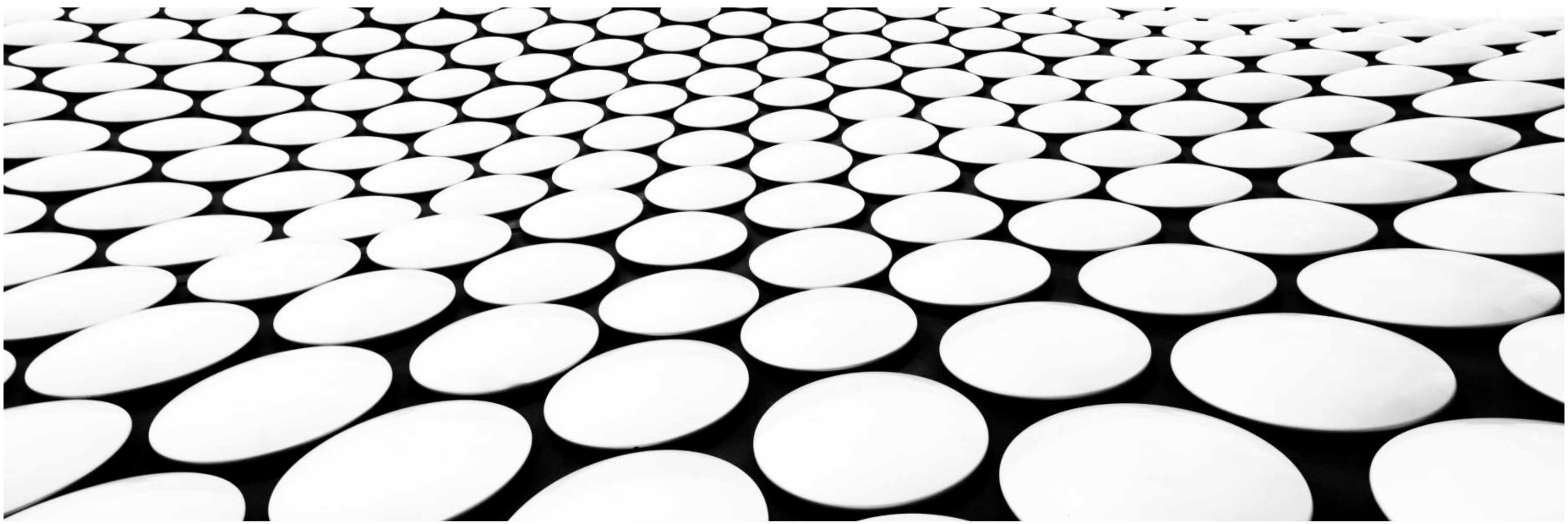
Radiopurity and cleanliness control in XLZD rare event observatory

Ferdos Dastgiri on Behalf of the XLZD Collaboration

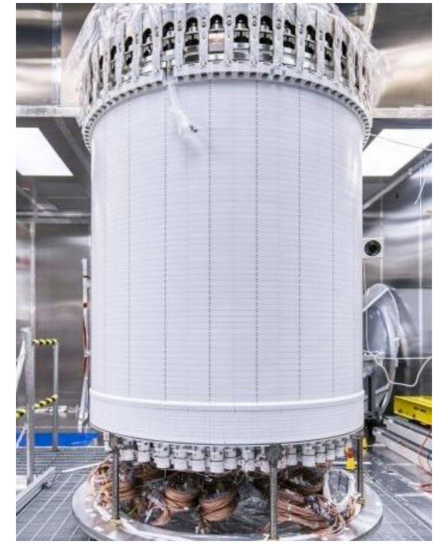
University College London

LOW RADIOACTIVITY TECHNIQUES, YORK, 2026



Technology over the years

PANDAX-4t/LUX-ZEPLIN/XENON-nT
2500, 7000, 5900 kg



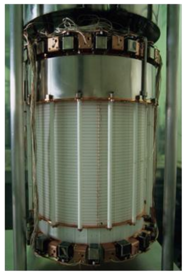
LUX-ZEPLIN (LZ) Detector

ZEPLIN-III/XENON10

12 kg/7 kg

2008

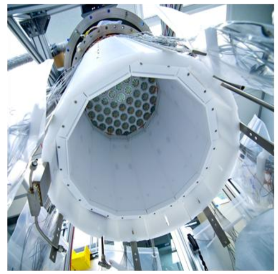
XENON100



62 kg

2013

LUX



118 kg

2016

PANDAX-II

362 kg

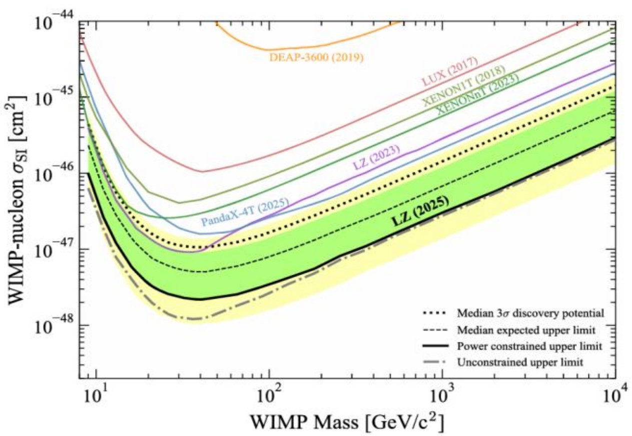
2017

XENON1T

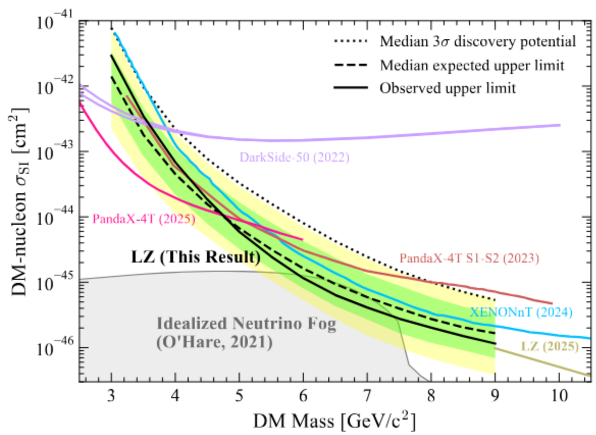
1300 kg

2018

PRL 135, 011802 (2025)



arXiv:2512.08065

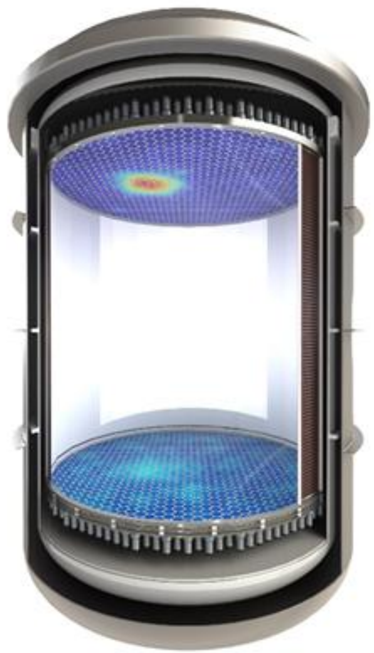


- Setting the most stringent WIMP limits
- ^{8}B neutrinos detected
- Still requires hundreds of tonne-years to fully probe the WIMP paradigm

