Neutrinoless double beta decay

LIP internship program - 2020

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Objectives

The goal of this project was to recreate a simplified version of the original analysis done to determine the sensitivity of the LUX-ZEPLIN experiment to the $0\nu\beta\beta$ decay of ^{136}Xe, using the homonymous article as a basis.

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Projected sensitivity of the LUX-ZEPLIN experiment to the $0\nu\beta\beta$ decay of ^{136}Xe

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Double beta decay

Two-neutrino double beta decay - $2\nu\beta\beta$

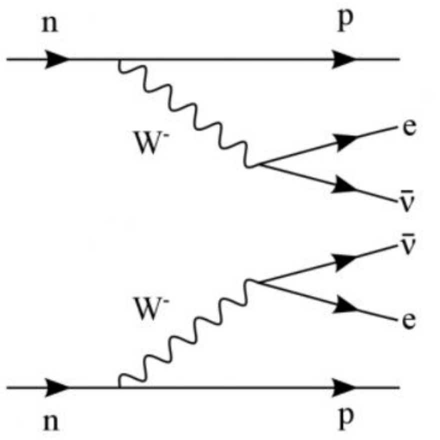
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

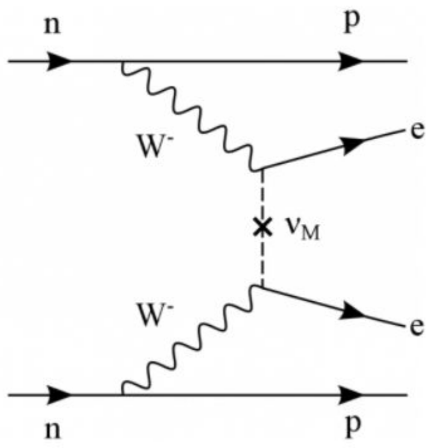
Neutrinoless double beta decay (NDBD) - $0\nu\beta\beta$

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

If observed, the $0\nu\beta\beta$ decay would have major implications for particle physics and cosmology:

- First evidence of fundamental Majorana particles
- Lepton number conservation violation
- B - L symmetry violation





Neutrinos

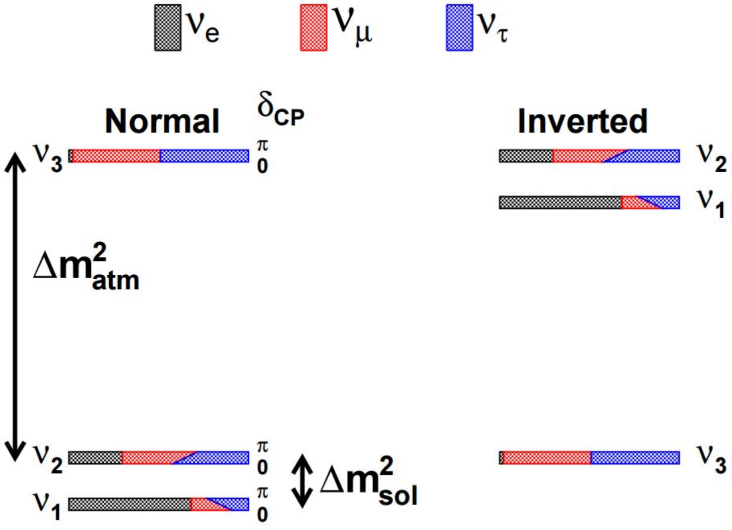
Neutrino oscillation:

Flavor states: ν_e, ν_μ, ν_τ
Mass states: ν_1, ν_2, ν_3

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

lepton mixing matrix (PMNS matrix)

$m_1 < m_2$
$|m_2 - m_1| << |m_3 - m_1|$

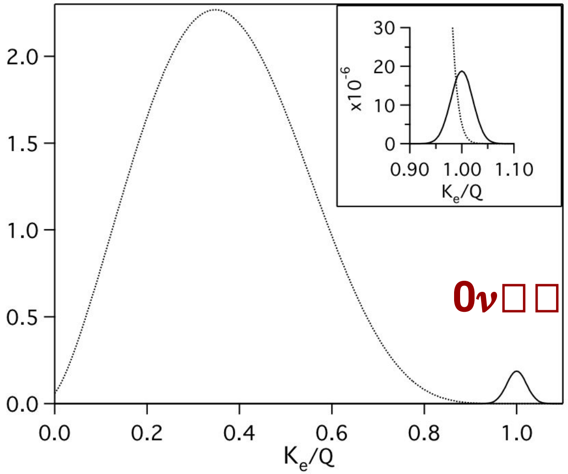


Mass hierarchy:

- **Normal hierarchy**: $m_3 >> m_2 > m_1$
- **Inverted hierarchy**: $m_3 << m_1 < m_2$

The LZ detector

The LUX-ZEPLIN detector is expected to start running in 2021, with the main goal of discovering dark matter particle interactions while searching for rare events such as the neutrinoless double beta decay.



