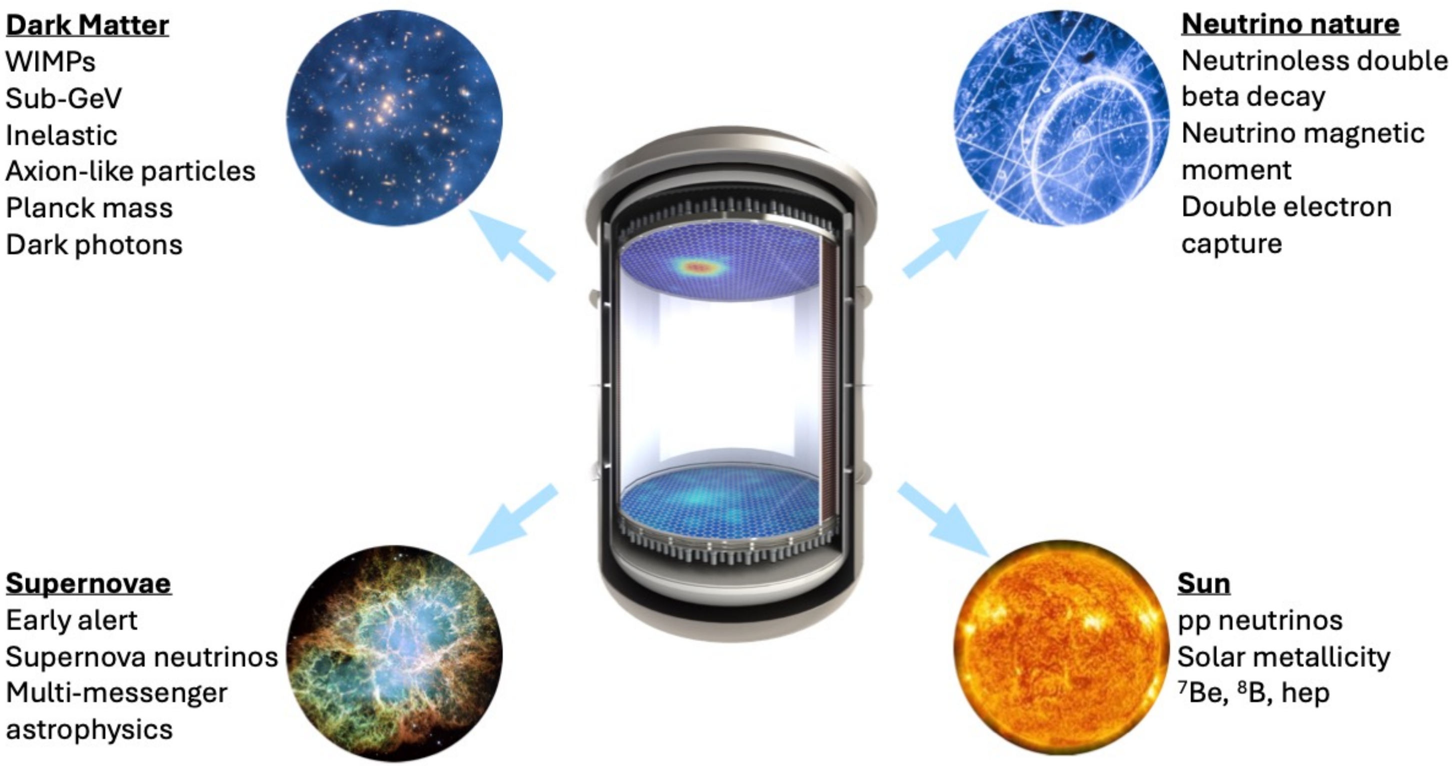
Initial simulations of the XLZD Outer Detector

Sean Hughes, University of Liverpool
s.p.hughes3@liverpool.ac.uk

Wednesday 9th April 2025,
IOP Joint APP and HEPP Annual Conference

Introduction

- For more than a decade, liquid xenon time projection chambers (LXe-TPCs) have led the way in the search for **Weakly-Interacting Massive Particle (WIMP)** (>few GeV/c^2) dark matter
- **XLZD** collaboration established
- Formed from XENONnT, LUX-ZEPLIN and DARWIN
- Projected **60-80 tonne** (active) liquid xenon (LXe) target mass



XLZD White Paper & Design book

The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

J. Aalbers[1], K. Abe[2], M. Adrover[3], S. Ahmed Maouloud[4], D. S. Akerib[5,6], A. K. Al Musalhi[7], F. Alder[7],

A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

J. Aalbers,[1,2] K. Abe,[3,4] V. Aerne,[5] F. Agostini,[6] S. Ahmed Maouloud,[7] D.S. Akerib,[1,2] D.Yu. Akimov,[8] J. Akshat,[9] A.K. Al Musalhi,[10] F. Alder,[11] S.K. Alsum,[12] L. Althueser,[13] C.S. Amarasinghe,[14] F.D. Amaro,[15] A. Ames,[1,2]

