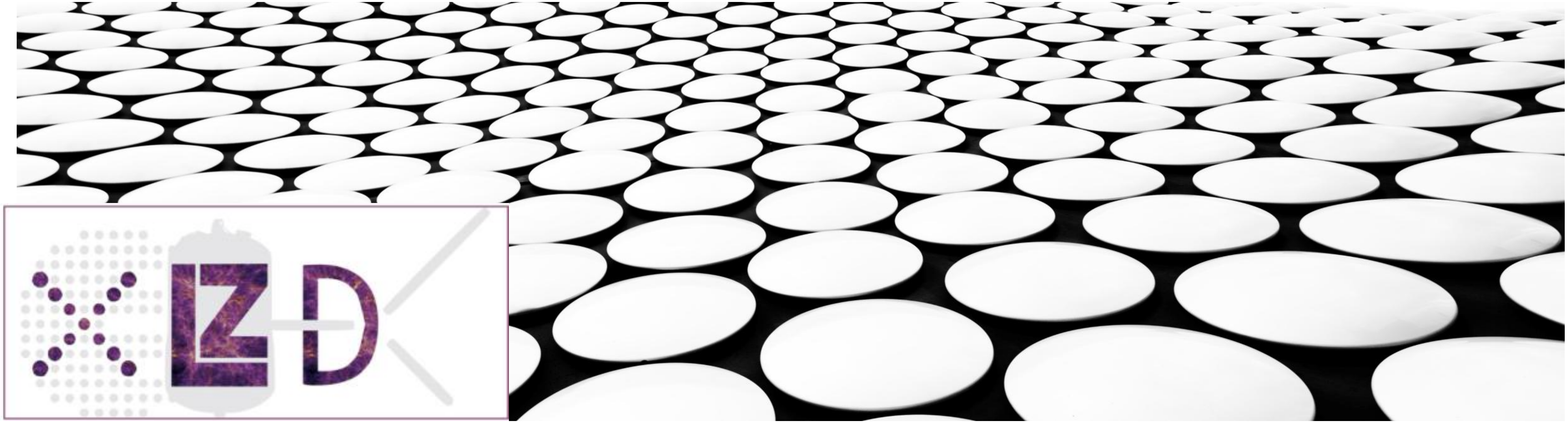
Radiopurity and cleanliness control in XLZD rare event observatory

Ferdos Dastgiri on Behalf of the XLZD Collaboration

University College London

IDENTIFICATION OF DARK MATTER, ZARAGOZA, 2026



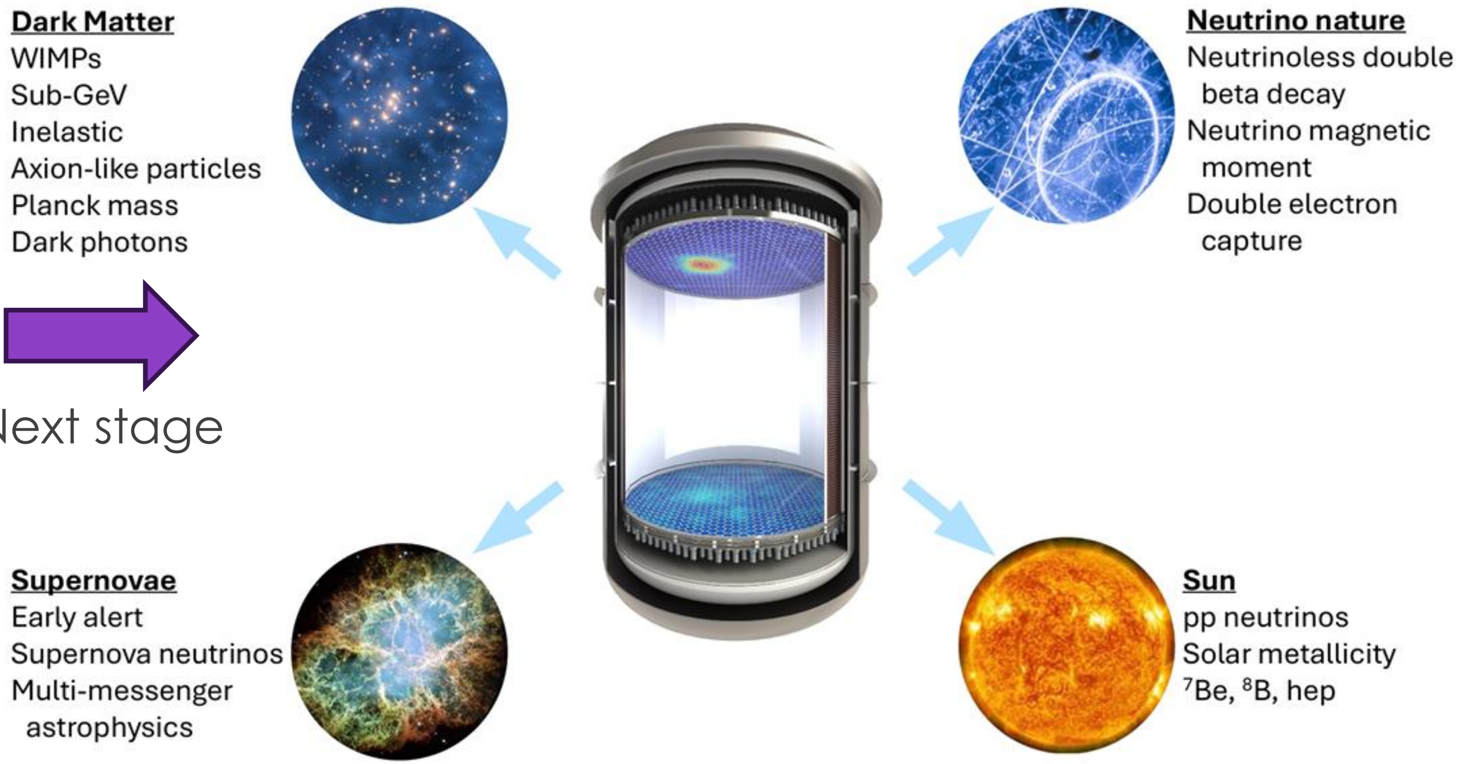
XLZD Next Generation LXe Rare Event Observatory

Overview by [Adam Softley-Brown talk] on Tuesday 1500 session

PANDAX-4t/LUX-ZEPLIN/XENON-nT

- Setting the most stringent WIMP limits
- ^{8}B solar neutrino CEvNS observed
- Still requires hundreds of tonne-years to fully probe the WIMP paradigm

Next stage



[XLZD Design Book] (2025)

- Multi-physics observatory for astroparticle and rare-decays

XLZD Detector Concept

- 60 – 80 tonne active natural LXe target (~10 fold mass increase)
- ~ Factor 2 linear scale-up
- Critical materials scale with length^2
- Expected greater than factor 3 run times