Experimental requirements:

- Abundance of the decaying element
- Complete understanding of the background in the event search region
- High energy resolution at the Q-value (2458 keV) of the decay

A 0ν□□ decay would result in a monoenergetic peak at Q□□.

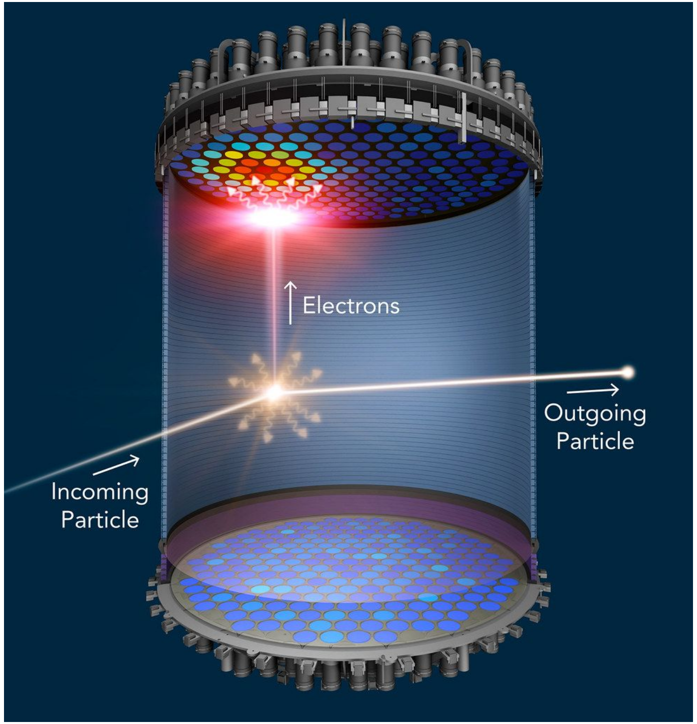
The LZ detector: operating principle

1. Energy deposits produces a **prompt scintillation light (S1)** and ionizes electrons.
2. Some of these electrons recombine with xenon ions, and the remaining ones drift in an electric field.
3. The electrons are extracted by another field into the gas region, creating **electroluminescence light (S2)**.

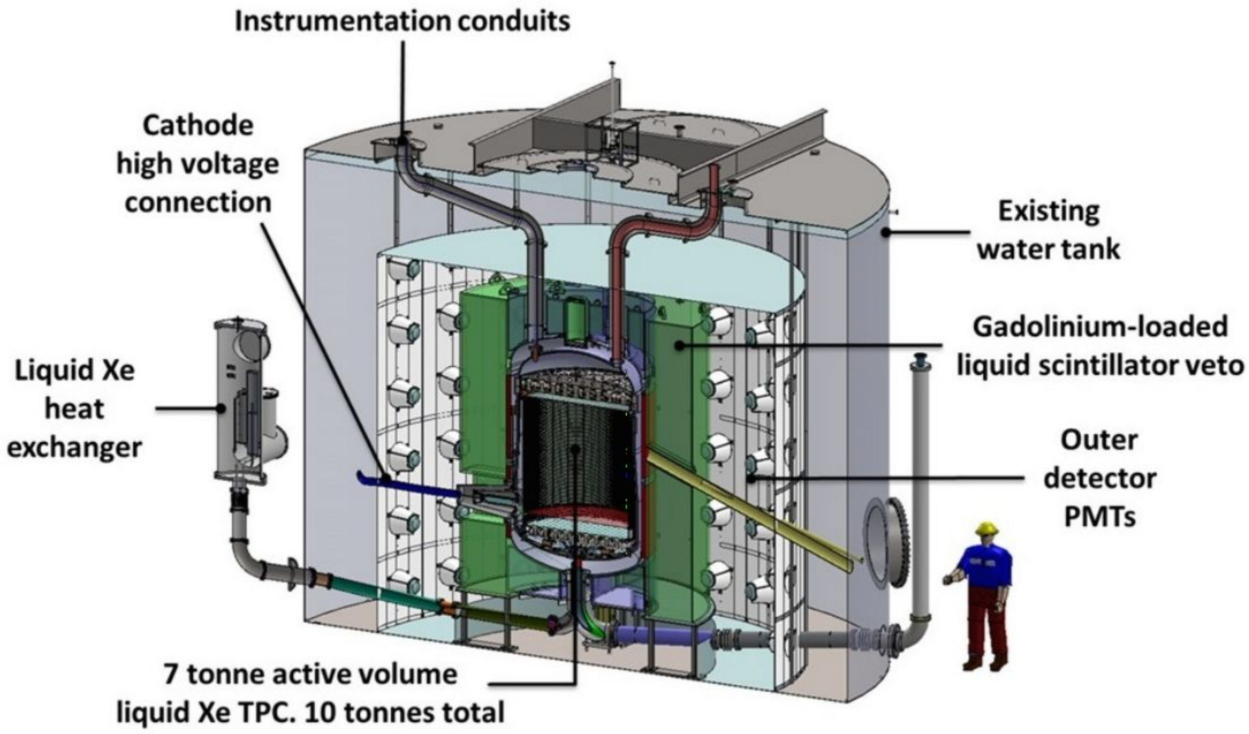
These signals are detected by two arrays of photomultiplier tubes (PMTs) at the top and bottom of the active LXe target.