Alberto Usón

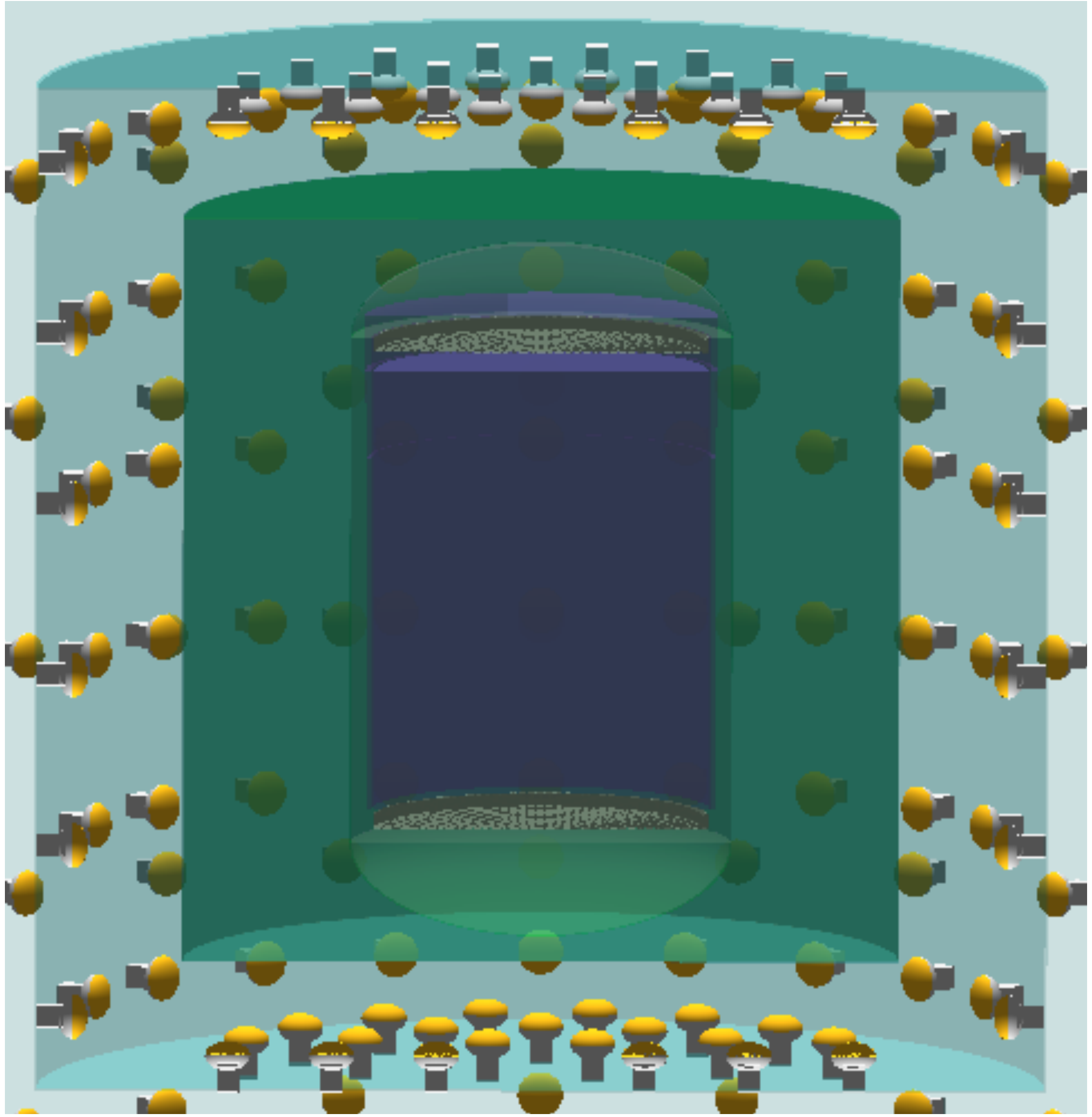
XLZD: the Next-Generation Liquid Xenon Rare-Event Observatory

