Status and prospects of KamLAND-Zen (FY2019-2023)

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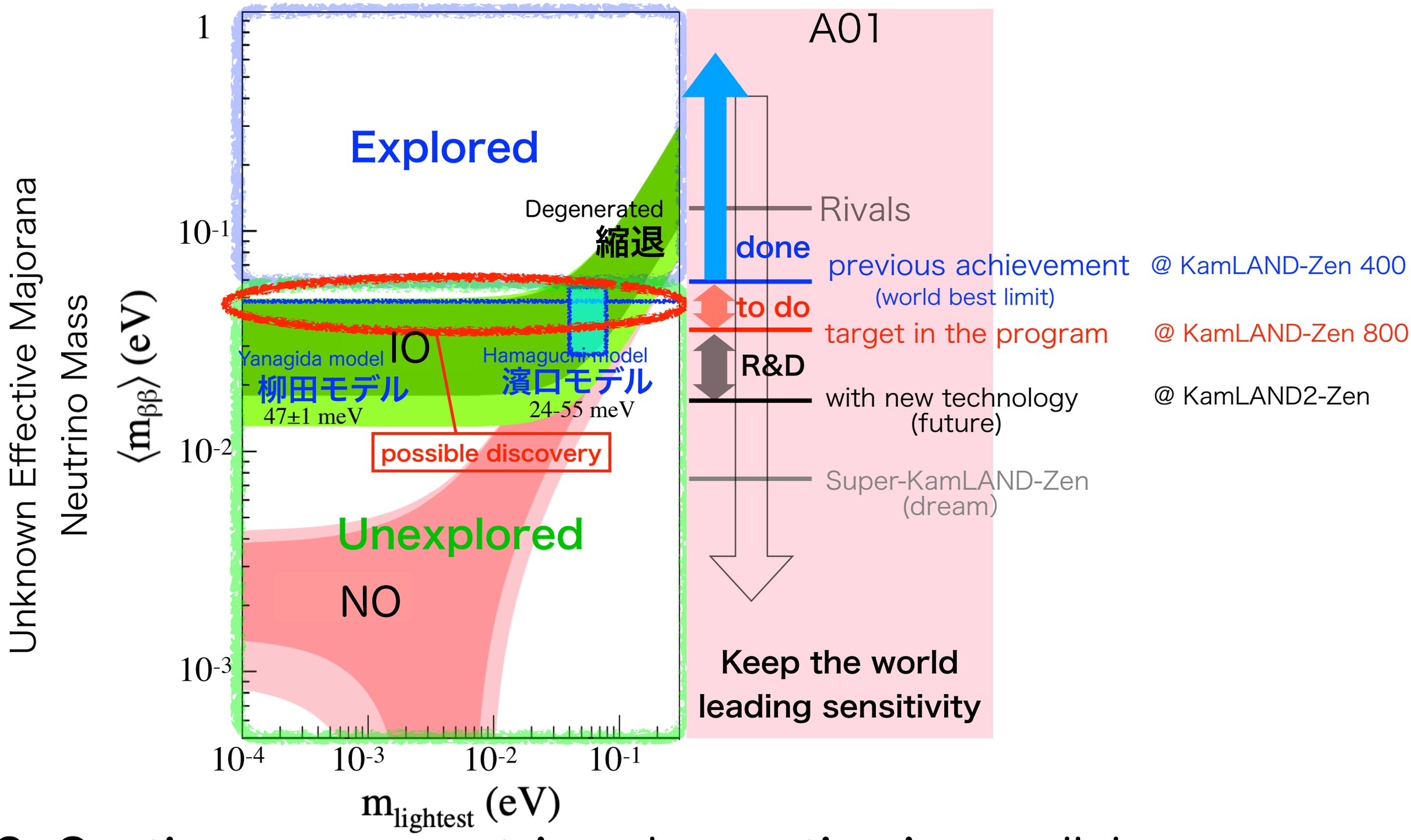
UGAP2024, 2024.03.04
“Unraveling the History of the Universe and Matter Evolution with Underground Physics”

Major targets of KamLAND-Zen for FY2019-2023

1. World leading search for $0\nu2\beta$

(sensitivity entering the inverted ordering region)

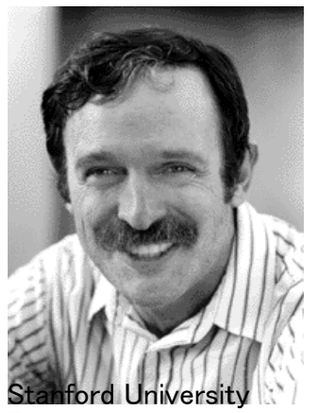


2. Continuous geoneutrino observation in parallel

(flux precision better than an earth model)

Breakthrough from geoneutrino observation

2005 Experimental investigation of geologically produced antineutrinos with KamLAND

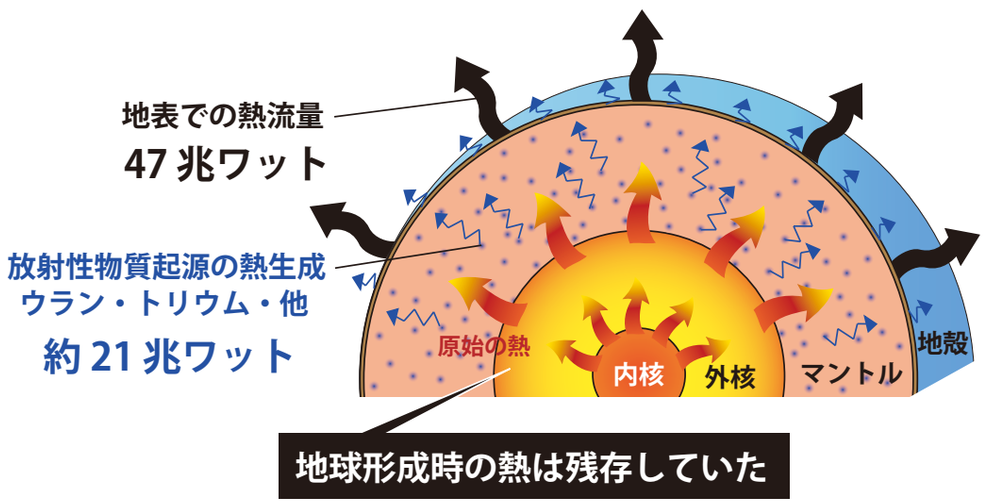


Stanford University
Professor Norman Sleep

This is not an evolution but a revolution!

Impossible once thought became possible!

2011 Partial radiogenic heat model for Earth revealed by geoneutrino measurement



Earth is cooling!

(Yeah, I thought so..)

World first direct measurement of terrestrial radiogenic heat

Big arguments in geoscience

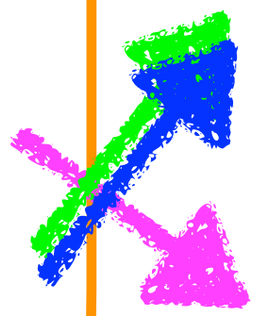
Arguments between geochemistry and geophysics

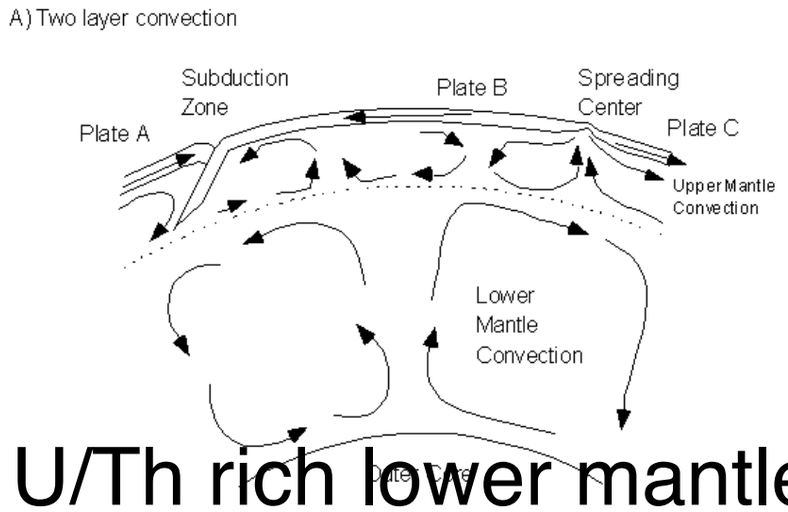
High-Q

Mantle convection

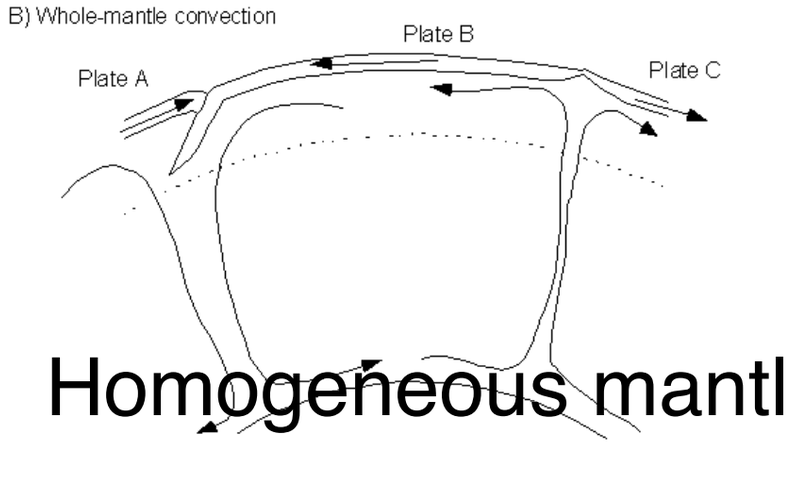
geophysical model
predicts **single convection**

geochemical model
predicts **multi-layer convection**





U/Th rich lower mantle



Homogeneous mantle

Arguments within geochemistry

Primordial meteorite

chemical abundance implies **“C1 chondrite”** (geochemical model)

Middle-Q

carbonaceous chondrite

U,Th amount

isotope ratio implies **“enstatite chondrite”** (geochemical model)

