The Outer Detector of the LUX ZEPLIN dark matter direct detection experiment

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LUX-ZEPLIN Dark Matter Experiment

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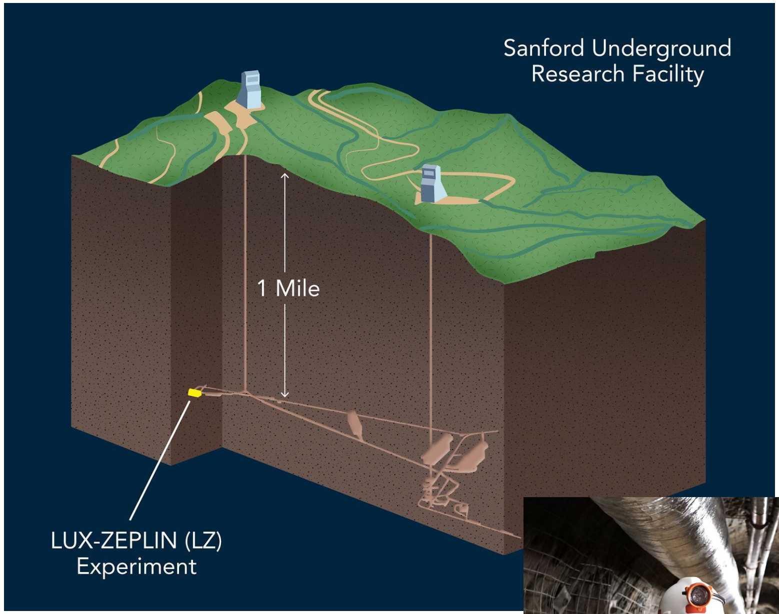
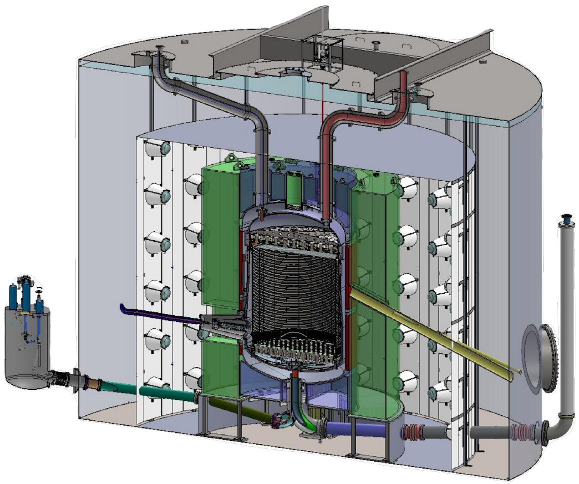
- LUX-ZEPLIN (LZ) is a second generation dark matter experiment.
- The detector operates in the Davis Cavern on 4850L of Sanford Underground Research Facility, South Dakota, USA.
- The LZ collaboration consists of about ~250 scientists in 38 institutions across the world.





Motivation for having a veto system

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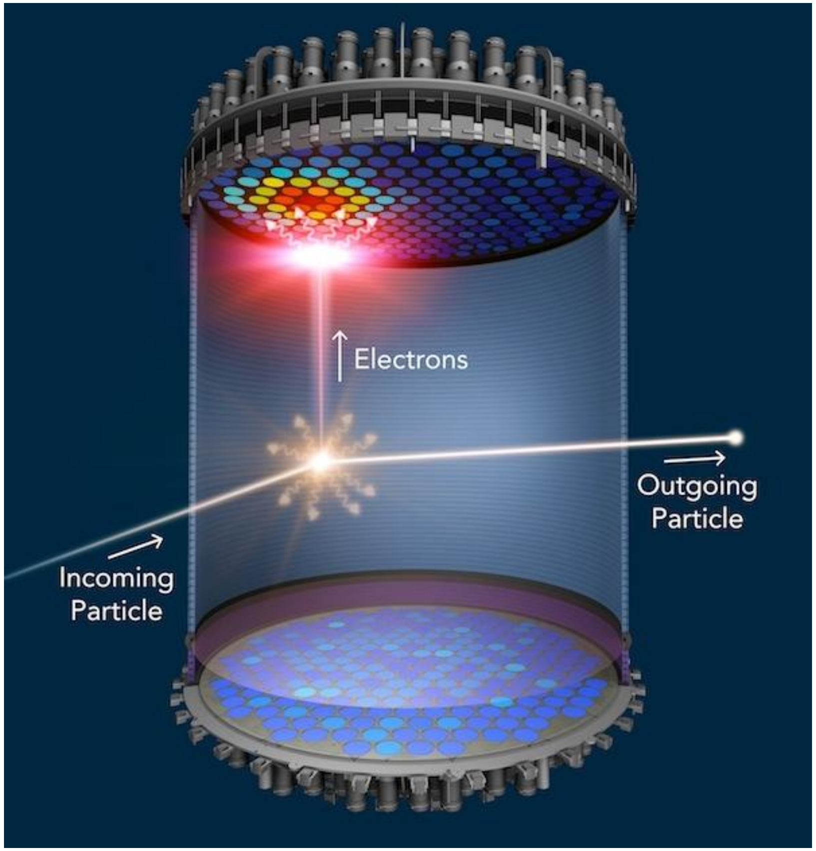
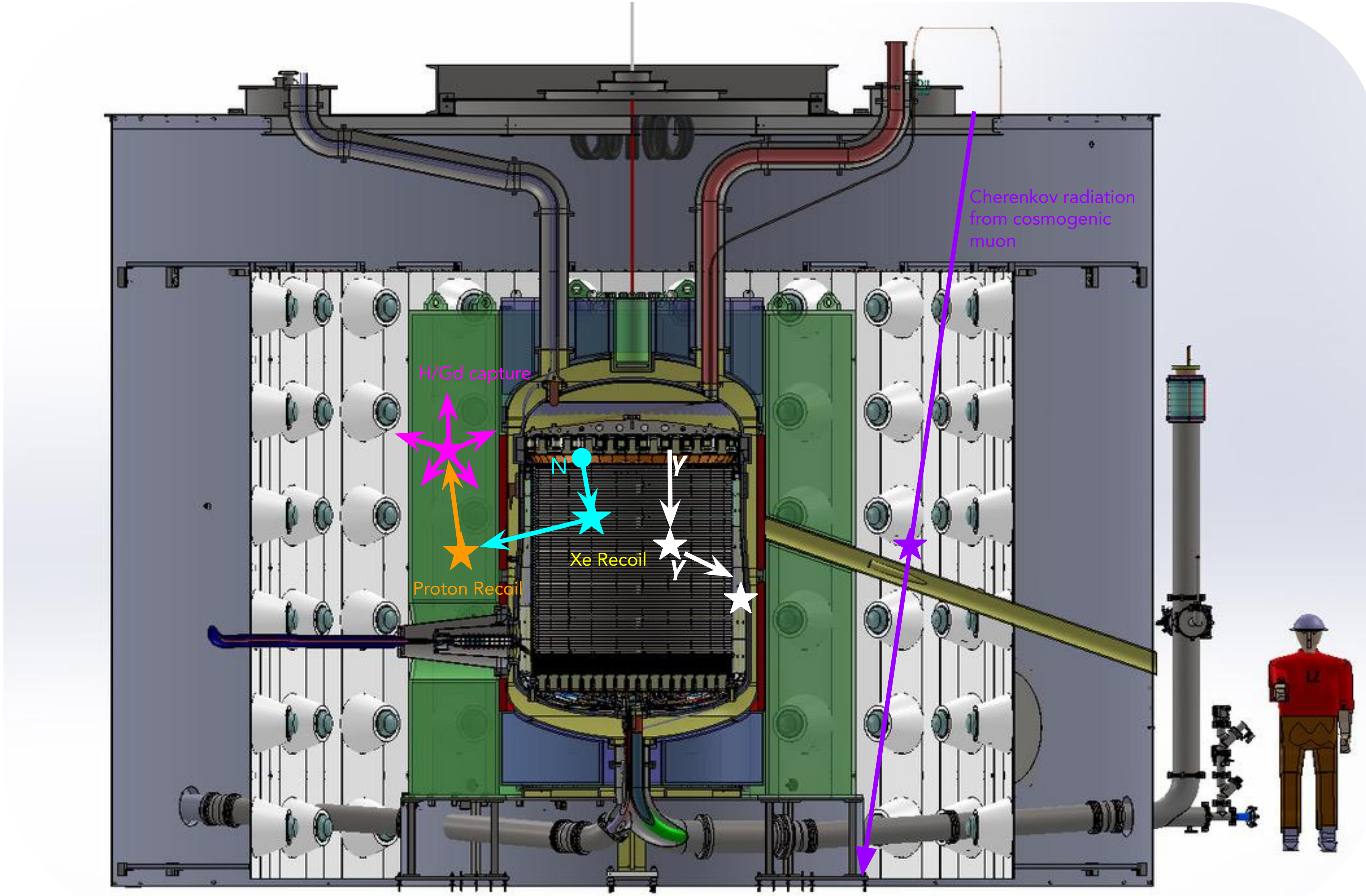
- A WIMP scattering in a noble element detector will not deposit energy in surrounding materials.
- Backgrounds induced by the surroundings and detector components can mimic WIMP-like signals.
  - Nuclear recoils produced through neutron scattering.
  - Electron recoils from γ-ray scattering.
- LZ surrounds its TPC with a veto system to reduce backgrounds.
- The veto system allows LZ to:
  - Increase the fiducial volume in the TPC.
  - Demonstrate possible dark matter signal was not induced by a background.



