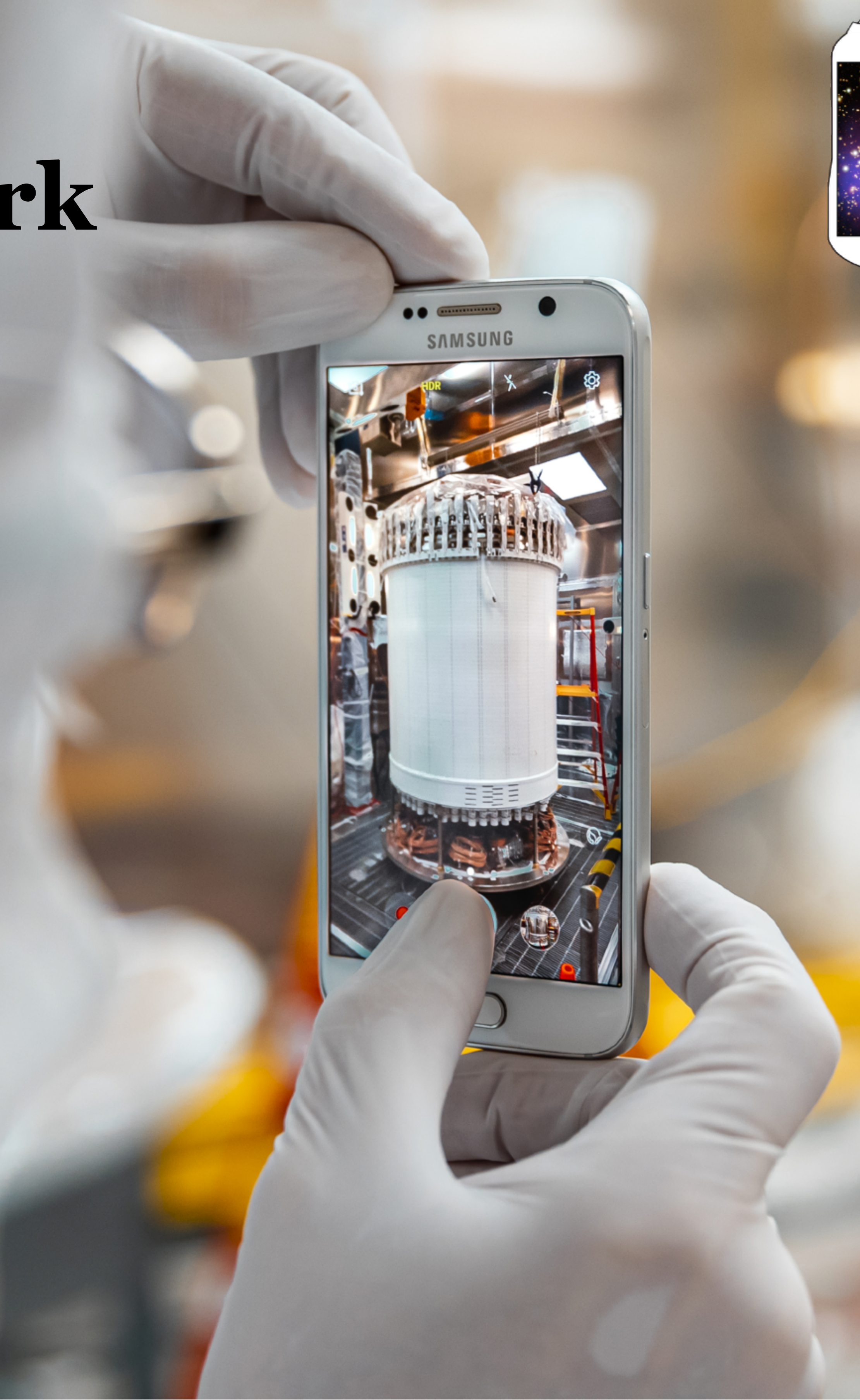
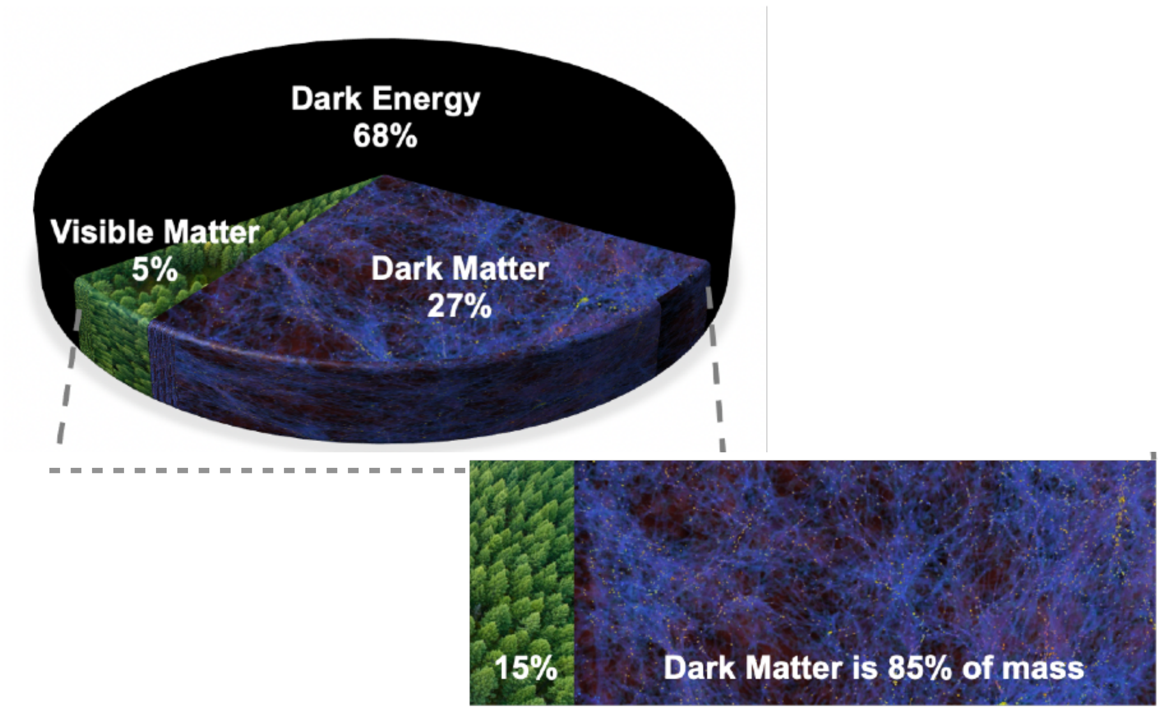
First results from the LUX-ZEPLIN (LZ) dark matter experiment