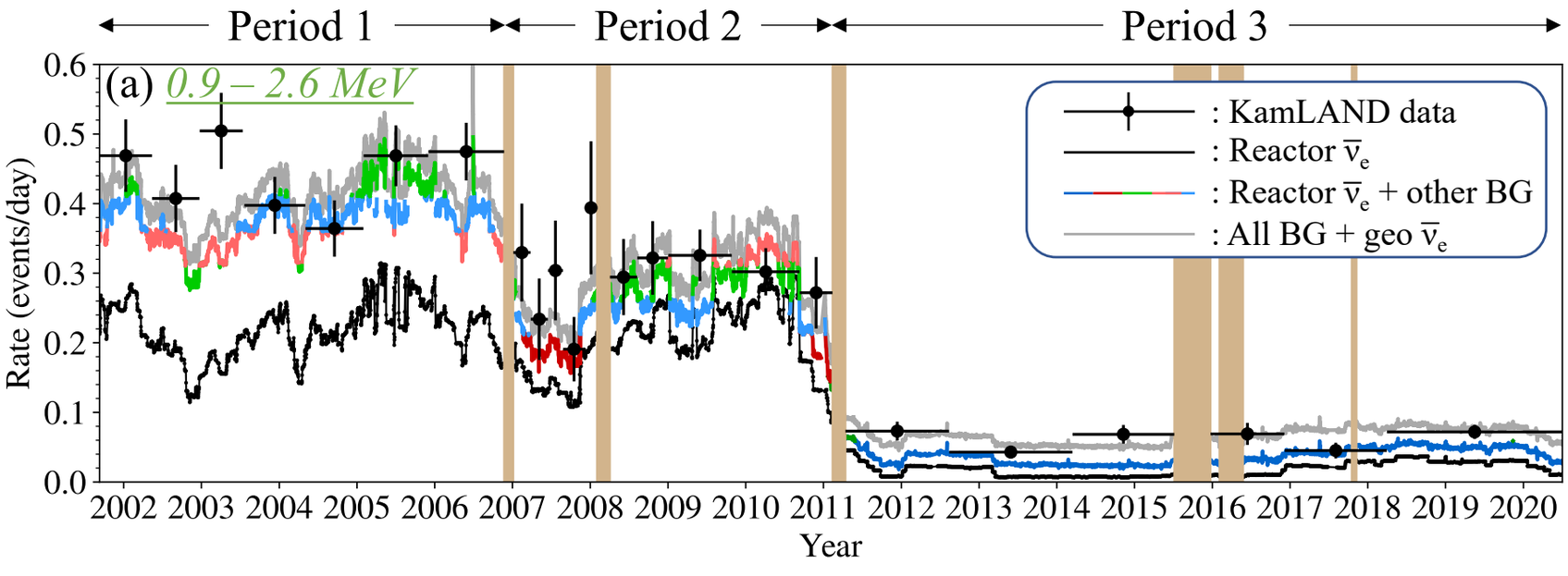
Low-Q

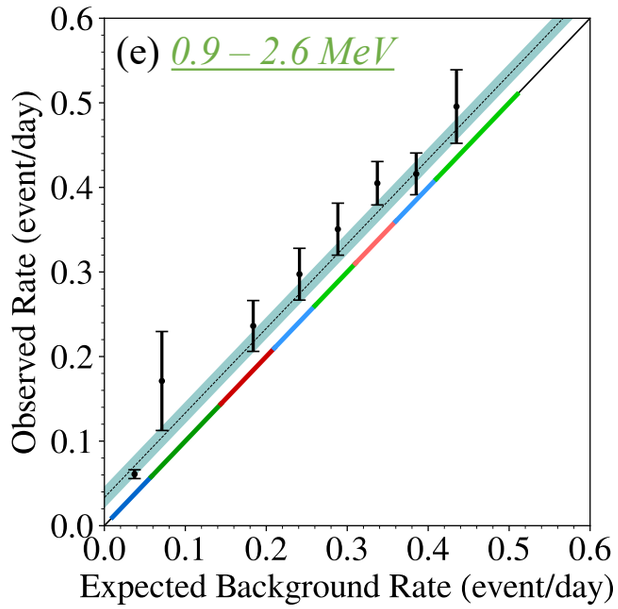
enstatite chondrite

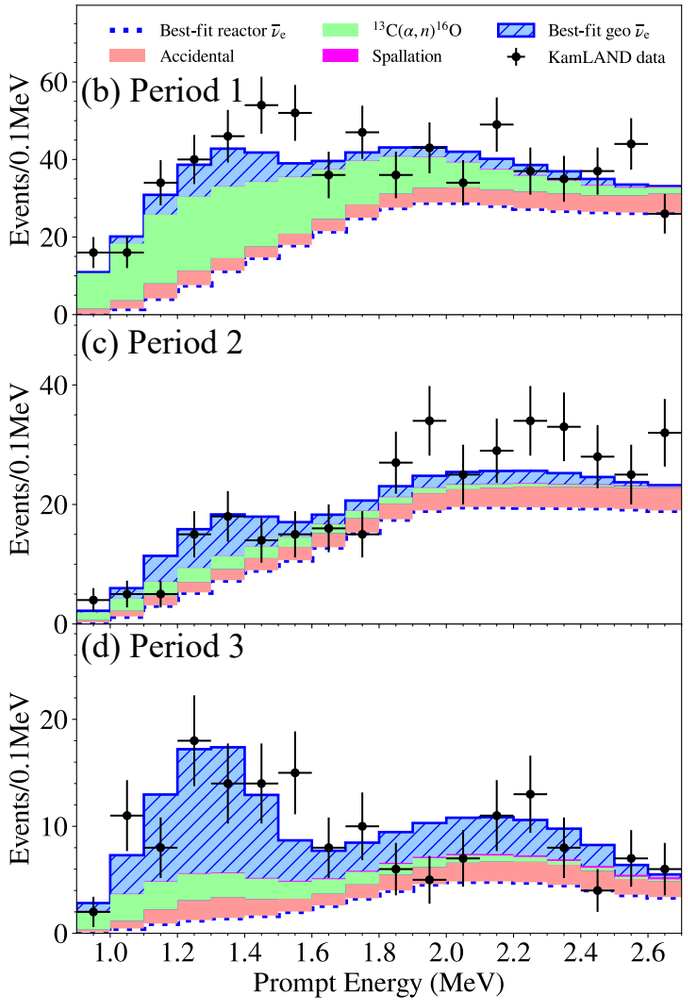
Each model predicts different radiogenic heat (geoneutrino flux)

KL is accumulating low reactor data

Geophysical Research Letters 49: 16 (2022)

