Dark matter detection with the LZ experiment

RIKEN/N3AS workshop (Waikoloa, HI)
November 26th 2023
Ibles Olcina Samblas

Direct detection of dark matter

All the seemingly disconnected observations of dark matter can be explained if we assume dark matter is composed of collisionless, cold, and non-baryonic particles.

The “WIMP”: a strongly motivated, well studied dark matter candidate

- Stable and weakly-interacting particle moving at non-relativistic velocities
- Mass in the GeV/c^2 – TeV/c^2 range
- Correct relic density from thermal production

[Nature.562,51-56]

Direct detection of WIMPs

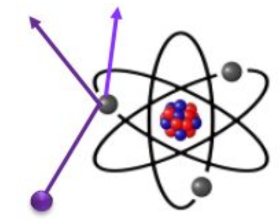
Goal: search for low-energy scatterings (~1-100 keV) of a galactic dark matter particle and a target nucleus on Earth

Types of signals

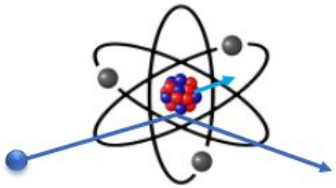
- Electron recoils (ER): gamma-rays, beta particles, ν-e scattering
- Nuclear recoils (NR): neutrons, coherent elastic ν-N scattering (CEνNS), WIMP

Main backgrounds

- Radon progeny attached to surfaces
- Cosmogenic activation
- Dispersed radioisotopes
- Astrophysical neutrinos



Electron recoil



Nuclear recoil

Dual-phase xenon TPC

A single scatter (SS) in the "active" region results in:

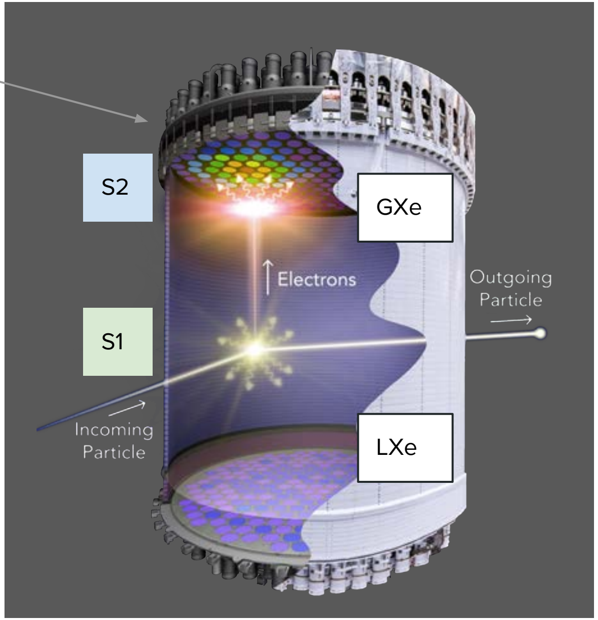
- Prompt scintillation signal in the liquid phase (S1)
- Secondary scintillation signal in the gaseous phase (S2)

The light signals are recorded by two arrays of photomultiplier tubes (PMTs) located at the top and bottom of the detector.

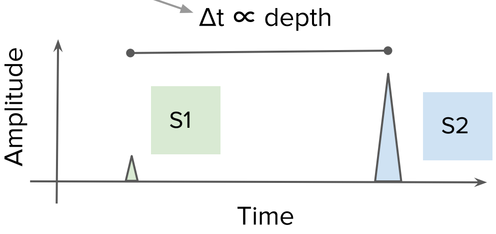
Advantages:

- Low detection threshold (~3 keV)
- 3D position reconstruction
- Self-shielding from xenon
- Absence of long-lived radioisotopes in natural xenon
- Excellent ER/NR discrimination

PMT hit map gives XY position



Time difference gives Z position



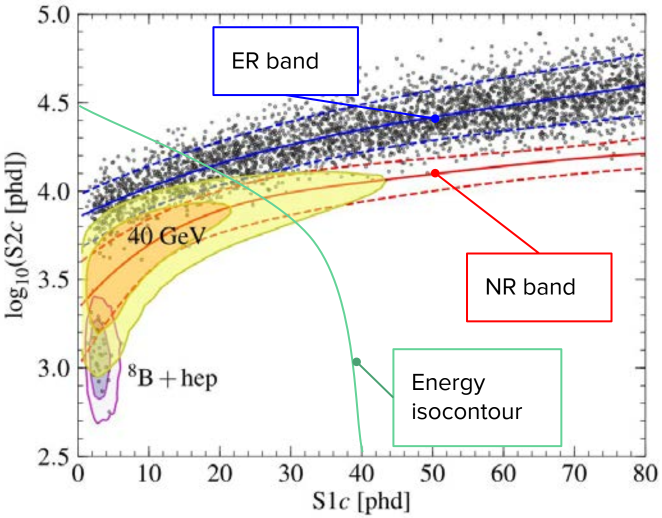
ER/NR discrimination

Any ionisation electron that is not captured by a positive ion will escape the interaction site as a free electron and contribute to the S2 signal.

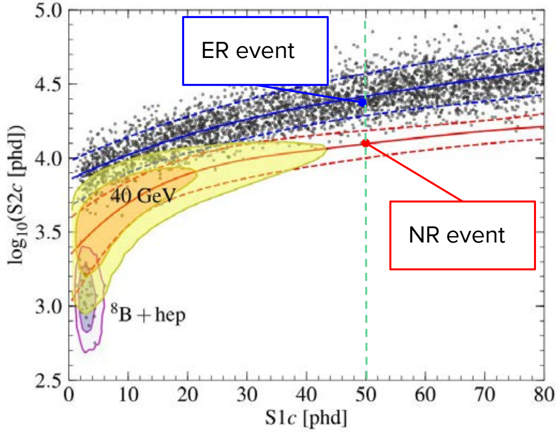
If captured by a Xe ion, it will create an extra Xe excimer and contribute to the S1 signal.

The S1 and S2 signals are *anti*-correlated!

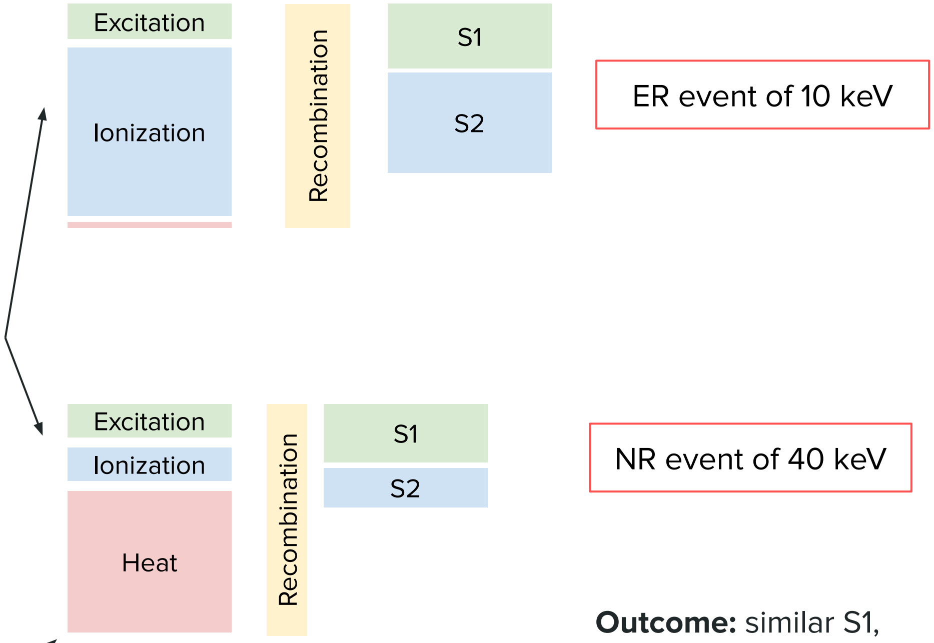
Key idea: The different, initial exciton-to-ion ratio for ERs and NRs results in distinct bands in the S1-S2 plane.



