Designing an Outer Detector for XLZD

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28th May 2025,
University of Liverpool

A quick outline

- Introduction to XLZD
- Motivation for the Outer Detector in Dark Matter search experiments
- Lessons from past experiments
- XLZD Outer Detector design

An Introduction to XLZD

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

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],

XLZD White Paper & Design book

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

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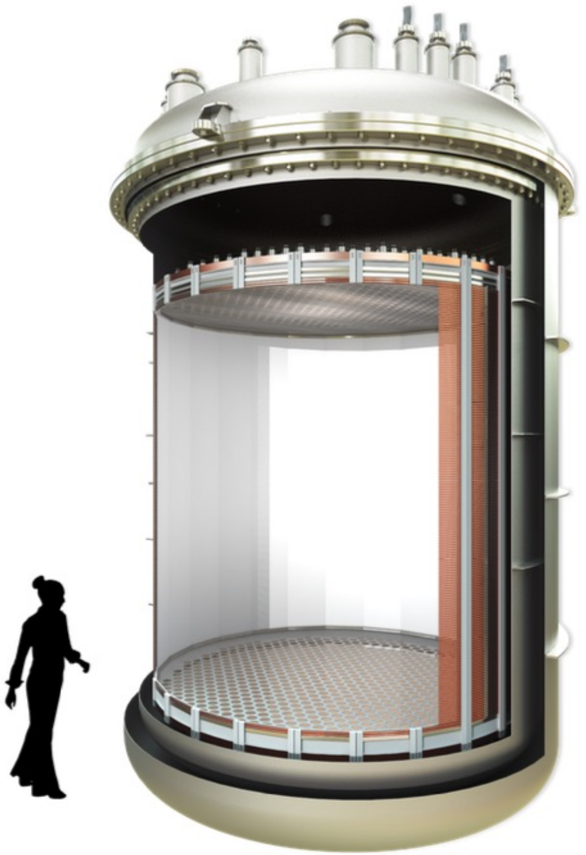

- Will nominally feature a LXe-TPC with a 1:1 aspect ratio => 60 tonnes of active mass
- PMT arrays at top and bottom
- Xe Skin veto, Outer Detector veto

TPC parameters	Nominal	Opportunity
Target diameter [cm]	298	298
Target drift length [cm]	297	396
Target Mass [tonne]	60	80
Total Mass [tonne]	78	104

A history of XLZD

- Consortium MoU signed in 2021 by **X**ENONnT, **L**UX-**Z**EPLIN, **D**ARWIN
- Collaboration formed in September 2024 => **XLZD**
- XENONnT and LZ:
  - Current-generation experiments
  - World leading sensitivity to WIMP dark matter
  - Technology progenitors
- DARWIN:
  - Initiated R&D, design studies and long-term planning of XLZD

XLZD@Boulby

- Preliminary Activity Infrastructure Funding from UKRI in 2024

XLZD-UK TEAM

M. Agostini[1], H. M. Araújo*[2], D. Bauer[2], C. Boehm[3], M. Borri[4], A. Boston[5], J. Brooke[6], S. Burdin[5], X. Calmet[7], G. Casse[5], J. Coleman[5], D. Colling[2], D. Costanzo[8], A. Cottle[1], G. J. Davies[2], A. De Santo[7], J. Dobson[9], J. Ellis[9], M. Fairbairn[9], H. Flaecher[6], H. Fox[10], C. Frenk[11], C. Ghag[1], A. Green[12], E. Hardy[5], J. Hays[13], S. Jones[8,14], A. Kaboth[15], A. Khan[16], L. L. Kormos[10], H. Kraus[17], V. A. Kudryavtsev[8], P. Kyberd[16], M. Labiche[4], I. Lazarus[4], P. A. Majewski[18], J. March-Russell[17], C. McCabe[9], A. Mehta[5], D. Muenstermann[10], A. StJ. Murphy[3], K. Nikolopoulos[19], K. Palladino[17], S. Paramesvaran[6], C. Patrick[3], K. Petridis[6], T. Potter[20], Y. Ramachers[21], R. Saakyan[1], P. Scovell[18], S. Shaw[3], J. Smirnov[5], M. Spannowsky[11], T. J. Sumner[2], A. Szelc[3], D. R. Tovey[8], Y. Uchida[2], C. Uhlemann[22], M. van der Grinten[18], J. Vossebeld[5], D. Waters[1], S. West[15], and I. Zavala[23]

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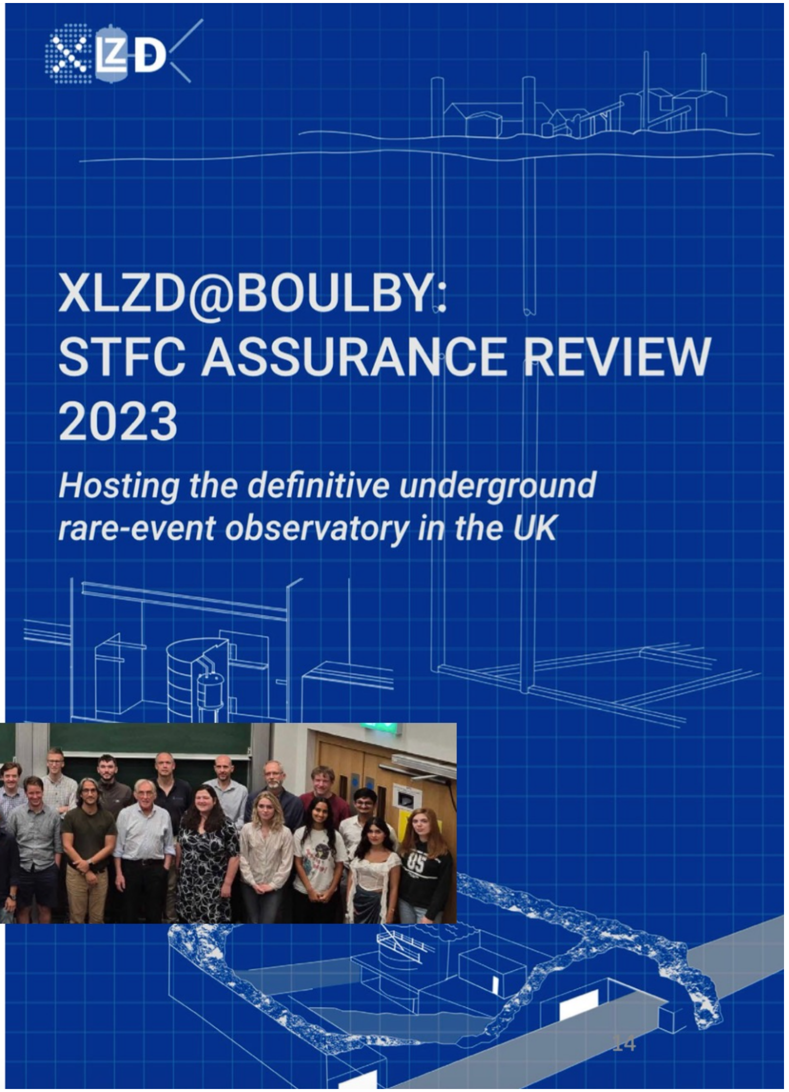
With key UK partners:

- STFC Boulby Underground Laboratory
- STFC Technology Department
- RAL/PPD Project Management Office
- Advanced Manufacturing Research Centre (N-AMRC & AMRC-TC)
- ICL-Boulby
- BUTTON, DarkSPHERE, LEGEND, AION



XLZD@Boulby Work Packages

WP0 Management

WP1 Xenon Acquisition: one-third of xenon stock & associated feed/recovery equipment

WP2 Outer Detector: GdW, GdLS, WBLS? R&D on the latter starting now, with BUTTON R&D project

WP3 Cryostat: u/g manufacture prototyping starting now; with N-AMRC & "on-site" manufacture industries

WP4 Xenon Detector Elements: skin and field-cage: large elements with significant coupling to cryostat

WP5 Data Centre & On-Site Computing: supporting design and operations, with sustainability in mind

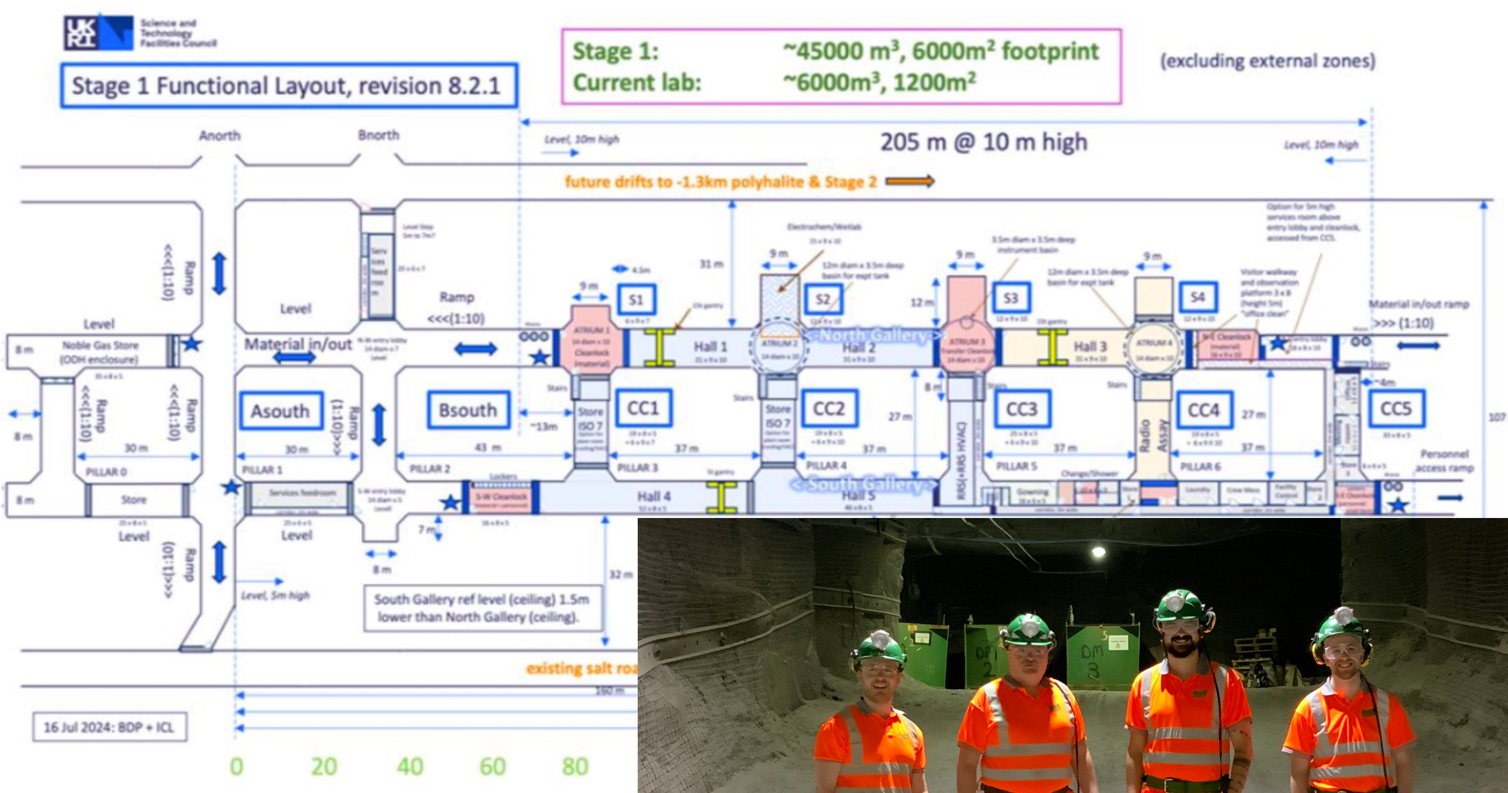
WP6 Clean Manufacture: radioassay, cleanliness, clean manufacture, with $0\nu\beta\beta$ & DM community, NAMRC

WP7 Engineering and Skills: engineering & technical effort, apprenticeship programme, with AMRC-TC

WP8 Environmental Sustainability: aiming for net-zero in operations, with STFC/Boulby and ICL-UK

Boulby Stage 1

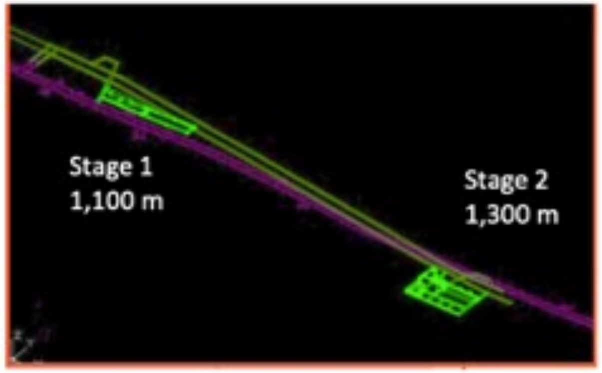
- STFC Boulby Development Project
- Working mine
  - Salt, potash
- 1100 m underground
- Underground manufacturing

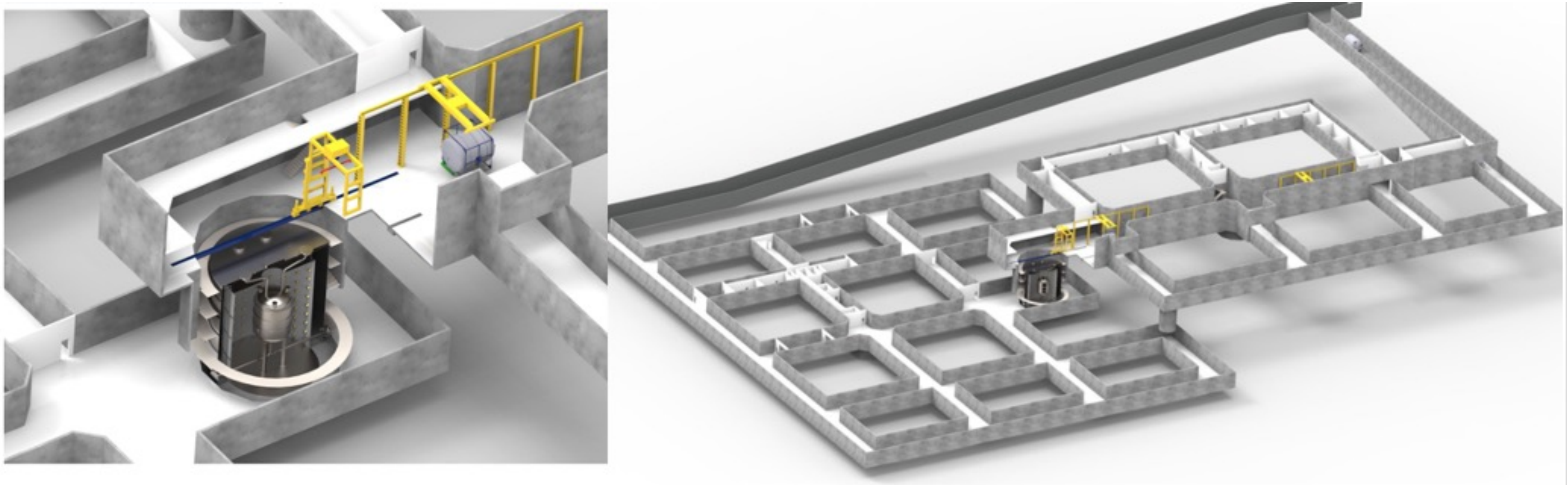


- Cryostat welding and cleaning
- Rn reduced cleanrooms

Boulby Stage 2

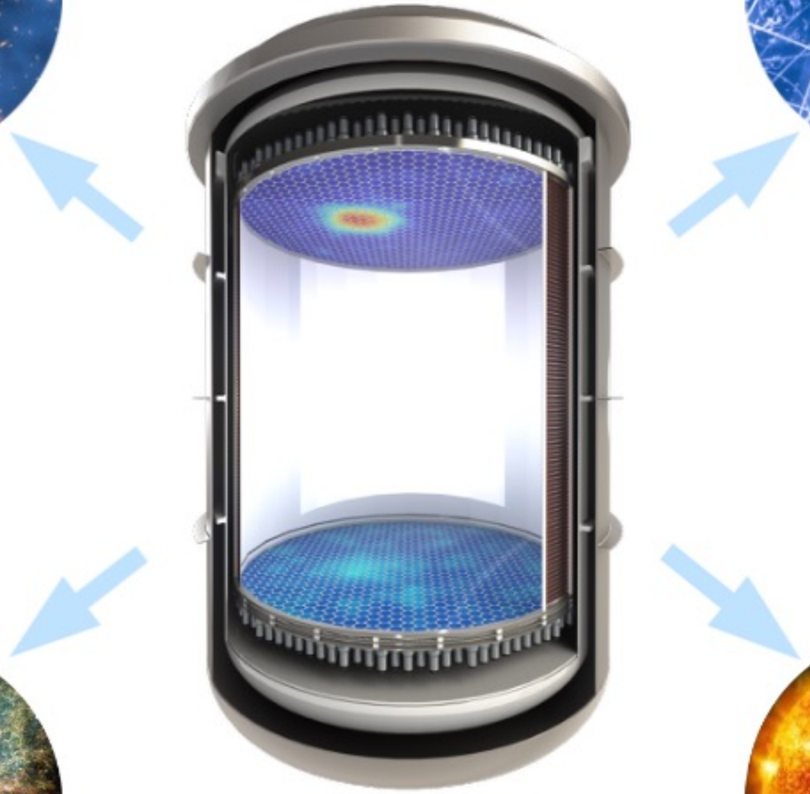
- 1300 m in polyhalite
- Preliminary design – using standard mining techniques
- Two levels joined by 16 m diameter experimental hall location





Physics Programme at XLZD

Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons

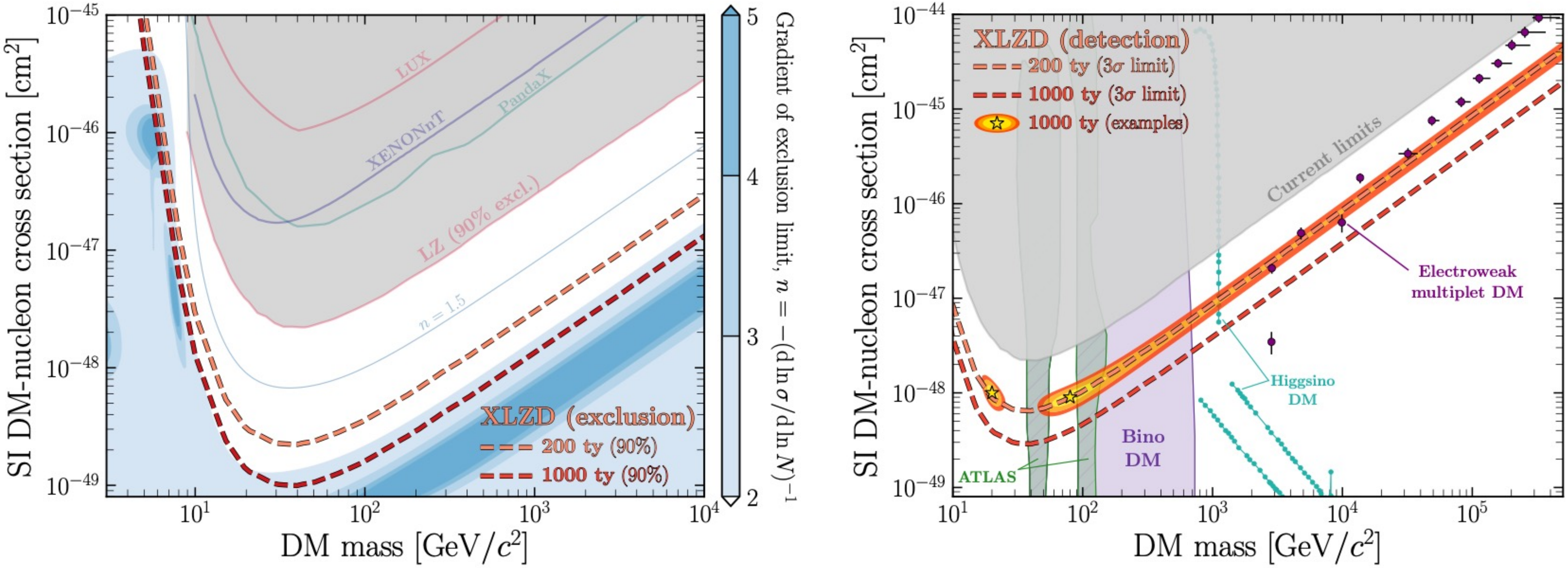


Neutrino nature
Neutrinoless double beta decay
Neutrino magnetic moment
Double electron capture

Supernovae
Early alert
Supernova neutrinos
Multi-messenger astrophysics

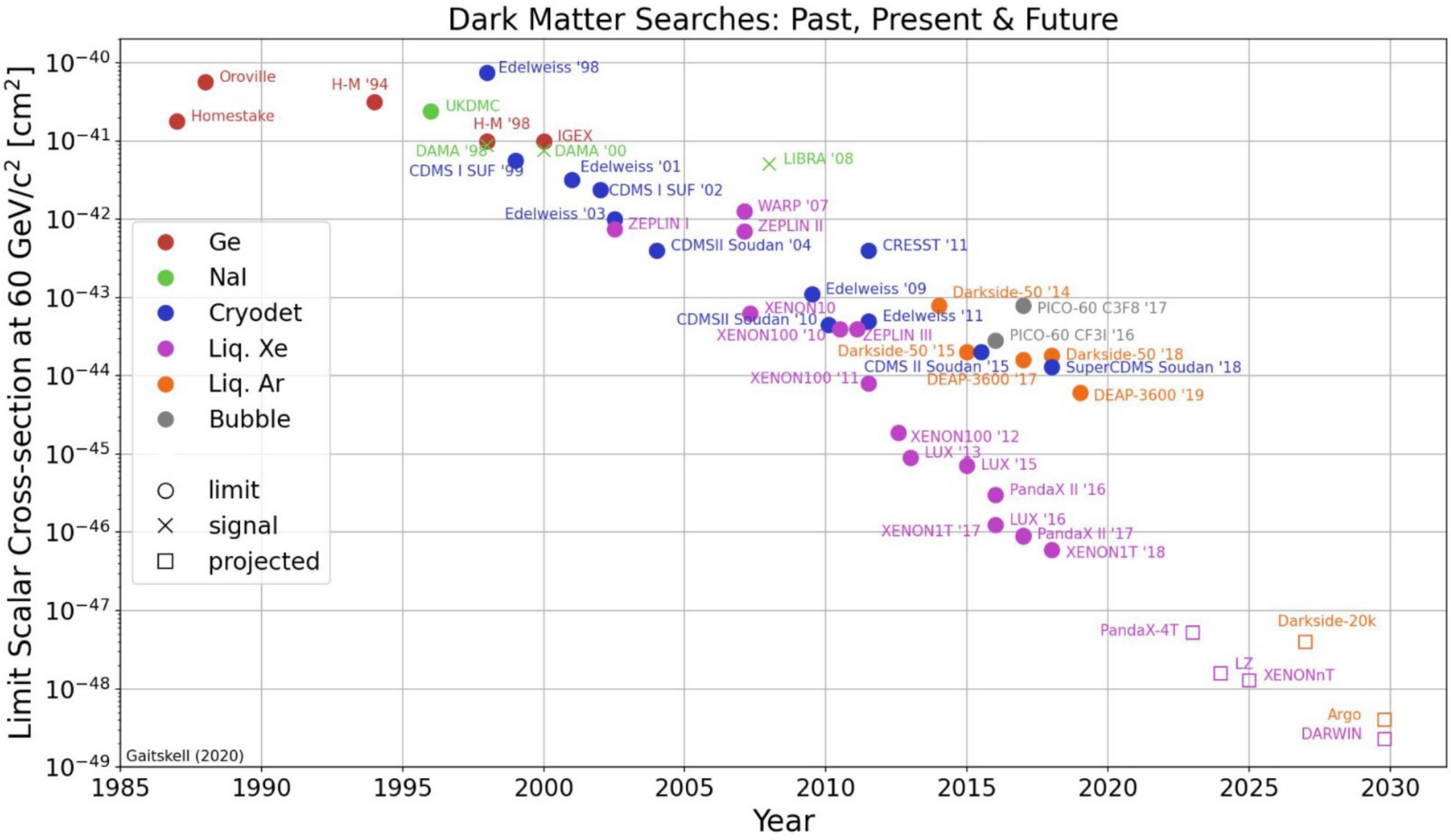
Sun
pp neutrinos
Solar metallicity
^{7}Be, ^{8}B, hep

Final Generation Liquid Xenon Detector for WIMPS?

