The Outer Detector of LUX-ZEPLIN

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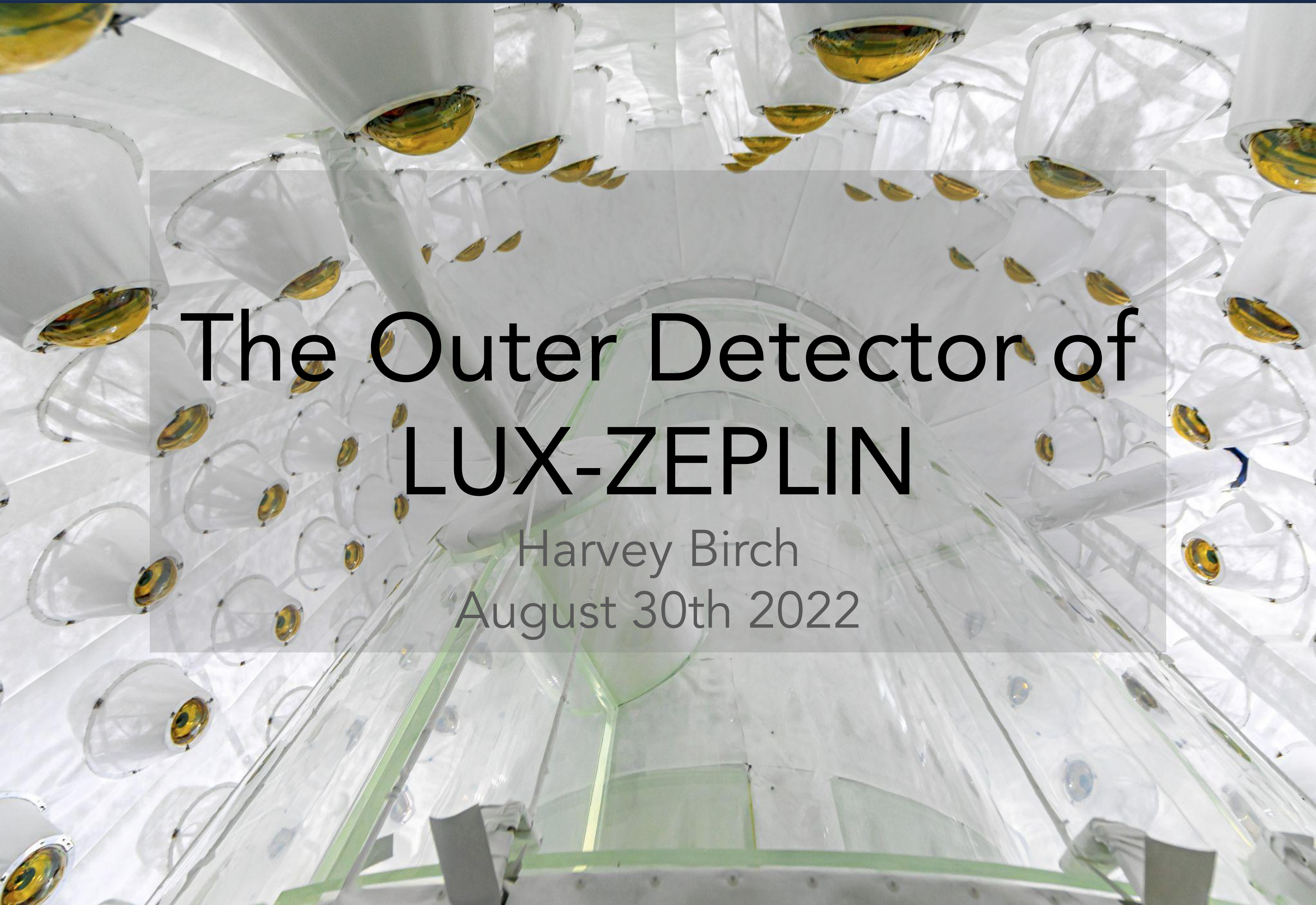
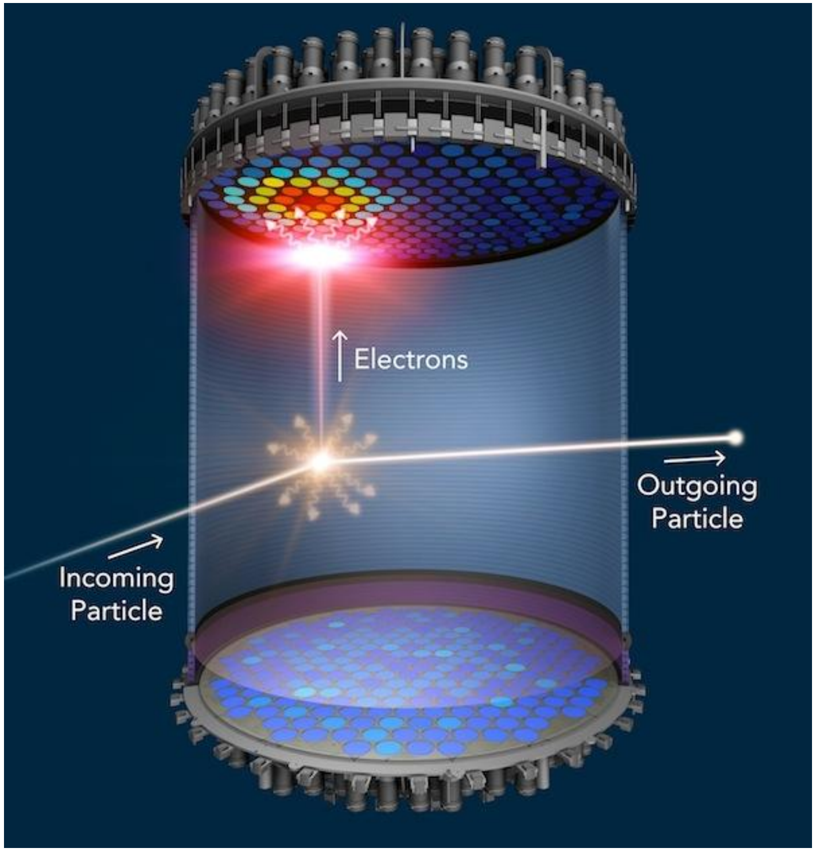
August 30th 2022

