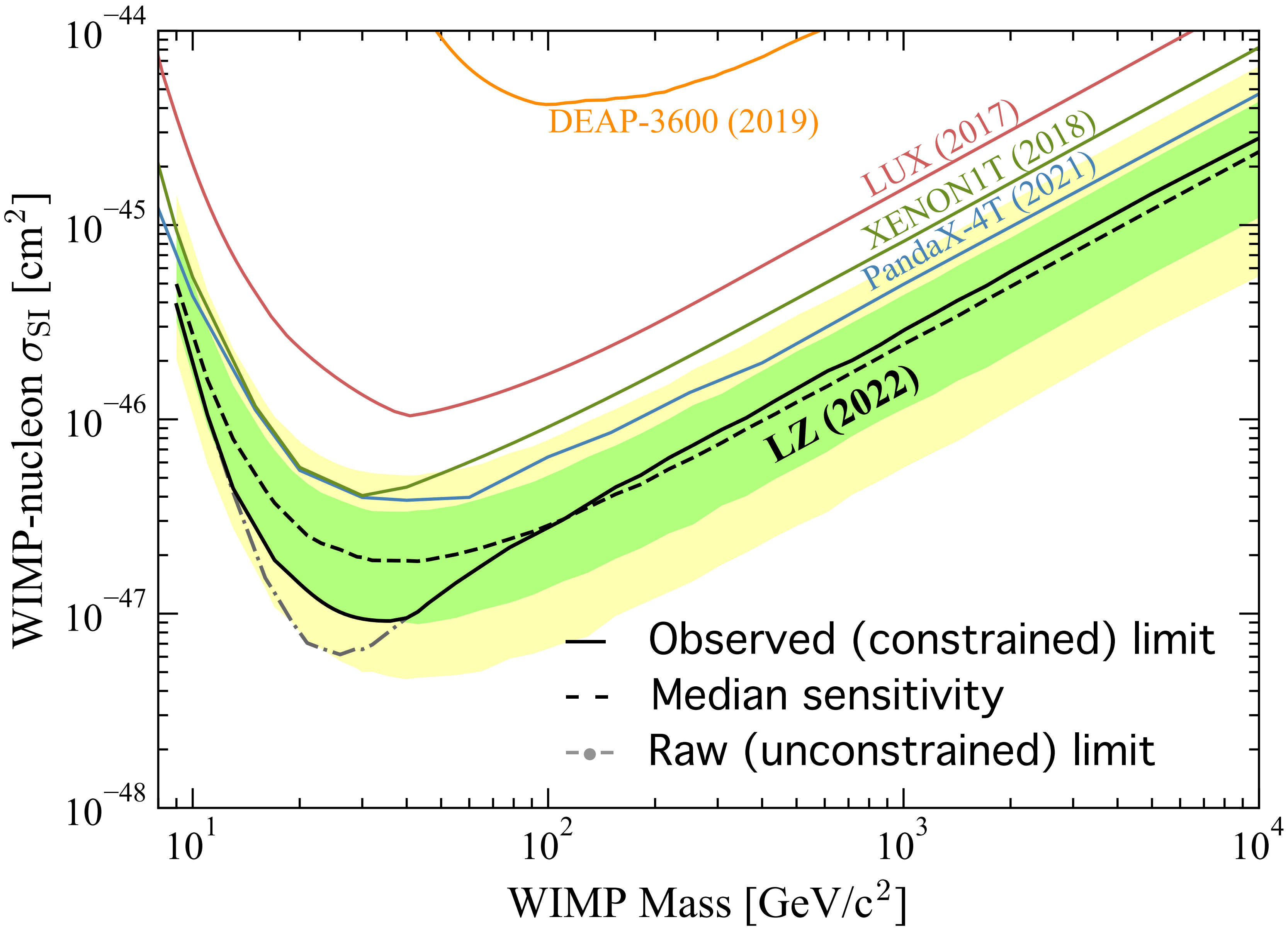
Combined fit to data with expected events as priors

Expected from LZ background studies (energy sidebands), auxiliary datasets (e.g. measured half lives, rate predictions from other data or simulations)

WIMP-nucleon upper limits (SI)