Robert Renz
Marcelo Gregorio

XLZD@Boulby: The Most Environmentally Sustainable Large-Scale Physics Experiment

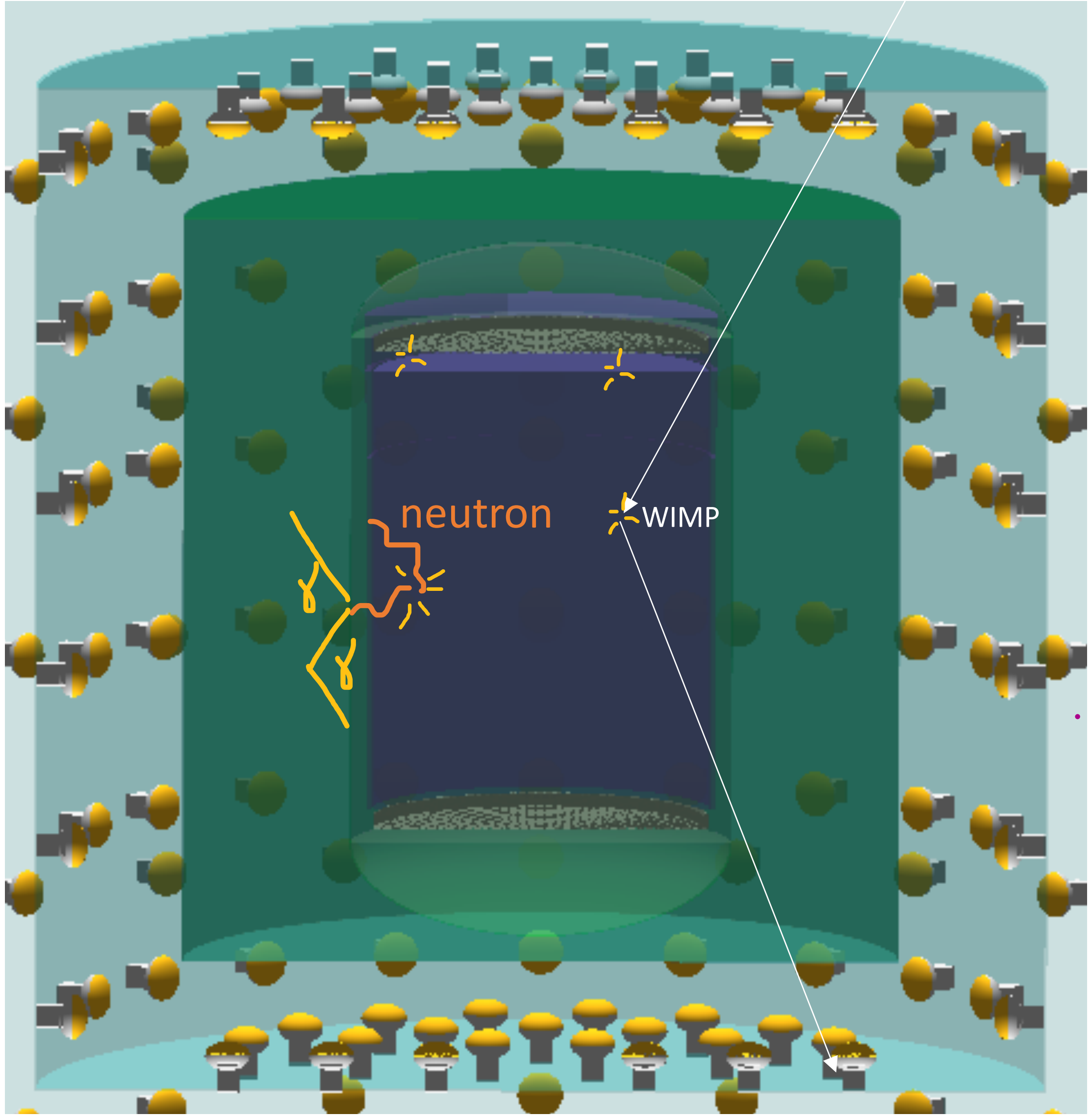
Background challenges of XLZD

- XLZD will be a **low-background observatory**, with a background dominated by neutrino interactions
- Methods and techniques will be employed to reduce all other backgrounds
- **Intrinsic backgrounds** (^{85}Kr, ^{222}Rn) can be controlled via xenon purification and screening techniques
- **Cosmogenic backgrounds** are reduced via a rock overburden
- **Neutron backgrounds** are mitigated through optimal selection of detector material, multiple scatters, and **vetoes**
    - The operation and design of XLZD's **neutron tagging capability** will be shown here



Background challenges of XLZD

- **Neutrons** originating from detector materials scatter elastically off nuclei, producing nuclear recoils in the LXe-TPC – which appear **WIMP-like** (scattering once in the TPC)
  - A world leading sensitivity to WIMP dark matter enforces stringent limits on the neutron background
- Unlike WIMPs - neutrons continue in the detector, scattering multiple times until they are captured by key materials, including:
  - **Hydrogen-capture**: 2.2 MeV gamma
  - **Gadolinium-capture**: 8 MeV gamma cascade
- The signals from gammas can be detected via an instrumented Gd-doped **Outer Detector**, and **Skin detector**

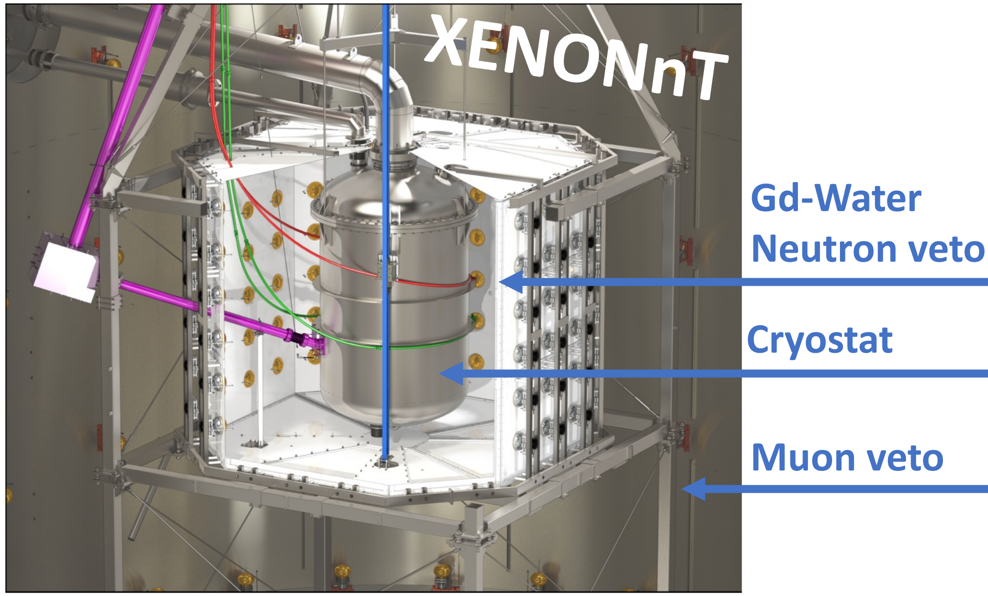


The XLZD Detector

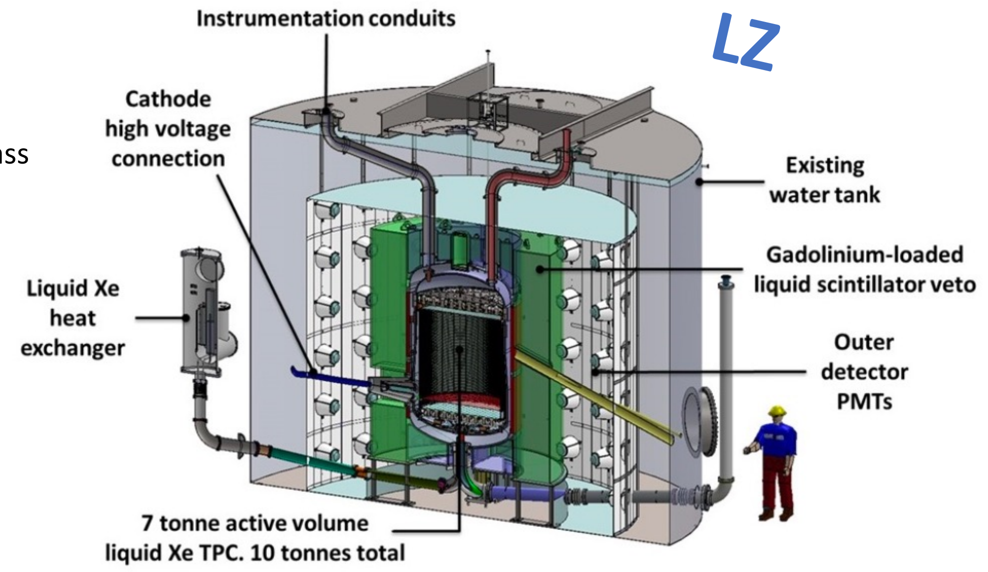
- Surrounding the LXe-TPC will be an instrumented thin layer of LXe known as the **Skin Detector**
- The cryostat will be all encompassed by a dedicated **neutron** and **muon** detector: The >1kt **Outer Detector (OD)**
- Current experiments vary in OD medium:
  - **XENONnT:** Gd-doped water **(Gd-Water)**
    - **LY:** 10 ph/MeV E. Aprile et al JCAP11(2020)031 XENONnT n-Veto paper
    - **Neutron tagging efficiency:** ~87% with 0.2% Gd
  - **LZ:** Gd-doped liquid scintillator **(Gd-LS)**
    - **LY:** 9000 ph/MeV arXiv:2410.17036
    - **Neutron tagging efficiency**: ~89% with 0.1% Gd
- Possible third option: **Gd-doped water based liquid scintillator (Gd-WbLS)**
- (Inc: Brookhaven, Eos, BUTTON)
  - Water with 1-10% LS component added through surfactant
  - LY varies depending on scintillator concentration: 100 – 1200 ph/MeV
- **What medium should XLZD use and how should the OD be instrumented?**

