Results from KamLAND-Zen

Neutrino 2024

XXXI Conference on Neutrino Physics and Astrophysics

June 18, 2024

Itaru Shimizu (Tohoku Univ.)

KamLAND-Zen Collaboration

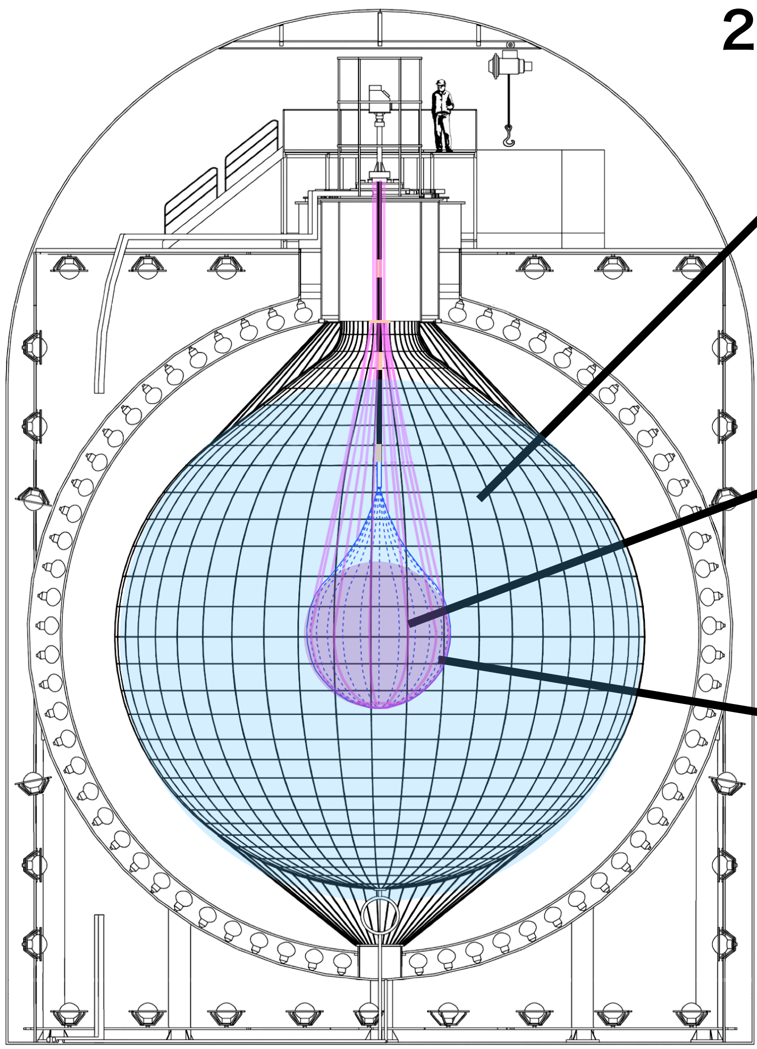
~50 physicists work on this project

Collaboration meeting in September, 2023

KamLAND-Zen

Zero Neutrino Double Beta

Kamioka underground KamLAND detector



2-type of liquid scintillator

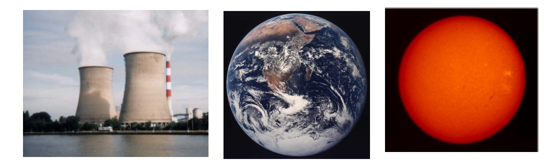
1000-ton pure liquid scintillator

U, Th < 10^{-17} g/g

745 kg Xe-loaded liquid scintillator (91% enrichment)

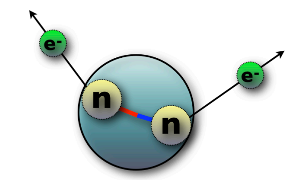
inner balloon (IB)

2002− KamLAND



reactor, geo, solar neutrino observation

2011− KamLAND-Zen



double beta decay measurement ($0\nu\beta\beta$ search)