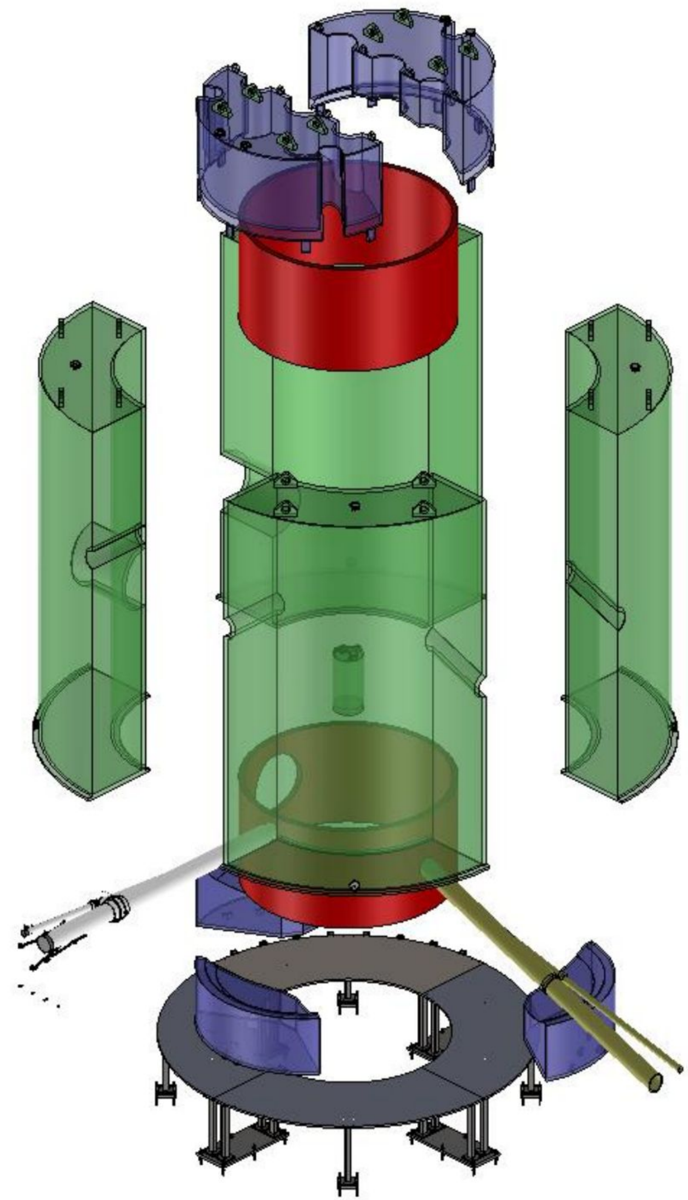
"Extraordinary claims require extraordinary evidence"

Principle of the veto system



The Outer Detector

- The Outer Detector is a near-hermetic system that surrounds the cryostat vessel which houses the TPC.
- 10 UV transparent acrylic vessels filled with 17t of Gadolinium loaded liquid scintillator (Gd-LS). NIM A 937 (2019)
    - 0.1% Gd by mass.
- Viewed by 120 8" Hamamatsu R5912 PMTs.
- Dedicated optical calibration system situated within the array of PMTs.
- All housed in water tank filled with 238t of ultra pure water to shield from ambient radioactive backgrounds.



Outer Detector Installation

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Side acrylic tank being lowered into the water tank

Gd-LS being moved UG for the filling of the tanks

Acrylic tanks in place

OCS Electronics Installation

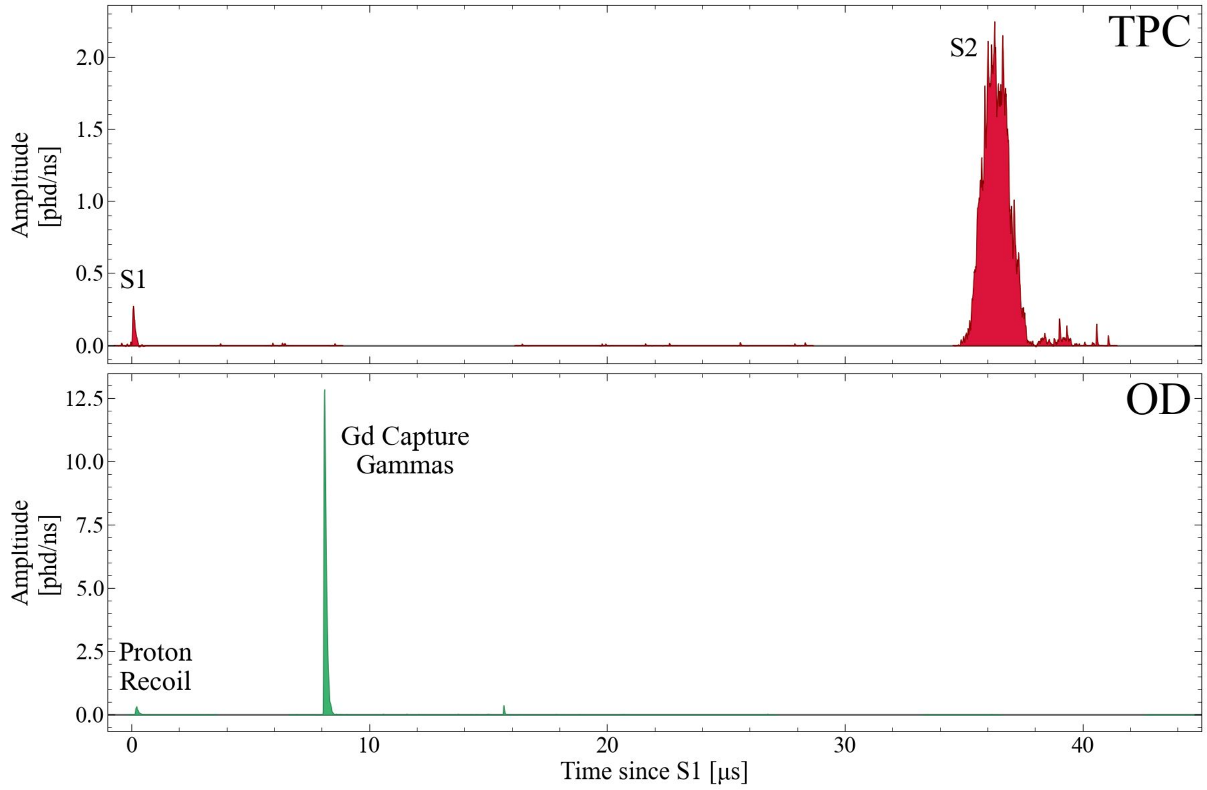
OD PMT Installation

OD PMT Installation Team

OD filled Spring 2021!