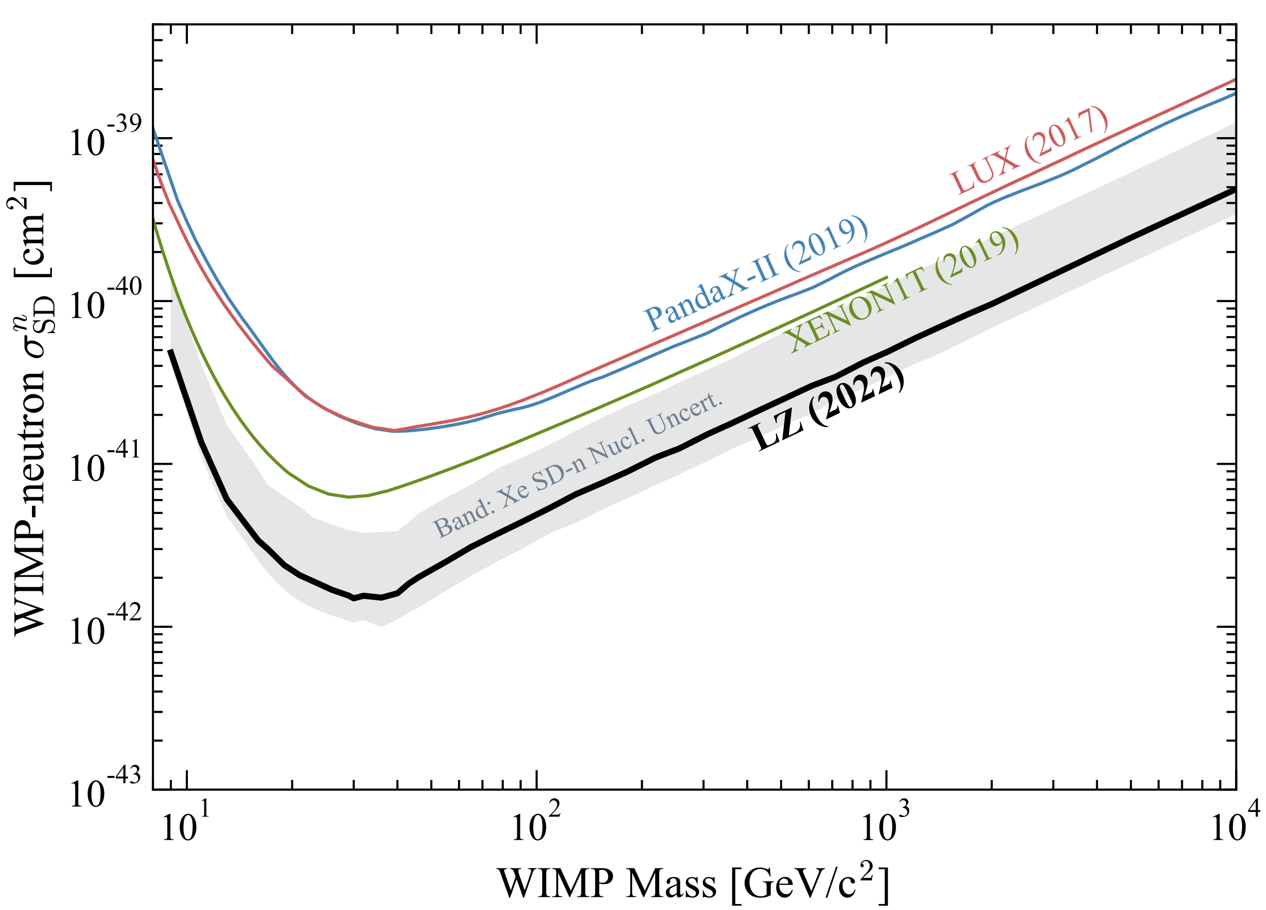
Phys. Rev. Lett. 131, 041002

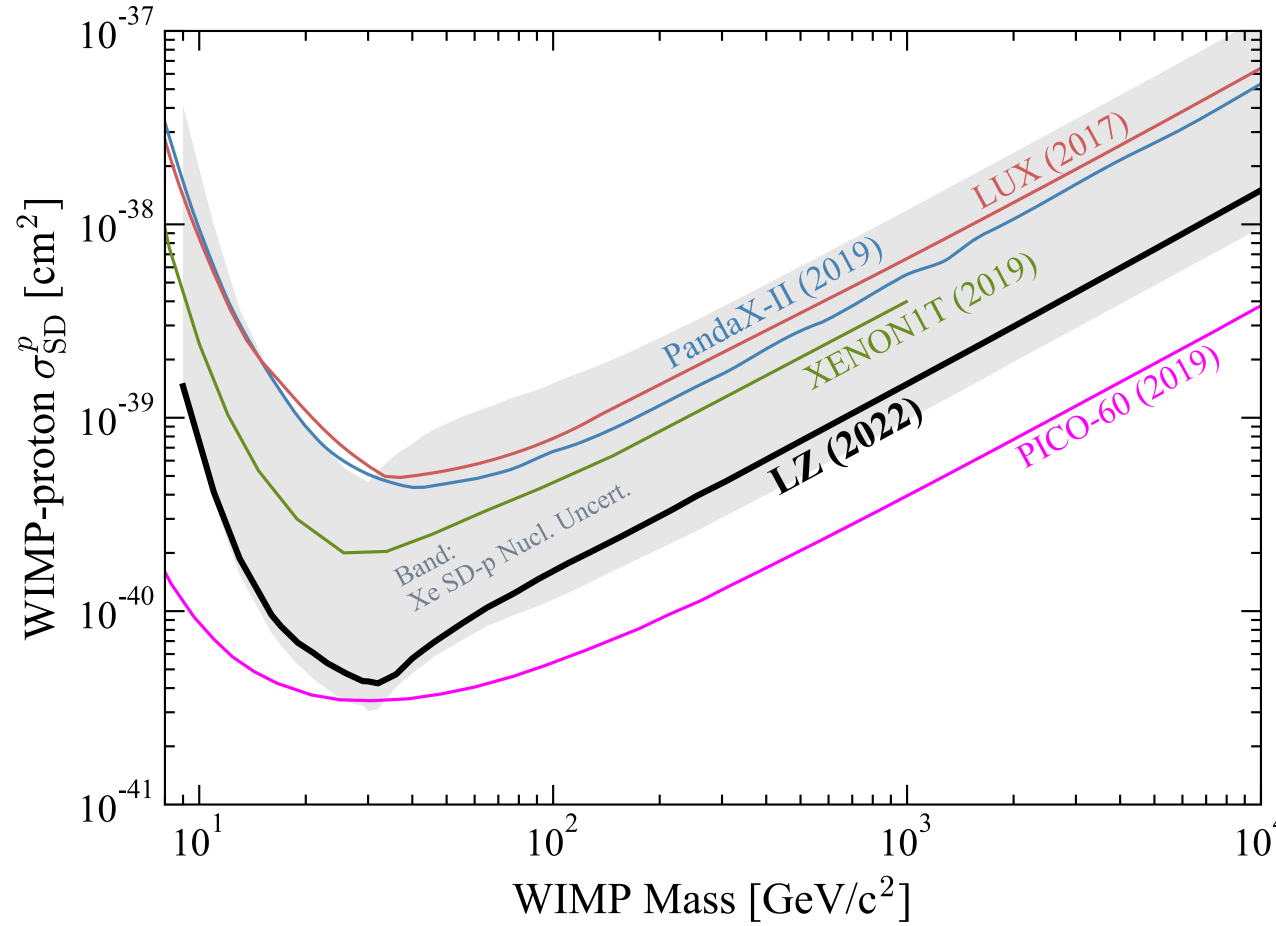
- Frequentist, 2-sided PLR test statistic
- Power constrain at -1σ sensitivity band to account for discovery power
- Best limit of $\sigma_{SI} = 9.2 \times 10^{-48}$ at 36 GeV/c^2
- Green and yellow are the 1σ and 2σ median sensitivity bands.
- Assume a spin independent (scalar) WIMP-nucleon interaction



WIMP-n, WIMP-p upper limits

[Phys. Rev. Lett. 131, 041002]



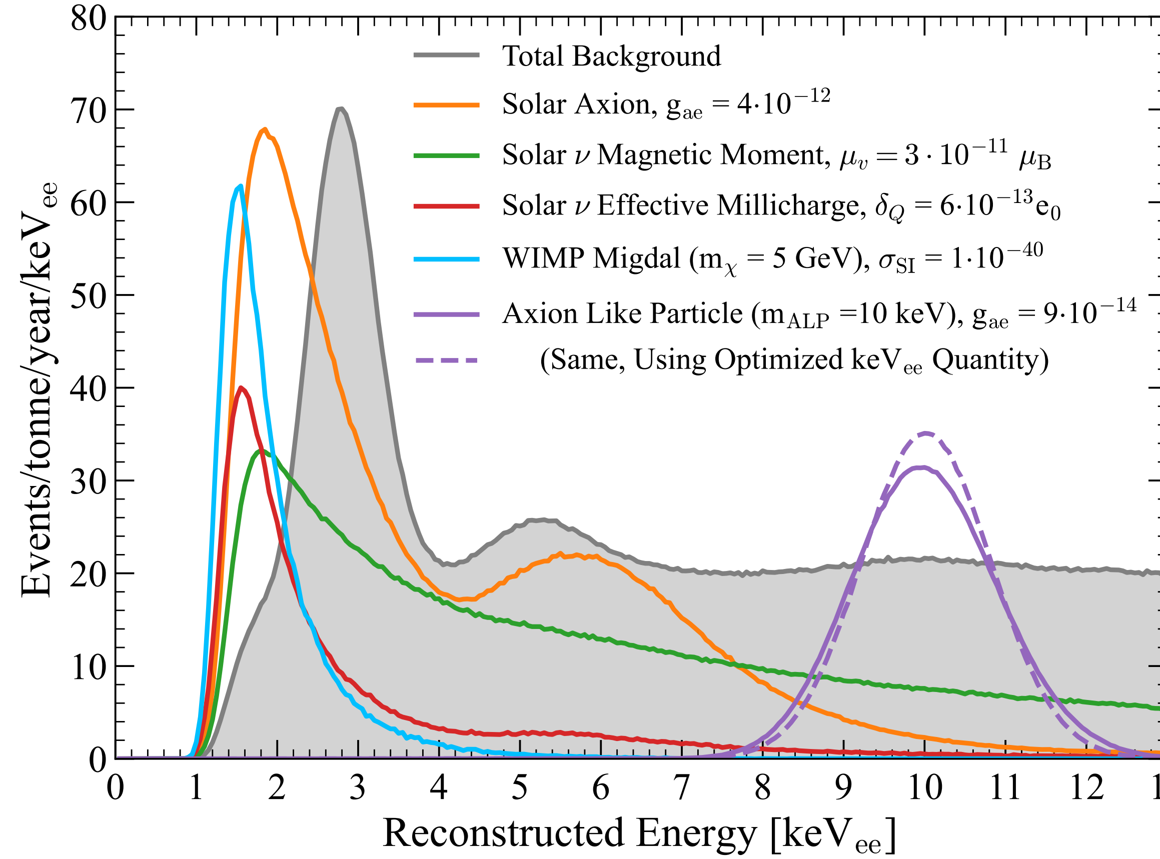


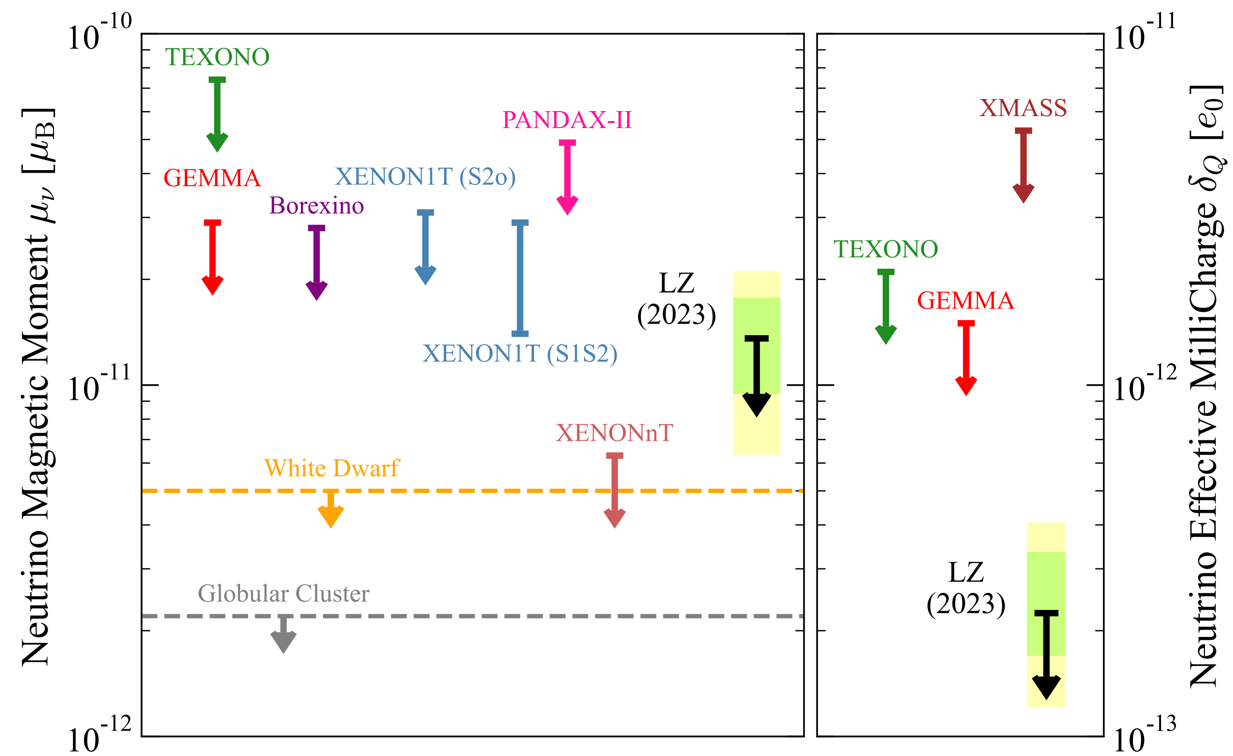
- Same statistical treatment as spin-independent case
- Assume a spin dependent WIMP-proton and WIMP-neutron interaction
- Xe has two isotopes with non-zero nuclear spin (both with unpaired neutrons)
  - WIMP-proton sensitivity through higher-order nuclear effects
  - Grey uncertainty band due to theoretical uncertainties on nuclear structure factors. A similar uncertainty applies for all other xenon experiments on this plot (i.e. PandaX-II, LUX, and XENON1T).

Searches for low-energy electron recoils

Phys. Rev. D 108, 072006

- Analyses in the electron recoil channel can probe other dark matter candidates and Beyond Standard Model (BSM) physics.
  - Same datasets as SR1 WIMP-search.
  - Same analysis selections.
  - Same detector model and simulations.
  - Time added as a parameter to statistical inference capitalize on Ar^{37} ($t_{1/2}$ = 35.0 d) and Xe^{127} ($t_{1/2}$ = 36.3 d) rate decay.
- Results are consistent with XENONnT (Phys. Rev. Lett. 129, 161805); ruling out the low-energy ER excess reported by XENON1T (Phys. Rev. D 102, 072004).
- New limits on Solar Axions, ALPs, Hidden Photons and Solar Neutrino Magnetic Moment. World-leading limit on Neutrino Effective MilliCharge.
- New LZ WIMP-scattering limits for masses between 0.5 - 9.0 GeV/c² using the Migdal Effect.

