The ^{136}Xe neutrinoless double beta decay search with LZ

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BEACH 2018 - Peniche, Portugal

Double beta decay process

Some isotopes are known to undergo a beta decay with the emission of two electrons and two electron antineutrinos **(2νββ)** - e.g. ^{76}Ge, ^{130}Te, ^{136}Xe

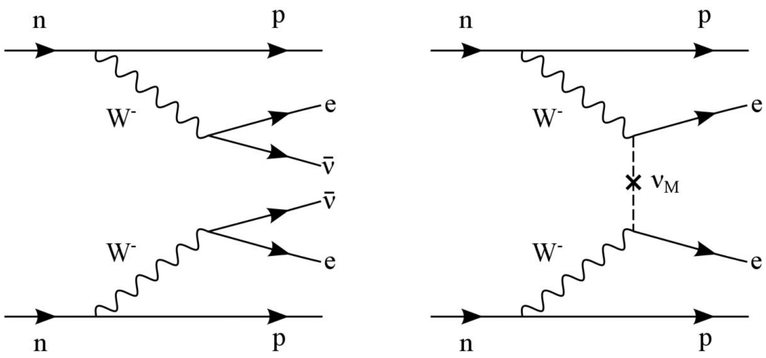
★ The neutrinos avoid detection.

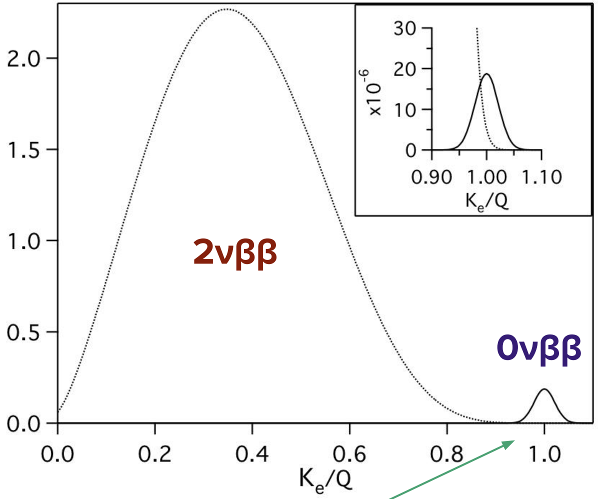
★ Only the summed energy of the two electrons is observed.

If neutrinos are Majorana particles, a neutrinoless double beta **(0νββ)** decay mode is possible - **not yet observed!**

★ The two electrons will carry the total energy of the decay.

A detector can look for the **0νββ** decay of a certain source by searching for an excess rate of events at the endpoint energy of the observed **2νββ** decay spectrum.





