Prototype Detector for Neutrinoless Double Beta Decay Studies

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Abstract: The search for rare events such as neutrinoless double beta decay (0ν2β) presents an opportunity to study new physics beyond the Standard Model. Although there are on-going dedicated experiments, liquid Xenon (LXe) detectors designed to searh for Dark Matter, such as LUX-ZEPLIN, can be competitive in this field given the large amount of the 0ν2β emitter isotope Xe-136 they contain and their extremely low background. However, they are not designed to detect such high energy decays, rather being optimised to search for low energy nuclear recoils. This work proposal consists of designing, simulating and optimising a LXe Time Projection Chamber (TPC) using SiPMs, maximising its sensitivity to 0ν2β in Xe-136. The long term goal of this project is to implement the newly developed design in the next generation of Xenon detectors to enable additional studies in particle physics.

1. Introduction

Neutrinos were theorised by Wolfgang Pauli in 1930 to explain how beta decay could conserve energy, linear and angular momentum. They were detected for the first time in 1956 and understanding the nature of these elusive particles has proven to be quite a challenge for physicists. They arise from several sources, among which are the Big Bang, supernovae explosions, fusion inside the Sun, cosmic rays interacting in the atmosphere, anthropogenic sources like nuclear reactors and Earth's natural radioactivity.

Neutrinos come in 3 flavours: electron (ν_{e-}), muon ($\nu_{\mu-}$) and tau ($\nu_{\tau-}$). They were thought to be massless until observation of neutrino oscillations by the Super-Kamiokande [1] and SNO [2] experiments. The results showed a neutrino in a well defined flavour state has a nonzero probability of being observed in a different flavour than the one it originally had, after travelling away from its source. This implies that neutrinos have non-zero mass and that flavour eigenstates are a superposition of mass eigenstates. The two are related by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix which gives the strength of lepton flavour mixing [3].

Besides having extremely low mass, these are the only type of fermion which do not possess EM or colour charge, meaning they do not participate in the electromagnetic and strong interactions, making them notoriously difficult to detect. They interact only via weak nuclear force and gravitational force [3].
Neutrino oscillation experiments have allowed us to establish relations between the masses of the mass eigenstates, written in the form of square mass differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$. Experimental data confirms Δm_{21}^2 (solar mass difference) is positive but the sign of Δm_{31}^2 (atmospheric mass difference) is unknown. If Δm_{31}^2 turns out to be positive, neutrinos have a normal mass hierarchy (NH); otherwise, it is inverted (IH) [4]. Figure 1 illustrates the difference in hierarchies and the probability of finding one of the flavour eigenstates if the neutrino is in a certain mass eigenstate.

