Sensitivity of the LUX-ZEPLIN experiment to rare xenon decays

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Overview

1. The LZ Experiment
2. Double beta decay process
3. Projected sensitivity of LZ to to the following rare xenon decays:
    a. Neutrinoless double beta (0vββ) decay of ^{136}Xe
    b. Two-neutrino double beta (2vββ) and neutrinoless double beta (0vββ) decay of ^{134}Xe
    c. Two-neutrino double electron capture (2v2EC) on ^{124}Xe
    d. Two-neutrino electron capture with positron emission (2vECβ$^+$) and two-neutrino double positron (2vβ$^+$β$^+$) decay of ^{124}Xe
4. Final remarks

LZ (LUX-ZEPLIN) Collaboration

34 Institutions: 250 scientists, engineers, and technical staff

@lzdarkmatter
https://lz.lbl.gov/

- 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.
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The LUX-ZEPLIN experiment

7 tonne dual-phase Xe ultra-low background TPC designed for dark matter searches ① observed by 2 arrays of 253 (top) and 241 PMTs (bottom).

Rare event observatory: Dark matter, rare xenon decays, neutrinos, axions, etc.

Two additional detectors for background modeling and mitigation:

★ 2 t Xe "Skin" detector surrounding the TPC with a 131 PMT readout ②

★ 17.3 t Gd-loaded liquid scintillator Outer Detector ③ with a 120 PMT readout ④

All instrumented volumes submerged in a 228 t water shield ⑤ also working as a muon veto.

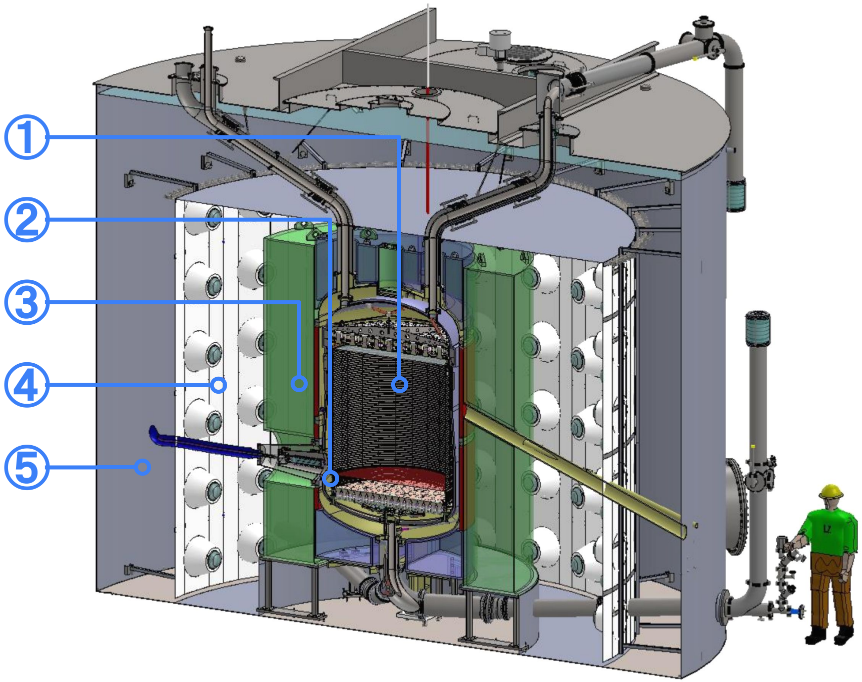


Fig. 1 - Schematic of the LZ experiment

The LUX-ZEPLIN experiment

Latest LZ updates:

- ★ TPC was installed in the Davis lab at SURF (Lead SD, USA).
- ★ Outer detector construction was completed this spring.
- ★ We have cold xenon in the TPC.
- ★ Currently undergoing detector commissioning.
- ★ PMT signals have been measured from LED pulses.
- ★ **First physics data is expected this year.**

LZ dual-phase TPC: operating principle

1. An energy deposition in the LXe 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)**.

★ Deposited energy is reconstructed using both the **S1 and S2 signals**.
★ Depth of the interaction can be obtained by the **time difference between the S1 and S2 signals.**
★ XY position can be reconstructed using the **light pattern generated by the S2** signal on the top PMT array.