Representation of an excess of events at the endpoint of the 2νββ spectrum

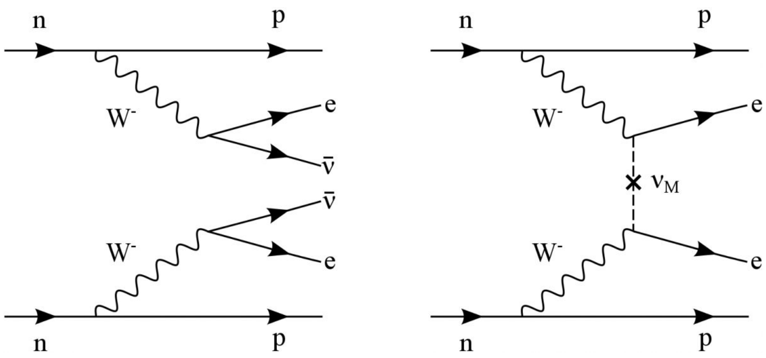
Double beta decay process

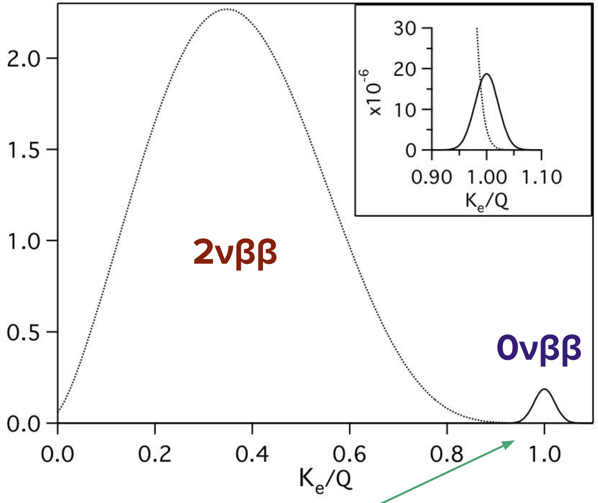
Experimental requirements:

- ★ Complete understanding of the backgrounds in the energy search region
- ★ High abundance of the decaying element
- ★ Excellent energy resolution

Detection of **0νββ** decay would have significant implications for both particle physics and cosmology:

- Violation of leptonic number conservation
- B-L symmetry violation
- The first evidence of fundamental Majorana particles





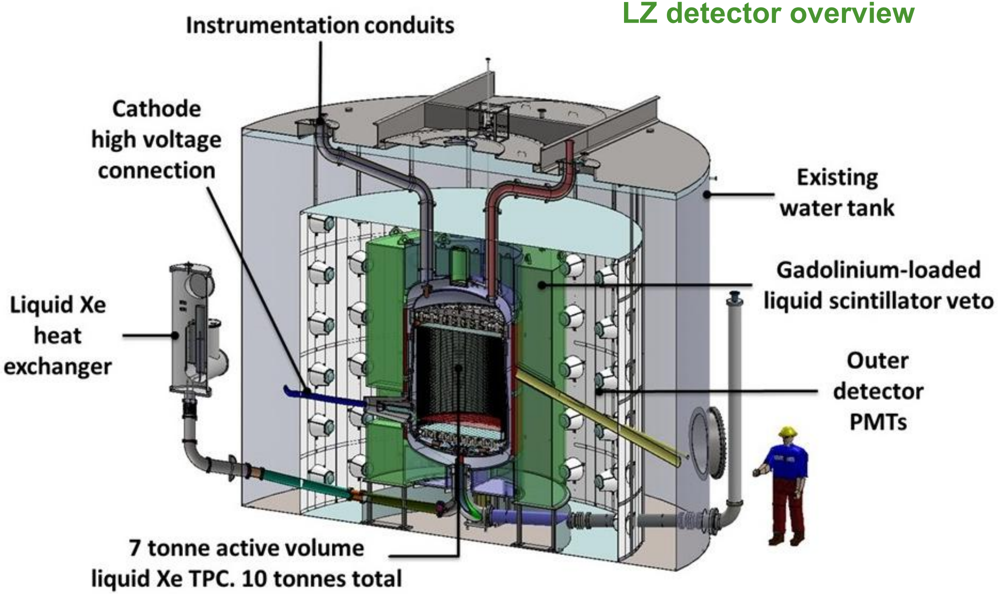
Representation of an excess of events at the endpoint of the 2νββ spectrum

The LZ detector

A **7 tonne** dual-phase xenon time projection chamber (TPC) designed for dark matter search

- ★ Will be operated at a depth of 1.5 km (4300 m.w.e.) in the Sanford Underground Research Facility (SURF) in Lead, South Dakota (USA)
- ★ Expected to start operating in 2020 and perform a science run of 1000 live-days
- ★ **Ultra-low BG environment within the detector is fitting for rare event searches**:
  - ○ <u>Direct search of dark matter</u> in the form of WIMPs (main goal)
  - ○ **Neutrinoless double beta decay!**
  - ○ CEvNS of solar neutrinos

LZ detector overview



The LZ detector

A **7 tonne** dual-phase xenon time projection chamber (TPC) designed for dark matter search.

