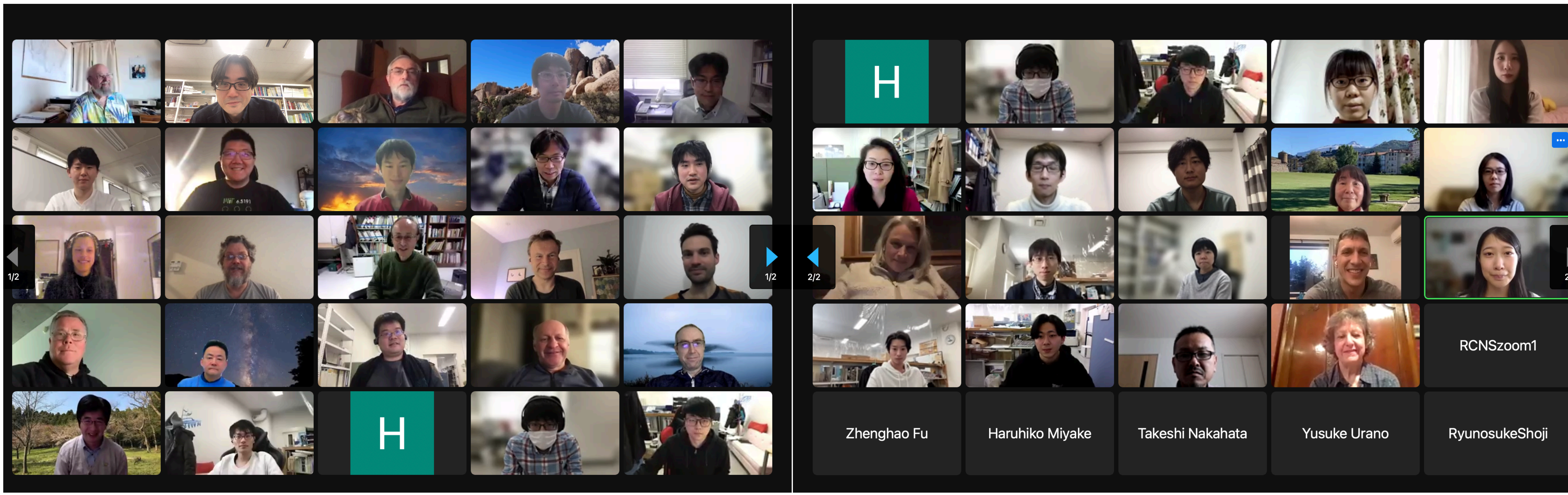
KamLAND-Zen 800

Azusa Gando for the KamLAND-Zen Collaboration
RCNS, Tohoku University

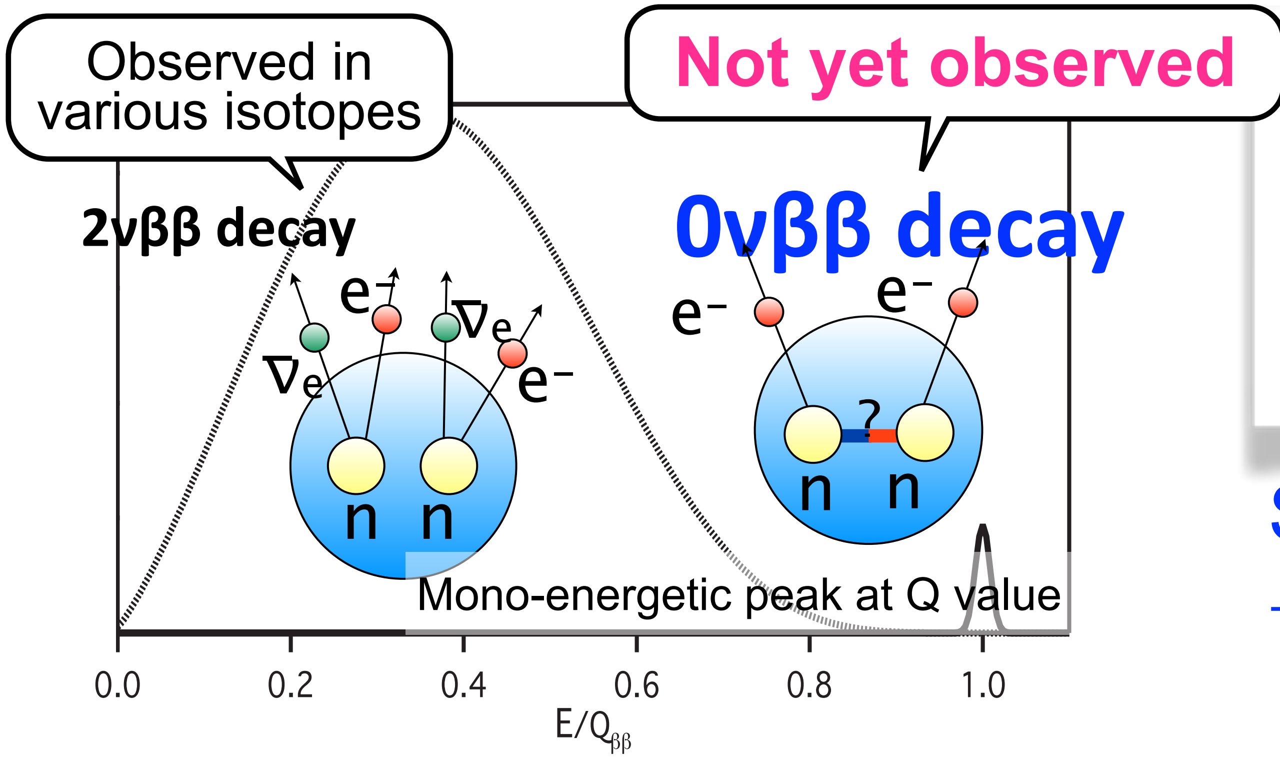
KamLAND-Zen Collaboration

Collaboration meeting in March, 2022



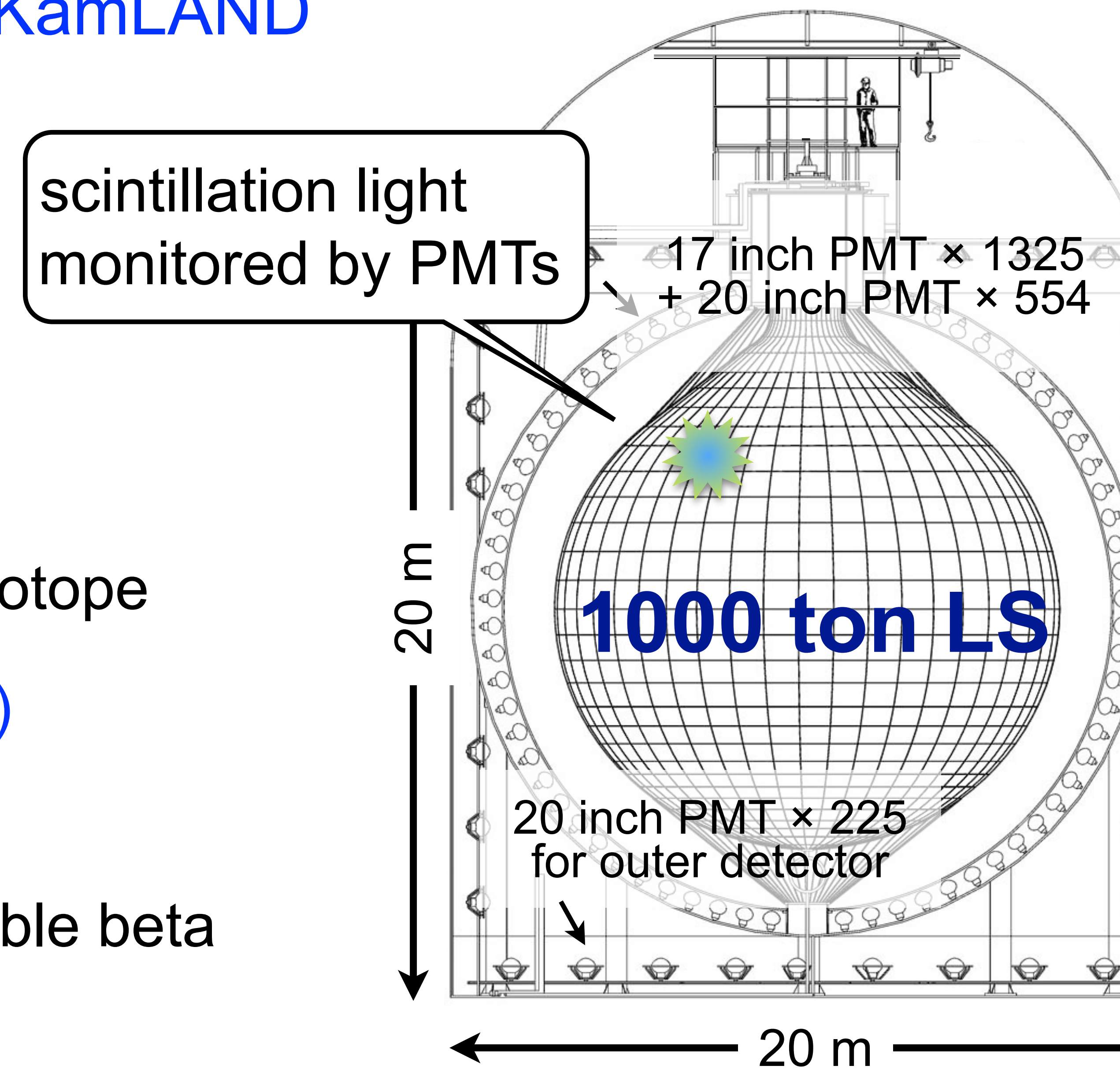
TOHOKU UNIVERSITY
東京大学 THE UNIVERSITY OF TOKYO
大阪大学 OSAKA UNIVERSITY
TOKUSHIMA UNIVERSITY
BERKELEY LAB
KYOTO UNIVERSITY FOUNDED 1897 KYOTO JAPAN
THE UNIVERSITY OF TENNESSEE KNOXVILLE
TUNL
VIRGINIA TECH.
UNIVERSITY of HAWAI'I
BOSTON UNIVERSITY
Nikhef