Reconstruction of the event position:

The depth of the interaction is determined by the time difference between S1 and S2, while the relative intensity of S2 in each PMT indicates the position in the horizontal plane.



The LZ detector: structure



The LZ detector is located in the Sanford Underground Research Facility (SURF), at a depth of 1.5 km

Main detector system:
two-phase xenon time projection chamber (TPC), supported by a titanium cryostat.

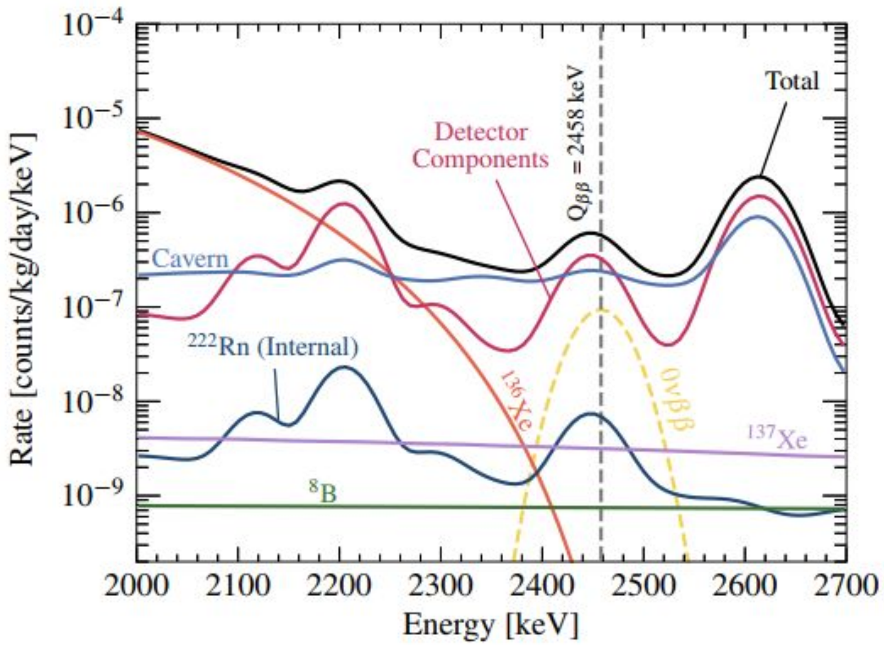
Veto systems:
Skin and Outer Detector (OD)

Background model

The current background model takes into account the contributions of:

- Radiation from detector components *
- Gamma rays from the cavern walls
- Neutron-induced ^{137}Xe
- Internal ^{222}Rn *
- ^{136}Xe double beta decay
- ^{8}B solar neutrinos

*Contributions considered for our analysis



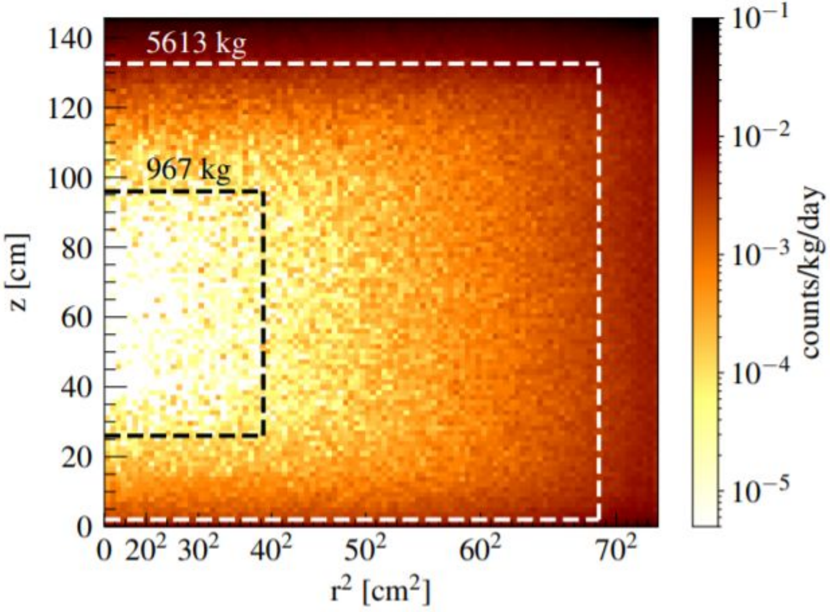
Selection criteria

Backgrounds are analysed based on:

- Energy (2000 < E < 2700 keV)
- Depth (2 < z < 132.6 cm)
- Radial position (r < 68.8 cm)

Selection criteria:

- *Fiducial Volume*, FV
- *Single Scatter*, SS_CUT
- *Veto*, detector skin and outer detector (OD)

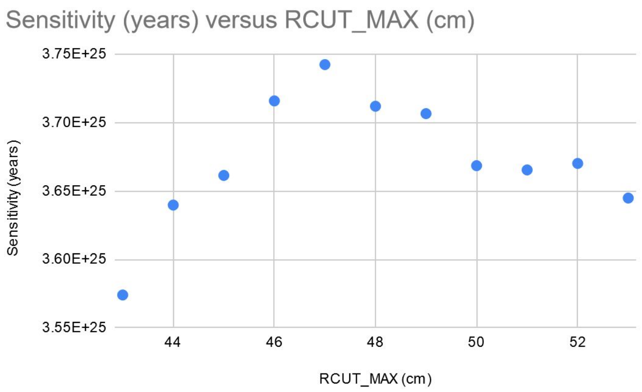


FV optimization method

The detector's **sensitivity** is defined as:

> *the median 90% confidence level (CL) upper limit on the **number of signal events** that would be obtained from a **repeated set of background-only experiments**, assuming **1000 days** of detector live time.*

For 10 < Z < 118 cm, R = 47 cm:



Detector's dimensions

Height = 147 cm
Diameter = 147 cm
LXe mass = 7 tonne
^{136}Xe mass = 623 kg

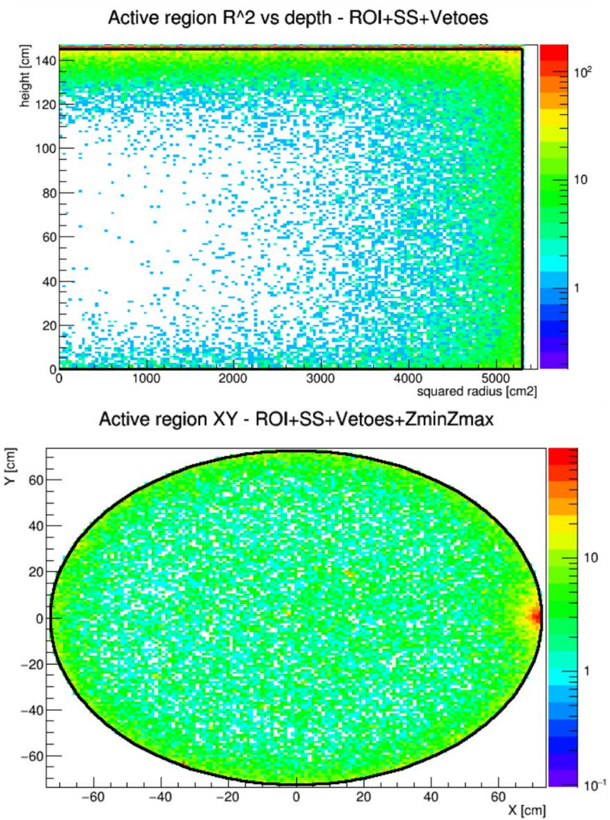
Optimized values

RCUT_MAX = 31 cm
ZCUT_MAX = 92 cm
ZCUT_MIN = 33 cm

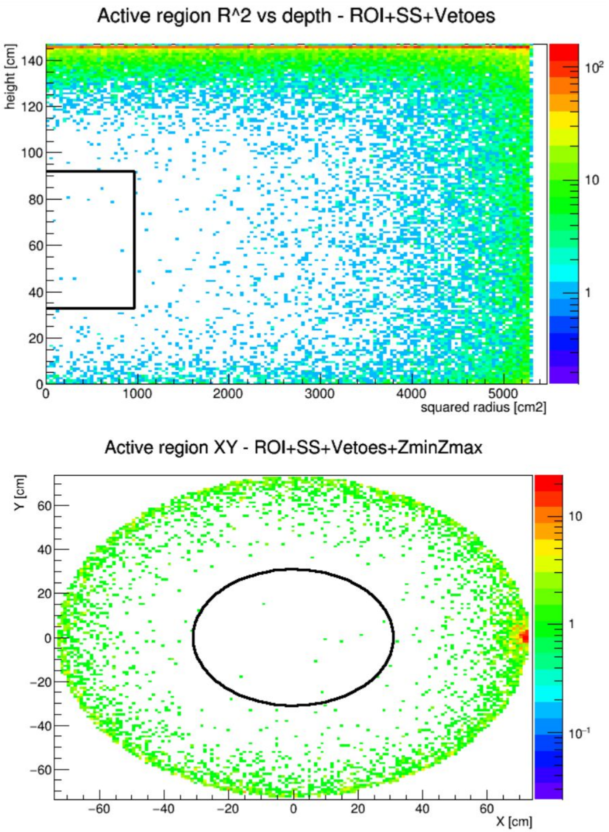
For R = 47 cm, 32 cm < Z < 99 cm:

	0	15	30	45	60
85	2.28E+25	3.82E+25	4.17E+25	3.69E+25	3.01E+25
100	2.62E+25	4.28E+25	4.58E+25	4.14E+25	3.51E+25
115	2.80E+25	4.00E+25	3.93E+25	3.46E+25	2.89E+25
130	2.33E+25	2.53E+25	2.29E+25	1.97E+25	1.65E+25
145	1.15E+25	1.06E+25	9.45E+24	8.24E+24	7.01E+24

Default values vs. Optimized values

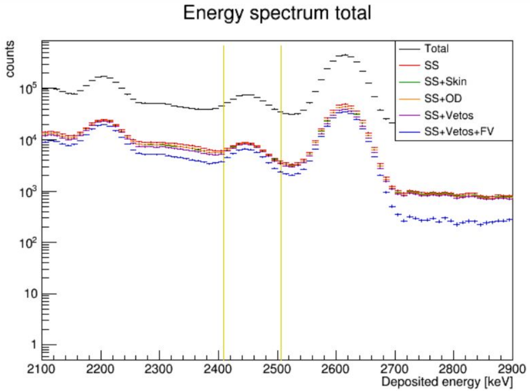


Default Volume

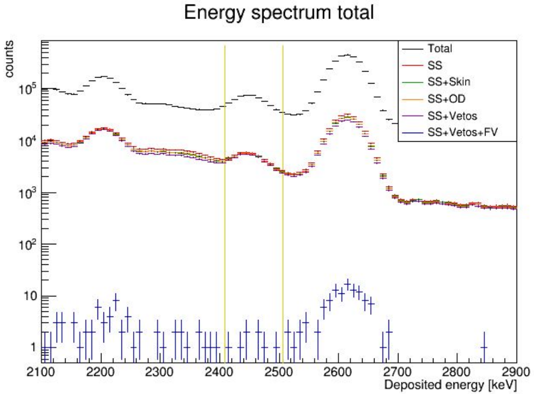


Optimized Volume

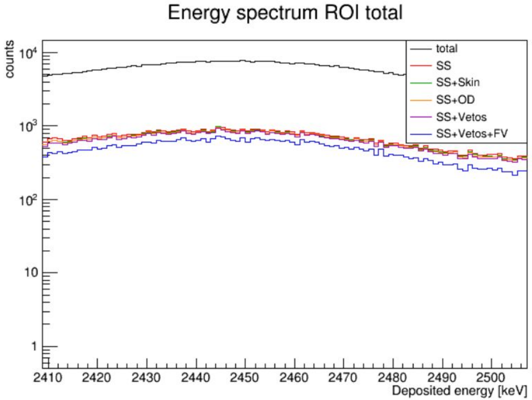
Default values vs. Optimized values



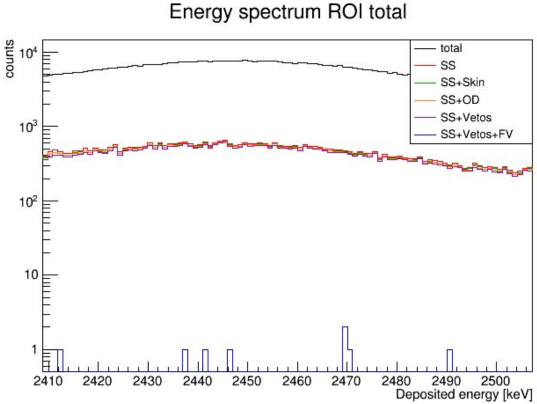
Total Spectrum - Default Volume



Total Spectrum - Optimized volume



ROI Spectrum - Default Volume



ROI Spectrum - Optimized volume

Fiducial Volume: Sensitivity

Default (**cut-and-count** analysis)

RCUT_MIN = 0 cm

RCUT_MAX = 72.8 cm

ZCUT_MIN = 0 cm

ZCUT_MAX = 145.0 cm

Sensitivity: 8.35×10^{24}

Optimized (**cut-and-count** analysis)

