Results from KamLAND/ KamLAND-Zen

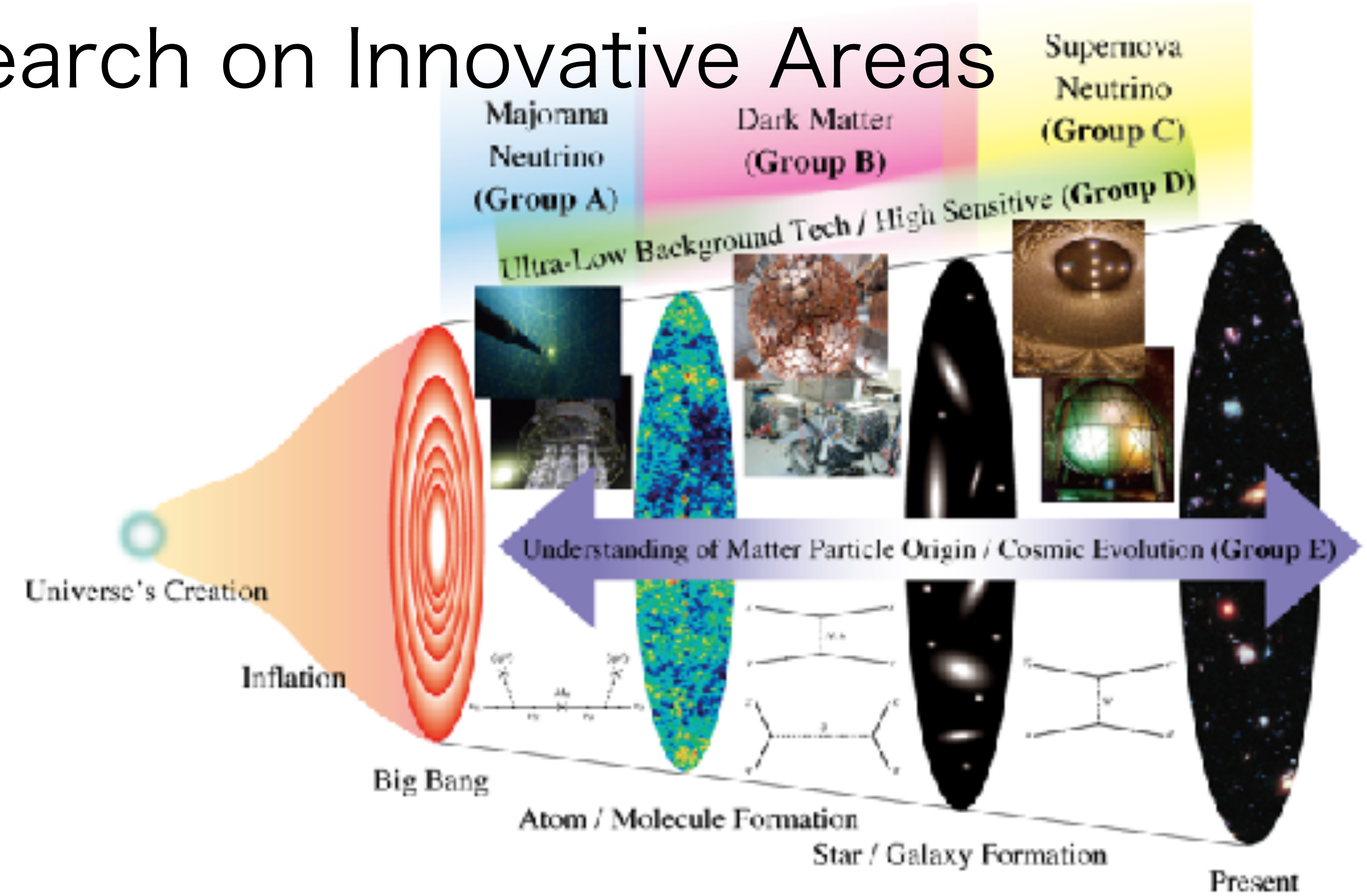
13 June 2022

Noda Campus, Tokyo University of Science

Kunio Inoue

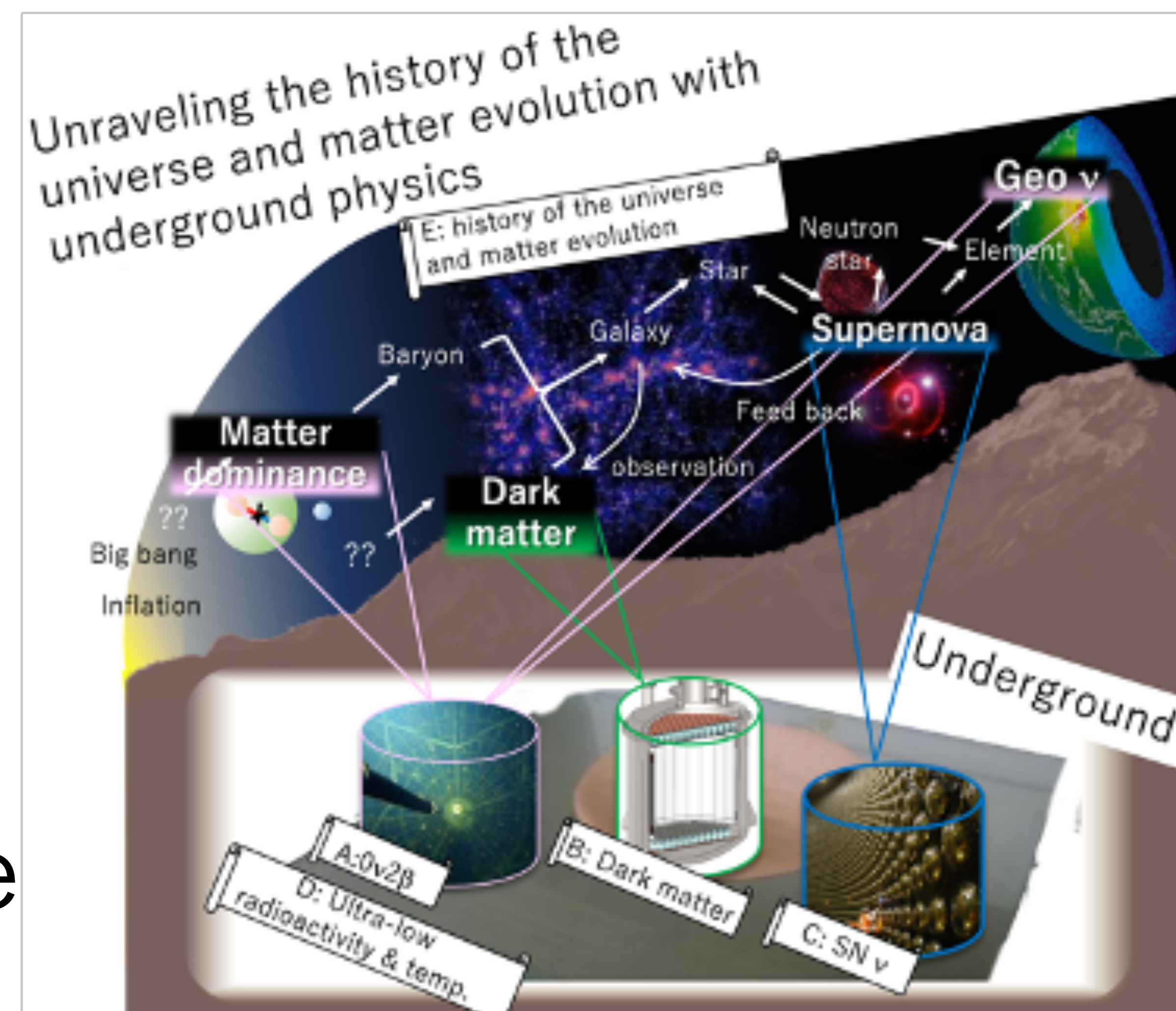
Research Center for Neutrino Science, Tohoku University

Grant-in-Aid for Scientific Research on Innovative Areas



"Revealing the history of the universe with underground particle and nuclear research" (FY2014-2018)

"Unraveling the History of the Universe and Matter Evolution with Underground Physics" (FY2019-2023)



A01 covers the beginning and present of the universe

The beginning: matter creation

New results from KamLAND-Zen 800

First Search for the Majorana Nature of Neutrinos in the Inverted Mass Ordering Region with KamLAND-Zen

arXiv: 2203.02139

The present: realized our dwelling earth

Geo-neutrino updates

Abundances if uranium and thorium elements in Earth estimated by geoneutrino spectroscopy

arXiv: 2205.14934

In-between: dark matter, star activities

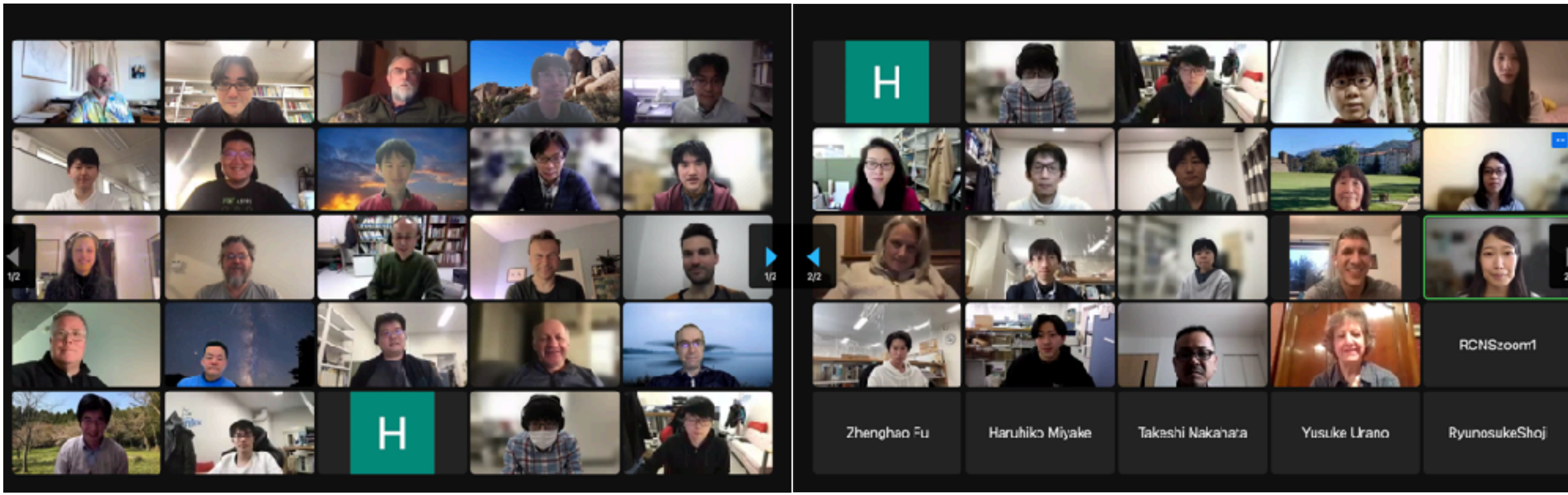
Astrophysical subjects

- A Search for Correlated Low-energy Electron Antineutrinos in KamLAND with Gamma-Ray Bursts, ApJ 927, 69 (2022)
- Limits on Astrophysical Antineutrinos with the KamLAND experiment, ApJ 925, 14 (2022)
- Search for Solar Flare Neutrinos with the KamLAND Detector, ApJ 924, 103 (2022)
- Search for Low-Energy Electron Antineutrinos in KamLAND Associated with Gravitational Wave Events, ApJ 909, 116 (2021)