★ A titanium cryostat supports the main detector system.
★ Active target is surrounded by a PTFE light reflector cage.
★ Two PMT arrays observe the active LXe target from the top (253 PMTs) and bottom (241 PMTs).
★ Four horizontal grids establish the vertical drift field and a high field extraction region in the liquid-gas interface

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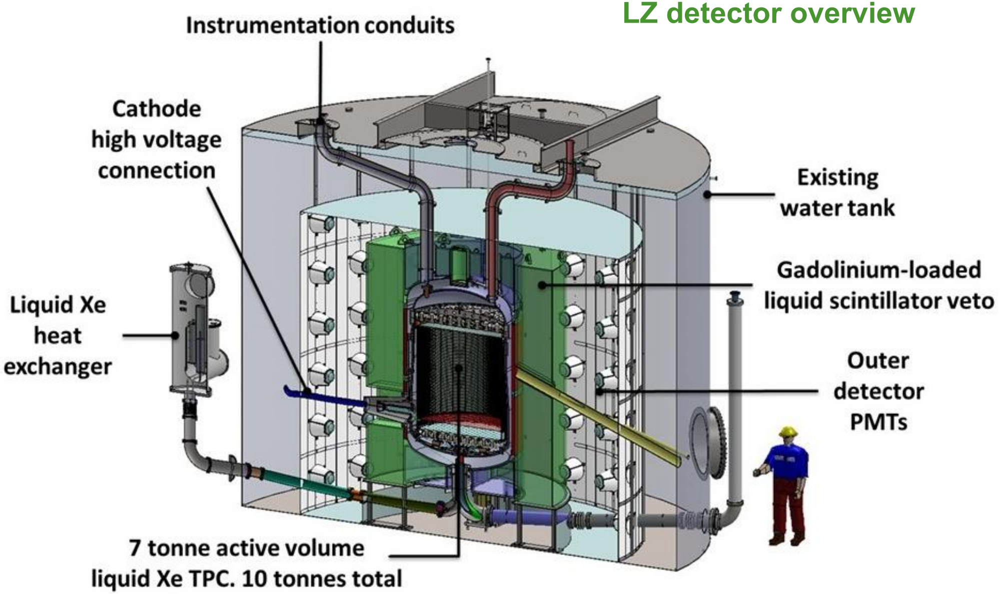

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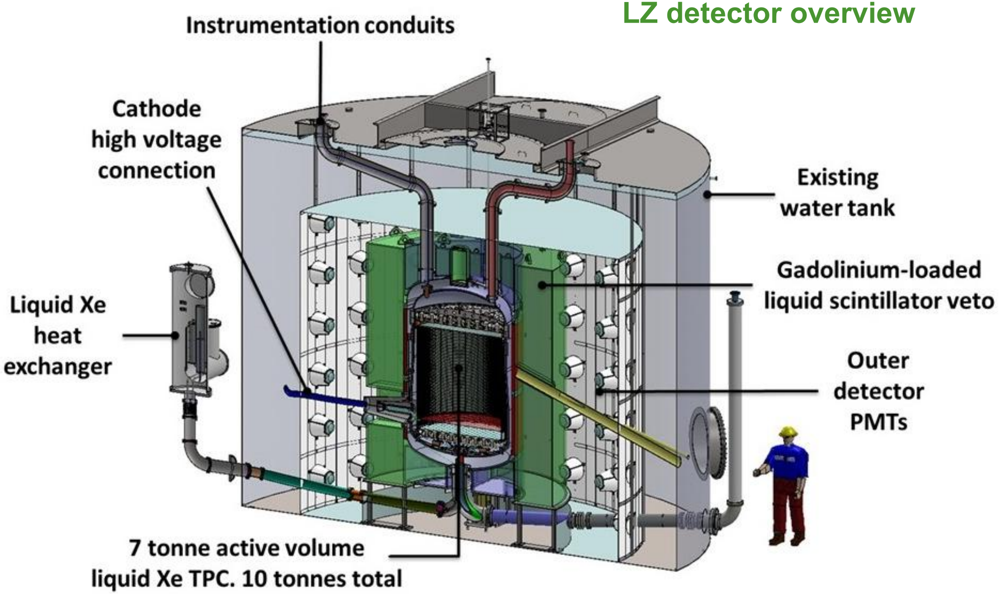