3 m x 3 (4) m

60-(80t) LXe active mass



Adam Tarrant
BUTTON and Beyond: Integrating Novel Technologies in RATPAC for Precision Neutrino Detection
BUTTON and Beyond: Integrating Novel Technologies in RATPAC for Precision Neutrino Detection
James Gooding
BUTTON WbLS Detector development at Boulby underground Lab

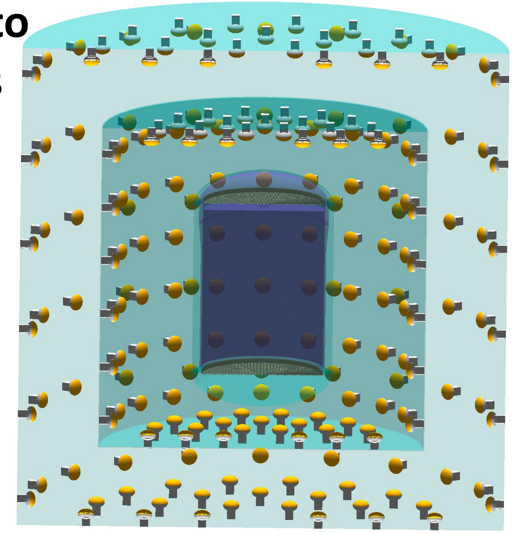


Simulation of the Outer Detector

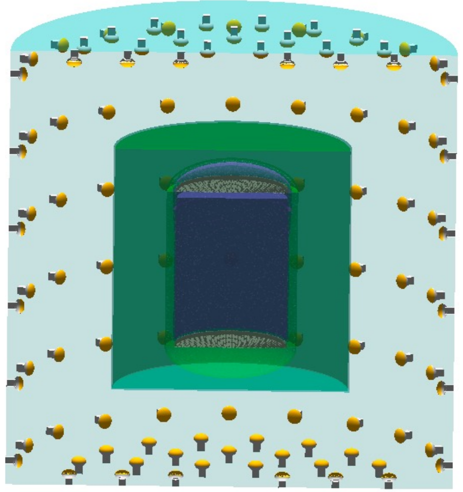
- An XLZD simulation was developed based on Geant4:
  - ‘XLZD Sandbox’
- The simulation is flexible, geometry modified via .json file
- **XENONnT**-Style, **LZ**-Style outer detectors can be examined. As well as:
  - Number/location of PMTs
  - Gd concentration,
  - Various media: Gd-Water, Gd-WbLS, Gd-LS
  - Sizes of various vessels
- Using this, we can optimise the outer detector and compare the performance of various media
- Able to examine **light collection** and **neutron tagging efficiency**