RCUT_MIN = 0 cm

RCUT_MAX = 31.0 cm

ZCUT_MIN = 33.0 cm

ZCUT_MAX = 92.0 cm

Sensitivity: 6.22×10^{25}

Article (**PLR** analysis)

RCUT_MIN = 0 cm

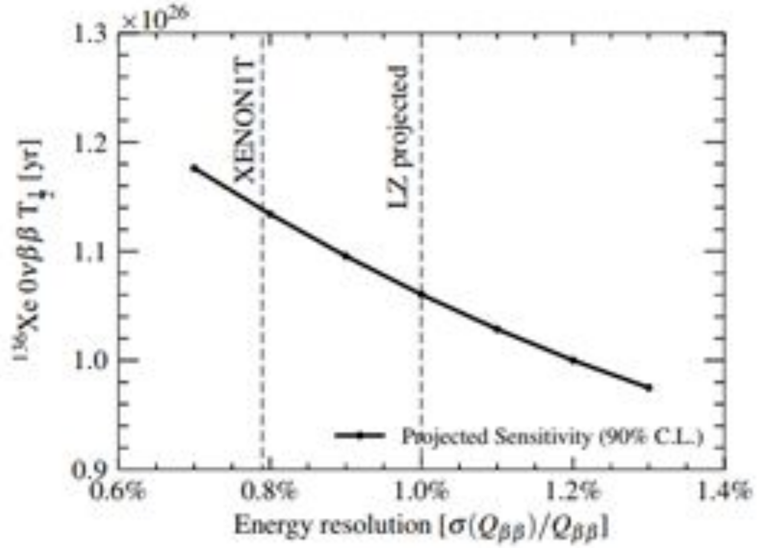
RCUT_MAX = 39 cm

ZCUT_MIN = 26 cm

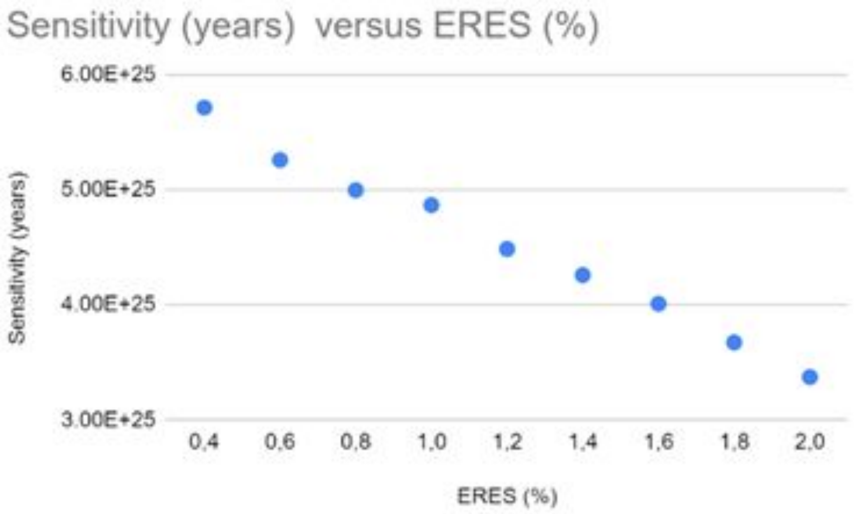
ZCUT_MAX = 96 cm

Sensitivity: 1.06×10^{26}

Energy resolution

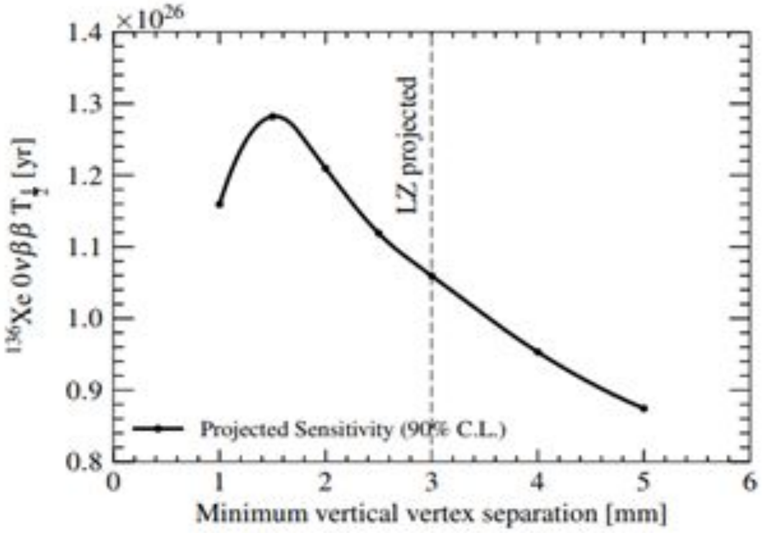


Published Results

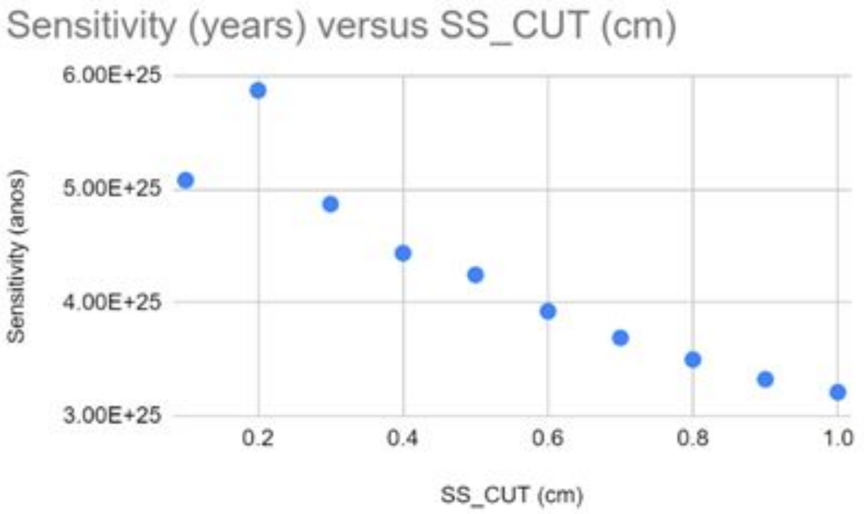


Our results
(Optimal Volume and SS_Cute of 3mm)