XLZD Next Generation LXe Rare Event Observatory

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

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

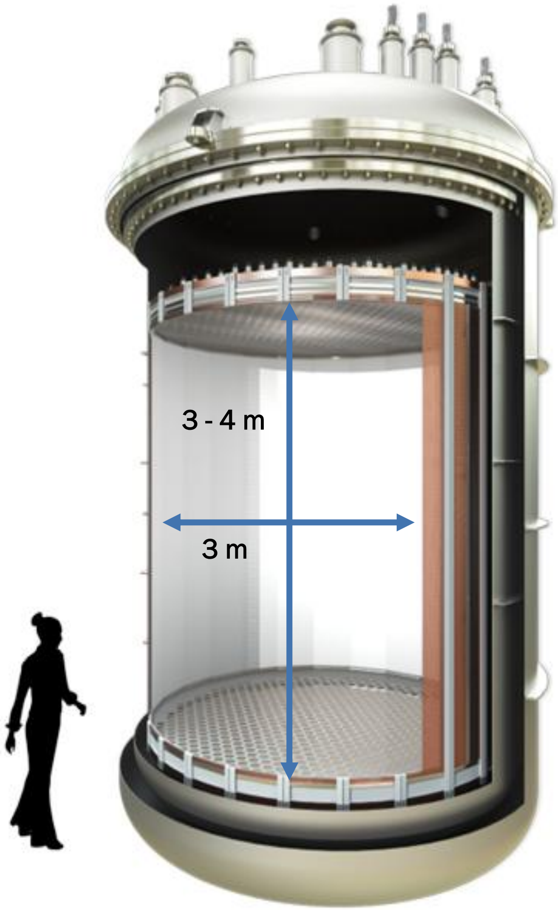
→ Increase in backgrounds

Strategies:

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

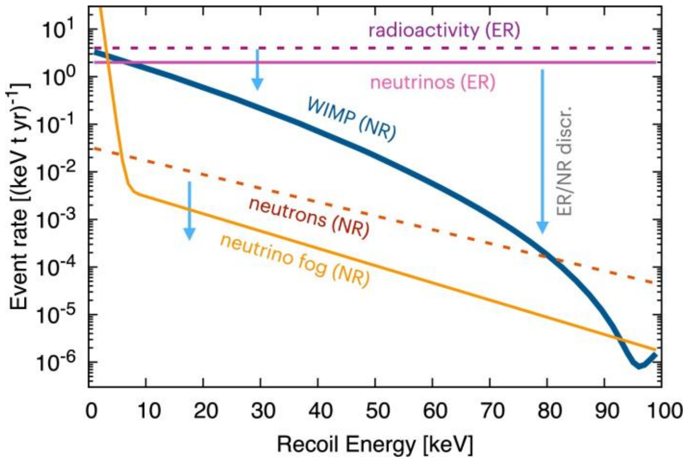
This talk (highlighting UK activities):

- Material selection
- Stricter cleanliness requirements

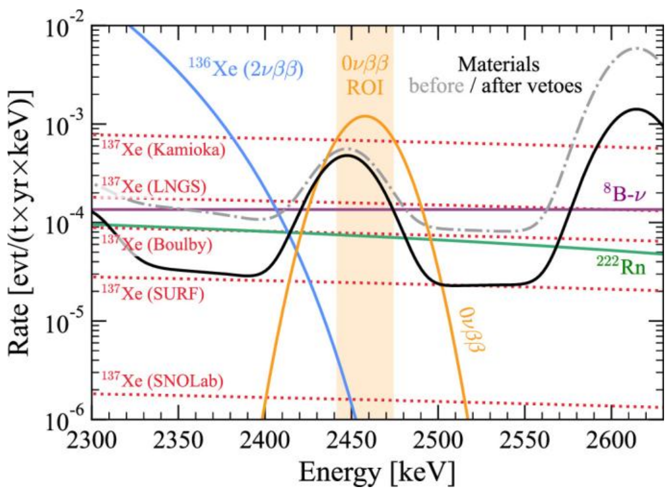


XLZD Design Book (2025)

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

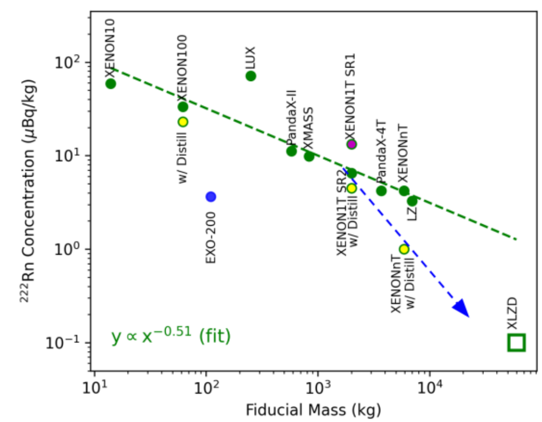
- Challenge with intrinsic background sources that are poorly fiducialised
  - Radon – low energy (DM, solar-ν)
  - High energy gammas ^{214}Bi and ^{208}Tl (0νββ)
- Overall goal: radiogenic background << neutrinos
- Requirements split between WIMP and 0νββ

WIMP Search

- NR:– 10% of irreducible backgrounds from solar neutrinos
- WIMP ER– 40% irreducible solar pp + ^{136}Xe + ^{124}Xe
- Radon
  ~ factor 10 – 100 improvement in sensitivity to be subdominant (~5x lower material emanation rates)

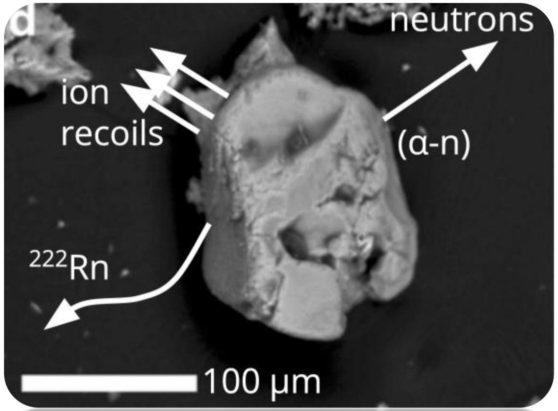
0νββ Search

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

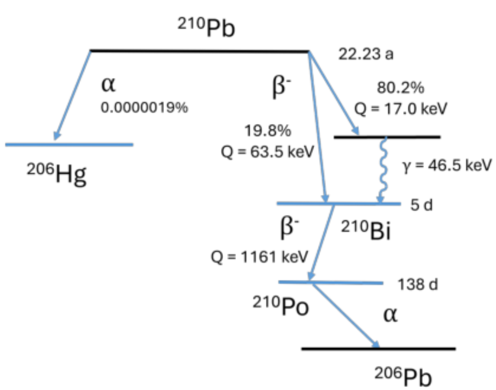


A. Kopec DOI:10.31526/jais.2024.480

Cleanliness Requirements



Many facets of dust



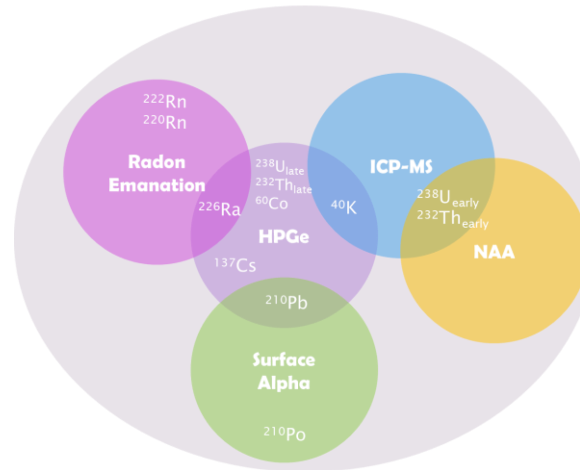
Contamination of surface of materials during handling and construction cause build up of ^{210}Pb