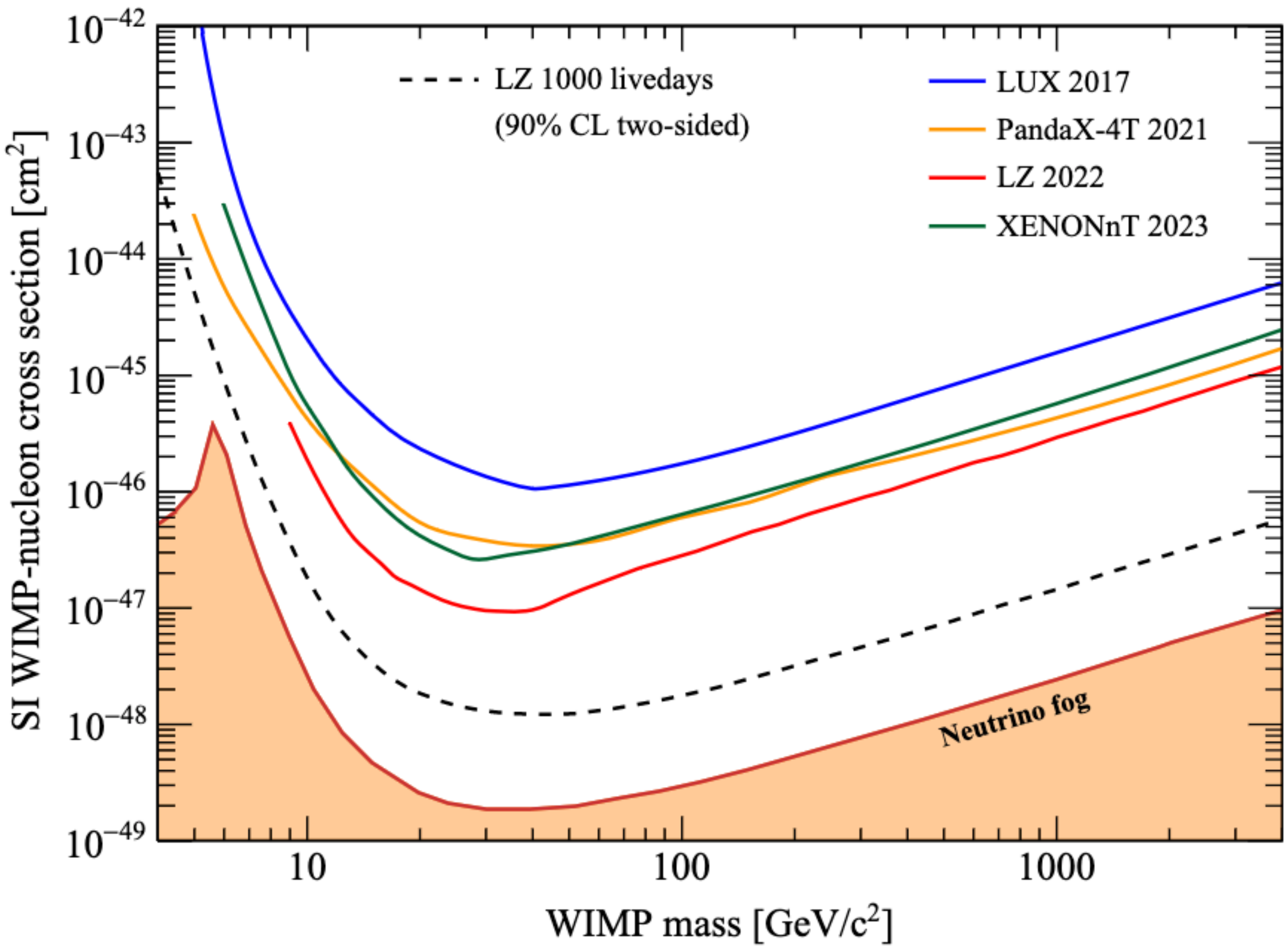




Part 3: Future Prospects

LZ can detect dark matter!

- SR1 result represents 6% of the planned LZ exposure (1000 live days).
- Since SR1: detector optimizations and extensive calibrations completed. Began a long science run in 'discovery mode' with experimenter bias mitigation (salting).



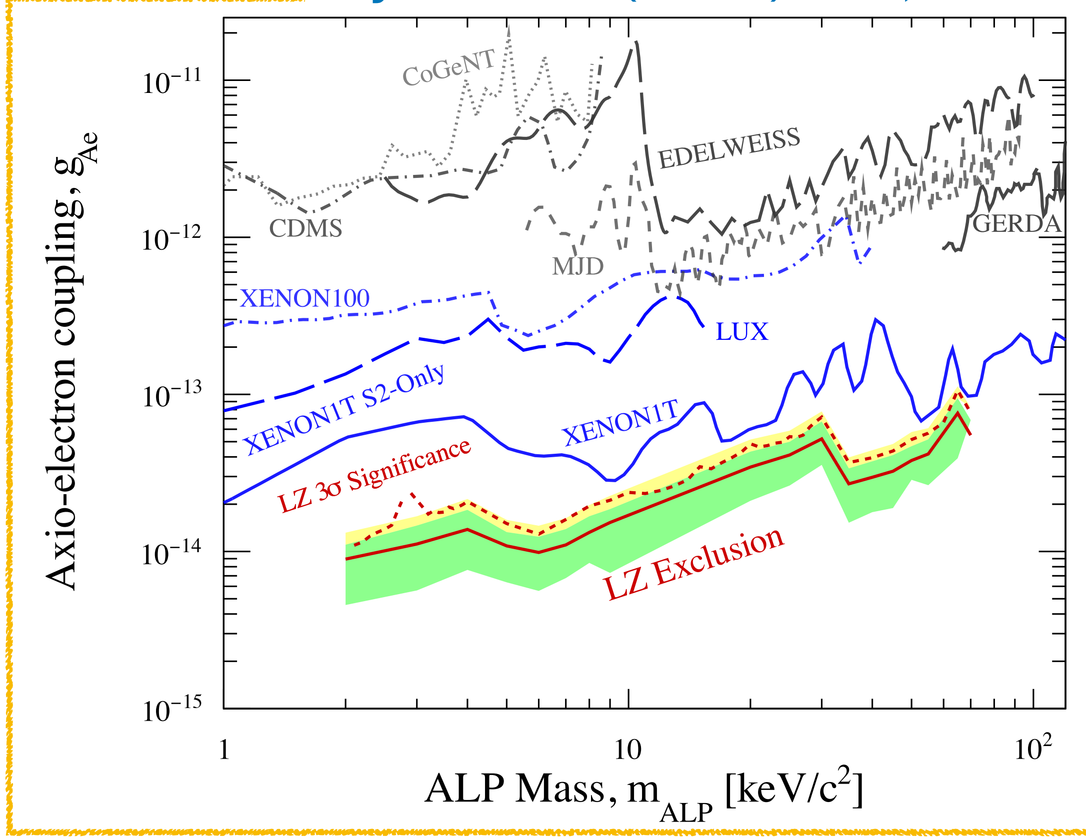
90% CL minimum (one sided) 1.4 x 10^{-48} cm^2 at 40 GeV/c^2

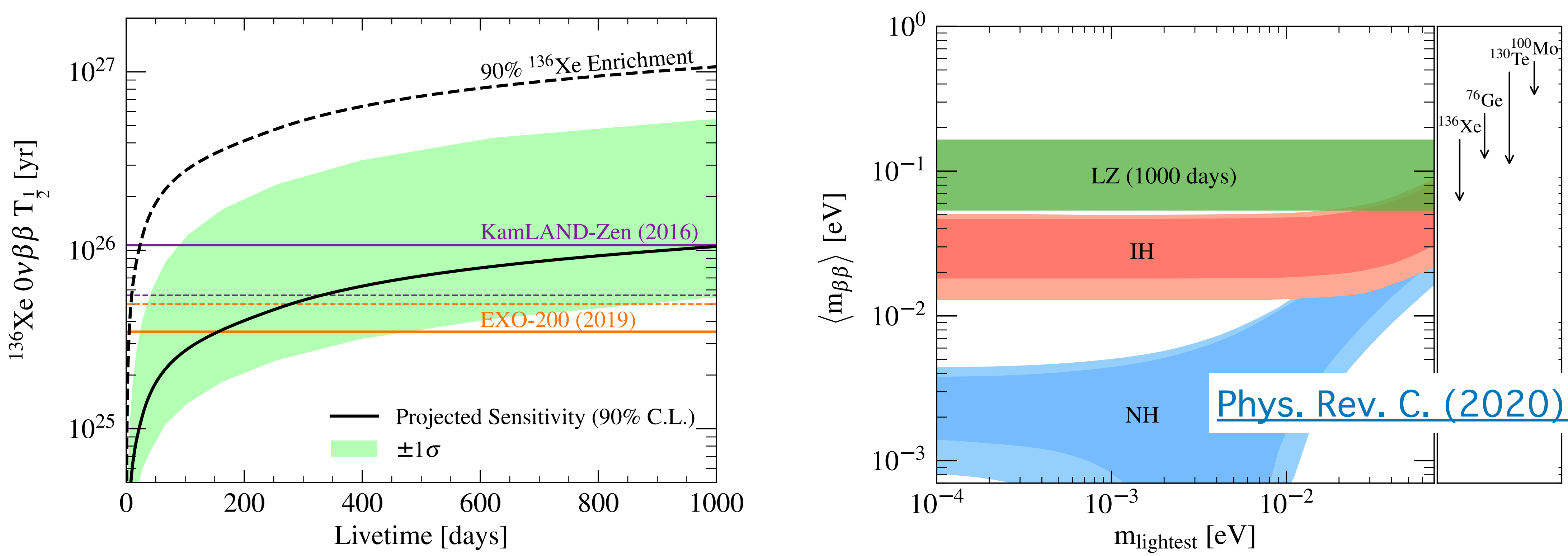
[Phys. Rev. D 101 (2020), 052002]