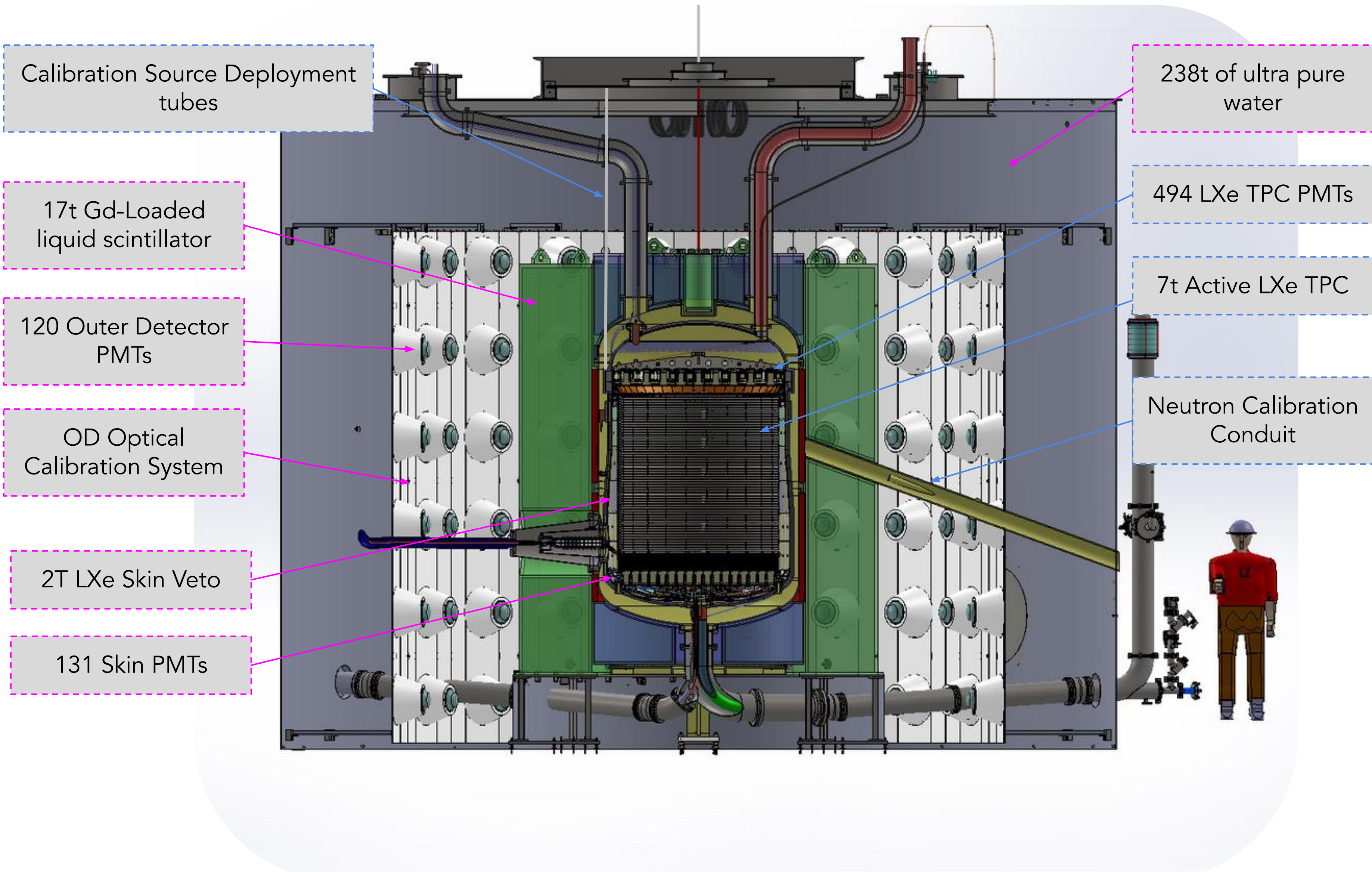


Motivation for having an Outer Detector

- 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 by up to 70%.
  - Demonstrate possible dark matter signal was not induced by a background.

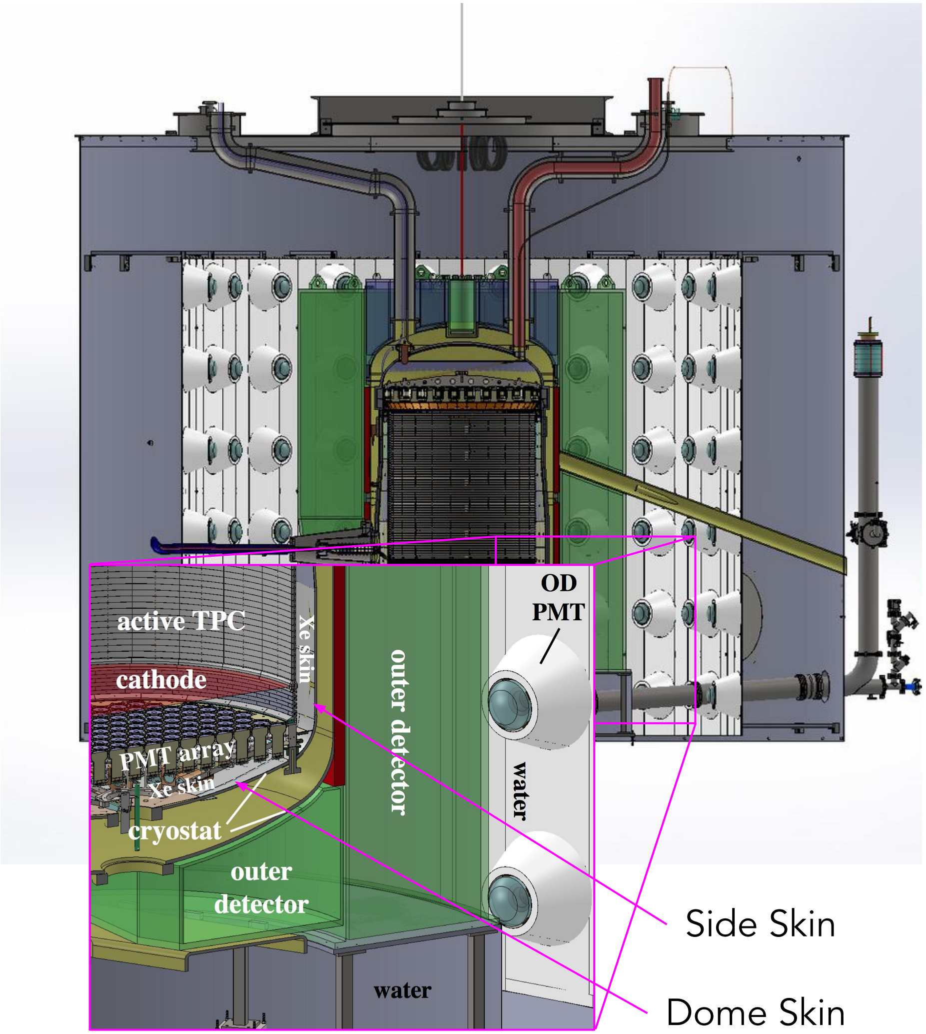


Overview of LUX-ZEPLIN



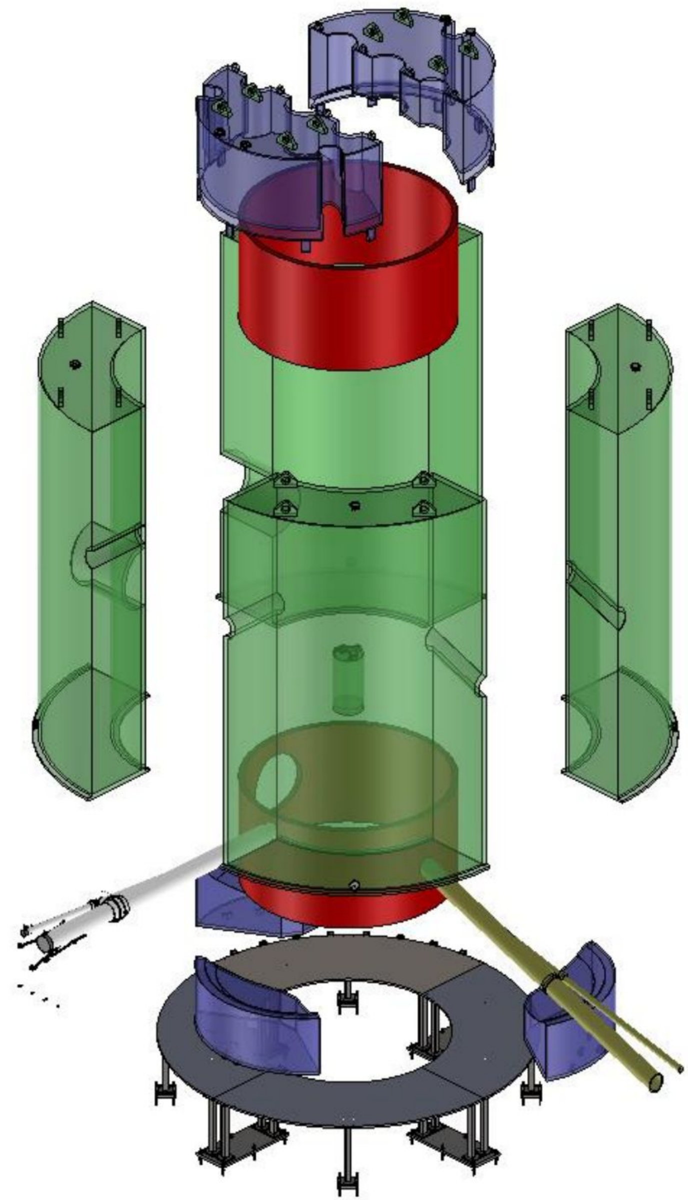
The Skin

- Due to design constraints such as the TPC HV feedthrough, space is needed between the TPC and cryostat.
- This region contains 2t of LXe and is instrumented with 131 PMTs.
- The purpose of the Skin region is to veto Compton recoils from ~MeV radiogenic γ-rays .
- The Skin is complementary to the Outer Detector since low energy γ-rays don't penetrate the titanium cryostat.
- Having both the Skin and Outer Detector creates a highly effective veto system for the TPC.

