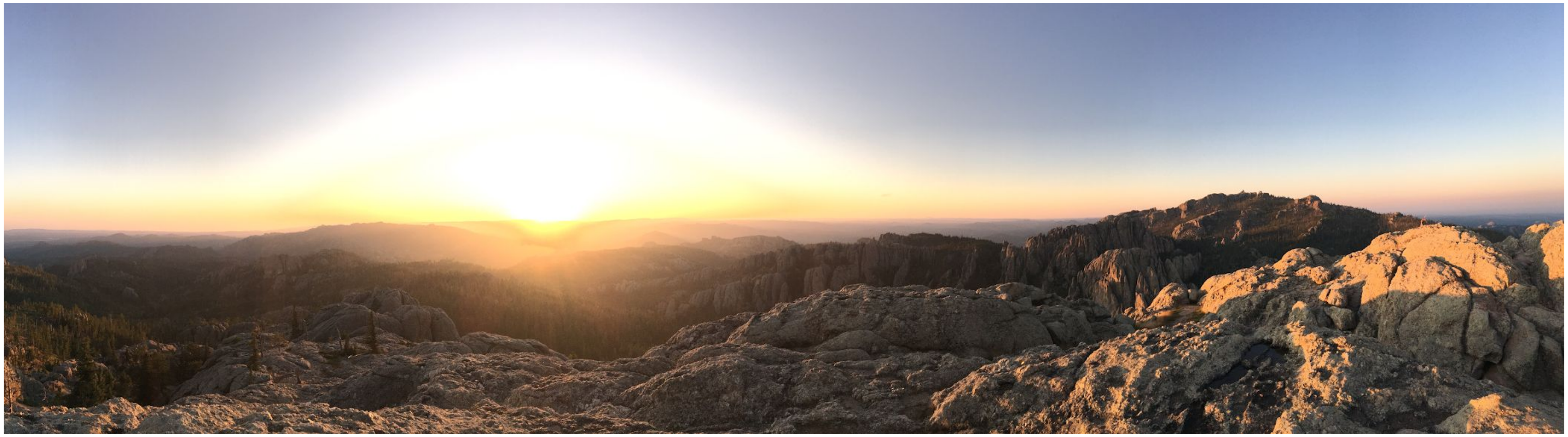
Highlights from the LUX-ZEPLIN experiment

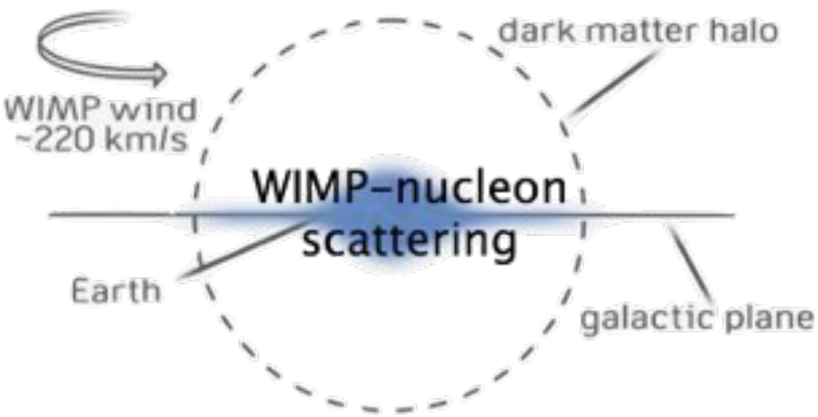


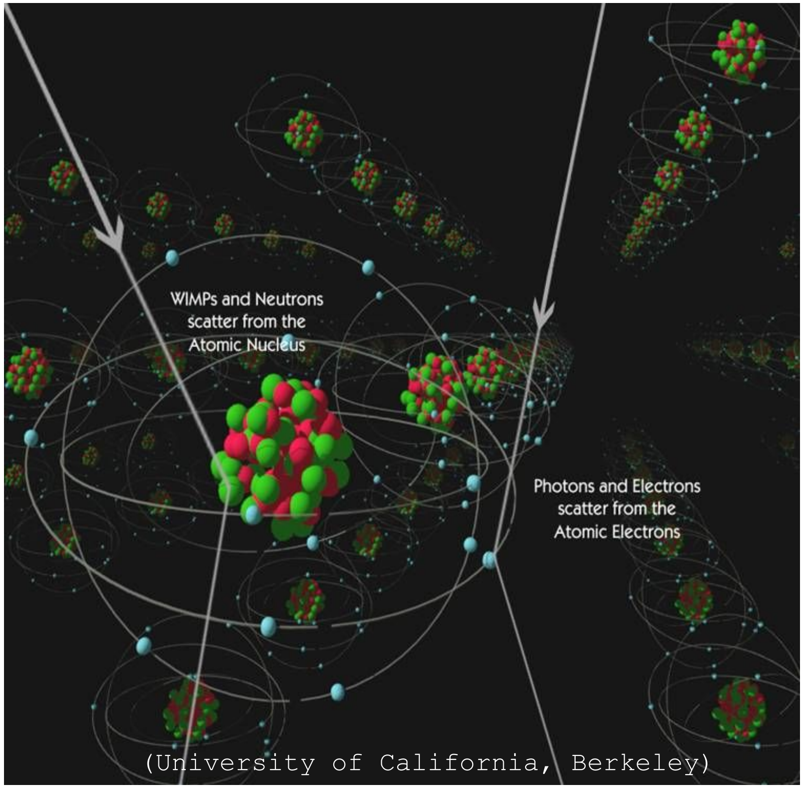
View from Black Elk Wilderness area, South Dakota, USA, home of @lzdarkmatter

Jim Dobson for the LZ Collaboration

DISCRETE 2024, Ljubljana, Slovenia

Direct detection of Dark Matter

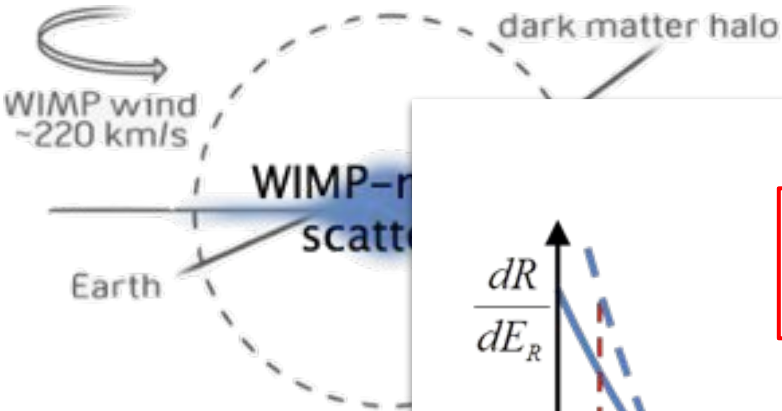


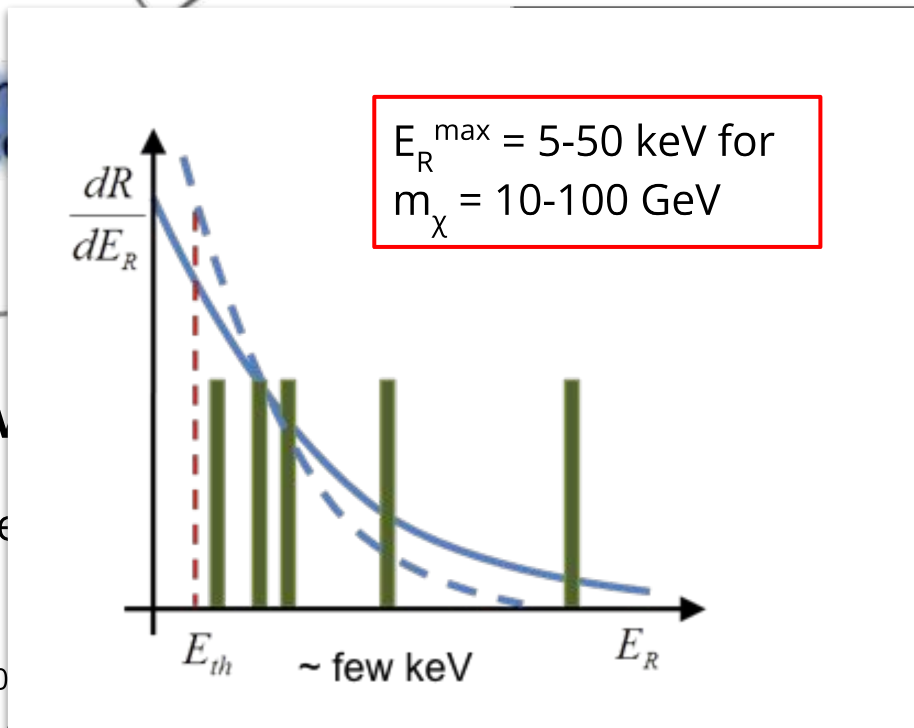


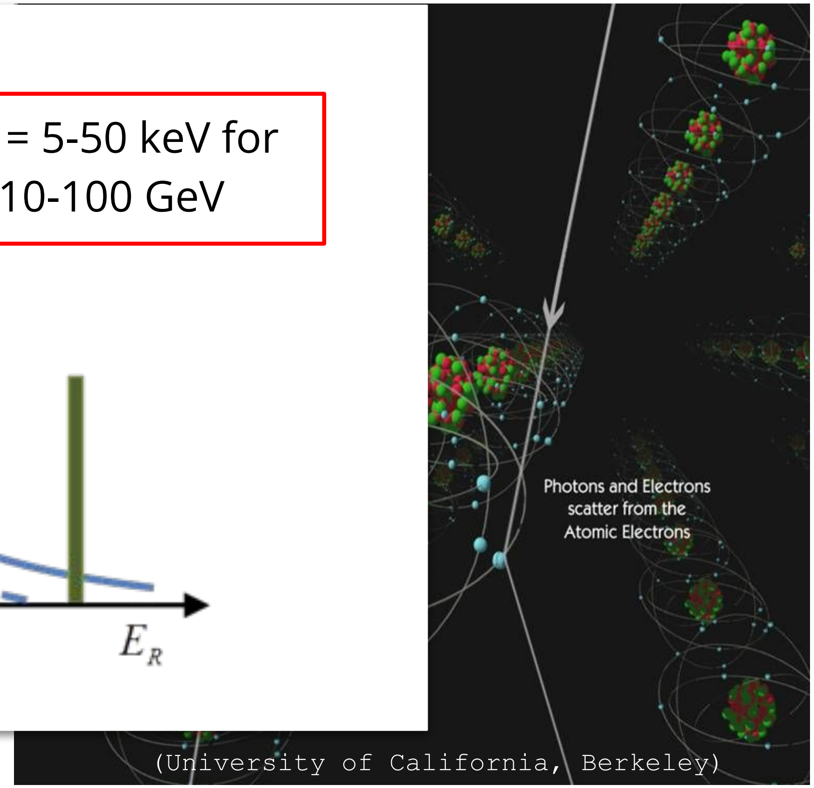
Standard Halo Model

- Isothermal sphere of DM, $\rho \propto r^{-2}$
- Local density ρ_0 ~ 0.3 GeV/cm3
- Maxwellian (truncated) velocity distribution
- Characteristic velocity v_0=220 km/s → non-relativistic!