Other LZ science searches

- Upcoming, from SR1 data:
  - Searches for WIMPs in Effective Field Theories
  - Ultra-heavy dark matter / multiply ionizing massive particles (see Ibles O at Riken/N3AS Workshop).
- Beyond SR1:
  - Axions and Axion-Like-Particles (full exposure)
  - Rate modulation searches
  - 'S2-only' searches (low mass WIMPs)
  - Neutrinos: B^8 CEvNS, $0\nu\beta\beta$ Xe^{134}, $0\nu\beta\beta$ Xe^{136}

Phys. Rev. D (2021) 104, 092009



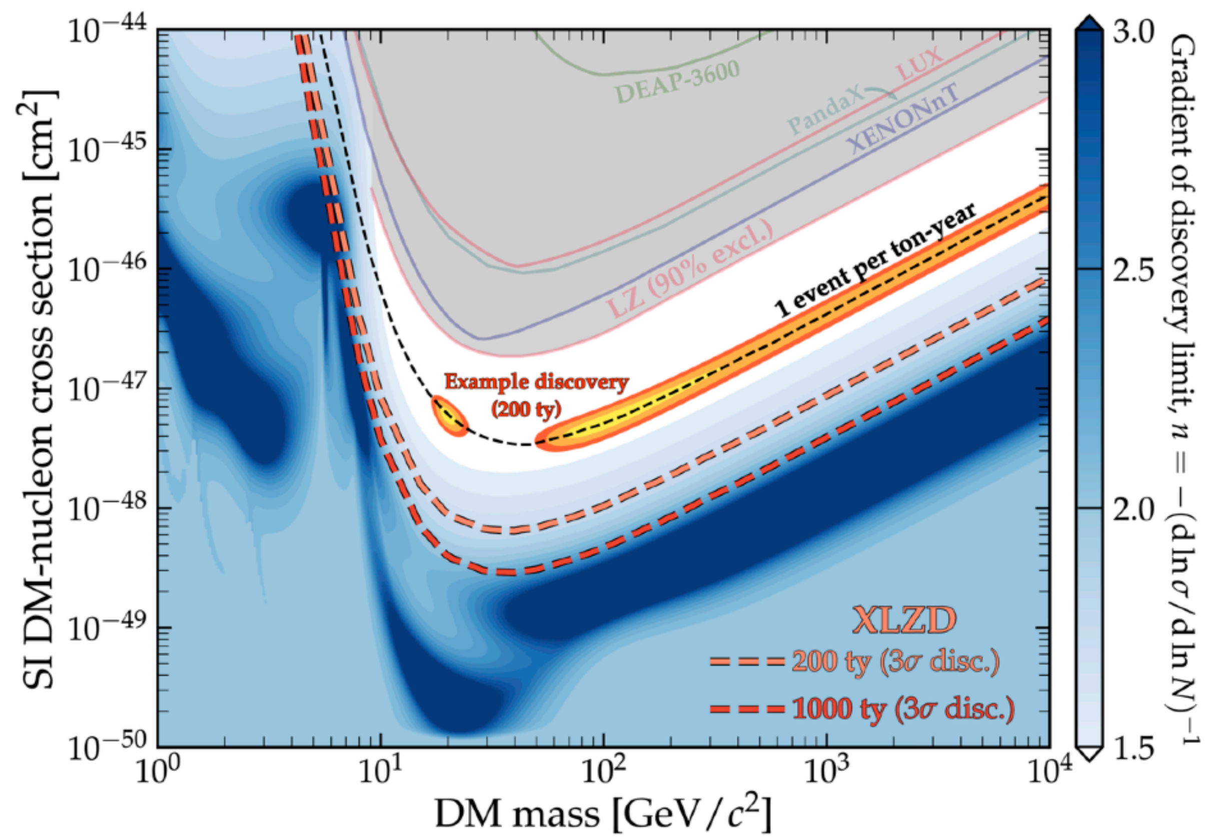


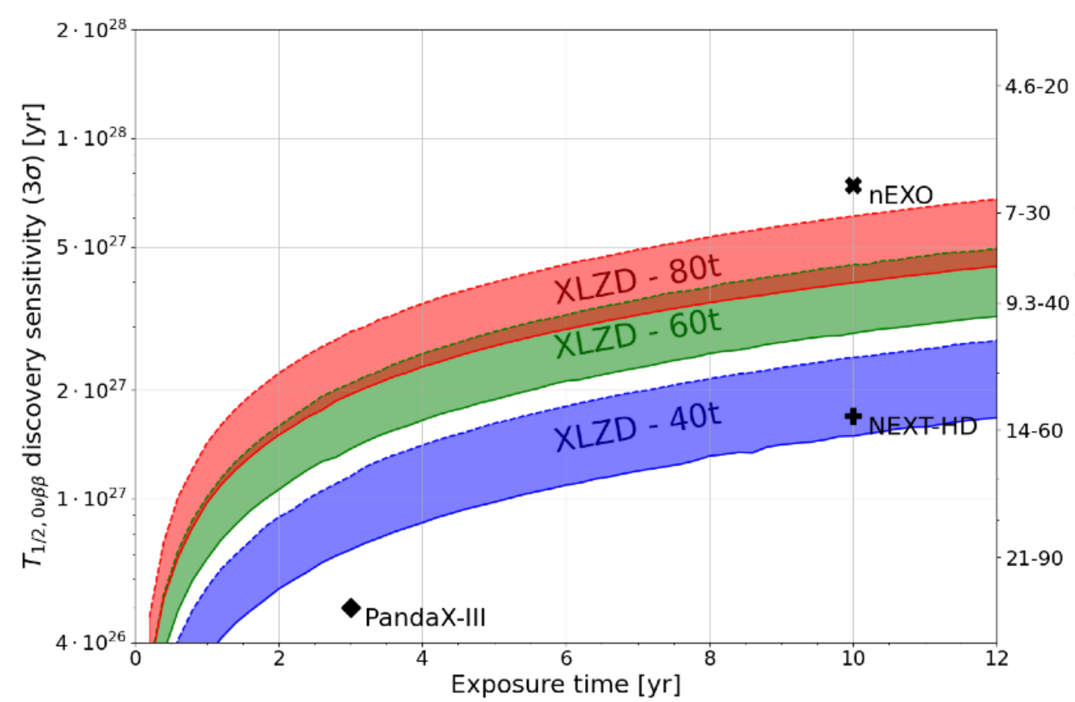
Phys. Rev. C. (2020) 102, 014602

XLZD - next generation liquid xenon experiment

[J. Phys. G: Nucl. Part. Phys. 50 013001](#)

- XENON, LZ and DARWIN collaborations working toward a G3 xenon observatory - consortium formed in 2022
- Multiple major science goals:
  - Test WIMP hypothesis all the way to the ‘neutrino fog’
  - Test other dark matter candidates
  - Neutrinoless double beta decay
  - Atmospheric neutrinos





Thank you for listening! Questions?