Minimum vertical vertex separation



Published Results



Our results
(Optimal Volume and Energy Resolution of 1%)

Veto systems: sensitivity

Veto OD ✓
Veto SKIN ✓
Sensitivity: $6.22\text{x}10^{25}$

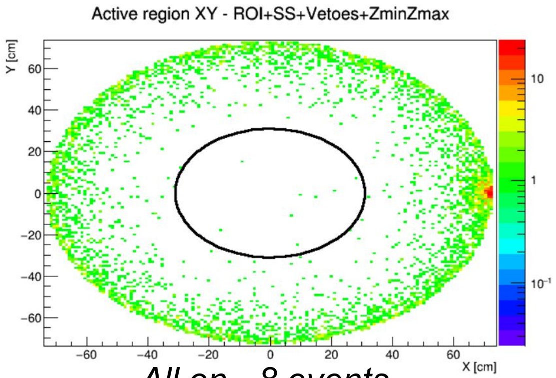
Veto OD ✗
Veto SKIN ✓
Sensitivity: $6.22\text{x}10^{25}$

Veto OD ✓
Veto SKIN ✗
Sensitivity: $5.83\text{x}10^{25}$

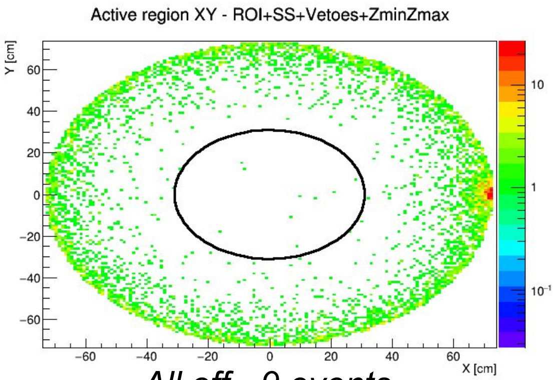
Veto OD ✗
Veto SKIN ✗
Sensitivity: $5.83\text{x}10^{25}$

The OD didn't have any impact on the results.