Direct detection of Dark Matter







Standard Halo M

- Isothermal sphe
  r^{-2}
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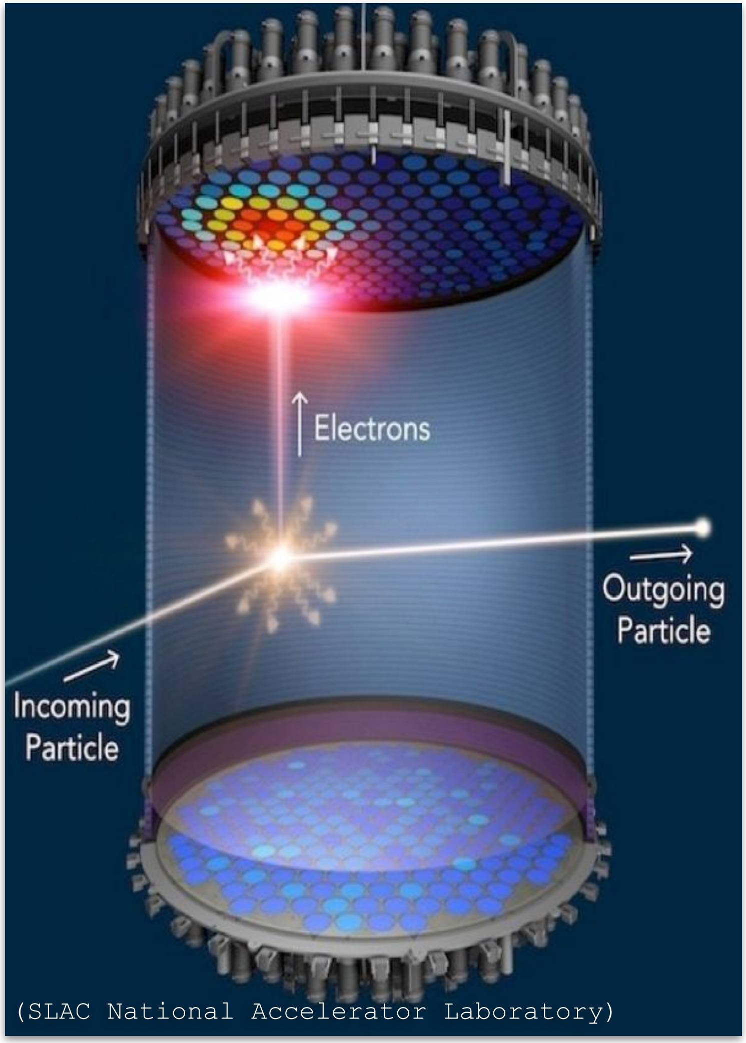
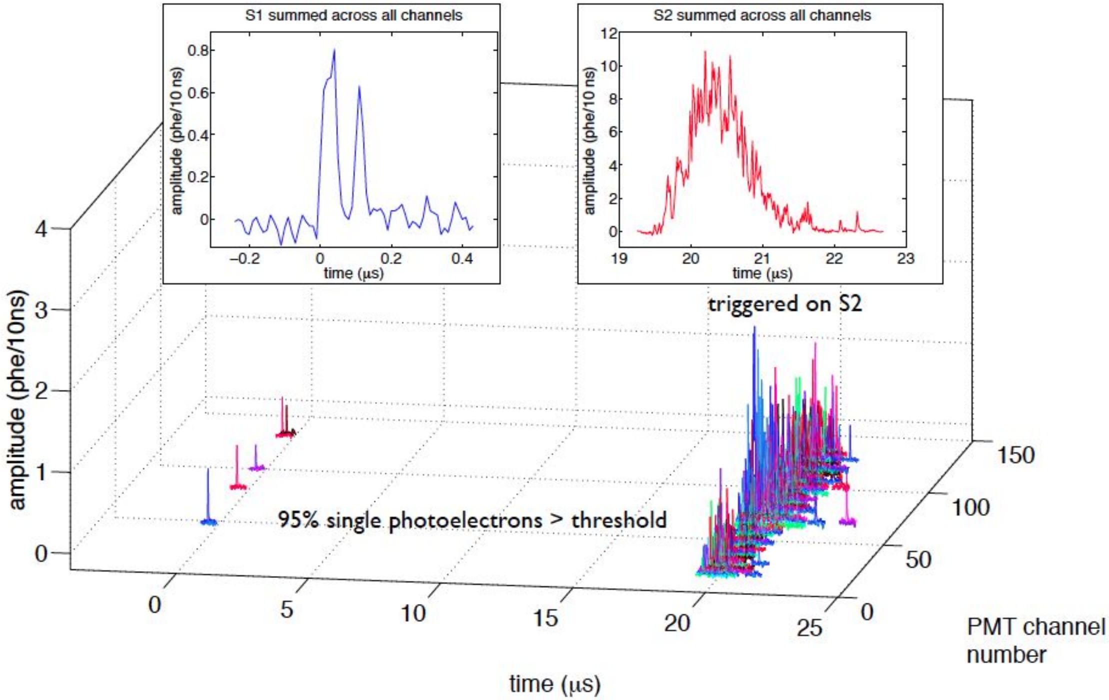
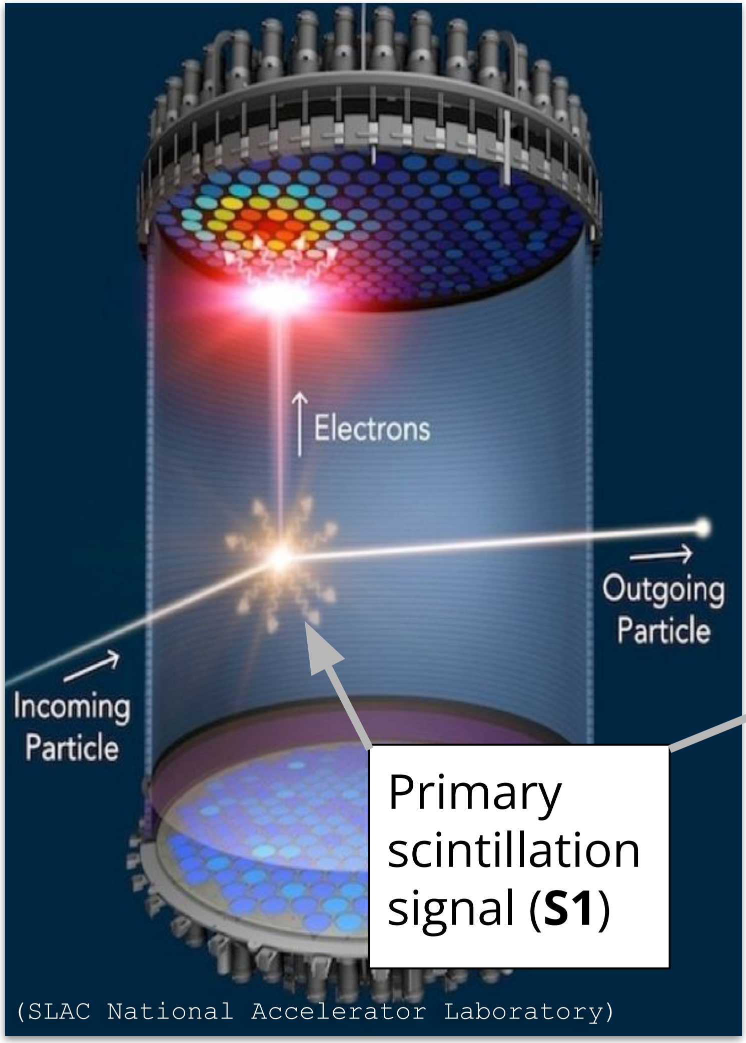
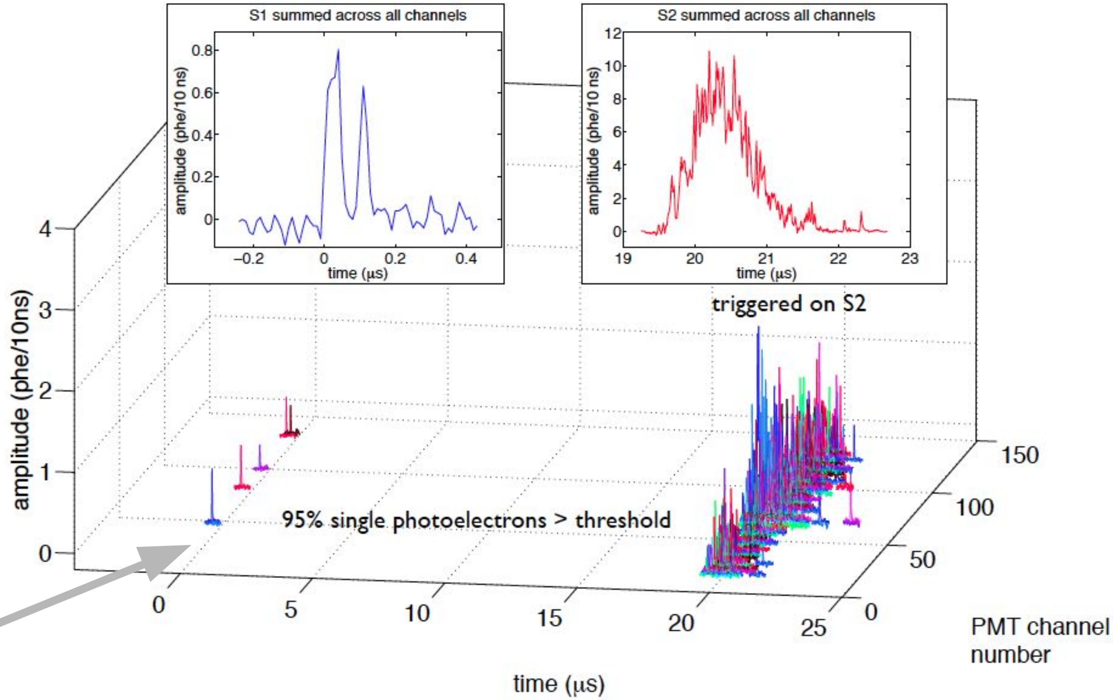
Liquid Xenon Time Projection Chambers