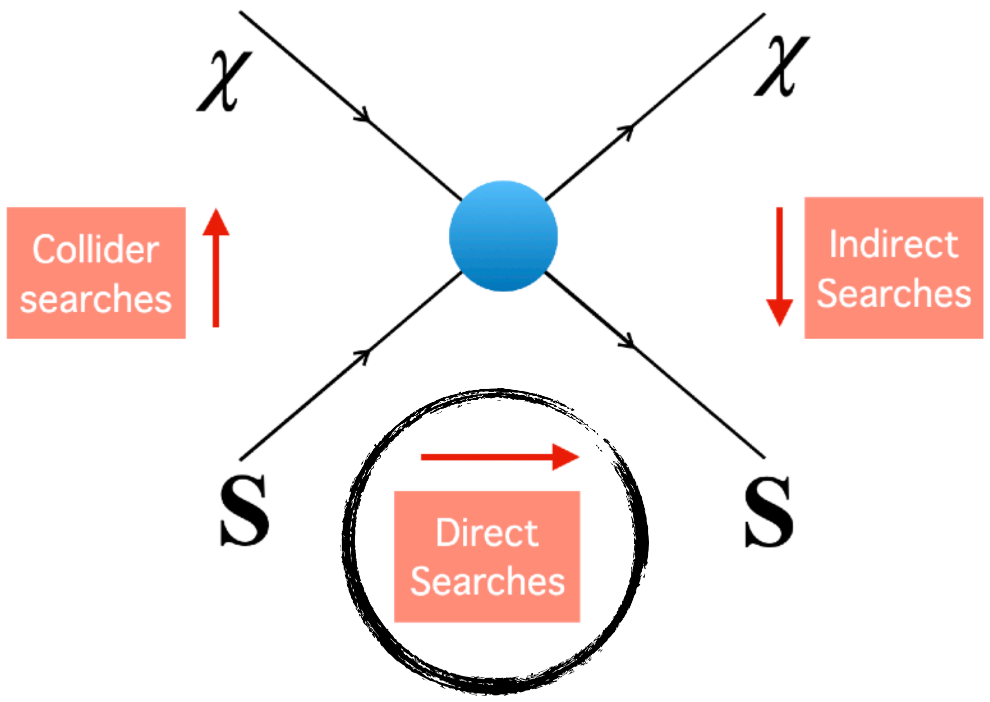
David Woodward
Penn State University

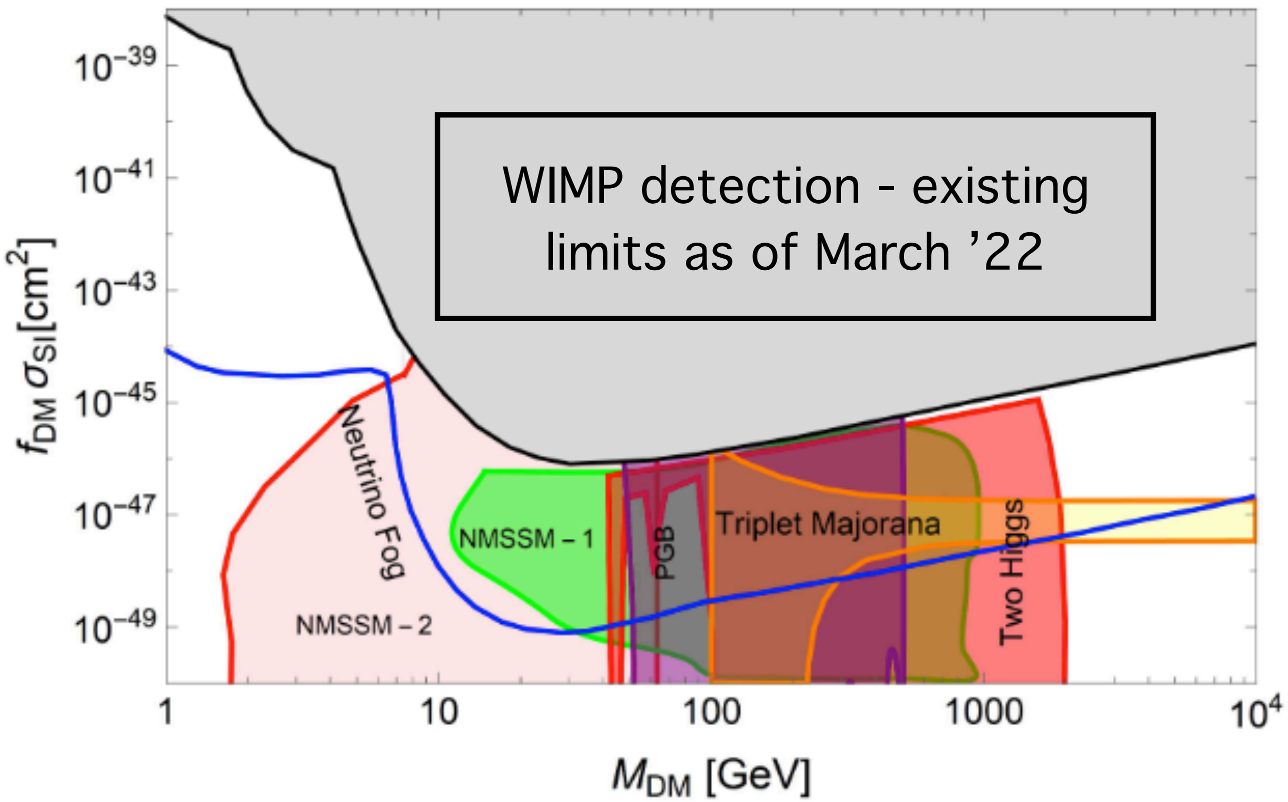


CIPANP 2022
14th Conference on the intersections of Particle and Nuclear Physics

Introduction



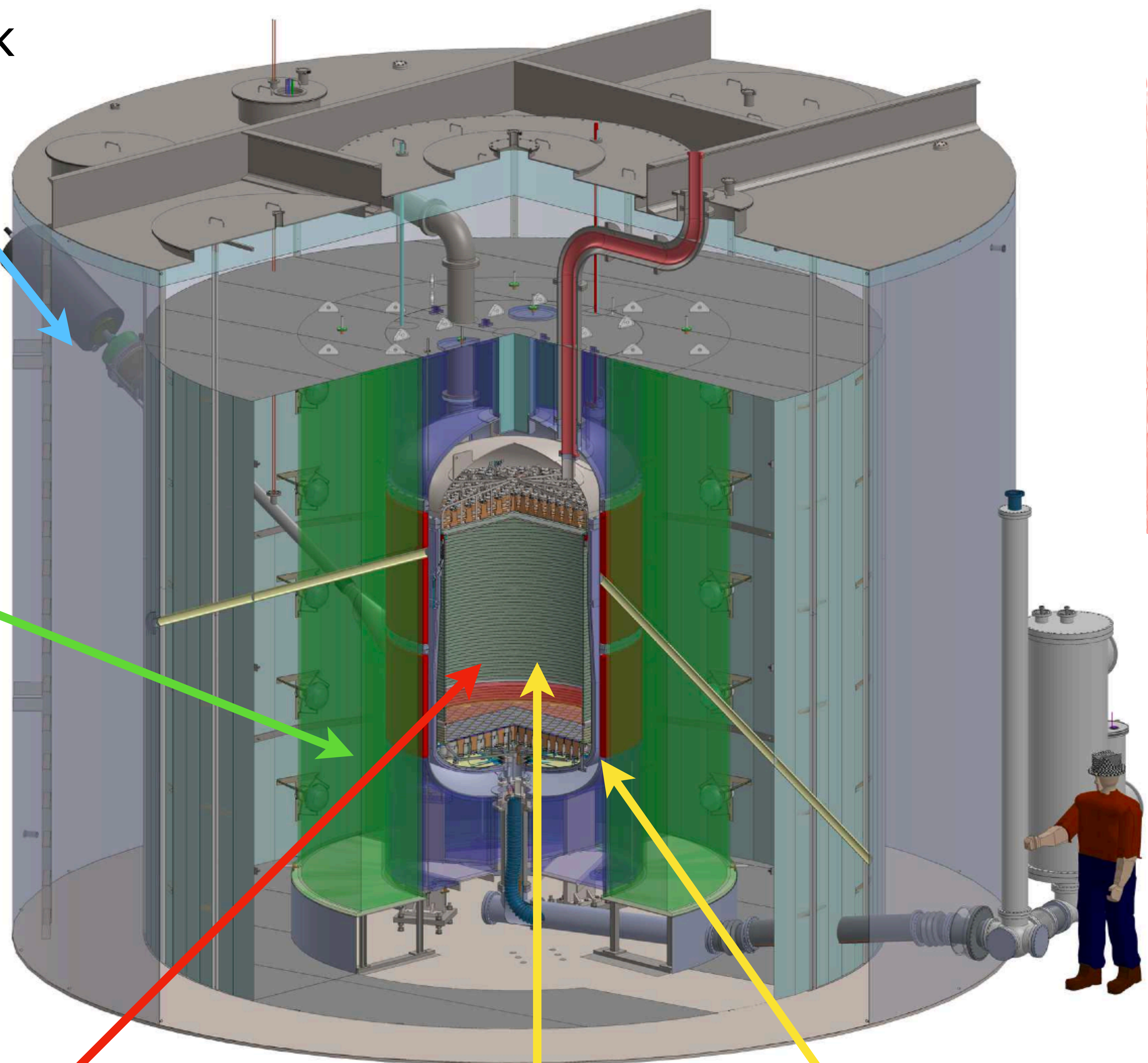


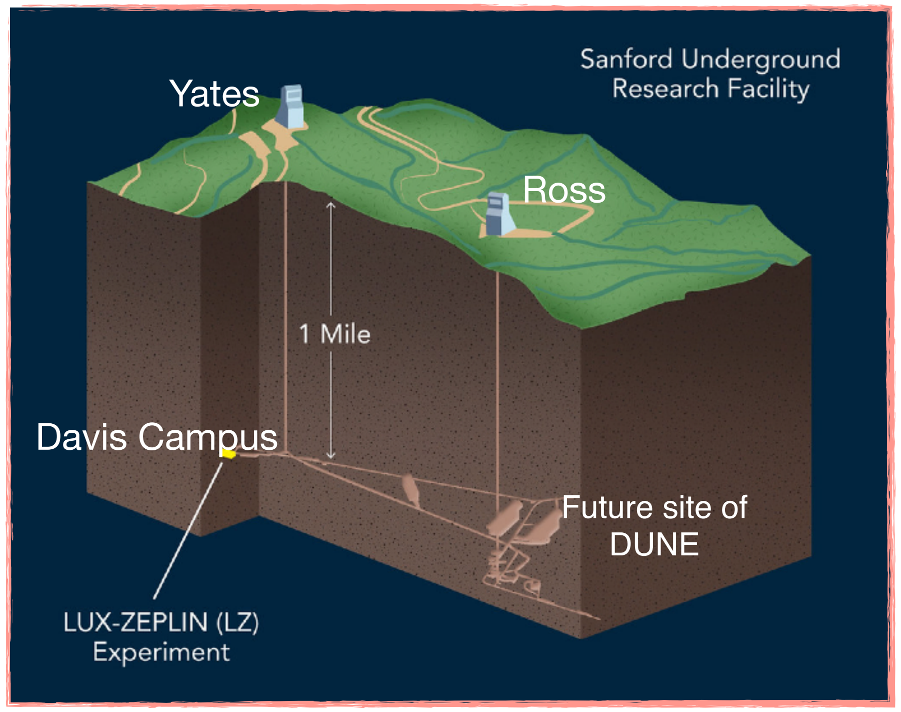


Snowmass CF1-WP1
arXiv:2203.08084

The LUX-ZEPLIN (LZ) experiment

LZ detector paper: NIM 953 (2019), 163047

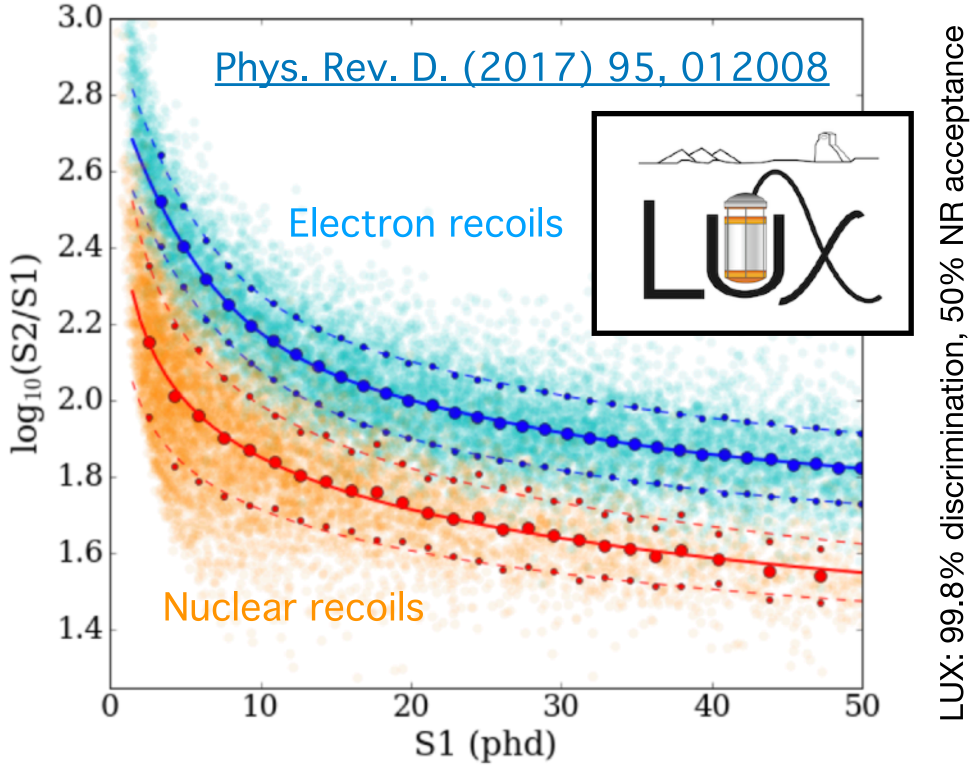




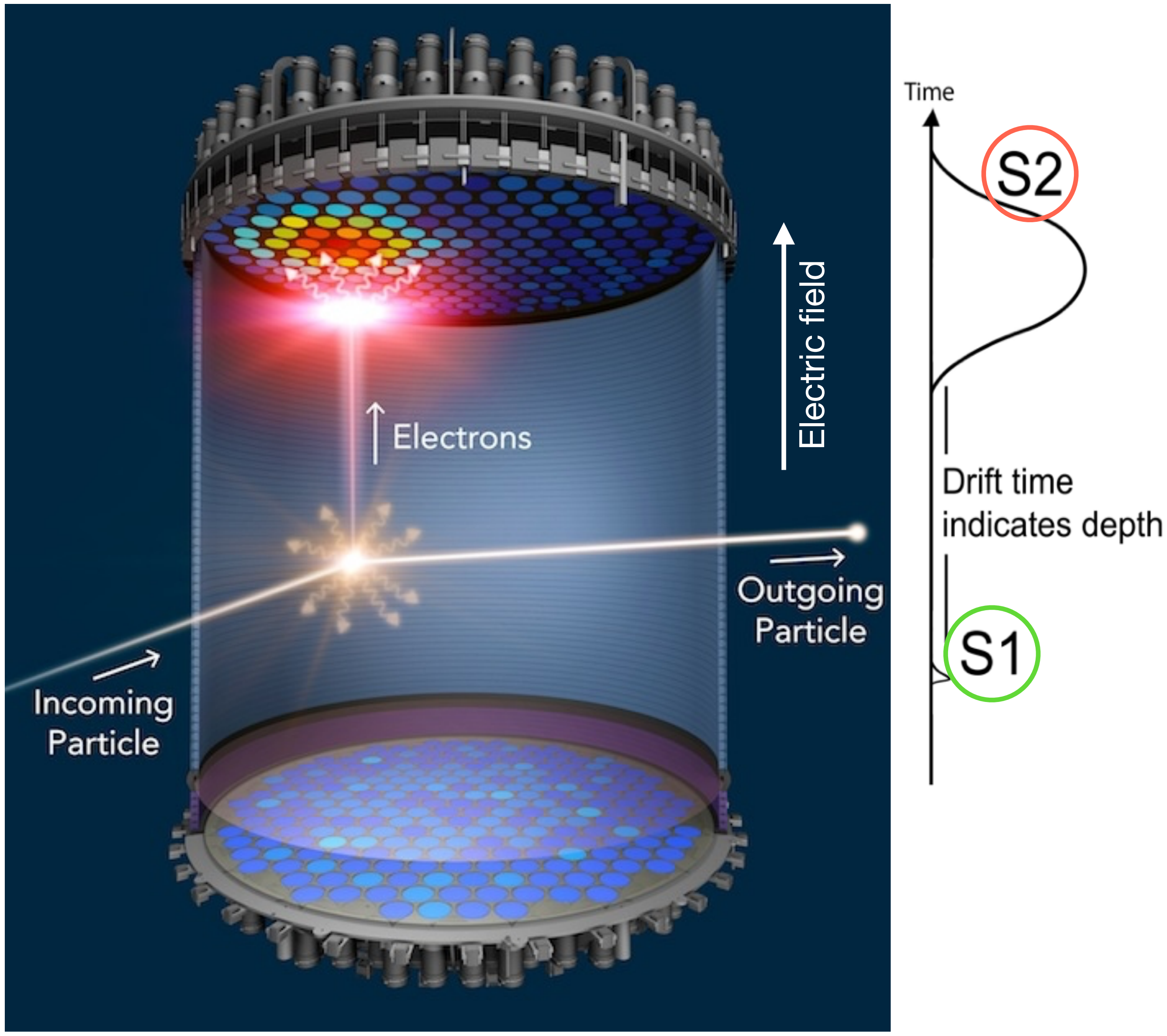
Low-background detector - extensive material screening campaign to select radiopure materials (see Eur.Phys.J.C 80 (2020) 11, 1044)

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

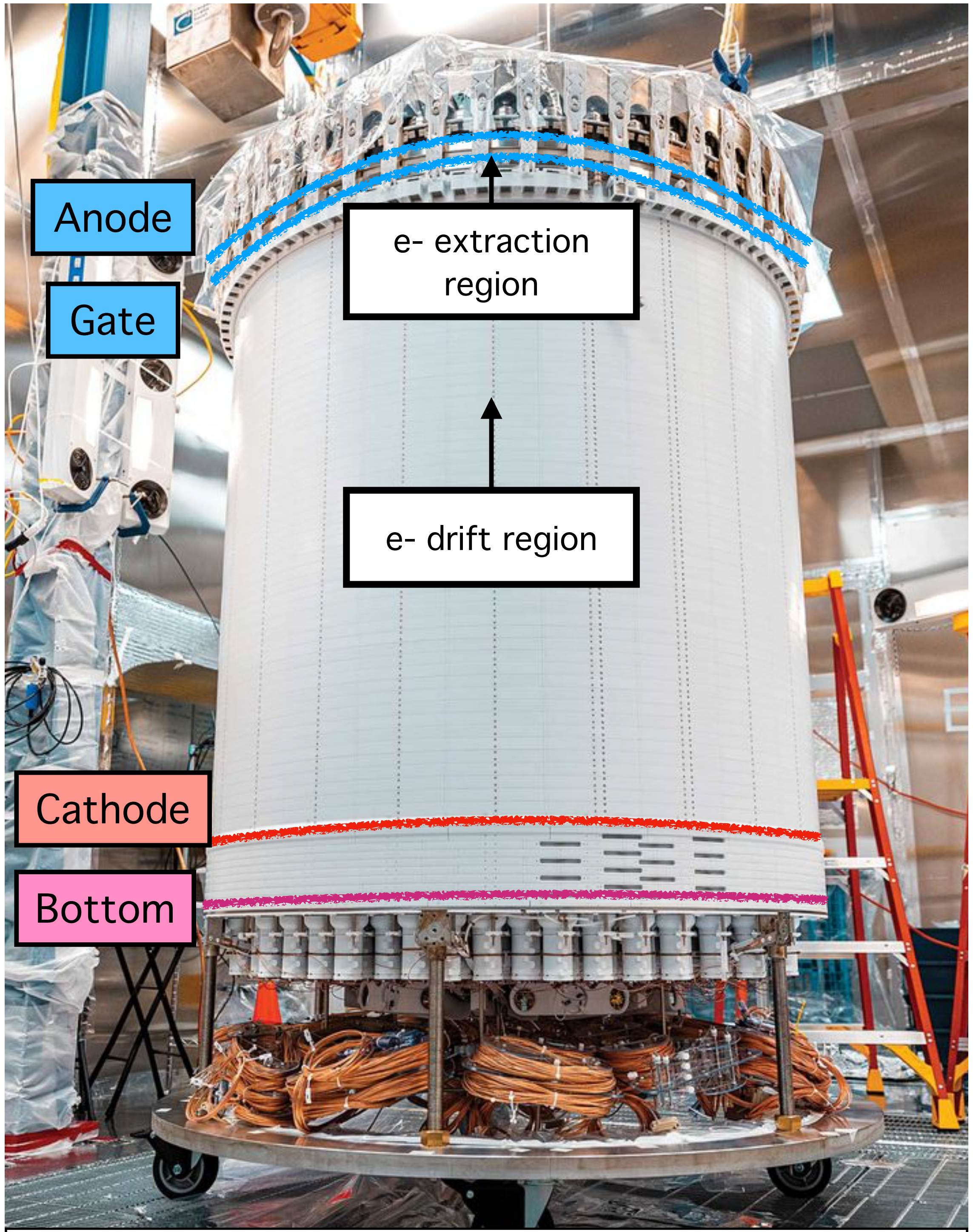


PMT hit map gives x, y position



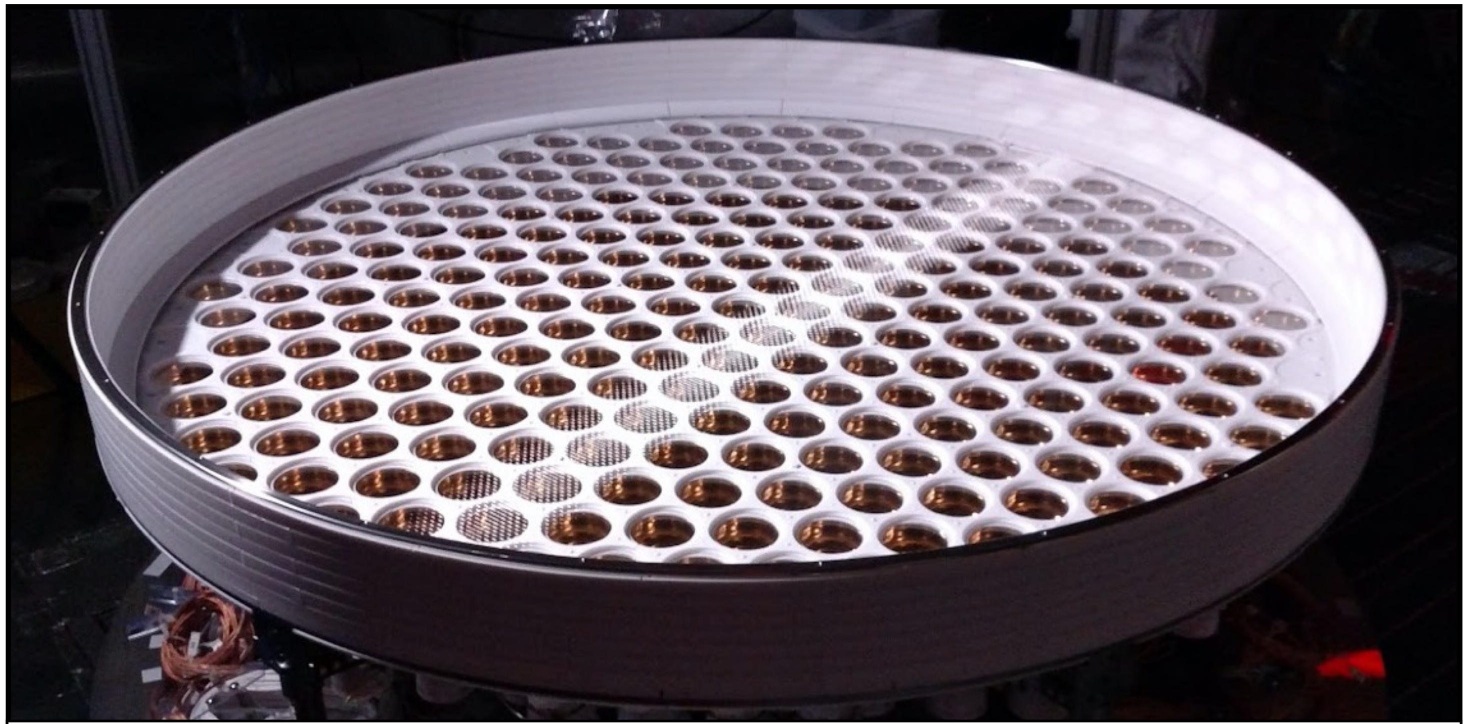
LZ: 494 PMTs in the top and bottom arrays combined
7 tonnes of liquid xenon in the 'active' region (where the electric field is applied)

