Latest results and prospects on neutrinoless double beta decay from KamLAND-Zen

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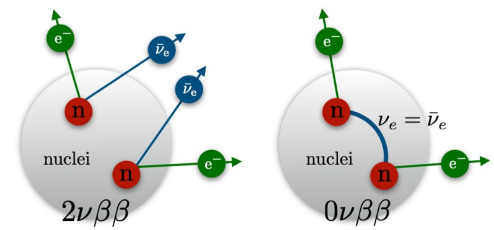
Neutrino Physics Conference in Vietnam 2025
July 23, 2025

Neutrinoless double beta decays ($0\nu\beta\beta$)

Neutrino can be **Majorana Neutrino ($\nu = \bar{\nu}$)**

- Majorana neutrino is key of
  - ✓ Tiny neutrino mass (via Seesaw mechanism)
  - ✓ Matter dominant universe (via Leptogenesis)



Allowed in S.M. **Observed**

Forbidden in S.M. **NOT observed**

Neutrinoless double beta decay mode ($0\nu\beta\beta$)

- Allowed only when the neutrino is the Majorana particle:

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

We measure the half-life of $0\nu\beta\beta$

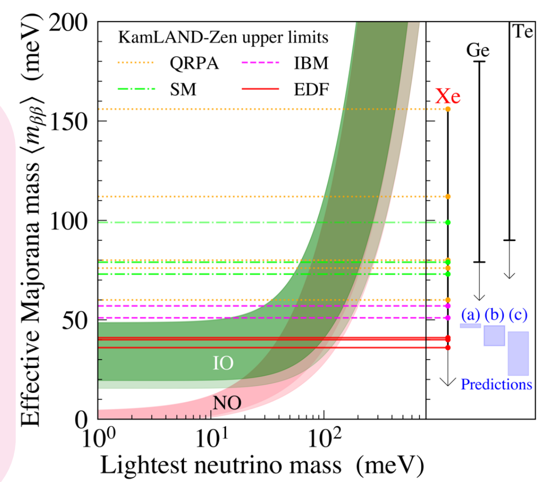
(^{48}Ca, ^{230}Te, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{136}Xe etc. are candidates)

Phase space factor / Nuclear matrix element

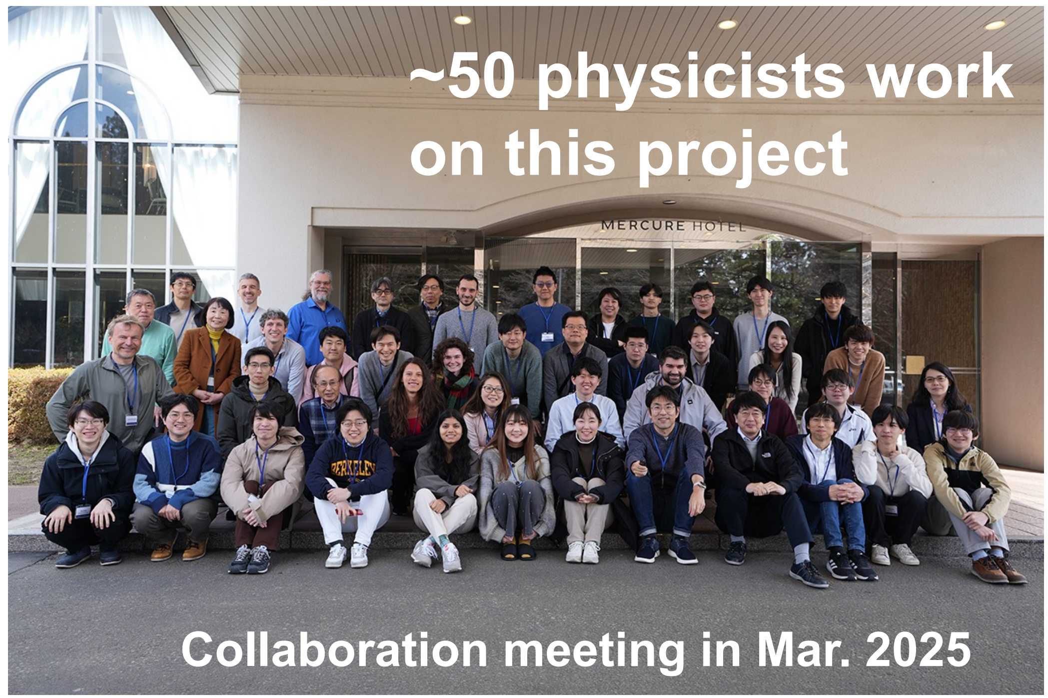
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

The half-life of $0\nu\beta\beta$ (measurement)

