International Symposium on
Neutrino Physics and Beyond
Feb, 19-21, 2024, Hong Kong

KamLAND-Zen / Geoneutrino

Hiroko Watanabe,
Research Center for Neutrino Science,
Tohoku University, Japan

KamLAND-Zen Collaboration

* Institutions :
- 5 from Japan
- 8 from US
- 1 from Europe

* ~50 collaborators

Sep 2023 @Obihiro (Hokkaido) + Online

TOHOKU UNIVERSITY

東京大学 THE UNIVERSITY OF TOKYO

大阪大学 OSAKA UNIVERSITY

VIRGINIA TECH.

BERKELEY LAB

MIT

THE UNIVERSITY OF TENNESSEE KNOXVILLE

W

BU BOSTON UNIVERSITY

Nikhef

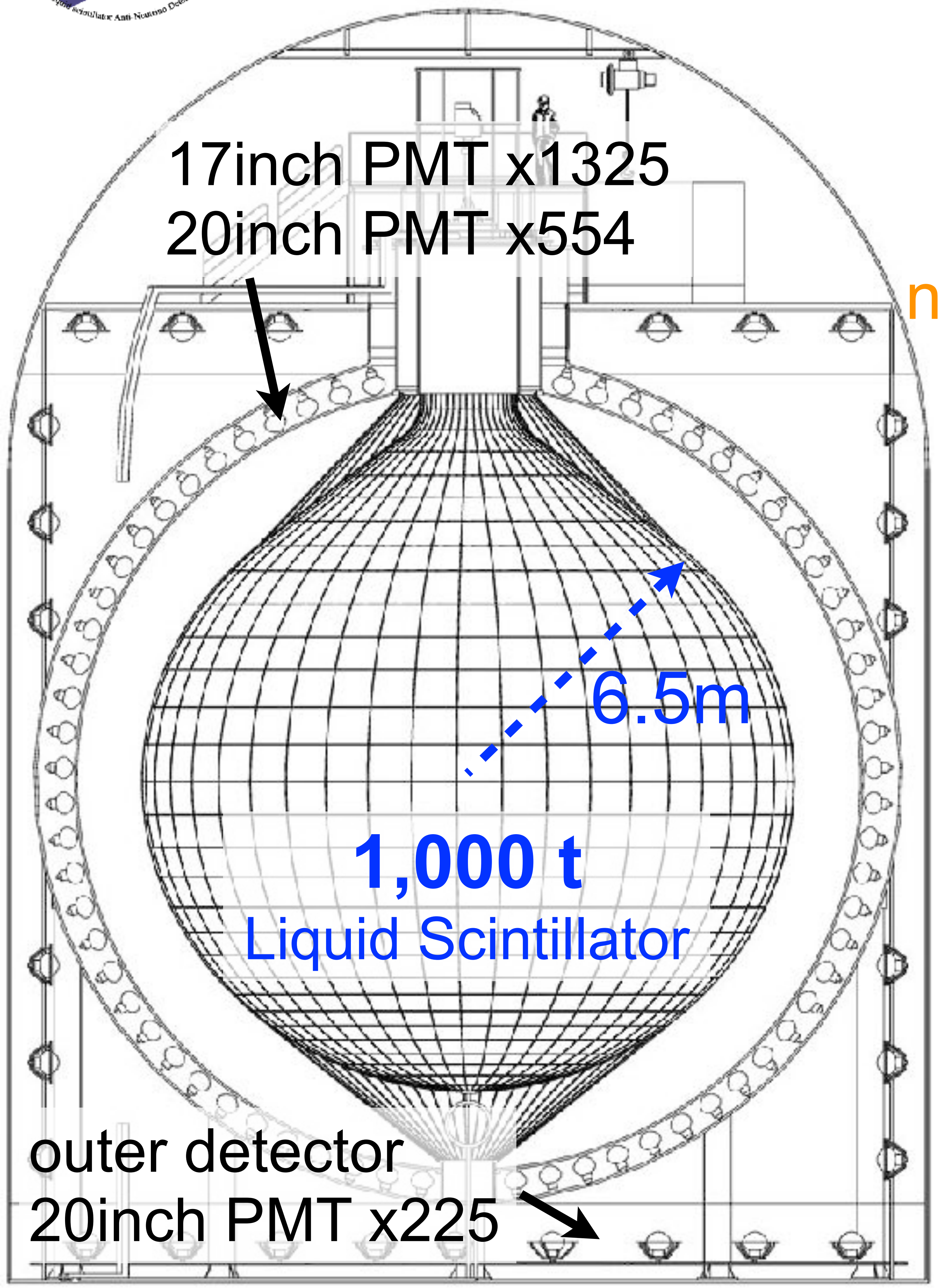
TUNL

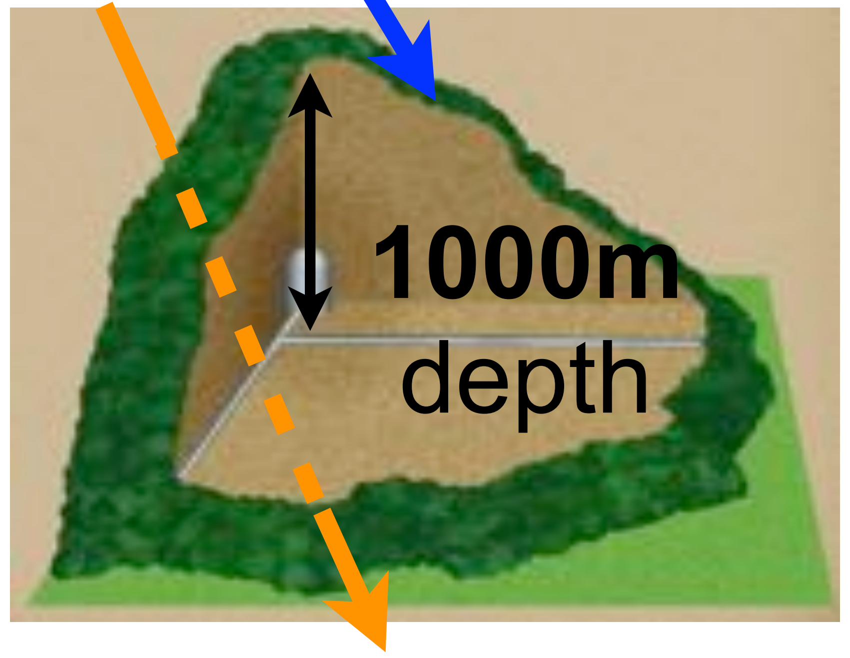
UNIVERSITY of HAWAIʻI

TOKUSHIMA UNIVERSITY

KamLAND

@Kamioka, Japan
2002~

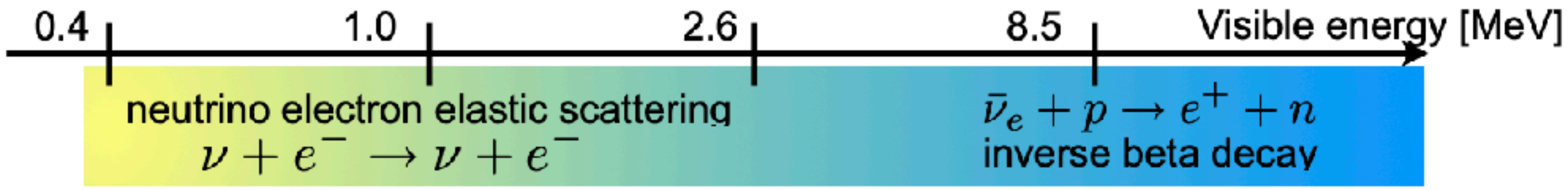


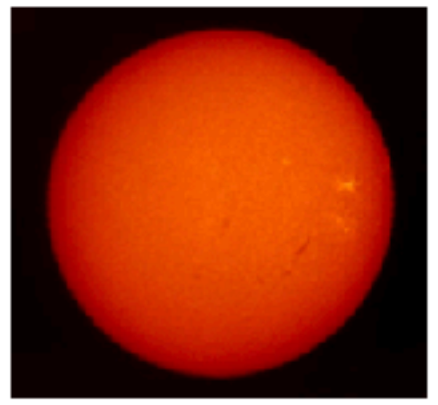


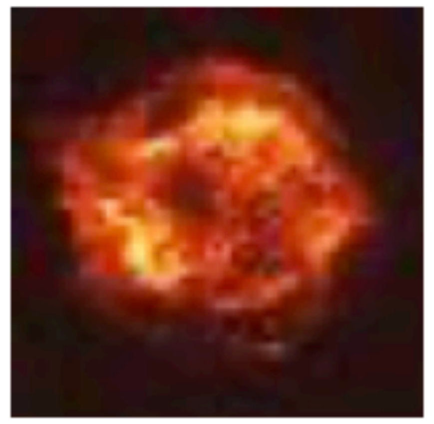
- * 1,000t ultra-pure liquid scintillator (LS)

  ^{232}U: 3.5x10^{-18} g/g, ^{238}Th: 5.2x10^{-17} g/g

- * well-known detector response





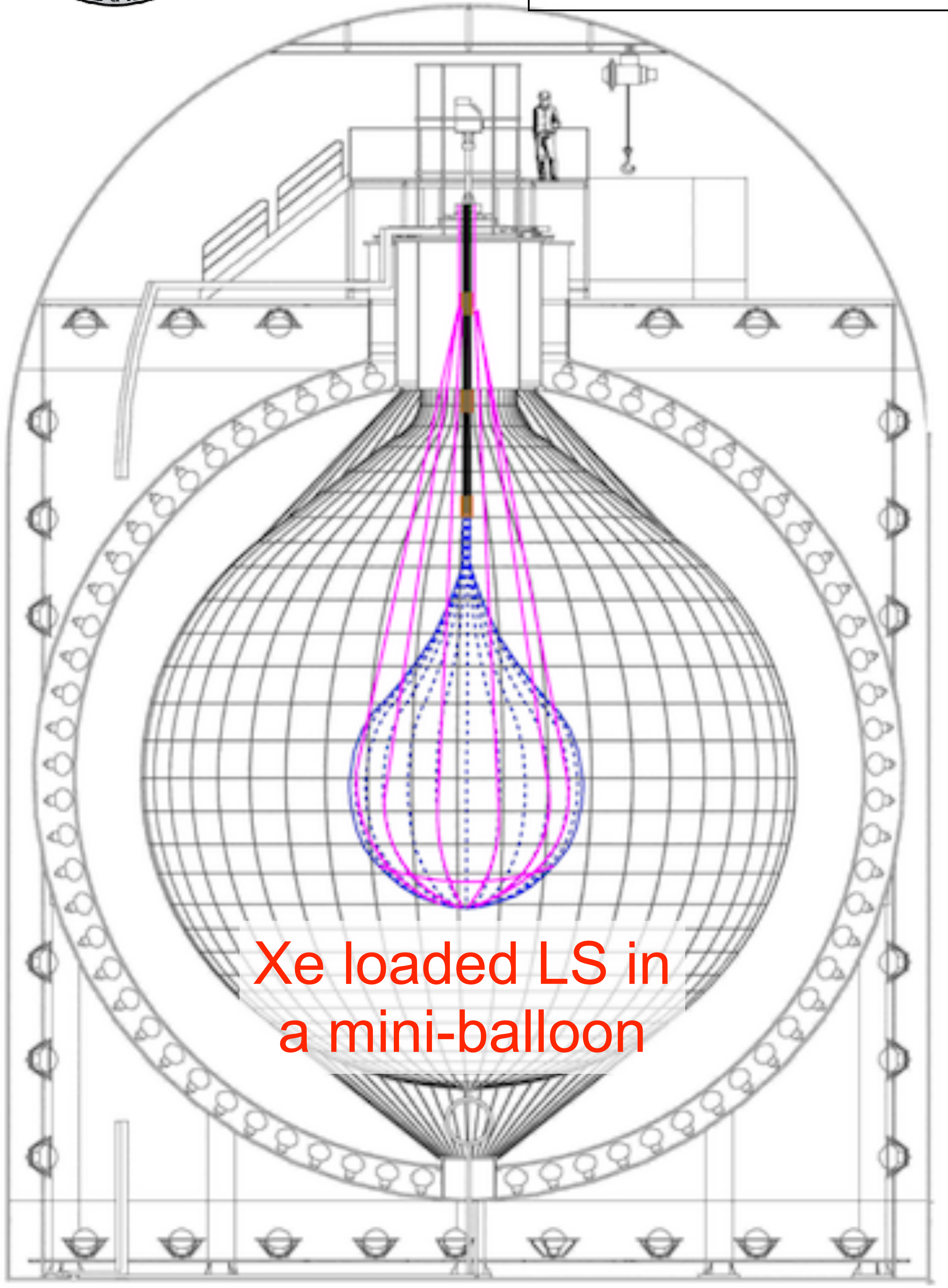
Different neutrino physics in a wide energy range

KamLAND-Zen

KamLAND-Zen

2011~

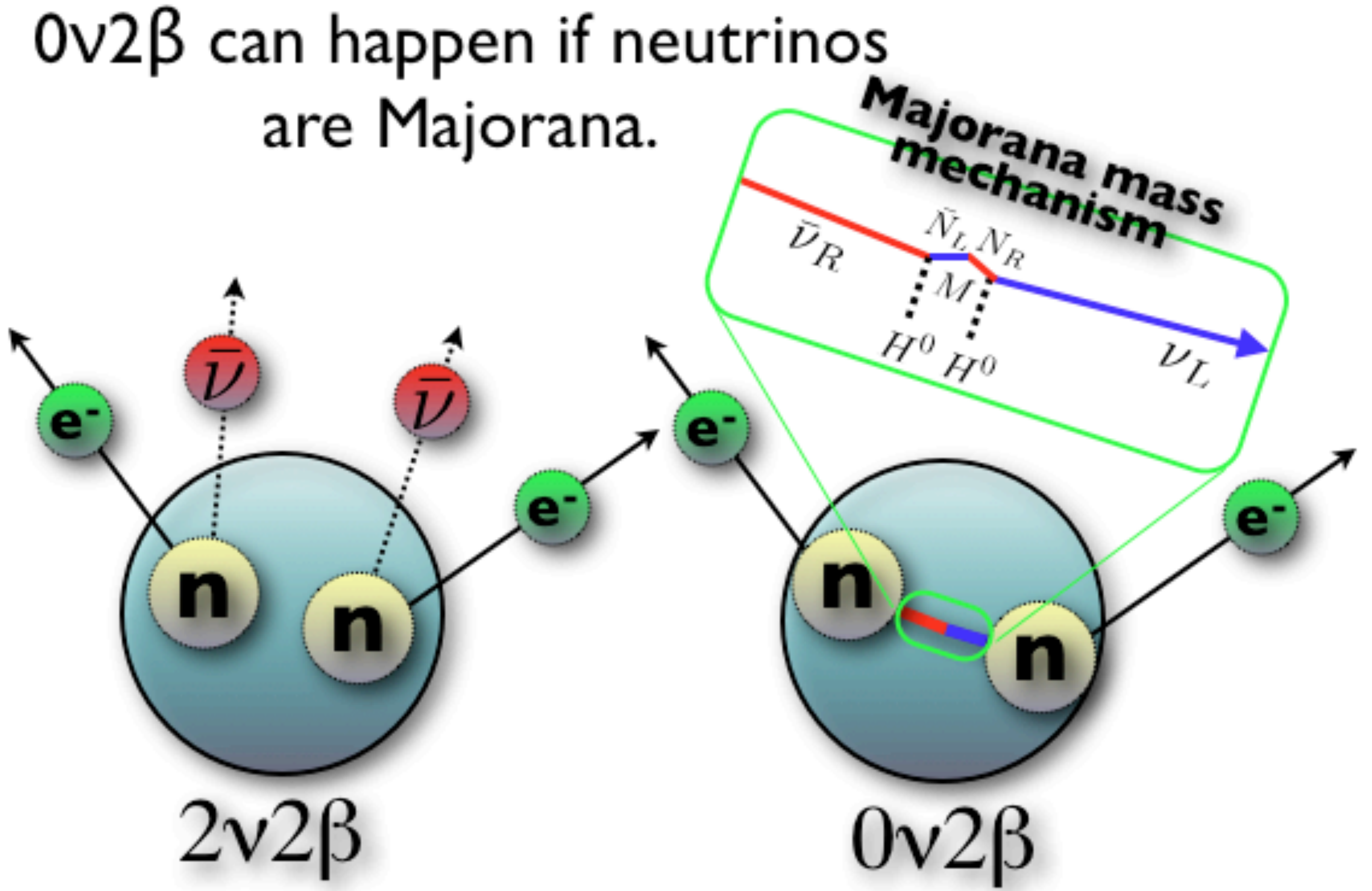
Zero Neutrino
double beta decay search



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

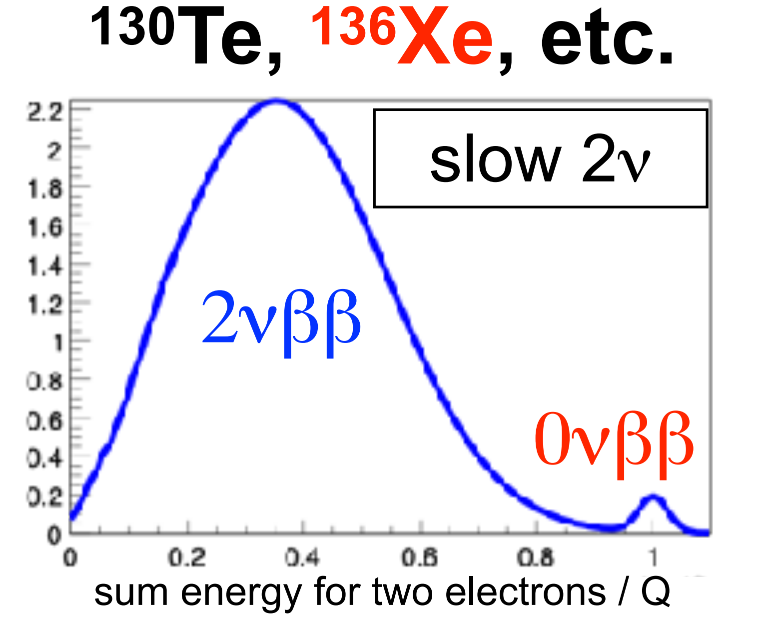
Why Xe? Q-value 2.458 MeV, 2νββ $T_{1/2}$~10^{21} yr

- Isotopic enrichment (centrifugal) established
- Gas purification is possible
- Soluble to LS more than 3 wt%, easily extracted
- Slow 2νββ requires modest energy resolution

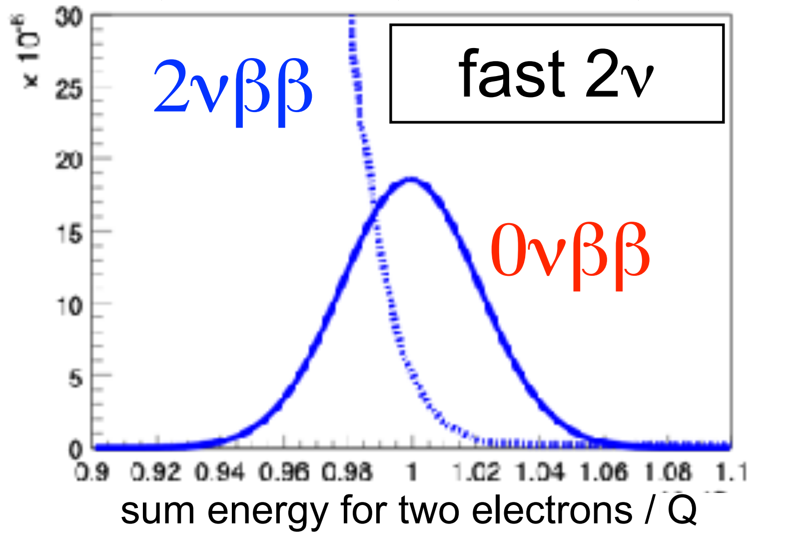


neutrino-less double beta decay

^{130}Te, ^{136}Xe, etc.



^{48}Ca, ^{116}Cd, ^{150}Nd, etc.

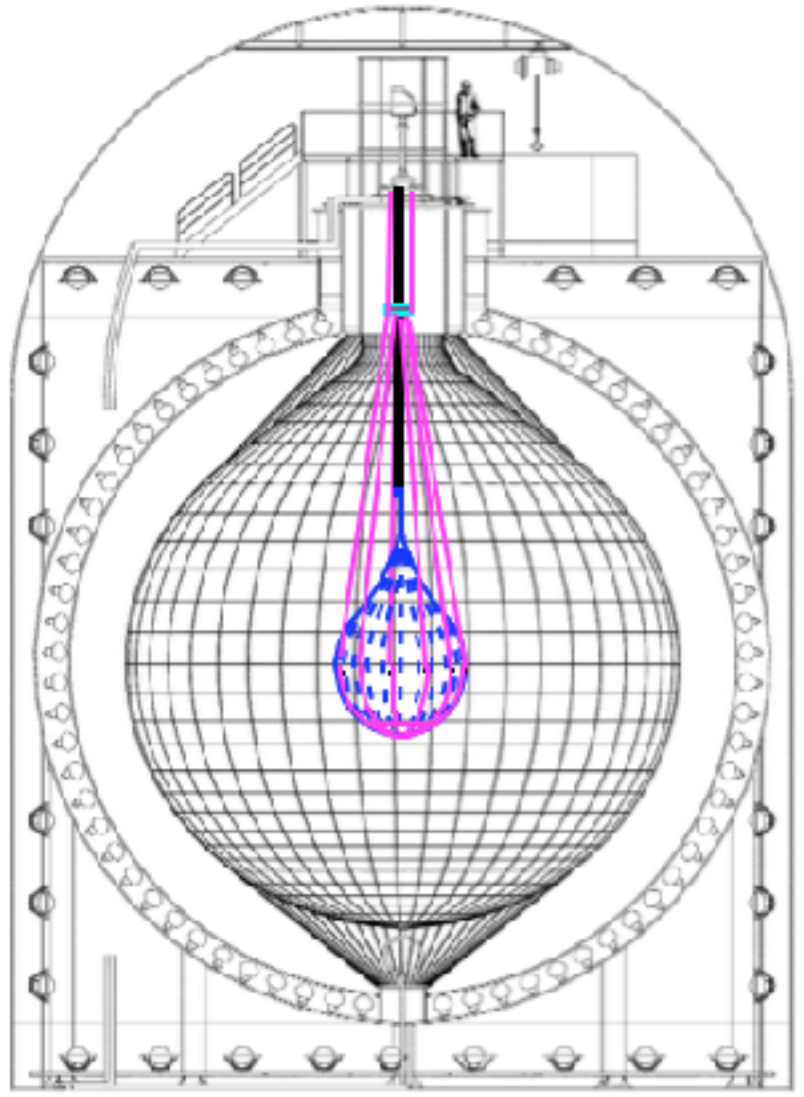


Continue to measure neutrinos with KamLAND LS volume outside of mini-balloon

KamLAND-Zen: upgrades

Past

2011-2015



KamLAND-Zen 400

Nylon balloon R 1.54 m

Xenon 320 − 380 kg

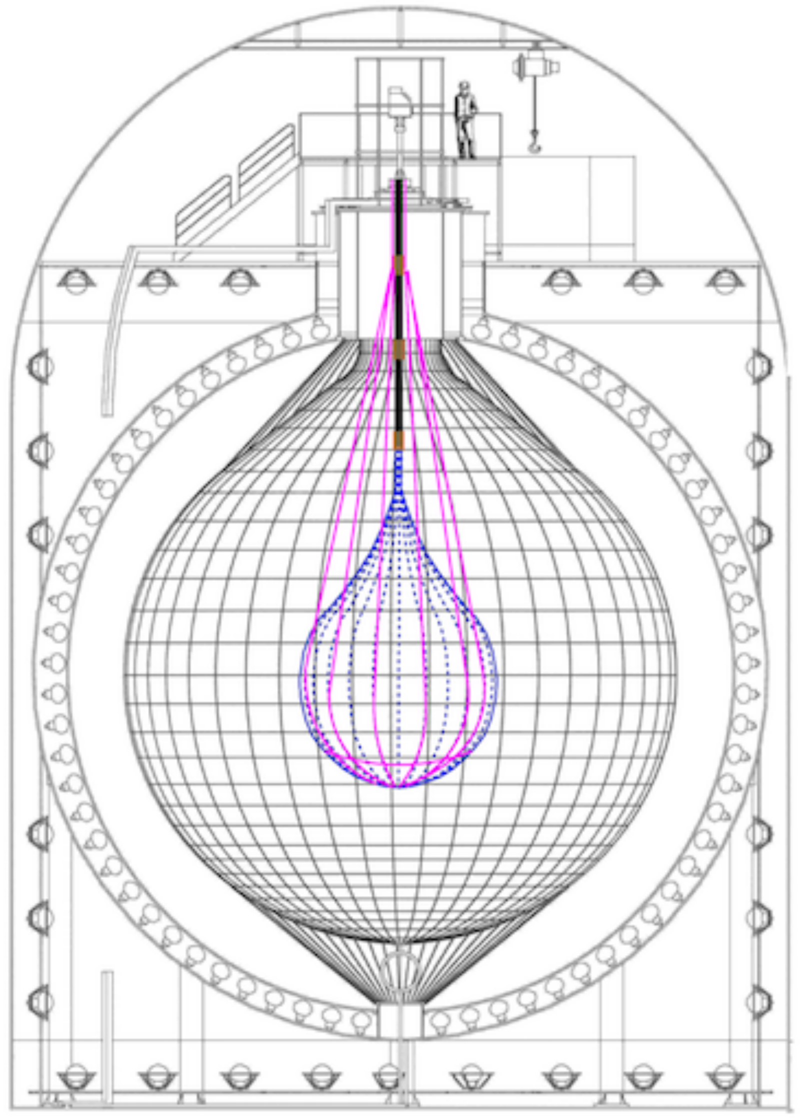
world top performance

$\langle m_{\beta\beta} \rangle < 61\text{–}165\ \mathrm{meV}$

Phys. Rev. Lett. 117, 082503 (2016)