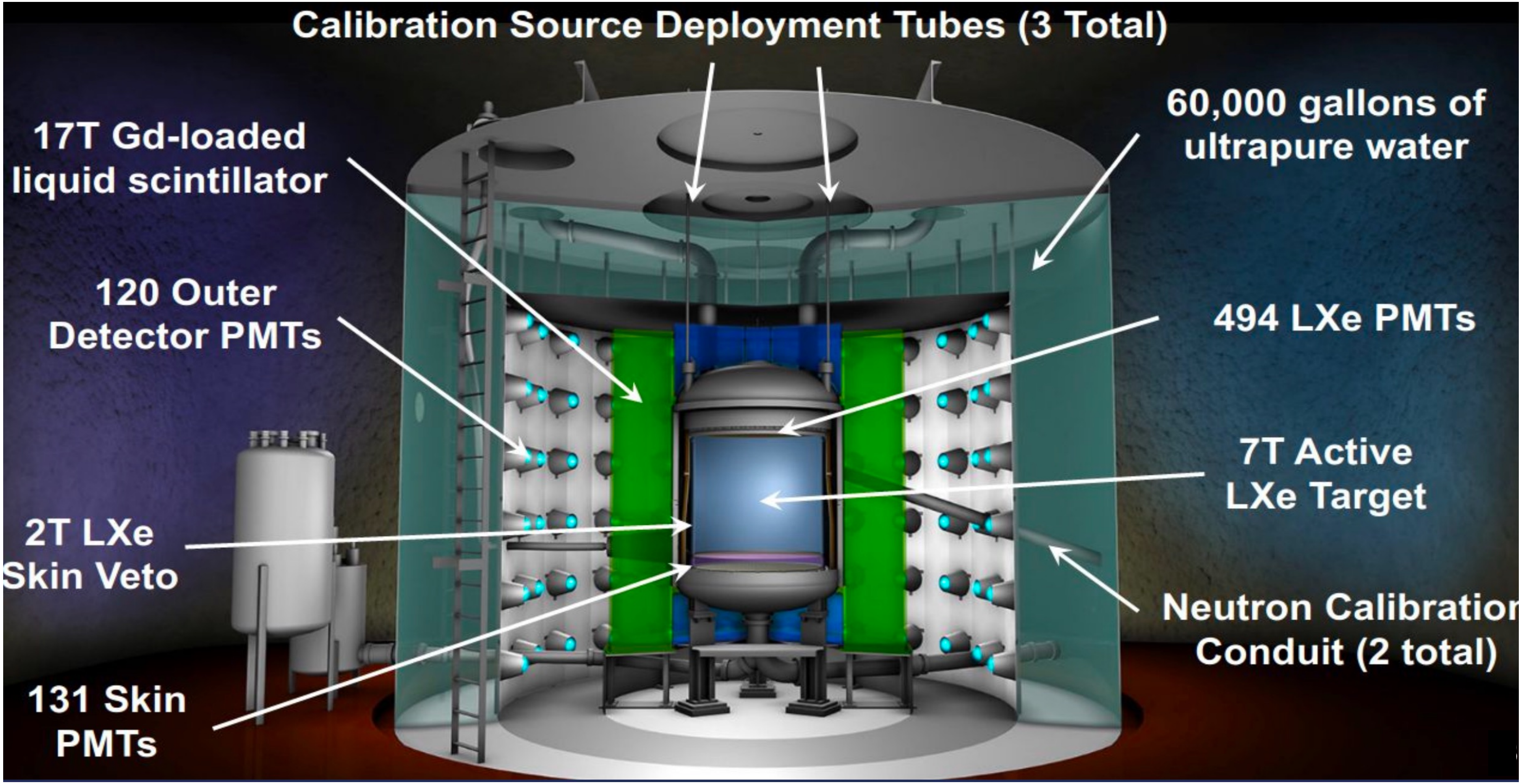


- Current technology will likely be unsuitable once “neutrino fog” is reached
  => Motivation to achieve the best possible sensitivity with this detector

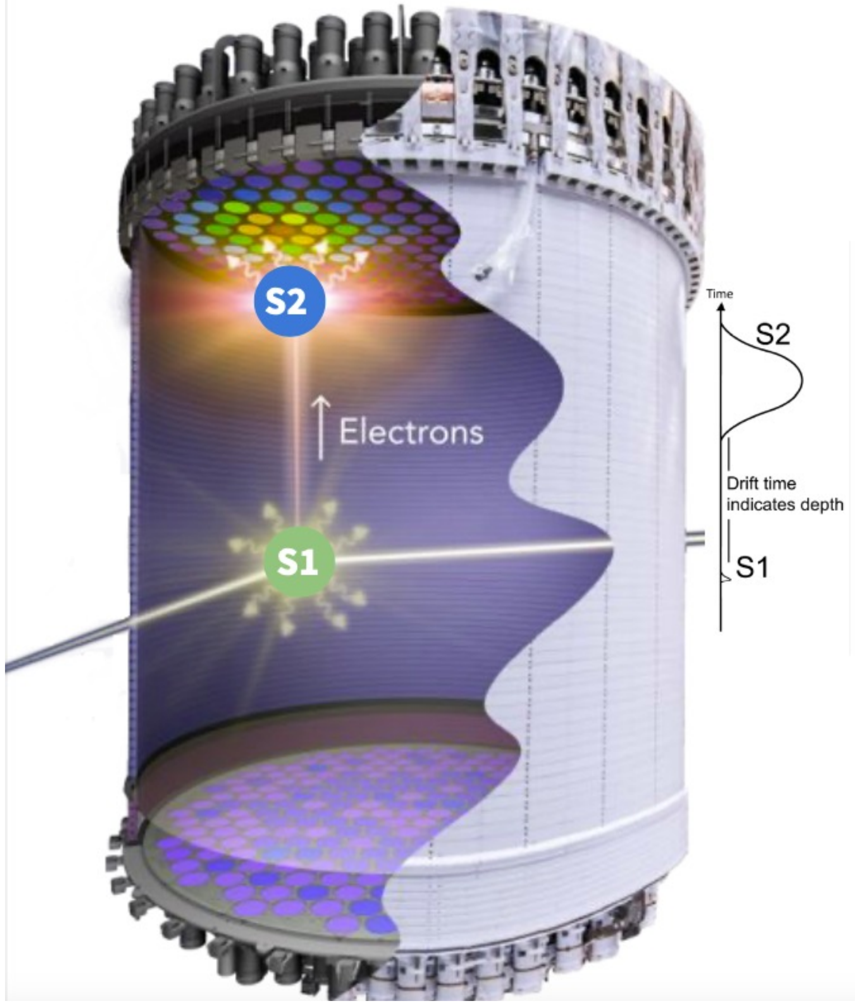
Success of Liquid Xenon Technique in WIMP searches



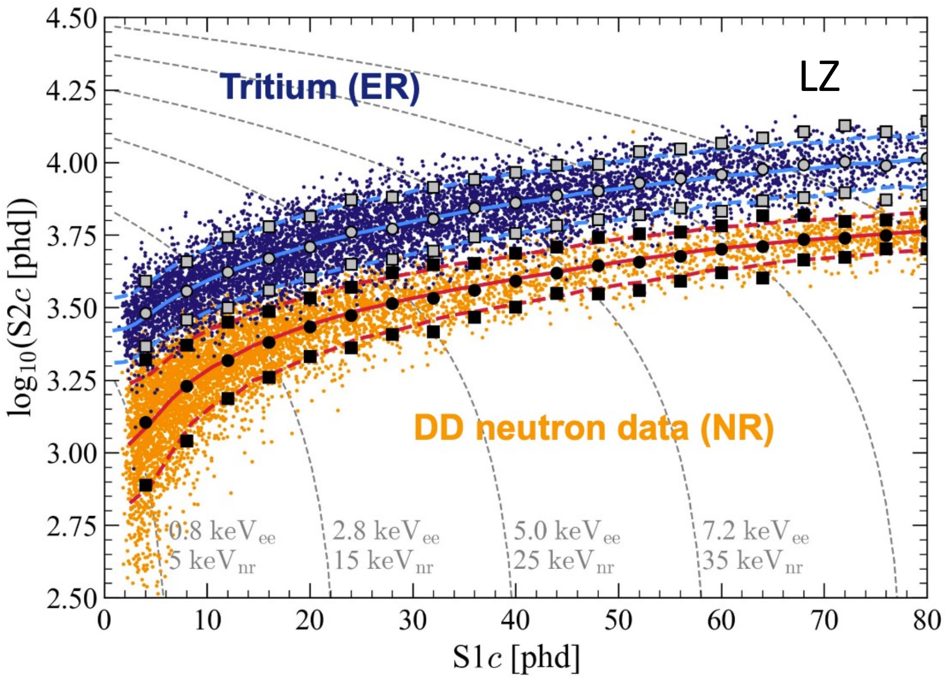
The LZ Detector as an example

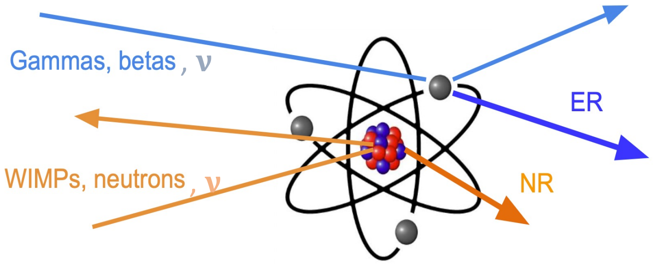


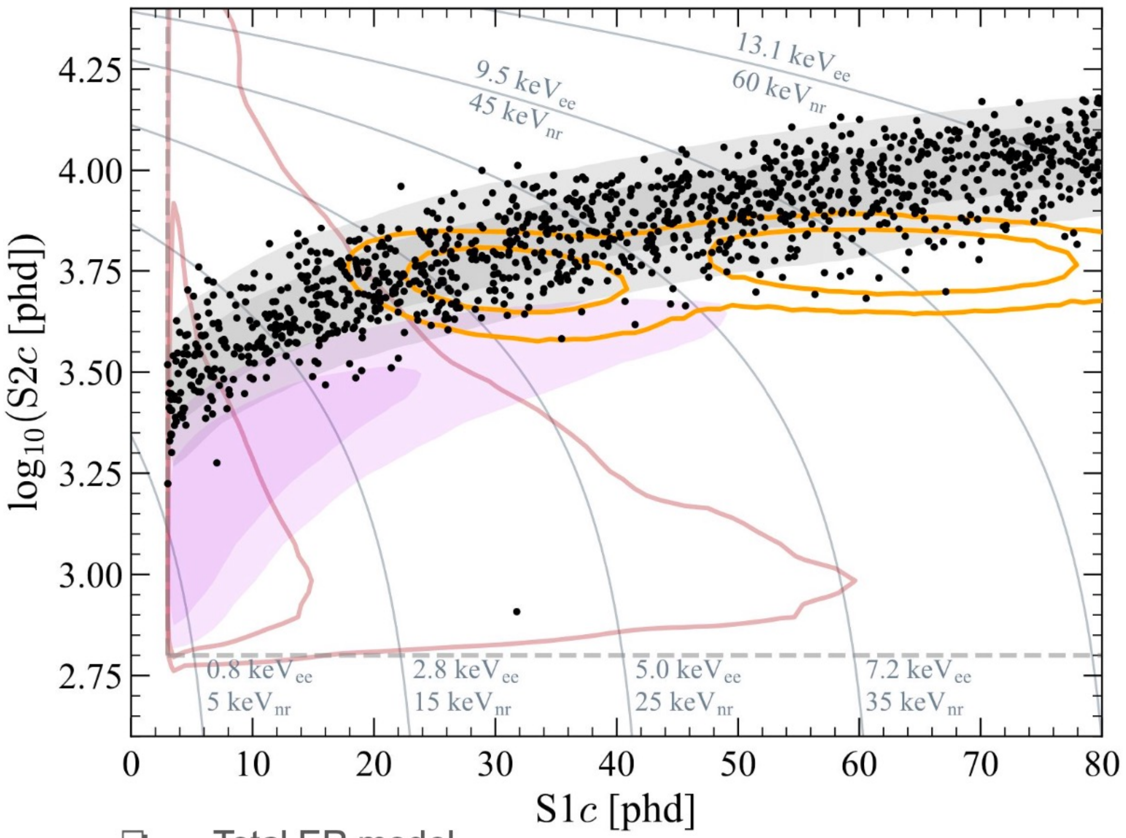
Detection principles in Liquid Noble Gas Detectors



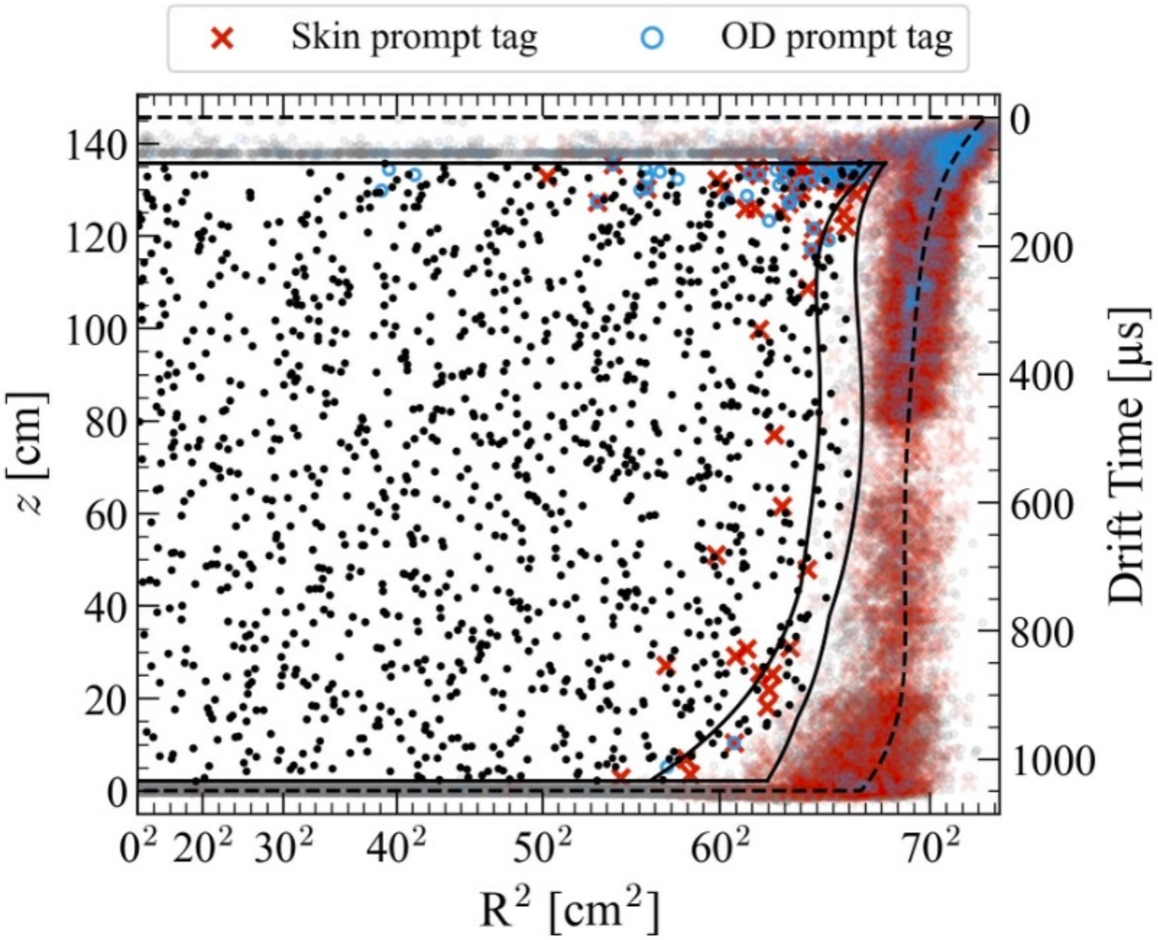
- Time Projection Chamber
- S2 hit pattern, drift time (xy, z)
- Energy deposited obtained from S1, S2
  - Particle discrimination (S1:log(S2))



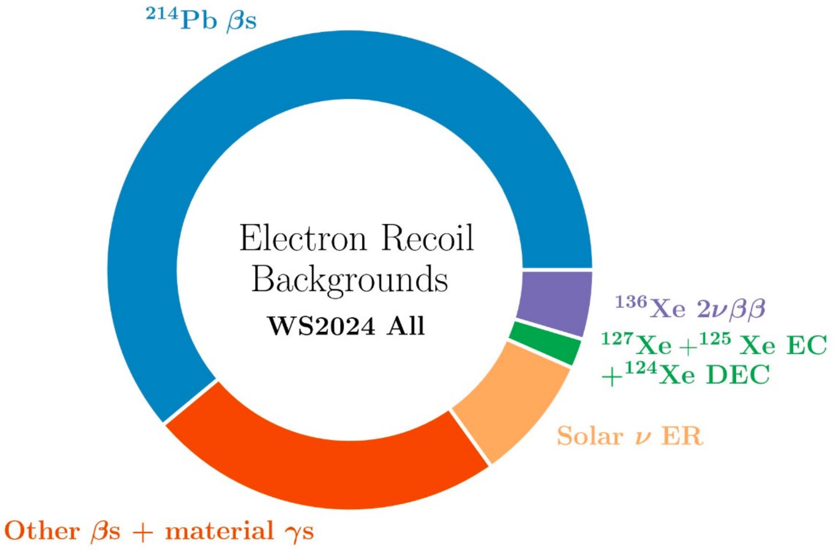




- Total ER model
- ^{124}Xe model: Q_{LL}/Q_{β} @ best fit
- 40 GeV/c^2 WIMP
- Accidentals model



Backgrounds



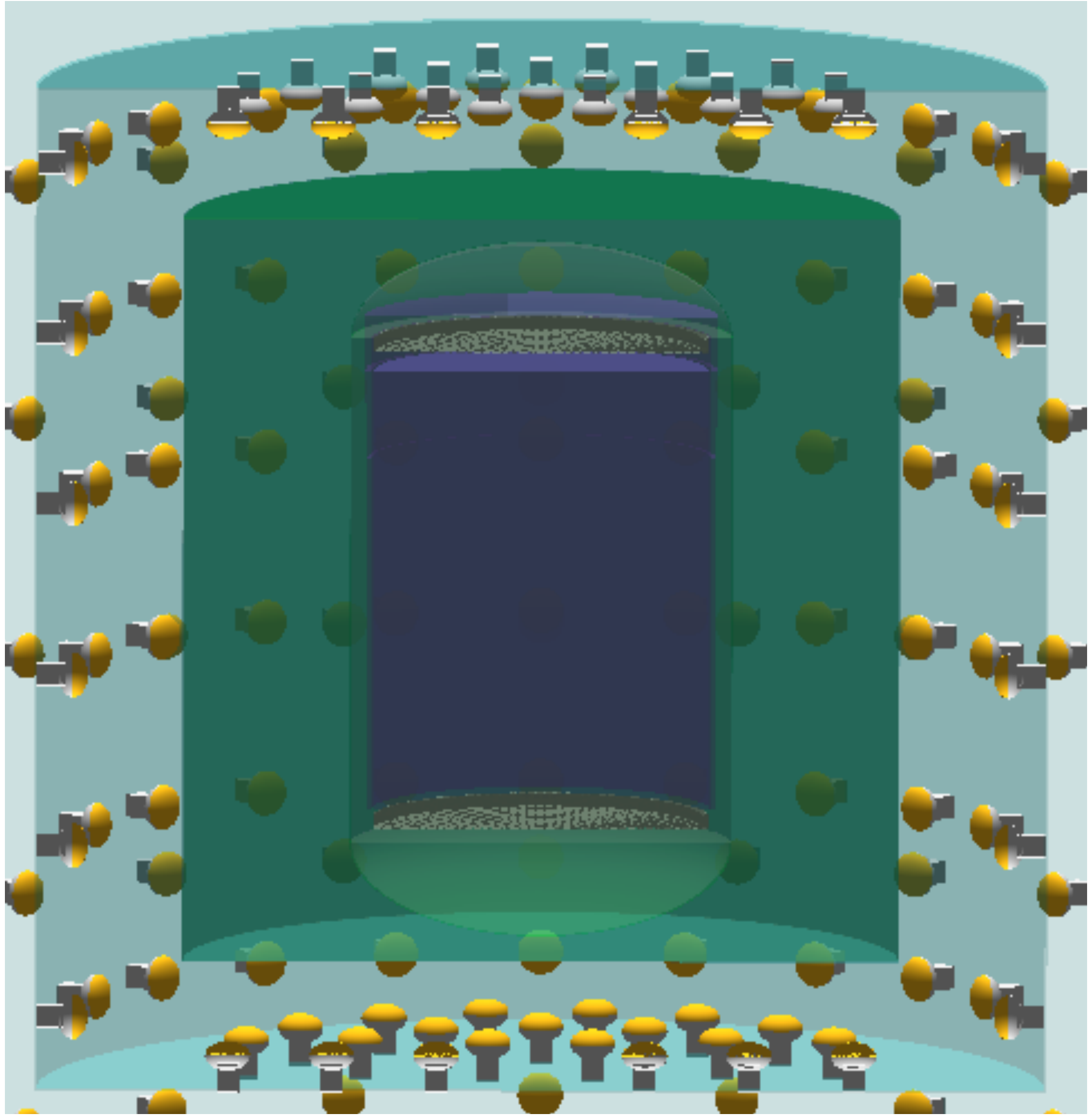
Source	Pre-fit Expectation	Fit Result
^{214}Pb βs	743 ± 88	733 ± 34
^{85}Kr + ^{39}Ar βs + det. γs	162 ± 22	161 ± 21
Solar ν ER	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po βs	62.7 ± 7.5	63.7 ± 7.4
Tritium+ ^{14}C βs	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe $2\nu\beta\beta$	55.6 ± 8.3	55.8 ± 8.2
^{124}Xe DEC	19.4 ± 3.9	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