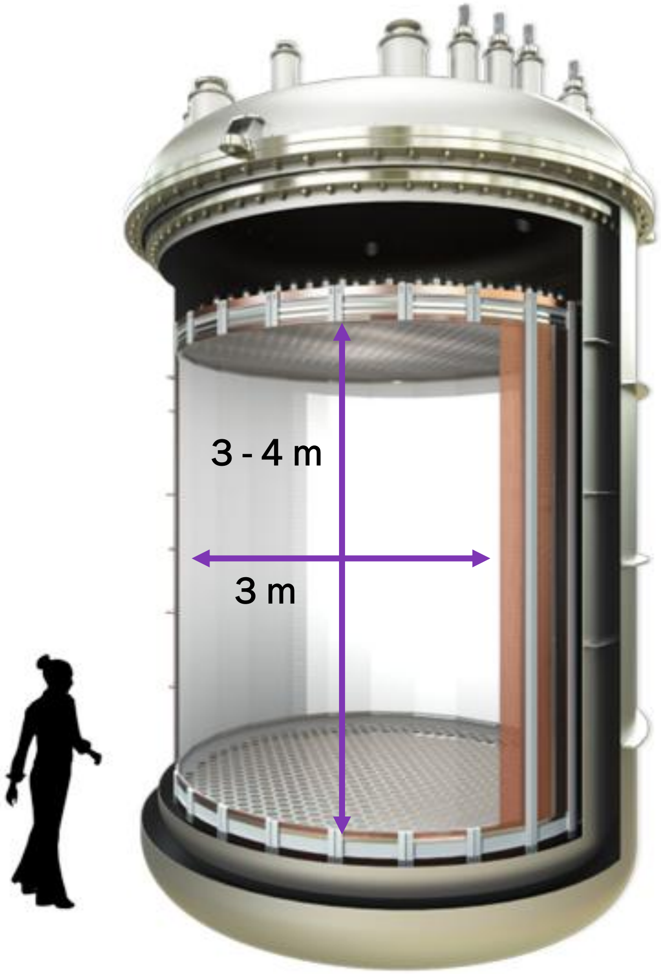
⟶ **Increase in backgrounds**

Strategies

- Self-shielding will improve
- Active veto detector
- Continuous radio-impurity reduction (Krypton/Radon)

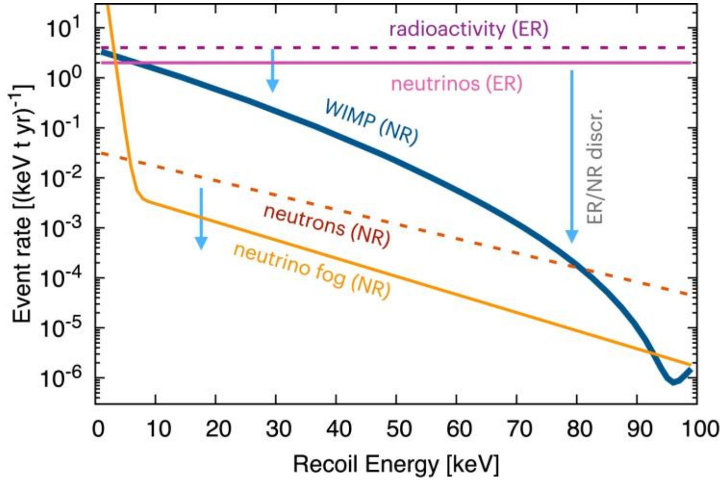
This talk:

- Material selection
- Stricter cleanliness requirements

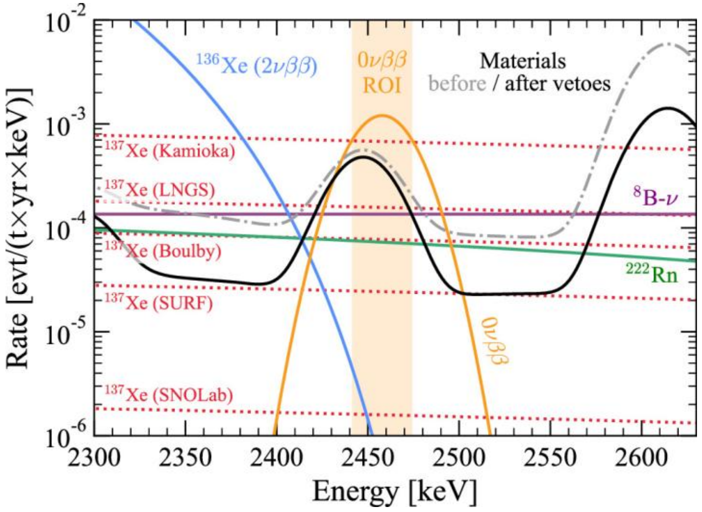


XLZD Design Book (2025)

Radiopurity and cleanliness Requirements



L Baudis (2024) DOI 10.1016/j.nuclphysb.2024.116473



J Aalbers et al (2025) DOI 10.1088/1361-6471/adb900

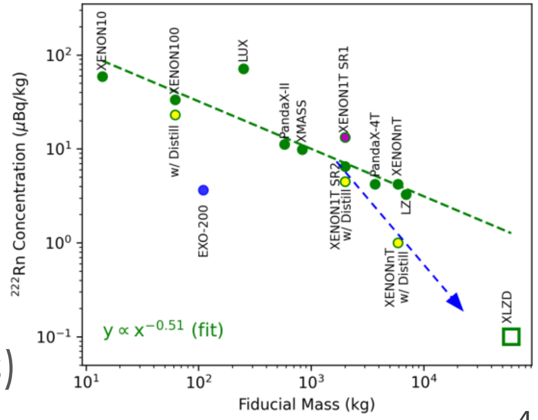
- Challenge with intrinsic background sources that are poorly fiducialised
  - Radon – low energy (DM, solar-ν)
  - High energy gammas **^{214}Bi** and **^{208}Tl** ($0\nu\beta\beta$)
- Overall goal: radiogenic background << neutrinos
- Requirements split between WIMP and $0\nu\beta\beta$

WIMP Search

- NR: [5, 60] keV_{NR} – 10% of irreducible backgrounds from solar neutrinos
- WIMP ER: [1.5, 13.5] keV_{EE} – 40% irreducible solar PP + ^{136}Xe + ^{124}Xe
- Radon ~ factor 10 - 100 decrease in activity required for radon to be subdominant (~5x more stringent material emanation rates)

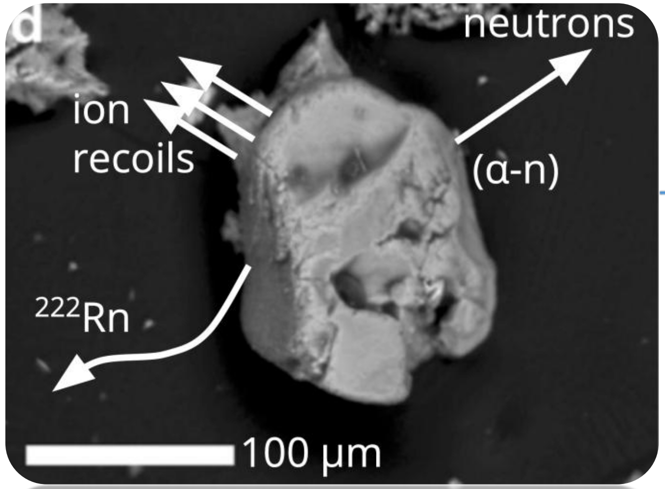
$0\nu\beta\beta$ Search

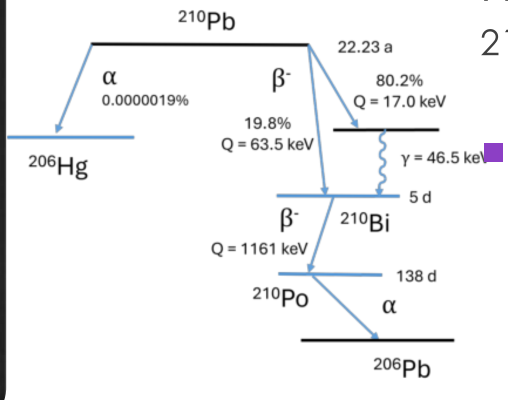
- Sets intrinsic/fixed contaminants
- 10 – 25% of LZ Material gamma flux