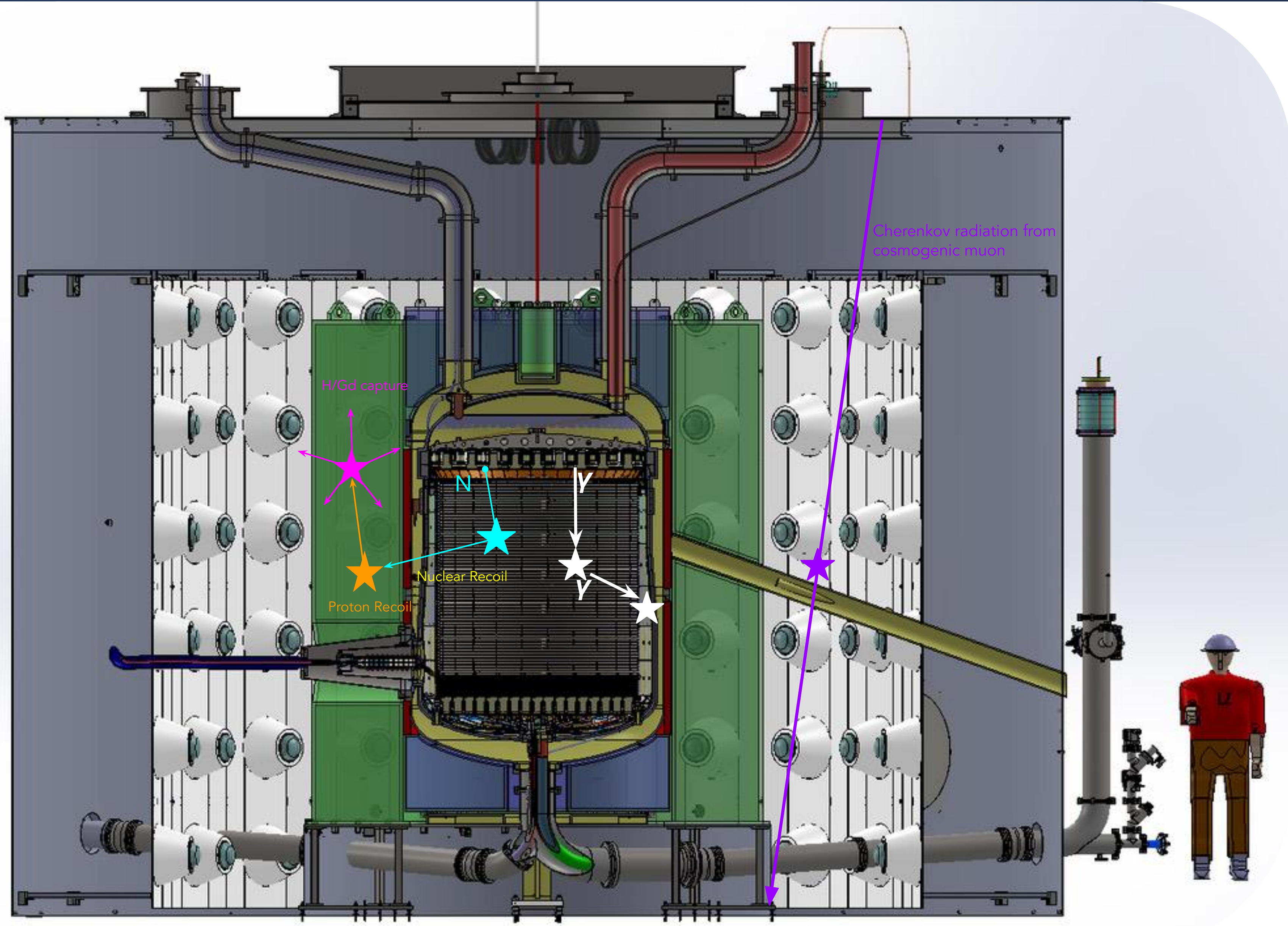


The Outer Detector

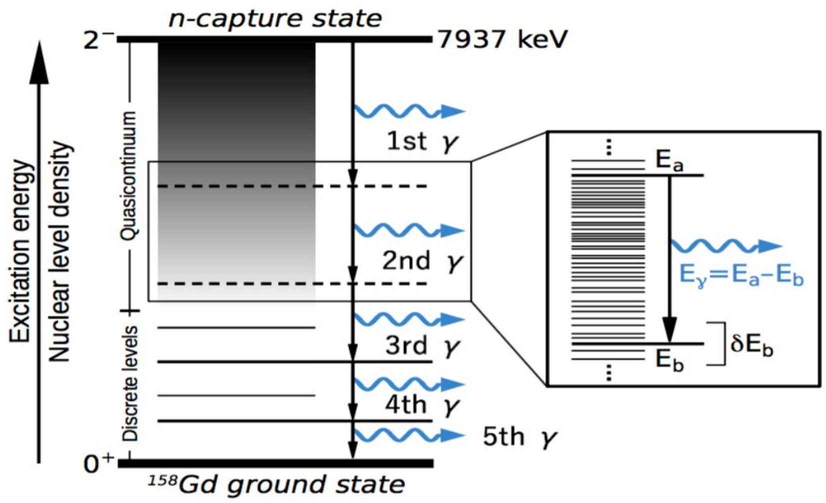
- The Outer Detector is a near-hermetic system that surrounds the cryostat vessel which houses the TPC.
- 10 UV transparent acrylic vessels filled with 17t of Gadolinium loaded liquid scintillator (Gd-LS). NIM A 937 (2019)
  - 0.1% Gd by mass.
- Viewed by 120 8″ Hamamatsu PMTs.
- Dedicated optical calibration 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.

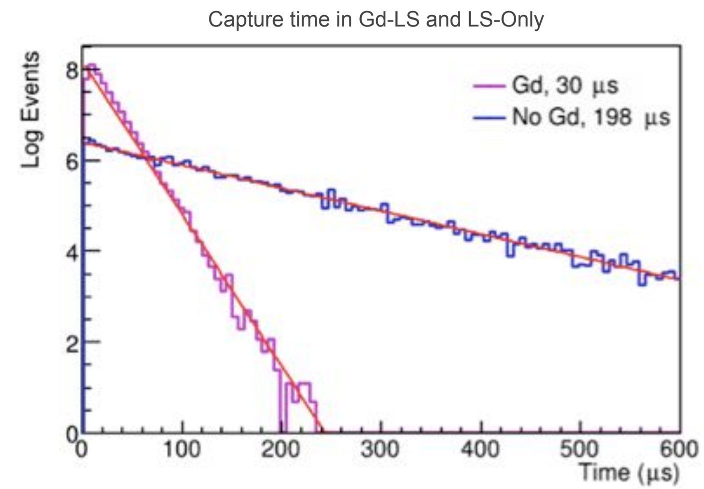


Principle of the Outer Detector



- Gadolinium has the largest thermal neutron cross sections of all stable elements: σ_N = 240kb (σ_N = 0.2kb for Xe).
- Doping with Gd also reduces the mean capture time.
- Neutron capture on Gd is followed by an emission 4-5 γ-rays emitting a total energy of ~8MeV.
    - n + ^{155}Gd → ^{156}Gd + 8.5 MeV (18%)
    - n + ^{157}Gd → ^{158}Gd + 7.9 MeV (82%)
- Whereas neutron capture of H produces only a 2.2MeV γ-ray.
- Having multiple γ's increases probability of detecting the interaction.





