Neutrinoless double beta decay search in LZ

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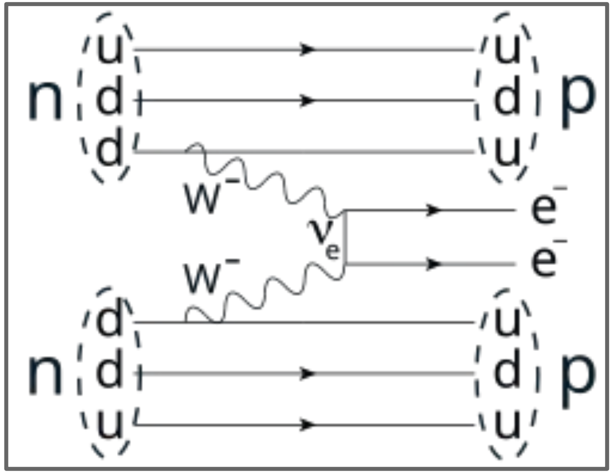
Neutrinoless double beta decay

- Neutrinoless double beta decay (0νββ) refers to a phenomenon where a nucleus emits two electrons and no neutrinos;
- 0νββ decay is the most effective way to detect whether neutrinos are Majorana particles;
- When a particle is the same as its antiparticle, it is known as a Majorana particle.



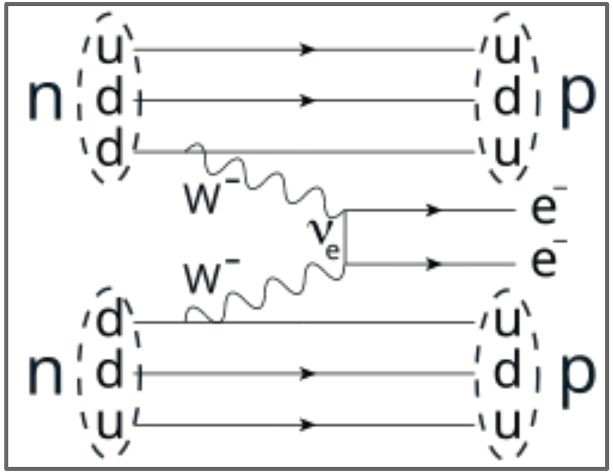
double beta decay diagram

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Neutrinoless double beta decay

Observing this process has major 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 absolute mass scale and mass hierarchy of the neutrino.

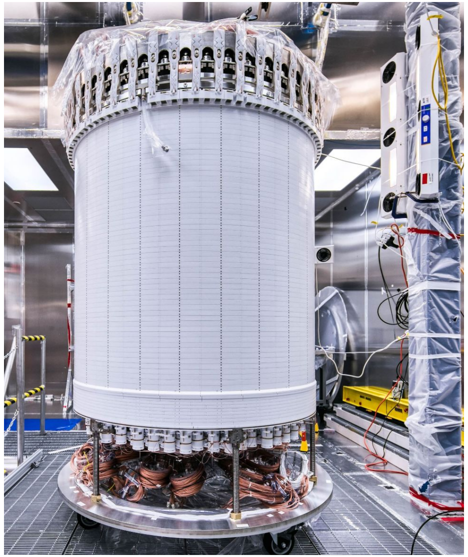


double beta decay diagram

The LUX-ZEPLIN experiment

A detector intended to observe neutrinoless double beta decay (0νββ) must possess:

- an ultra-low background,
- a low energy threshold,
- a high concentration of the decaying element,
- and exceptional energy resolution at the decay's Q-value.