KamLAND
KamLAND-Zen Collaboration

~50 physicists

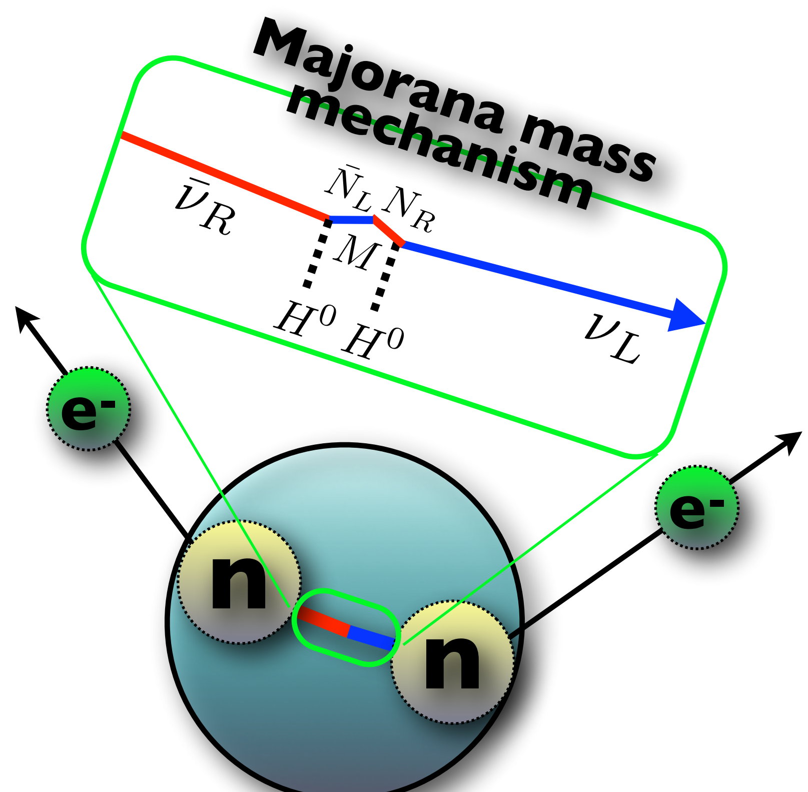
Collaboration meeting in March, 2022



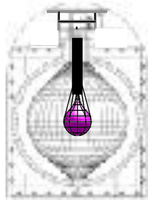
KamLAND-Zen: physics with xenon

KamLAND: all the other subjects

0ν2β



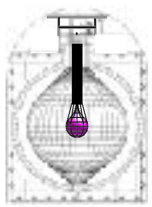
List of publications



KamLAND-Zen 800

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

1st paper [$0\nu\beta\beta$]: 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 [$0\nu\beta\beta$ & $2\nu\beta\beta$]: 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 [$0\nu\beta\beta$, $2\nu\beta\beta$ & 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 [$0\nu\beta\beta$]: 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 [$0\nu\beta\beta$ & $2\nu\beta\beta$]: 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"

Dirac vs. Majorana

Discovery of neutrino mass requires right-handed composition.

e

LH electron (e^-_L)	RH electron (e^-_R)
LH positron (e^+_L)	RH positron (e^+_R)

Matter particle (Fermion) has at least 4 components.

It is naturally derived from quantum mechanics and special relativity (Dirac equation).

ν

LH ν_L	RH ν_R (N_R) not discovered
LH $\bar{\nu}_L$ ($\bar{N}_L$) not discovered	RH $\bar{\nu}_R$

Dirac neutrino

$\nu_L \quad \underbrace{\nu_R \quad \bar{\nu}_L}_{\text{unobservable}} \quad \bar{\nu}_R$

$$\nu \neq \bar{\nu}$$

Majorana neutrino (1937)

$\nu_L \quad \bar{\nu}_R \quad \underbrace{\bar{N}_L \quad N_R}_{\text{just heavy}}$

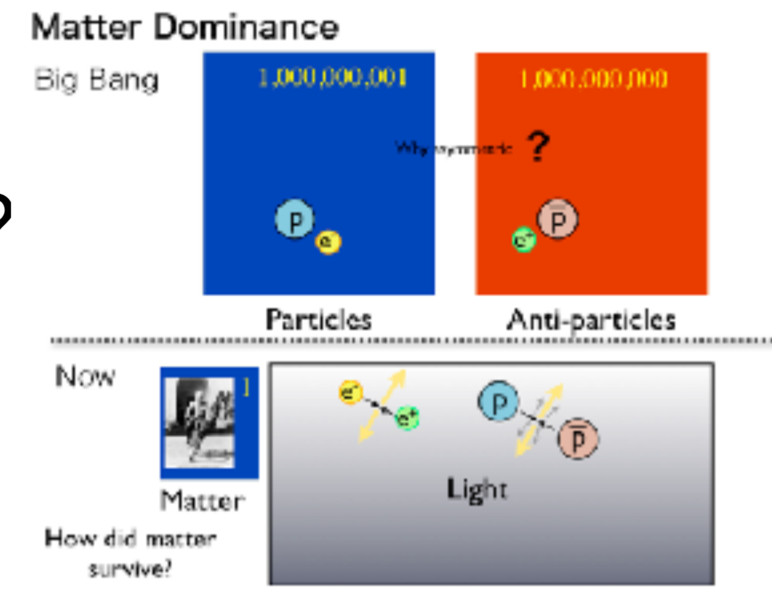
$$\nu = \bar{\nu}$$

Majorana neutrino violates Lepton #.

Big mysteries of the universe/ particle physics

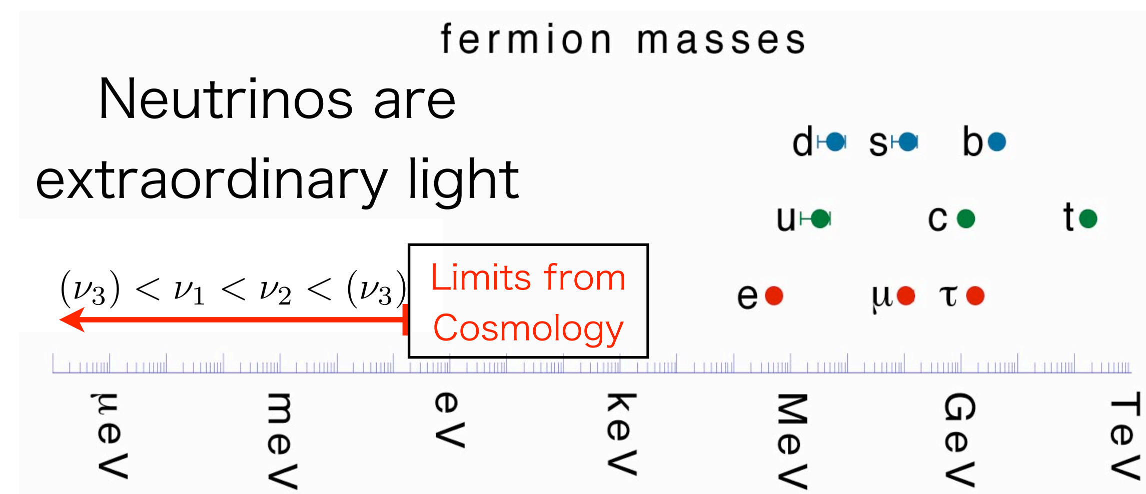
How did the matter created from nothing?

Heavy neutrino (N_R) can explain it with the Leptogenesis theory.



How does neutrino get its extraordinarily light mass?

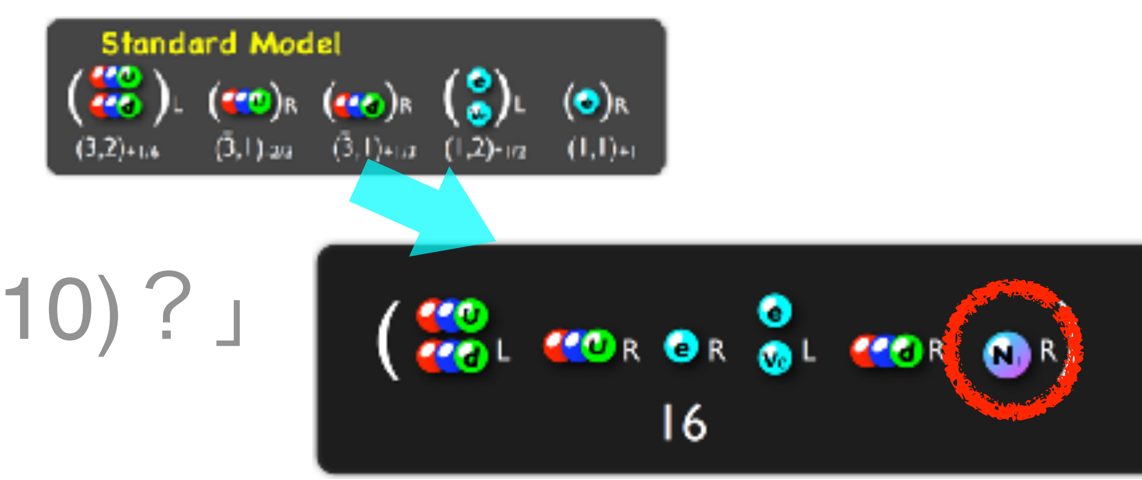
N_R can explain it with the Seesaw mechanism.



What is the origin of dark matter?

If N_R exists, ・・・

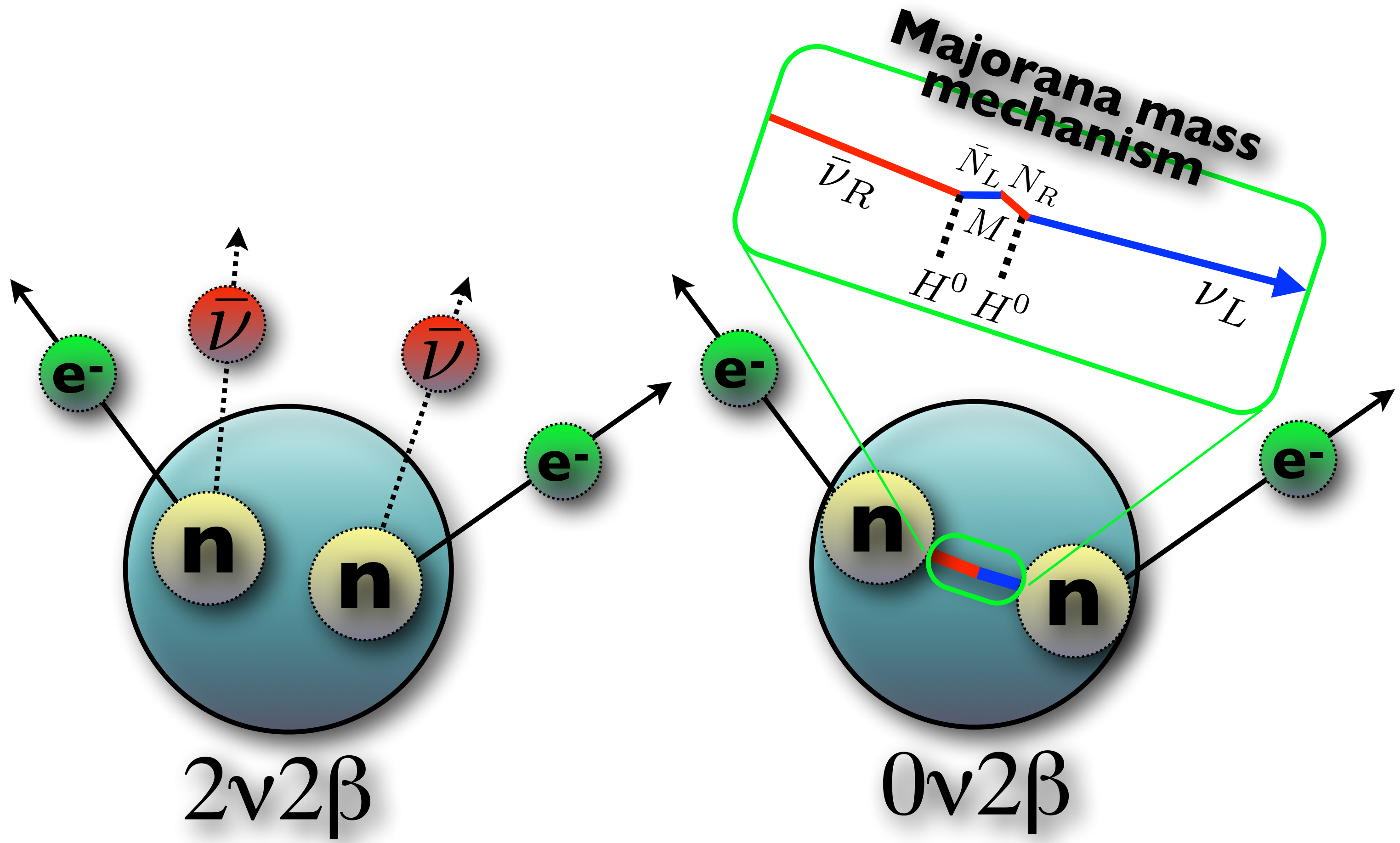
「$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(5) \Rightarrow SO(10)$?」