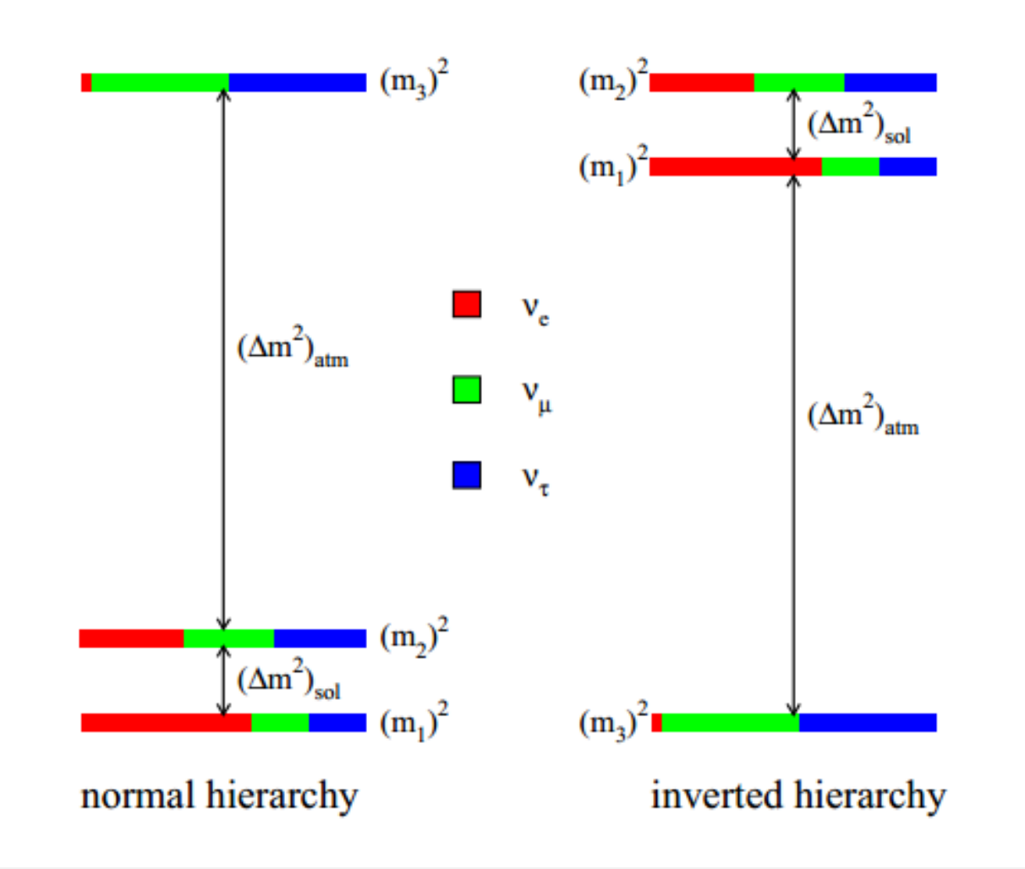

Fig.1 - Two possible layouts of neutrino mass hierarchy. Normal Hierarchy predicts two light neutrinos and a heavy neutrino while Inverted Hierarchy calls for one light neutrino and two heavy neutrinos. The colour indicates the fraction of each flavor ν_α, $\alpha = e^-, \mu^-, \tau^-$ contained in each mass eigenstate ν_i, i=1,2,3. [3]

2. Neutrinoless Double Beta Decay (0ν2β)

Double beta decay (2ν2β) is one of the rarest known decays, where a transition between isobaric nuclei occurs in which two neutrons decay into protons with the emission of two electron antineutrinos [5]. In 1937, Ettore Majorana demonstrated that the results of beta decay theory were unchanged under the assumption that neutrinos were their own antiparticles, resulting in a *neutrinoless* decay, as represented in Figure 2.

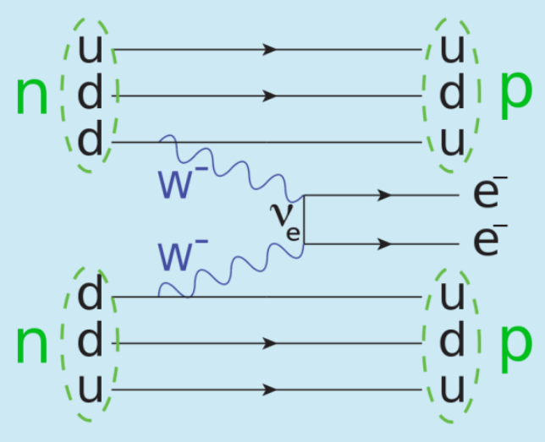

Fig. 2 - Diagram of the *0ν2β* process due to the exchange of massive Majorana neutrinos .

This started a debate around the possibility that the neutrino could be a "Majorana" particle and its implications in the SM. Observation of 0ν2β decay would therefore reveal that Majorana particles exist, meaning the current models for elementary particles would have to be re-evaluated and modified to agree with the new findings. This would prove the existence of processes which do not conserve leptonic number and hence B-L number violation, which is a fundamental symmetry of the SM [5]. Another issue that would arise would be CP violation. The half-life of 0ν2β is directly linked with the effective Majorana mass of the neutrino $\langle m_{\beta\beta} \rangle$ by equation (1) [6].

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

0ν2β could help us understand the matter/antimatter asymmetry in our Universe and would provide insight into the mass mechanism of neutrinos. Current experiments are working with sensitivities for 0ν2β up to $T_{1/2}^{0\nu} \approx 10^{26}\ yrs$ allowing us to set limits for $\langle m_{\beta\beta} \rangle$ as shown in Figure 3.