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

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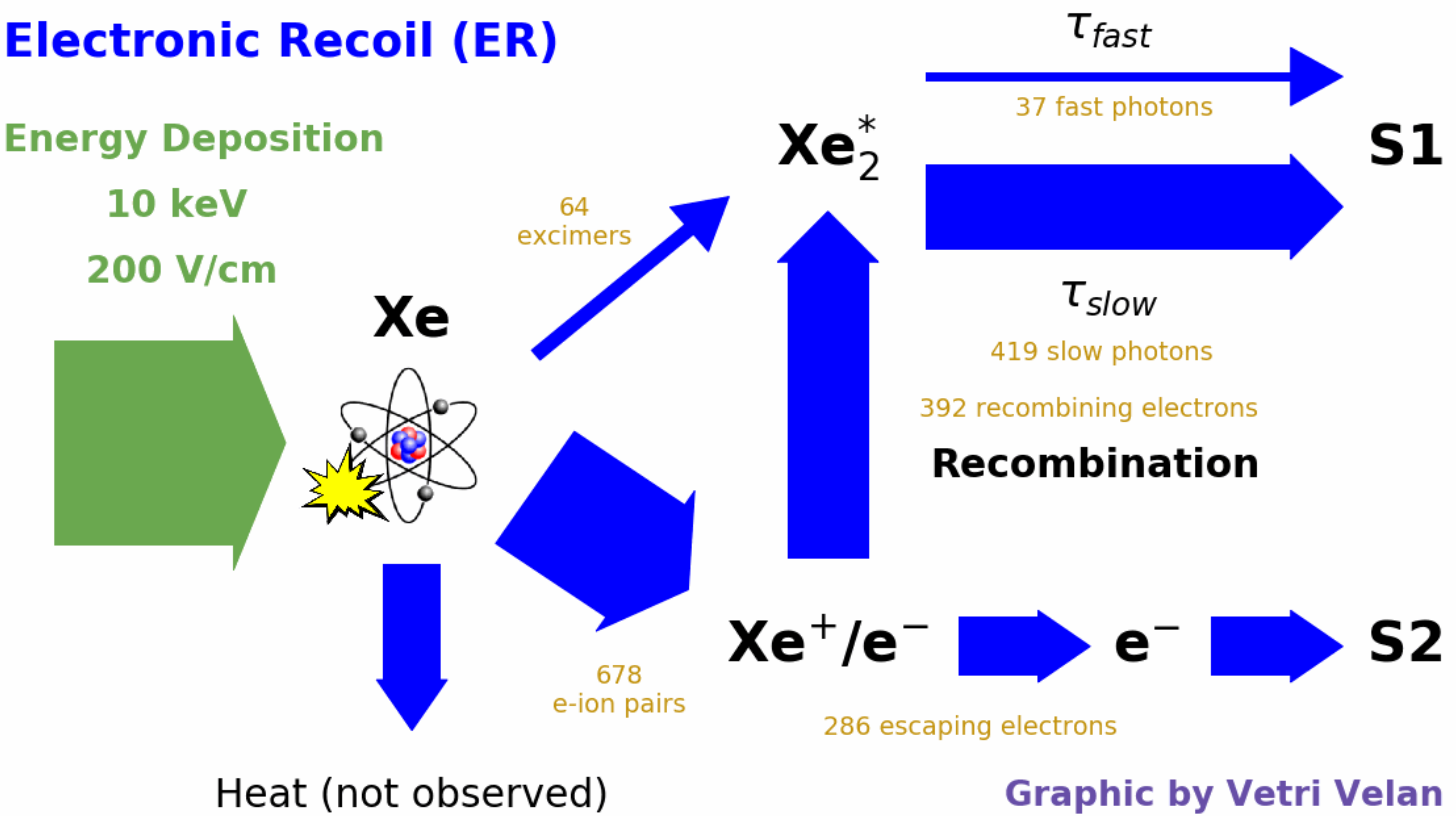
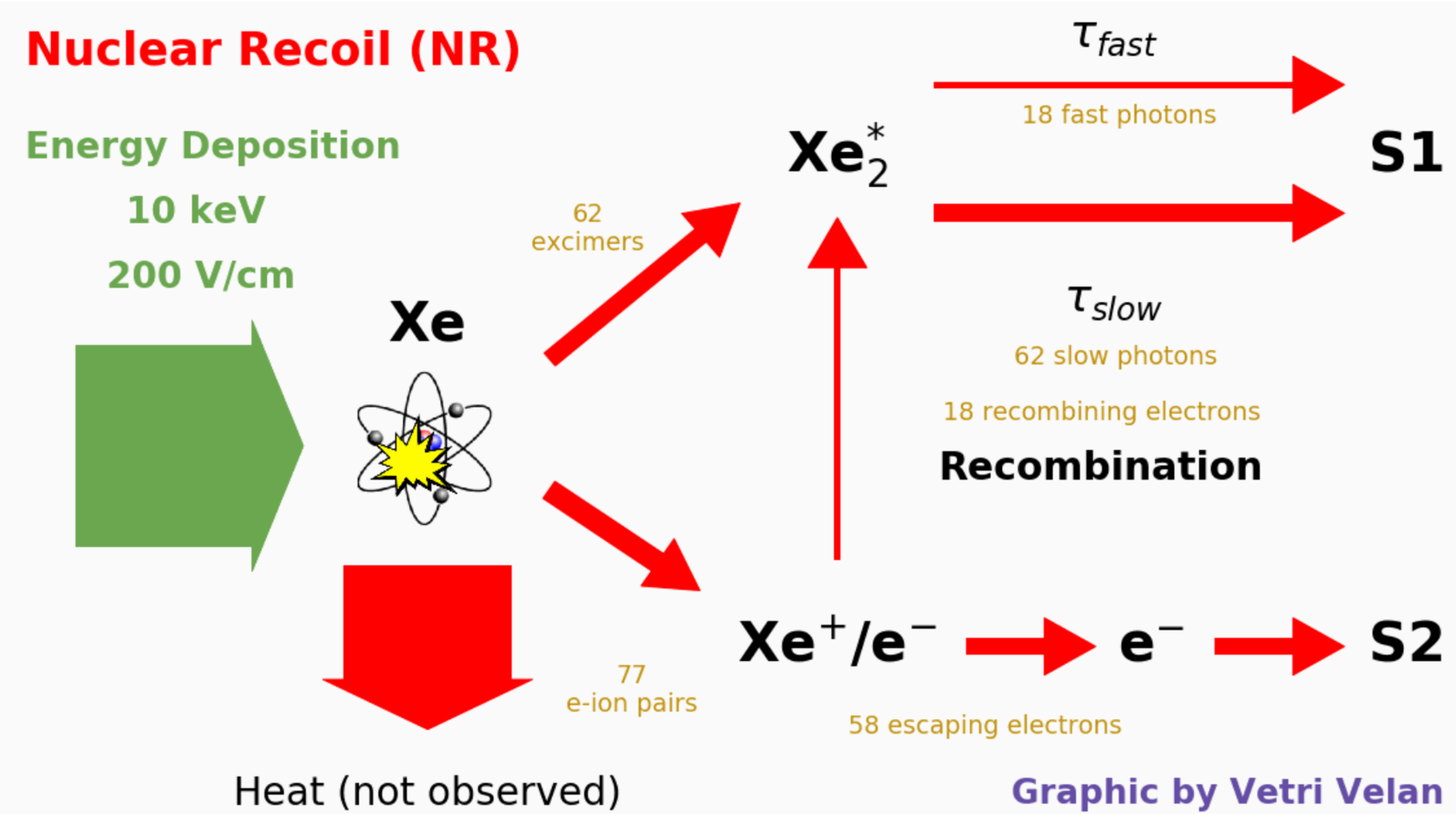
Thanks to our sponsors and participating institutions!