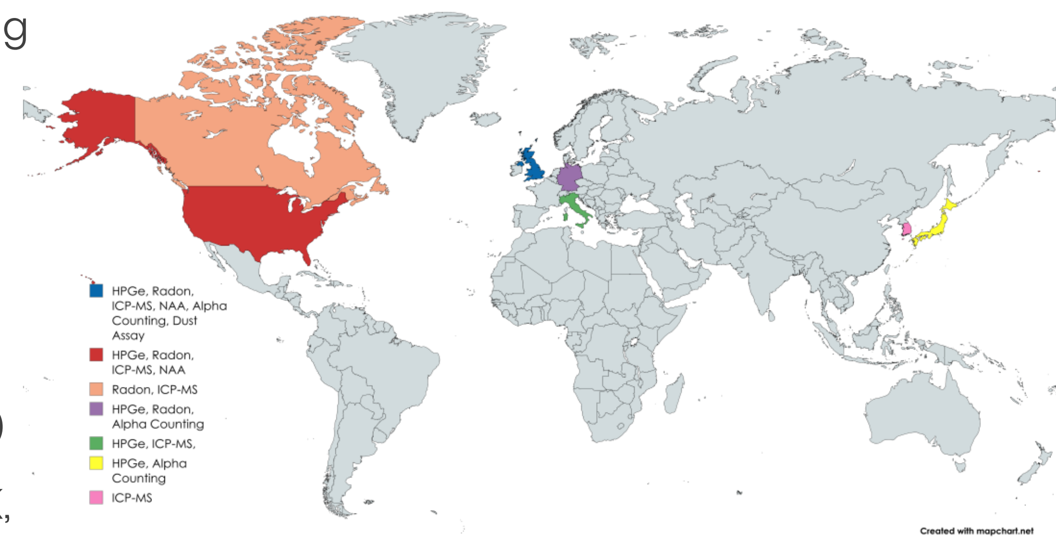
- Dust
  - Contains radon that can emanate -> electron recoils and (α, n) production
  - Easily built up on electrostatic materials like PTFE
  - Goal is to keep below 200-500 ng/cm^2 – similar to current experiment but larger area to consider (few grams in all of TPC)
- Plate-out:
  - (α, n) reactions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

PTFE components under UV, LZ Cleanliness (2022)

Material Selection

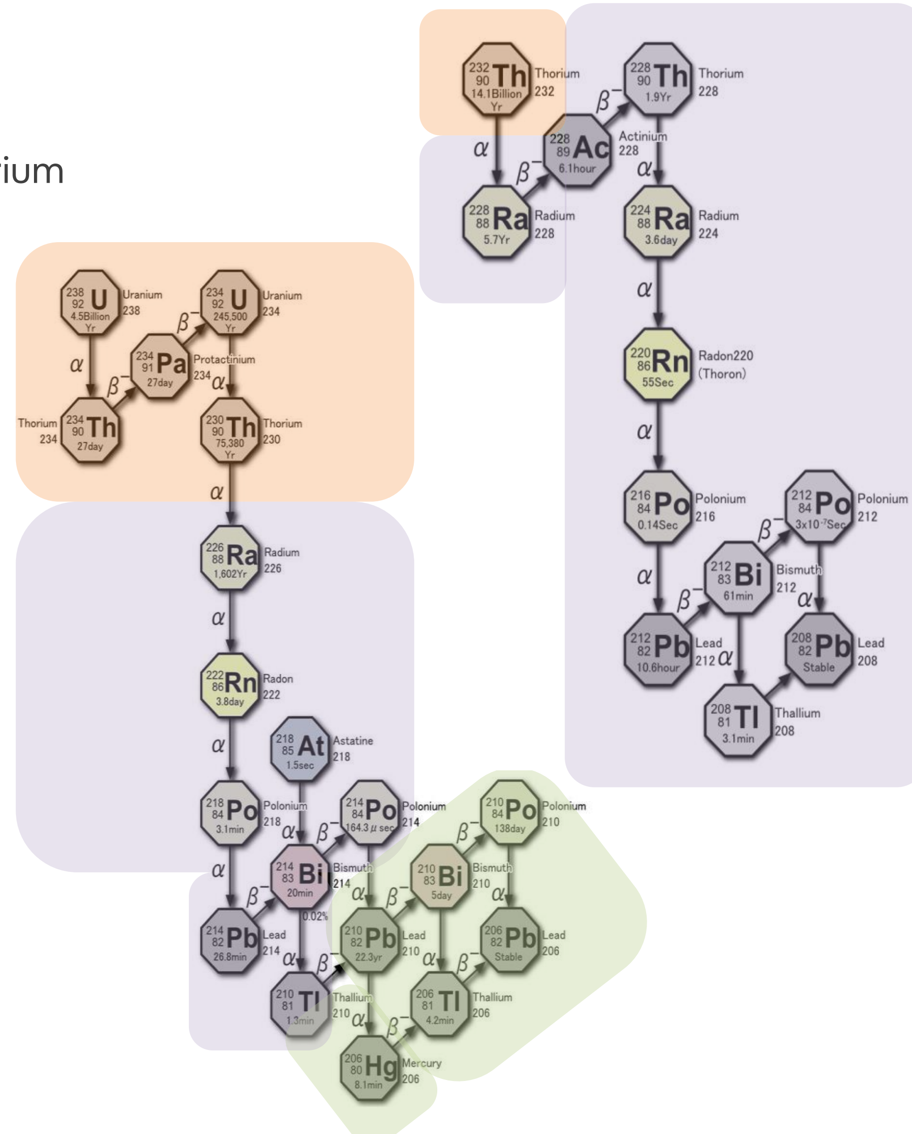
- Most important strategy for achieving background targets
- More stringent material selection across all components
- Conducting extensive screening campaigns
  - High Purity Germanium γ screening (HPGe)
  - Inductively Coupled Plasma Mass Spectrometry (ICP-MS)
  - Radon Emanation
  - Surface Alpha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





Full Chain Characterisation

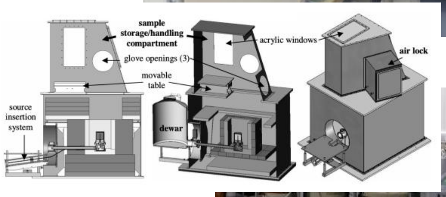
- Typically the chain is not in secular equilibrium
  - Broken up by chemistry and processing
- Characterise early chain using ICP-MS
- Middle chain using HPGe
  - ^{214}Bi and ^{208}Tl contribute to $(0\nu\beta\beta)$
  - Surface radon using radon emanation
- Late chain ^{210}Po using alpha spectroscopy
  - ^{210}Po contributes to (α, n)
  - Or ^{210}Pb bulk using low energy HPGe



