LZ sensitivity to Majoron-emitting double beta decay modes of ^{136}Xe:

A Preliminary Study

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IOP 2022

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The LZ Experiment

- LUX-ZEPLIN (LZ) is a two-phase xenon detector operating at the Sanford Underground Research Facility, USA.
- A 7-tonne (active) LXe TPC with 10 tonnes of LXe in total.
- The TPC measures approximately 1.5 m in diameter and height, viewed by two arrays of PMTs.
- Two active veto systems:
    - Xe Skin: 2 tonnes of LXe around and underneath the TPC, also instrumented with PMTs.
    - Outer Detector (OD): gadolinium-doped liquid scintillator, observed by PMTs standing in the water tank.

The assembled Xenon Detector:
TPC and its Xe Skin veto companion

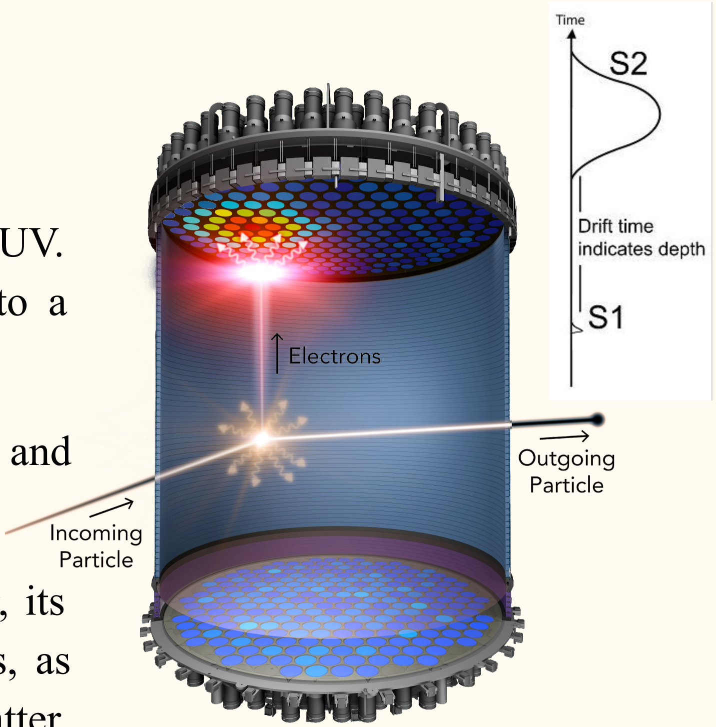
Principle of Operation

Particle interactions in the active LXe produce two signals:

- **S1 (scintillation)** - Initial interaction causes LXe to emit VUV.
- **S2 (ionisation)** - Electrons are drifted and extracted into a gaseous xenon layer, producing a secondary signal.

S2/S1 ratio can be used to discriminate electronic recoils (ER) and nuclear recoils (NR).

The primary science goal of LZ is WIMP discovery. However, its large xenon mass also enables searches of double beta decays, as well as solar axions, axion-like particles, mirror dark matter, neutrino magnetic moment and so on.



Majoron-emitting Double Beta Decay

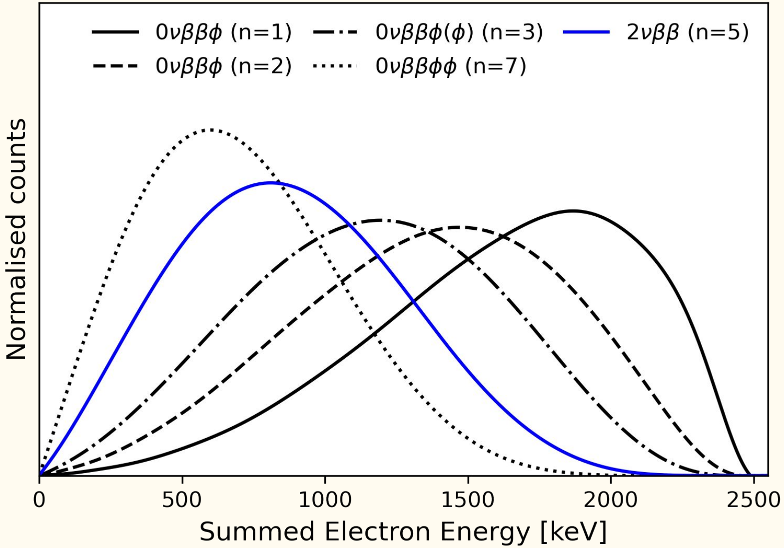
- Majoron was originally proposed as a Goldstone boson associated with global spontaneous lepton number symmetry breaking.
- The original Majoron models have been disfavoured by measurement of the Z boson decay width to invisible channels.
- Other analogous models were proposed without such constraint.
- Majoron-like bosons in these models are not necessarily Goldstone bosons and can carry a lepton charge.
- $(A, Z) \rightarrow (A, Z + 2) + 2e^- + \phi$