Outer Detector Installation

Side acrylic tank being lowered into the water tank

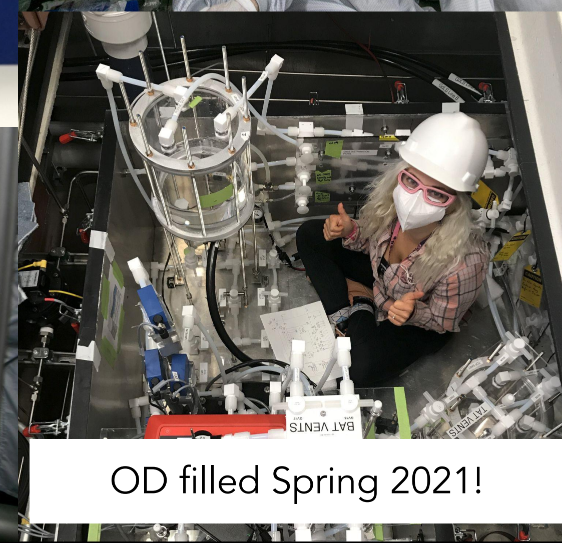
Gd-LS being moved UG for the filling of the tanks

Acrylic tanks in place

OCS Electronics Installation

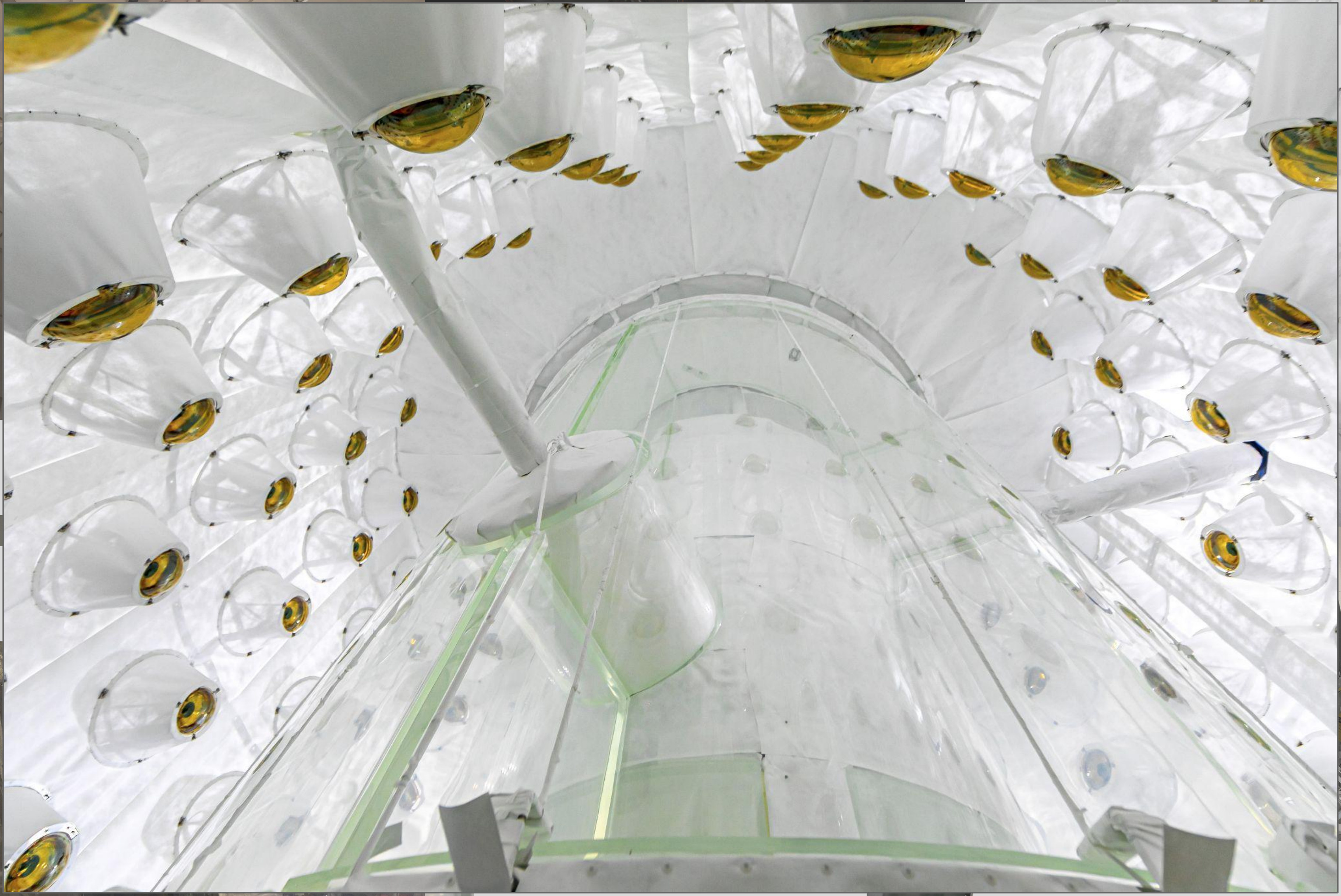
OD PMT Installation

OD PMT Installation Team



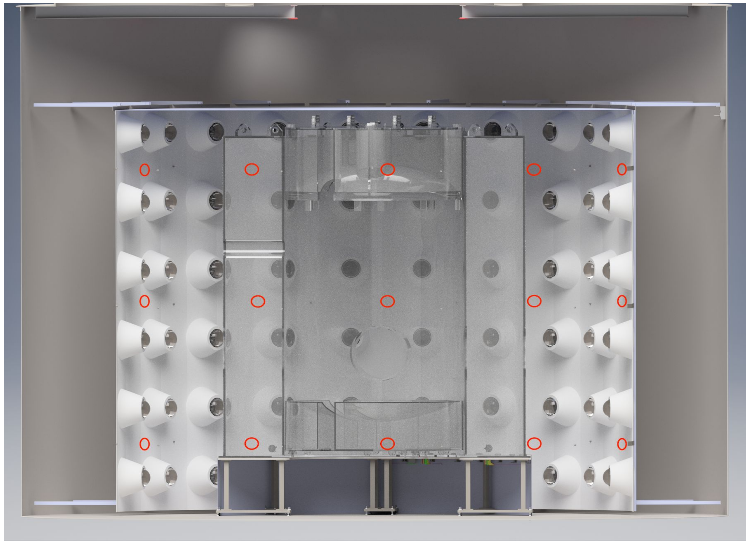
OD filled Spring 2021!

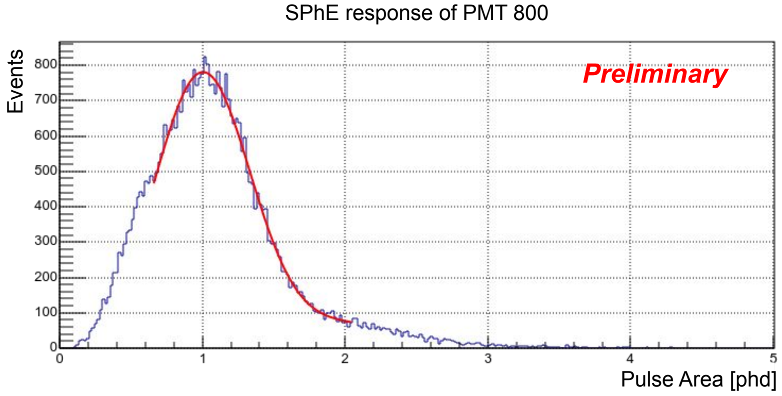
Outer Detector Installation

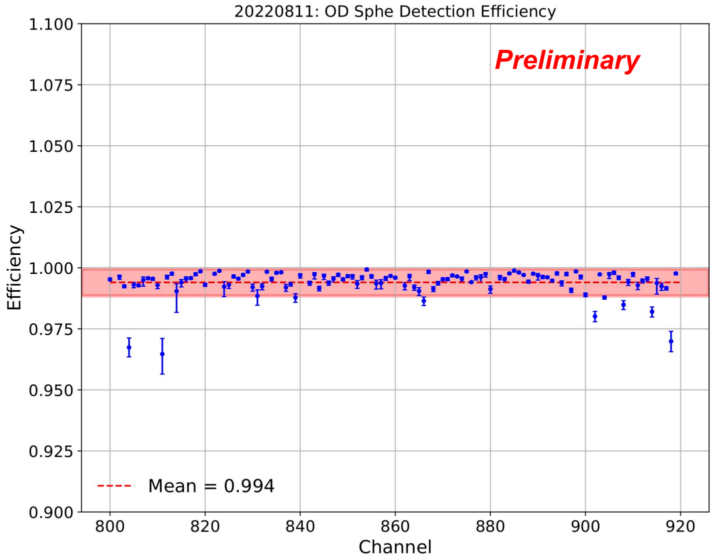


Outer Detector Calibration: OCS

- 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%!
  [NIM A 1010 (2021)]