The LZ TPC



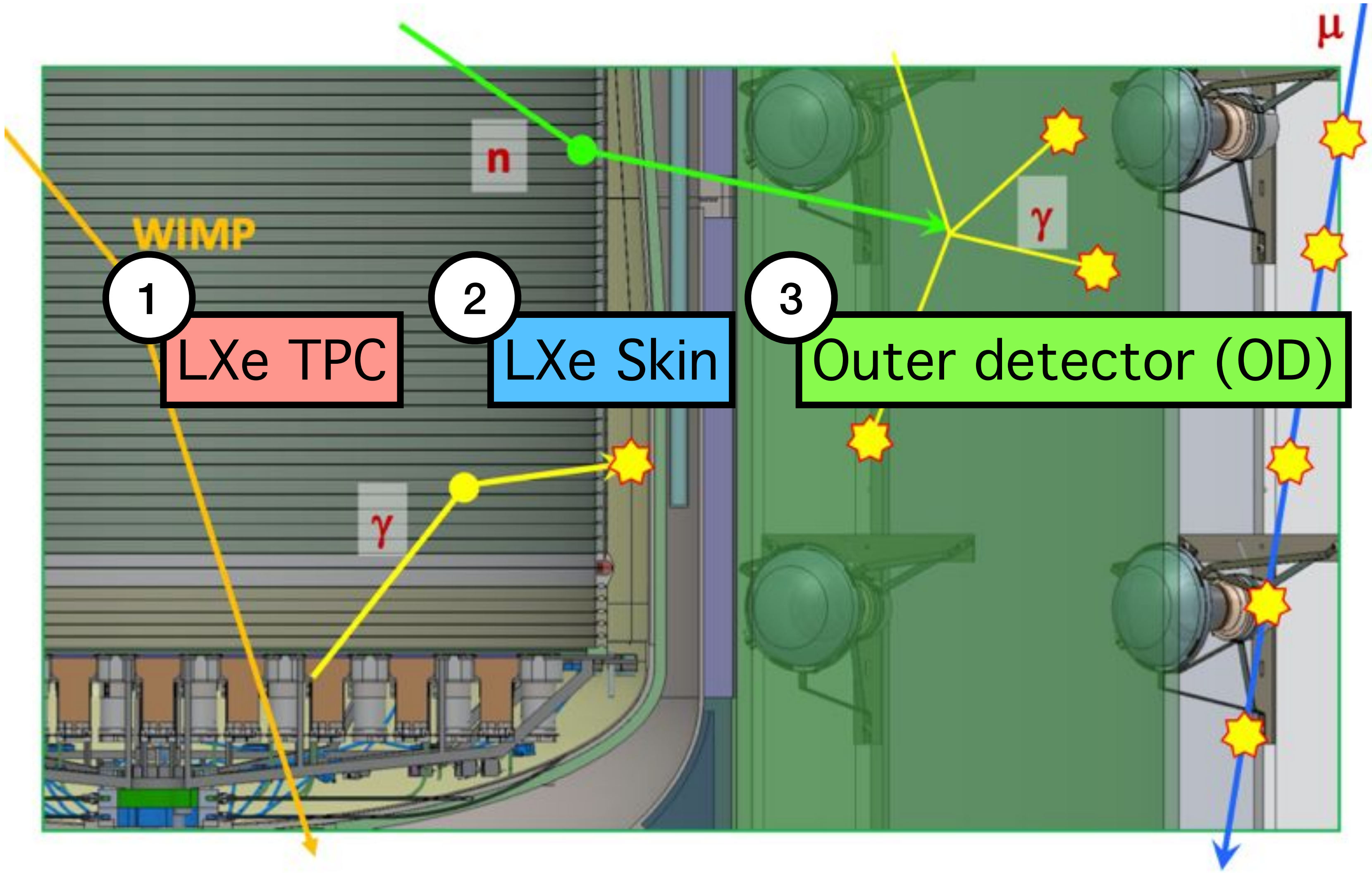
Construction in radon reduced clean room at surface assembly lab completed in 2019

- 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

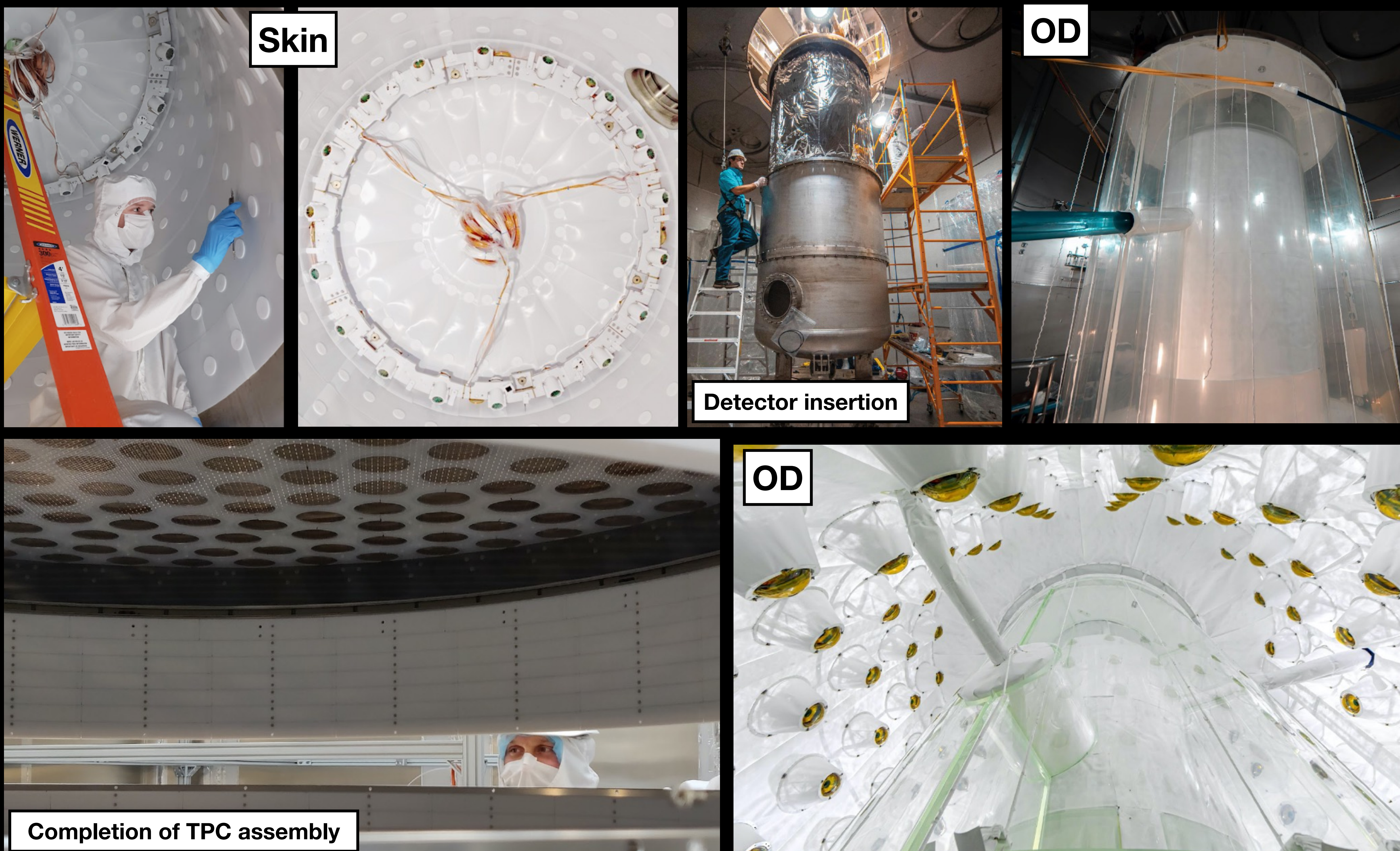


See talk on the LZ OD by H. Birch in session DM-2

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 (88% tagging efficiency, measured in situ with AmLi neutrons)

Picture Round!



The LZ timeline

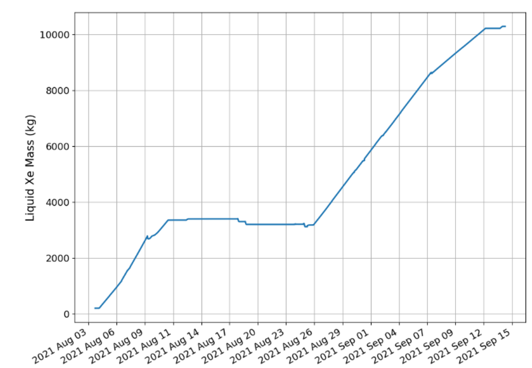
TPC assembled
Aug 2019

Circulation Test
July 2020

Electronics installation
Fall 2020

Kr Reduction
Jan-Aug 2021

Xenon Fill
Aug-Sep 2021



Commissioning
Fall 2021

2019

2020

2021

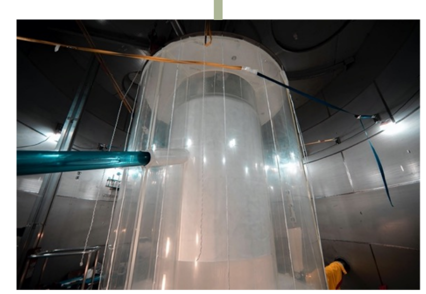
2022

First science

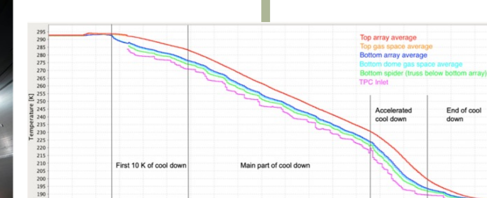
Detector construction at
surface lab
Aug 2018 – Aug 2019