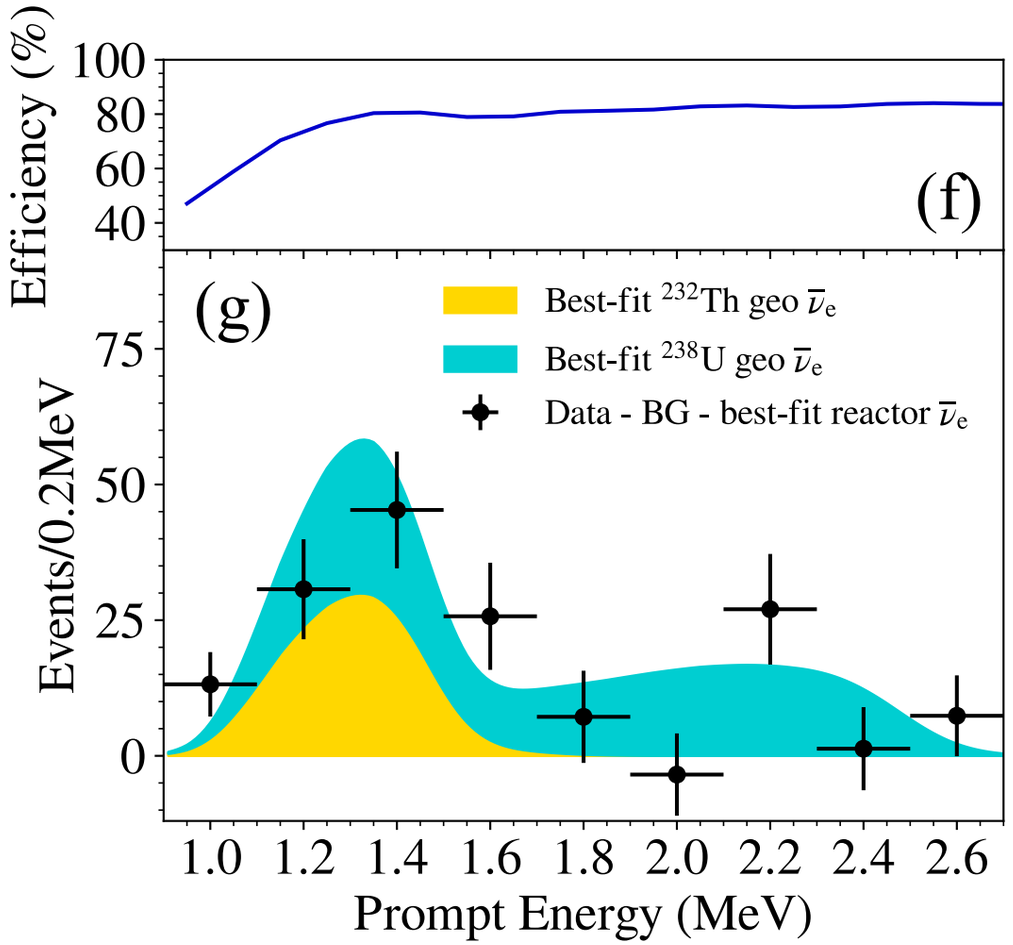






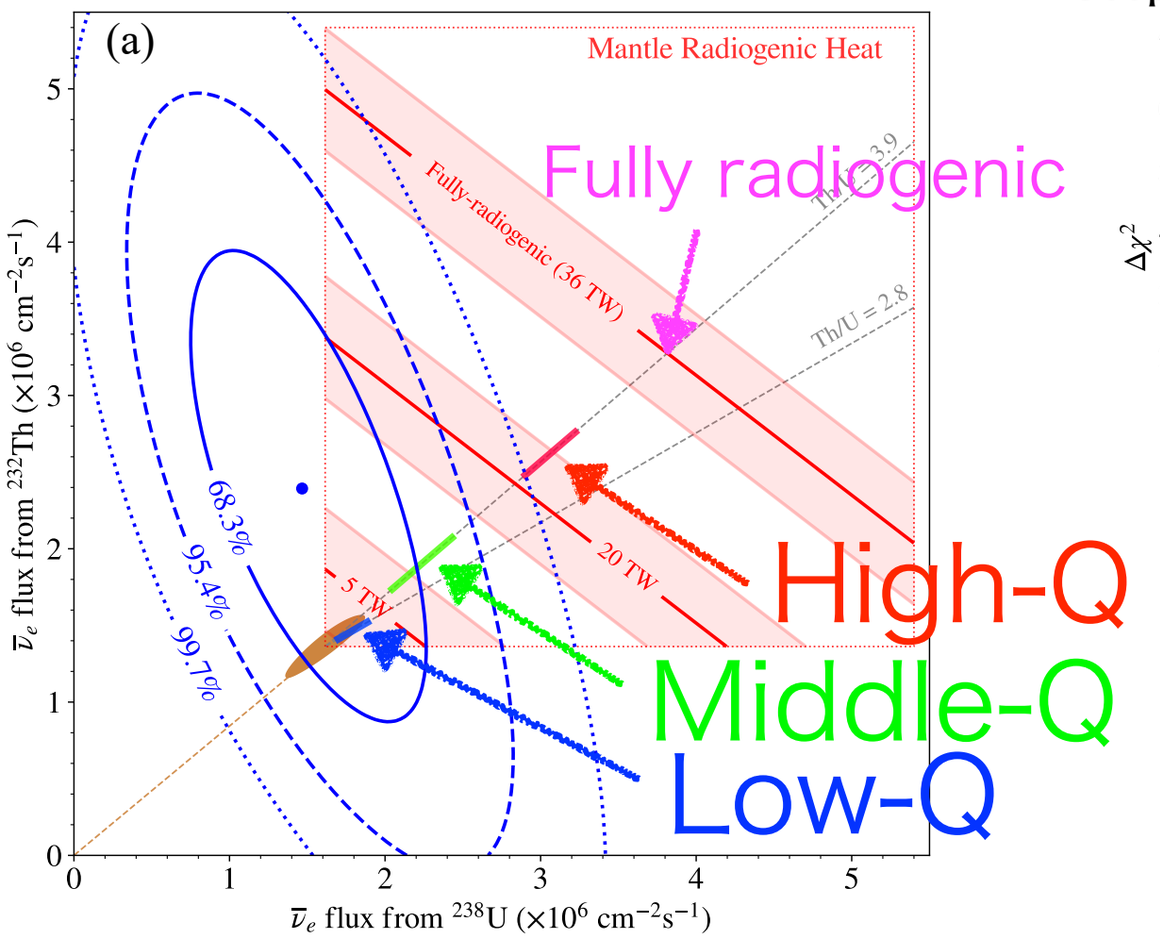
distillation

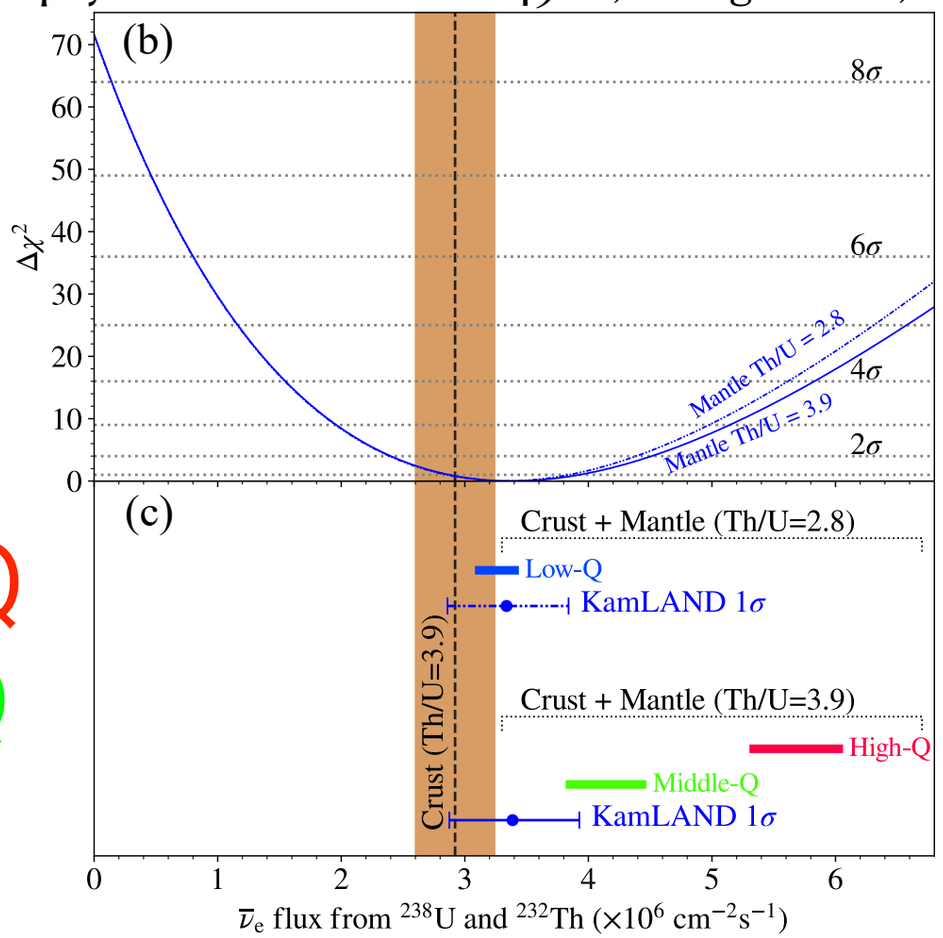
low reactor



Results from 18 years of observation (8 years low reactor period)

Geophysical Research Letters 49. 16, 28 August 2022, e2022GL099566





117^{+41}_{-39} events from ^{238}U

58^{+25}_{-24} events from ^{232}Th

Zero Uranium excluded at 3.3 σ.

Fully radiogenic excluded at 5.2 σ.

Assuming Th/U mass ratio of 3.9

183^{+29}_{-28} events observed 8.3 σ

$\bar{\nu}$ flux of 3.4±0.5 × 10^6 cm^{-2}s^{-1}.

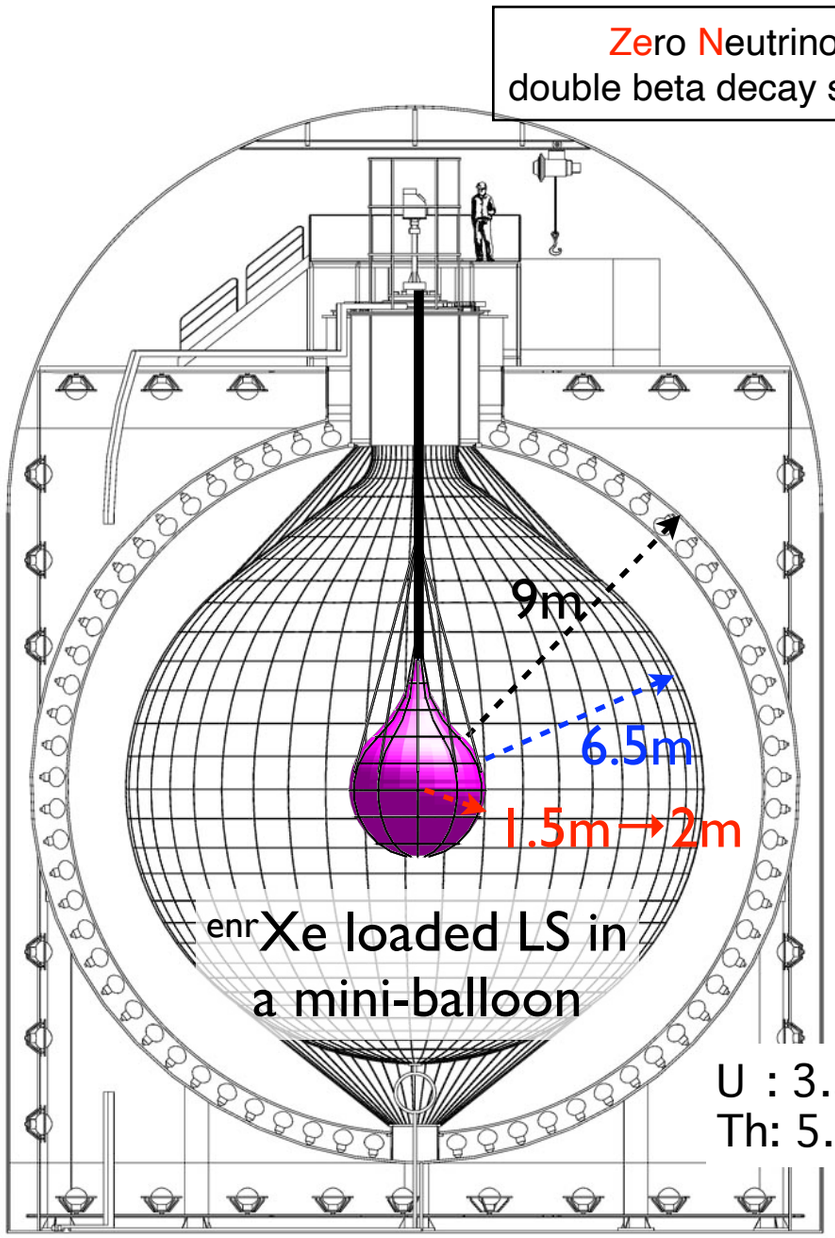
High-Q (geophysical) disfavored at 99.76% CL.

Successful breakthrough again!

Model discrimination started!!

2022 New knowledge in geoscience unobtainable without geoneutrino measurement

KamLAND-Zen



90% enriched ^{136}Xe

320kg for phase-I

380kg for phase-II

745kg for Zen 800 (started in Jan. 2019)

largest amount so far

^{136}Xe can be loaded in LS up to ~3 wt%.

Noble gas

Centrifugal enrichment possible

$Q_{\beta\beta}$=2459 keV

(below ^{208}Tl 3198-5001 keV)

Advantages of using KamLAND

⓪ low cost and quick start
(running detector)

① BG can be identified
(full active thick shielding)

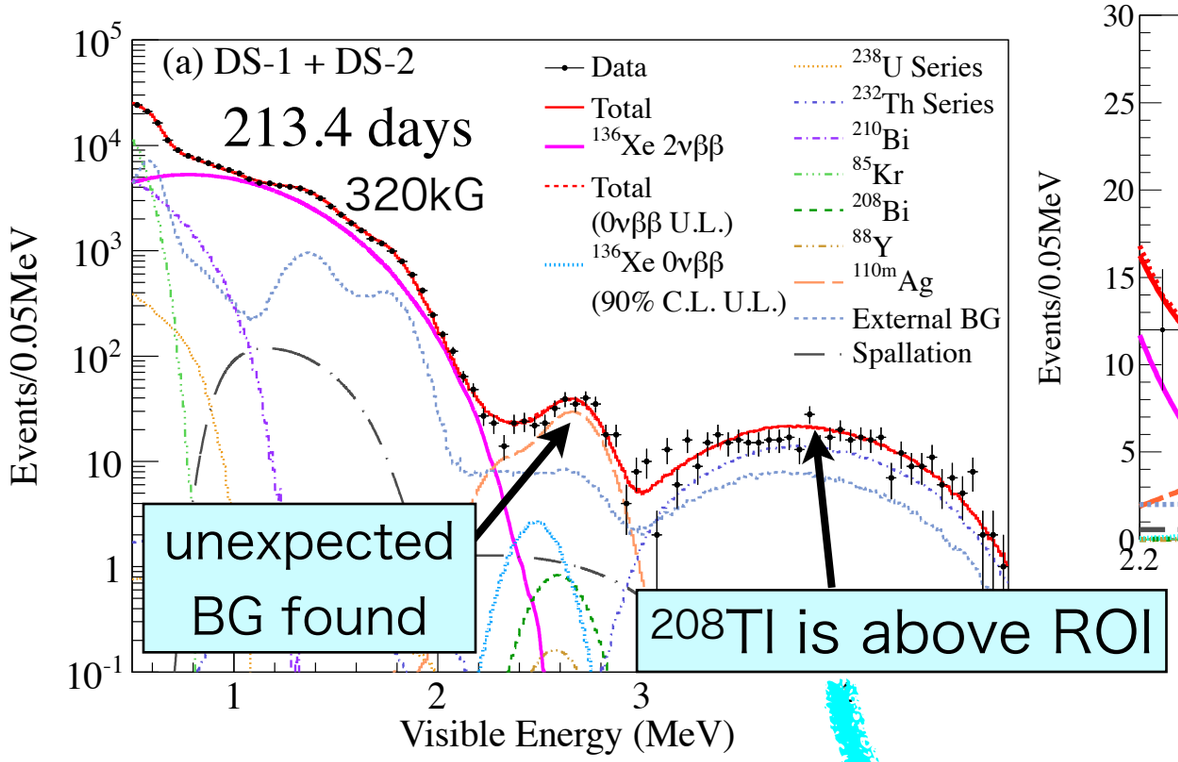
② In-situ purification possible
(liquid media)

③ On/Off measurements possible
(xenon is removable)