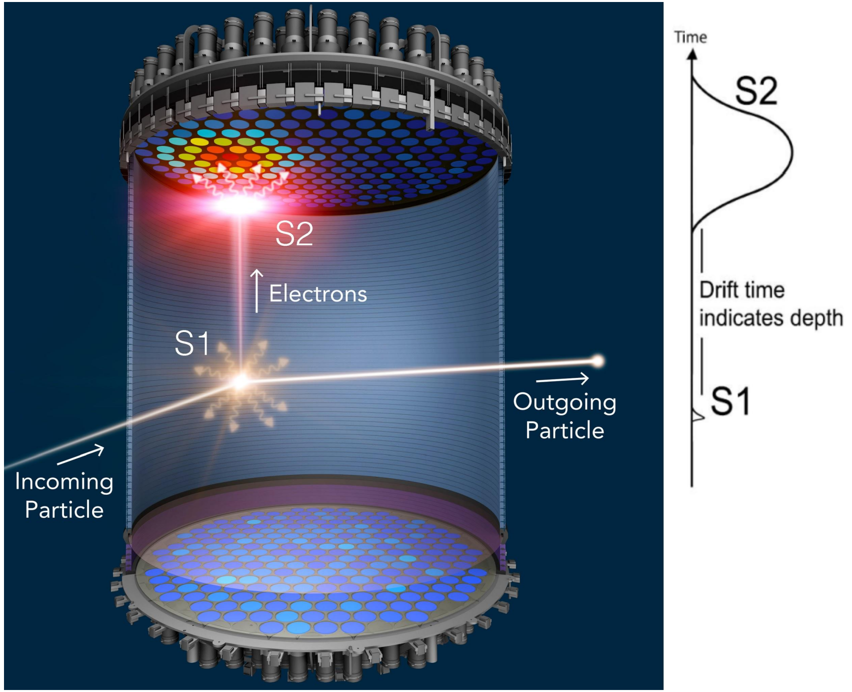
Built using ultra-pure materials to reduce backgrounds from detector components

LZ detector dual-phase TPC: operating principle

1. An energy deposition in the LXe produces **prompt scintillation light (S1)** and ionization electrons.
2. The electrons that do not recombine are drifted to the liquid-gas interface and extracted into the gas phase, creating **electroluminescence light (S2)**

- ★ **Deposited energy is reconstructed using both the S1 and S2 signals.**
- ★ The depth of the interaction can be obtained by the **time difference between the S1 and S2 signals.**
- ★ The XY position can be reconstructed using the **light pattern generated by the S2** signal on the top PMT array.

We get a full 3D reconstruction of the interaction!