Present

2019-**2024**



KamLAND-Zen 800

Nylon balloon R 1.90 m

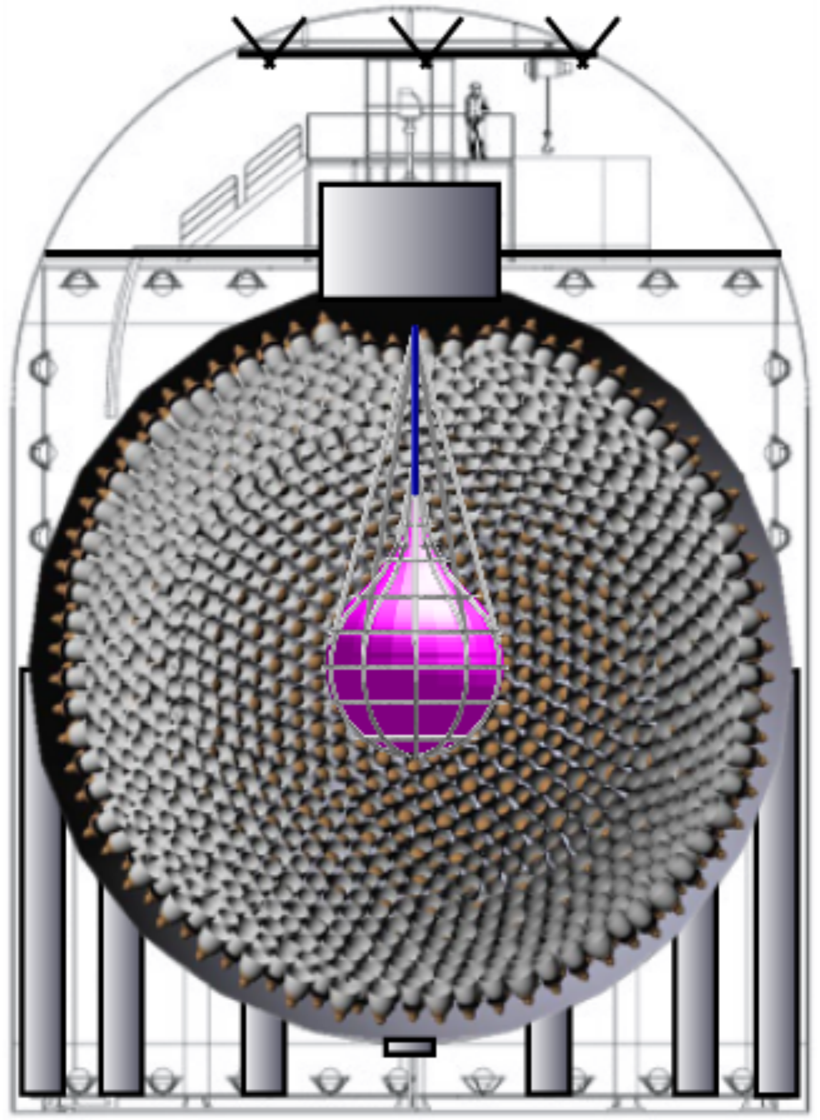
Xenon 745 kg

target $\langle m_{\beta\beta} \rangle \sim$ **40 meV**

reduced radioactive BG

demonstration of scalability

“Near” Future



KamLAND2-Zen

Xenon 1 ton

target $\langle m_{\beta\beta} \rangle \sim$ **20 meV**

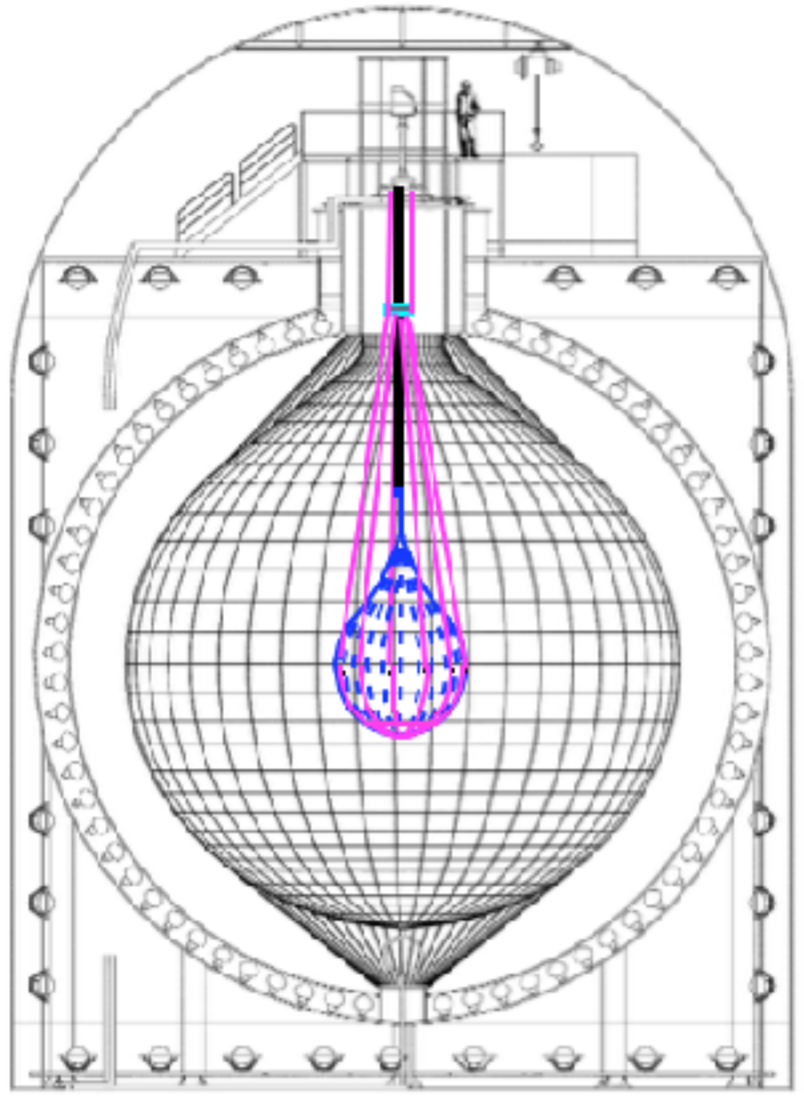
high light yield

better performance

KamLAND-Zen: upgrades

Past

2011-2015



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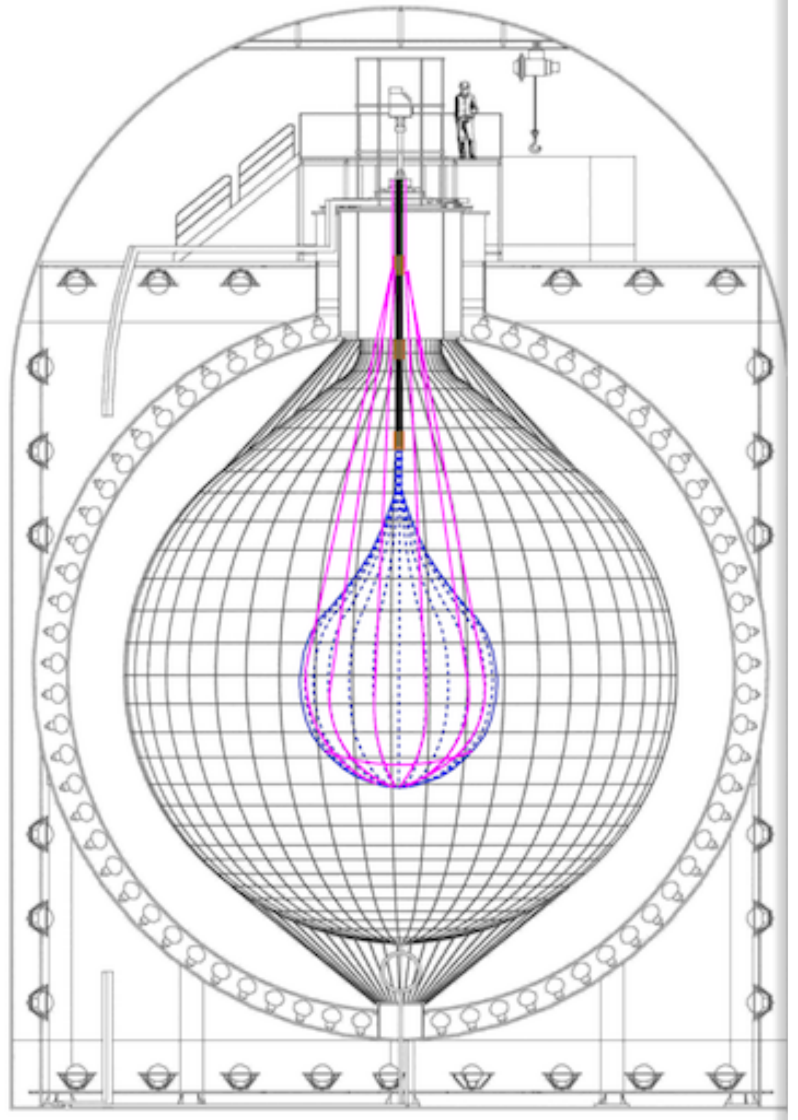


KamLAND-Zen 8

Nylon balloon R 1.90

Xenon 745 kg

target $\langle m_{\beta\beta} \rangle$ ~ **40 me**

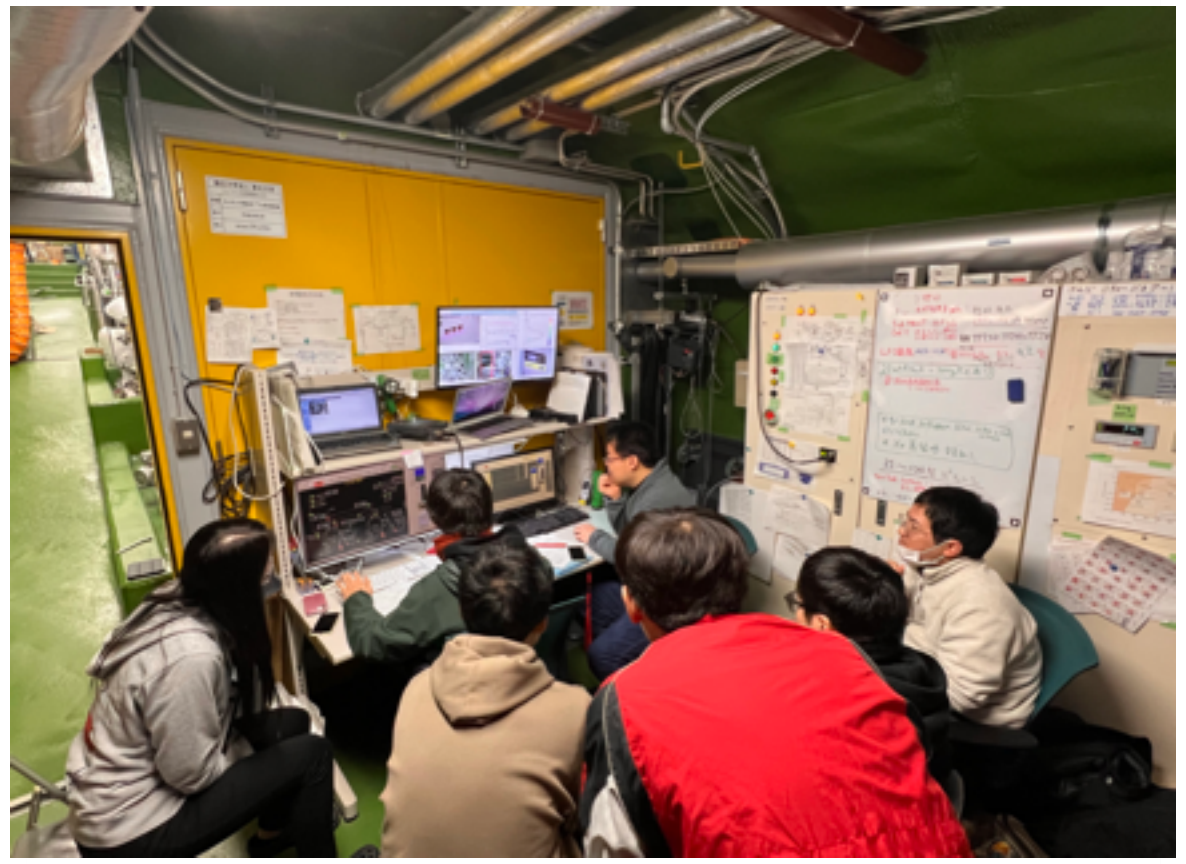
reduced radioactive

demonstration of scal

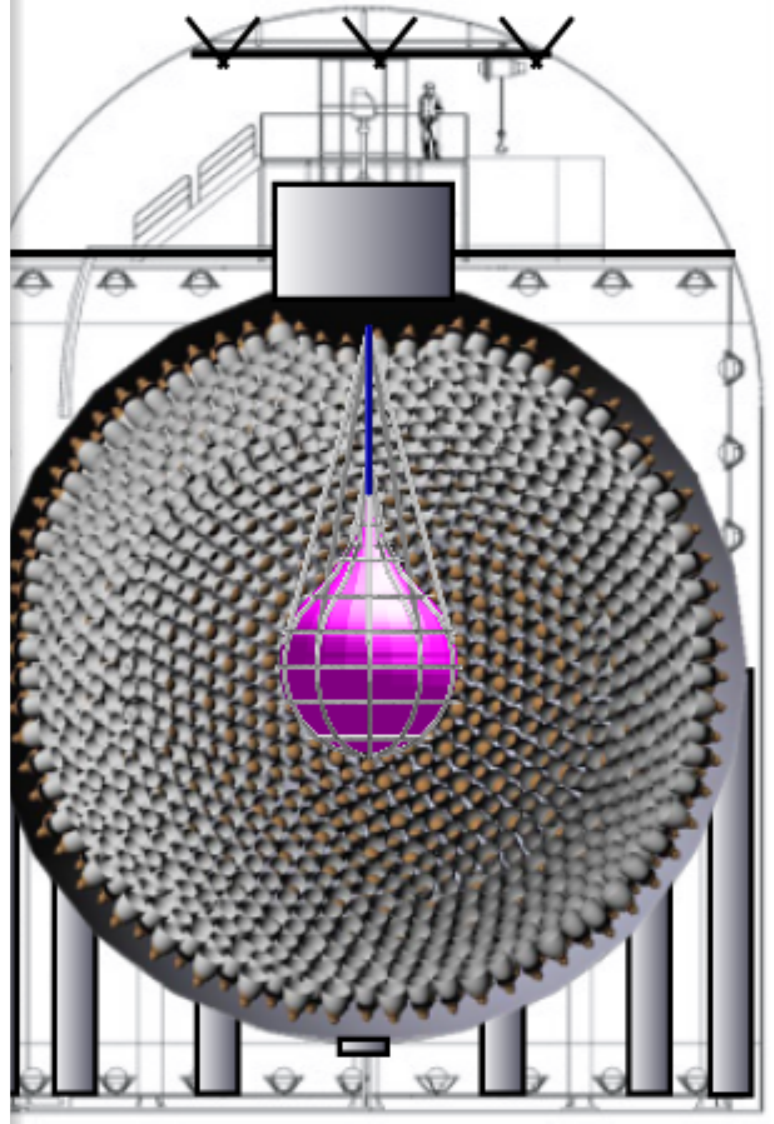
Jan, 2024
completed operation!

preparation for Xe LS extraction

Xe extraction started



Near” Future



KamLAND2-Zen

Xenon 1 ton

get $\langle m_{\beta\beta} \rangle$ ~ **20 meV**

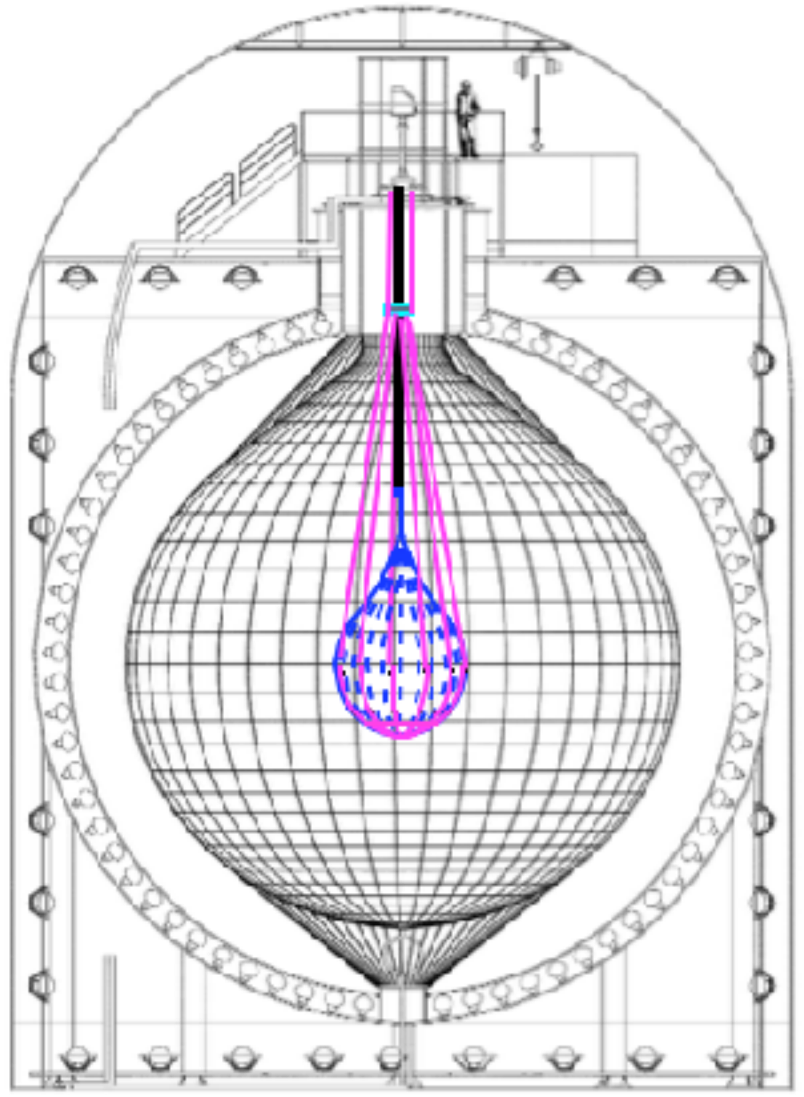
high light yield

etter performance

KamLAND-Zen: upgrades

Past

2011-2015



KamLAND-Zen 400

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Xenon 320 − 380 kg

world top performance

$\langle m_{\beta\beta} \rangle < 61\text{–}165\ \mathrm{meV}$

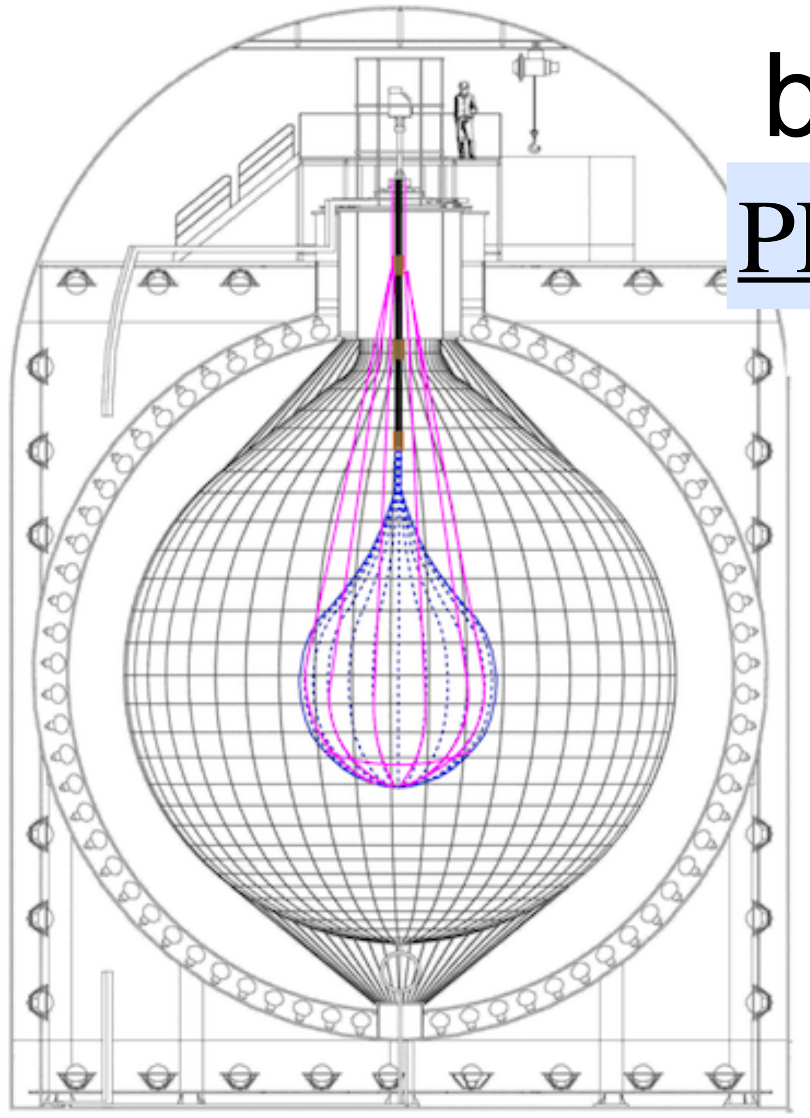
Phys. Rev. Lett. 117, 082503 (2016)

Present

2019-**2024**

This talk

based on PRL 130, 051801 (2023)



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Xenon 745 kg

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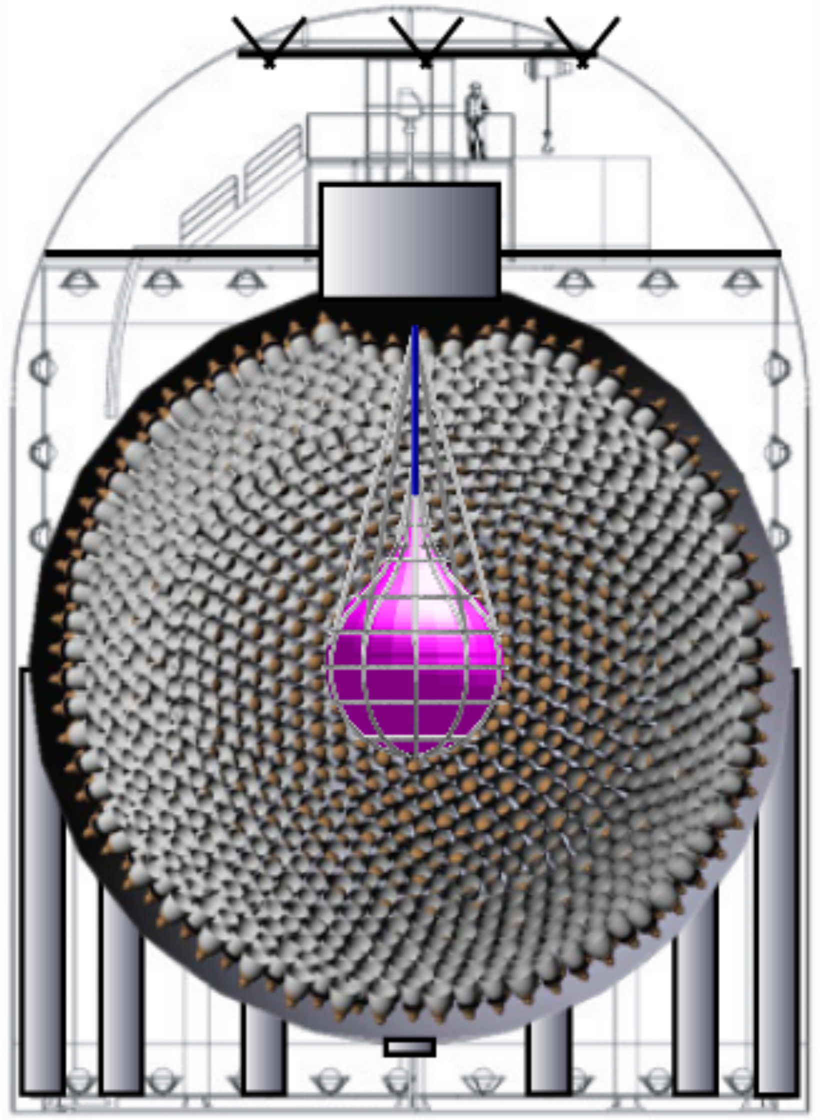
“Near” Future