Effective Majorana mass



KamLAND/KamLAND-Zen Collaboration

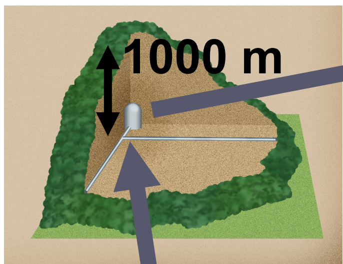


KamLAND-Zen

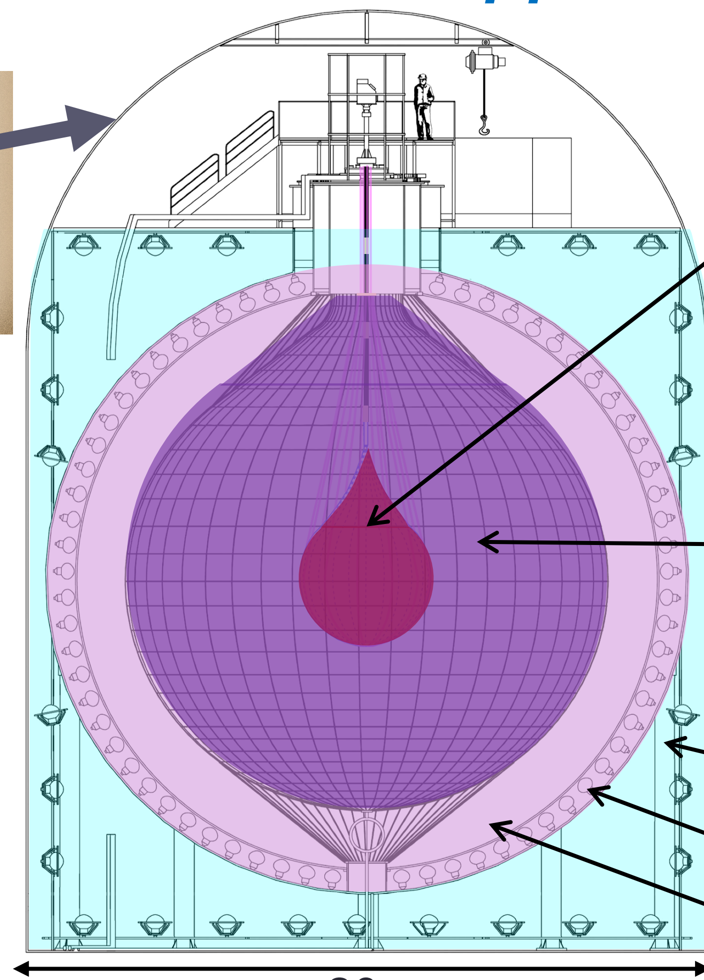
Zero Neutrino Double Beta

$0\nu\beta\beta$ of ^{136}Xe search experiment

Cosmic-muon rate
~ 0.34Hz



Kamioka, Gifu, Japan



20 m

Xe loaded LS (XeLS)

- Enrichment ~90%
- Dissolved into LS 3%wt
- Xe is installed only within ultra-clean inner-balloon (IB)

1kton purified LS (KamLS)

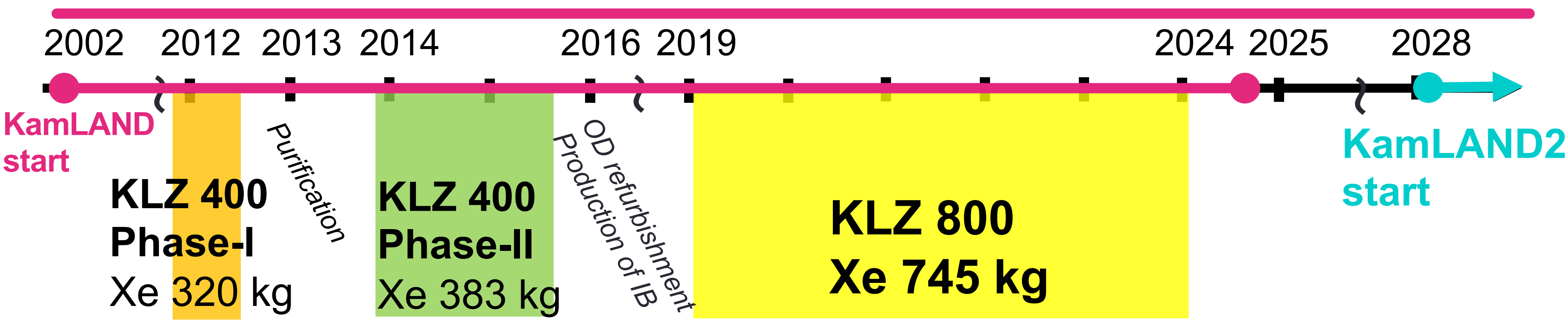
- ^{238}U~5.0x10^{-18} g/g
- ^{232}Th~1.8x10^{-17} g/g