Backup slides

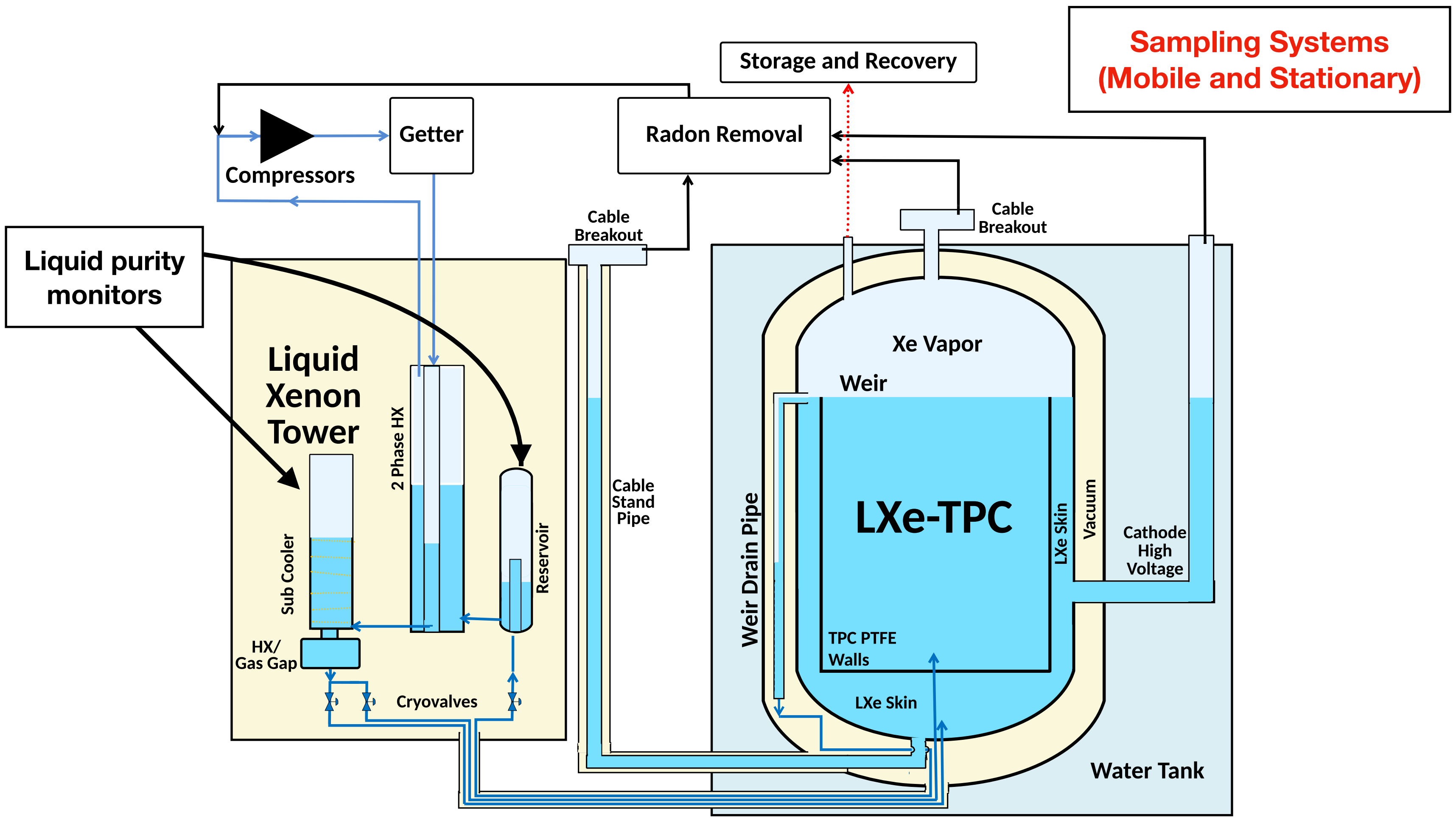
Xenon microphysics



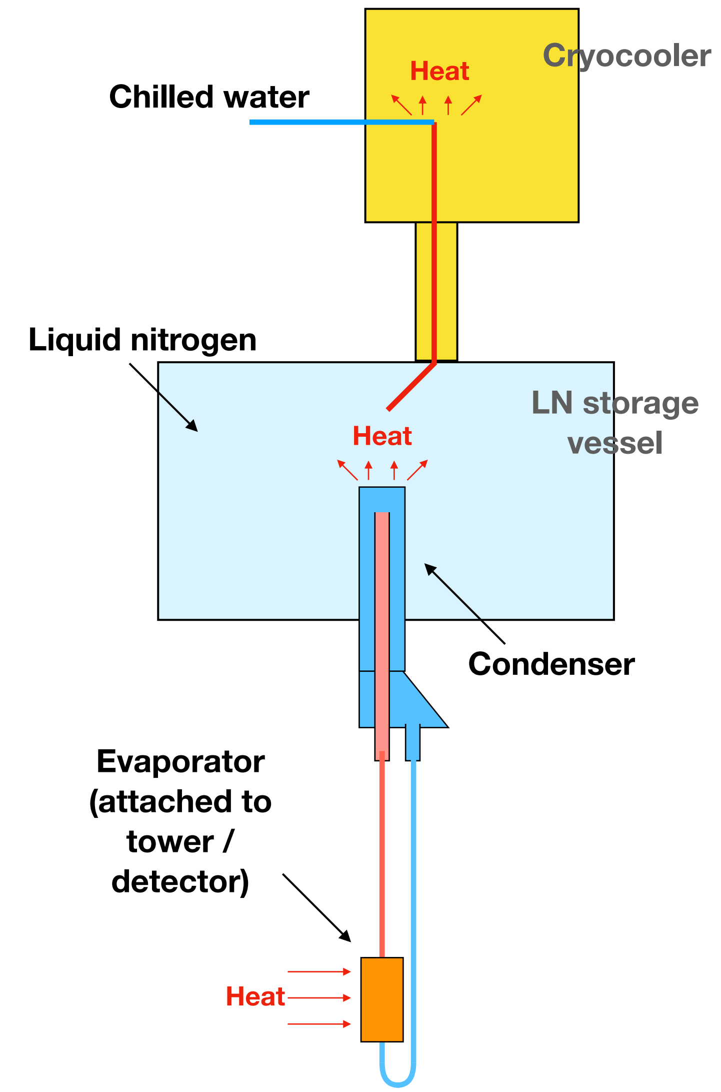
Xenon microphysics



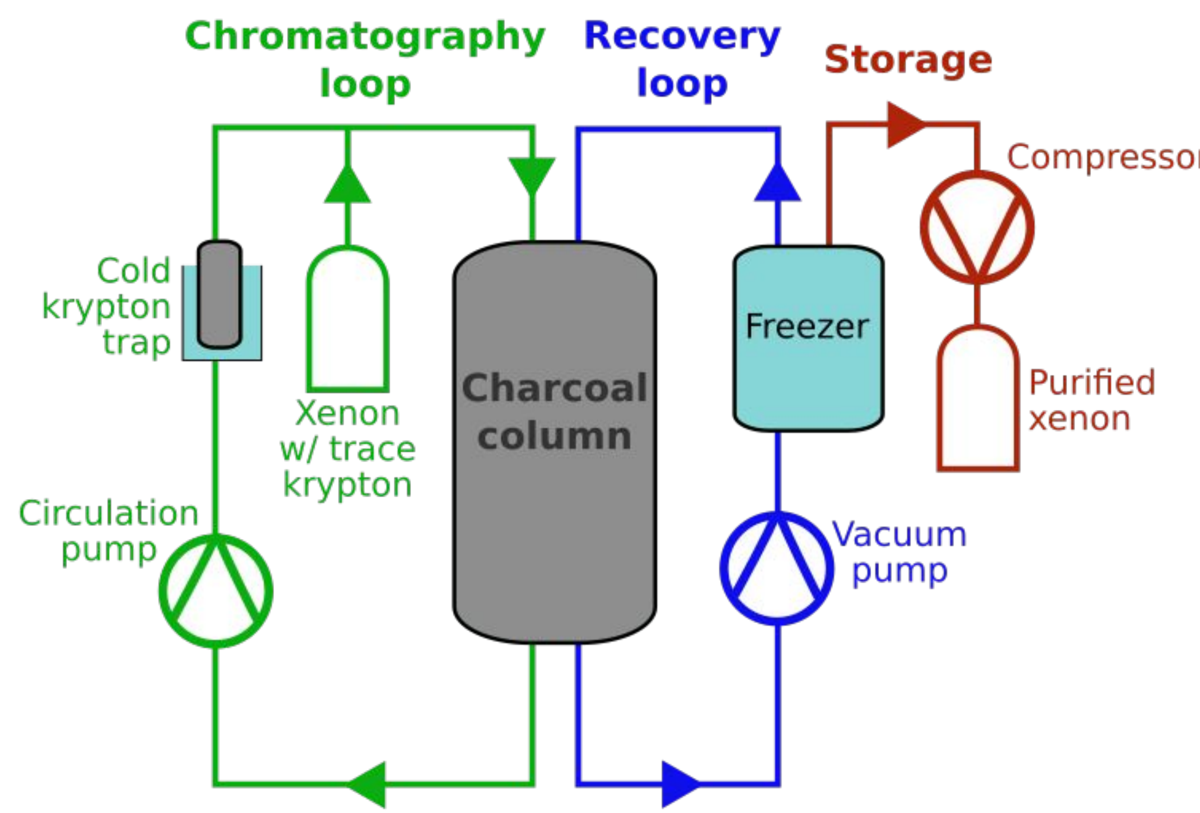
LZ circulation system



Cooling provided by thermosyphon technology (also used in LUX)

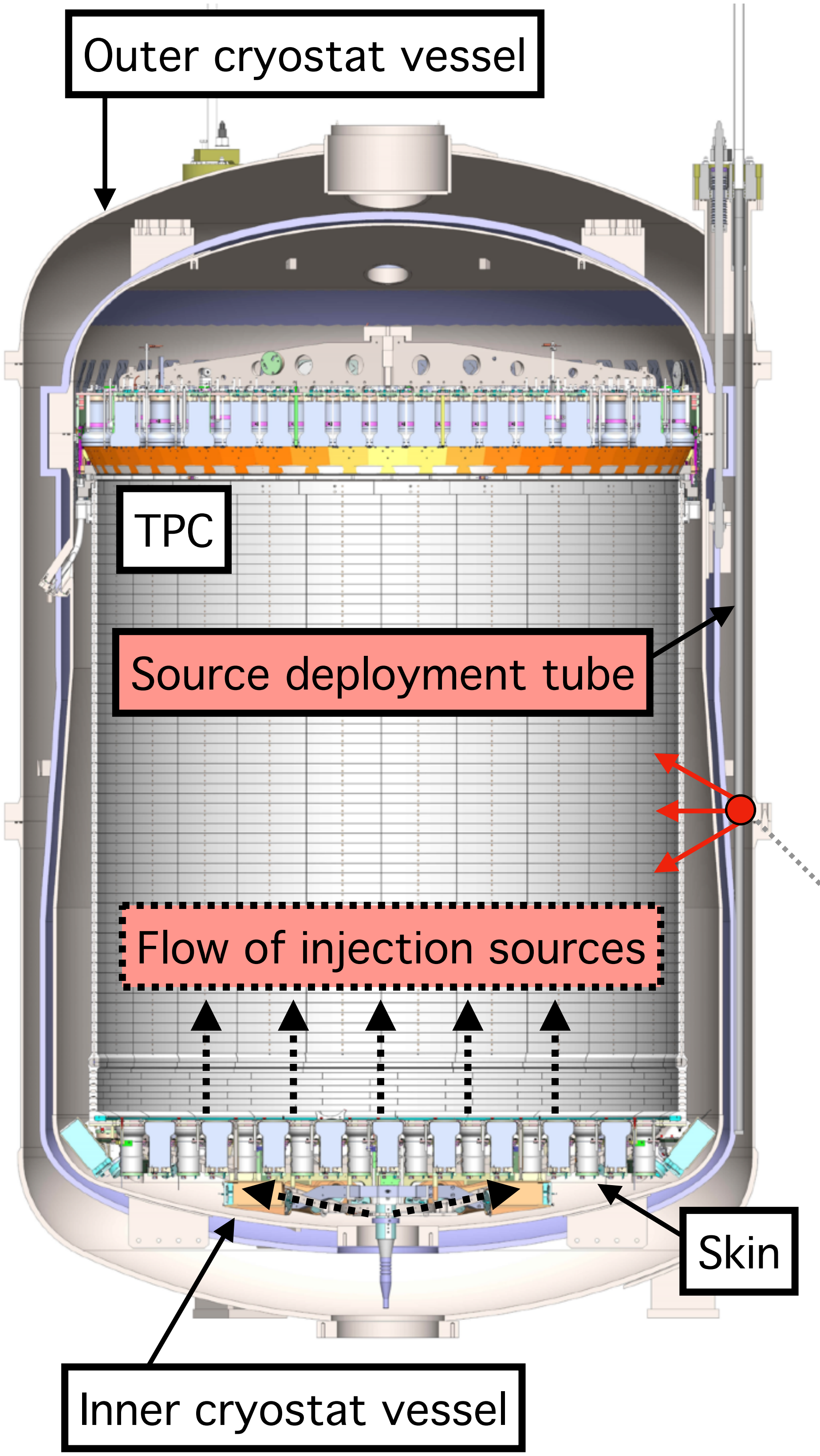


LZ Krypton removal (gas chromatography)

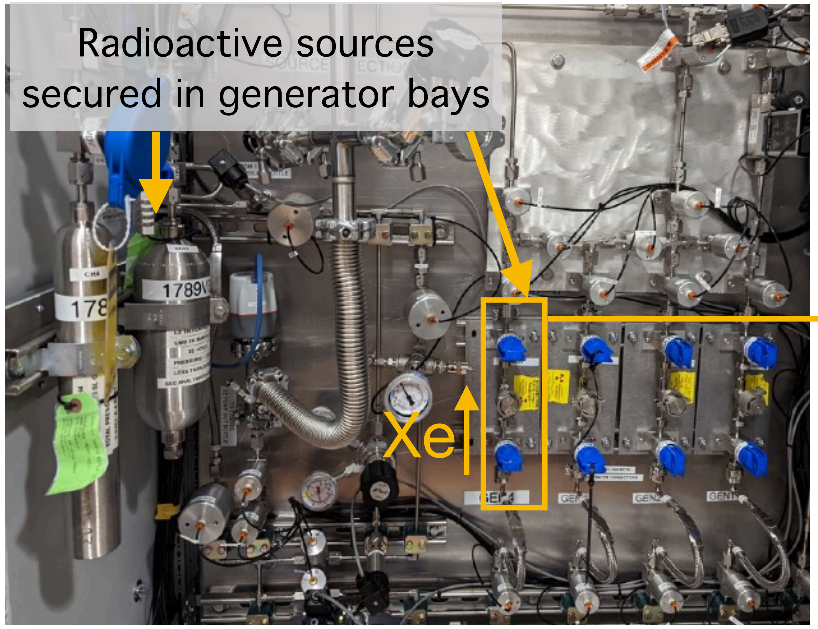


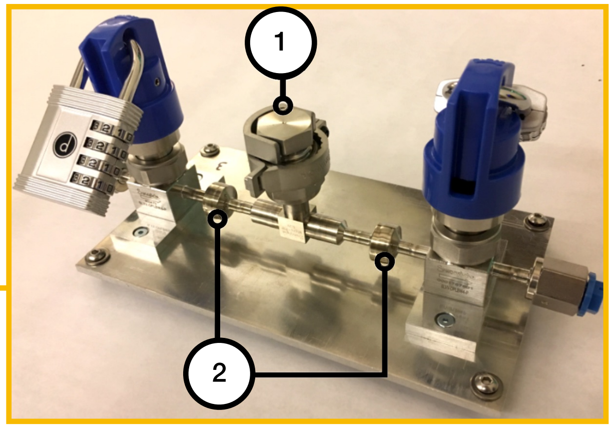
- Xenon purified prior to being added to LZ.
  - Concentration reduced from 1-10 ppb (g/g) to < 300 ppq (g/g).
  - Naked beta-decay Kr85 no longer a limiting background