A. Kopec DOI:10.31526/jais.2024.480

Cleanliness Requirements





Many facets of dust

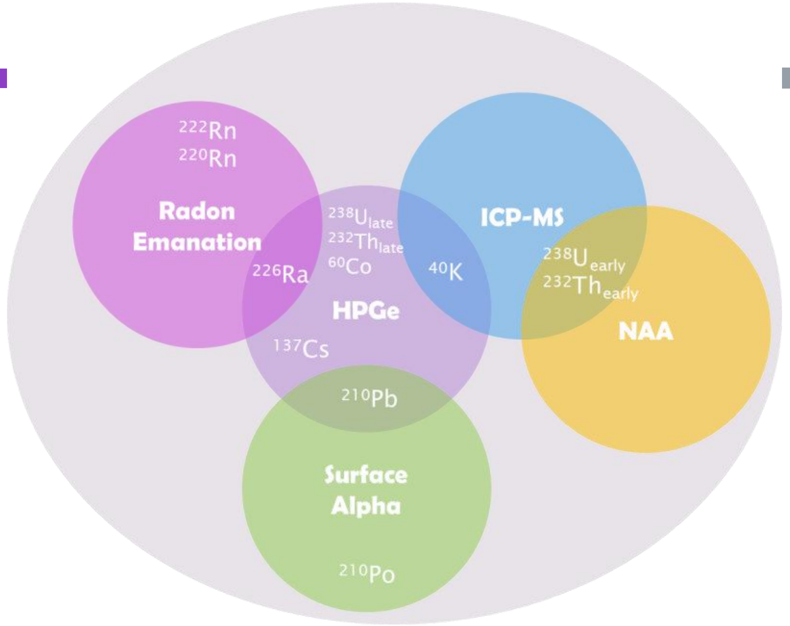
PTFE components under UV, LZ Cleanliness (2022)

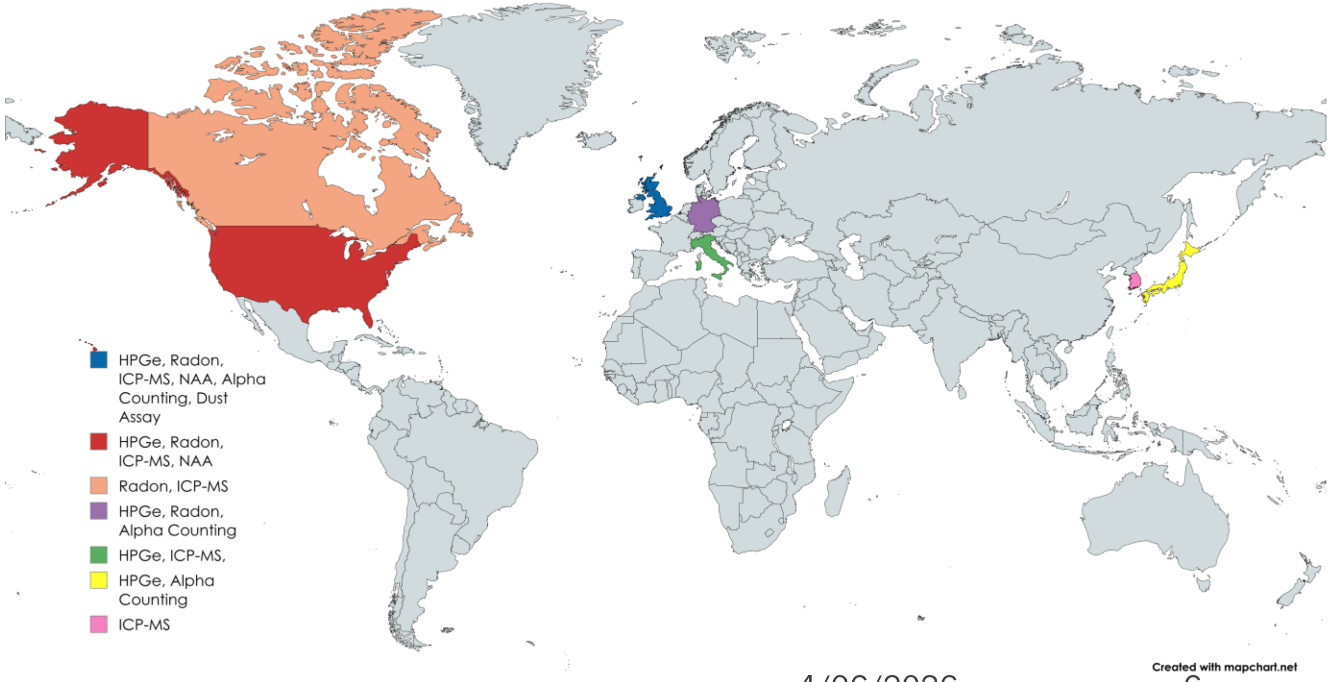
Contamination of surface of materials during handling and construction cause build up of ^{210}Pb

- Dust
  - Contains radon that can emanate -> electron recoils and (a, n) production
  - Goal is to keep below 200-500 ng/cm^2 – similar to current experiment but larger area to consider (few grams in all of TPC)
- Plate-out:
  - (a, n) reactions particularly important for PTFE, Al, etc
  - Implantation of radon progeny (^{210}Pb) [0.2 – 0.5 mBq/m^2]

Material Selection

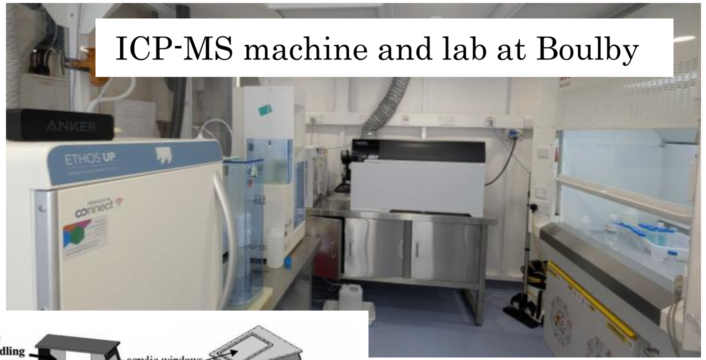
- Most important strategy for achieving background targets
- More stringent material selection across all components
- Conducting extensive screening campaigns
  - High Purity Germanium γ screening (HPGe)
  - Inductively Coupled Plasma Mass Spectrometry (ICP-MS)
  - Radon Emanation
  - Surface Alpha counting
  - Neutron Activation Analysis (NAA)
- Utilise network of facilities across UK, US, Canada, Italy, Germany, Japan, South Korea