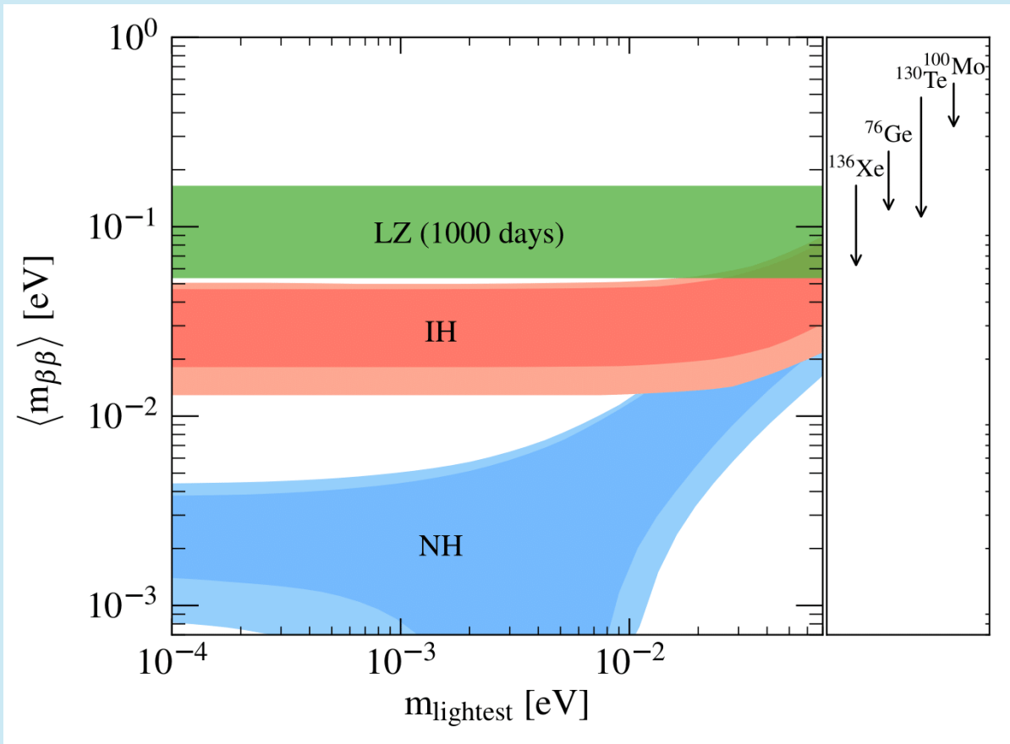

Fig. 3 – Effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle$ as a function of the lightest neutrino mass $m_{lightest}$. The darker colours are the best-fit values of neutrino oscillation parameters for each hierarchy. The lighter colours are the oscillation parameter uncertainties. In green are depicted the expected limits on $\langle m_{\beta\beta} \rangle$ using Xe-136 in the LUX-ZEPLIN experiment. The vertical arrows on the right show the current best limits for different nuclei [7].

3. Signal Signature

In a hypothetical 0ν2β decay, we are interested in detecting the two emitted electrons that carry most of the kinetic energy of the transition, considering the energy of the recoiling nucleus is negligible. The signal produced would be a monoenergetic peak at Q-value as represented in Figure 4.
Xe-136 is one of the most widely used isotopes for these experiments as it has high isotopic abundance in natural Xe, masses are reasonably easy to scale and has high Q-value at 2.458 MeV ($T_{1/2}^{0\nu}$ is expected to scale with Q^{-5}).
In order to observe a few decays, the amount of source material used in the experiment should be around hundreds of kilograms up to tonnes. Even then, the detection of the two electrons is complicated by background events, which originate mostly from high energy γ-rays from internal and external radioactivity, and 2ν2β itself [5].