[Phys. Rev. D 101, 052002]



For an S1 signal of 50 photons detected (phd):



The exciton-to-ion ratio is ~1:10 for ERs and ~1:1 for NRs

A larger fraction of energy is “lost” to heat in NR events

~50% of free electrons are recombined for NRs (~60% for ERs)

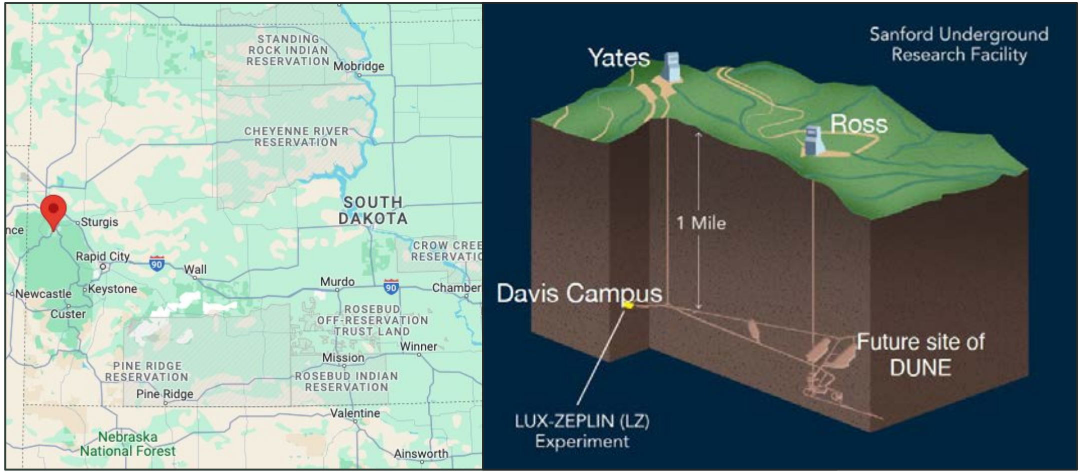
Outcome: similar S1, but larger S2 for an ER event.

First dark matter search results from LZ

Overview

Deep underground

- Located at the Sanford Underground Research Facility (SURF), in South Dakota
- 1 mile deep (4.3 km.w.e)



SURF is located in Lead, SD. LZ is in the Davis Campus, 4850 feet underground.

The Yates shaft

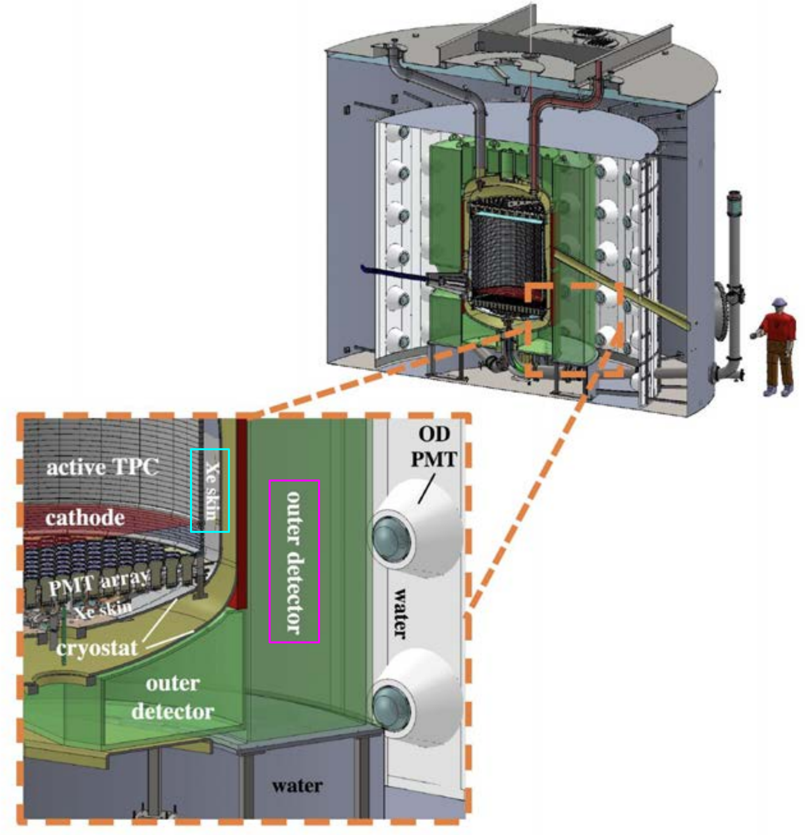
Transport of the TPC underground from the surface laboratory

Largest Xe TPC in the world

- 1.5 m tall and wide
- 7 tonnes of liquid xenon
- 494 x 3'' PMTs distributed in two arrays
- 4 wire mesh electrodes:
    - Anode
    - Gate
    - Cathode
    - Bottom
- Field cage composed of titanium rings embedded in highly reflective teflon (PTFE) panels

Multi-detector system

- Integrated veto system that can effectively reject multi-site background events:
  - Xe Skin
    - Located between the active TPC and the inner cryostat vessel
    - ~2 tonnes of liquid Xe
    - Anti-coincidence detector for gamma-rays
  - Outer detector (OD)
    - Located between the outer cryostat vessel and the water tank
    - 17 tonnes of Gd-loaded liquid scintillator contained in acrylic vessels
    - Anti-coincidence detector for gamma-rays and neutrons



[NIM A, 163047 (2019)]

LZ in pictures!

Background mitigation

- Rock overburden:
  - Muons reduced by ~10^6 at SURF
- Material selection:
  - Extensive material screening campaign to select radiopure materials
    - [Eur.Phys.J.C 80 11, 1044]
    - [Astropart. Phys. 96, 1]
- Strict cleanliness protocol:
  - TPC assembled in Rn-reduced cleanroom
  - Extensive dust control underground
- Xenon purification:
  - Off-site Xe distillation for Kr removal
  - In-line Rn removal system

Inspecting for dust with UV light

Kr-removal system at SLAC, CA

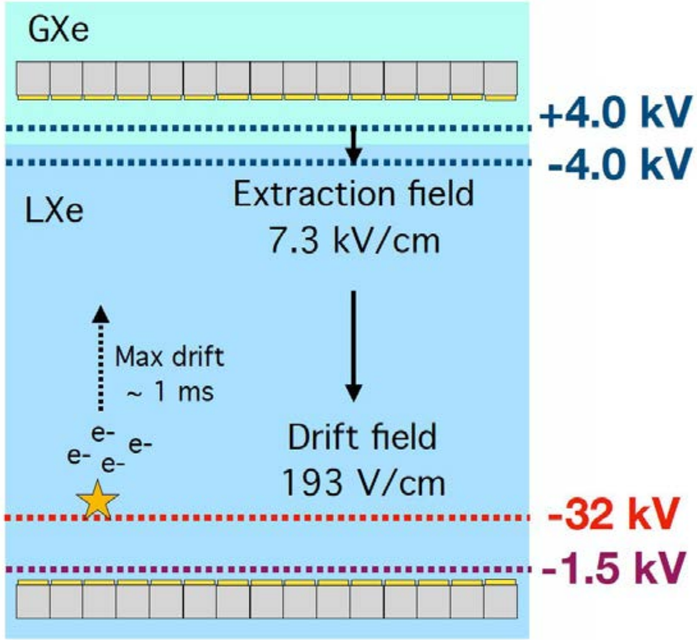
Science Run 1 (SR1)

First light!