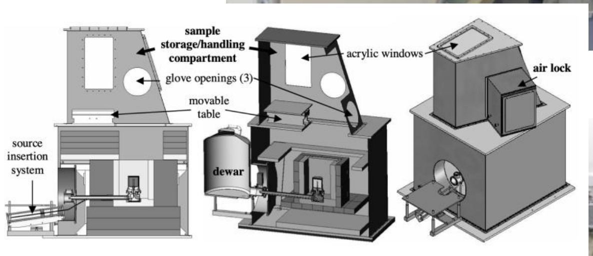




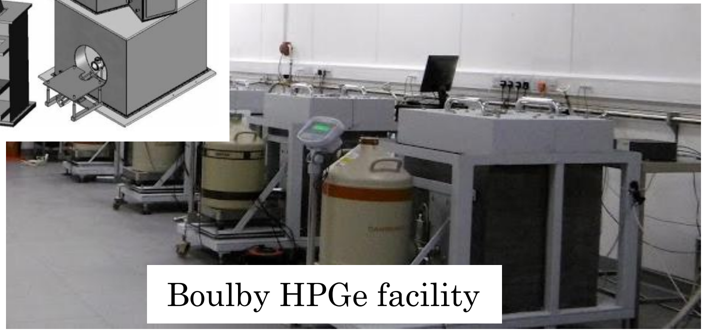
Radioassay Challenges

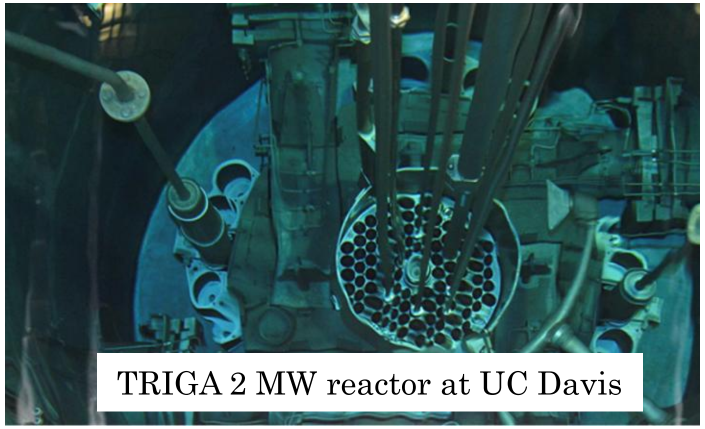
- ICP-MS - $^{238}U_{early}$ and $^{232}Th_{early}$ reached ~ U/Th ppt (pg/g)
  Require ~factor 10 reduction in sensitivity
  - Improving sample pre-concentration
- HPGe - ^{214}Bi and ^{208}Tl sensitivity using HPGe requires ~ factor 5 improvement for the Boulby detector; for eg the cryostat material
  - Some detectors will be upgraded with improved radon purge and shielding
- NAA - Lowest detection limits for $^{238}U_{early}$ and $^{232}Th_{early}$ in PTFE (~0.01 mBq/kg for LZ) (Akerib et al. Eur. Phys. https://doi.org/10.1140/epjc/s10052-020-8420-x)
  - Investigating several facilities – sufficient neutron flux
- Other:
  - Throughput (emanation takes ~30 days)
  - Cross-calibration


ICP-MS machine and lab at Boulby



GeMPI at LNGS (2006)


Boulby HPGe facility


TRIGA 2 MW reactor at UC Davis

Material Selection - Cryostat

- Extensive material screening underway
- Cryostat material second highest contributor to $0\nu\beta\beta$

J Aalbers et al (2025) DOI 10.1088/1361-6471/adb900

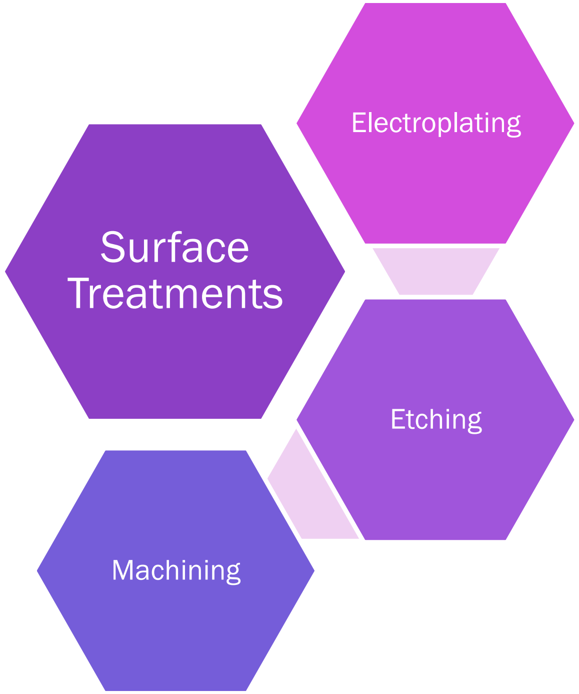
	^{214}Bi events		
	LZ (967 kg × 1000 d)		XLZD (8.2 t × 10 years)
Component	Nominal	Reduced	Projected
TPC PMTs	2.95	0.98	0.61
PMT structures	2.75	0.54	0.33
Field-cage resistors	2.46	0	0
Internal sensors	1.81	0.22	0.14
PMT bases	1.52	0.39	0.24
Cryostat	1.26	0.82	0.51
PMT cables	1.01	0.16	0.10
Field-cage rings	0.97	0.40	0.25
OD tank supports	0.73	0	0
OD foam	0.71	0	0
Skin PMTs	0.69	0.06	0.04
Other skin parts	0.68	0.05	0.03
Other components	3.56	1.42	0.88
Total	21.10	5.05	3.15

Cryostat Material choices

- Stainless steel - Several sources, not all equally radiopure
- Chemical Vapour Deposition (CVD) nickel
  - International Investigation of feasibility of CVD nickel [10.1016/j.nima.2026.171402]
- Titanium - LZ titanium
  - higher than expected ^{222}Rn