If N_R exists, ・・・

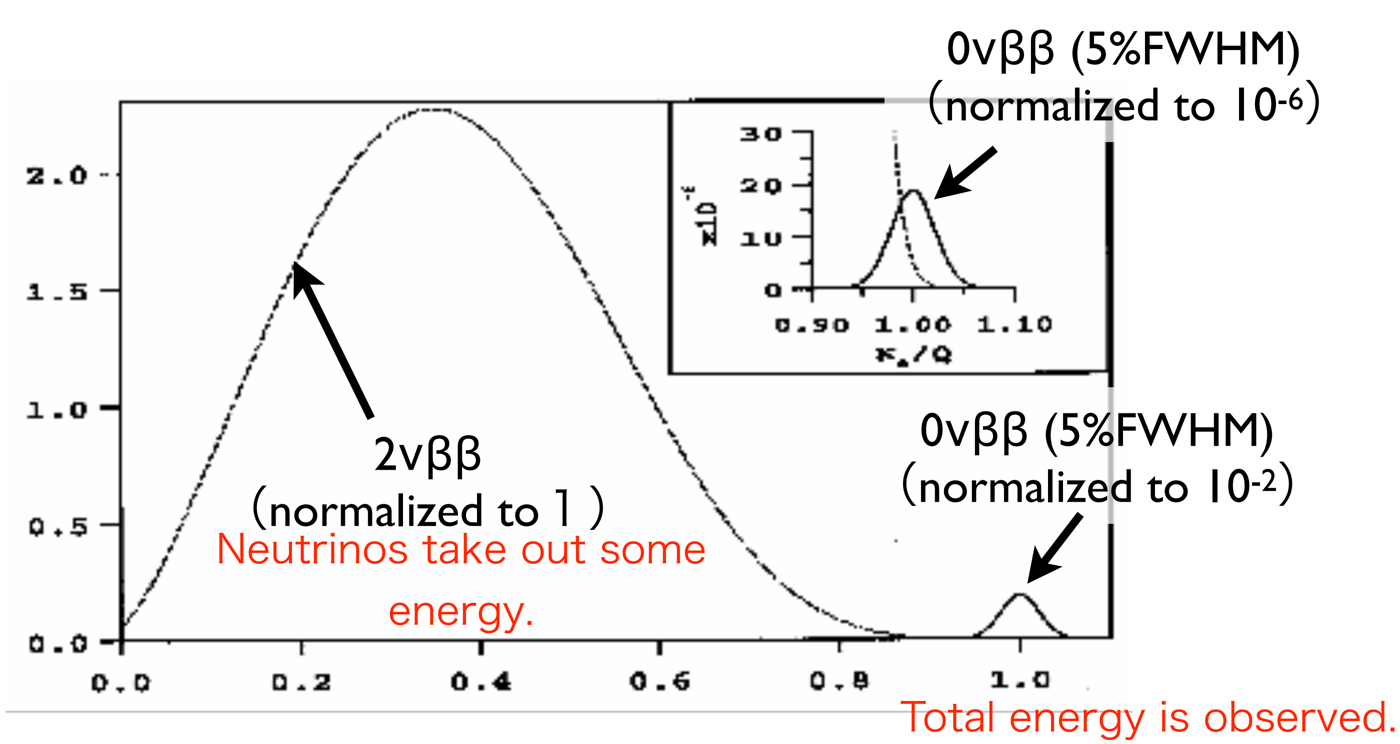
N_R is great, but **Current technology cannot create N_R. Is there any supporting evidence?**

If neutrinos are Majorana, N_R is naturally introduced. And neutrino less double beta decay（0ν2β） can happen.



theoretical history

1930 light neutral particle (W.Pauli)
1933 β decay theory (E.Fermi)
1935 2ν2β (M.Goeppert-Mayer)
1937 Majorana neutrino (E.Majorana)
1939 0ν2β (W.H.Furry)



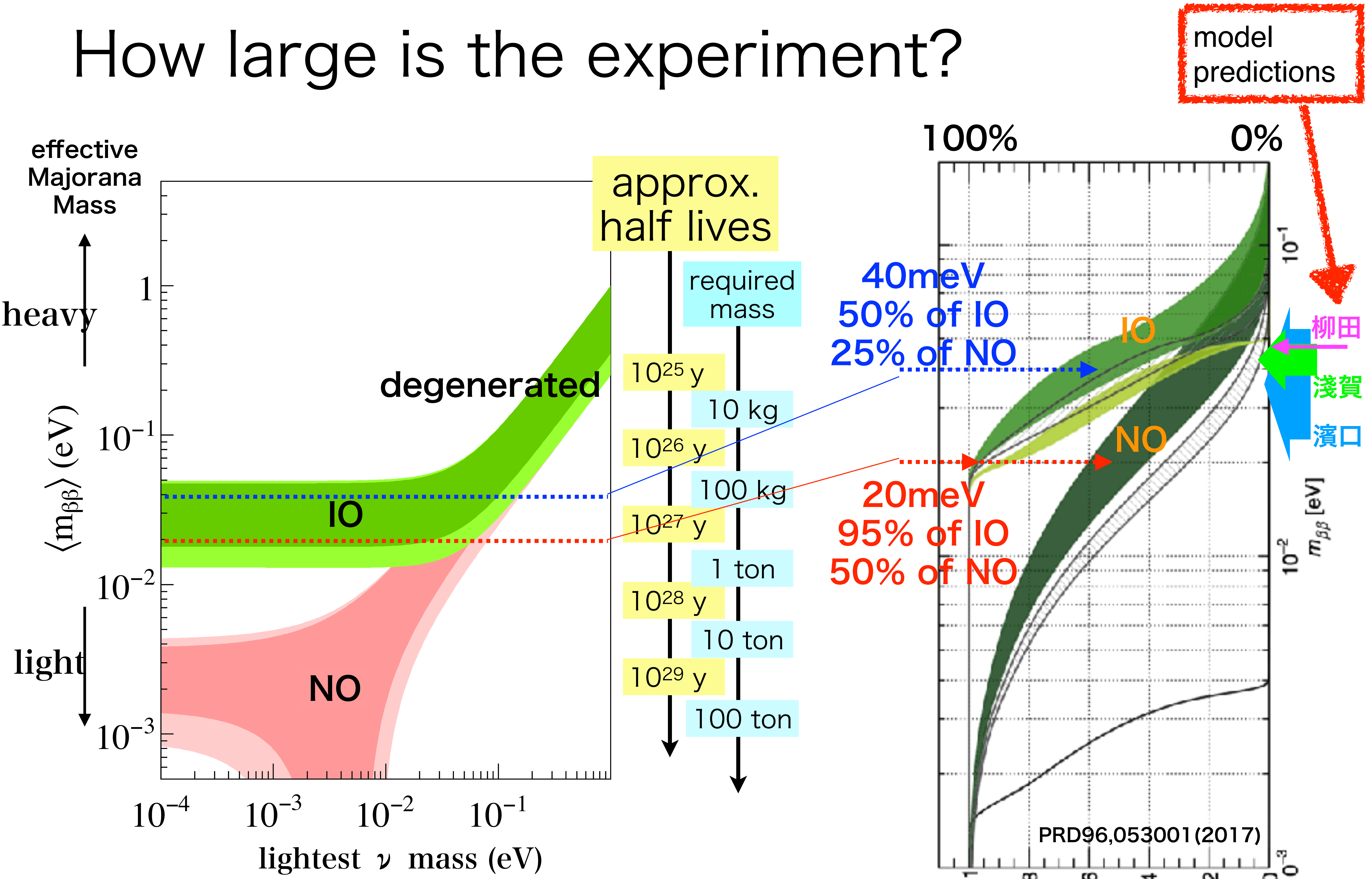
Larger the mass, easier to observe 0ν2β

Majorana CP

$$\langle m_{\beta\beta}\rangle = |\Sigma\, m_i\, |U_{ei}|^2\, \varepsilon_i|$$

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

How large is the experiment?



allowed by neutrino oscillation

degenerated: 3 types are heavy
inverted ordering (IO): 2 types are heavy
normal ordering (NO): 1 type is heavy

Strategy

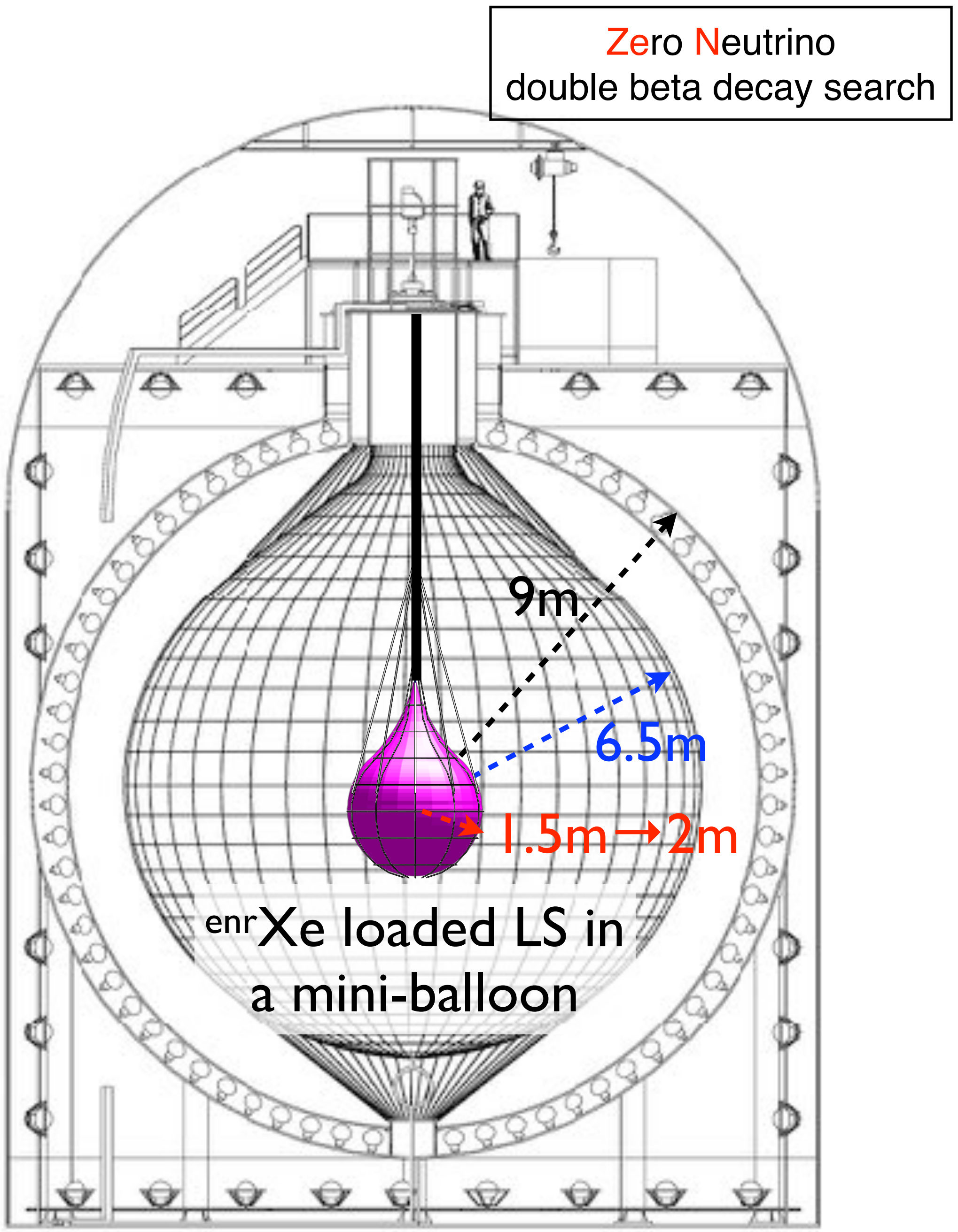
Without signal any high performance detectors cannot find the signal.