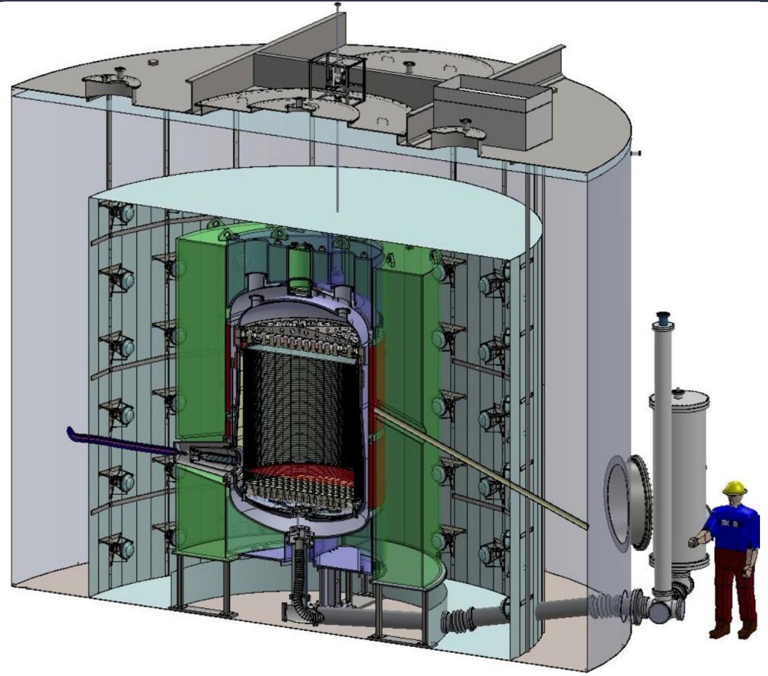
LUX-ZEPLIN PTFE light cage

The LUX-ZEPLIN experiment

A 10-tonne liquid xenon dark matter detector with ultra-low background, situated 1478 meters underground in a U.S. gold mine, uses the surrounding rock as overburden to shield against penetrating cosmic ray muons.

The LZ experiment employs a liquid xenon target because:

- Liquid xenon is highly dense (2.9 g/cm³).
- It offers self-shielding and active vetoing capabilities.
- It has high ionization and scintillation yields.
- It contains two isotopes that undergo double beta decay, ^{134}Xe and ^{136}Xe.



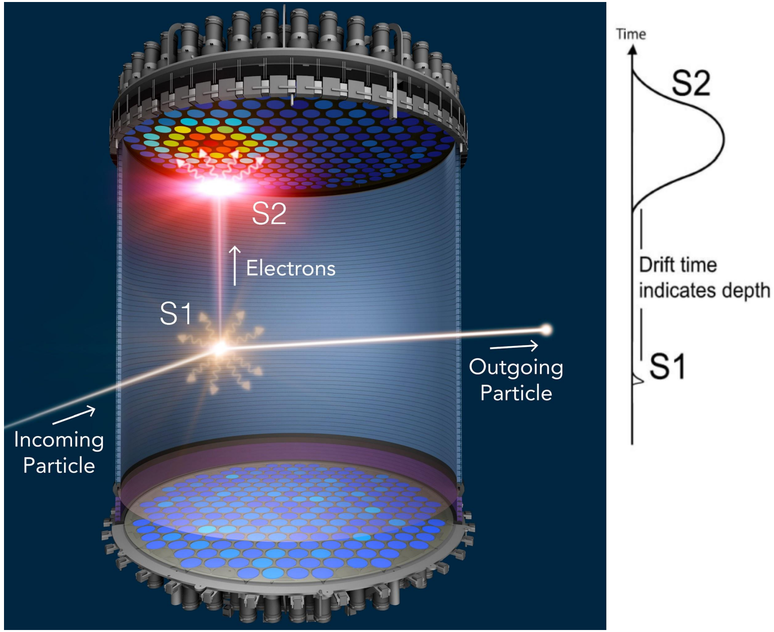
Cutaway rendering of the LUX-ZEPLIN (LZ) detector.

Dual-phase noble element TPC

Time Projection Chamber (TPC) operation:

1. Energy deposited in the target generates prompt scintillation light (S1) and ionization electrons.
2. Electrons that avoid recombination are drifted to the liquid-gas interface, where they are extracted into the gas phase, producing electroluminescence light (S2).

