Latest results from KamLAND-Zen

The search for neutrinoless double beta decay ($0\nu\beta\beta$) with the complete dataset

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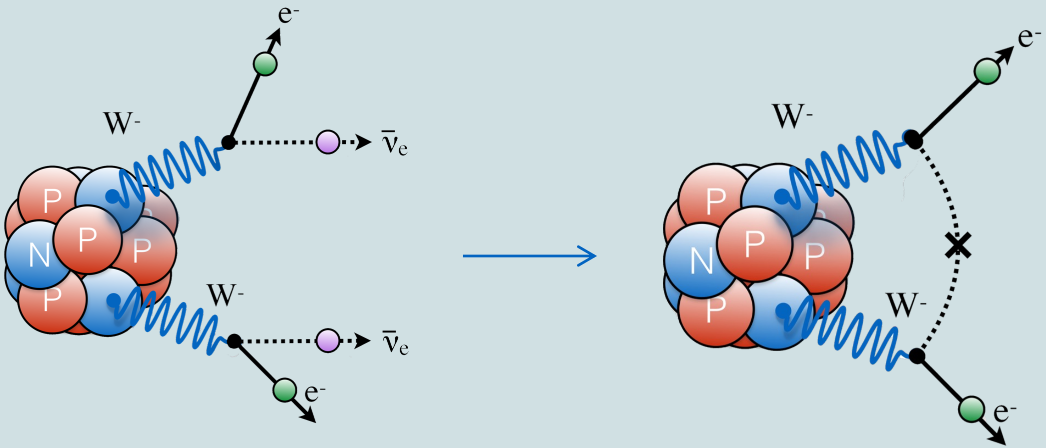
Observation of $0\nu\beta\beta$ to confirm neutrinos' majorana nature

$2\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^- + \cancel{2\bar{\nu}_e}$ $0\nu\beta\beta$ $(T^{0\nu}_{1/2})^{-1} \propto \langle m_{\beta\beta} \rangle^2$

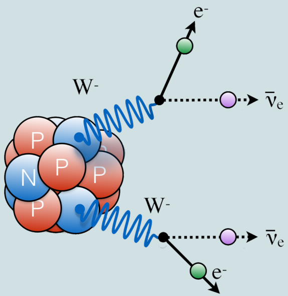


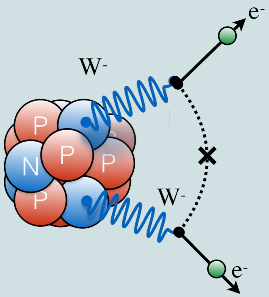
Majorana ($\nu = \bar{\nu}$) relevant for

- Neutrino mass via the seesaw mechanism
- Matter-antimatter asymmetry via leptogenesis

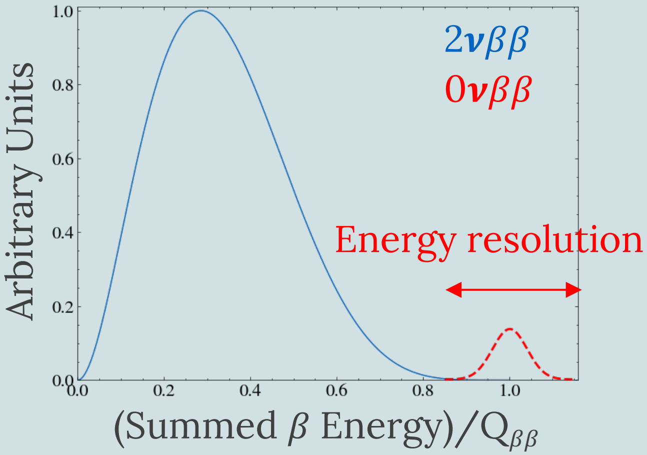
$2\nu\beta\beta$ exceptionally slow nuclear process, $T_{1/2} \sim 10^{18\text{-}24}$ years

Expected signal for neutrinoless double beta decay





Energy distribution of created electrons



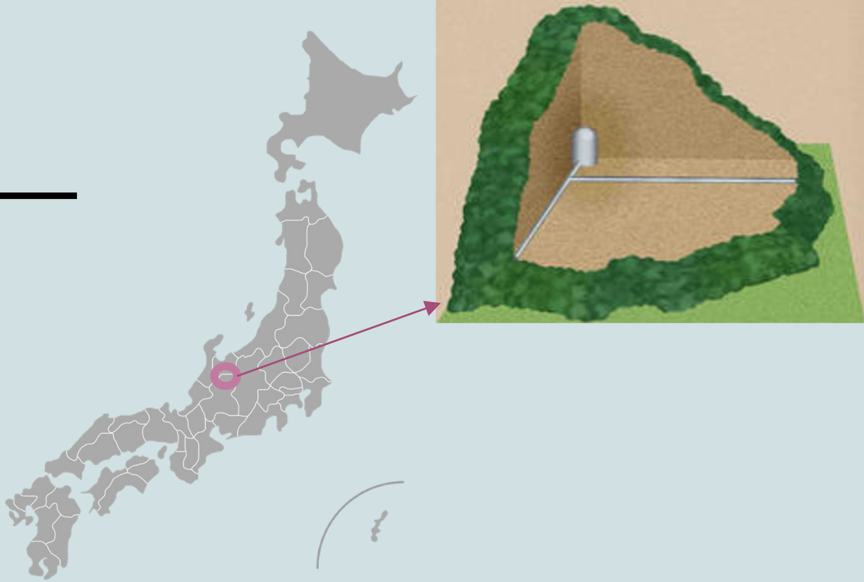
$$^{136}_{54}\mathrm{Xe} \rightarrow \, ^{136}_{56}\mathrm{Ba} + 2e^-$$

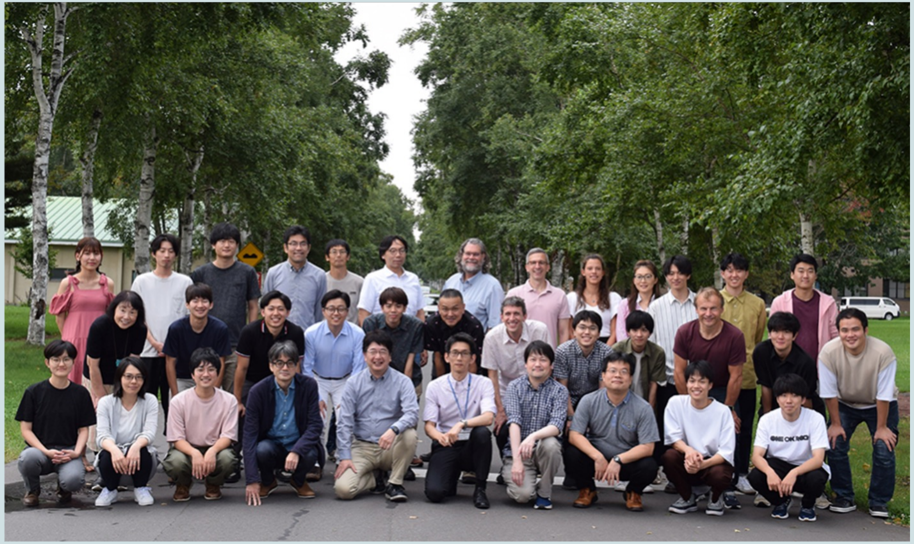
Abundance: 8.86%

Q-value: 2.458 MeV

Most stringent limit on $0\nu\beta\beta$ in **xenon** from KamLAND-Zen: $T_{1/2}$ > 3.8 x 10^{26} years