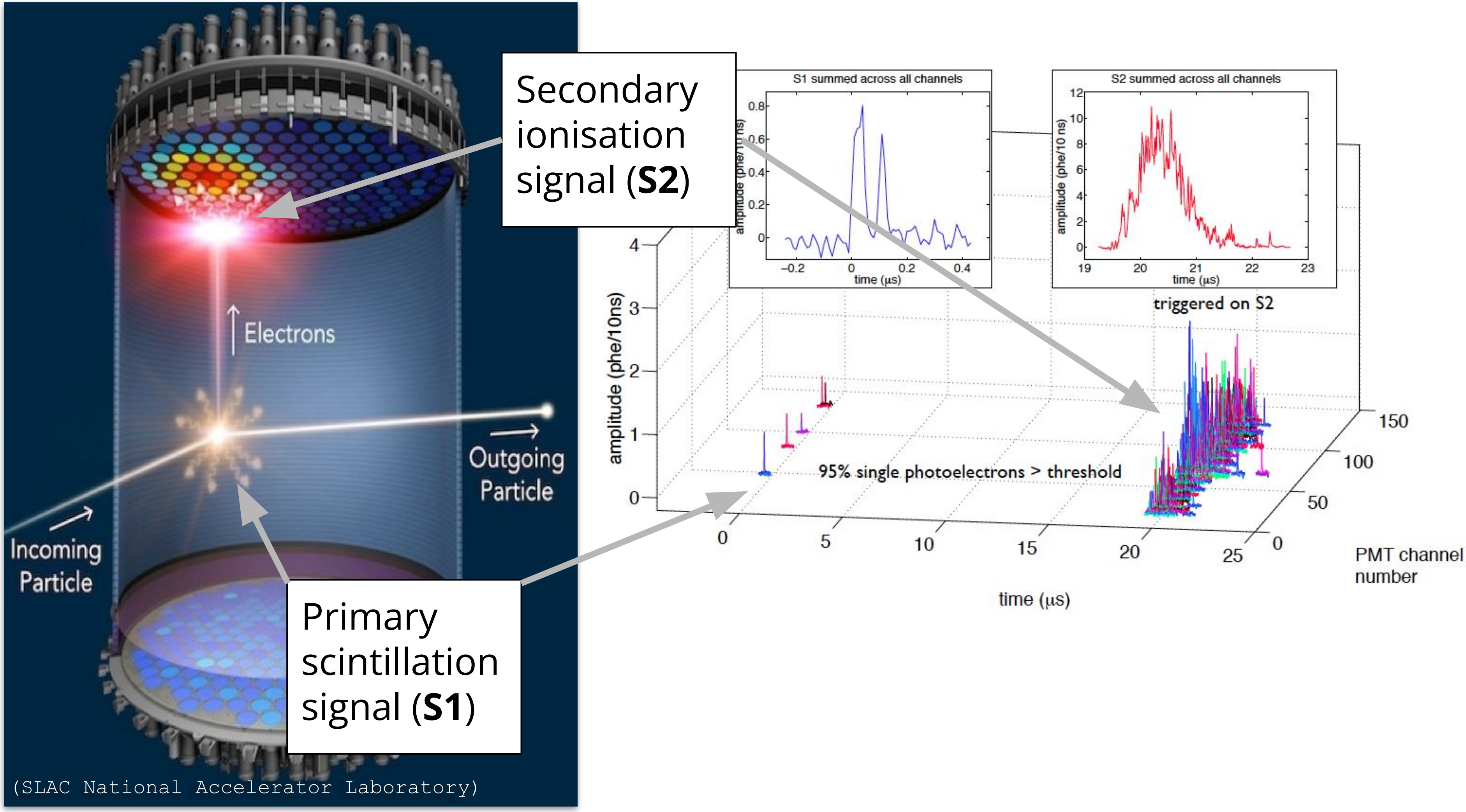


Liquid Xenon Time Projection Chambers

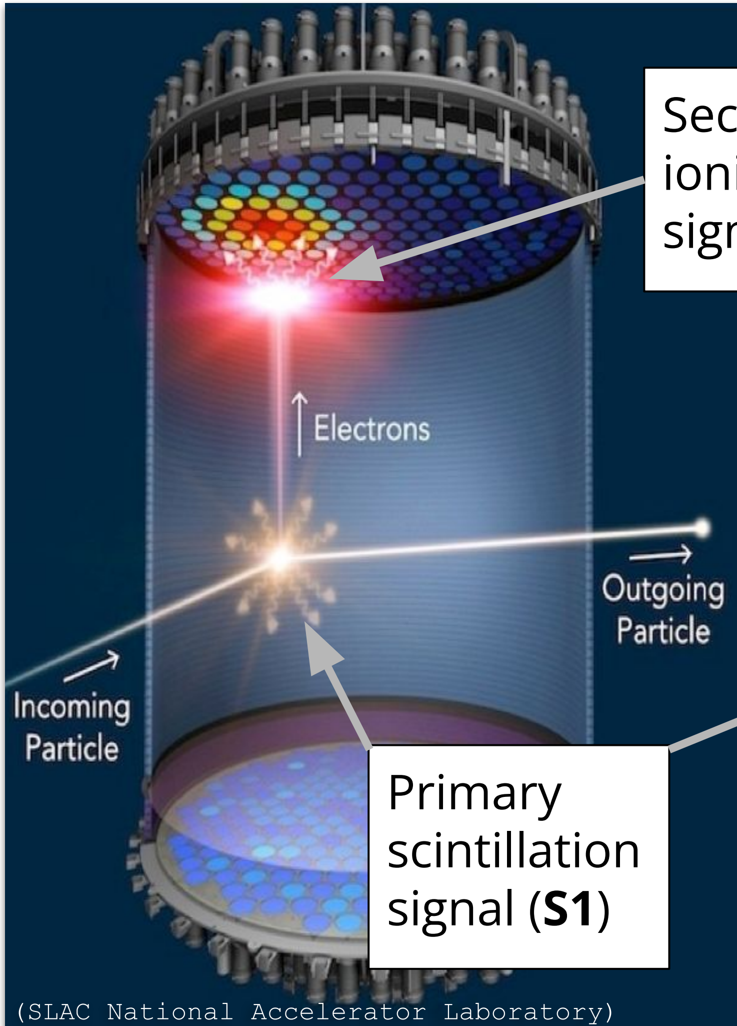


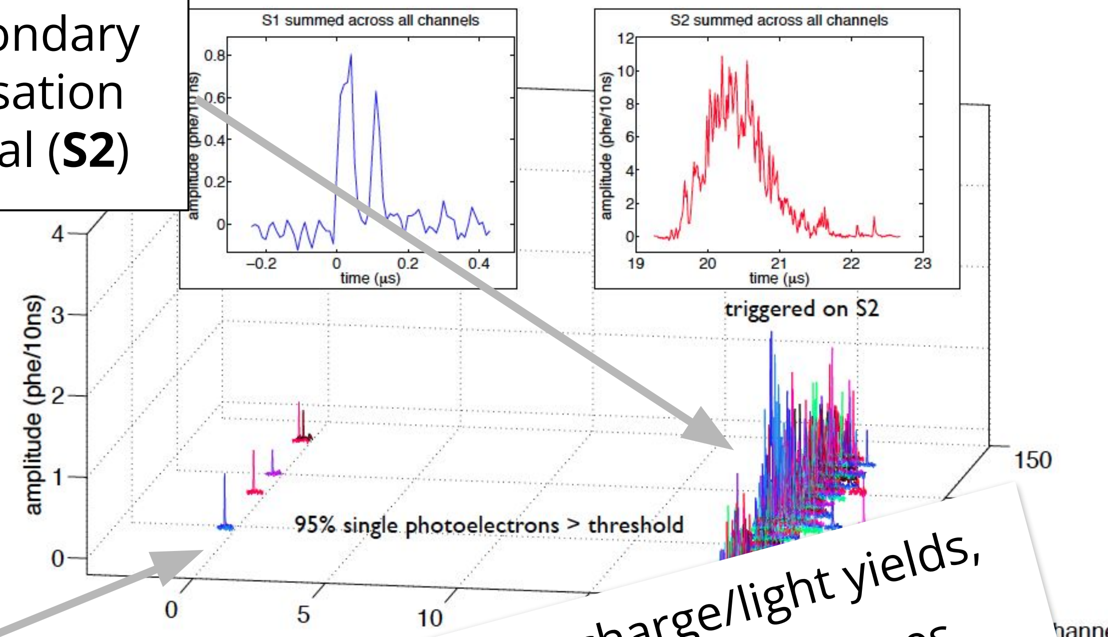


Liquid Xenon Time Projection Chambers



Liquid Xenon Time Projection Chambers





Key features: excellent charge/light yields, σ ∝ A^2, lack of long-lived radioisotopes, fiducialisation →highly scalable.

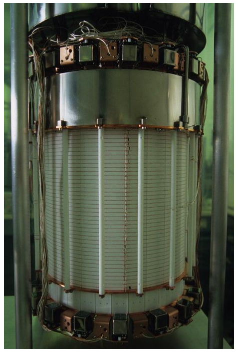
Leading technology above a ~few GeV

ZEPLIN-III

12 kg (7 kg)

2008

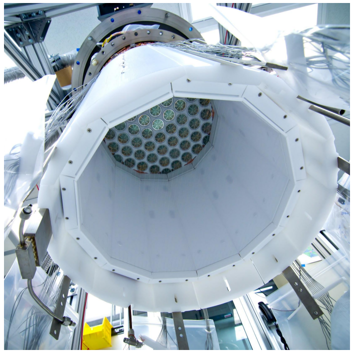
XENON100



62 kg (34 kg)

2013

LUX



250 kg (100 kg)

2016

PANDAX-II

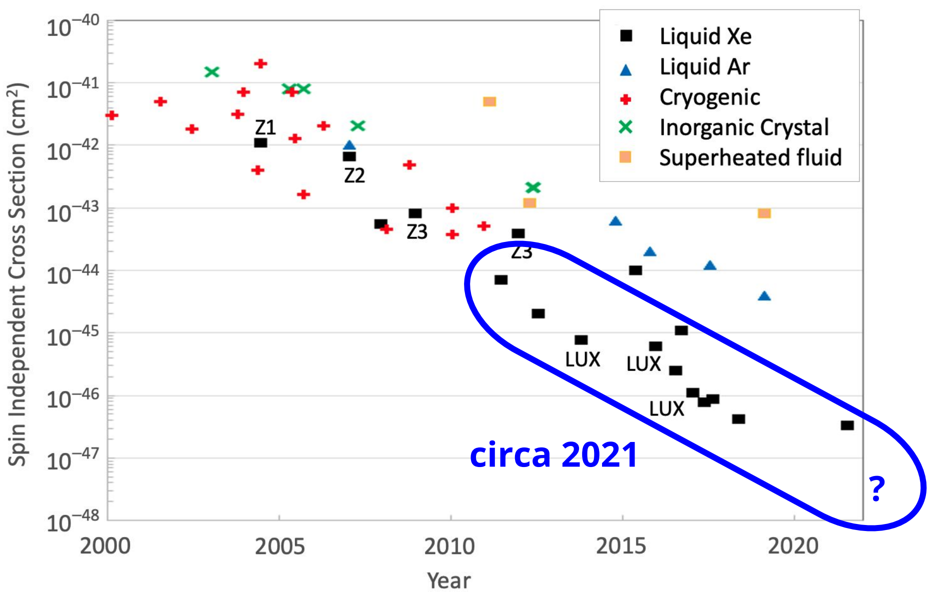
580 kg (362 kg)

2017

XENON1T

2,000 kg (1,042 kg)

2018

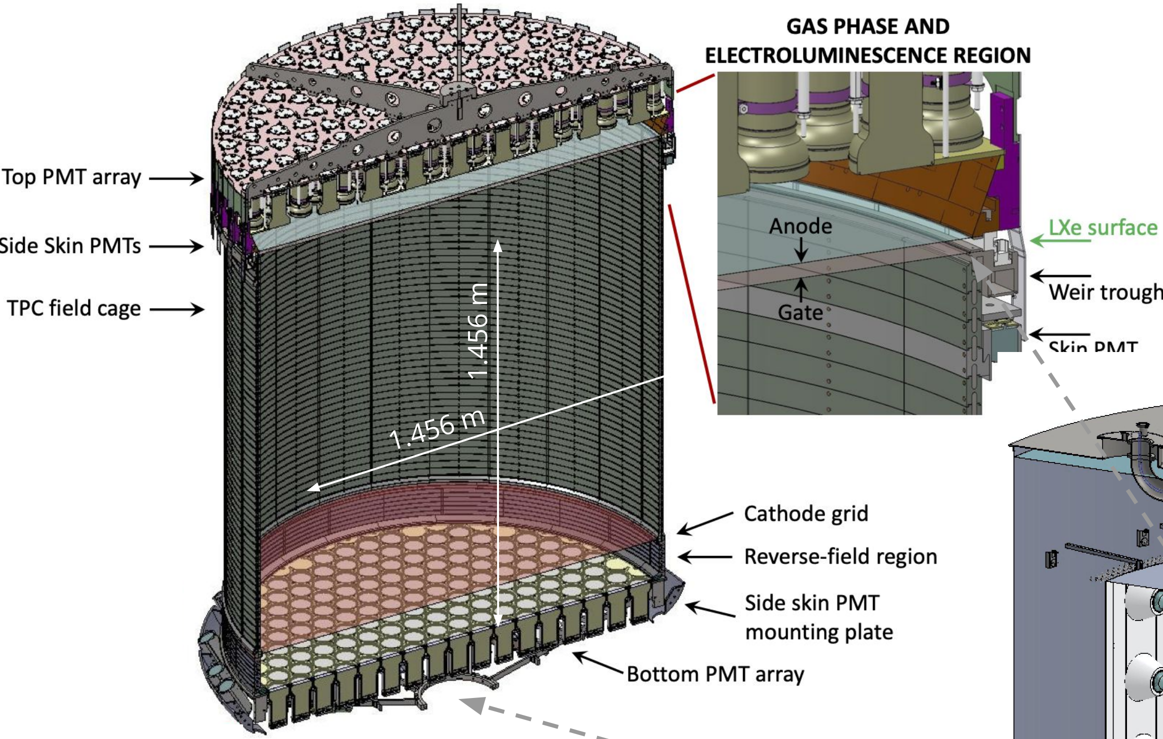


LUX-ZEPLIN

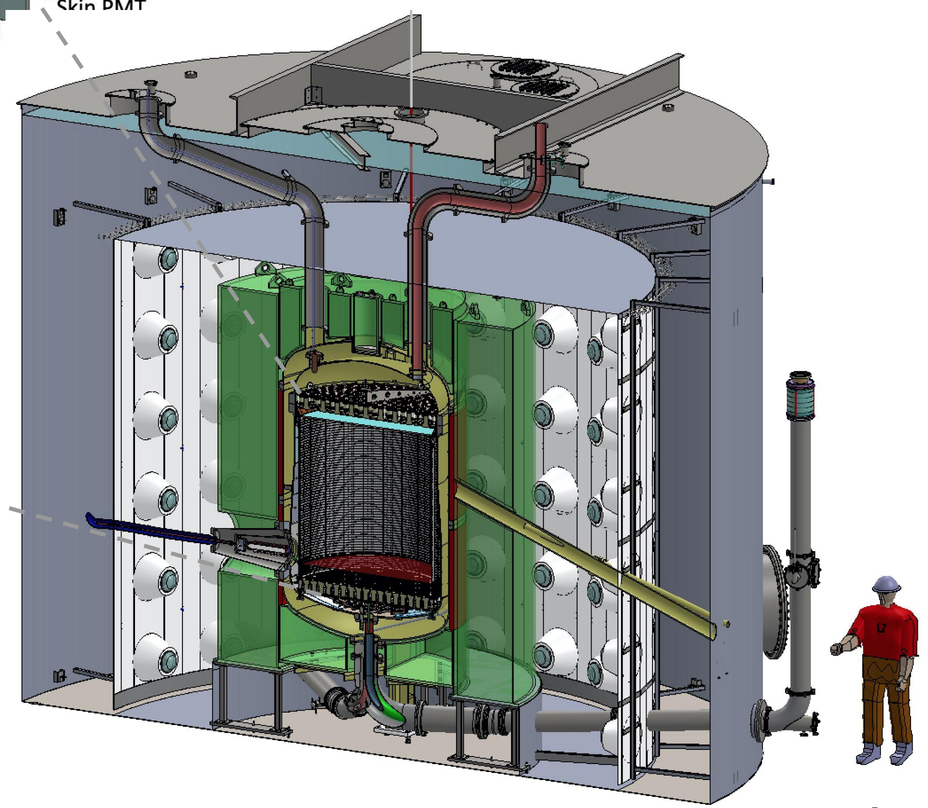
7,000 kg (5,600 kg)

2022-25

The LUX-ZEPLIN Detector



[Nucl.Instrum.Meth.A 953 (2020) 163047]