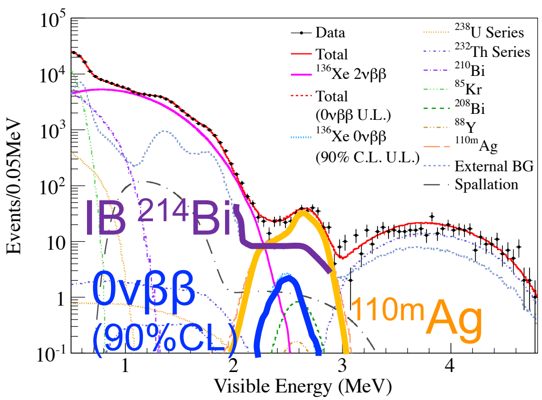
3.2kton purified water

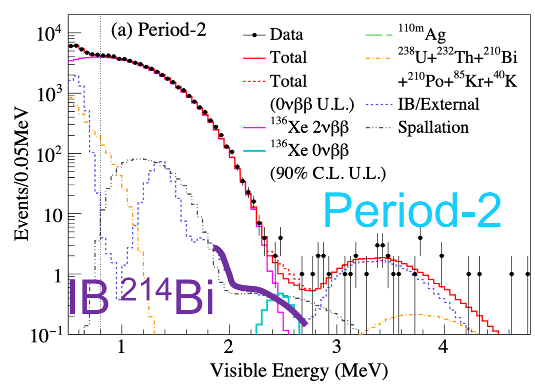
1879 PMTs

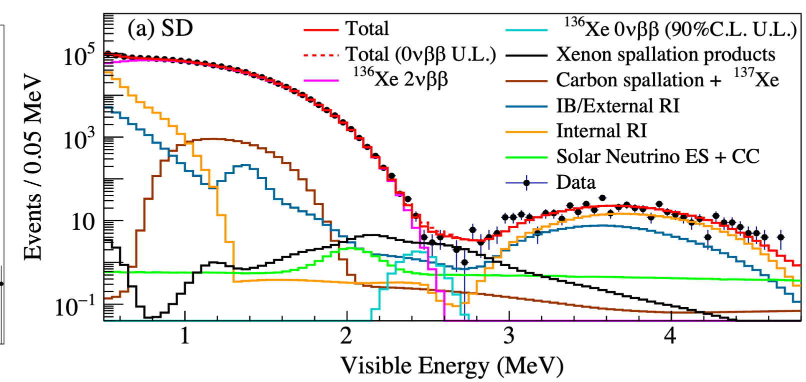
Buffer Oil

History of KamLAND-Zen









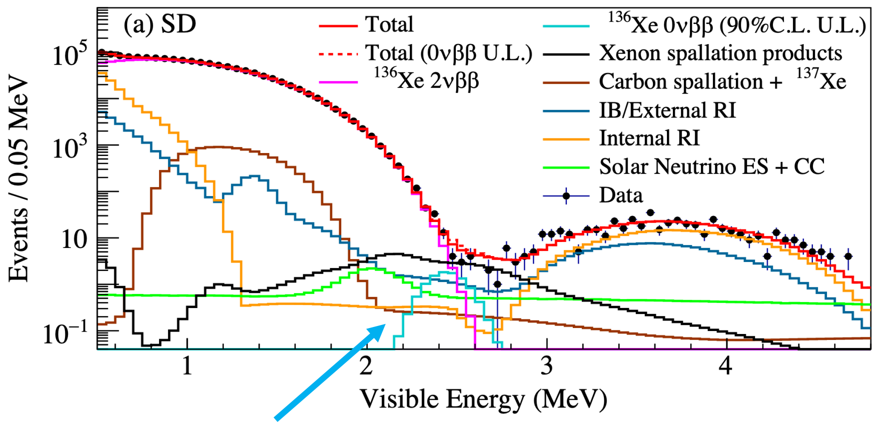
✓ Reduced ^{110m}Ag by purification

✓ Successfully produced a low-BG IB (~1/10)

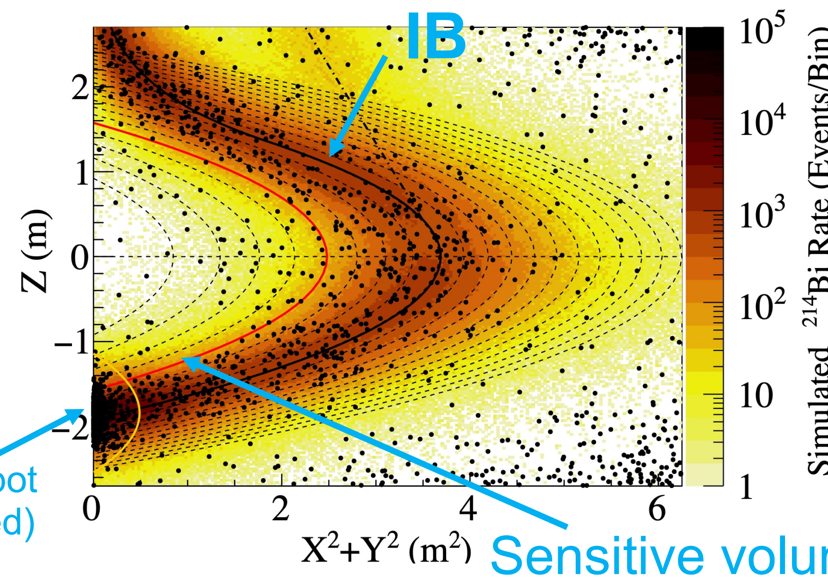
✓ Double Xe

- KamLAND-Zen 800 completed DAQ on Jan.11, 2024.
- We started detector upgrades in 2024 and plan to launch KamLAND2 in 2028!!

Dominant Backgrounds for $0\nu\beta\beta$ search



$0\nu\beta\beta$ (90% C.L.)
(Q-value 2.458 MeV)



Hot spot (vetoed)

Sensitive volume (R < 1.57 m)

Double-beta decay of ^{136}Xe

- Inevitable BG source below 2.46 MeV

Radioactive impurities on the IB

- The delayed coincidence, ^{214}Bi(β)→^{214}Po(α), does not effectively work on the film due to the quenching of α decays.

Cosmic-ray muon spallation products

- Short-life time: Carbon spallation products + ^{137}Xe
- Long-life time: Xenon spallation products → **LL-veto**

Inner ballon production

The nylon balloon was produced in class 1 clean room

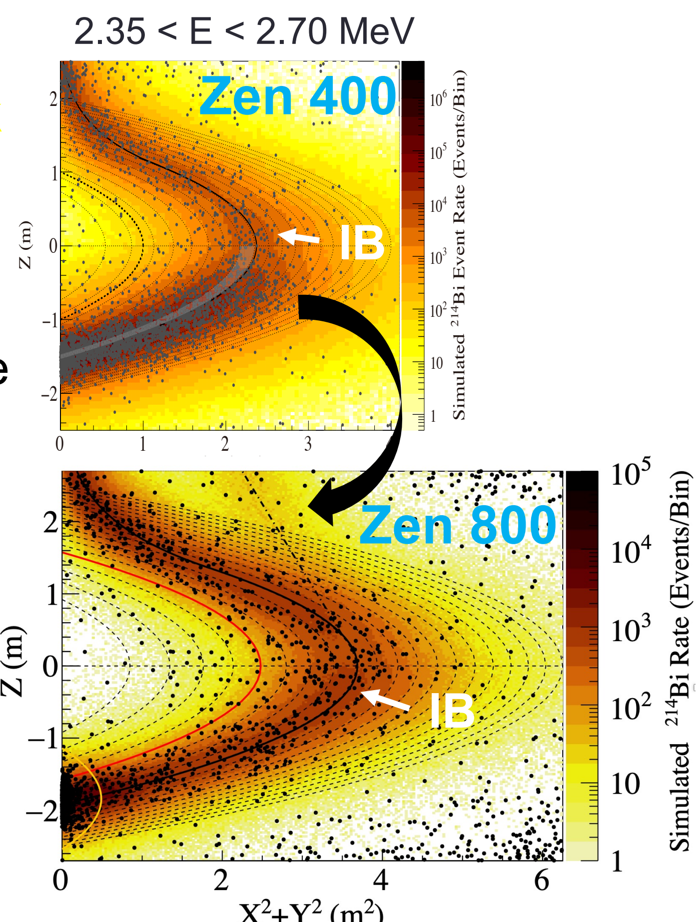
- All items in the room are thoroughly cleaned with ethanol and pure water.
- Personnel wear full-body suits, goggles, and double gloves.
- The suits are sent to laundry after just one use.