Calibrations: Electronic Recoil Response



Injection sources (dispersed into LXe)



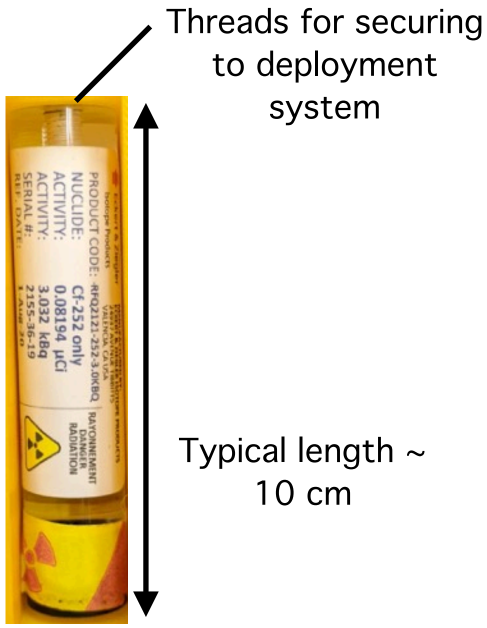


1: Parent nuclide (producing daughter calibration isotope) enclosed in VCR cap.
2: Filter elements for incoming and outgoing xenon flow

Methane tagged with tritium, CH_3T (β; 18.6 keV endpoint) or C14 (β; 156 keV endpoint)
Kr83m (e-; 32.1 keV, 9.4 keV)
Rn220 (γ, β, α; various energies)

Sealed sources in calibration tubes

- x3 deployment tubes between inner and outer cryostat vessels
- Laser-guided deployment to specific z-positions at 5 mm precision



Calibrations: Nuclear Recoil Response

AmLi source

JINST 18 P05006

$$\alpha + {}^{7}\textbf{Li} \rightarrow n + {}^{10}\textbf{B}$$

- Three AmLi sources deployed in calibration source tubes.
- Allows for a scan of different detector depths.
- Tungsten enclosure to contain low energy γ-rays.

YBe source

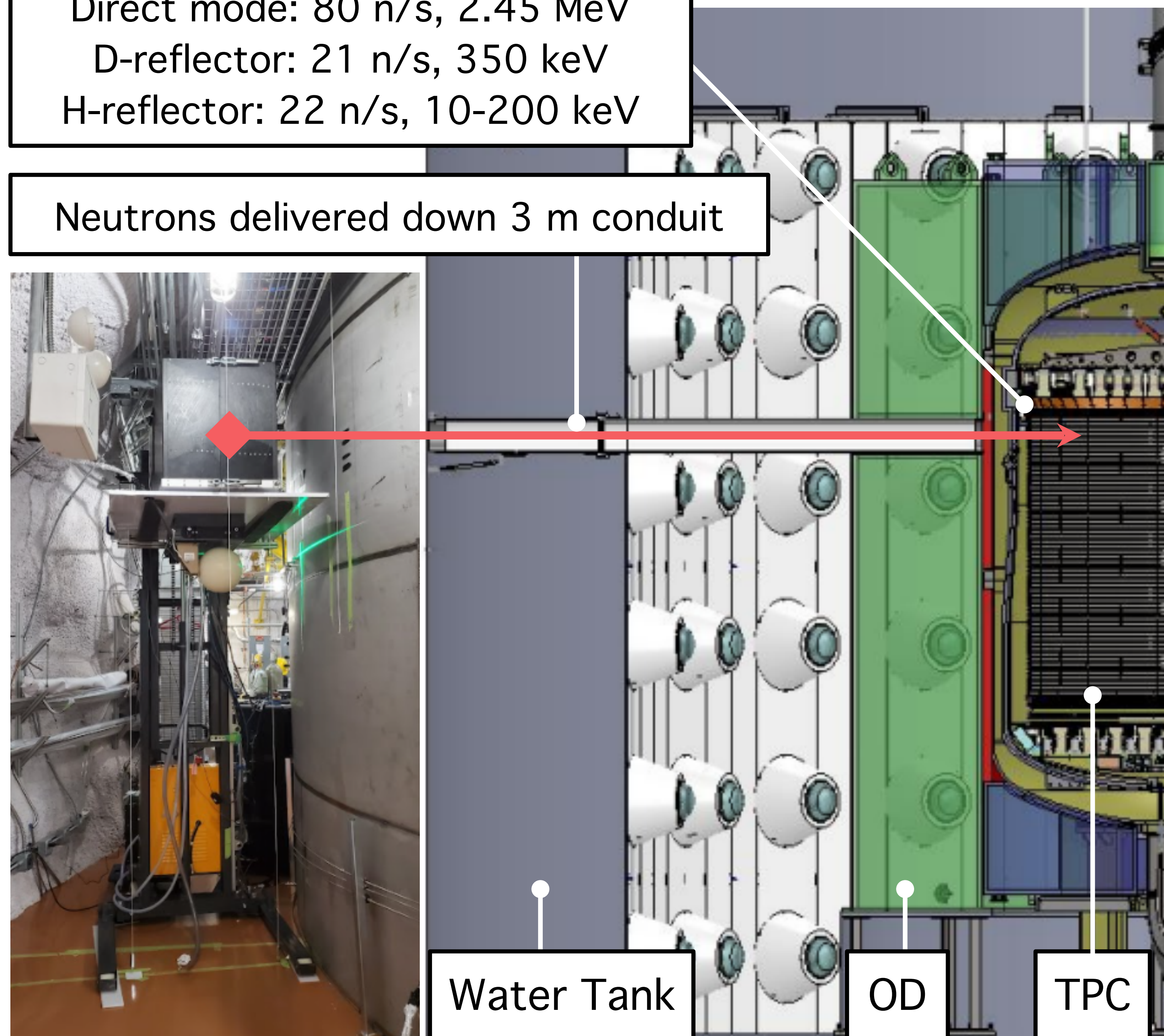
$$\gamma + {}^{9}\textbf{Be} \rightarrow n + {}^{8}\textbf{Be}+$$

- Photoneutron source for low energy nuclear recoil calibration at threshold.
- Deployment to top of cryostat vessel (between OD top tanks).
- Demonstrated during commissioning at different fields to the final WIMP-search.