Double beta decay search with KamLAND



DBD nuclei: ^{76}Ge, ^{130}Te, ^{136}Xe…
Half-life (2νββ): ~$10^{19\text{-}24}$ yr
Decay rate (0νββ) ∝ (effective ν mass)^2
Q-value: ~ a few MeV

Search for a rare decay at a few MeV
→ KamLAND



Advantage of KamLAND

Big

1,000 tons of highly purified **liquid scintillator** (LS) in the 6.5-m-radius balloon
→ high scalability, can use ~1ton of isotope

Low BG

Background level of LS (^{238}U, ^{232}Th) are at **$10^{-17\sim-18}$ g/g**
→ Clean environment
KamLS act as active shield for double beta decay experiment

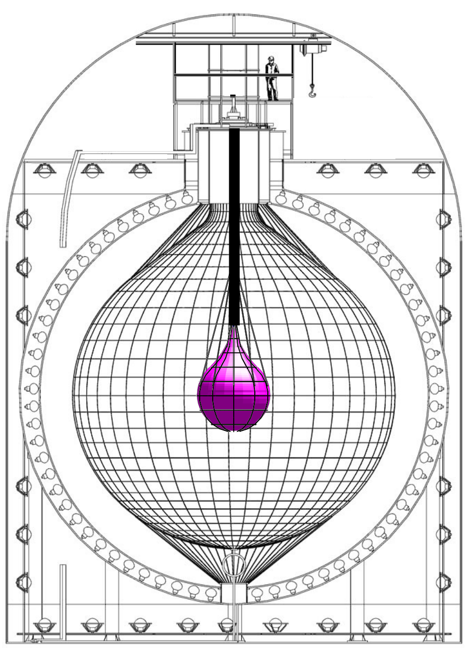
KamLAND-Zen Modification of KamLAND

Double beta decay isotope: ^{136}Xe

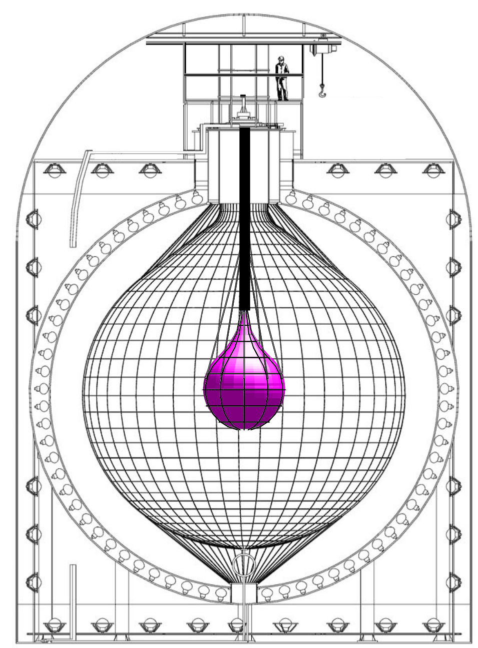
- Q-value 2.458 MeV
- Dissolved into LS ~3% by weight
- Enrichment ~90%
- Half life of 2νββ decay is long (~10^{21} yr)

^{136}Xe loaded LS
into KamLAND center
with inner balloon

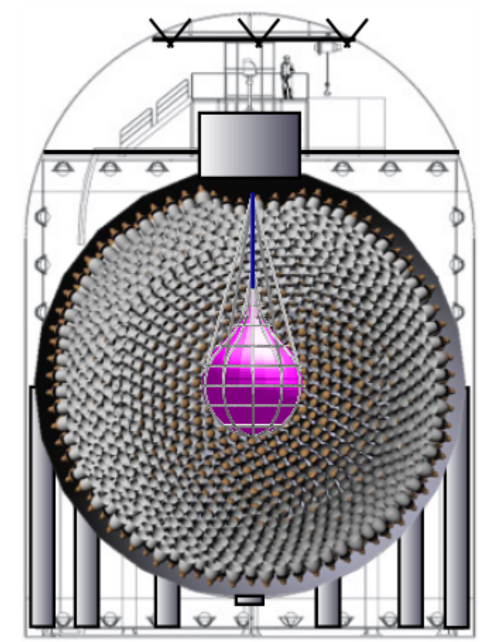
Past
KamLAND-Zen 400
320-380 kg of Xenon
Data taking in 2011 - 2015



Present
KamLAND-Zen 800
~750 kg of Xenon
DAQ started in 2019



Future
KamLAND2-Zen
~1 ton of ^{136}Xe
Better energy resolution



Reanalysis —combined→ **1st result**
Feb. 2019 - May 2021

arXiv:2203.02139v1 [hep-ex]
& Long paper in preparation

Hardware improvement from KL-Zen 400

(1) Almost **doubled xenon amount** (~750 kg, 91% enriched)

(2) Bigger, cleaner Xe-LS container (made of 25-um-thick nylon, radius=1.9 m)

Production@class-1 clean room with **very very** careful dust control

- Clean wear control
- Static-electricity control
- Particle flow check
- Film cover setting
- Semi-automatic welding machine… etc

JINST 16 P08023

Background level

^{214}Bi: one of main BG

^{238}U ~3×10^{-12} g/g$_{film}$

ref. initial film (after washed)