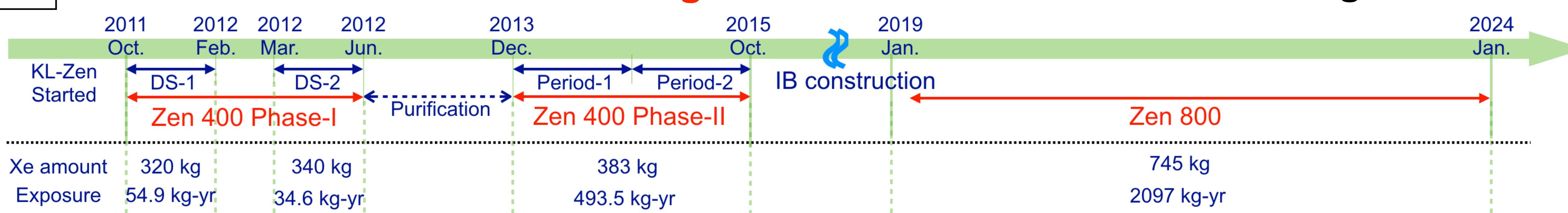
2019− Xe increase, cleaner balloon

big and pure : no background from external gamma-rays

purification of LS, replacement of mini-balloon are possible

→ **high scalability**

Xe **320 kg** **340 kg** **383 kg** **745 kg** **largest ^{136}Xe !!**

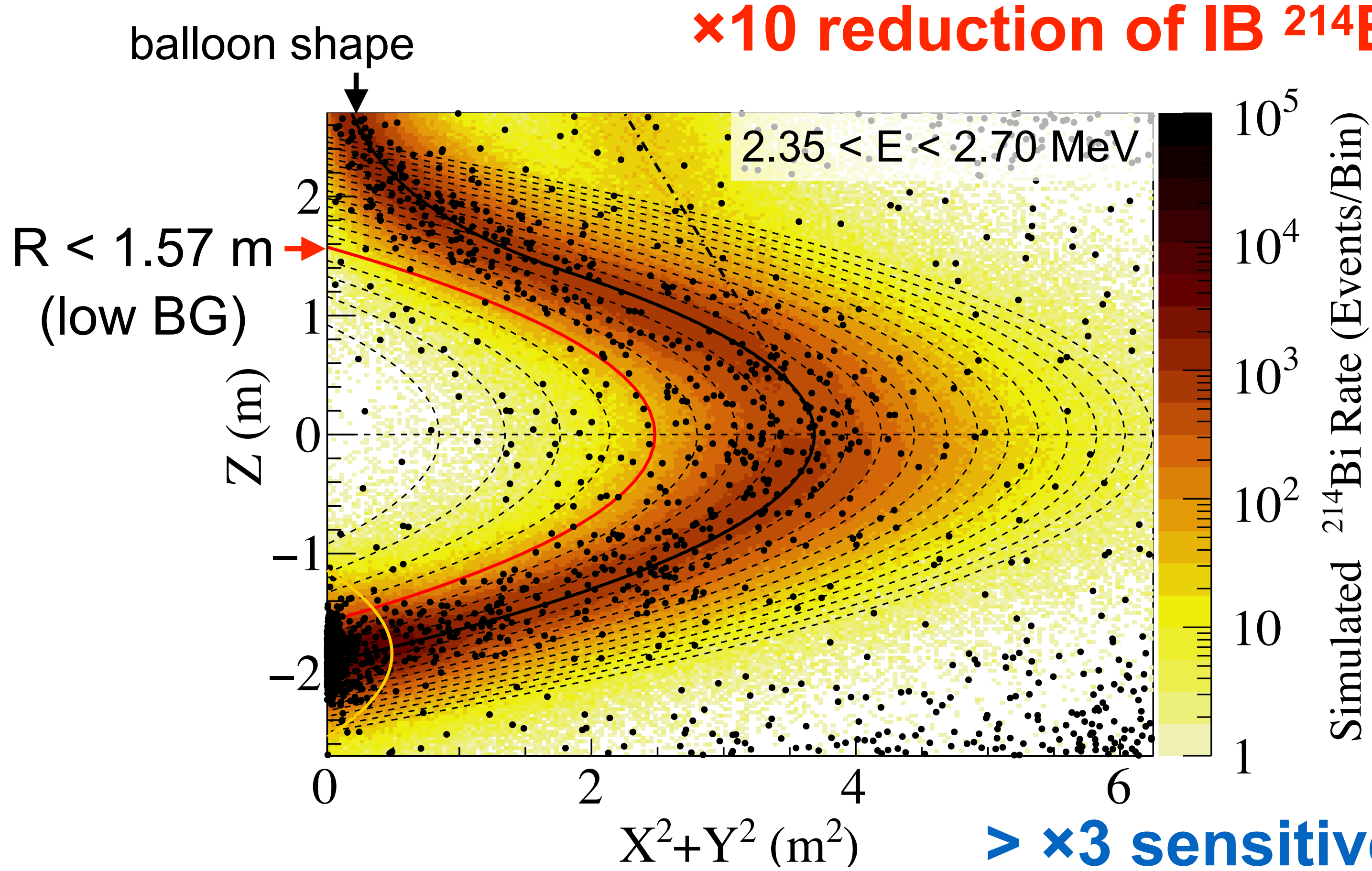


Inner Balloon Production

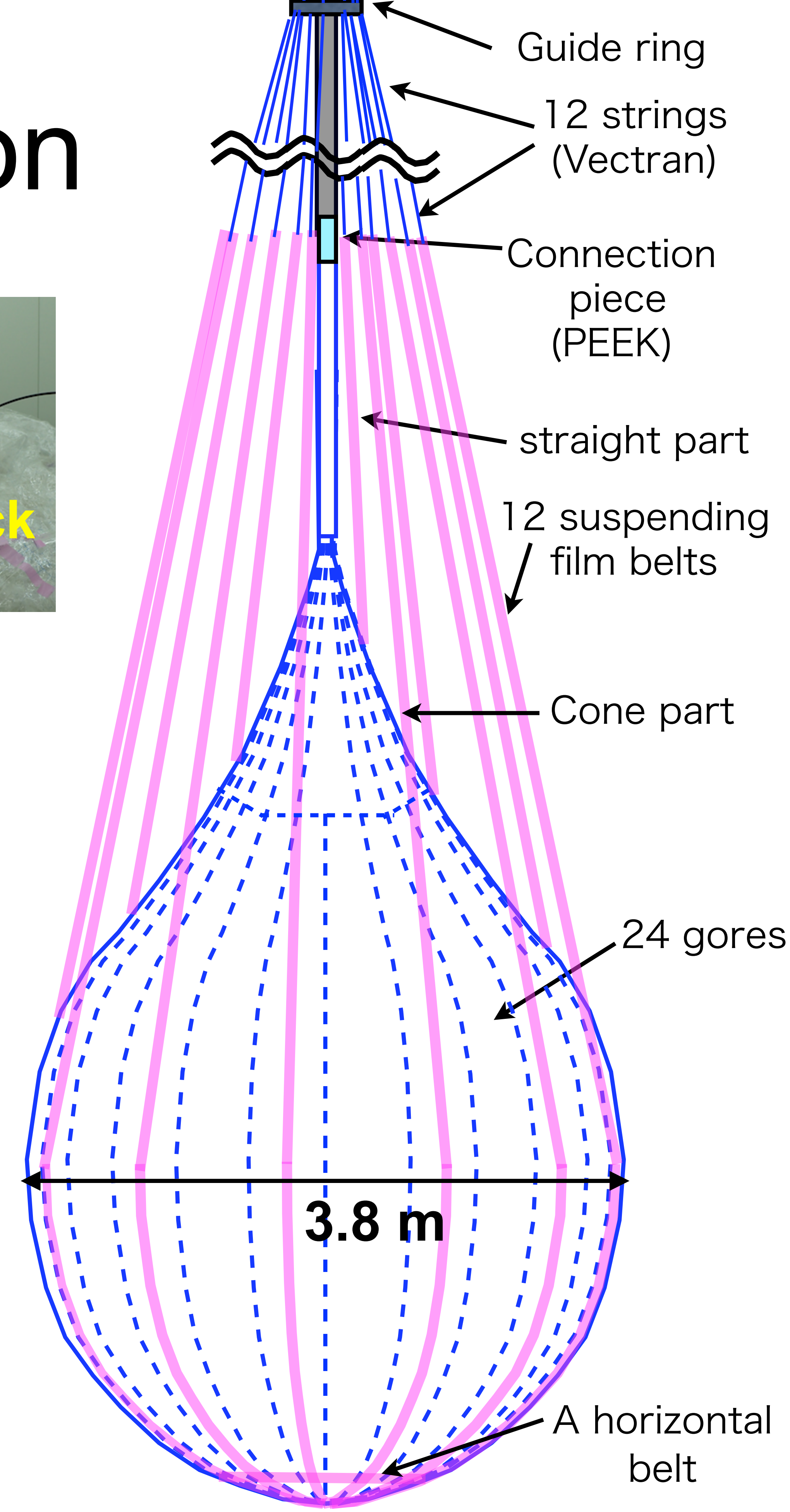
nylon balloon was produced in class 1 clean room

Zen 400 (R 1.54 m)		Zen 800 (R 1.90 m)
^{238}U : 5×10^{-11} g/g	→	^{238}U : ~4×10^{-12} g/g
^{232}Th : 3×10^{-10} g/g		^{232}Th : ~2×10^{-11} g/g

×10 reduction of IB ^{214}Bi



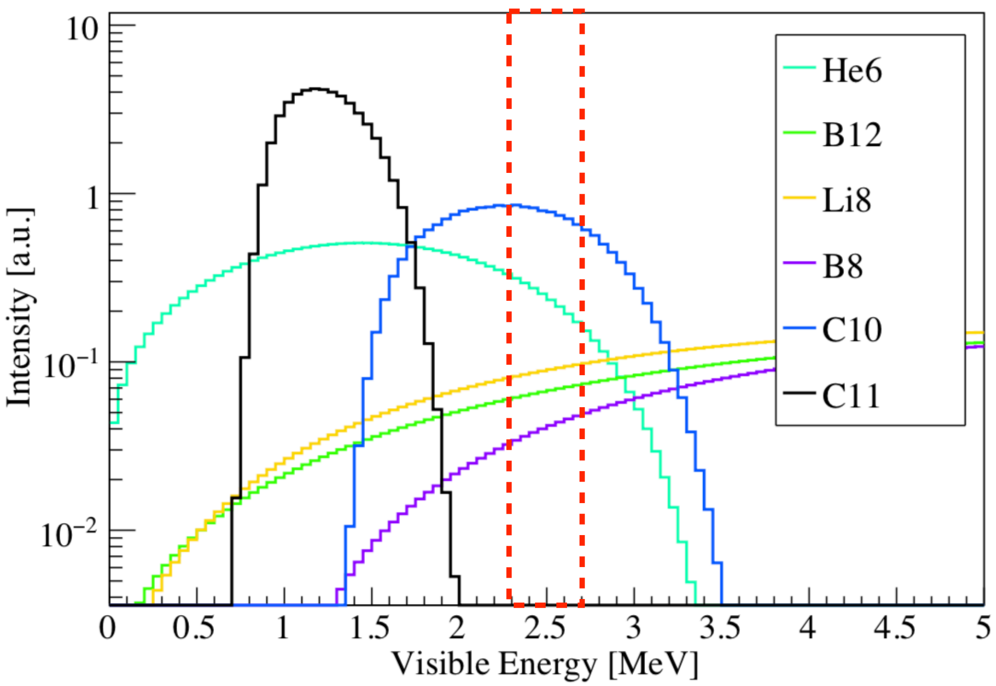
> ×3 sensitive volume !!



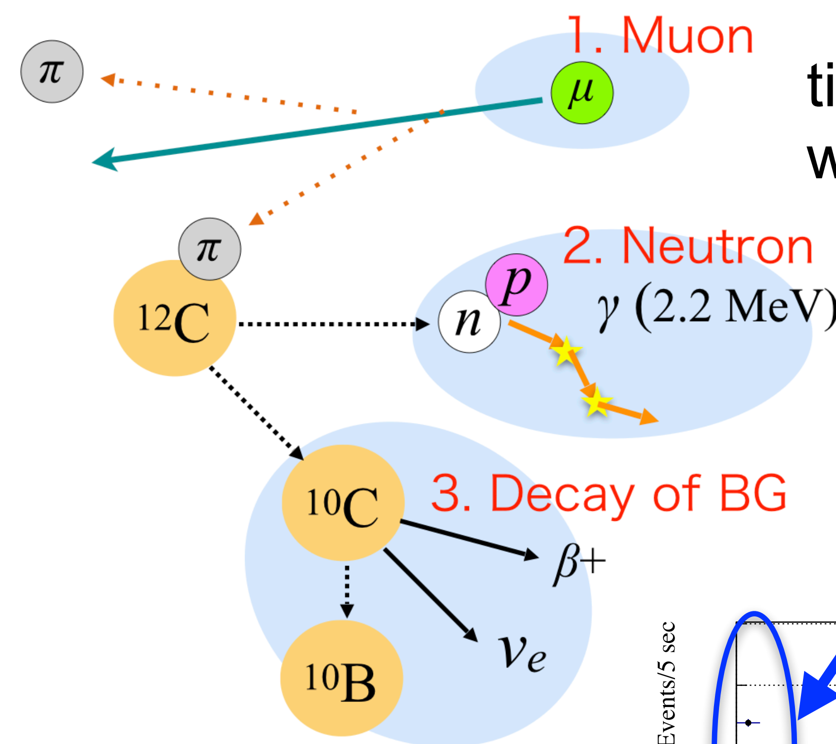
KamLAND-Zen 800

Short-lived Spallation Products

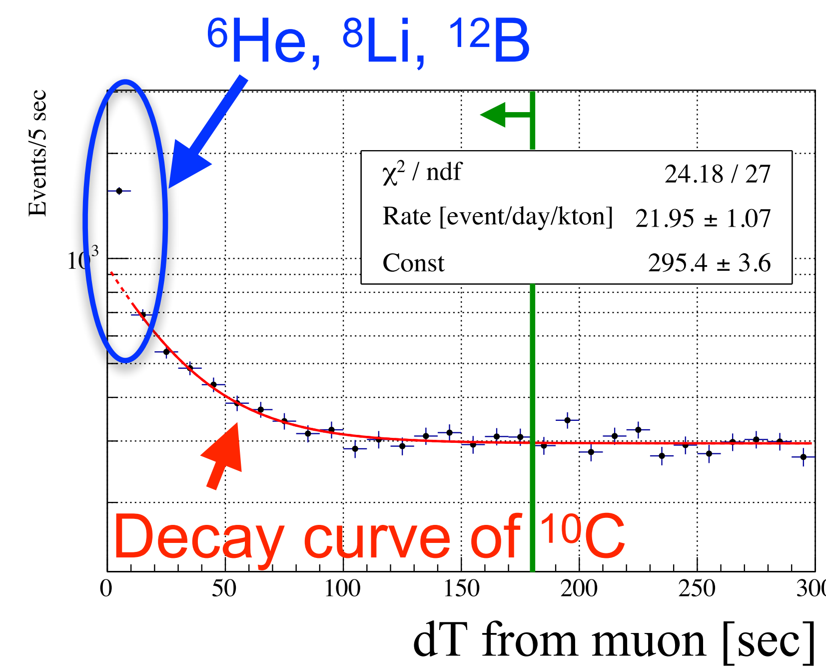
carbon spallation products



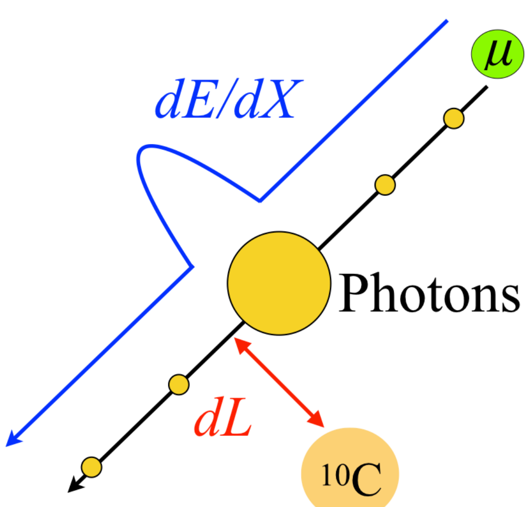
Triple coincidence tagging (dT, dR)