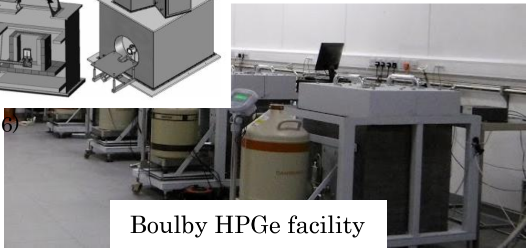
Radioassay Challenges

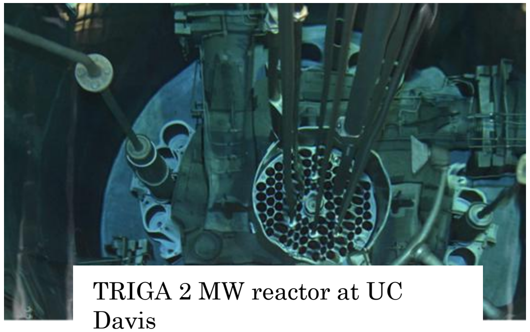
- ICP-MS – $^{238}U_{early}$ and $^{232}Th_{early}$ reached U/Th 5-10 ppt (pg/g)
  - Require **~factor 10 improvement in sensitivity**
  - Improving sample pre-concentration (demonstrated 0.1 ppt)
- HPGe – ^{214}Bi and ^{208}Tl sensitivity using HPGe requires ~ **factor 5 improvement for the Boulby** (Belmont) detector; for eg cryostat material
  - Some detectors will be upgraded with improved radon purge and shielding
  - Analysis improvements, using Remage and accounting for self-shielding
- NAA – Lowest detection limits for $^{238}U_{early}$ and $^{232}Th_{early}$ in PTFE (~0.01 mBq/kg for LZ) (Akerib et al. EPJC Eur. Phys. https://doi.org/10.1140/epjc/s10052-020-8420-x)
  - Investigating several facilities – sufficient neutron flux
- Other:
  - **Throughput** (emanation can take ~30 days)
  - **Cross-calibration** of different facilities
  - **Surface alpha counting** – improving analysis techniques


ICP-MS machine and lab at Boulby



GeMPI at LNGS (2006)


Boulby HPGe facility


TRIGA 2 MW reactor at UC Davis

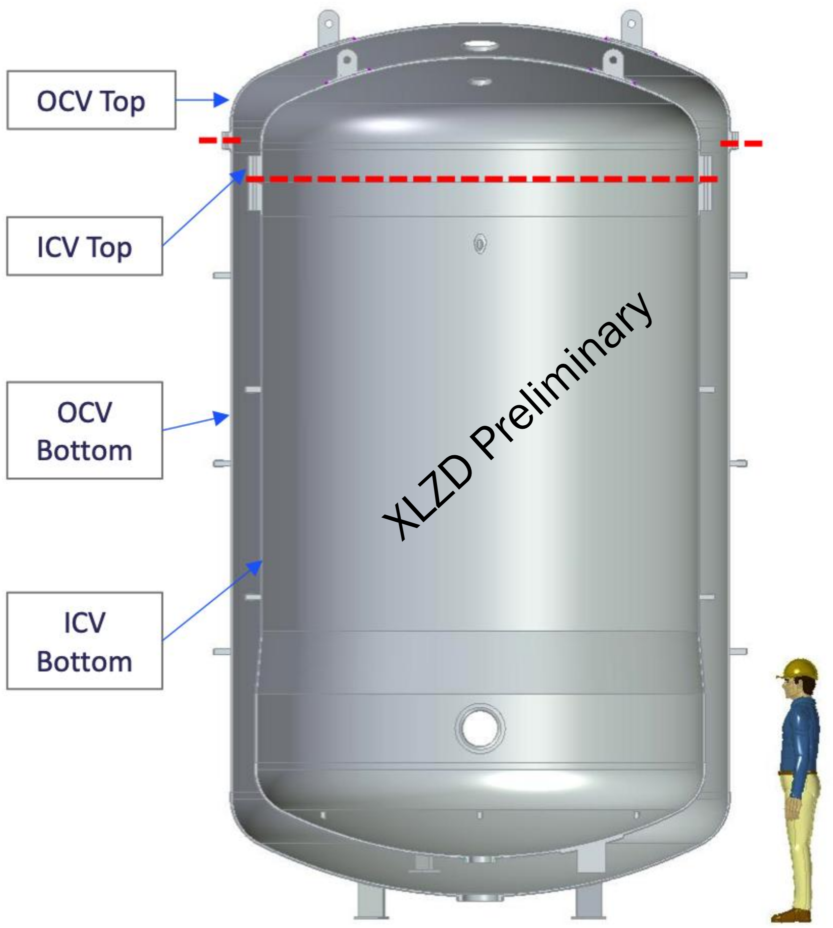
Material Selection - Cryostat

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 second highest contributor to 0νββ

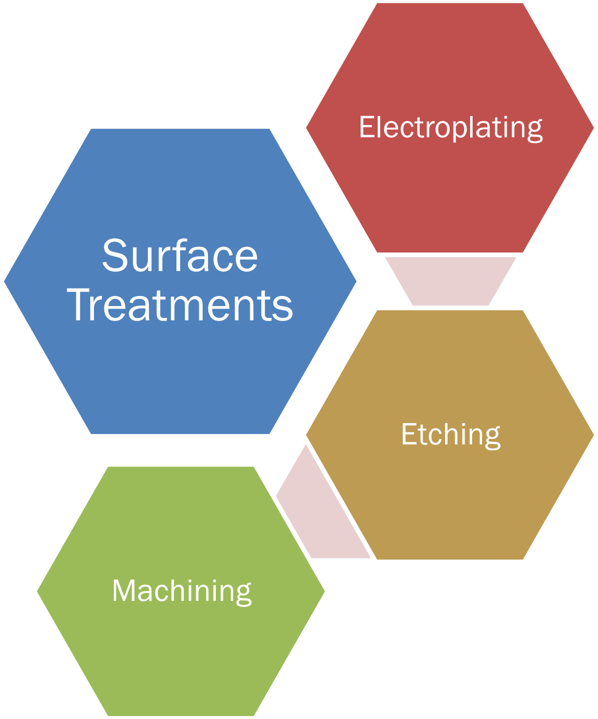
Cryostat Prelim Design



Material Selection - Cryostat

Material choices

- Stainless steel – Several sources, not all equally radiopure
- Chemical Vapour Deposition (CVD) nickel
  - Canadian Collaborators Investigating feasibility of CVD nickel [10.1016/j.nima.2026.171402]
- Titanium – used in LZ
  - 12.5 tonnes
  - Stainless steel ~ 1.3 x more mass



LZ Titanium was found to have higher than expected ^{222}Rn

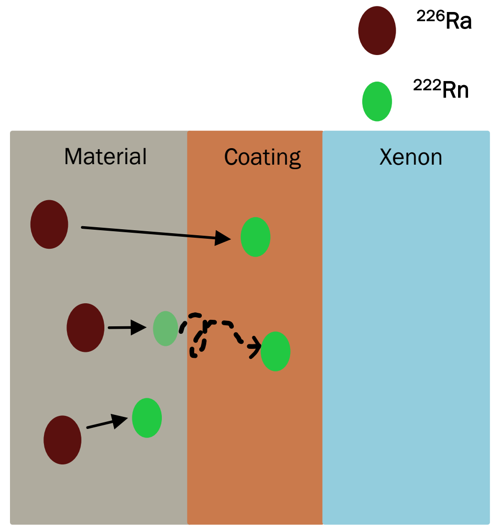
- Suspected to be surface contamination
- Investigating source and mitigation methods