A complete 3D reconstruction of the event is achieved by analysing the time difference between the signals and the light pattern created by S2.



Time Projection Chamber representation

Dual-phase noble element TPC

The energy of the interaction in the TPC can be estimated using both the S1 and S2 signals.

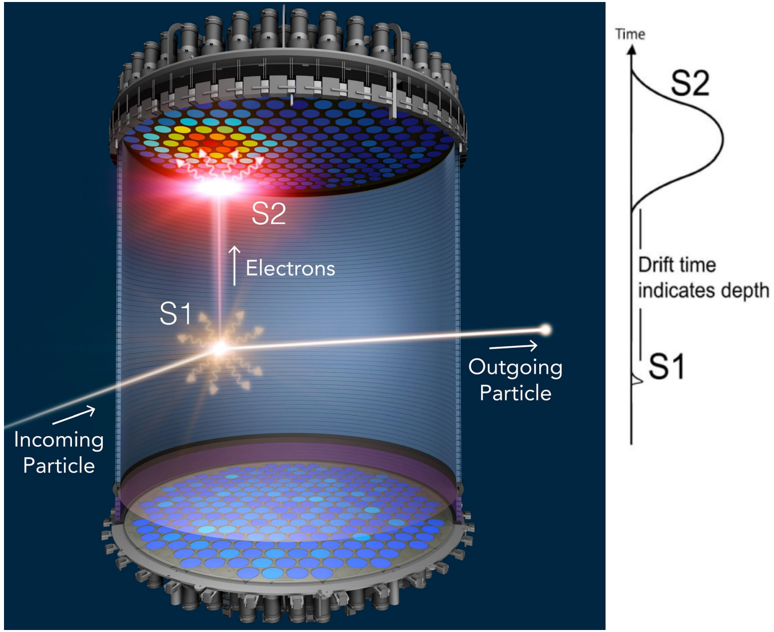
$$E = W\left(\frac{S1}{g1} + \frac{S2}{g2}\right)$$

- W = 13.7 eV

W-value of liquid xenon;

- g1 = 0.1153
- g2 = 50

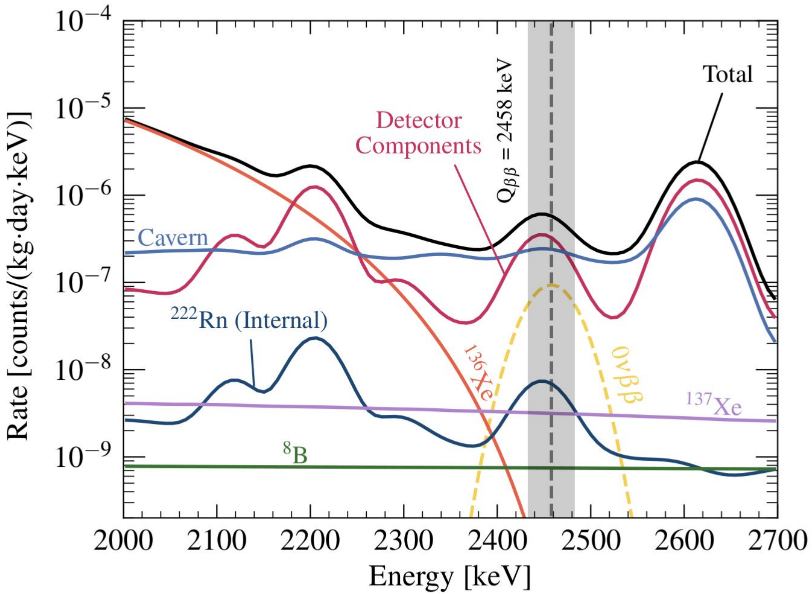
g1, g2 are detector dependent gain factors