Zen 400 (R 1.54 m)
^{238}U~5.0x10^{-11} g/g
^{232}Th~1.8x10^{-10} g/g

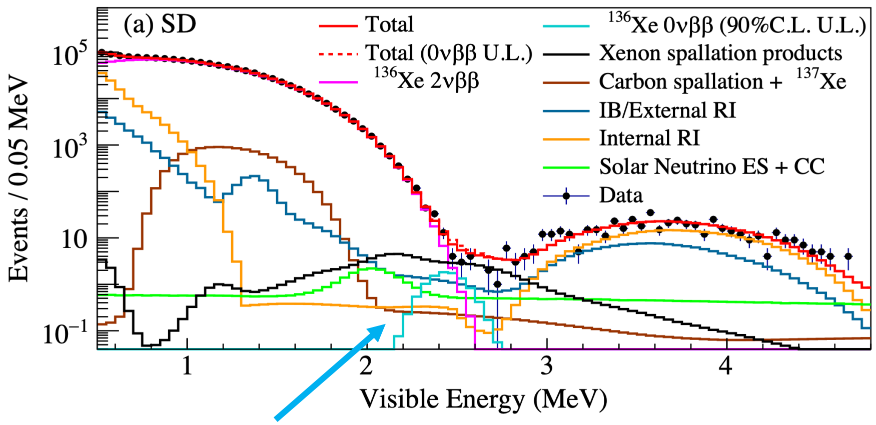
Zen 800 (R 1.90- m)
^{238}U~4x10^{-12} g/g
^{232}Th~2x10^{-11} g/g

✓ x10 reduction of IB ^{214}Bi
✓ x3 sensitive volume!!

JINST 16 P08023(2021)



Dominant Backgrounds for $0\nu\beta\beta$ search



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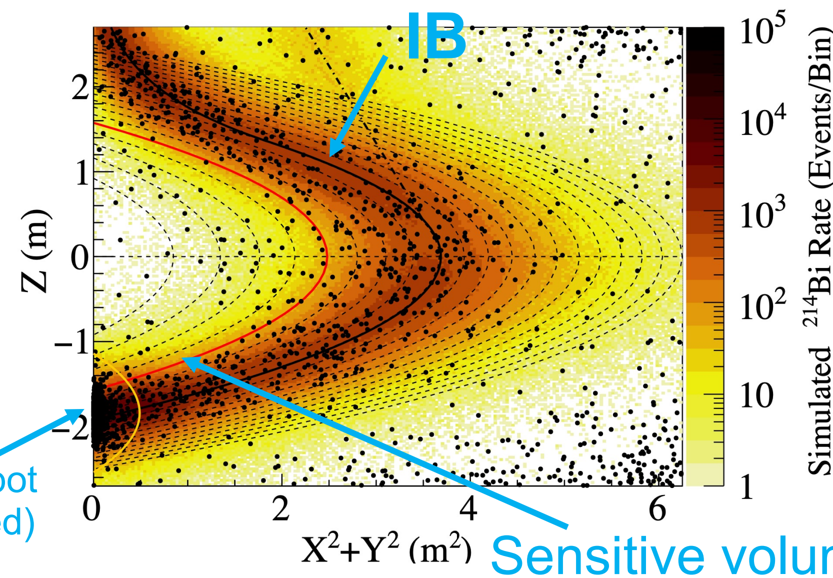

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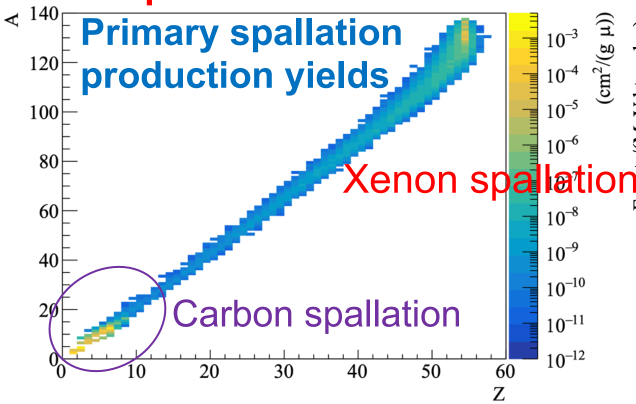
Cosmic-ray muon spallation products

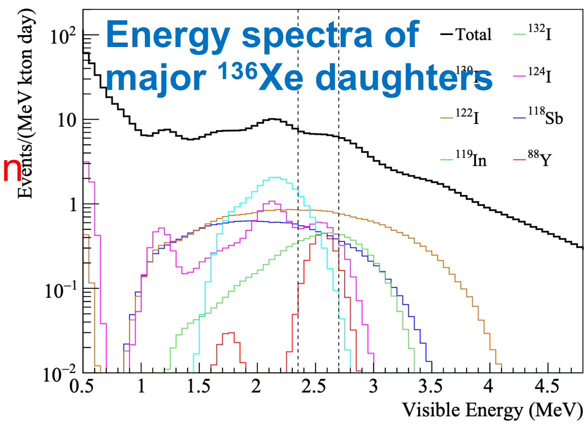
- Short-life time: Carbon spallation products + ^{137}Xe
- Long-life time: Xenon spallation products → **LL-veto**

