Neutrinoless double beta decay search in LZ

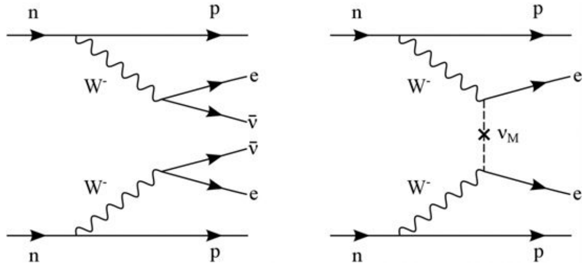
Summer Internship 2023

Nuno Mandeiro, João Simões

Neutrinoless double beta decay

The LZ experiment is a dark matter experiment mainly searching for WIMP dark matter. However, the same characteristics allow us to study much more about physics, including the nature of neutrinos

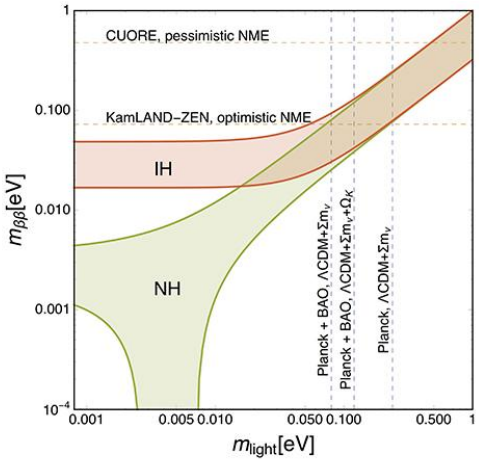
-The **neutrinoless double beta decay (0νββ)** is a process by which a nucleus emits two electrons and no neutrinos



0νββ decay is the <u>most sensitive probe to the Majorana nature of the neutrino</u>. Also sensitive to <u>neutrino mass scale and hierarchy</u>.

Observation has far-reaching implications:

- Lepton number-violation
- Neutrinos are Majorana
- Leptogenesis: possible explanation of the matter-antimatter asymmetry of the universe
- The 0νββ decay is also sensitive to the <u>absolute mass scale and mass hierarchy of the neutrino.</u>

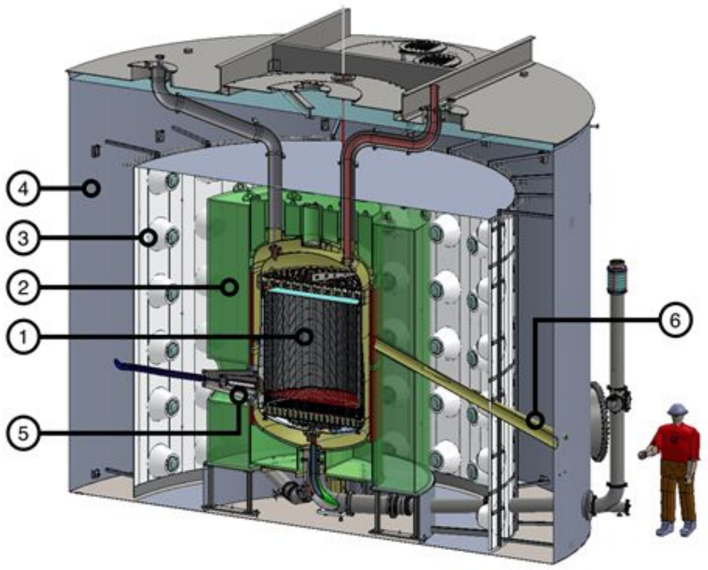


The LUX-ZEPLIN Experiment

A 10 tonne liquid Xe ultra-low background dark matter detector, located 1478 m underground in a gold mine in the USA. Using rock overburden to shield from penetrative cosmic ray muons.

A detector designed to observe the **0νββ** decay needs to have:

- ultra-low background;
- low energy threshold;
- high abundance of the decaying element
- excellent energy resolution at the Q-value of the decay.



The LZ experiment uses a liquid Xe target because:

❖ Liquid Xe is very dense (2.9 g/cm^3)

➢ Self-shielding and active vetoing

❖ High **ionization** and **scintillation** yields

➢ 55 ph/keV @10keV ER ; 8 ph/keV @10keV NR

❖ Contains two 2νββ decaying isotopes

➢ ^{134}Xe and ^{136}Xe, with the latter having large $Q_{\beta\beta}$ = 2.558 MeV

Dual-phase noble element TPC

Time Projection Chamber (TPC) working:

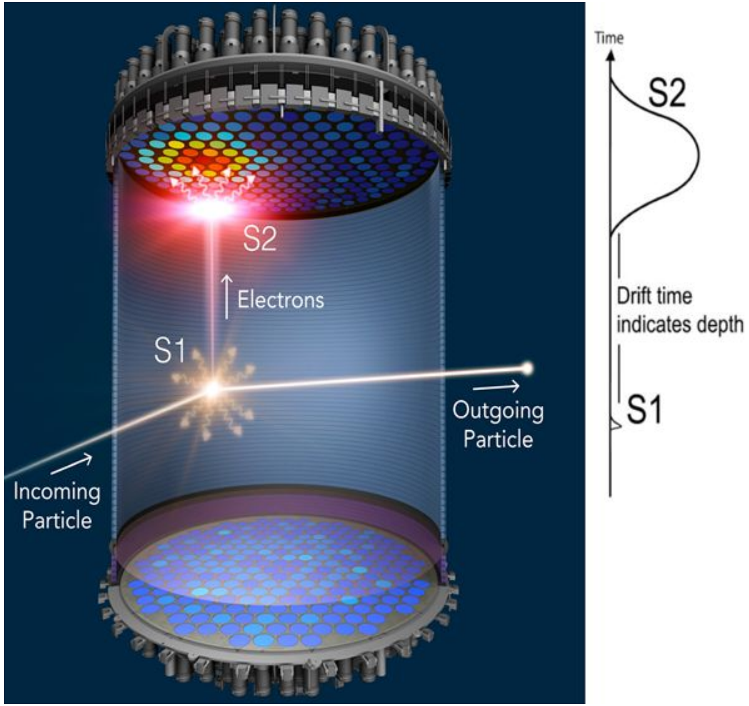
1. An energy deposition in the target produces **prompt scintillation light (S1)** and ionization electrons.

2. The electrons that do not recombine are drifted to the liquid-gas interface and extracted into the gas phase, creating **electroluminescence light (S2)**

A full 3D reconstruction of the event is obtained using the temporal difference between signals and the light pattern produced by S2

$$E = LW\left(\frac{S1}{g1} + \frac{S2}{g2}\right)$$

W≈13.7 eV;
L is a quenching factor
g_1 & g_2 are detector parameters

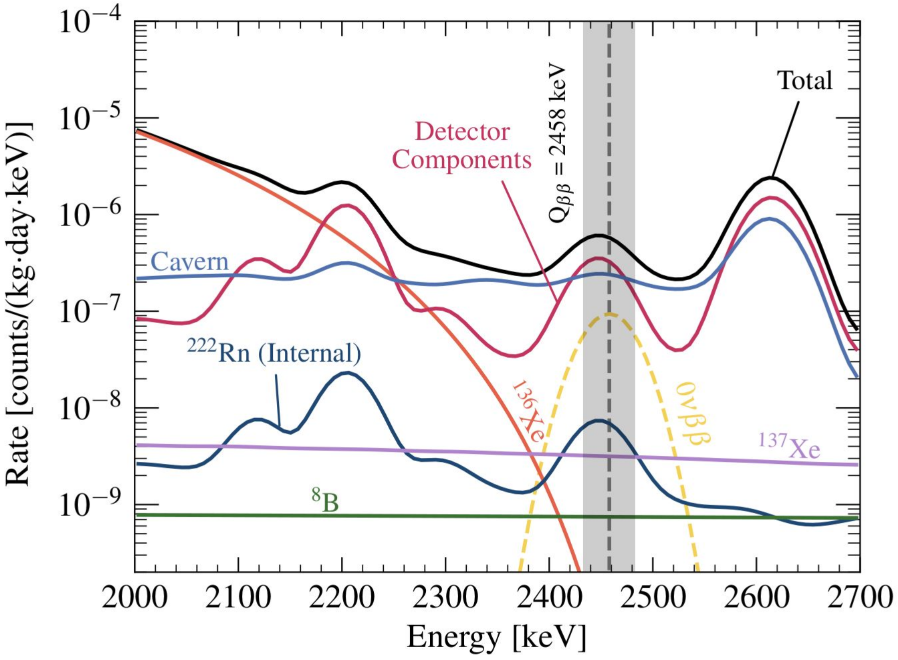


Backgrounds for a $0\nu\beta\beta$ search with ^{136}Xe

It includes most backgrounds for the neutrinoless sensitivity analysis:

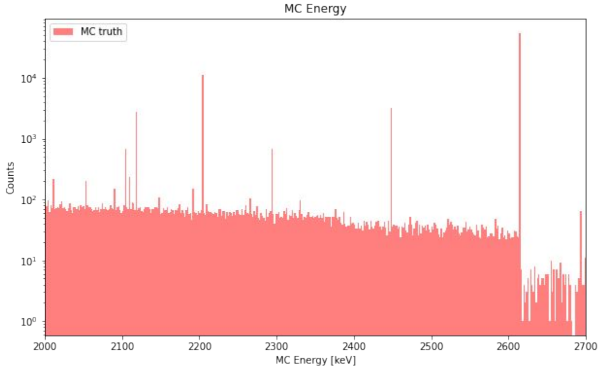
- ^{214}Bi gamma line with $E\gamma$ = 2447.7 keV
- ^{208}Tl gamma line with $E\gamma$ = 2615 keV
- ^{60}Co summed peaks
- $2\nu\beta\beta$ decay of ^{136}Xe
- ^{8}B solar neutrinos