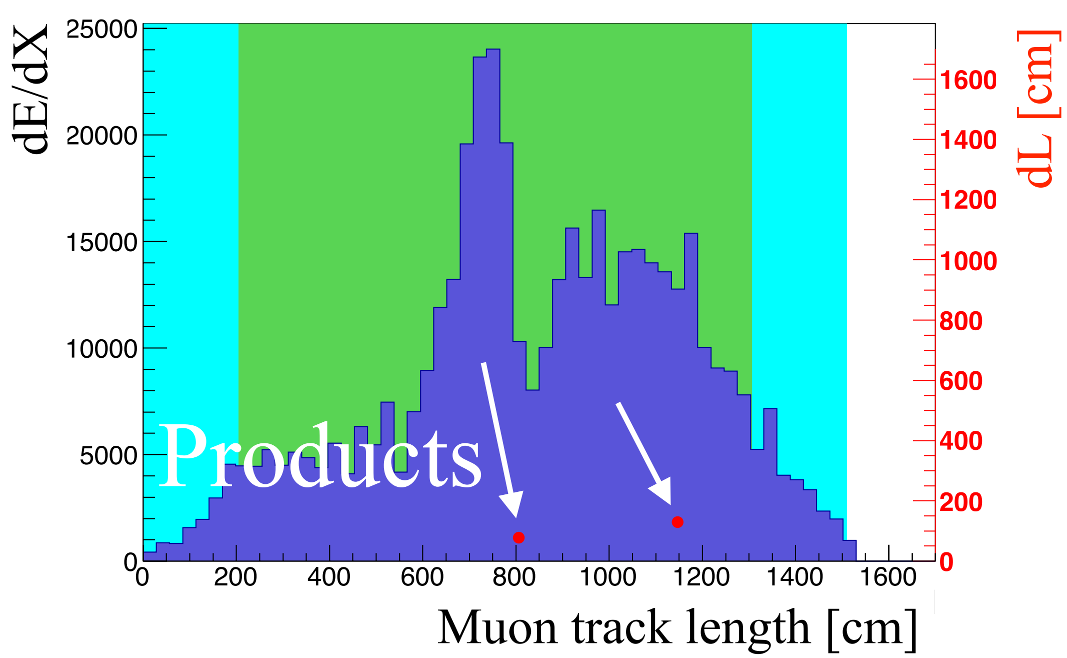
time and space correlation with muon and neutrons



Shower tagging (dE/dX, dL)



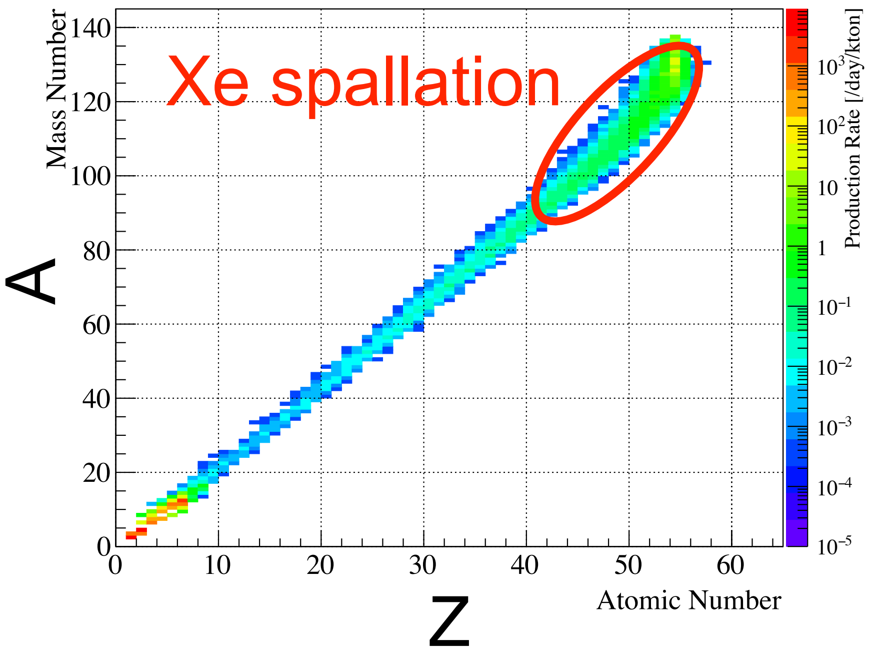
space correlation with muon shower



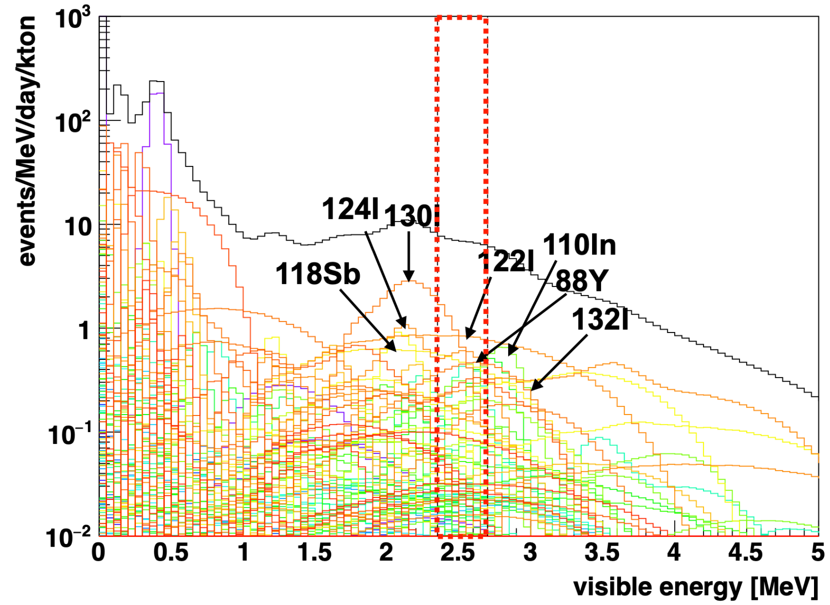
carbon spallation products > 95% rejection efficiency