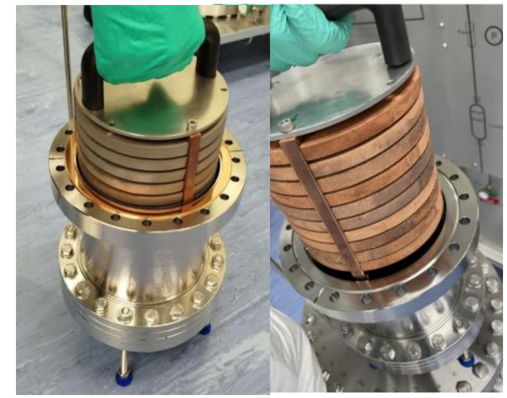
Talk on this Wednesday by R. Schnee!

- Extensive screening and treatment campaign

Copper Electroplating

- Majority of radon that emanates is close to the surface
- Stop emanation by coating greater than maximum recoil distance
- Coating using electroplating of great interest – XLZD collaborators (MPIK) conducting extensive studies [https://arxiv.org/abs/2606.26190]
- 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, DOI 10.1088/1748-0221/21/09/P09016)
- Also investigating electroplating with industrial partners

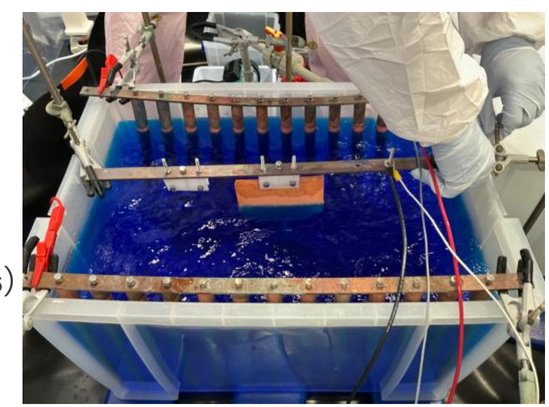


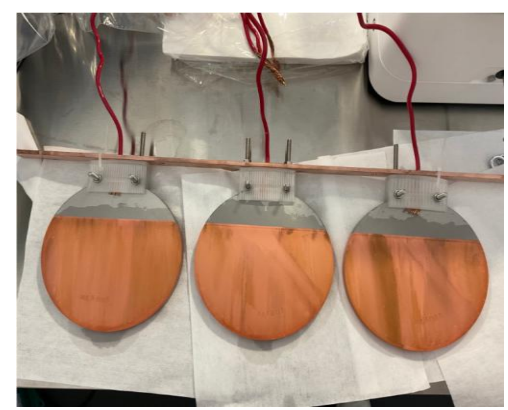


Before and after emanations at CREF

Other talks on coating:
Sophie Armbruster, Monday
Margherita Noia, Wednesday

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





Etching and Machining

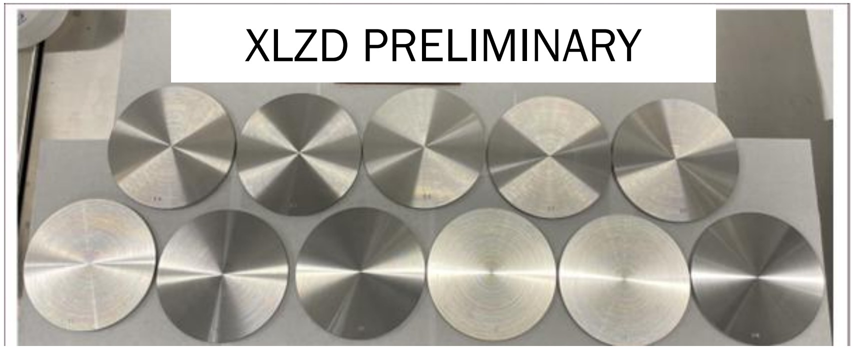
Goal is to remove some amount of surface layer
Hot milling and rolling contribute to surface contamination

Etching

- Etching – Titanium and stainless steel typically require HF
  - Safer possible alternative: Hot H_2SO_4 – ~ 7 um
  - Poster on this by P. Knights
- Hot H_2SO_4 : Radon emanation results showed ~ 10 x drop in surface radon emanation
  - Also large reduction in surface alphas
- HF etch : promising results being finalised
- Results will determine surface treatment of ultimate XLZD cryostat material
- Huge engineering effort to carry out in some sites

Machining

- Machining: removal of a surface layer
  - Requires use of clean tooling
- Removed 250 µm
- Radon emanation close to detection limit
- Large drop in surface alphas
- This also still requires further improvement in radon sensitivity (~ 5x)



Cleanliness

- Control contamination of surfaces during manufacture
- Developed protocols from LZ and XENONnT available:
  - Bagging and purge
  - Cleaning protocols
- New cleanroom in Boulby to test current protocols and develop improved, standardised ones
  - PTFE bagging, cleaning and dust counting
  - Surface alpha counting
- 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

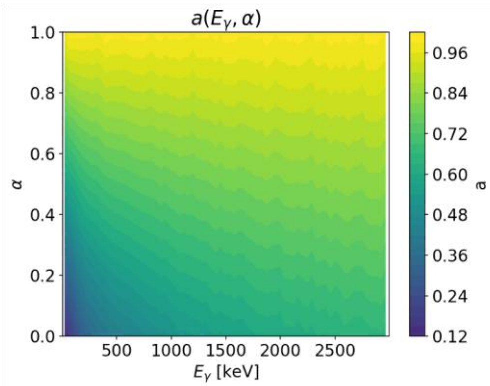
Assembly and QA in LZ

SUMMARY

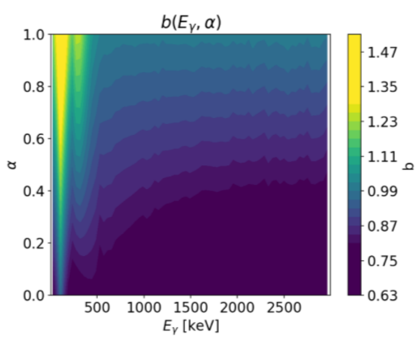
- XLZD will be a multi-science rare event observatory
- Extensive challenges in reducing background load but they are well understood
- Main requirements split into low energy WIMP and high energy 0$\nu\beta\beta$
- Several strategies to mitigate background, including:
  - Material selection
  - Maintaining 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