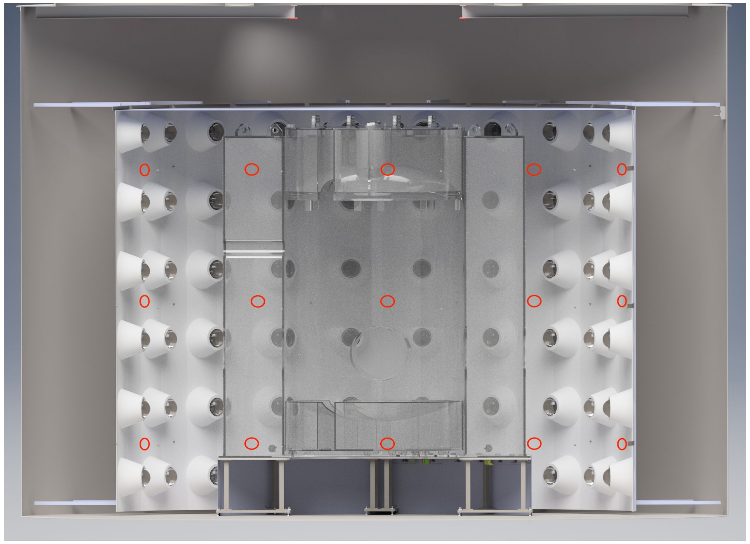
Veto Selection - Outer Detector

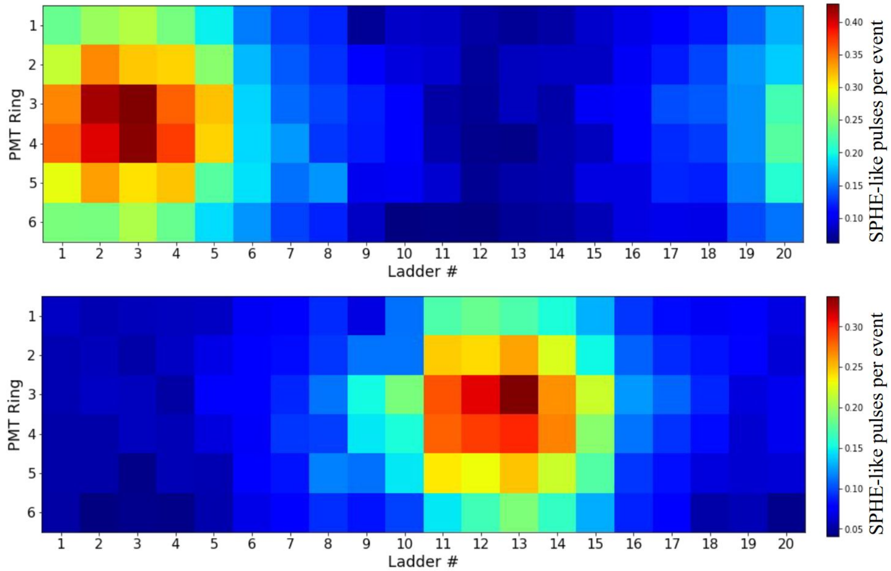
- Prompt OD veto removes events containing γ-rays and proton recoils.
  - ± 0.3 μs of TPC S1
  - Coincidence > 5
  - Pulse Area > 5 phd (34 keV)
- Delayed OD veto removes events where neutrons have be captured in the OD.
  - +0.3 μs to +600 μs of TPC S1
  - Coincidence > 5
  - Area > 32 phd (200 keV)

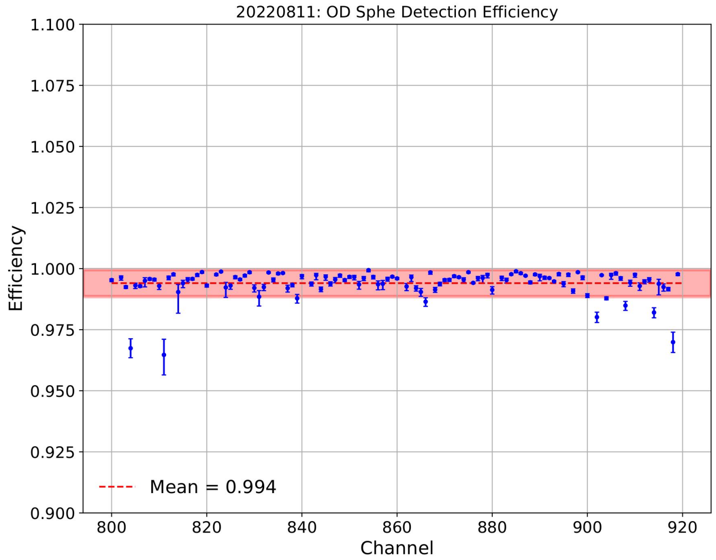


Outer Detector Optical Calibration

- LZ uses an LED driven Optical Calibration System (OCS) to monitor and calibrate the OD PMTs.
- 30 injection points situated within the array of OD PMTs.
- 5 upward facing injection points to monitor optical properties of acrylic and Gd-LS.
- SPhE Detection Efficiency ~99%!

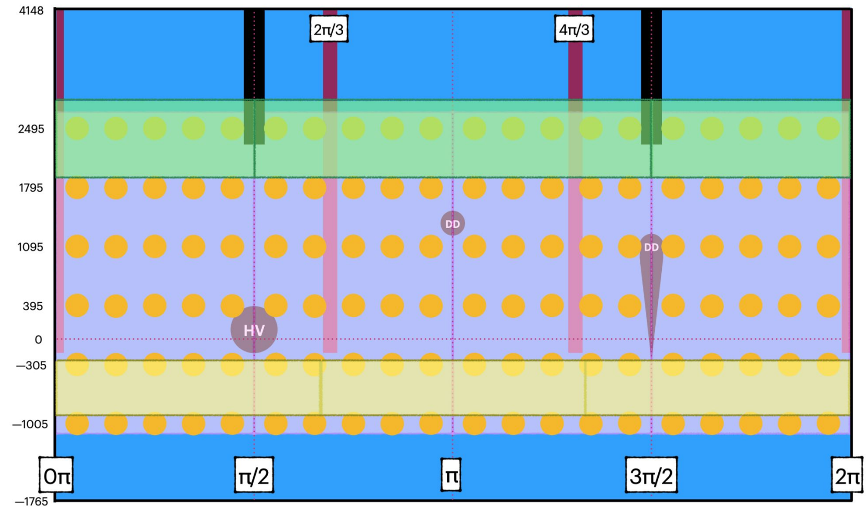


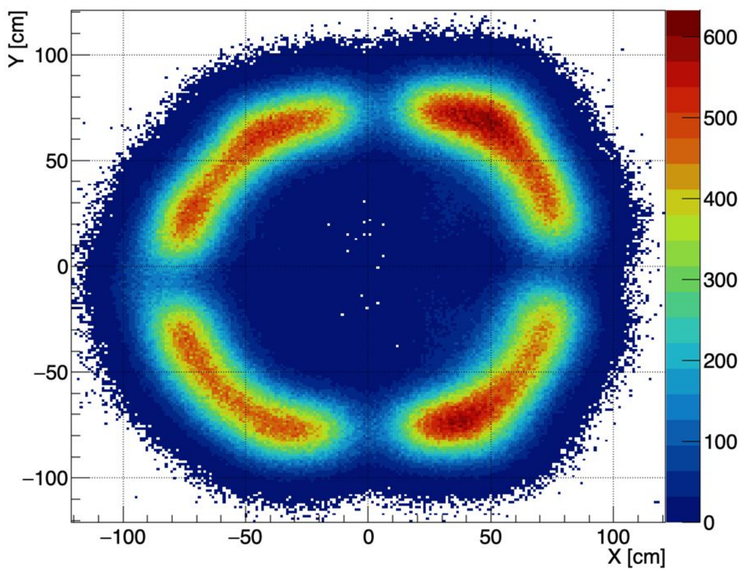


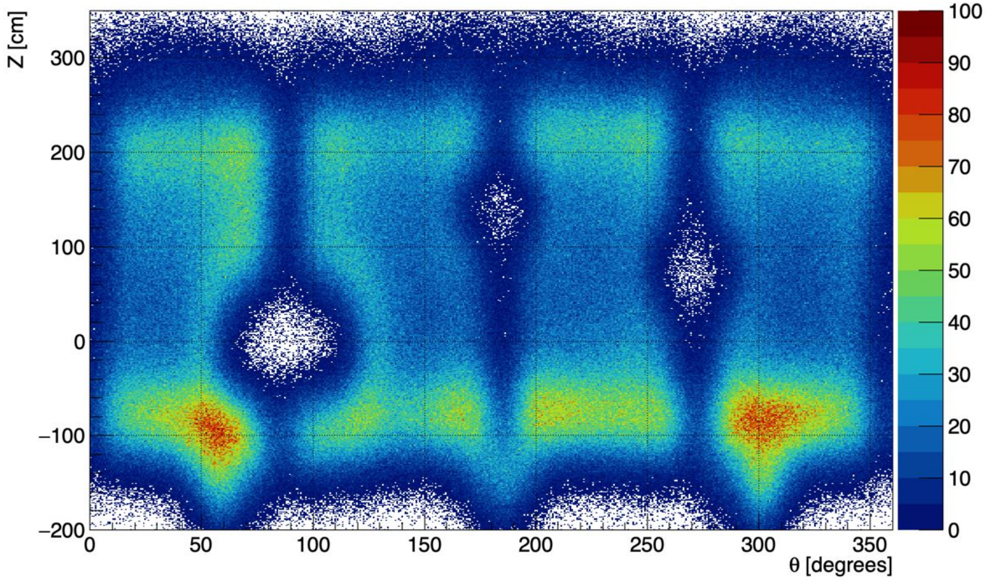


Outer Detector Position Reconstruction

- Individual acrylic tanks and other geometric features can be resolved from the data using centroid position reconstruction.
- Z-position corrections are developed by varying the position of CSD gamma sources.