Long-lived Spallation Products

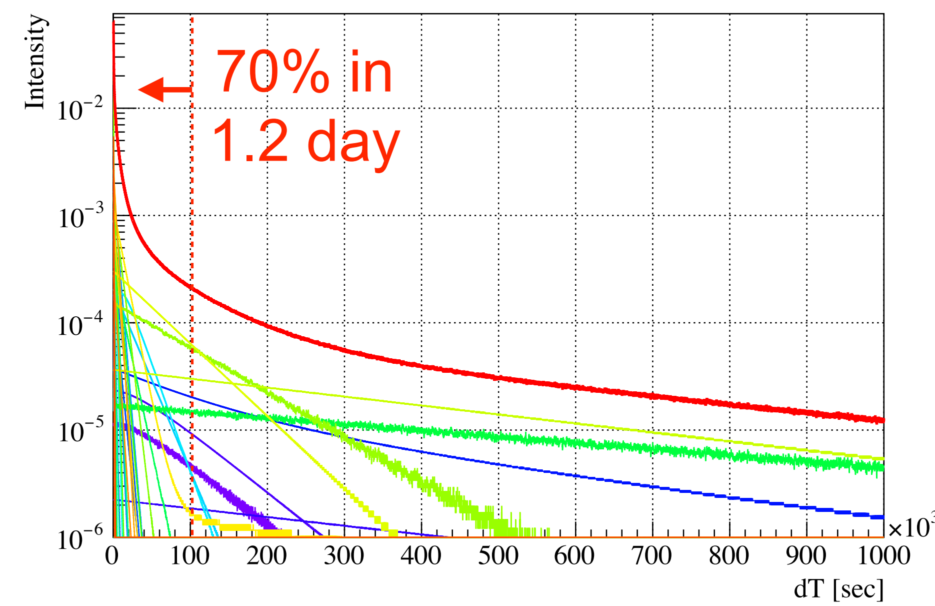
production yield



energy spectrum



time difference from muon

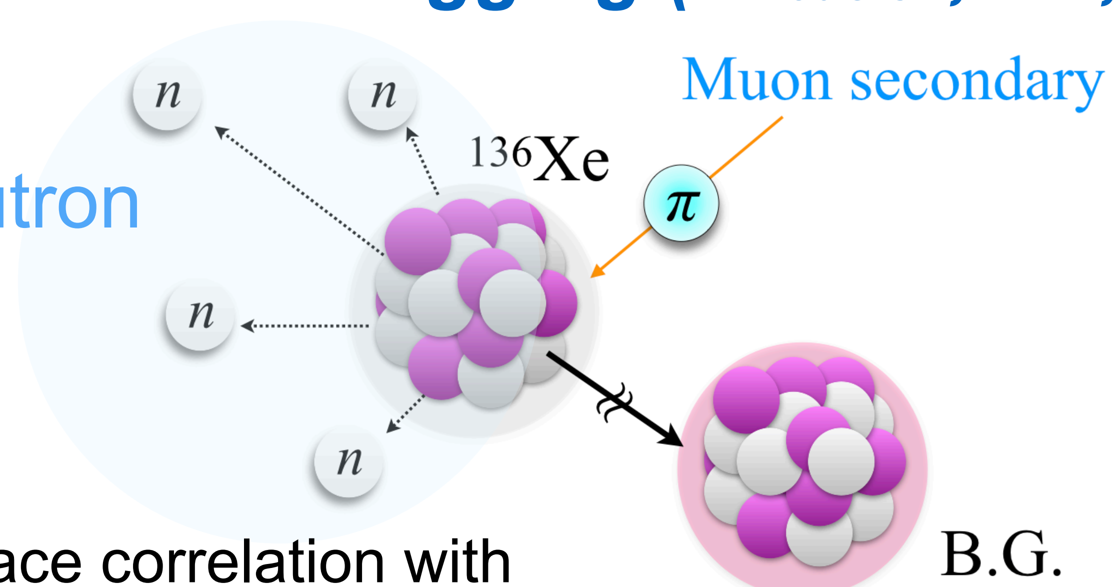


rate in ROI : 30.0 events/Xe-ton/yr

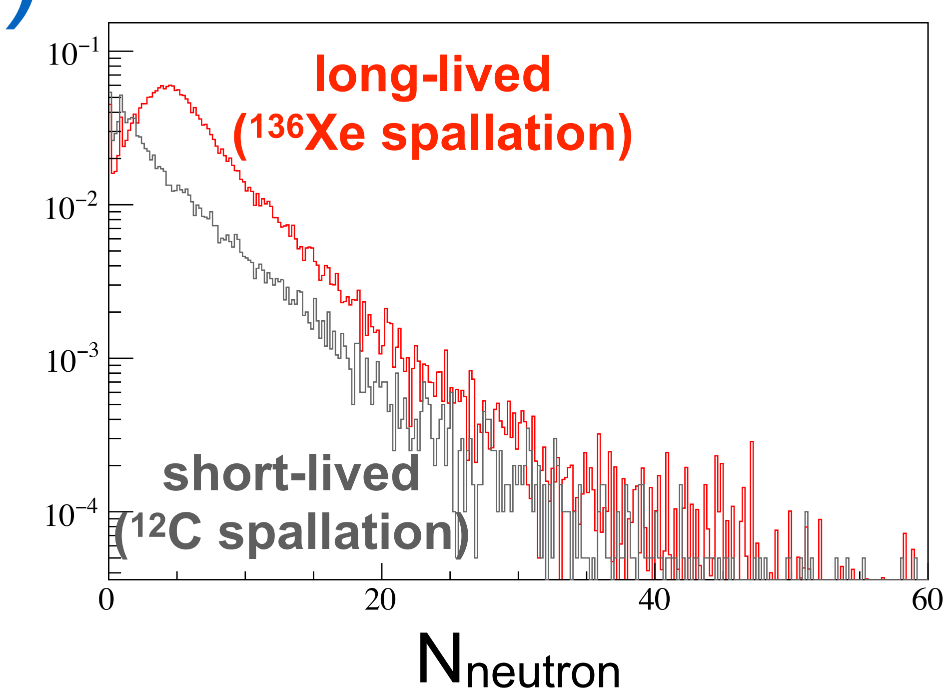
need long-time veto

Likelihood-based tagging ($N_{neutron}$, dR, dT)