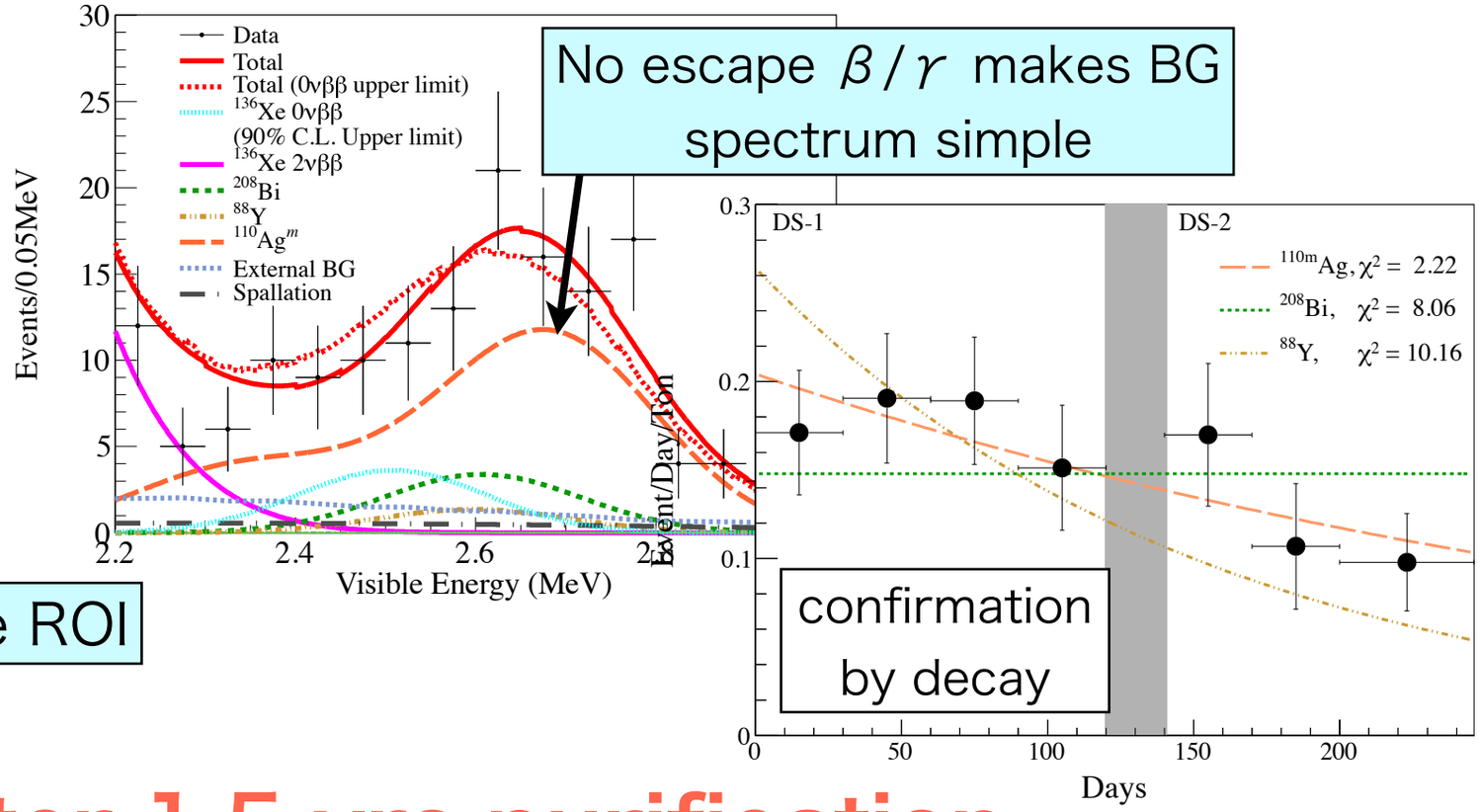
④ multi-purpose
(geo-neutrino)

⑤ easily scalable
(mini-balloon)

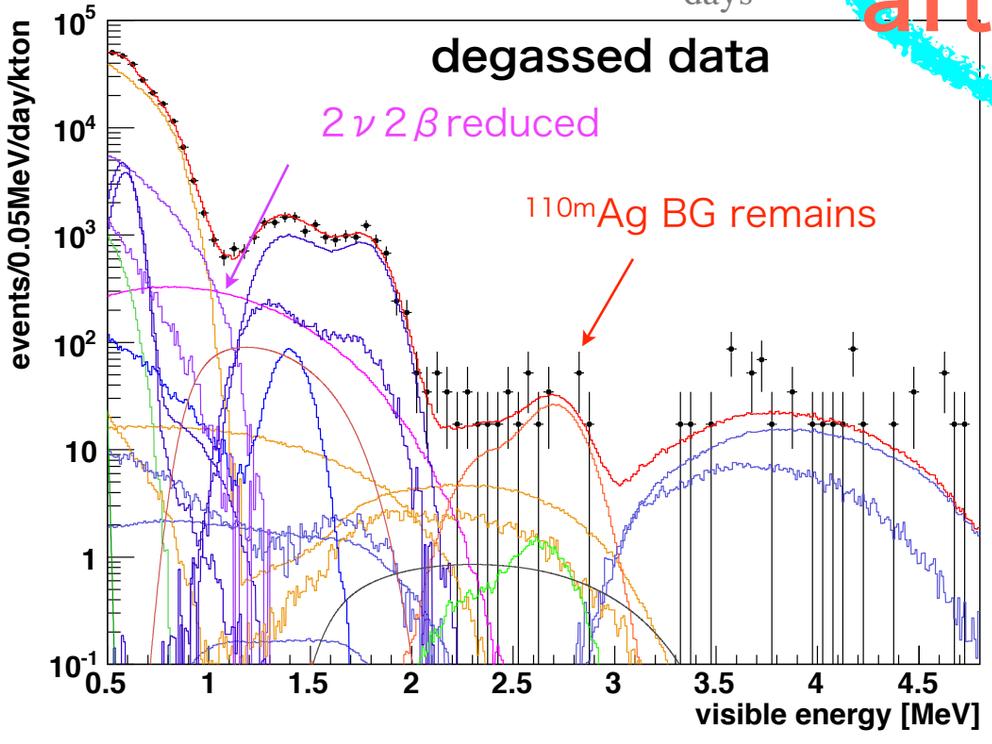
Thanks to full active apparatus,



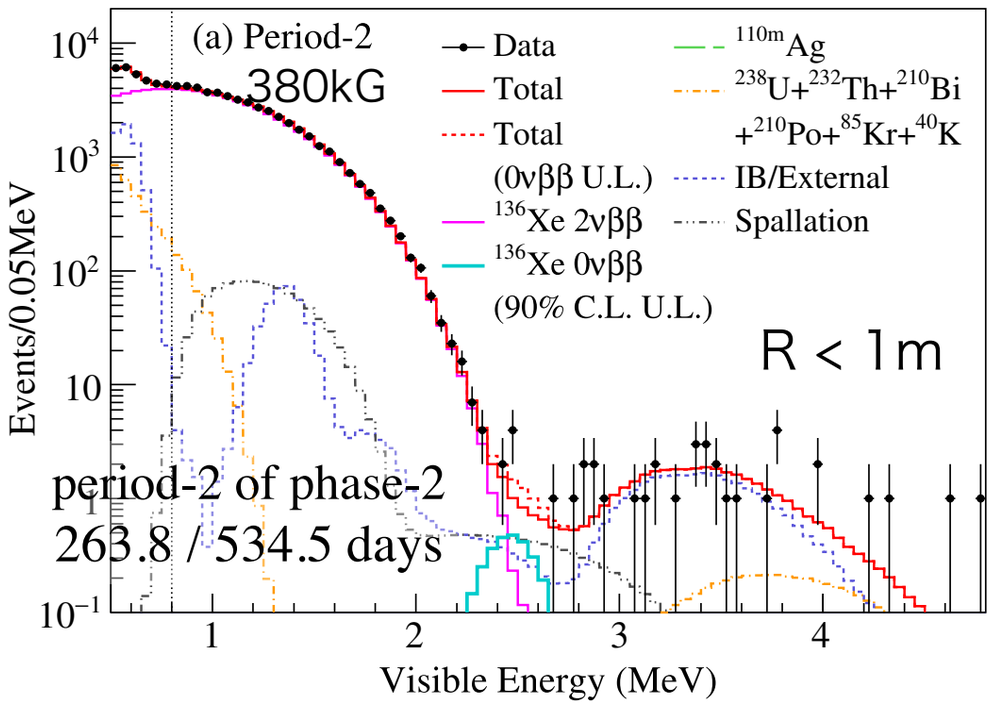
Dominant ①BG identified as ^{110m}Ag



after 1.5 yrs purification



^{110m}Ag reduction 1/20

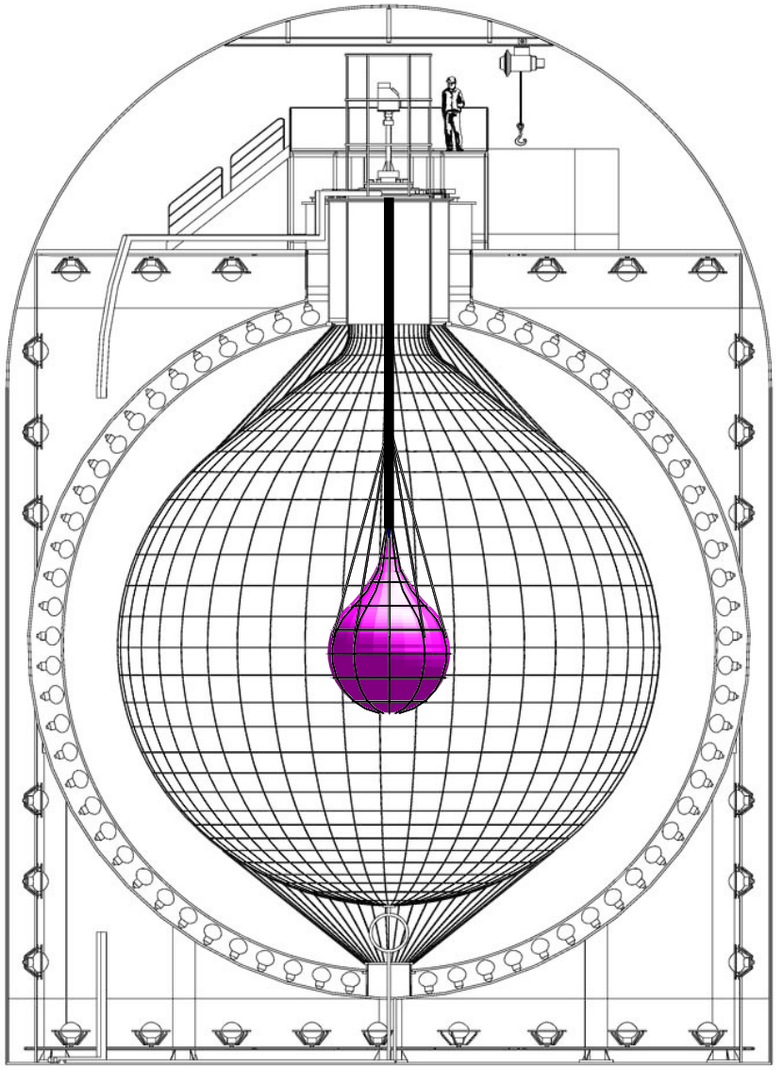


③on/off measurement demonstrated
(useful for signal confirmation)

②in-situ purification possible!!