Full 3D reconstruction of the interaction

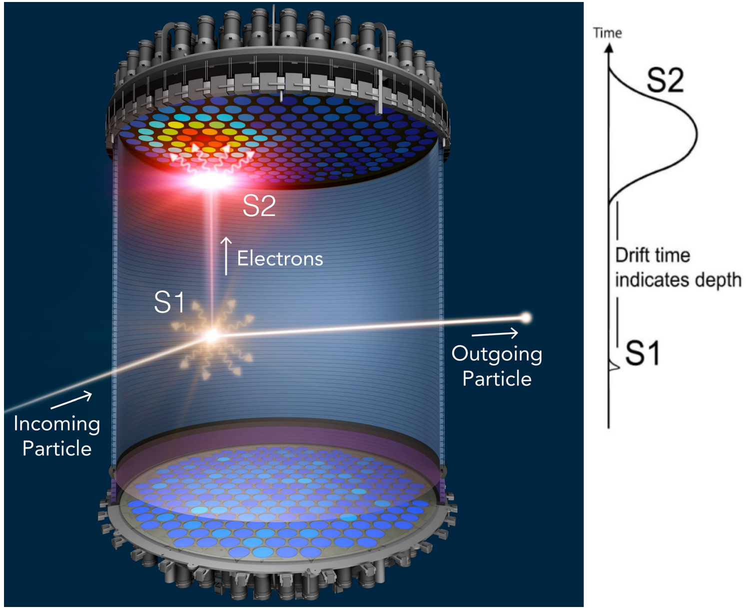


Fig. 2 - Schematic representation of the signals generated by an interaction within the TPC of LZ

Double beta decay

Beta decay with the emission of two electrons and two electron antineutrinos **(2νββ)**

$$(A, Z) \longrightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e. \qquad (2\nu\beta\beta)$$

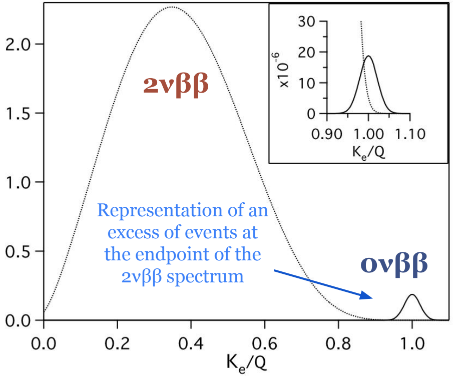
- ★ Only occurs on even nuclei when single beta decay is forbidden or highly suppressed;
  - 14 confirmed double beta emitters
- ★ The antineutrinos avoid detection and only the summed energy of the two electrons is observed.

Other four-lepton decays allowed by the Standard Model:

$$(A, Z) + 2e^- \longrightarrow (A, Z-2) + 2\nu_e \qquad (2\nu\text{ECEC}),$$
$$(A, Z) + e^- \longrightarrow (A, Z-2) + e^+ + 2\nu_e \qquad (2\nu\text{EC}\beta^+),$$
$$(A, Z) \longrightarrow (A, Z-2) + 2e^+ + 2\nu_e \qquad (2\nu\beta^+\beta^+),$$

If neutrinos are **Majorana** particles, a neutrinoless **(0νββ)** decay mode is possible:

- ★ Not yet observed;
- ★ The two electrons carry the total energy of the decay, **Qββ;**
- ★ Look for the **0νββ** decay by searching for an excess rate of events at **Qββ**.



Significant implications for particle physics and cosmology:

- ★ Evidence of fundamental Majorana particles;
- ★ Violation of leptonic number conservation;
- ★ B-L symmetry violation;
- ★ May have a role in leptogenesis.

^{136}Xe 0νββ decay sensitivity

10.1103/PhysRevC.102.014602

LZ features a 7 tonne LXe target, implying around **623 kg of ^{136}Xe** in the active region without enrichment.

- ★ Q-value of 2458 keV;
- ★ Measured 2νββ decay half-life: 2.11×10^{21} years;
- ★ Current best limit for the 0νββ decay half-life is 1.07×10^{26} years at 90% CL (KamLAND-Zen).