KamLAND2-Zen

Xenon 1 ton

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

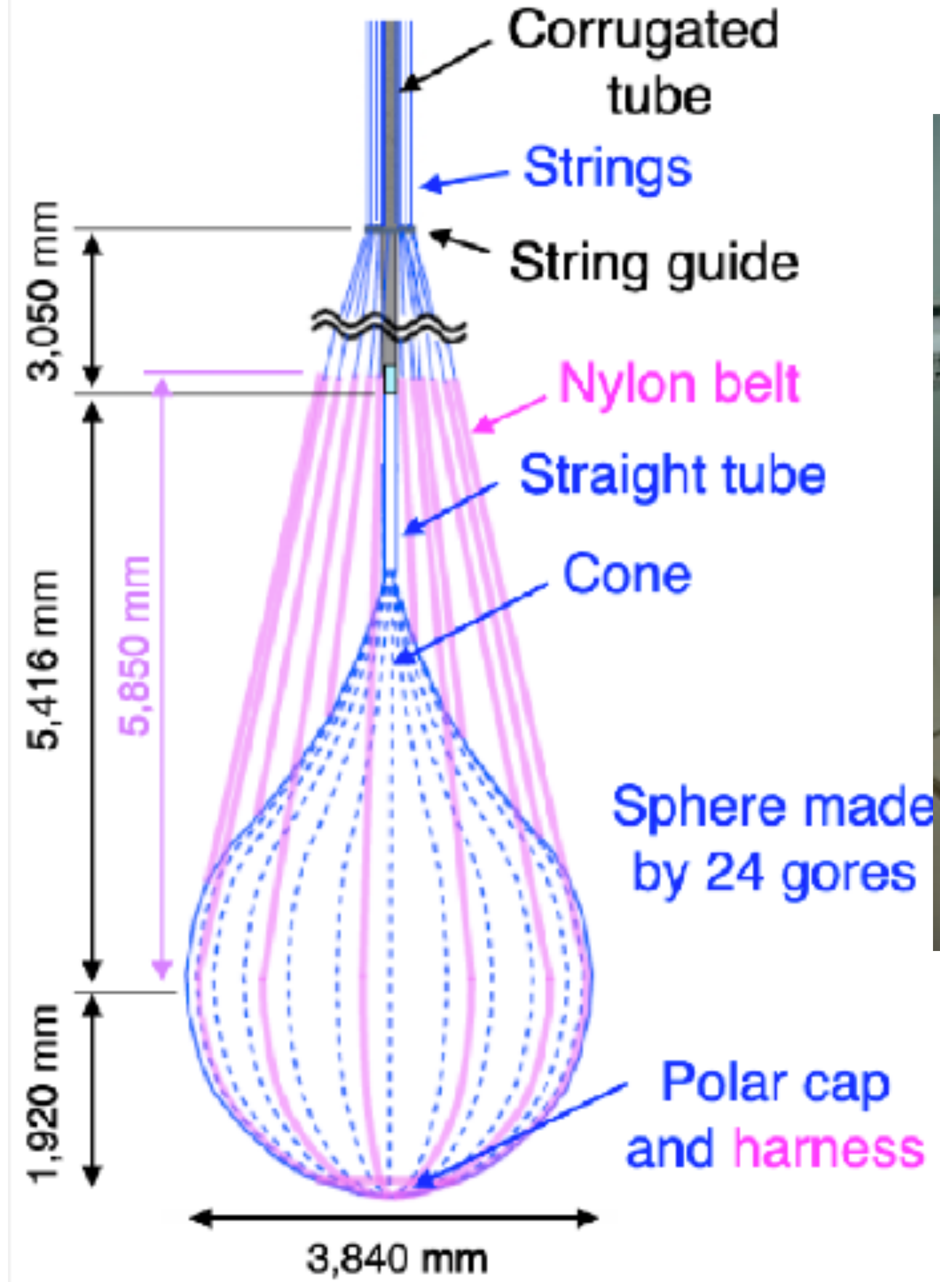
high light yield

better performance

Improvements: cleaner balloon

* Hand-made mini-balloon production at class-1 clean room (>1.5 yr, >20 researchers)

JINST 16, P08023 (2021)

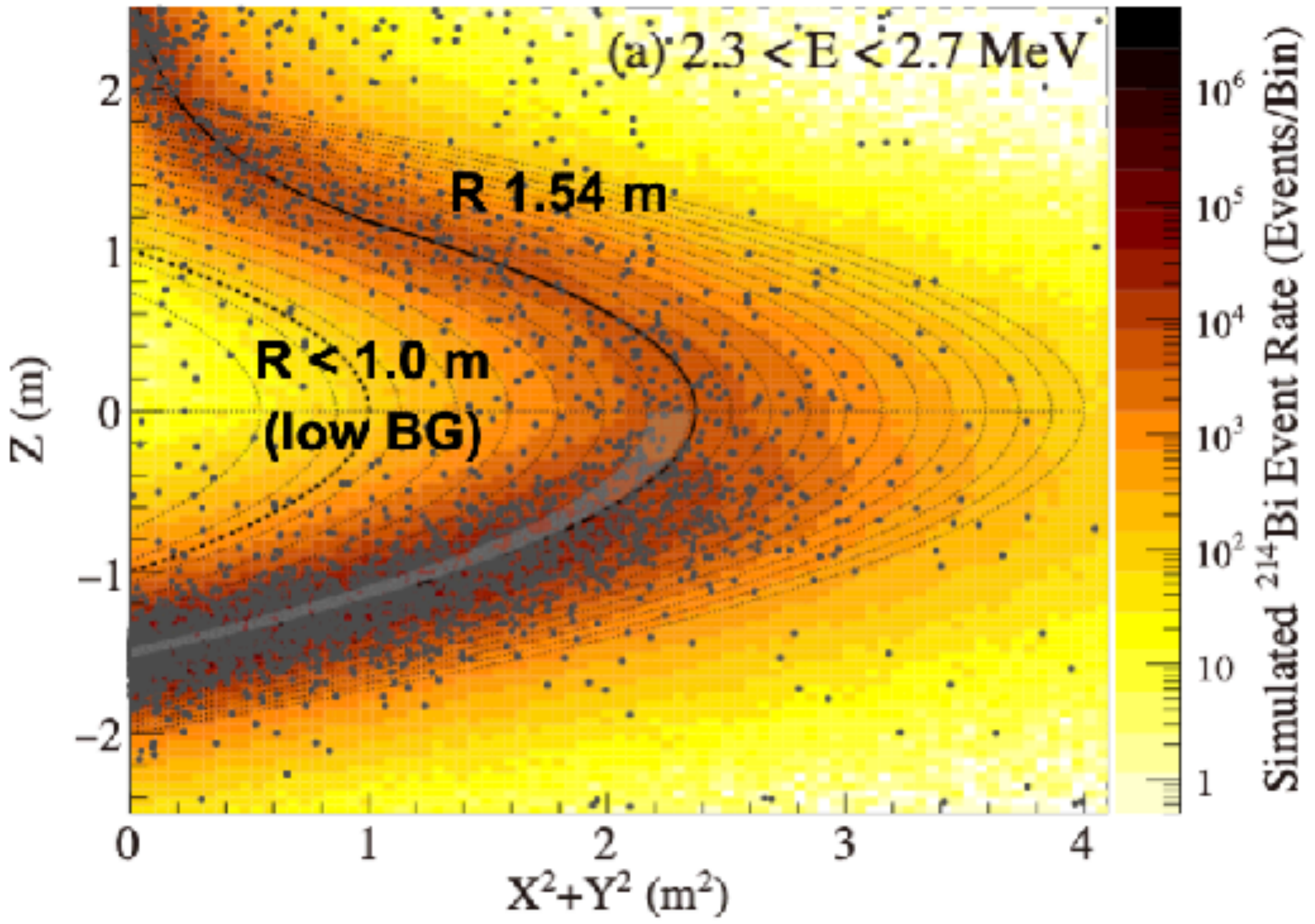


25μm nylon

dust level was carefully controlled
(e.g.: goggle, laundry twice a day, welding machine, more neutralizer, cover sheet…)

*** ×10 reduction of Inner Balloon ^{214}Bi**
*** > ×3 sensitive volume**

* Background reduction & sensitive volume increase

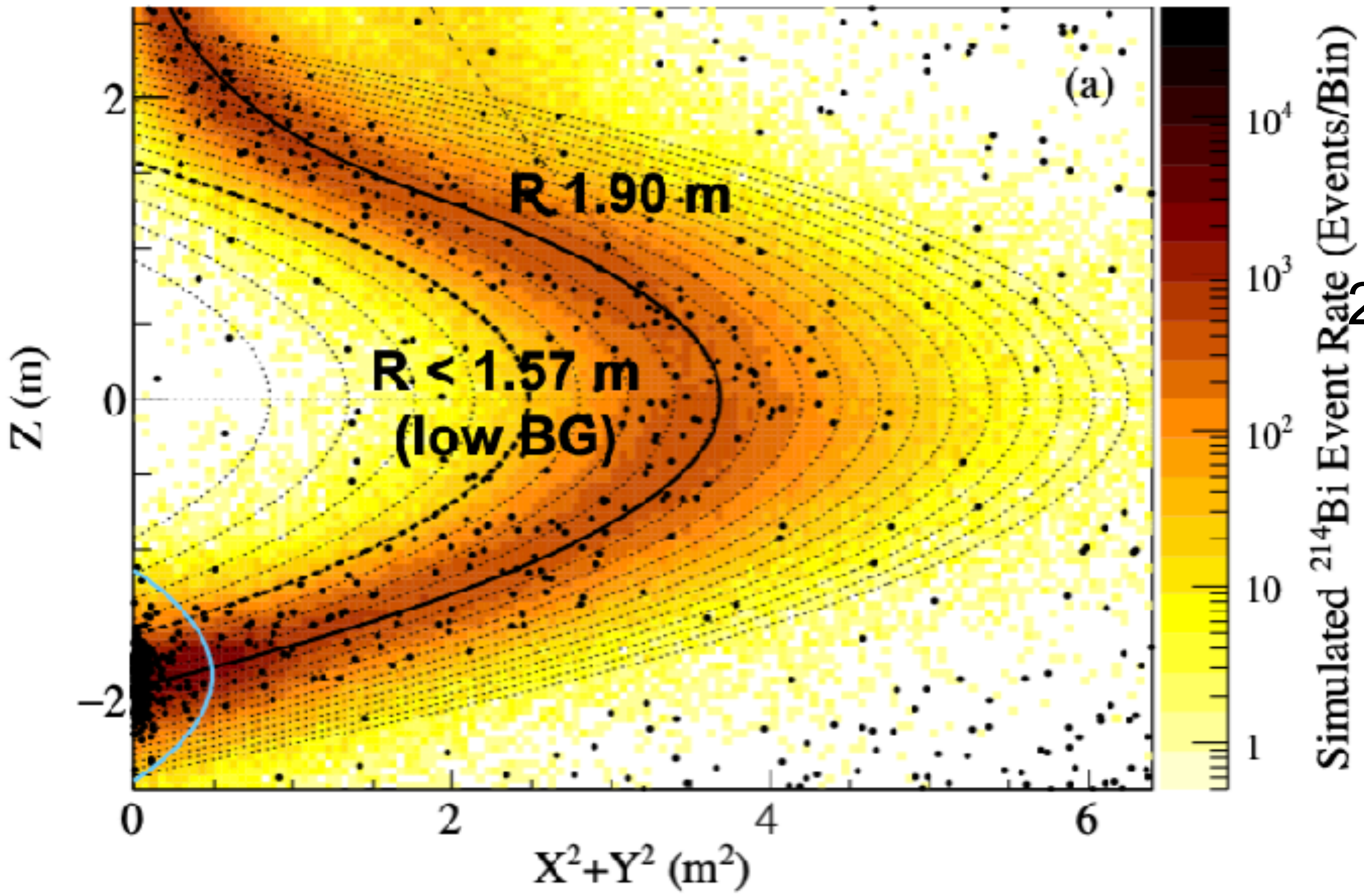


Zen 400 Phase-II

^{238}U : 5×10^{-11} g/g

^{232}Th : 3×10^{-10} g/g

sensitive volume :
R < 1.0 m



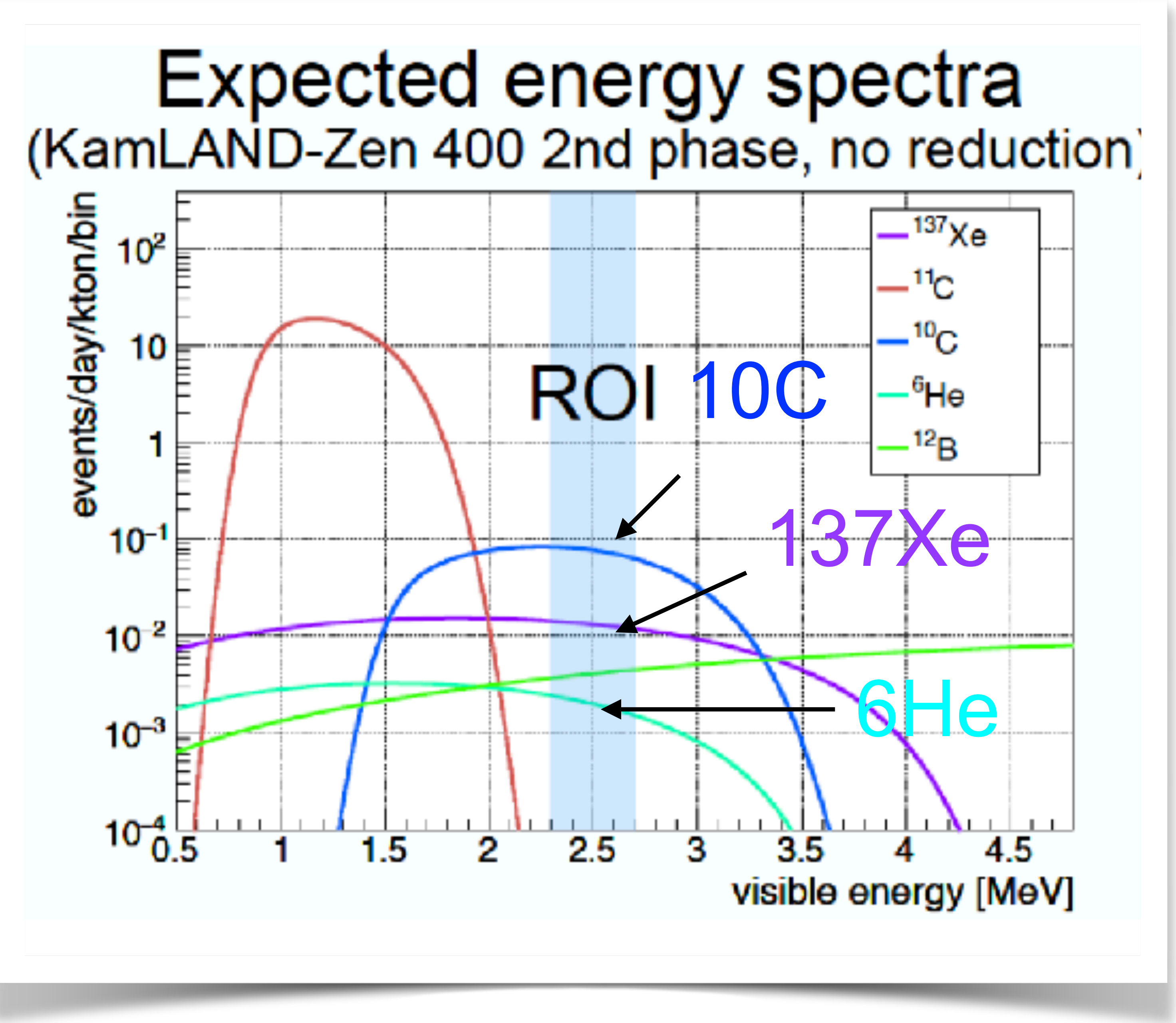
Zen 800

^{238}U : ~3×10^{-12} g/g

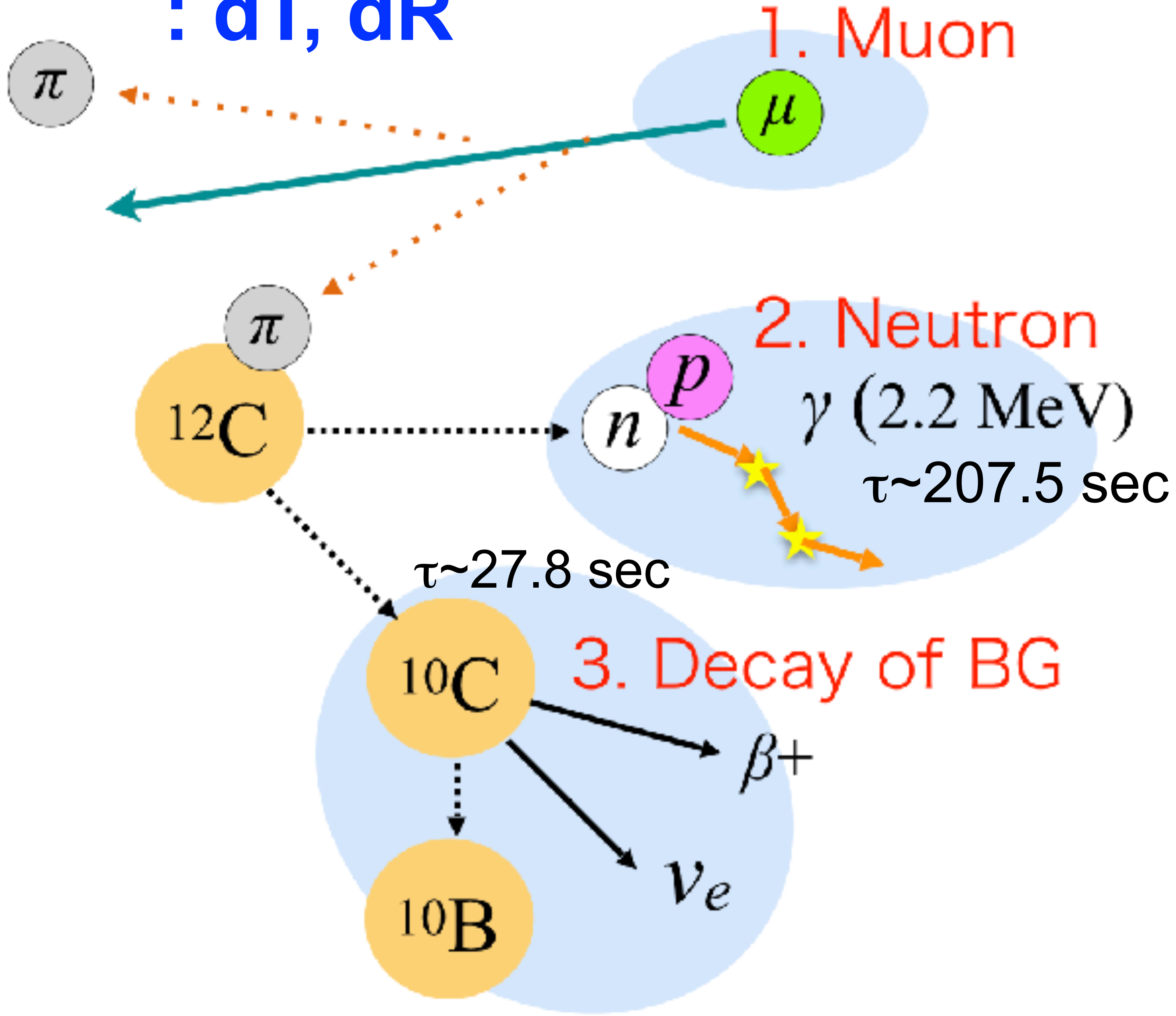
^{232}Th : ~4×10^{-11} g/g

sensitive volume :
R < 1.57 m

Improvements: short-lived spallation backgrounds



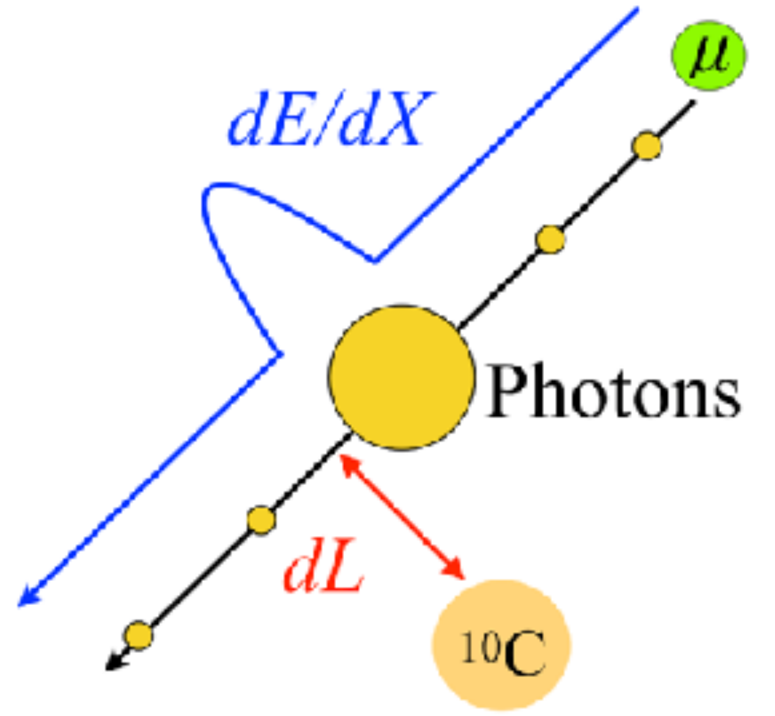
1. Triple coincidence tagging
: dT, dR



time and space correlation
with muon and neutrons

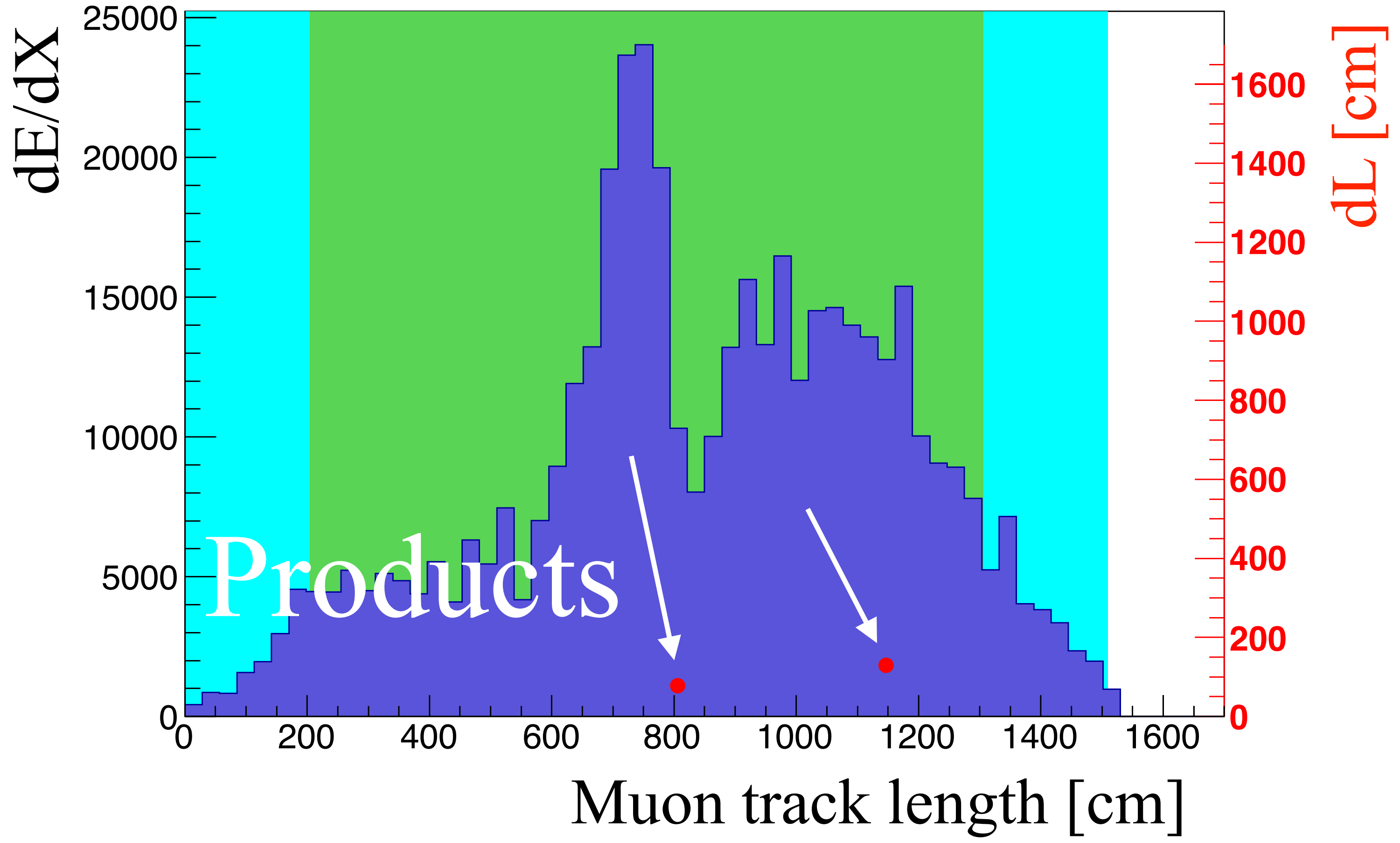
2. Shower tagging
: dE/dX, dL

newly developed



space correlation
with muon shower

likelihood method using muon
energy deposit (dE/dX)