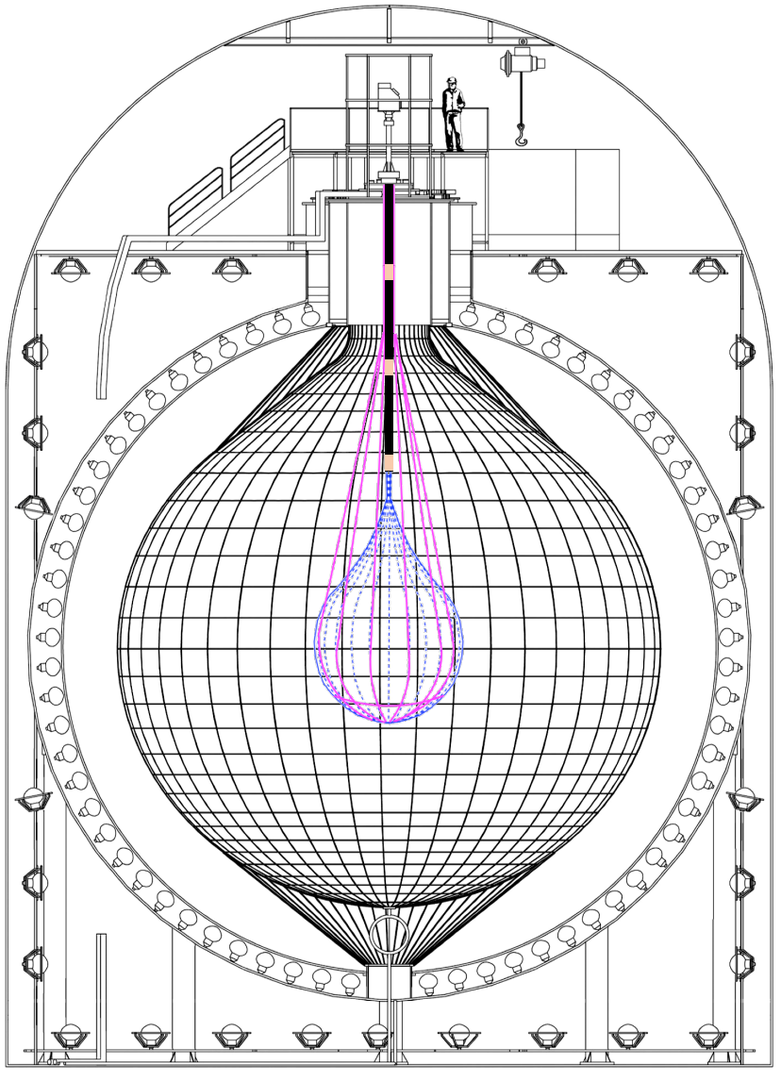
⑤ easily scalable

KamLAND-Zen 400



380kg (2011-)

KamLAND-Zen 800



745kg (2019-)

By the way, KLZ800 is already terminated on 12 January 2024.

Example of improvements

before

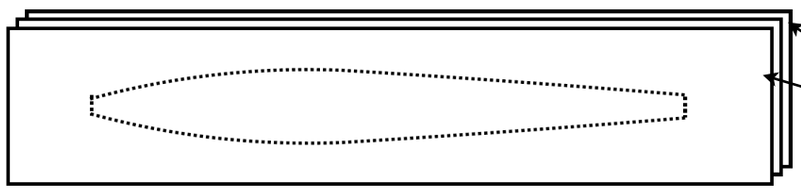
after

clean underwear

changing room in a clean room

keep staying away
goggle
welding machine
cover sheet
glove on glove
laundry twice a day
clean underwear
changing room in a clean room
dust visualization
more neutralizer
. . .

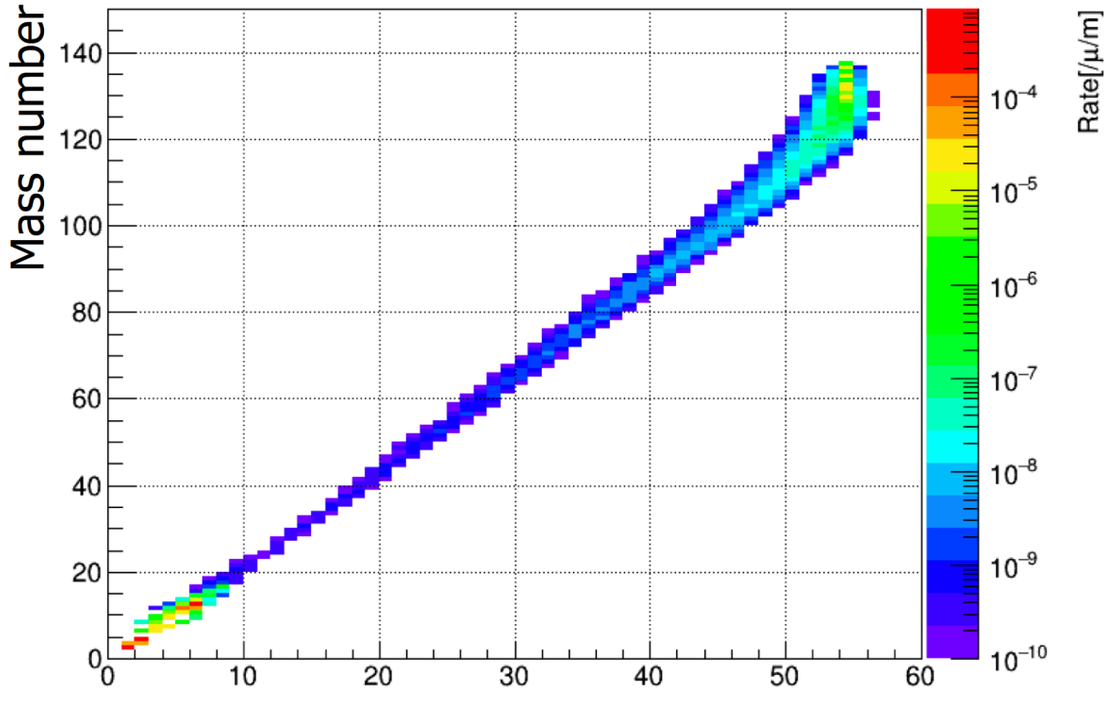
laundry twice a day



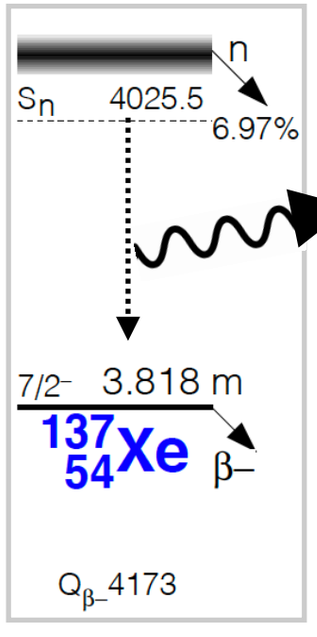
cover sheets

As getting better sensitivity, ^{136}Xe spallation became a new issue.

Xe spallation products (FLUKA)



^{137}Xe



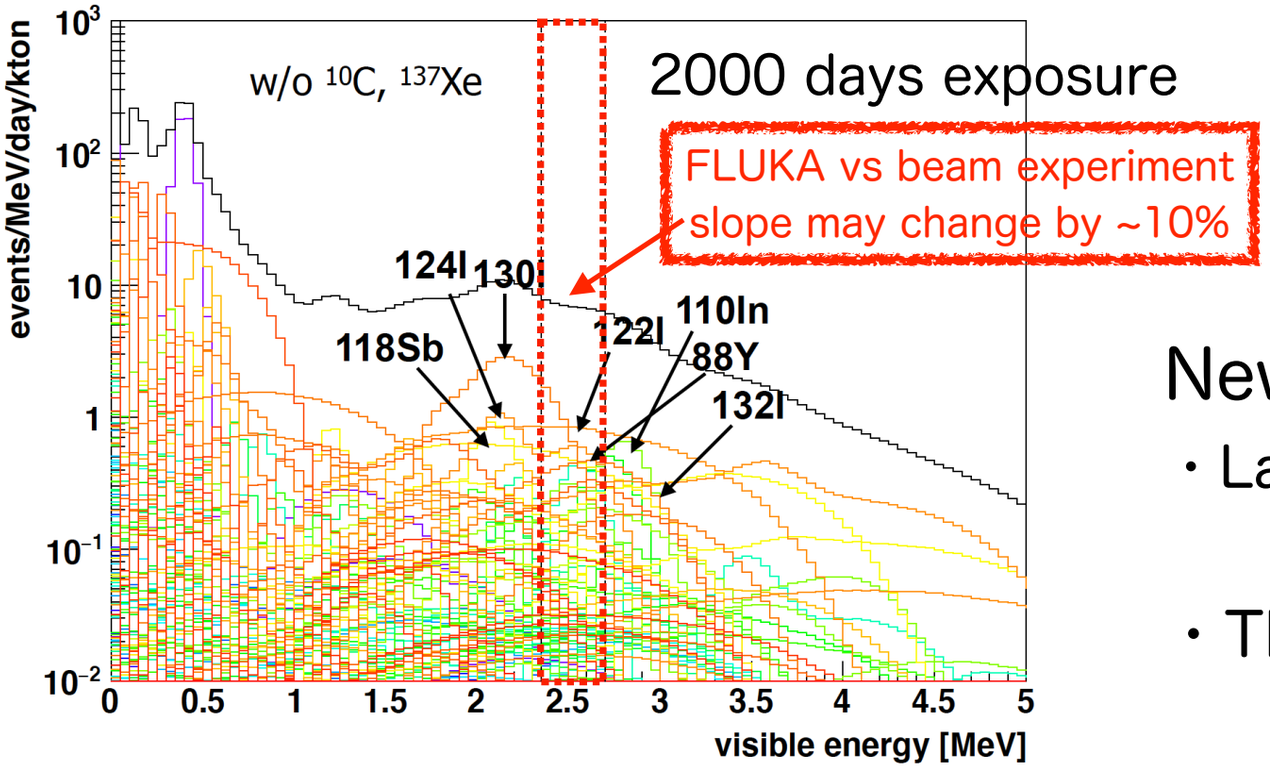
tagging with characteristic 4MeV neutron capture gamma is effective.

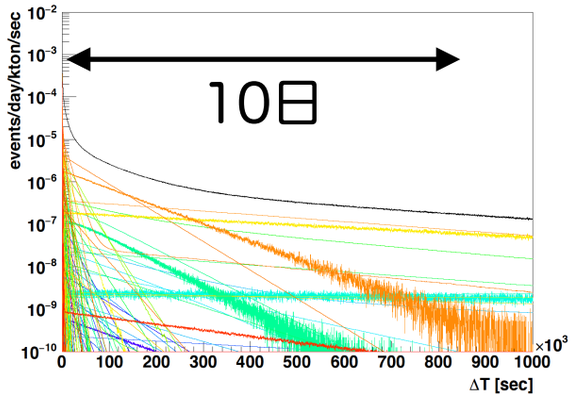
Q-value 4.2MeV
(possible BG)

Xe spallation contains long-lived nuclei.