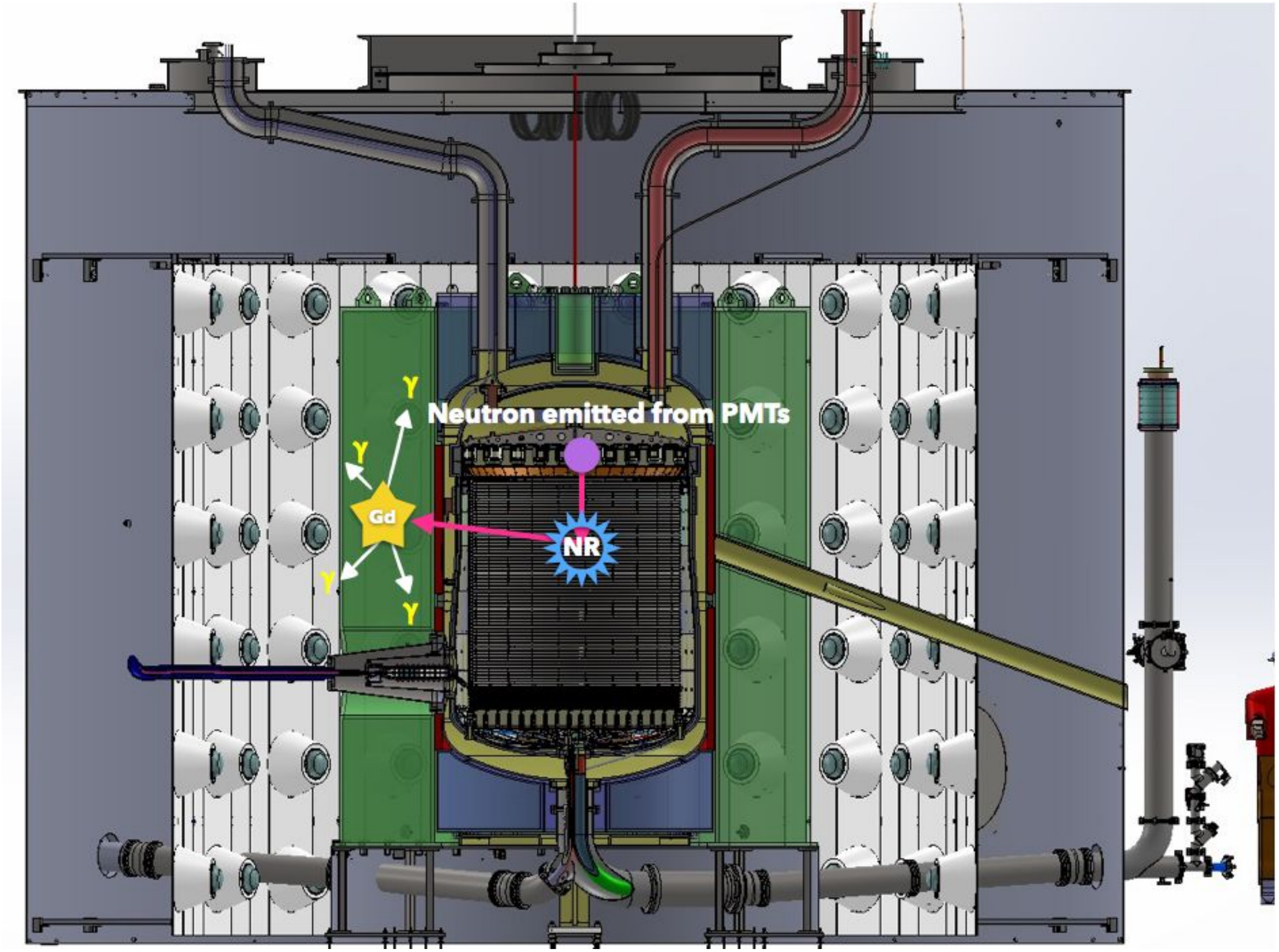


TPC key stats:

- 1.456 m between cathode and gate grid
- **7 tonne active region**
- 494 Hamamatsu R11410-22 3” PMTs
- High reflectivity PTFE for light collection

Multi-detector active veto system

Optically separated Xe **Skin** detector + Outer Detector (**OD**) with 17 tonnes of Gd-doped LS → BG suppression and in-situ characterisation



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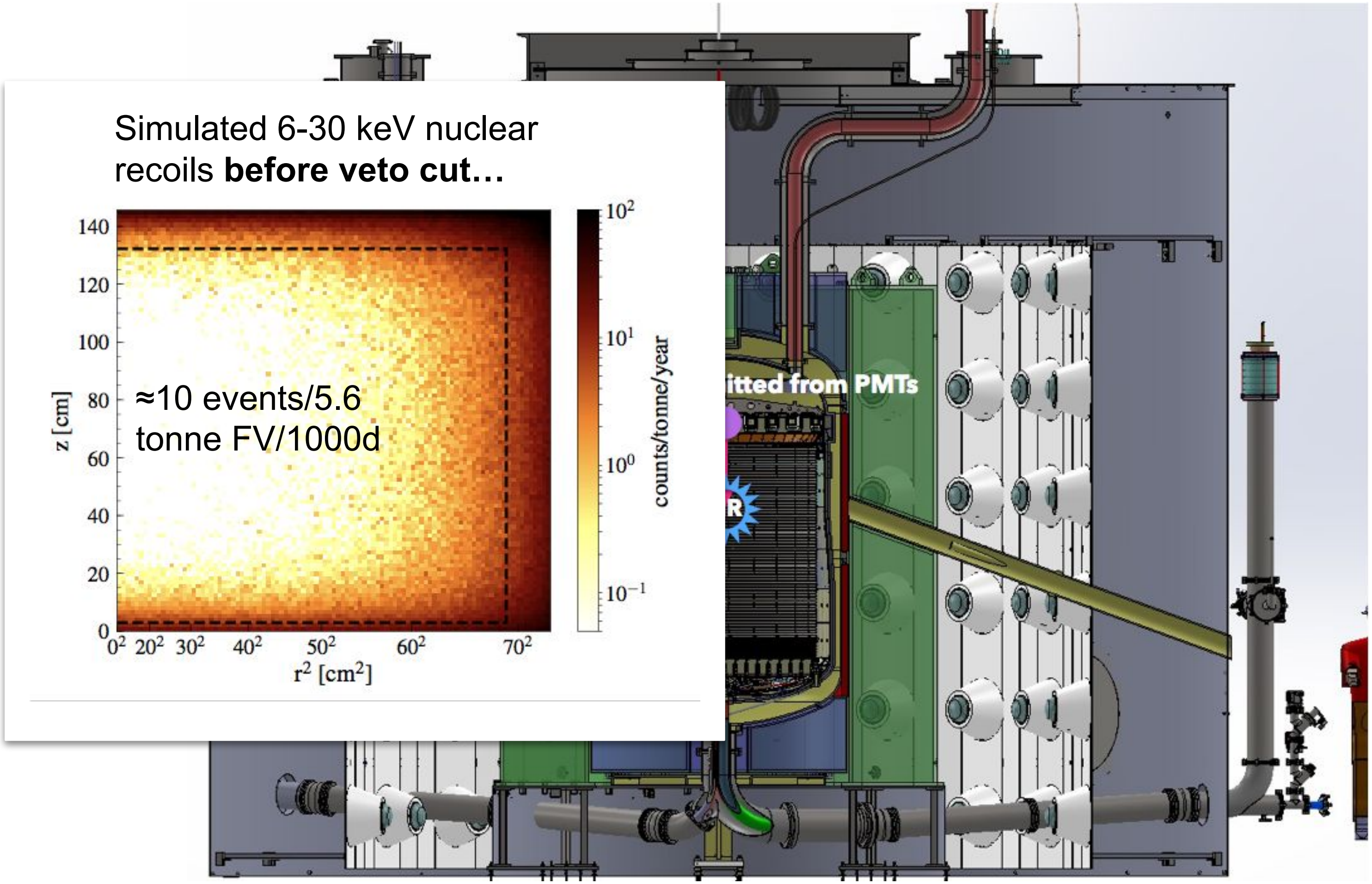

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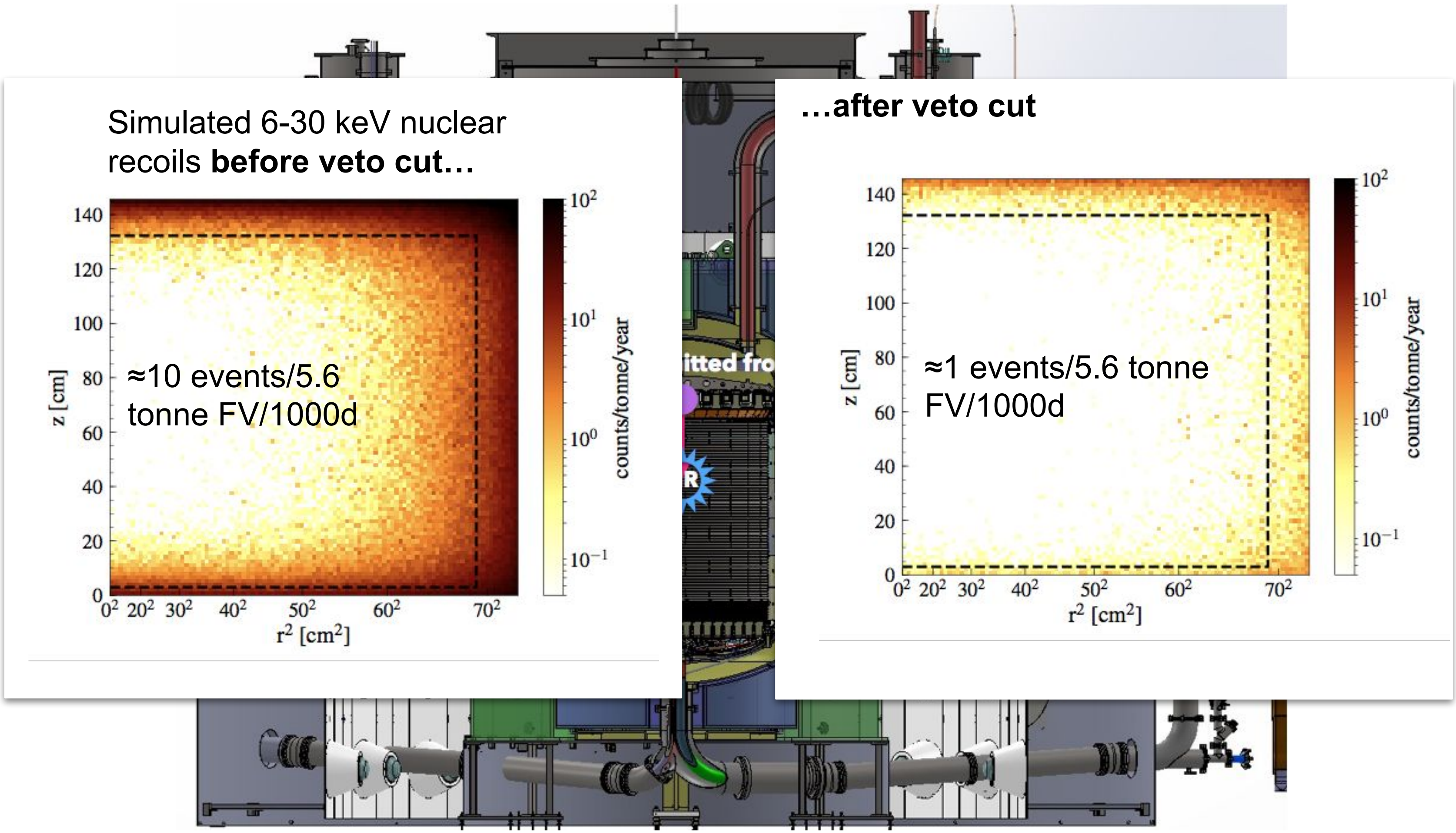
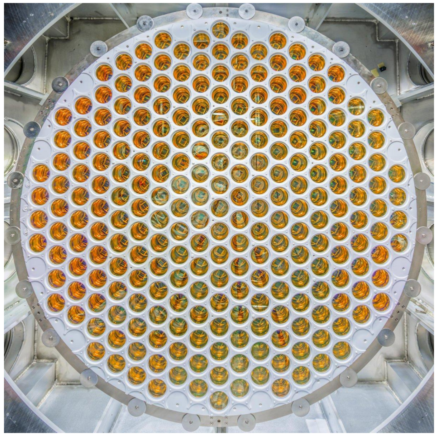