KamLAND Collaboration





General purpose detector

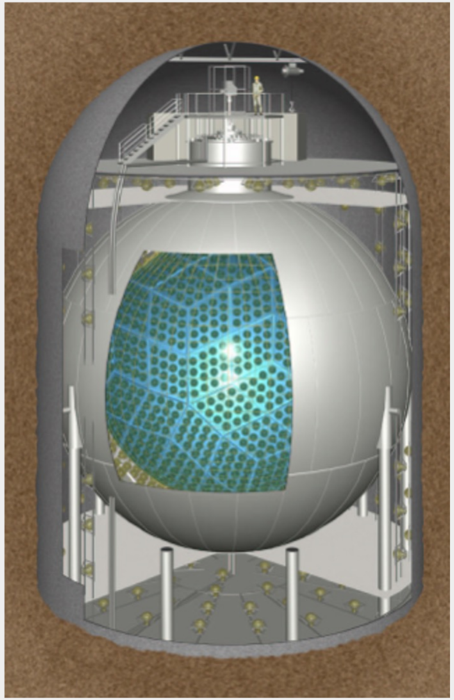
Solar neutrinos

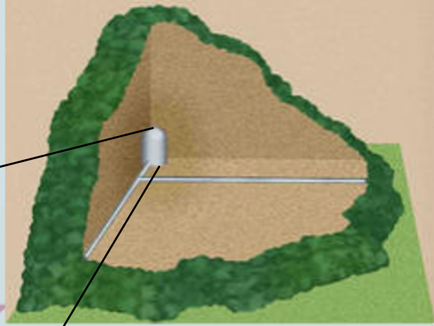
Geo and reactor neutrinos

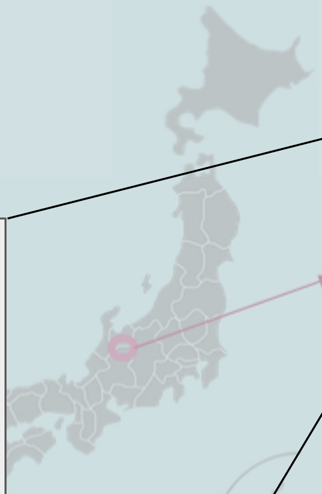
Accelerator neutrinos

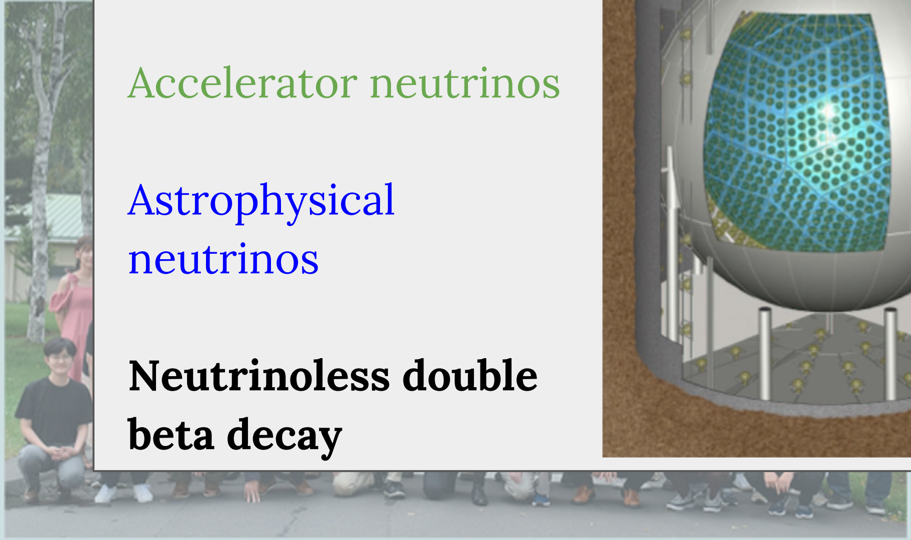
Astrophysical neutrinos

Neutrinoless double beta decay

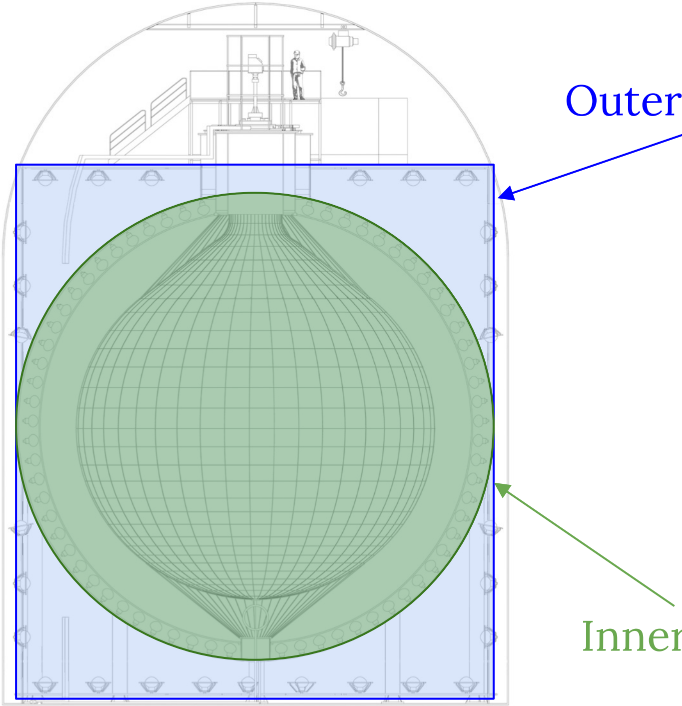








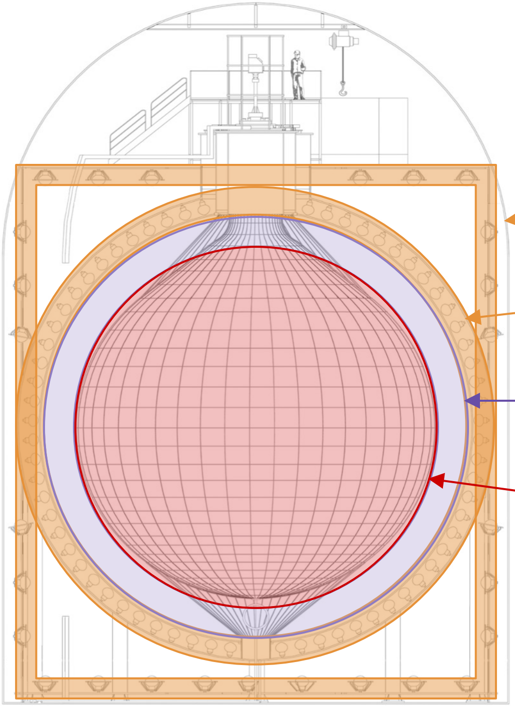
Kamioka Liquid Scintillator Antineutrino Detector



Cylindrical tank, ⌀18m

- 3.2kt pure water

Kamioka Liquid Scintillator Antineutrino Detector



Cylindrical tank, ⌀18m

- 3.2kt pure water

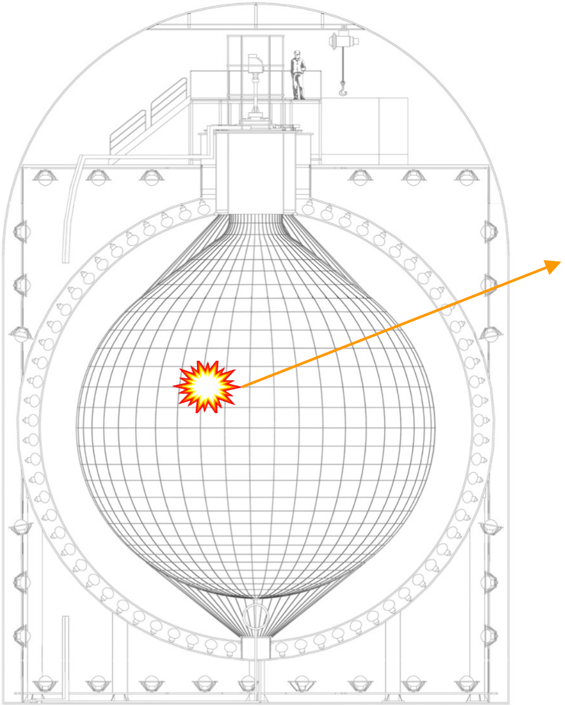
~1800 17- & 20-inch PMTs

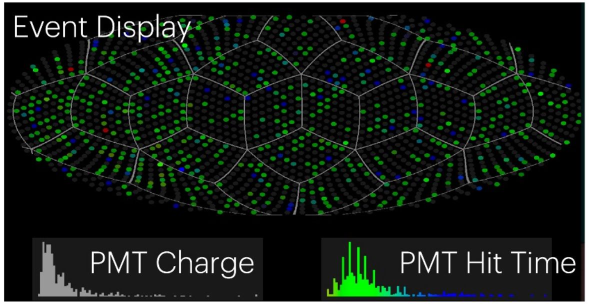
Non-scintillation oil 1.4kt

KamLAND-LS, ⌀13m, 1kt

- Dodecane 80.2%
- Pseudocumene 19.8%
- PPO 1.36g/L

Kamioka Liquid Scintillator Antineutrino Detector





Charge & Timing

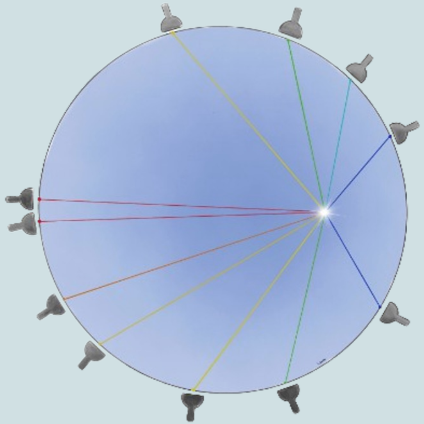
↓

Energy & Vertex

$$\frac{6.7\%}{\sqrt{E(\mathrm{MeV})}} \qquad \frac{13.7\mathrm{cm}}{\sqrt{E(\mathrm{MeV})}}$$

Inner detector

- ~ 1300 17-inch PMTs
- ~ 550 20-inch PMTs



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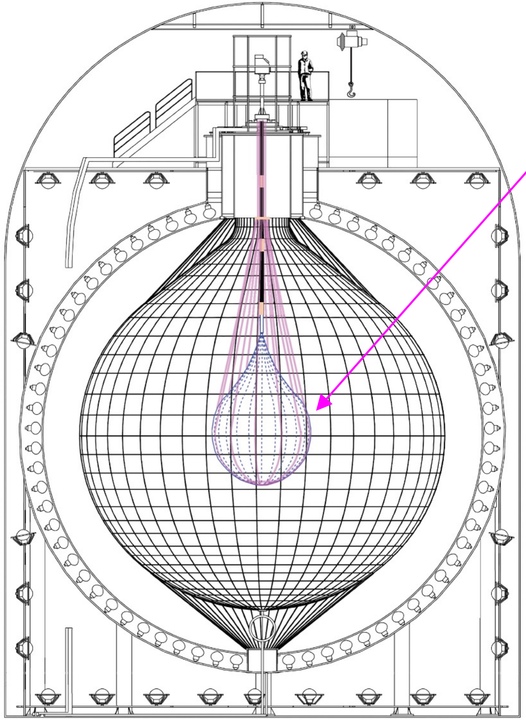
KamLAND-Zen: Zero Neutrino Double Beta

Inner Balloon Xe-LS



Zen 400 (Oct. 2011 – Oct. 2015)

Phase I: PRL 110 (2013): 0625023
Phase II: PRL 117.8 (2016): 082503

Zen 800 (Feb. 2019 – Jan. 2024)

First dataset: PRL 130.5 (2023): 051801
Complete: arXiv preprint 2406.11438

First → Complete dataset

Livetime 523 → **1131** days
Exposure 0.97 → **2.1** ton yr ^{136}Xe

$$^{136}_{54}\mathrm{Xe} \rightarrow {}^{136}_{56}\mathrm{Ba} + 2e^-$$

Xe-LS balloon, ⌀3.8m, 24t

- 3.13% enriched xenon
  ➔ 745 kg Xe
- 90.85% ^{136}Xe

$Q_{\beta\beta}$ = 2.458 MeV

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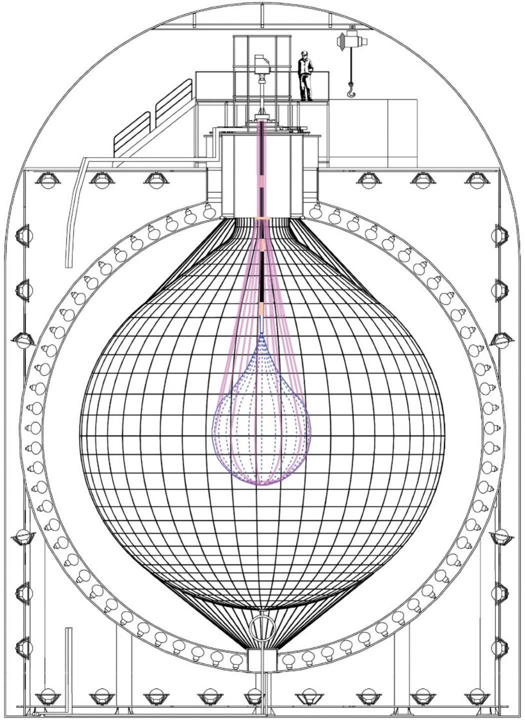
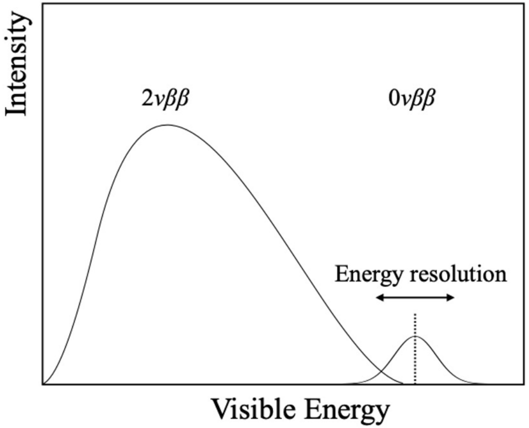
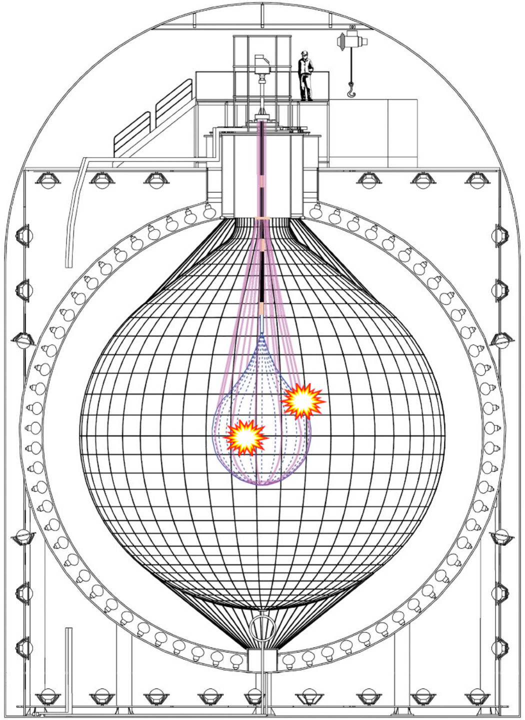
Dominant backgrounds for the $0\nu\beta\beta$ search