No neutron veto
192 PMTs

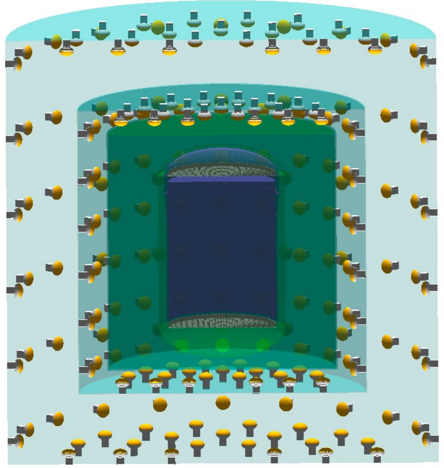
Neutron veto and
Muon veto
192 PMTs



Muon veto with container
192 PMTs

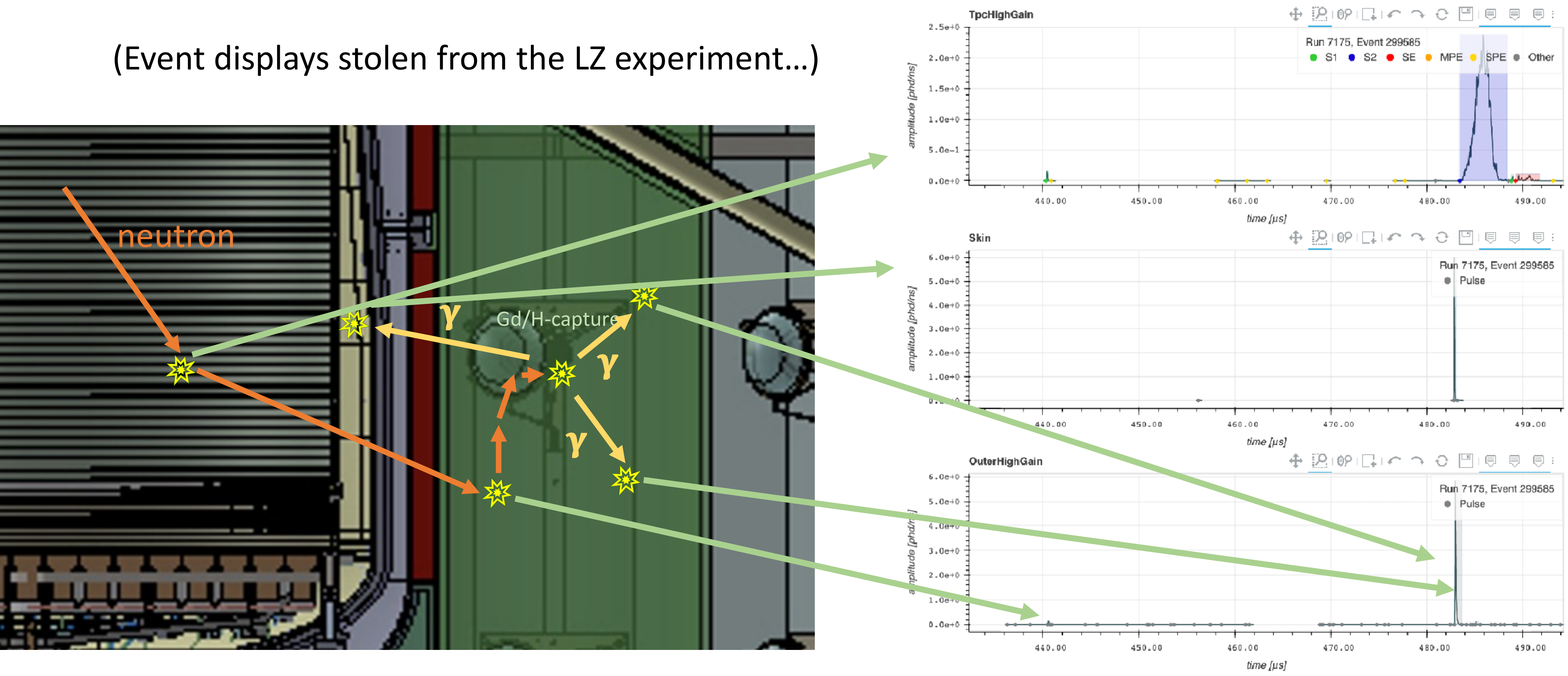


Neutron veto with
containment
vessel and
Muon veto
192 PMTs



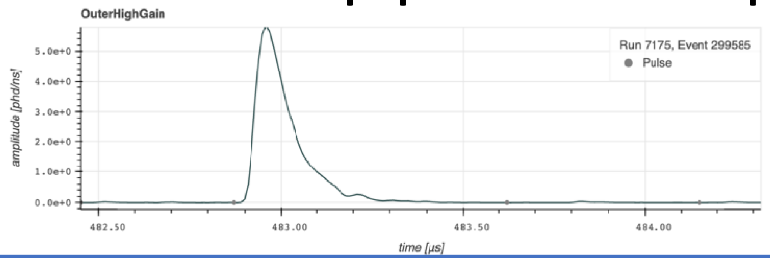
Neutron Tagging Efficiency

(Event displays stolen from the LZ experiment…)

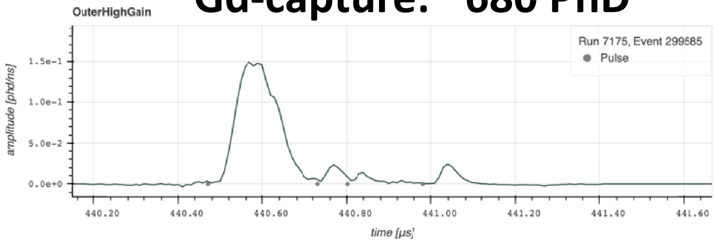


~30 keV$_{nr}$ nuclear recoil Single scatter in TPC Tagged by the OD

Prompt proton recoil ~17 phe



Gd-capture: ~680 PhD



Neutron Tagging Efficiency

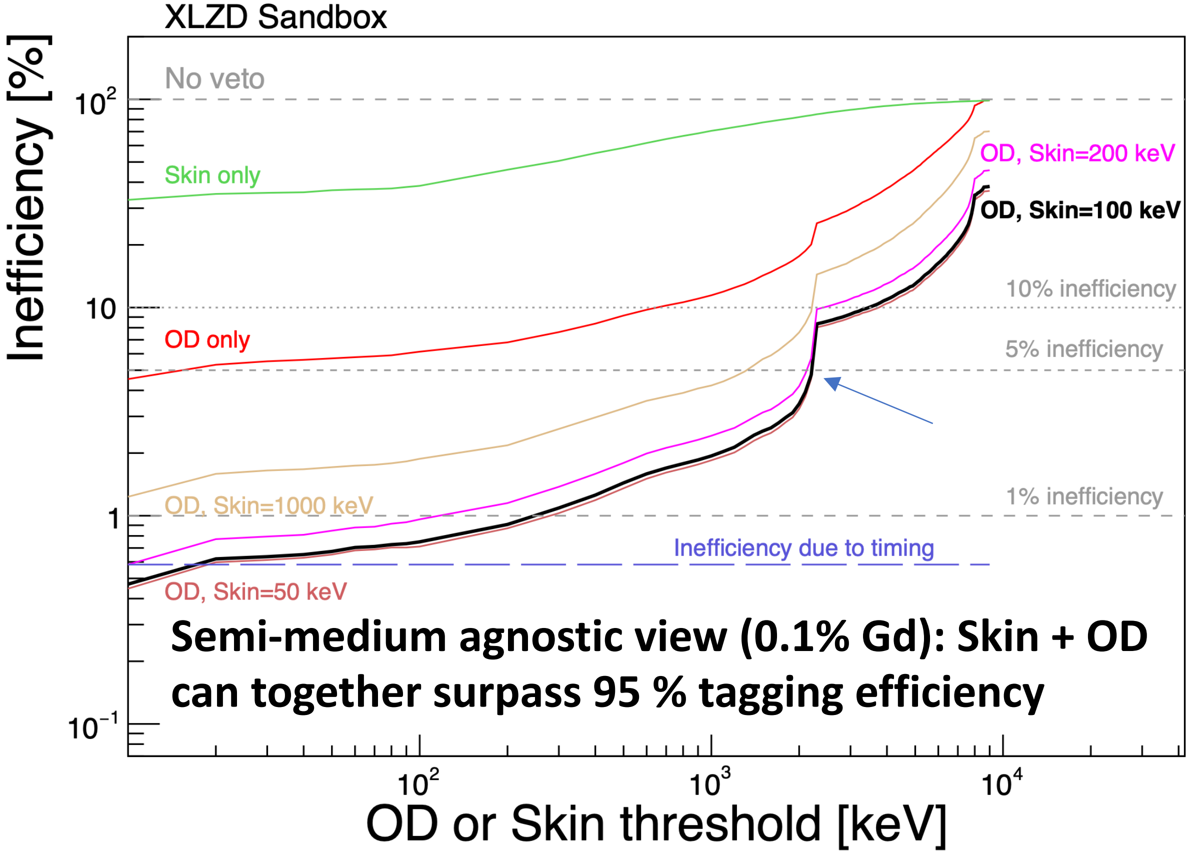
- Neutrons scatter elsewhere in the detector after depositing energy in the TPC
- These hits are combined assuming LZ spatial (Radial, Z) and timing (t) resolutions:
  - R = 30 mm
  - z = 2 mm
  - t = 100 ns
- For the analysis, the neutron clusters are considered that:
  - Are within a **Fiducial Volume (FV),**
  - **Scatter once within the TPC (SS),**
  - Deposit energy in the TPC within the WIMP **Region of Interest (ROI)**