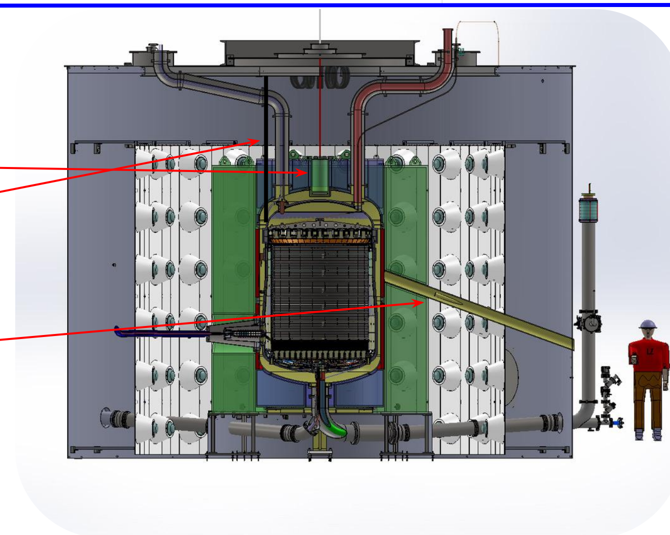


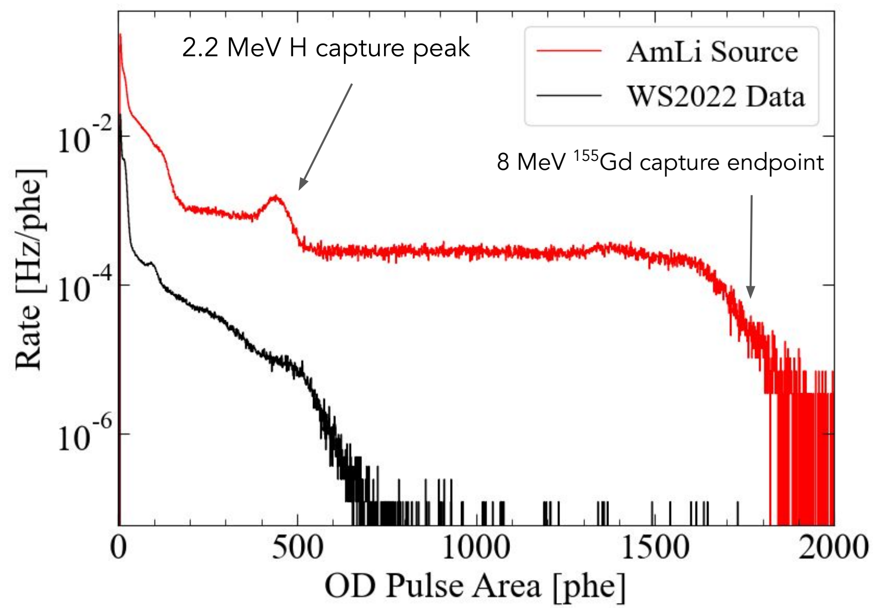




Source deployment calibration

- LZ utilizes different types of controlled source deployment systems.
  - Photoneutron sources: YBe
  - Three external CSD tubes - Neutrons and gammas (AmLi, AmBe, ^{252}Cf, ^{22}Na and ^{228}Th).
  - 2 neutron conduits: DD neutrons, D-reflector and H-reflector.
  - Flow through sources for TPC calibration.
- The photoneutron source is lowered into the detector from above in tungsten shield (low energy neutrons).
- Gamma and neutron sources are loaded into CSD tubes and are lowered to specific Z-Position. These tubes sit between the cryostat vessels.
- The two neutron conduits, one horizontal and one angled, are used for localized NR calibrations using a DD generator.





Neutron Tagging Efficiency with AmLi

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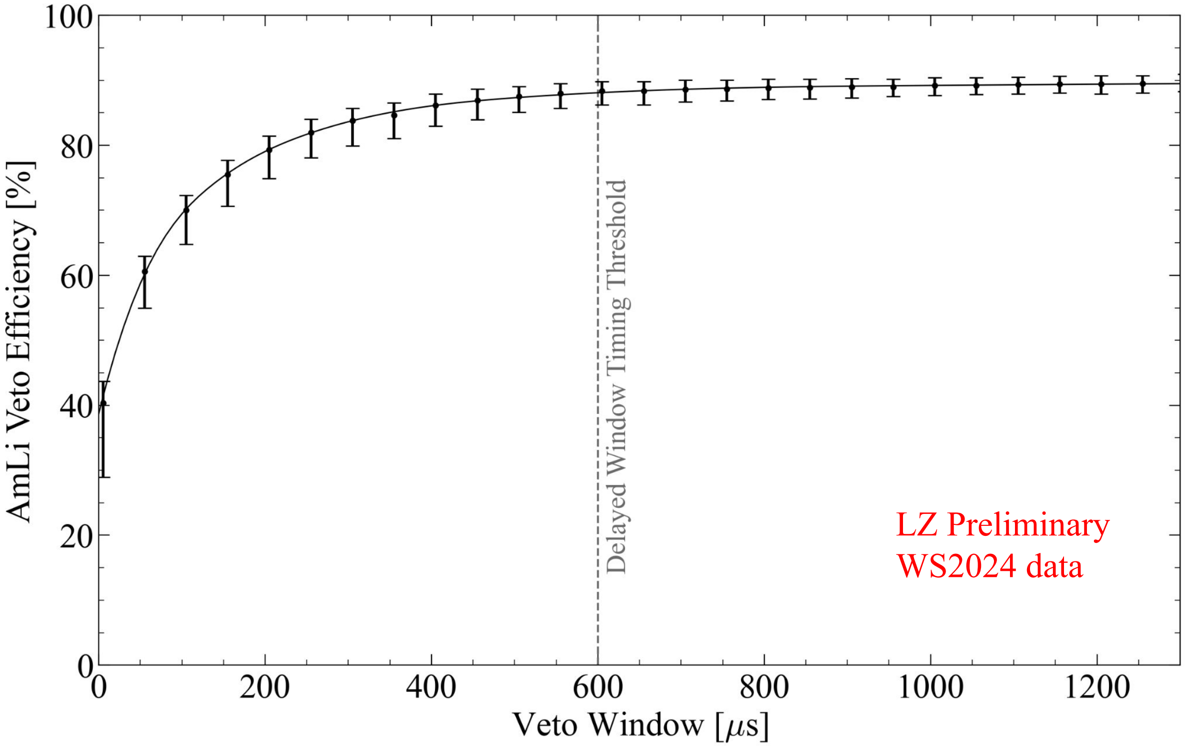
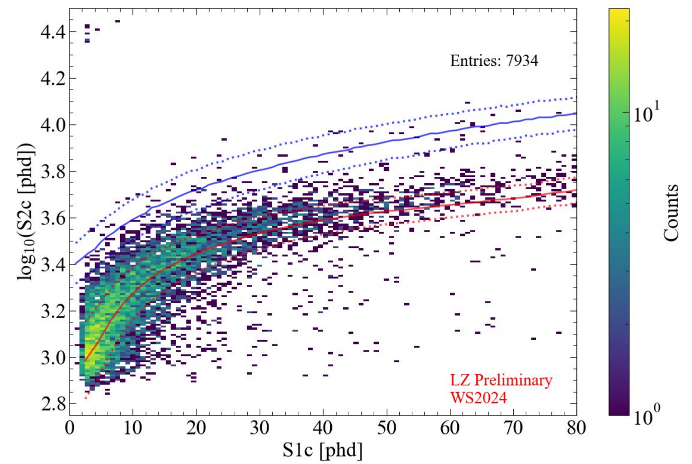
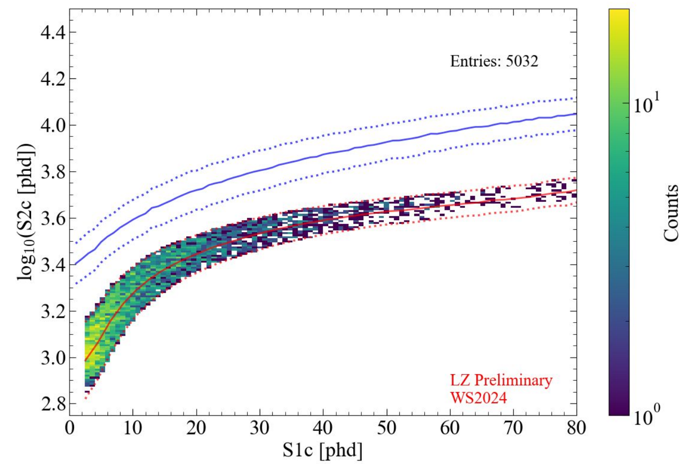
- Efficiency and false veto fraction is assessed using different windows and thresholds whilst also taking into account detector geometry.