- Data collected from Dec 23rd 2021 to May 12th 2022
- Mid-run and post-run calibrations
- WIMP search livetime of 60 days
- Engineering run, with the goals to:
    - Demonstrate physics capability of the detector systems
    - Set competitive limits to WIMPs

Stable detector conditions

- >97% of PMTs stayed operational
- Stable liquid temperature (174.1 K) and gas pressure (1.8 bara)
- Uniform drift field (193 V/cm)
- High electron lifetime (> 5 ms) throughout the run
- High extraction field in gas (7.3 kV/cm)

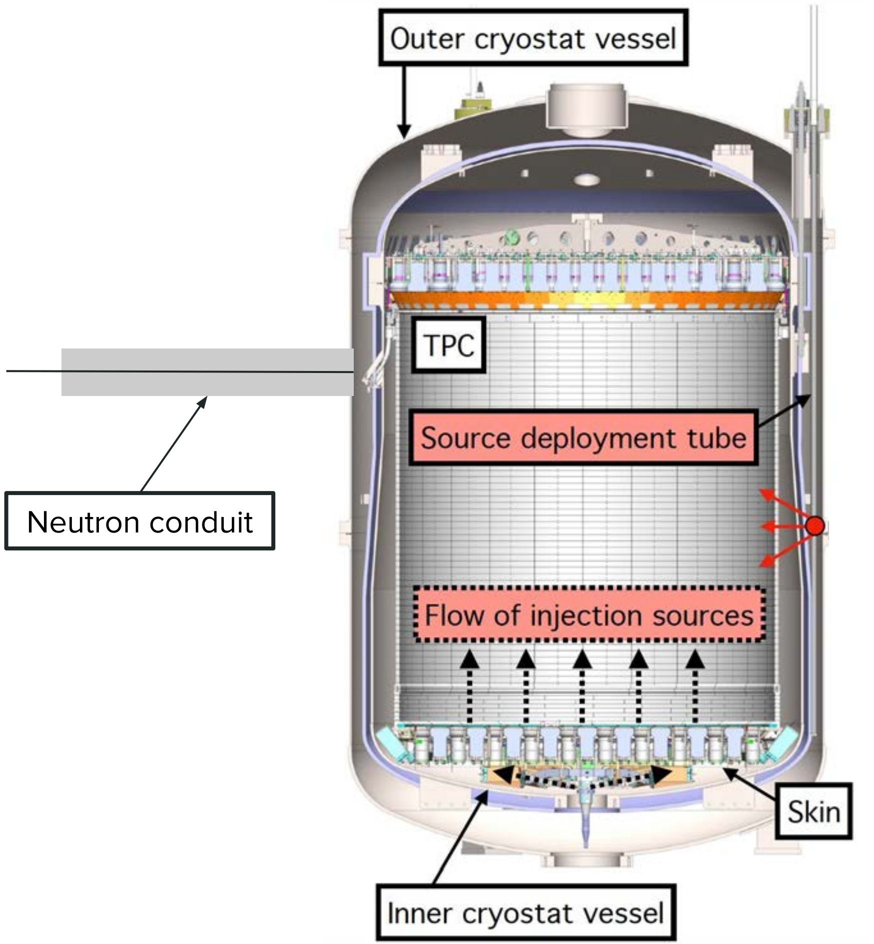


A uniform drift field of 193 V/cm was maintained during the entire SR1 period

Calibrations

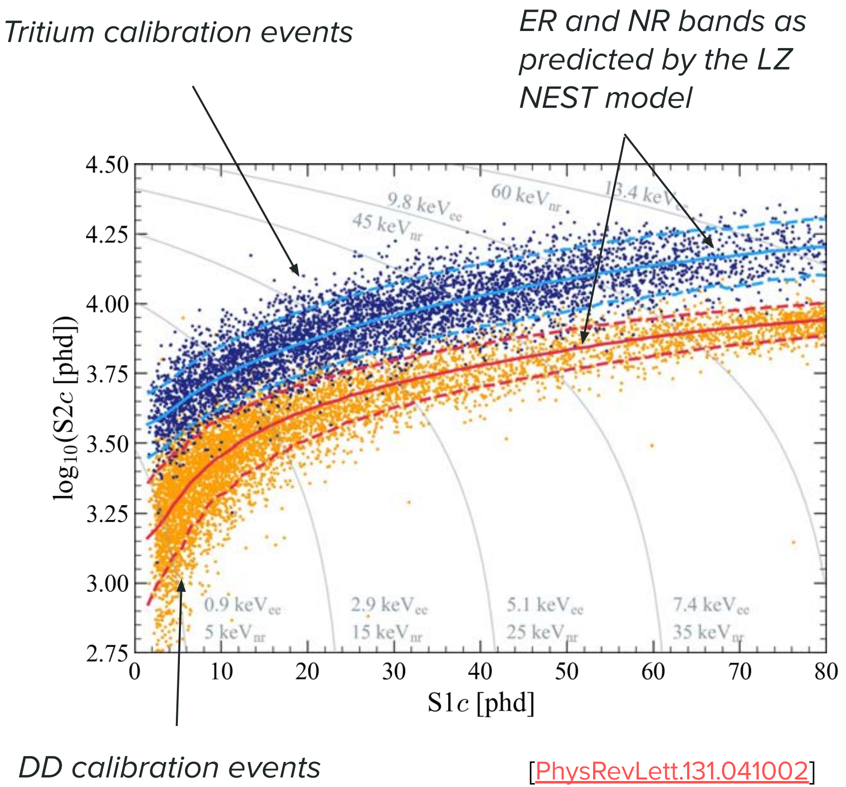
A full suite of calibration sources was used to calibrate the detector response of the TPC, Skin, and OD

- ER calibration
  - Injection sources: CH3T (β; 18.6 keV endpoint), ^{83m}Kr (γ; 32.1 and 9.4 keV), 220Rn (α, β, γ; various energies)
  - Sealed sources placed near the TPC
- NR calibration
  - AmLi source: three separate sources deployed around the TPC
  - YBe source: deployed to the top of the cryostat vessel
  - DD neutron generator: delivered down a 3m conduit from outside the water tank



Detector model

- *NEST-based electron recoil model tuned to tritium data, then propagated to nuclear recoil model and verified with DD data.
- Detector parameters:
  - Light gain of g1 = 0.114 \pm 0.002 phd/ph
  - Charge gain of g2 = 47.1 \pm 1.1 phd/e-
  - Single electron size = 58.5 phd
  - 99.9% discrimination below the NR median
- A header file with the LZ tuned detector is available for public use [NEST GitHub project]



[PhysRevLett.131.041002]

*[NEST official website]