HPGe Analysis Improvements

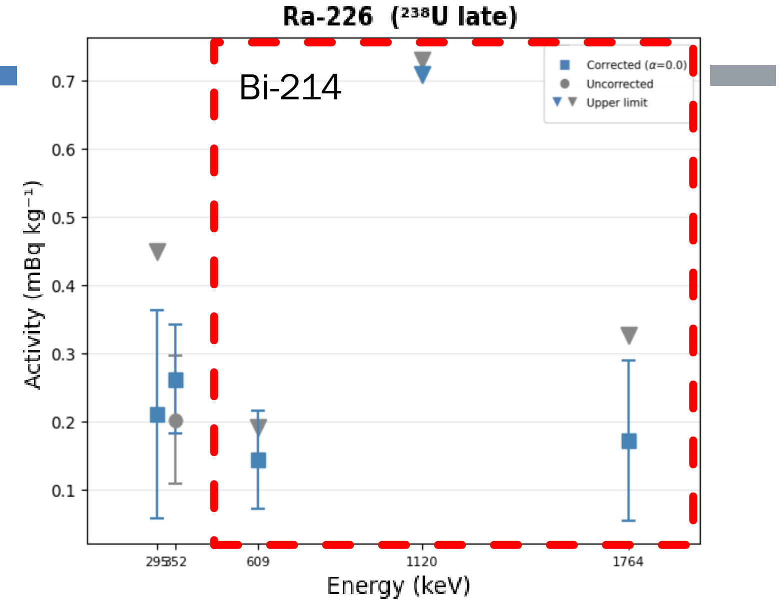


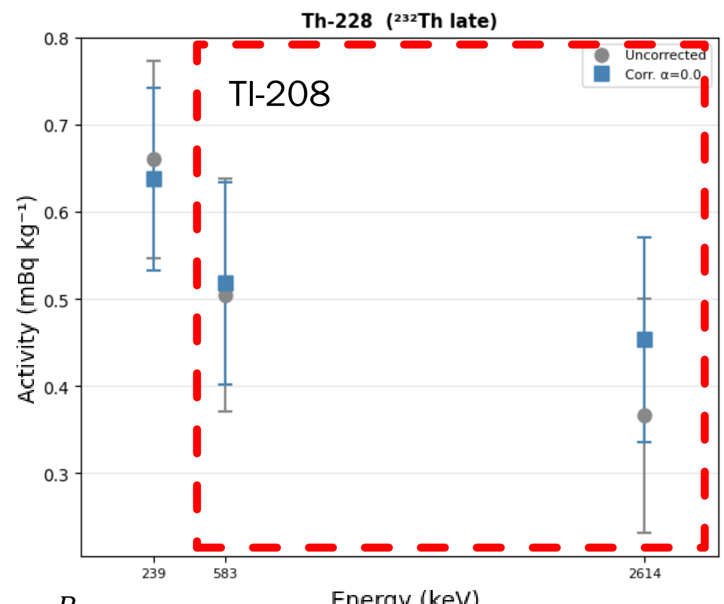
Background peak attenuation correction factor, $a(E_\gamma) = \frac{\epsilon_B^*(E_\gamma)}{\epsilon_B(E_\gamma)}$.



Change in Compton continuum correction factor, $b(E_\gamma) = \frac{B^*(E_\gamma)}{B\ (E_\gamma)}$.

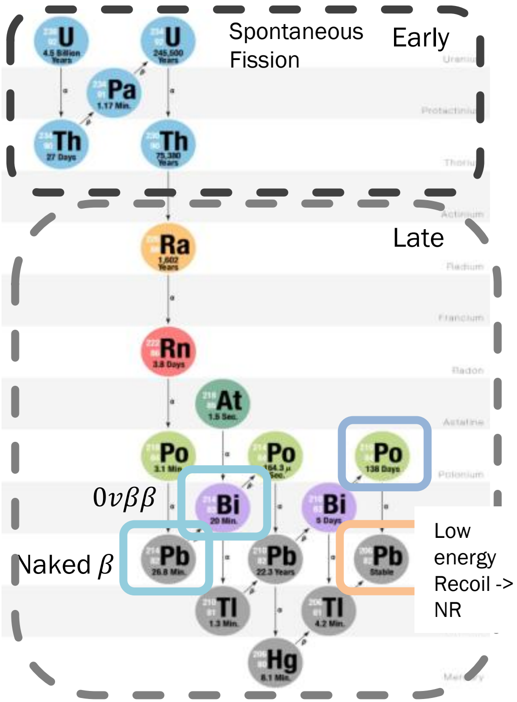
α, fraction of background coming from internal sources (between detector and sample). ie. $\alpha = 1$ is only internal backgrounds, $\alpha = 0$ is only external backgrounds.

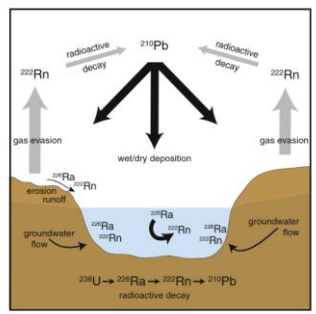


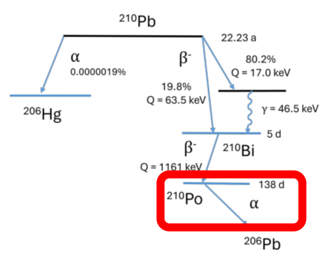


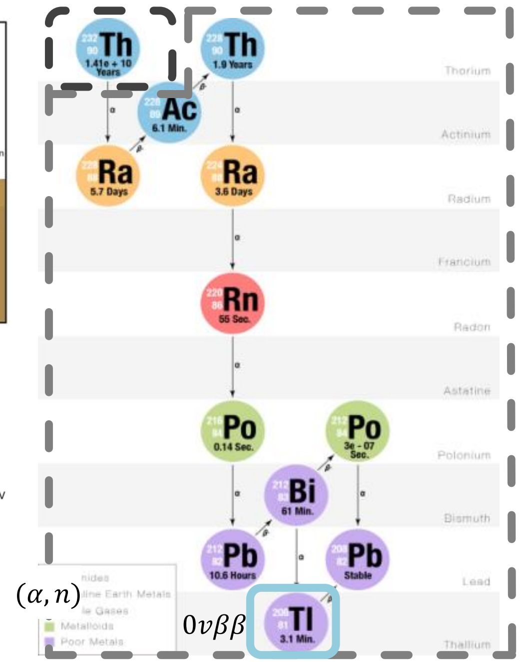
$$B_{corrected} = (\alpha a_I + (1-\alpha)a_E) \cdot B(E_\gamma)_{peak} + (\alpha b_I + (1-\alpha)b_E) \cdot B(E_\gamma)_{bkg}$$

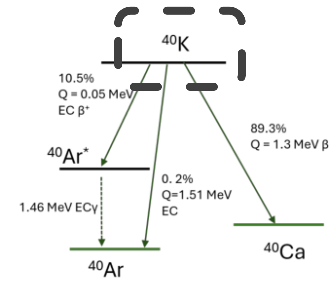
Backup

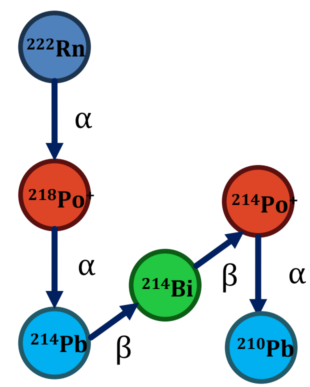

Spontaneous Fission
Early
Late
$0\nu\beta\beta$
Naked β
Low energy Recoil -> NR


radioactive decay
gas evasion
wet/dry deposition
erosion runoff
groundwater flow
radioactive decay


210Pb
206Hg
α 0.0000019%
β- 19.8% Q = 63.5 keV
22.23 a
80.2% Q = 17.0 keV
γ = 46.5 keV
5 d
210Bi
β- Q = 1161 keV
210Po
138 d
α
206Pb