dense neutron cluster



time and space correlation with muon and multiple neutrons

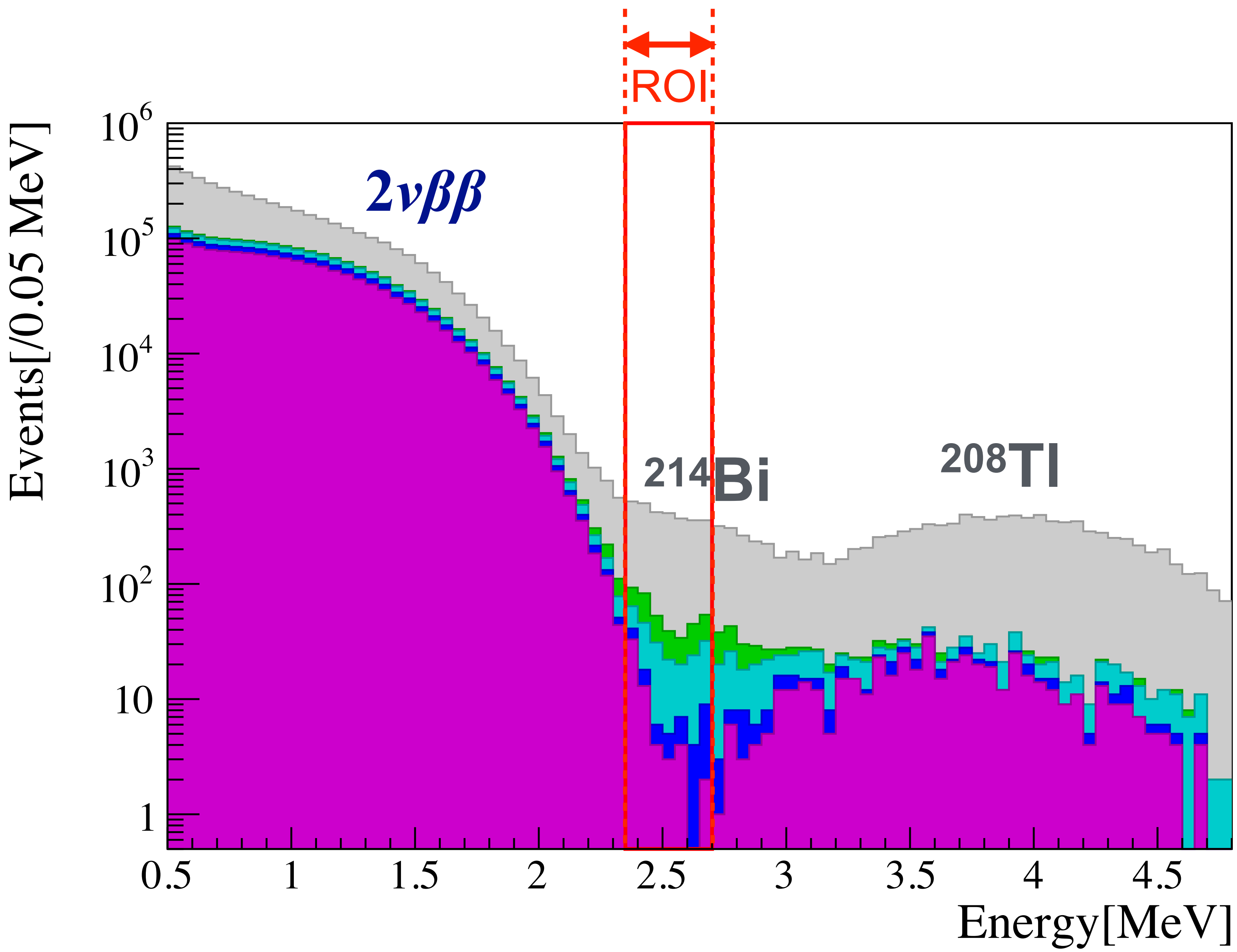


xenon spallation products ~47% rejection efficiency

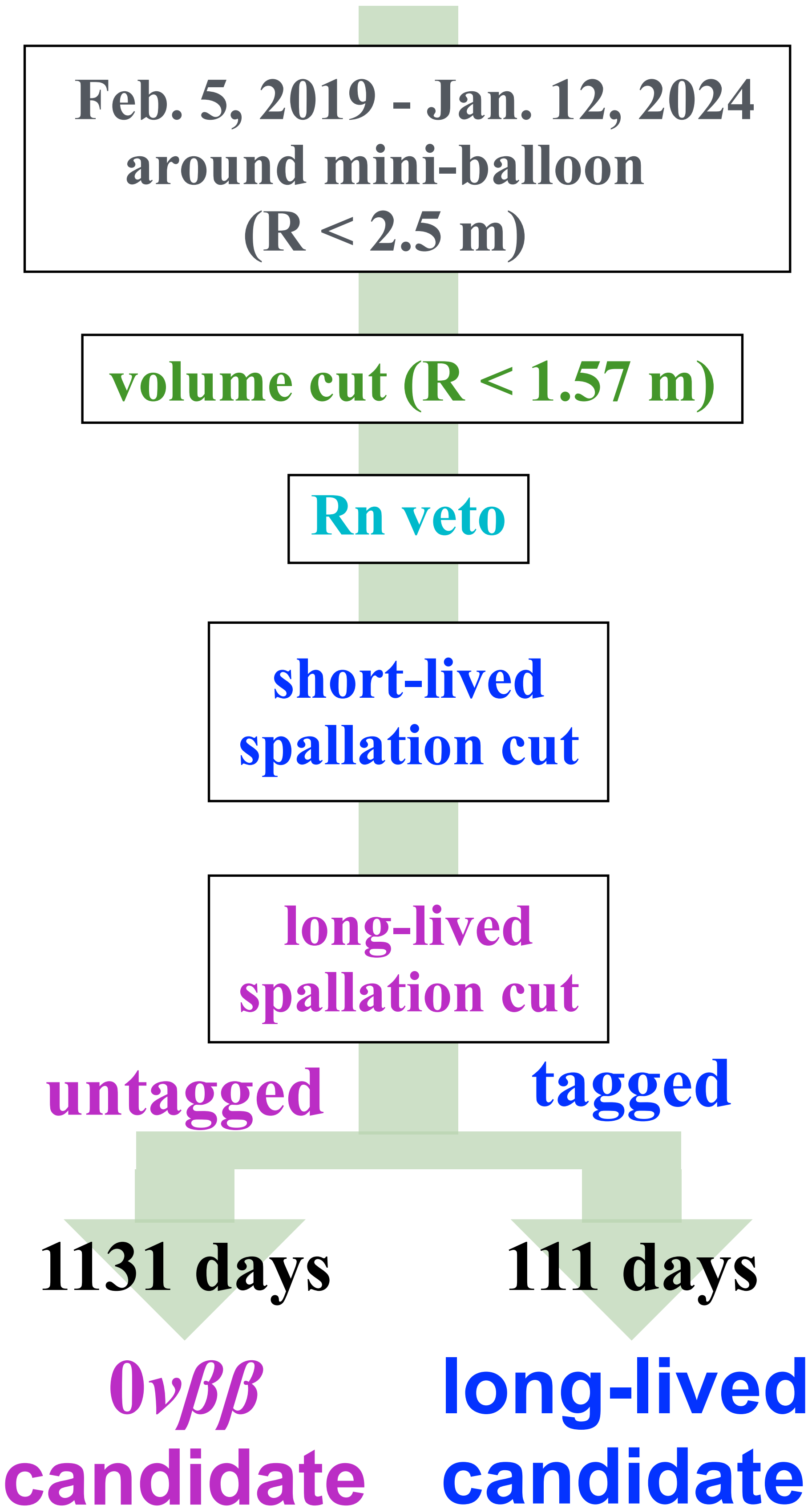
Event Selection

ββ isotope ^{136}Xe **90.85% enriched** $Q_{\beta\beta}$ = 2458 keV

745 kg Xe in all volume Feb. 5, 2019 - Jan. 12, 2024



Two energy spectra (0νββ, long-lived) are fitted simultaneously



Fit to Energy Spectra for 0νββ

0νββ candidate

(sensitive to 0νββ signal)

1131 days livetime

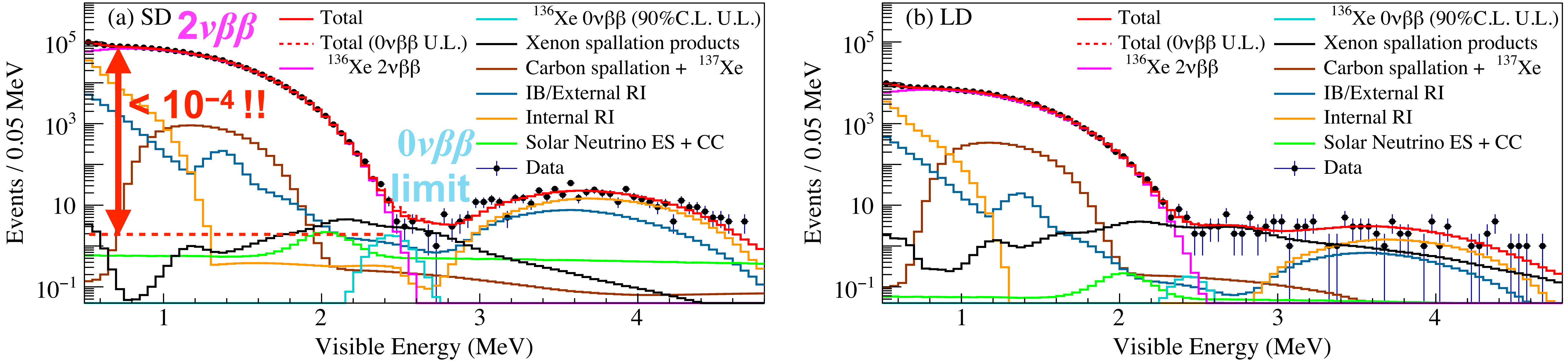
R < 1.57 m

long-lived candidate

(Long-lived BG constraint)

111 days livetime

R < 1.57 m



0νββ best-fit : **0 event**

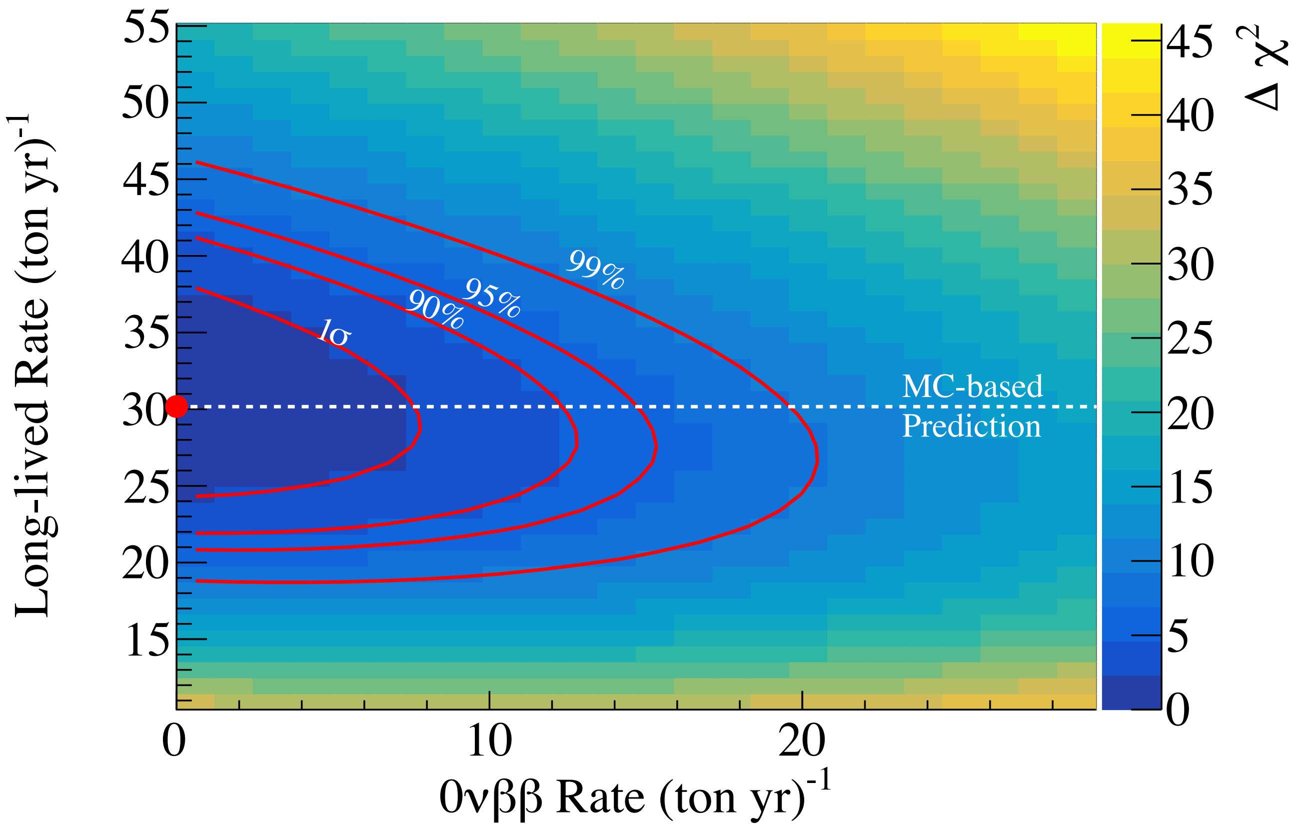
upper limit : **< 10.0 event** at 90% C.L.