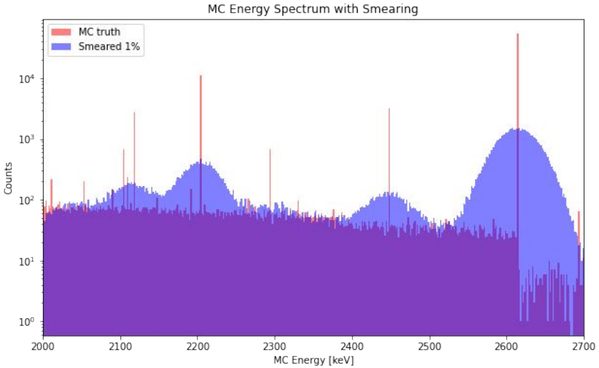
- Radioactivity from detector materials (like ^{238}U and ^{232}Th contaminants as well as many other internal, external and cosmogenic sources that have not been addressed here)



“Truth” energy and “smearing”

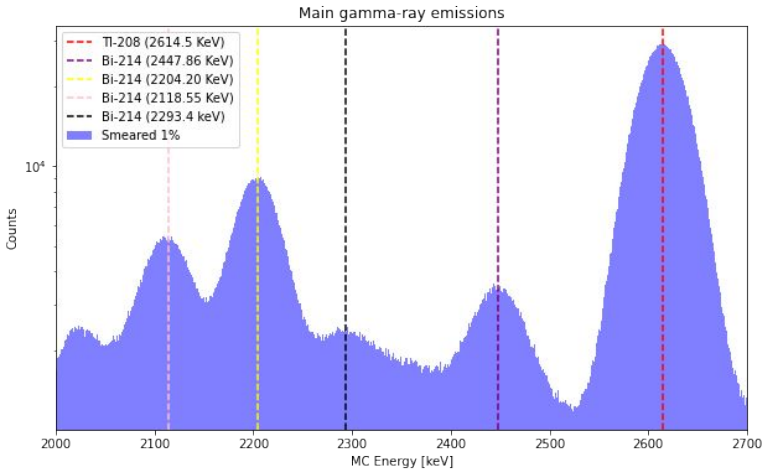
The truth energy is the actual energy that a particle deposits in the TPC. In a realistic case, the spectrum of energy is never precise because of the detector resolution, noise, and other instrumental defects.



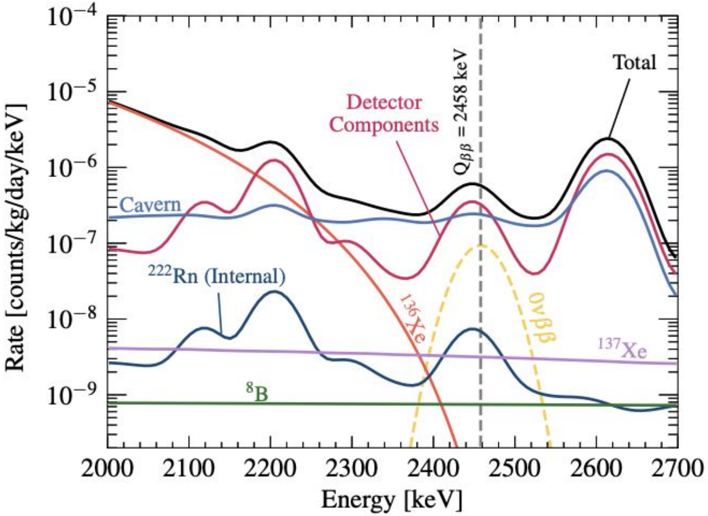


Doing a Gaussian smearing of the truth energy of 1%, we simulate a experimental energy spectrum.

Comparison



Main gamma-ray emissions
Tl-208 (2614.5 KeV)
Bi-214 (2447.86 KeV)
Bi-214 (2204.20 KeV)
Bi-214 (2118.55 KeV)
Bi-214 (2293.4 keV)
Smeared 1%
10^4
Counts
2000
2100
2200
2300
2400
2500
2600
2700
MC Energy [keV]



10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Rate [counts/kg/day/keV]
Total
Detector Components
$Q_{\beta\beta}$ = 2458 keV
Cavern
^{222}Rn (Internal)
^{136}Xe
$0\nu\beta\beta$
^{137}Xe
^{8}B
2000
2100
2200
2300
2400
2500
2600
2700
Energy [keV]

Fiducial volume optimization

In this stage we have used the metric FV_mass/sqrt(events) as a proxy for sensitivity, where FV_mass is the Xe mass in the fiducial volume [kg], and events is the number of events within the volume.