$$\epsilon = N_{Cluster}^{ROI+SS+FV+(OD_{pass}\,||\,Skin\_pass)+\Delta T\_pass} \Big/ N_{Cluster}^{ROI+SS+FV}$$

- Neutron Tagging Efficiency '**ε**' is defined in the equation above
- Neutron clusters that pass FV, SS and ROI cuts make the denominator
- The numerator consists of neutron clusters that, whilst passing FV, SS and ROI cuts, also deposit enough energy to pass the OD threshold **or** Skin threshold (ODpass/Skinpass)
- Whilst time between neutron capture and energy deposition time is within the OD time window (ΔTpass)

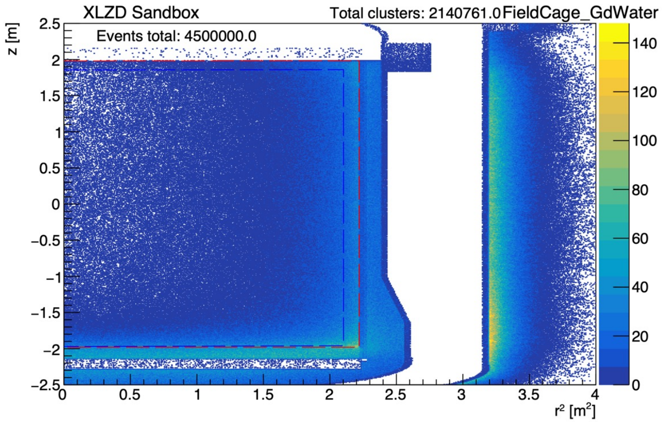
Neutron Tagging Efficiency

ROI : (6 to 30 keVnr) [keV]
+SS : Check no other neutron cluster is within 600µs time coincidence
+FV : 12 cm from top, 4 cm radially, and 1 cm from cathode

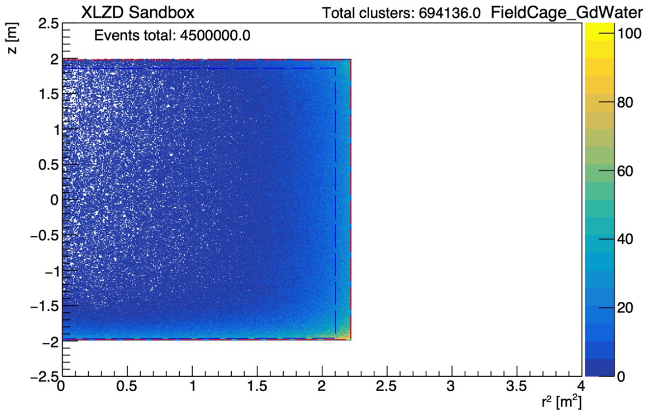


Semi-medium agnostic view (0.1% Gd): Skin + OD can together surpass 95 % tagging efficiency