^{238}U~2×10^{-12} g/g$_{film}$

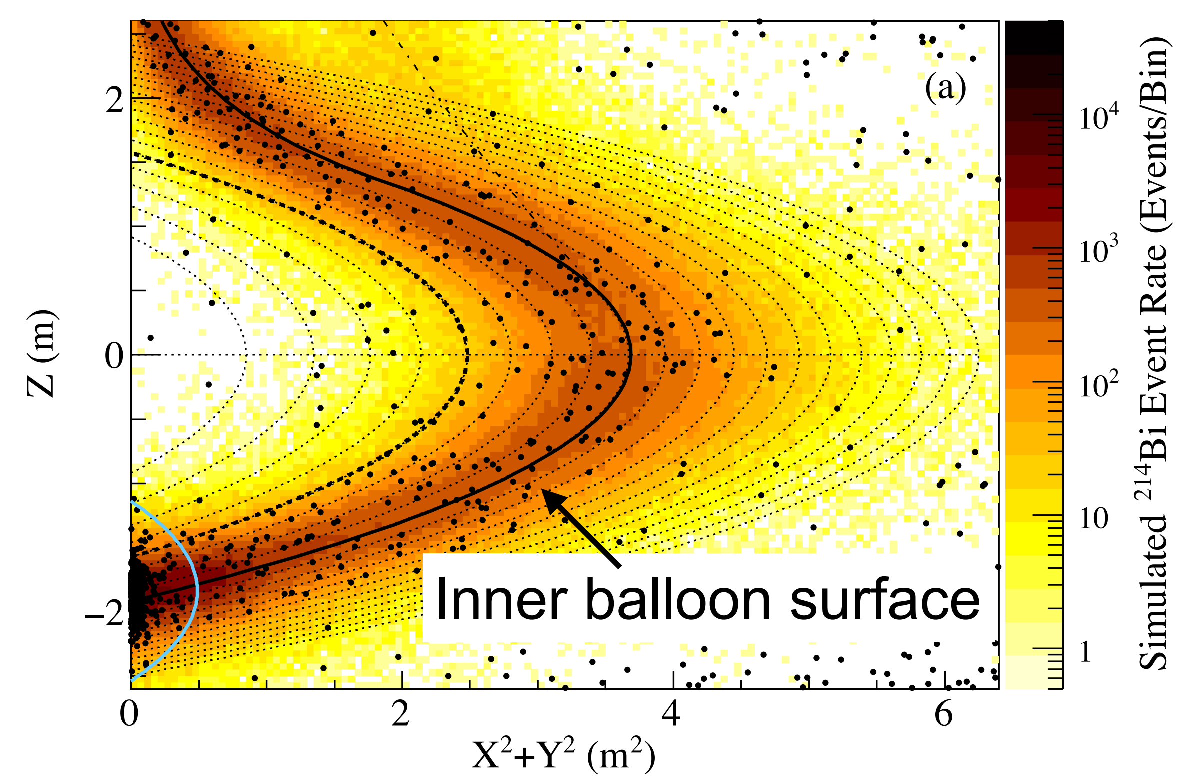
Almost same level

^{232}Th ~4×10^{-11} g/g$_{film}$

×10 reduction of RI

compared to KL-Zen 400

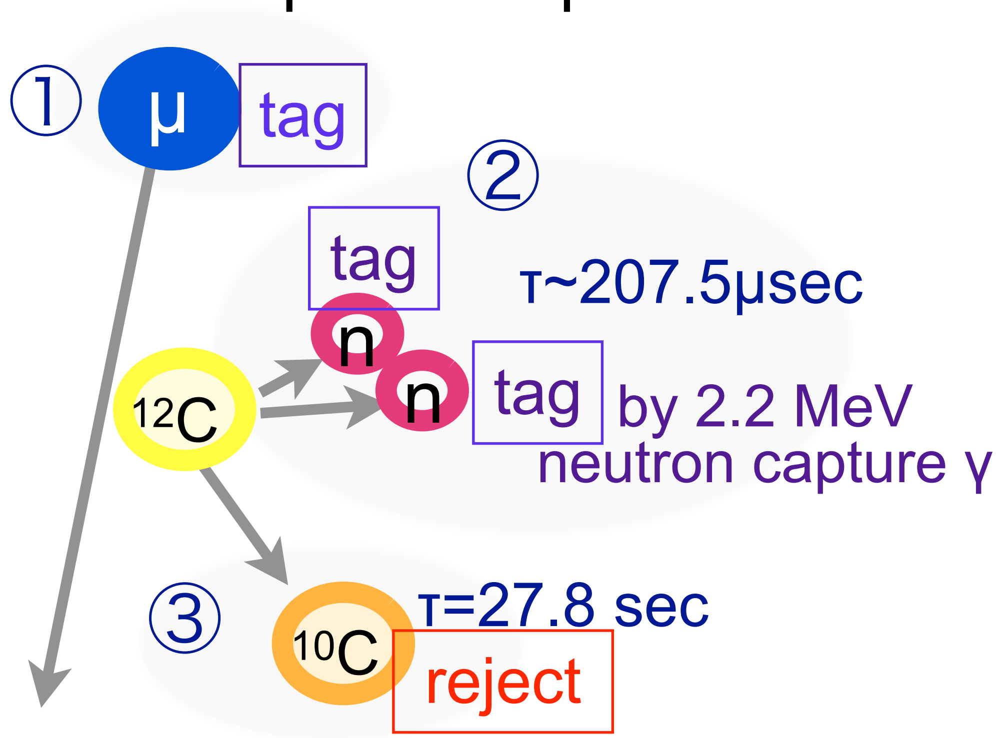
Vertex distribution in ROI & ^{214}Bi MC

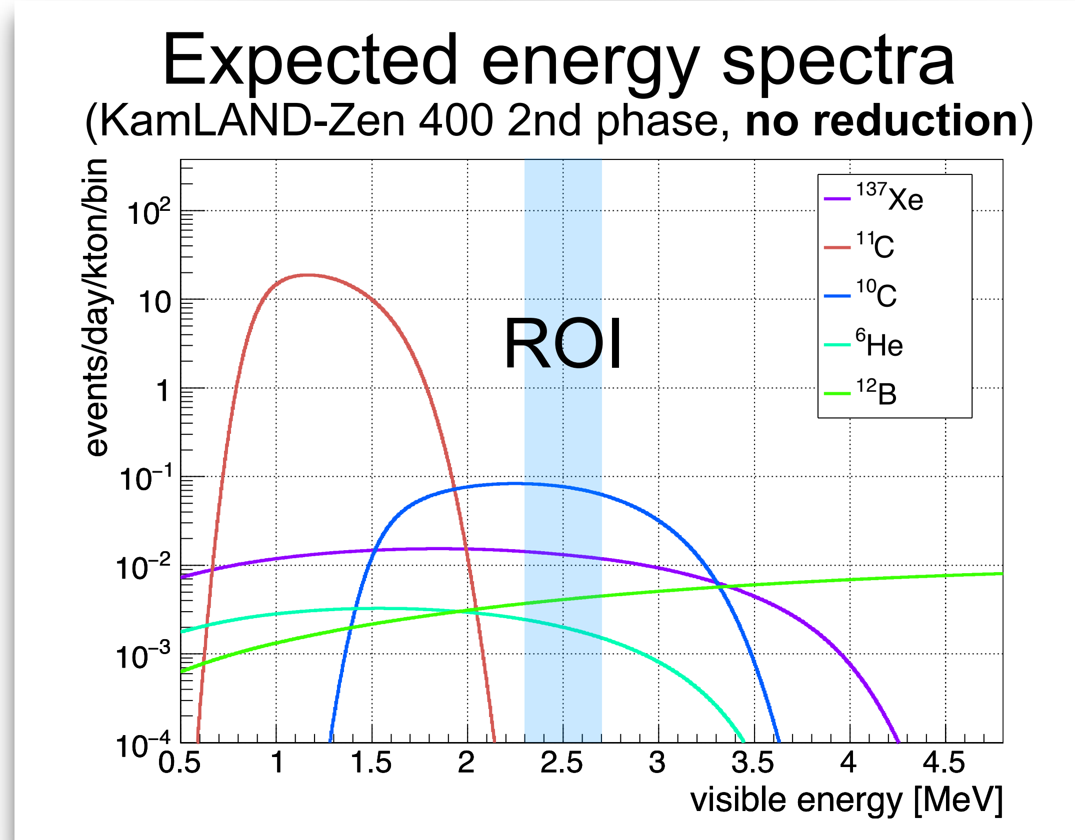


Software improvement from KL-Zen 400

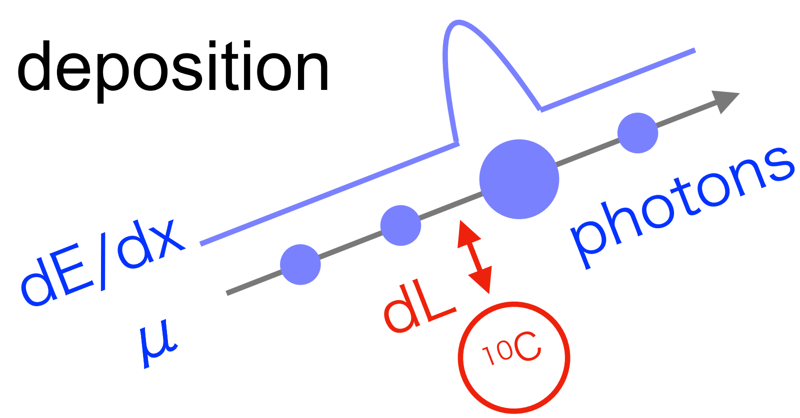
Carbon spallation & ^{137}Xe rejection method