- Dissolved β emitters:
  - ^{214}Pb (^{222}Rn), ^{212}Pb (^{220}Rn), ^{85}Kr, ^{136}Xe (ββ)
- Dissolved EC decays (x-rays/Auger electrons)
  - ^{127}Xe & ^{125}Xe produced by activation from neutron calibration
  - ^{124}Xe (double EC), 0.095% natural abundance
- Solar ν's: ^{8}B (NR), pp+^{7}Be (ER)
- Detector ER, γ emitters from detector materials
  - ^{238}U, ^{232}Th, ^{40}K, ^{60}Co decay chains
- Neutrons from USF and (α,n) in detector materials
- Accidentals - random coincidence of isolated S1 and S2s

Motivation for an Outer Detector

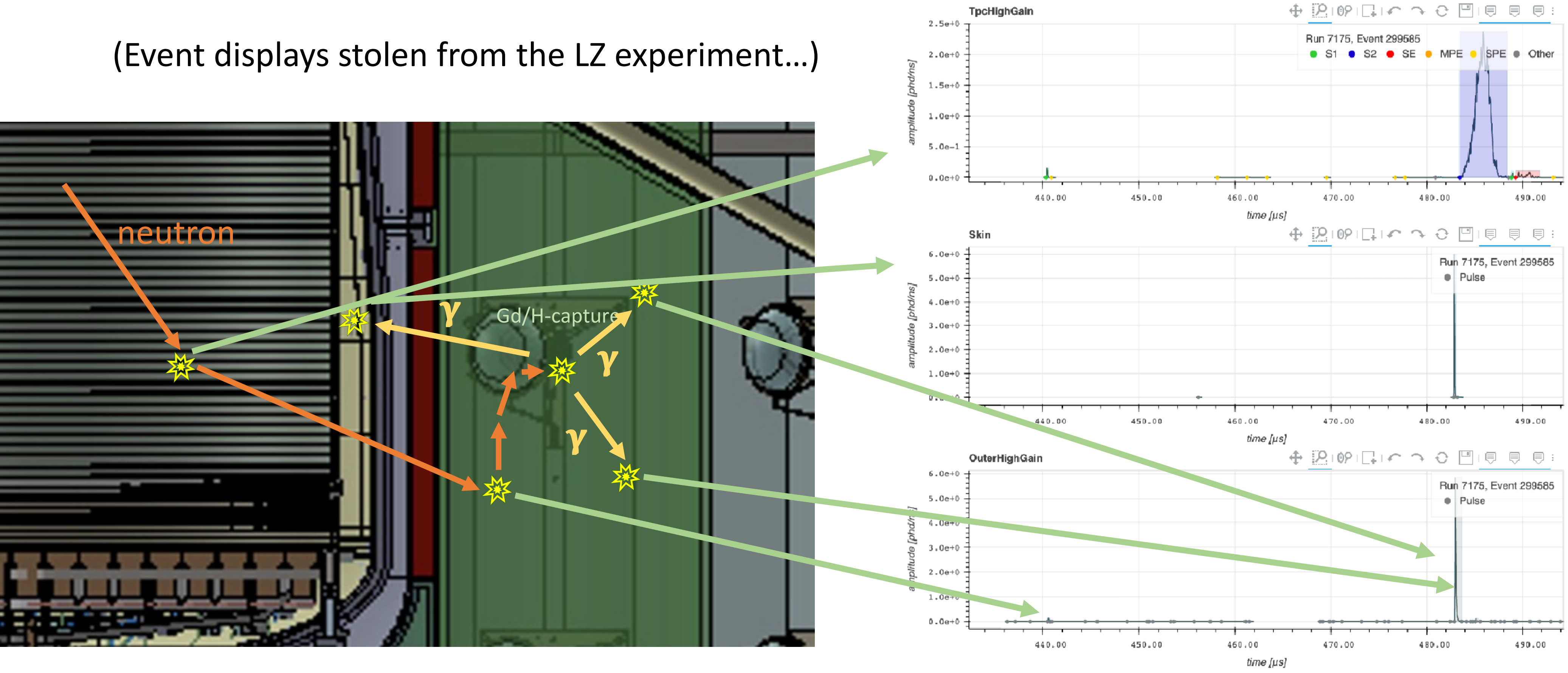
Background paradigm

- 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**



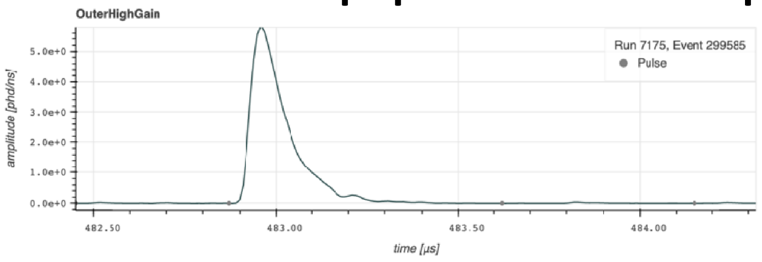
Neutron Background Suppression

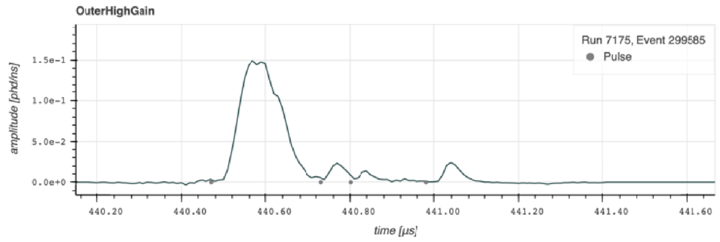
(Event displays stolen from the LZ experiment…)



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

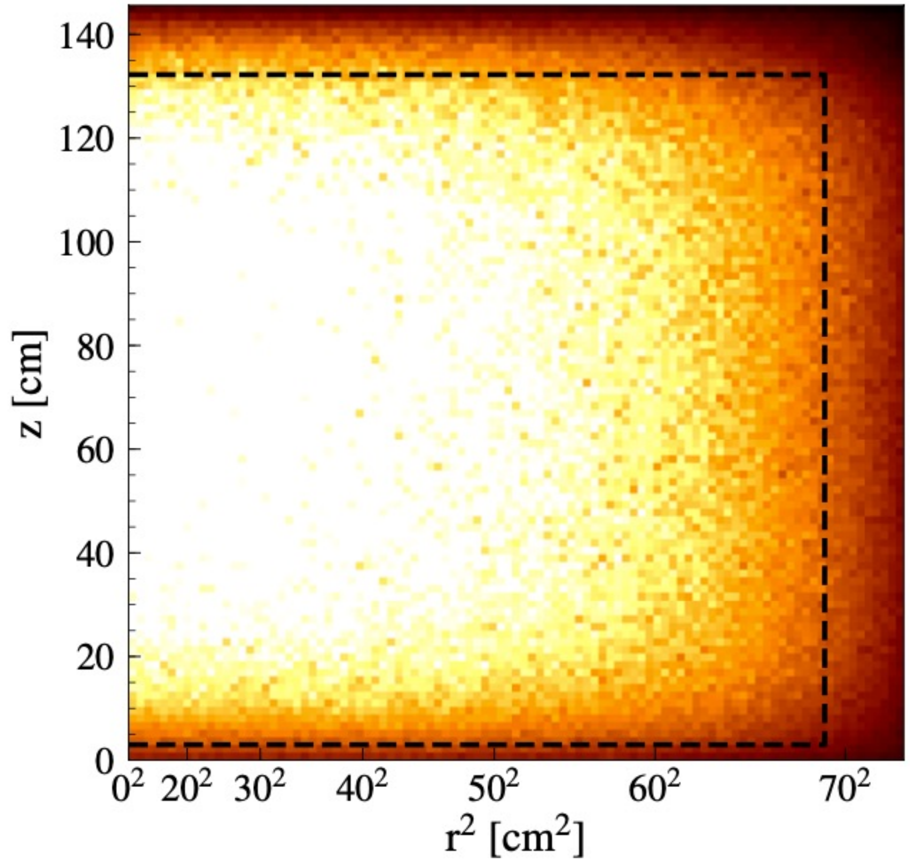
Prompt proton recoil ~17 phe





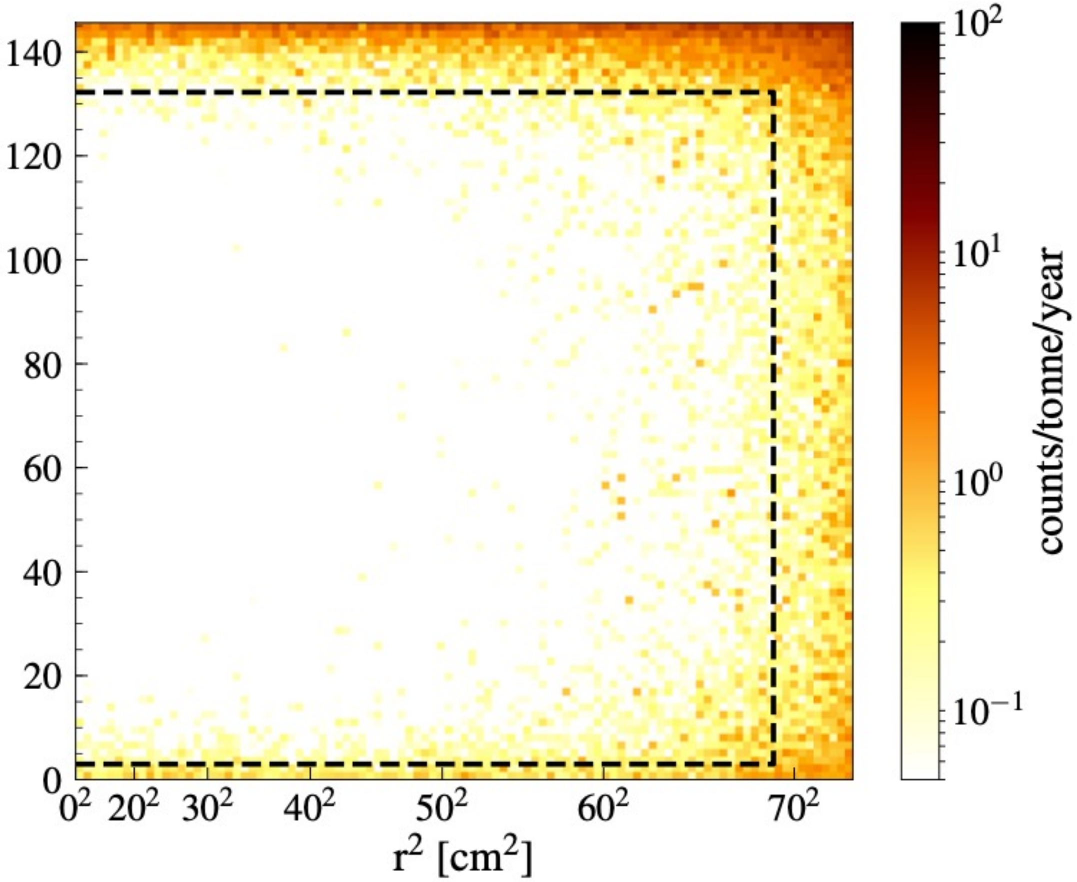
Fiducial Volume

No OD



VETO

OD



Searches for Neutrino-less Double Beta Decays

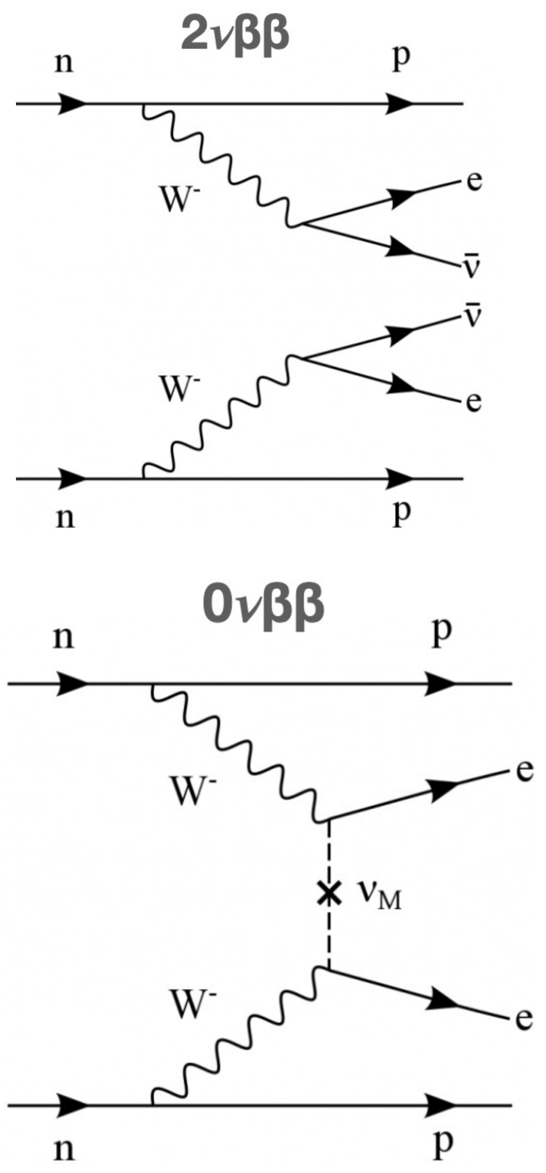
- arXiv:2410.19016, Alex Lindote @ XeSAT 23
- Standard double beta decay:

$$(A, Z) \longrightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

  - Rare process, occurs when single beta decay is forbidden or highly suppressed
  - Confirmed in 14 isotopes
    - $T_{1/2}$ in the 10^{19} — 10^{21} yr range
- **Neutrino-less double beta decay**

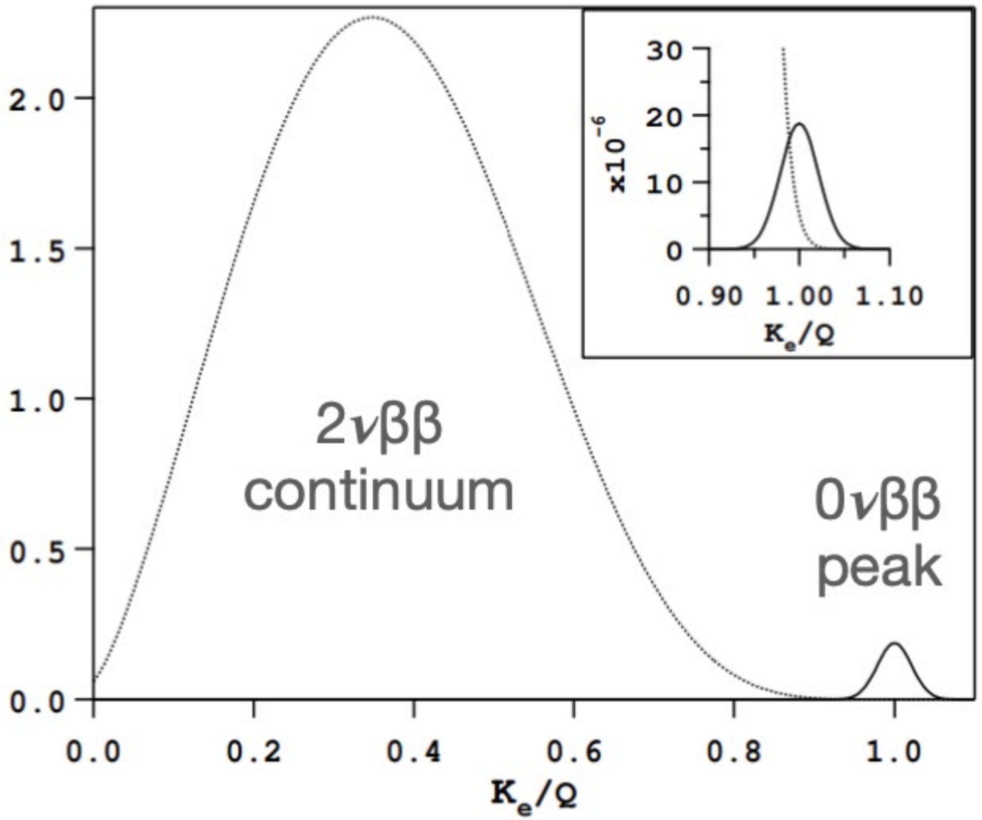
$$(A, Z) \longrightarrow (A, Z+2) + 2e^-$$

  - Violates lepton number conservation
  - Possible if neutrinos are Majorana particles
  - $T_{1/2} > 2.3\text{x}10^{26}$ yr in ^{136}Xe (KamLAND-Zen, PRL **130**, 051801)



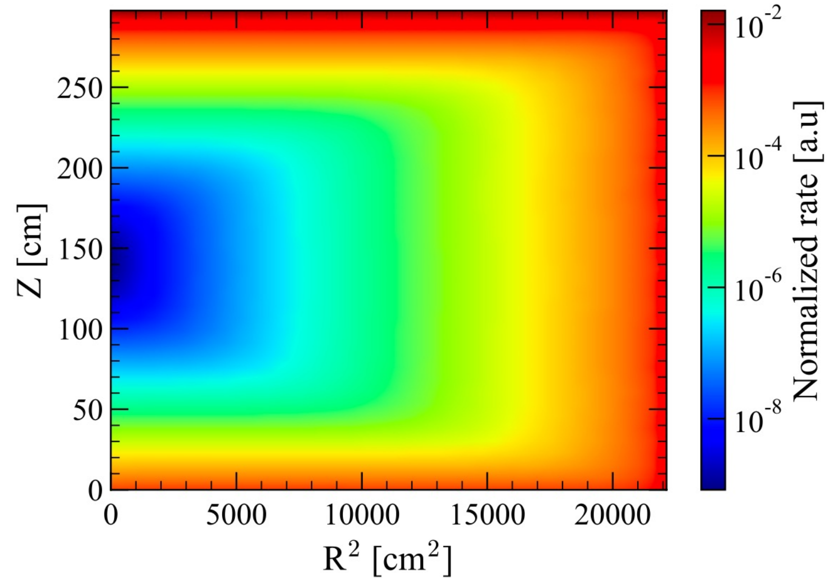
Neutrino-less Double Beta Decays in XLZD

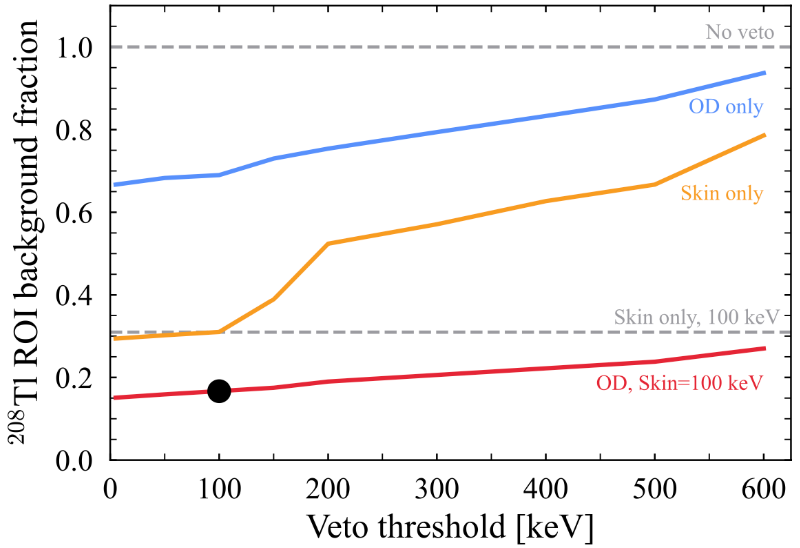
- ^{136}Xe $0\nu\beta\beta$ decay in XLZD visible as a monoenergetic peak at the end of the $2\nu\beta\beta$ specrtum
- ^{136}Xe is 8.9% of natural xenon
  - 80 t target mass → 7 t of ^{136}Xe
- ^{136}Xe $0\nu\beta\beta$ Q = 2458 keV



Backgrounds for Neutrino-less Double Beta Decays

- **External gamma-ray background**
- ^{214}Bi γ in the ^{238}U chain (2447 keV)
- ^{208}Tl γ in the ^{232}Th chain (2615 keV) — can be highly suppressed by vetoes
- **From detector materials, rock gammas are negligible (need large water tank)**
- Large TPC volume provides excellent self-shielding
- **External vetoes and ability to separate multiple scatters is critical**