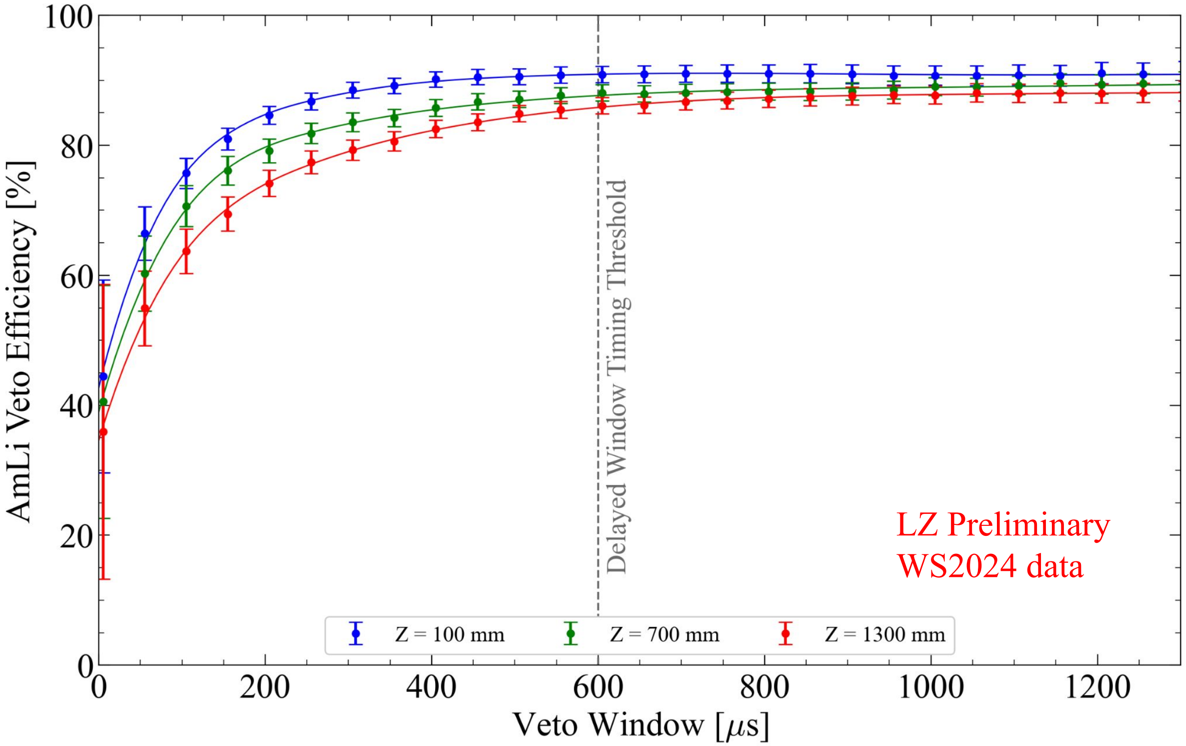


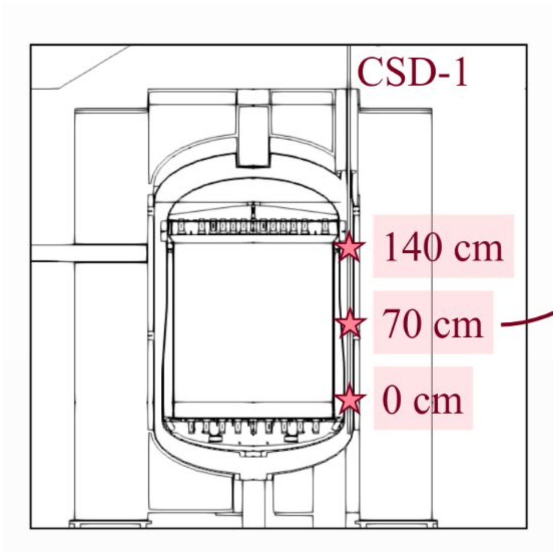
200 keV threshold with a 600μs window: Average efficiency: 89 ± 3%*

*Neutrons tagged from LZ AmLi source

Neutron Tagging Efficiency versus position

- Efficiency and false veto fraction is assessed using different windows and thresholds whilst also taking into account detector geometry.

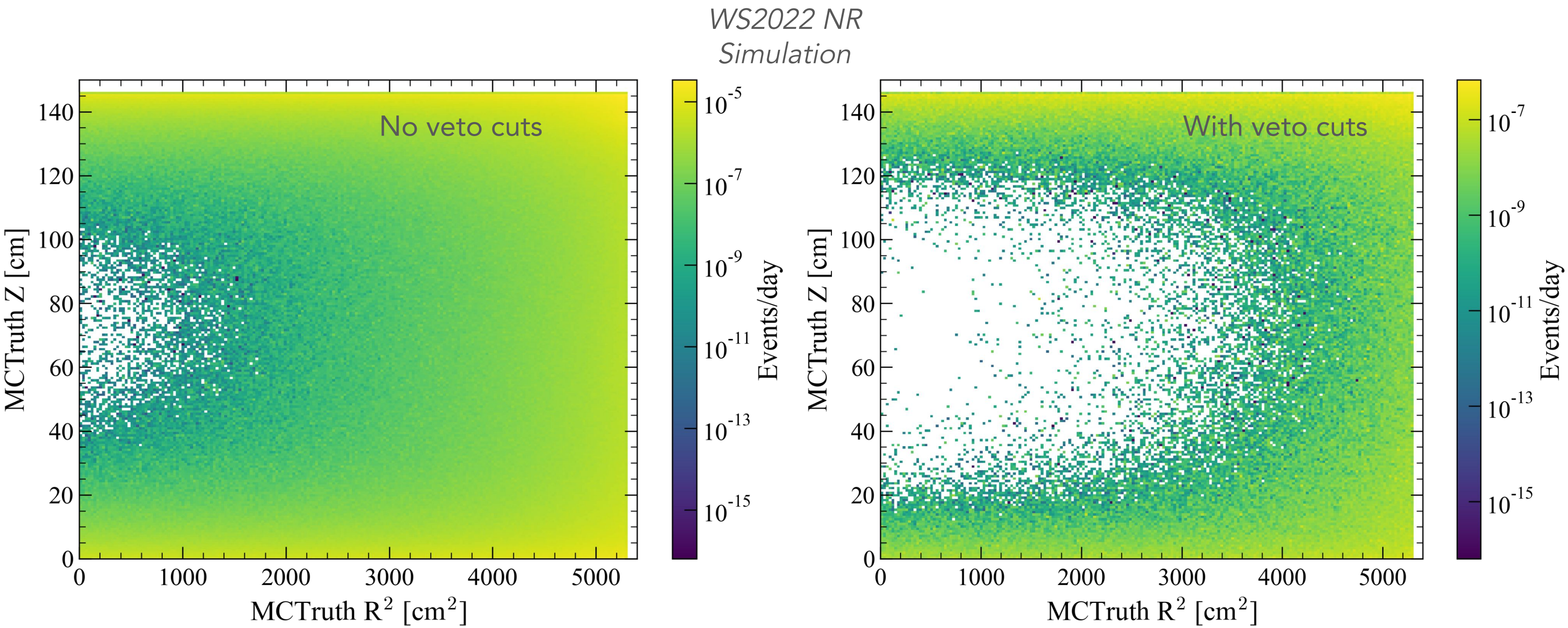




Where does the OD inefficiency come from?

- Neutron capture on H in LS, acrylic, water and foam.
  - Just one 2.2 MeV γ ray released which can escape without depositing energy.
- Neutrons wander around in the acrylic for too long, hence a longer veto window.
- Energy deposited is below threshold (nominal 200 keV).

The veto system and the WIMP Search



- Applying the veto cuts removes background events from the fiducial volume and WIMP region of interest.
- Past studies with simulation have seen increases in FV of upto 70%.