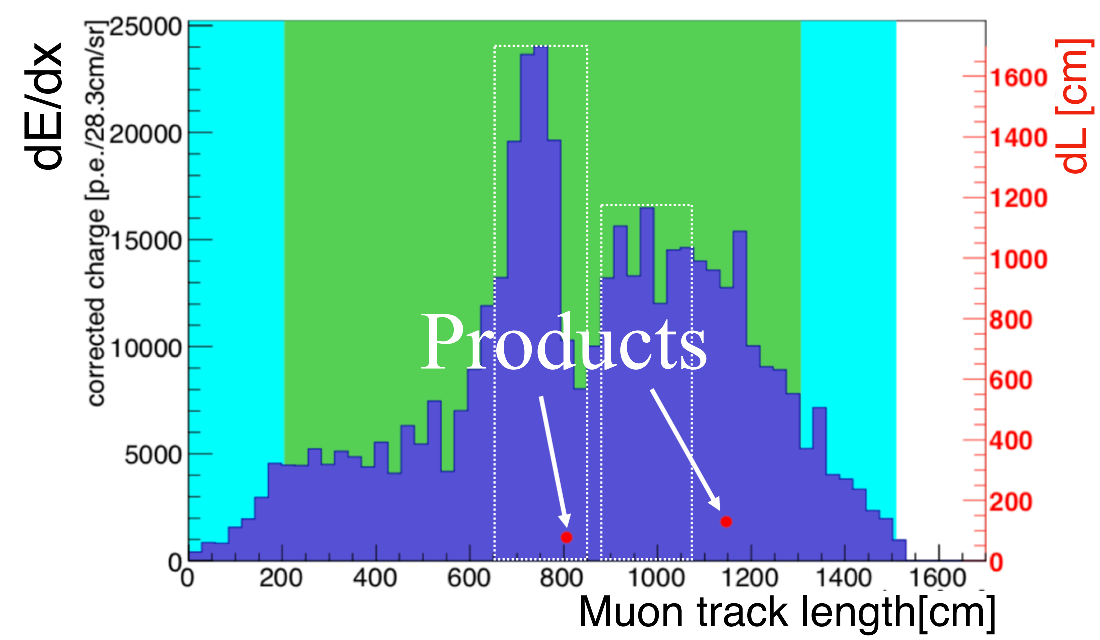
(1) Triple coincidence of muon-neutron-spallation products





NEW (2) A likelihood method based on muon energy deposition (dE/dx) is developed





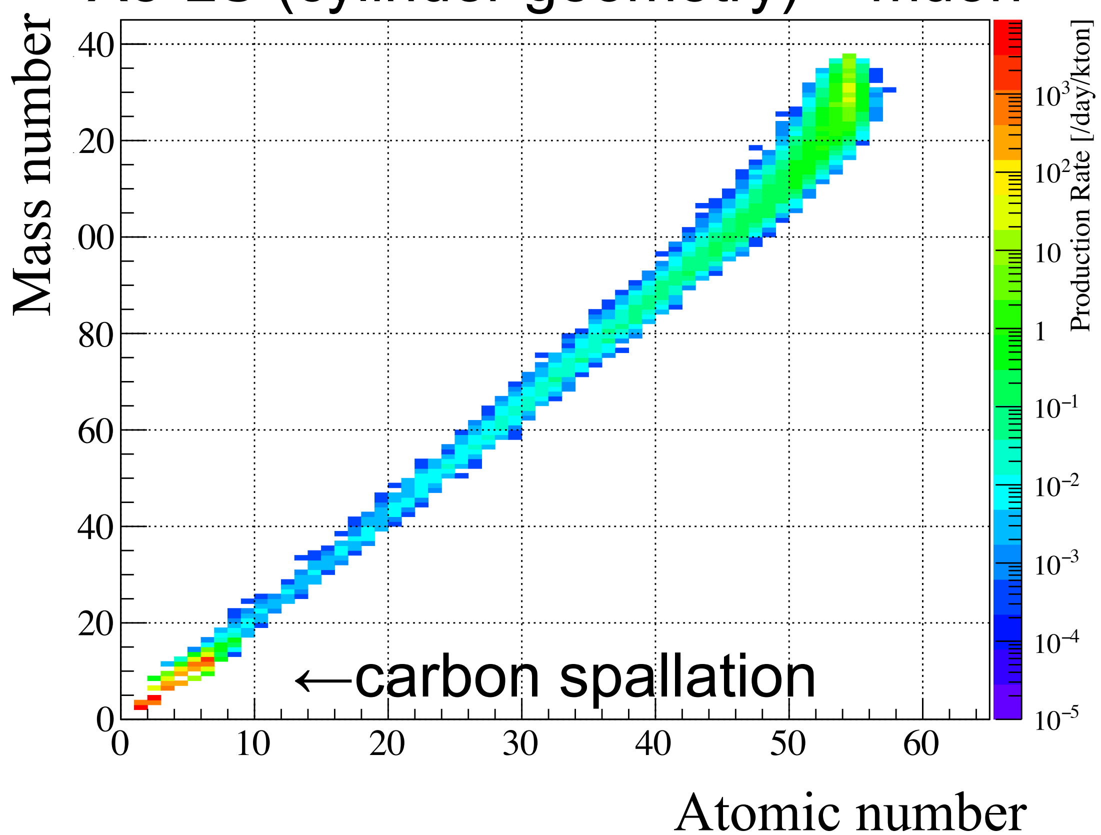
Rejection efficiencies: ^{10}C > 99.3%, ^{6}He ~98%, ^{137}Xe ~74%

(τ = 27.8 s, Q = 3.65MeV) (τ = 1.16s, Q = 3.51MeV) (τ = 5.5 min, Q = 4.17 MeV)

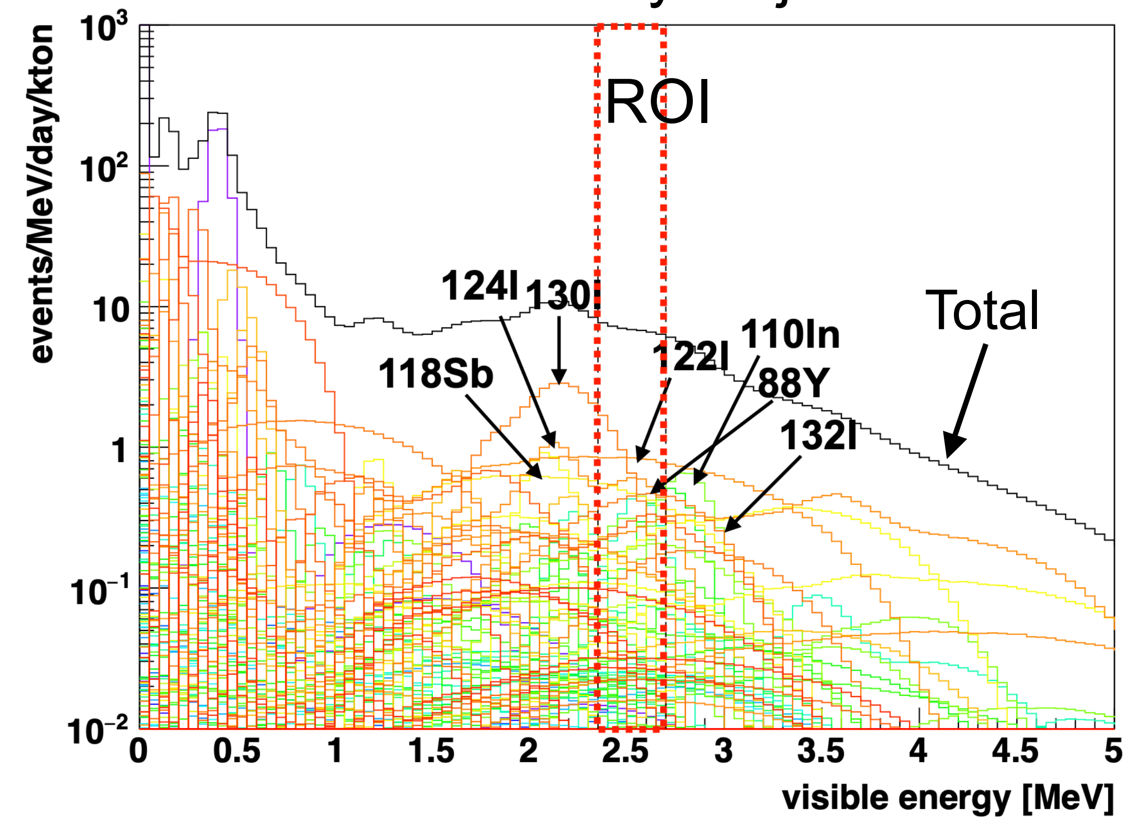
Xenon spallation products (Long-lived products)

- Individual yields are small but many candidates are produced
- Total yield become one of the main background → new major background

FLUKA
Xe-LS (cylinder geometry) + muon



Energy spectra of products
~90% by major 32 nuclei



- Longer half-lives (~hours to ~days)
- Neutron multiplicity is higher than carbon's

A likelihood method is developed

Parameters: Time difference from muon, distance between Xe-spallation and neutron capture gamma, effective number of neutron