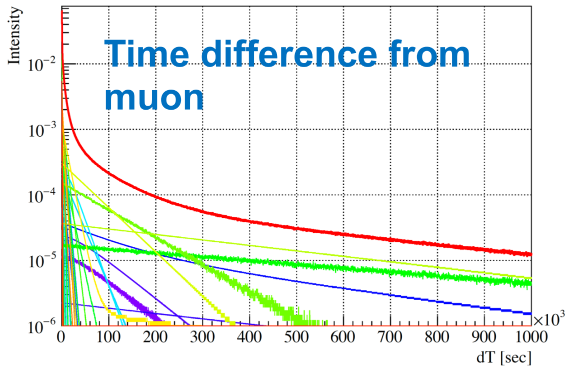
Xenon spallation veto method : LL-veto

- Long-life time: a few hours ~ a few days
- Expected rate in ROI : 30.0 event /Xe-ton/yr

The most dominant BG for $0\nu\beta\beta$ search

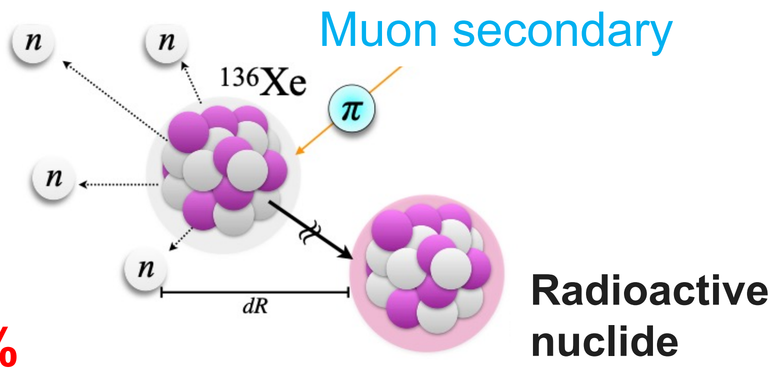






Reject with a likelihood method (LL-veto)

- Parameters:
  - ① time difference from muon
  - ② distance between Xe-spallation and neutron capture gamma
  - ③ effective number of neutron
- **Rejection efficiency : 47.1 +/- 8.7 %**



Energy spectrum after BG cut

Events with KamLAND-Zen 800
(R<2.50 m, muon itself and 2msec veto)

Within sensitive volume (R<1.57m)

Cut ^{214}Bi from IB film

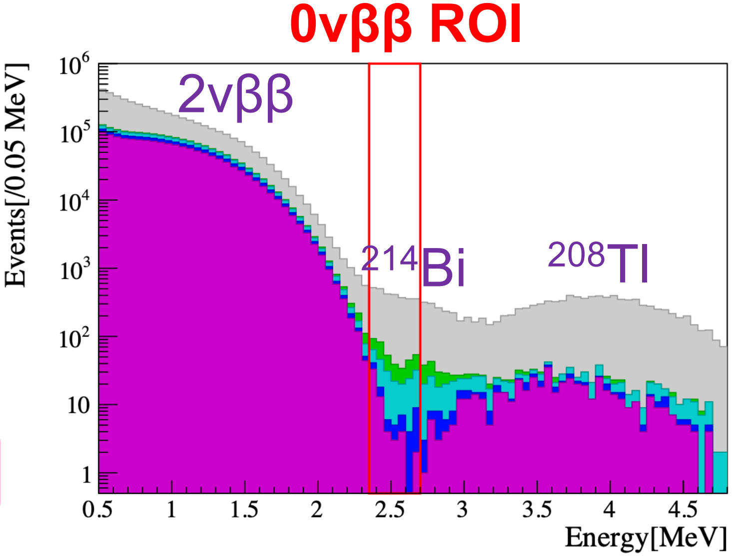
Delayed coincidence cut

Cut ^{212}Bi-Po, ^{214}Bi-Po and anti-neutrino events

Short-lived spallation cut

Cut ^{10}C, ^{6}He, ^{12}B etc.

Long-lived spallation cut



Two datasets are fitted simultaneously

untagged

tagged

$0\nu\beta\beta$ candidate (Livetime: 1131 days)

Xenon spallation candidate (Livetime: 111 days)

^{136}Xe $0\nu\beta\beta$ decay Half-life limit

aiXiv: 2406.11438

Singles data (SD)

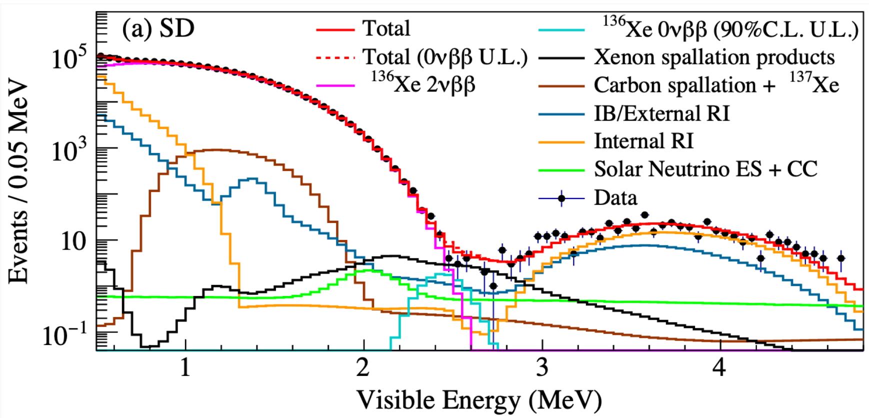
(sensitive to $0\nu\beta\beta$ signal)