Background model

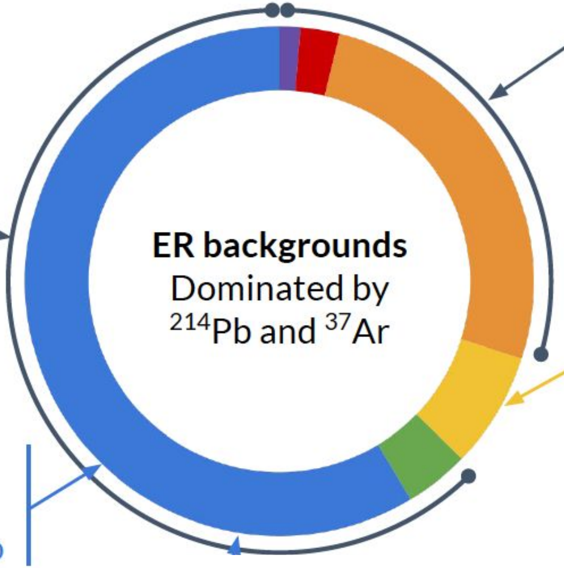
Large nuclear model uncertainties on cosmic-ray-induced spallation [Phys. Rev. D 105, 082004]

Total expected **ER** counts in ROI in first run: **276** + [0, 291] from ^{37}Ar

Total expected **NR** counts in ROI in first run: **0.15**

Dissolved e-captures (mono-energetic x-ray/Auger cascades):
- ^{37}Ar
- ^{127}Xe
- ^{124}Xe (double e-capture)

Dissolved β-emitters
- ^{214}Pb (^{222}Rn daughter)
- ^{212}Pb (^{220}Rn daughter)
- ^{85}Kr
- ^{136}Xe ($2\nu\beta\beta$)



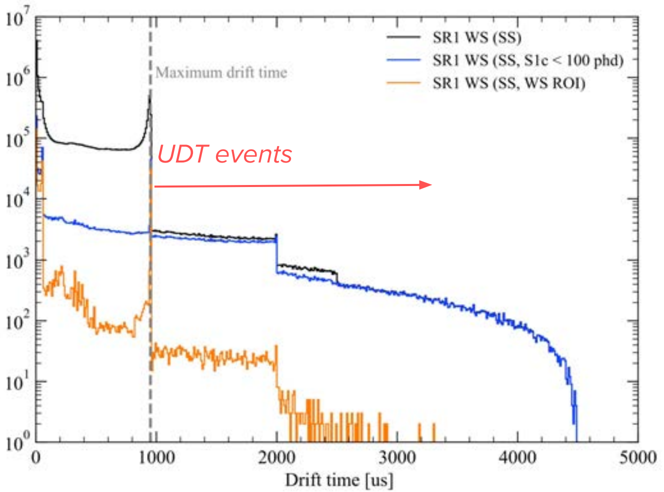
Solar neutrinos (ER)
- pp + ^{7}Be + ^{13}N

Includes γ-emitters in detector materials
- ^{238}U chain, ^{232}Th chain, ^{40}K, ^{60}Co

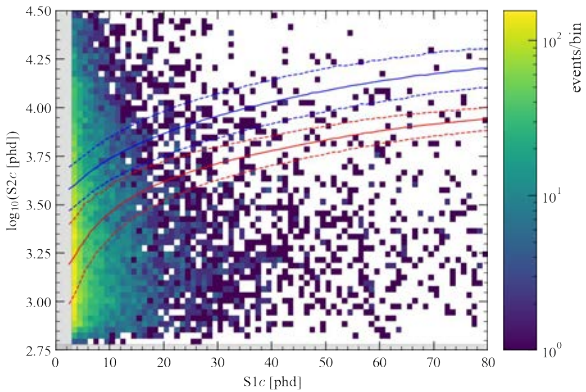
NR backgrounds:
- Neutron emission from spontaneous fission and (α,n)
- ^{8}B solar neutrinos

Accidental background

- Caused by the accidental coincidence of isolated S1 and S2 pulses occurring within one maximum drift time
- Can use Unphysical Drift Time (UDT) events as a proxy
  - Limited by statistics after cuts :(
- A data-driven approach was employed to build a model for this background
  - Combine two half-events at the waveform level to produce a new event
  - Apply full LZ event reconstruction chain and data analysis cuts



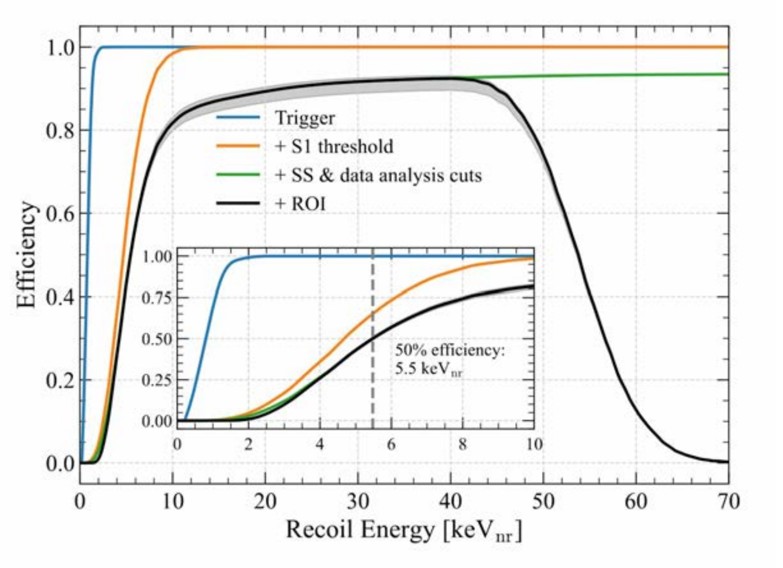
Drift time distribution of single scatters (SS) after consecutive cuts



Distribution of “Chopstitch events” after applying all data quality cuts (250x reduction)