Mass first!
Then performance necessary.

KamLAND-Zen has moderated performance but deployed the largest amount of double beta decay nuclei,
and provides ultra low radioactive environment!

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

KamLAND-Zen



90% enriched ^{136}Xe

320kg for phase-I (2011-2012)

380kg for phase-II (2013-2015)

745kg for Zen 800 (2019-) ⇐ New Results

^{136}Xe

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)

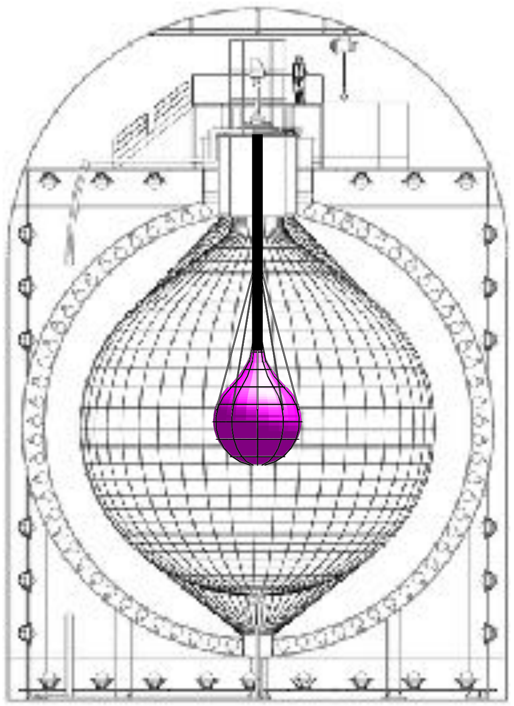
② In-situ purification possible (liquid media)

③ On/Off measurements possible (xenon is removable)

④ multi-purpose (geo-neutrino)

⑤ easily scalable (mini-balloon)

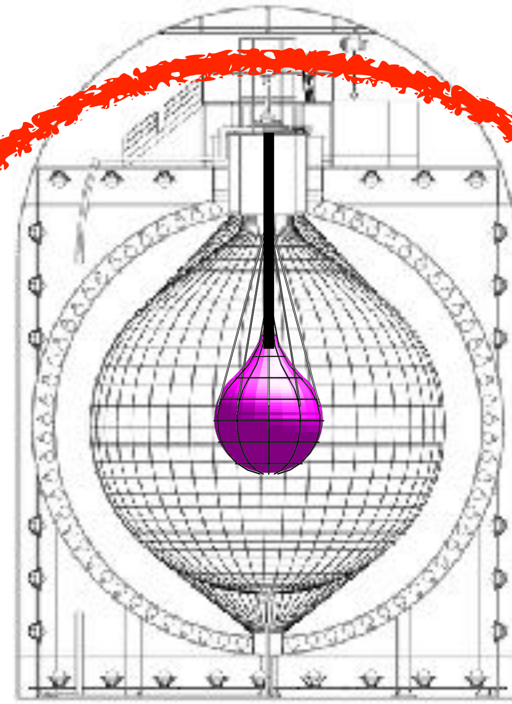
KamLAND-Zen 400



380kg deployed

World top performance

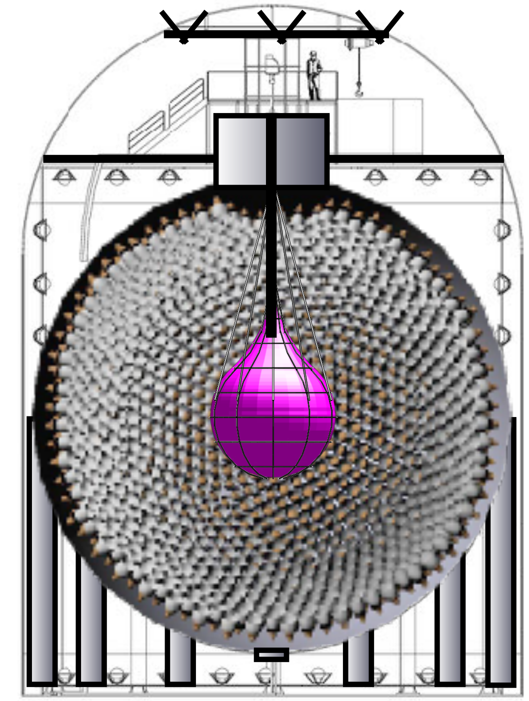
KamLAND-Zen 800



Now,745kg deployed

target 40meV

KamLAND2-Zen

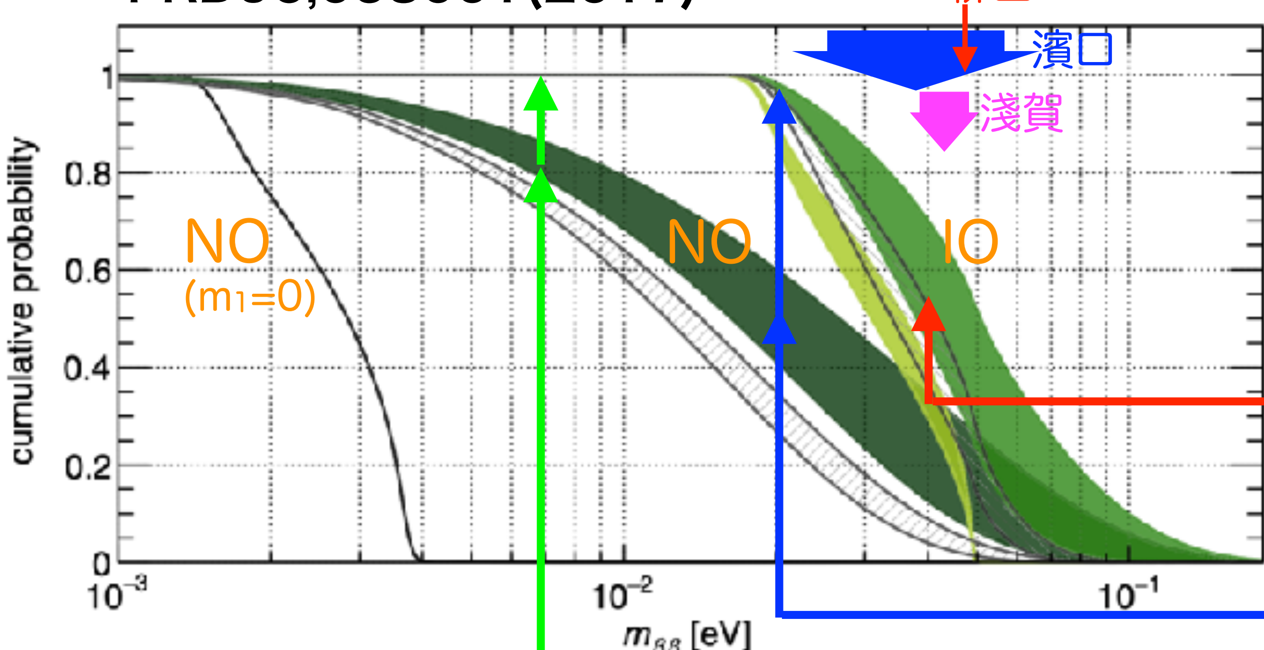


Mirror
HQE-PMT
new LS
} x5 p.e.
scintillation film

High resolution future plan

target 20meV

PRD96,053001(2017)

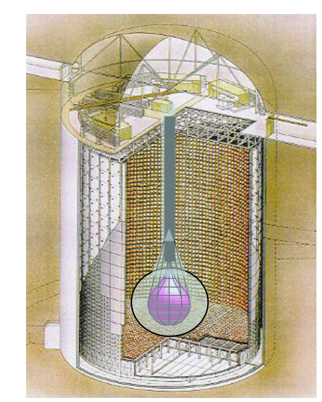


8meV 100% of IO
80% of NO

Parameter Coverage

40meV 50% of IO
25% of NO

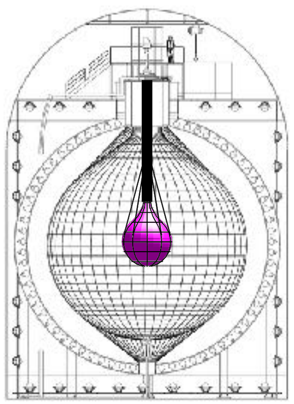
20meV 95% of IO
50% of NO



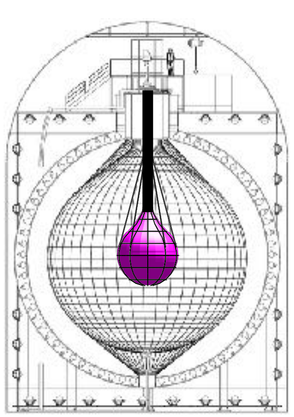
Super-KamLAND-Zen after Hyper-K starts in 2027 !?

Timeline of KamLAND-Zen

KamLAND-Zen 400



KamLAND-Zen 800



2011
- MIB production
- ← MIB installation, xenon installation
- 400 phase1 320kg
- ← Filtration

2012
- ← Xenon extraction
- LS purification
- Recovery from fire ← Fire

2013
- LS purification
- ← Xenon installation

2014
- 400 phase2 380kg

2015
- MIB production
- ← Calibration, xenon extraction, MIB extraction

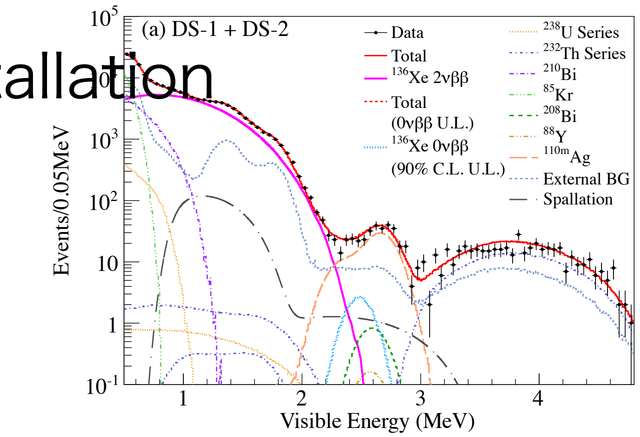
2016
- OD refurbishment
- MIB production
- ← MIB installation, characterization
- ← MIB extraction, hole inspection
- Leak

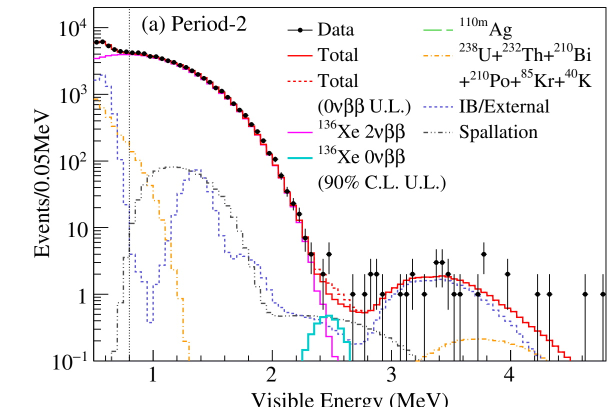
2017
- Welding improvement
- MIB production

2018
- ← MIB installation, characterization
- LS purification
- Xenon installation