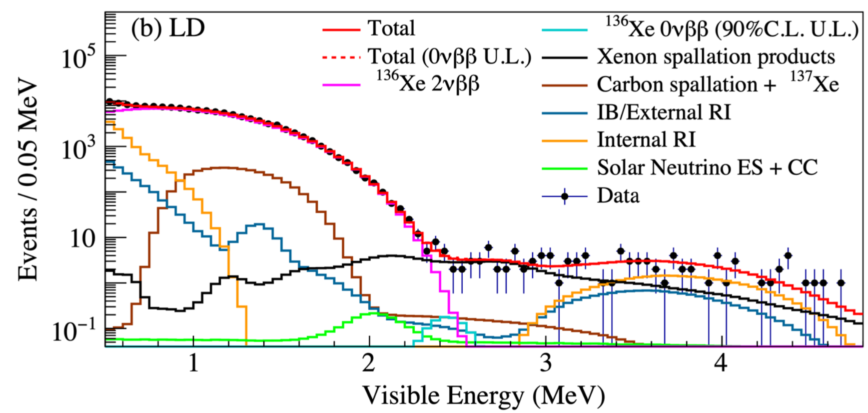
1131 days livetime, R < 1.57 m

Long-lived product data (LD)

(Long-lived BG constraint)

111 days livetime, R < 1.57 m





$0\nu\beta\beta$ best fit : **0 event**

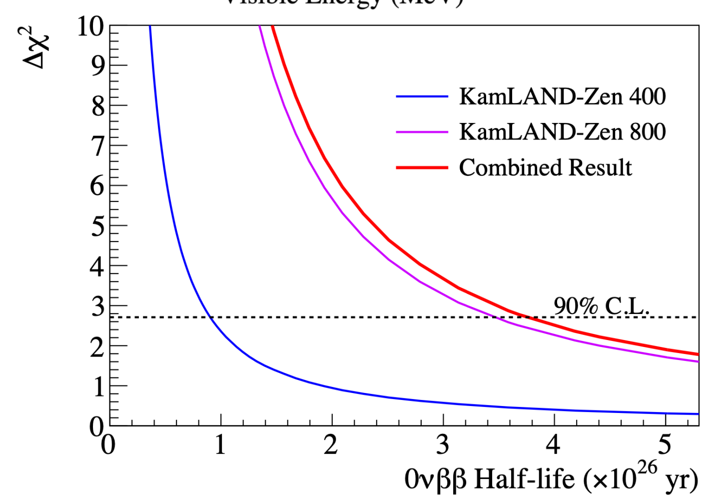
U.L. : **< 10.0 event** at 90% C.L.

Half-life limit at 90% C.L.

KLZ 400 $T^{0\nu}{}_{1/2} > 0.9 \times 10^{26}$ yr

KLZ 800 $T^{0\nu}{}_{1/2} > 3.4 \times 10^{26}$ yr

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



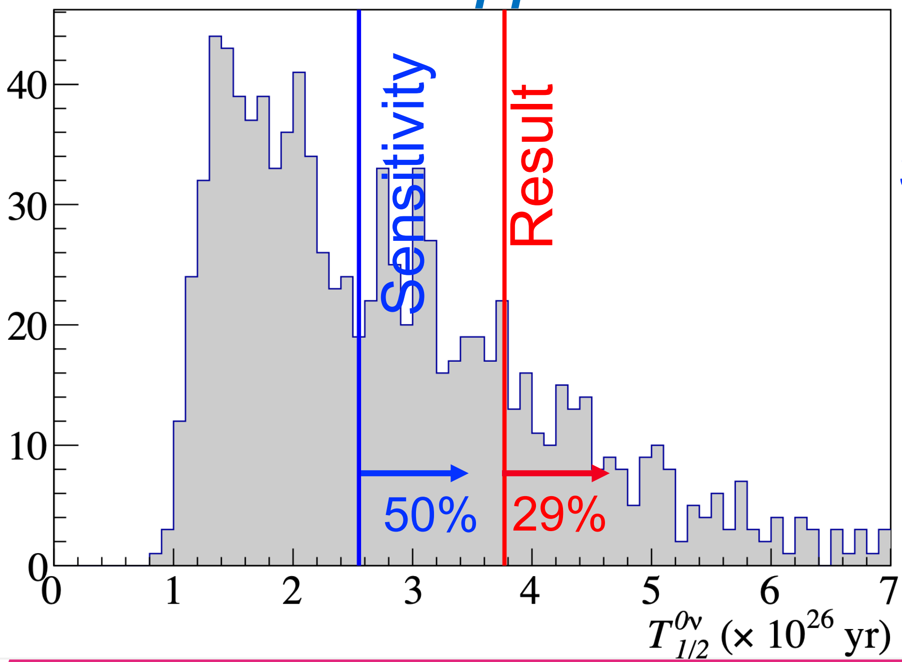
Upper Limits from Toy MC

aiXiv: 2406.11438

Sensitivity is checked by MC assuming best-fit BG rate

1. Generated 1500 ToyMC datasets assuming a Poisson distribution based on the best-fit model.
2. Calculated the 90% C.L. limit for each of the 1500 MC datasets.
3. Defined the median of the 1500 trials as the experimental sensitivity (Median Sensitivity).