  or

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

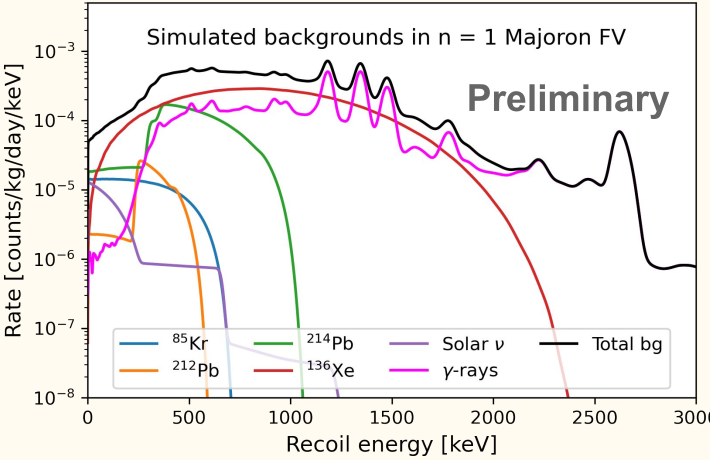
Signal Energy Spectrum

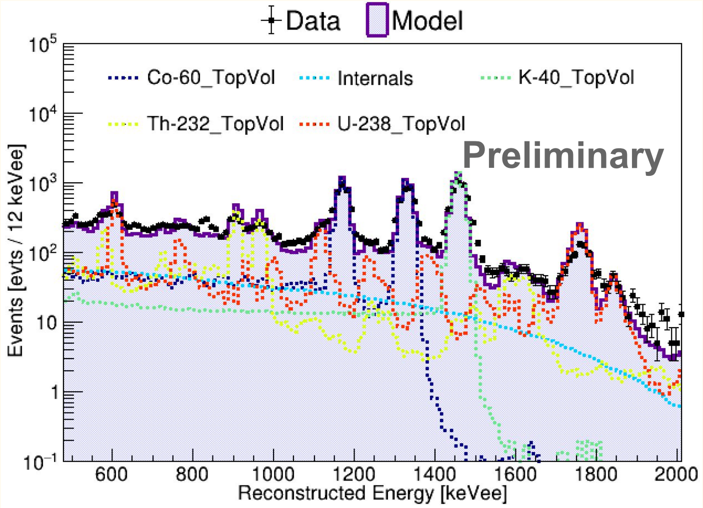
- Majoron carry away “missing” energy due to its small coupling to matter.
- The “visible” energy spectrum comes from electrons only.
- An integer spectral index n characterises the shape of the energy spectrum.
- ^{136}Xe: 8.9% natural abundance.



Background Model

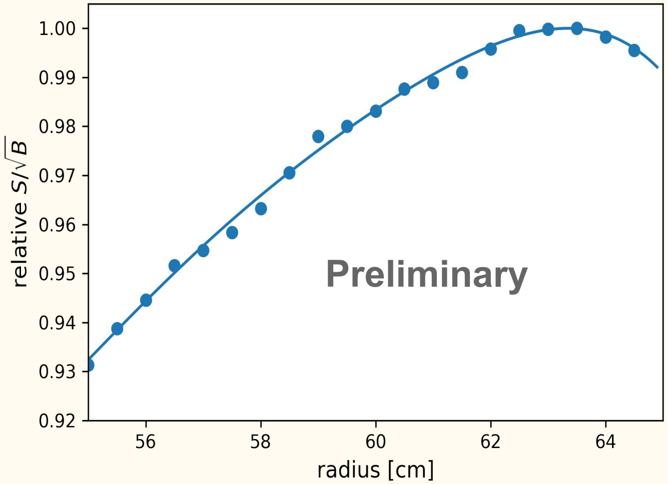
- Constructed using the most recent material assays and detector simulations of detector components.
- List of major ER background sources:
    - ^{136}Xe ($2\nu\beta\beta$)
    - ^{214}Pb and ^{212}Pb ("naked" beta emission)
    - ^{85}Kr
    - Solar neutrinos (pp, ^{7}Be, CNO, pep)
    - γ (detector components and cavern rock)
- Simulation vs. data comparison shows good agreement (D. Kodroff, April APS 2022).
- Provides validation to using the simulated background model for sensitivity studies.