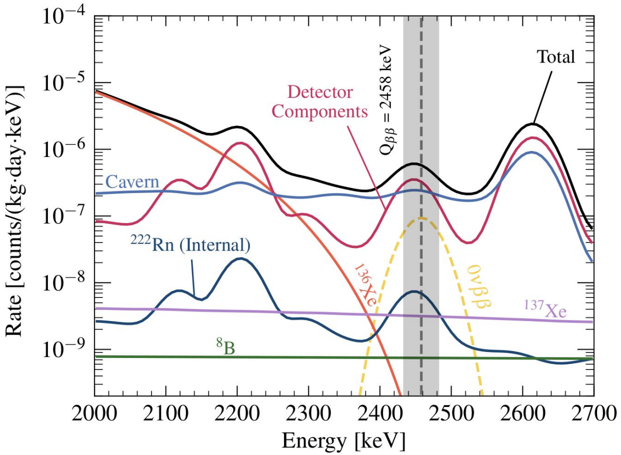


Fig. 3 - Projected LZ background spectrum near $Q_{\beta\beta}$ of ^{136}Xe

Extensive **simulations** and detailed **radioactive assays** used for BG modeling:

- ★ **Detector materials and cavern rock**;
    - ○ ^{214}Bi 2447.7 keV and ^{208}Tl 2615 keV γ's
- ★ Internal ^{222}Rn (^{214}Bi beta decay);
- ★ Muon and neutron-induced ^{137}Xe;
- ★ 2νββ decay of ^{136}Xe;
- ★ ^{8}B solar neutrinos.

Detector performance assumptions expected to be conservative:

- ★ 1% E-resolution (σ/E);
    - ○ 0.8% at Qββ is achievable (XENON1T);
- ★ 3 mm vertical vertex separation;
    - ○ No XY vertex separation considered;
    - ○ Signal efficiency of 80%.

^{136}Xe 0νββ decay sensitivity

10.1103/PhysRevC.102.014602

A **5.6 t** Xe mass was considered for Profile Likelihood Ratio (PLR) sensitivity calculation, using both position and deposited energy information.

Median 90% CL exclusion sensitivity of **$T_{1/2}$>1.06×10^{26} years** for 1000 day exposure, corresponding to **⟨$m_{\beta\beta}$⟩< 53-164 meV**.

- Comparable to the current best result (KamLAND-Zen);
- Achievable without any modification to detector operation.

A dedicated 0νββ run with **90% enrichment in ^{136}Xe** would result in a sensitivity of **$T_{1/2}$>1.06×10^{27} years** and **⟨$m_{\beta\beta}$⟩< 17-52 meV**.

- 10× increase in sensitivity, accounting for all BGs that scale with enrichment;
  - Additional 20 cm HDPE around Xe purification system.
- Would probe the IH scenario.

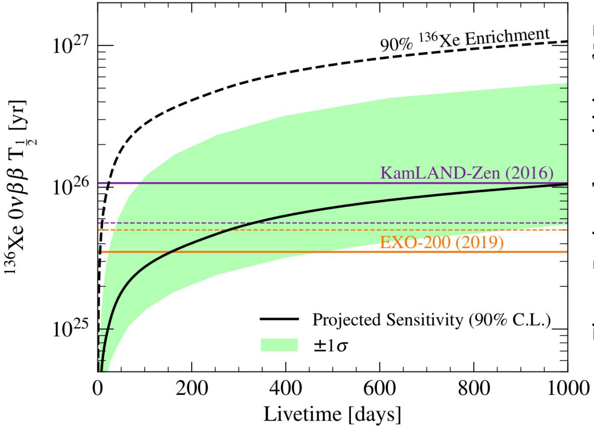


Fig. 4 - Projected sensitivity of LZ to 0νββ decay of ^{136}Xe vs exposure

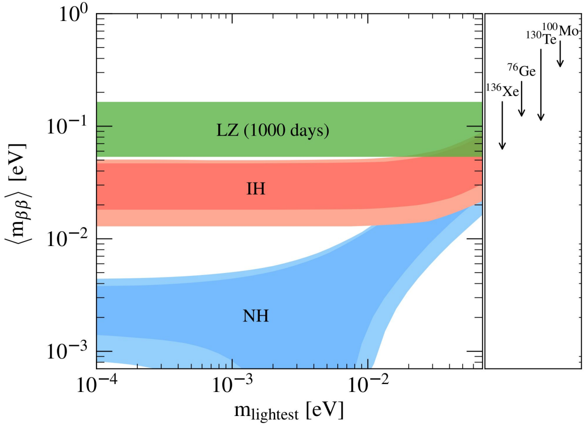


Fig. 5 - Projected sensitivity of LZ to the effective Majorana neutrino mass

^{134}Xe 2νββ and 0νββ decay sensitivity

e-Print 2104.13374

Around **741 kg of ^{134}Xe** is present in the 7 t active region of LZ.