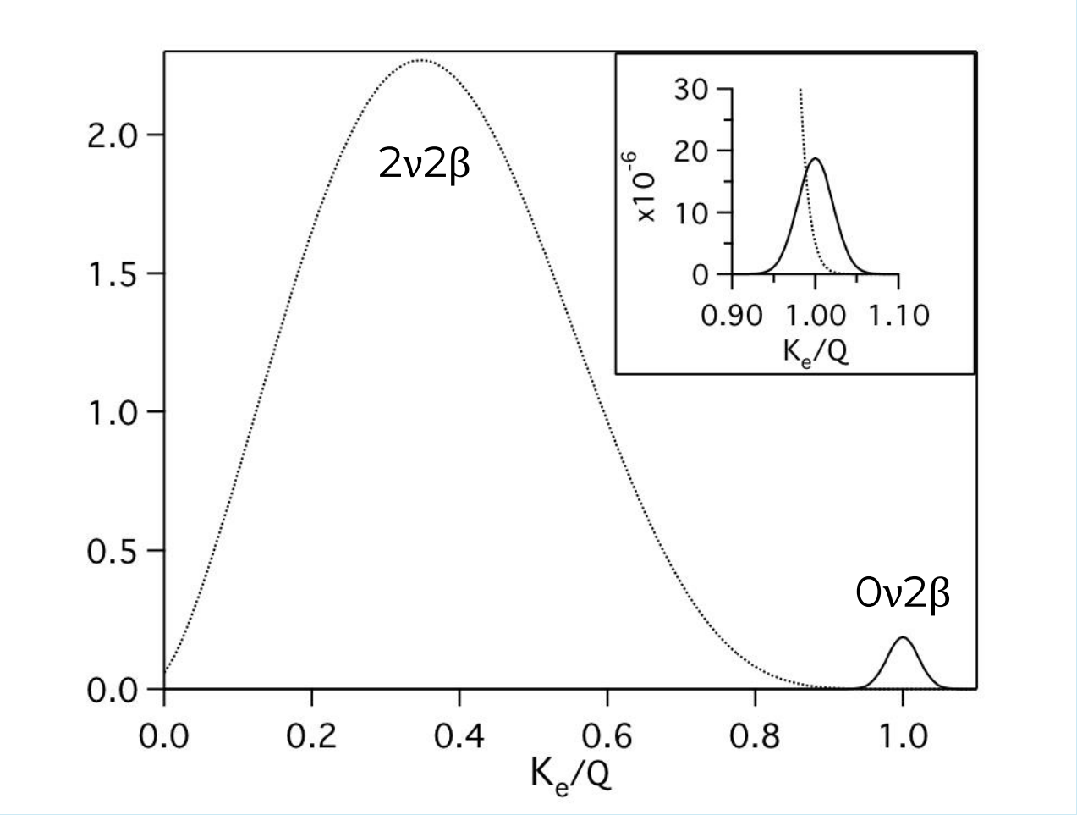

Fig. 4 – Normalised sum of the kinectic energies of the two electrons present in 2ν2β. The peak at Q-value corresponds to the hypothetical 0ν2β decay as seen by a detector with a finite resolution [5].