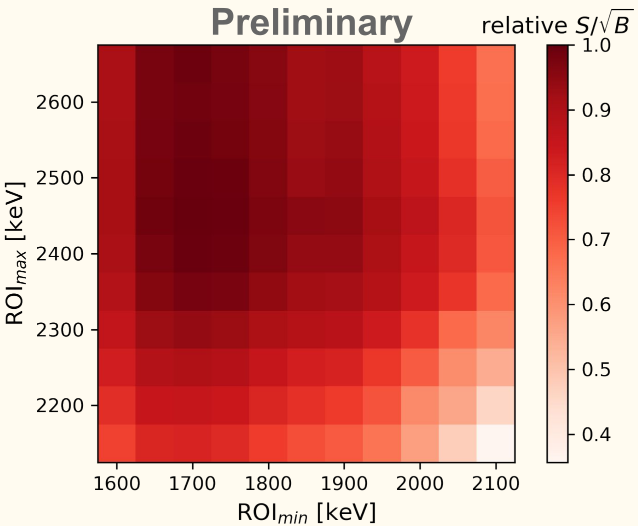
Fiducial Volume (FV) and Region of Interest (ROI)

- Optimisation of S/√B (ROI_{min}, ROI_{max}, r, z_{min}, z_{max}) based on simulation.
- For a given ROI, optimise r, z_{min} and z_{max} one at a time. Then change the ROI.
- Start from some reasonable estimates to reduce computational burden.



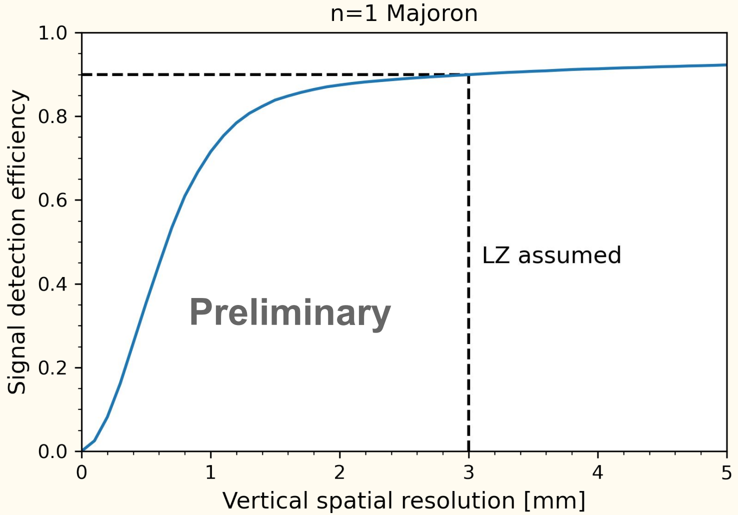
Take n = 1 as an example:

- r = 63.4 cm
- z_{min} = 11.0 cm
- z_{max} = 121.5 cm
- LXe mass in FV = 4.0 tonne