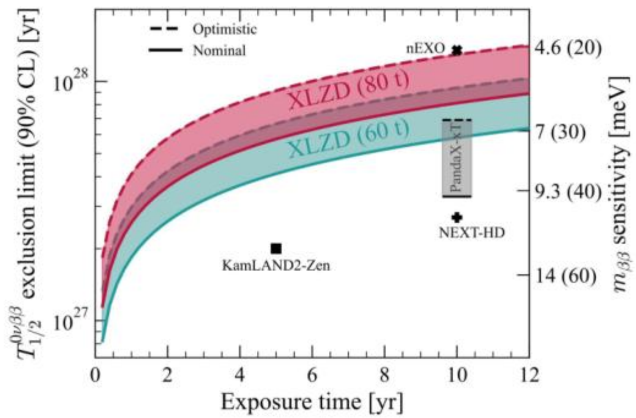

(α, n)
$0\nu\beta\beta$

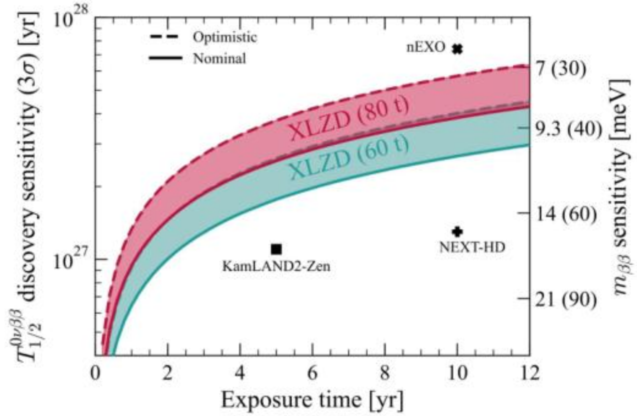

40K
10.5% Q = 0.05 MeV EC β+
89.3% Q = 1.3 MeV β
40Ar*
1.46 MeV ECγ
0. 2% Q=1.51 MeV EC
40Ar
40Ca

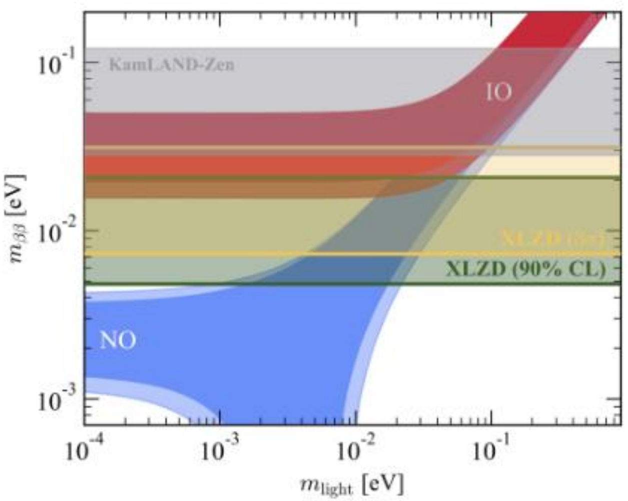

222Rn
α
218Po
α
214Pb
β
214Bi
β
214Po
α
210Pb

Neutrinos

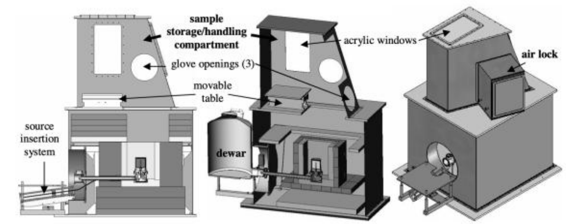
- Irreducible Backgrounds: ^{124}Xe - two-neutrino double electron capture. ^{136}Xe - two-neutrino double beta decay
- Neutrinoless Double Beta Decay: Assuming: 0.1 uBq/kg ^{222}Rn,
- achievable improvements in material radiopurity, 0.65% energy resolution, 99.99% Bi-Po tagging.
- Majority of Inverse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







GeMPI and Gator at LNGS



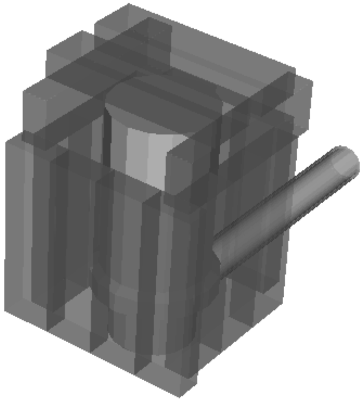
GeMPI at LNGS (2006)

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

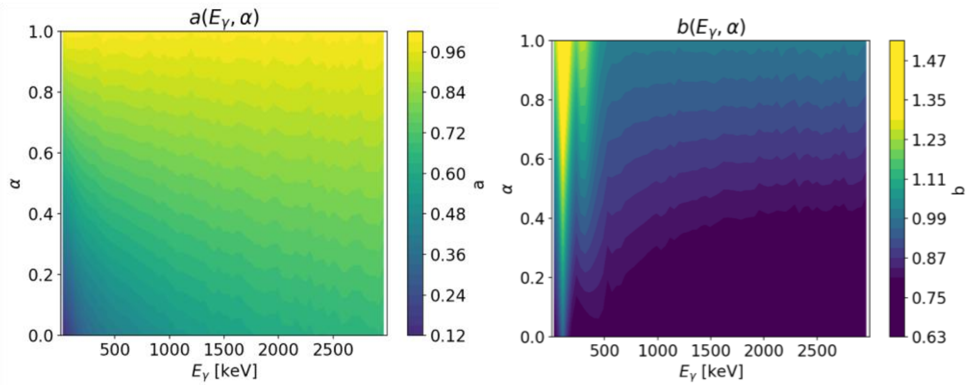
HPGe Analysis Improvements at Boulby

- Simulations performed using Remage (Ge-based detector simulation framework developed by LEGEND)
- XLZD, target of O($10\ \mu Bq/kg$) for Bi-214 and Tl-208 lines (0νββ ROI). Updated analysis techniques drive towards that required sensitivity
  - Also allow better accounting for sample self-shielding
- Dense samples are currently accounting for a large proportion of our assays
  - Alter the detector background -> dropping simple background subtraction

XLZD Titanium samples around **Boulby** HPGe Detector



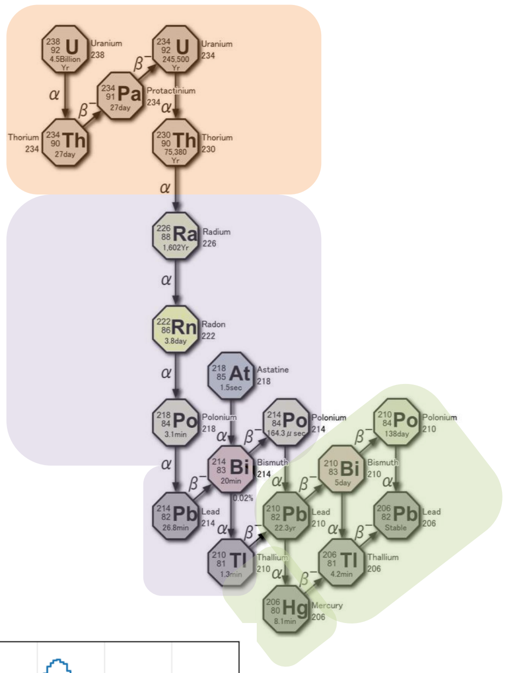
- Detector backgrounds scaled using correction factors ($a(E\_\gamma$) and b(E_γ)) found using internal and external background sims.
  - **lowers detection thresholds and in e.g. titanium sample**
- Tl-208 2614 keV line also shifted, background peak attenuated so **higher signal count in ROI. Some peaks went from UL to activity.**
- For dense samples who have large 4π coverage, now implemented into pipeline.