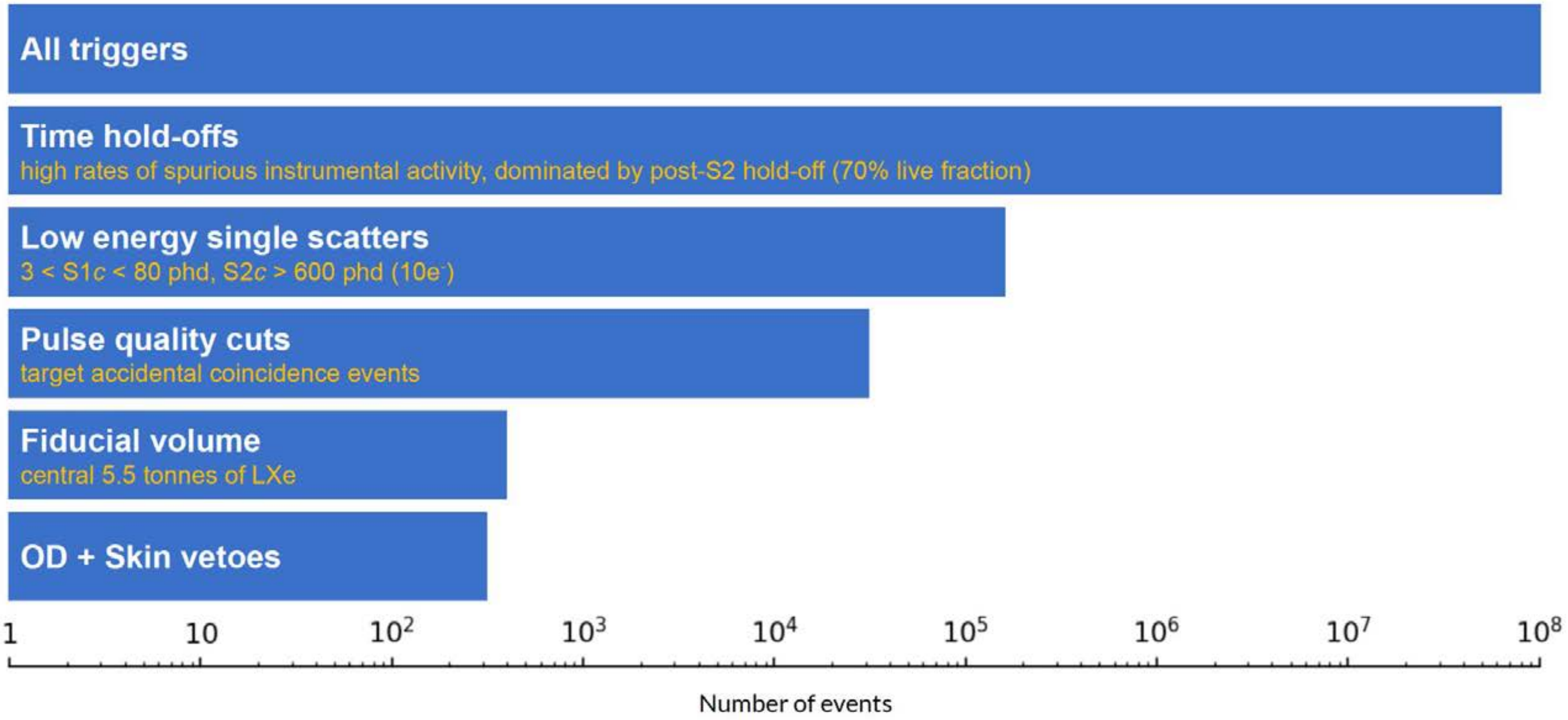
WIMP search

- Bias mitigation: analysis cuts developed on non-WIMP ROI background & calibration data + vetoes (skin & OD)
- Two types of data analysis cuts
  - Time-based: exclude periods with high rates of spurious activity
  - Pulse-based: exclude events based on pulse characteristics. Mainly targets accidentals background
- A fiducial volume (5.5 tonnes) was defined, where wall background leakage is negligible



Signal efficiency evaluated using tritium and AmLi calibration data

Data selection



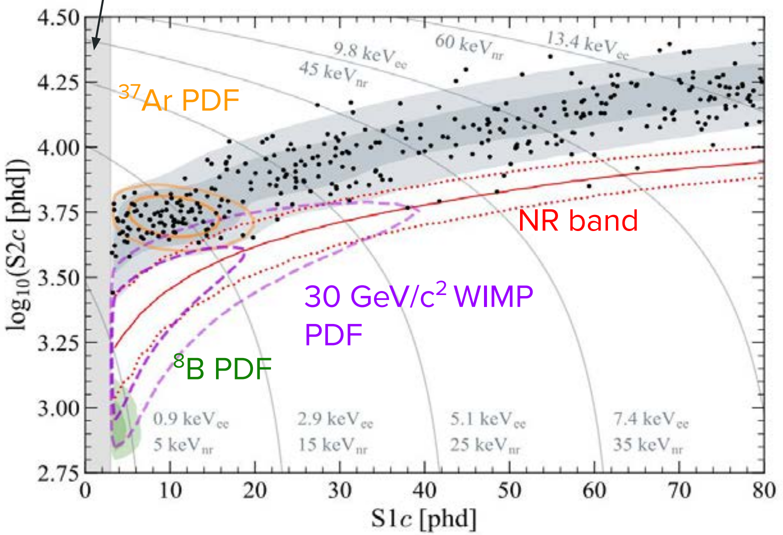
Results: best fit

The energy region below S1 = 3 phd was masked

ER background model (1- and 2-σ bands)

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

[PhysRevLett.131.041002]



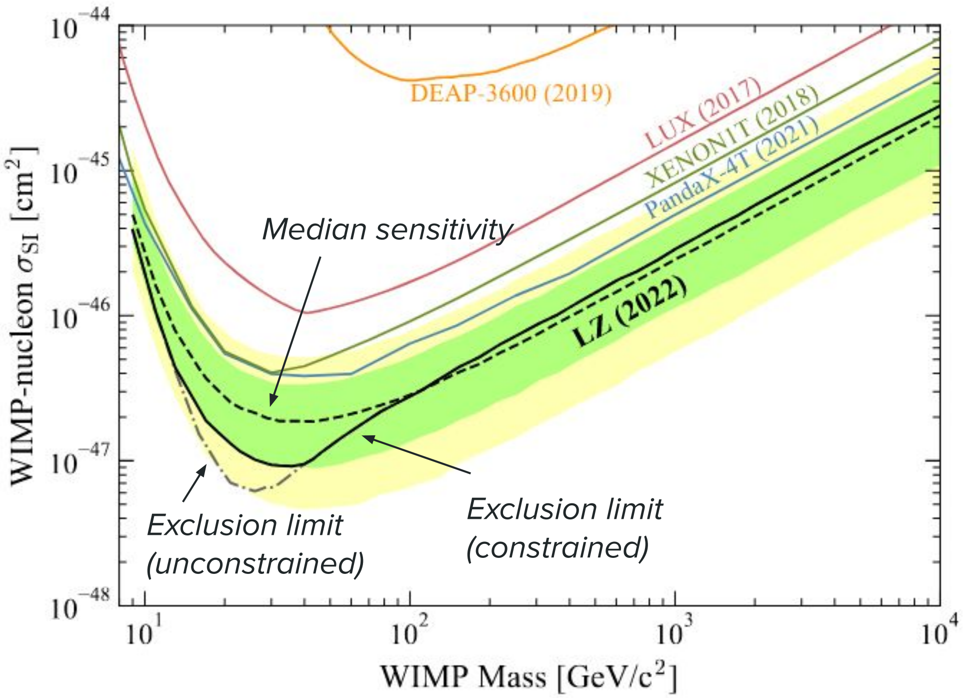
335 events remain after applying all data analysis cuts for an exposure of 60 livedays and 5.5 tonne fiducial volume

A best-fit value compatible with 0 events is observed for all WIMP masses

Results: upper limits

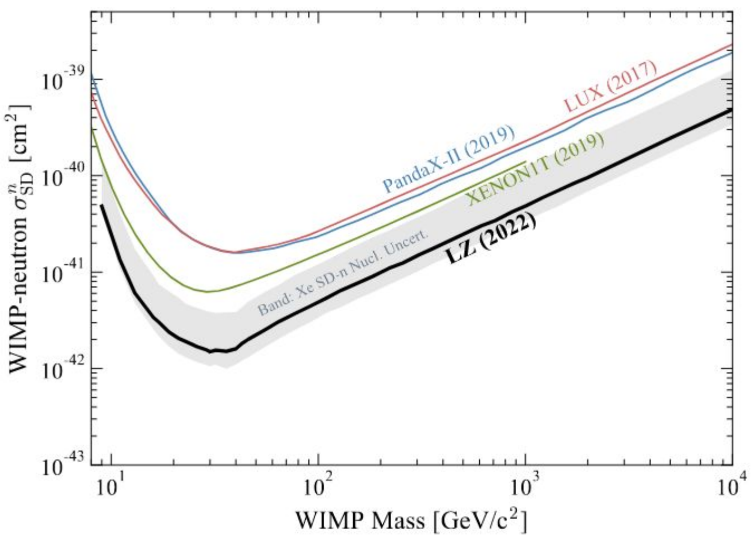
Spin-independent WIMP-nucleon scattering