The veto system and the WIMP Search

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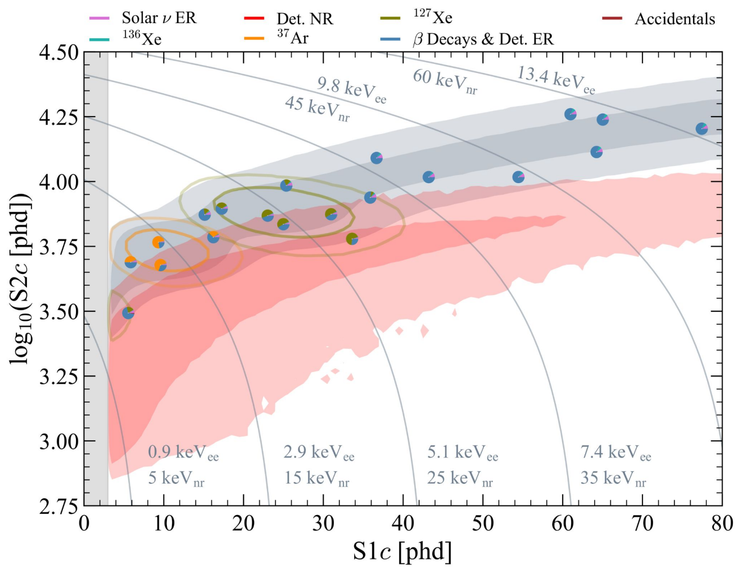
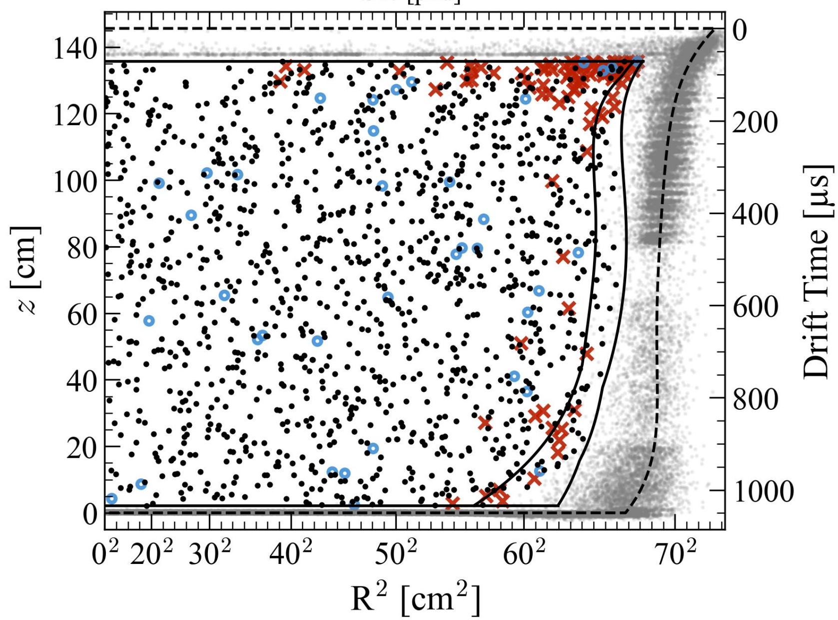
- Neutron backgrounds, “Det. NR”, with OD tag are 7.7 times larger than without (tagging efficiency is 89 ± 3%).
- By design, 3% of non-neutron backgrounds have an accidental OD-tag.
- We use OD-tagged data to set data driven constraints on Det. NR rate: < 0.2 events in WS2024 result.
- Data can be reconstructed r^2 and z after all analysis cuts within the TPC.
    - Black (gray) points show the data inside (outside) the FV.
    - Red crosses and blue circles show events vetoed by a prompt or a delayed signal, respectively.





Summary

- LUX-ZEPLIN is the world leading direct detection dark matter experiment.
- When a discovery of WIMPs is made, we need to be certain of this. The veto system will be used to verify such claims.
- Neutrons pose as the main background in the WIMP search due to the interaction via nuclear recoils (NR).
- The veto system has a tagging efficiency of 89 ± 3% determined using calibration sources.
- Currently the veto system is used to constrain "Detector NR" rates down to 0.2 events in our last science run.

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

250 scientists, engineers, and technical staff

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
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- 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

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Backup

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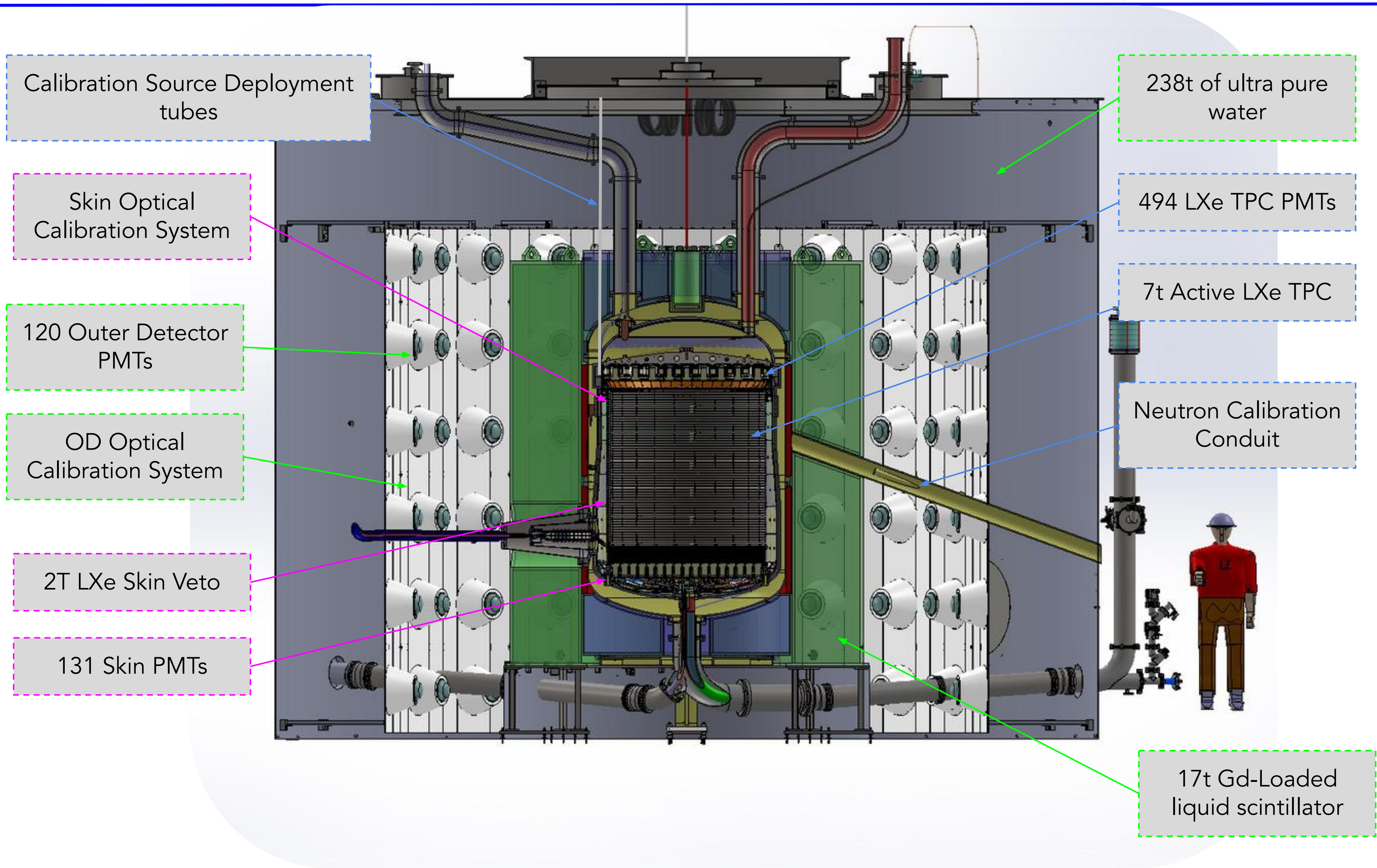
Overview of LUX-ZEPLIN