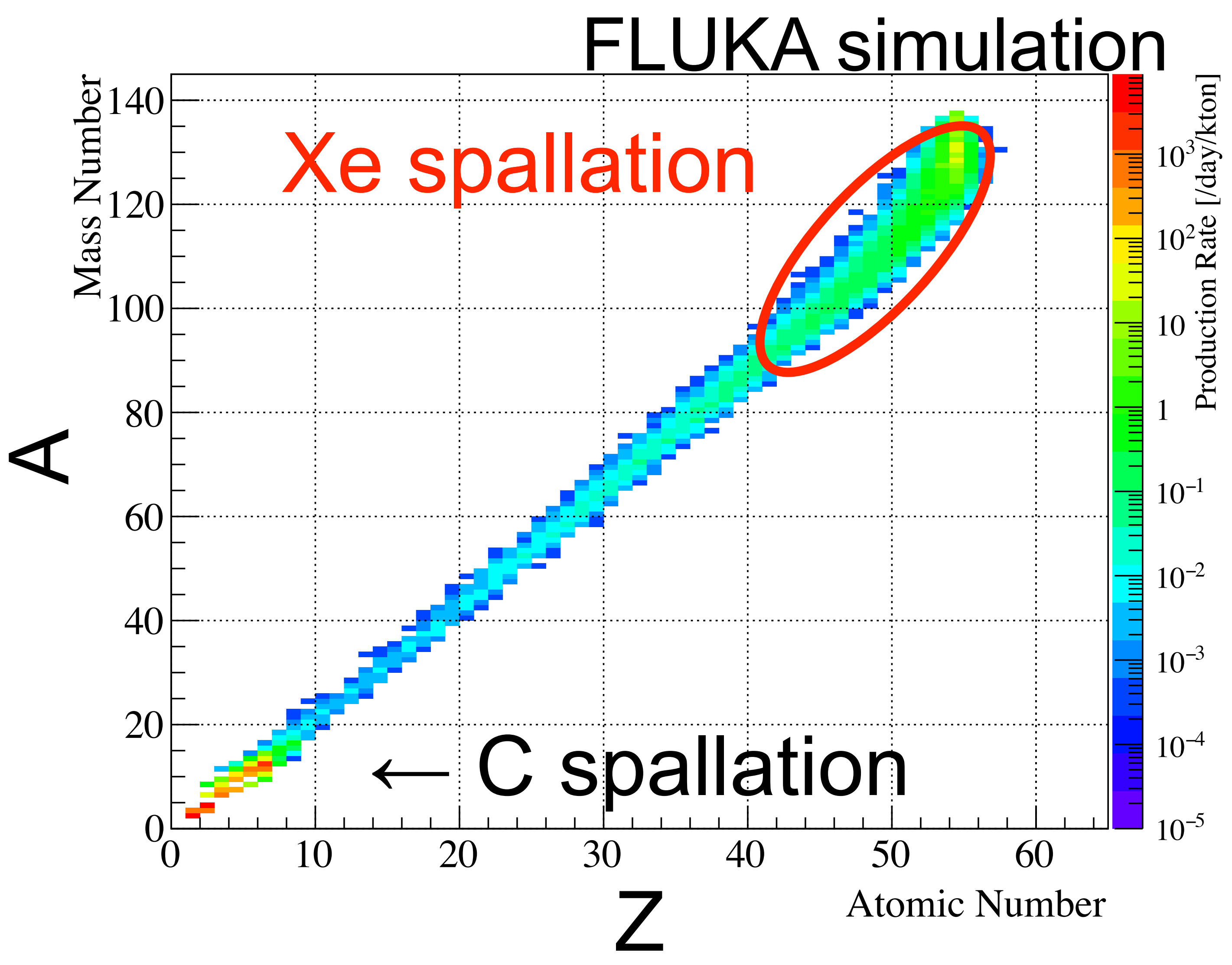
Rejection efficiency: ^{10}C > 99.3 %, ^{6}He 97.6±1.7 %, ^{137}Xe 74±7 %

Improvements: long-lived spallation backgrounds

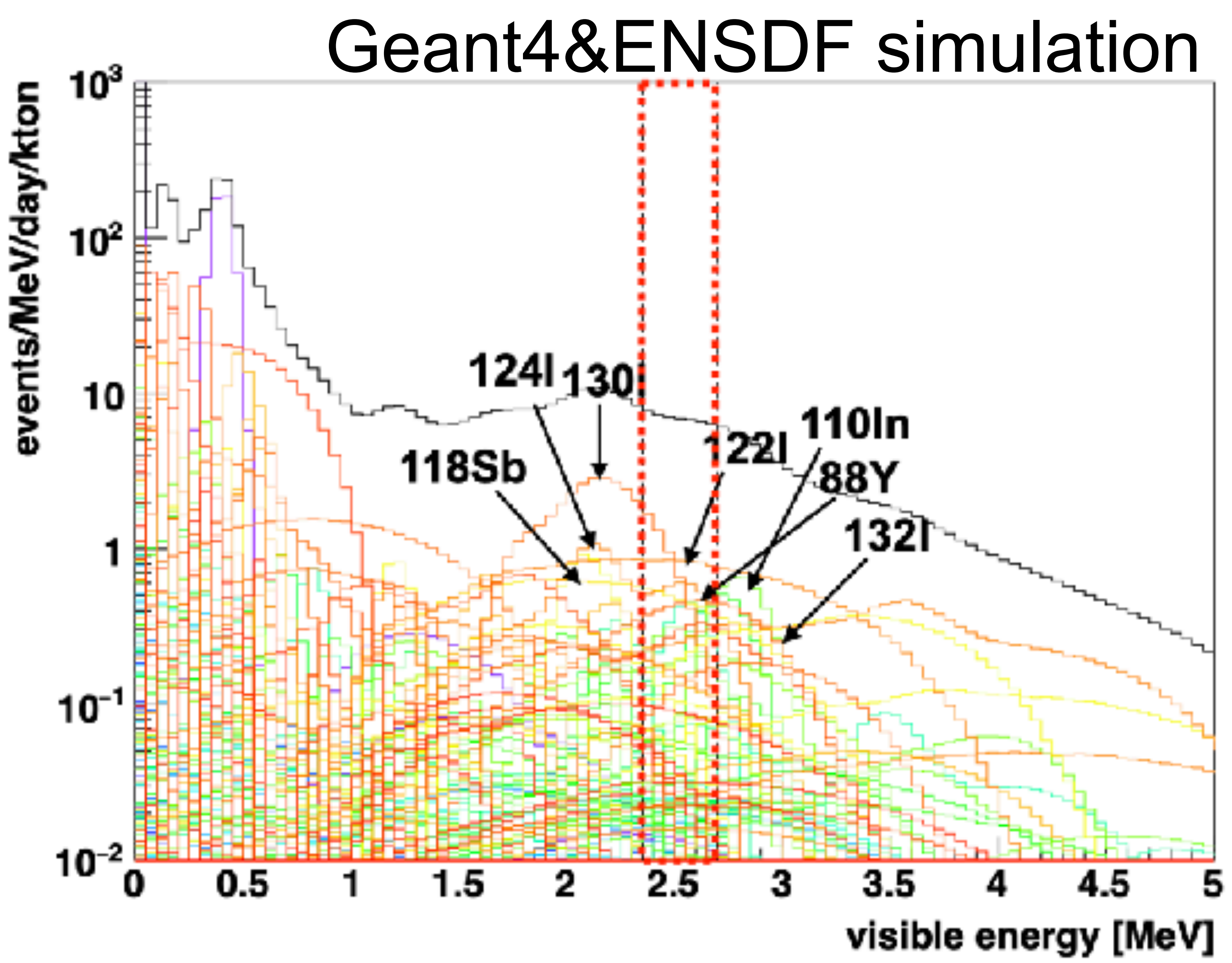
- Each isotopes yields are small, but **many candidates** are produced
- Total yield becomes one of the **main background**
- **long half-life** (~hours to ~days)
- **neutrino multiplicity** is higher than carbon's

rate in ROI : 0.082 events/day/Xe-ton

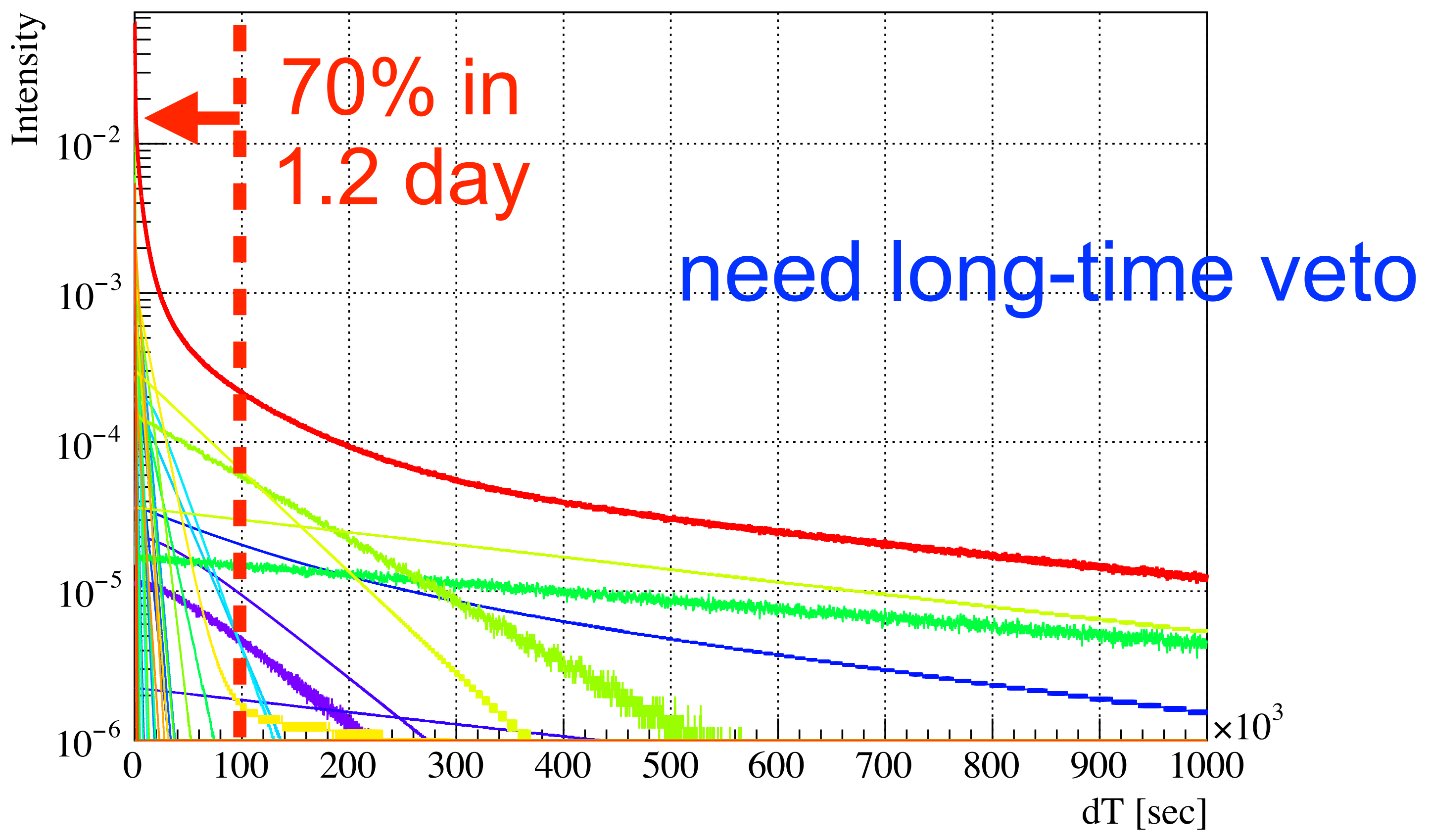
production yield



energy spectrum

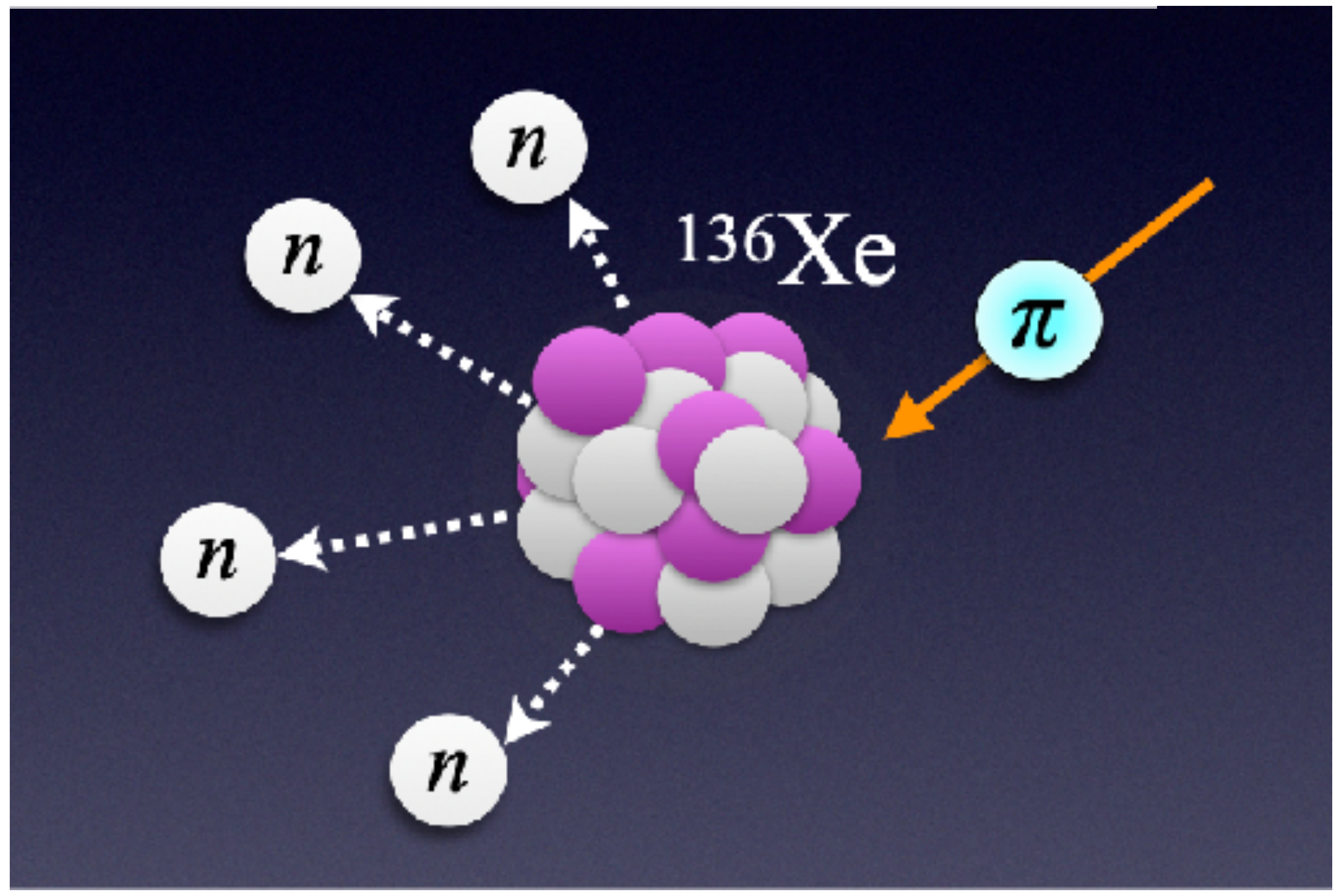


time difference from muon

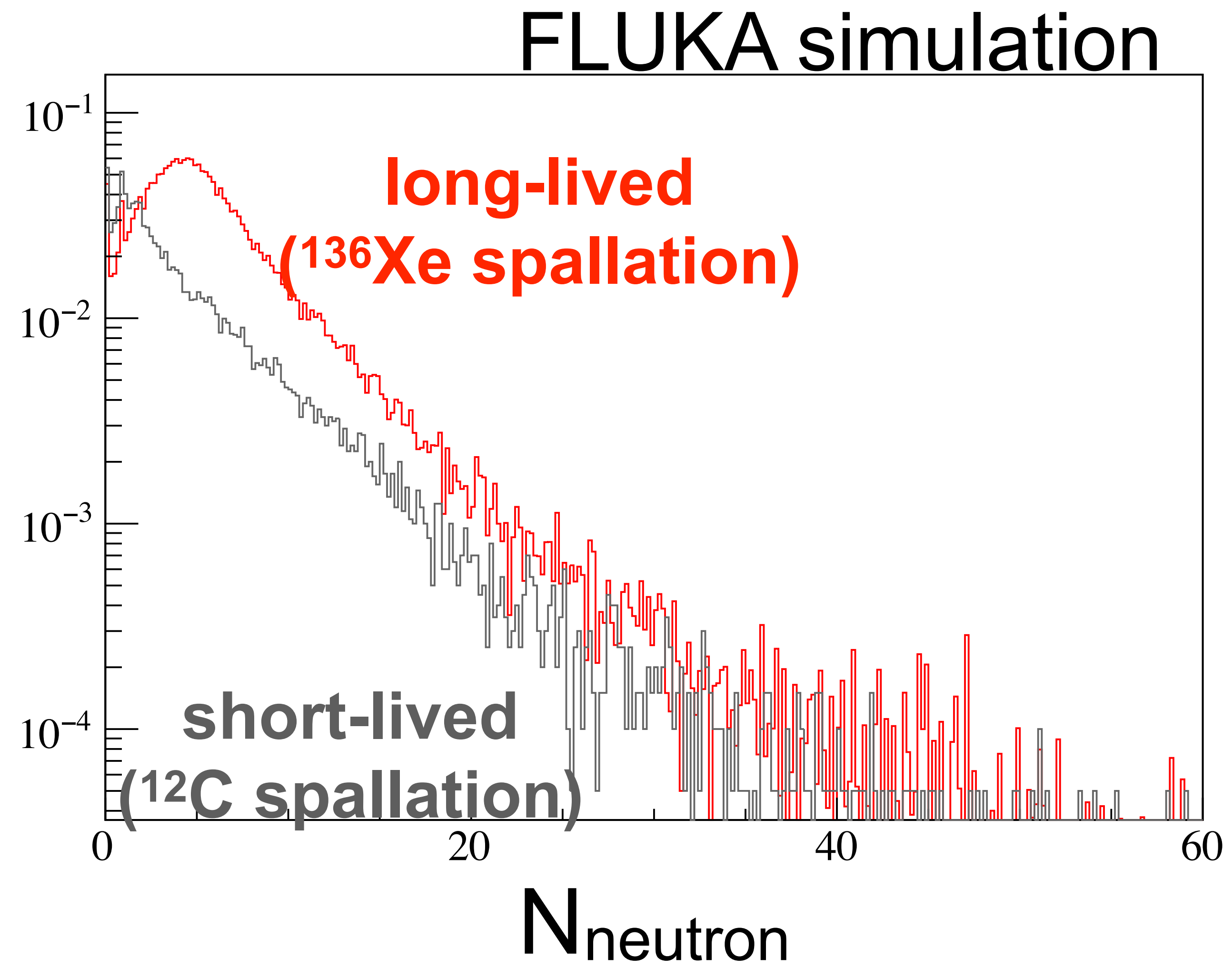


Likelihood-based tagging
: $N_{neutron}$, dR, dT

N: effective number of neutron
dR: distance between Xe-spallation and neutron capture gamma
dT: Time difference from muon



neutron multiplicity

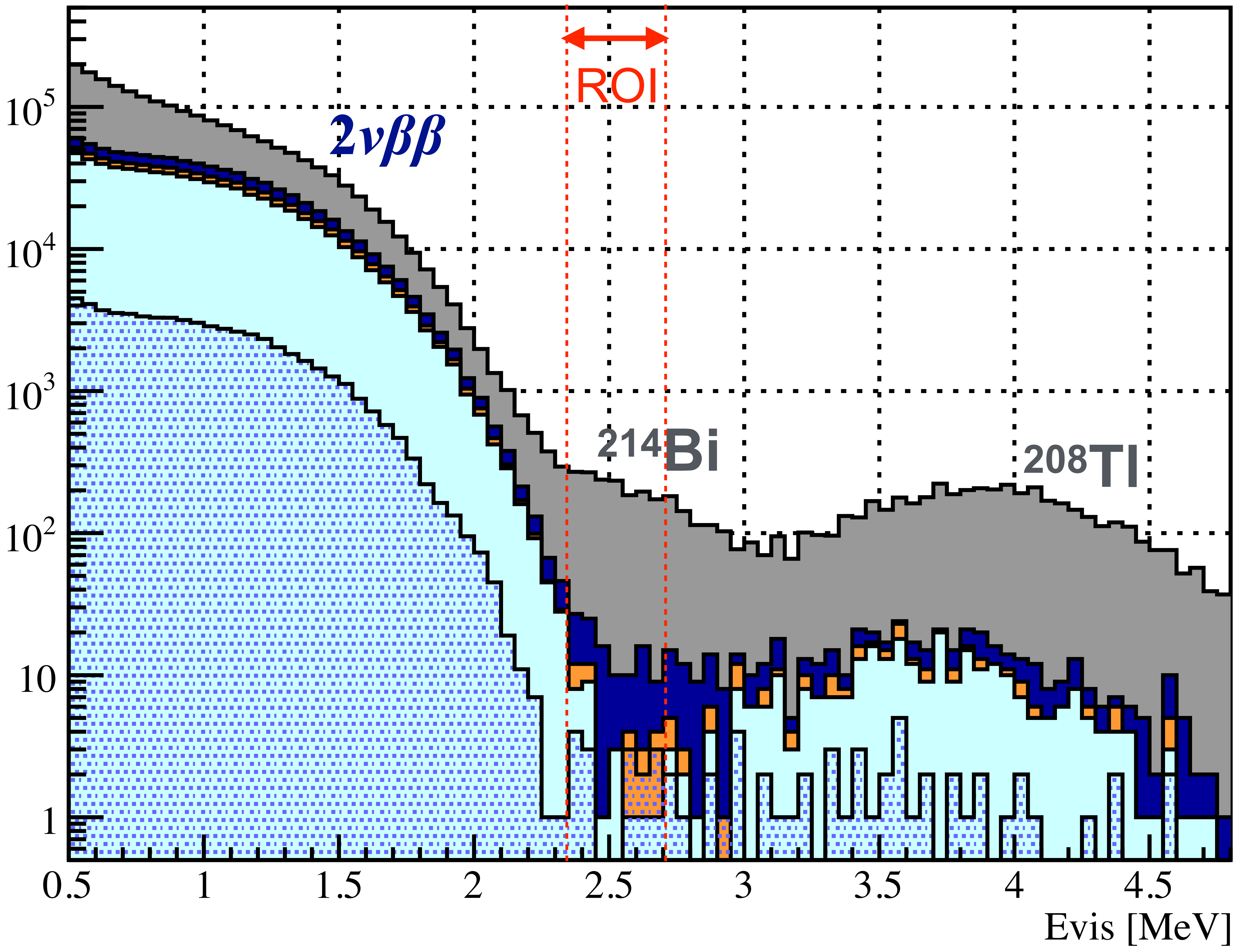


Rejection efficiency: ~40 %

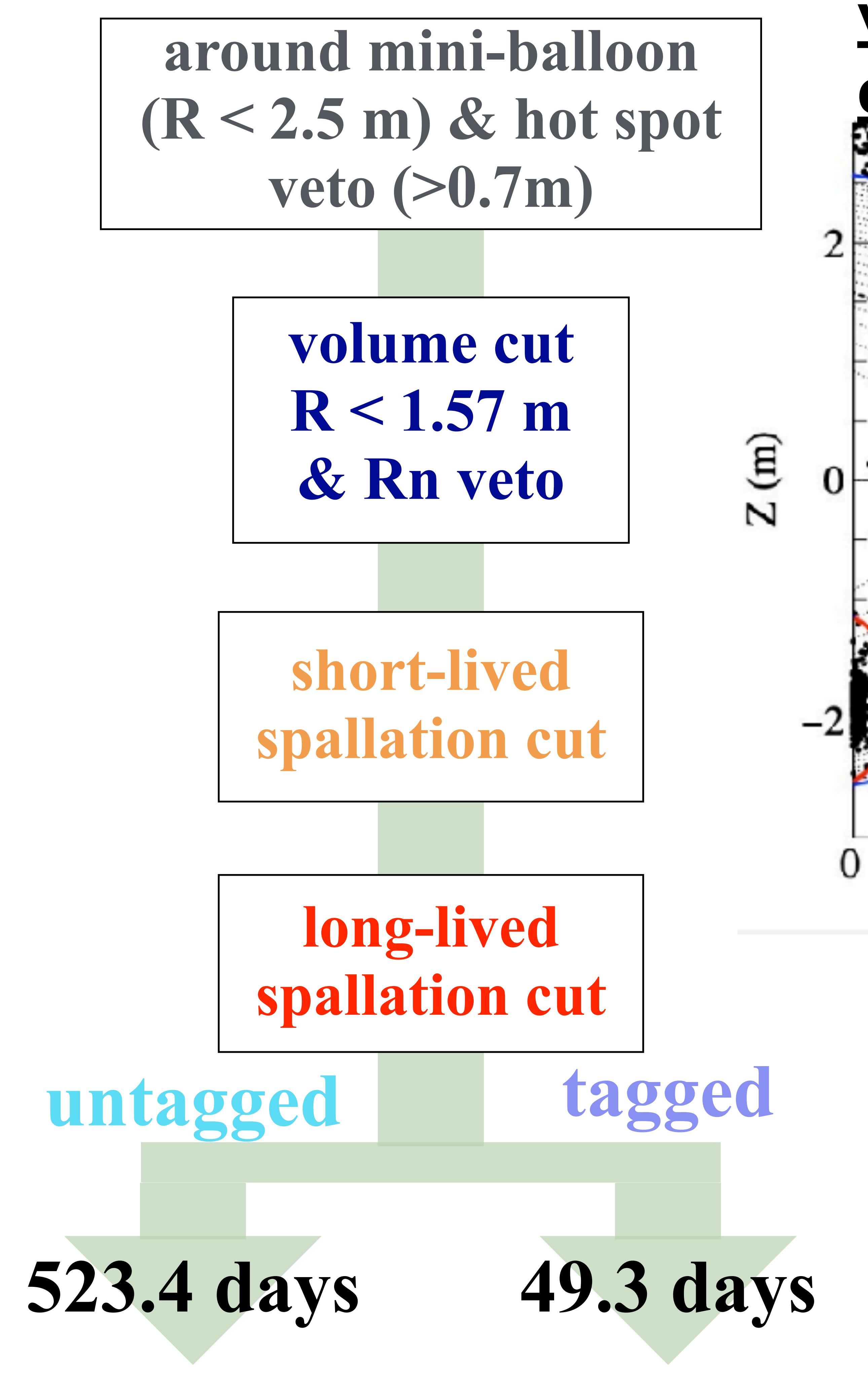
Data Analysis

Data set: Feb. 5, 2019 - May 8, 2021
Exposure: 970 kg • yr

Data divided into "$0\nu\beta\beta$ candidate" and "long-lived candidate"