- 90% CL upper limit of 9.2x10^{-48} cm^2 at 36 GeV/c^2 WIMP mass
- Frequentist, two-sided, profile likelihood ratio (PLR) test statistic
- Power constrained at the -1 sigma band
- Following conventions from the community white paper
  - [Eur. Phys. J. C 81, 907]

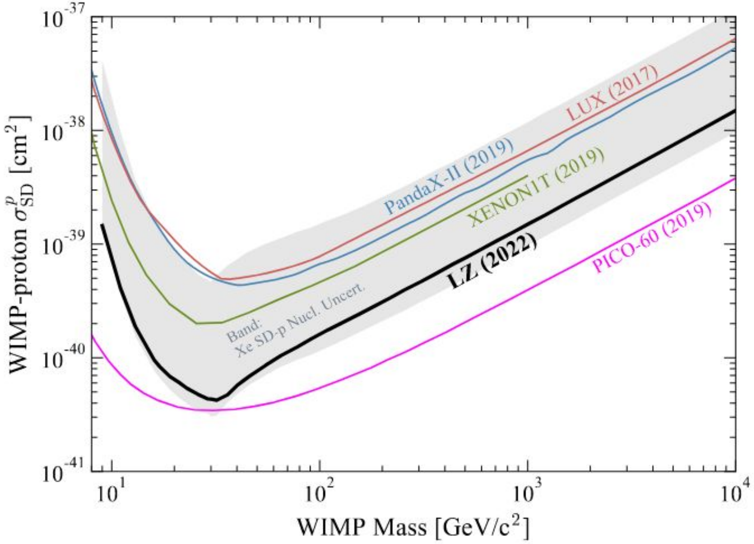


[PhysRevLett.131.041002]

Spin-dependent WIMP-neutron scattering



Spin-dependent WIMP-proton scattering

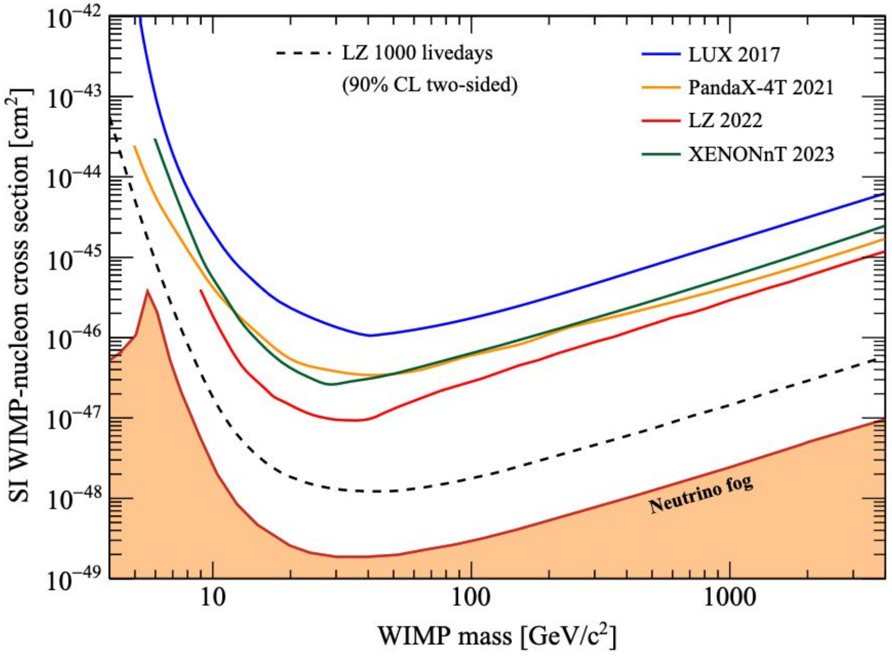


- Xe has two isotopes with unpaired neutrons that have non-zero nuclear spin (^{129}Xe and ^{131}Xe)
  - WIMP-proton sensitivity arises from higher-order nuclear effects
- The grey bands reflect the current uncertainty on nuclear structure factors [Phys. Rev. D 88, 083516]
- LZ currently is the most sensitive experiment in the WIMP-neutron channel!

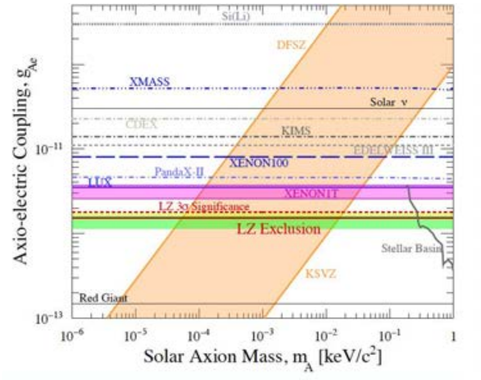
Future prospects for LZ

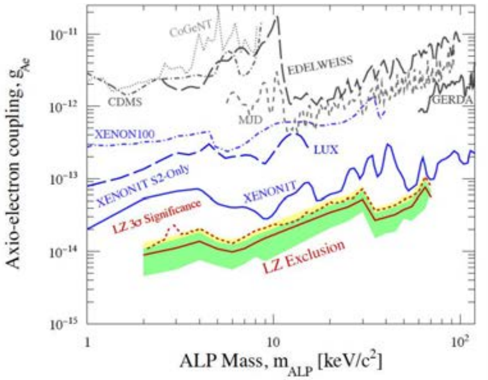
WIMP search prospects

- LZ continues to take data ("salted data"), with ongoing improvements to detector operation and data analysis
- The SR1 exposure covers only 6% of the total planned exposure (1000 livedays)
- Still a large swath of parameter space left to explore!
  - Projected sensitivity of 1.4 x 10^{-48} cm^2 at 40 GeV/c^2 in the full exposure [Phys. Rev. D 101, 052002]

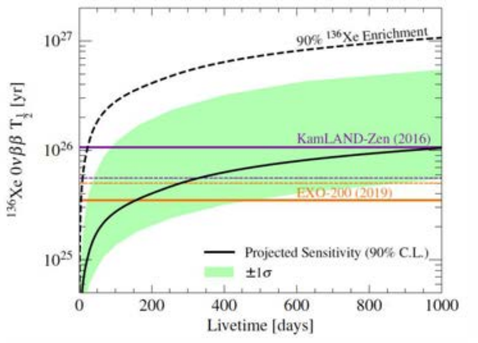


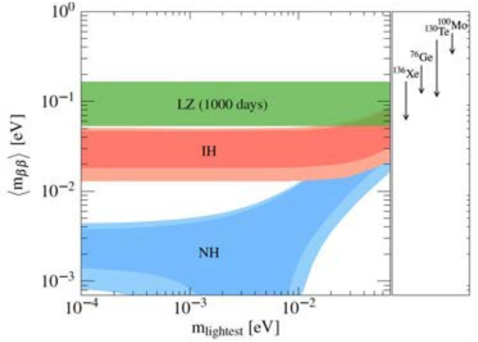
Other (exciting!) searches





Axions and ALPs
[Phys. Rev. D 104, 092009]