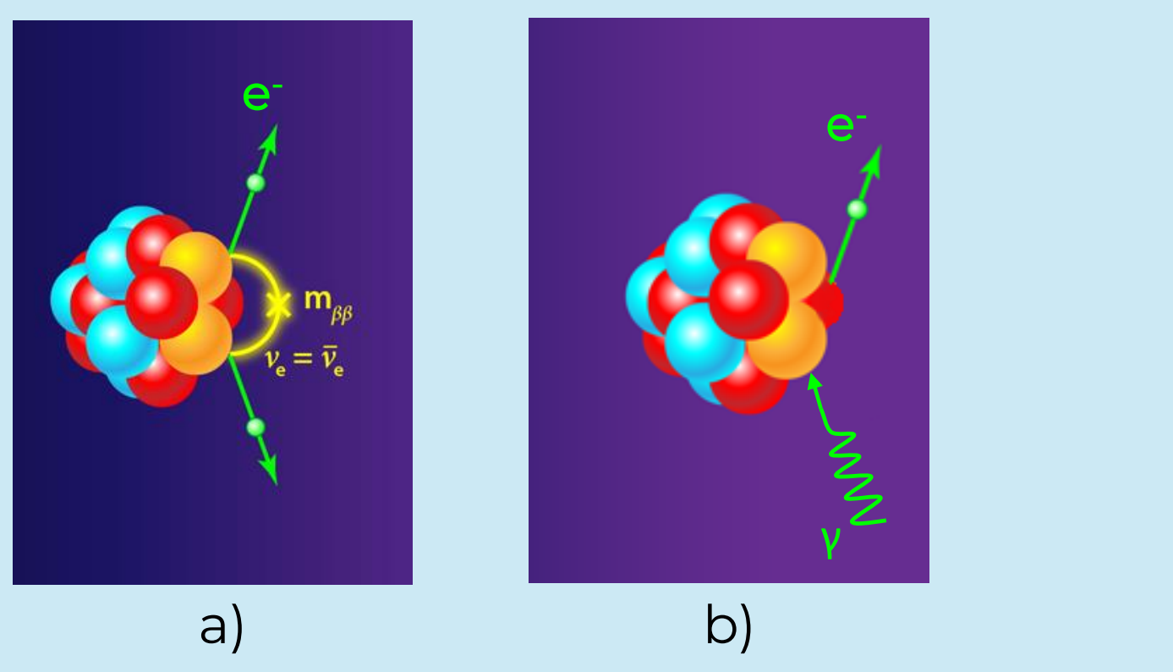

Fig. 5 – a) Illustration of 0ν2β decay. The energy carried by the two electrons in Xe-136 is 2.458 MeV.
b) Illustration of a common background source in 0ν2β signal: a photoelectron is emitted with an energy close to 2.458 MeV.

4. Experiments

KamLAND-Zen

The detector has an outer balloon filled with a liquid scintillator acting as a shield and inside it another balloon with a total of 13 tonnes of Xenon-loaded liquid scintillator with 345 kg of Xe-136. Light collection from interactions is collected by photomultiplier tubes (PMTs). This collaboration reached the current best limit of $T_{1/2}^{0\nu} \approx 1.1 \times 10^{26}\ yrs$ at 90% C.L., making it the first experiment to reach the limit of the quasi-degenerate mass region [5].

NEXT

This collaboration uses an electroluminescent high-pressure TPC filled with Xe-136. Their prototypes proved an energy resolution better than 1% FWHM at Q-value in comparison to liquid TPCs and liquid scintillators. One important feature of this detector is that it explores the topological signature of the decay by identifying the two individual electrons, allowing to discriminate it from most background events [5].

LUX-ZEPLIN

The detector was designed for searching for low energy Dark Matter interactions and consists of a LXe TPC with a gaseous Xe phase and PMT readout (see Figure 6). It contains 7 tonnes of target mass, of which 900 kg are the isotope of interest Xe-136. Although not optimised for this energy range, it is expected to be able to reach a competitive half-life limit of $1.1 \times 10^{26}\ yrs$ (see Figure 7). Data runs are expected to start in 2020 [8].