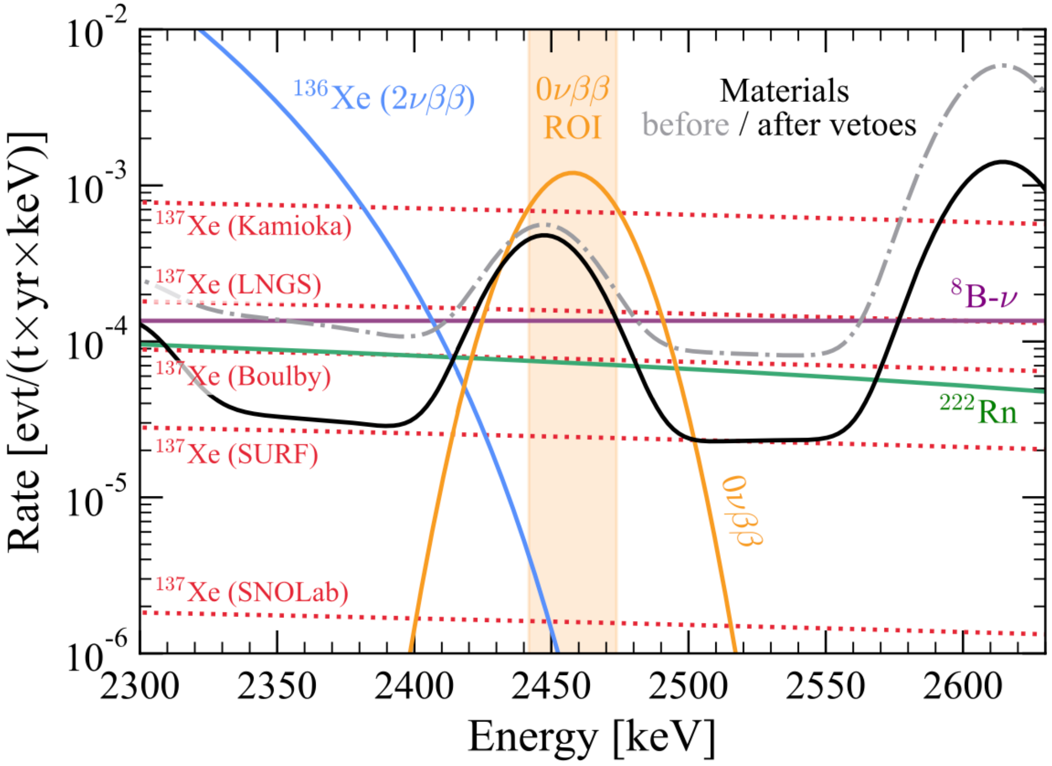


Backgrounds for Neutrino-less Double Beta Decays

- **Internal and intrinsic backgrounds** (uniform)
- Electron recoils from

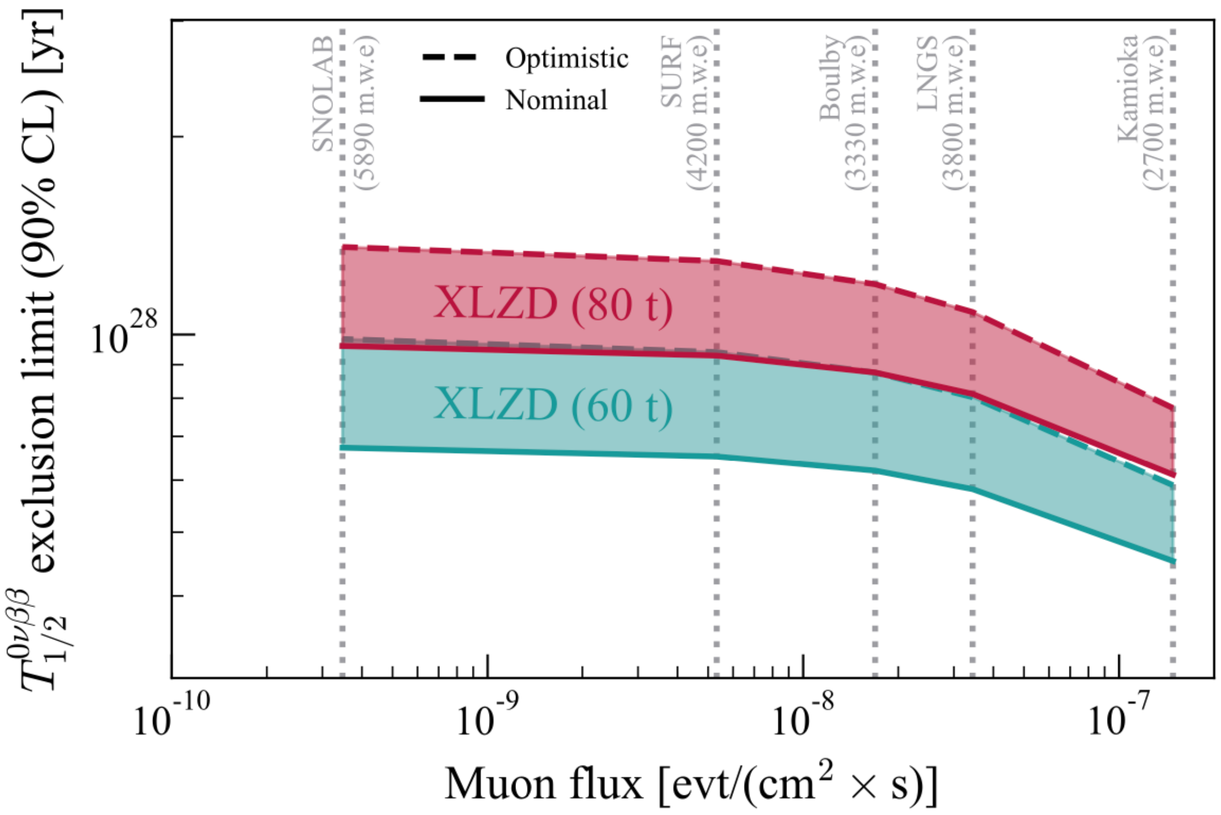
$\boldsymbol{\nu}$-e-scattering (^{8}B), irreducible

- ^{214}Bi β from ^{222}Rn mixed in the xenon (Q = 3270 keV)
- ^{137}Xe β (Q = 4170 keV), neutron activation of ^{136}Xe
  - **Mostly by muon induced neutrons, depends on installation site**
- $2\boldsymbol{\nu}\beta\beta$ leakage is very small, given the excellent energy resolution



Site	Depth [m]	Depth [m w.e.]	μ flux [/(m^2·d)]	^{137}Xe rate [/(t·yr)]	SS ROI rate [evt/(t·yr·keV)]
SNOLAB	2070	5890	<0.3	0.007	1.29×10^{-6}
SURF	1490	4300	4.6	0.142	2.72×10^{-5}
Boulby	1300	3330	14.6	0.404	7.73×10^{-5}
LNGS	1400	3800	29.7	0.822	1.57×10^{-4}
Kamioka	1000	2700	128	3.54	6.78×10^{-4}

Main drivers for $0\nu\beta\beta$ sensitivity

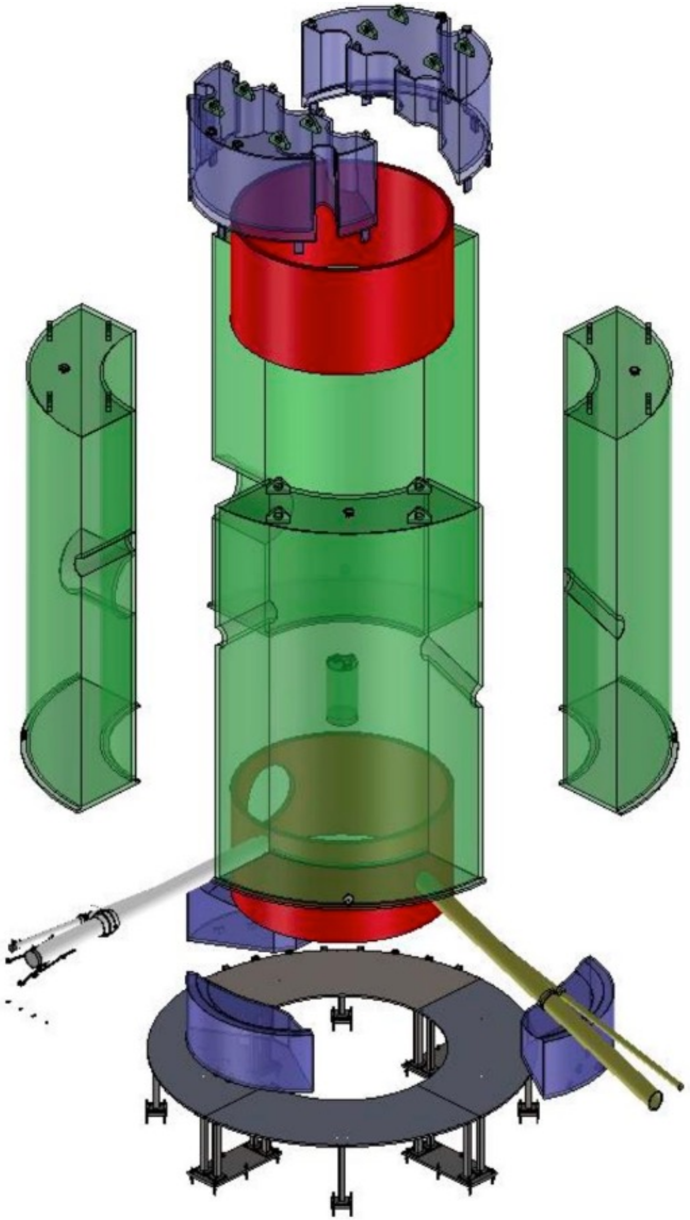


- Target mass
- **External gamma background** and ^{222}Rn contamination
- Laboratory depth (**muon flux**)
- Energy resolution and SS/MS discrimination

Lessons learned from past experiments

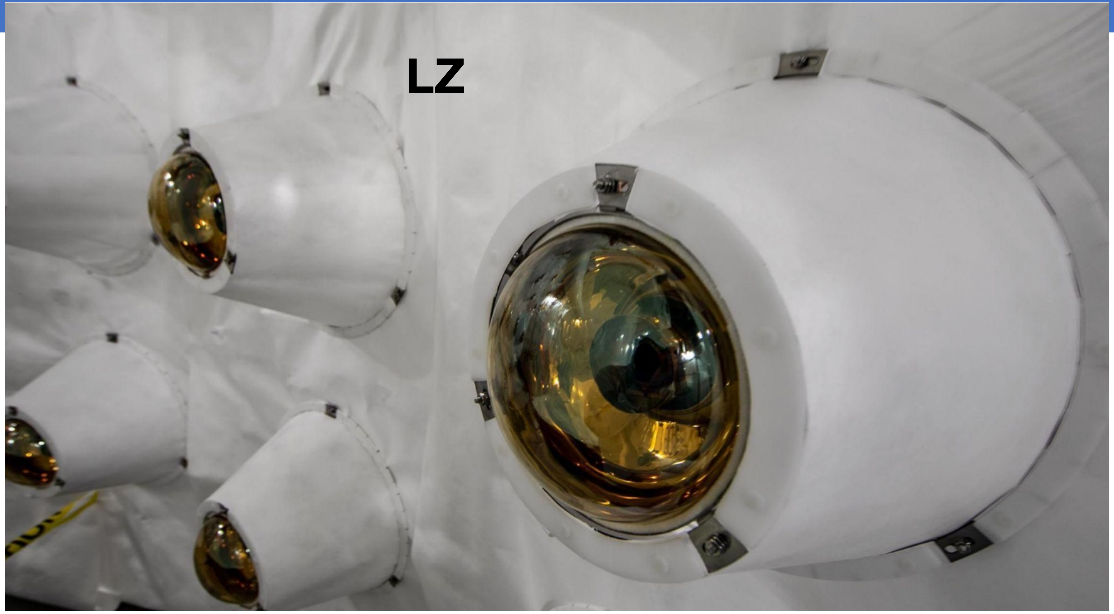
LZ’s Outer Detector

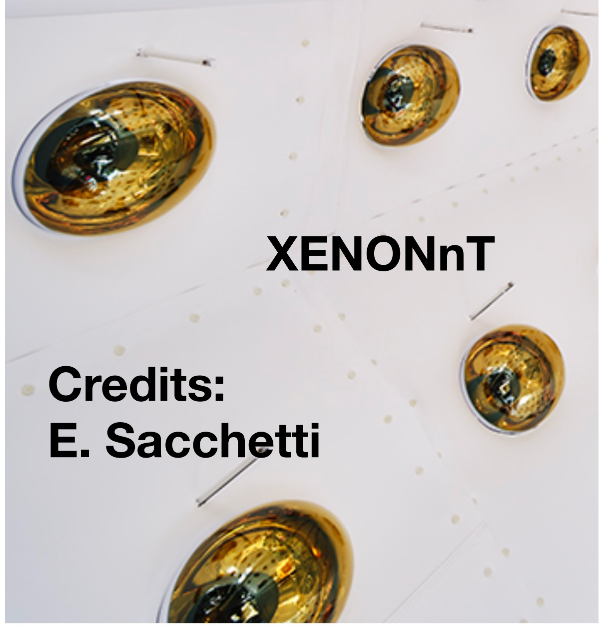
- The Outer Detector is a near-hermetic system that surrounds the cryostat vessel which houses the TPC.
- 10 UV transparent acrylic vessels filled with 17t of Gadolinium loaded (0.1% Gd by mass) liquid scintillator (Gd-LS). NIM A 937 (2019)
    - Lesson: It is impossible to avoid a gap between the acrylic vessels and cryostat which is likely to be filled with water which will decrease the neutron tagging efficiency by several percents (not easy to reproduce in simulation).
- 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.



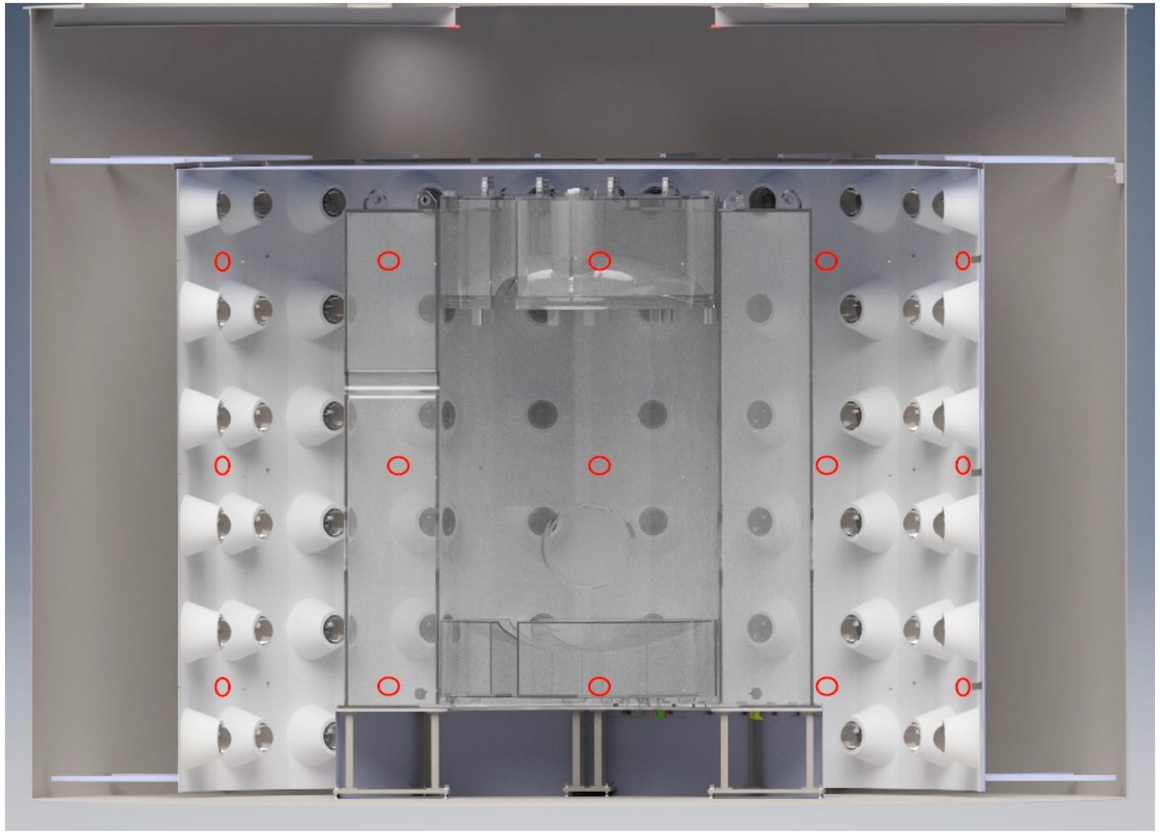
OD PMT placements

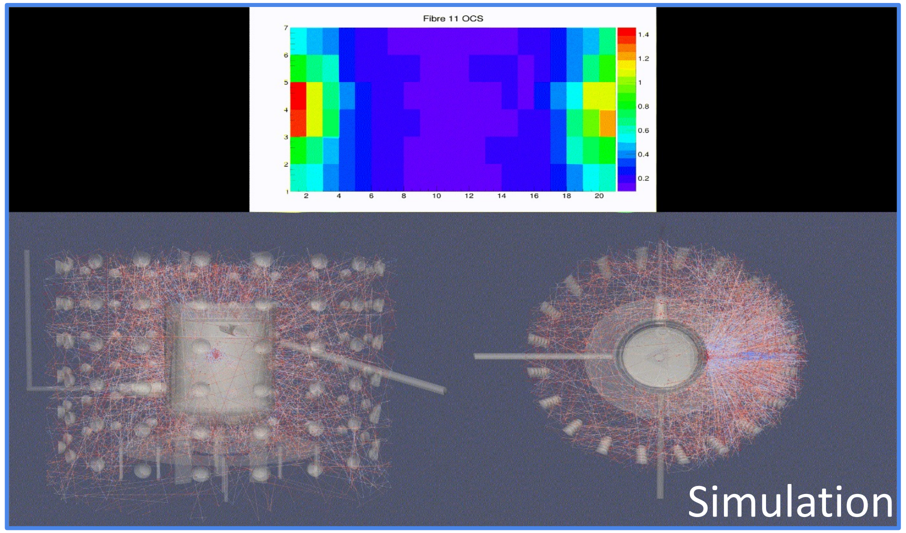
- XENONnT seem to have lower background rate from OD PMTs which could be due to their arrangements
- Only PMT face is inside the optical volume while the main PMT body is outside
- Bodies of LZ PMTs are inside the optical volume though they are screened → signals from the PMT background radiation could be contributing to the background rate
- Not a big effect if they are in water but could be significant if they are in the scintillating medium.



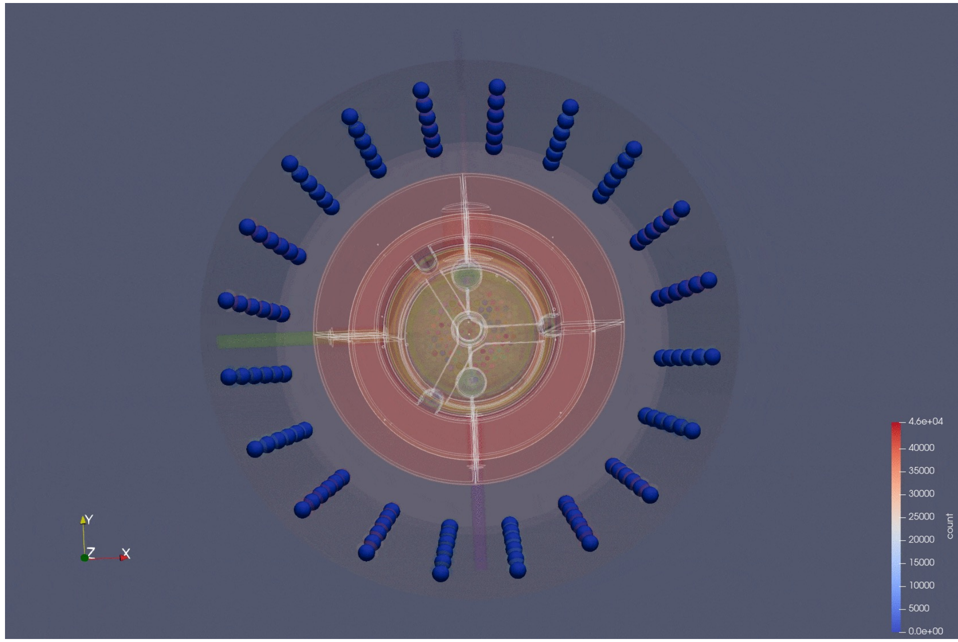


LZ’s OD Optical Calibration System (OCS)

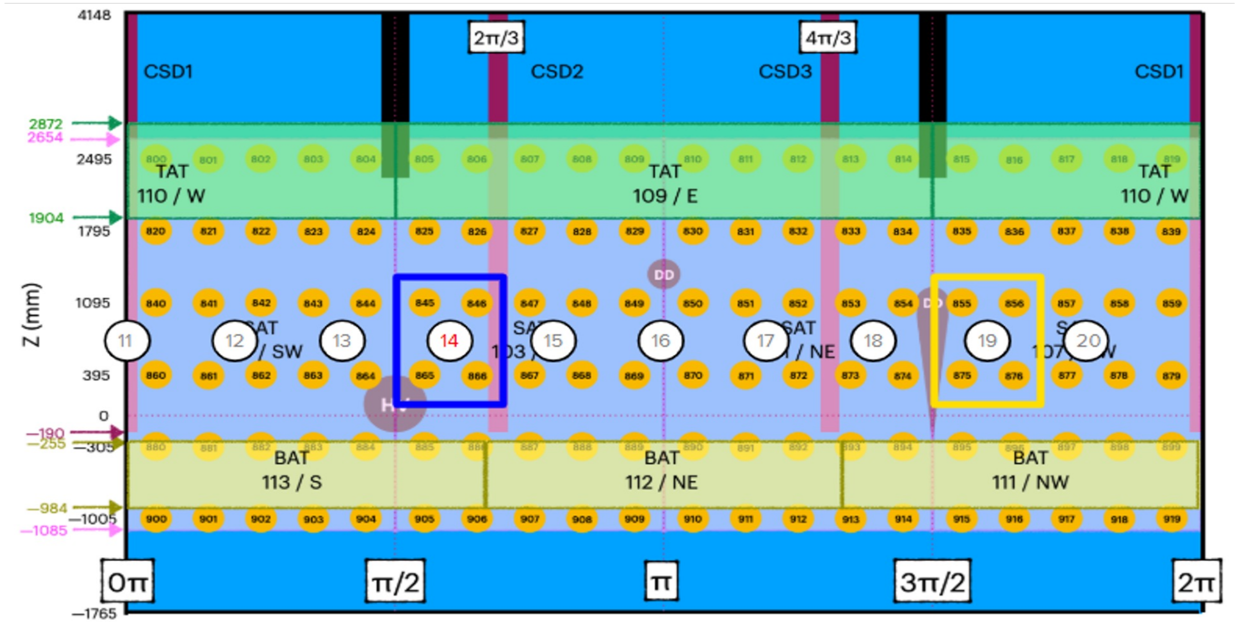


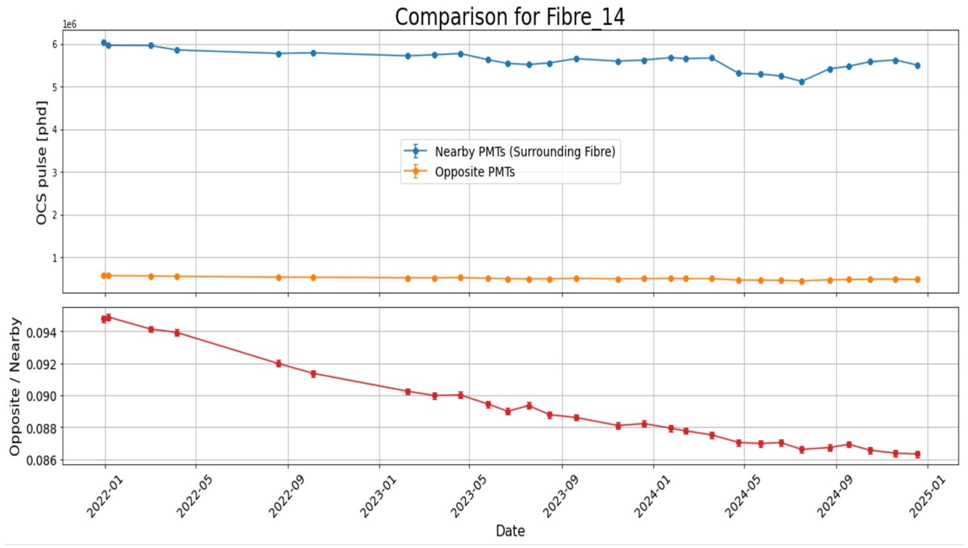


- 35 light injection points
  - 5 injection points have two wavelengths
- Gain calibration
- Stability Monitoring