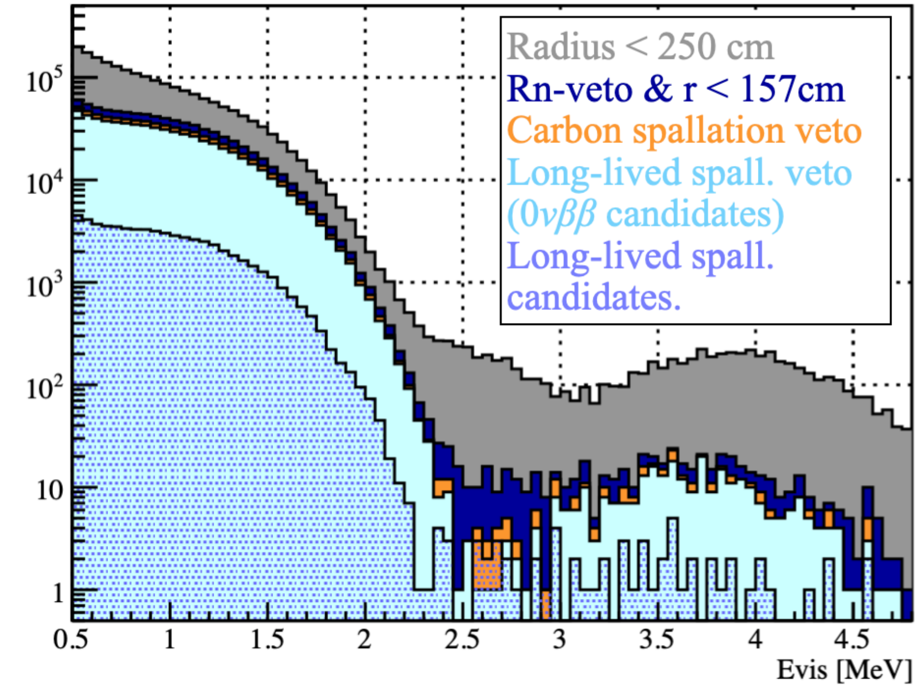
Rejection efficiency
42.0±8.8%

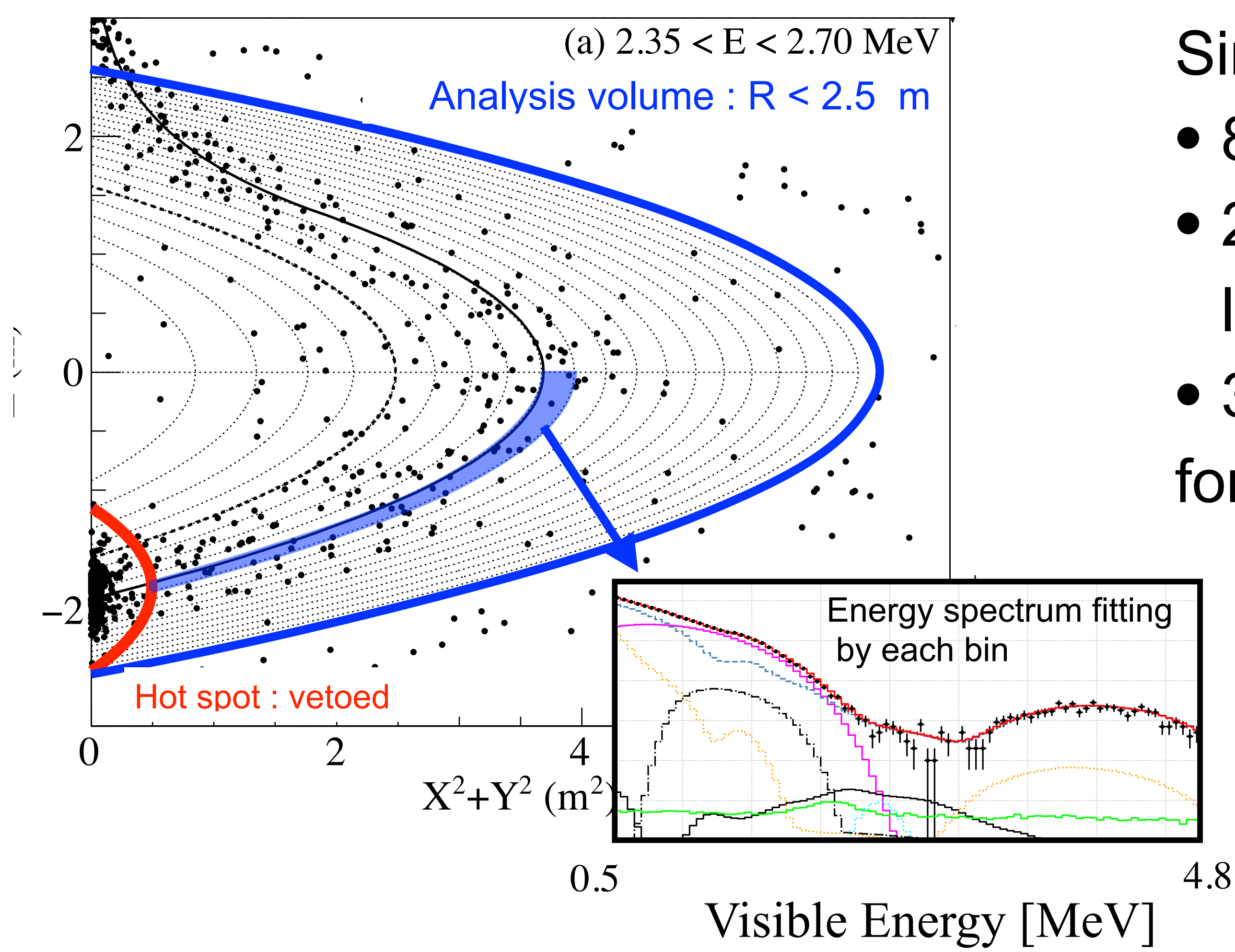
This rejected data-set is also used for simultaneous fitting (next page)

Event selection and fit

exposure reaches 970 kg yr!

- Events <2.5m of center and >0.7m away from bottom
- Events >2 ms after muons
- Radioactive decays vetoed by coincidence cut
- $\bar{\nu}$ identified by coincidence cut
- Poorly reconstructed events are rejected





Simultaneous fitting with

- 86 energy bins (0.5-4.8 MeV, 0.05 MeV/bin),
- 20 equal-volume bins each in the upper and lower hemispheres in R<2.5m,
- 3 time bins

for each **single** and **long-lived** data

Free parameters:
0nu, 2nu, ^{85}Kr, ^{40}K, 2^{10}Bi, the ^{228}Th-^{208}Pb sub-chain of the ^{232}Th series, and long-lived spallation products etc
The energy spectral distortion parameter for the long-lived spallation background

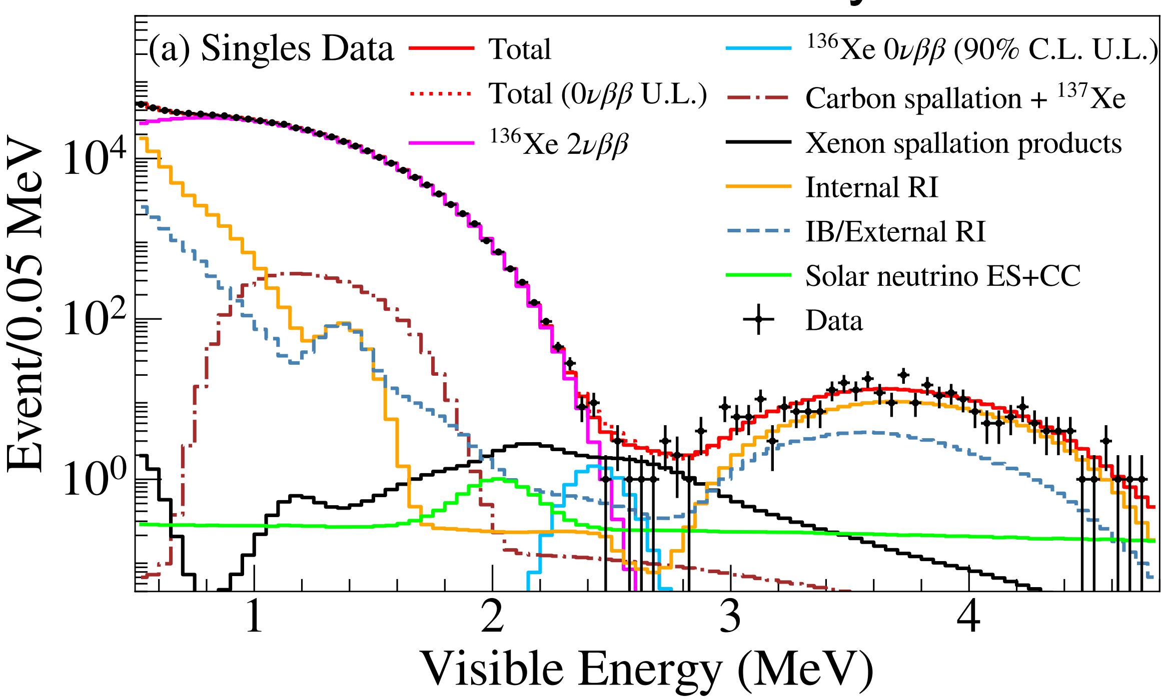
Constraint:
^{222}Rn-^{210}Pb sub-chain of the ^{238}U series, short- lived spallation products etc
Detector energy response parameters