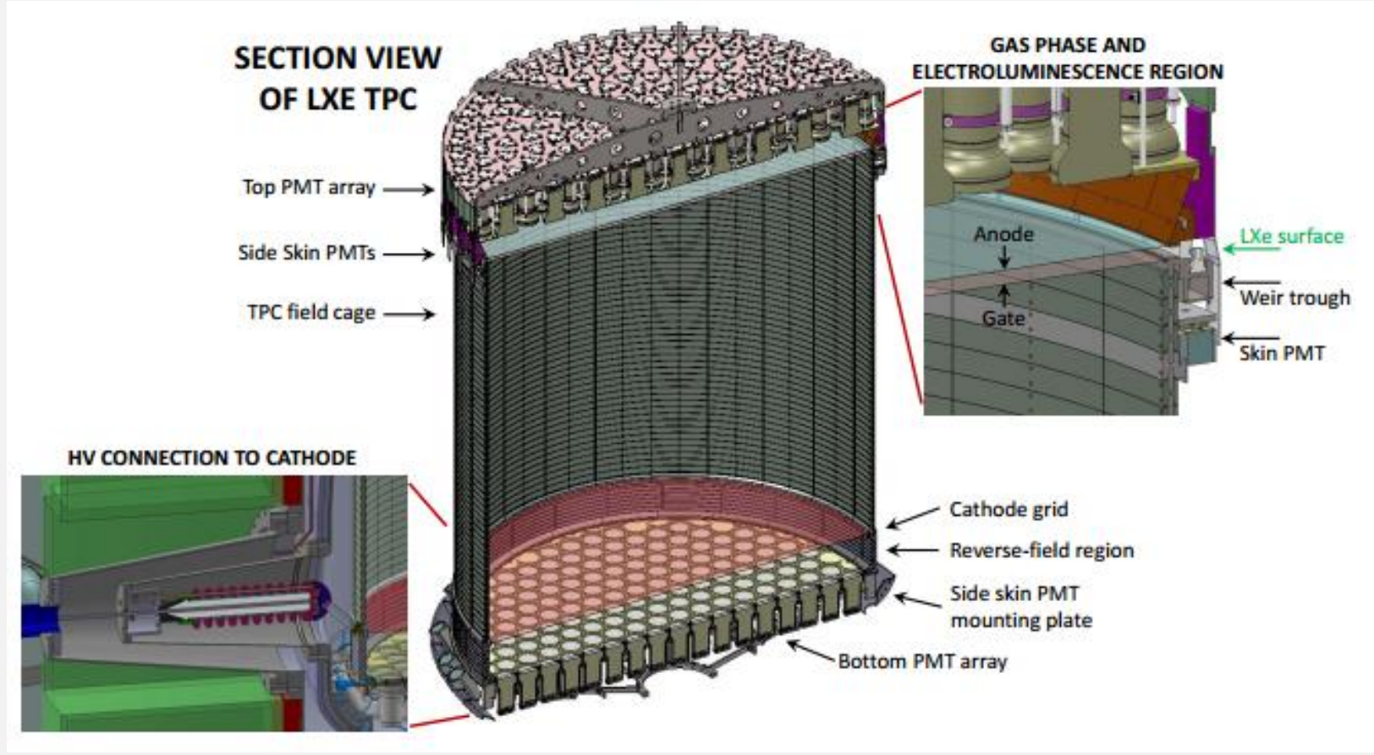

Fig. 6 – Schematic view inside LUX-ZEPLIN's TPC [8].