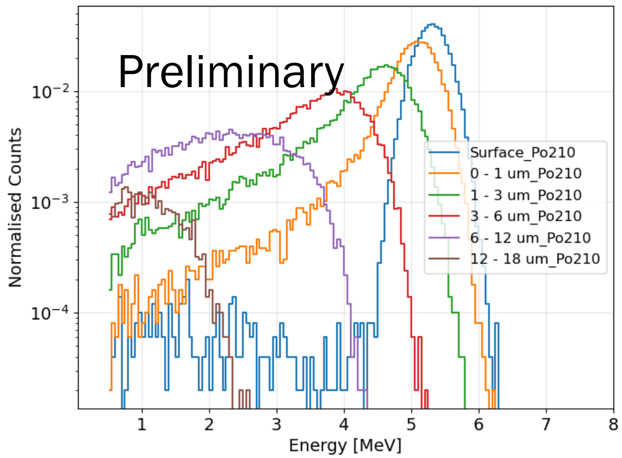


Generated for titanium sample

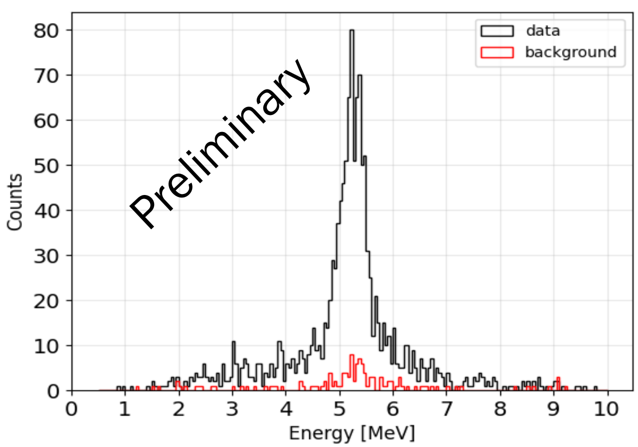
Alpha Counting Analysis

- Currently using XIA UltraLo 1800 in Boulby
- Thin flat samples
- Developing simulation and analysis framework
- Peak around 5.3 MeV – ^{210}Po
  - Shoulder below straggled alphas
- Derive ^{210}Po Surface and bulk contributions using simulations
- Characterise ^{222}Rn daughter plate-out on material surfaces
- Test cleaning and bagging techniques



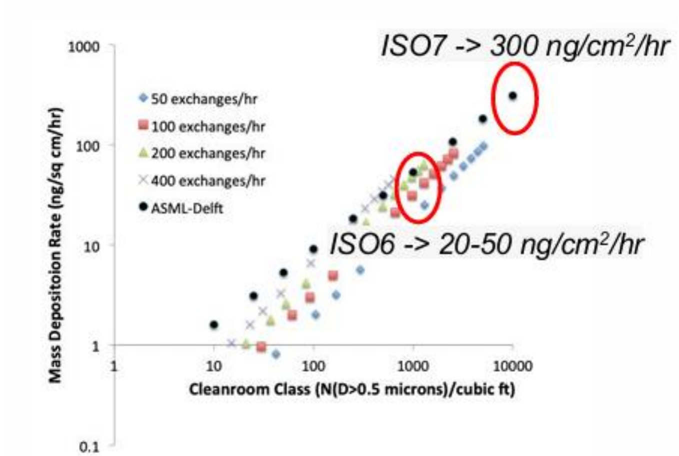


Simulations of 210Po at different depths in titanium



Requirements expanded

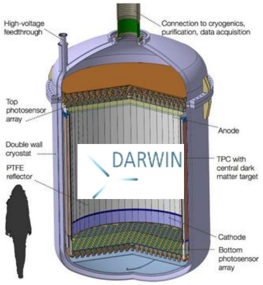
- Neutron backgrounds to be set by 10% the atmospheric neutrino flux (LNGS as most conservative case) 0.046 cts/tonne.yr -> 2.5 cts/yr (for 60 tonne detector) – 95 % veto efficiency
- Plate-out
  - Different plateout requirements for detector regions/materials – High, Medium, Low targets.
  - Low is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

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



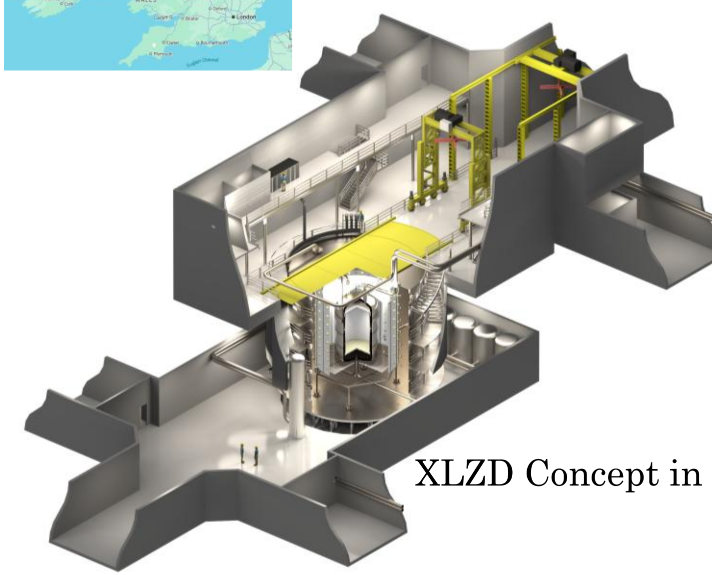
Ongoing activities

- 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

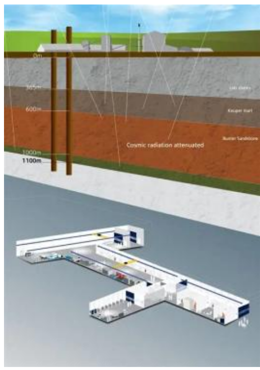
- Boulby Development Project (2022-now) building on dark matter since 1990
  - Develop facility design
  - Excavation of new lab space complete
- Pre-construction Project (2024-2027)
  - Technical design of UK hardware system and interfaces
  - Planning and capacity-building (eg **clean manufacture**)
  - 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+

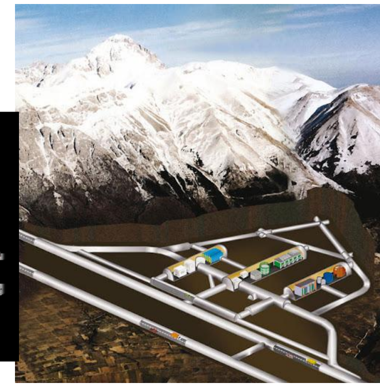
Boulby current lab



XLZD Concept in Boulby

Hosting Site





- Four 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)