- ★ Q-value of 826 keV;
- ★ Predicted 2νββ decay half-life: 3.7-4.7×10^{24} years (IBM-2) to 6.1×10^{24} years (QRPA);
- ★ Current best experimental limits (EXO-200):
  - ○ 2νββ half-life >8.7×10^{20} years 90% CL
  - ○ 0νββ half-life >1.1×10^{23} years 90% CL (EXO-200)

BG model built with the same **radioactive assay** and **simulation** efforts as for WIMP search and ^{136}Xe 0νββ analysis:

- ★ **2νββ decay of ^{136}Xe.**
- ★ **Detector materials and cavern rock.**
  - ○ ^{238}U, ^{232}Th, ^{60}Co and ^{40}K γ's
- ★ **Internal ^{85}Kr beta decay (Qβ=698 keV).**
- ★ Internal ^{222}Rn and ^{220}Rn (^{214}Pb and ^{212}Pb beta decay, resp.).
- ★ Solar neutrino ER from *pp* chain and CNO cycle.

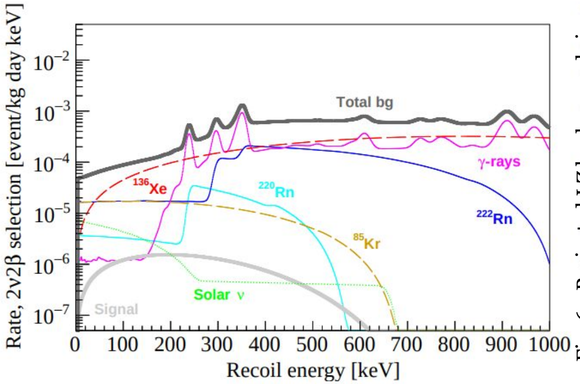


Fig. 6 – Projected LZ backgrounds in the search region of 2νββ decay of ^{134}Xe

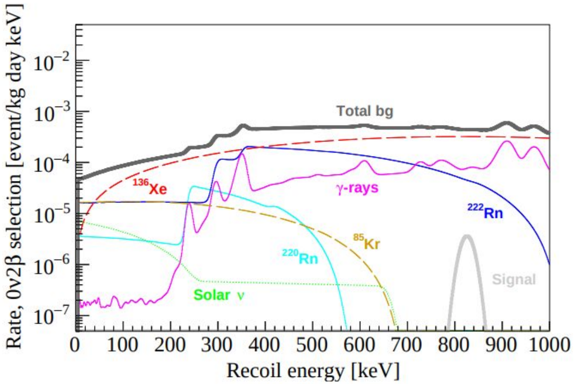


Fig. 7 - Projected LZ backgrounds in the search region of 0νββ decay of ^{134}Xe

^{134}Xe 2νββ and 0νββ decay sensitivity

e-Print 2104.13374

Optimized volumes with **5.44 t** (2νββ) and **4.59 t** (0νββ) for PLR sensitivity calculation, which uses E deposition info only.

- ★ E resolution of 2.6% at 200 keV (1.64% at Qββ);
  - Estimated using NEST
- ★ 3 cm radial and 0.2 cm vertical vertex separation;
  - Signal efficiency of 97.87% at Qββ

Median 90% CL sensitivity for 1000 day exposure is **$T^{2\nu}_{1/2} > 1.7\times10^{24}$ years** and **$T^{0\nu}_{1/2} > 7.3\times10^{24}$ years.**

- Possibly reaching $T^{2\nu}_{1/2}$ predictions from IBM-2, QRPA models;
- Improvement of current best limit on $T^{0\nu}_{1/2}$ (EXO-200) by almost 2 orders of magnitude.