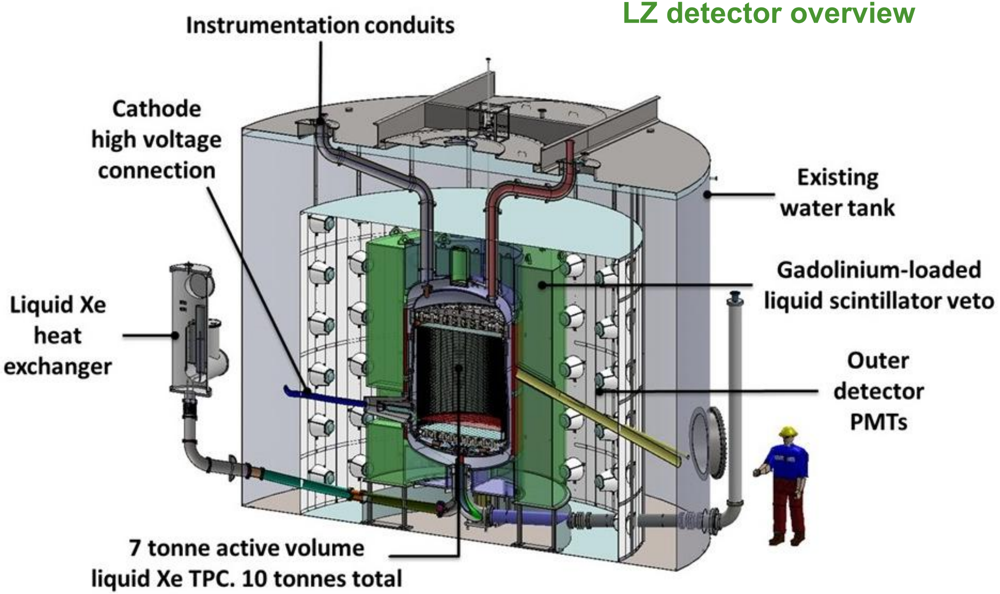
LZ detector: veto systems

The detector features two active veto systems:

- ★ **LXe layer** between the PTFE and cryostat surrounds the TPC on the sides and bottom
  - ○ Anti-coincidence detector with 131 PMT readout **(dubbed LXe "Skin")**
- ★ Titanium cryostat is surrounded by a **Gadolinium-loaded liquid scintillator**
  - ○ Active veto with 120 PMT readout **(dubbed the outer detector, OD)**

All the detector systems are within a water tank that provides additional shielding and also serves as a muon veto.

LZ detector overview



Search for ^{136}Xe neutrinoless double beta decay

Natural xenon contains the isotope ^{136}Xe, a known double beta emitter:

- ★ Measured $2\nu\beta\beta$ decay half-life of **2.11×10^{21} years**
- ★ Q-value of **2458 keV**
- ★ Average concentration in natural xenon is **8.9%**

LZ features a **7 tonne** instrumented LXe target, implying that around **623 kg of ^{136}Xe** will be present in the active region without enrichment of the LXe volume!

Xenon is a particularly good target for neutrinoless double beta decay searches:

- ★ High-density provides self-shielding and makes large mass detectors manageable.
- ★ Excellent scintillation yields.
- ★ **Excellent background discrimination ability.**

Background model for 0νββ decay of ^{136}Xe

The model is continuously updated with most recent **material assays** and **background simulations**.

- ★ Extensive Monte Carlo simulations of BGs from radioactive contamination in detector components.
- ★ **Full detector geometry is modeled!** Using BACCARAT, a framework based on GEANT4 that evolved from the LUXSim simulation package developed for LUX.

Backgrounds will be measured with high precision once the detector begins the first science run!

Model includes contributions from:

- ★ **Radiation from detector components**
- ★ ^{136}Xe double beta decay
- ★ ^{8}B solar neutrinos
- ★ **Gammas from cavern walls**
- ★ “Naked” beta from ^{214}Bi (internal ^{222}Rn)
- ★ Neutron-induced ^{137}Xe

Dominated by detector materials!