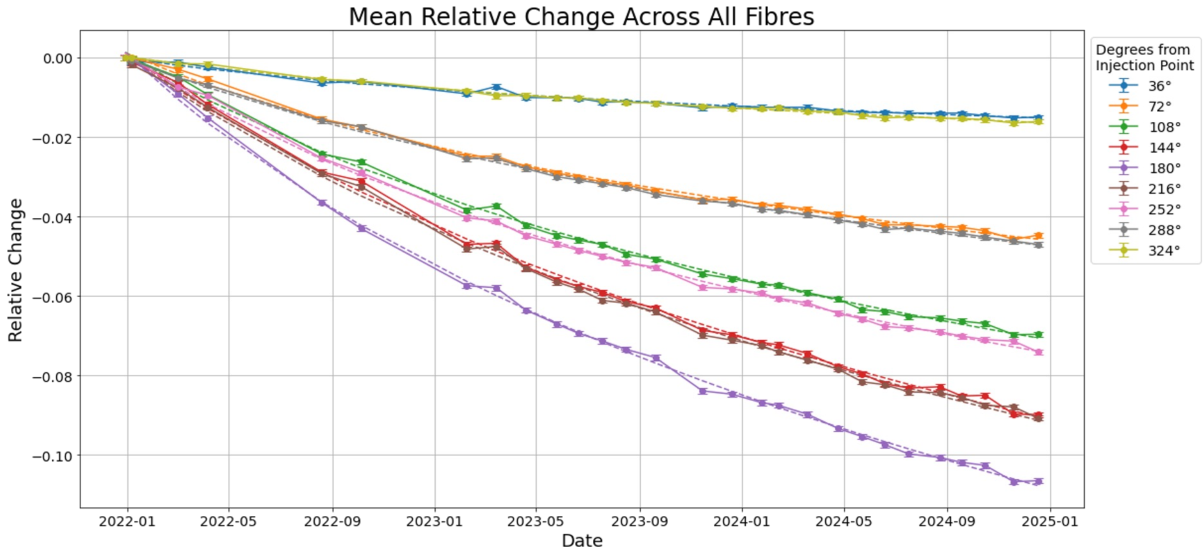


OCS for light transmission monitoring in the OD

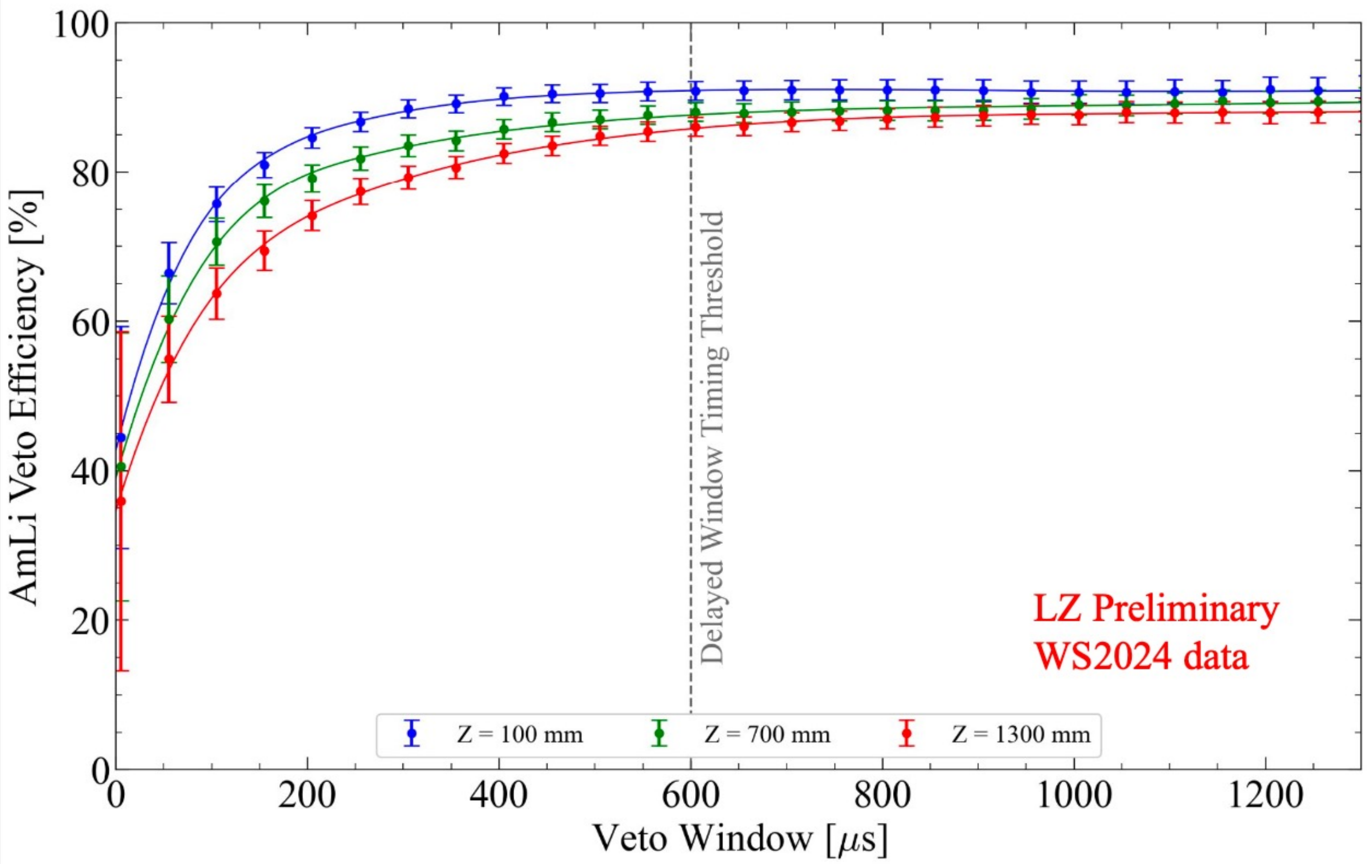


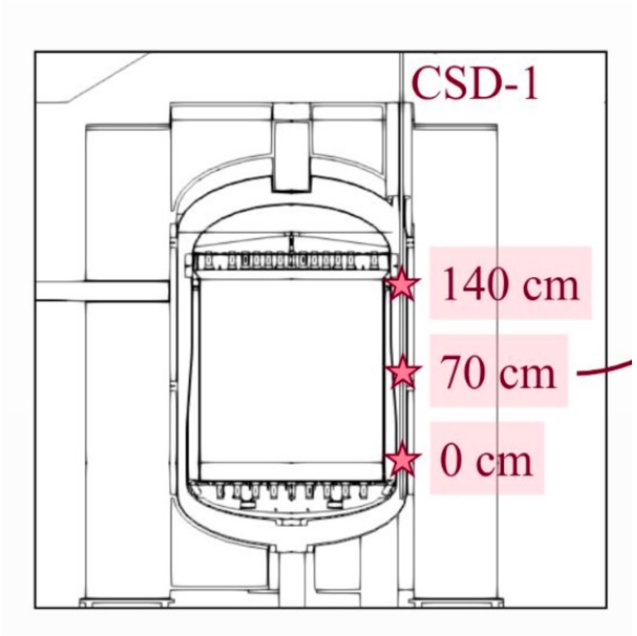


- Many light injection points and comparison of PMT signals near and far from the light injection allow monitoring stability of light transmission
- ~10% light transmission degradation over 3 years has been observed
  - Gd-LS has a very high light yield → Neutron veto efficiency is not affected
- **Lessons**
  - **Rigorous calibration systems can not be underestimated**
  - **There is no circulation system for Gd-LS which could be a reason for the light transmission degradation**



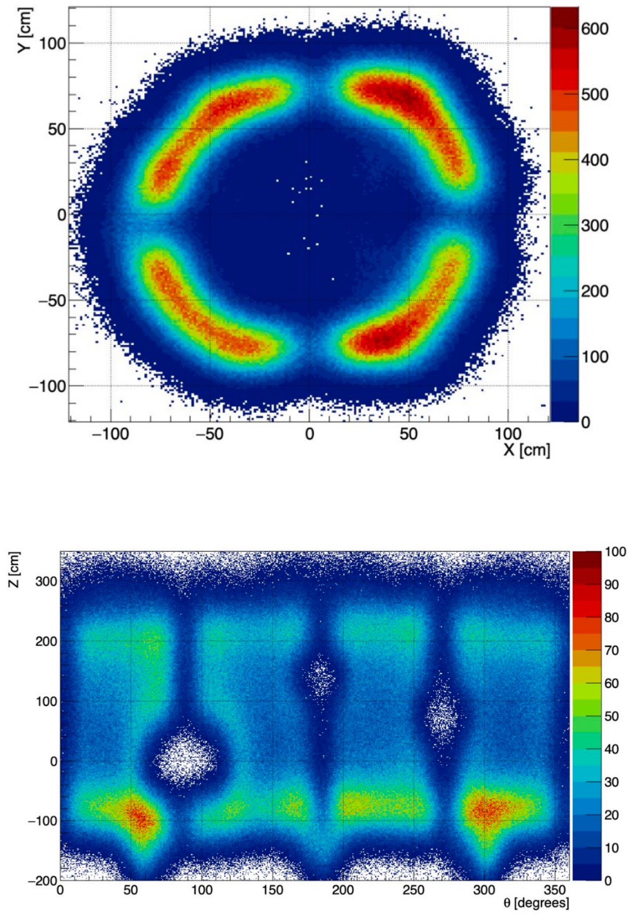
LZ’s Neutron Tagging Efficiency versus position



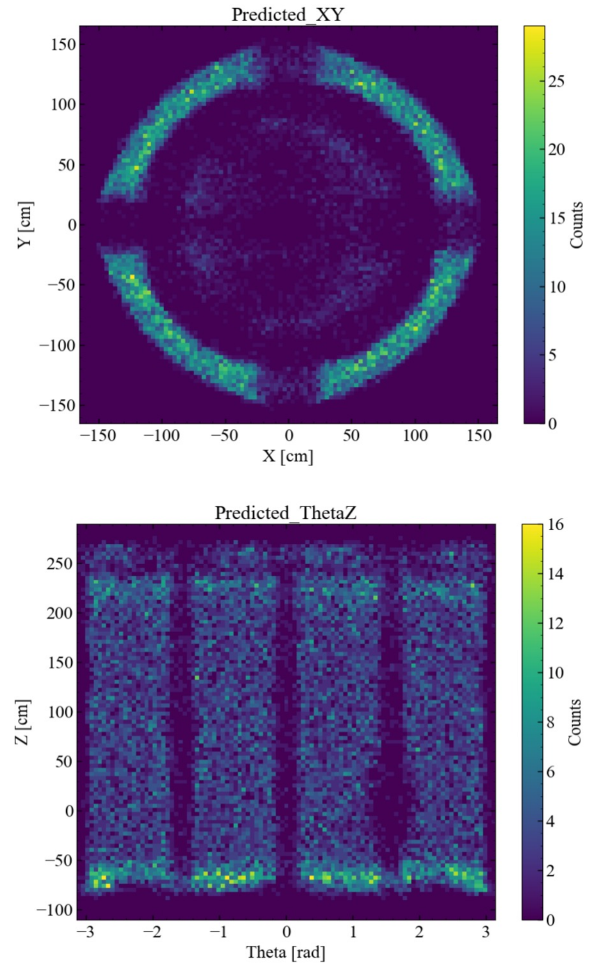


- Sources of OD inefficiency
  - Neutron capture on H in LS, acrylic, water and foam.
    - Just one 2.2 MeV γ ray released which can escape without depositing energy.
  - Neutrons wander around in the acrylic for too long, hence a longer veto window.
  - Energy deposited is below threshold (nominal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

Using ML Algorithms



Centre of gravity method

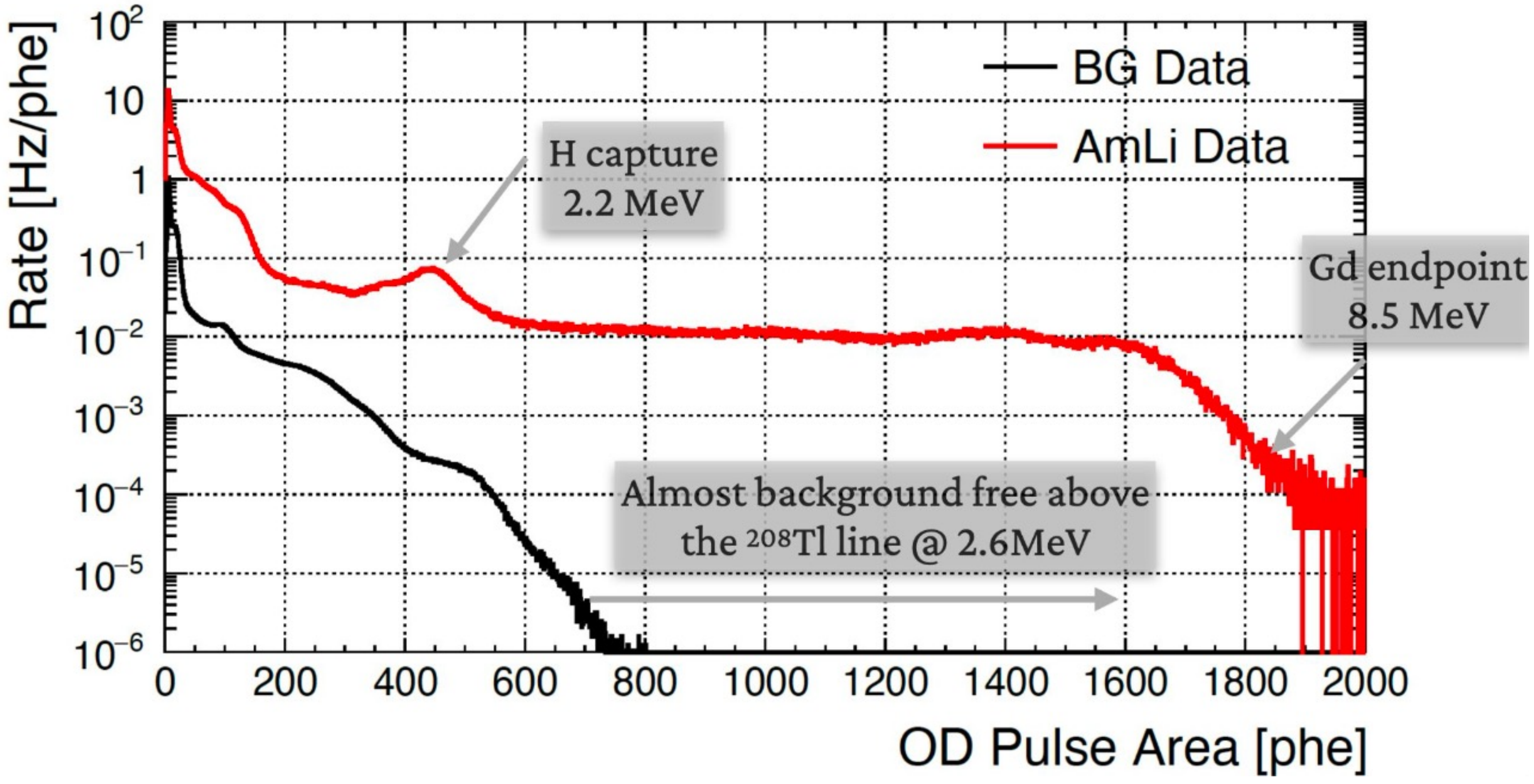


CNN

Convolutional neural network (CNN) is currently being made and trained to make accurate predictions of event positions and their energy depositions within the OD scintillator tanks.

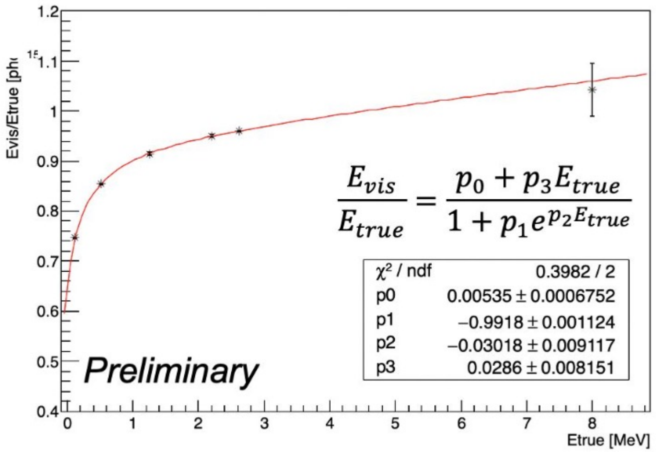
It could be beneficial to use the ML algorithms during the OD design

OD energy calibration



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



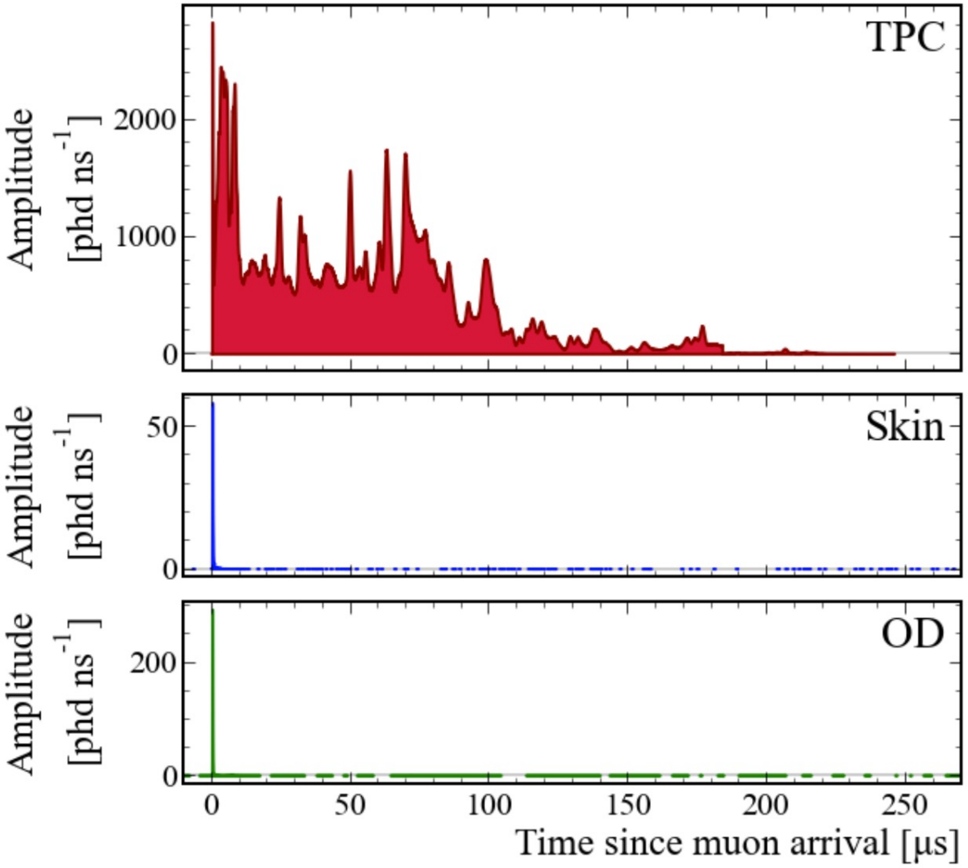
$$\frac{E_{vis}}{E_{true}} = \frac{p_0 + p_3 E_{true}}{1 + p_1 e^{p_2 E_{true}}}$$

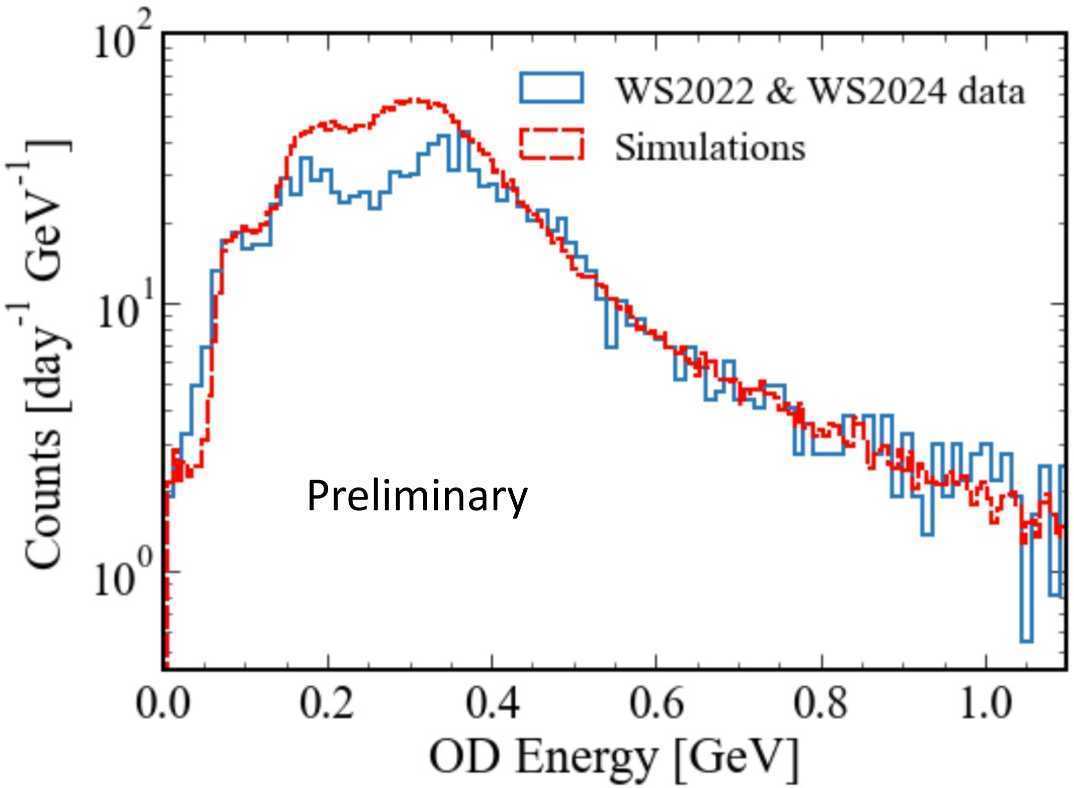
E_{true} is the true energy deposited in the GdLS
E_{vis} is the visible energy accounting for nonlinear GdLS response