Two energy spectra ($0\nu\beta\beta$, long-lived) are fitted simultaneously


around mini-balloon (R < 2.5 m) & hot spot veto (>0.7m)

volume cut
R < 1.57 m
& Rn veto

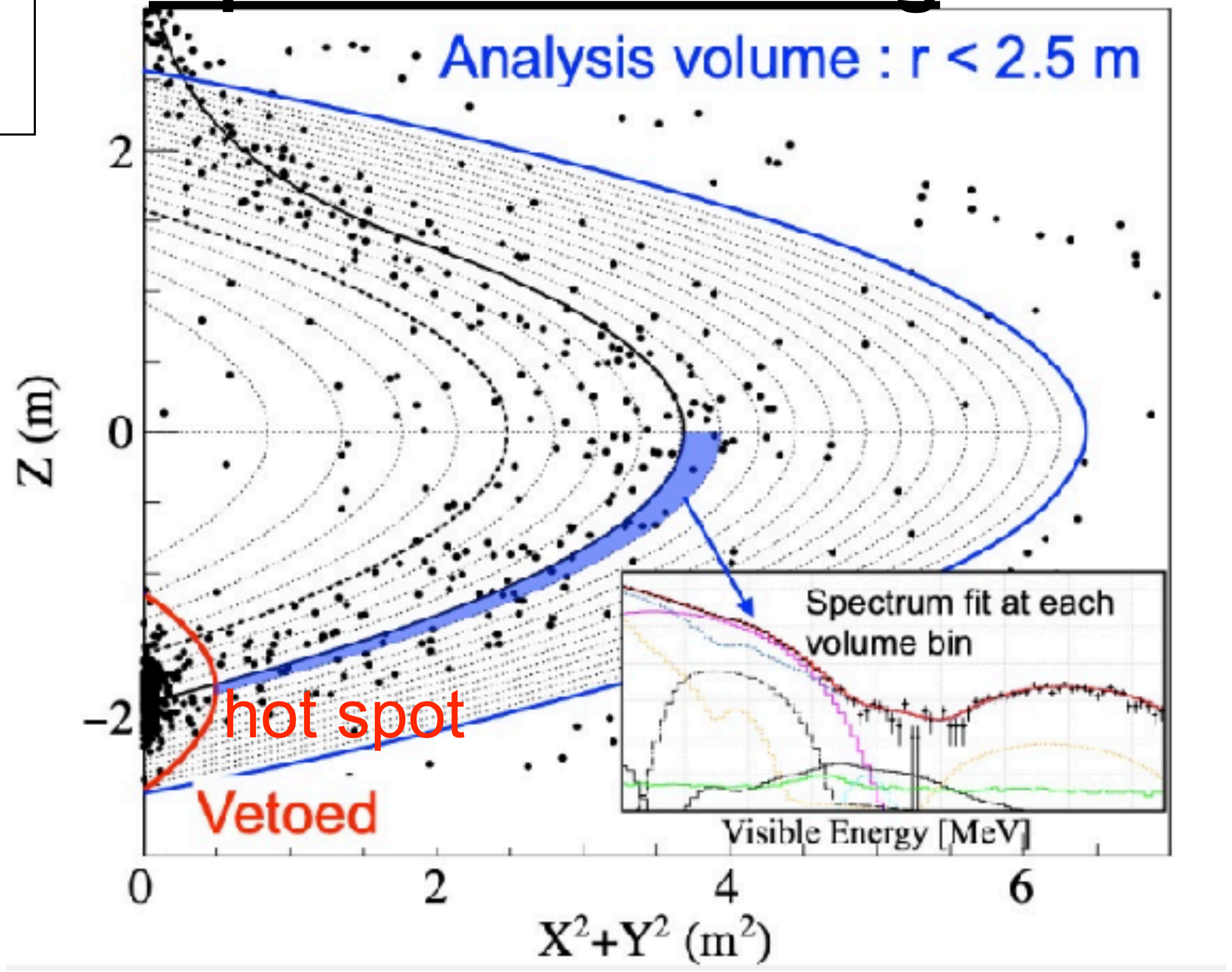
short-lived spallation cut

long-lived spallation cut

untagged — 523.4 days — $0\nu\beta\beta$ candidate

tagged — 49.3 days — long-lived candidate

volume cut &
equal-volume binning



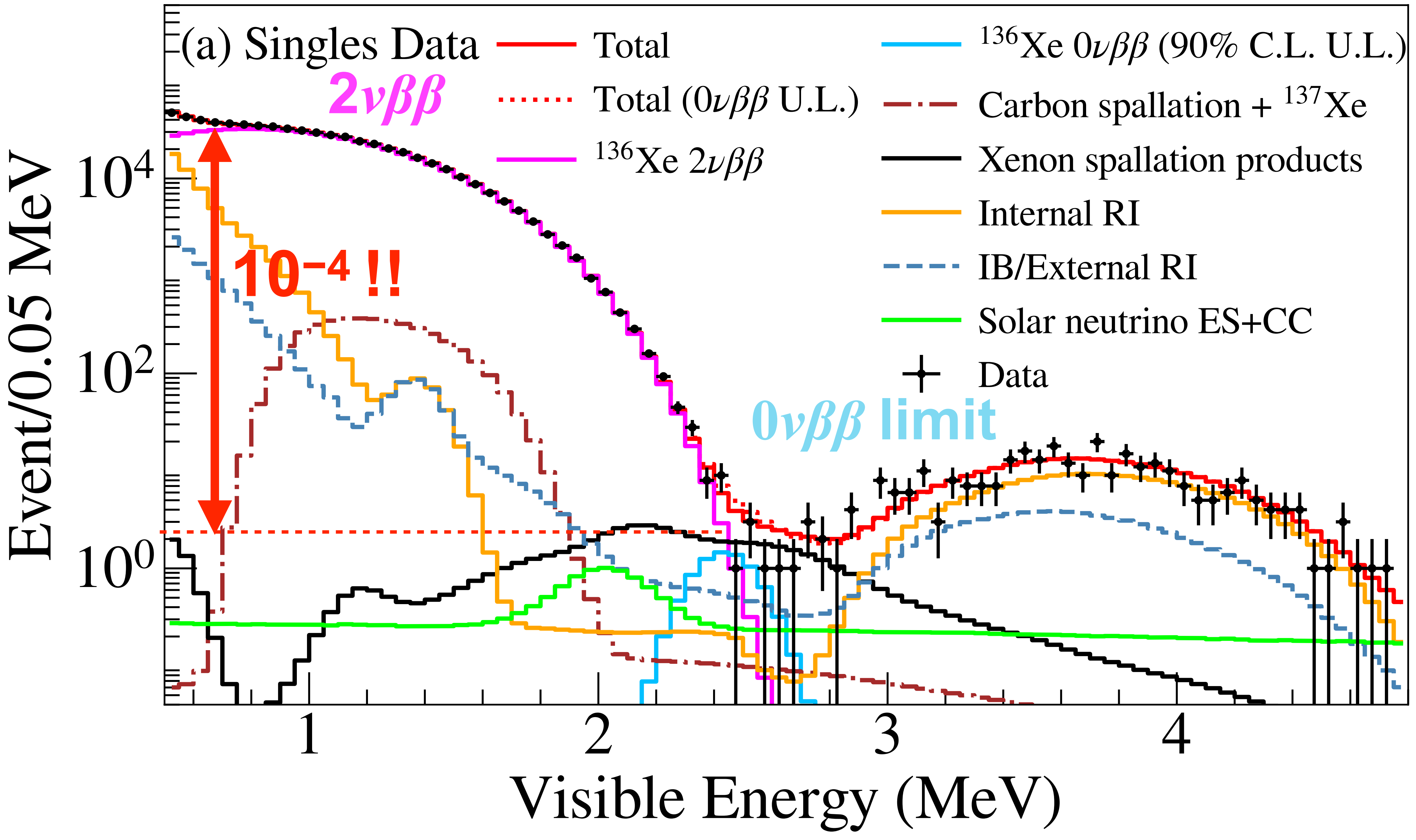
- * 86 energy bins
- * 40 equal-volume bins
- * 3 time-period bins

for two datasets

Best-fit Energy Spectra

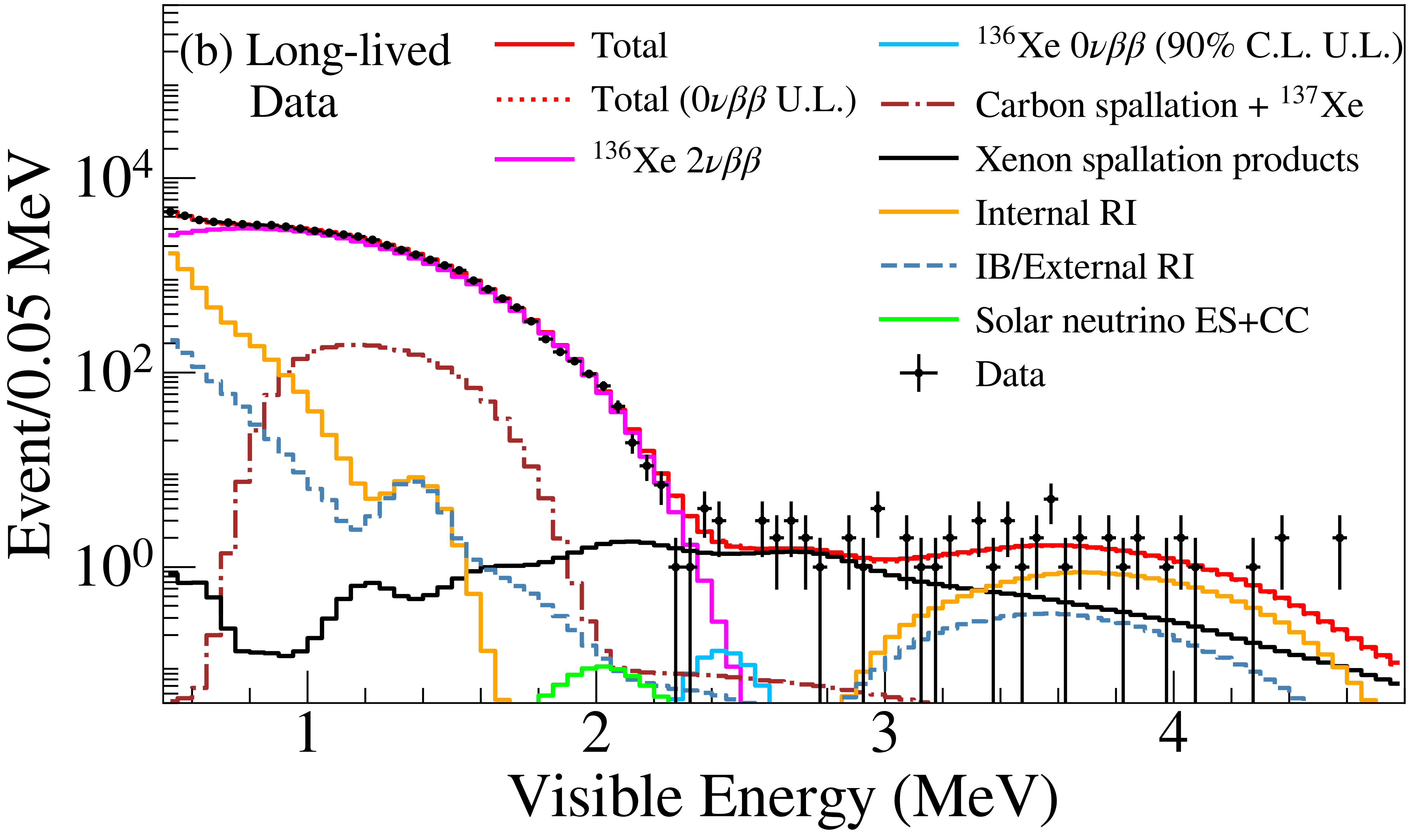
$0\nu\beta\beta$ candidate (sensitive to $0\nu\beta\beta$ signal)

523.4 days livetime R < 1.57 m

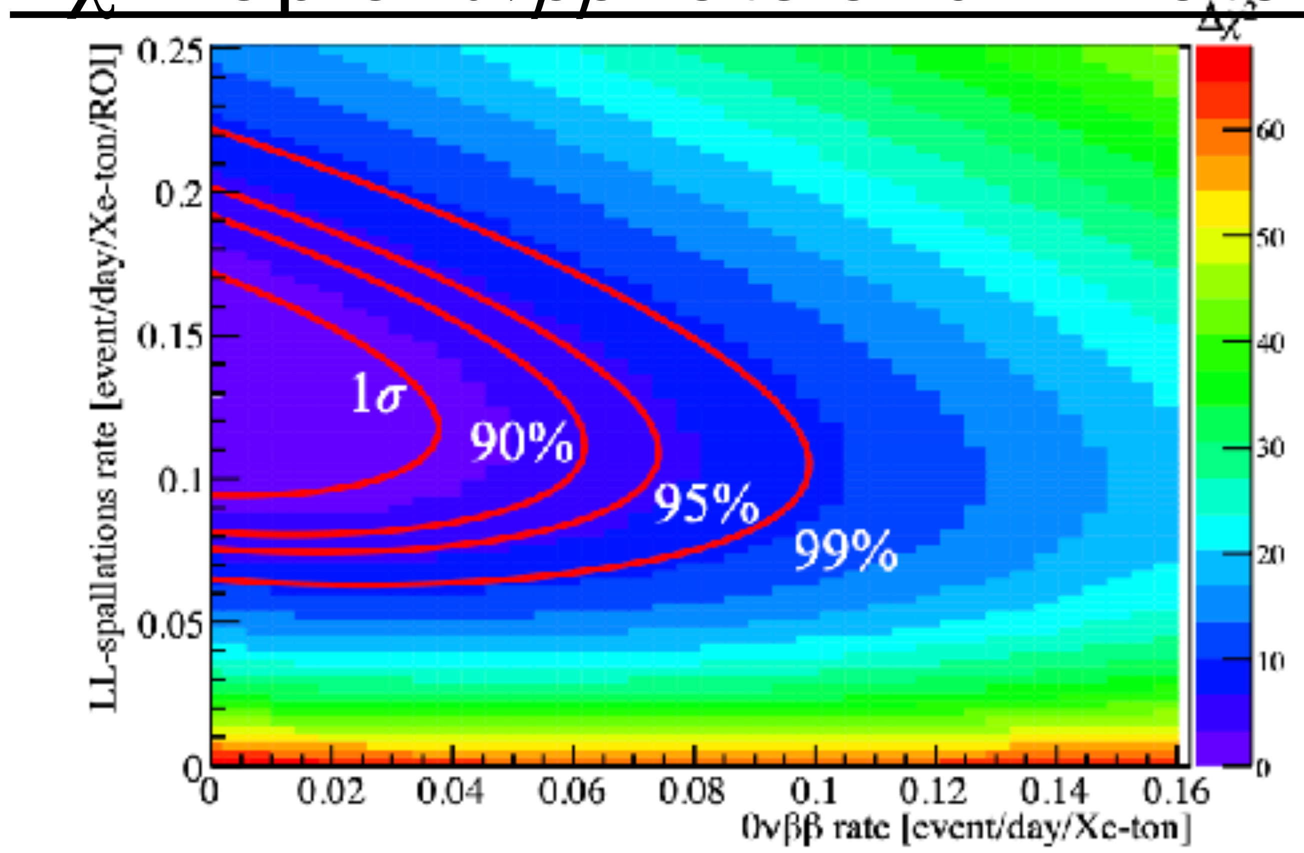


long-lived candidate (Long-lived BG constraint)

49.3 days livetime R < 1.57 m



$\Delta\chi^2$map of $0\nu\beta\beta$ rate and LL rate in ROI



- Dominant background: **$2\nu\beta\beta$** and **long-lived spallation**
- **0νββ**
  - Best-fit $0\nu\beta\beta$ rate : **0**
  - Upper limit (90% C.L.) : **<7.9 events/Xe-LS (30.5m³)**

$T^{0\nu}_{1/2} > 2.0 \times 10^{26}$ yr (90% C.L.)

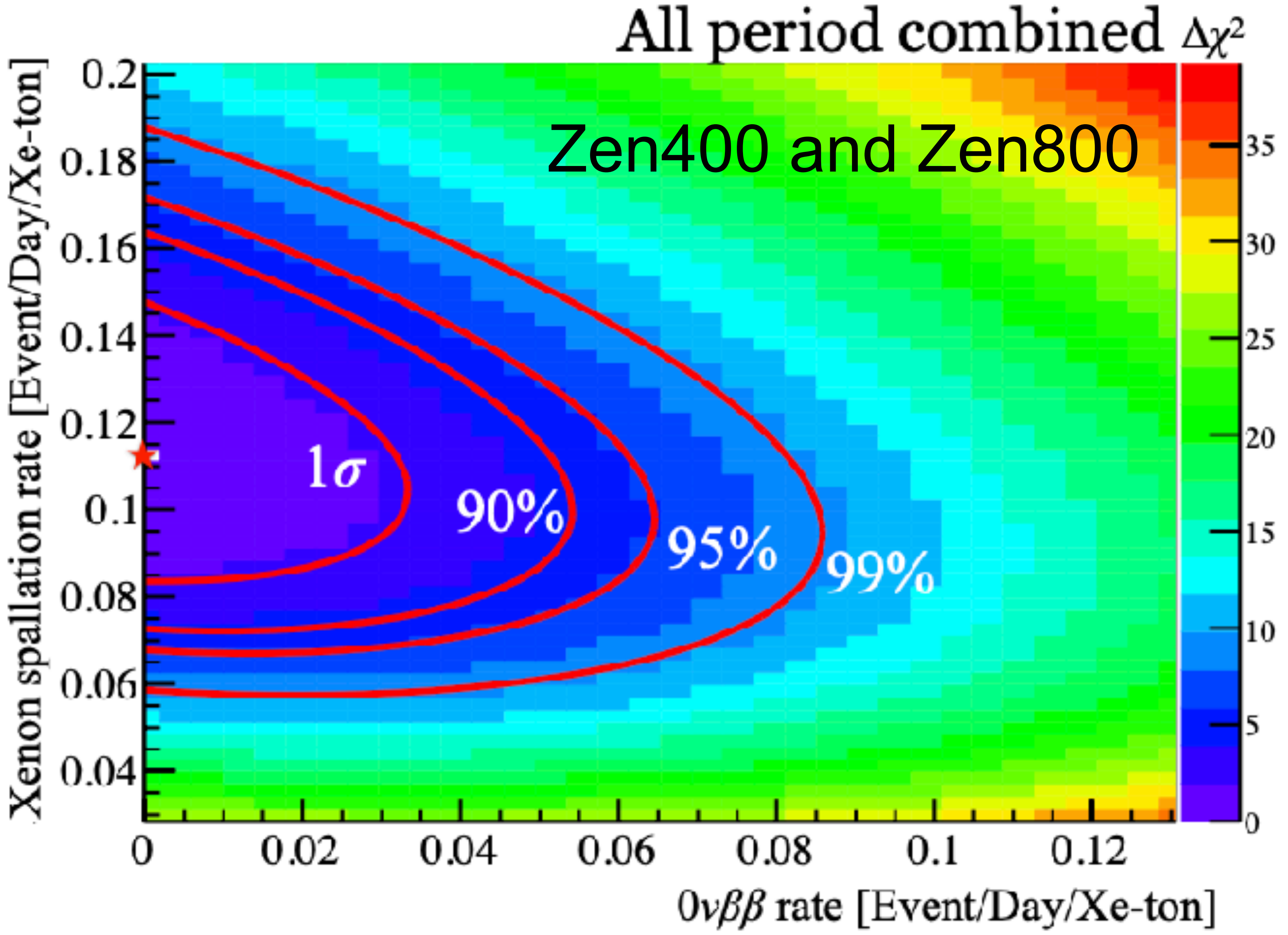
^{136}Xe 0νββ Decay Half Life (KamLAND-Zen 400+800)

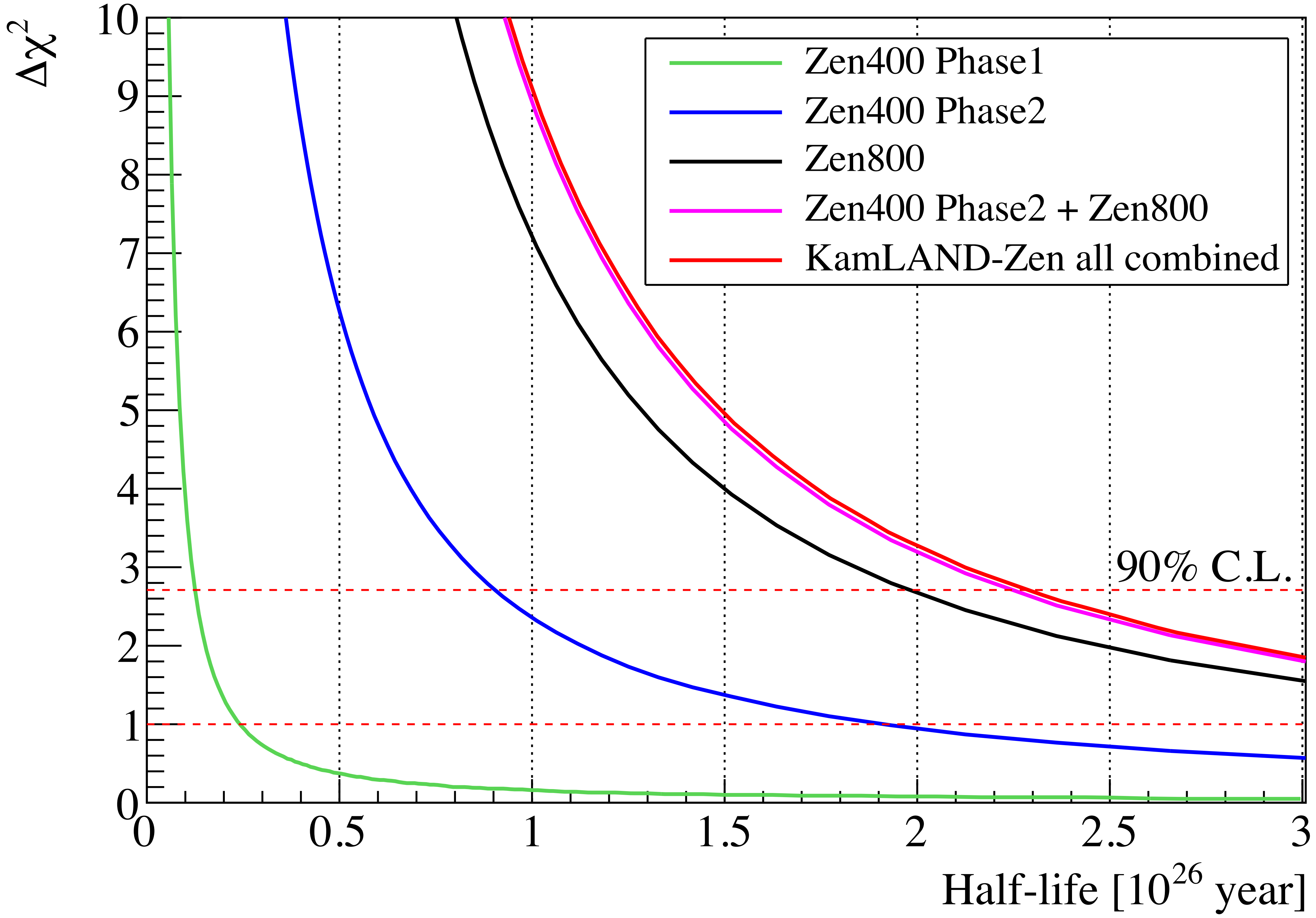
- KamLAND-Zen 400 dataset was **reanalyzed** with updated background rejection techniques and long-lived spallation consideration.
- Zen400 and Zen800 dataset were **combined in $\Delta\chi^2$map**.