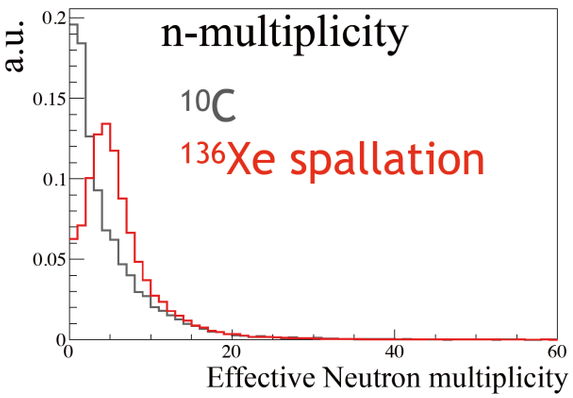
Atomic number

simulation with GEANT+ENSDF





neutron multiplicity

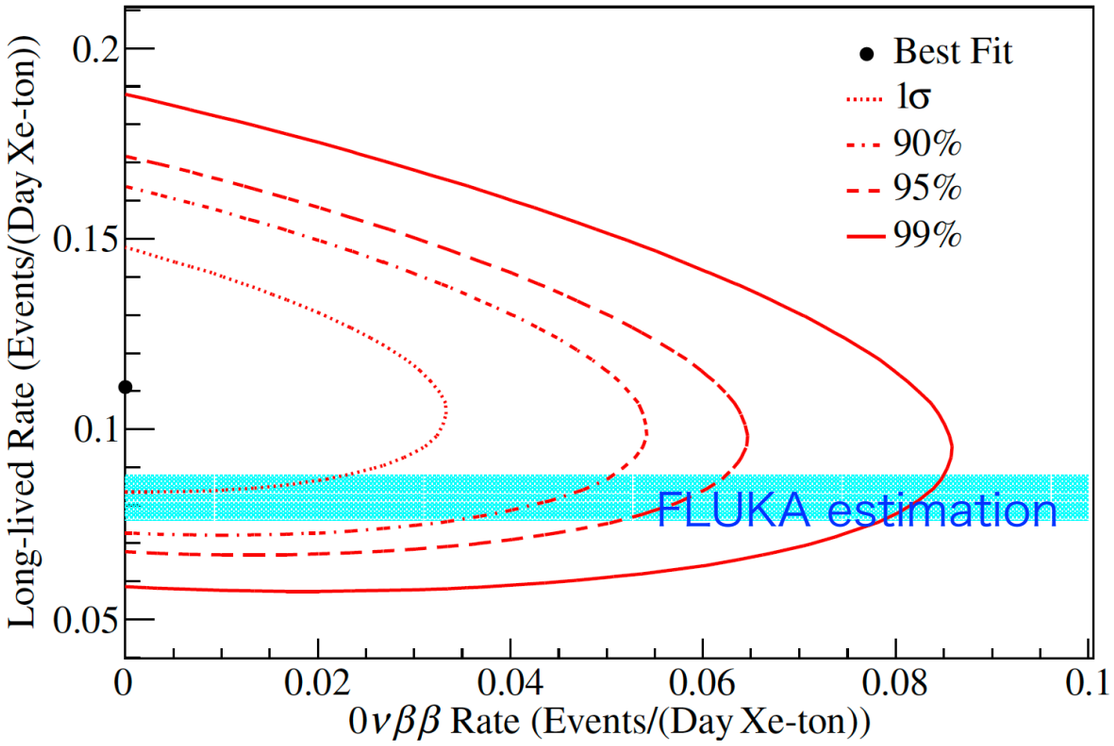


New tools

- Larger neutron multiplicity is a key estimator.
  - ⇒ LL tagging
- They mostly associates multiple gammas.
  - ⇒ neutral-net discrimination (option)

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

KL-Zen 400 data reanalyzed with new tools (spallation shower tagging, neural net gamma tagging)
and new knowledge of long-lived spallation, then combined with KL-Zen 800 data.



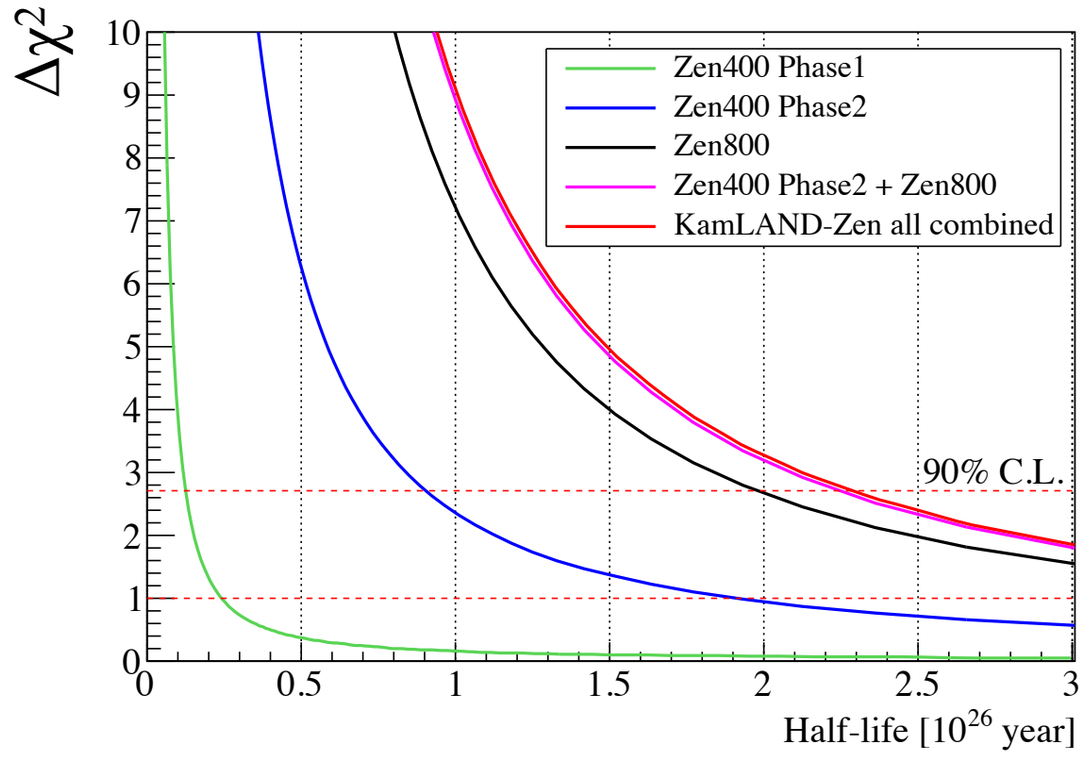
LL rate (2.35-2.79MeV)

measured : 0.111± 0.019 ev/d/Xe-ton

FLUKA estimation : 0.082 ± 0.006 ev/d/Xe-ton

~1.5σ discrepancy

Obtained LL tagging efficiency $40.1^{+10.2}_{-8.2}$ %
is consistent with the estimation 42.0±8.8 %



Combined result (90% C.L.)

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

Sensitivity (90% C.L.)

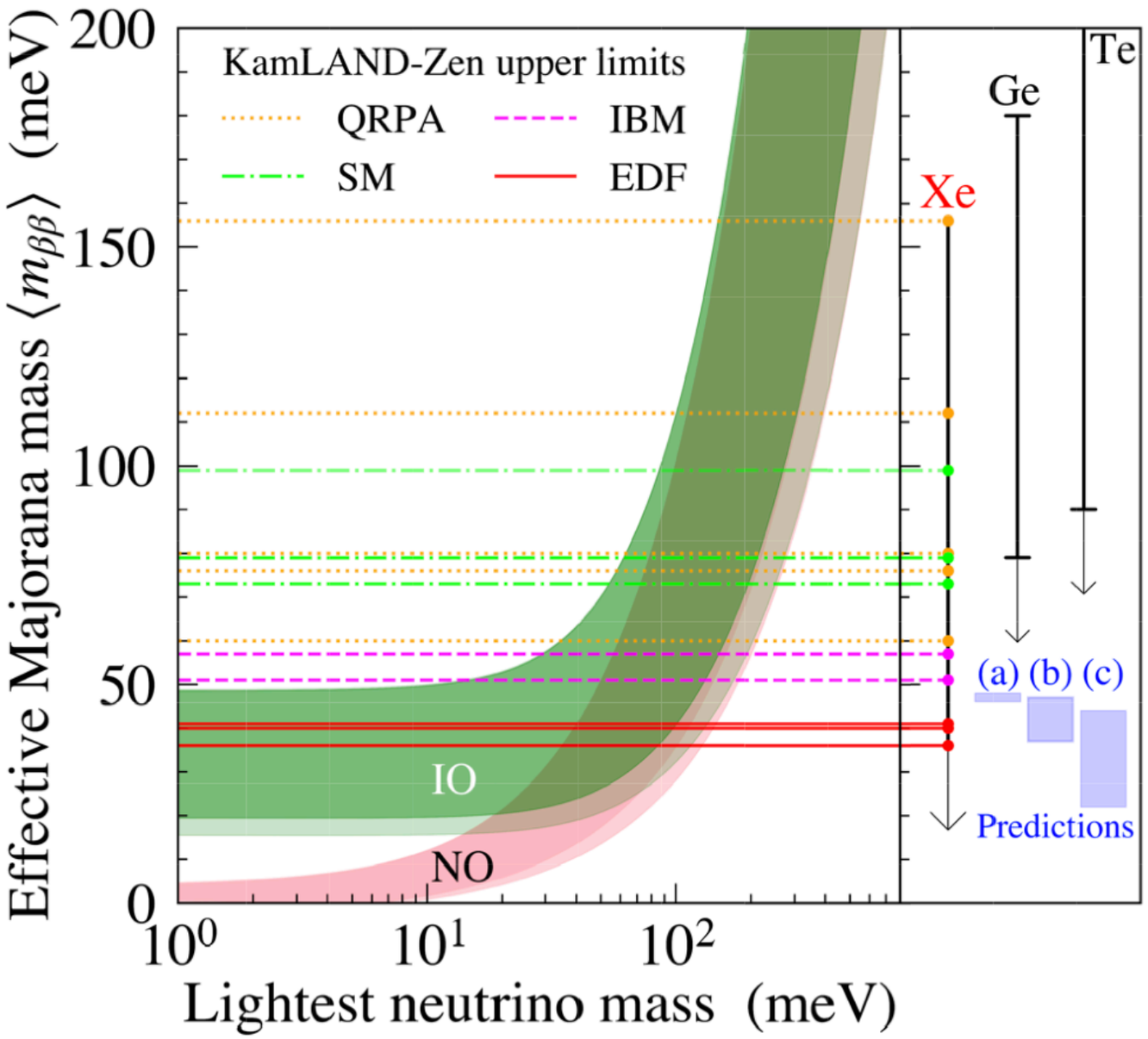
$T^{1/2} > 1.5\times10^{26}$ yr

The probability of obtaining
a stronger limit : 23%

PRL 130, 051801 (2023)

KLZ400 & 800 combined

PRL 130, 051801 (2023)



$$\langle m_{\beta\beta}\rangle = 1/\sqrt{G_{0\nu}|M_{0\nu}|^2\, T_{1/2}}$$

NME: 1.11 ~ 4.77

NME references
Quasi-particle Random Phase Approximations:
Phys.Rev.C 102, 44303 (2020), Phys.Rev.C 91, 024613 (2015), Phys.Rev.C 87, 045501 (2013), Phys.Rev.C 87, 064302 (2013), Phys.Rev.C 97, 045503 (2018).

Shell models:
Phys. Rev. C 101, 044315 (2020), Phys. Rev. C 91, 024309 (2015), Phys. Rev. A 818, 139 (2009).

Interacting boson models:
Phys. Rev. D 102, 095016 (2013), Phys. Rev. C 91, 034304 (2015).

Energy density functional theory:
Phys. Rev. Lett. 111, 142501 (2013), Phys. Rev. C 91, 024316 (2015), Phys. Rev. Lett. 105, 252503 (2010).