- $2\nu\beta\beta$ decay



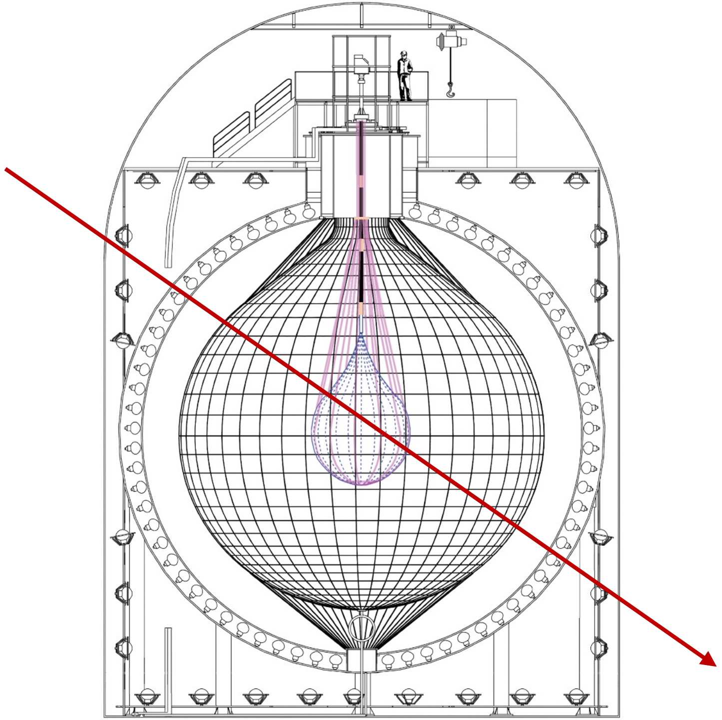
Dominant backgrounds for the $0\nu\beta\beta$ search



- $2\nu\beta\beta$ decay
- Radioactive Impurities (RI)
  - **In** Xe-LS: ^{232}Th (97.9±0.5%) & ^{238}U (99.95±0.03%) tagging effiency
  - **External**
    Dominated by ^{238}U because delayed coincidence ^{214}Bi(β) - ^{214}Po(α) efficiency ~50% due to absorption of α on non-scintillating IB

$^{214/212}$Bi $\xrightarrow{\beta^-}$ $^{214/212}$Po $\xrightarrow{\alpha}$ $^{214/208}$Pb

Dominant backgrounds for the $0\nu\beta\beta$ search



➢ $2\nu\beta\beta$ decay

➢ Radioactive Impurities (RI)

➔ **In** Xe-LS: ^{232}Th (97.9±0.5%) & ^{238}U (99.95±0.03%) tagging effiency

➔ **External:** IB material

➢ Muon spallation products

➔ Short-lived: carbon spallation products dominated by ^{6}He, ^{8}Li, ^{10}C, ^{12}B

➔ **Long-lived: xenon spallation**

μ^-

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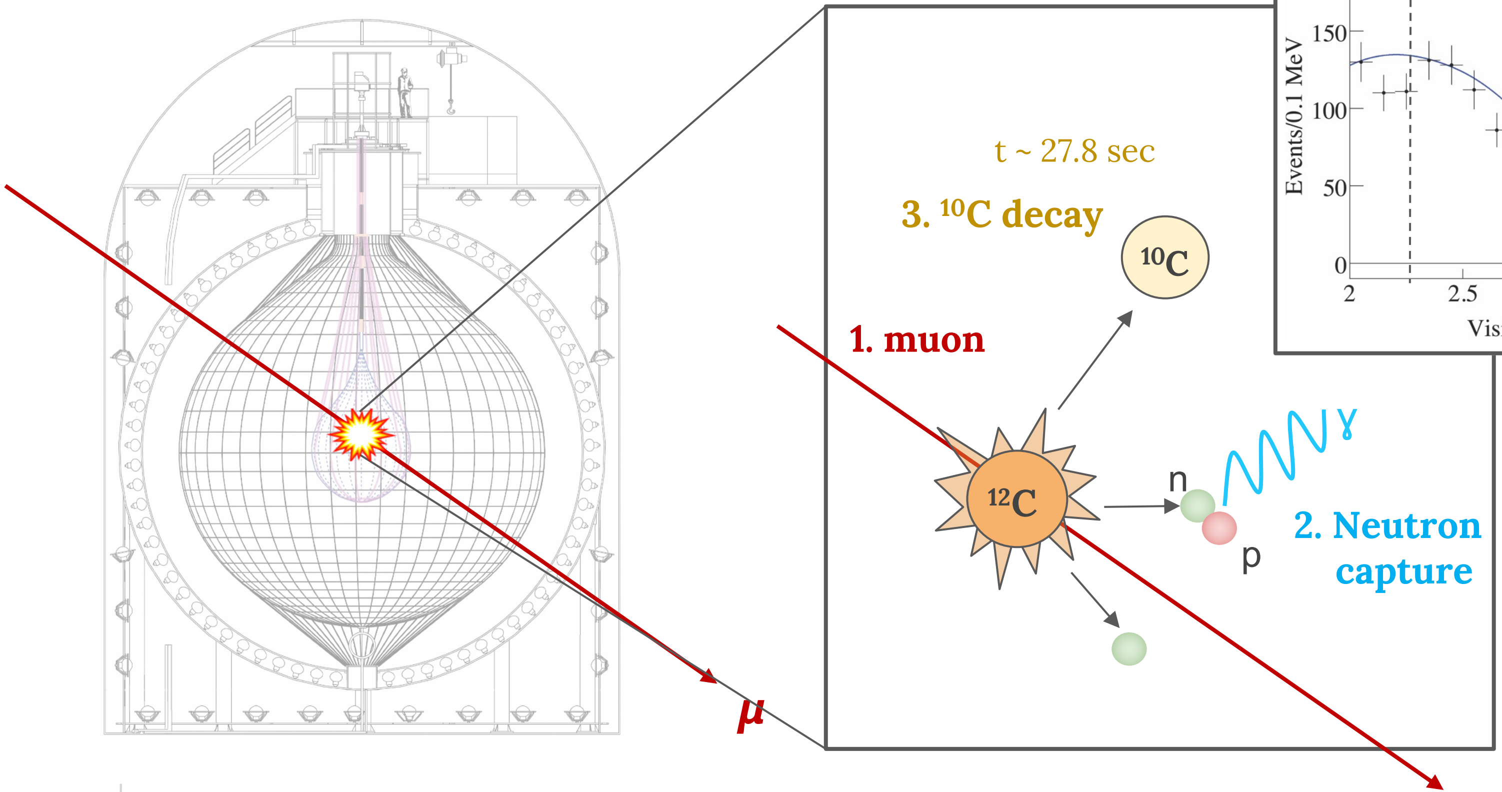
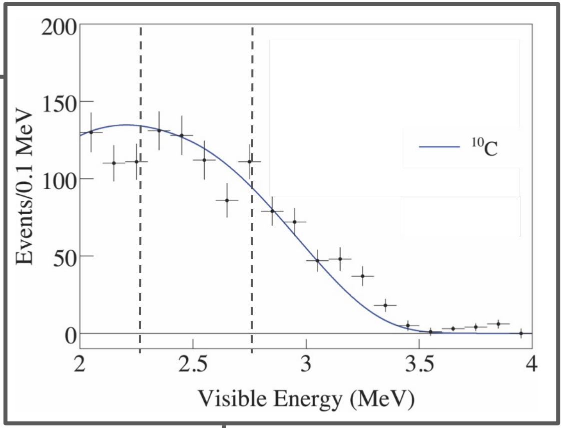
Long-lived isotope production from carbon spallation



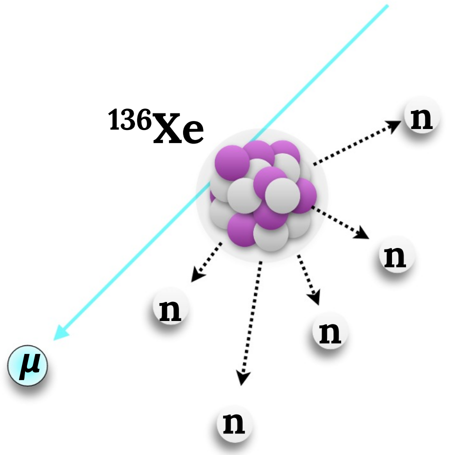


Triple coincidence tagging

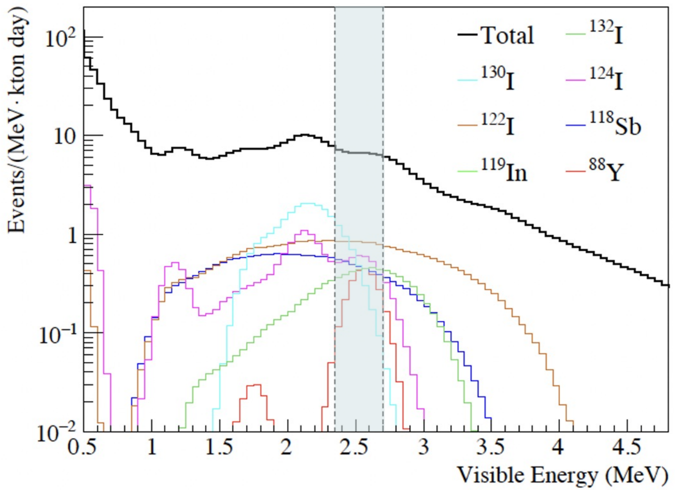
+ shower likelihood
→ ^{10}C (99.7%)

Long-lived isotope production from xenon spallation

Muon spallation on xenon results in long-lived isotopes $T_{1/2}$ ~ (sec - months)