Signal Detection Efficiency

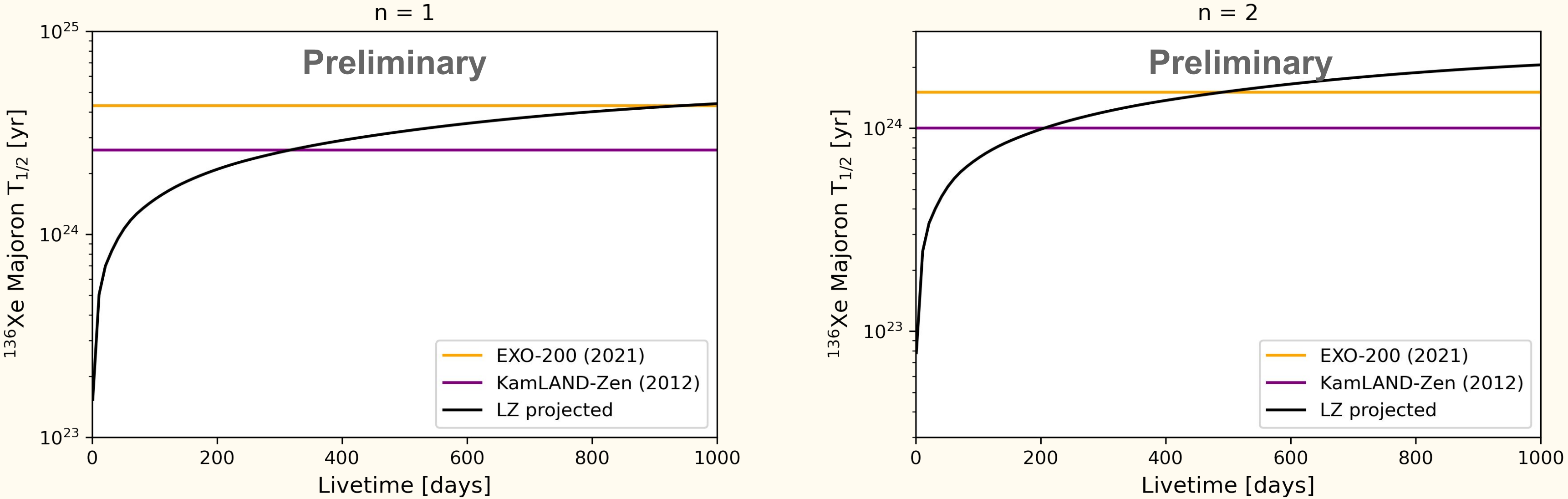
- Majoron-emitting decays have a typical spatial extent below the assumed LZ vertical spatial resolution – single scatters.
- Using Decay0 to generate electron kinematics.
- Pass the kinematics through the LZ Monte Carlo simulation model based on GEANT4.
- A non-negligible fraction of events are reconstructed as multiple scatters due to Bremsstrahlung photons.



	n = 1	n = 2	n = 3	n = 7
Signal Detection Efficiency	89.9%	92.5%	94.2%	97.8%

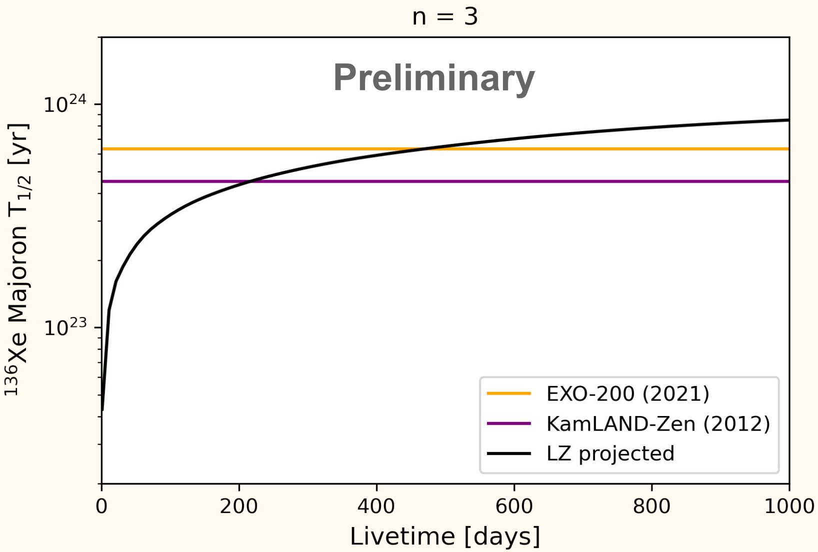
Preliminary LZ sensitivities

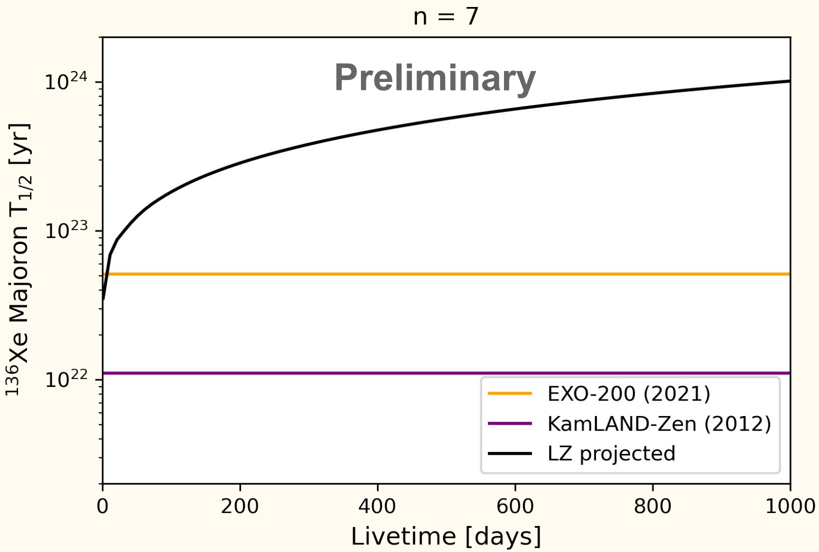
- Sensitivity projection based on the simulated background model.
- One-sided profile likelihood ratio test at 90% CL.
- Compared with current best limits from experiments using enriched ^{136}Xe.