Time Projection Chamber representation

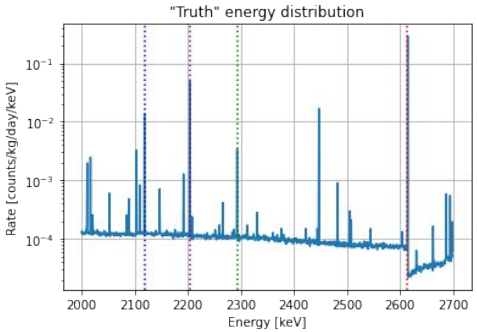
Backgrounds for a 0$\nu\beta\beta$ search with ^{136}Xe

- ^{214}Bi gamma line with Eγ = 2447.7 keV
- ^{207}Ti gamma line with Eγ = 2615 keV
- ^{60}Co summed peaks
- 2νββ decay of ^{136}Xe
- ^{8}B solar neutrinos

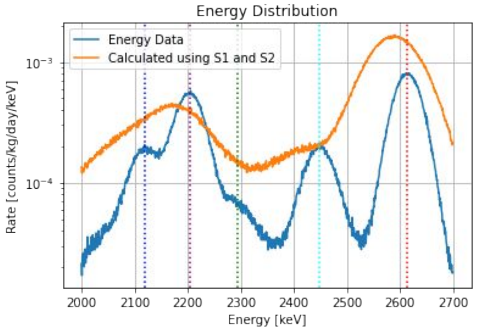


LZ background spectrum in the energy search region of 0$\nu\beta\beta$ decay of ^{136}Xe

“Truth” energy and “smearing”



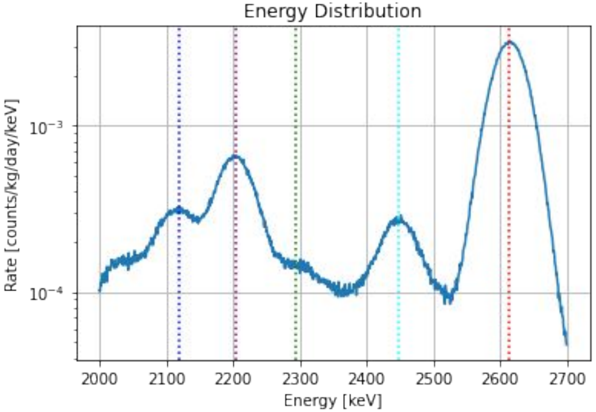
The truth energy refers to the actual energy that a particle deposits in the TPC. In practice, the energy spectrum is never exact due to factors like detector resolution, noise, and other instrumental imperfections.

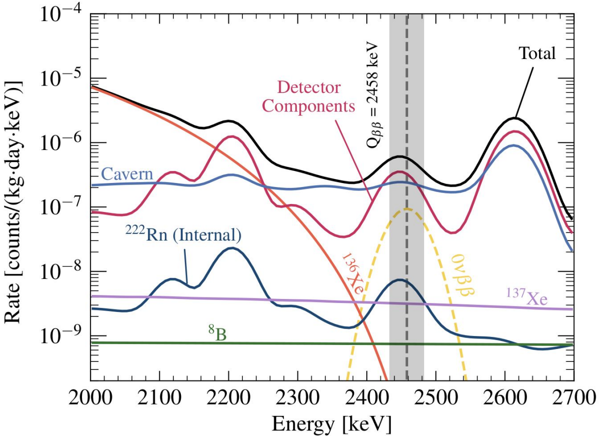


Comparing the simulated experimental energy spectrum obtained from the Gaussian smearing of the truth energy of 1% to the energy spectrum obtained using S1 and S2 we can see clear differences.