TPC moves
underground
Oct 2019

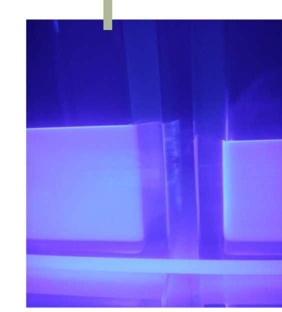
Detector sealed up
March 2020



OD Construction
Winter 2020-2021



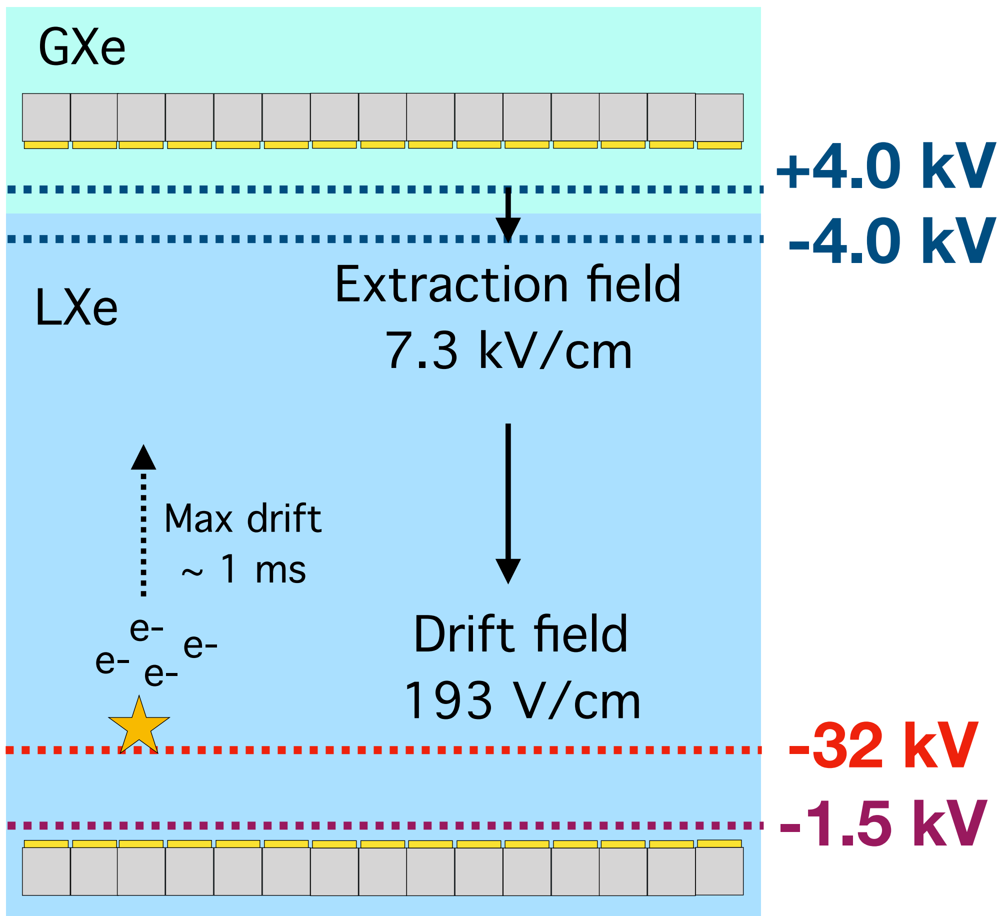
Cold Xe gas,
March 2021

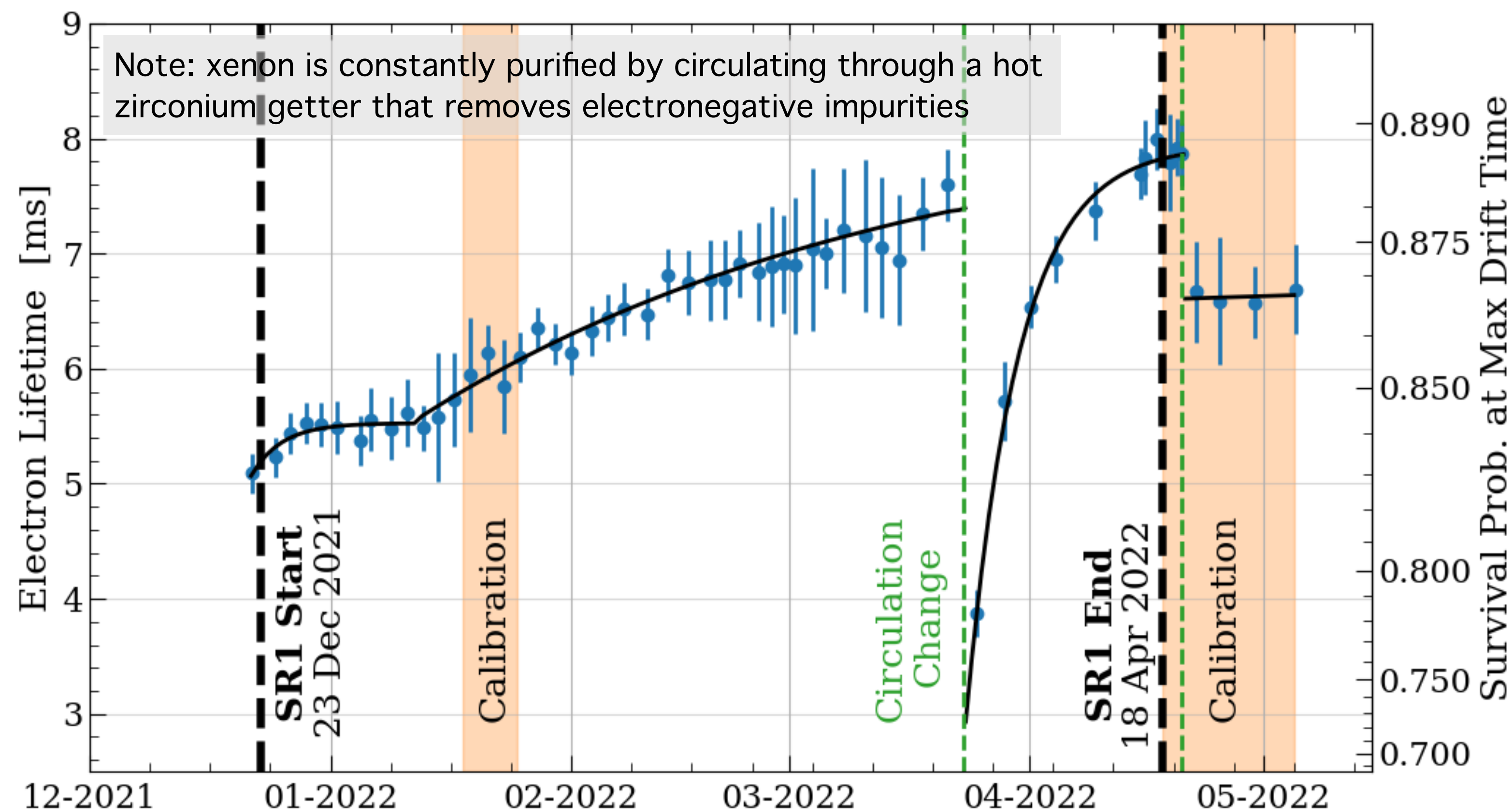


OD Fill
June 2021

LZ Science Run 1

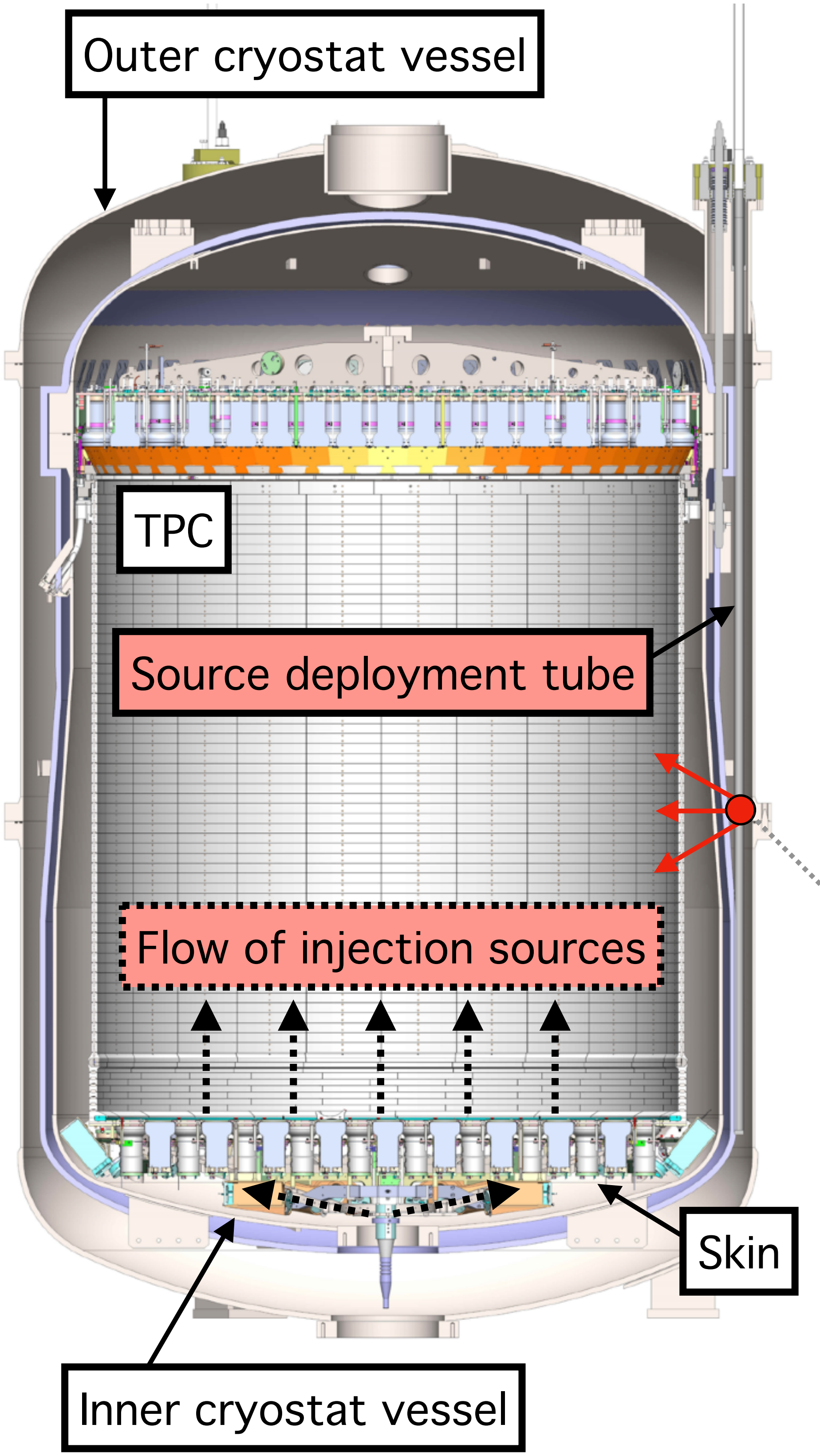
Goal: Demonstrate physics capability of the LZ detector



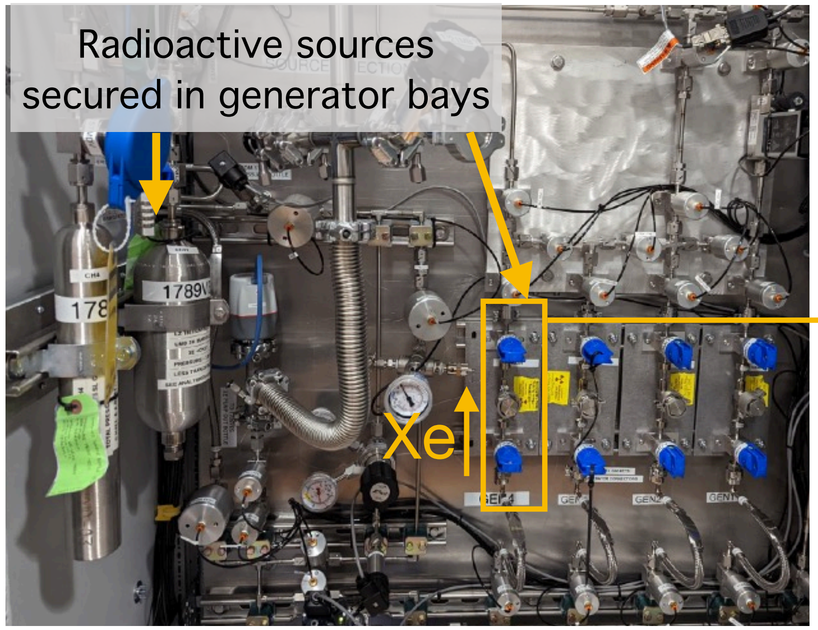


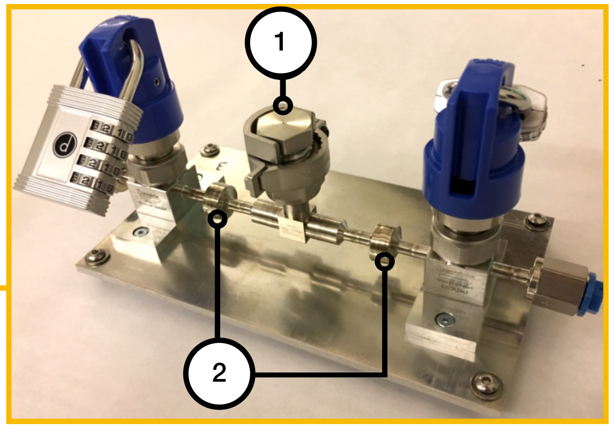
- Data from Dec 23rd ’21 to May 12th ’22
- Mid-run and post-run calibrations
- <u>WIMP search live time = 60 days</u>
- Engineering run — data not blinded
- > 97% of PMTs operational
- Liquid T = 174.1 K (0.02% variation)
- Gas P = 1.791 bar(a) (0.2% variation)
- Liquid level stable within 10 microns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

Electron recoil calibrations



Injection sources (dispersed into LXe)



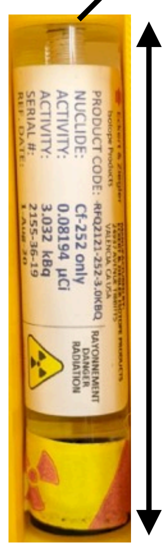


1: Parent nuclide (producing daughter calibration isotope) enclosed in VCR cap.
2: Filter elements for incoming and outgoing xenon flow

Methane tagged with <u>tritium</u>, CH_3T (β; 18.6 keV endpoint)
<u>Kr83m</u> (γ; 32.1 keV, 9.4 keV)
<u>Rn220</u> (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



Nuclear recoil calibrations

AmLi source

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

- 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

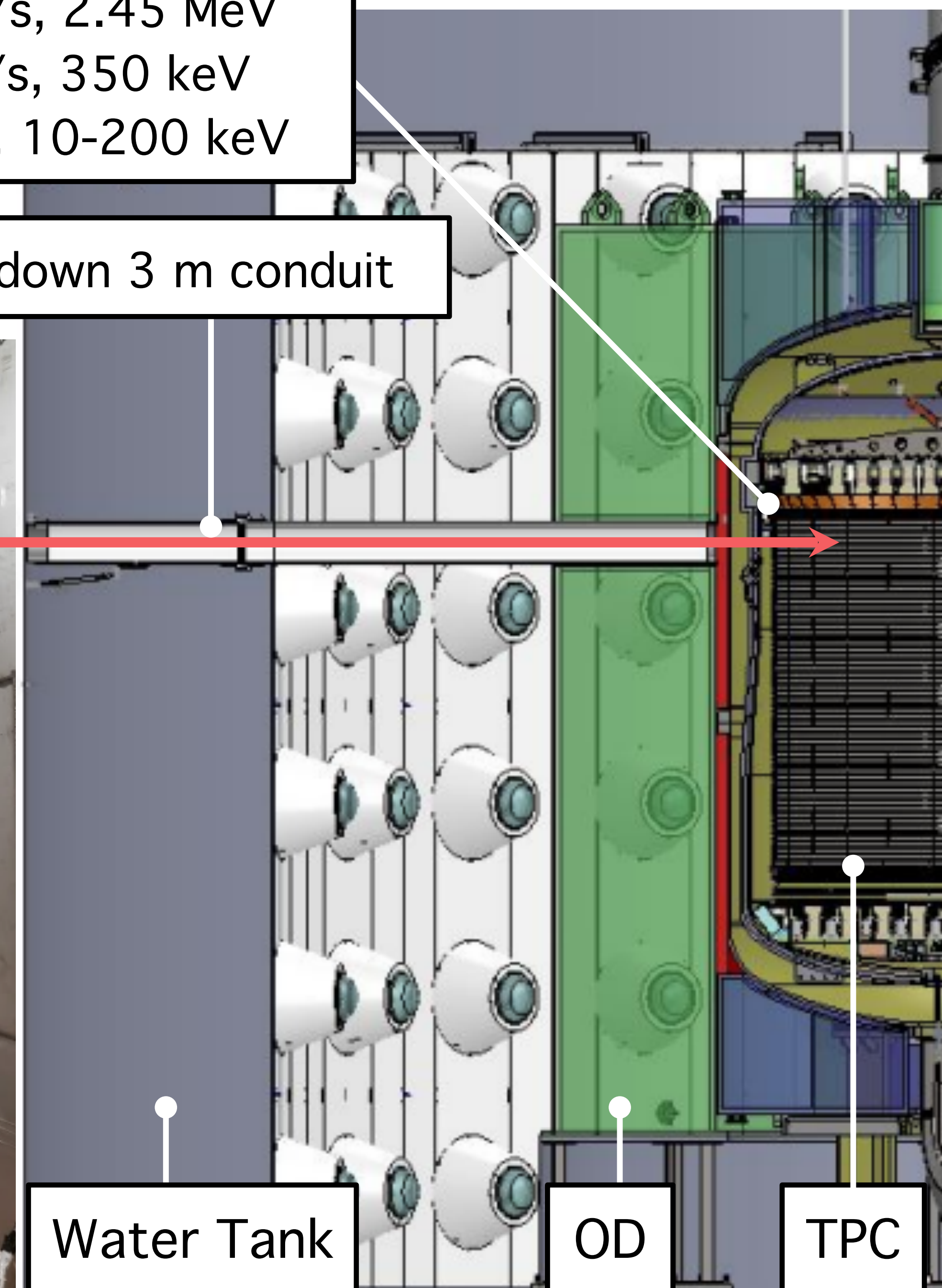
$$\gamma + {}^{9}\textbf{Be} \rightarrow n + {}^{8}\textbf{Be}+$$

- 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

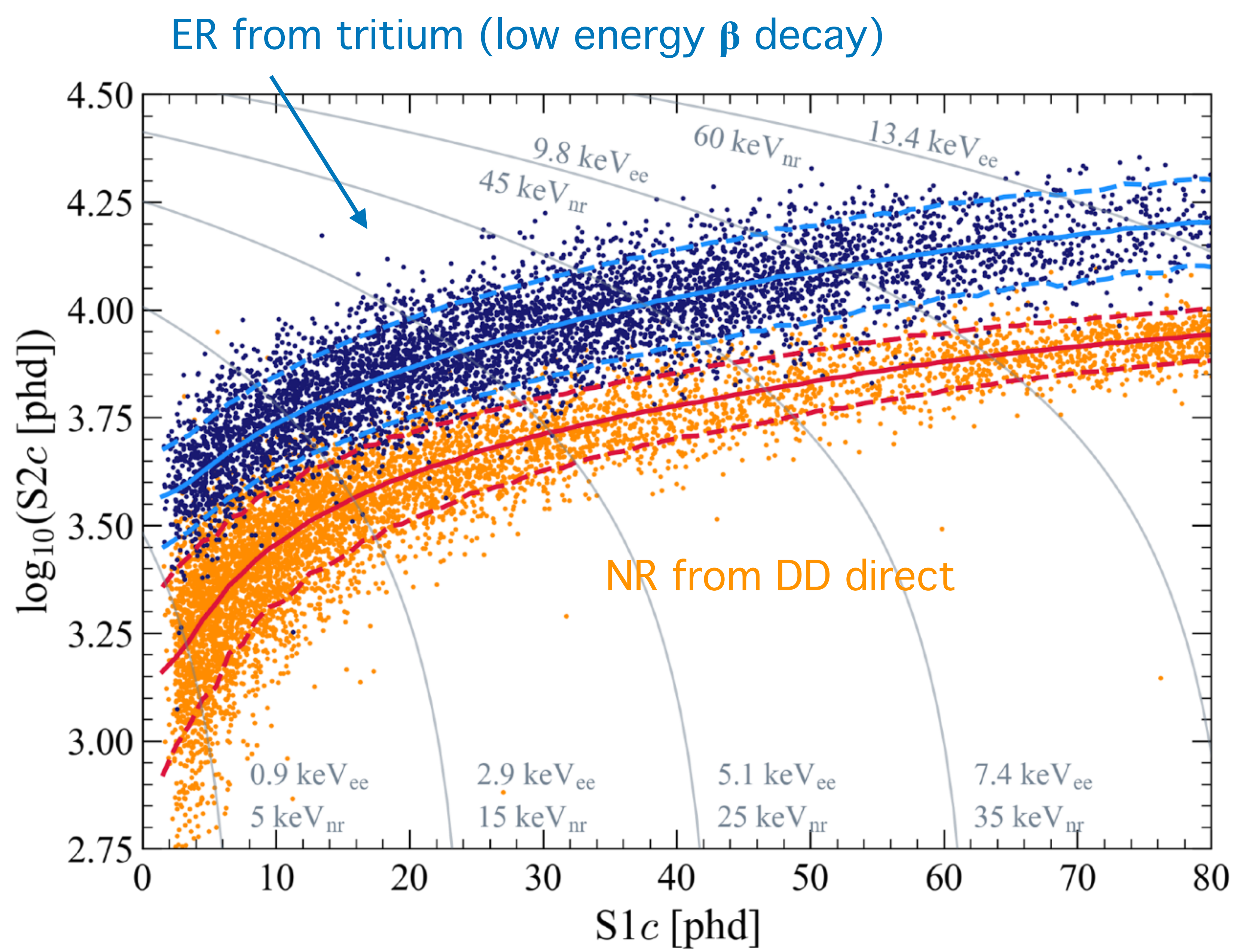


Calibrations

- NEST-based electron recoil model tuned to tritium data, then propagated to nuclear recoil model and verified with DD data.