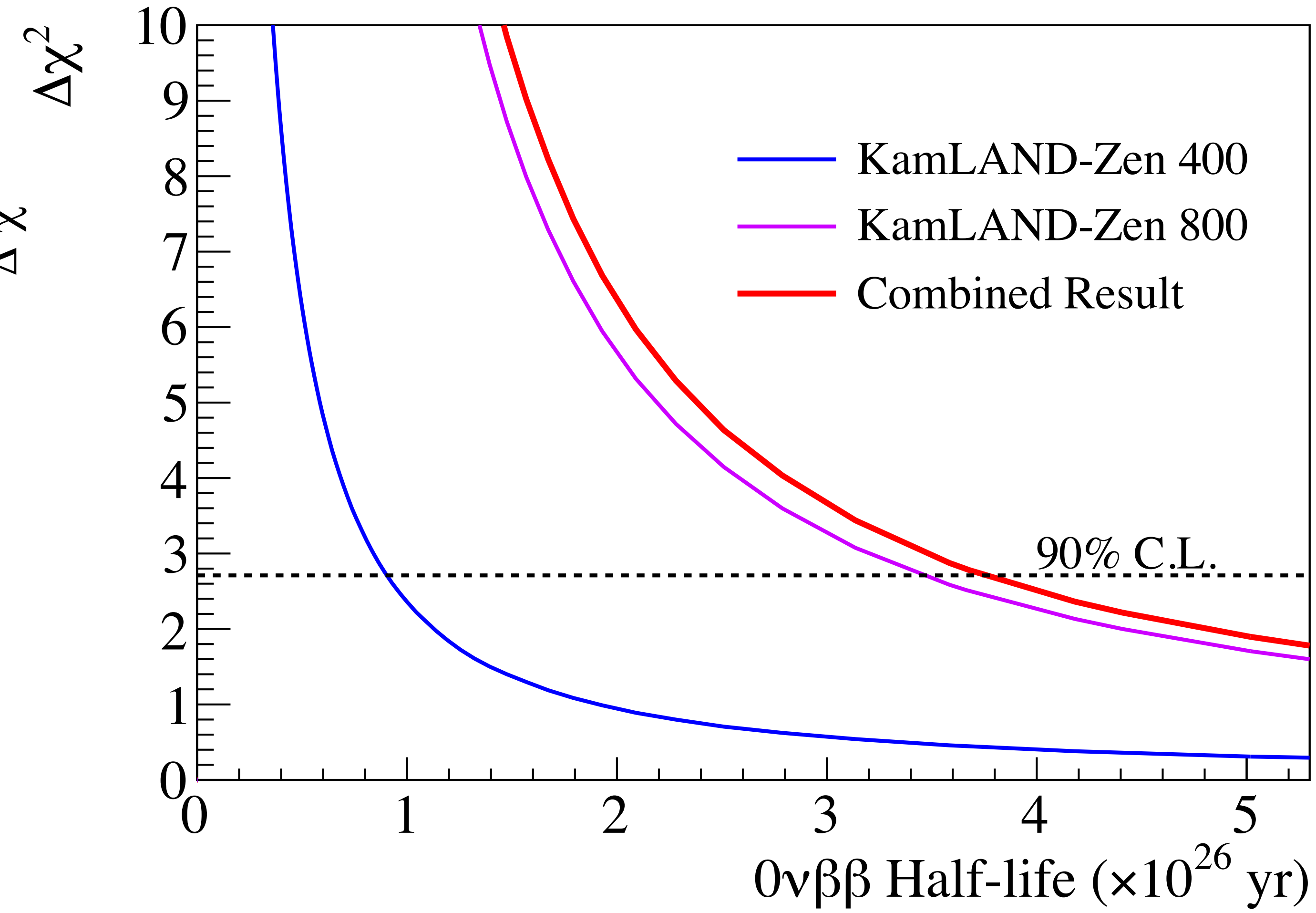
in R < 1.57 m

No positive signal, but we obtained a stringent upper limit

^{136}Xe 0νββ Decay Half-life

(0ν rate, Long-lived BG rate)





Long-lived BG rate in 2.35-2.70 MeV = 30.2 ± 4.5 events/Xe-ton/yr

(MC prediction = 30.0 ± 2.2 events/Xe-ton/yr)

Long-lived BG rate was measured

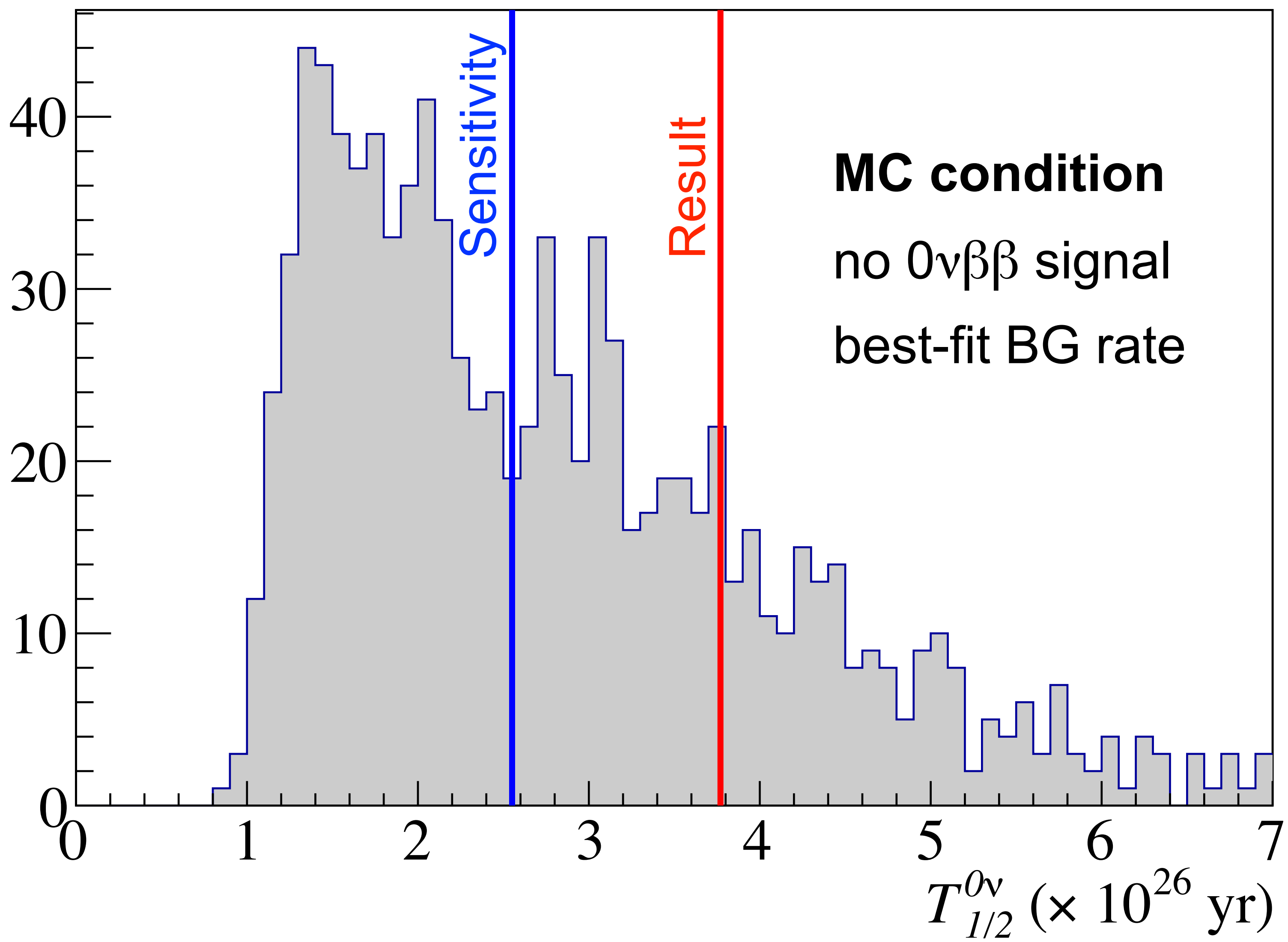
Half-life limit at 90% C.L.

Zen 400	$T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr
Zen 800	$T^{0\nu}_{1/2} > 3.4 \times 10^{26}$ yr
Combined	**$T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr**

Limits on ^{136}Xe half-life are improved (~1.7 times better than previous)

Upper Limits from Toy MC

distribution of 0νββ limits at 90% C.L. from Toy MC



$T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr 29% of the time

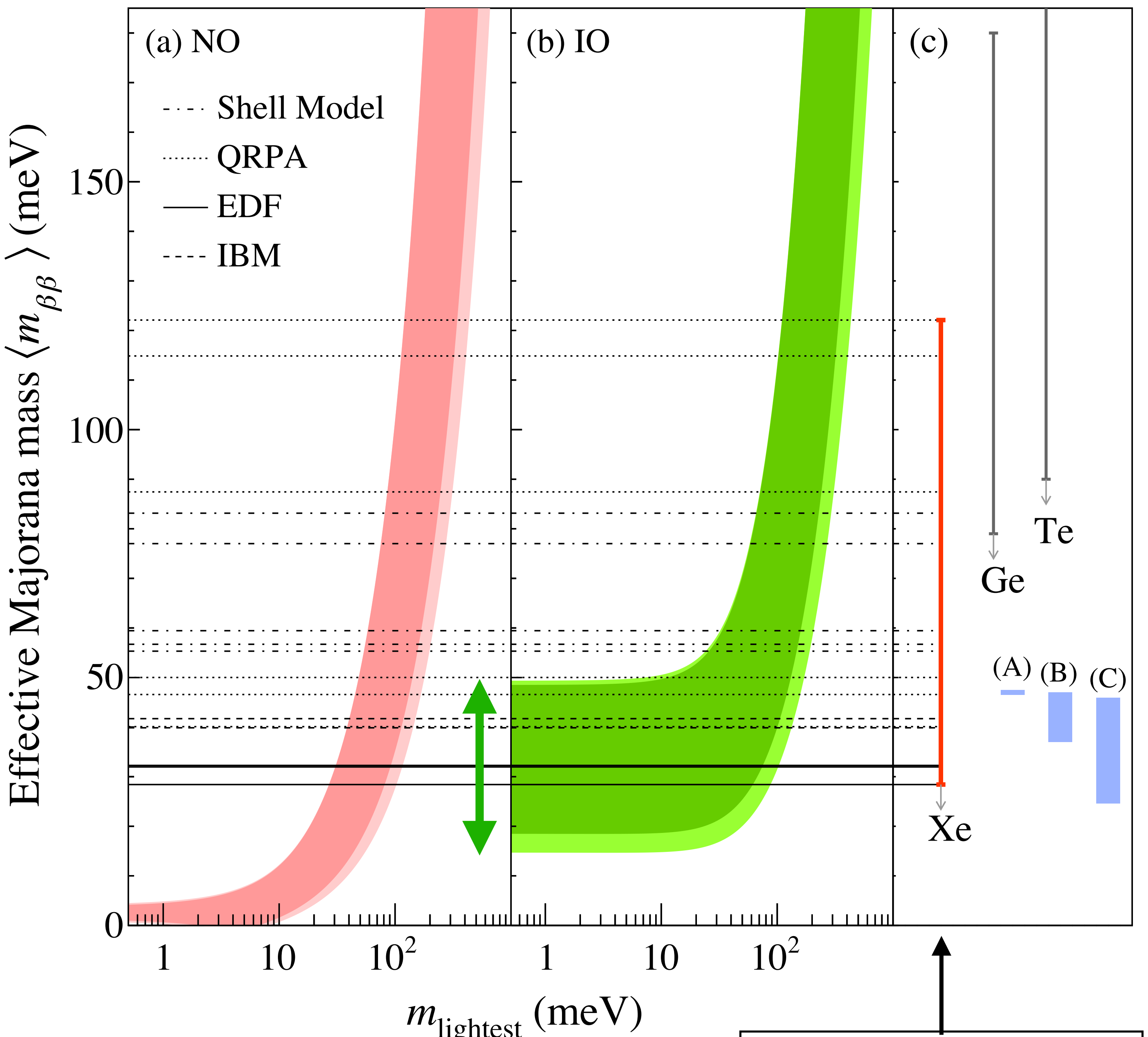
$T^{0\nu}_{1/2} > 2.6 \times 10^{26}$ yr 50% of the time

Sensitivity is checked by MC assuming best-fit BG rate

Limits on Neutrino Mass

90% C.L. upper limit

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$



Xe is leading!