Distribution of $0\nu\beta\beta$ limits at 90% C.L. from Toy MC



Sensitivity: $T^{0\nu}{}_{1/2} > 2.6 \times 10^{26}$ yr

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

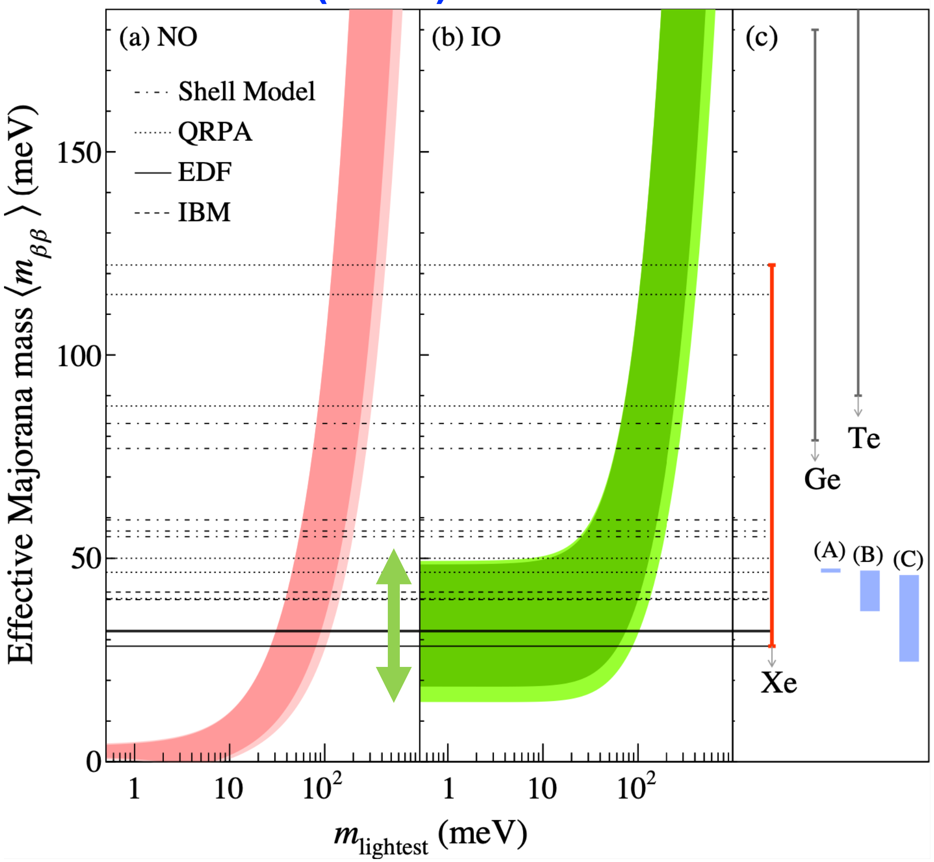
Limit on the effective Majorana mass

aiXiv: 2406.11438

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

nuclear matrix element **(NME)**

NME ($M^{0\nu}$) for ^{136}Xe : 1.11-4.77
(NME calculations assuming g_A ~ 1.27)

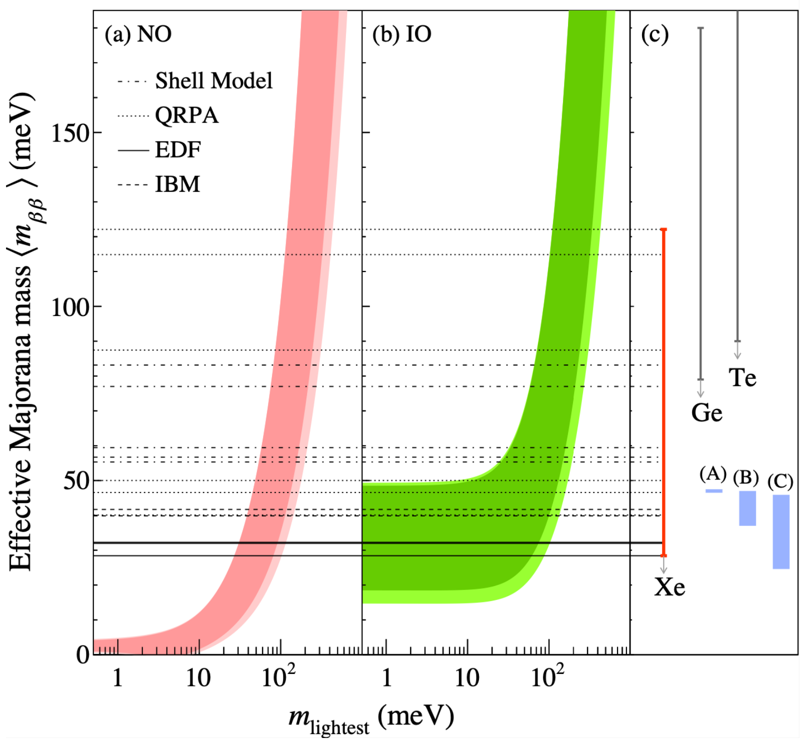


	Ref.	$M^{0\nu}$	$\langle m_{\beta\beta}\rangle$ (meV)
Shell model	[1]	2.28, 2.45	59.4, 55.3
	[2]	1.63, 1.76	83.1, 77.0
	[3, 4]	2.39	56.7
QRPA	[5]	1.55	87.4
	[6]	2.91	46.6
	[7]	2.71	50.0
	[8]	1.11, 1.18	122, 115
	[9]	3.38	40.1
EDF theory	[10]	4.20	32.3
	[11]	4.77	28.4
	[12]	4.24	32.0
IBM	[13]	3.25	41.7
	[14]	3.40	39.9

Reached the IO horizontal band (< 50 meV) with half of the NMEs!

Limit on the effective Majorana mass

aiXiv: 2406.11438



NME ($M^{0\nu}$) for ^{136}Xe : 1.11-4.77
(NME calculations assuming g_A ~ 1.27)

Shell model

[1] J. Menéndez, J. of Phys. G **45**, 014003 (2018).
[2] M. Horoi and A. Neacsu, Phys. Rev. C **93**, 024308 (2016).
[3] L. Coraggio, A. Gargano, N. Itaco, R. Mancino, and F. Nowacki, Phys. Rev. C **101**, 044315 (2020).
[4] L. Coraggio *et al.*, Phys. Rev. C **105**, 034312 (2022).