2019
- Zen 800 745kg
- We are here

PMT aging



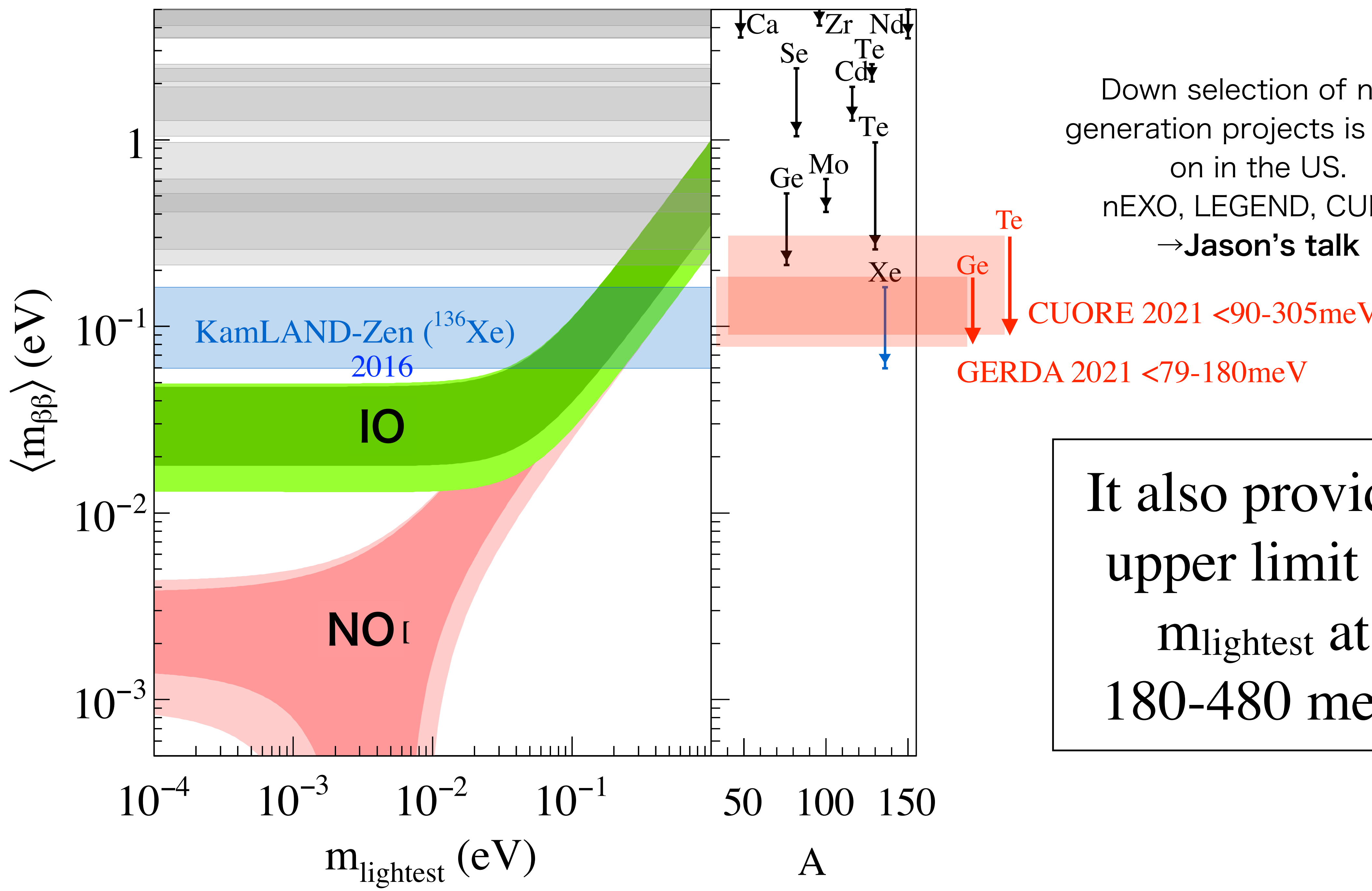


KamLAND-Zen 400 Phase 1+2 combined

2011-2015

$$T_{1/2}^{0\nu} > 1.07 \times 10^{26}\ \text{yr}$$

(sensitivity 5.6×10^{25} yr)



Down selection of next generation projects is going on in the US.
nEXO, LEGEND, CUPID
→**Jason's talk**

It also provides upper limit of $m_{lightest}$ at 180-480 meV.

$$\langle m_{\beta\beta}\rangle < (61 - 165)\ \text{meV}$$

PRL117, 082503 (2016)

Big leap toward IO region !

Hardware improvement from KL-Zen 400

Almost **doubled xenon amount** (~745 kg, 91% enriched)

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

JINST 16 P08023

Background level

^{214}Bi: one of main BG

$^{238}U \sim 3\times10^{-12}$ g/g$_{film}$

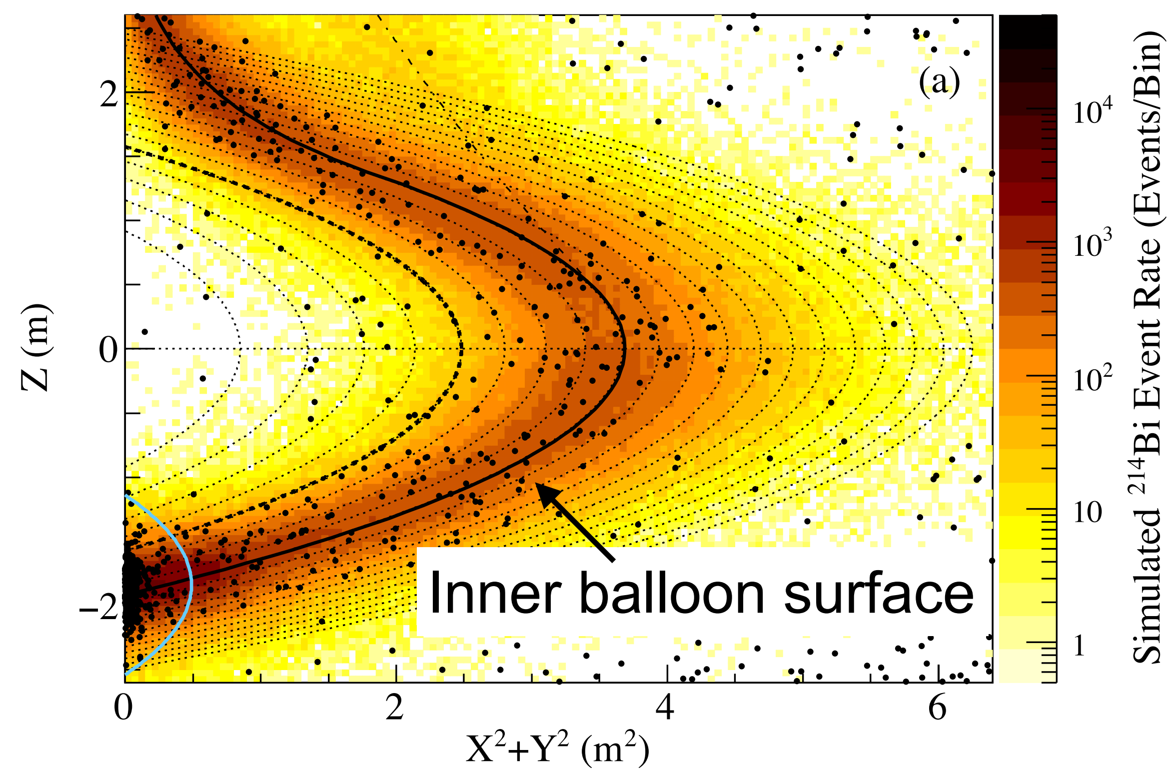
ref. initial film (after washed)

$^{238}U \sim 2\times10^{-12}$ g/g$_{film}$ — Almost same level

$^{232}Th \sim 4\times10^{-11}$ g/g$_{film}$

×10 reduction of RI
compared to KL-Zen 400

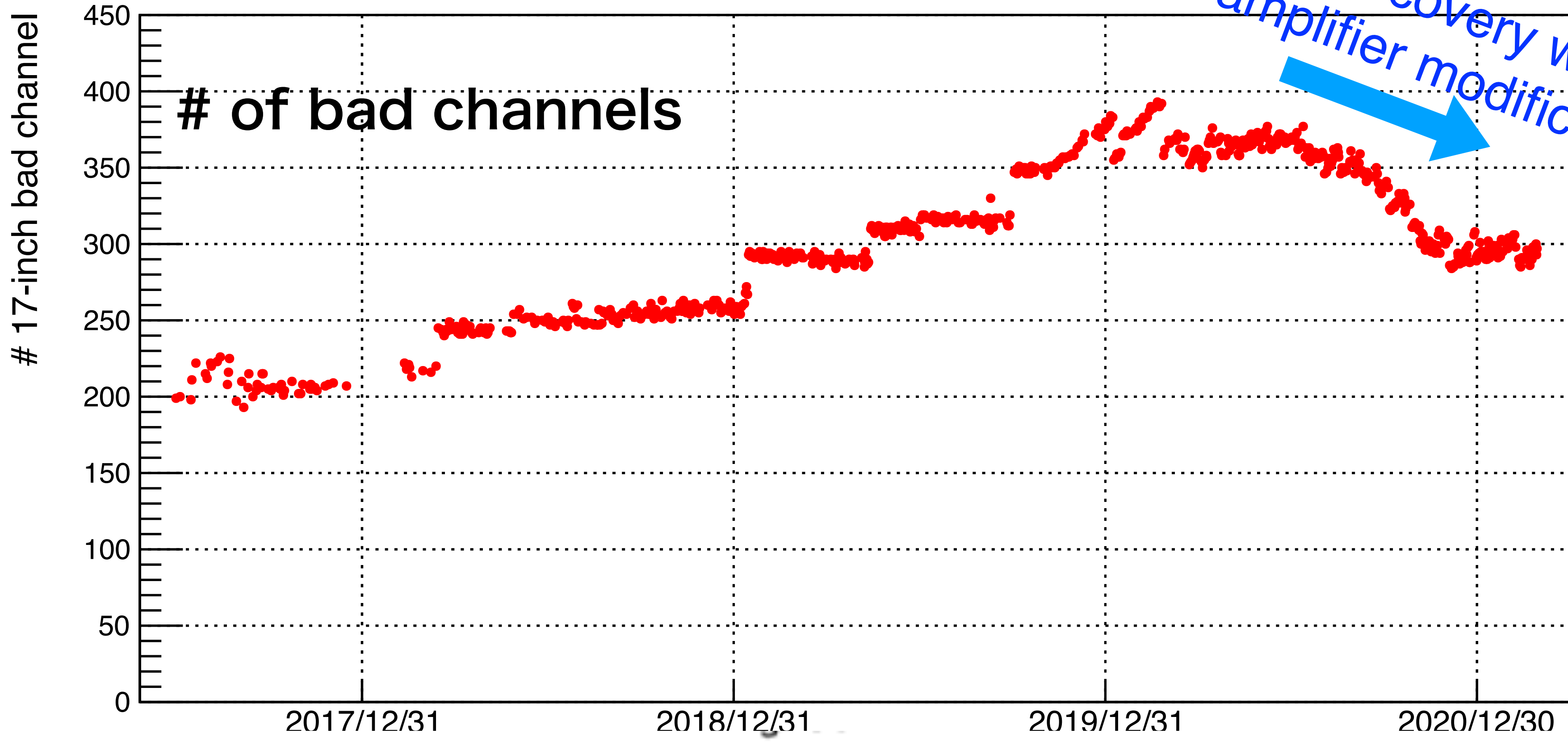
Vertex distribution in ROI & ^{214}Bi MC