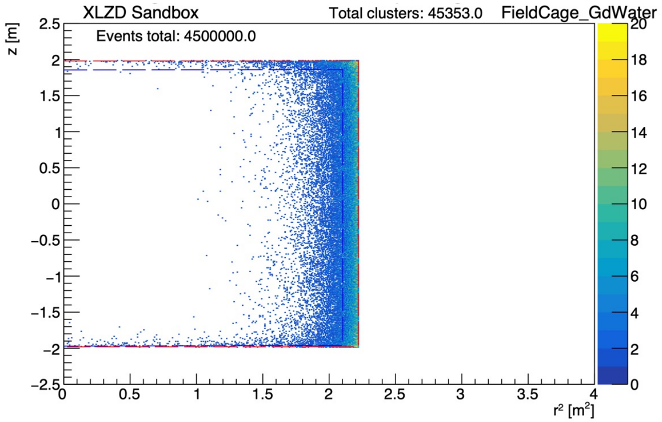
No cuts



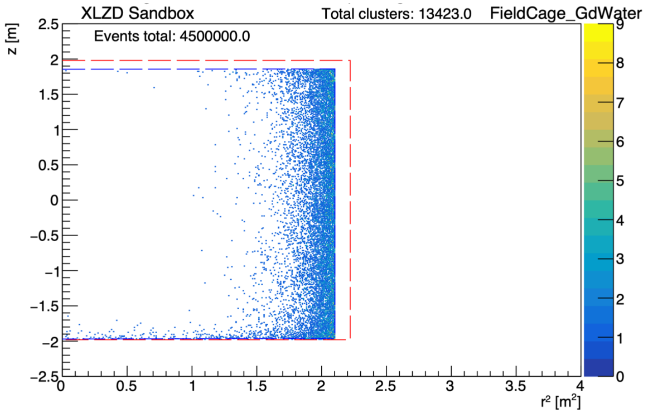
ROI



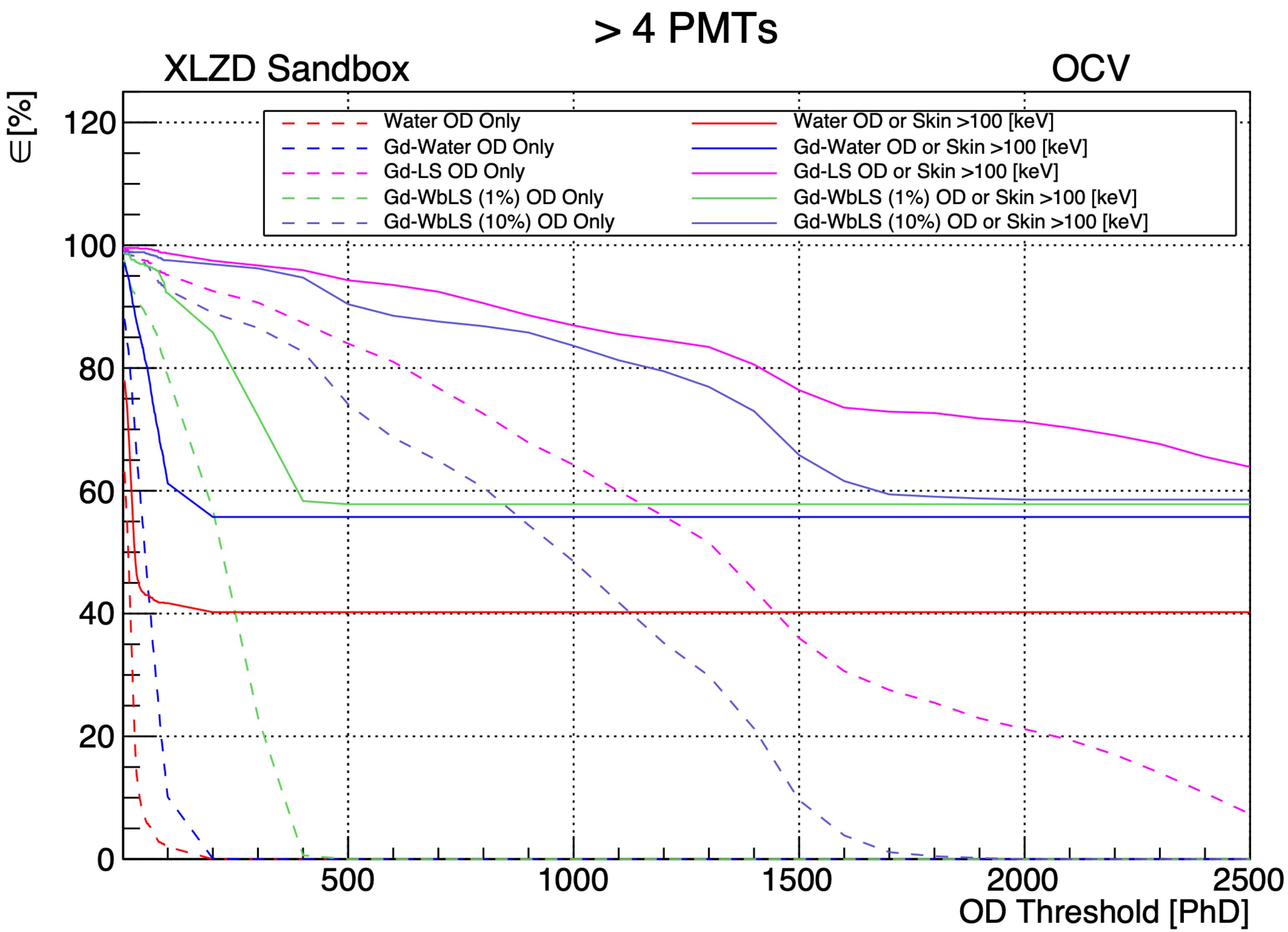
ROI+SS



ROI+SS+FV



Neutron Tagging Efficiency



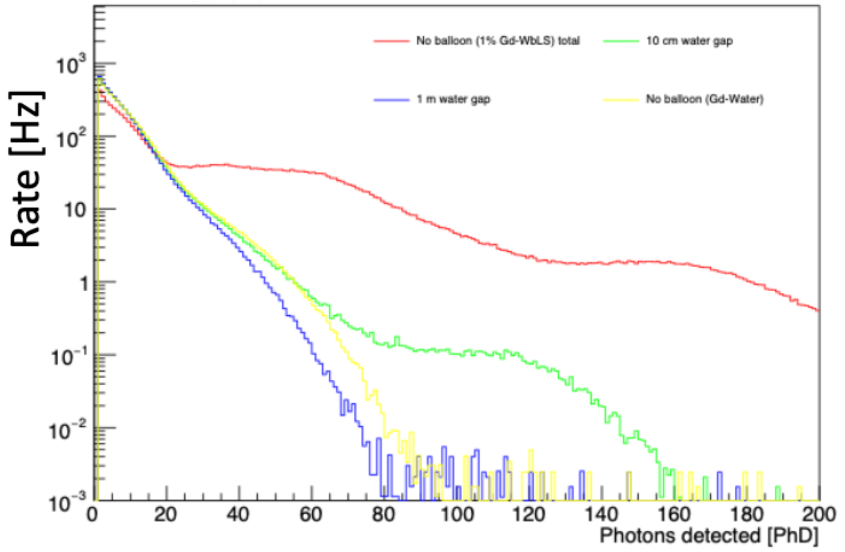
For different media, the neutron tagging efficiency is shown as a function of threshold in photons detected

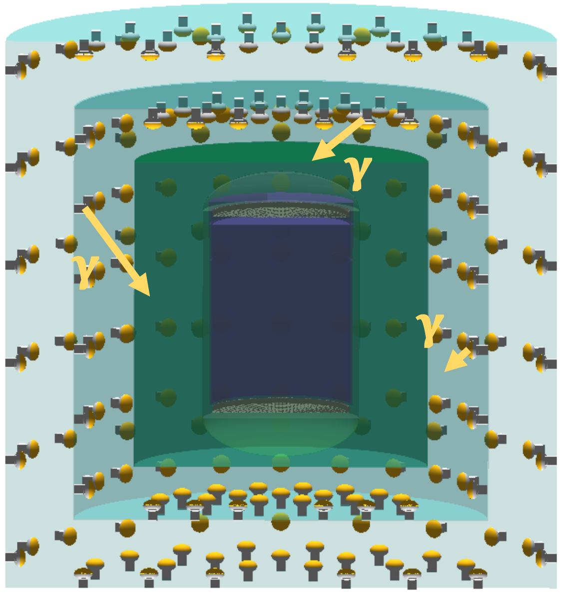
Difficult to directly compare the different media