Phys. Rev. C 107.5 (2023): 054612



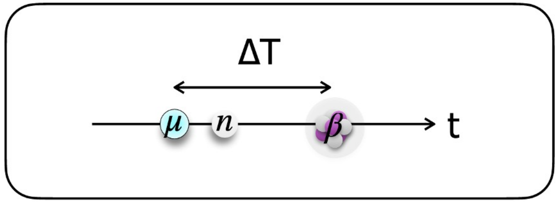
Neutron tagging

74.5 ± 0.4%

LL tagging

47.1 ± 8.7%

Deadtime **9%**

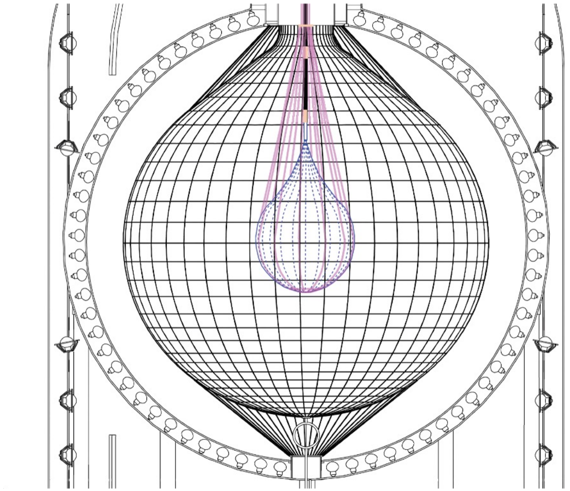


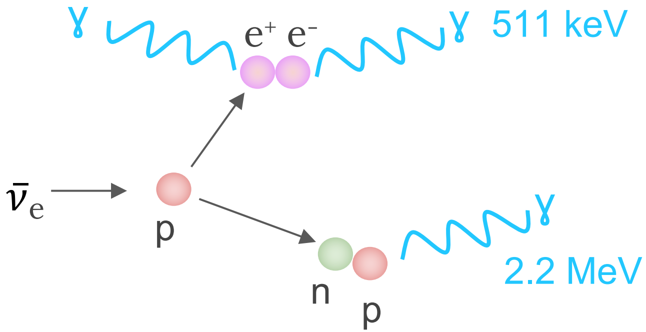
Likelihood based on number of neutrons (ENN), distance ($dR_{nearest}$) and time ($dT < 4.6$ days)

Data selection criteria and fit method

Events selected within analysis volume (r < 2.5m):

- Muons & 2ms after muons rejected
- $\bar{\nu}$ rejected with inverse-β decay coincidence cut
- Short-lived spallation coincidence & shower cut





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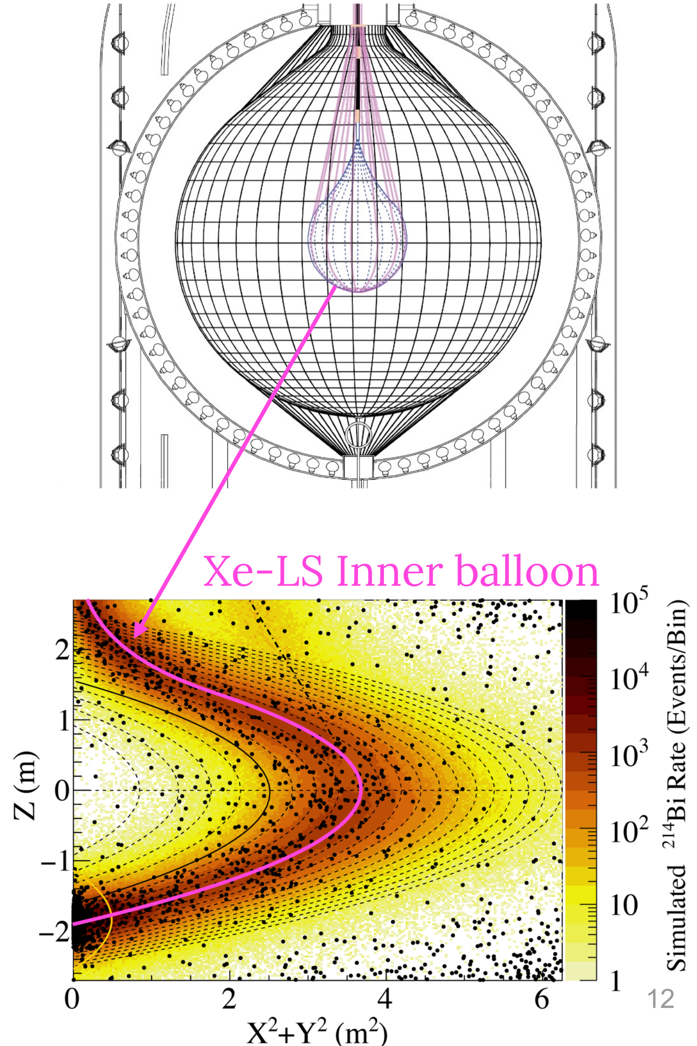
- RI rejected with BiPo coincidence and FV



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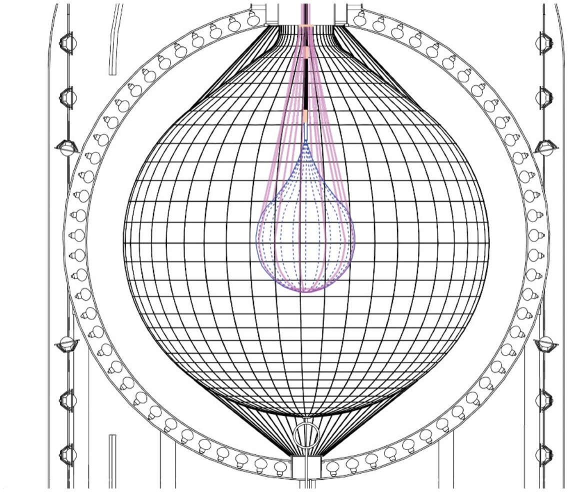

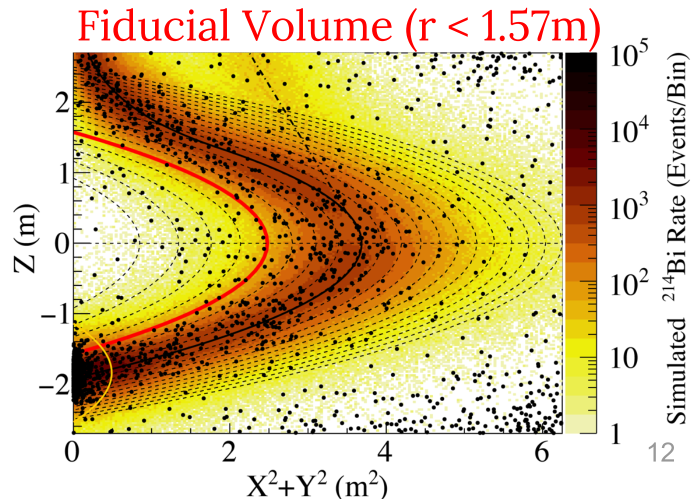

Data selection criteria and fit method

Events selected within analysis volume (r < 2.5m):

- Muons & 2ms after muons rejected
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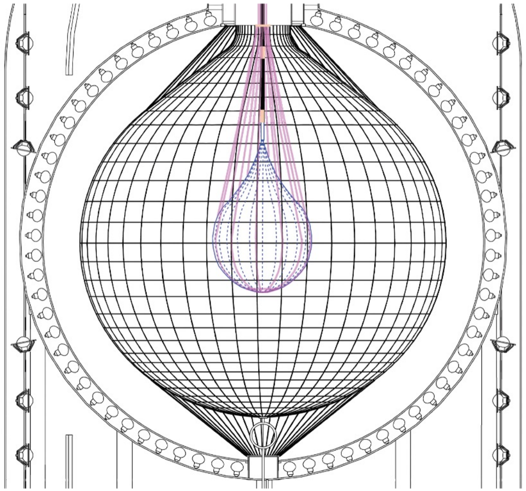
- Short-lived spallation coincidence & shower cut
- RI rejected with BiPo coincidence and FV

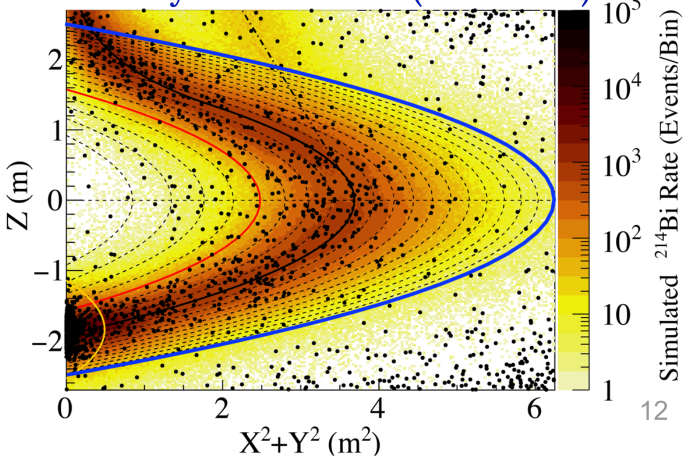
Fitting procedure:

- 40 equal volume bins within r < 2.5m
- Energy bins ∈ (0.5–4.8) MeV | ROI (2.35–2.70) MeV

Simultaneous fit of Long-Lived likelihood tagged (LD) data and $0\nu\beta\beta$ selected events (SD) to constrain LD rate

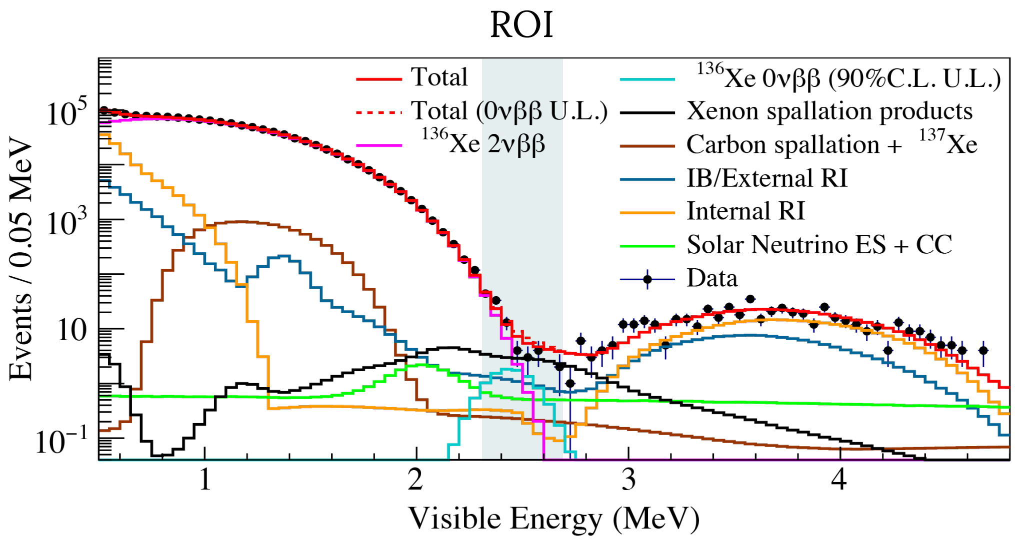


Analysis volume (r < 2.5m)