<u>Detector parameters</u>

- Light gain, g1 = 0.114 ± 0.002 phd/photon
- Charge gain, g2 = 47.1 ± 1.1 phd/photon
- Single electron size = 58.5 phd
- ER / NR discrimination = 99.75% for flat NR response

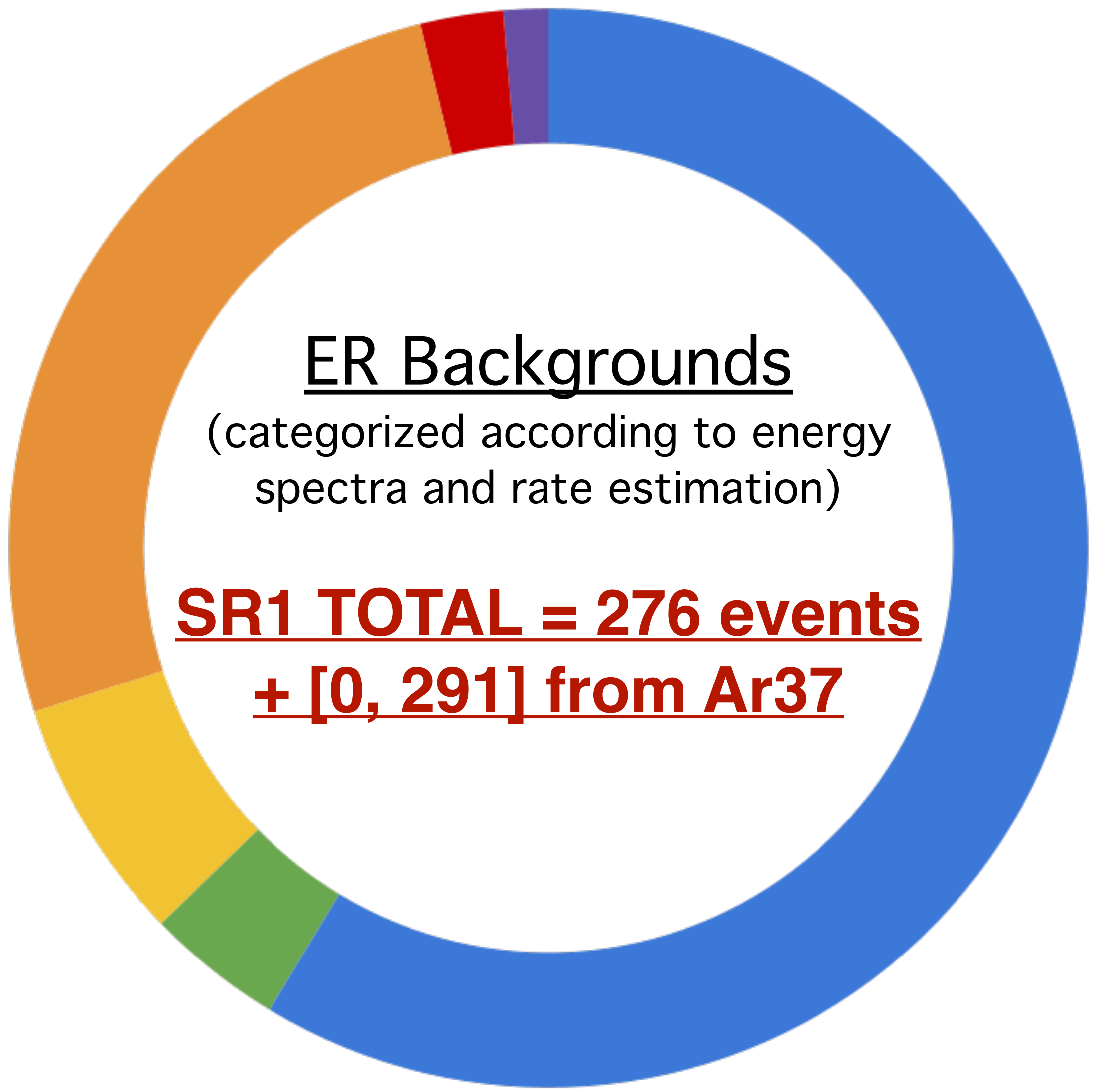


Background model

See talk by DQ. Huang in DM-1

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

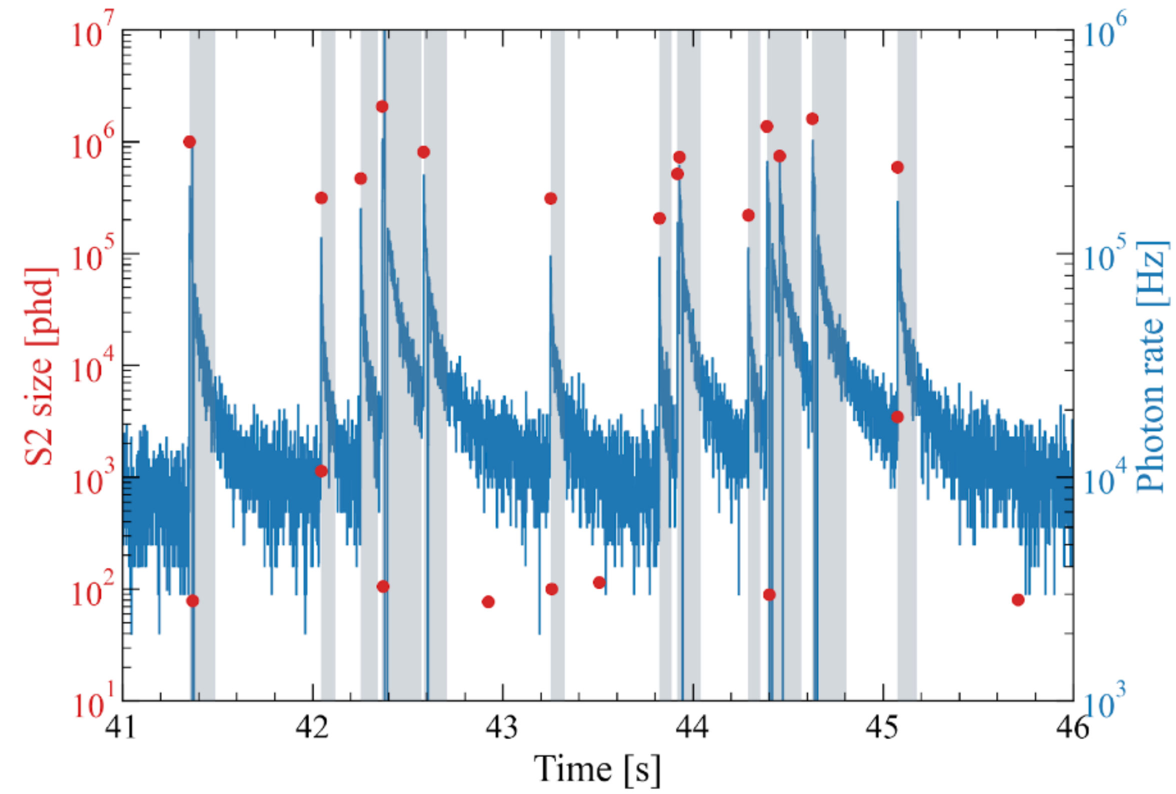
Data quality selections

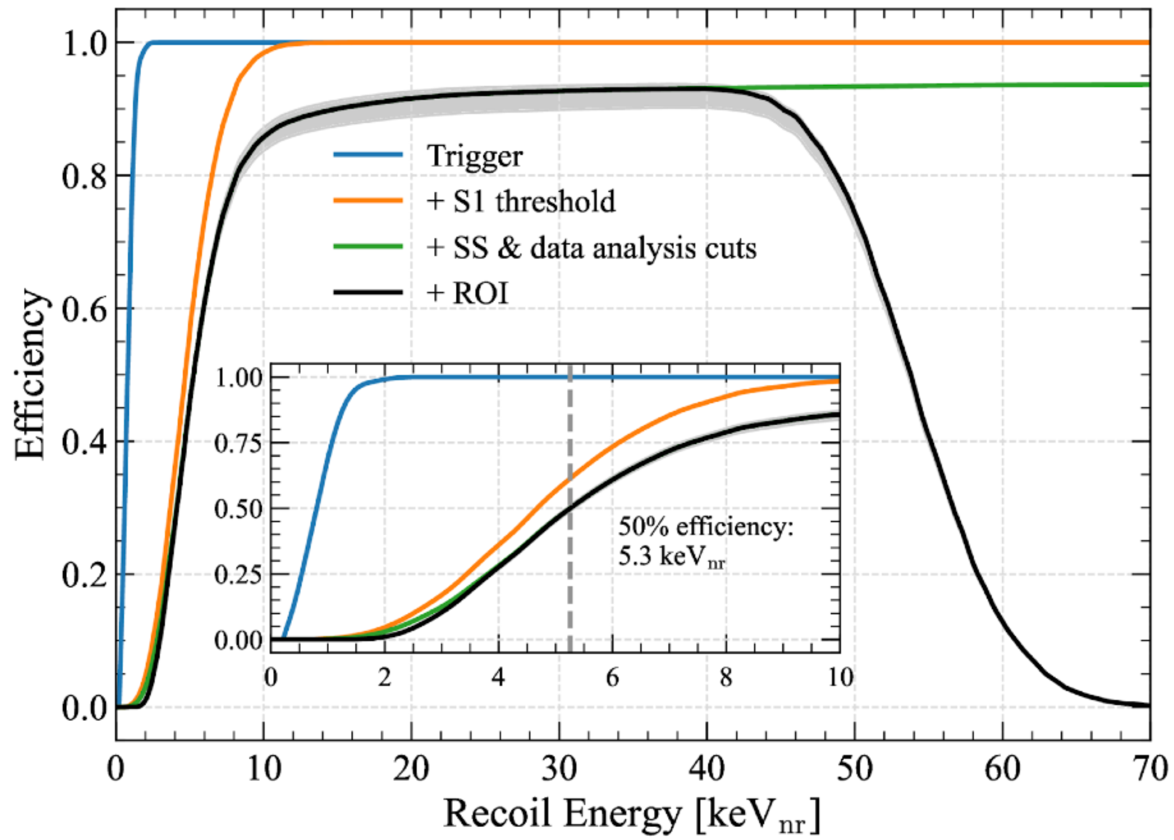
- Two broad categories of data selections allow us to remove data based on bad quality:

  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 data
     - 50% efficiency at 5.3 keV nuclear recoil energy

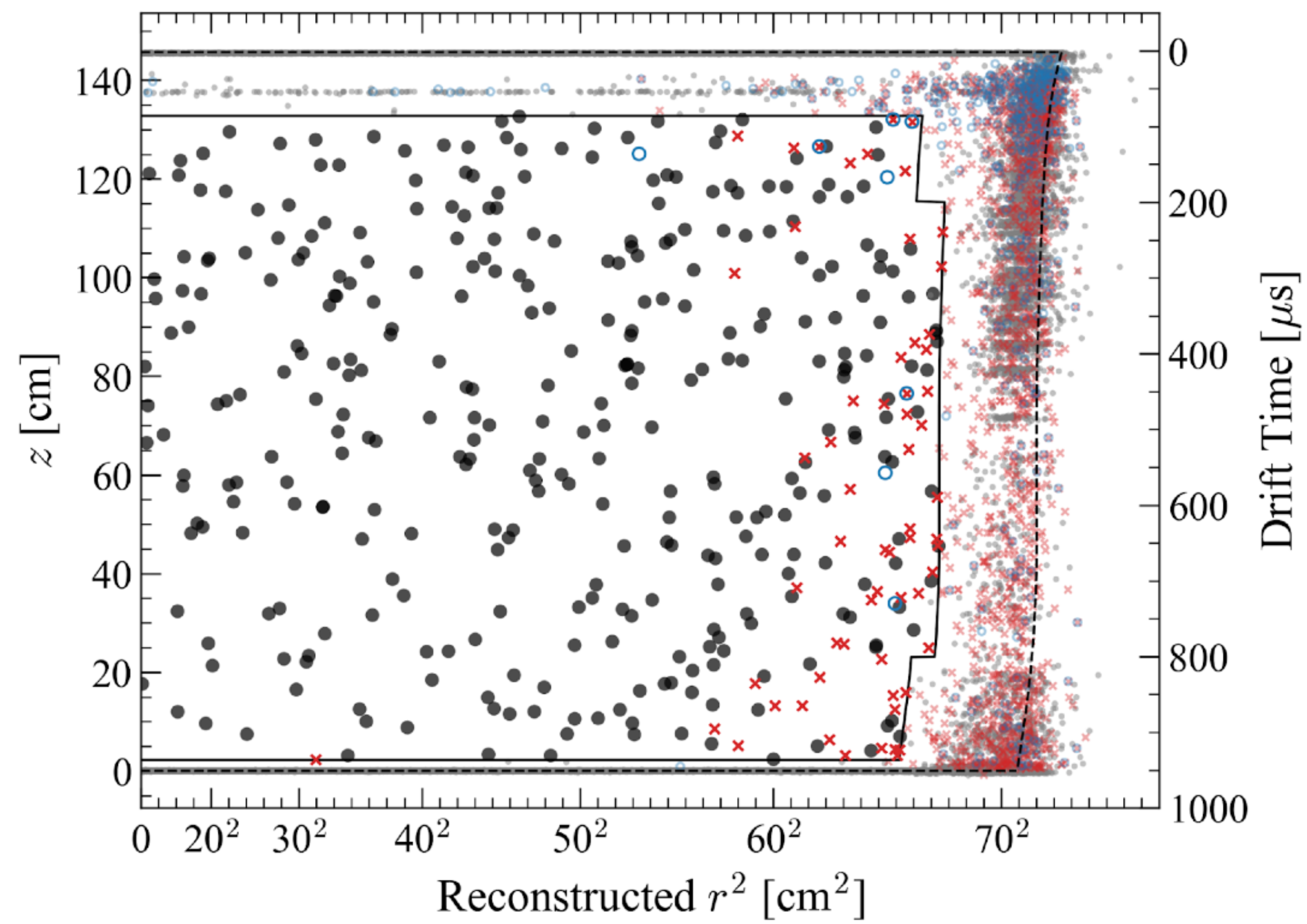
<u>All cuts developed on calibration data or search data outside the WIMP search region of interest</u>





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 background leakage 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

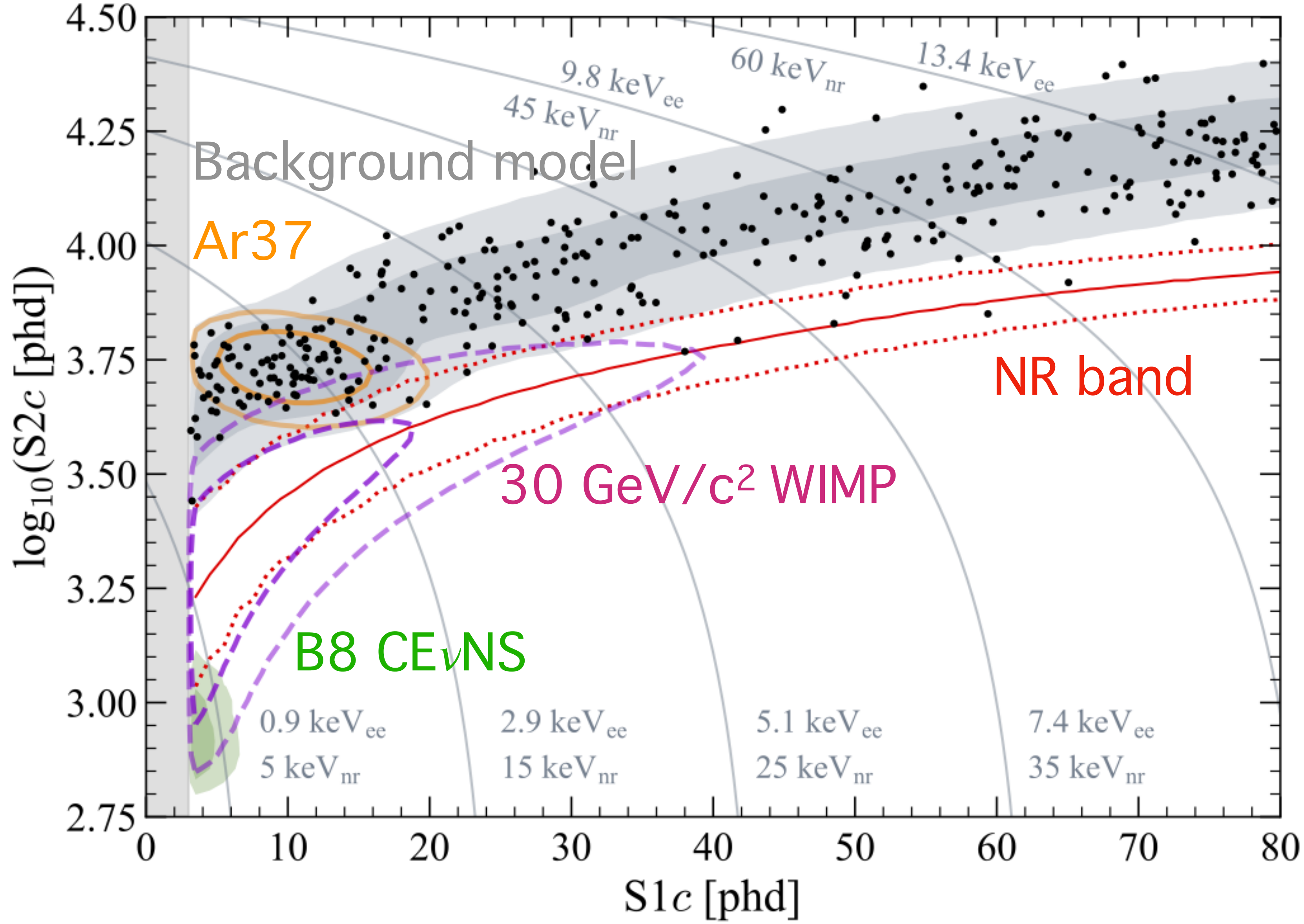
- Prompt (< 0.5 μs) Skin and OD tag:
  - Reduces naked L-, M-shell Xe127 background by x5 by tagging γ-ray that escapes the TPC