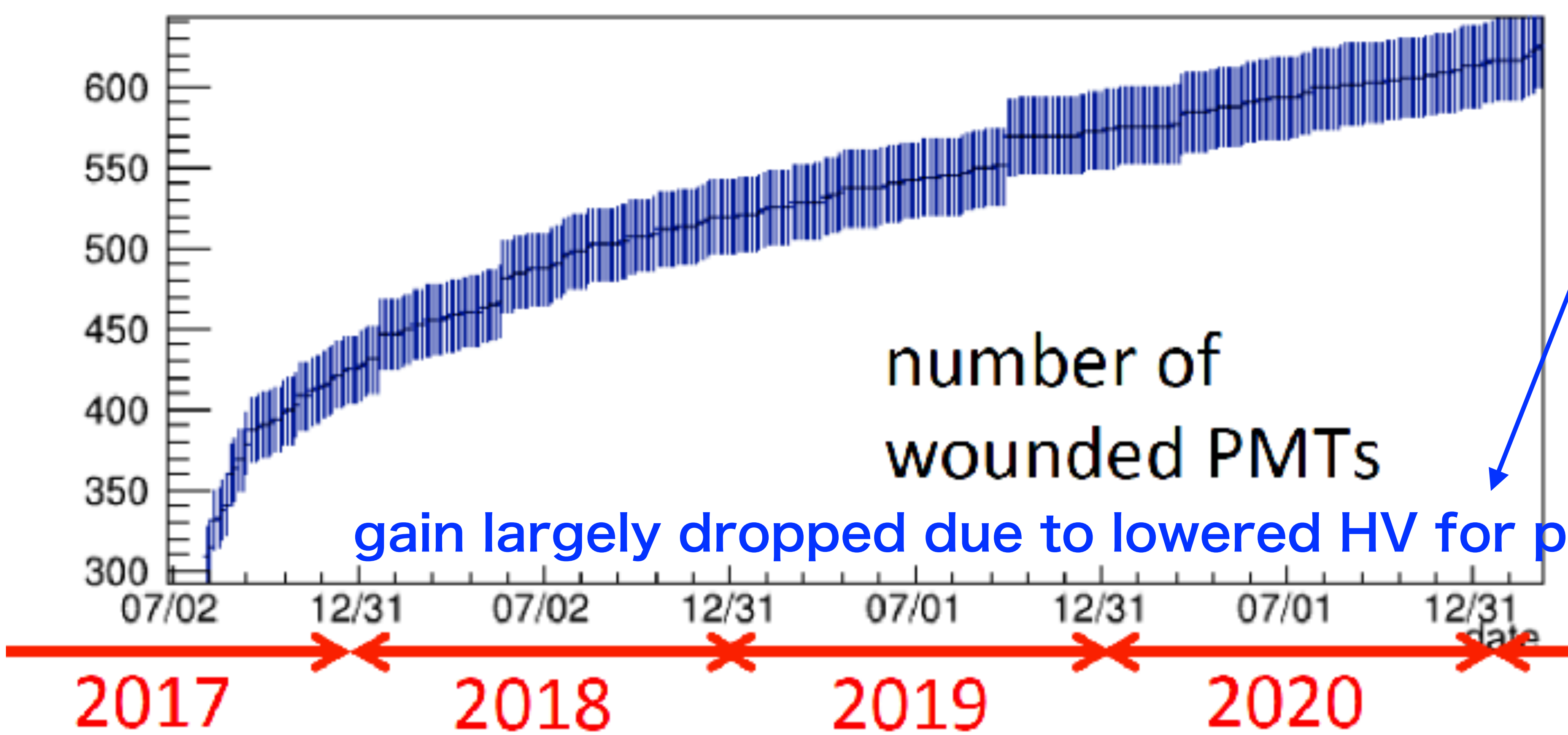
New issues in KLZ 800

1. Aging of 17" PMTs

gain recovery with amplifier modification

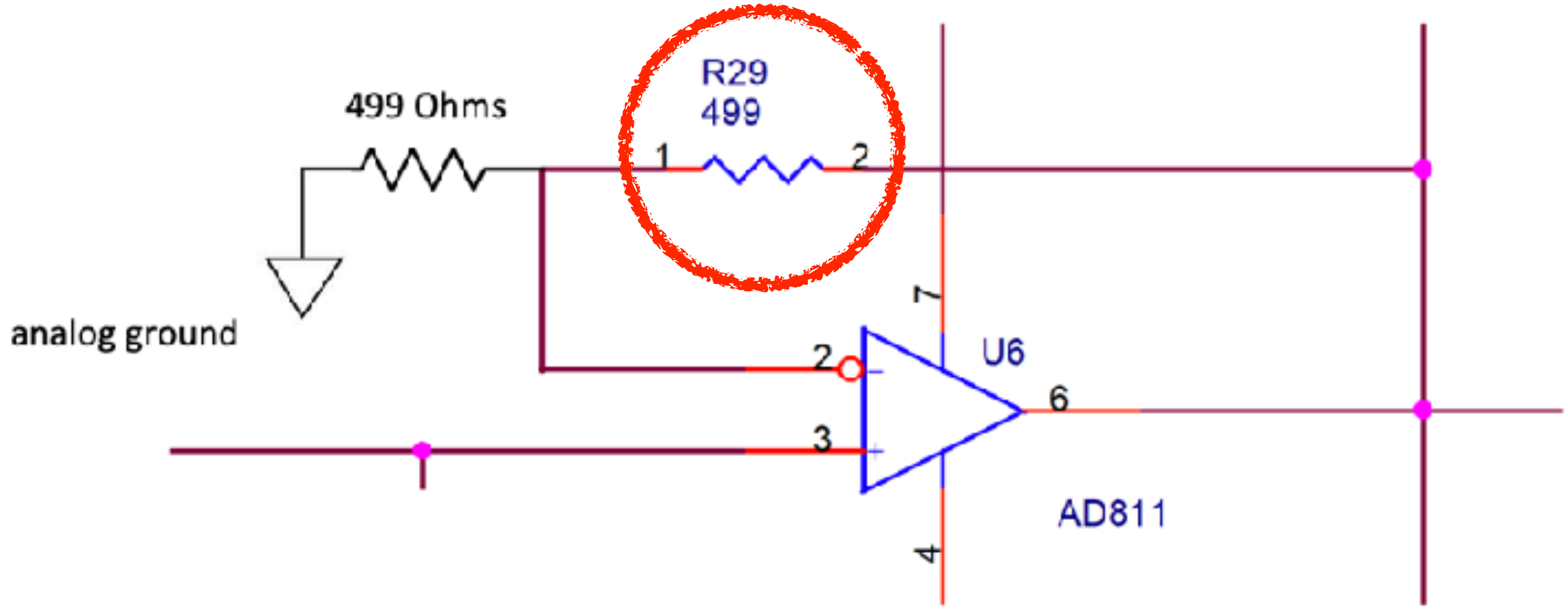


reuse of bad channels
⟹ new tool

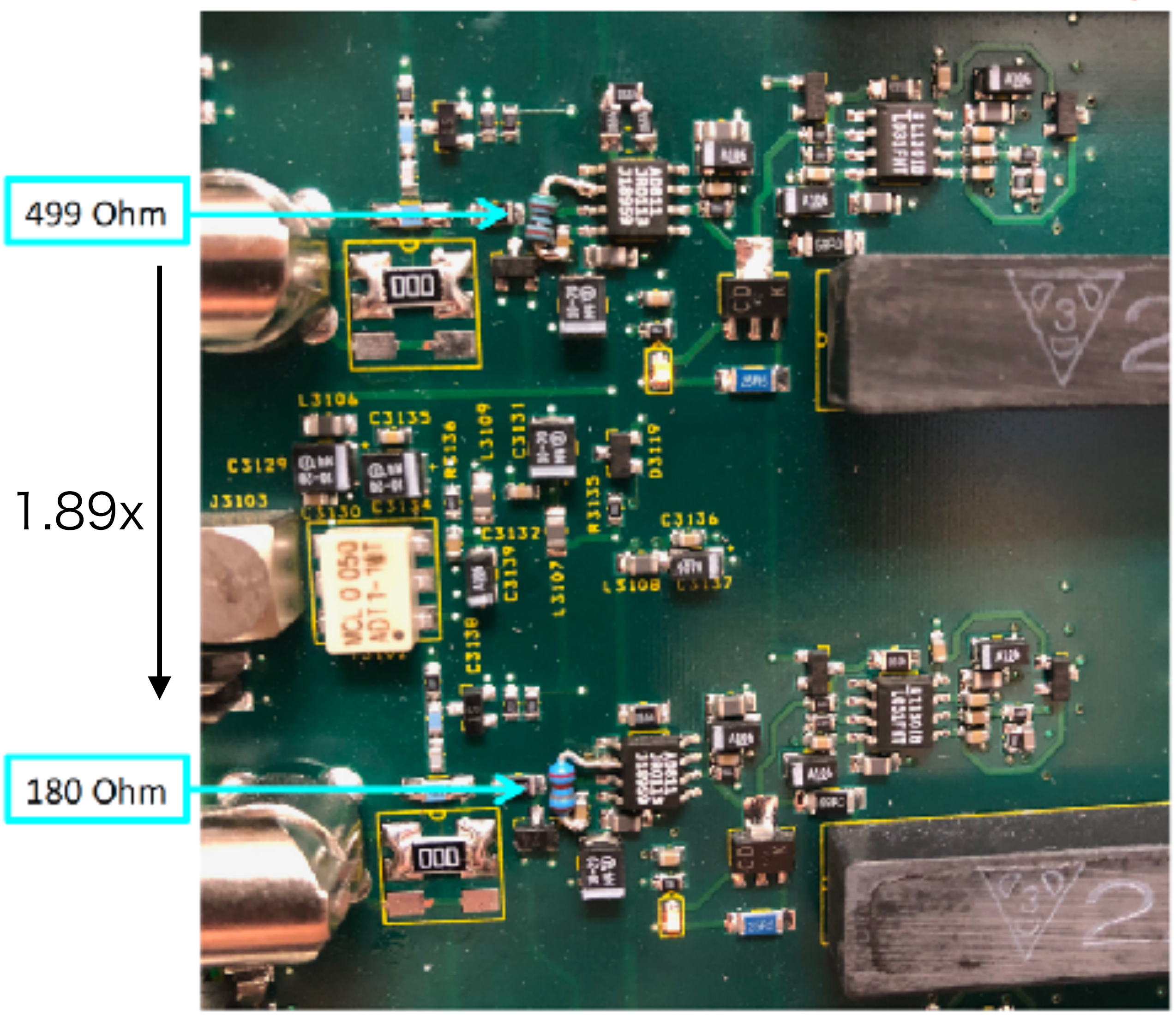


gain largely dropped due to lowered HV for protection

Change the first amplifier gain of KamFEE



MoGURA amplifier is modified similarly.



Wounded channels are connected to 2x, 4x, 10x gains.

All modifications done by one researcher in the US

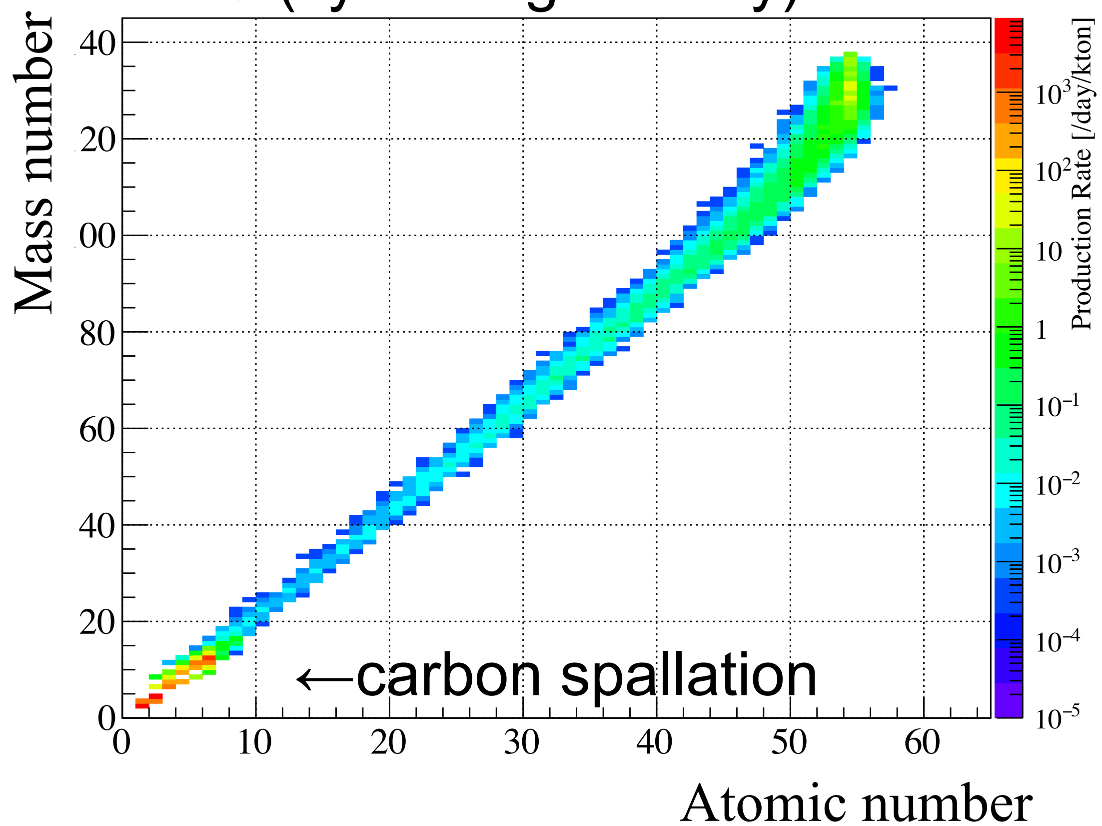
New energy fitter uses individual time-dependent no-hit probabilities as a function of expected PEs.