Long-lived BG rate in 2.35-2.70 MeV
= 0.111 ± 0.019 events/day/Xe-ton

Long-lived BG rate was measured

(FLUKA = 0.082 ± 0.006 events/day/Xe-ton)



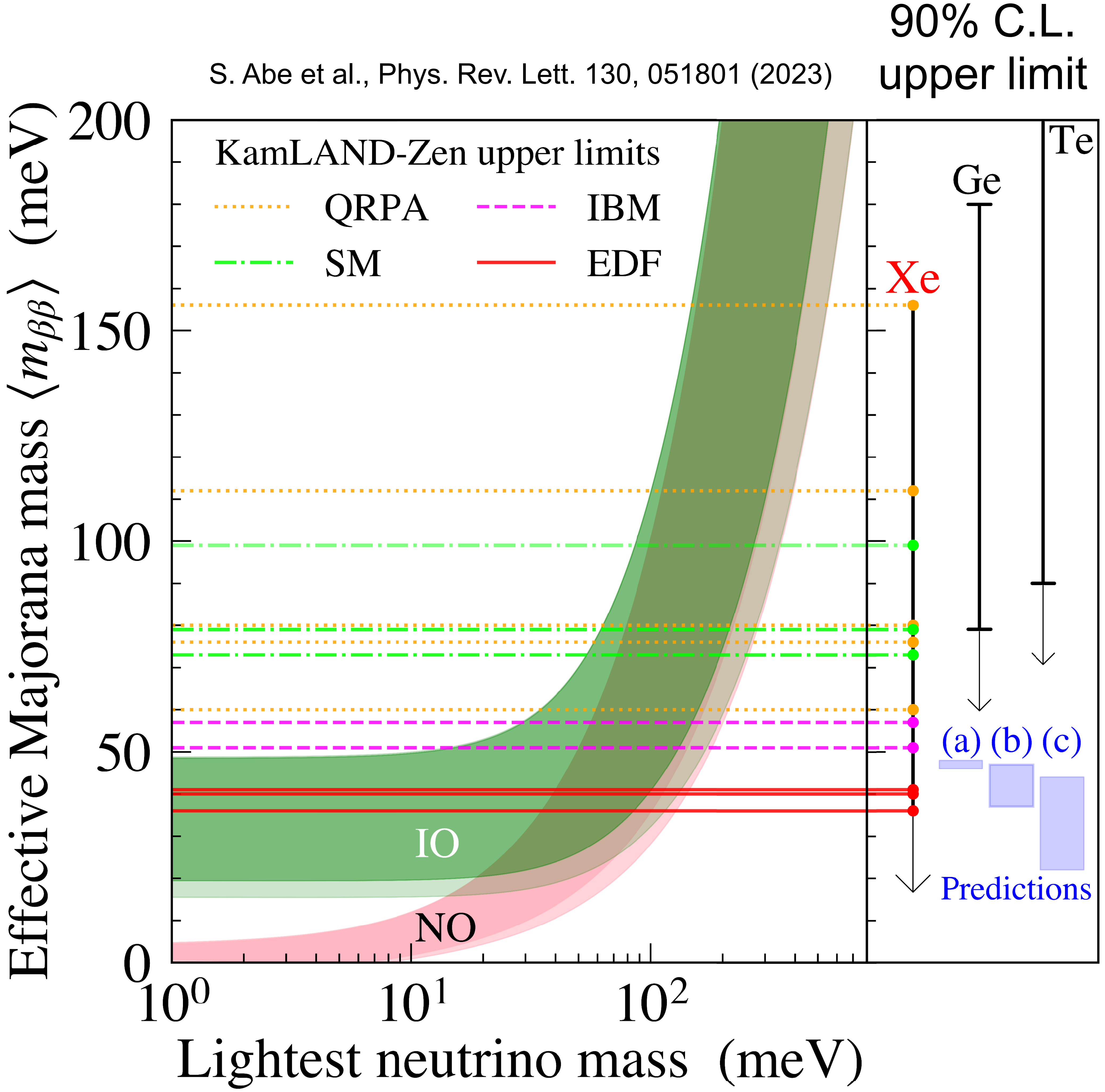


Half-life limit at 90% C.L.

Zen 400	**$T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr**
Zen 800	**$T^{0\nu}_{1/2} > 2.0 \times 10^{26}$ yr**
Combined	**$T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ yr**

2 times better!

Limits on Neutrino Mass



S. Abe et al., Phys. Rev. Lett. 130, 051801 (2023)

* Decay rate → proportional to (neutrino mass)^2

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

NME calculations assuming $g_A \sim 1.27$

QRPA

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SM

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EDF

- N. L. Vaquero, T. R. Rodríguez, and J. L. Egido, Phys. Rev. Lett. **111**, 142501 (2013).
- J. M. Yao, L. S. Song, K. Hagino, P. Ring, and J. Meng, Phys. Rev. C **91**, 024316 (2015).
- T. R. Rodríguez and G. Martínez-Pinedo, Phys. Rev. Lett. **105**, 252503 (2010).

KamLAND-Zen (^{136}Xe)

$\langle m_{\beta\beta} \rangle$ < 36-156 meV

*** KamLAND-Zen started to enter the "Inverted-Ordering" region search.**

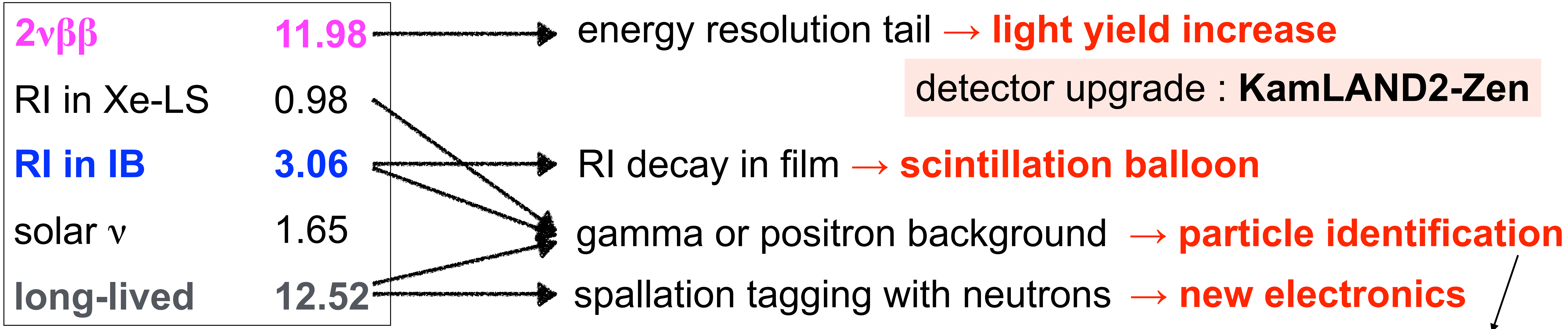
*** Xe is the leading experiment**

For Further Improvements

Current status

Improvement

ROI event (2.35 < E < 2.70 MeV)



2νββ	11.98
RI in Xe-LS	0.98
RI in IB	**3.06**
solar ν	1.65
long-lived	**12.52**

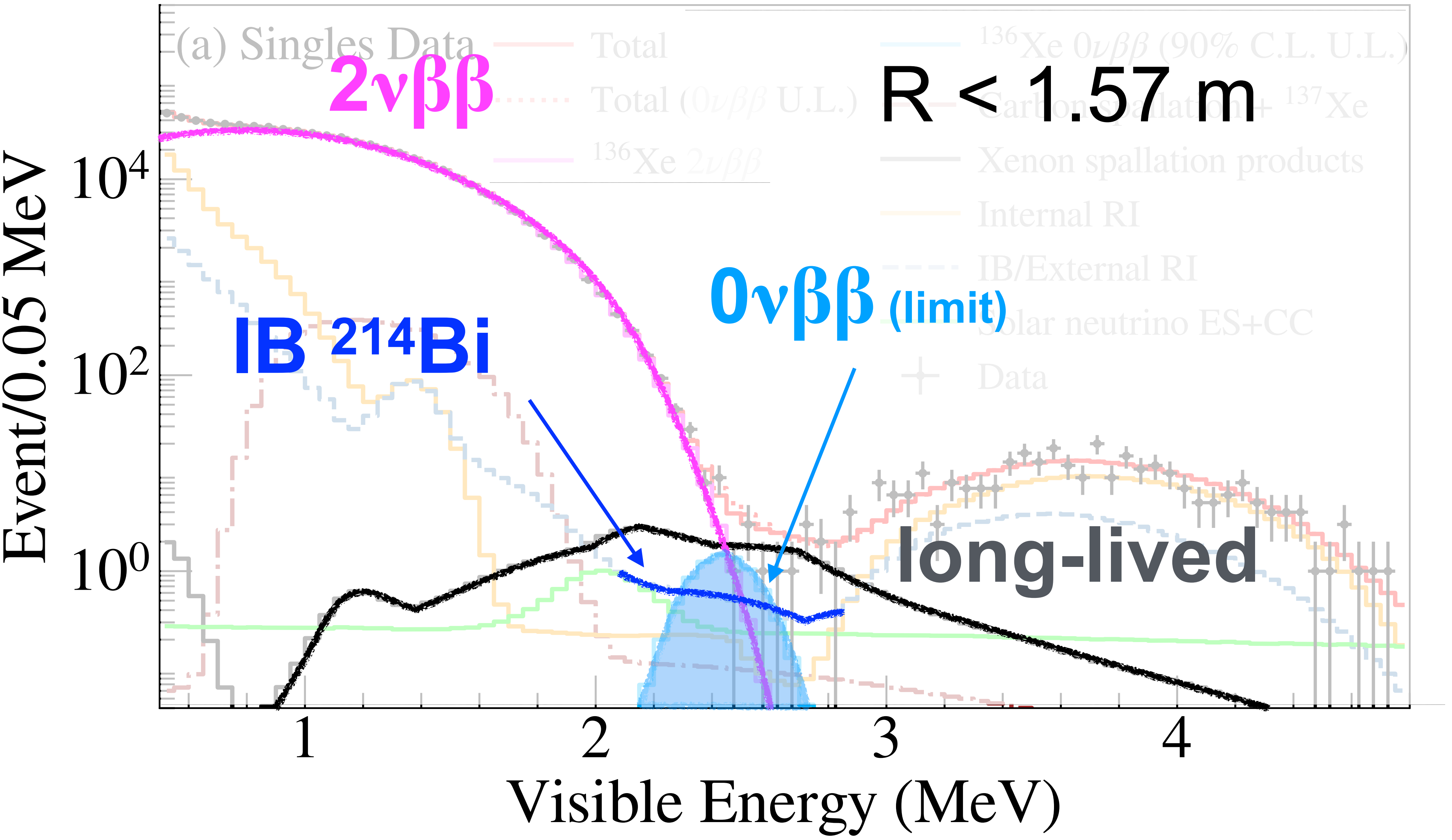
energy resolution tail → **light yield increase**

detector upgrade : **KamLAND2-Zen**

RI decay in film → **scintillation balloon**

gamma or positron background → **particle identification**

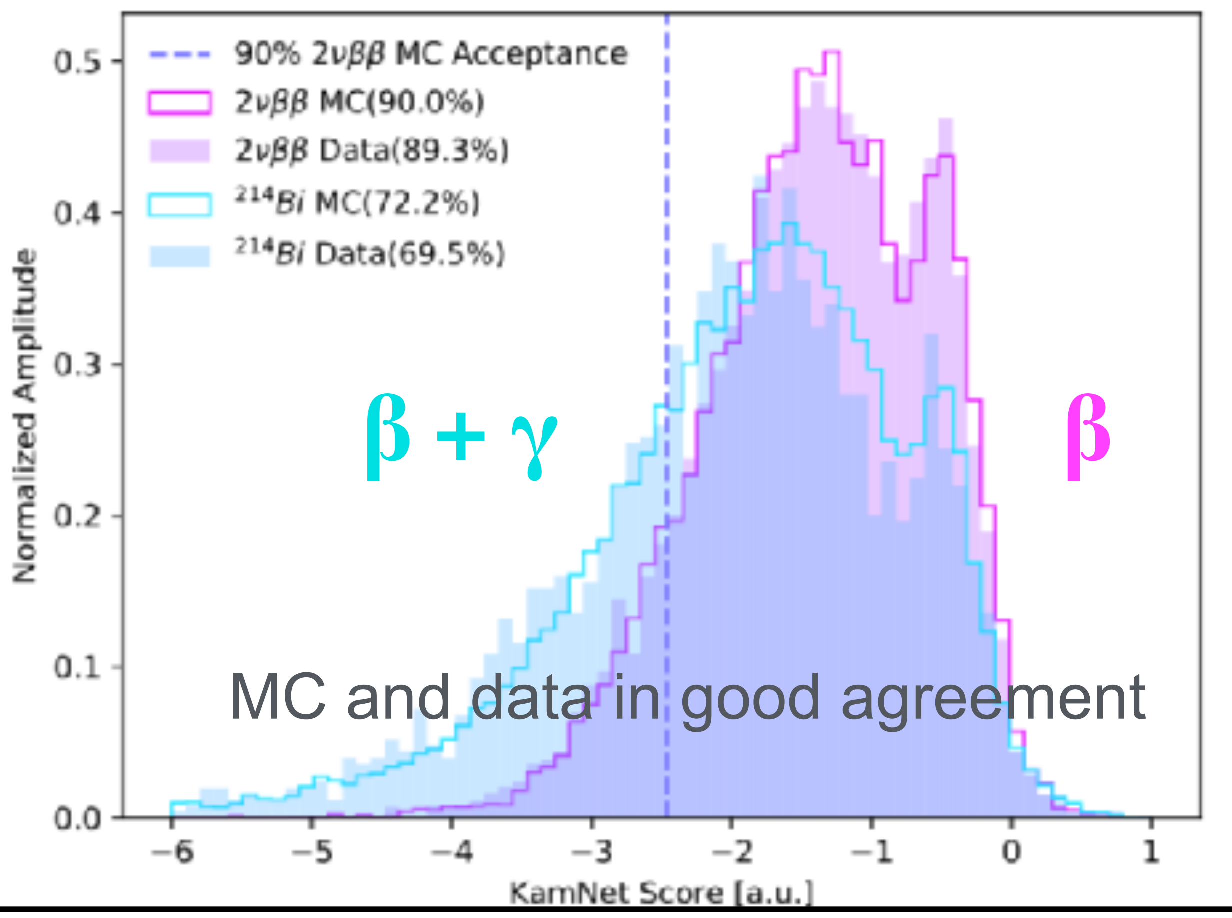
spallation tagging with neutrons → **new electronics**



KamNET Deep neural network

A. Li et al.,
Phys. Rev. C **107**, 014323 (2023)

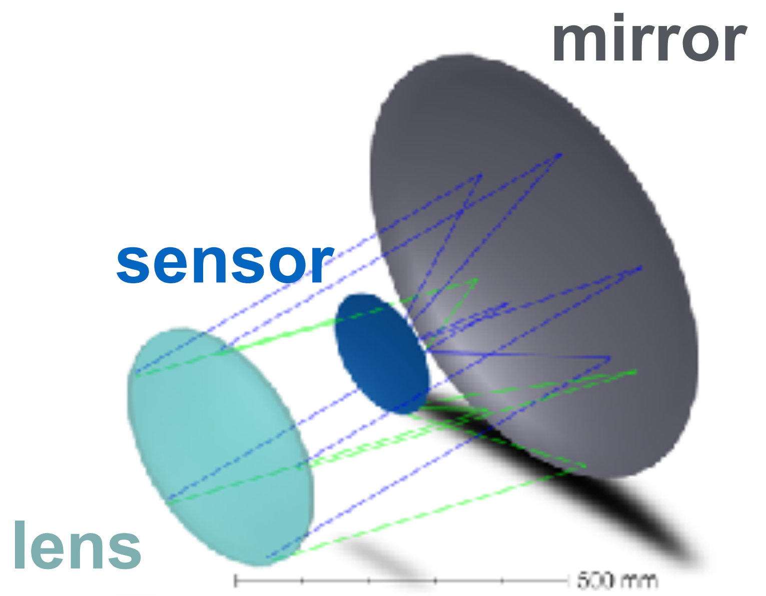
BG like ⟷ Signal like



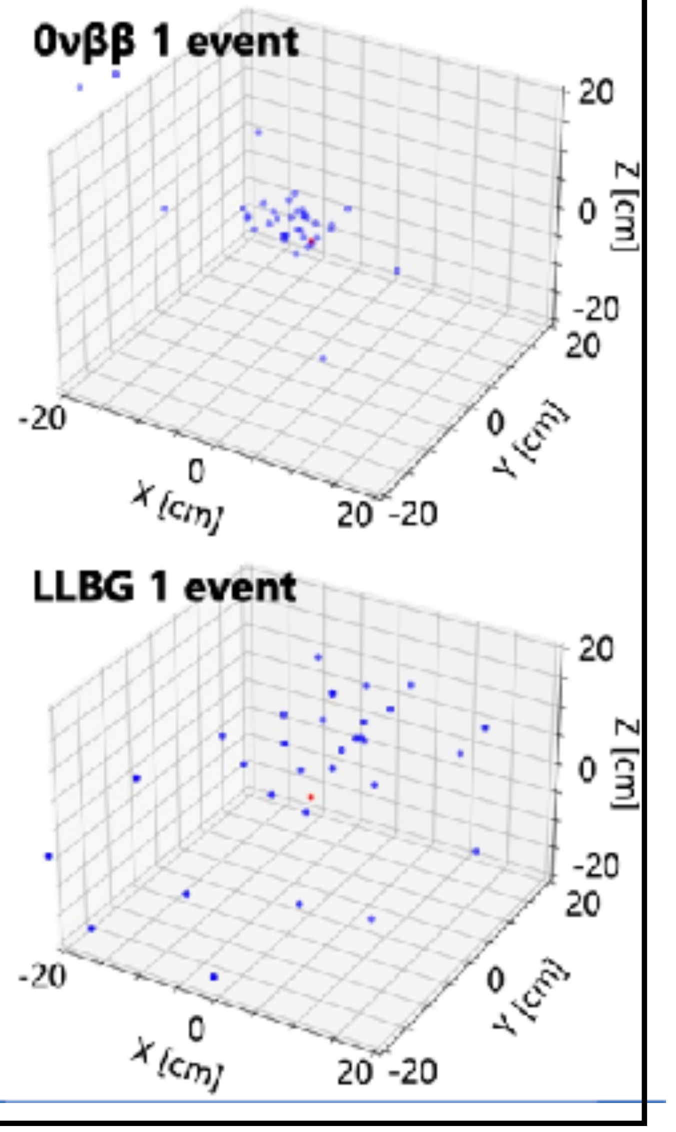
MC and data in good agreement

Imaging Detector

Detect difference in
spread of photon emission



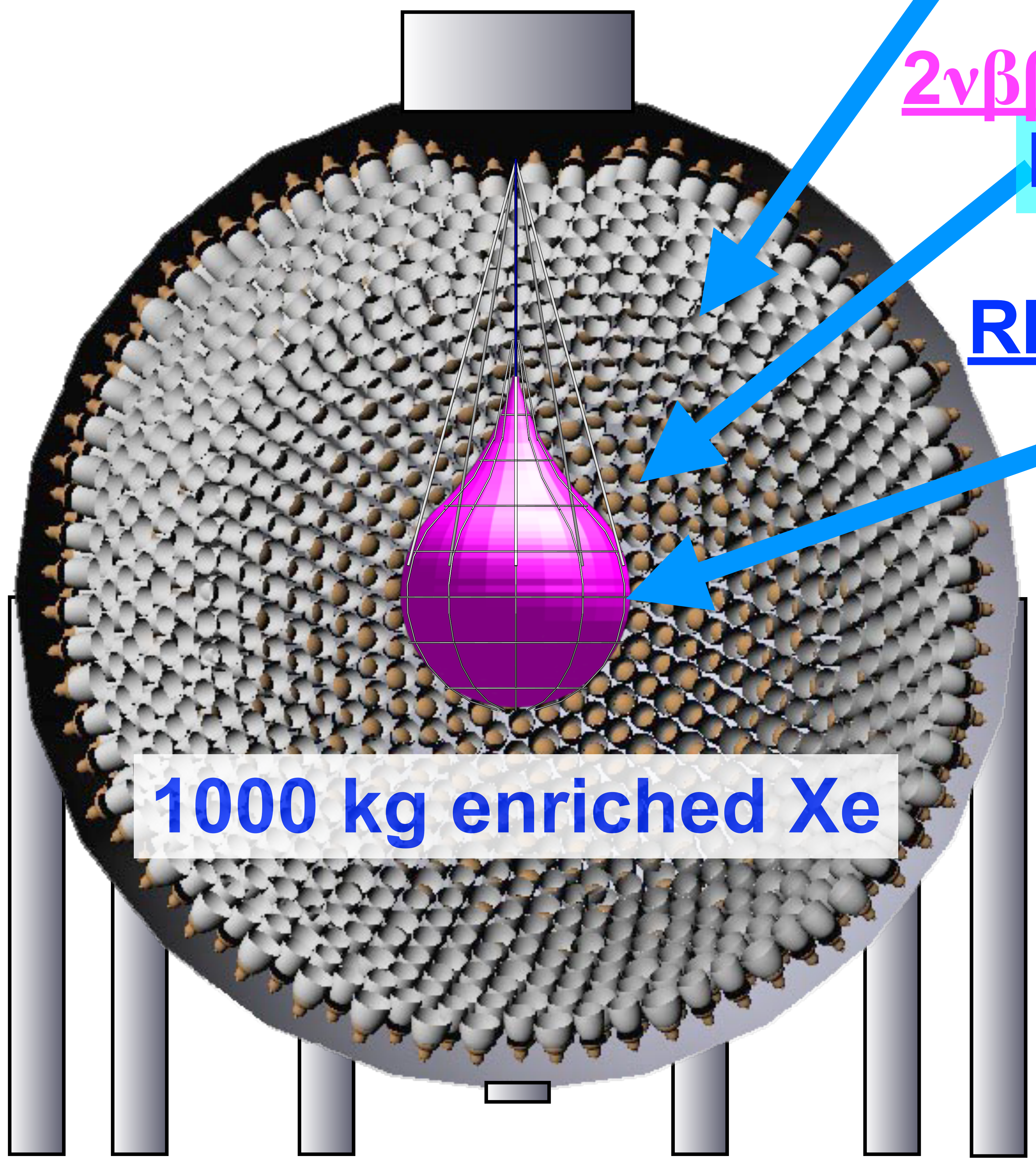
simulation



KamLAND2-Zen

more light, higher resolution, more Xe → **covering** inverted neutrino mass ordering!

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



1000 kg enriched Xe

$2\nu\beta\beta$

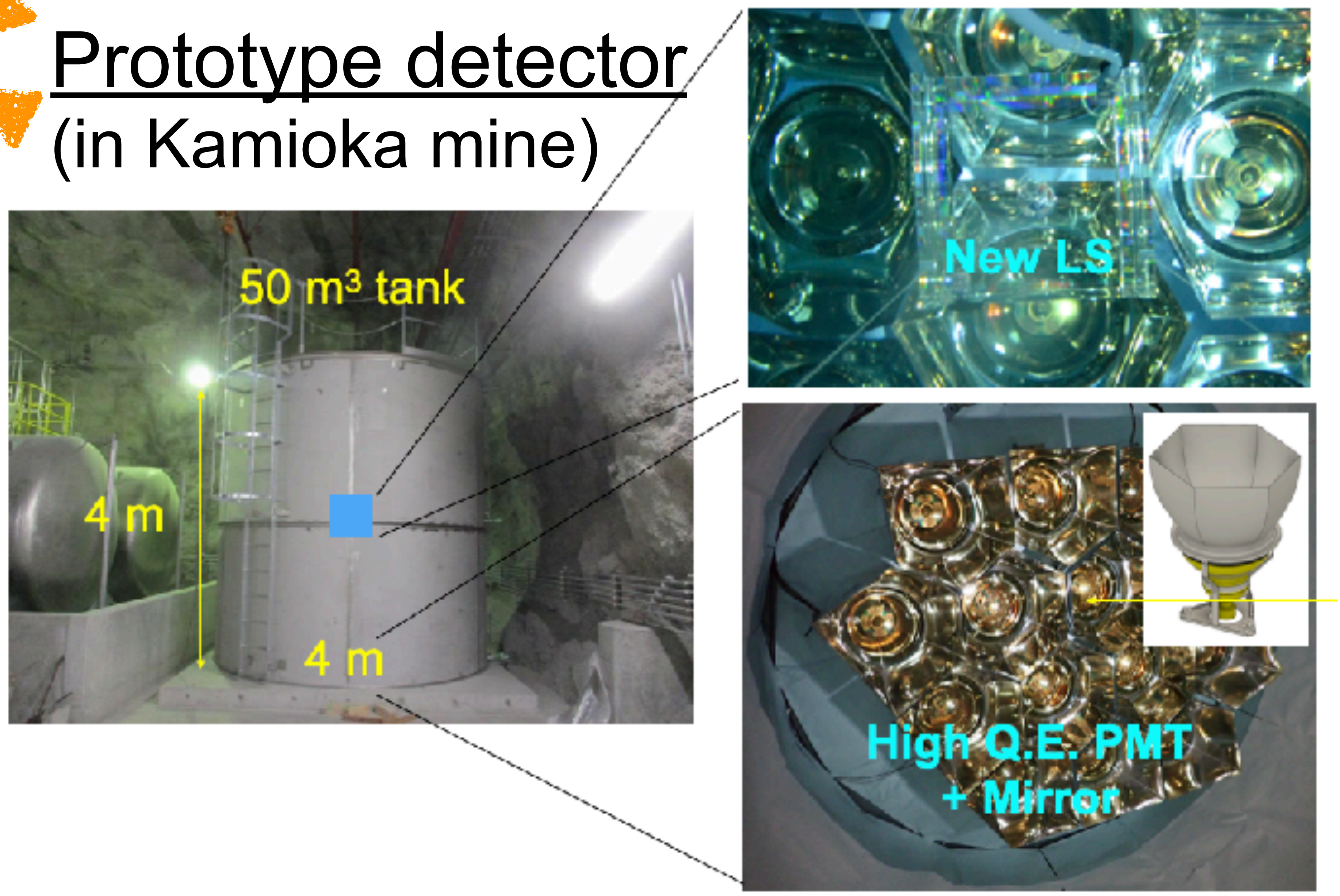
High QE PMT, Winston corn

$2\nu\beta\beta$

Brighter liquid scintillator

tested

Prototype detector
(in Kamioka mine)



RI in IB

Scintillation balloon

(PEN film)

100% fiducial volume

^{214}Bi rejection by α tagging

long-lived

New electronics

improve neutron tagging efficiency

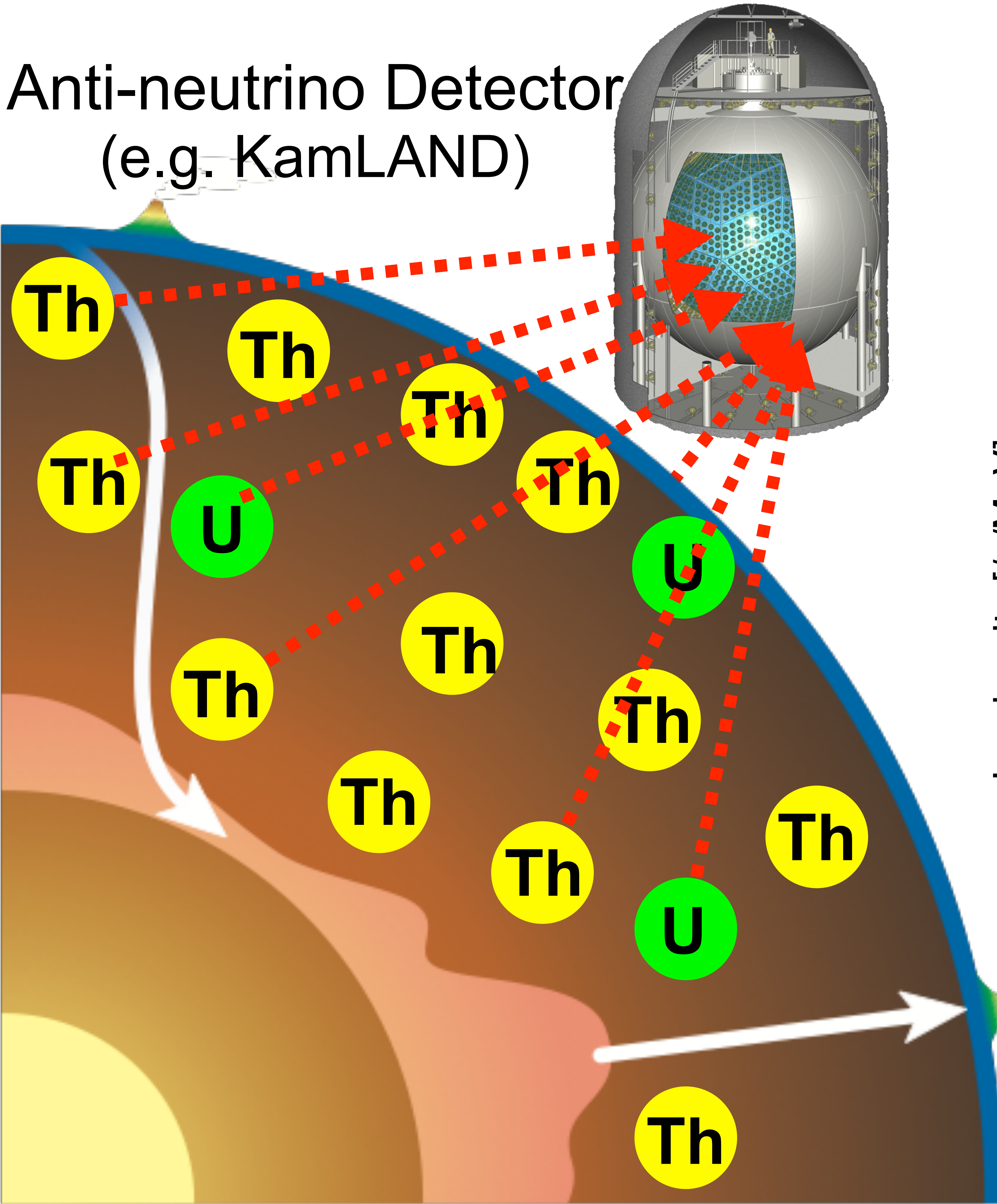
Super-clean room will be constructed in the mine in 2024.
→Promote international corporative joint research regarding extremely rare event research.