Most stringent limit on the half-life of $0\nu\beta\beta$

- Livetime 1131 days | Exposure 2.1 ton yr ^{136}Xe



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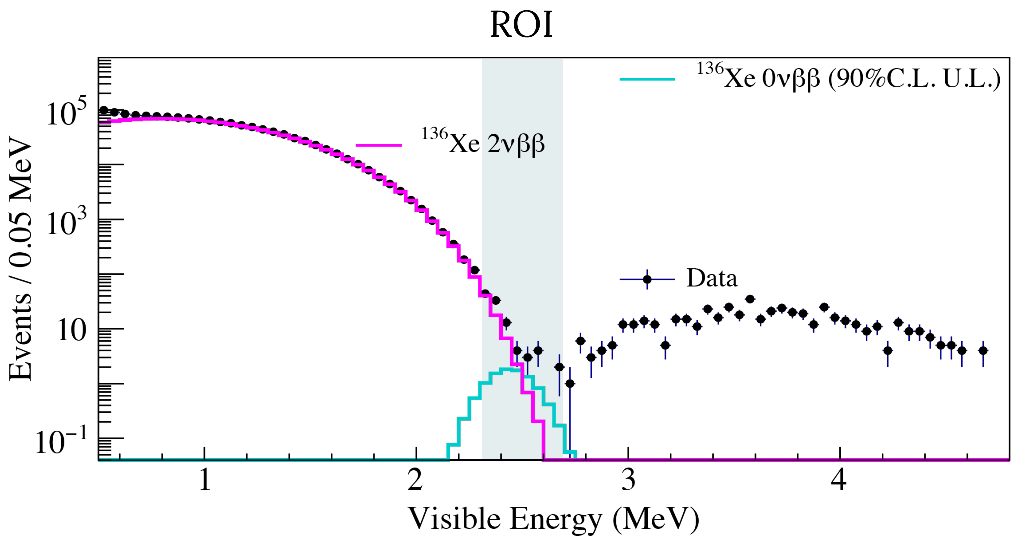

- $2\nu\beta\beta$ decay

Most stringent limit on the half-life of $0\nu\beta\beta$

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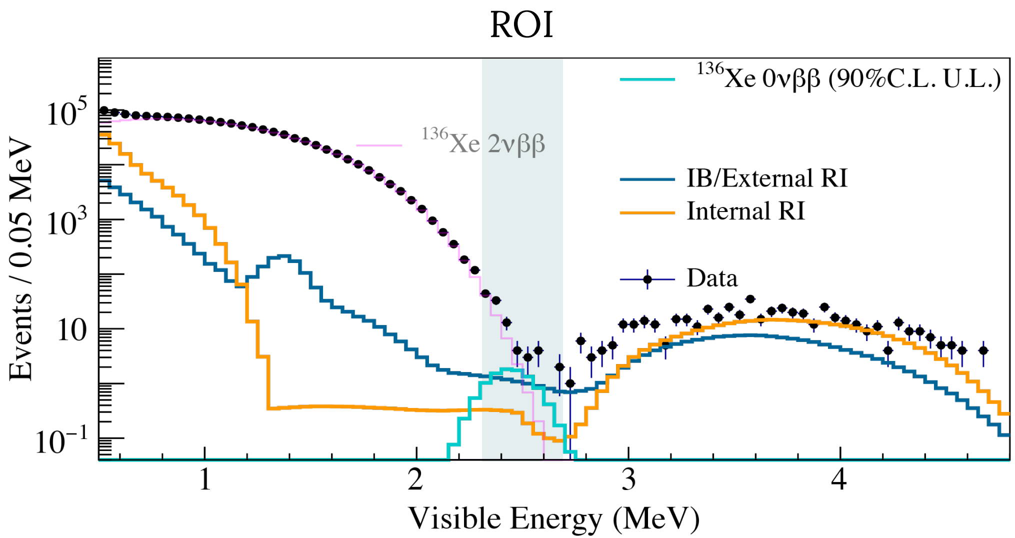
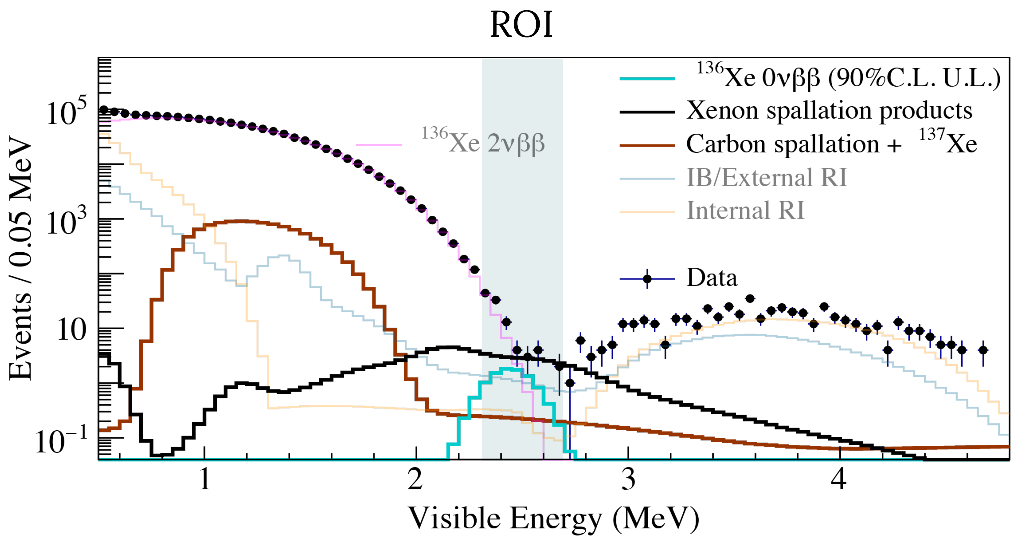


- $2\nu\beta\beta$ decay
- Radioactive contamination

Most stringent limit on the half-life of $0\nu\beta\beta$

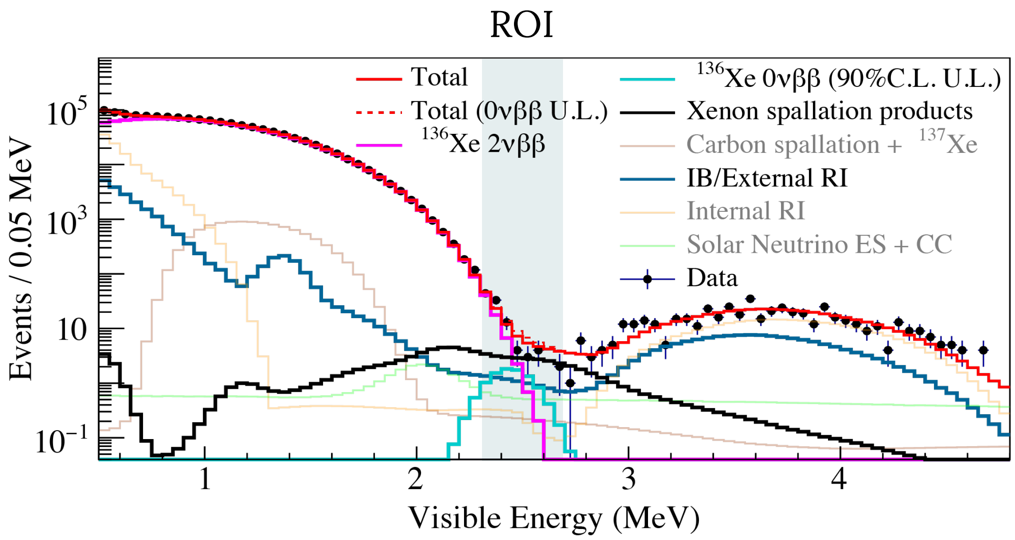
- Livetime 1131 days | Exposure 2.1 ton yr ^{136}Xe



- $2\nu\beta\beta$ decay
- Radioactive contamination
- Cosmogenic spallation products

Most stringent limit on the half-life of $0\nu\beta\beta$

- Livetime 1131 days | Exposure 2.1 ton yr ^{136}Xe



- $2\nu\beta\beta$ decay
- Radioactive contamination
- Cosmogenic spallation products

Fitting results (90% C.L.):

Before: $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ yr

Latest: $\mathbf{T^{0\nu}_{1/2} > 3.8 \times 10^{26}}$ **yr**

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Implications for the neutrino mass ordering

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)\boxed{|M_{0\nu}|^2}\langle m_{\beta\beta}\rangle^2 \longrightarrow \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

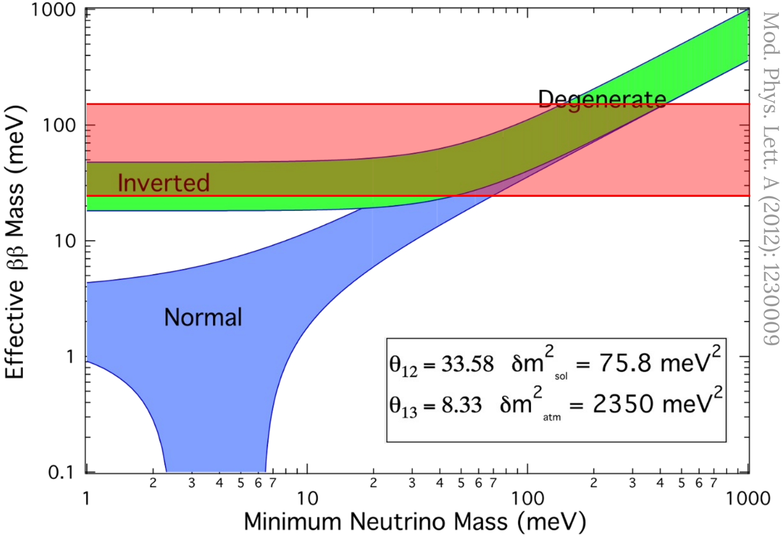
Nuclear Matrix Element

$T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr

$\langle m_{\beta\beta}\rangle < (28 - 122)$ meV

$m_{\nu 1} > m_{\nu 3}$

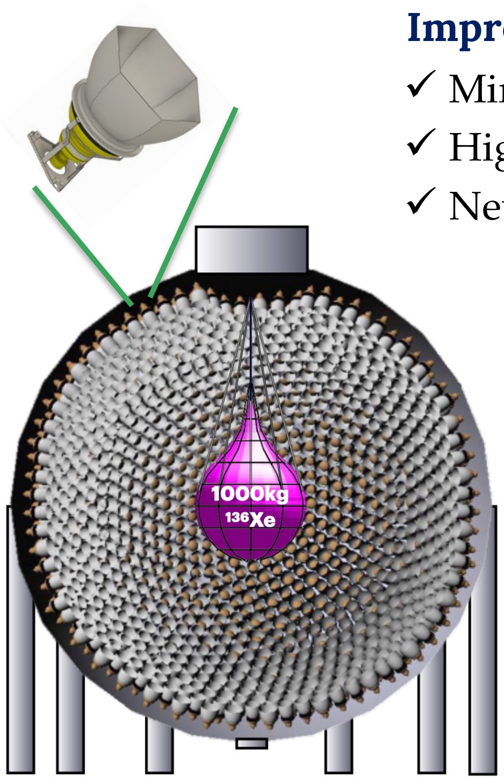
$m_{\nu 3} > m_{\nu 1}$



Mod. Phys. Lett. A (2012): 1230009

Upgrade to KamLAND2-Zen

Last physics run on August 27th 2024 → dismantling of detector started



Improved energy resolution

✓ Mirrors around PMTs (x1.8)
✓ Higher QE PMTs (x1.9)
✓ New liquid scintillator (x1.4)

4% ⟶ 2% at 2.6 MeV

Scintillation inner balloon (PEN)