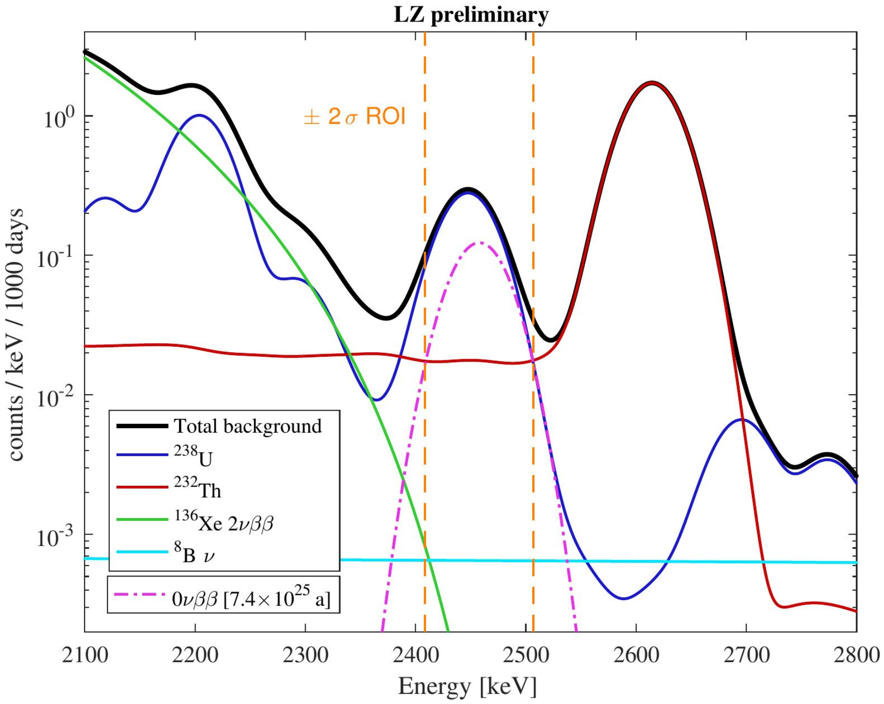
Cavern walls are expected to contribute with ~2 counts

Background model for 0νββ decay of ^{136}Xe

Contamination from detector materials:

- ^{214}Bi gamma line with Eγ = 2447.7 keV
  ^{238}U chain, 1.4% BR
- ^{208}Tl gamma line with Eγ = 2615 keV
  ^{232}Th chain, 35% BR ^{210}Bi→^{208}Tl
- ^{60}Co summed peaks
  completely removed by selecting single scatters in the active region

- Naked beta from ^{214}Bi (internal radon)
  - Tagged by ^{214}Po alpha (T_{hl}=164.3 μs)
- Muon-induced ^{137}Xe
  - Low muon flux at SURF



Background analysis

A Feldman-Cousins cut and count analysis is performed, considering that no signal is observed on a data acquisition run of 1000 live-days.

- Simulations of ^{238}U and ^{232}Th decay chains on main detector components.
- Contributions from 2νββ decay and solar ^{8}B neutrinos calculated in dedicated analysis

Analysis cuts:

- Region Of Interest (ROI)
  - 2σ on each side of the Q-value (1.0% E-res)
  - **2409 < E < 2507 keV**
- Fiducial Volume (FV)
  - **957 kg** of natural xenon - **85 kg of ^{136}Xe**
  - $R < 42$ cm & $\sqrt{((x-70)^2 + y^2)} > 39$ cm
  - $33 < z < 96$ cm
- Single Scatter (SS)
  - Energy deposition spread in **z < 0.3 cm**
  - no cut for spread in xy plane
- Skin and outer detector (OD) vetos
  - Edep >100 keV in **Skin** within 800 μs coincidence window
  - Edep >200 keV in **OD** within 500 μs coincidence window