Energy resolution is slightly improved!

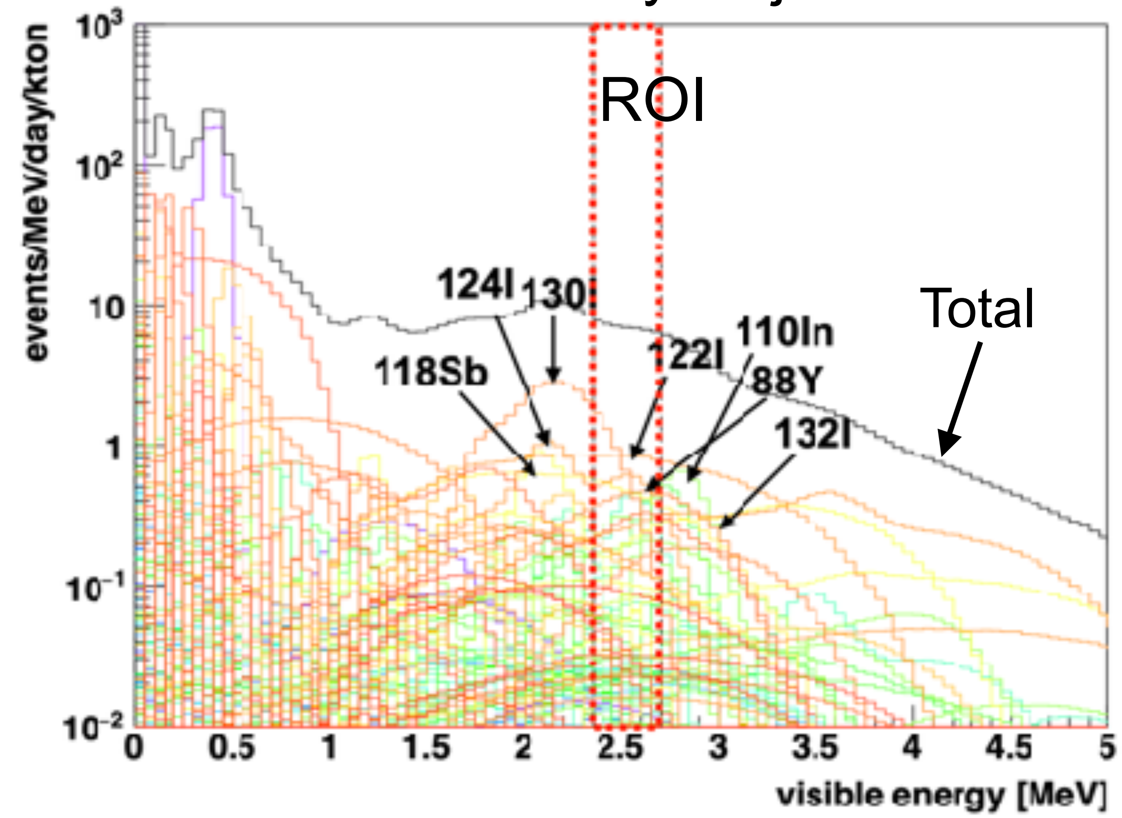
$$6.7\%/\sqrt{E}$$

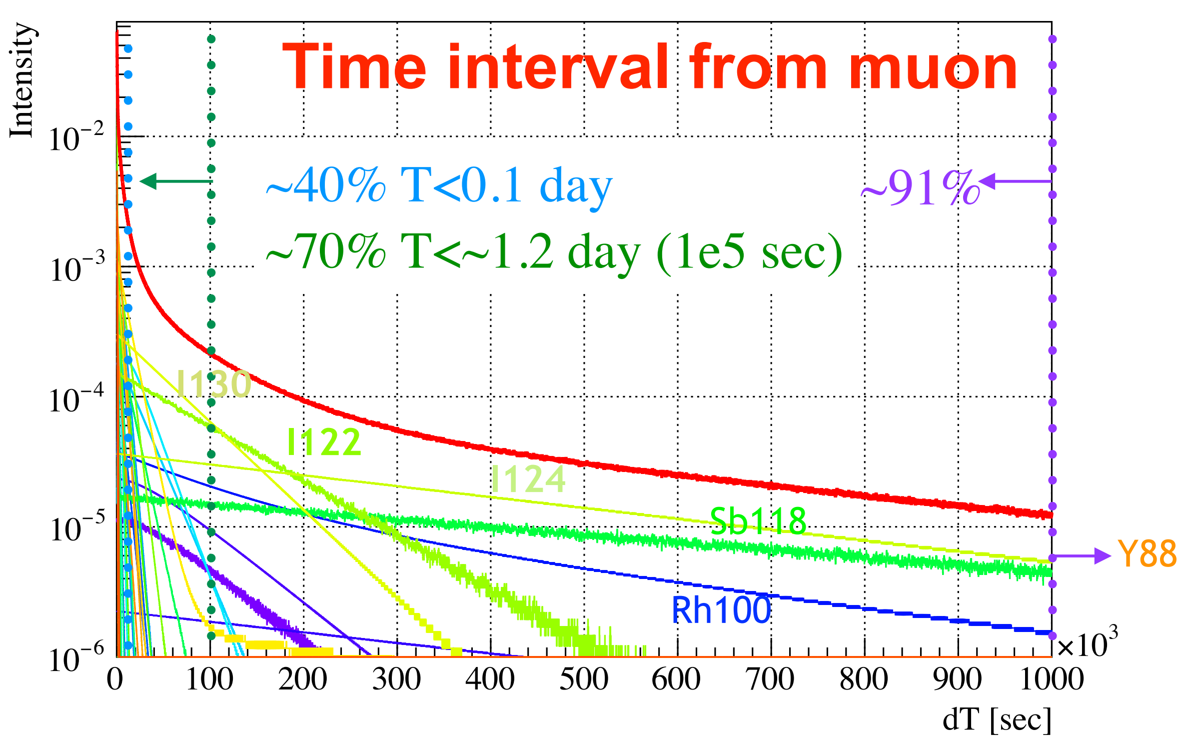
New issues in KL-Zen 800
2. Long-lived Xe spallation BGs

FLUKA
Xe-LS (cylinder geometry) + muon



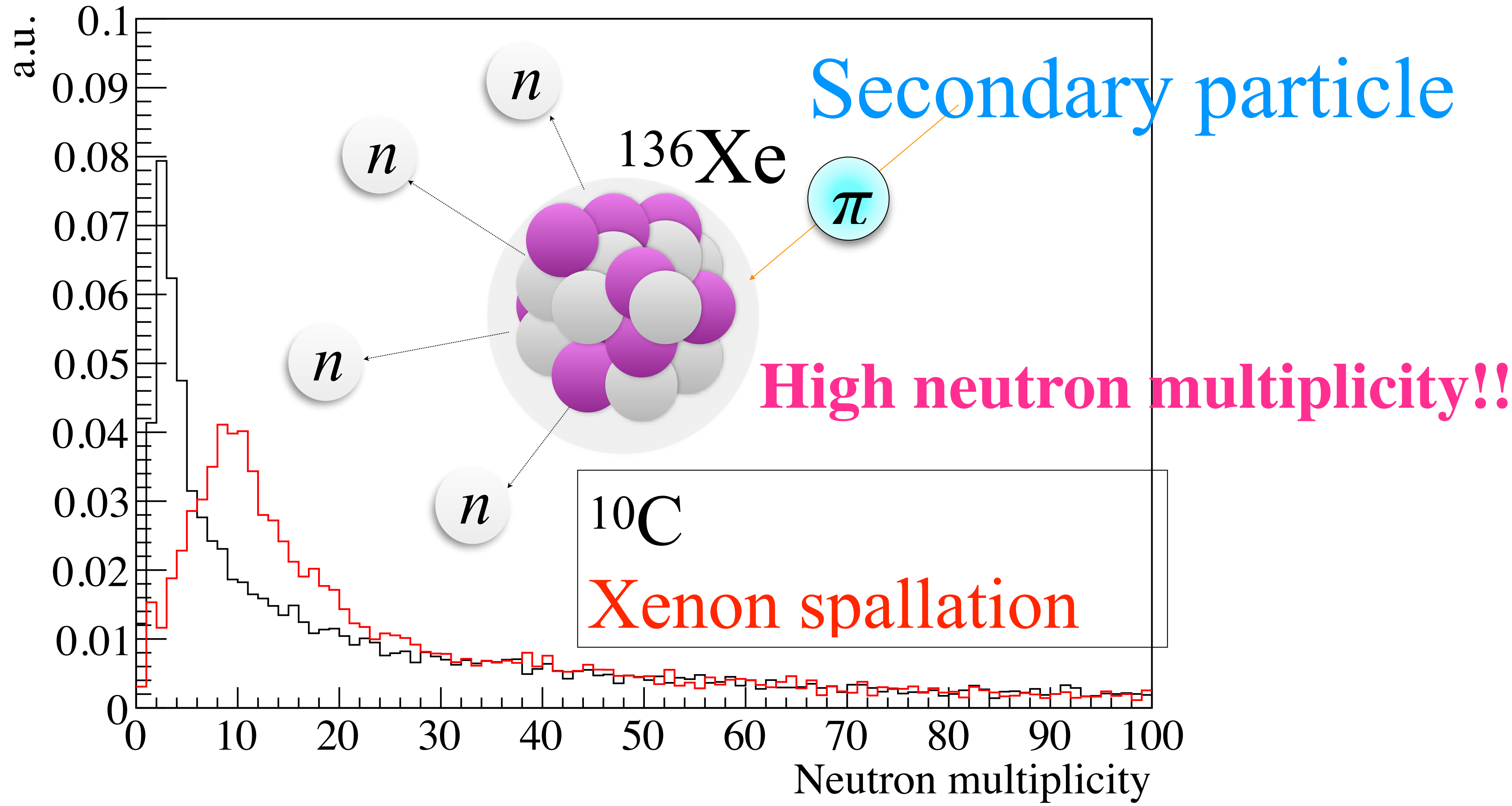
Energy spectra of products
~90% by major 32 nuclei





- Individual yields are small but many candidates are produced
- Total yield become one of the main background → new major background
- In order to mitigate the BG, day scale veto is necessary.

of neighbor neutron captures by FLUKA



$$\mathrm{ENN} = \sum_{\mathrm{neutrons}} \frac{\mathrm{PDF}_{\mathrm{spallation}}(dR)}{\mathrm{PDF}_{\mathrm{spallation}}(dR) + \mathrm{PDF}_{\mathrm{accidental}}(dR)}$$

A new likelihood method using ENN provides a rejection efficiency of 42.0±8.8%.

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

Our dataset is now 970 kg-yr ^{136}Xe exposure!

arXiv:2203.02139

Simultaneous fit has been performed to the entire volume and LL tagged and untagged events.