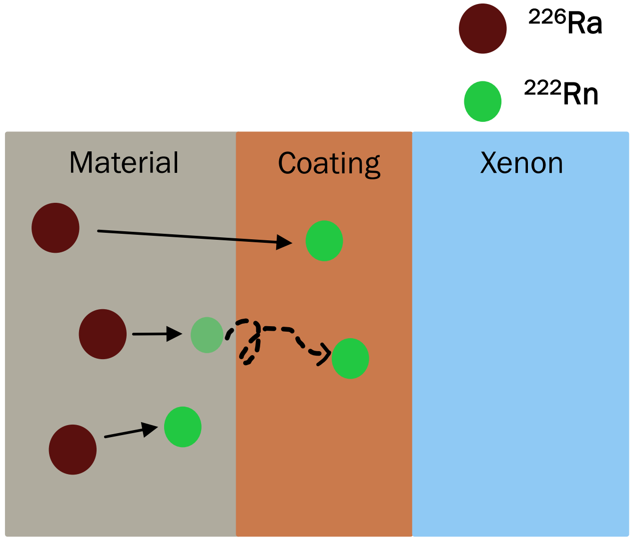
LZ Titanium investigations

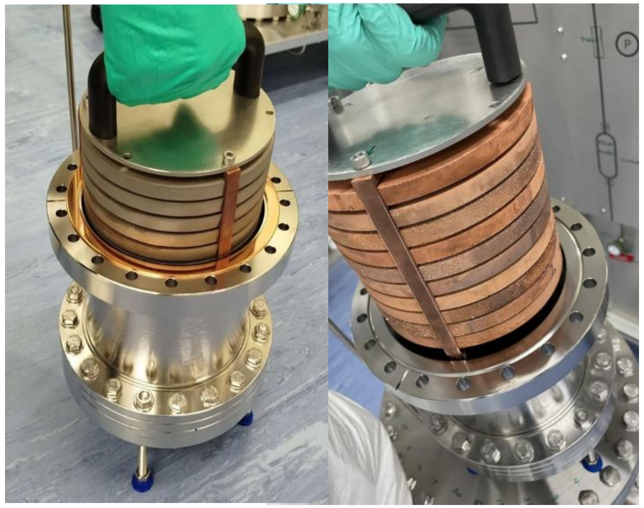
- Suspected to be surface contamination
- Investigating source and mitigation methods
- Extensive screening and treatment campaign



Titanium Copper Electroplating

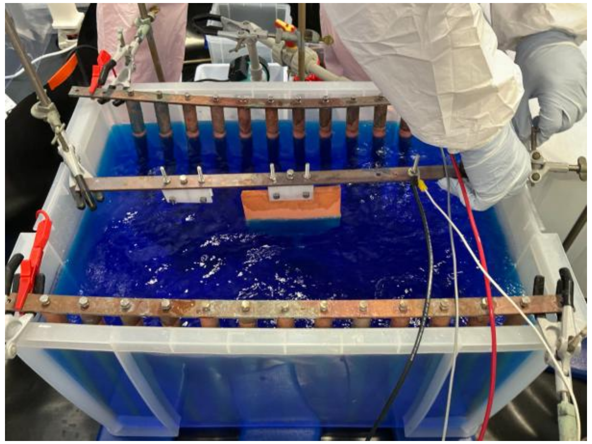
- Majority of radon that emanates is close to the surface
- Stop emanation by coating greater than maximum recoil distance
- Cu plating on titanium non-standard process – requires surface pre-treatment
- Electroplating successfully performed in the Boulby underground laboratory ~ 100 μm of high purity copper
- Extensive screening 'before' and 'after'
  - radon emanation dropped to below detectable limit– further improvements required at Cryogenic Radon Emanation Facility (CREF)
- Also investigating electroplating with industrial partners
- Coating using electroplating of great interest – XLZD collaborators (MPIK) conducting extensive studies

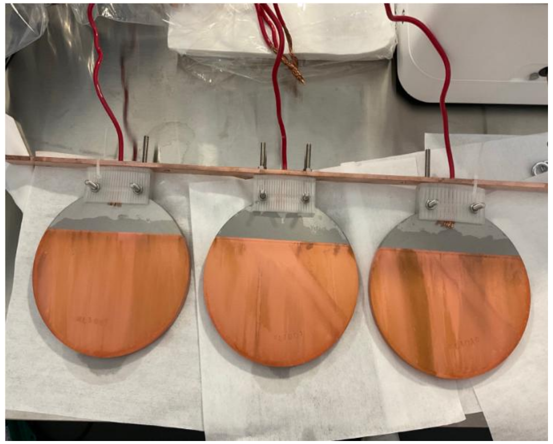




Before and after emanations at CREF

Credit P. Knights, D. Spathara, G. Rogers, P. Walters





Cleanliness

- Control contamination of surfaces during manufacture
- Developed protocols from LZ and XENONnT available:
  - Bagging and purge
  - Cleaning protocols
- New cleanroom to test current protocols and develop improved, standardised ones
- Monitoring cleanliness
  - UV inspections, Rn/dust counters, assays
  - Exposure tracking - witness plates/tape lifts, fallout/deposition models
- Surface treatment of some material, remedial cleaning of components once underground prior to assembly

New ISO6 Clean Room at Boulby

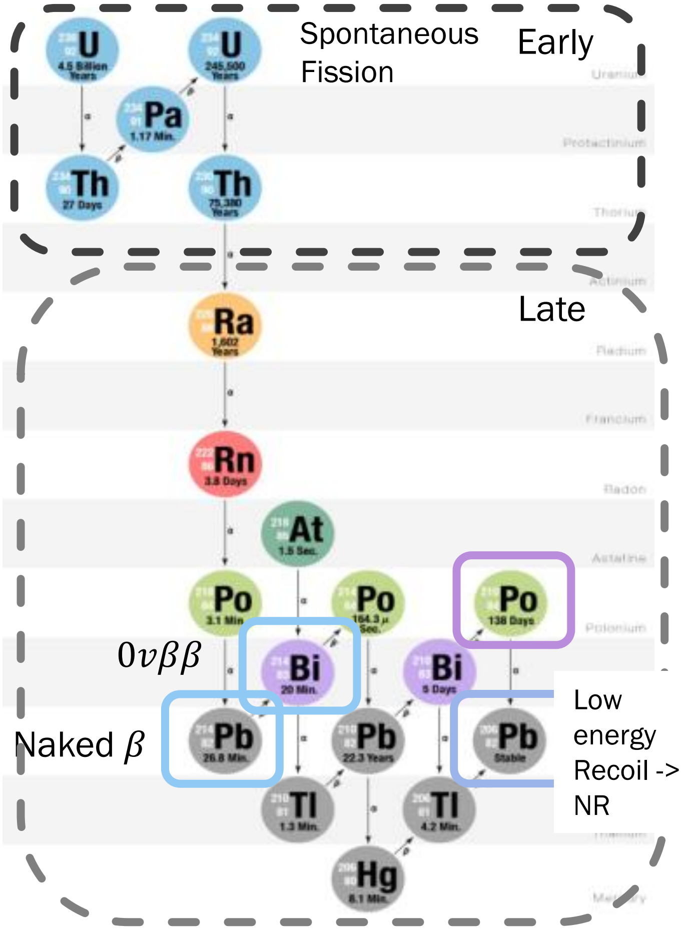
Assembly and QA in LZ

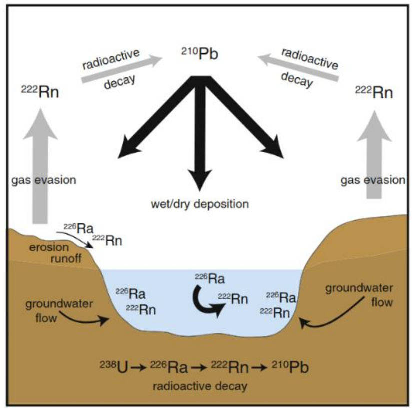
SUMMARY

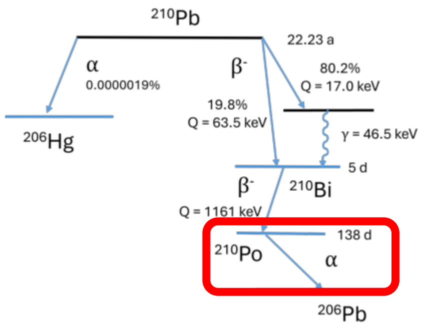
- XLZD will be a multi-science rare event observatory
- Extensive challenges in reducing background load but they are well understood
- Main requirements split into low energy WIMP and high energy $0\nu\beta\beta$
- Several strategies to mitigate background, including:
  - Material selection
  - Maintaining cleanliness
- Well positioned to achieve these with material selection and treatments underway
- Cleanliness protocols being tested and produced
- Build on experience from multiple past DM and $0\nu\beta\beta$ experiments