W = 13.7e-3
g1 = 0.115
g2 = 50

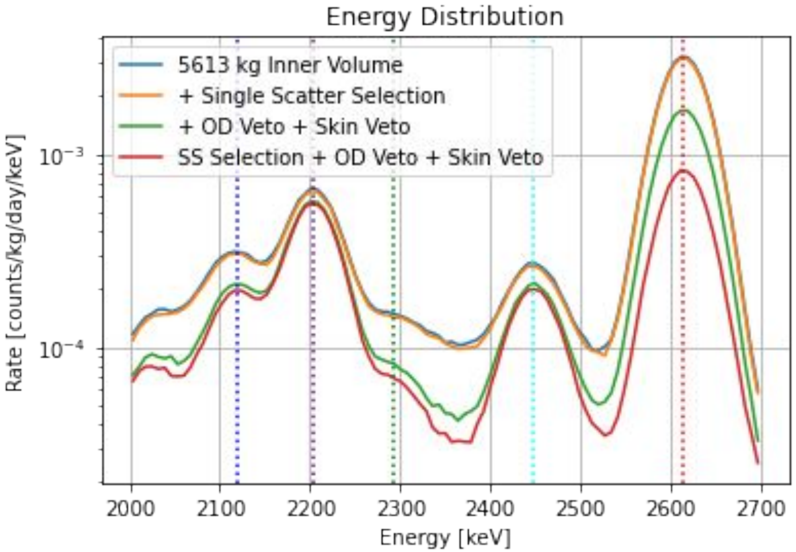
Comparison


Energy Distribution
Rate [counts/kg/day/keV]
10^{-3}
10^{-4}
2000
2100
2200
2300
2400
2500
2600
2700
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]

Cuts

- Fiducial Volume
    - 5613 kg Inner Volume
- Single Scatter
    - ΔZ < 3 mm
- Veto (outer detector or skin)
    - > 100 keV
    - < 1µs

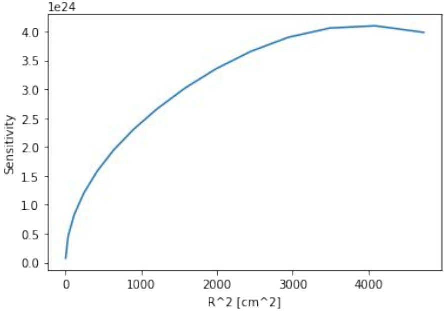


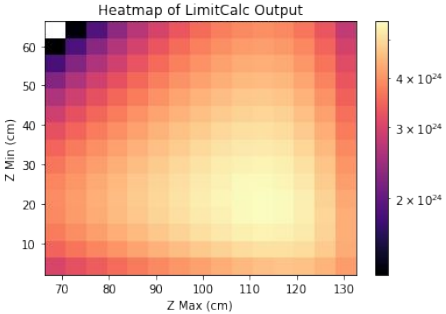
Fiducial volume optimization

The aim was to determine the set of position analysis cuts that would maximize sensitivity, considering an energy resolution of 1%, a single scatter rejection at 3 mm, and OD and Skin veto thresholds set at 100 keV each.

The process began by fixing the Z values to those corresponding to the large 5.6-tonne FV, then varying the radius to examine how sensitivity depends on it.

After selecting the optimal radius, it was kept constant while optimizing the Z cuts, and then the sensitivity dependence on the Z cuts was plotted.



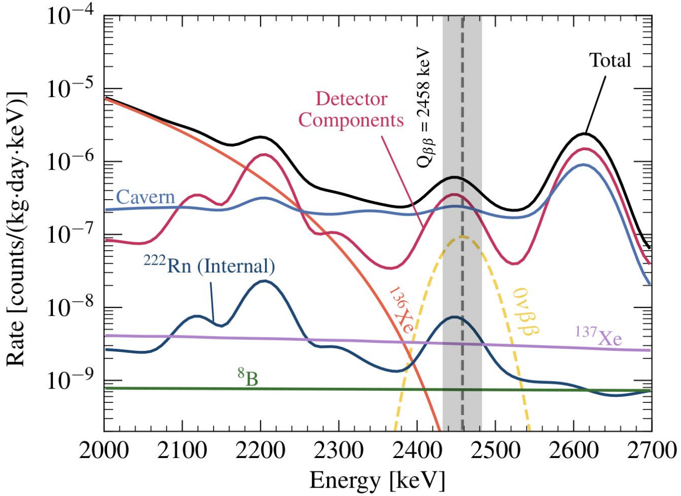


Fiducial volume optimization

Iterations	Radius cut (cm)	Min Z cut (cm)	Max Z cut (cm)
Initial	68.8	2	132.6
1st	63.9	20.4	113.6
2nd	46.4	28.9	100.8
3rd	39.9	36.2	97.7