- 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

Candidates

- 335 events in 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

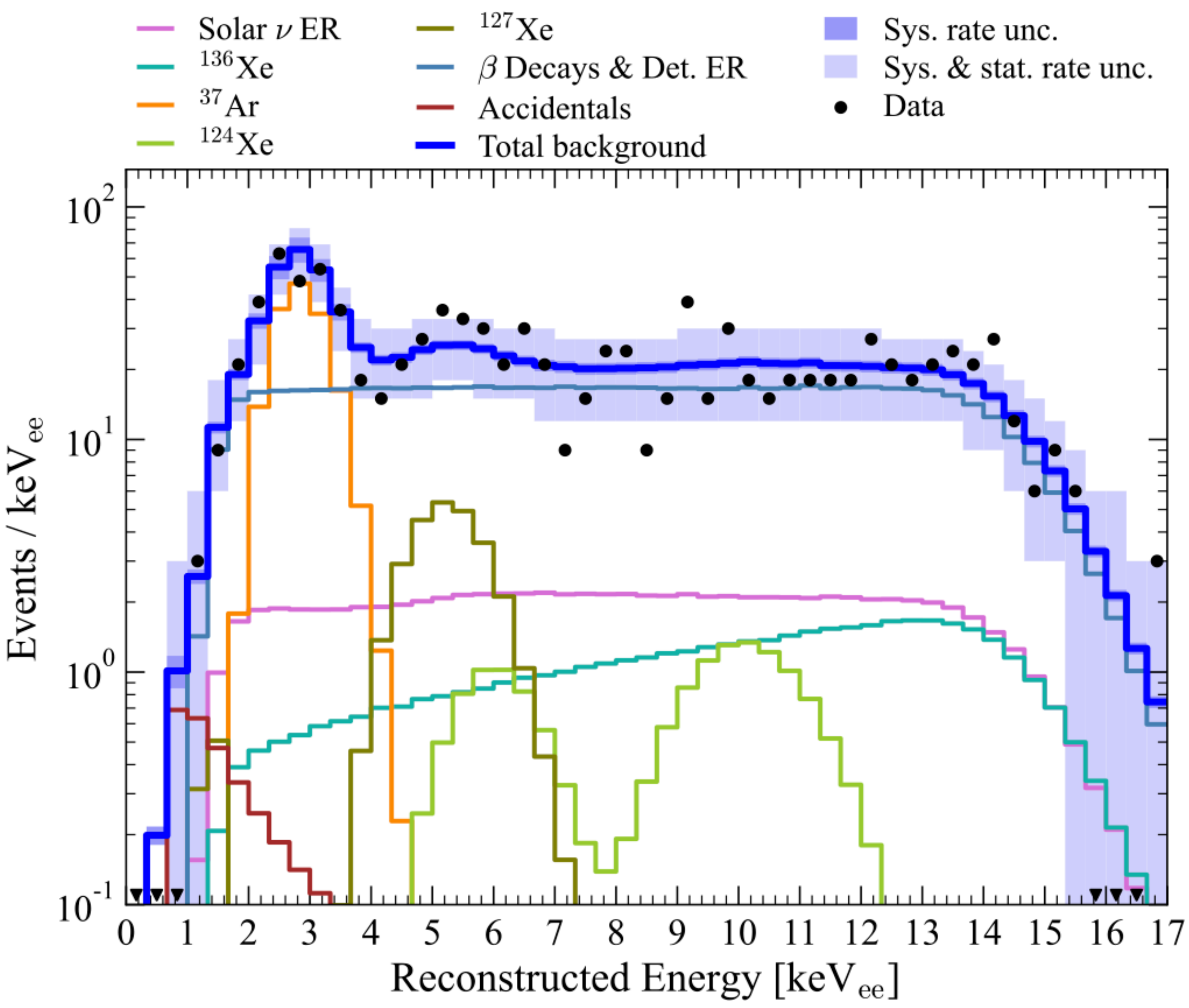
60 live days, 5.5 t fiducial volume, 0.9 t years exposure



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

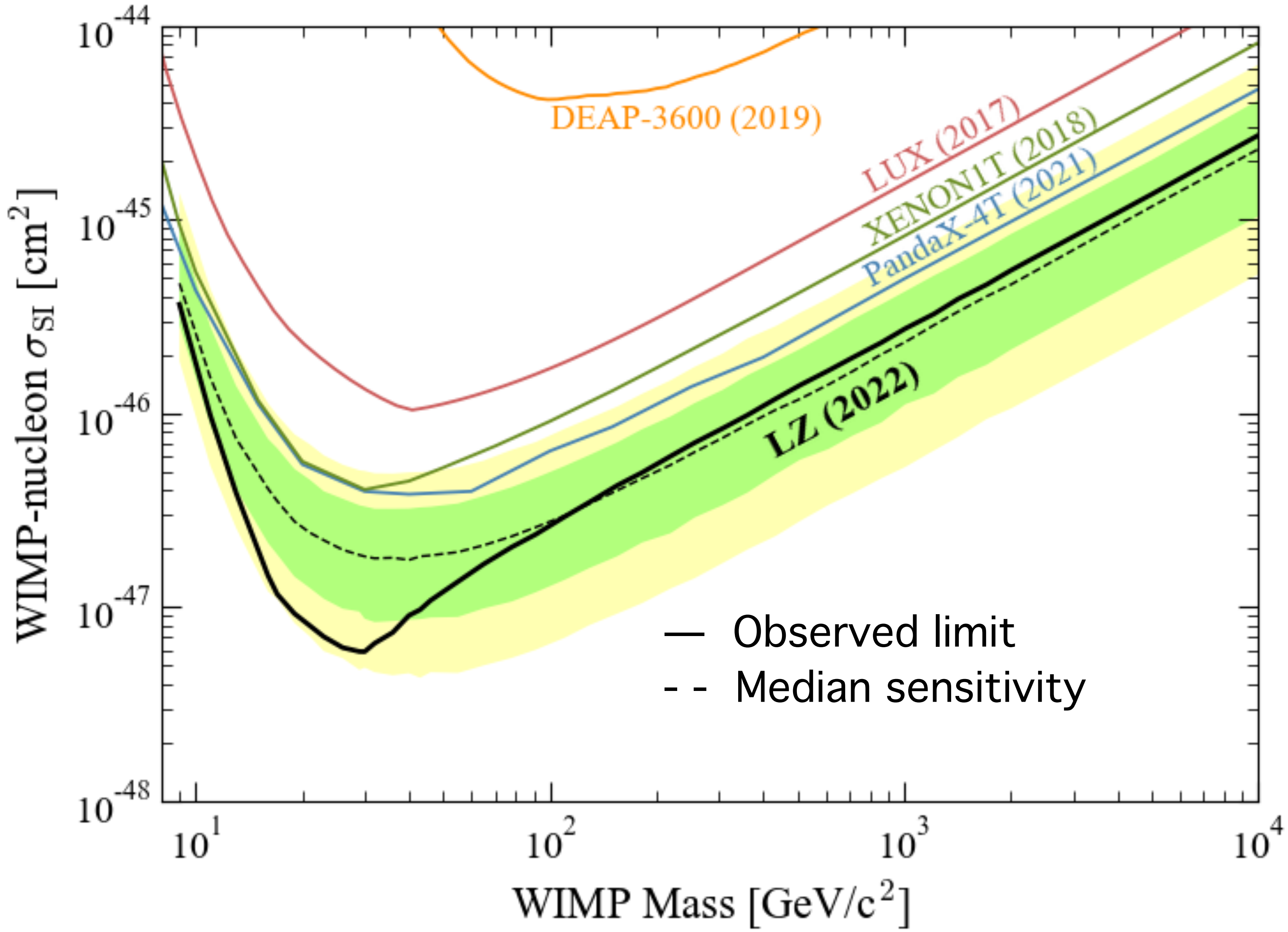


Combined fit to data with expected events as priors

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

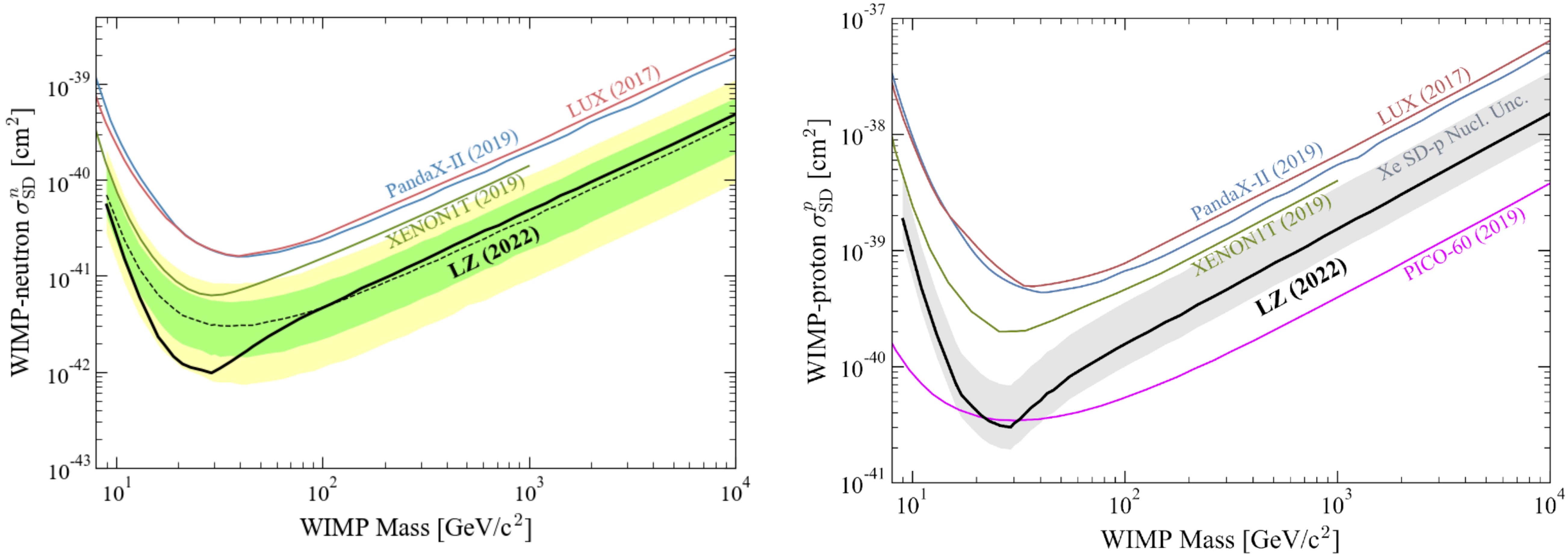
Results - spin independent interactions

- Frequentist, 2-sided PLR test statistic
- Power constrain (*) at π_{crit} = 0.32 for discovery power
- Best limit of σ_{SI} = 5.9 x 10^{-48} at 30 GeV/c^2
- Green and yellow are the 1σ and 2σ sensitivity bands.
- Assume a spin independent (scalar) WIMP-nucleon interaction



(*) Following recommendations from community white paper: Eur. Phys. J. C 81, 907 (2021)

Results - spin dependent interactions



- 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).

Conclusions

- LZ is up and running and taking science data
  - All detectors are performing well and backgrounds are within expectation

- With its first run, LZ has set new limits on WIMP interactions:
  - Paper: arXiv:2207.03764 (currently under PRL review)

- LZ is expected to run for 1000 live days, and a broad physics program lies ahead - stay tuned!

Next generation - XLZD consortium

- MOU between LZ, XENON and DARWIN collaborations to work toward a G3 xenon observatory.
- First meeting 27-29 June 2022 at Karlsruhe Institute of Technology.
- See https://xlzd.org and white paper (arXiv:2203.02309).

Thank you for listening

35 Institutions: 250 scientists, engineers, and technical staff

- 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
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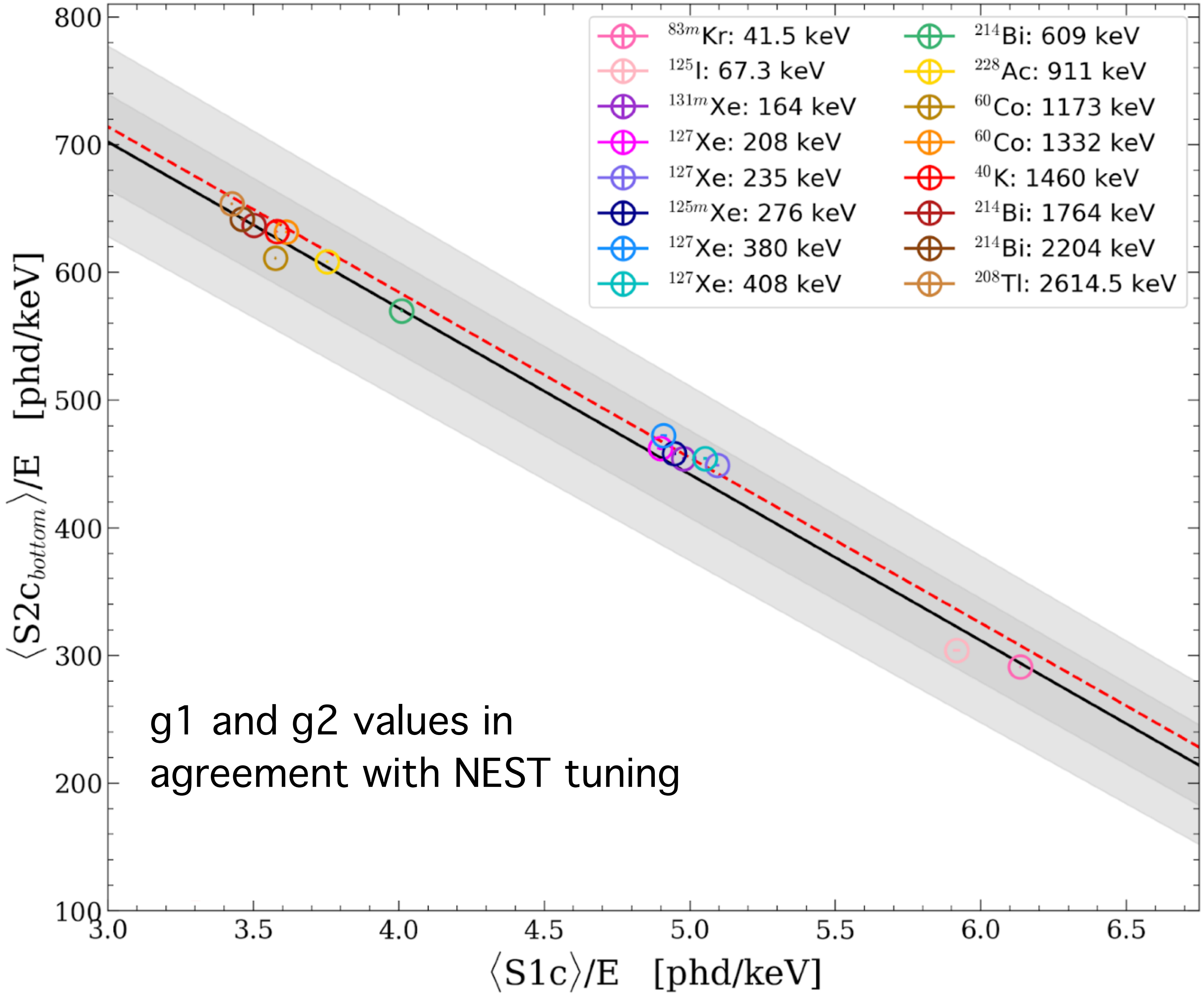
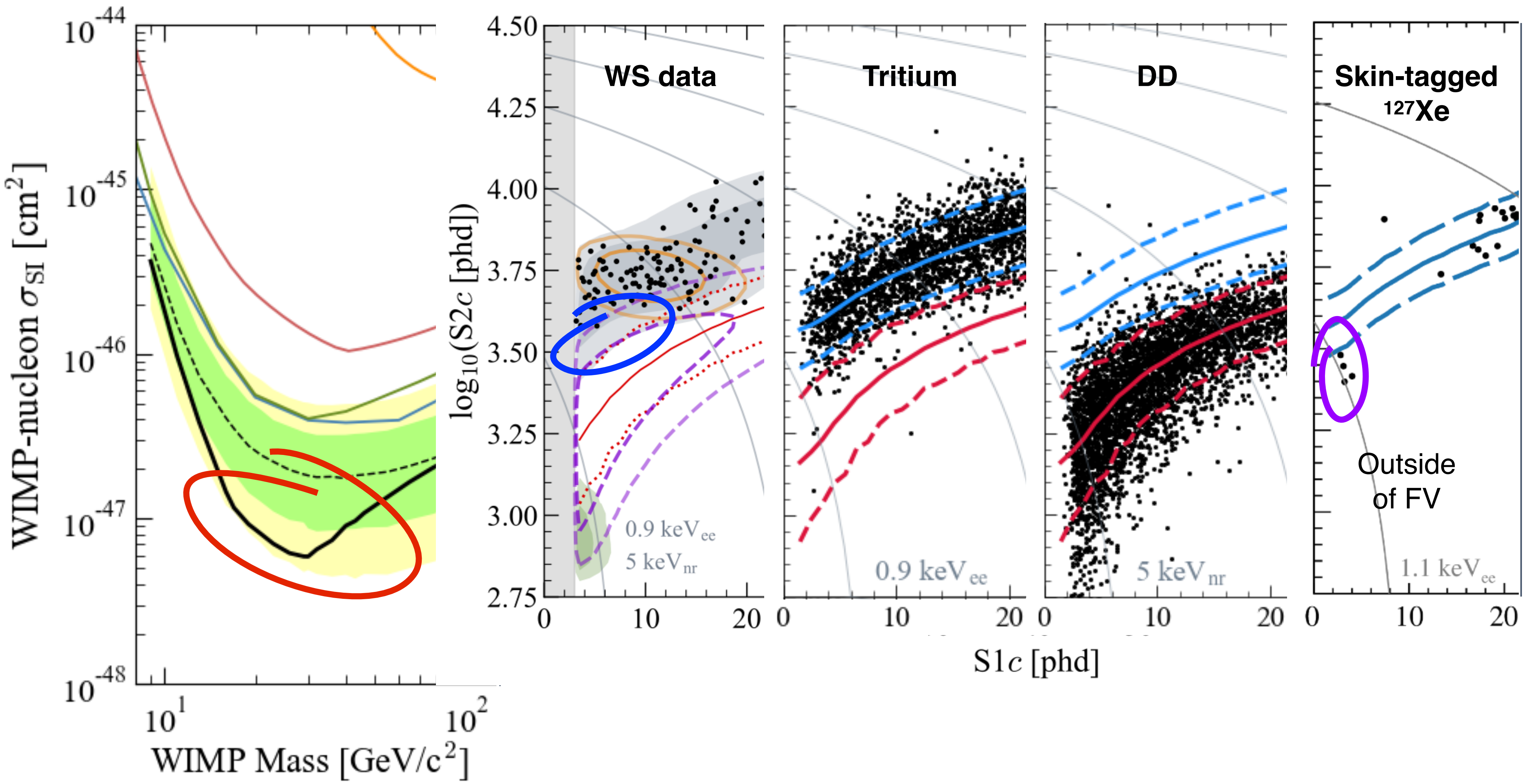
Backup slides