BACK-UP SLIDES

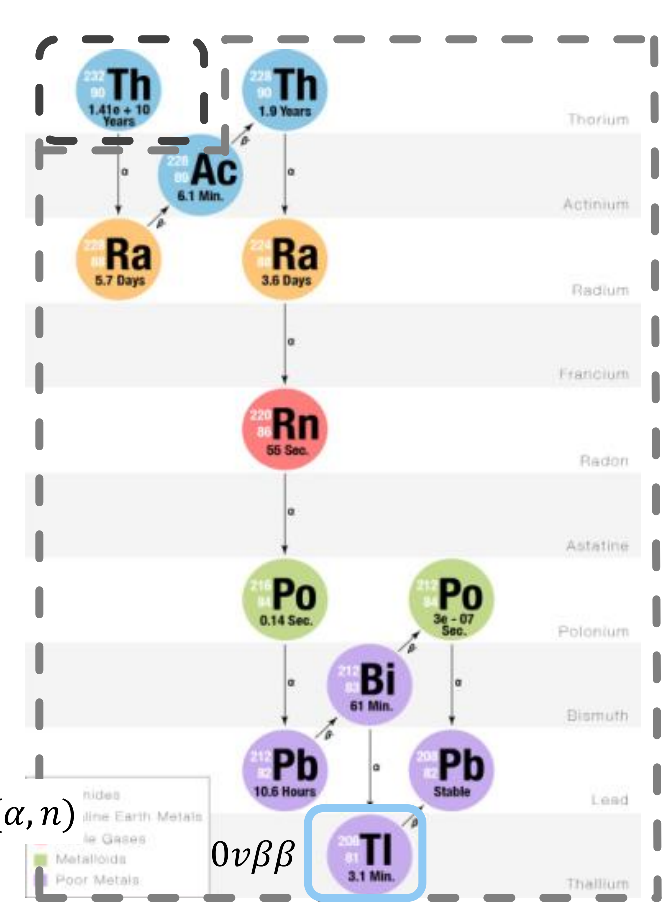
Backup

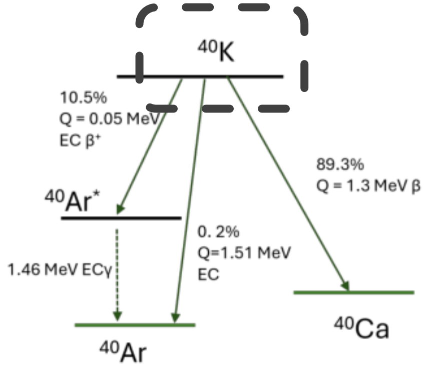


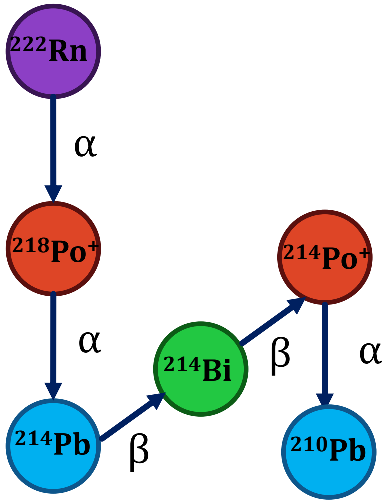




(α, n)