Paper already submitted for publication (e-Print 2104.13374).

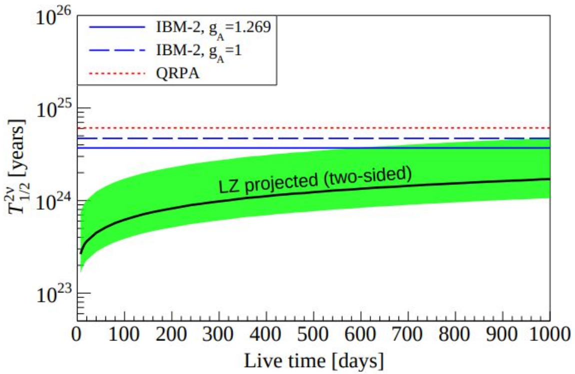


Fig. 8 - Projected sensitivity of LZ to 2νββ decay of ^{134}Xe vs exposure

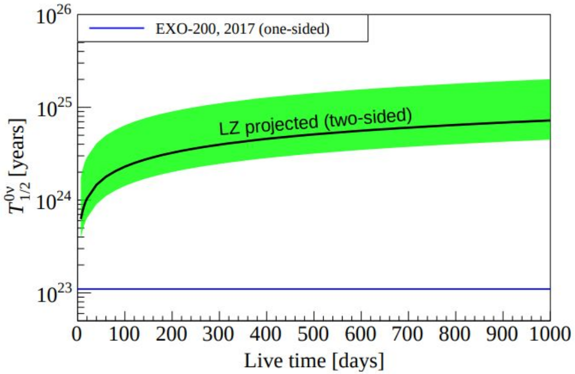


Fig. 9 - Projected sensitivity of LZ to 0νββ decay of ^{134}Xe vs exposure

^{124}Xe 2ν2EC observation in LZ

Around **6.65 kg of ^{124}Xe** is present in the 7 t active volume of LZ.

Largest contribution to 2ν2EC is from two K-shell e$^-$ (**2ν2K**):

- ★ Daughter ^{124}Te emits total **64.5 keV** on X-rays and Auger e$^-$
- ★ Measured 2ν2K half-life of 1.8×10^{22} years (XENON1T)
  - ○ Estimated 1243 2ν2EC events/year in LZ

Outstanding Background: ^{125}I from neutron activation of ^{124}Xe

- ★ ^{125}I (59.4 d, EC) ➜ ^{125}Te* (1.6 ns) ➜ ^{125}Te + nuc. deexc. (35.5 keV);
  - ○ 67.3 keV total energy (~80% of EC from K-shell)
- ★ E resolution estimated around 4% (4.1% in XENON1T, 4.2% in LUX);
  - ○ Just 1-sigma away from the 2ν2K signal
- ★ ^{125}I efficiently removed by the getter.

LZ will measure the half-life of ^{124}Xe 2ν2K **at 5σ in a few months** after data taking begins.

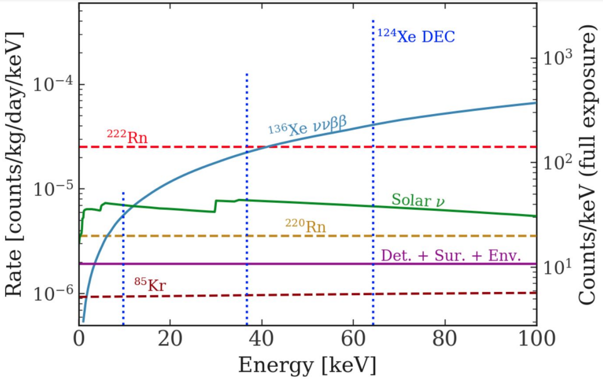


Fig. 10 - Expected LZ single scatter ER BG spectrum within a 5.6 tonne fiducial volume, showing the monoenergetic peaks from ^{124}Xe 2EC from KK, KL and LL shells. arxiv.2102.11740

^{124}Xe 2vECβ^{+} and 2vβ^{+}β^{+} searches in LZ

Around **6.65 kg of ^{124}Xe** is present in the 7 t active volume of LZ.