- A clear hydrogen capture peak and gadolinium end point help the energy calibration

Muon Flux Measurements in LZ

Muon signal in LZ





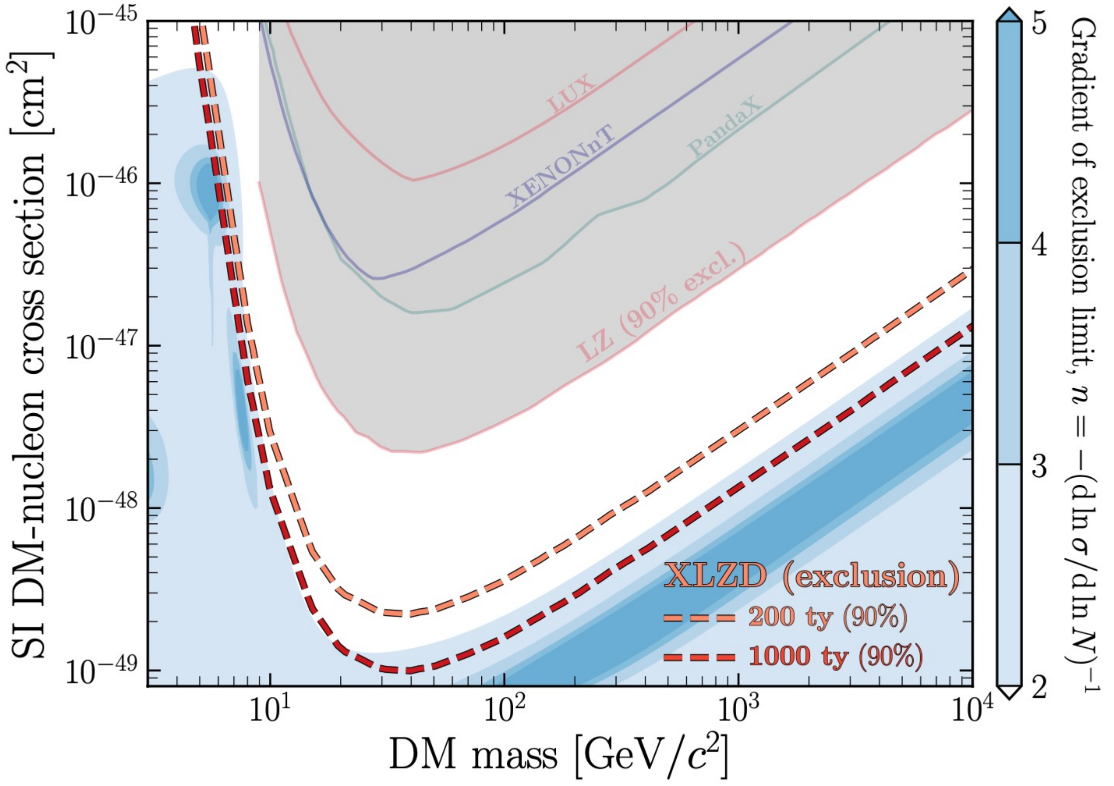
- Measurements show ~15% lower muon rate than predicted by simulation
- TPC PMTs are saturated by muons → measurements in the OD are essential

XLZD Outer Detector optimisation

- Optimisation with respect to efficiency and dead time
- Parameters
  - Dimensions
  - Medium
    - Material compatibility
    - Addition containment may be necessary
  - Location, number and type of photosensors

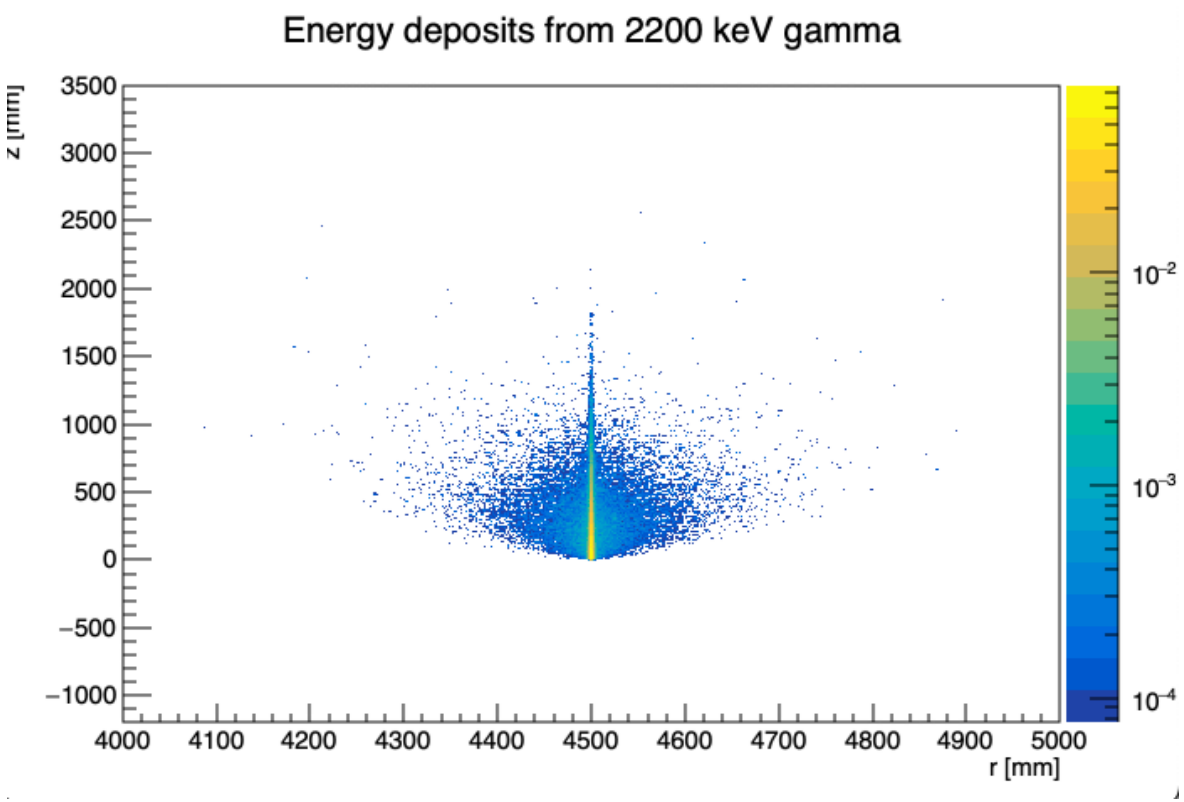
OD Efficiency and dead time

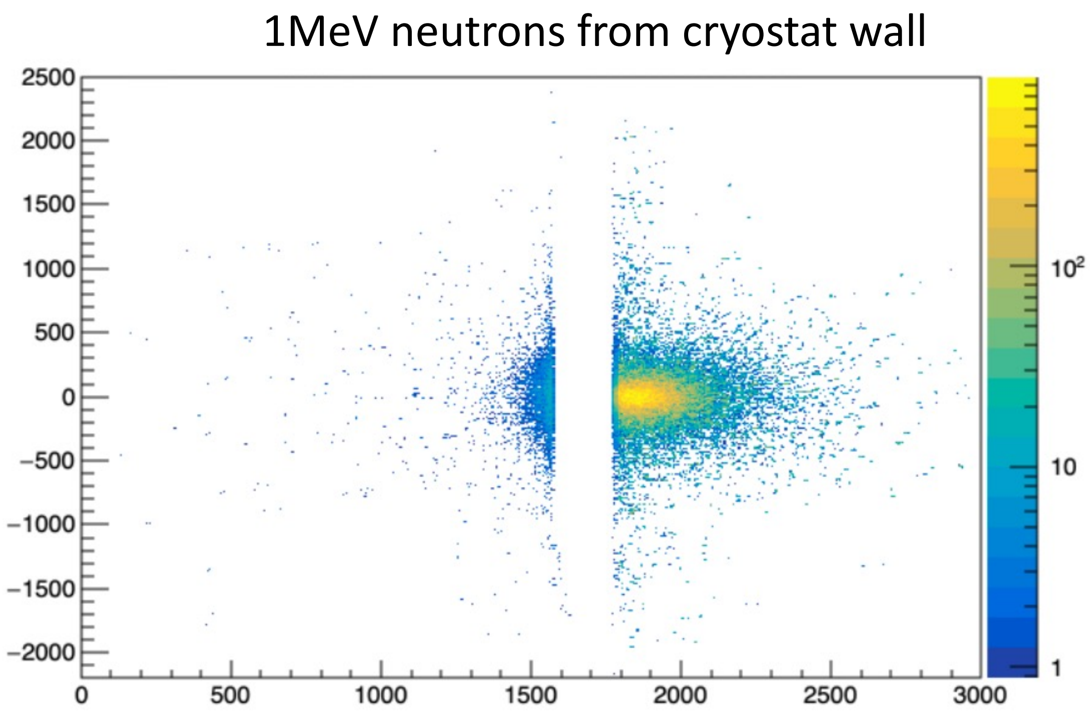
- XLZD sensitivity should be limited by neutrino fog → number of neutron background events during all the exposure time should be ~10-20% of the expected number of neutrino fog events
  - 1-2 neutron events passing the veto
  - Current neutron background estimate leads to ~91% neutron tagging efficiency →~10 times suppression
  - We shall add a possible systematic uncertainty (~4%) due to non-perfect modelling of the detector → we should aim at ~95%
- The dead time is due to applying veto to random coincidences of the signal in the OD and TPC and the fraction could be estimated as the product of width of the neutron veto (~500 μs) and background rate in the OD
  - Requiring 5% dead time → ~100 Hz background rate

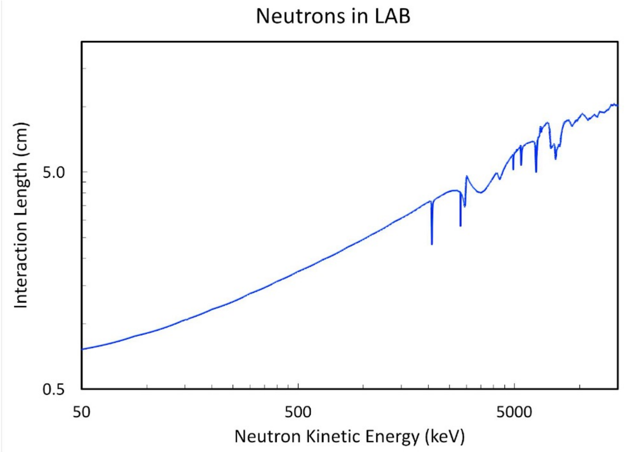


There are uncertainties in the neutrino fog level at different locations and constraints from BUTTON or even the OD would be very useful

Characteristic lengths in OD

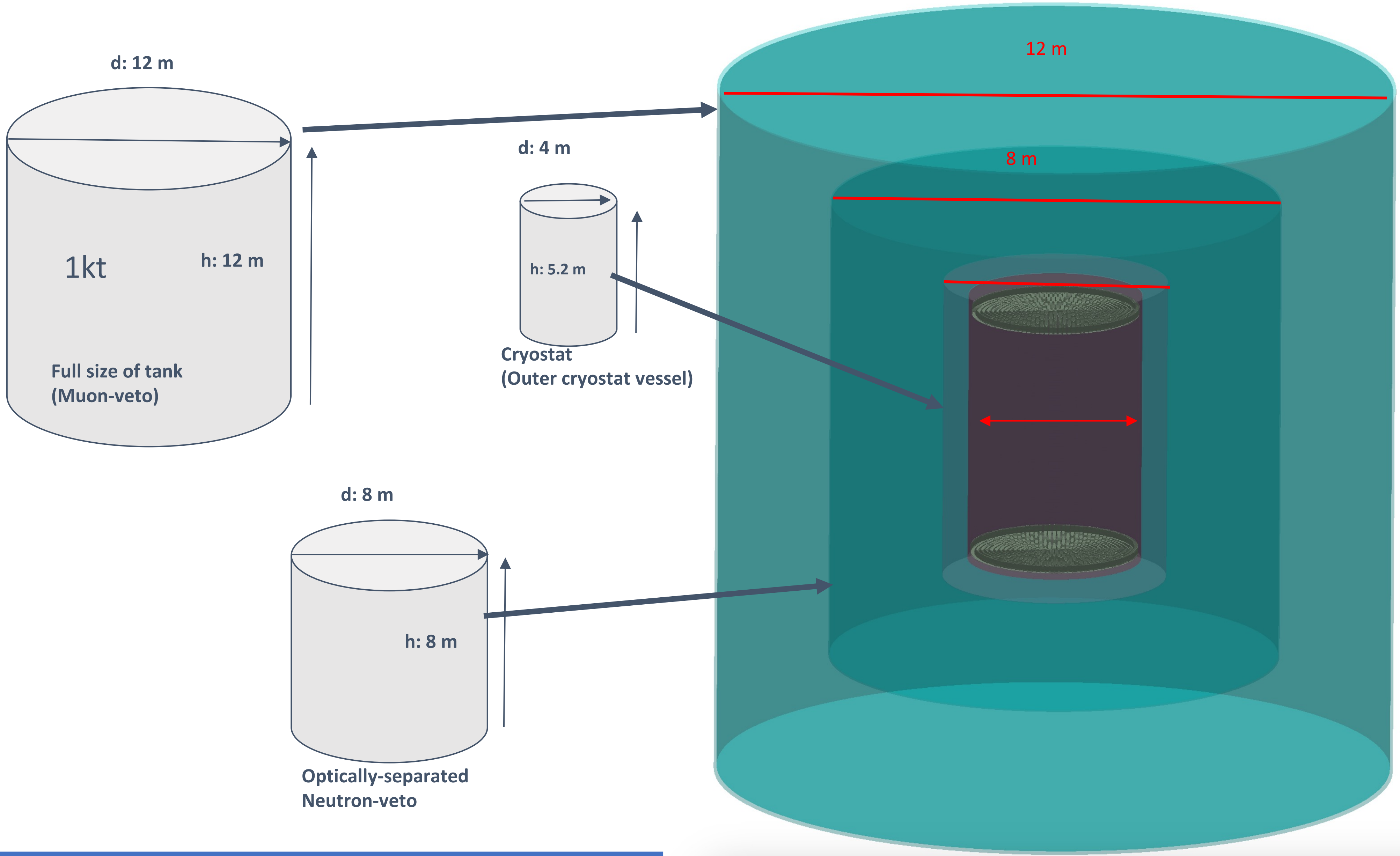






- ~2m of water is enough to attenuate the external (~2MeV) gamma background to ~1% level
  - ~1m of water (or a scintillator) is enough to detect gammas with high efficiency
- ~1m of water (or a scintillator) is enough to detect neutrons

OD Dimensions

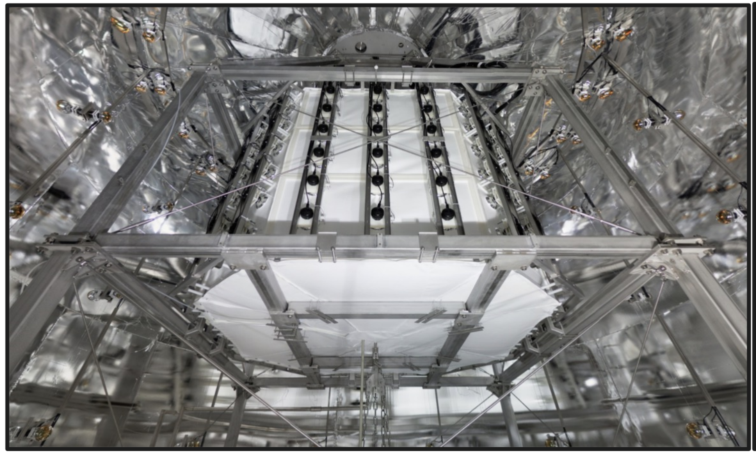


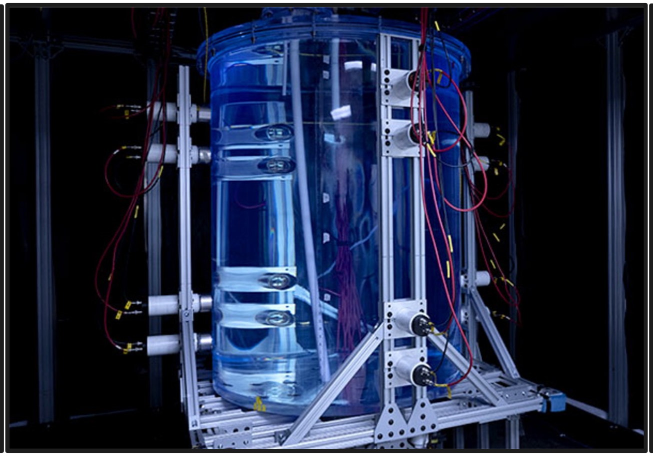
Possible medium options…

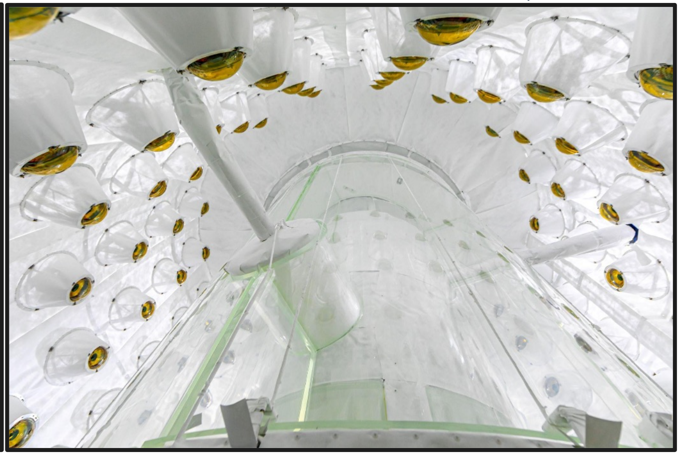
Option	Gd	Example Technology	Pros	Cons	Uncertainties	Design Implications
Water	N **Y**	Many **XENONnT** **EGADS**	Simple Safe Experience from LZ (water) and XENON (Gd-water)	Lowest LY (**~10 photons/MeV**) No access to low thresholds or additional physics Lower efficiency	Does Gd lower LY?	Circulation system Purification/filtering UV treatment
LS	N **Y**	Daya Bay, **LZ, Daya Bay**	High LY (**~10k photons/MeV**) LZ experience Access to widest range of physics (0vbb etc)	More H&S considerations Transportation of 1kT of liquid Higher background rate (^{14}C) Acrylic manufacture	Is cryostat suspended or on legs + geometry? (Implications for acrylic tank) Manufacturers Flammability? **Are there alternatives to acrylic?**	PMTs need standoff - additional tank (acrylic) Circulation not necessary? Need some sort of vent/reservoir + nitrogen blanketed
WbLS	N **Y**	EOS **BUTTON, THEIA**	Safer than LS Lower BG than LS Undergoing protoyping by BNL, BUTTON	Low LY (**100-1000 photons/MeV**) Gd-loading not demonstrated above 1% LS yet PMT rate → high threshold	Possible bacterial problem High circulation rate needed? How much does Gd lower the light yield? Does separation of LS from WbLS damage it? Temperature control? Material compatibility with reflectors?	Need complex 2/3 stage purification/filtering system Additional tank seems to be needed Nitrogen blanket
Solid	N Y	Many ZEPLIN-III, Darkside-20K	Much easier handling and installation than liquid Good LY ~ 5500 ph/MeV (ZEPLIN-III)	Hard to avoid gaps around cryostat Is having the solid scintillator inside the cryostat an option?		Stacked scintillator bars? PMT support etc would look very different, smaller PMTs? Surrounded by water
Opaque/Cold	N Y	LiquidO, PandaX-xT (design) Untested	High LY (~10K photons/MeV) If PandaX stye, can have thin inner cryostat	Low LCE with WLS fibres (~10%) Additional cooling required (needs to be < 15C) Early stages of development, doping said to be "possible" but not tested yet		Read out with WLS fibres to PMTs or SiPMs Heat exchange needed Could mean serious design changes to cryostat.

OD Medium Options under consideration

Light Yield







Option 1: Gd-Water

XENONnT expertise, Gd-loaded water in entire tank with a smaller optically separated volume for neutrons, outer volume used to detect muons

Option 2: WbLS

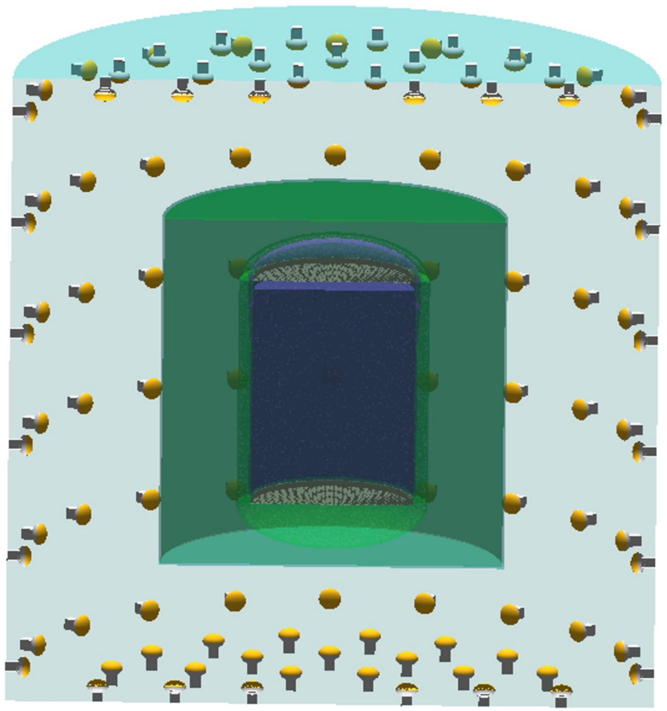
BNL/EOS/BUTTON expertise (but still least well-known option). Water with 1-10% LS component added through surfactant (micelles)

Option 3: GdLS

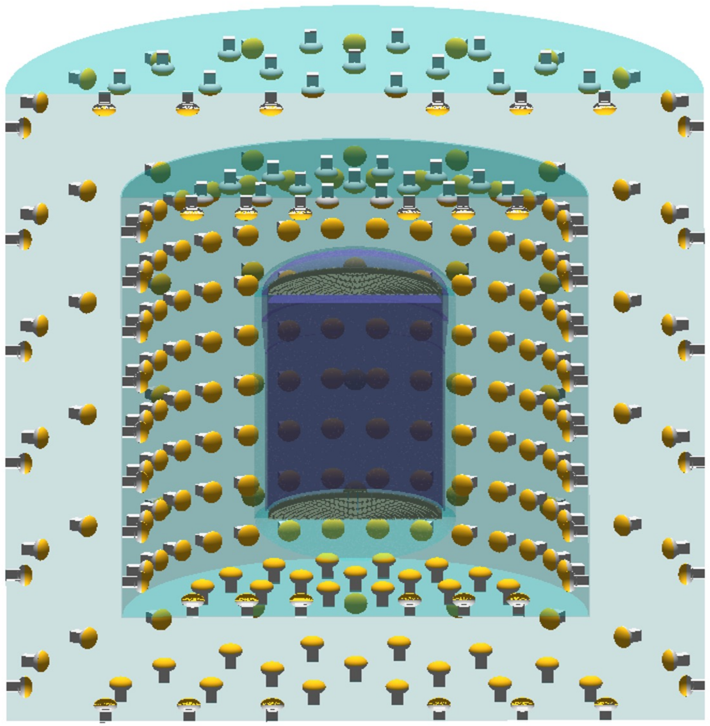
LZ expertise, 100% liquid scintillator. Gd-LAB contained within a vessel surrounding the cryostat.