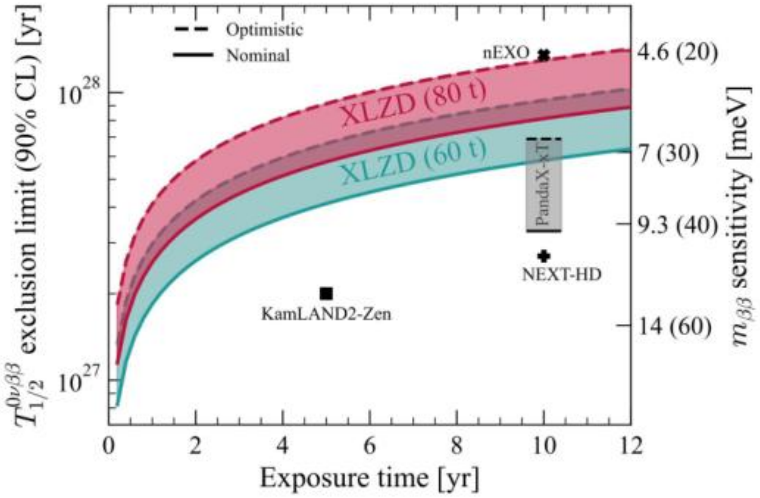


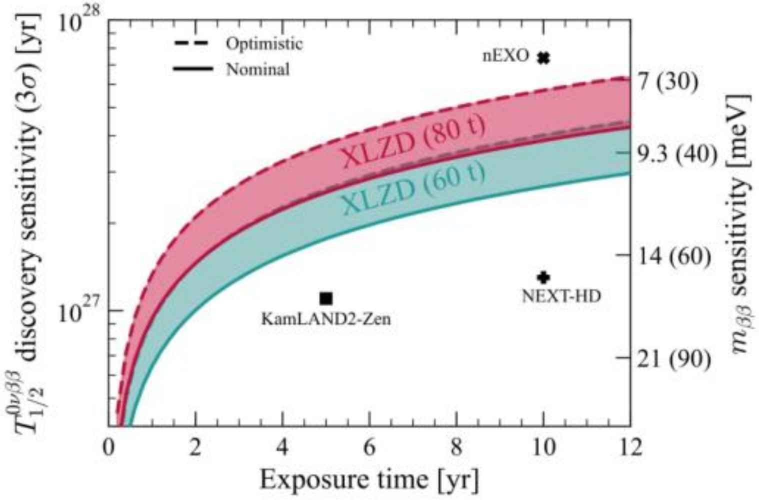


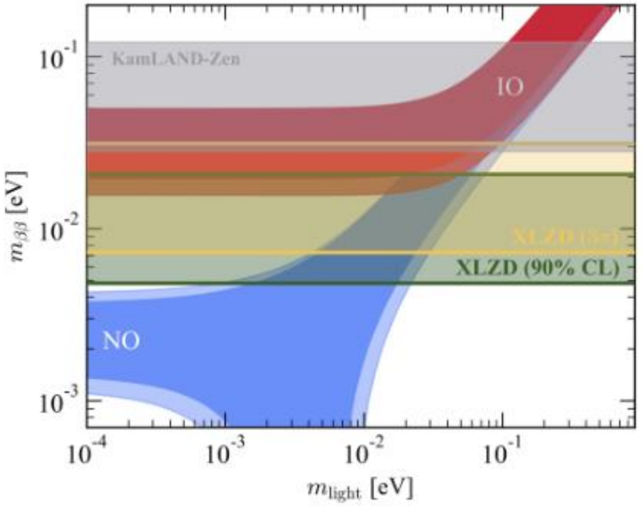


Neutrinos

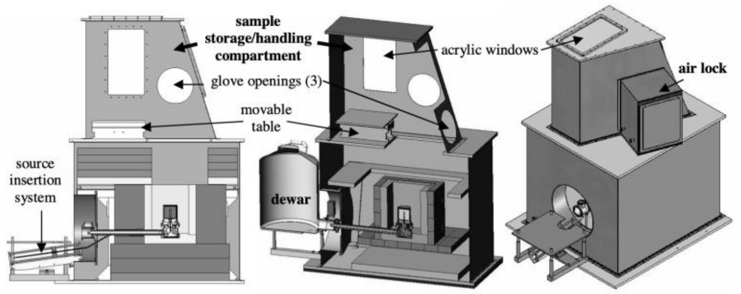
- Irreducible Backgrounds: ^{124}Xe - two-neutrino double electron capture. ^{136}Xe - two-neutrino double beta decay
- Neutrinoless Double Beta Decay: Assuming: 0.1 uBq/kg ^{222}Rn,
- achievable improvements in material radiopurity, 0.65% energy resolution, 99.99% Bi-Po tagging.
- Majority of Inverse Ordering parameter space covered at 3σ
- Exclude some of Natural ordering
- Other background: cosmogenic ^{137}Xe activation







GeMPI and Gator at LNGS

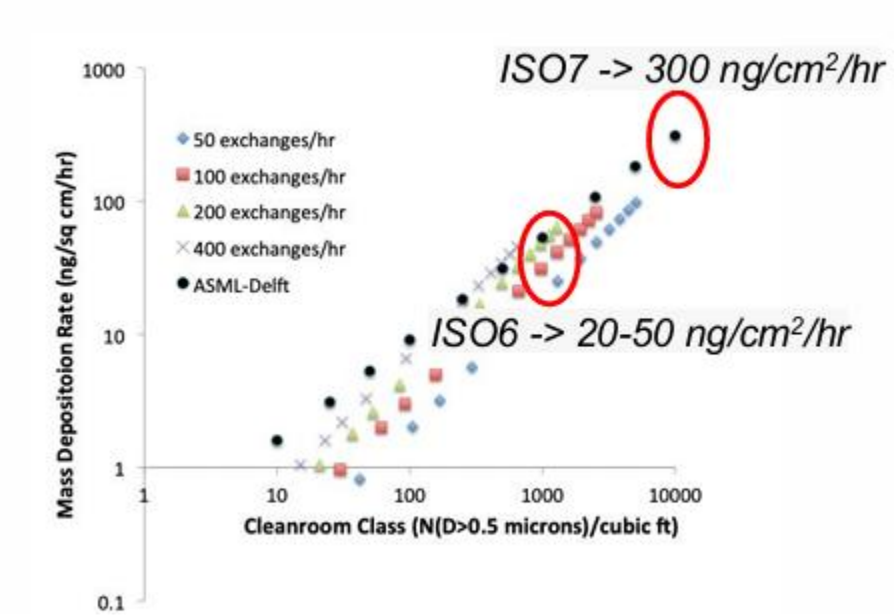


GeMPI at LNGS (2006)

Detector	Laboratory	Type	Mass [kg]	Relative Eff %	Background (60-2700 keV) [cpd/kg]	Background (100-2700 keV) [cpd/kg]	Links
Chaloner	Boulby	BEGe	~0.8	48		1045(30)	https://iopscience.iop.org/article/10.1088/1748-0221/19/01/P01017
Lumpsey	Boulby	SAGe well	1.5	69		515(25)	4pi coverage. Diameter 28mm, Depth 40mm. https://doi.org/10.1088/1748-0221/19/01/P01017. Ultra low background.
Lunehead	Boulby	p-type Coax	2	92		540(25)	https://doi.org/10.1088/1748-0221/19/01/P01017. Ultra low background
Roseberry	Boulby	BEGe	0.9	60		130(11)	https://doi.org/10.1088/1748-0221/19/01/P01017. Ultra- Low background
Belmont	Boulby	p-type Coax	3.2	160	135	90(9)	100-2700: https://doi.org/10.1088/1748-0221/19/01/P01017. 60-2700keV: arXiv:2204.12478v. Ultra low background
Merrybent	Boulby	p-type Coax	2	110		145(12)	https://doi.org/10.1088/1748-0221/19/01/P01017
Gator	LNGS	p-type Coax	2.2	100.5	89		arXiv:2204.12478v
GeMPI 3	LNGS	p-type Coax	2.2	98.7	24(1)		arXiv:2204.12478v. Apparently lowest U/Th sensitivity at 10 uBq/kg. https://www.mpi-hd.mpg.de/gerda/tg11_files/GeMPIpub2e4b.pdf

Requirements expanded

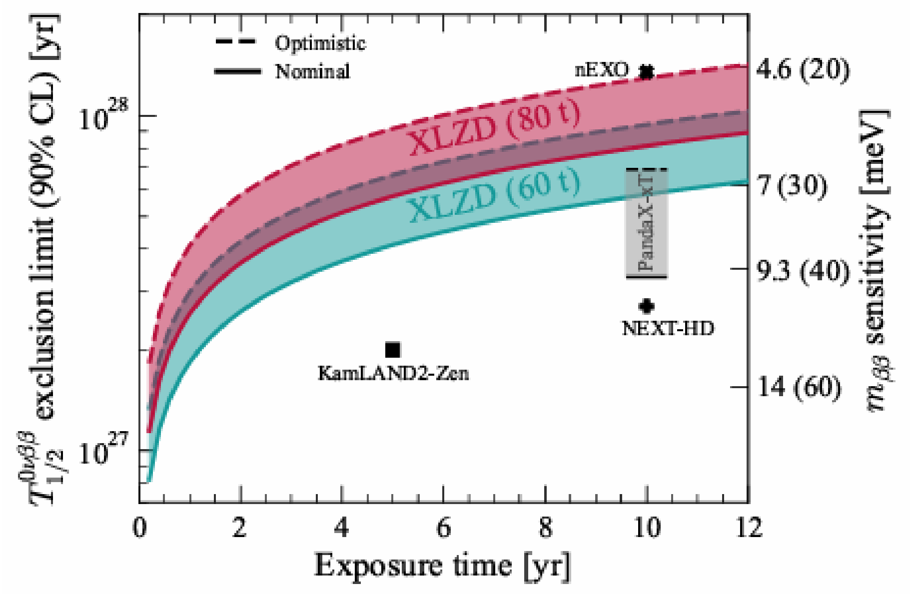
- Neutron backgrounds to be set by 10% the atmospheric neutrino flux (LNGS as most conservative case) 0.046 cts/tonne.yr -> 2.5 cts/yr (for 60 tonne detector) – 95 % veto efficiency
- Plate-out
  - Different plateout requirements for detector regions/materials – High, Medium, Low targets.
  - Low is mostly PTFE field case
- Dust
  - Alpha – n from instric contaminants and dust