NME 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

Limits on Neutrino Mass

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$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$

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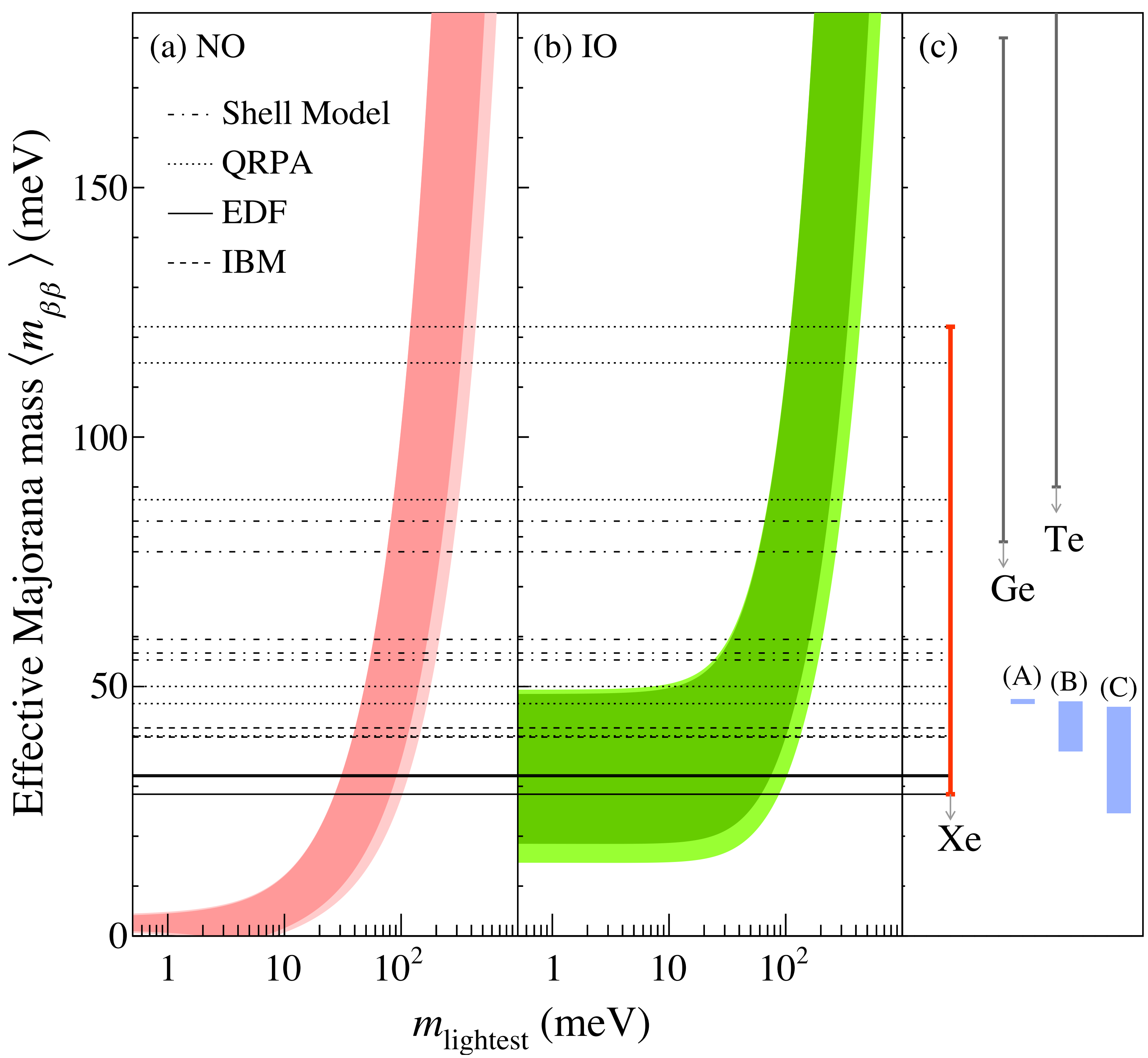


Shell Model

[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).

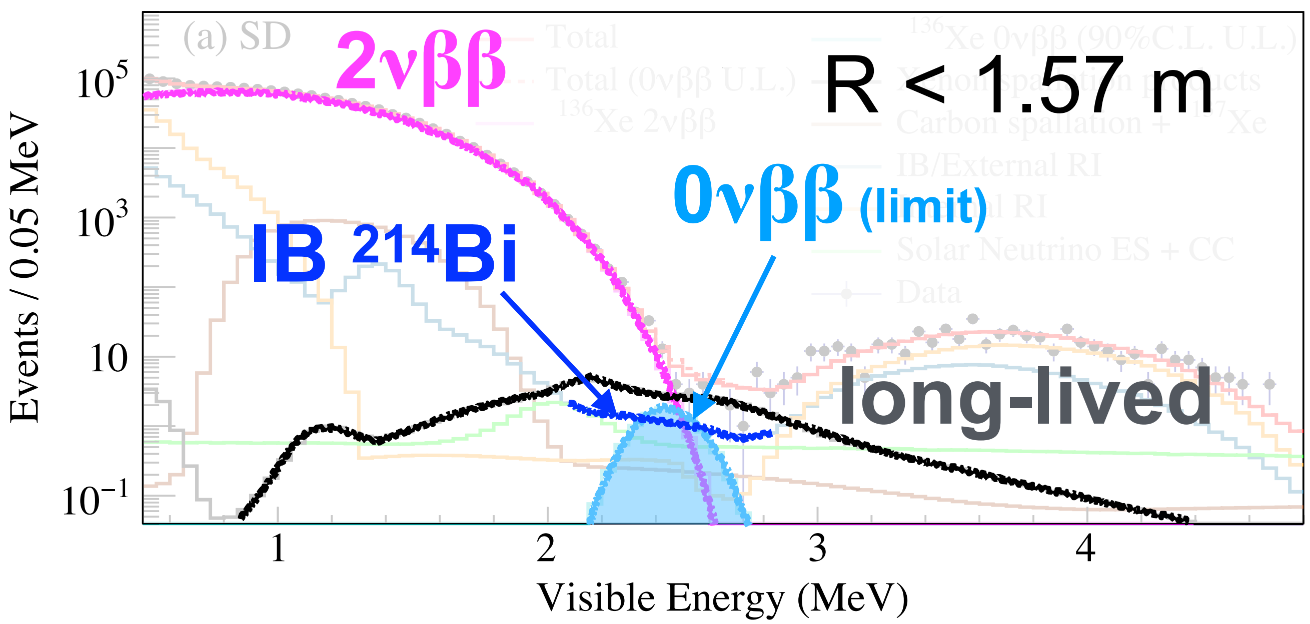
KamLAND-Zen (^{136}Xe)

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

m_{lightest} < 84−353 meV

Most stringent tests of the neutrino mass in the IO region

Background Measures in Future



current status

Search sensitivity will be limited by the backgrounds from **2νββ** and **long-lived spallation**

ROI event (2.35 < E < 2.70 MeV)

2νββ	**27.60**
RI in Xe-LS	1.43
RI in IB	**6.65**
solar ν	3.57
long-lived	**19.39**

measures in future

energy resolution tail → **light yield increase**

detector upgrade plan : **KamLAND2-Zen**

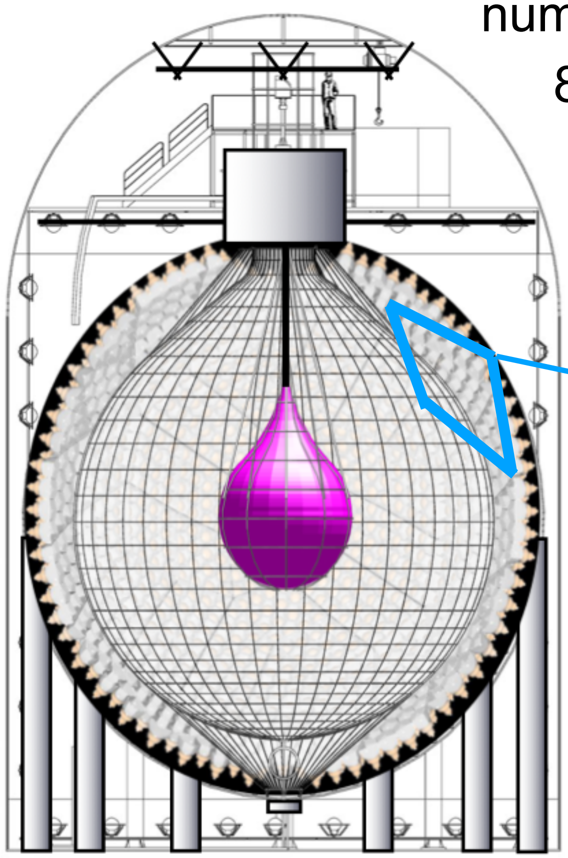
RI decay in film → **scintillation balloon**