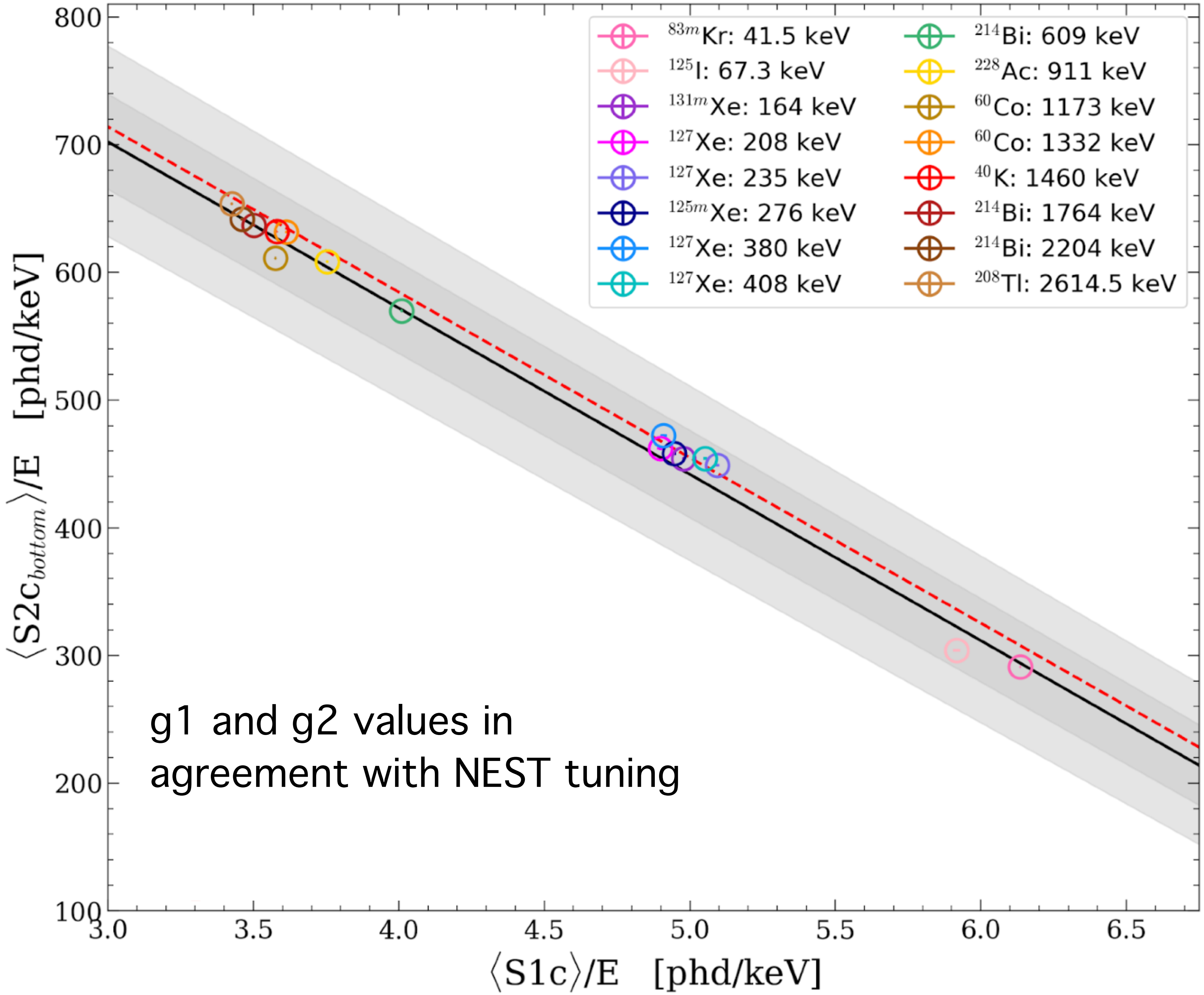
DD Neutron Generator

Direct mode: 80 n/s, 2.45 MeV
D-reflector: 21 n/s, 350 keV
H-reflector: 22 n/s, 10-200 keV

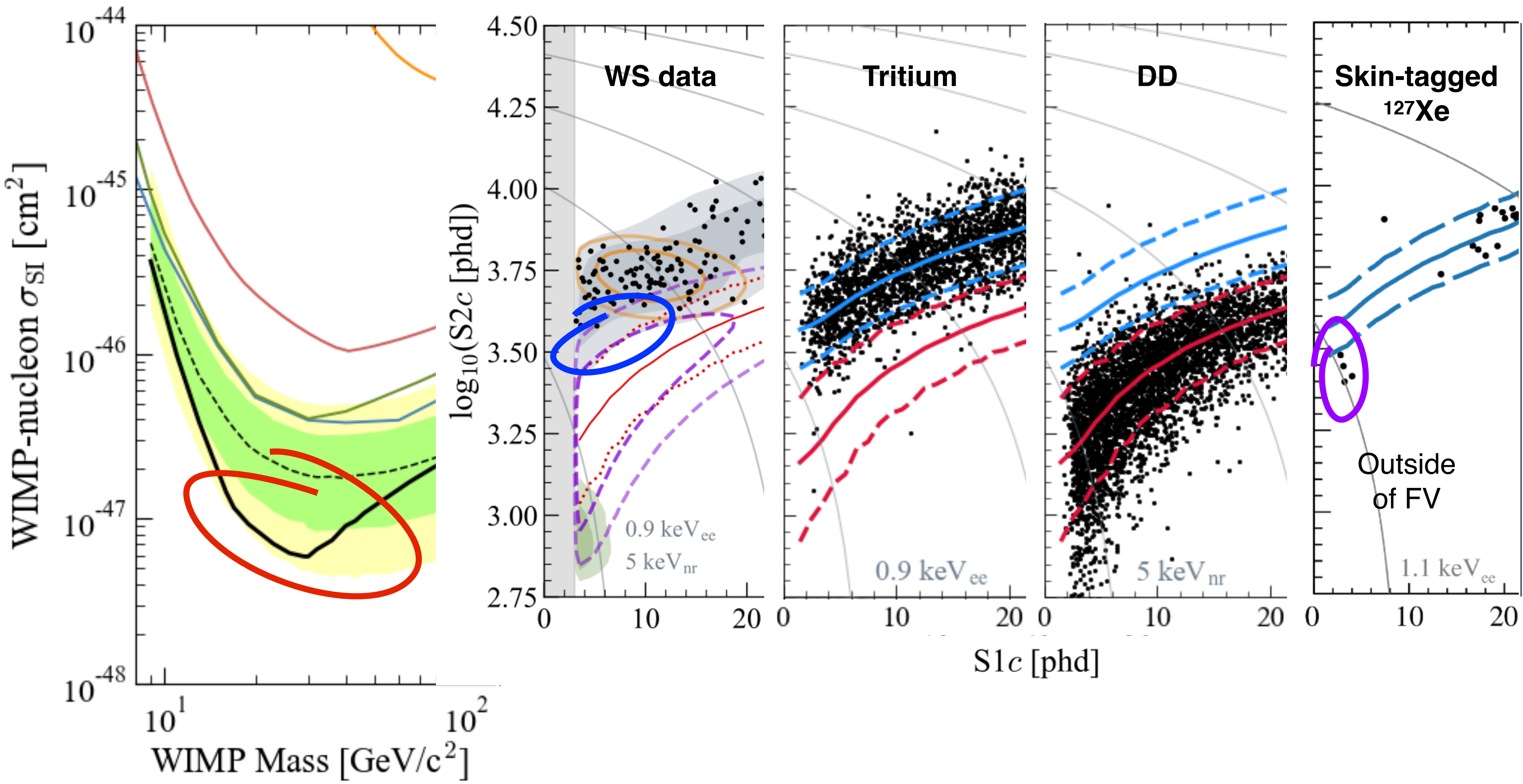
Neutrons delivered down 3 m conduit



LZ SR1 Doke Plot



Downward fluctuation of SR1 limit



Bare M-shell decays of 127Xe populate near deficit region. Observed rate of M-shell decays with coincident γ-ray tagged by the skin is consistent with expectation, given signal efficiencies.

Deficit appears consistent with under-fluctuation of background.

↑

Downward fluctuation in the observed upper limit near 30 GeV/c2 is a result of the <u>deficit</u> of events under the 37Ar population.

Due to background under-fluctuation or unaccounted for signal inefficiency? Probe the latter.

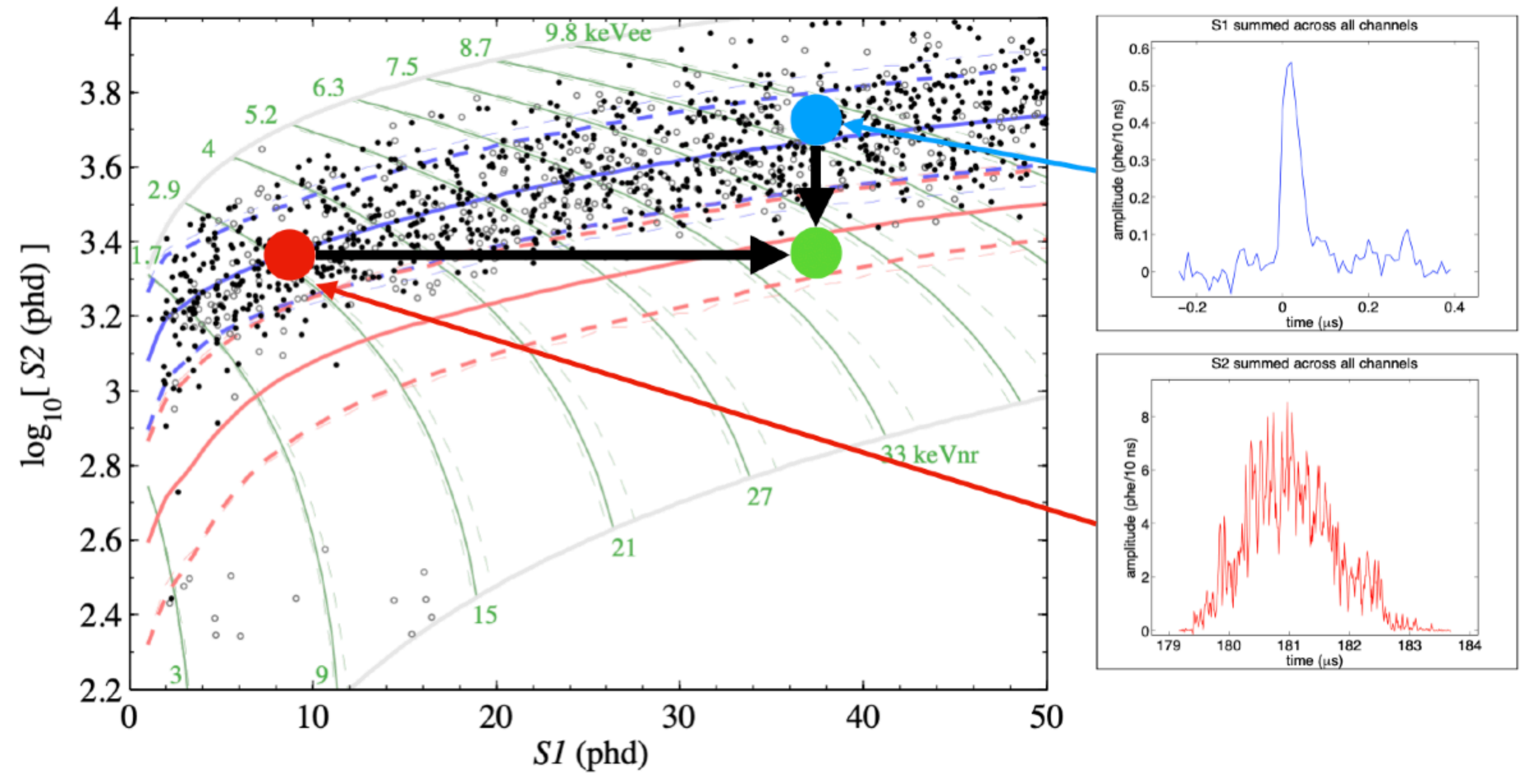
→

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.

Data Salting

- Salting is a bias mitigation strategy: we inject synthetic events into raw data stream that look like signal events.
- Build signal events by chopping and stitching high stats ER and NR calibration data.



Mock ‘WIMP-search’ dataset