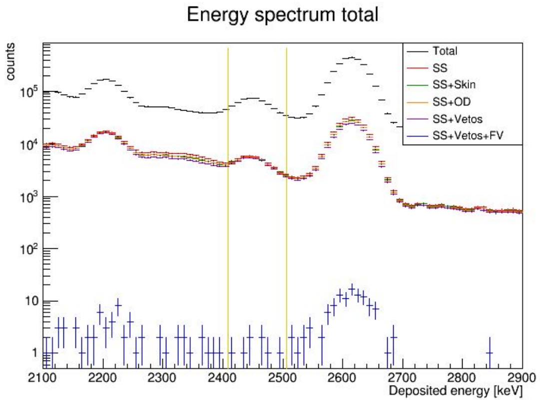
Veto systems



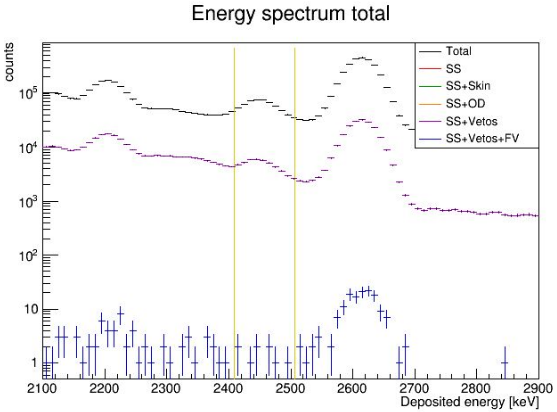
All on - 8 events



All off - 9 events

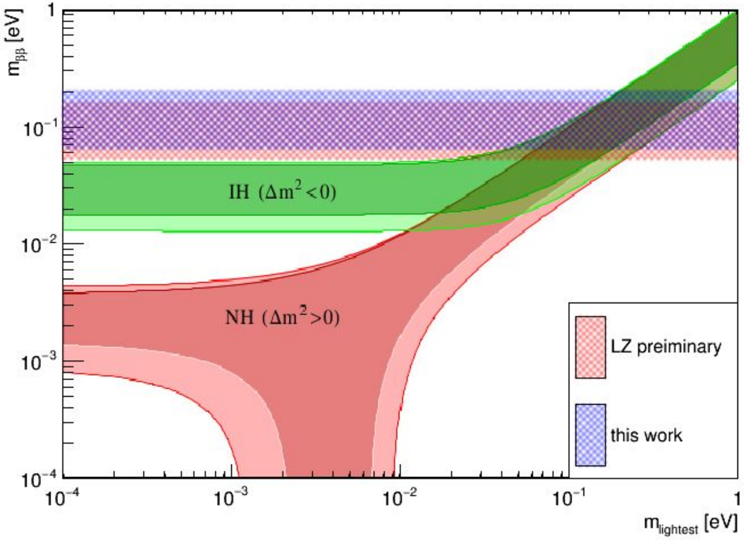


All on



All off

Effective neutrino mass



Our results: m□□: 65 - 200 meV

LZ preliminary: m□□: 53 - 164 meV

Theoretical relation:

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

Conclusion

RCUT_MIN = 0 cm

RCUT_MAX = 31.0 cm

ZCUT_MIN = 33.0 cm

ZCUT_MAX = 92.0 cm

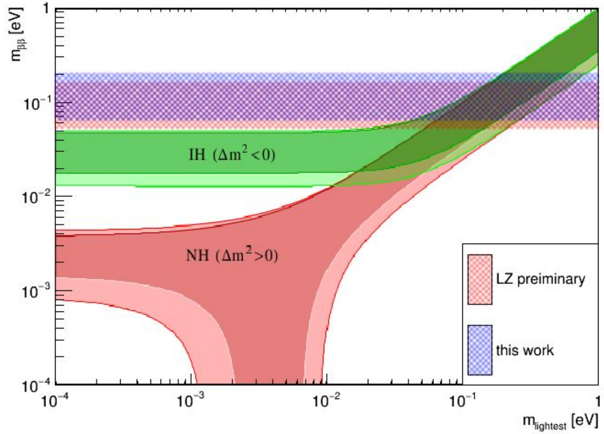
SS_CUT = 0.3 cm

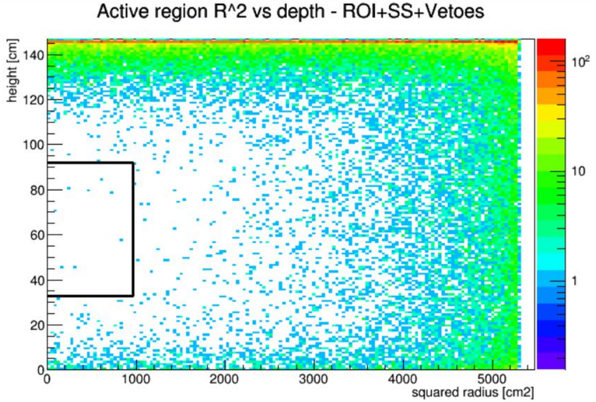
ERES = 0.01

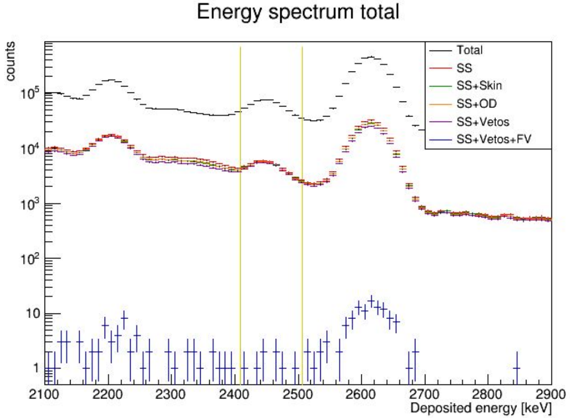
Sensitivity: 6.22×10^{25} yrs

Best result yet: 1.07×10^{26} yrs

m□□: 65 - 200 meV







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