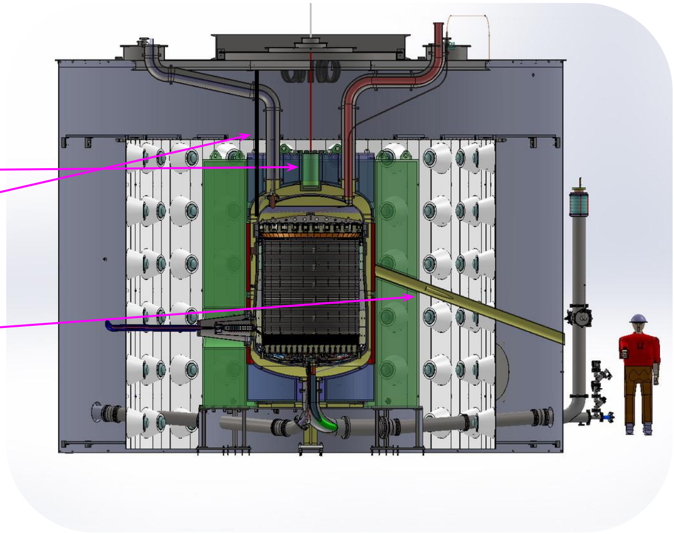


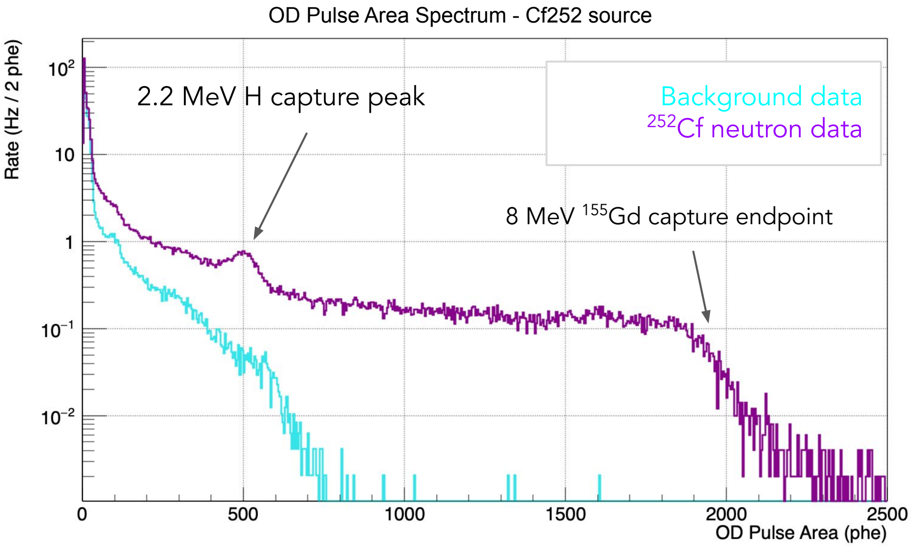




Outer Detector Calibration: Source deployment

- LZ utilizes three different types of controlled source deployment systems.
  - Photoneutron sources: YBe
  - Three external CSD tubes - Neutrons and gammas (AmLi, ^{252}Cf, ^{22}Na and ^{228}Th).
  - 2 neutron conduits: DD neutrons, D_2O reflector.
- 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.





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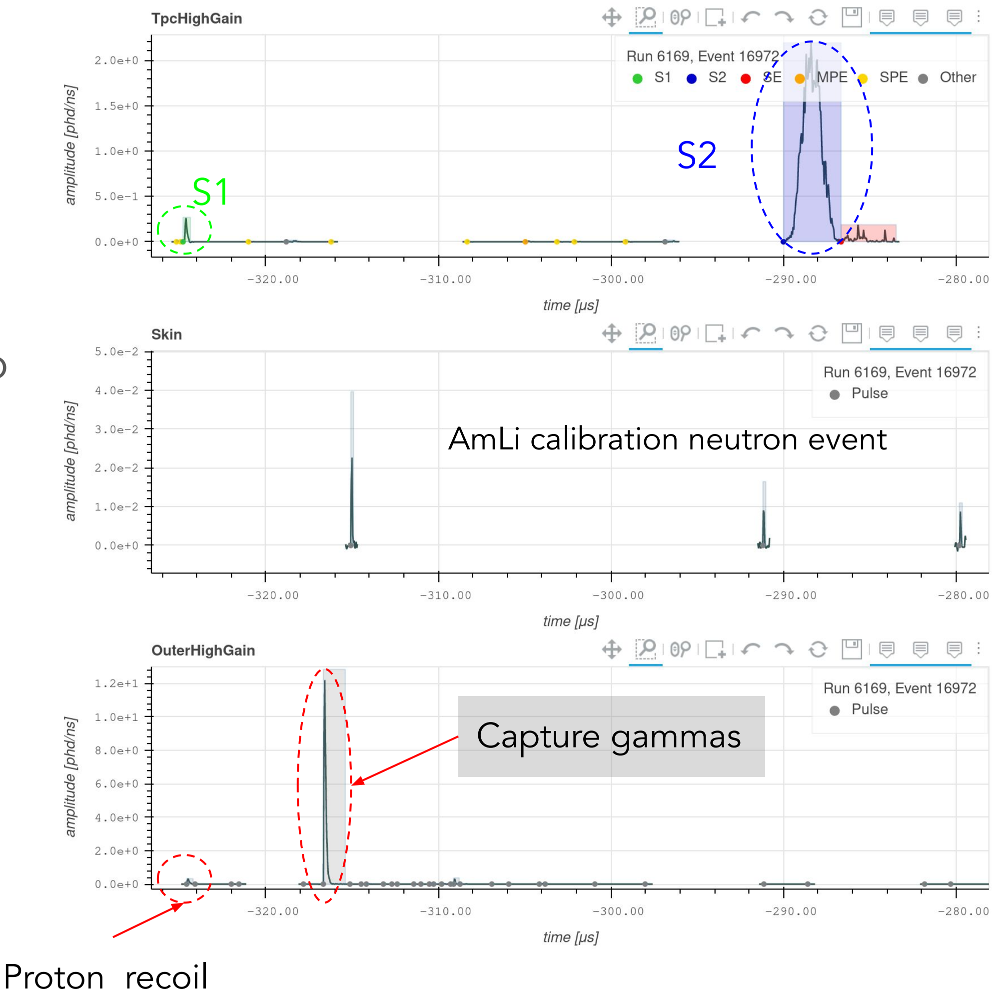
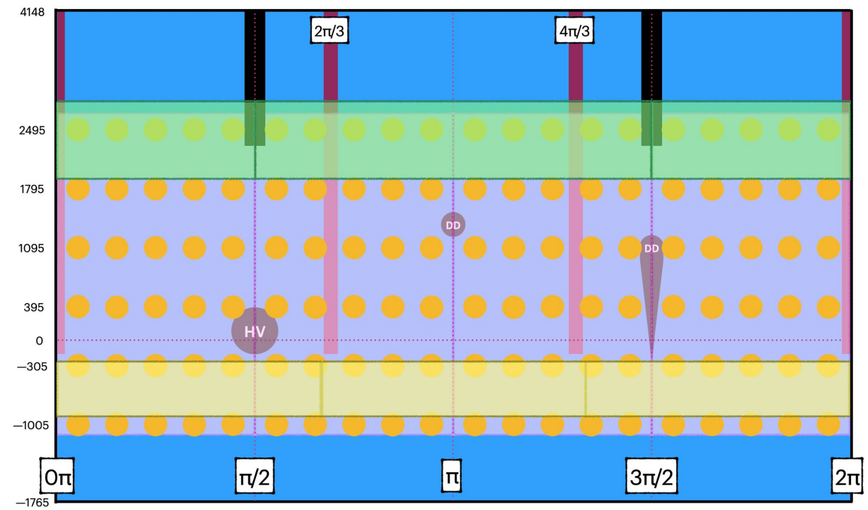
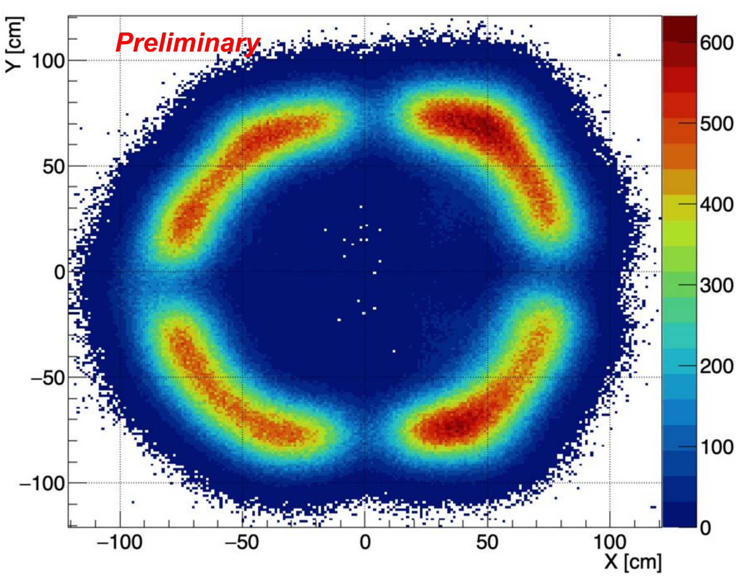
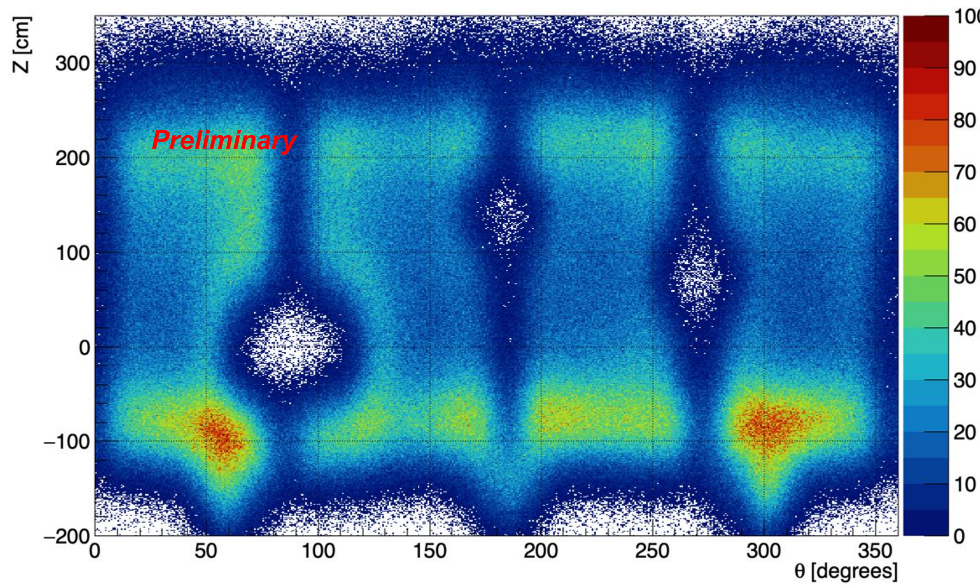