^{136}Xe Half-life limit (KL-Zen 800)

Internal 10 volume bins (1.57-m-radius spherical volume) × 3 time bins

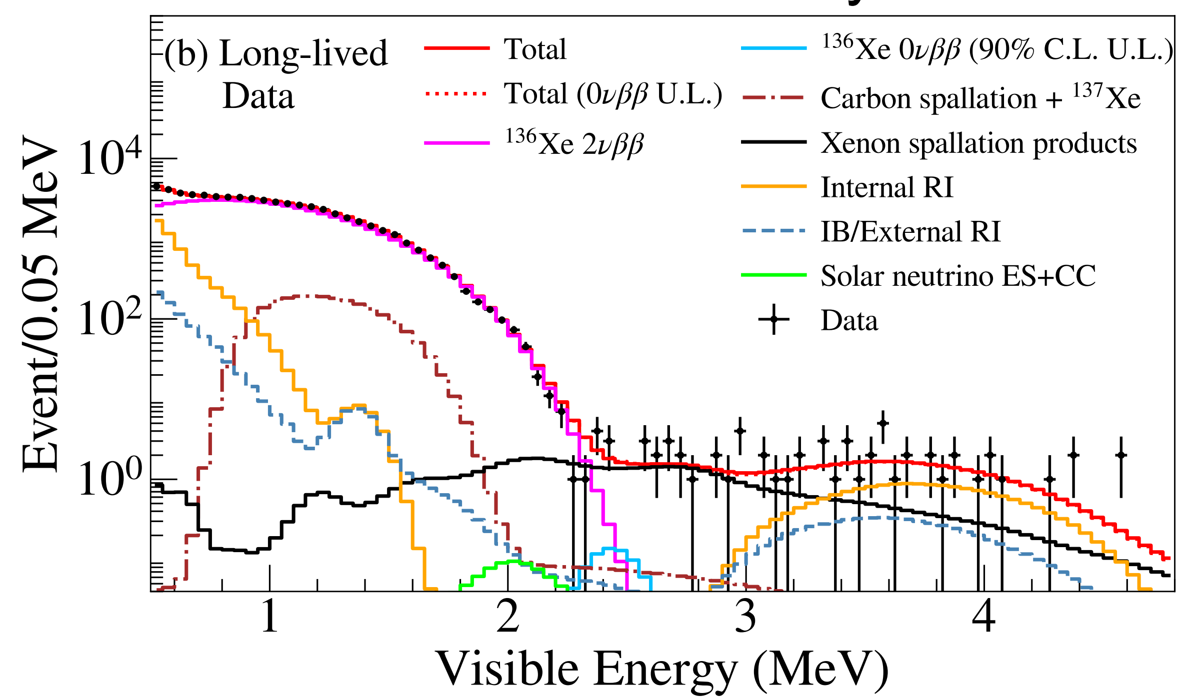
Singles data
(sensitive to 0νββ rate)

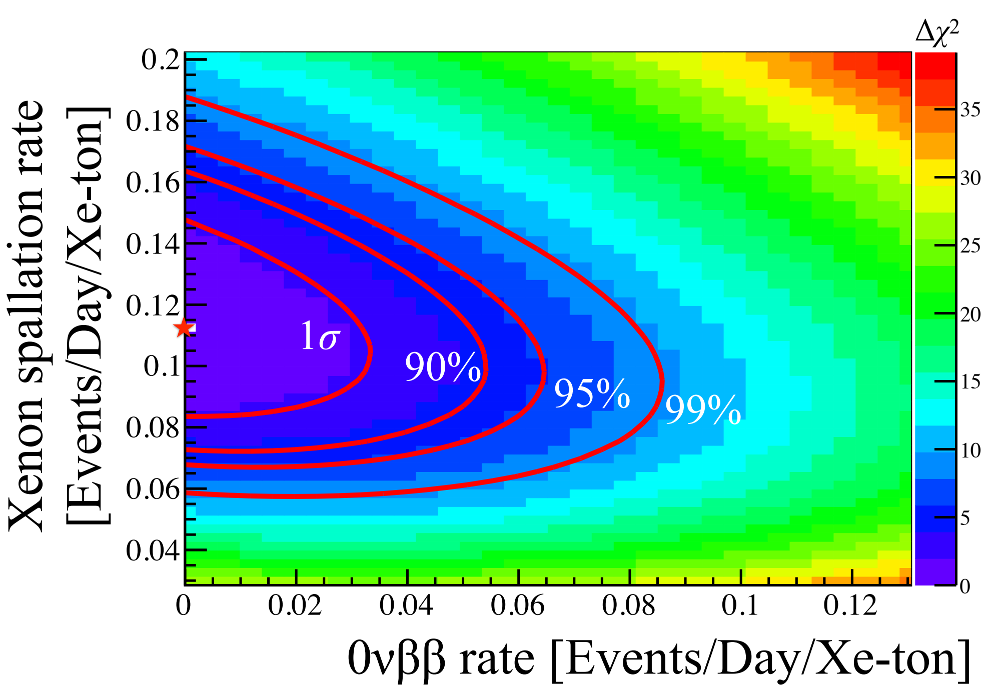
Livetime = 523.4 days



Long-lived product data
(used to constrain the LL rate)