gamma or positron background
→ **particle identification**

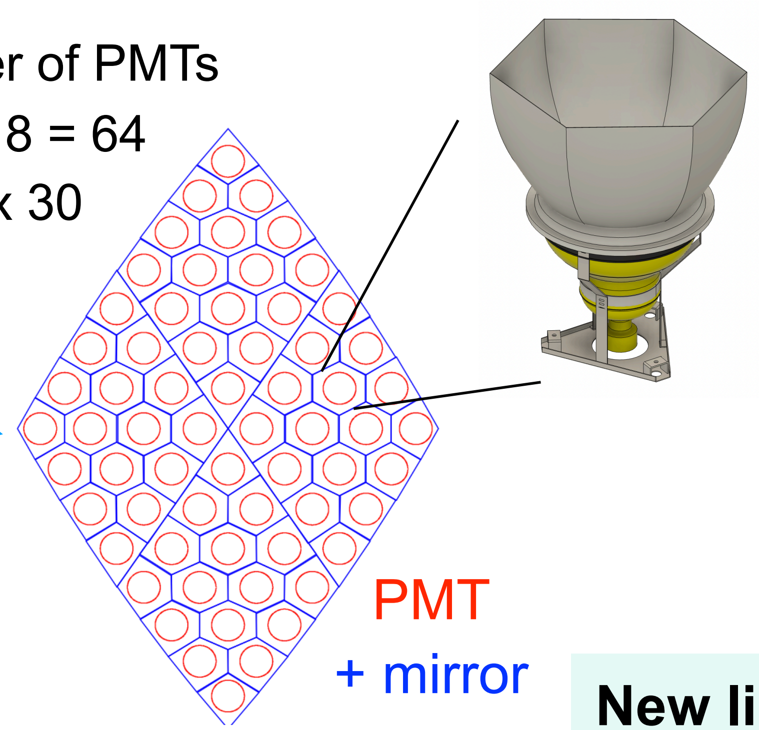
spallation tagging with neutrons
→ **new electronics**

KamLAND2-Zen

KamLAND2



number of PMTs
8 x 8 = 64
x 30



Mirror

Light Collection Eff.
> **x1.8**

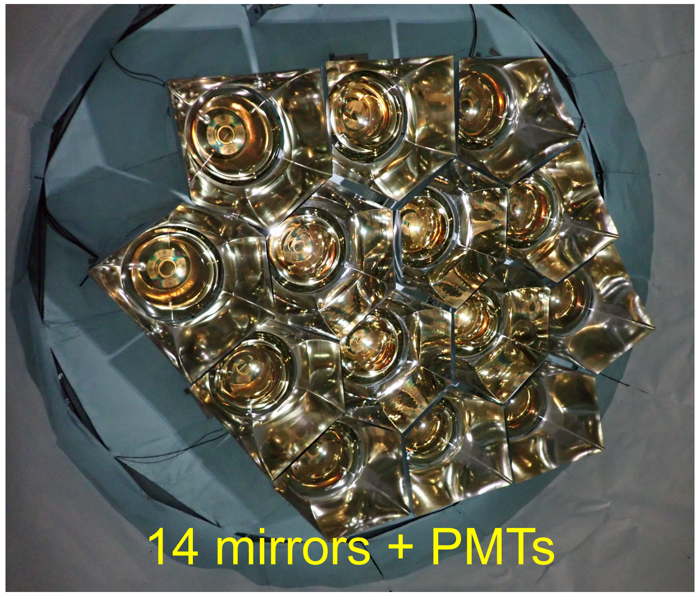
High QE PMT

x1.9

New liquid scintillator

x1.4

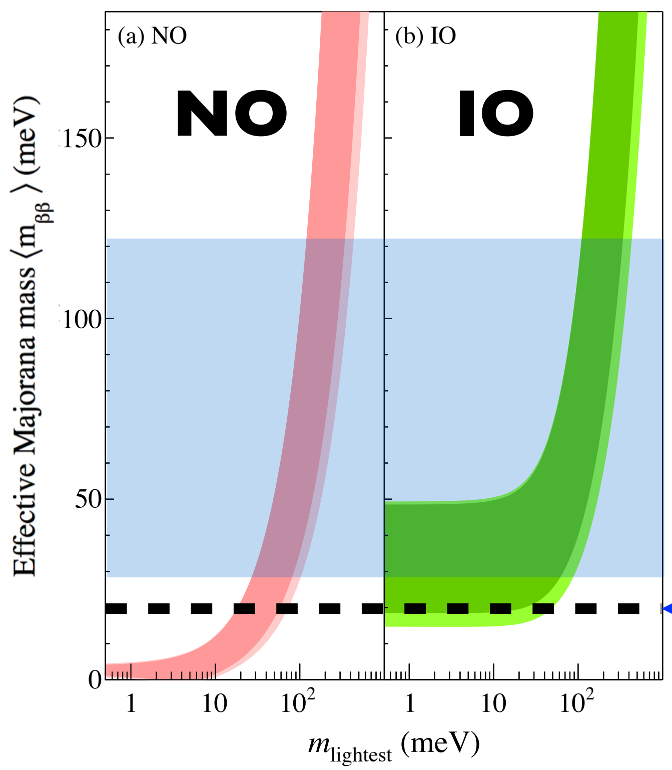
KamLAND2 prototype



performance test

better energy resolution
with **high light yield**

State-of-the-art electronics



background
reduction

Scintillation balloon

KamLAND-Zen
latest result

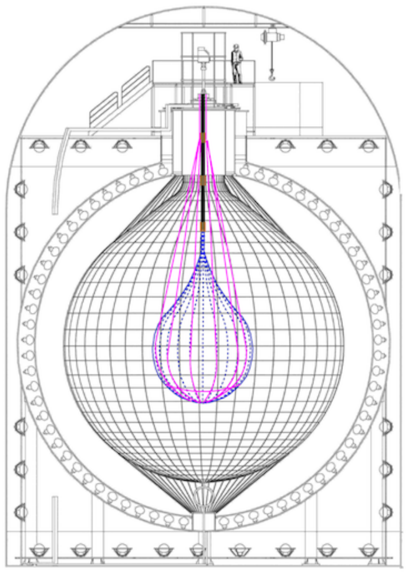
goal

KamLAND2-Zen will cover the IO region

target $\langle m_{\beta\beta} \rangle$ ~ **20 meV / 5 year**

Plan of Detector Upgrade

KamLAND dismantling | KamLAND2 construction



2024 — 2027

Now

LS & Oil extraction

dismantling (PMT, balloon)

Clean balloon

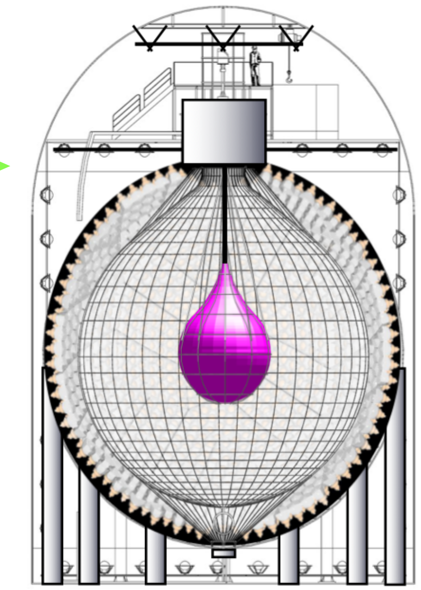
enriched Xe collection

Super clean facility (KERNEL)

High QE PMT / Mirror

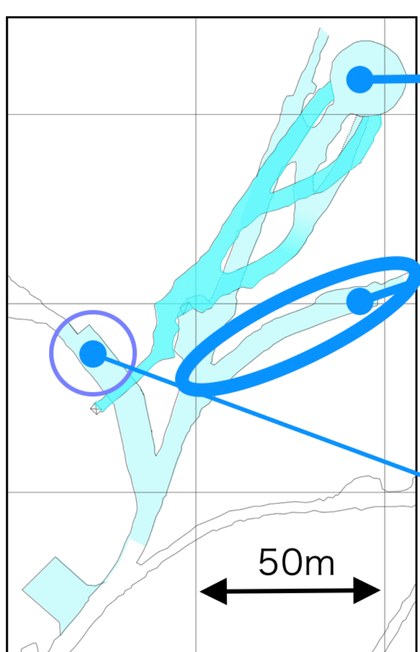
High light yield LS

New electronics



Top access hole & Calibration system

Scintillation balloon



KamLAND

Super clean facility (KERNEL)

clean facility

underground area

We aim to start KamLAND2 in 2027 (fiscal year)

New collaborators are welcome!

Summary

- Neutrinoless double-beta decays provide an important probe for physics beyond the Standard Model.

- Results with the complete KamLAND-Zen data-set

KamLAND-Zen limits on $0\nu\beta\beta$ at 90% C.L.

KamLAND-Zen 400	$T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr
KamLAND-Zen 800	$T^{0\nu}_{1/2} > 3.4 \times 10^{26}$ yr
Combined	$\mathbf{T^{0\nu}_{1/2} > 3.8 \times 10^{26}}$ **yr**
	↓
NME calculations assuming $g_A \sim 1.27$	$\langle m_{\beta\beta} \rangle$ **< 28−122 meV**

Most stringent tests of the neutrino mass in the IO region!

- We will start KamLAND2-Zen to achieve the search sensitivity covering the entire IO region.