Geoneutrinos

Geo-neutrinos

Electron-antineutrinos from natural radioactive decays

$\bar{\nu}_e \;\; 4.1 \times 10^6/\mathrm{cm}^2/\mathrm{sec}$



β-decay

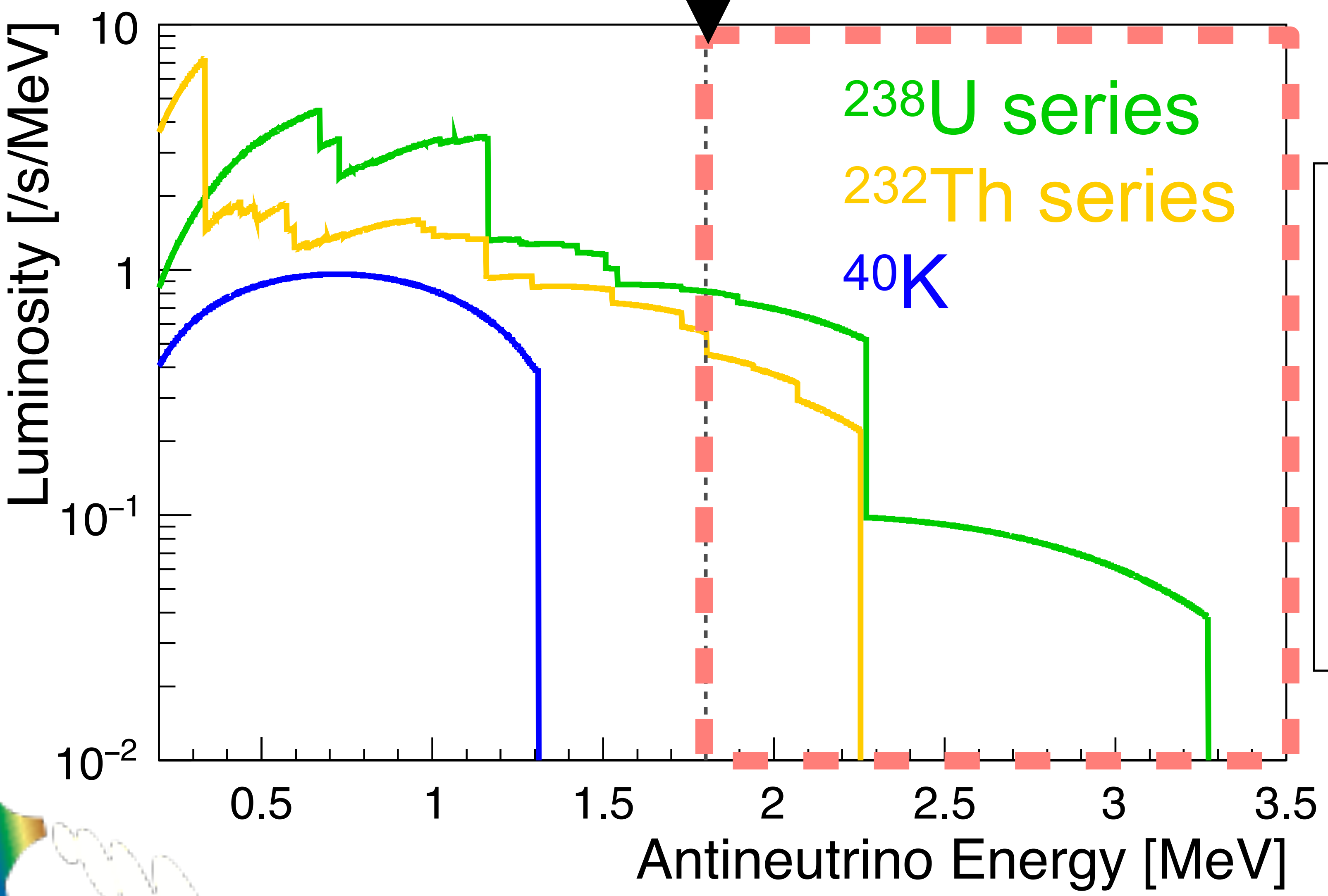
geo-neutrinos

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\bar{\nu}_\mathrm{e} + 51.7\,\mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\bar{\nu}_\mathrm{e} + 42.7\,\mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + 1.311\,\mathrm{MeV}\,(89.28\%)$$

Energy threshold, 1.8 MeV



inverse β-decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

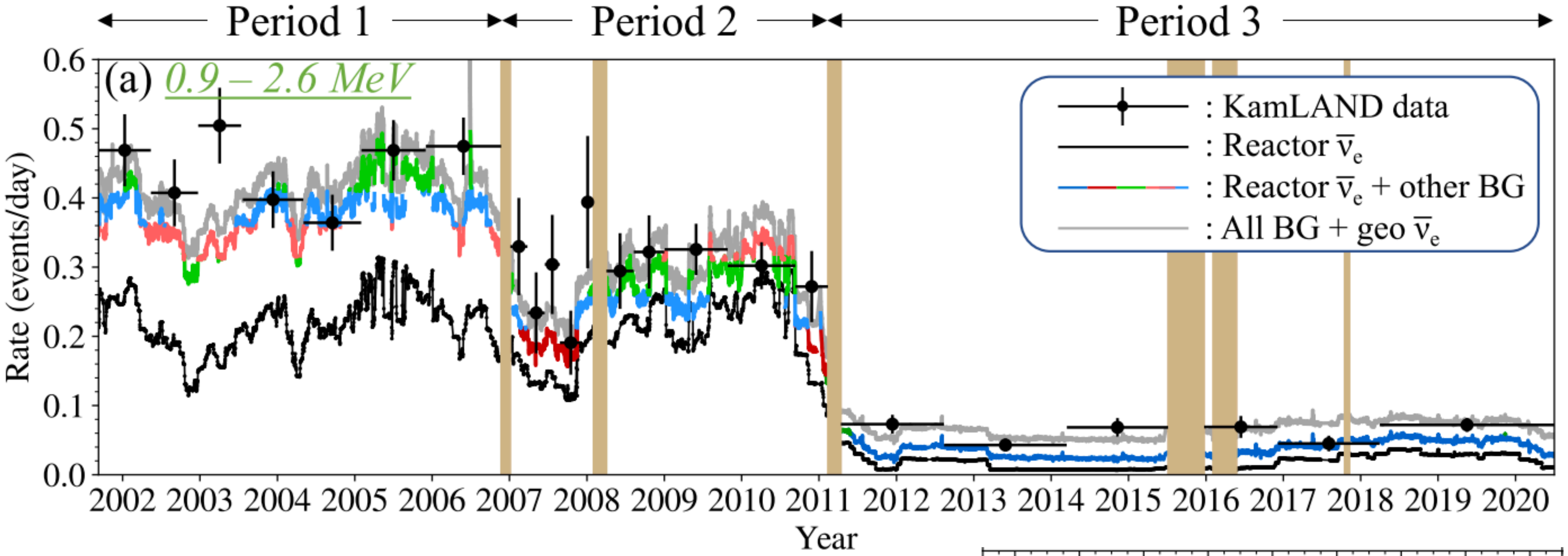
- *Only geo-neutrinos from U and Th are detectable right now
- *^{40}K geo-neutrino detection needs another technology.

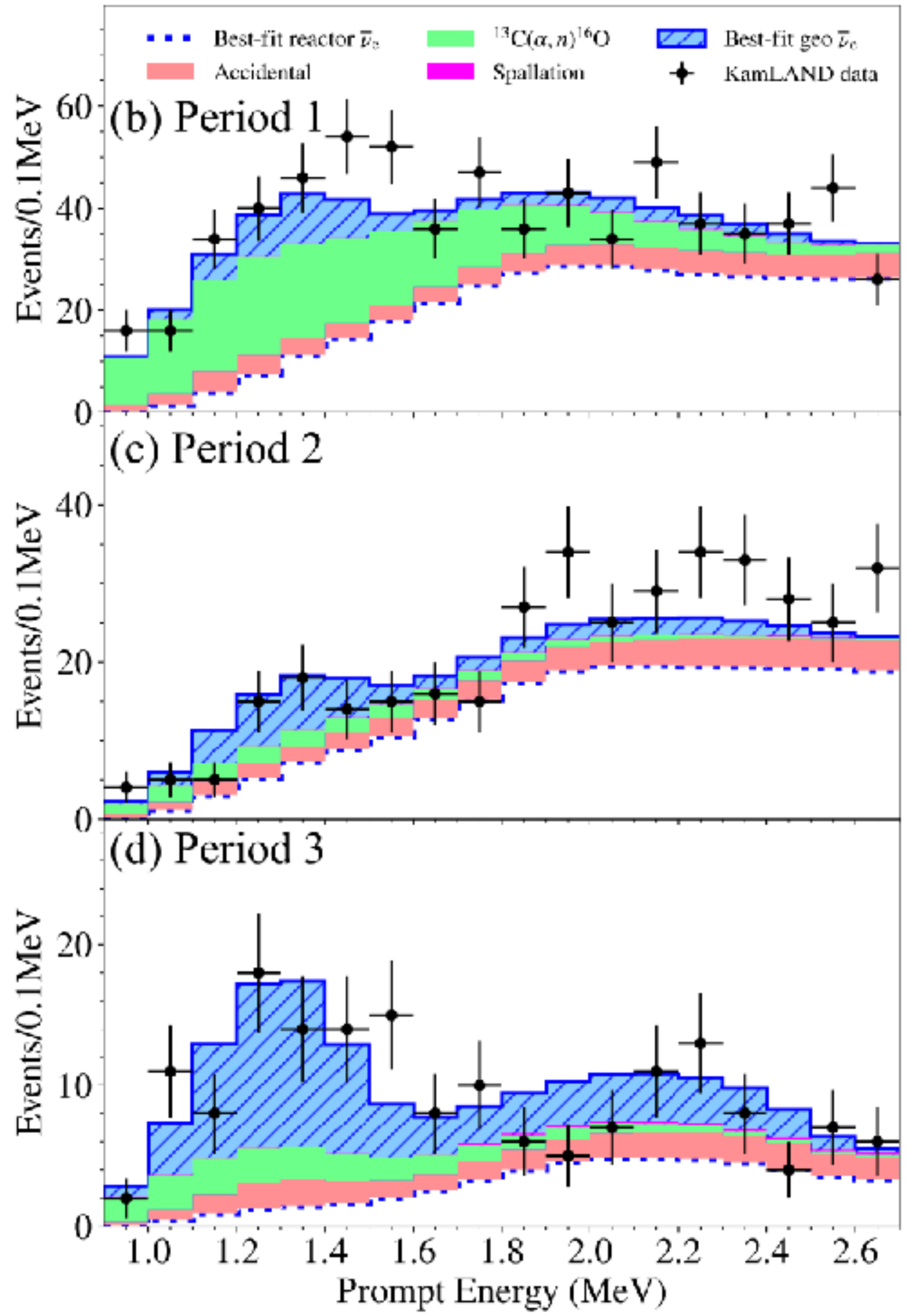
2 experiments (KamLAND and Borexino) have observed so far.

Number of geo $\bar{\nu}_e \propto$ amount of U Th, **radiogenic heat**

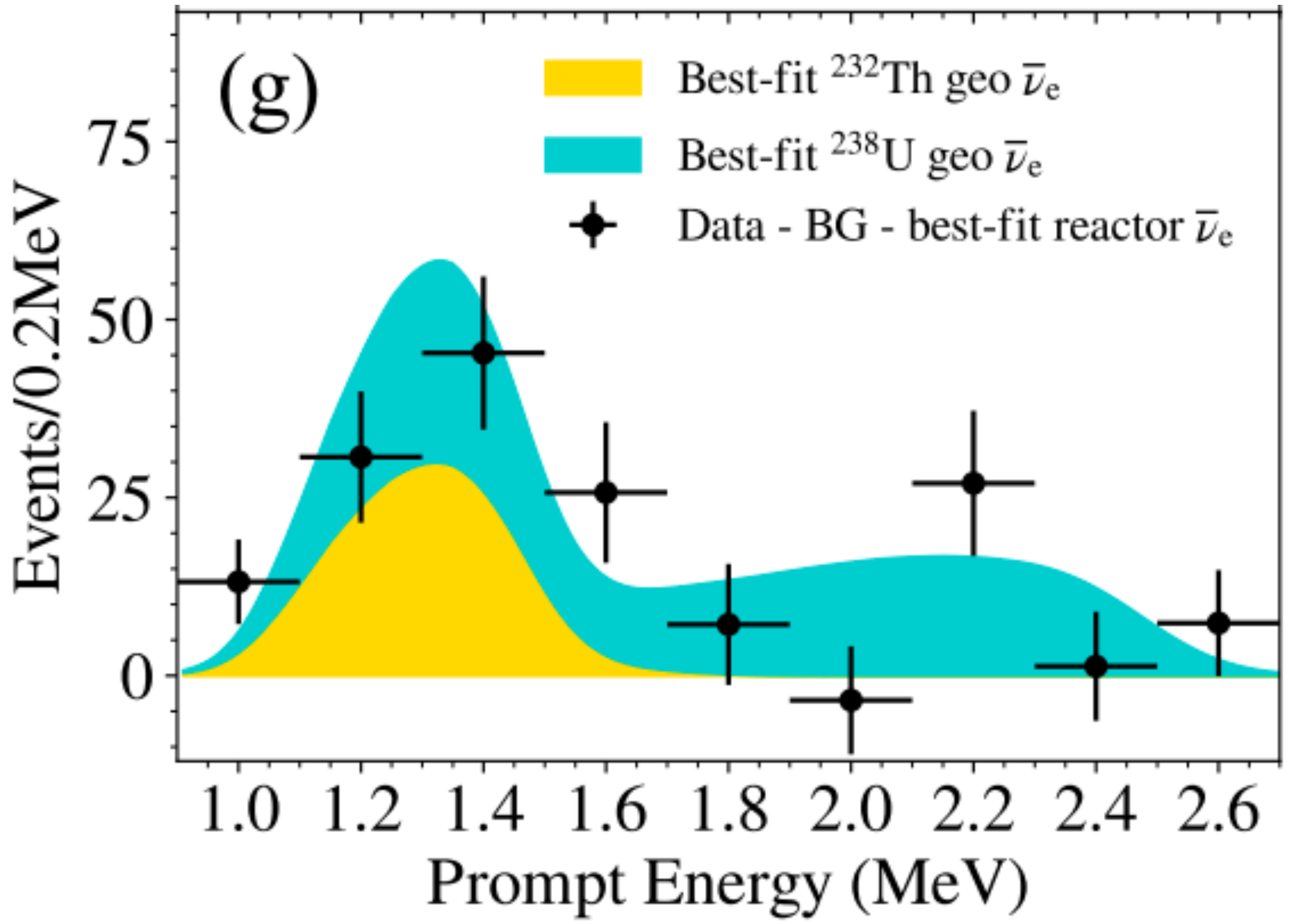
KamLAND Latest Results

S. Abe et al, “Abundances of uranium and thorium elements in Earth estimated by geoneutrino spectroscopy”, GRL, 49, e2022GL099566





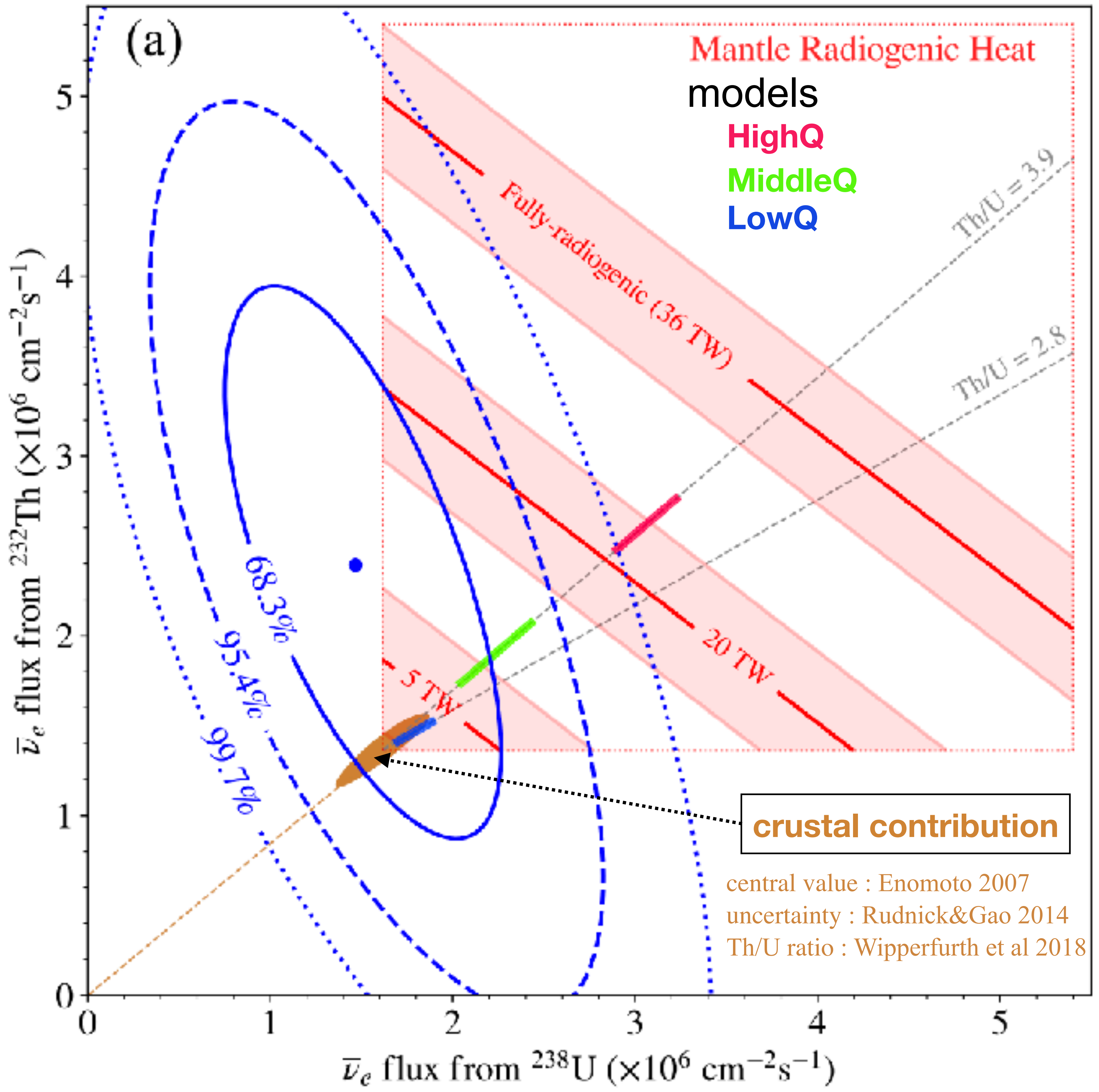
Dataset : Mar, 2002-Dec, 2021
Livetime : 5227 days
(low-reactor phase : 2590 days)



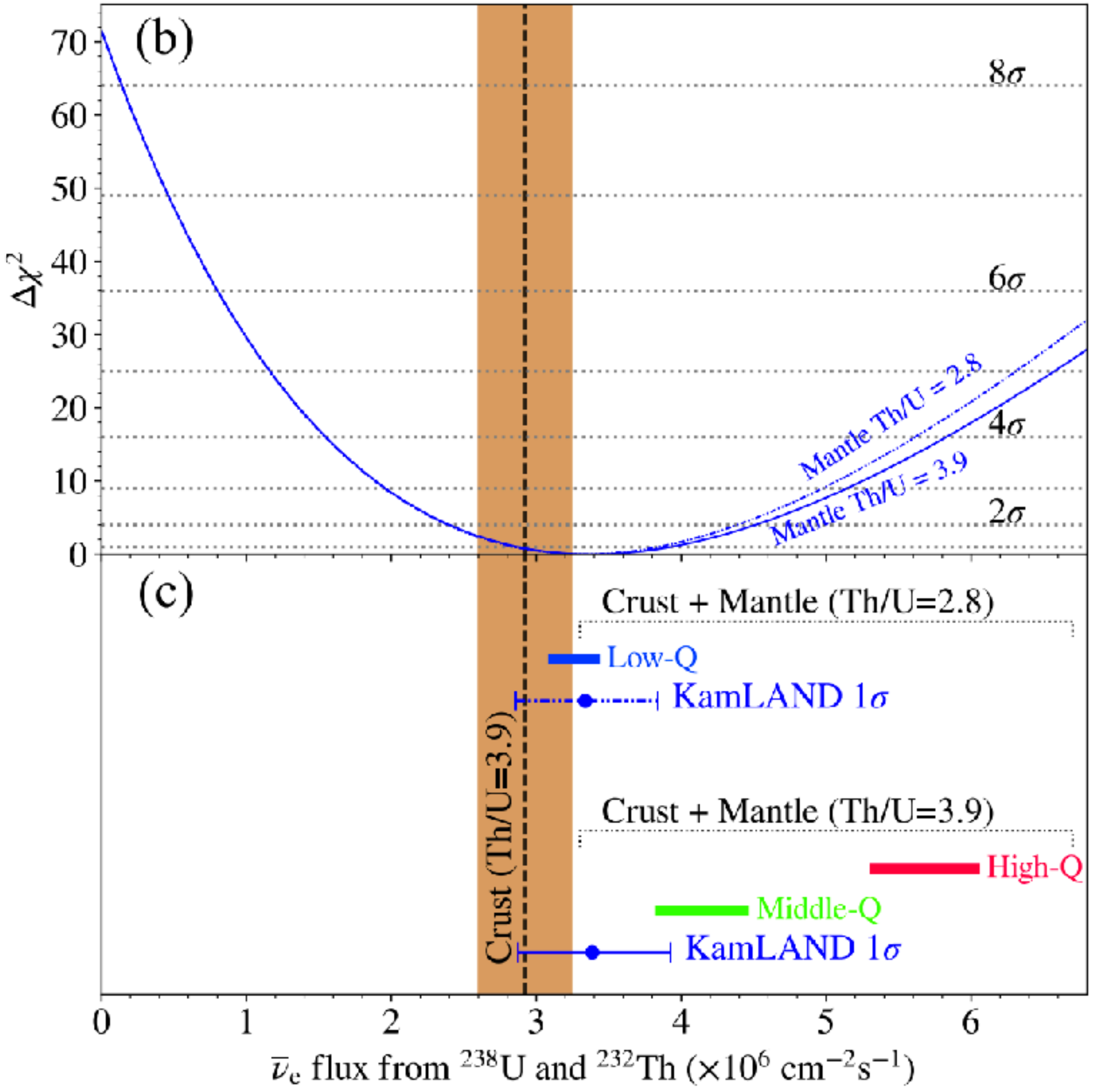
☑ **massive dataset of low-reactor period**
→ precise measurement of U and Th contributions