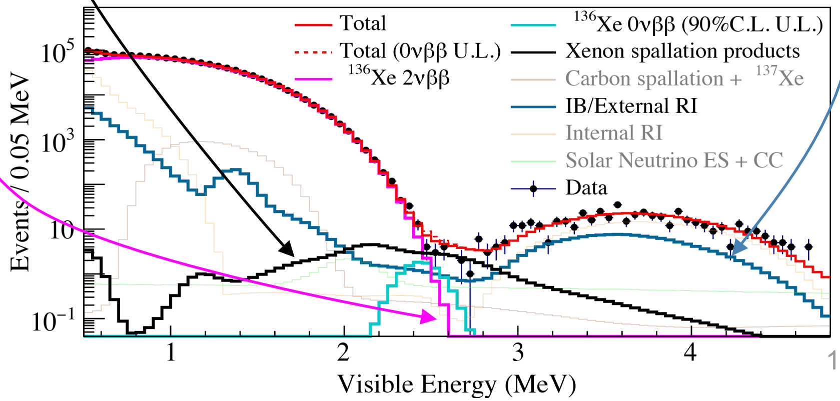
→ Larger fiducial volume

Dead-time free electronics

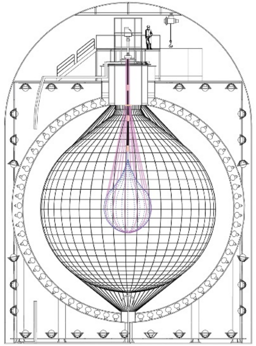
→ Higher neutron tagging efficiency

After 5 year:

$T^{0\nu}_{1/2} > 2 \times 10^{27}$ yr



KamLAND2-Zen construction timeline



KamLAND dismantling — **KamLAND2 construction**

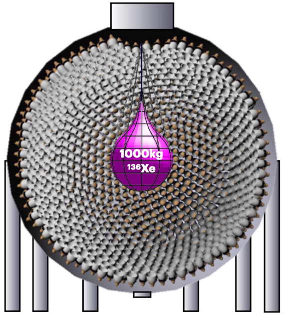
2024 → 2027

- ✓ Xe & LS extraction
  - → LS extraction
  - → Dismantling OB & PMTs

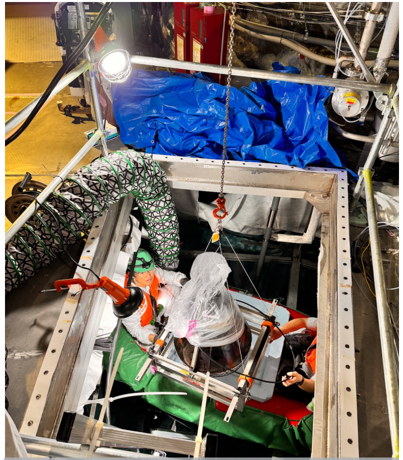
PMT & mirror installation

Cleaner OB | LS | new electronics

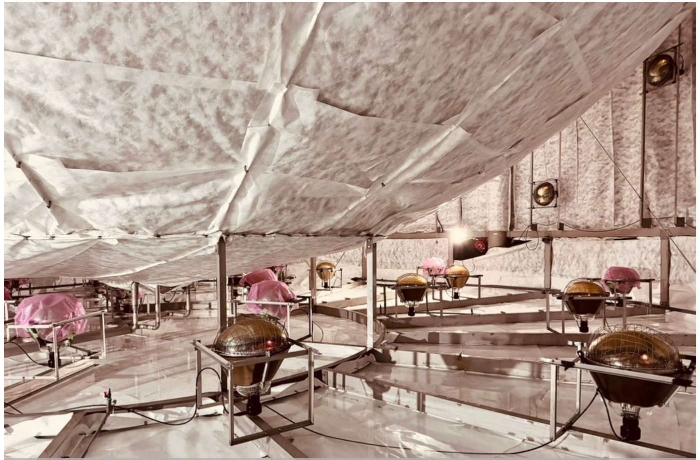
Calibration system



Water tank



Dismantling OB PMTs



The bottom of the water tank

Future prospects

KamLAND-Zen is searching for $0\nu\beta\beta$ with ^{136}Xe dissolved in liquid scintillator

- ➢ Current most stringent limit of is $T_{1/2} > 3.8 \times 10^{26}$ yr → $m_{\beta\beta} < (28 - 122)$meV

The detector upgrade of KamLAND to KamLAND2 has started

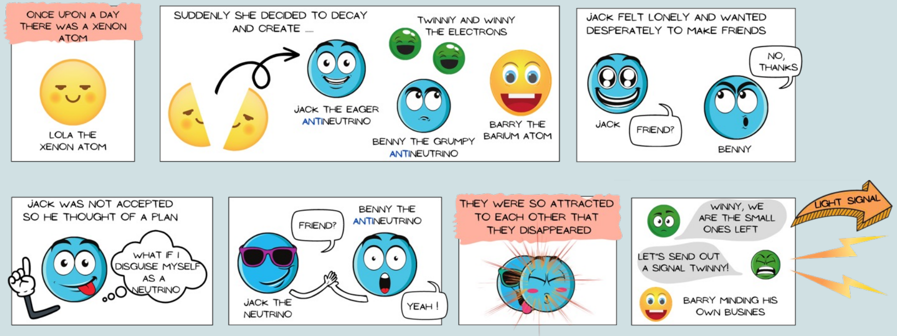
- ➢ Scintillating inner balloon
- ➢ Improved energy resolution
- ➢ New electronics for enhanced tagging efficiency

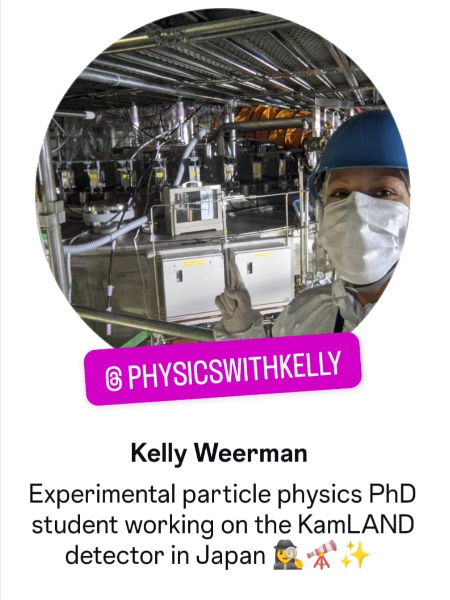
KamLAND2-Zen aims to cover the IO region | target sensitivity $\langle m_{\beta\beta} \rangle = 20$ meV

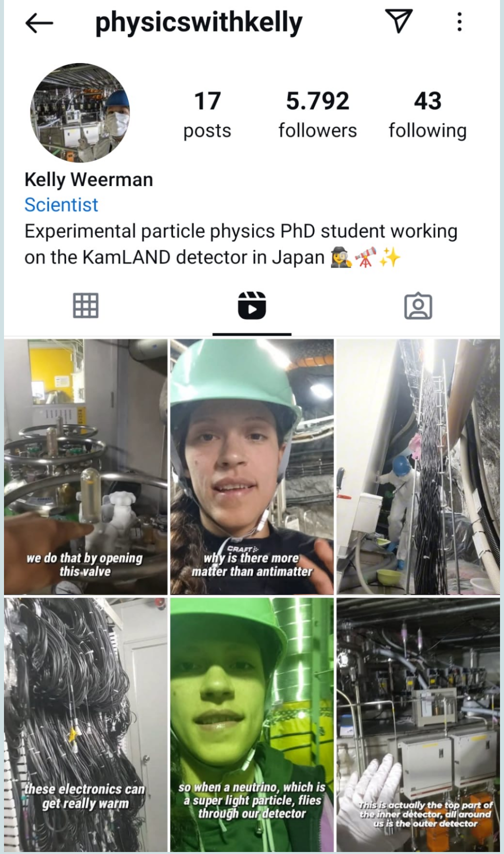
KamLAND2 dismantling & constrution ongoing → expected launch in 2027!

Thank you for your attention!

Follow me for fun videos & comics on KamLAND







Backup slides

KamLAND-Zen $0\nu\beta\beta$ half-life and mass limits

Majorana mass expectation from the KamLAND-Zen half-life limit using different nuclear matrix elements

	$M^{0\nu}$	$\langle m_{\beta\beta} \rangle$ (meV)
Shell model	2.28, 2.45	59.4, 55.3
	1.63, 1.76	83.1, 77.0
	2.39	56.7
QRPA	1.55	87.4
	2.91	46.6
	2.71	50.0
	1.11, 1.18	122, 115
	3.38	40.1
EDF theory	4.20	32.3
	4.77	28.4
	4.24	32.0
IBM	3.25	41.7
	3.40	39.9

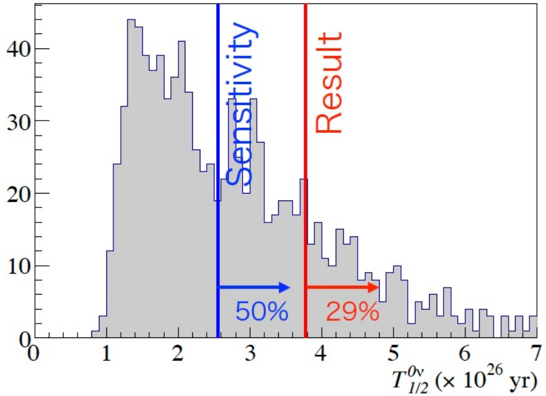
Confidence limits

KamLAND-Zen 800 only:

$T_{1/2} > 3.4 \times 10^{26}$ yr

Combined Zen 400 + 800:

$T_{1/2} > 3.8 \times 10^{26}$ yr



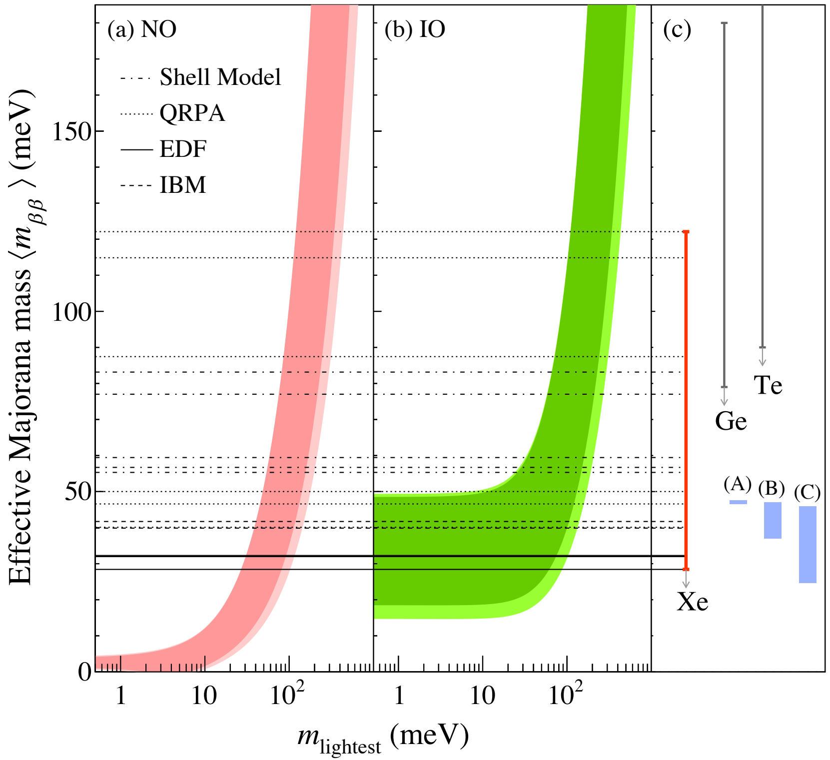
	Dataset	Exposure	$T_{1/2}$ (90% C.L.)
KamLAND-Zen 400	Phase I	85.9 kg yr	1.9×10^{25} yr
	+ Phase II	504 kg yr	1.07×10^{26} yr
KamLAND-Zen 800	First dataset	970 kg yr	2.3×10^{26} yr
	Complete dataset	2097 kg yr	3.8×10^{26} yr

Majorana neutrino mass prediction

Dark shaded regions: predictions based on best-fit values of neutrino oscillation parameters
Light shaded regions: 3σ ranges from oscillation parameter uncertainties.