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

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

KLZ400 only

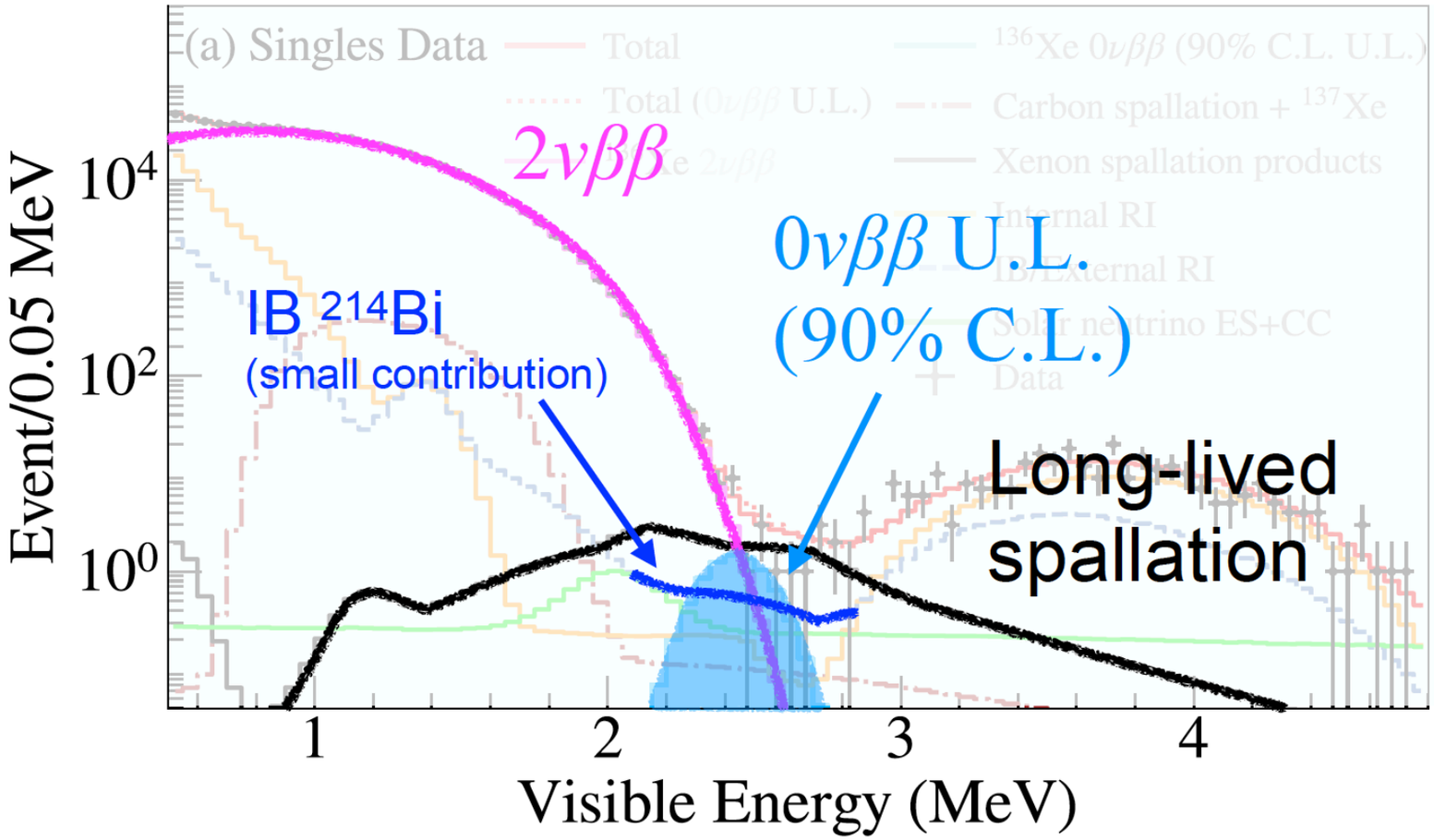
$$T^{0\nu}_{1/2} > 1.07\times10^{26}\,\mathrm{yr}$$
$$\langle m_{\beta\beta}\rangle < (61-165)\,\mathrm{meV}$$

KLZ400 & 800 combined (sensitivity: 1.5×10^{26} yr)

$$> 2.3\times10^{26}\,\mathrm{yr}$$
$$< (36-156)\,\mathrm{meV}$$

We successfully entered the inverted ordering region!

BG summary and future



BG summary (events)	
(2.35<E<2.70 MeV, R<1.57m)	
$2\nu2\beta$	11.98
RI in Xe-LS	0.98
RI in mini-balloon	3.06
Solar ν	1.65
Spallation	12.52

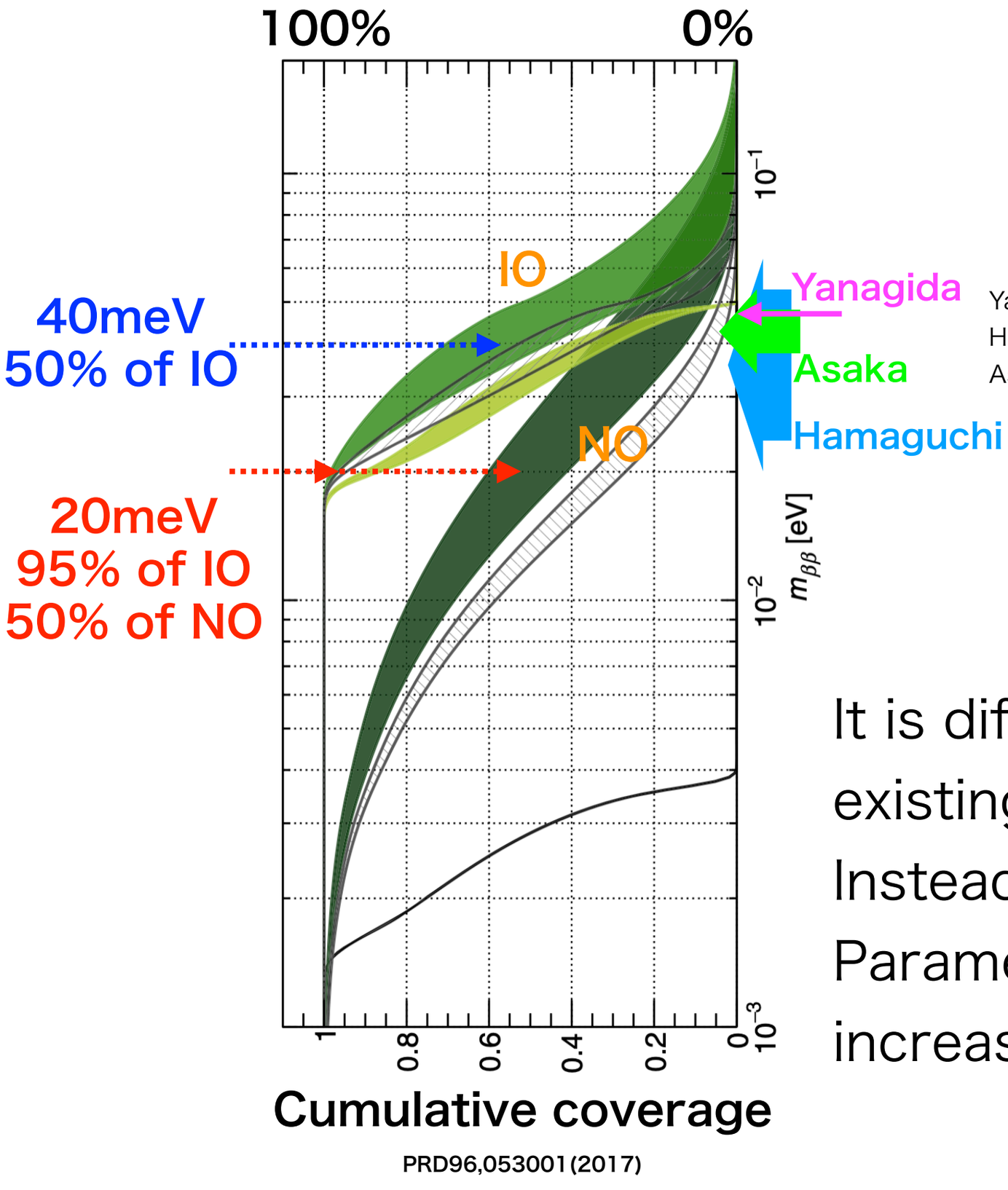
Possible measures

$2\nu2\beta$ → better energy resolution → KamLAND2-Zen

^{214}Bi → scintillation balloon,
neural net (enlarging FV)

Spallation → new electronics, new muon tracking,
neural net (beta/gamma discrimination)

Next target

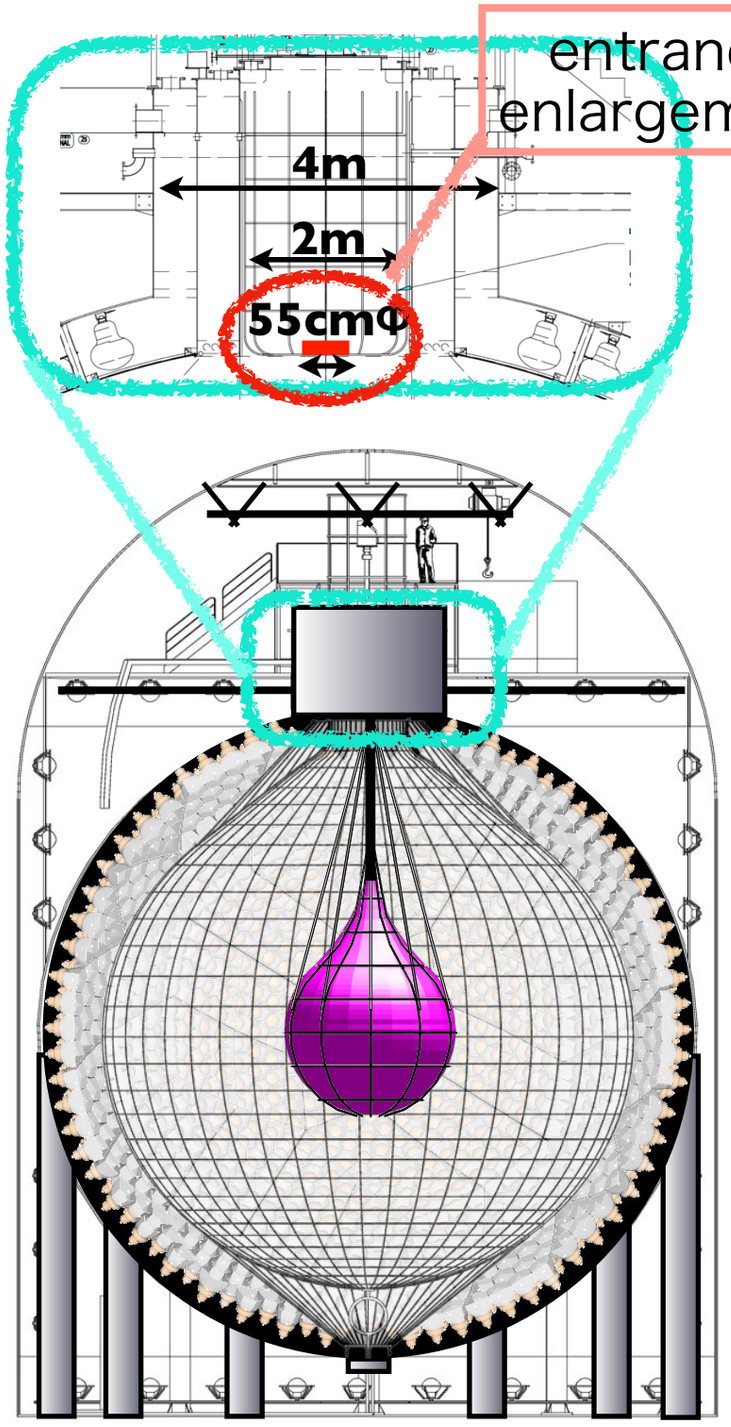


Yanagida：PRD86,013002(2012)
Hamaguchi：Eur.Phys.J.C77 (2017) 763
Asaka：Phys.Lett. B811(2020)135956