Preliminary LZ sensitivities

- n = 7 is more competitive due to LZ's low energy threshold.





Summary

- LZ is sensitive to a variety of Majoron-emitting modes, in parallel to its primary science goal of direct dark matter detection.
- LZ has high signal detection efficiencies for Majoron-emitting decays.
- LZ projected sensitivities are competitive when compared with current best limits from other experiments using enriched xenon.
- Sensitivity to $n = 7$ Majoron emission is about an order of magnitude better than current limits.

LZ (LUX-ZEPLIN) Collaboration

@lzdarkmatter

https://lz.lbl.gov/

35 Institutions: 250 scientists, engineers, and technical staff

- Black Hills State University
- Brandeis University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
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- University of Rochester
- University of Sheffield
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Thanks to our sponsors and participating institutions!

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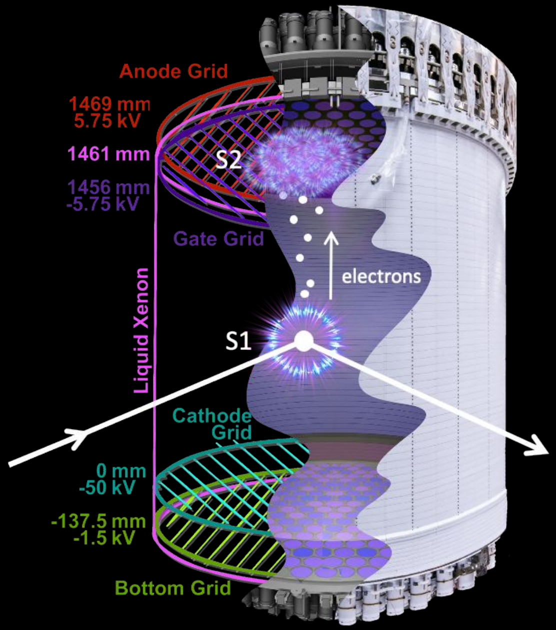

Find more graphics here or directly contact Nicolas (Imperial)

Thank you!

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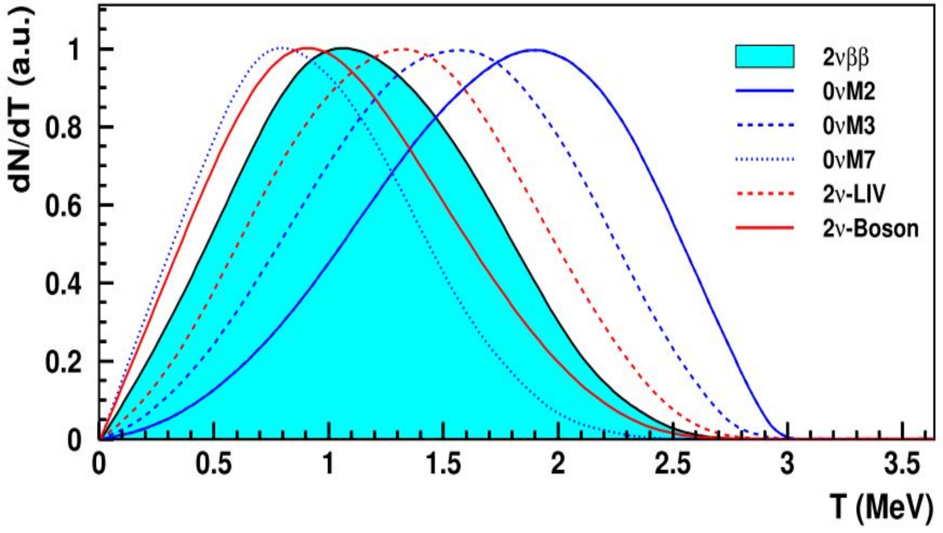
Backup