Outer Detector Installation

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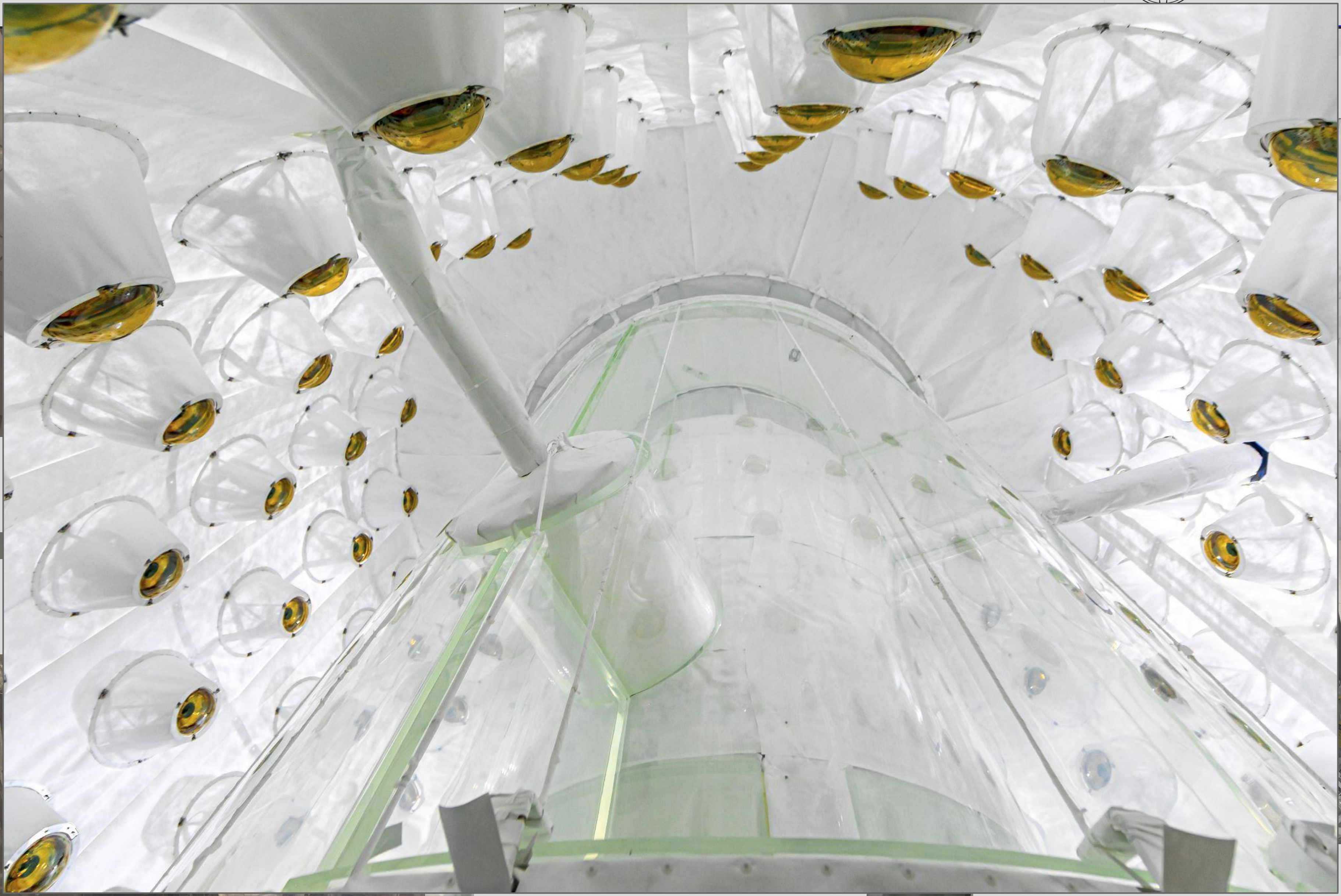

Gadolinium-Loaded Liquid Scintillator (Gd-LS)

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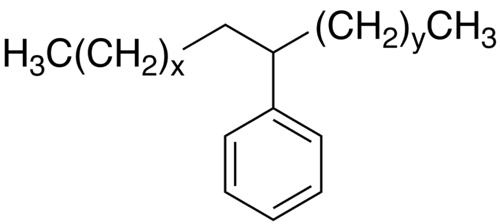
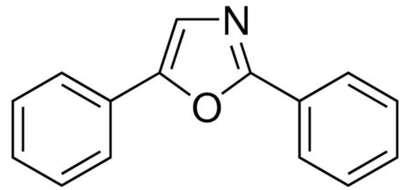
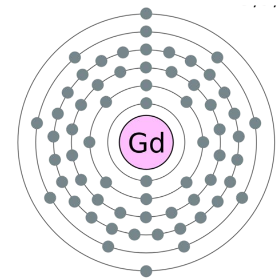


Linear Alkylbenzene (LAB), solvent



2,5-Diphenyloxazole (PPO), fluor



Gadolinium (Gd), neutron eater

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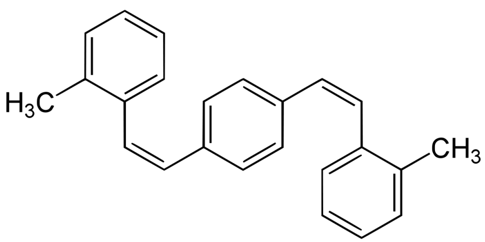
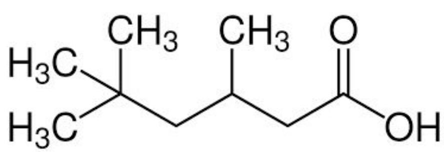


1,4-bis(methylstyryl)benzene (Bis-MSB), wavelength shifter



Trimethylhexanoic Acid (TMHA), chelation agent

Table 2: Chemical components in 1 L of GdLS.

Acronym	Molecular Formula	Molecular Weight (g/mol)	Mass (g)
LAB	$C_{17.14}H_{28.28}$	234.4	853.55
PPO	$C_{15}H_{11}NO$	221.3	3.00
Bis-MSB	$C_{24}H_{22}$	310.4	0.015
TMHA	$C_9H_{17}O_2^-$	157.2	2.58
Gd	Gd	157.3	0.86
GdLS	$C_{17.072}H_{28.128}O_{0.0126}N_{0.0037}Gd_{0.0015}$	233.9	860.0

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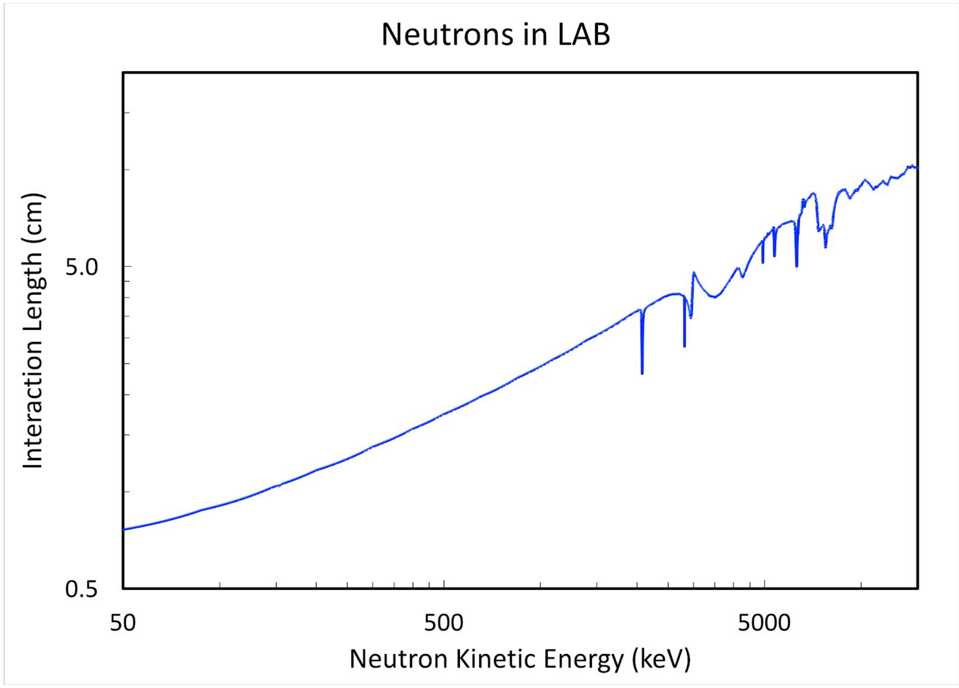
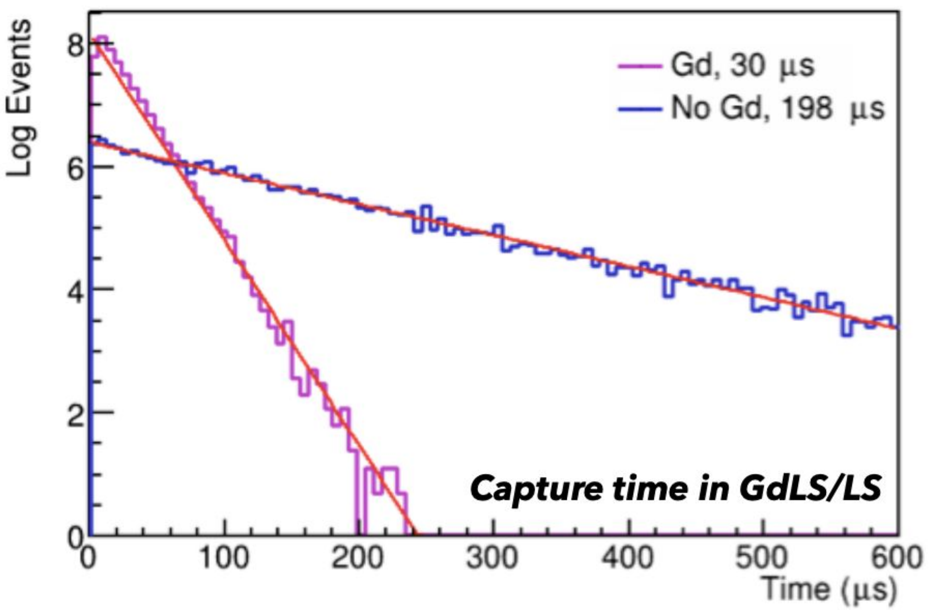
Neutron interactions with the OD