LZ Doke Plot



^{83m}Kr: 41.5 keV
^{125}I: 67.3 keV
^{131m}Xe: 164 keV
^{127}Xe: 208 keV
^{127}Xe: 235 keV
^{125m}Xe: 276 keV
^{127}Xe: 380 keV
^{127}Xe: 408 keV
^{214}Bi: 609 keV
^{228}Ac: 911 keV
^{60}Co: 1173 keV
^{60}Co: 1332 keV
^{40}K: 1460 keV
^{214}Bi: 1764 keV
^{214}Bi: 2204 keV
^{208}Tl: 2614.5 keV
g1 and g2 values in agreement with NEST tuning
$\langle S2c_{bottom} \rangle$/E [phd/keV]
$\langle S1c \rangle$/E [phd/keV]
800
700
600
500
400
300
200
100
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5

Downward fluctuation of the 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 deficit of events under the 37Ar population.

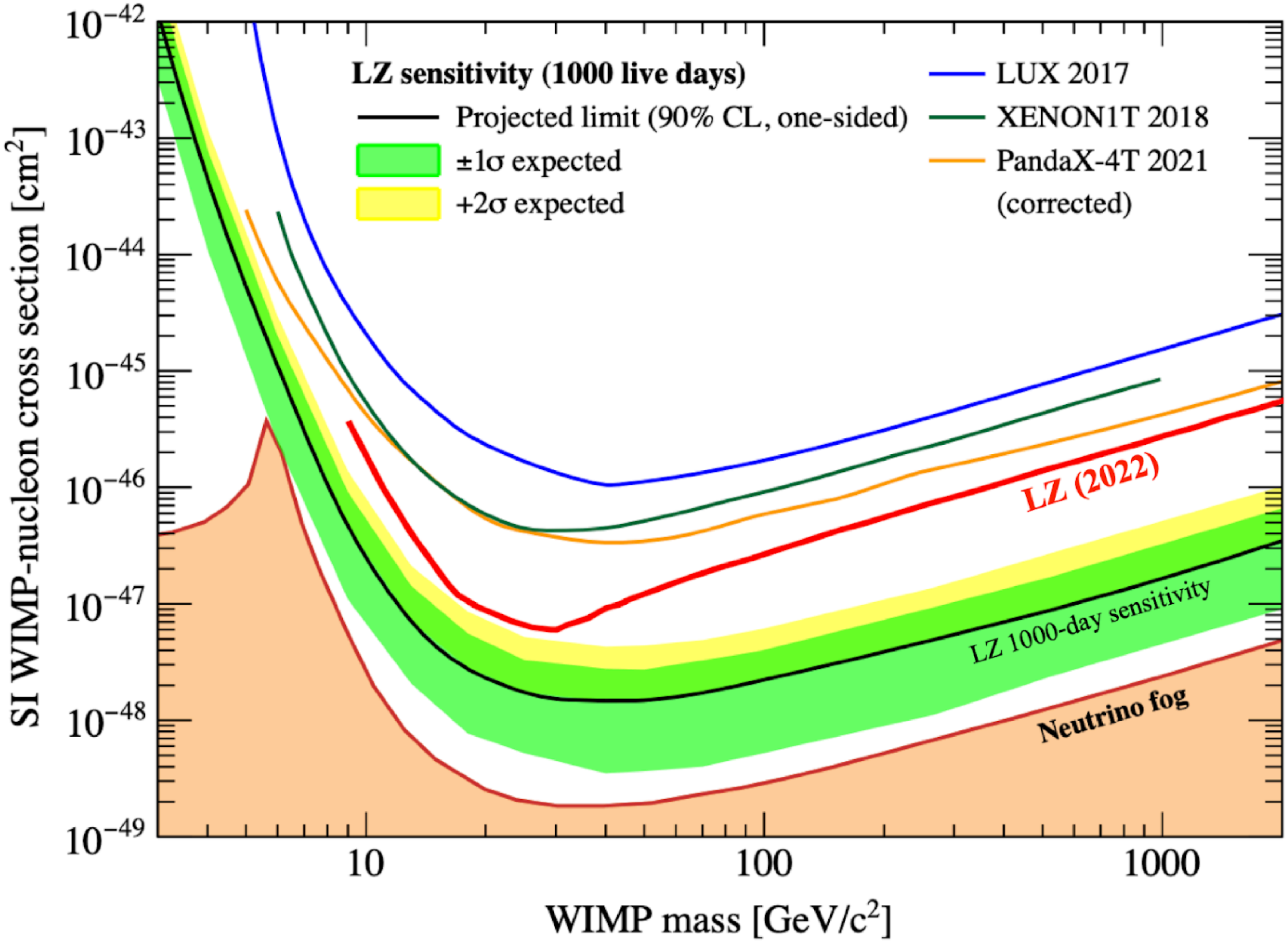
Due to background under-fluctuation or unaccounted for signal inefficiency? Probe the latter.

→

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.

LZ projected 1000 day WIMP sensitivity

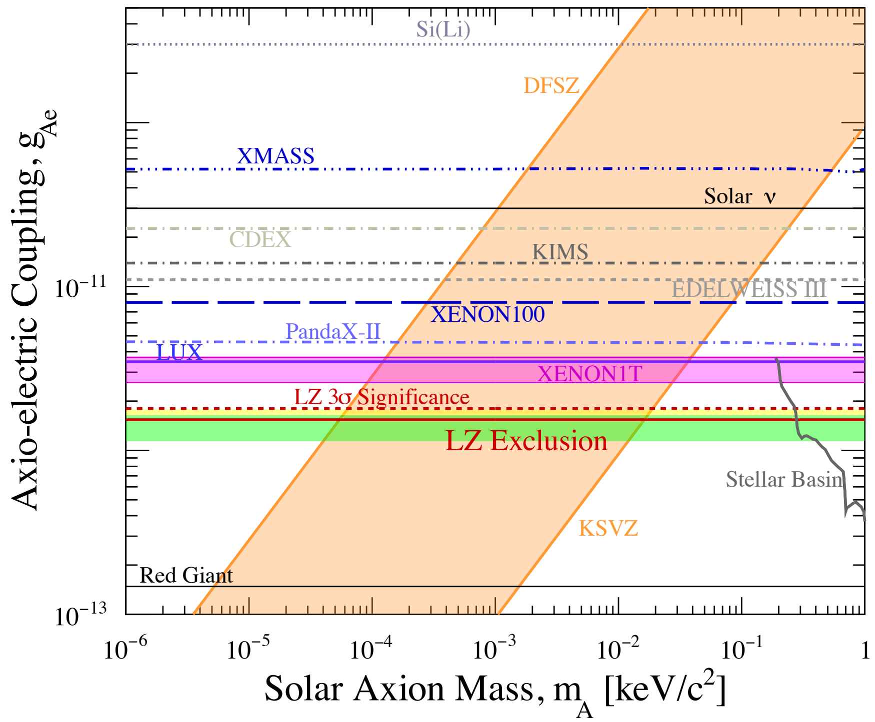


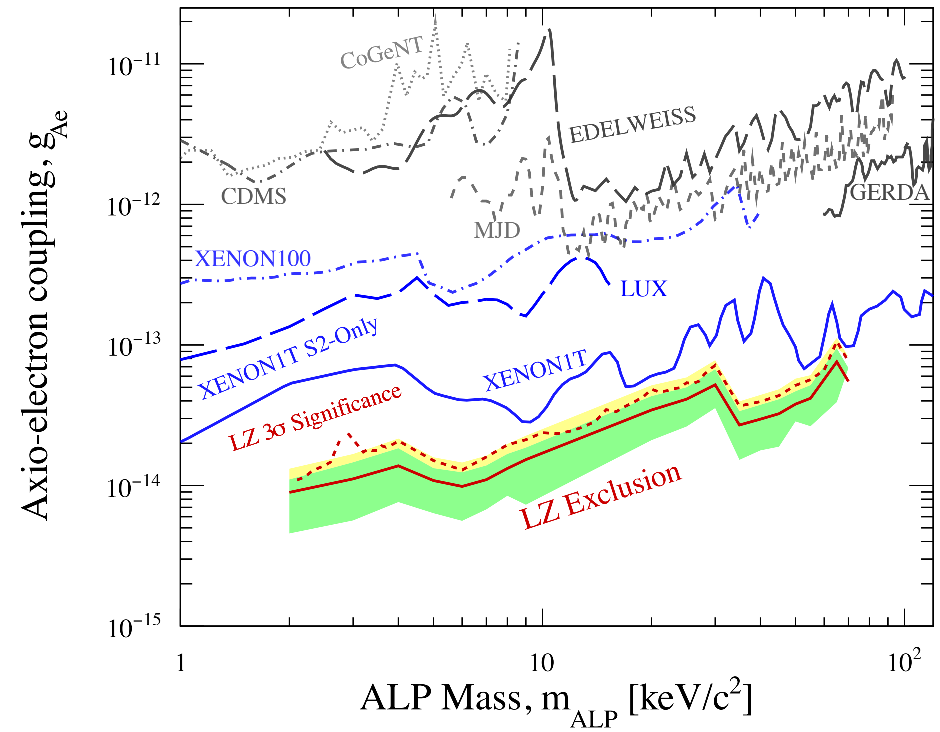
90% CL minimum (one sided) of 1.4×10^{-48} cm^2 at 40 GeV/c^2 from [Phys. Rev. D 101 (2020), 052002]