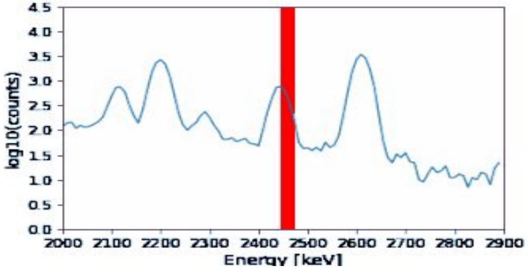
- Mass of Xe = 891.7 kg
- Mass of Xe-136 = 79.4 kg

The Region of Interest (ROI)

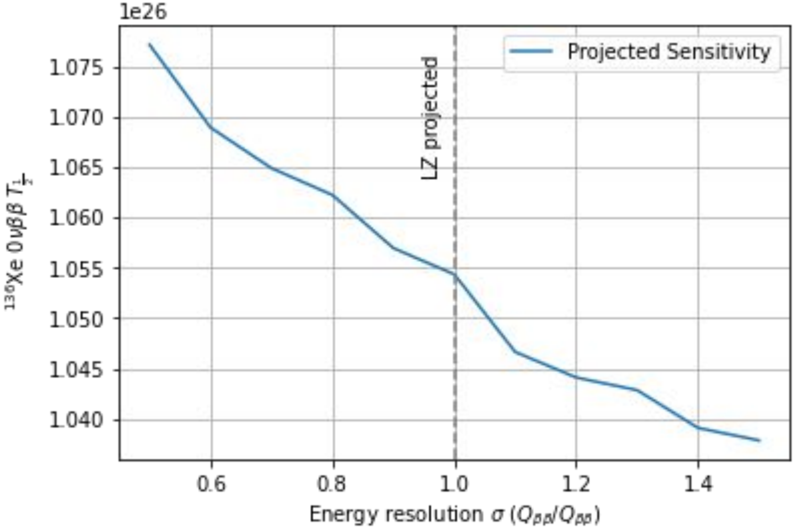


The gray area shows the ROI.

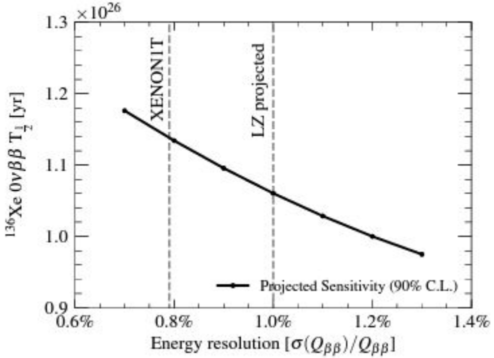
The region-of-interest (ROI) considered on this analysis is **2433.3 < Edep < 2482.4 keV**, representing a ± 1σ energy window around Qββ, considering an energy resolution (σ/E) of 1%.



Sensitivity vs energy resolution



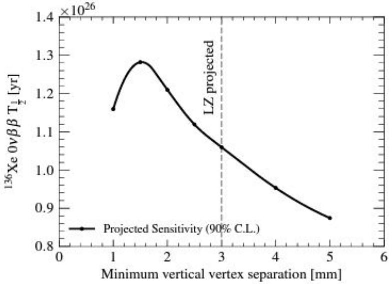
As the ability to distinguish signal events from the neighbouring Bi-214 and Tl-208 peaks relies heavily on the energy resolution, the dependence of the sensitivity on the energy resolution at the Xe-136 Q-value is shown in the graph.