Background analysis

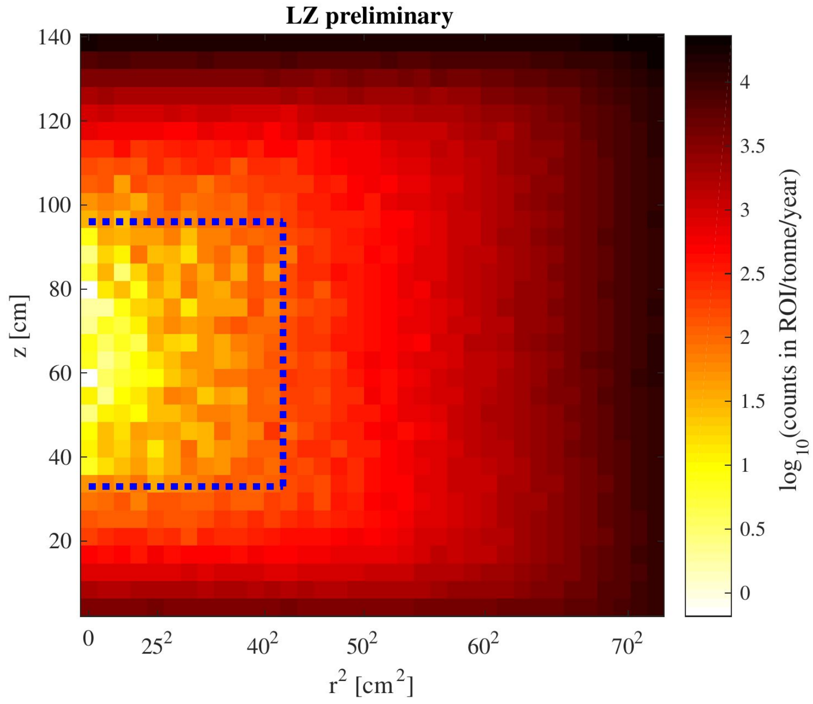
Optimized fiducial volume (FV) - Trade-off between mass and background reduction to obtain the best sensitivity to the half-life of the decay

- ★ **957 kg mass** in the center of the detector
- ★ Vertical cut between 33 cm and 96 cm from the cathode.
- ★ Main radial cut at 42 cm (31 cm from the walls)

Additional radial cut to avoid contamination from the **field-cage resistors**:

- ★ Exclusion of events within 39 cm from the vertex [x=70; y=0]

Background event rate in the active region and in the ROI for a 1000 live-days run



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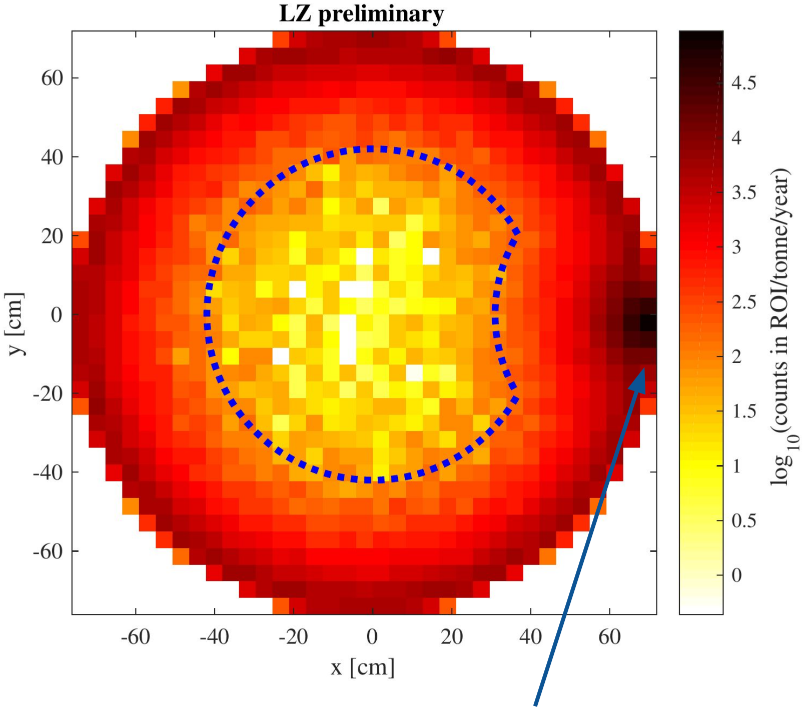
Background event rate in the active region and in the ROI for a 1000 live-days run (33 < z < 96)