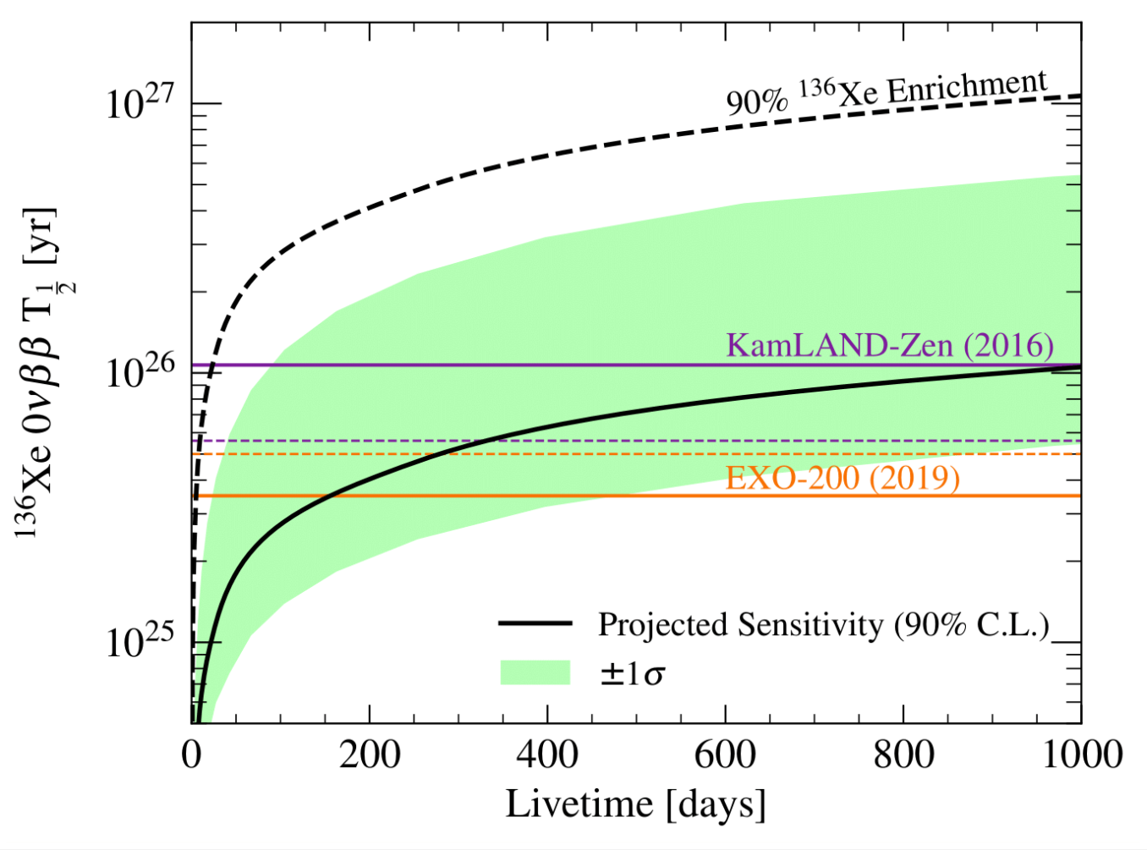

Fig. 7 – Sensitivity of LZ to the half-life of 0ν2β decay from Xe-136 as a function of the duration of data acquisition (continuous black line). Sensitivity projections (dashed coloured lines) and observed limits (continuous coloured lines) from KamLAND-Zen and EXO-200 are also shown [7]

5. Future Work

The main goal of this project, developed in collaboration with the Imperial College of London, is to design, simulate and build a prototype LXe TPC using SiPMs as light detectors, and optimising its sensitivity to neutrinoless beta decay (0ν2β) in Xe-136:

- Optimise chamber and electric field design to minimise the energy resolution at the 0ν2β Q-value
- Installation of an 8 × 8 VUV SiPM array with cryogenic readout for improved position reconstruction
- Simulation of internal and external calibration sources
- Event topology studies, exploring Machine Learning techniques to discriminate signal and background events

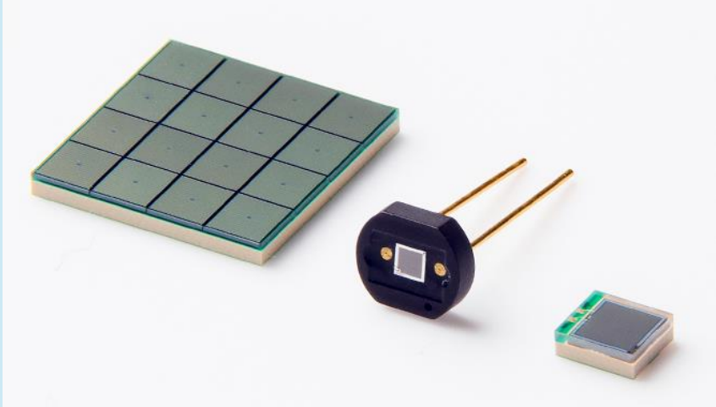

Fig. 7 – Different types of SiPM arrays (MPPCs).

[1] Y. Fukuda et al. "Measurements of the Solar Neutrino Flux from SuperKamiokande's First 300 Days". In: *Phys. Rev. Lett.* 81 (6 Aug. 1998).
[2] Q. R. Ahmad et al. "Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory". In: *Phys. Rev. Lett.* 89 (1 June 2002).
[3] A. de Gouvea et al. Neutrinos. 2013. arXiv: 1310.4340 [hep-ex].
[4] P. Brás. New physics phenomenology and development of data processing tools for the LZ Dark Matter direct search experiment. Ph.D. Thesis Proposal DAEPHYS doctoral programme in Physics. Coimbra, 2016.
[5] L. Cardani. Neutrinoless Double Beta Decay Overview. 2018.
[6] M. Biassoni. "Review of neutrinoless double beta decay experiments". In: Neutrino Oscillation Workshop (NOW). (2016). Vol. 238.Session IV. 2017.
[7] LUX Collaboration. "Search for two neutrino double electron capture of ^{124}Xe and ^{126}Xe in the full exposure of the LUX detector", 2019.
[8] LZ Collaboration. "LUX-ZEPLIN (LZ) Technical Design Report", 2017.

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