Neutron loses energy scattering on protons in scintillator/acrylic



Neutron captures on Gd or H



H produces a 2.2 MeV γ, Gd produces 4-5 γs totaling ~8 MeV

^{155}Gd: 8.5 MeV

^{157}Gd: 7.9 MeV

The Outer Detector during WS2022

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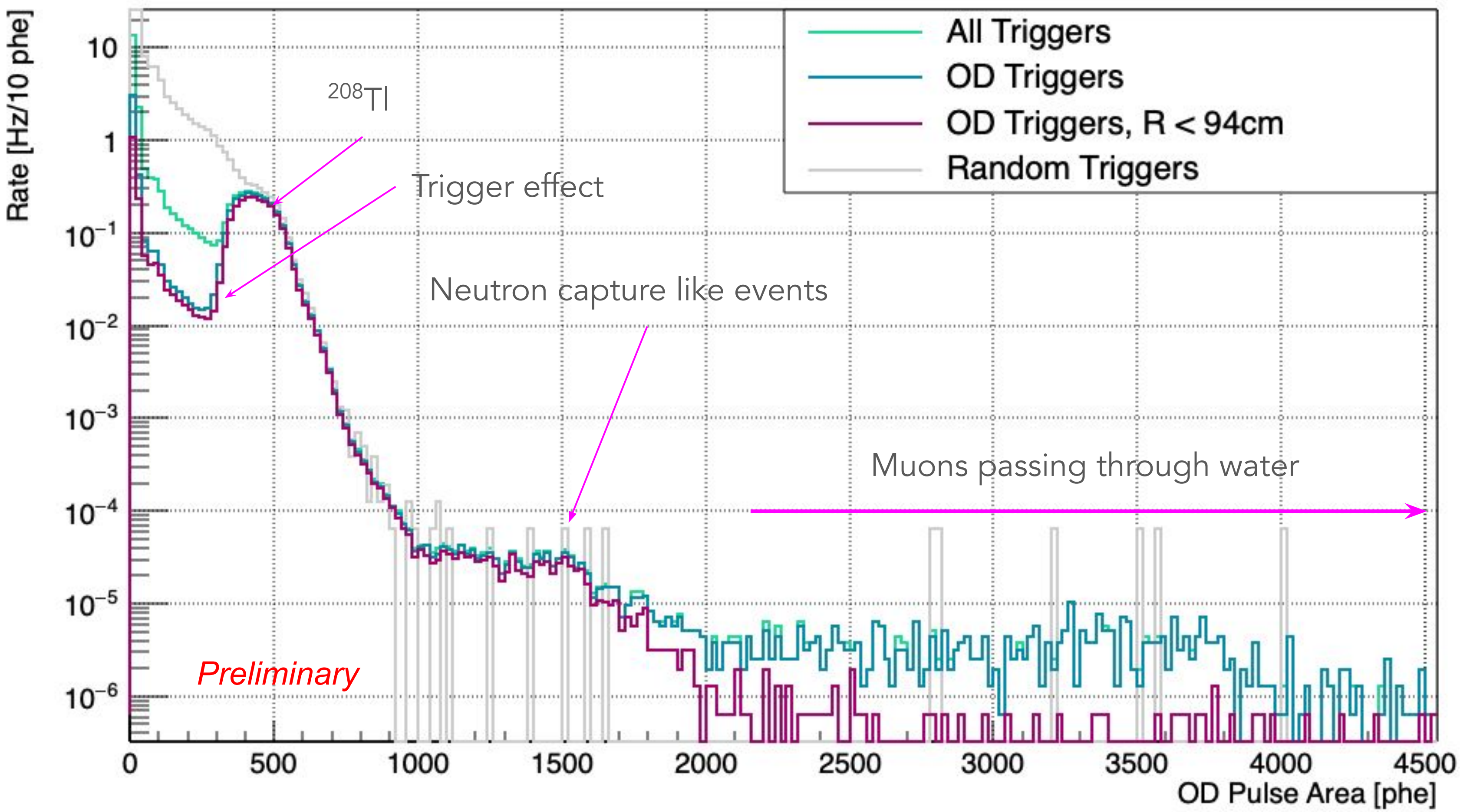

Outer Detector Energy Resolution

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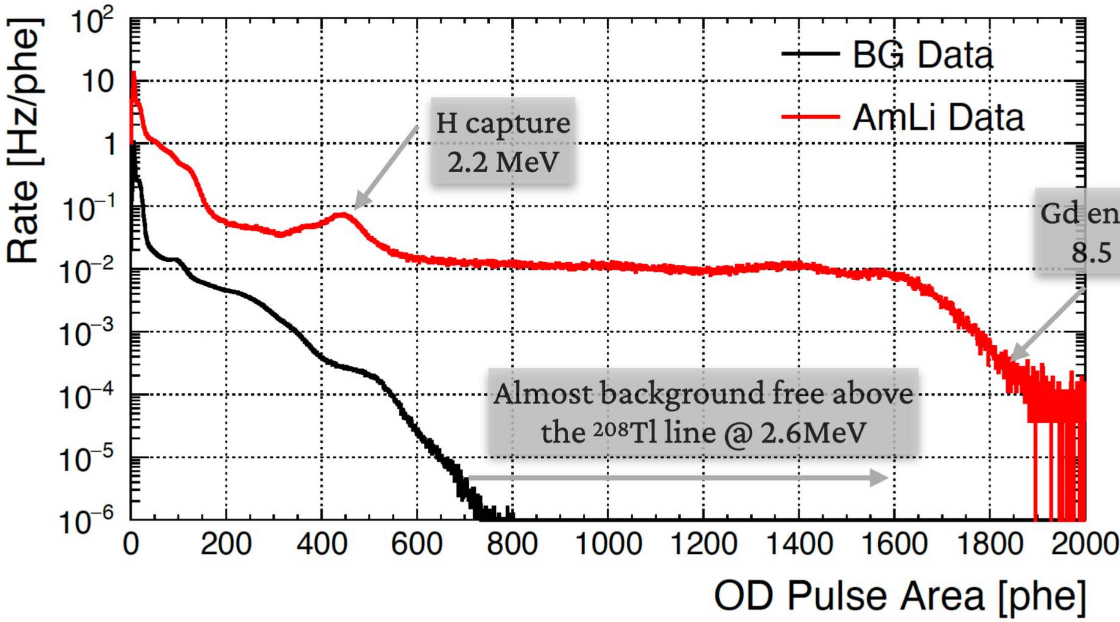
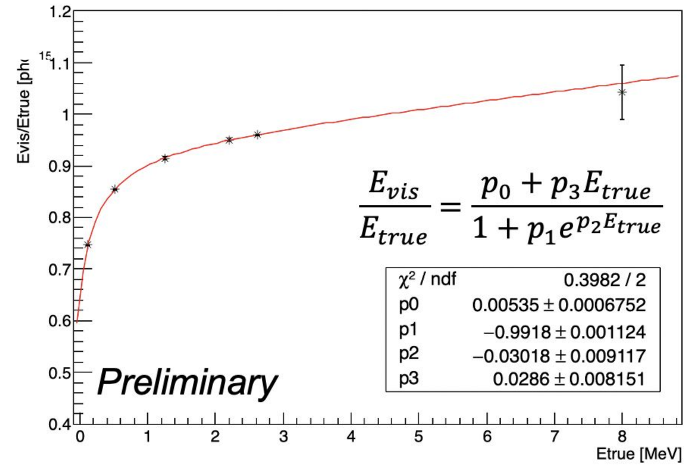


Experiment	phe/MeV
RENO	150
Borexino	438
Daya Bay	162
Kamland	200
SNO+	300
LZ OD	230

GdLS response measured with ^{208}Tl, ^{22}Na, ^{57}Co, H/Gd-captures



$$\frac{E_{vis}}{E_{true}} = \frac{p_0 + p_3 E_{true}}{1 + p_1 e^{p_2 E_{true}}}$$

E_{true} is the true energy deposited in the GdLS
E_{vis} is the visible energy accounting for nonlinear GdLS response

- Identifiable H-capture peak and Gd endpoint observed in calibration data.
- Comparable energy resolution to previous LS-based experiments.