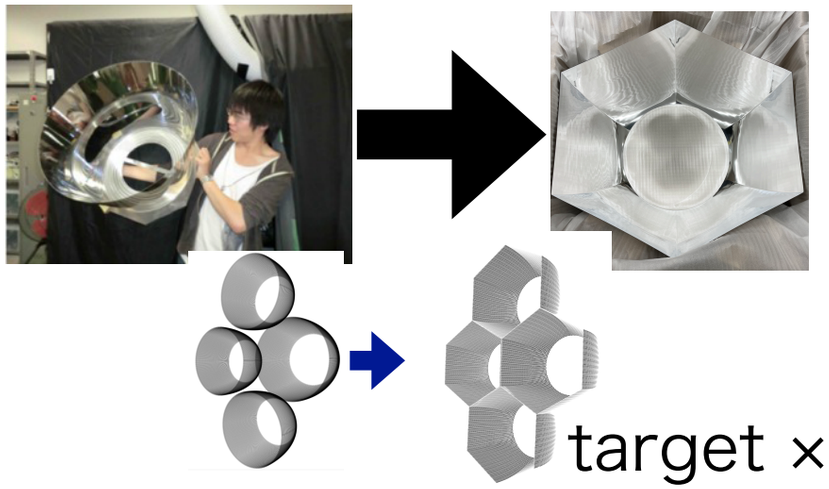
It is difficult to cover all with an existing technology.
Instead, covering IO is efficient.
Parameter coverage steeply increases and there are theories.

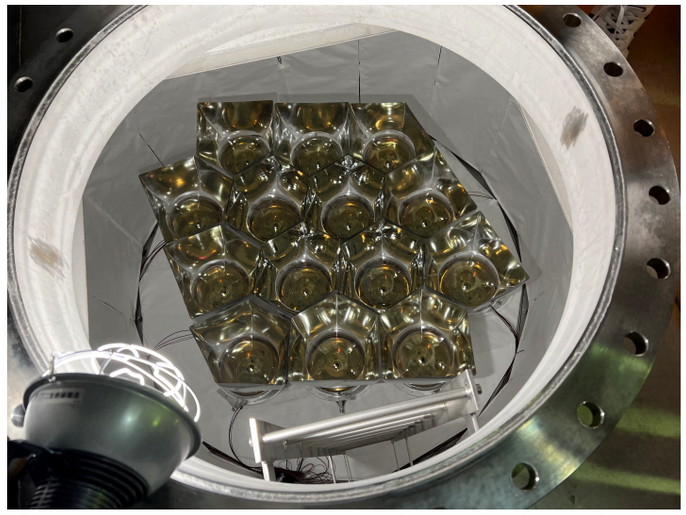
KamLAND2-Zen project

better energy resolution with higher light yield



Modified Winstone cone





performance test with 14 mirrors

target ×1.8, simulation ×2.2~2.3

HQE PMT

q.e. 20→30%, photocathode 17→20”ϕ

target ×1.9

Improved LS

higher transparency, Bis-MSB addition to Xe-LS

target ×1.4

×~5 light yield expected in total

Target sensitivity: 2×10^{27} yrs (5 yrs livetime), corresponding to ~20meV

95% of IO, 50% of NO

Status of KamLAND2-Zen project

MEXT provided a start-up fund for KamLAND2 in the supplemental budget of FY2023, and supplemental money must be spent within FY2024. It can cover only part of KamLAND-Zen decommissioning. But it means there is no going back for KamLAND, Tohoku University (and MEXT).

In parallel, KamLAND2 project has been selected as a MEXT roadmap 2023 project in December 2023.

It means the KamLAND2 project is qualified to apply for the large-scale frontier project with which SK, HK, KAGRA and so on are running. If approved, it is not an annual funding but 10 years support with of course construction money. This is an unprecedented opportunity for entire Tohoku University.

Most importantly, Tohoku University is convinced with the importance of KamLAND2 and decided to pursue the whole KamLAND2 project.

Following the decision, KLZ800 has been terminated on 12 January 2024 and xenon extraction work has been started. (~one quarter is already extracted)

rough schedule	2024 LS draining 2025-2026 dismantling 2026-2027 reconstruction, LS filling FY2027 KL2 start FY2028 KL2-Zen start

also

Kamioka Extremely Rare-phenomena and NEutrino-research Laboratory (KERNEL) as joint project between Tohoku and Osaka Universities has been approved (personnel expenses, operational money).

It becomes a joint usage/research base of the LOWBG community spun by a series of grant-in-aid for scientific research on innovative area, UGND & UGAP.

“Revealing the history of the universe with underground particle and nuclear research”

“Unraveling the history of the universe and matter evolution with underground physics”.

KERNEL is a proof of the success of these efforts!!

I want to grow this KERNEL to a kind of consortium in which many institutes in this community participate.

What is KERNEL, initially?

This community opened new “Extremely Rare Phenomena” frontier in nuclear/particle physics, covering double beta decay, dark matter, and other LOWBG sciences.

This new frontier will be important for decades.

We want to lead the field continuously. For the purpose, having a flagship project, growing young talents and new technologies with the community is essential.

Initially, RCNS (Tohoku) KamLAND2 will play a role to lead the DBD/geoneutrino/low-energy-astronomical neutrino researches as a flagship.

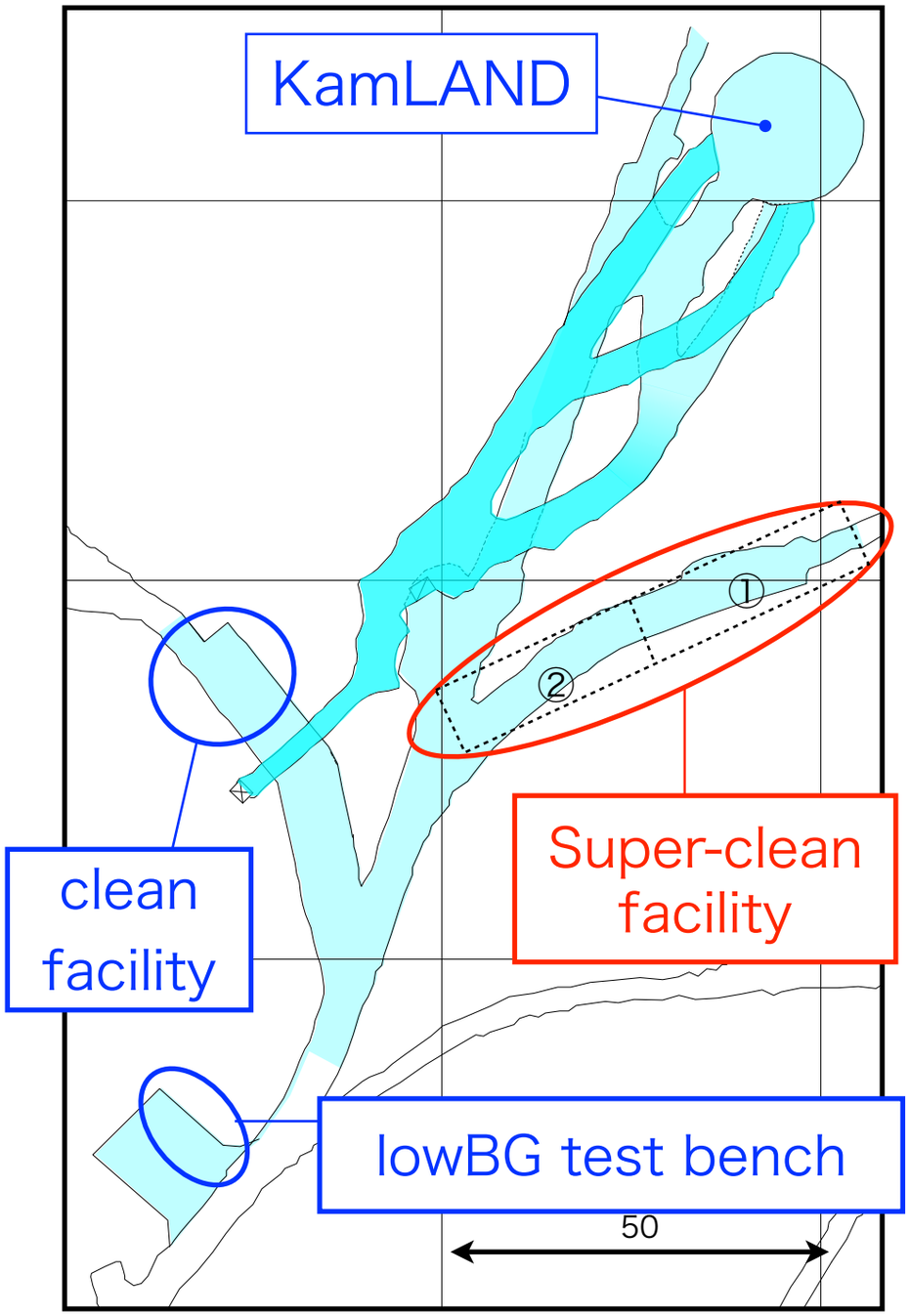
In parallel, accumulated technologies in this community needs to be inherited and more innovations have to be made for future flagship projects.

RCNP(Osaka) is the international joint usage/research center and has a lot of experiences working with a community. Also innovative technologies are being developed both in RCNS and RCNP.

KERNEL as a joint effort between RCNS and RCNP is a seed to make continuous community efforts.

What does KERNEL have, initially?

Underground facility with a super-clean room has also been funded.



Initially, KERNEL has;
- a class 1 super-clean room,
- clean air system (cooled charcoal ~200 m^3/h),
- pure water system,
- and experimental space.

Construction will be completed in FY2024.

Key technologies for big leaps of KamLAND

	2001-2010	2011-2020	2021-2030
Science	reactor neutrino geoneutrino	DBD geoneutrino ^{7}Be solar ν	DBD geoneutrino
Problem	^{210}Bi/^{85}Kr/^{210}Po	^{110m}Ag/^{208}Tl ^{12}C spallation	$2\nu2\beta$ Xe spallation solar ν
Key technology	water extraction, distillation	new electronics, super-clean room, neutron/shower/ ^{220}Rn-Po tag	new electronics, underground super-clean room, neutral-net

Summary

KL-Zen exclusion of $0\nu2\beta$ has entered the IO region.

achieved the goal

Discrimination of earth models has started. High-Q model (uniform mantle, total convection) has been excluded.

achieved the goal and more

KamLAND dismantling for KL2 started.

KERNEL and its super-clean facility has been funded.

important outcome of this grant-in-aid program