Dust deposition rates from LZ technical note "Dust Deposition and Radon Plate-out Calculators" J. Busenitz, J. Dobson

Neutrinoless Double Beta decay

DOI 10.1088/1361-6471/adb900 (2025)

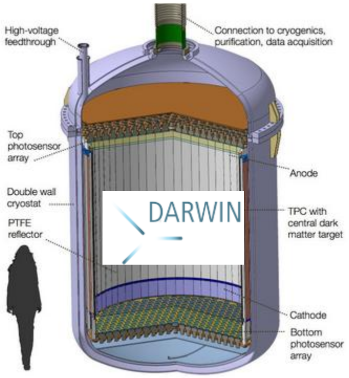


Neutrinoless double beta decay (0νββ)

- Forbidden in the SM
- Confirm Majorana nature
- Info on matter/anti-matter asymmetry

XENON-LUX-ZEPLIN-DARWIN

- XLZD Consortium signed MoU between competing collaboration in 2021
- Collaboration agreement signed in 2024 by 70+ institutions in 17 countries
- Largest liquid Xe TPC teams still operating competitively: LZ and XENON-nT
  - Both currently operating underground (SURF and LNGS)
  - Experience and track record of two major collaborations



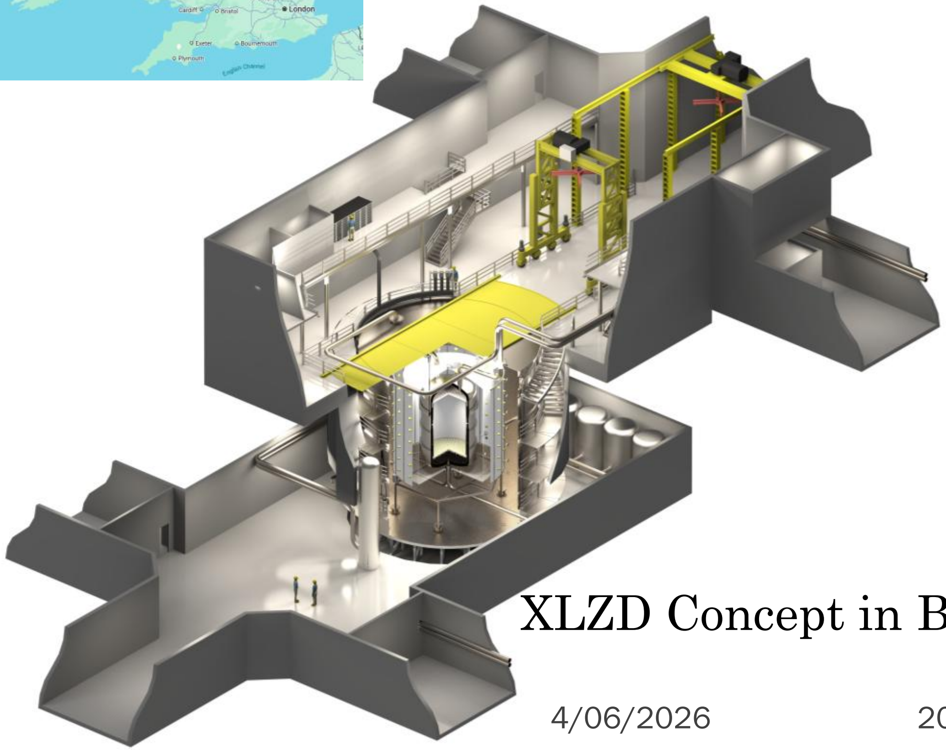
Ongoing activities

- Pre-conceptual Design and sensitivity reports developed
- Working Groups in a “Global WBS” on science, technical, and siting
- Also developing and costing the project
- Working on design options (incorporating and learning from current experiments)

XLZD UK and Boulby Underground Laboratory

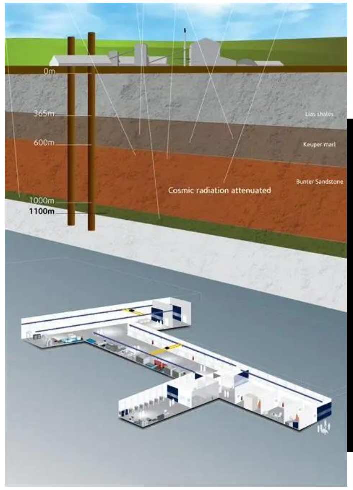
- Boulby Development Project (2022-now)
  - Develop facility design
  - Excavation of new lab space complete
- Pre-construction Project (2024-2027)
  - Technical design of UK hardware system and interfaces
  - Planning and capacity-building (eg **clean manufacture**)
  - Position UK to host the experiment at Boulby
- Boulby working polyhalite and salt mine operated by ICL UK
- Current and proposed laboratory 1,100 m (2,805 m.w.e) depth
- Low natural radon levels
- Large experimental cavern plus additional spaces made to measure for XLZD
  - Beneficial occupancy ~2030+

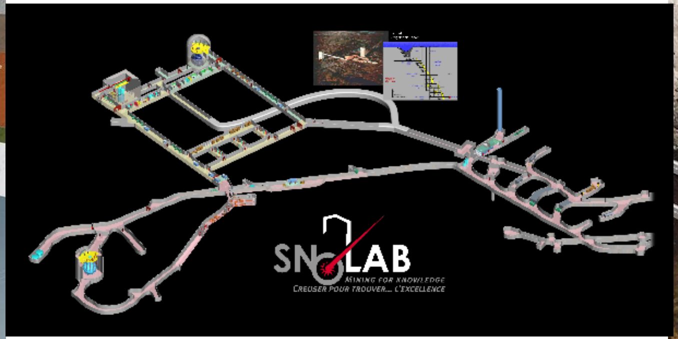
Boulby current lab

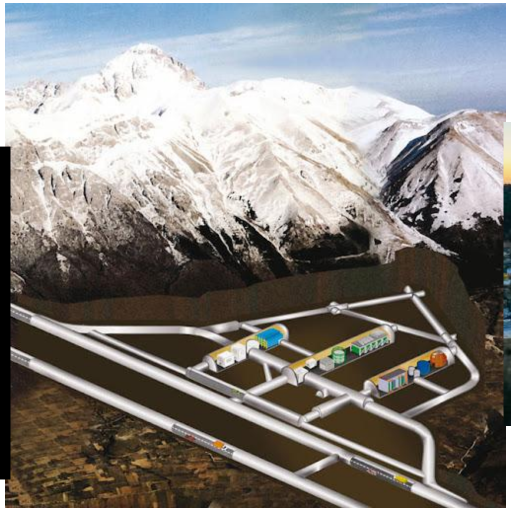


XLZD Concept in Boulby

Hosting Site







- Five laboratories expressed interest, four shortlisted: Boulby (UK), SNOLAB (Canada), LNGS (Italy), SURF (USA)
- Selection involves both science/technical and other factors
  - Lab depth determines backgrounds for DM and 0νββ-decay search
  - Access, space, timeline, investment

Science white paper (2023)