OD Geometries

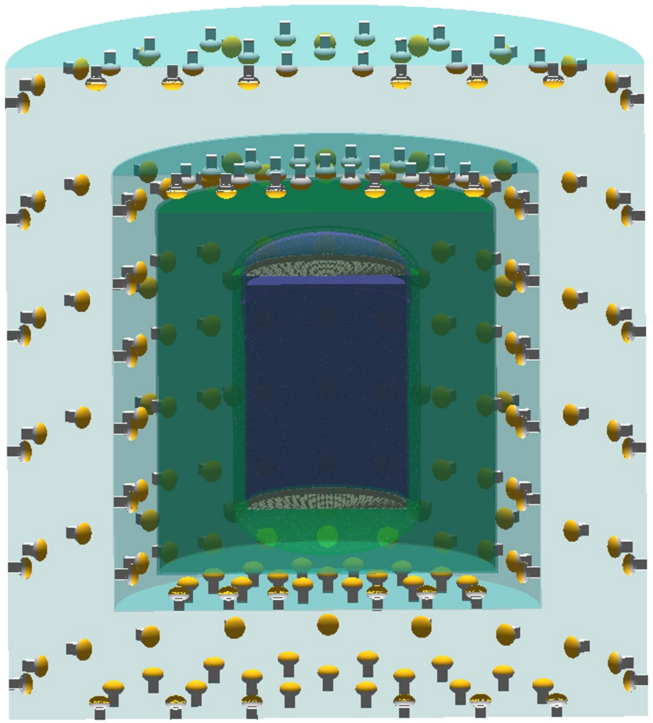
Muon veto with container
192 PMTs



Neutron veto
316 PMTs in neutron veto
192 in muon veto

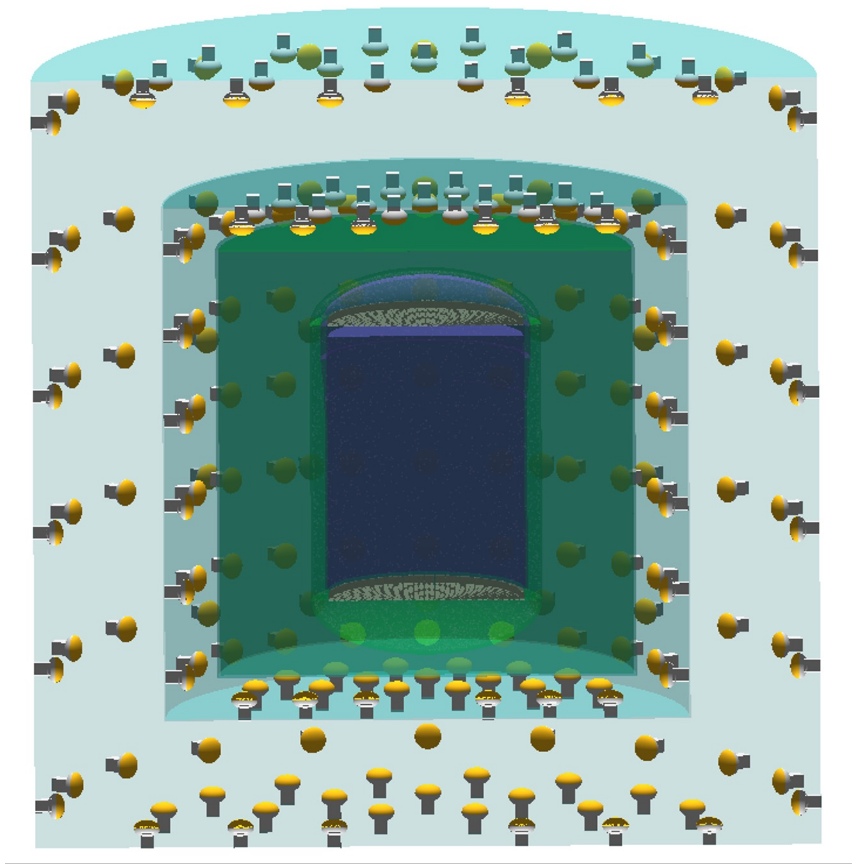


Neutron veto with container and a muon veto
192 PMTs in each



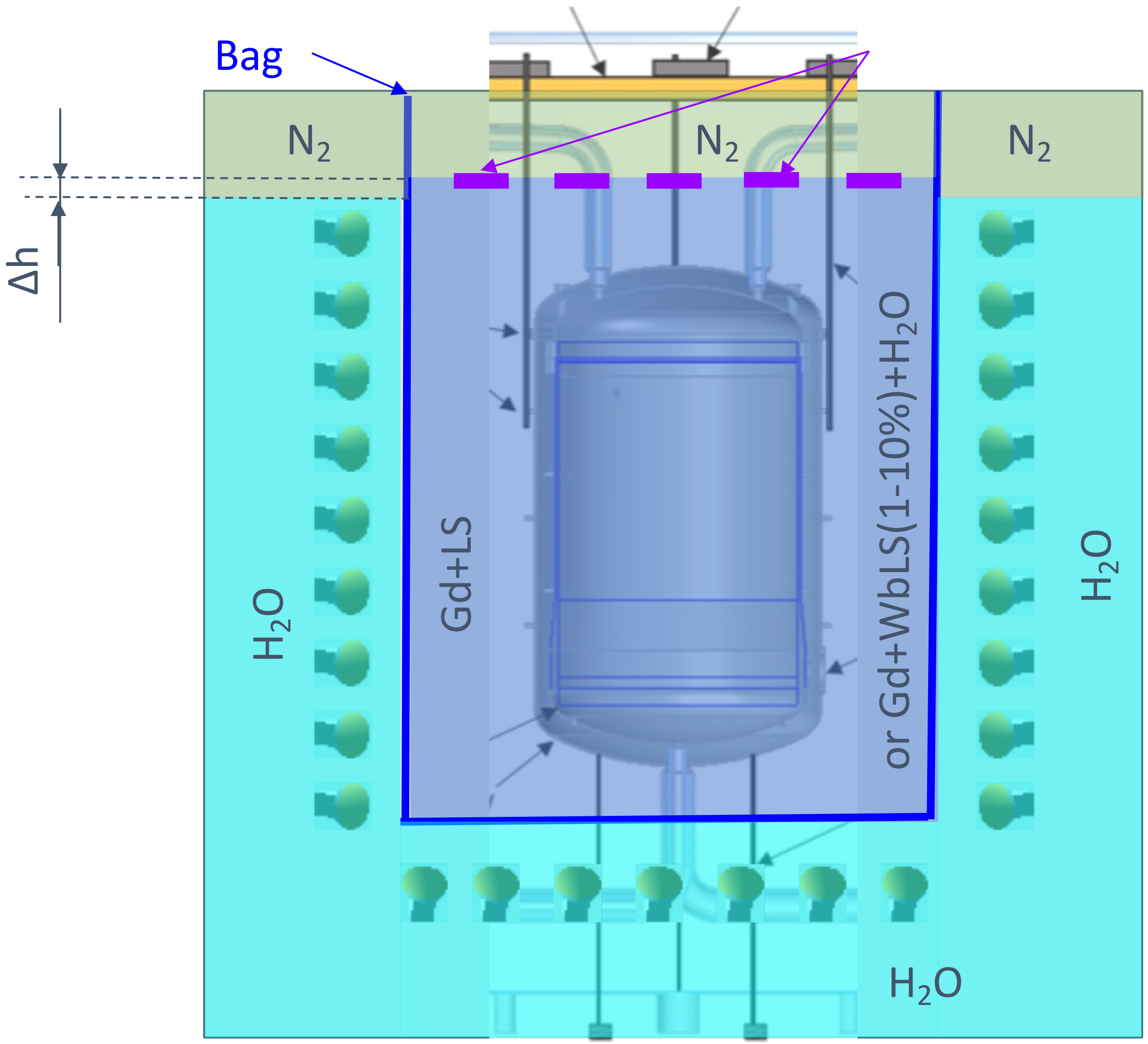
- If PMTs are submerged in WbLS or LS, they produce a very high background rate (from ^{40}K), significantly increasing the dead time
  - Being checked but most probably the scintillation medium should be placed in a containment (acrylic tank?) separated from the PMTs by a ~1m water buffer

A containment for the OD scintillator

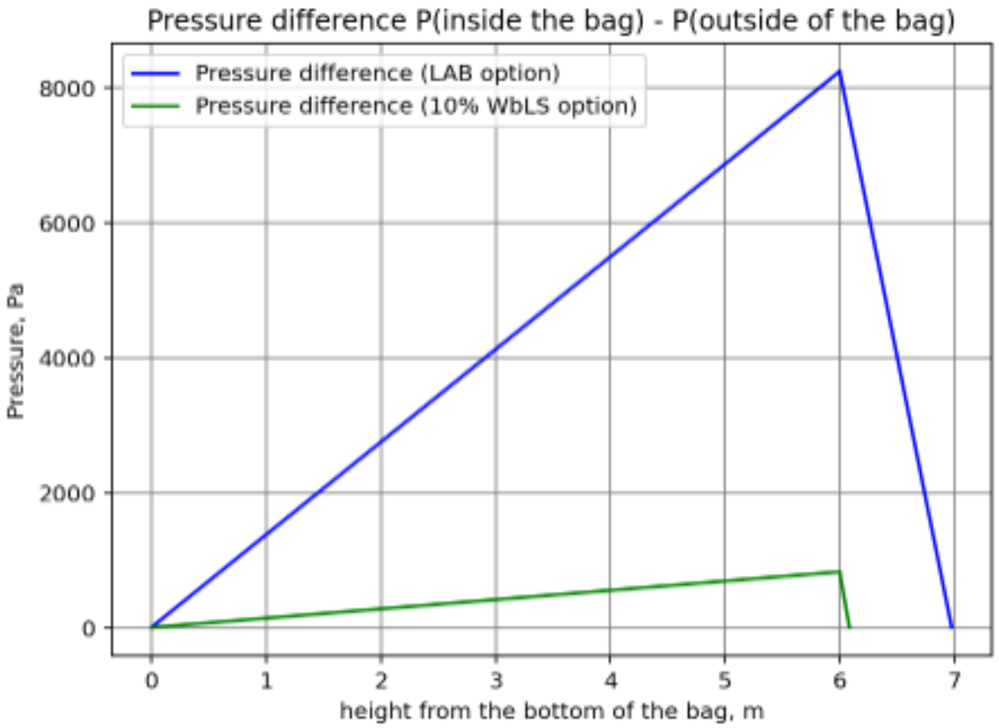


- Acrylic tank surrounding the cryostat represents significant problems for manufacturing and integration
- If the tank is completely submerged under water → significant buoyant force due to the density differences between LS/WbLS and water
  - The volume inside the tank is equivalent to ~150 tonnes of water
  - The density difference is 14 % for GdLS or 1-2% for GdWbLS → The buoyant force could be several tonnes

A bag for the OD scintillator?

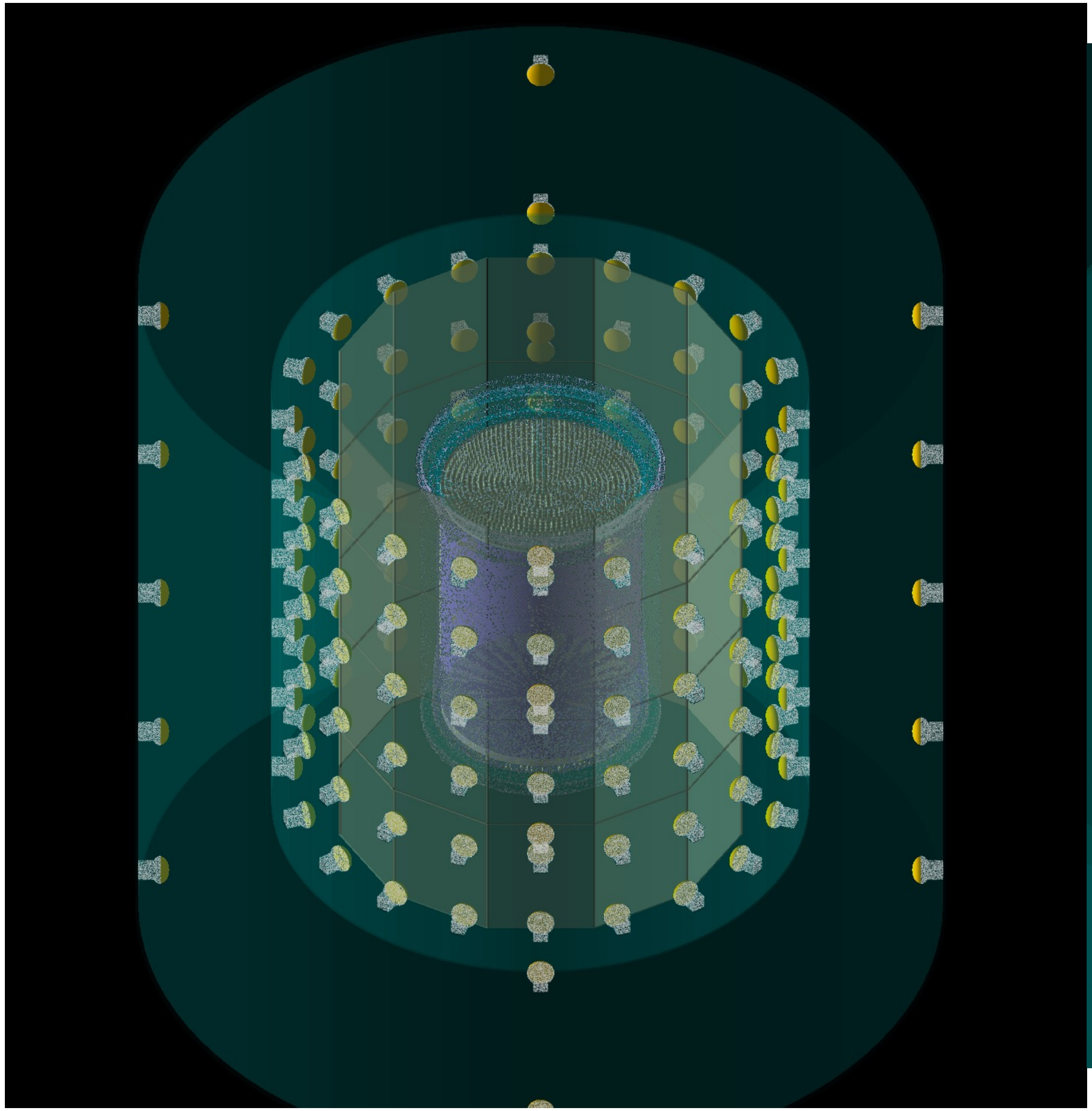


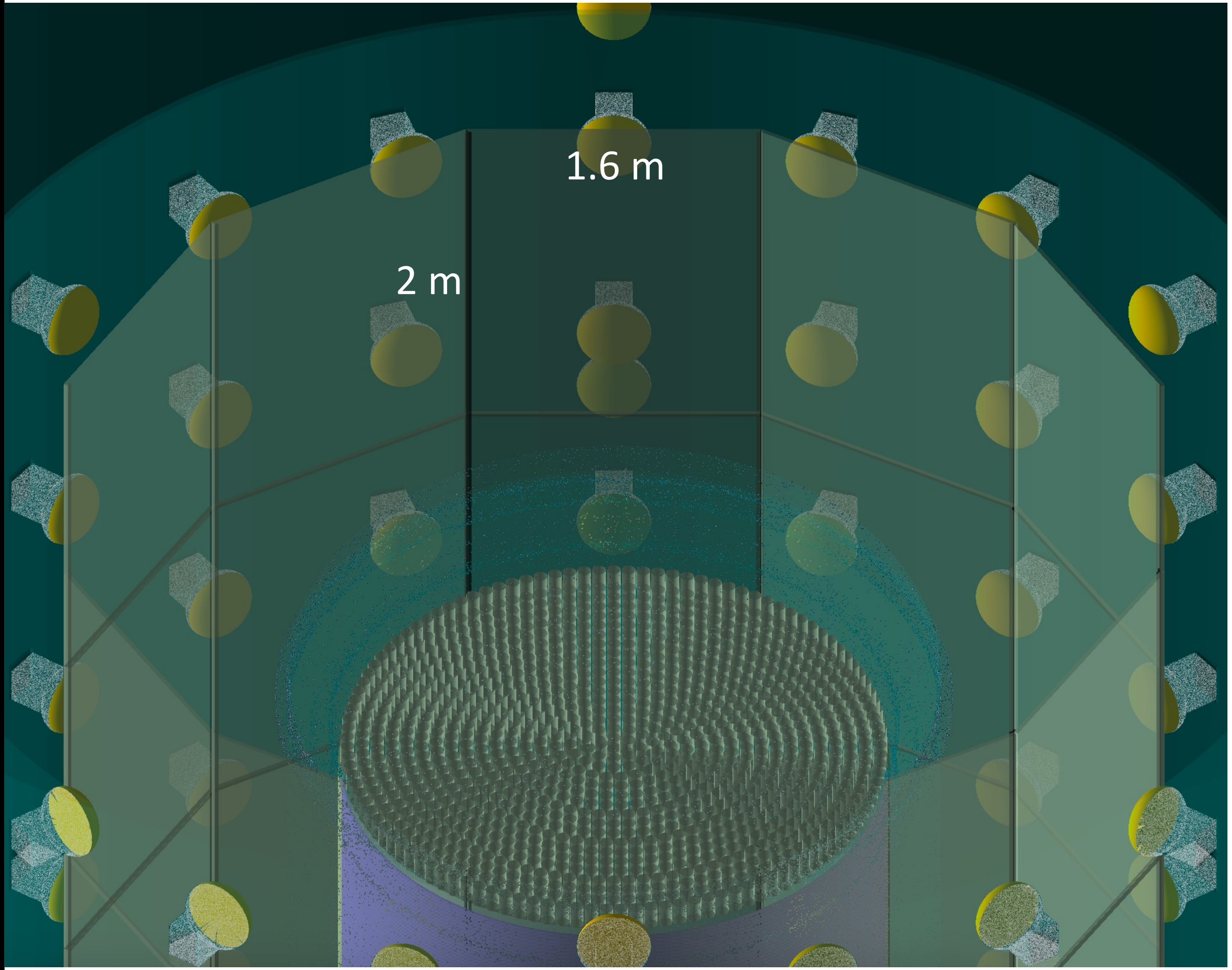
To have balanced pressure at the bottom of the bag we need to add ~1m more LAB (860 kg/m^3) assuming 6m water level from the bottom of the bag which indeed would be quite inconvenient. For 10% WbLS (986 kg/m^3) it will be only 8.5 cm and maximum pressure difference ~800 Pa.



KamLAND-ZEN used a radiopure nylon balloon, but nylon is not compatible with WbLS

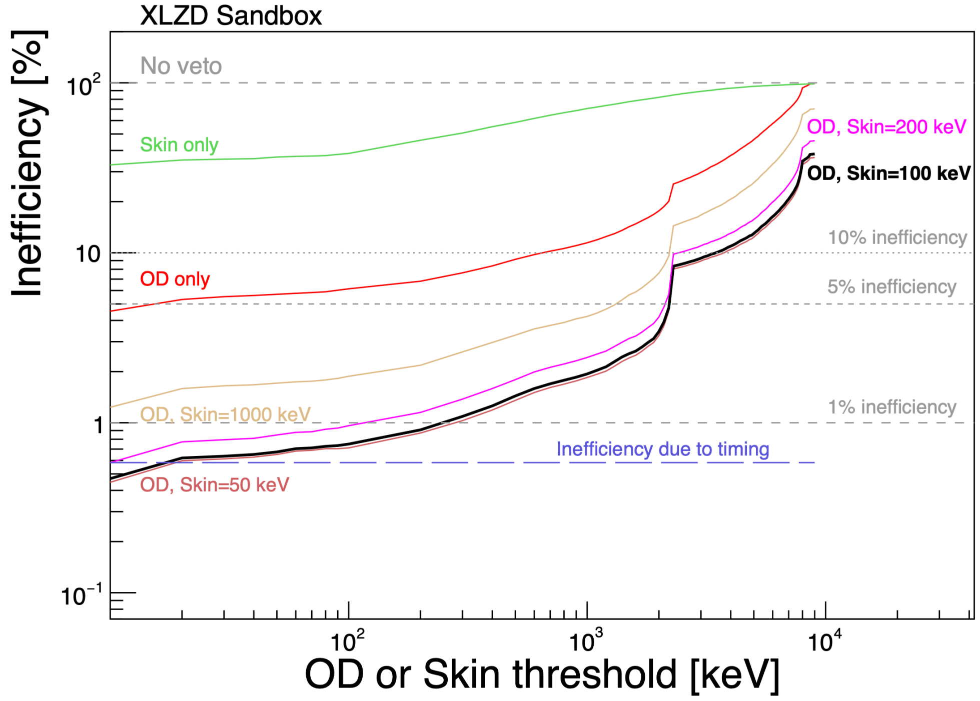
Greenhouse design?