Started taking physics data December 2021

2018



Bottom PMT array after assembly at Brown University

2020-2021

Offsite Kr removal of 10t of LXe at SLAC

2019

Fully assembled TPC at SURF surface lab

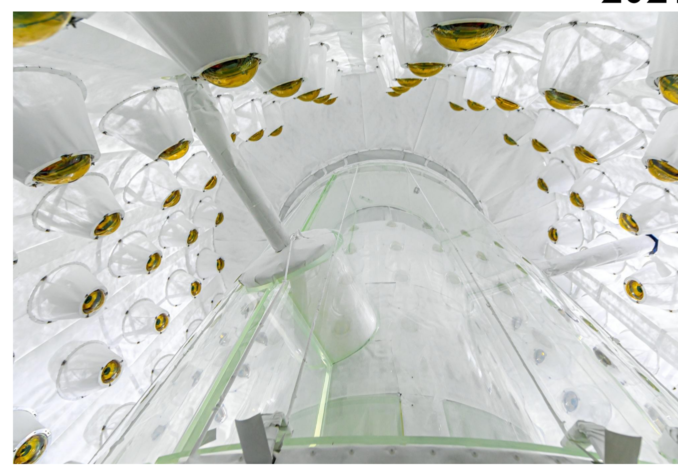
2021

TPC inside inner cryostat vessel (ICV) being transported underground

2021

ICV being lowered into the outer vessel inside the water tank

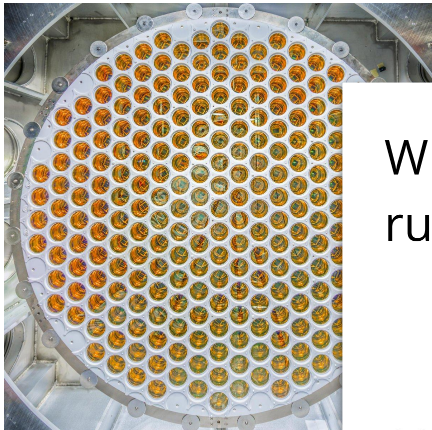
2021



Fully assembled detector
- OD ready for GdLS + water fill

Started taking physics data December 2021

2018



Bottom PMT array after
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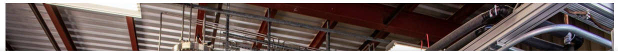
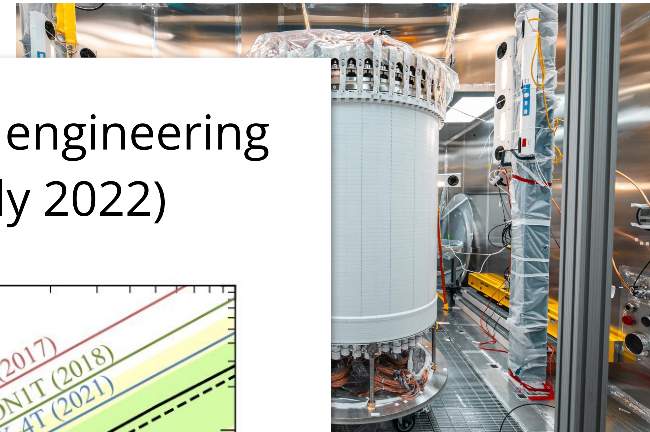
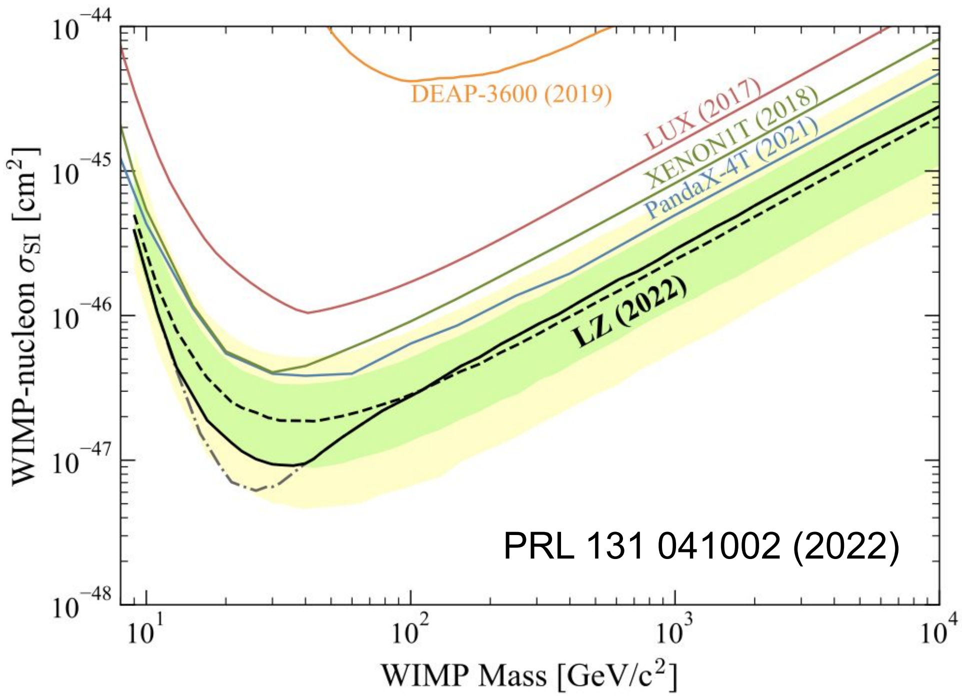


2019

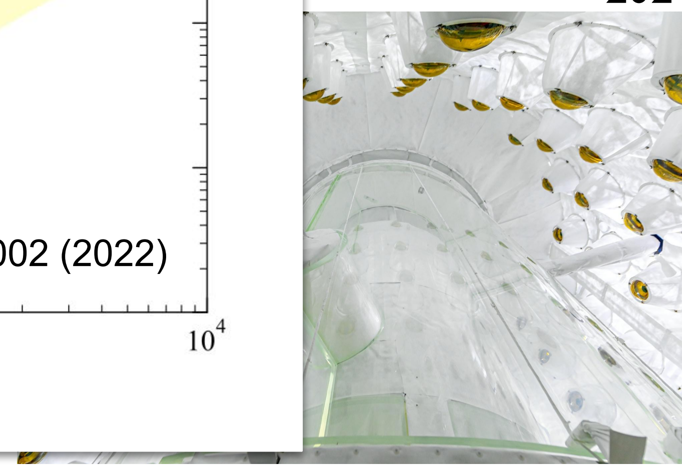


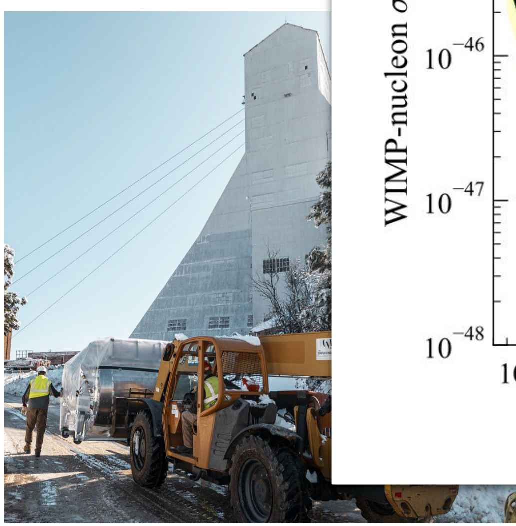
C at SURF surface lab

WIMP search results with initial engineering run with 60 live-days of data (July 2022)



2021





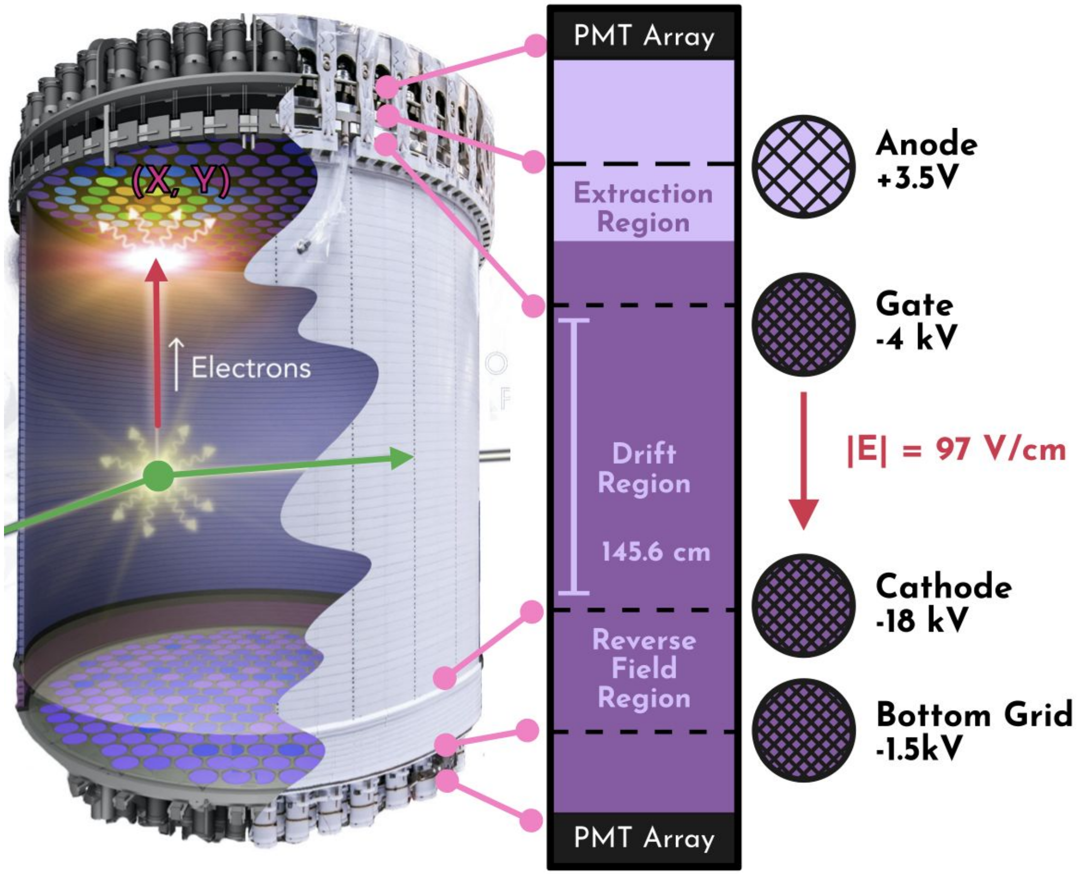
TPC inside inner cryostat vessel (ICV)
being transported underground

ICV being lowered into the outer
vessel inside the water tank

Fully assembled detector
- OD ready for GdLS + water fill

Changes Since LZ’s 1st Result (WS2022)

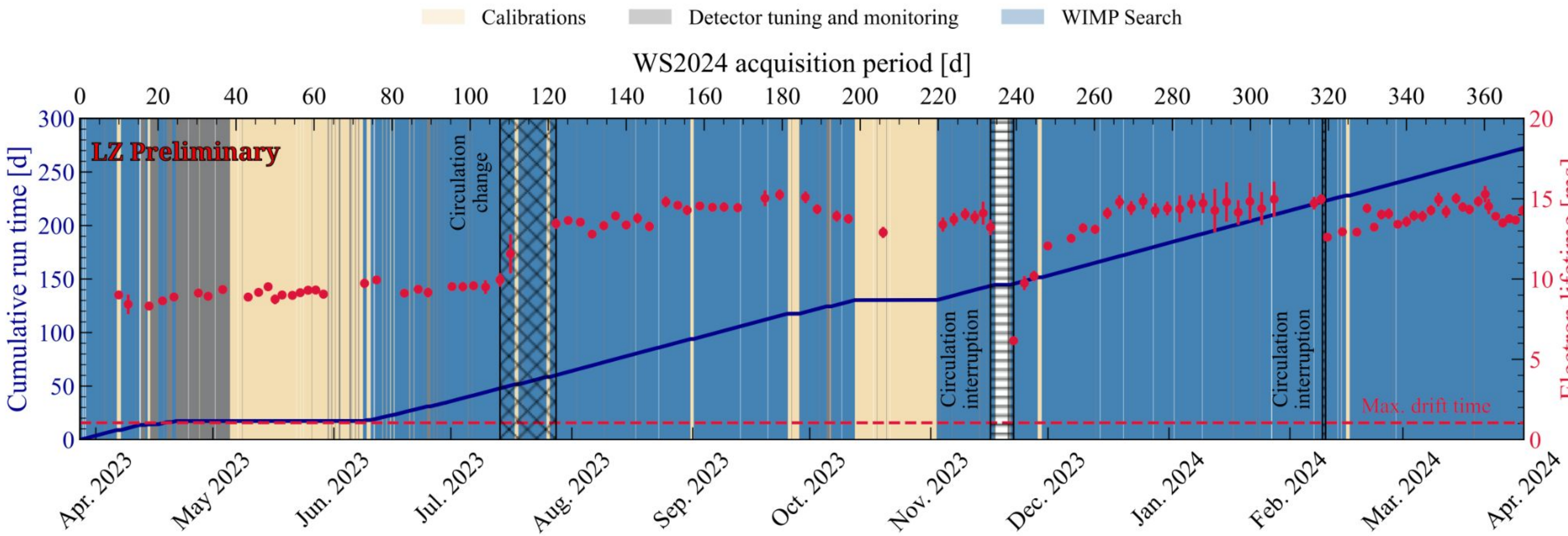
- Following LZ’s first results, various optimisation campaigns carried out:
  - grid voltages
  - Xe circulation
  - trigger configuration
  - Calibrations
- **Extraction region lowered by ΔV by 0.5 kV (anode)** to reduce spurious emission
- **Cathode voltage lowered (from -32 kV to -18 kV)** in response to light emission observed in Skin
  - ER/NR discrimination not affected
- **LZ detector is performing well, stable running!**



New physics run Apr 23⟶ Apr 24

370 days of WIMP search data interspersed with calibrations

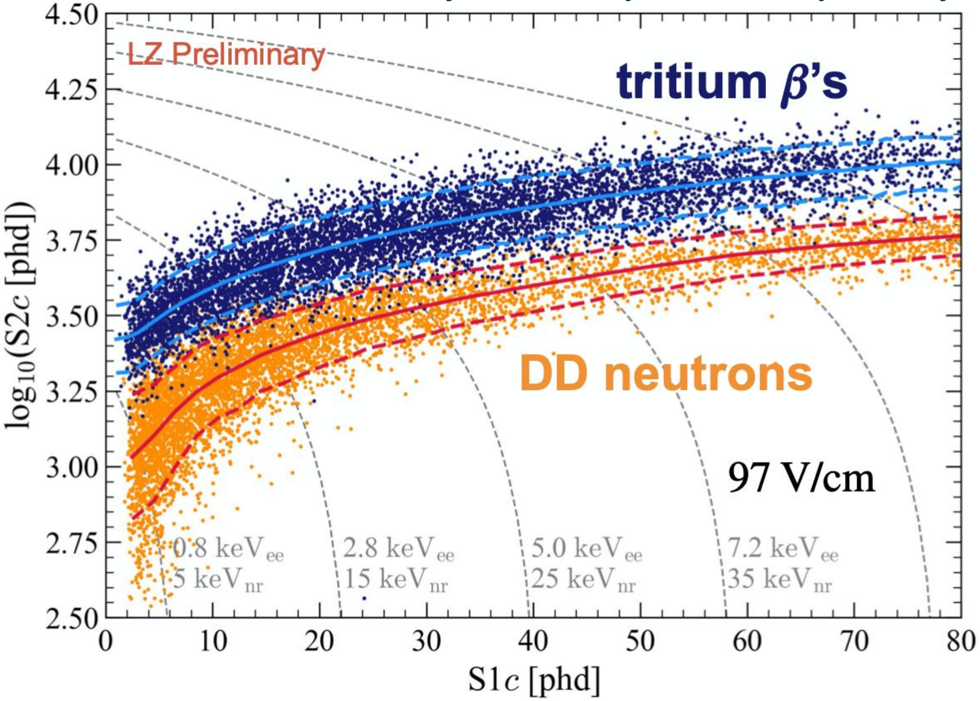
95.2% detector up-time during WIMP search → **220 live-day exposure**