NME calculations:
Shell model → dot-dashed lines
QRPA→ dotted lines
EDF theory → solid lines
IBM → dashed lines

Three theoretical predictions in IO regio: A, B, C



KamLAND-Zen $0\nu\beta\beta$ confidence limits

Frequentist confidence limit (Wilks'):

$$T_{1/2}^{0\nu\beta\beta} > 3.4 \times 10^{26}\text{yr (90 \% C.L.)}$$

Frequentist Feldman-Cousins calculation result:

$$T_{1/2}^{0\nu\beta\beta} > 4.3 \times 10^{26}\text{yr (90 \% C.L.)}$$

Combined KLZ 400 + 800 Analysis (Wilks')

$$T_{1/2}^{0\nu\beta\beta} > 3.8 \times 10^{26}\text{yr (90 \% C.L.)}$$

Bayesian result:

$$T_{1/2}^{0\nu\beta\beta} > 3.4 \times 10^{26}\text{yr (90 \% C.I.)}$$

Experimental design criteria for $0\nu\beta\beta$

Direct searches: kinematic parameters of the two electrons

➔ Total energy and individual electron paths

$$T^{0\nu}_{1/2} = \ln 2 \frac{N_A}{W} \left(\frac{a \cdot \epsilon \cdot M}{N_{\text{obs}}} \right) t \quad \propto \begin{cases} a\epsilon \cdot Mt \\ a\epsilon \sqrt{\dfrac{Mt}{N_{\text{bkg}} \cdot \Delta E}} \end{cases}$$

Detector and isotope choice depending on:

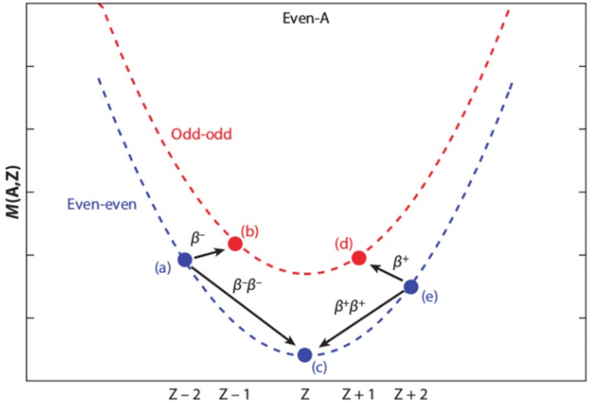
- High isotopic abundance — a
- Deployment in large quantity — M
- High-resolution detector — ΔE
- Low-background conditions — N_{bkg}

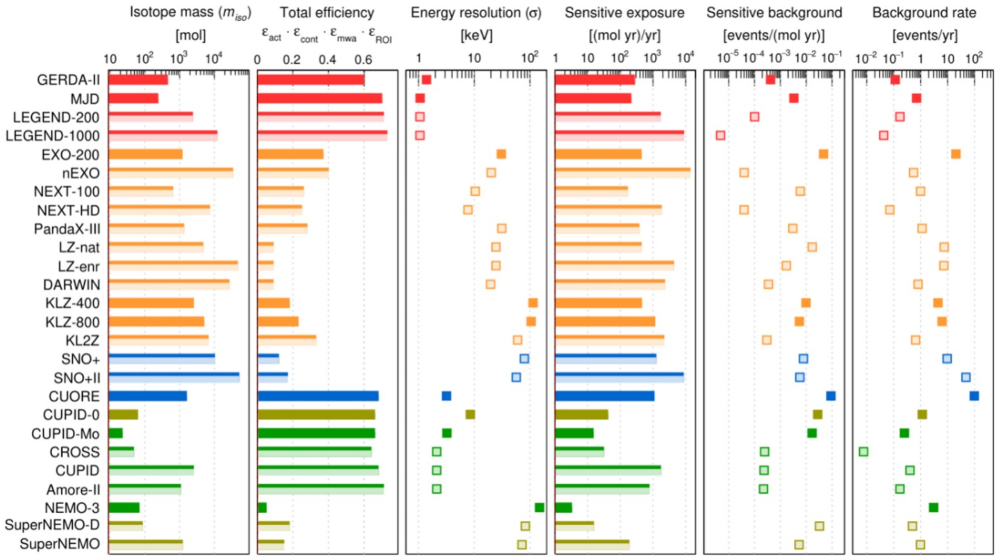
Different isotope choices for detecting $0\nu\beta\beta$

Isotope	$G^{0\nu}$ (10^{-14} y^{-1})	$Q_{\beta\beta}$ (keV)	Nat. ab. (%)
^{48}Ca	6.35	4273.7	0.187
^{76}Ge	0.623	2039.1	7.8
^{82}Se	2.70	2995.5	9.2
^{96}Zr	5.63	3347.7	2.8
^{100}Mo	4.36	3035.0	9.6
^{110}Pd	1.40	2004.0	11.8
^{116}Cd	4.62	2809.1	7.6
^{124}Sn	2.55	2287.7	5.6
^{130}Te	4.09	2530.3	34.5
^{136}Xe	4.31	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

Isotope	Abundance (%)	$Q_{\beta\beta}$ (MeV)	$G^{2\nu}$ (10^{-18} year^{-1})
^{48}Ca	0.187	4.263	15.6
^{76}Ge	7.8	2.039	0.0482
^{82}Se	9.2	2.998	1.60
^{96}Zr	2.8	3.348	7.83
^{100}Mo	9.6	3.035	4.13
^{116}Cd	7.6	2.813	3.18
^{130}Te	34.08	2.527	1.53
^{136}Xe	8.9	2.459	1.43
^{150}Nd	5.6	3.371	36.4

^{76}Ge
^{136}Xe
^{130}Te
^{100}Mo
^{82}Se





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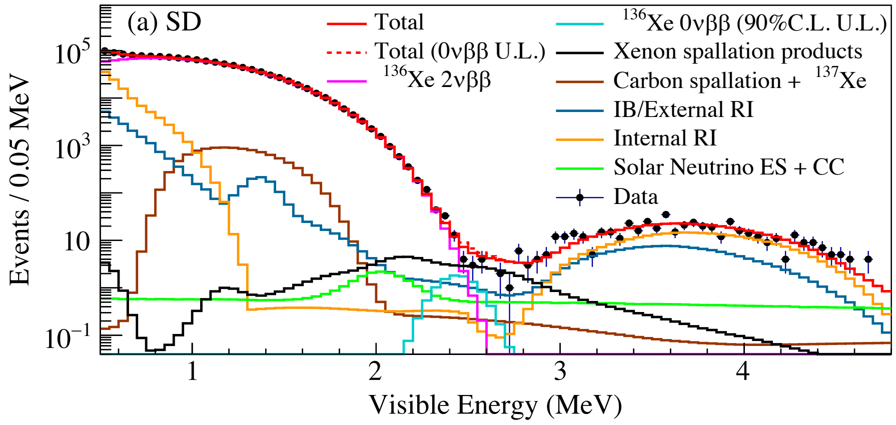
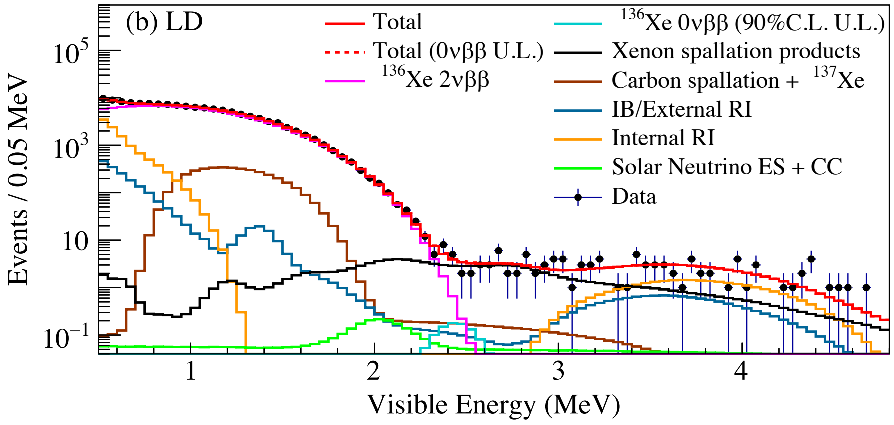
KamLAND-Zen Singles- and LL-spectrum

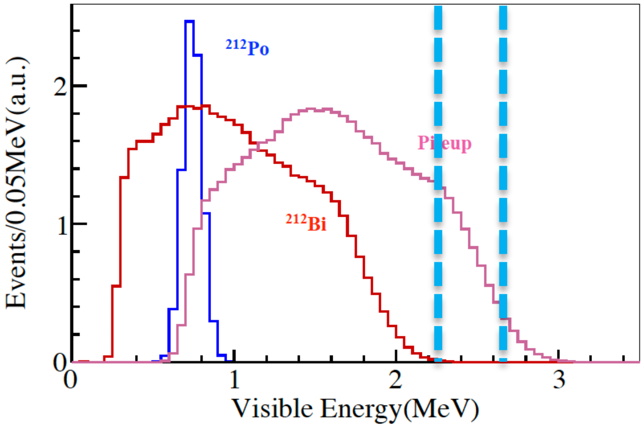
Singles data: $0\boldsymbol{\nu\beta\beta}$ candidates