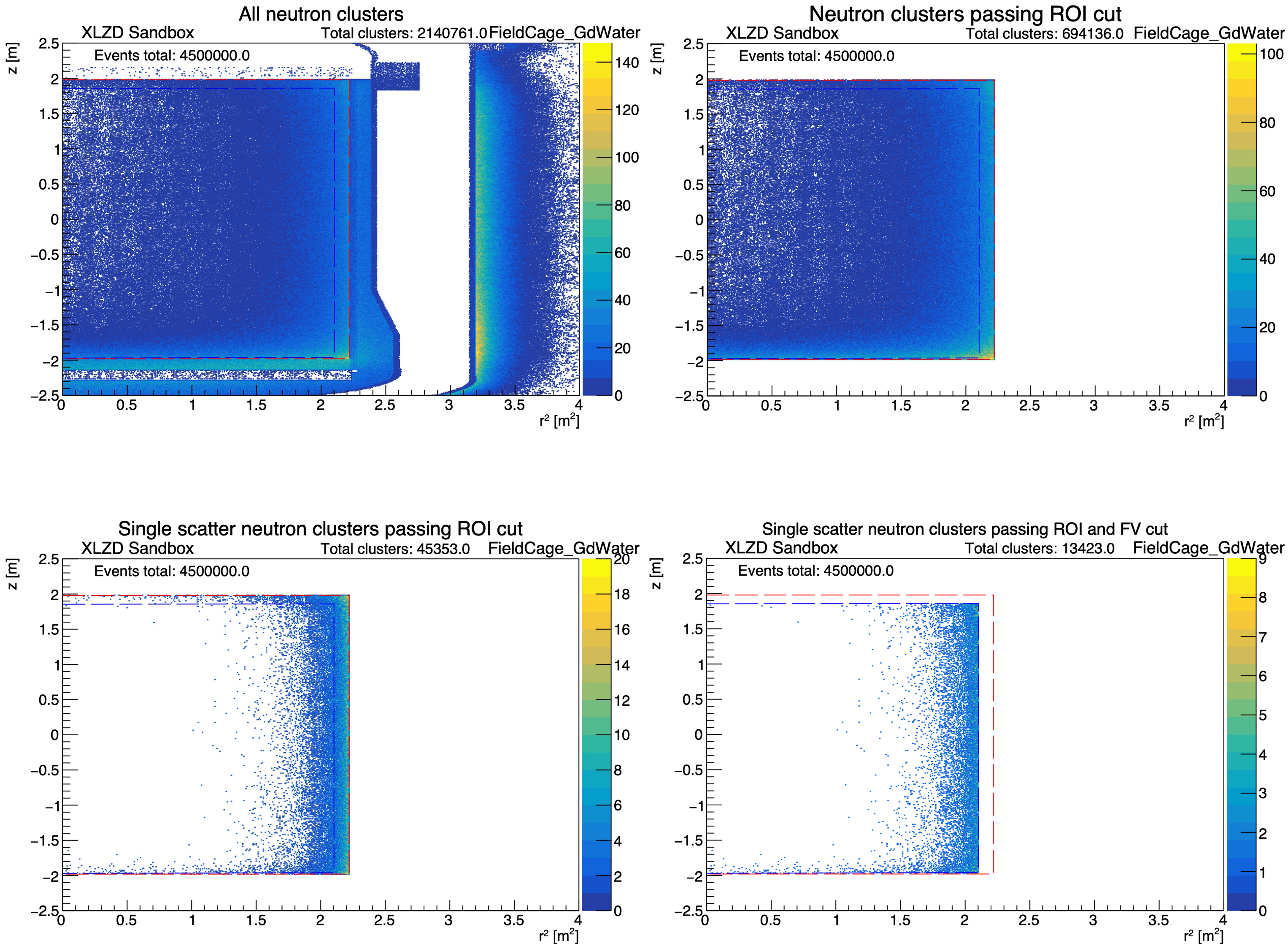




Neutron tagging efficiency versus threshold

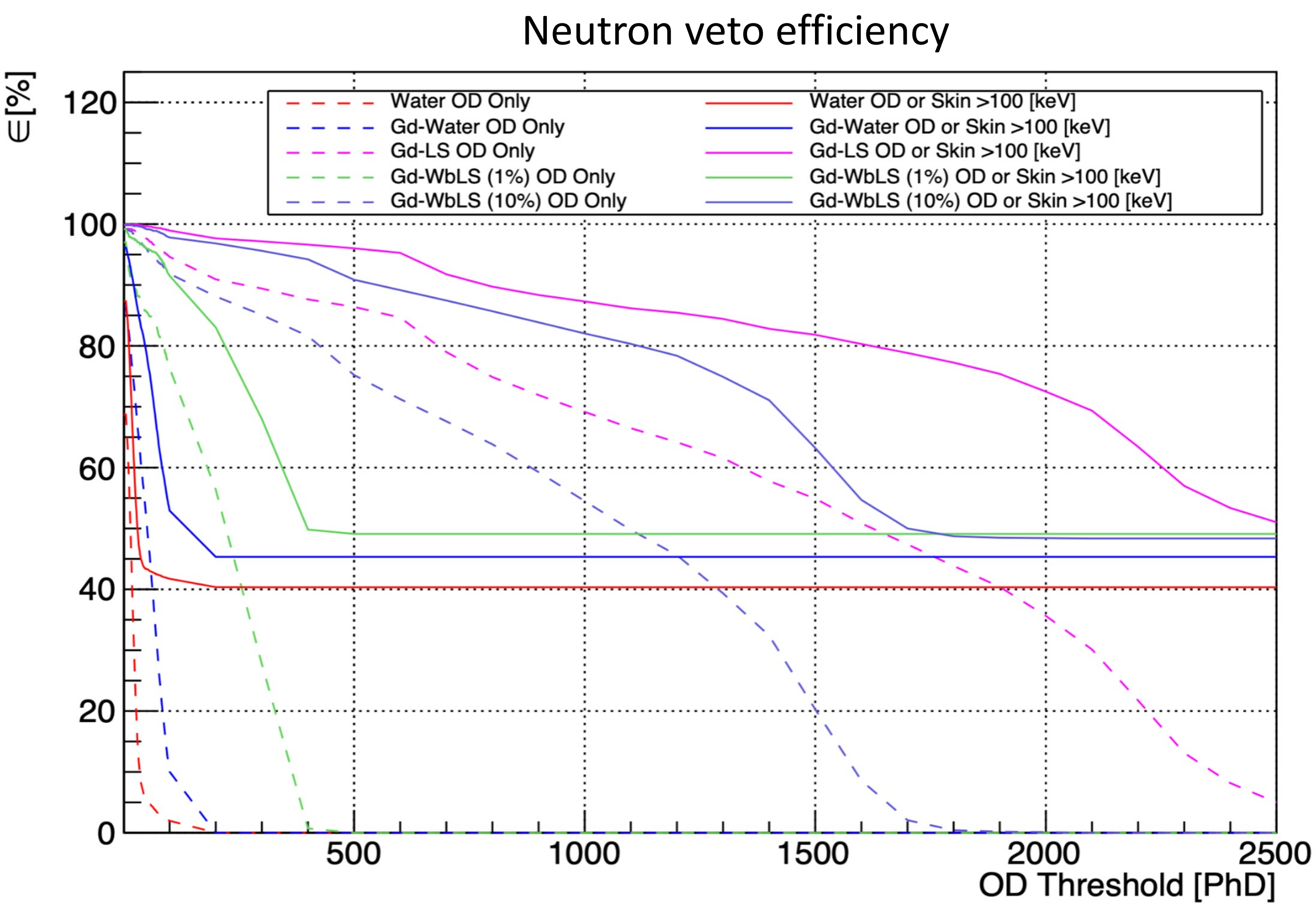
ROI : (6 to 30 keVnr) [keV]
+SS : Check no other neutron cluster is within 600µs time coincidence
+FV : 12 cm from top, 4 cm radially, and 1 cm from cathode

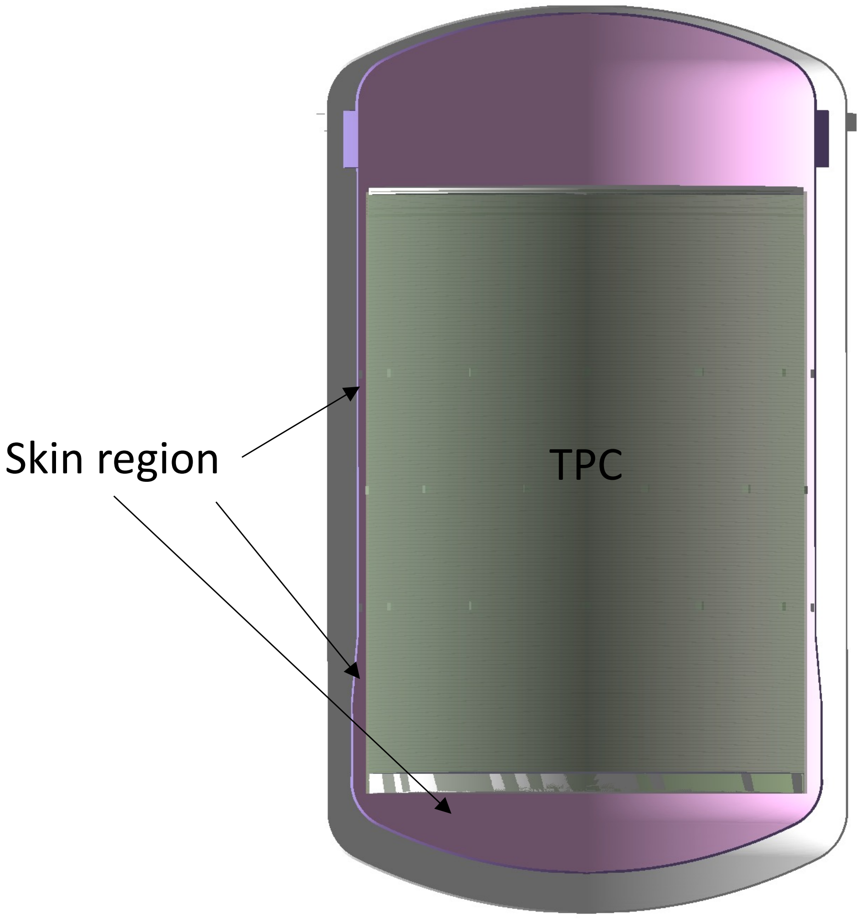




Semi-medium agnostic view (0.1% Gd): Skin + OD can together surpass 95 % tagging efficiency

Neutron tagging efficiency versus OD Threshold

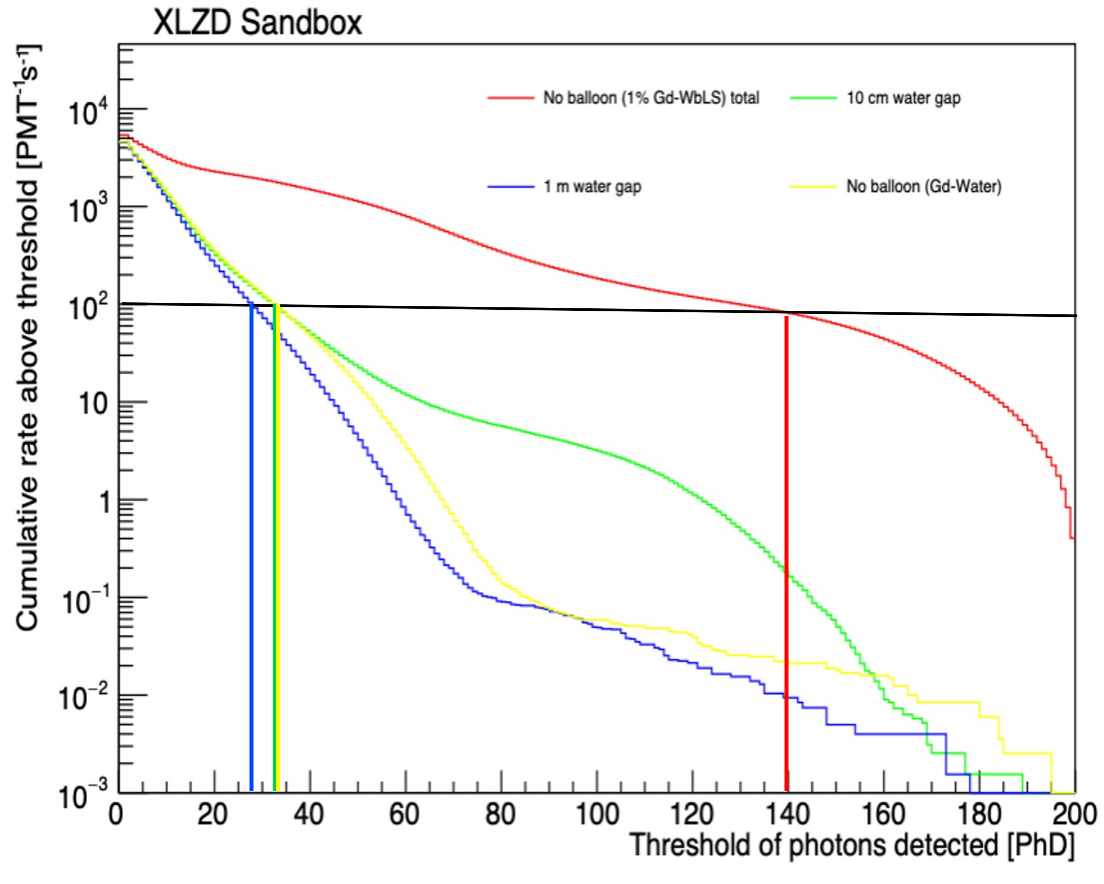




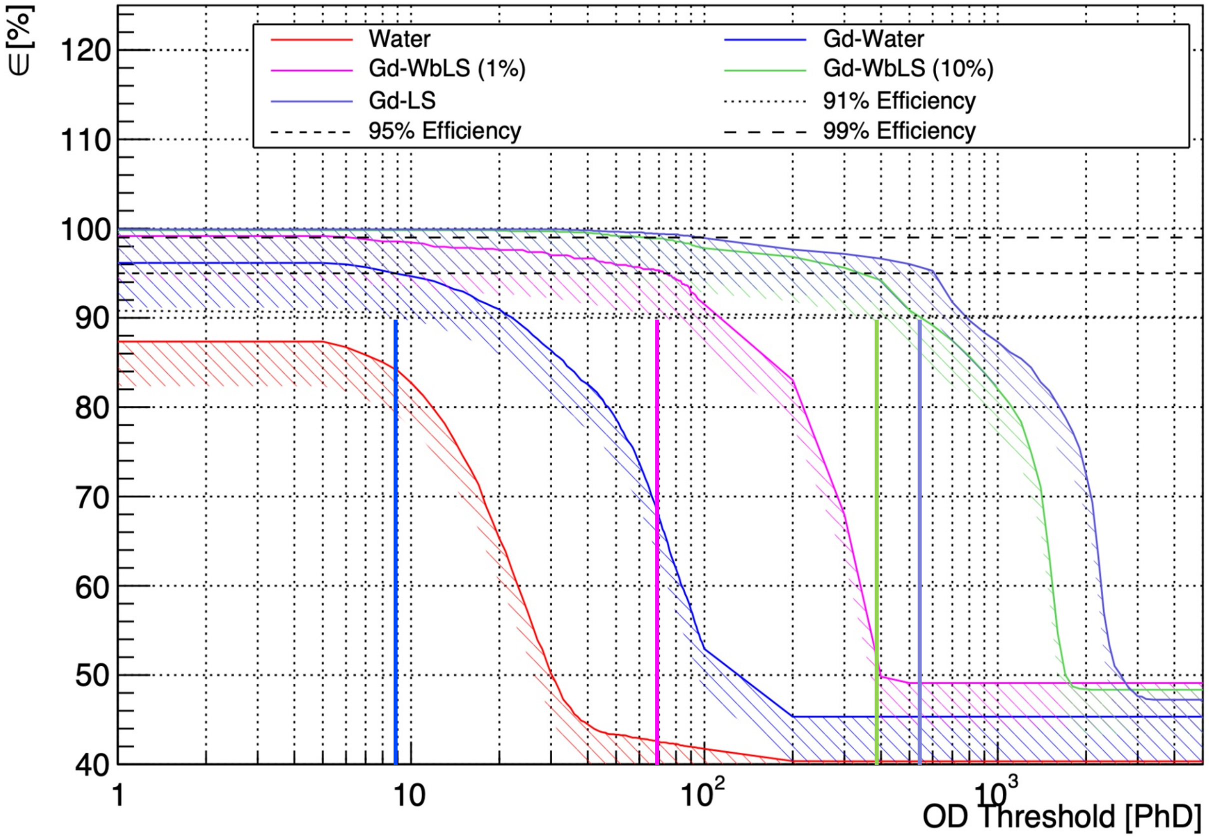
Skin provides an essential contribution to the neutron veto efficiency

Background and Efficiency vs OD Threshold

Background from PMTs



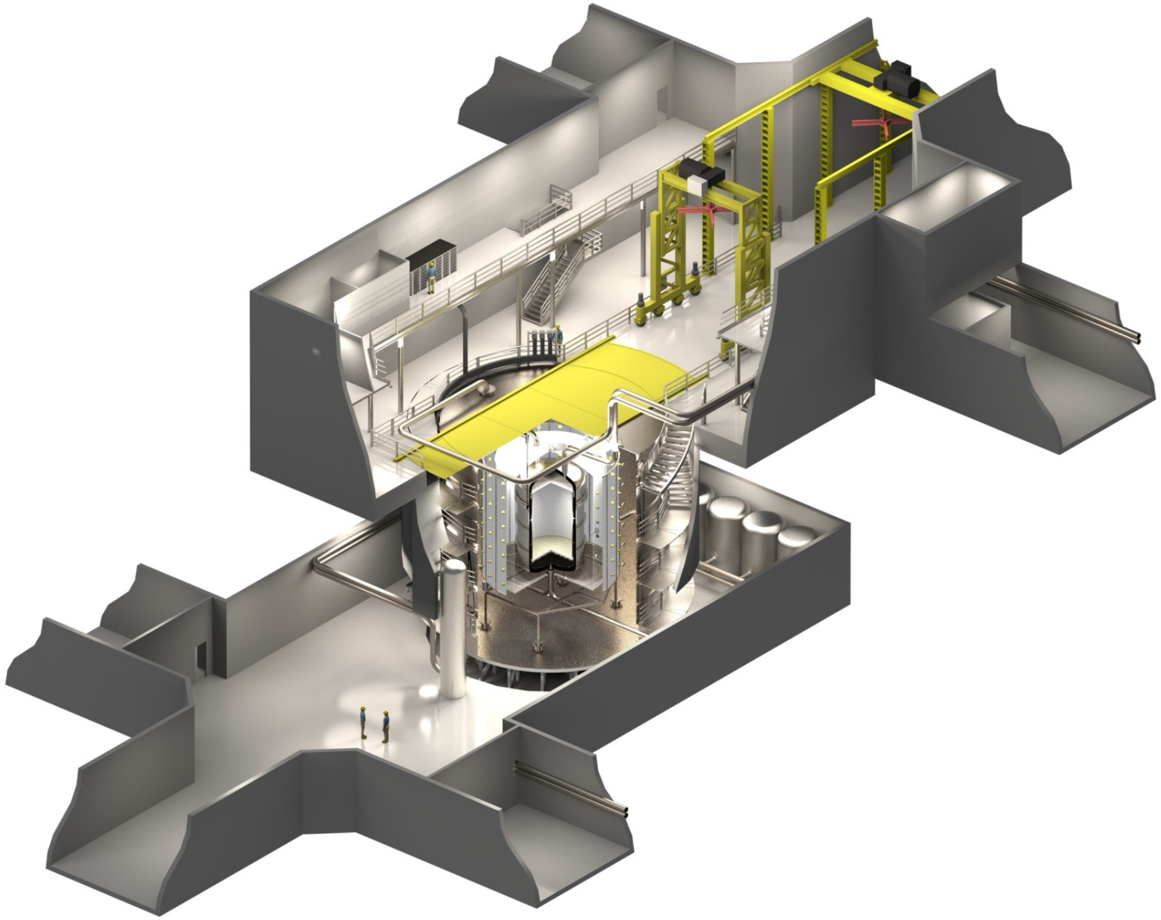
Neutron veto efficiency (assumed skin contribution)



- If the threshold required for neutron veto efficiency is lower than the threshold needed to reduce the background rate below 100 Hz, then this option is not viable.
- So far, the studies show that the Gd+LS and Gd+WbLS satisfy the requirements

Summary

- XLZD presents an exciting opportunity for Dark Matter searches and neutrino physics
  - XLZD@Boulby option is very real
- Lessons from LZ have provided invaluable experience essential for the design of XLZD
- Designing the XLZD Outer Detector represents a multi-factor and complex challenge involving numerous parameters
- Significant progress has been made in understanding the requirements and identifying options which can meet them



backup

Outdated schedule

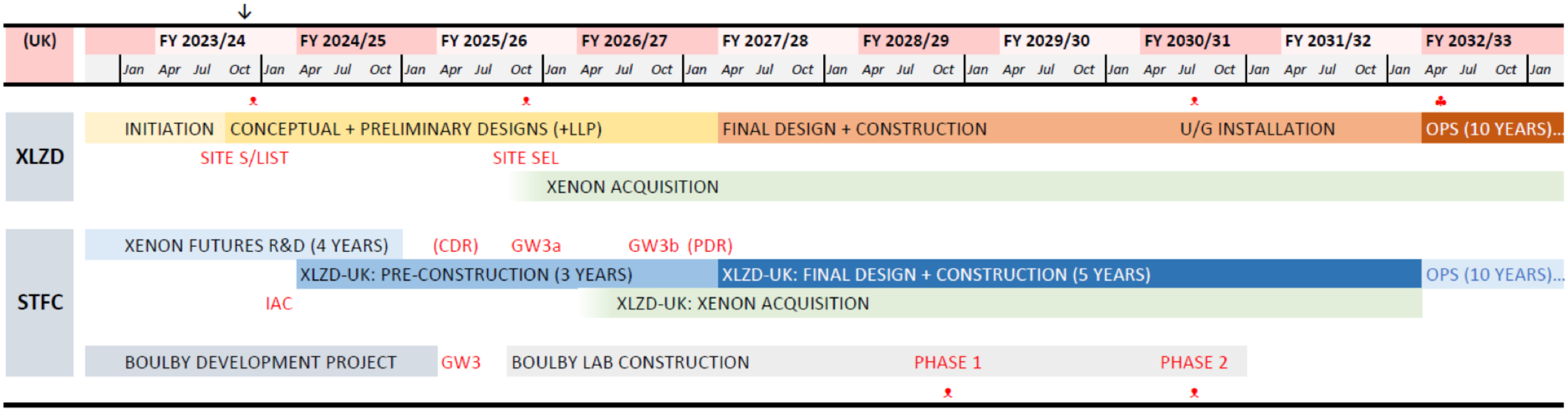


Table 3. Summary of the background assumptions and detector performance parameters used in the two scenarios considered for the sensitivity projections in this study. Irreducible backgrounds from ^{8}B neutrinos and ^{136}Xe $2\nu\beta\beta$ are constant.

Parameter	Scenario: Nominal	Scenario: Optimistic
^{222}Rn concentration [μBq/kg]	0.1	
BiPo tagging efficiency [%]	99.95	99.99
External γ-ray [% LZ]	25	10
Installation site	LNGS	SURF
Energy resolution [%]	0.65	0.60
SS/MS vert. separation [mm]	3	2