RCUT, ZCUT_MIN and ZCUT_MAX (RZZ) define a cylindrical volume.

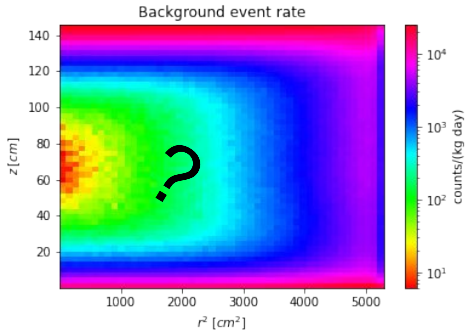
Our goal is to find the RZZ values that give us the best sensitivity. So, we optimise them using the metric FV_mass/sqrt(events).

How does the optimization work?

1. Start fixing RZZ values (we know that the volume we search for is in the initial volume).
2. Subtract step size to RCUT and ZCUT_MAX and add to ZCUT_MIN, for each operation (independently) we calculate the sensitivity.
3. Scan all RZZ values and find the combination of the three who have the highest sensitivity.
4. Repeat 2 and 3 each time with smaller step sizes.

Step sizes used for each complete iteration: 1st → 2cm; 2sd → 1cm; 3rd → 0.5cm; 4th → 0.1cm;

Note: A complete interaction means that all RZZ values vary, whereas an interaction is just when a single value varies.

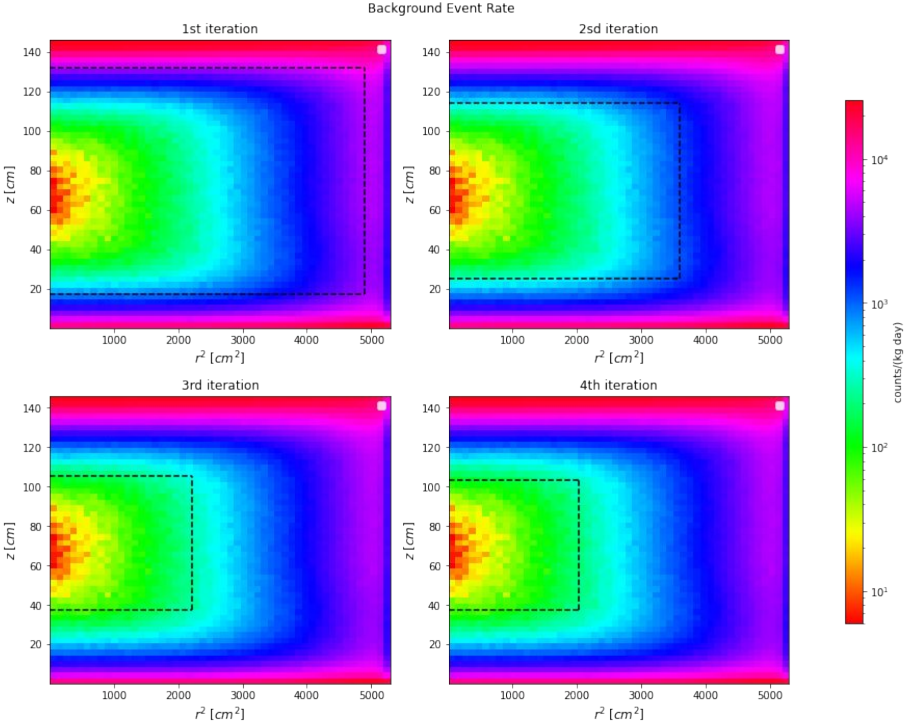


Fiducial volume optimization

Results:

Iterations	RCUT (cm)	ZCUT_MIN (cm)	ZCUT_MAX (cm)
Initial	70	1	140
1st	70	17	132
2sd	60	25	114
3rd	47	37.5	105.5
4th	45.1	37.5	103.2

Complete iterations:



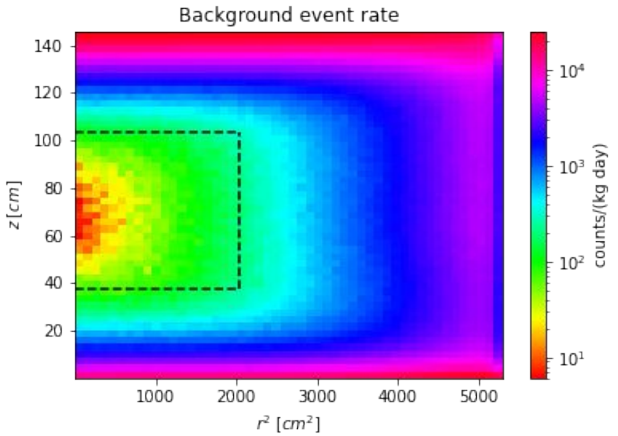
Fiducial volume optimization

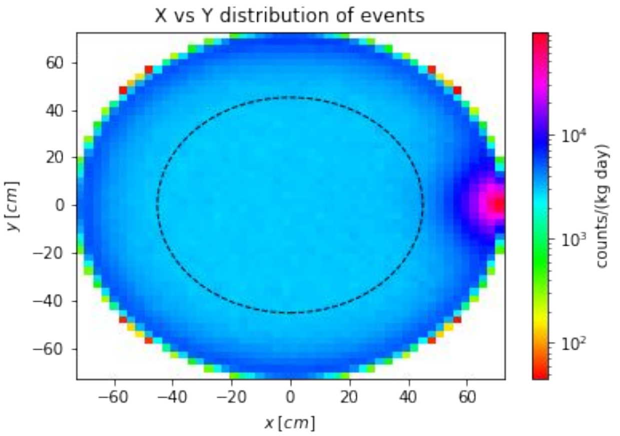
- RCUT = 45.1cm
- ZCUT_MIN = 37.5cm
- ZCUT_MAX = 103.2cm

Total volume = 419.8 L
Mass of Xe = 1217.5 Kg

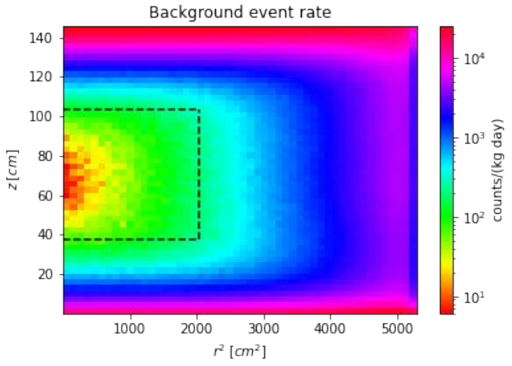
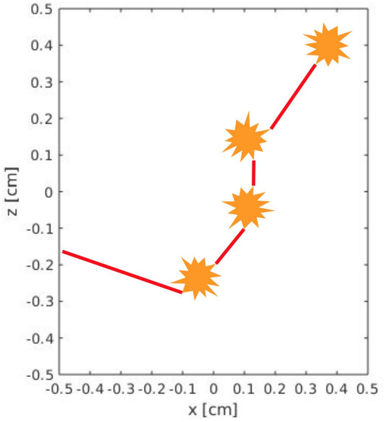
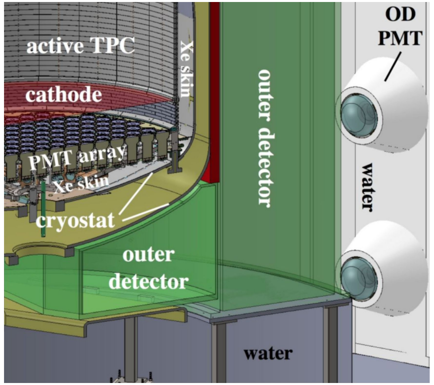
<u>The natural abundance of 136-Xe is 8,9%:</u>