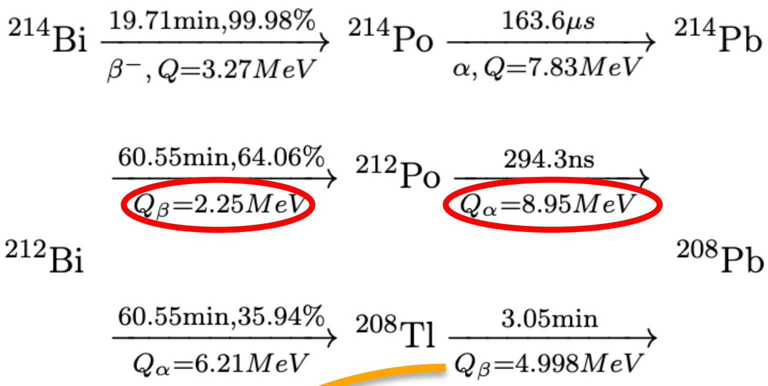


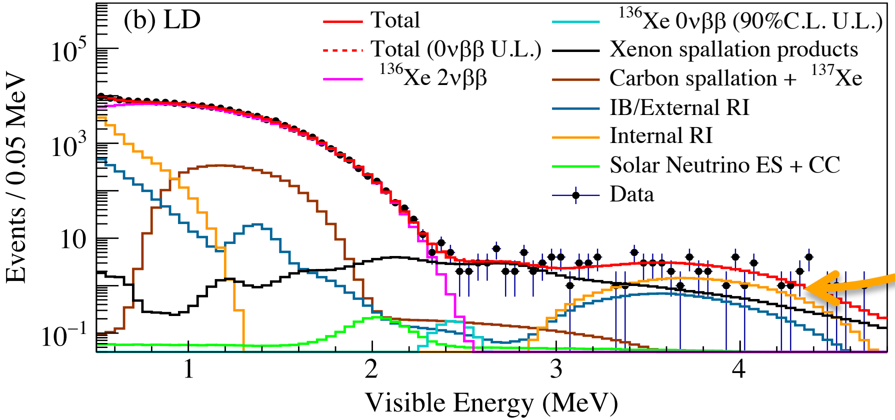
Long-lived data: LL-candidates | 10% of SD

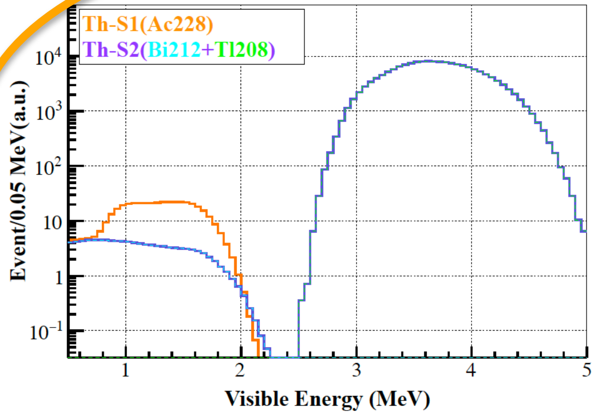


Radioactive background: ^{232}Th decay series



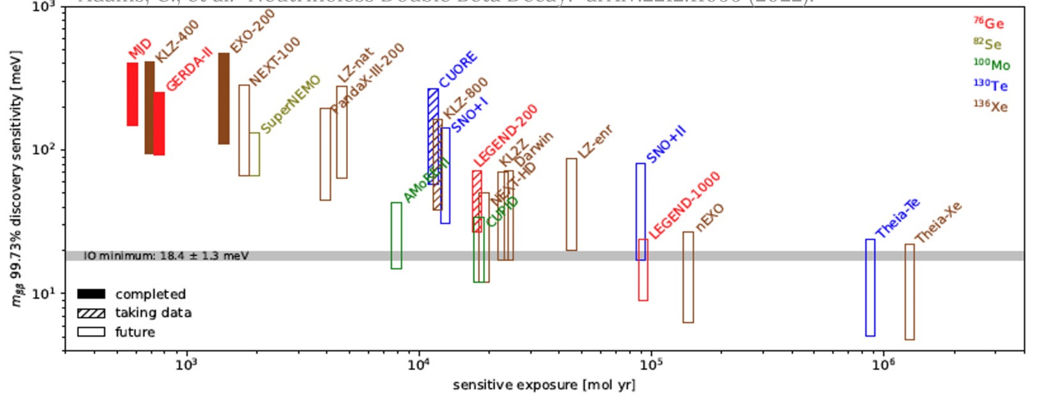




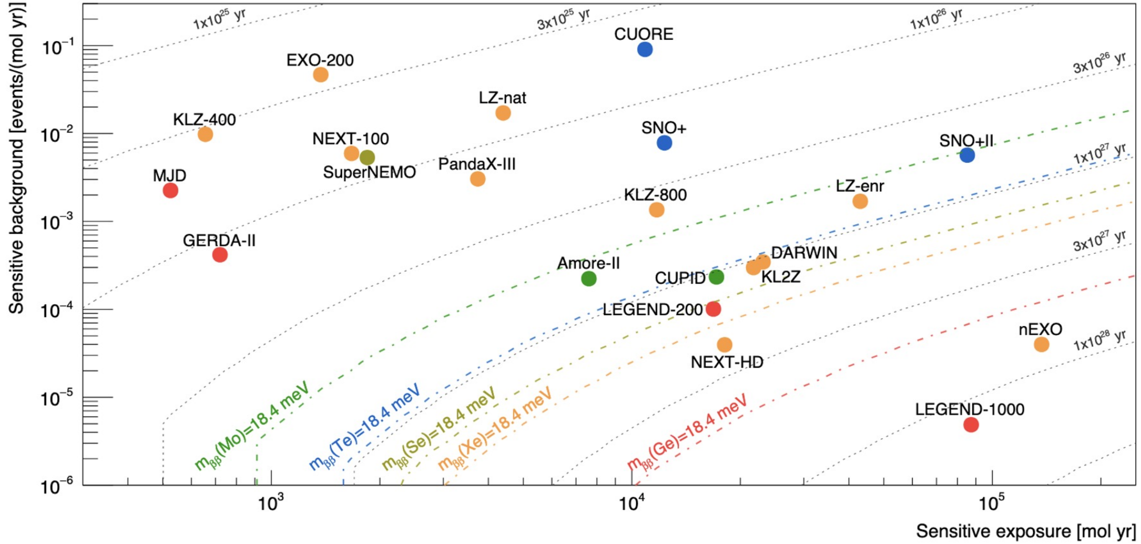


$0\nu\beta\beta$ detector limits

Adams, C., et al. "Neutrinoless Double Beta Decay." arXiv:2212.11099 (2022).



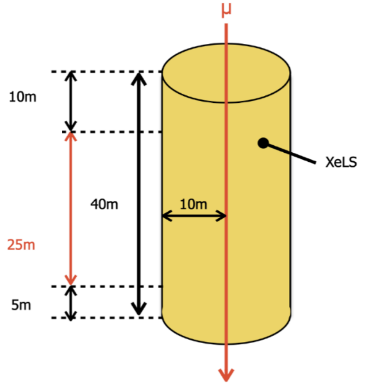
Agostini, Matteo, et al. Rev. Mod. Phys. 95, 025002 (2023)



^{76}Ge
^{136}Xe
^{130}Te
^{100}Mo
^{82}Se

Xenon spallation FLUKA simulations

FLUKA simulation geometry setup
→ 9yr detector livetime



FLUKA simulated muon spallation isotopes in KamLAND-Zen Xe-LS

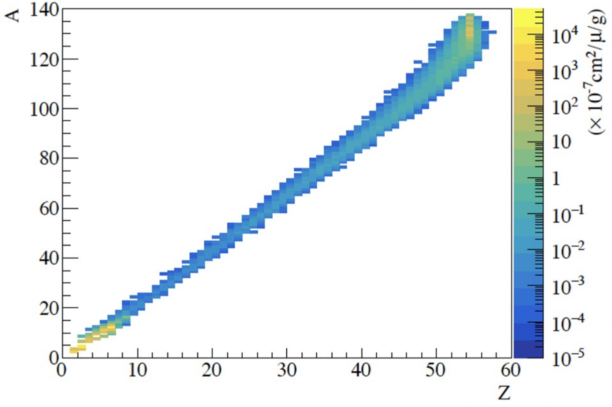


TABLE IX. Simulated production rate of dominant isotopes in $2.35 \leq E \leq 2.70$ MeV in Xe-LS.

	$\tau_{1/2}$ (s)	Q (MeV)	$(\text{kton day})^{-1}$ ROI	Total
^{88}Y	9.212×10^6	3.62 (EC/$\beta^+\gamma$)	0.110	0.136
^{90m1}Zr	8.092×10^{-1}	2.31 (IT)	0.012	0.093
^{90}Nb	5.256×10^4	6.11 (EC/$\beta^+\gamma$)	0.024	0.095
^{96}Tc	3.698×10^5	2.97 (EC/$\beta^+\gamma$)	0.012	0.059
^{98}Rh	5.232×10^2	5.06 (EC/$\beta^+\gamma$)	0.011	0.076
^{100}Rh	7.488×10^4	3.63 (EC/$\beta^+\gamma$)	0.088	0.234
^{104}Ag	4.152×10^3	4.28 (EC/$\beta^+\gamma$)	0.012	0.160
^{104m1}Ag	2.010×10^3	4.28 (EC/$\beta^+\gamma$)	0.018	0.111
^{107}In	1.944×10^3	3.43 (EC/$\beta^+\gamma$)	0.019	0.135
^{108}In	3.480×10^3	5.16 (EC/$\beta^+\gamma$)	0.089	0.194
^{110}In	1.771×10^4	3.89 (EC/$\beta^+\gamma$)	0.053	0.236
^{110m1}In	4.146×10^3	3.89 (EC/$\beta^+\gamma$)	0.066	0.351
^{109}Sn	1.080×10^3	3.85 (EC/$\beta^+\gamma$)	0.027	0.122
^{113}Sb	4.002×10^2	3.92 (EC/$\beta^+\gamma$)	0.036	0.231
^{114}Sb	2.094×10^2	5.88 (EC/$\beta^+\gamma$)	0.020	0.297
^{115}Sb	1.926×10^3	3.03 (EC/$\beta^+\gamma$)	0.031	0.839
^{116}Sb	9.480×10^2	4.71 (EC/$\beta^+\gamma$)	0.071	0.939
^{118}Sb	2.160×10^2	3.66 (EC/$\beta^+\gamma$)	0.165	1.288
^{124}Sb	5.201×10^6	2.90 (EC/$\beta^-\gamma$)	0.016	0.054
^{115}Te	3.480×10^2	4.64 (EC/$\beta^+\gamma$)	0.012	0.124
^{117}Te	3.720×10^3	3.54 (EC/$\beta^+\gamma$)	0.052	0.594
^{119}I	1.146×10^3	3.51 (EC/$\beta^+\gamma$)	0.053	0.533
^{120}I	4.896×10^3	5.62 (EC/$\beta^+\gamma$)	0.091	0.953
^{122}I	2.178×10^2	4.23 (EC/$\beta^+\gamma$)	0.289	1.965
^{124}I	3.608×10^5	3.16 (EC/$\beta^+\gamma$)	0.190	1.654
^{130}I	4.450×10^4	2.95 ($\beta^-\gamma$)	0.195	1.188
^{132}I	8.262×10^3	3.58 ($\beta^-\gamma$)	0.148	0.427
^{134}I	3.150×10^3	4.18 ($\beta^-\gamma$)	0.043	0.183
^{121}Xe	2.406×10^3	3.75 (EC/$\beta^+\gamma$)	0.100	0.540
^{125}Cs	2.802×10^3	3.09 (EC/$\beta^+\gamma$)	0.012	0.266
^{126}Cs	9.840×10^1	4.82 (EC/$\beta^+\gamma$)	0.011	0.080
^{128}Cs	2.196×10^2	3.93 (EC/$\beta^+\gamma$)	0.031	0.229