KamLAND Latest Results

S. Abe et al, “Abundances of uranium and thorium elements in Earth estimated by geoneutrino spectroscopy”, GRL, 49, e2022GL099566



central value : Enomoto 2007
uncertainty : Rudnick&Gao 2014
Th/U ratio : Wipperfurth et al 2018



☑ Radiogenic Heat

Th/U free

Adding heat estimate from crust,
^{238}U : 3.4 TW, ^{232}Th : 3.6 TW

$$Q^{\mathrm{U}} = 3.3^{+3.2}_{-0.8}\ \mathrm{TW}$$
$$Q^{\mathrm{Th}} = 12.1^{+8.3}_{-8.6}\ \mathrm{TW}$$
$$Q^{\mathrm{U}} + Q^{\mathrm{Th}} = 15.4^{+8.3}_{-7.9}\ \mathrm{TW}$$

☑ Model Rejection

HighQ model is rejected at

99.76 % C.L. (homogeneous mantle)

97.9% C.L. (concentrated at CMB)

☑ best-fit

Th/U free

	N of event	0signal rejection
U	117^{+41}_{-39}	3.3σ
Th	58^{+25}_{-24}	2.4σ
U+Th	174^{+29}_{-28}	8.3σ

Achieved the accuracy level can further geoscientific discussion

Improve the distinct spectroscopic contributions of U and Th

Beyond: Multi-site Measurement

Observation = **Crust** + **Mantle**

(y = x + b)

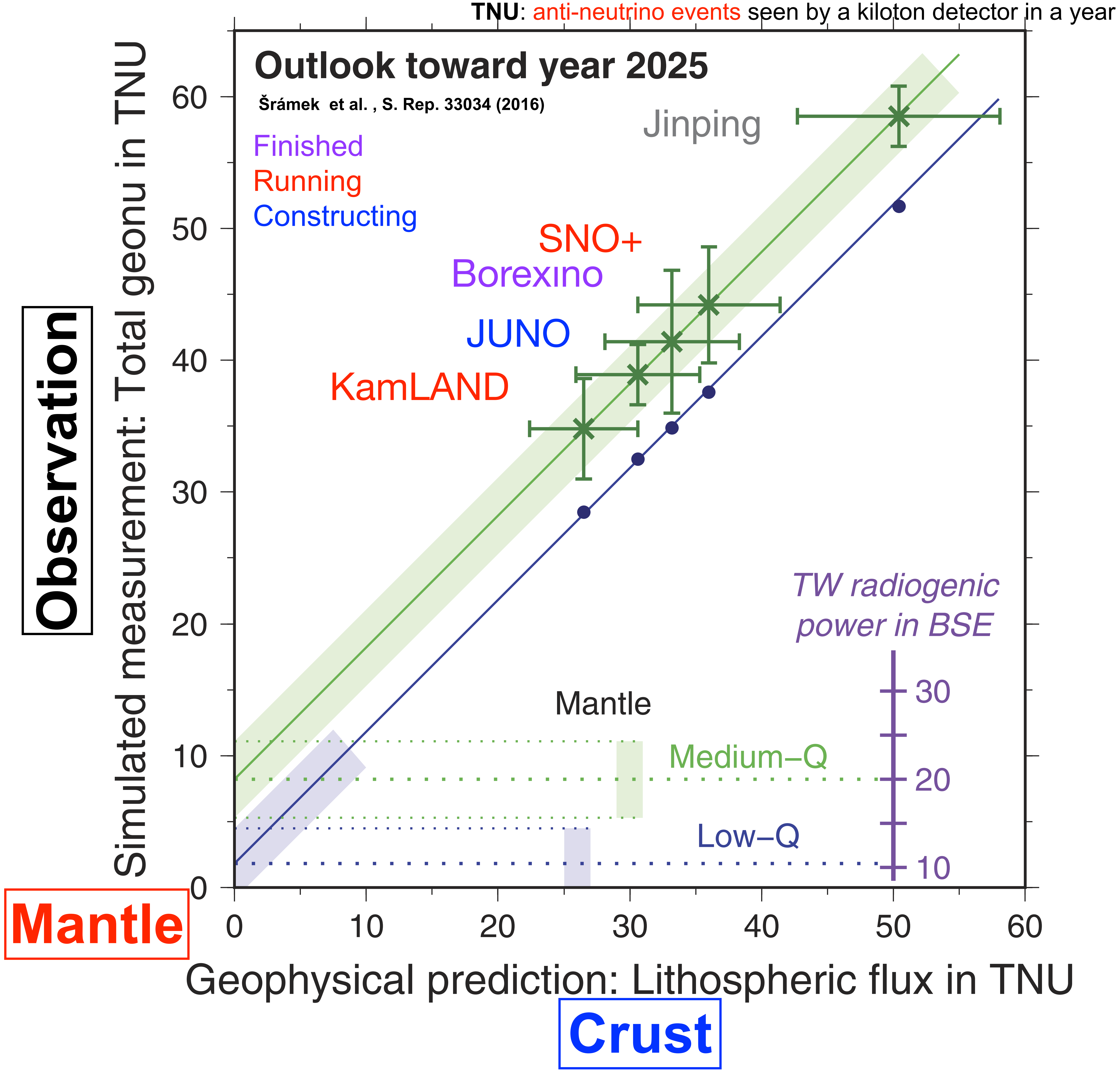
Near Future…

4 multi-site measurements can constrain mantle contribution.

* KamLAND, Borexino, SNO+, JUNO

* Crust estimation needs to be accurate.

TNU: anti-neutrino events seen by a kiloton detector in a year



Beyond: Multi-site Measurement+OBD

Observation = **Crust** + **Mantle**

(y = x + b)

Near Future…

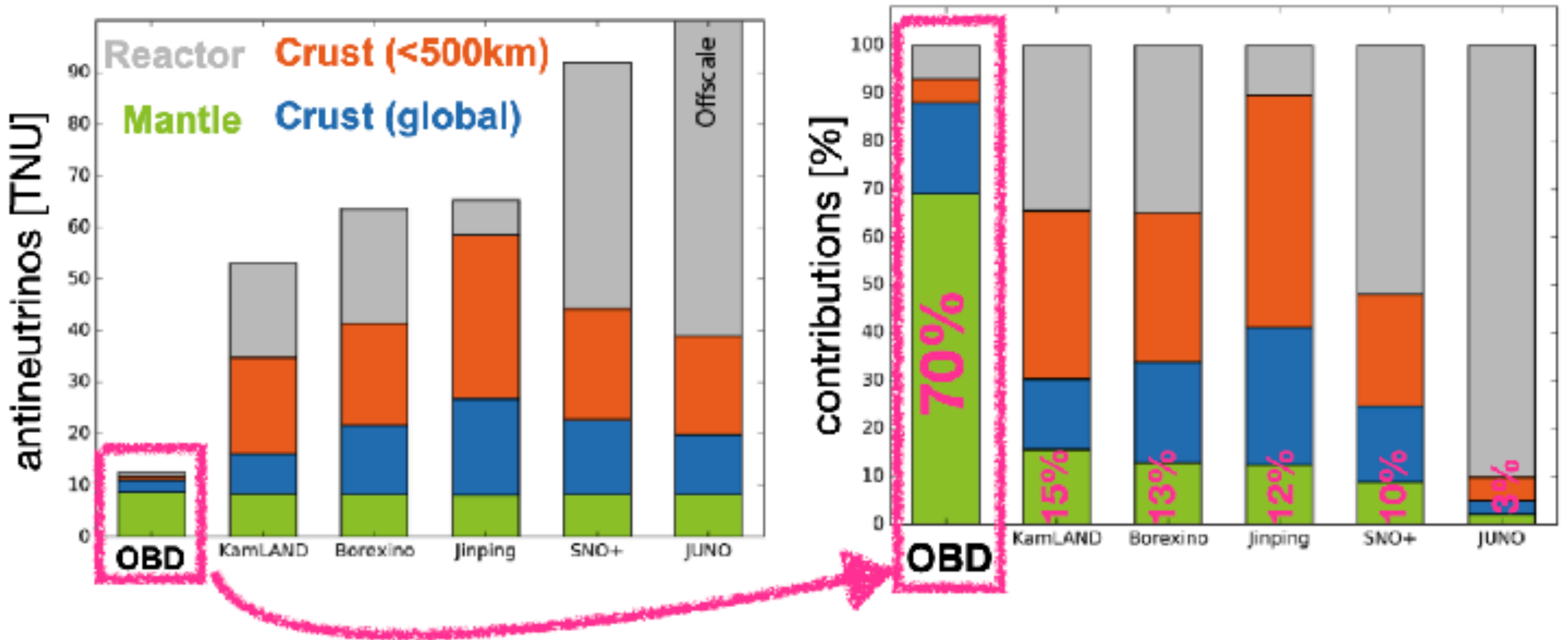
4 multi-site measurements can constrain mantle contribution.

* KamLAND, Borexino, SNO+, JUNO

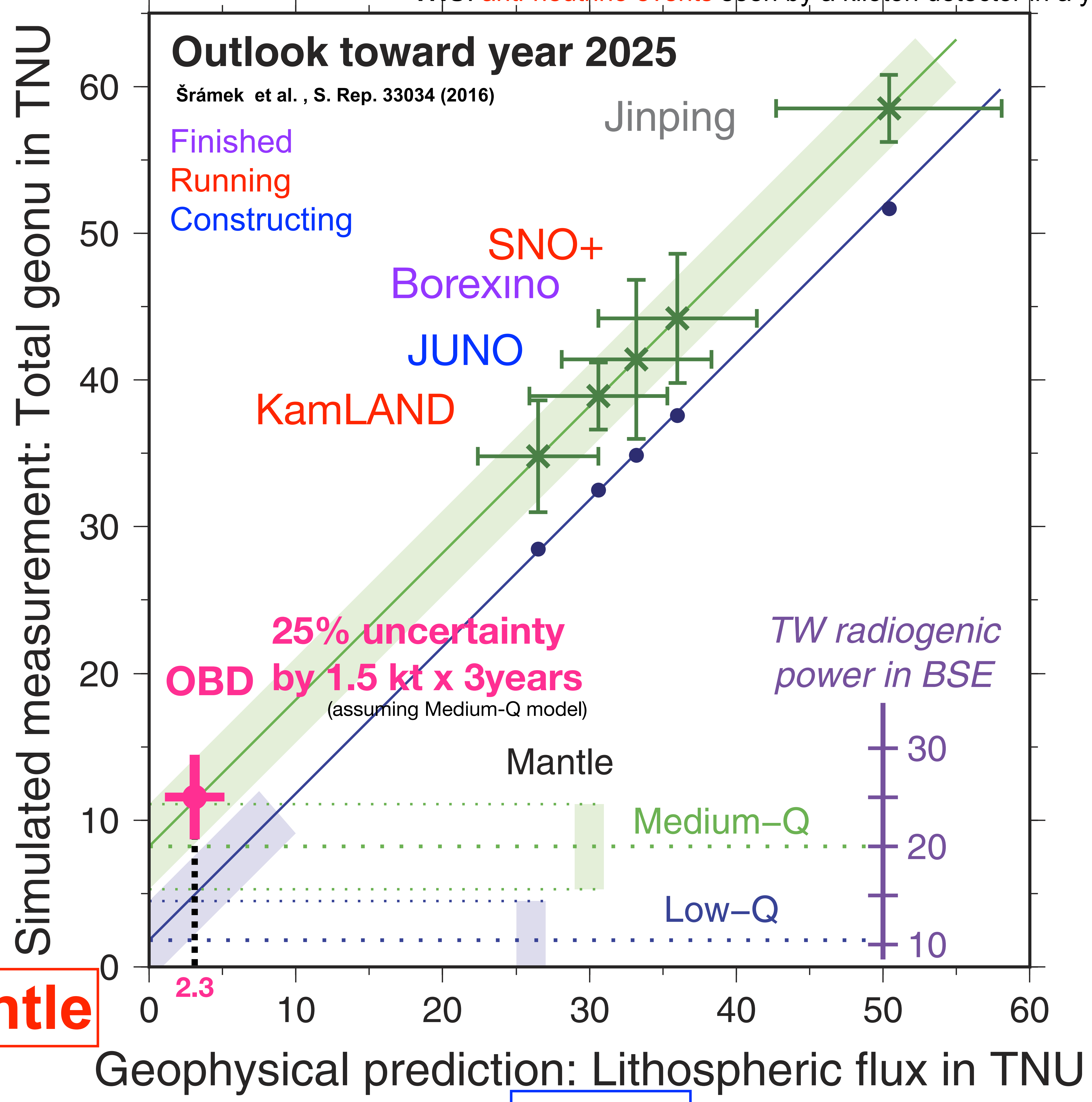
* Crust estimation needs to be accurate.

+ Ocean Bottom Detector

directly measure mantle contribution.



TNU: anti-neutrino events seen by a kiloton detector in a year



Observation

Mantle

Crust

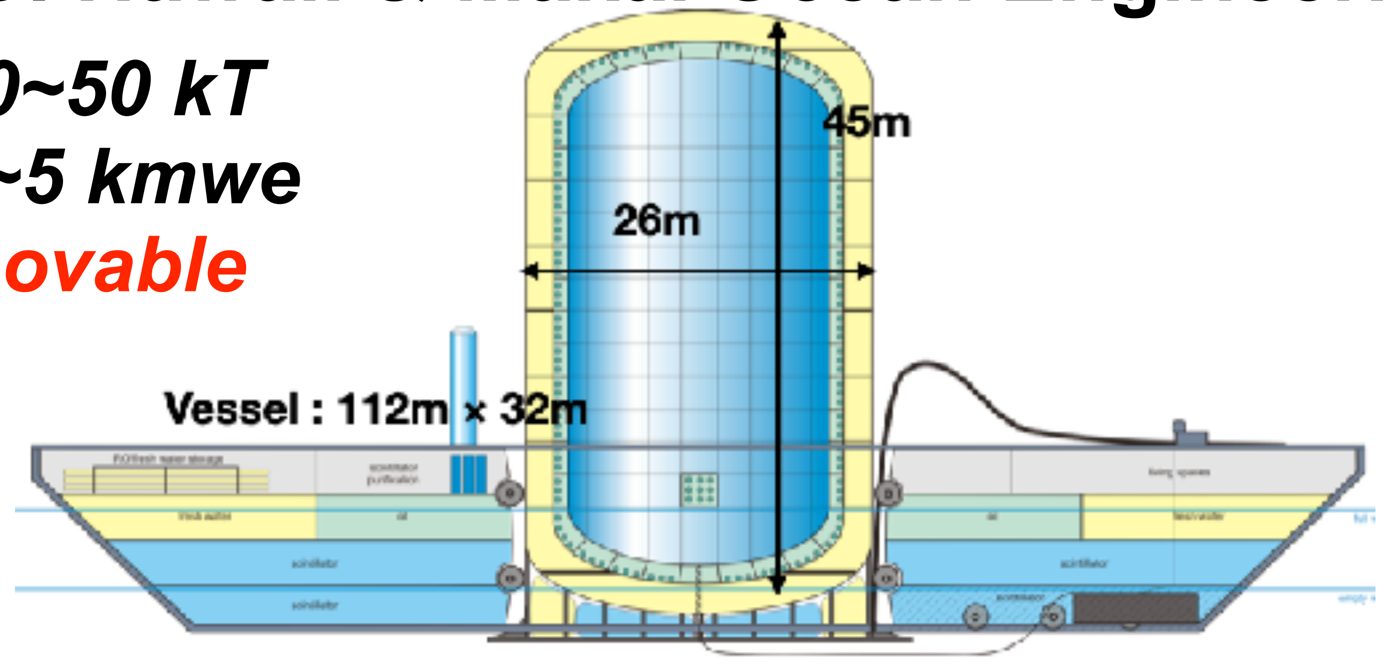
Beyond: OBD

Original idea (2005)

“Hanohano”

U. Hawaii & Makai Ocean Engineering

10~50 kT
1~5 kmwe
movable



Technical tests and detector design

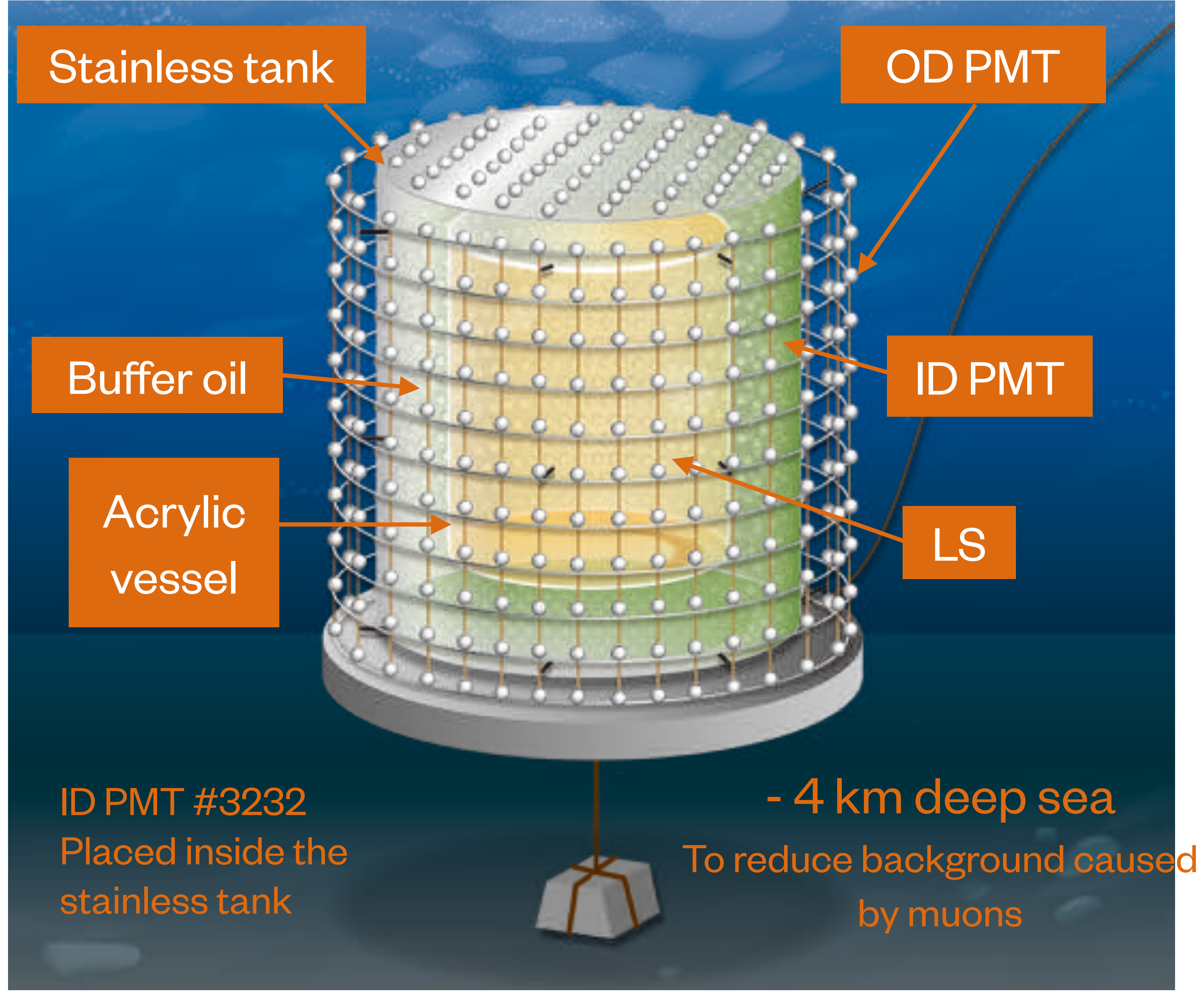
started with JAMSTEC* & Tohoku U.!

July 9, 2019

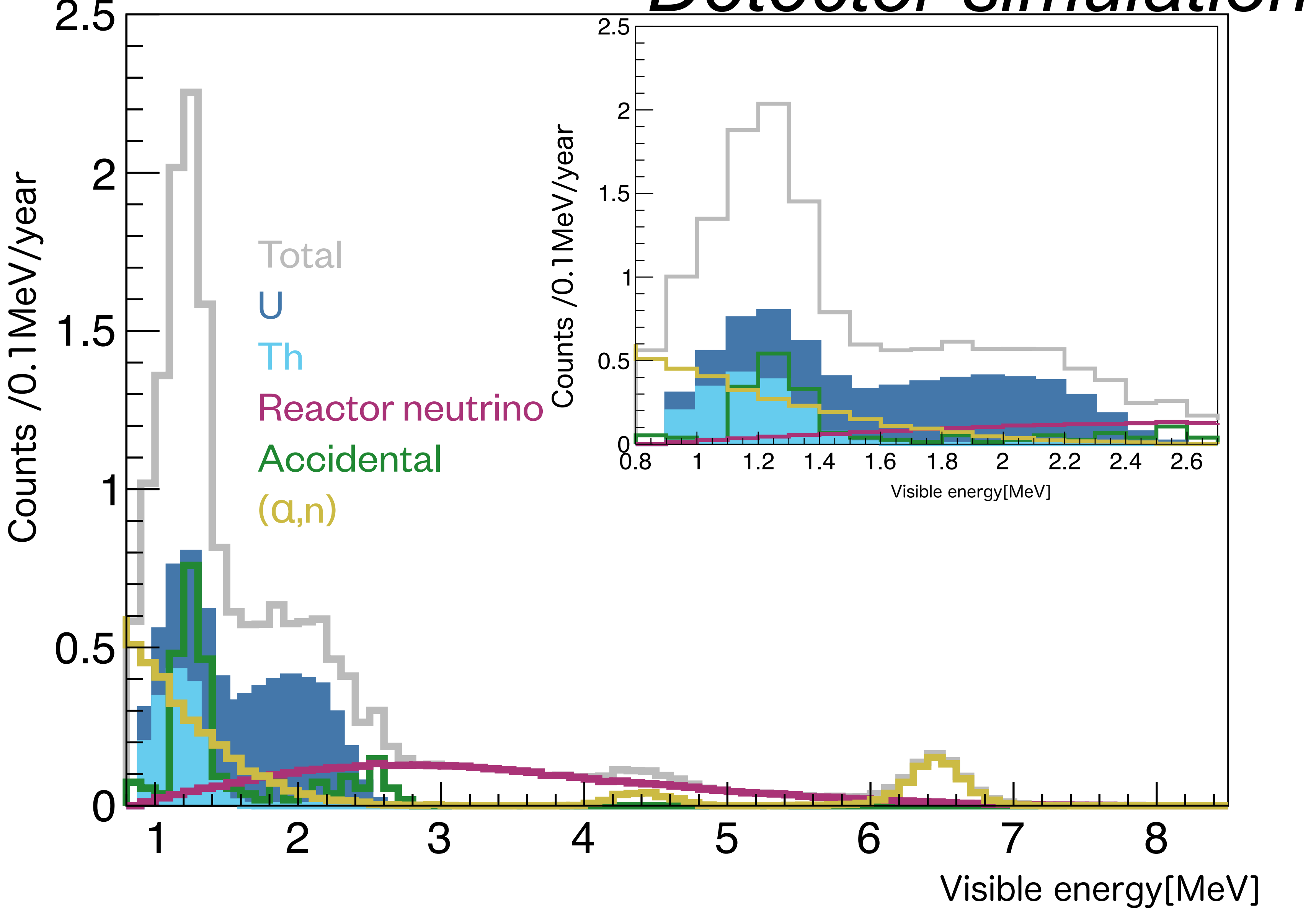
Joint workshop on OBD with Ocean Engineering, Earth Science and Neutrino Physics

Ocean Bottom Detector project (2019~)

1.5 kt LS detector @4km seafloor



Detector simulation



*** Mantle geoneutrino sensitivity**

highQ model: 1year → 3.7σ
middleQ model: 3year→ 3.5σ
lowQ model: 10year→ 2.5σ

Unique detector which can have sea water and LS as neutrino targets !

- ✦ Working on development of detector components (workable **@40 MPa, 2-4 °C**)
- ✦ **Prototype detector** is under construction to be installed into **1km depth**
- ✦ Collaboration and community supports are being enhanced. (U. Hawaii, Chiba U., LLNL)

H. Watanabe et al., Underwater Technology 2023

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* Japan Agency for Marine-Earth Science and Technology

Summary

KamLAND-Zen

$\langle m_{\beta\beta} \rangle < 36\text{-}156\ \mathrm{meV}$

- KamLAND-Zen 800 achieved to enter the inverted ordering region.
- **hardware and analysis improvements** from KamLAND-Zen 400 were clearly effective to enhance the sensitivity
- KamLAND-Zen 800 was completed in January 2024.
- **KamLAND2-Zen** is planned to search deeper into inverted ordering region.

Geoneutrinos

- Geoneutrinos are unique tool to measure the Earth's radiogenic engine.
- To date, physics experiments have shown the **usefulness of geoneutrinos.**
  - Interdisciplinary community has furthered its connection over these past 15 years.
- **"Neutrino Geoscience"**
  - Now it's exciting generation for 4 multi-site measurements
  - **OBD** has strong power to measure mantle contribution directly