Volume of 136-Xe = 37.4 L
Mass of 136-Xe = 108.4 Kg

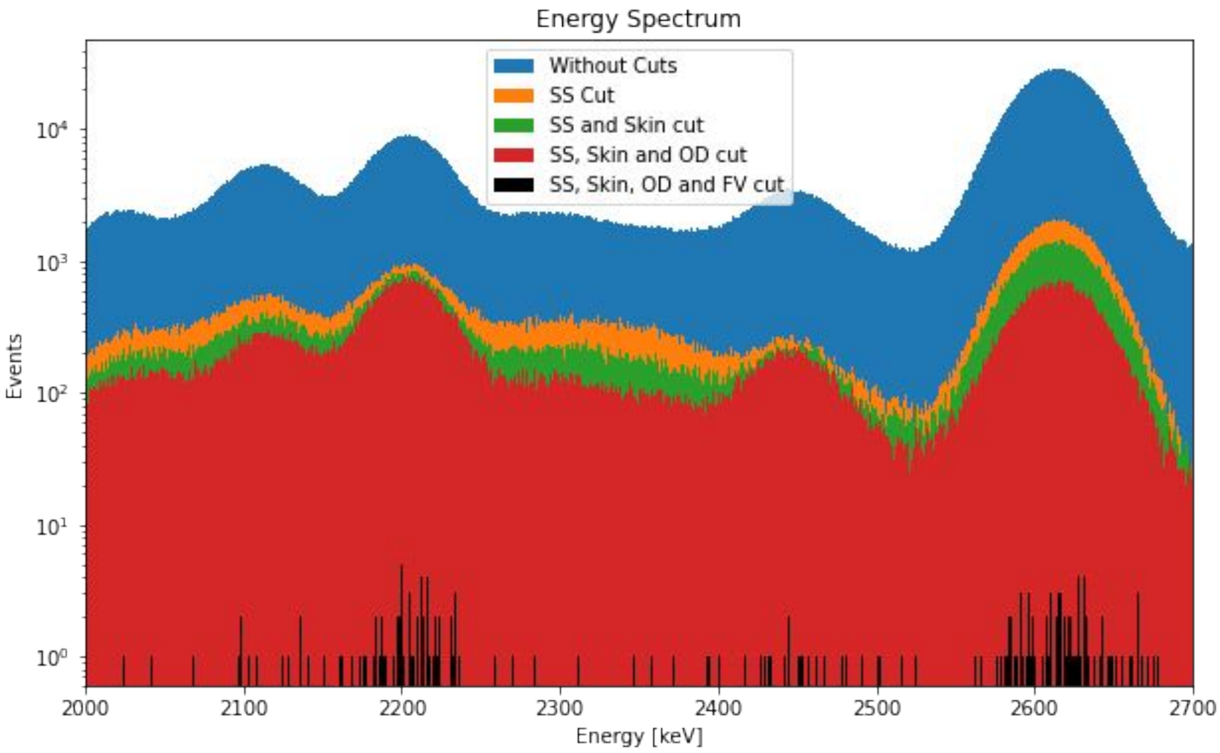




Cuts

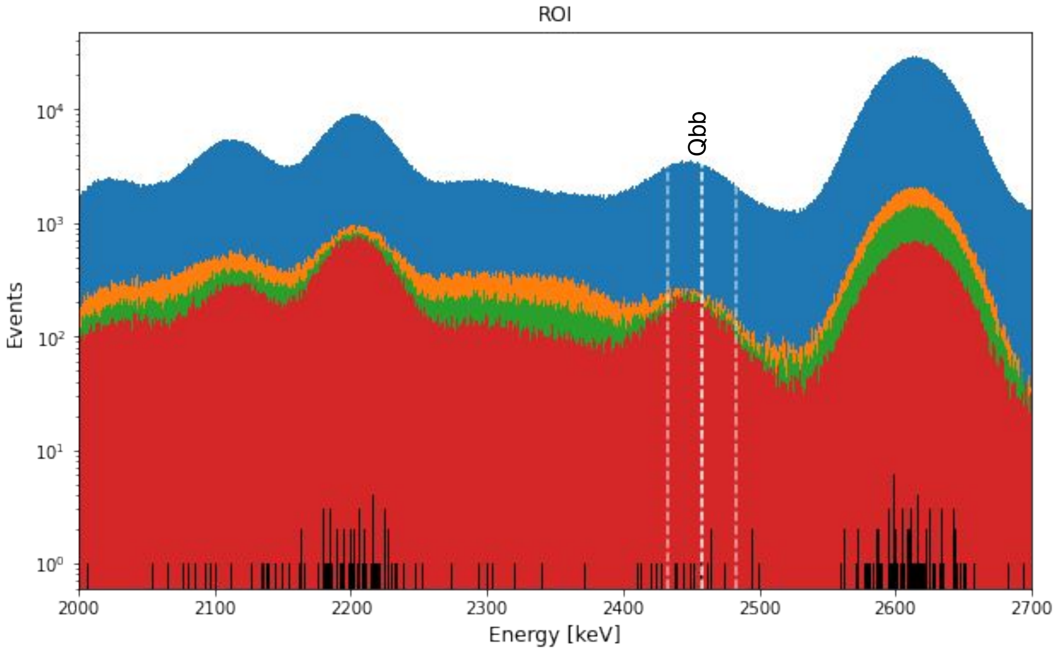
Fiducial Volume	Single Scatter	Vetoes
• R < 45.1 cm • Z > 37.5 cm • Z < 103.2 cm 	• ΔZ < 0.3 cm (signal acceptance of 80%) 	• Less than 100 KeV in the Outer Detector or Skin • Less than 1us difference within the TPC and the Outer Detector or Skin 

Data quality cuts



From 7,889,437 (blue) only survive 346 (black).

The ROI - Region of Interest



Qbb = 2457.83 KeV
±1σ around Qbb - ROI
(coverage of 68%)

ROI_min = 2433.25 KeV
ROI_max = 2482.41 KeV

From 346 events (black) 20.8 survive the ROI cut (mean value attain for 100 smerings).