- Individual acrylic tanks and other geometric features can be resolved from the data using centroid position reconstruction.
- Z-position corrections are developed by varying the position of CSD gamm sources.

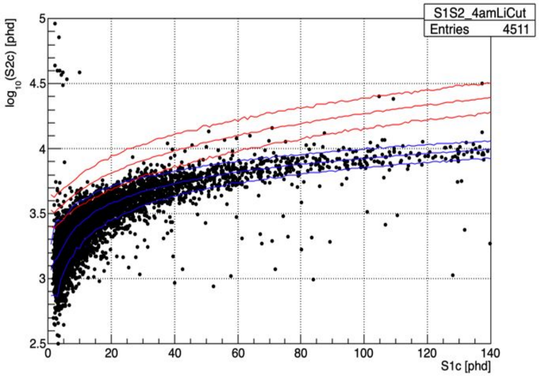




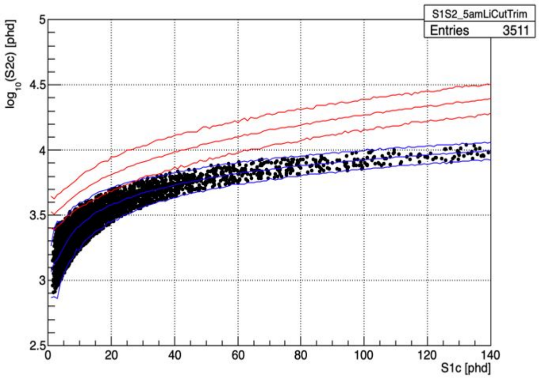


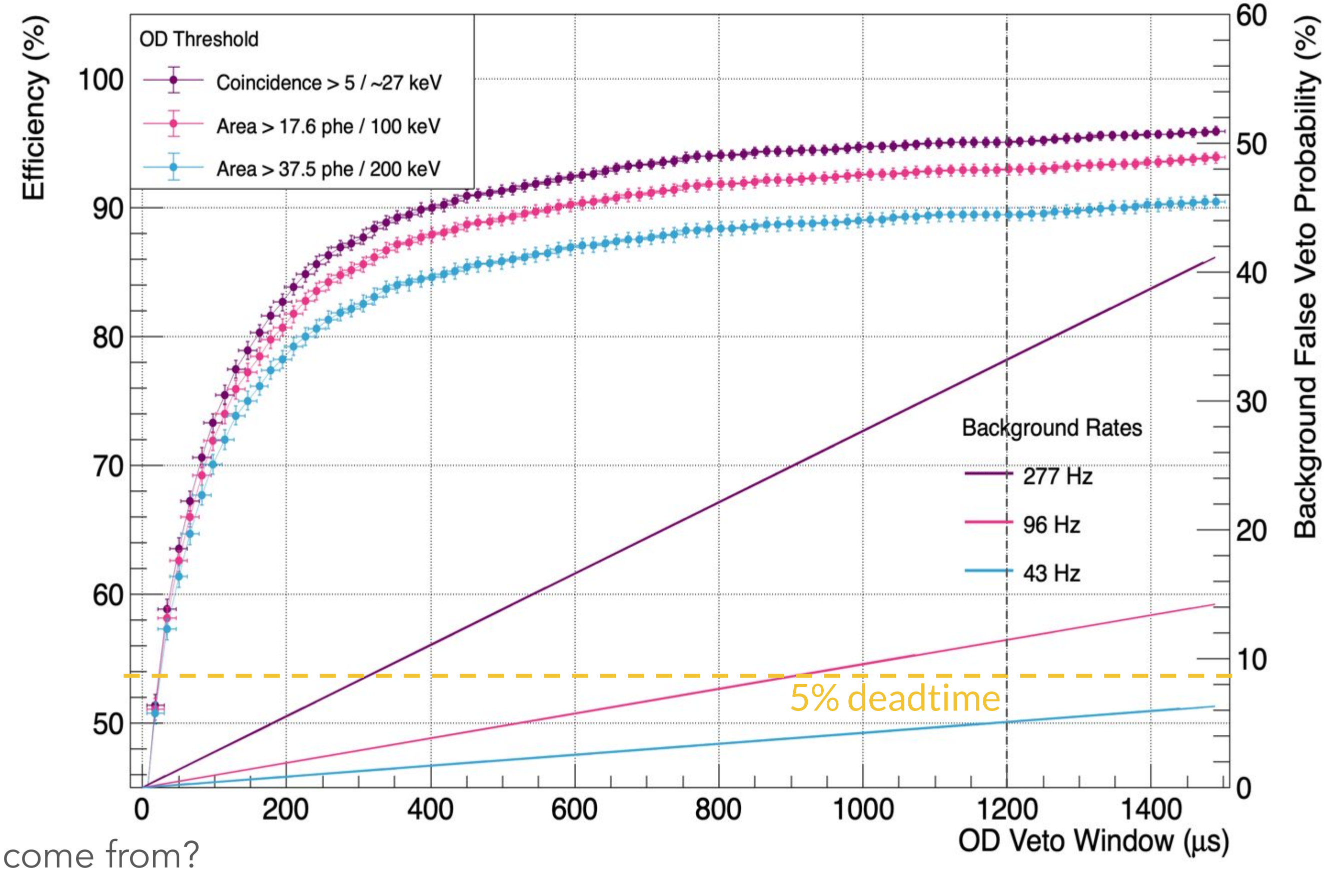
Neutron Tagging Efficiency with sources

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



+/- 1 σ NR band



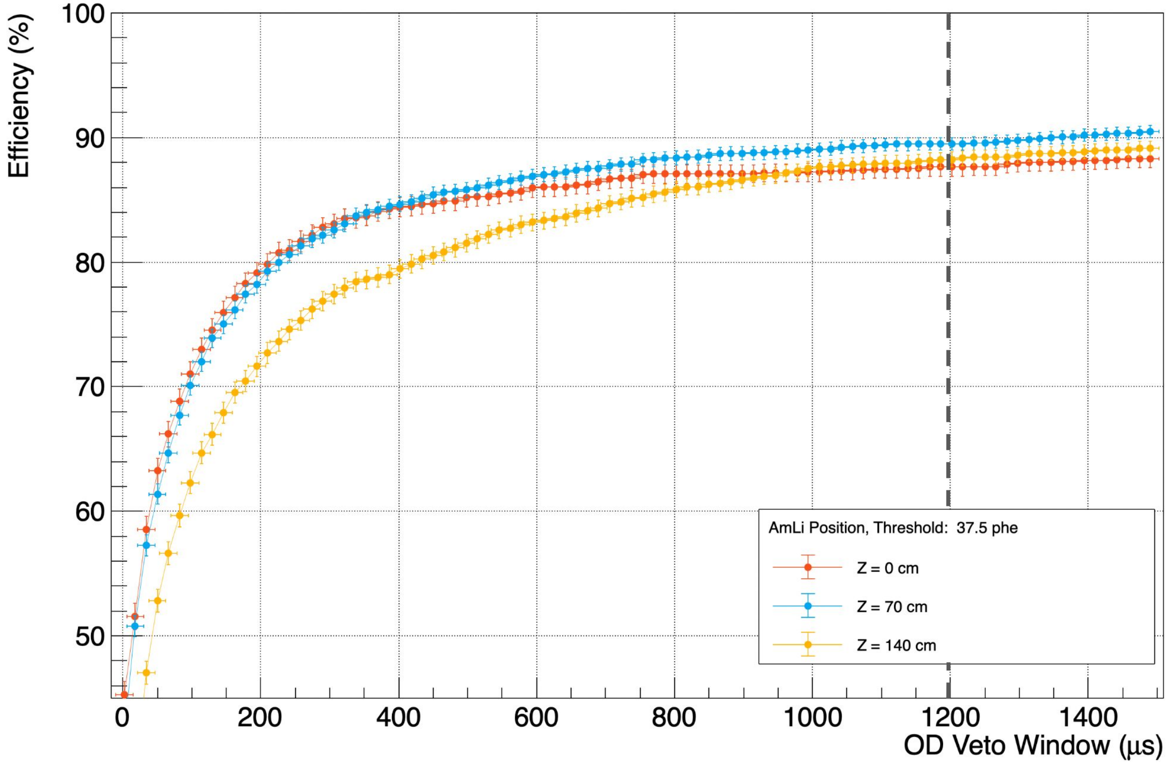


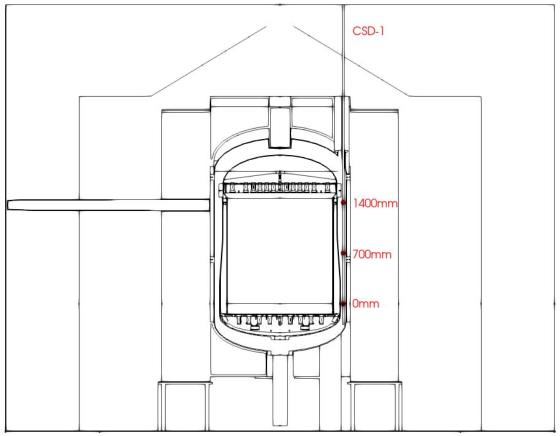
Where does the OD inefficiency come from?

- Neutron capture on H in LS or acrylic