Classification of Majoron Models

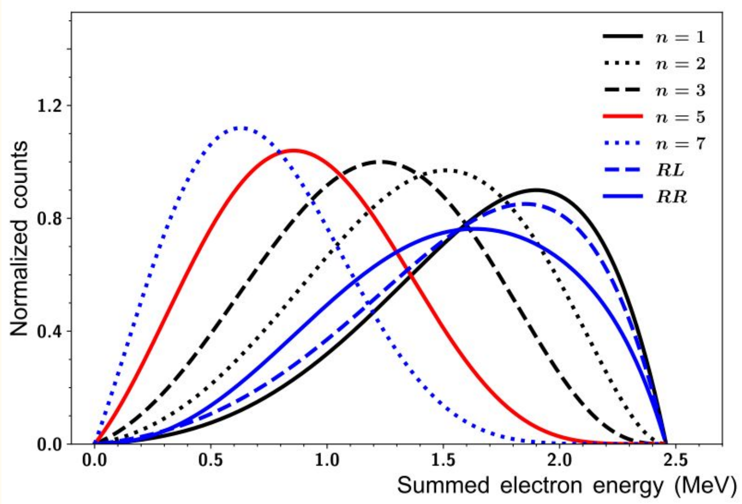
Model	L_e symmetry	$0\nu\beta\beta$	L	Decay Mode	Goldstone boson	Spectral Index
IA	Broken	Yes	N.A.	N.A.	N.A.	N.A.
IB	Broken	Yes	0	ϕ	No	1
IC	Broken	Yes	0	ϕ	Yes	1
ID	Broken	Yes	0	$\phi\ \phi$	No	3
IE	Broken	Yes	0	$\phi\ \phi$	Yes	3
IF	Broken	Yes	0	ϕ	bulk field	2
IIA	Unbroken	No	N.A.	N.A.	N.A.	N.A.
IIB	Unbroken	No	-2	ϕ	No	1
IIC	Unbroken	No	-2	ϕ	Yes	3
IID	Unbroken	No	-1	$\phi\ \phi$	No	3
IIE	Unbroken	No	-1	$\phi\ \phi$	Yes	7
IIF	Unbroken	No	-2	ϕ	gauge boson	3

Classification follows that in Nucl.Phys. B449 (1995) 25-48

n = 4, n = 6, right-handed currents



NEMO-3
Eur. Phys. J. C (2019) 79:440



EXO-200
arXiv:2109.01327

Initial Estimate of FV and ROI

- ROI estimate:
  - Start with a central 1 tonne FV.
  - External gammas are negligible compare to internal backgrounds.
  - Compare signal model vs internal backgrounds to maximise S/√B (ROI_{min}, ROI_{max}).
- Assumptions for FV estimate:
  - Signal of interest is internal and uniform in the LXe
  - Internal background sources distribute uniformly in the LXe
  - $B = B_{Xe}$ (internal) + B_γ (external)
  - For the total LXe volume, $B_\gamma > B_{Xe}$
  - LXe shields B_γ well enough in this ROI such that there is a central volume where $B_\gamma < B_{Xe}$
- Given the above assumptions, the FV that optimises S/√B is expected to be where $B_{Xe} = B_\gamma$

$$\left.\frac{\partial B_\gamma}{\partial r}\right|_{r=\tilde{r}} = 6\pi b(z_{max} - z_{min})\tilde{r}$$

$$\left.\frac{\partial B_\gamma}{\partial z_{max}}\right|_{z_{max}=\tilde{z}_{max}} = 3\pi r^2 b$$

$$\left.\frac{\partial B_\gamma}{\partial z_{min}}\right|_{z_{min}=\tilde{z}_{min}} = -3\pi r^2 b$$

Optimisation Strategy

- $S/\sqrt{B}$ (ROI_{min}, ROI_{max}, r, z_{min}, z_{max})
- Start from the estimated ROI and fiducial cut values:
    - First fix the ROI_{min} and ROI_{max}
    - For this ROI, fix z_{min} = 0 cm and z_{max} = 145.6 cm, scan r around the initial estimate to find $r_{optimal}$
    - Fix $r = r_{optimal}$, scan z_{min} and z_{max} separately around the initial estimates
    - Record $S/\sqrt{B}$ at the set of optimal FV parameters for this given ROI
    - Change ROI_{min} and ROI_{max} and repeat.
- Because of multiple loops over parameters, first perform a coarse scan then fine tune.

Other Experiments and Technologies

- ^{136}Xe: EXO-200, KamLAND-Zen, DAMA
- ^{76}Ge: GERDA
- ^{100}Mo: NEMO-3, ELEGANT-V
- ^{116}Cd, ^{82}Se, ^{96}Zr, ^{130}Te: NEMO-2 and NEMO-3