Sensitivity

$$T_{1/2}^{0v} = \ln 2 \frac{m_{Xe}\eta_{Xe136}N_A}{M_{Xe136}} \frac{\epsilon}{\mu_s} t$$

$T_{1/2}^{0v}$ – half-life of the 0vbb decay

η_{Xe136} – natural abundance of 136-Xe

M_{Xe136} – molar mass of 136-Xe

N_A – Avogadro constant

ϵ – signal efficiency (combined effect from the SS and ROI cuts)

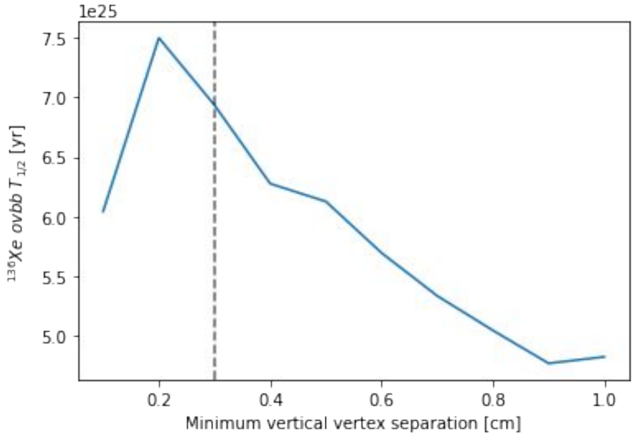
m_{Xe} – mass of natural xenon

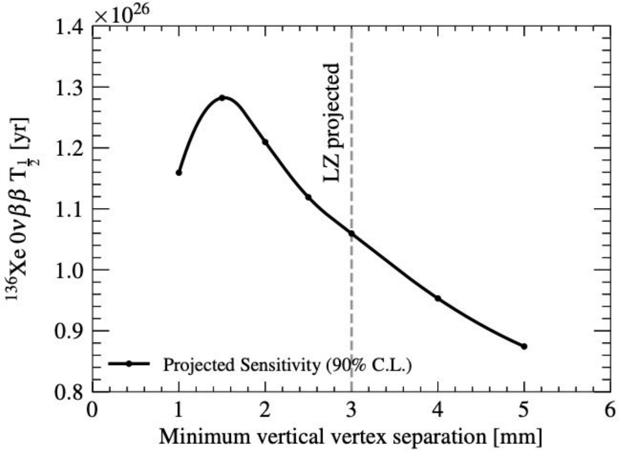
μ_s – Upper limit (number of excess signal events that are statistically consistent with the background-only hypothesis).

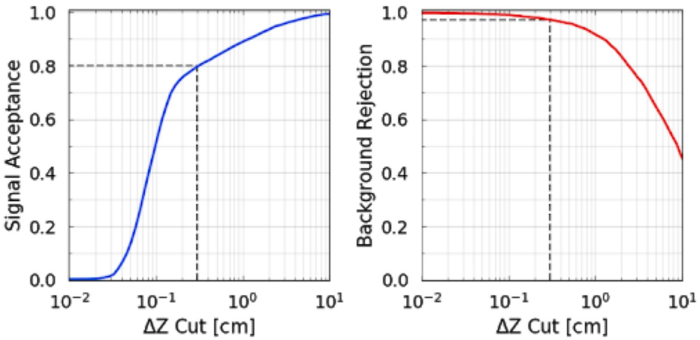
t – Exposure (1000 days)