Livetime = 49.3 days



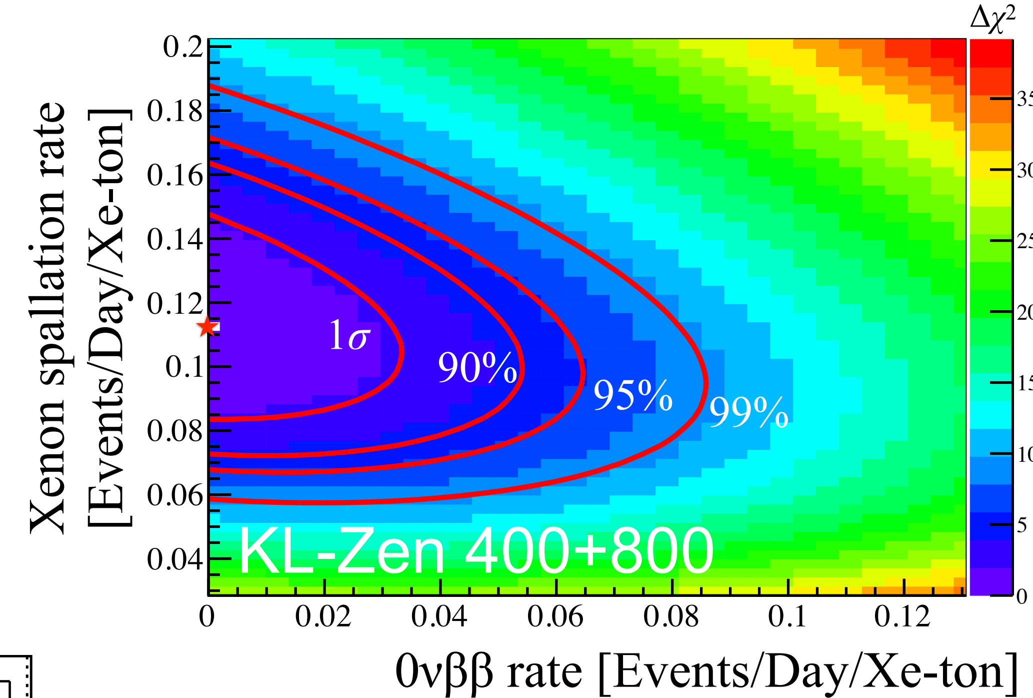


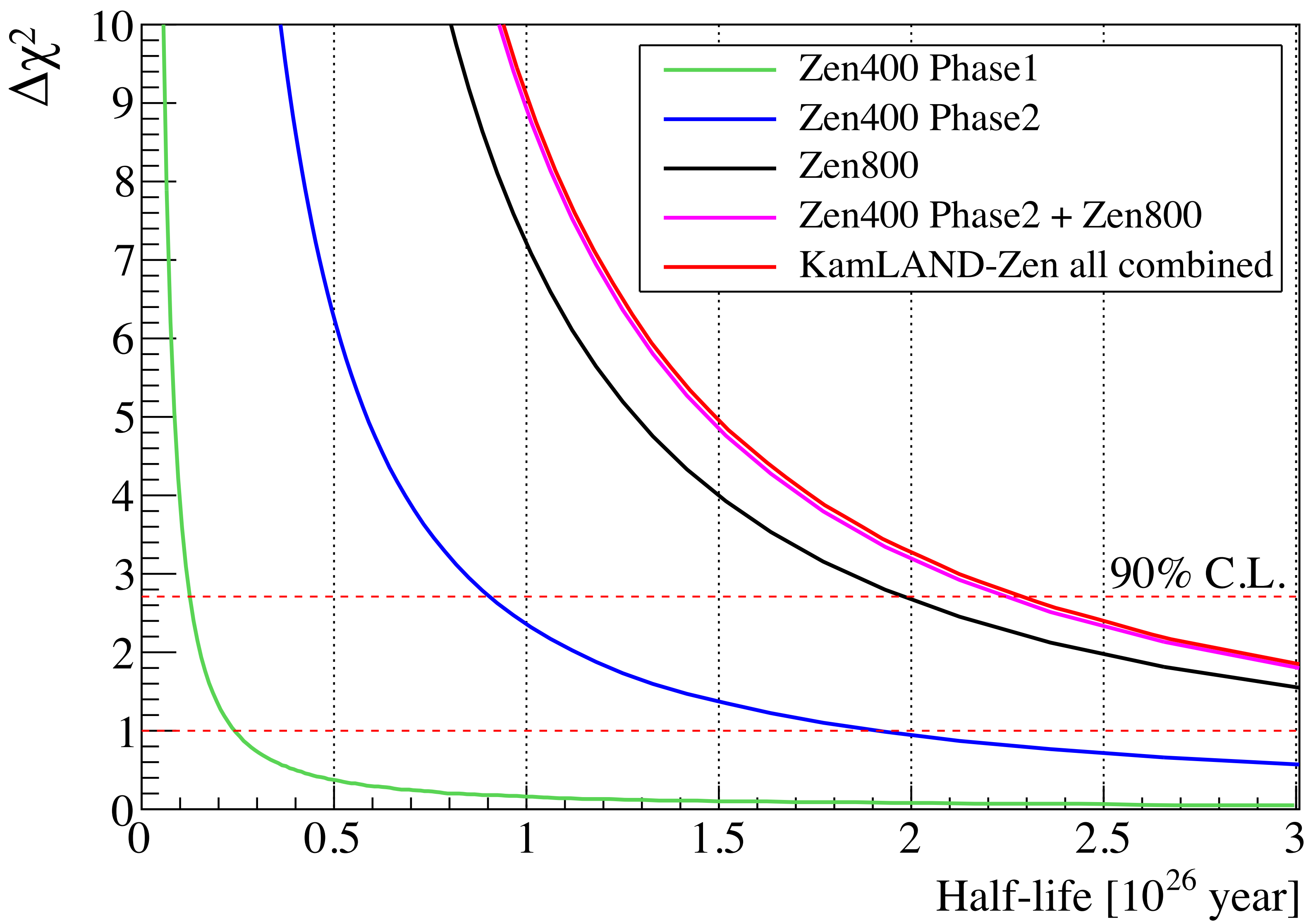
^{136}Xe 0νββ decay rate for KamLAND-Zen 800
Best fit rate = 0
Upper limit (90% C.L.): < 7.9 events/Xe-LS(30.5 m^3)

$T^{1/2} > 2.0\times10^{26}$ yr (90% C.L.)

^{136}Xe Half-life limit (KL-Zen 400 + 800)

KamLAND-Zen 400 data is reanalyzed with updated background rejection techniques and long-lived spallation consideration.





Combined result (90% C.L.)

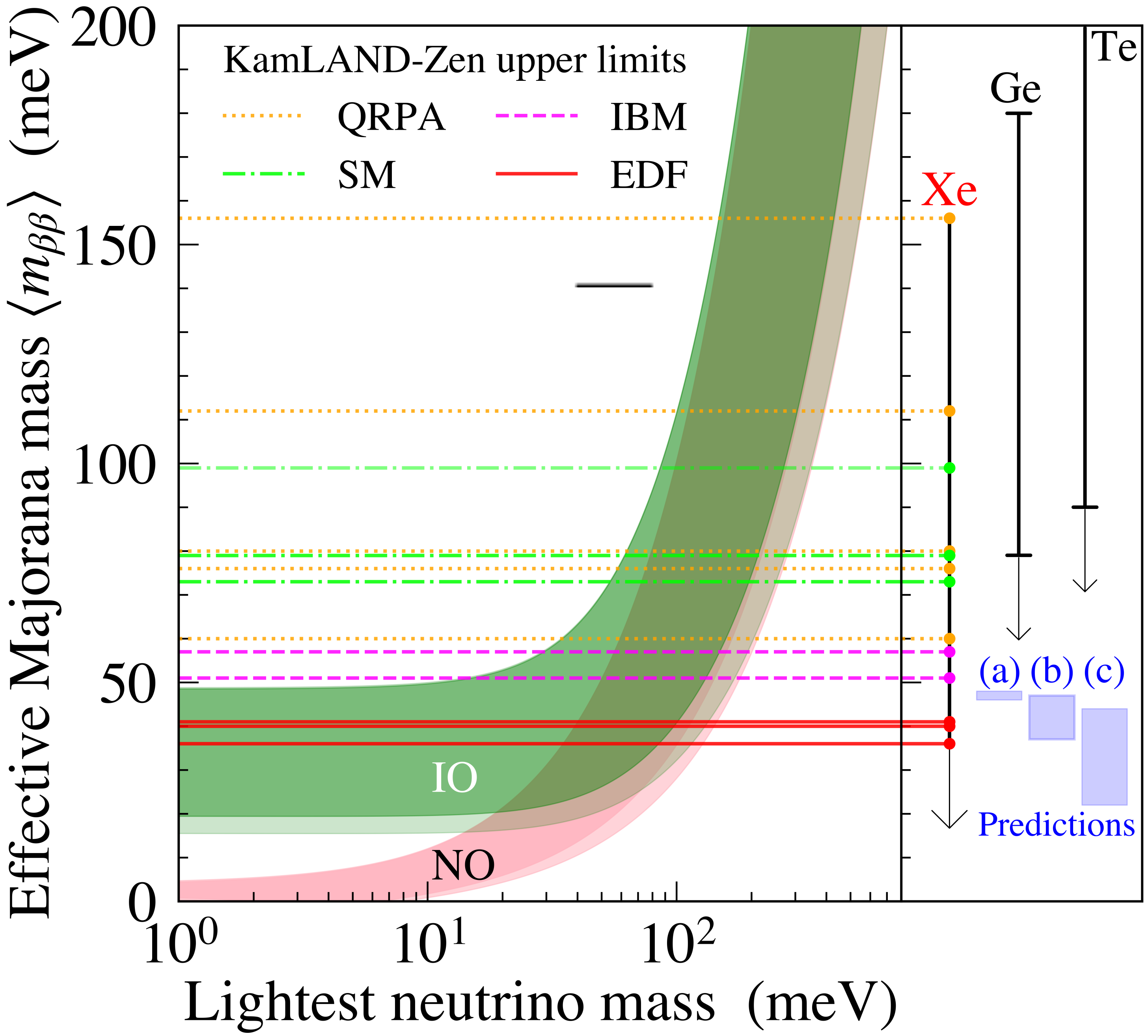
$T^{1/2} > 2.3\times10^{26}$ yr

Sensitivity (90% C.L.)