  - Just one 2.2 MeV ray released which can escape without depositing energy.
- Neutrons wander around in the acrylic for too long.
- Energy deposited is below threshold (nominal 200 keV).

Neutron Tagging Efficiency versus position

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





200 keV threshold with a 1200μs window: Average efficiency across all positions: 88.5 ± 0.7%

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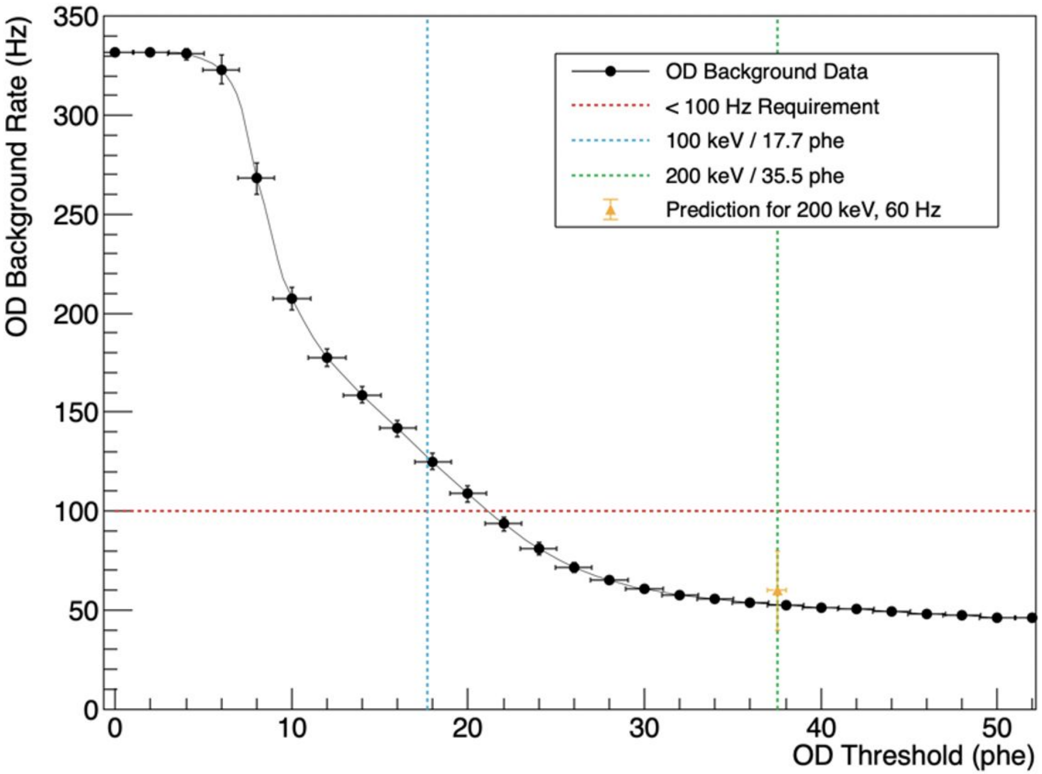
OD Background rate - In situ measurement

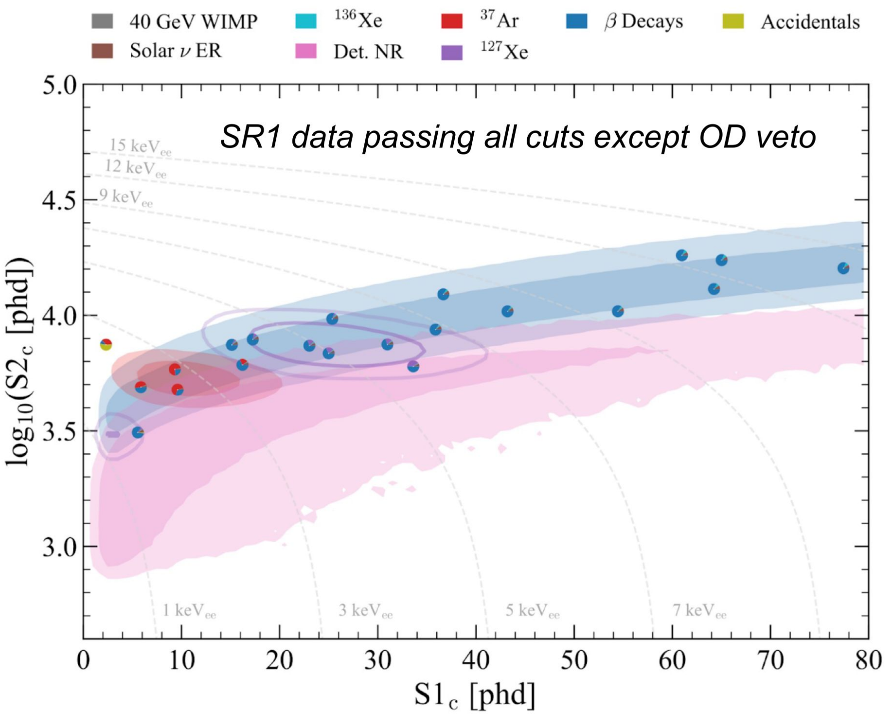
- Simulation predicts 60 Hz background rate above 200 keV threshold.
- Measured background rate is consistent with prediction!