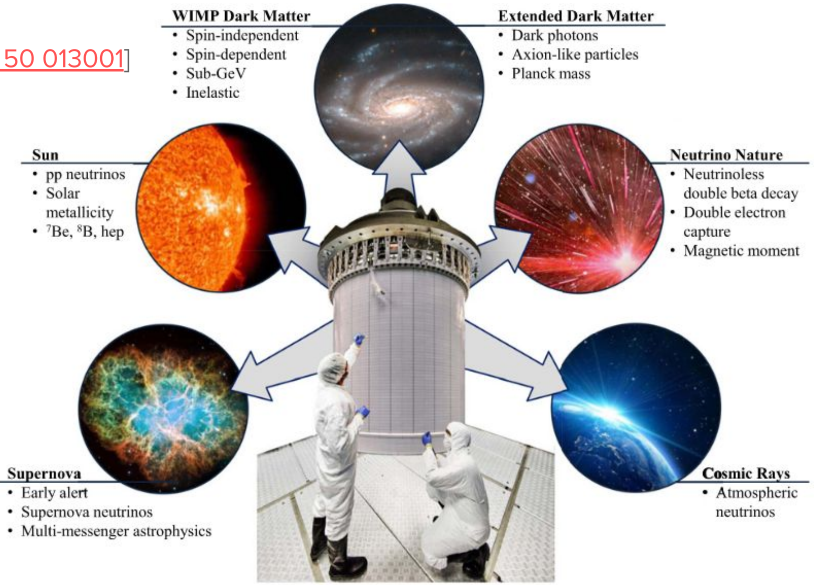
Neutrinoless double beta decay of ^{136}Xe
[PhysRevC.102.014602]

And many other searches: light dark matter, ultraheavy dark matter, EFT, ^{8}B neutrinos, etc.

XLZD

[J. Phys. G: Nucl. Part. Phys. 50 013001]

- Three major experiments (XENON, LZ, and DARWIN) are joining forces
  - No formal collaboration yet, but a consortium [https://xlzd.org]
- XLZD will not simply be a larger dark matter experiment, but rather the definitive xenon observatory for dark matter and neutrino physics
- Rich physics program:
  - Closing the gap on the WIMP hypothesis
  - Competitive search for neutrinoless double beta decay in ^{136}Xe
  - Measurement of multiple astrophysical neutrino signals: solar, supernova, atmospheric



Physics opportunities with a next-generation Xe TPC experiment

XLZD meeting at UCLA on April 2023

Conclusions

- The LZ experiment is working to specs
  - All detectors are performing well
  - Backgrounds are within expectation
- With its first science run, LZ has set new limits on WIMP interactions
- A broad physics program lies ahead until LZ reaches its projected livetime of 1000 days
- The xenon community is coalescing into the XLZD consortium to build the definitive xenon rare event observatory

- 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

Mahalo!

https://lz.lbl.gov/
@lzdarkmatter

Science and Technology Facilities Council

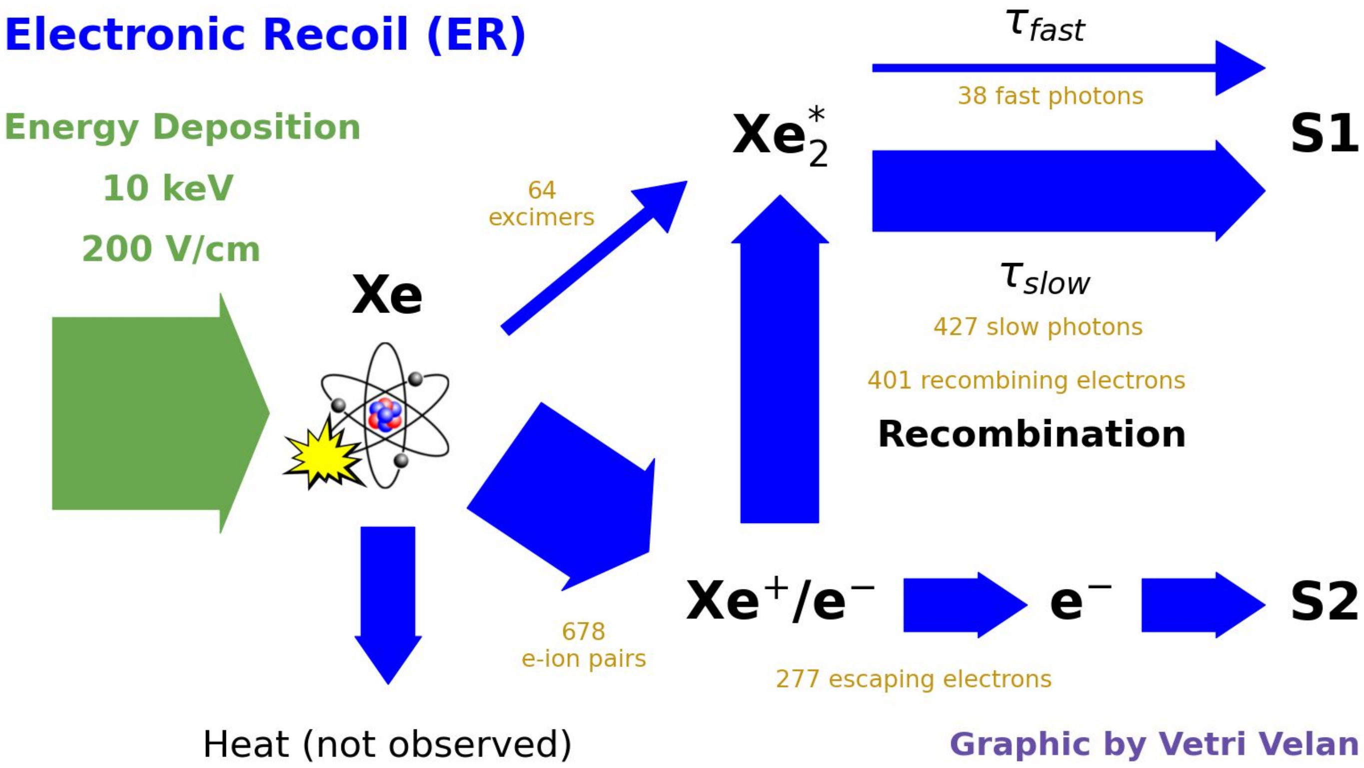
Sanford Underground Research Facility
South Dakota Science and Technology Authority