$T^{1/2} > 1.5\times10^{26}$ yr

The probability of obtaining a stronger limit : 23%

Limit on the effective neutrino mass



$T^{1/2}$ > 2.3×10^{26} yr

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

NME ($M^{0\nu}$) : 1.11–4.77

assuming gA ~ 1.27

⟨$m_{\beta\beta}$⟩ < 36-156 meV

First search for inverted mass ordering

Experimental limit for Ge & Te:
(Ge) GERDA: Phys.Lett. **125** 252502
(Te) CUORE: arXiv: 2104.06906v1

Theoretical predictions:
(a) Phys. Rev. D 86, 013002
(b) Phys. Lett. B 811, 135956
(c) Euro. Phys. J. C 80, 76

Near future improvement

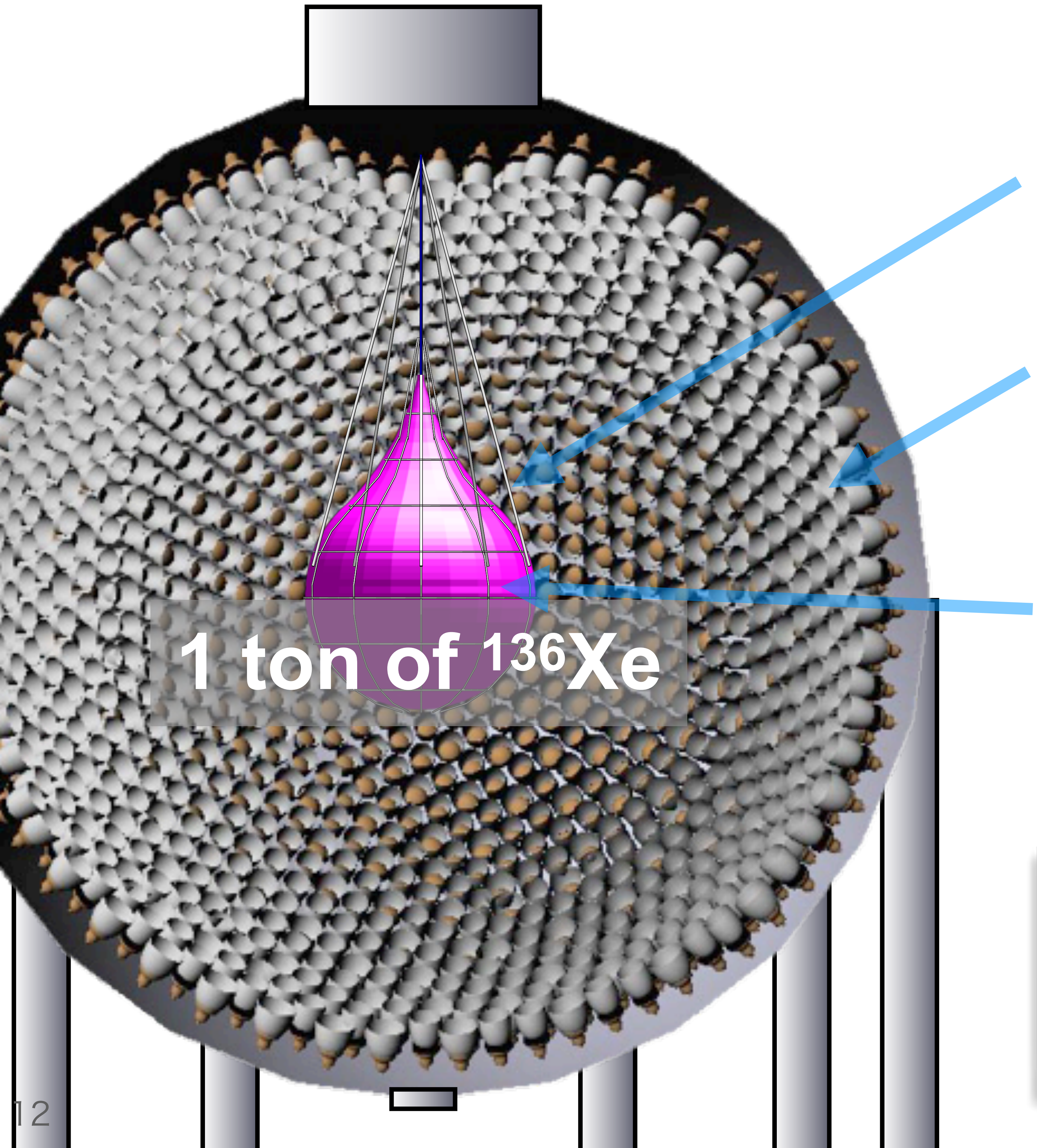
- Upgraded electronics
- PID with neural networks
  arXiv:2203.01870v1[physics.ins-det]
- Update waveform analysis tool
- New Energy & vertex fitter with machine learning

Future: KamLAND2-Zen

KamLAND → KamLAND2

Enlarge opening

General use: accommodate various devices such as $CdWO_4$, NaI, CaF_2 detectors



New electronics

To improve background suppression.
Tagging long lived isotope from cosmic ray spallation.

Scintillation inner balloon

BG reduction from Xe-LS container

R&D paper: PTEP. Volume 2019, Issue 7, 073H01

Winstone cone & High QE PMT

Improve light collection efficiency and photo coverage

Brighter LS

Current LS ~8,000 photon/MeV
LAB based new LS ~12,000 photon/MeV

σ(2.6MeV) = 4% → ~2%

Target $\langle m_{\beta\beta} \rangle$ ~20 meV in 5 yrs

Summary

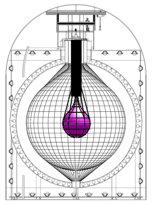
- Neutrinoless double beta decay is a key to search for physics beyond the Standard Model.
- KamLAND-Zen searches for it with ^{136}Xe loaded liquid scintillator.
- KamLAND-Zen 800 1st result: $T^{1/2} > 2.0\times10^{26}$ yr
- Combined result for KamLAND-Zen 400 + 800

$T^{1/2} > 2.3\times10^{26}$ yr, $\langle m_{\beta\beta} \rangle < 36\text{-}156$ meV

Start to search for inverted mass ordering

- KamLAND2-Zen (~1ton of enriched Xenon) is planned to search deeper into inverted hierarchy region of $\langle m_{\beta\beta} \rangle$

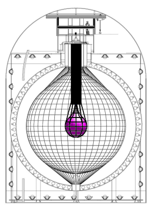
List of publications



KamLAND-Zen 800

1.90-m-radius clean inner balloon, ~750 kg of Xenon (2019-)

1st paper [0νββ]: arXiv:2203.02139v1 [hep-ex], KamLAND-Zen Collaboration
"First Search for the Majorana Nature of Neutrinos in the Inverted Mass Ordering Region with KamLAND-Zen"
Hardware [IB construction]: JINST 16 P08023 (2021), KamLAND-Zen Collaboration
"The nylon balloon for xenon loaded liquid scintillator in KamLAND-Zen 800 neutrinoless double-beta decay search experiment"
Machine learning [KamNet]: arXiv:2203.01870v1[physics.ins-det]
A. Li, Z. Fu, L. Winslow, C. Grant, H. Song, H. Ozaki, I. Shimizu, A. Takeuchi
"KamNet: An Integrated Spatiotemporal Deep Neural Network for Rare Event Search in KamLAND-Zen"



KamLAND-Zen 400

1.54-m-dadius inner balloon
Phase I: 320 kg of Xenon (2011-2012), Phase II: 383 kg of Xenon (2013-2015)

1st paper [0νββ & 2νββ]: Phys. Rev. C 85, 045504 (2012), KamLAND-Zen Collaboration
"Measurement of the double-β decay half-life of ^{136}Xe with the KamLAND-Zen experiment"
2nd paper [0νββ, 2νββ & Majoron]: Phys. Rev. C 86, 021601(R) (2012), KamLAND-Zen Collaboration
"Limits on Majoron-emitting double-β decays of ^{136}Xe in the KamLAND-Zen experiment"
3rd paper [0νββ]: Phys. Rev. Lett. 110, 062502 (2013), KamLAND-Zen Collaboration
"Limit on Neutrinoless Decay of ^{136}Xe from the First Phase of KamLAND-Zen and Comparison with the Positive Claim in ^{76}Ge"
4th paper [excited states]: Nucl. Phys. A 946 (2016) 171–181, KamLAND-Zen Collaboration
"Search for double-beta decay of ^{136}Xe to excited states of ^{136}Ba with the KamLAND-Zen experiment"
5th paper [0νββ & 2νββ]: Phys. Rev. Lett. 117, 082503 (2016), KamLAND-Zen Collaboration
"Search for Majorana Neutrinos Near the Inverted Mass Hierarchy Region with KamLAND-Zen"
6th paper [gA]: Phys. Rev. Lett. 122, 192501 (2019), KamLAND-Zen Collaboration
"Precision Analysis of the ^{136}Xe Two-Neutrino ββ Spectrum in KamLAND-Zen and Its Impact on the Quenching of Nuclear Matrix Elements"

R&D for KamLAND2-Zen

Scintillation balloon: PTEP. Volume 2019, Issue 7, 073H01, S. Obara, Y. Gando, K. Ishidoshiro
"Scintillation balloon for neutrinoless double-beta decay search with liquid scintillator detectors"