QRPA

[5] M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).
[6] J. Hyvärinen and J. Suhonen, Phys. Rev. C **91**, 024613 (2015).
[7] F. Šimkovic, A. Smetana, and P. Vogel, Phys. Rev. C **98**, 064325 (2018).
[8] D.-L. Fang, A. Faessler, and F. Šimkovic, Phys. Rev. C **97**, 045503 (2018).
[9] J. Terasaki, Phys. Rev. C **102**, 044303 (2020).

EDF

[10] T. R. Rodríguez and G. Martínez-Pinedo, Phys. Rev. Lett. **105**, 252503 (2010).
[11] N. L. Vaquero, T. R. Rodríguez, and J. L. Egido, Phys. Rev. Lett. **111**, 142501 (2013).
[12] L. S. Song, J. M. Yao, P. Ring, and J. Meng, Phys. Rev. C **95**, 024305 (2017).

IBM

[13] J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C **91**, 034304 (2015).
[14] F. F. Deppisch, L. Graf, F. Iachello, and J. Kotila, Phys. Rev. D **102**, 095016 (2020).

Theoretical model

(A) K. Harigaya, M. Ibe, and T. T. Yanagida, Phys. Rev. D **86**, 013002 (2012).
(B) T. Asaka, Y. Heo, and T. Yoshida, Phys. Lett. B **811**, 135956 (2020).
(C) K. Asai, The European Physical Journal C **80**, 76 (2020).

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

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

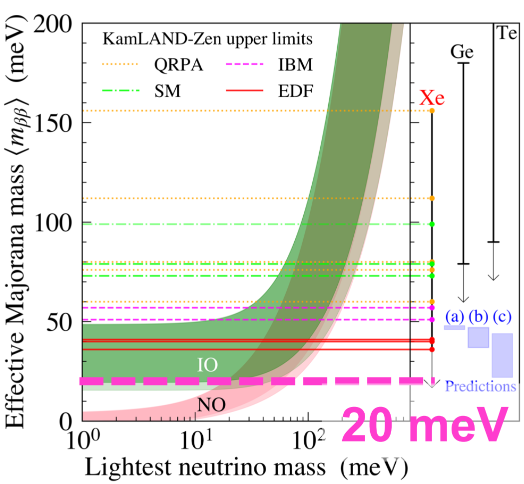
Upper limit of Majorana mass

$\langle m_{\beta\beta}\rangle$ **< 28 – 122 meV**

Most stringent tests of the neutrino mass in the IO region

Next generation of KLZ: **KamLAND2-Zen**

Next-generation detector R&D is now in progress



Film BG

Scintillation balloon film

Enlarge sensitive volume by tagging $^{214}Bi \rightarrow ^{214}Po$ sequential decay on the film

$2\nu\beta\beta$ decay

Enhance detector energy resolution (4%→2% @2.46 MeV)

High QE PMT & Light guide mirror

Improve light collection efficiency and photo coverage

Brighter LS

Higher light yield and transmittance

Xe spallation products

New Dead-time free electronics

Collect all the neutron information from the noisy period after the muon.

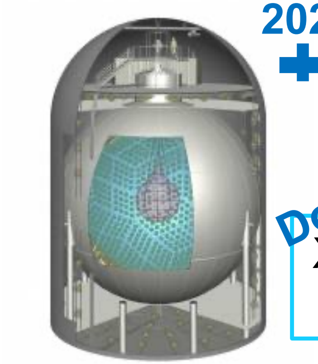
Target $\langle m_{\beta\beta} \rangle \sim 20$ meV (5 yrs)

KamLAND2-Zen aim to cover the Inverted-Ordering band!!

Plan of Detector Upgrades

KamLAND Dismantling — **KamLAND2 construction**

2024 — 2025 — 2028



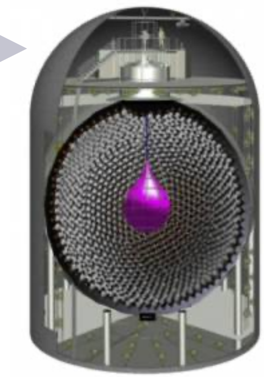
KamLAND &
KamLAND-Zen

- Done: XeLS & IB extraction
- Done: KamLS & BO extraction
- Super clean facility (KERNEL)
- Done: Outer Balloon dismantling
- Ongoing: PMT dismantling

- High QE PMT & Mirror

- Cleaner Outer Balloon
- High light yield LS
- New electronics

- Calibration system



KamLAND2 &
KamLAND2-Zen

- Scintillation Balloon
- XeLS

We started detector upgrades in 2024.

We aim to start KamLAND2 in 2028!!

Summary

- KamLAND-Zen is an experiment that searches for $0\nu\beta\beta$ of ^{136}Xe with xenon loaded liquid scintillator.
  - Half-life limit at 90% C.L. : $T^{0\nu}{}_{1/2} > 3.8 \times 10^{26}$ yr
  - KLZ set limit : $\langle m_{\beta\beta} \rangle < 28 - 122$ meV
  - [aiXiv: 2406.11438](https://arxiv.org/abs/2406.11438)

- KamLAND2-Zen is the next generation detector of KLZ.
  - The target of KL2-Zen is $\langle m_{\beta\beta} \rangle = 20$ meV
  - KamLAND2-Zen aim to cover the Inverted-Ordering band!!

カムランド禅
KamLAND-Zen
Kamioka Liquid Scintillator Anti-Neutrino Detector
Zero neutrino double-beta decay search

https://higgstan.com