System	Component	OD Rate (Hz)
PMTs	PMTs	0.31
	PMT Bases	0.11
	Skin PMTs	0.11
	Skin PMT Bases	0.01
	PMT Supports	0.16
	PMT Cabling	0.14
	Total	**0.85**
TPC	PTFE	0.00
	Grid Holders & Wires	0.23
	Field Rings	0.03
	Sensors & Thermometers	0.03
	Conduits Cables, Tubing	0.22
	Total	**0.52**
Cryostat	Vessels	1.43
	Seals	0.63
	Insulation	0.45
	Total	**2.51**
Outer Detector	Acrylic Tanks & Support	5.42
	OD PMTs	2.48
	PMT Supports	0.09
	Externals Total	**7.99**
	Internal - LS	**5.88**
Davis Cavern		**42.0**
Grand Total		**60 Hz**



The Outer Detector and the WIMP Search

- Neutron backgrounds, "Det. NR", with OD tag are 7.7 times larger than without (tagging efficiency is 88.5 ± 0.7%).
- By design, 5% 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.
- SR1 data is consistent with simulation estimate of 0.06 events in 60 live-days.
- The Outer Detector is performing well and has helped LZ to reach its first science result and increase sensitivity!



See David Woodward's "LZ results" talk and Dongqing Huang's "LZ Backgrounds" talk for more!

Thank you!

Thank you to our sponsors and participating institutions!

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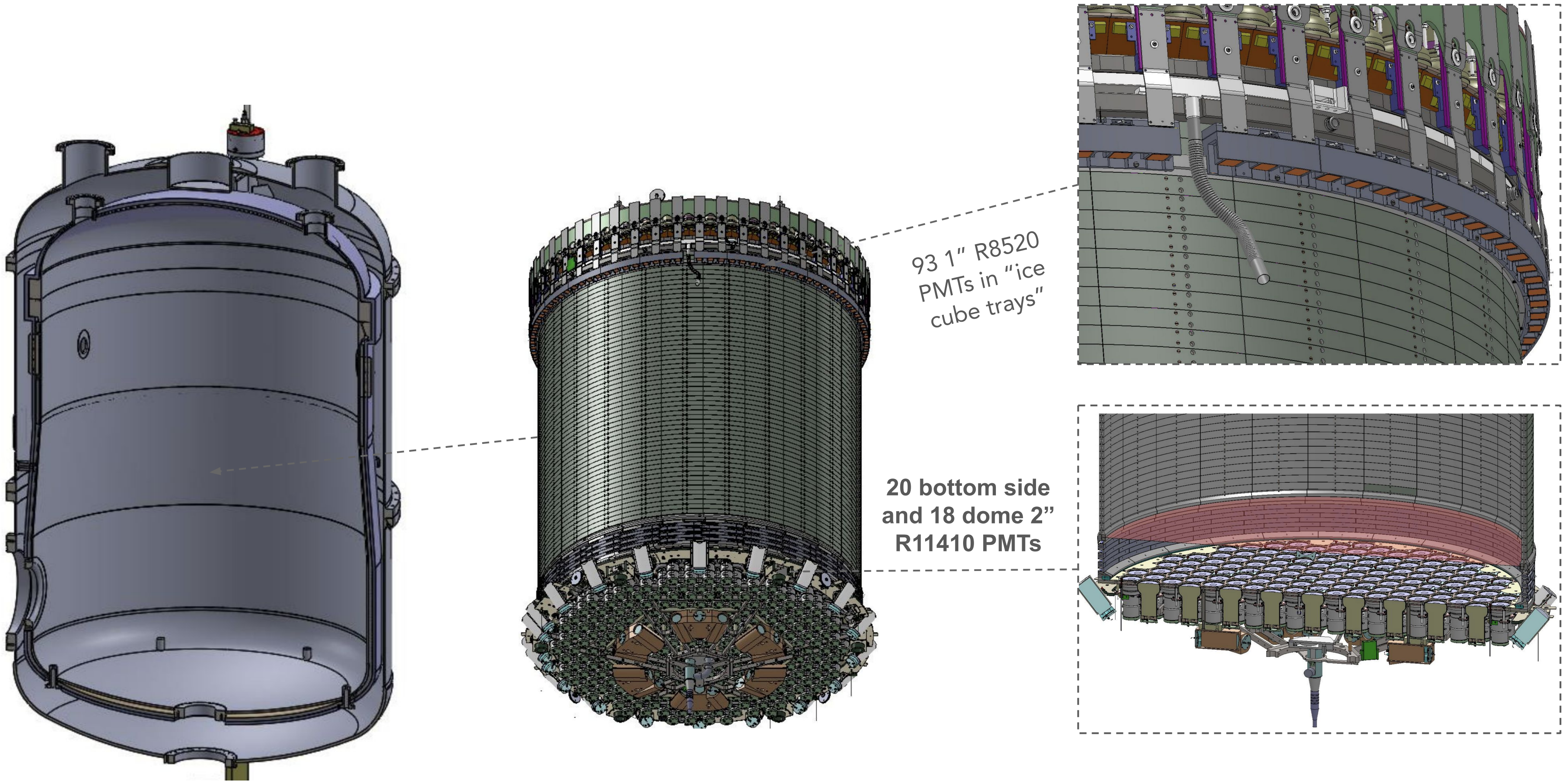
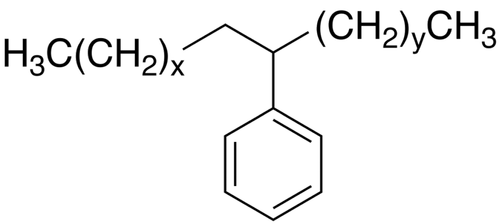
Backup

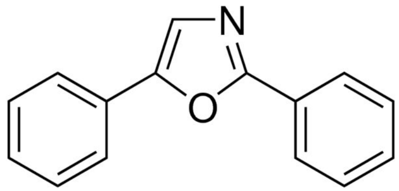
Skin detector geometry



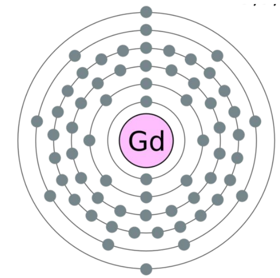
Gadolinium-Loaded Liquid Scintillator (Gd-LS)



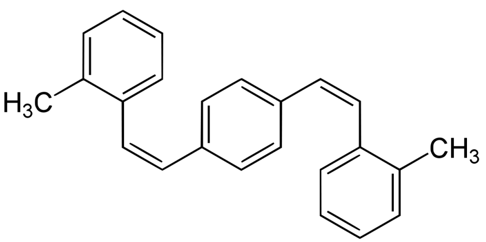
Linear Alkylbenzene (LAB), solvent



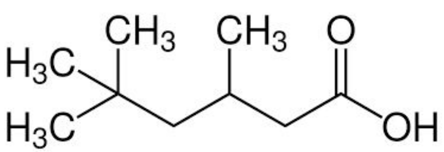
2,5-Diphenyloxazole (PPO), fluor



Gadolinium (Gd), neutron eater



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

The Outer Detector during Science Run 1 (SR1)