FCT Fundação para a Ciência e a Tecnologia

Institute for Basic Science

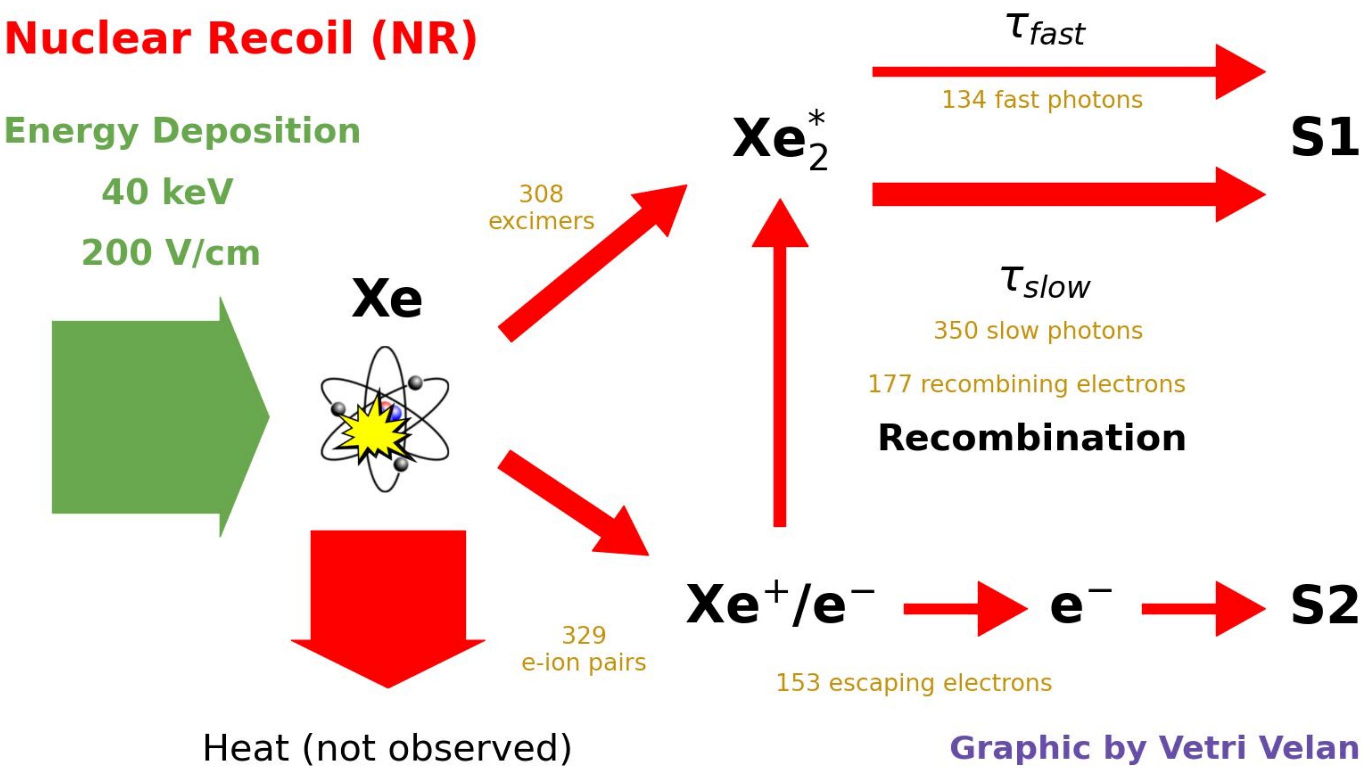
Back-up slides

ER event



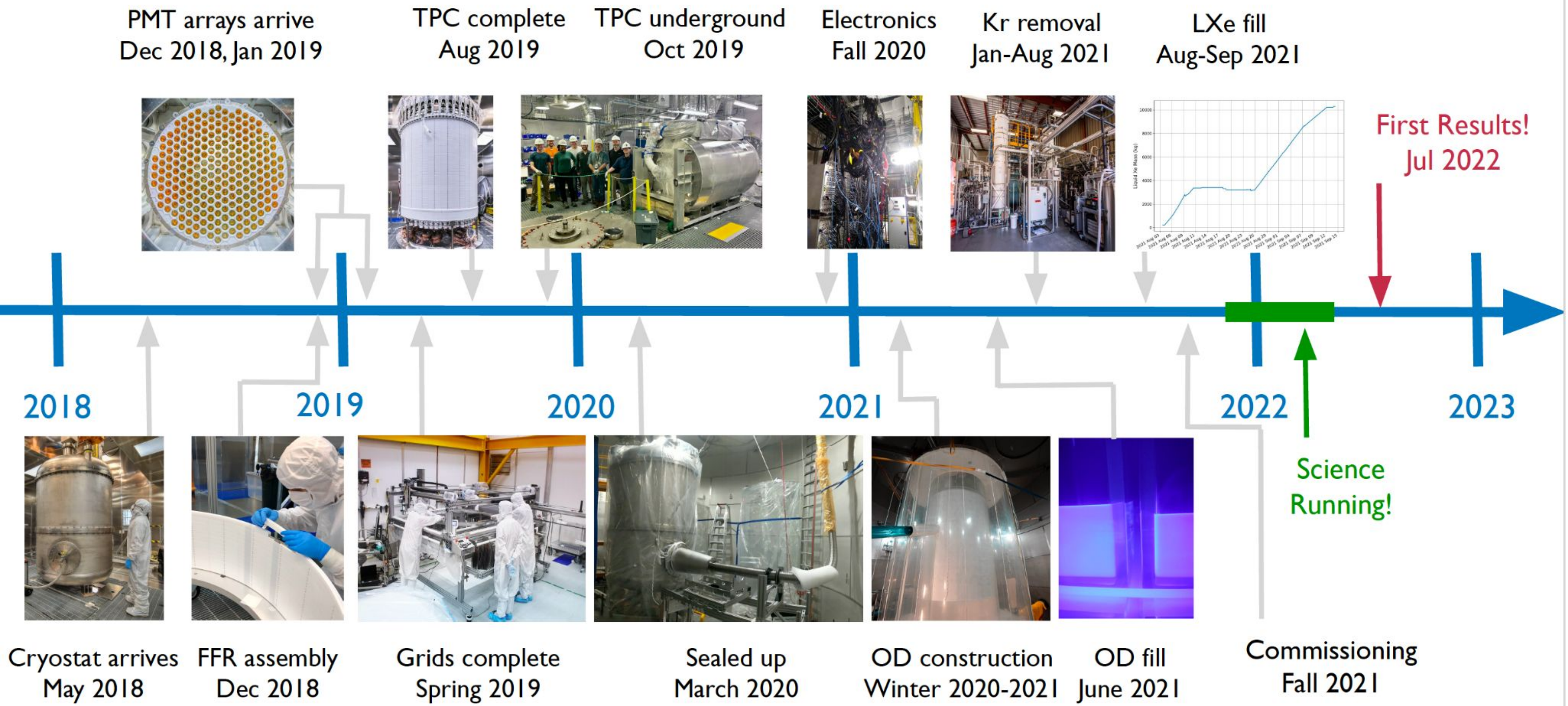
Electronic Recoil (ER)
Energy Deposition
10 keV
200 V/cm
Xe
64
excimers
Xe_2^*
τ_{fast}
38 fast photons
S1
τ_{slow}
427 slow photons
401 recombining electrons
Recombination
678
e-ion pairs
Xe^+/e^-
e^-
S2
277 escaping electrons
Heat (not observed)
Graphic by Vetri Velan

NR event



Nuclear Recoil (NR)
Energy Deposition
40 keV
200 V/cm
Xe
308
excimers
Xe_2^*
τ_{fast}
134 fast photons
S1
τ_{slow}
350 slow photons
177 recombining electrons
Recombination
329
e-ion pairs
Xe^+/e^-
e^-
S2
153 escaping electrons
Heat (not observed)
Graphic by Vetri Velan

Timeline


PMT arrays arrive
Dec 2018, Jan 2019
TPC complete
Aug 2019
TPC underground
Oct 2019
Electronics
Fall 2020
Kr removal
Jan-Aug 2021
LXe fill
Aug-Sep 2021
First Results!
Jul 2022
2018
2019
2020
2021
2022
2023
Science
Running!
Cryostat arrives
May 2018
FFR assembly
Dec 2018
Grids complete
Spring 2019
Sealed up
March 2020
OD construction
Winter 2020-2021
OD fill
June 2021
Commissioning
Fall 2021

E-lifetime and ^{37}Ar decay in SR1