Sensitivity to other physics searches

Axions and ALPs

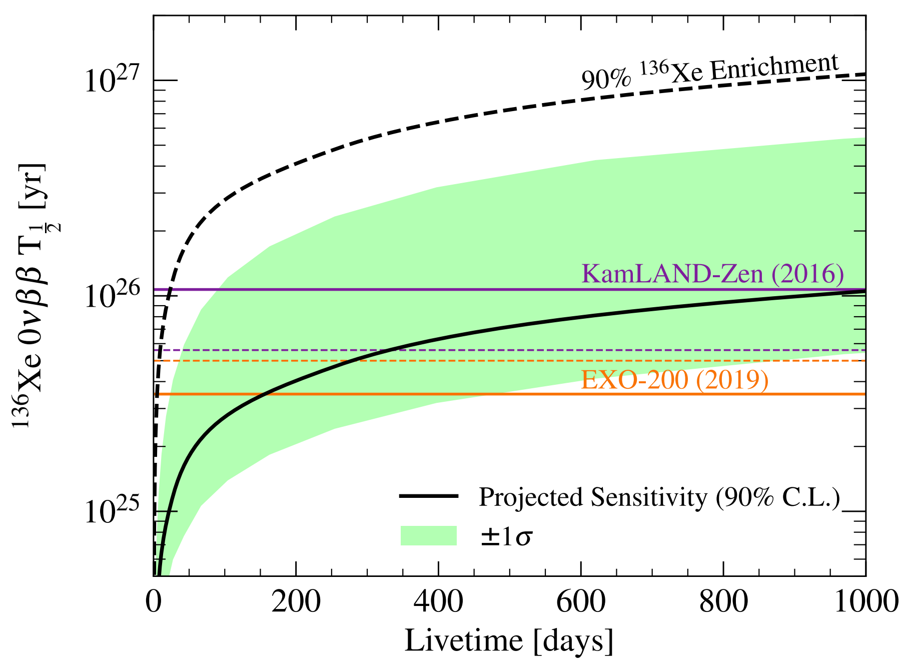
Phys. Rev. D (2021) 104, 092009

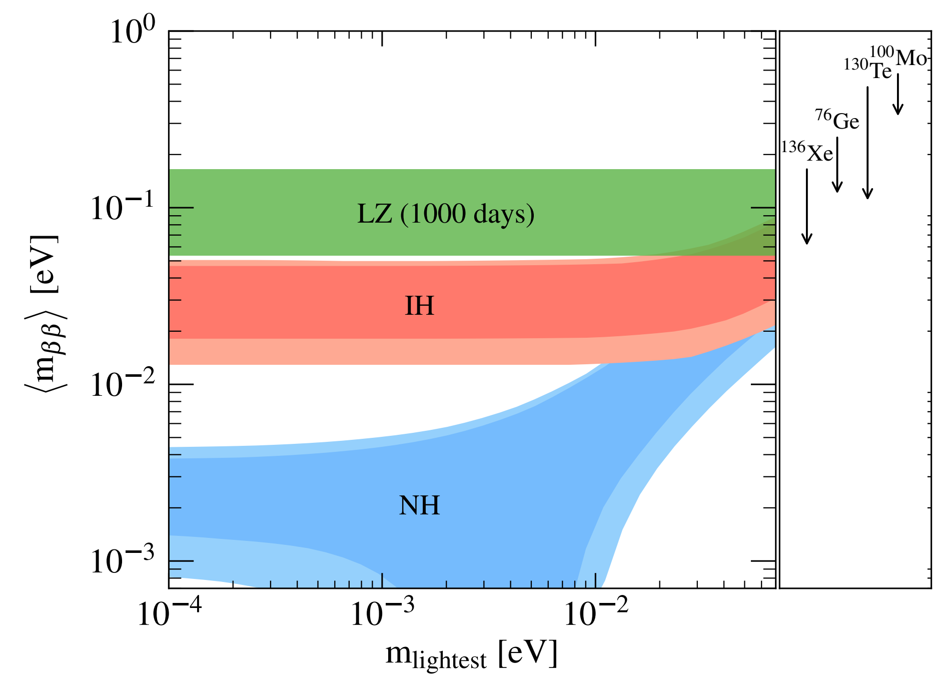




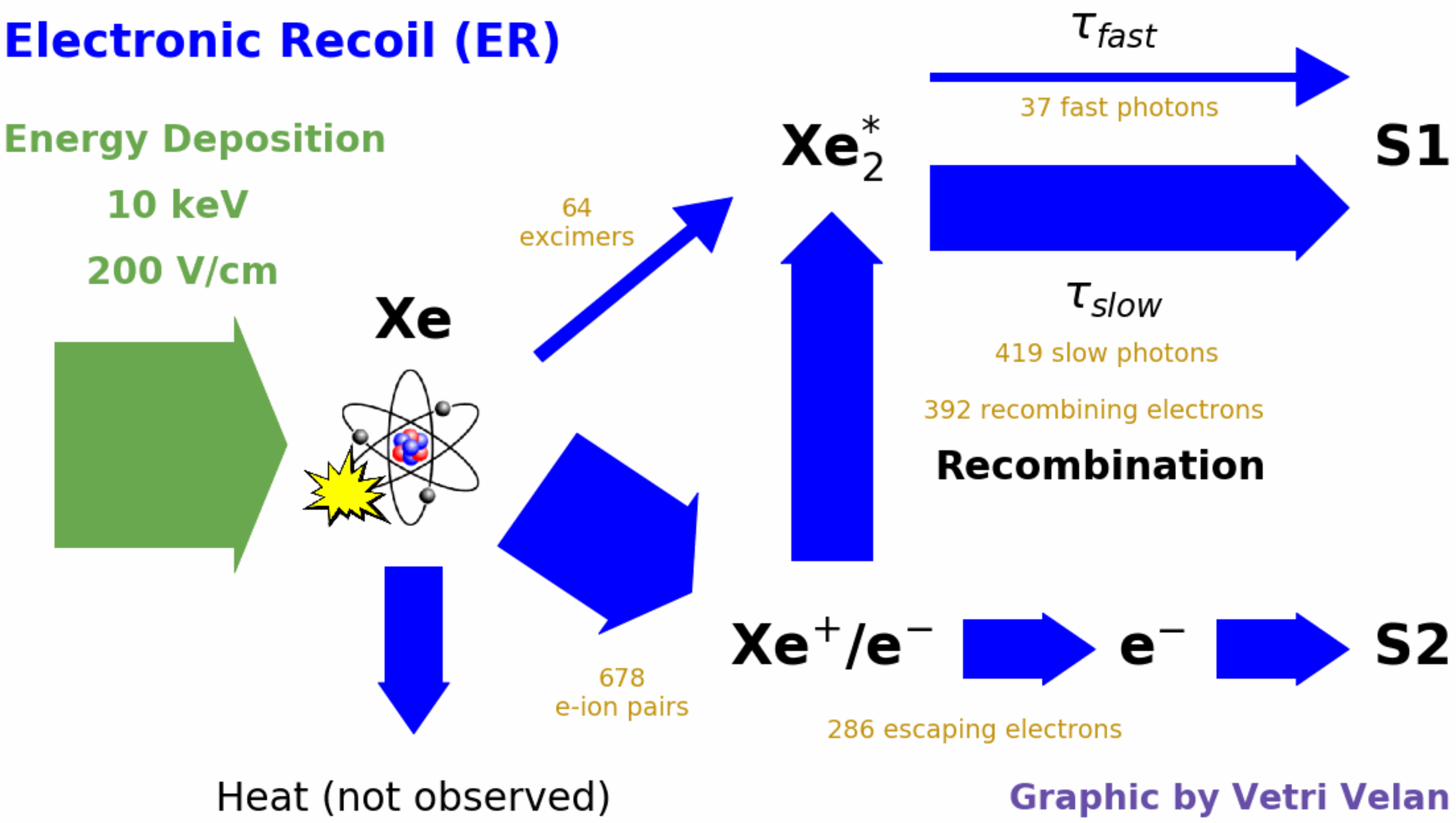
Neutrinoless double-beta decay

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

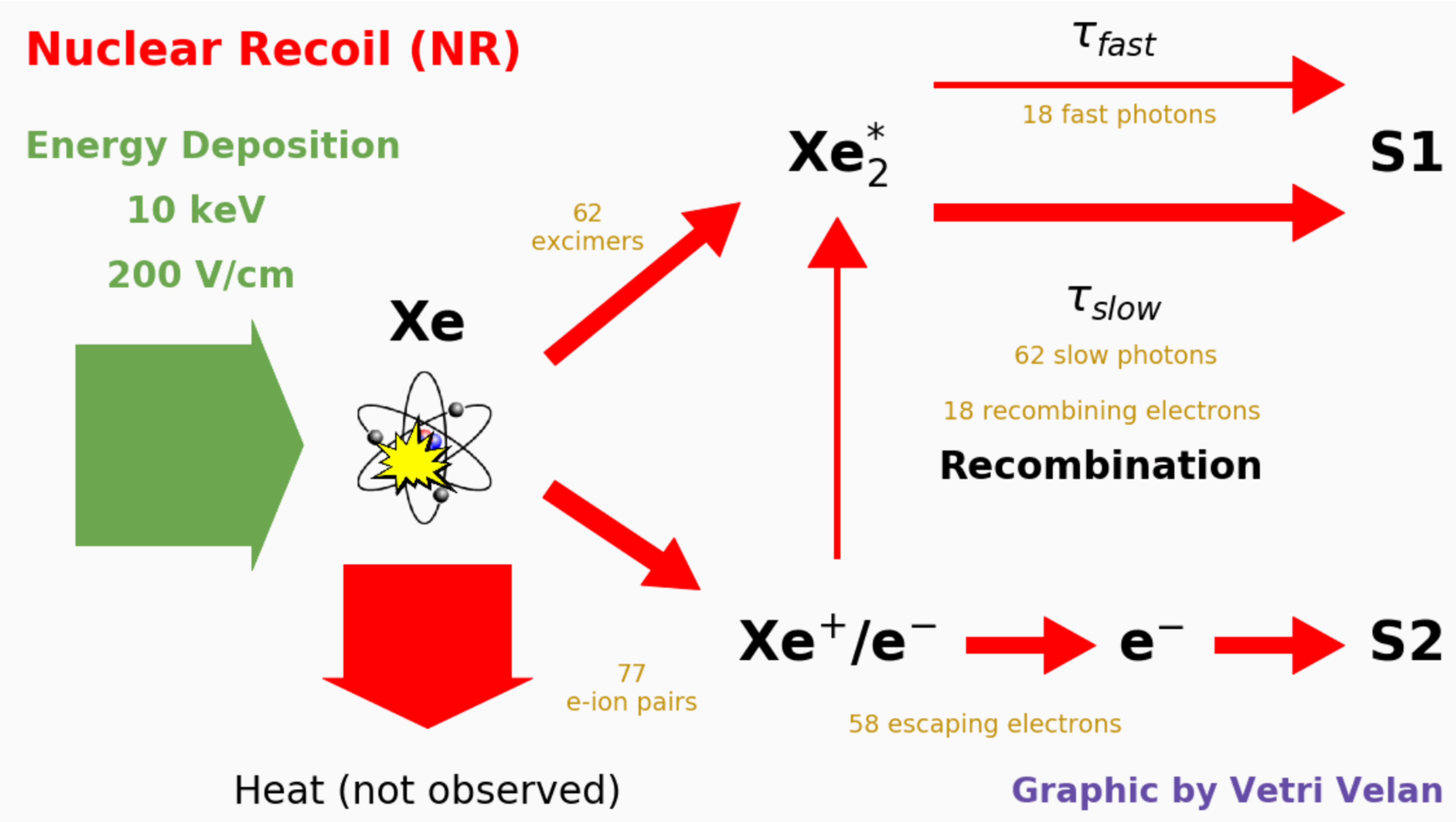




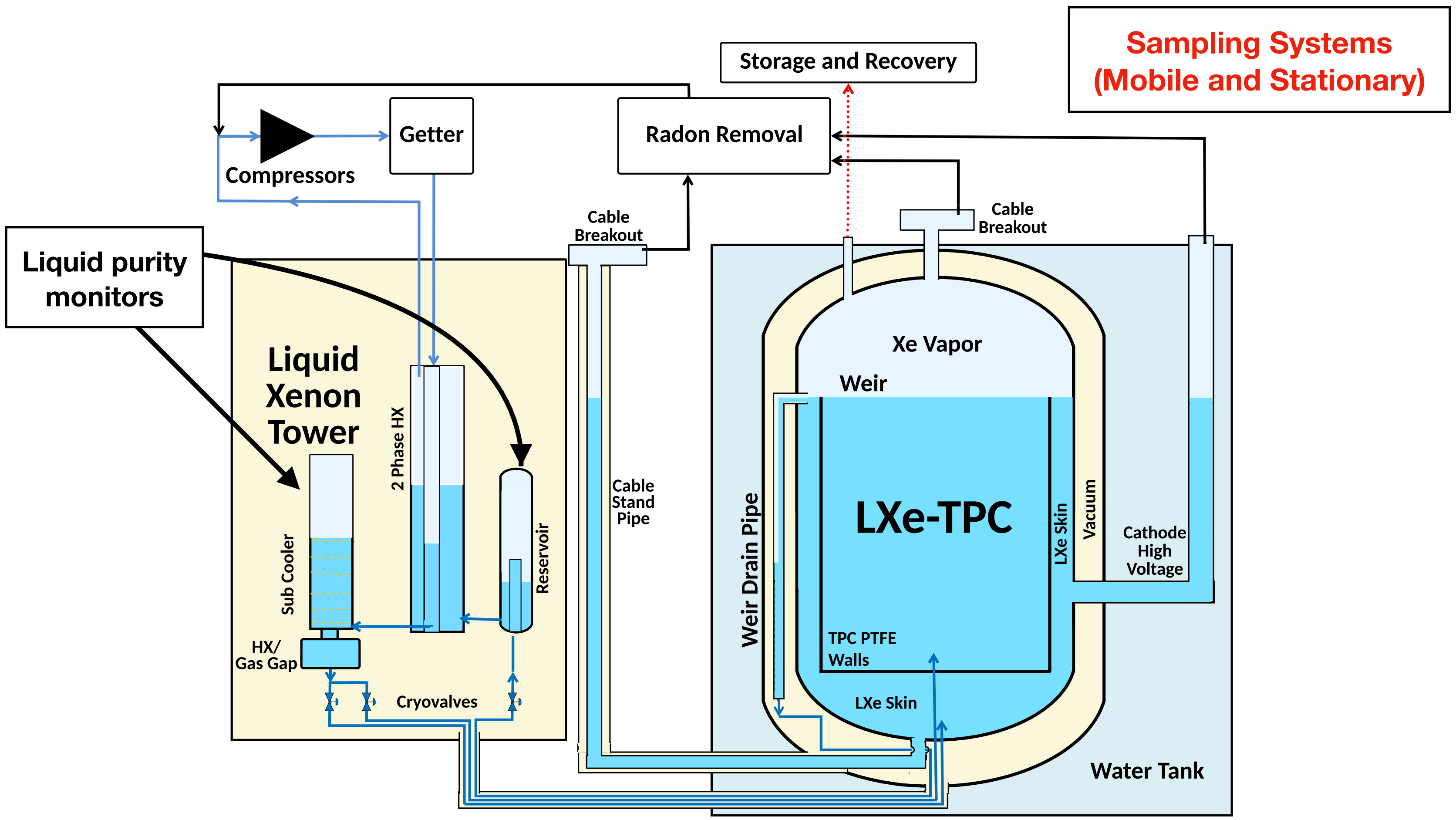
Xenon microphysics



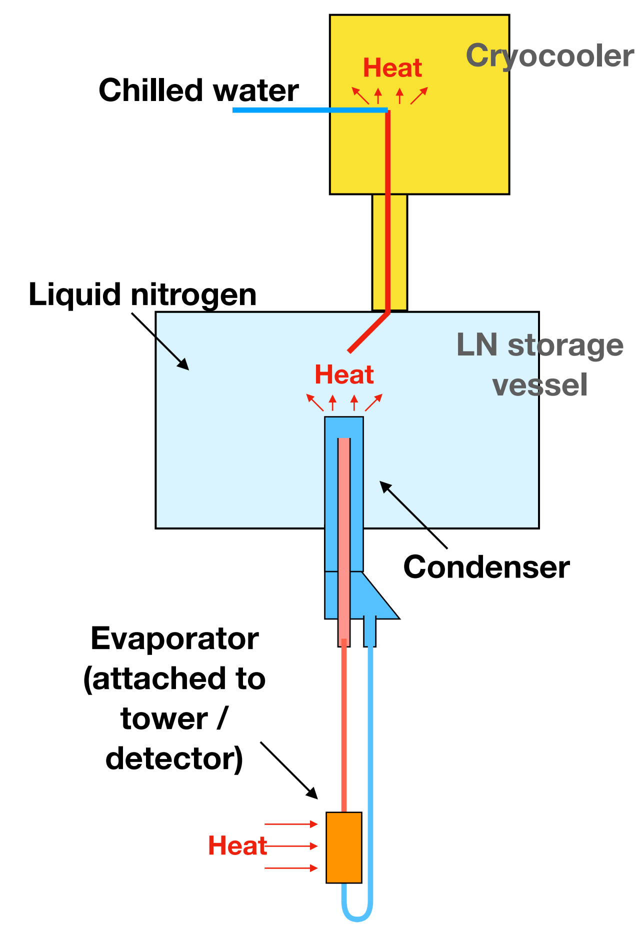
Xenon microphysics



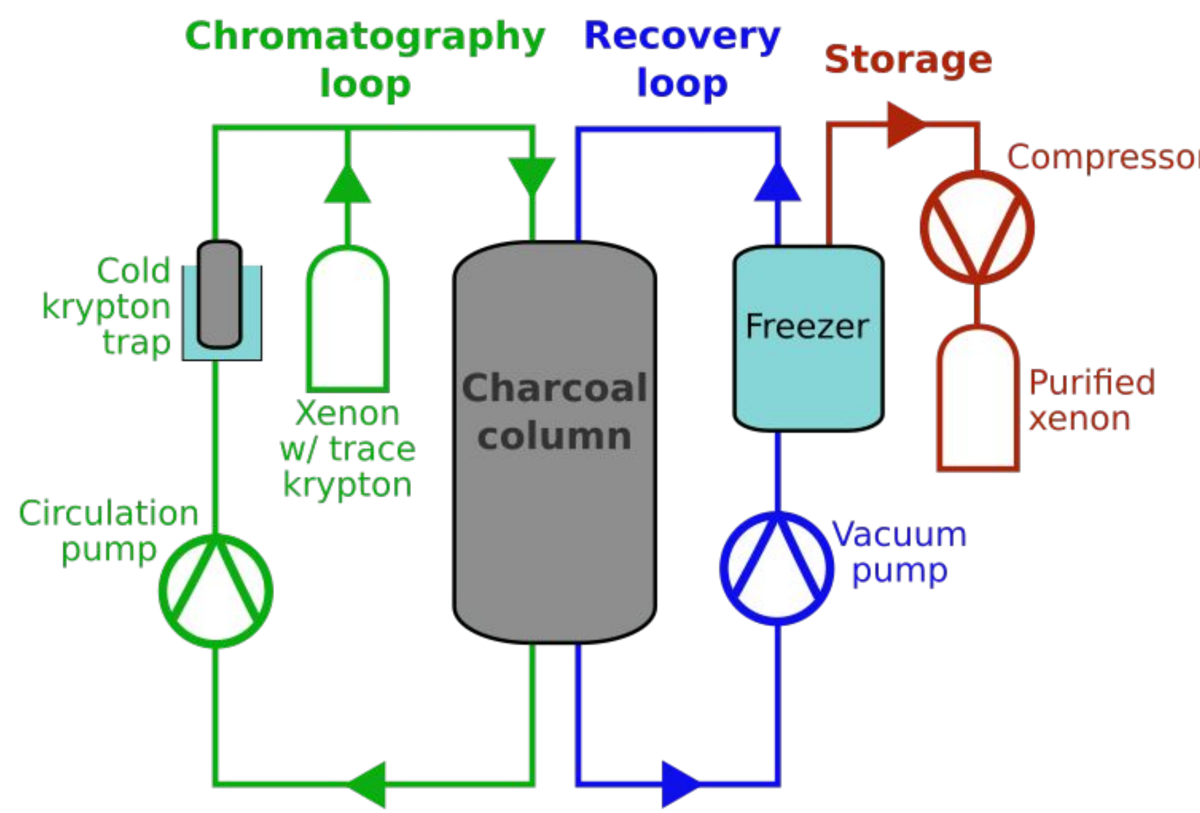
LZ circulation system



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