Extensive in-situ calibrations

- **Electronic recoils (background)**
  - Spatially homogeneous β decays
  - High stats (165k events) injection of tritium radiolabeled methane (CH3T, 18.6 keV) + ^{14}C (156 keV)
  - Also: injected ^{83m}Kr, ^{131m}Xe, activation lines
- **Nuclear recoils (signal-like)**
  - High stats (~11k evts) run of Deuterium-Deuterium generator: collimated 2.45 MeV neutrons
  - Also: AmLi neutrons in calibration tubes
- **Used to tune NEST-based response model**
  - Light gain: 0.112 ± 0.002 phd/photon
  - Charge gain: 34.0 ± 0.9 phd/electron
  - Single electron size: 44.5 phd

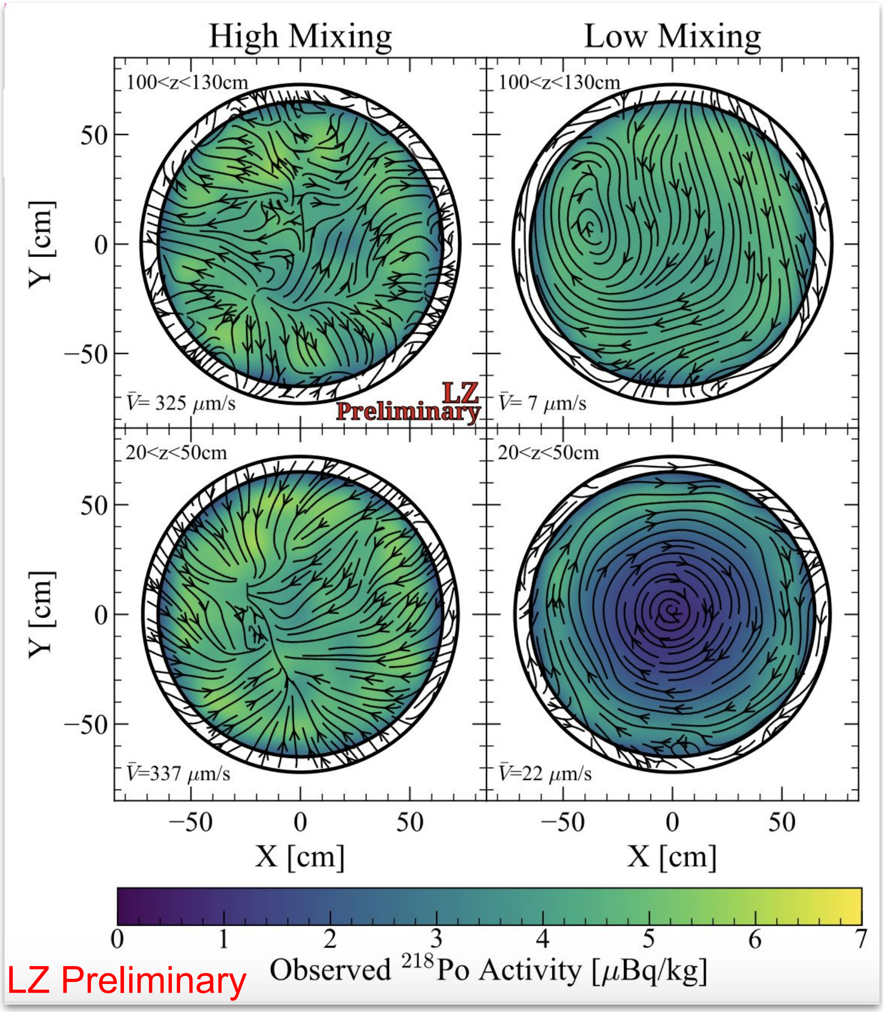
only 8k events of each shown for clarity



99.9% discrimination of flat ER background below median for 40 GeV WIMP (same as WS2022)

Xe flow model to remove dominant ^{214}Pb background

- Fine control of circulation/Xe cooling → control Xe flow pattern
- Two flow states for 2024 data:
  - **High Mixing** - turbulent flow, uniform distribution of Rn & injected sources
  - **Low Mixing** - laminar-like flow, low-radon central region
- In low mixing state, use ^{222}Rn-^{218}Po coincidences → map liquid flow to efficiently tag ^{214}Pb β's



Xe flow model to remove dominant ^{214}Pb background

- Fir
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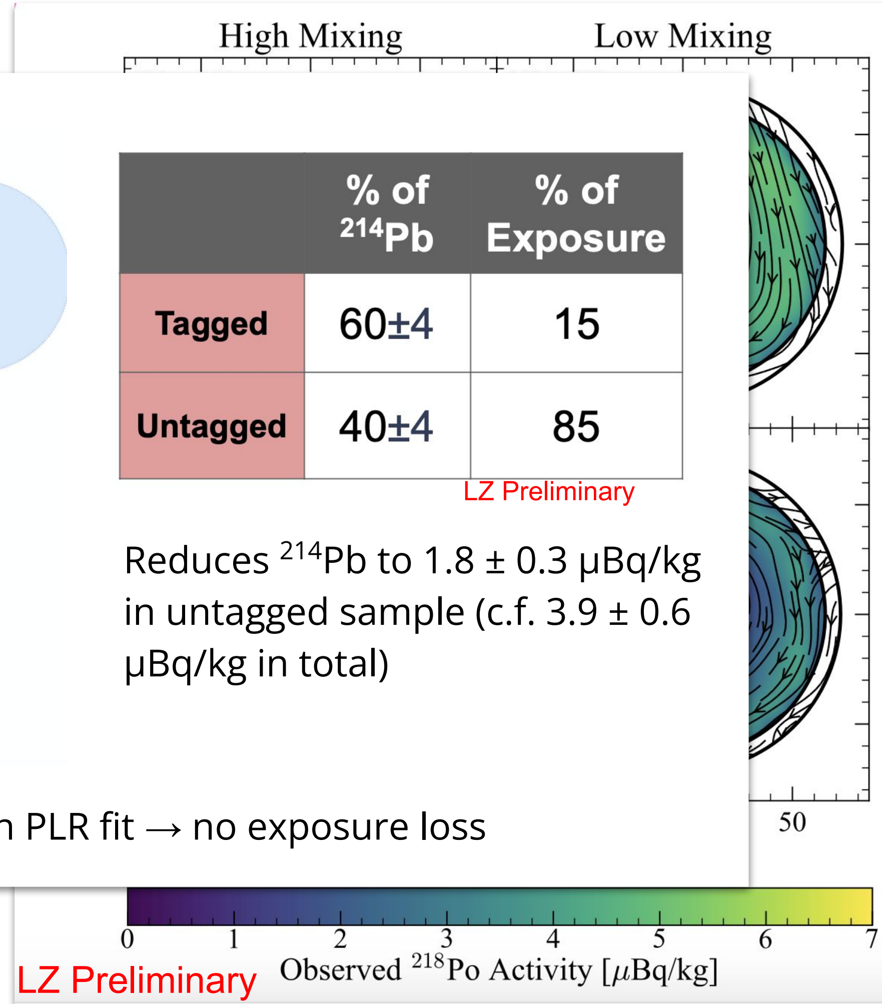
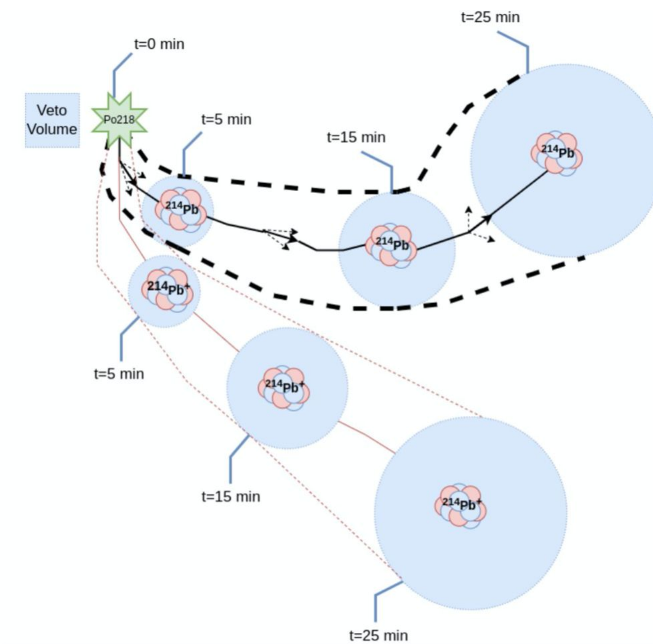
222
→ map liquid flow to
efficiently tag ^{214}Pb β's





	% of ^{214}Pb	% of Exposure
Tagged	60±4	15
Untagged	40±4	85

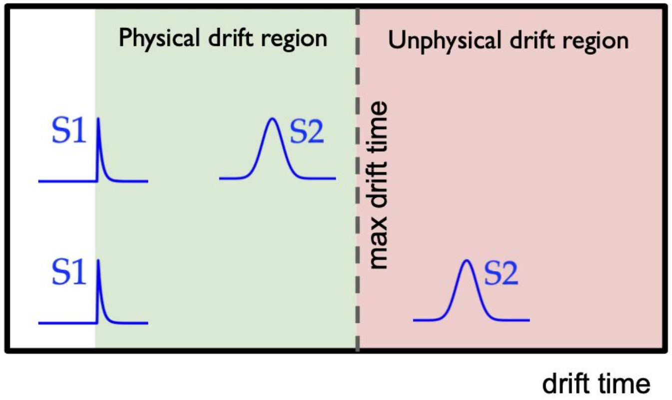
LZ Preliminary

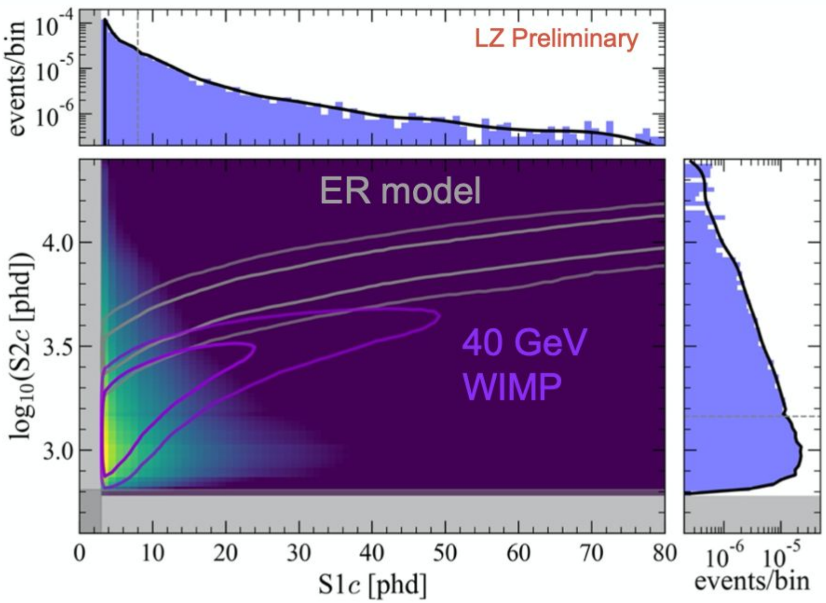
Reduces ^{214}Pb to 1.8 ± 0.3 μBq/kg in untagged sample (c.f. 3.9 ± 0.6 μBq/kg in total)

Both tagged and untagged used in PLR fit → no exposure loss

Accidental coincidence background

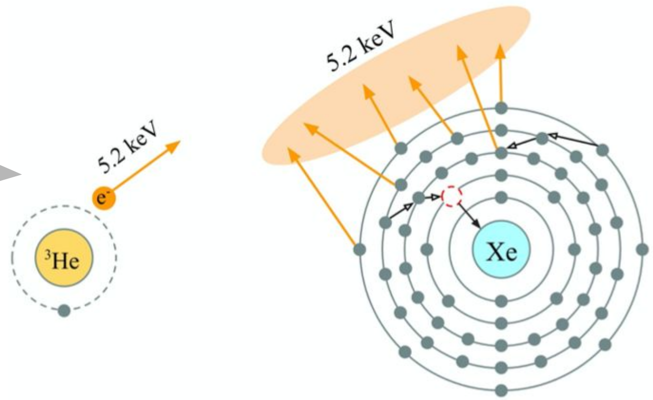
- Pile-up of uncorrelated isolated S1 and S2 pulses
- Extensive analysis cuts to reject
  - **99.5% rejection, minimal signal loss**
- Rate constrained by events with unphysical drift times
  - **2.8 ± 0.6 events expected in 2024 exposure**
- Shape modelled through random pairing of isolated S1-only and S2-only events (trigger-less data)
  - Apply all analysis cuts to manufactured accidental events