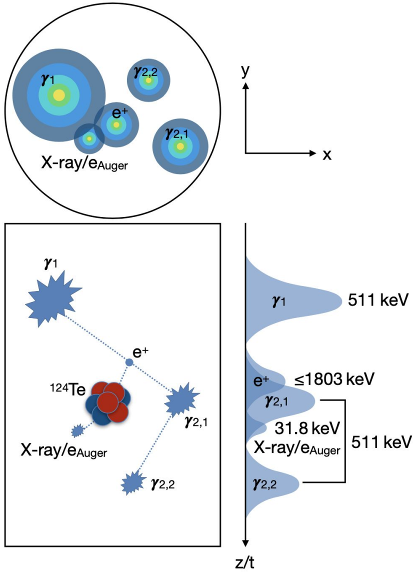
Estimated half-lives of **2vECβ^{+} is O(10^{23})** years and **2vβ^{+}β^{+} is O(10^{28})** years

- ★ **~200 2vECβ^{+} events/year** and ~2×10^{-3} 2vβ^{+}β^{+} events/year in LZ.

LZ is in a strong position to directly observe 2vECβ^{+} of ^{124}Xe, assuming O(10^{23}) years half-life. Analysis strategies are already in development.

Unique decay topologies from 2vECβ^{+}:

- ★ Q-value of 2857 keV ➜ low rates of high-energy BGs;
- ★ Vertical position resolution of LZ can resolve both 511 keV γ-rays with high efficiency;
- ★ Some BGs might mimic topology (e.g., ^{214}Bi ➜ ^{214}Po* on TPC surface and bulk, CC anti-v scattering, etc.).



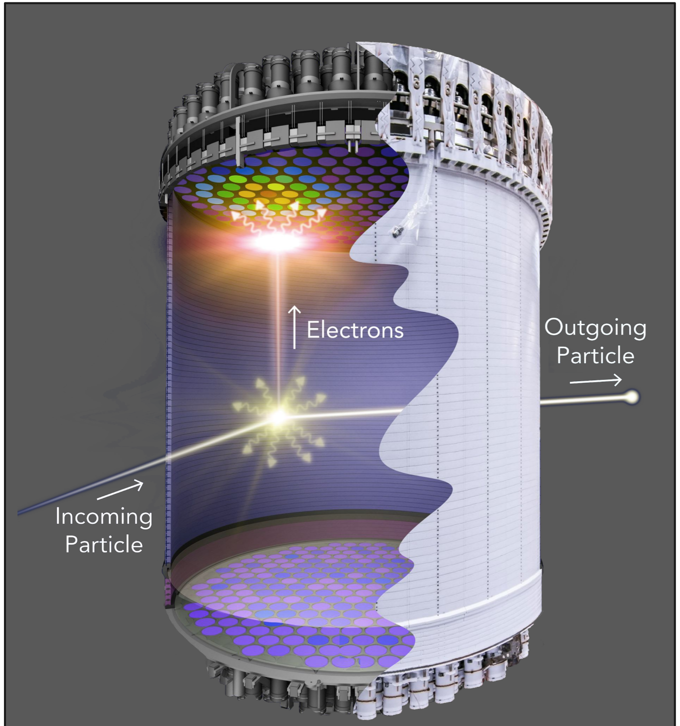
arXiv:2002.04239

Summary

The LZ experiment is a multi-purpose rare event observatory capable of physics searches beyond dark matter.

- ★ Projected sensitivity to the $0\nu\beta\beta$ decay half-life of ^{136}Xe of 1.06×10^{26} years for 1000 live-days, comparable to current dedicated experimental searches;
- ★ Projected sensitivity to the $2\nu\beta\beta$ decay half-life of ^{134}Xe of 1.7×10^{24} years, reaching half-life predictions of most prominent nuclear models;
- ★ Expect to improve the current best limit on the half-life of $0\nu\beta\beta$ decay of ^{134}Xe by almost 2 orders of magnitude;
- ★ Expect to measure the half-life of ^{124}Xe $2\nu2K$ at 5σ in a few months after first science run;
- ★ In a strong position to directly observe $2\nu EC\beta^{+}$ of ^{124}Xe for the first time, assuming $O(10^{23})$ years half-life.

Thank you!



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