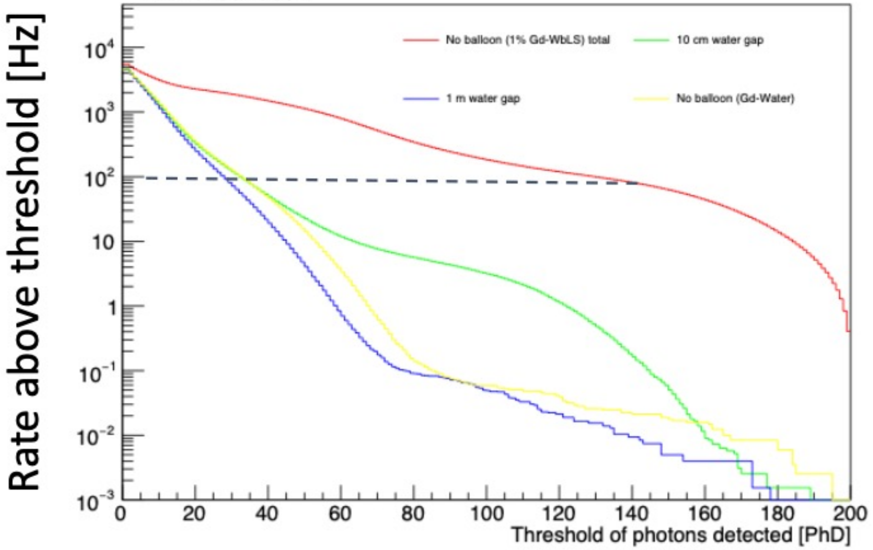
Dependent on light yields and light collection efficiencies

Background rates due to PMTs

- PMT self trigger due to their own radioactivity
- The rate was examined in the various outer detector media, (Gd-Water, Gd-WbLS and Gd-LS)
- Rate is found to be too high if PMTs are submerged in organic scintillator material
- High threshold is required
  - Negatively impacting the tagging efficiency
  - Possible solution:
    - Water barrier between PMTs and scintillating material
    - Walls with only PMT's poking through?

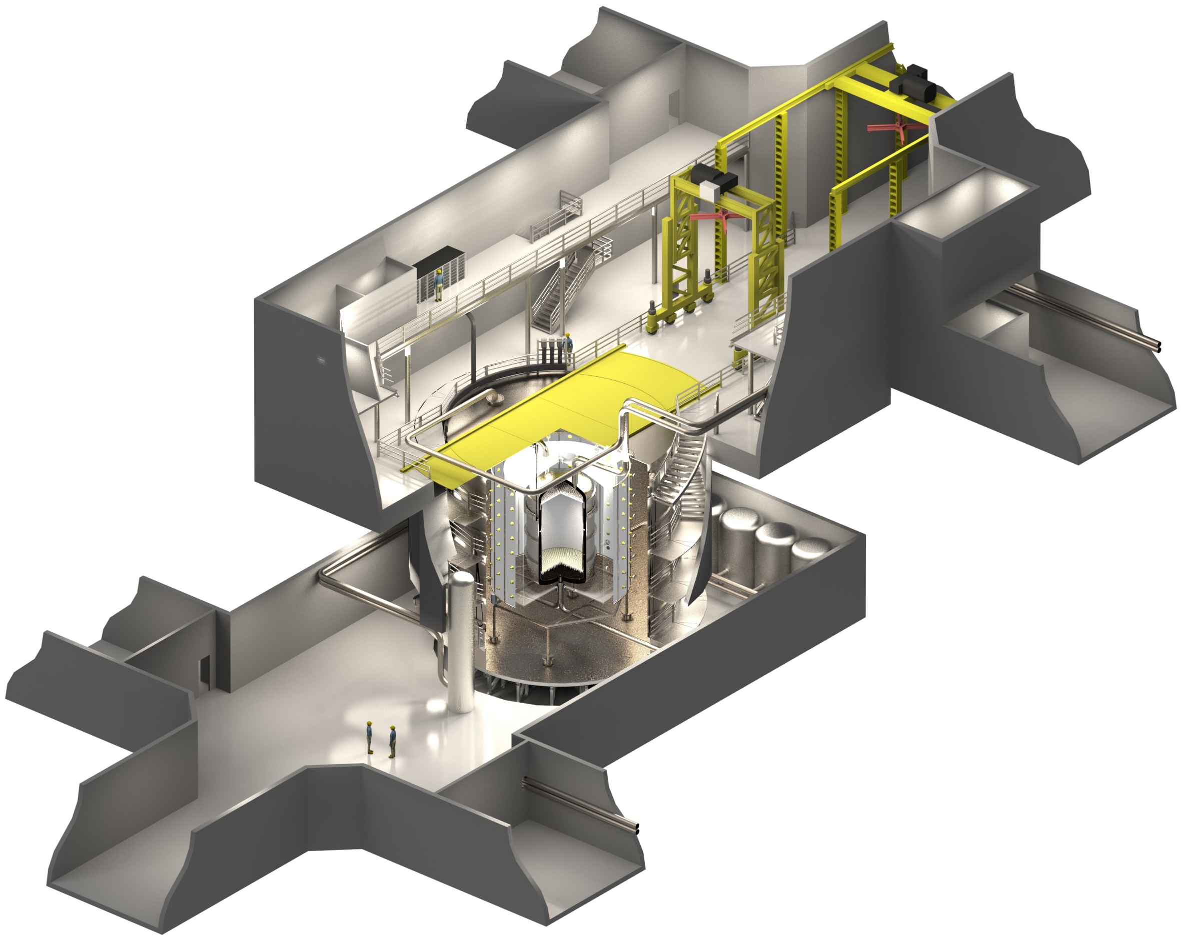






Conclusions

- XLZD will feature a >1kt outer detector
  - Required to reject 95% of neutron events in the LXe-TPC
  - Acts as a passive shield, neutron and muon detector
- A simulation framework has been developed using Geant4 and is used to motivate medium selection
- Conclusions:
  - **Skin** and **Outer Detector** together can reach a 95% tagging efficiency
  - PMT rates are substantial for WbLS if an additional containment vessel is not considered
    - Negatively impacts neutron tagging efficiency



Backup