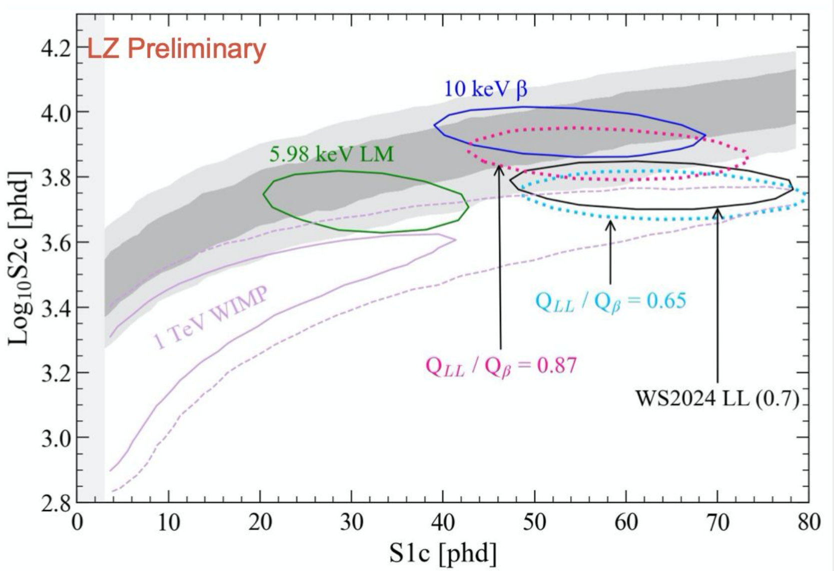


Electron Capture (EC) decay backgrounds

- Single EC: ^{127,125}Xe - NR calibration activation
  - Field-dependent suppressed charge yield related to β
  - Q_L/Q_β = 0.87 +/- 0.03 (5.2 keV L-shell)
  - Measured in-situ [paper in progress] and external test setup*



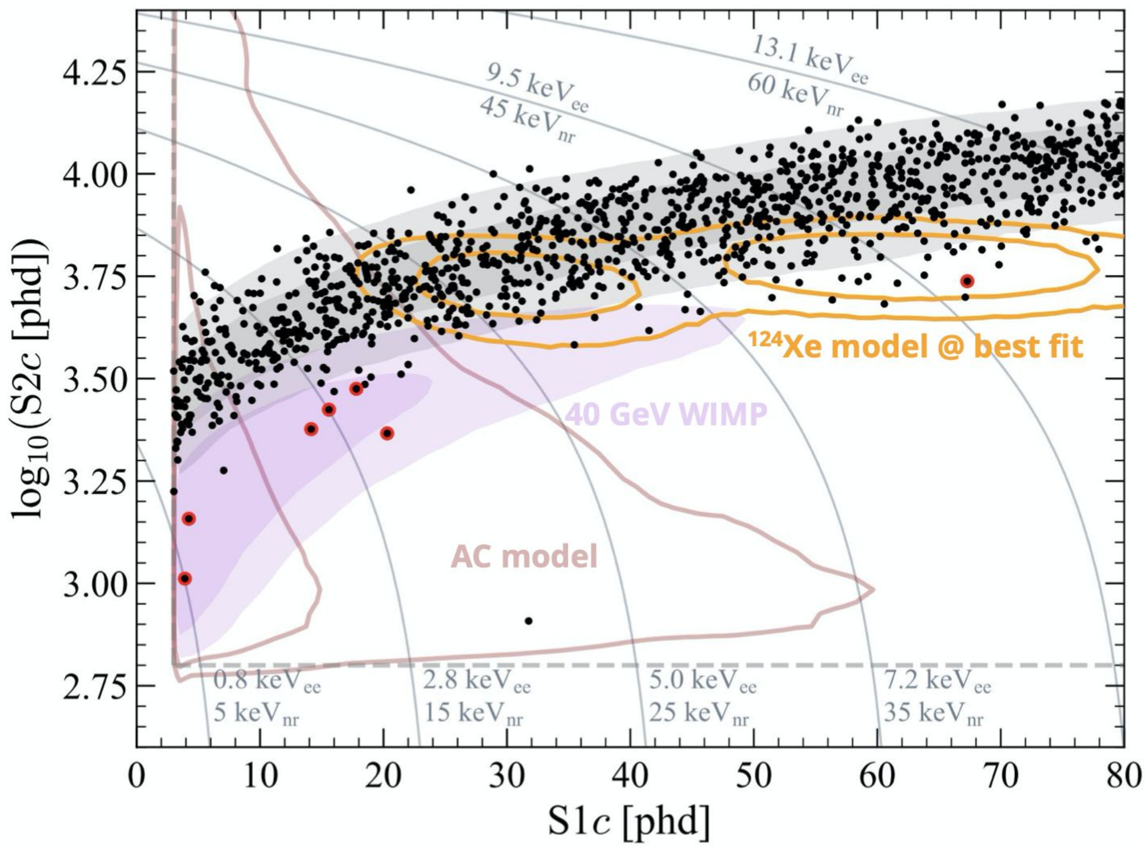
- Double EC: ^{124}Xe - 0.095% nat. Abundance
  - LL mode has increased ionization density relative to single-L capture
  - Float as parameter in final profile likelihood fit
  - **Best fit Q_{LL}/Q_β = 0.7**
  - **In-situ rate measurement 19.4 ± 3.9 events**



** Temples et al, Phys. Rev. D 104, 112001 (2021)*

WIMP-search 2024 dataset

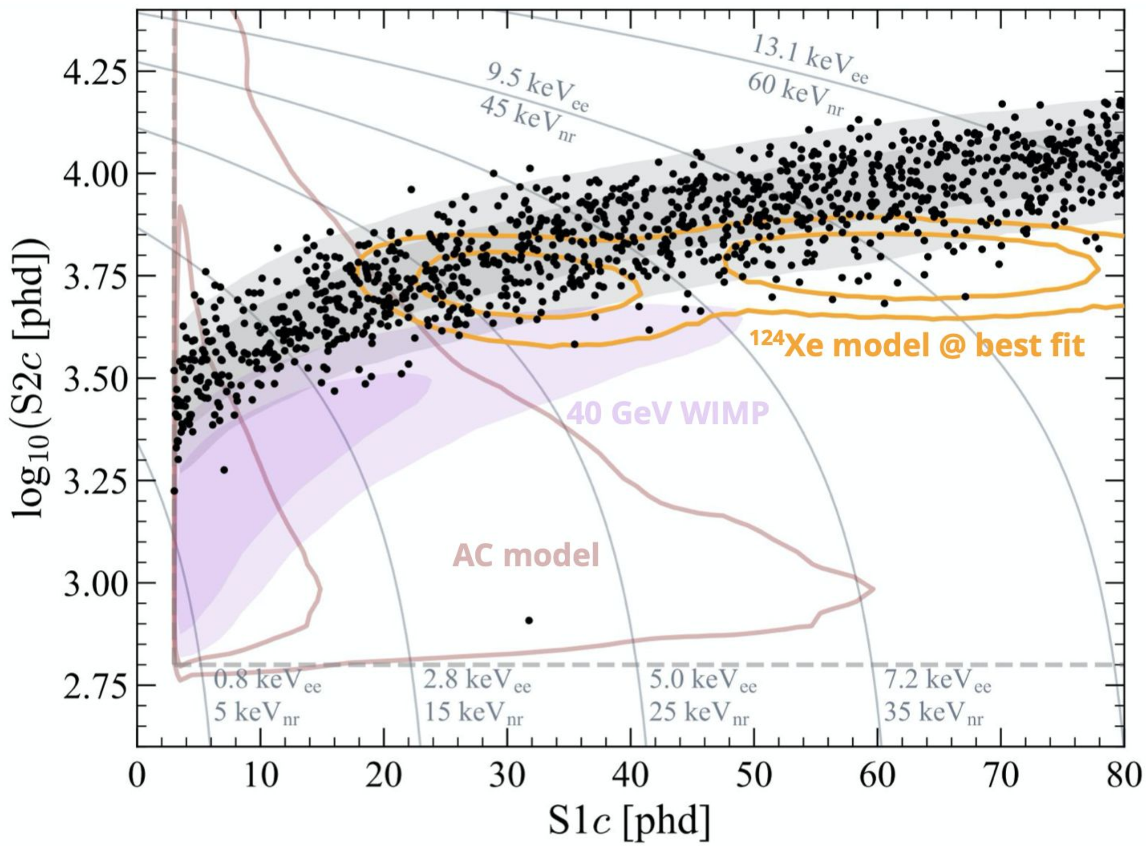
- Bias mitigation: fake WIMP events added “salted” into raw data
- 1227 events in WS2024 before “unsalting”, after all cuts
  - 7 of these were salt events. 8 total salt events injected



WS2024 corresponds to 3.3 ± 0.1 t.y (c.f. 0.9 ty for WS2022)

WIMP-search 2024 dataset

- Bias mitigation: fake WIMP events added "salted" into raw data
- 1227 events in WS2024 before "unsalting", after all cuts
  - 7 of these were salt events. 8 total salt events injected
- **1220 events remain in after "unsalting"**

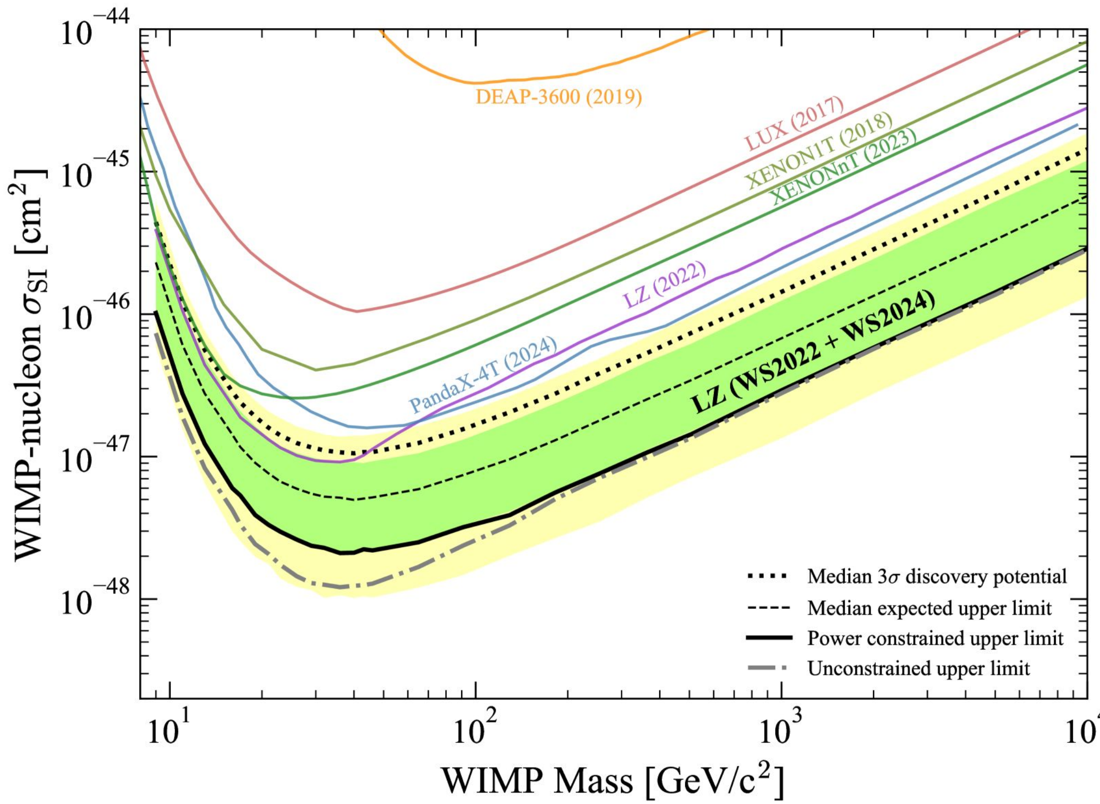


WS2024 corresponds to 3.3 ± 0.1 t.y (c.f. 0.9 ty for WS2022)