Sensitivity obtained to the 0vbb decay half-life of 136-Xe is 6.93e+25 years

Sensitivity vs minimal vertical vertex separation



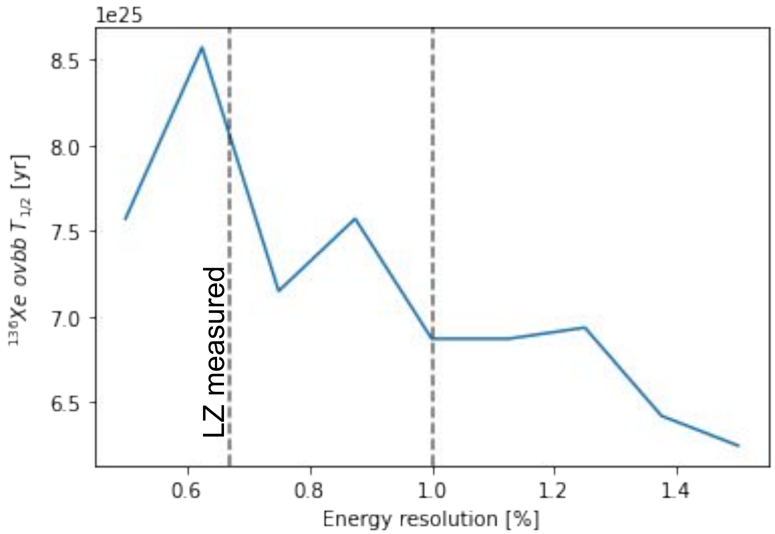


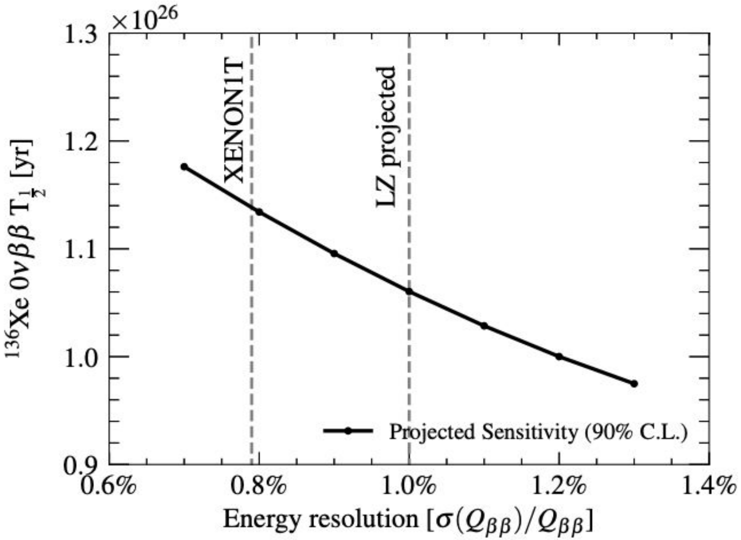


For single scatter cut of 0.3 cm:

- 80% signal acceptance
- >97% background rejection

Sensitivity vs energy resolution

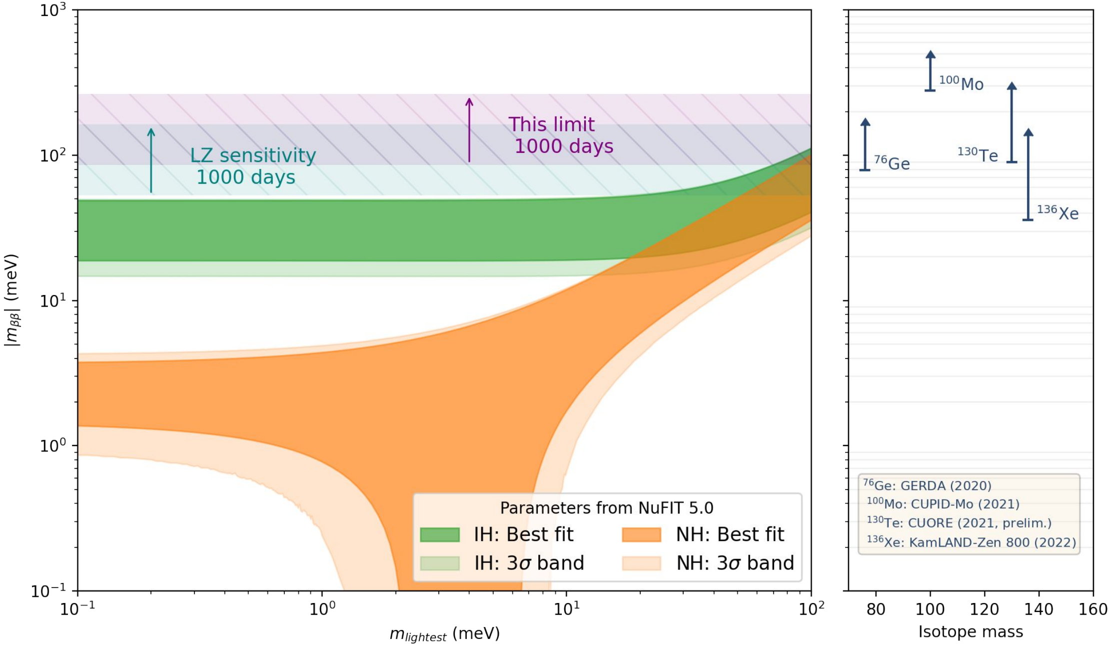




Sensitivity to the Effective Majorana neutrino mass

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\,|\mathcal{M}^{0\nu}|^2\,\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Effective Majorana mass: mbb = 86.1 - 265.1 meV



The arrows are the most recent limits for the main isotopes where this rare decay is sought.

Conclusion

Even with a very simple dataset and very conservative assumptions about LZ performance, we achieved a sensitivity result similar to those experiments dedicated to the search for the 0vbb decay.

Sensitivity obtained to the 0vbb decay half-life of 136-Xe is 6.93e+25 years
Projected LZ sensitivity: 1.06e+26 years (in a 90% confidence interval)

The sensitivity obtained is similar to that of LZ (same order of magnitude), with the main difference being the more sophisticated statistical analysis used by LZ (PLR).

Reference paper: https://arxiv.org/abs/1912.04248 end.