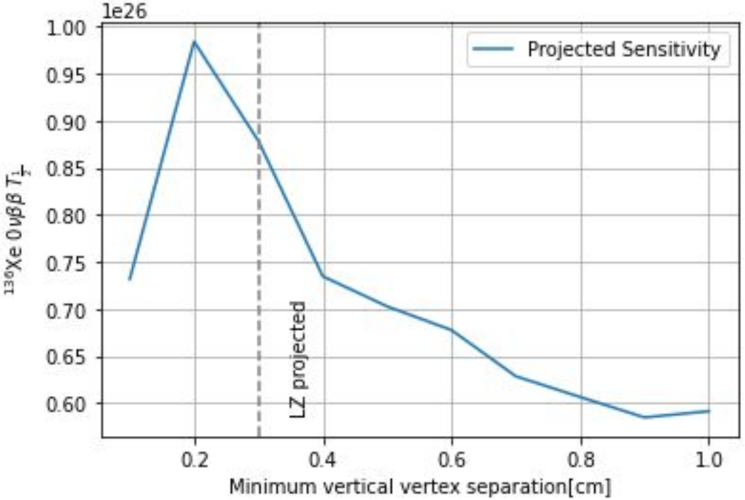


Sensitivity vs minimal vertical vertex separation

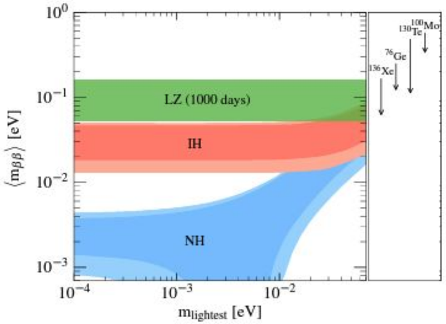
- It is assumed in this analysis that multiple scatter events can be rejected with a depth-based vertex separation cut, as multiple energy deposits at different depths in the TPC will have multiple S2 pulses.

- The graph demonstrates that there is a large variation in sensitivity with this cut as multiple scatter events form the dominant background contribution.



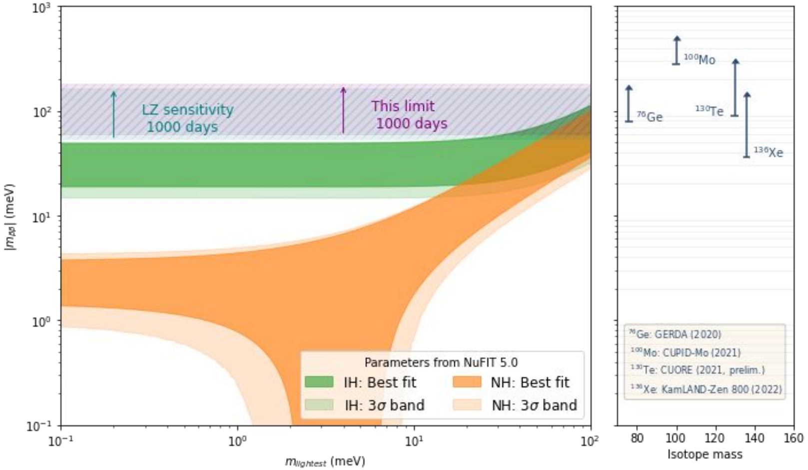


Sensitivity to the Effective Majorana neutrino mass



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

Effective Majorana mass: mbb = 58.4 - 179.6 meV
Obtained sensitivity to the 0νββ decay half-life of ^{136}Xe: 8.79e+25 years



- M0v_min = 1.55
- M0v_max = 4.77
- gA = 1.273
- G0v = 1.458e(-14)
- m_e = 0.511 MeV

Conclusion

Obtained sensitivity to the 0νββ decay half-life of ^{136}Xe: 8.79e+25 years

Using a new dataset and following the assumptions of our reference paper we were able to obtain a result for the sensitivity that is very similar to what was estimated in previous experiments dedicated to the search of the 0vbb decay.

Projected LZ sensitivity: 1.06e+26 years (in a 90% confidence interval)

As we saw during this analysis, the results from the paper are similar with the real data that was acquired by the LZ experiment.

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

Thank you

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