2024 WIMP-search results

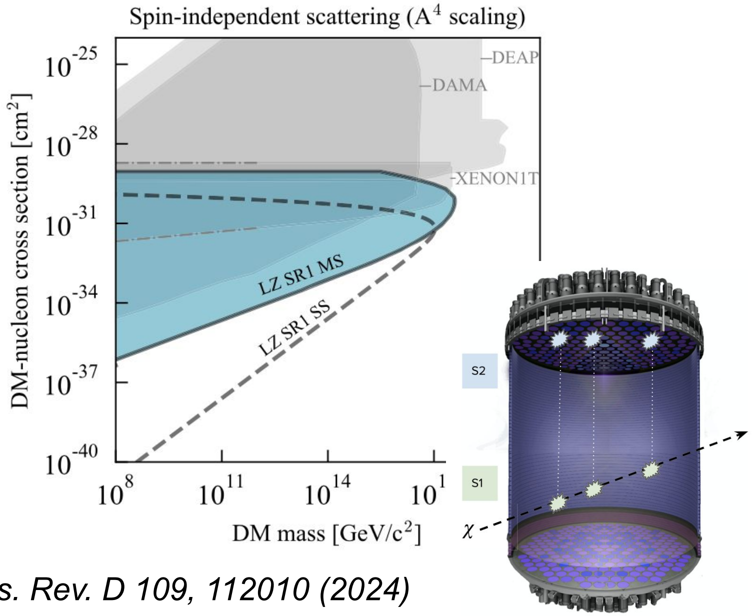
- Combined likelihood WS2024 + WS2022
  - Total 4.2 tonne.year exposure
- Frequentist two-sided profile likelihood ratio test statistic
  - Power constrained at -1σ
- Data consistent with BG-only,
- World leading constraints at all WIMP masses tested
  - **Strongest constraint at σ_{SI} = 2.1 x 10^{-48} cm^2 at 36 GeV**

arxiv/2410.17036



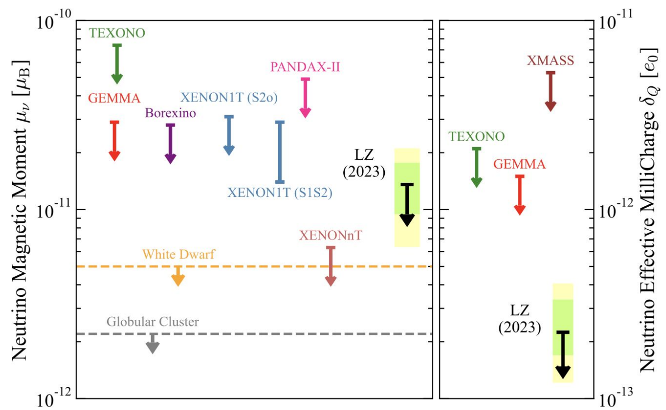
+ broad physics programme ongoing

Ultra-heavy DM:



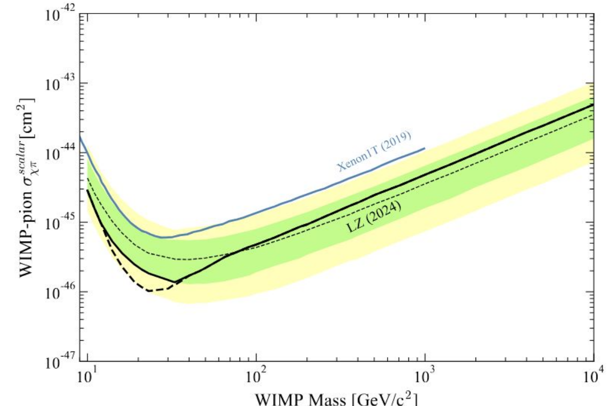
Phys. Rev. D 109, 112010 (2024)

Electron recoil band searches:



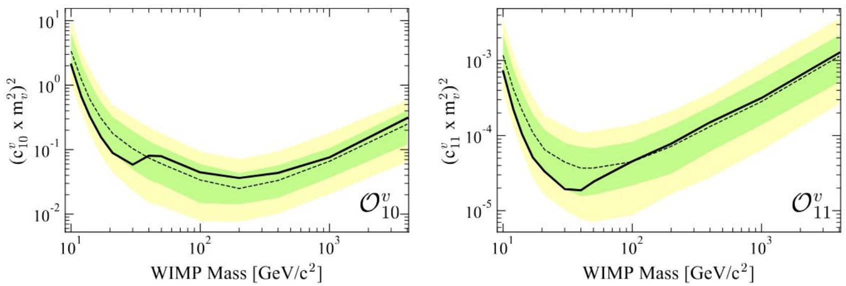
Phys. Rev. D 108, 072006 (2023)

WIMP-pion coupling:



Commun.Phys. 7 (2024) 1, 292

WIMP-nucleon EFT:



Phys.Rev.D 109 (2024) 9, 092003

Conclusions and outlook

- World's largest Xe-TPC operating stably
- **Most stringent WIMP constraints from a 4.2 tonne-year exposure**
- Leveraging novel analysis techniques for background reduction
- Around 1/3rd of the eventual 1000 live-day dataset
- **Updated WIMP and other physics searches to come!**

Thanks to our sponsors and 38 participating institutions!

U.S. Department of Energy
Office of Science

UKRI Science and Technology Facilities Council

Sanford Underground Research Facility

fct Fundação para a Ciência e a Tecnologia

ibs Institute for Basic Science

Swiss National Science Foundation

Backups

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

https://lz.lbl.gov/

- 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
- University of Zürich

US Europe Asia Oceania

250 scientists, engineers, and technical staff

Science and Technology Facilities Council

Swiss National Science Foundation

Fundação para a Ciência e a Tecnologia

SANFORD UNDERGROUND RESEARCH FACILITY

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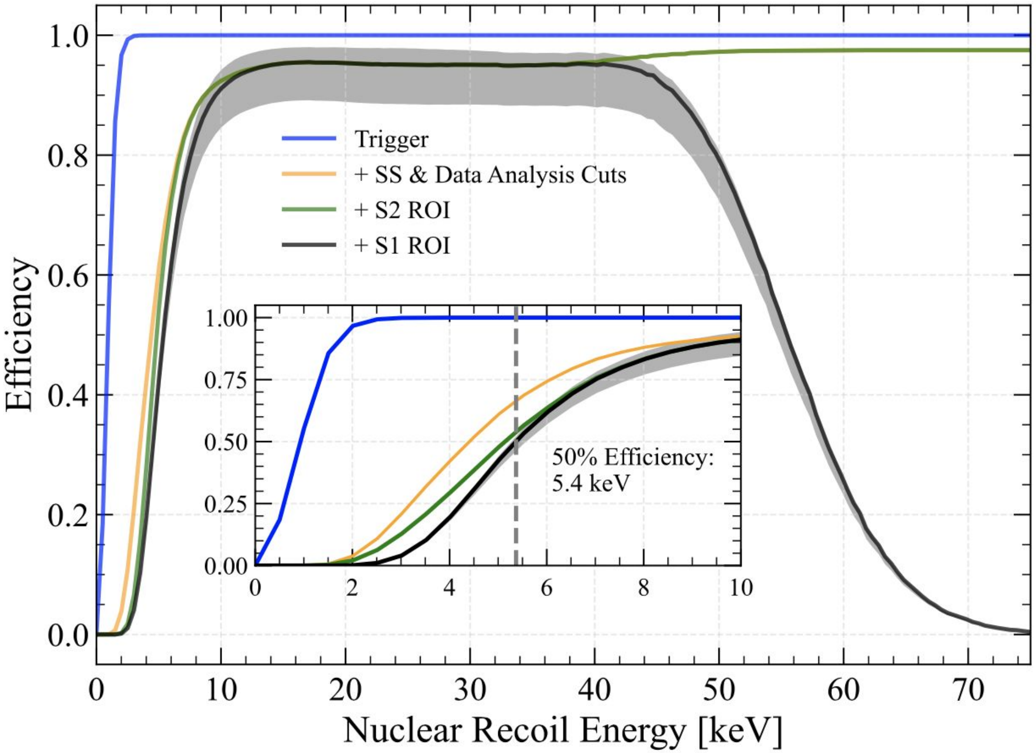
Thanks to our sponsors and participating institutions!

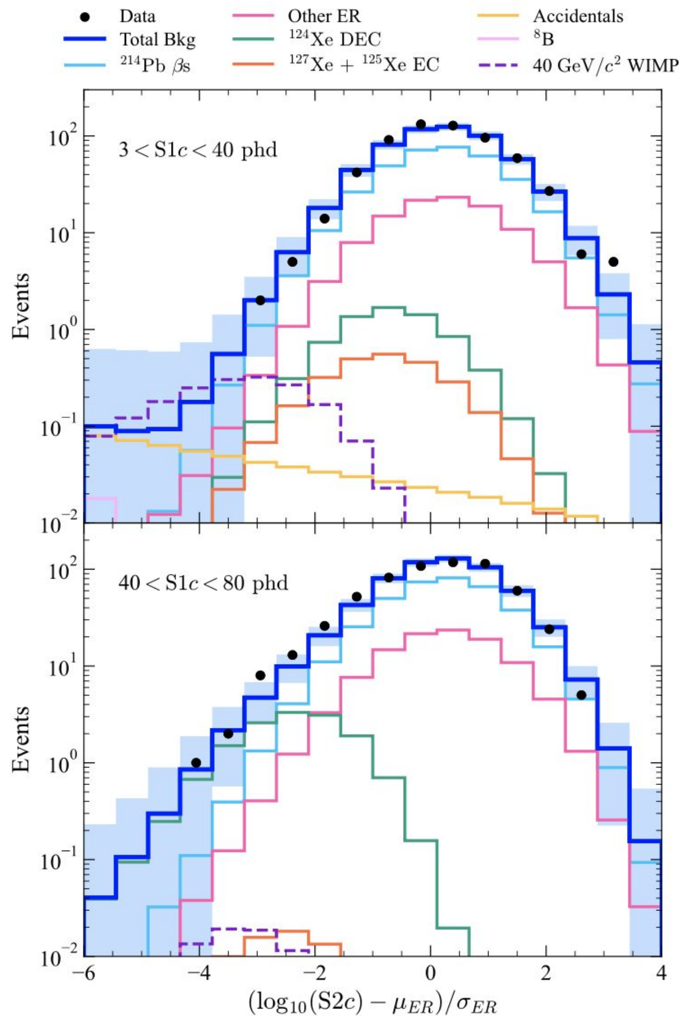
Data cuts and efficiency



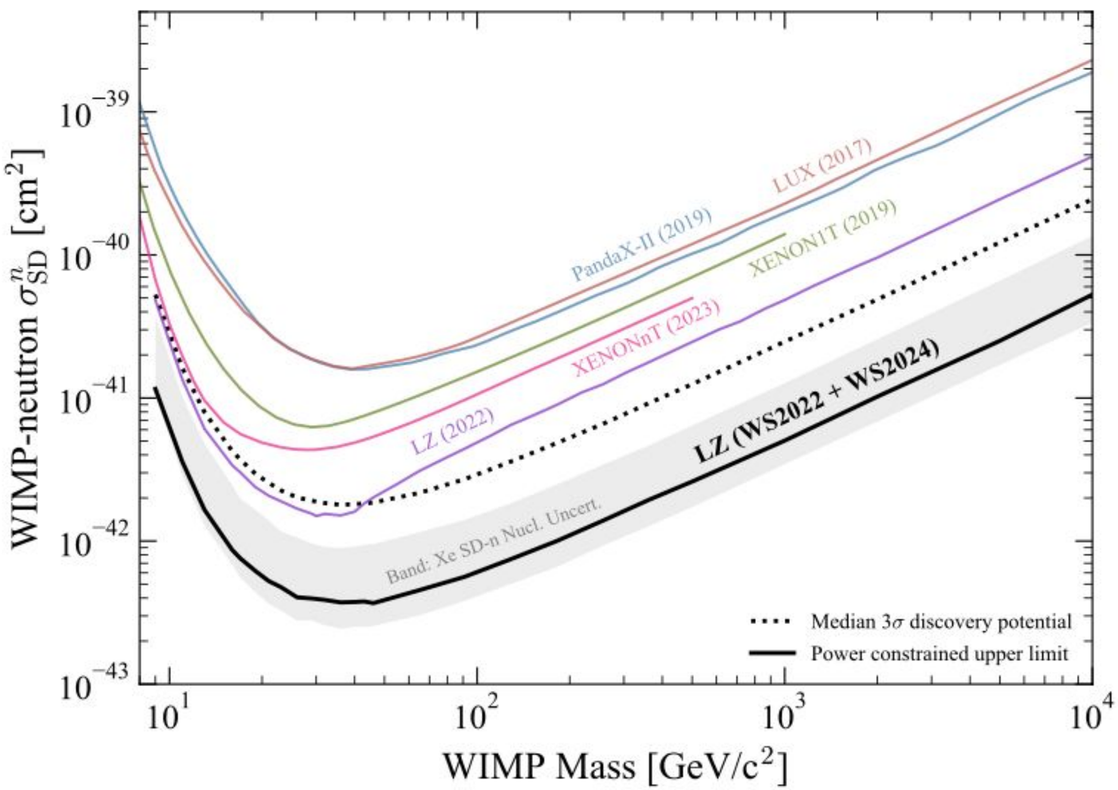
Background fit

Source	Pre-fit Expectation	Fit Result
^{214}Pb βs	743 ± 88	733 ± 34
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22	161 ± 21
Solar ν ER	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po βs	62.7 ± 7.5	63.7 ± 7.4
Tritium+ ^{14}C βs	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe $2\nu\beta\beta$	55.6 ± 8.3	55.8 ± 8.2
^{124}Xe DEC	19.4 ± 3.9	21.4 ± 3.6
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
Accidental coincidences	2.8 ± 0.6	2.6 ± 0.6
Atm. ν NR	0.12 ± 0.02	0.12 ± 0.02
^{8}B+*hep* ν NR	0.06 ± 0.01	0.06 ± 0.01
Detector neutrons	[a] $0.0^{+0.2}$	$0.0^{+0.2}$
40 GeV/c^2 WIMP	–	$0.0^{+0.6}$
Total	1210 ± 91	1203 ± 42

[a] The expected number of neutron events results from a fit to the sample of veto detector-tagged events. This expectation is not explicitly used in the final combined fit as this sample is included directly in the likelihood, as described in the text.



WS2022+24 spin-dependent neutron results



WS2022+24 spin-dependent proton results