Field-cage resistors are aligned on one side of the detector

Background analysis

The main contributors†

- ★ **TPC PMTs and surrounding structures**
- ★ **Cryostat**
  - **Ultra-pure Ti** but a mass of 2.6 tonnes!
- ★ **Outer detector acrylic tanks**
  - Also ultra-pure, but with a mass of 4.3 tonnes!
- ★ **Field cage resistors**
  - Less than 50 grams combined but have high contamination levels.
  - Partially solved with dedicated FV optimization

An additional 8 cm of steel-equivalent shielding is considered above the detector to minimize the contributions from the **cavern walls**.

†Some contamination values for detector materials are measured upper-limits.

Item	Counts from 238U	Counts from 232Th	Other counts	Total Counts
TPC PMTs	1.72	0.33	0.0	2.05
TPC PMT bases	1.03	0.02	0.0	1.05
TPC PMT structures	1.47	0.21	0.0	1.68
TPC PMT cables	1.23	0.13	0.0	1.35
Skin PMTs	0.42	0.02	0.0	0.45
Skin PMT bases	0.04	0.0	0.0	0.04
PTFE walls	0.25	0.0	0.0	0.25
TPC sensors	1.45	0.0	0.0	1.45
TPC thermometers	0.04	0.0	0.0	0.04
Field grids	0.15	0.0	0.0	0.15
Field grid holders	0.99	0.08	0.0	1.07
Field-cage Resistors	1.47	0.05	0.0	1.51
Field-cage rings	0.75	0.01	0.0	0.76
Cryostat	4.27	0.86	0.0	5.13
Outer detector	1.52	1.12	0.0	2.63
Other components	0.54	0.13	0.0	0.67
Cavern walls	<0.1*	2*	0.0	2*
$2\nu\beta\beta$	-	-	0.01	0.01
^8B solar neutrinos	-	-	0.07	0.07
Neutron-induced ^{137}Xe	-	-	<0.01	<0.01
Total	17.44	4.97	0.09	22.50

**preliminary estimate*

Sensitivity projections

With the total background levels expected for a run of 1000 live-days, the 90% confidence level (CL) upper limit is **7.58 counts**, corresponding to a

> Median 90% CL sensitivity to the ^{136}Xe $0\nu\beta\beta$ decay half-life of **0.74×10^{26} years**

Current best results from **KamLAND-ZEN are $T_{1/2}^{0\nu}$ > 1.07×10^{26} years** and a sensitivity of **0.56×10^{26} years**

- ★ The signal acceptance efficiency is calculated to be of 77%
  - ○ 95.4% efficiency imposed by the the 2σ ROI definition
  - ○ 80% estimated for the single scatter cut
- ★ Estimated resolution of 1.0% at the Q-value is achievable assuming an average photon detection efficiency of 7.5%, a 95% electron extraction efficiency and 50 detected photons per extracted electron.
- ★ For these energies, the S2 signal will saturate some PMTs in the top array, but using only the bottom PMT array for energy reconstruction will not affect the resolution.

Conclusions

★ The LZ experiment will be able to achieve a competitive limit for the half-life of the 0νββ decay of ^{136}Xe without a dedicated run - Sensitivity to the ^{136}Xe 0νββ decay half-life of **0.74×10^{26} years**

★ The sensitivity analysis is being upgraded:

  ○ Use of PLR method with full background model and detector response.

  ○ Identify material contamination upper limits and request new assays.

★ **A paper is being drafted and will soon be published!**

★ A post-WIMP search dedicated run with an enriched xenon volume could improve the projected sensitivity of LZ by an order of magnitude.

  ○ 90% enrichment implies 10 times more ^{136}Xe in the active region.

  ○ The neutron-activated ^{137}Xe background would increase - further studies required.

Thank you!

PD/BD/114114/2015

PTDC/FIS-NUC/1525/2014