Binning:	Parameters:	BGs
3 time bins LL tagged/untagged 20 radius bins upper/lower 86 energy bins	each BG rates LL efficiency, LL shape Energy scales (each time, non-linear responses)	Xe LS: 2ν, Xe-spallation, ν-ES, ^{238}U, ^{232}Th, etc IB film: ^{238}U, ^{232}Th, ^{40}K, ^{210}Bi, etc Kam LS: C-spallation, ^{85}Kr, ^{40}K, etc

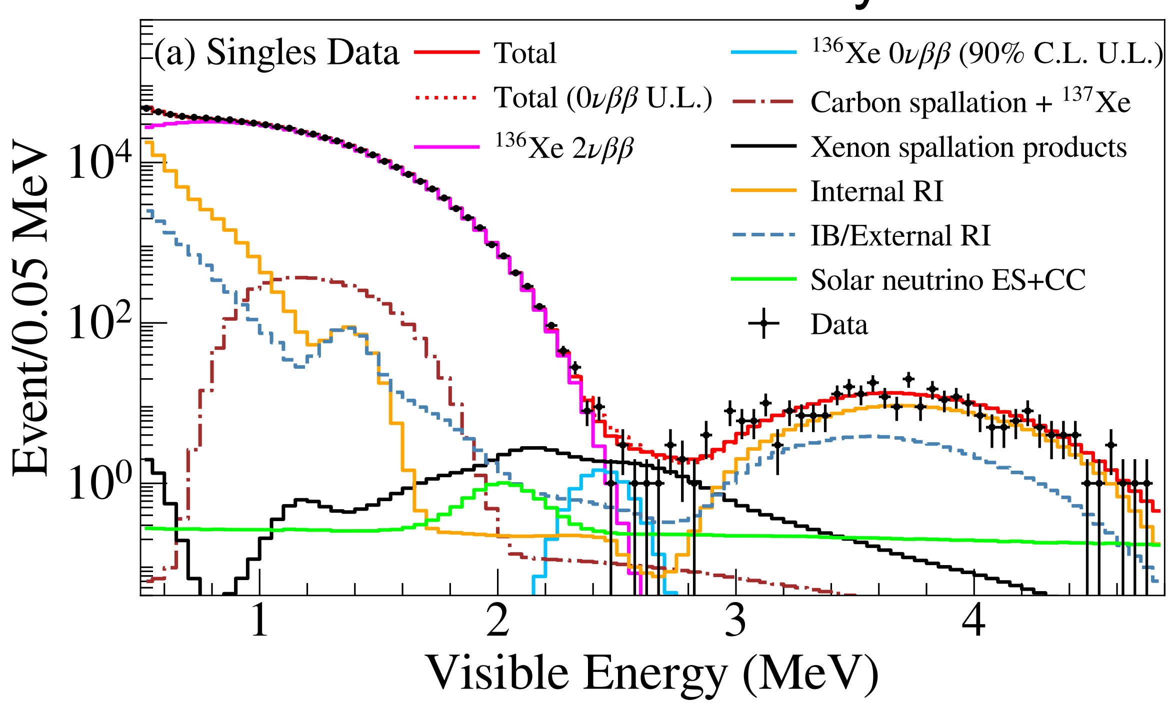
Singles data
(LL untagged, spallation suppressed)

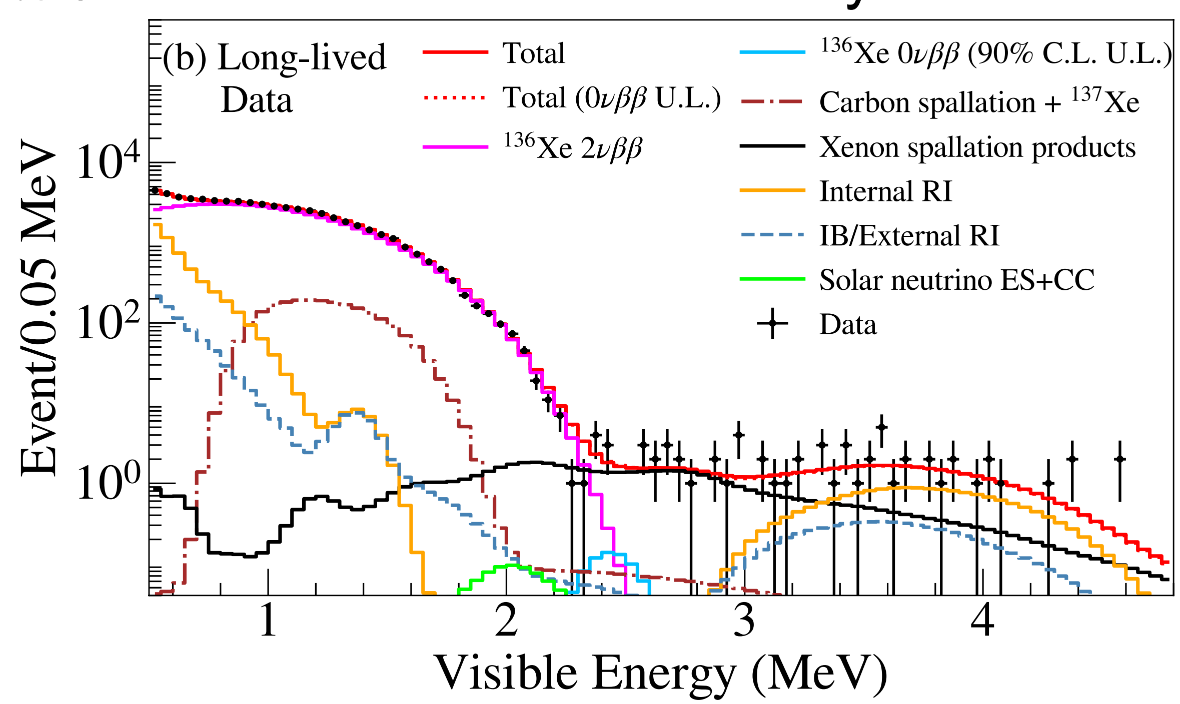
Livetime = 523.4 days

R<1.57m

Long-lived product data
(LL tagged, spallation-rich)

Livetime = 49.3 days





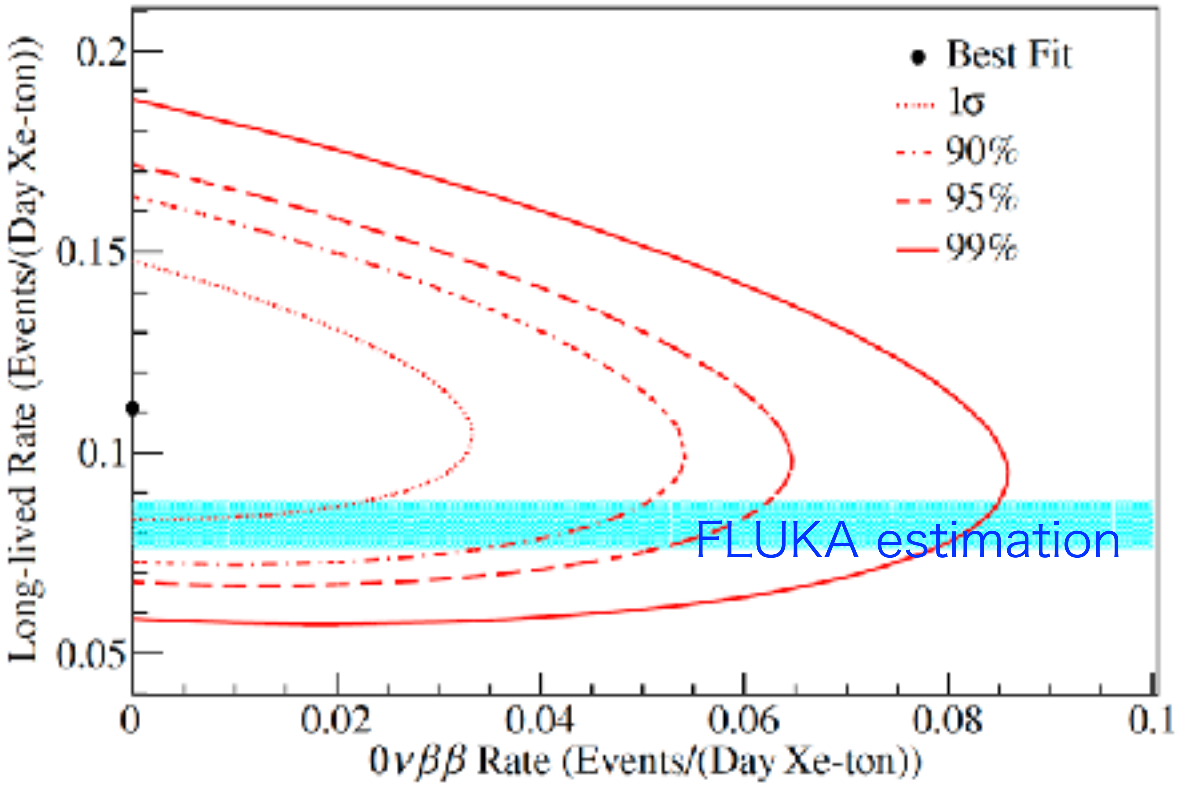
Best fit 0ν2β : 0

90% CL upper limit : <7.9 events/Xe-LS(30.5m^3)

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

^{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.



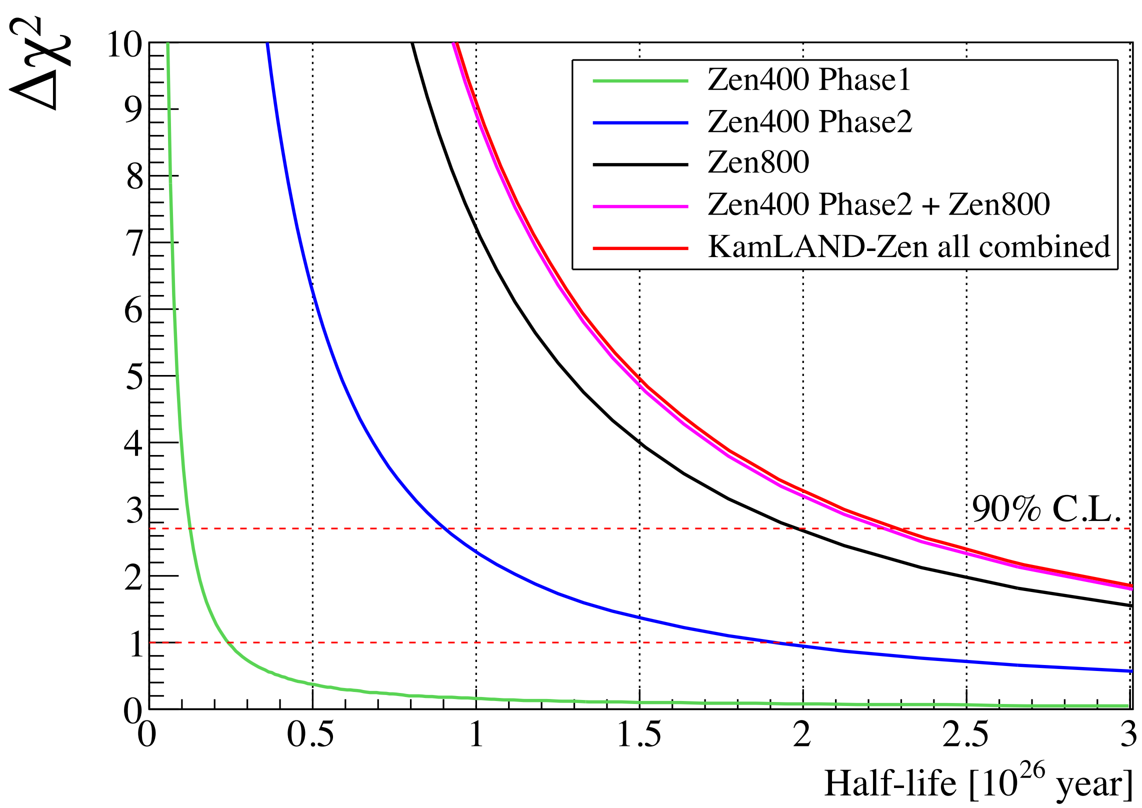
LL rate (2.35-2.79MeV)

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.)

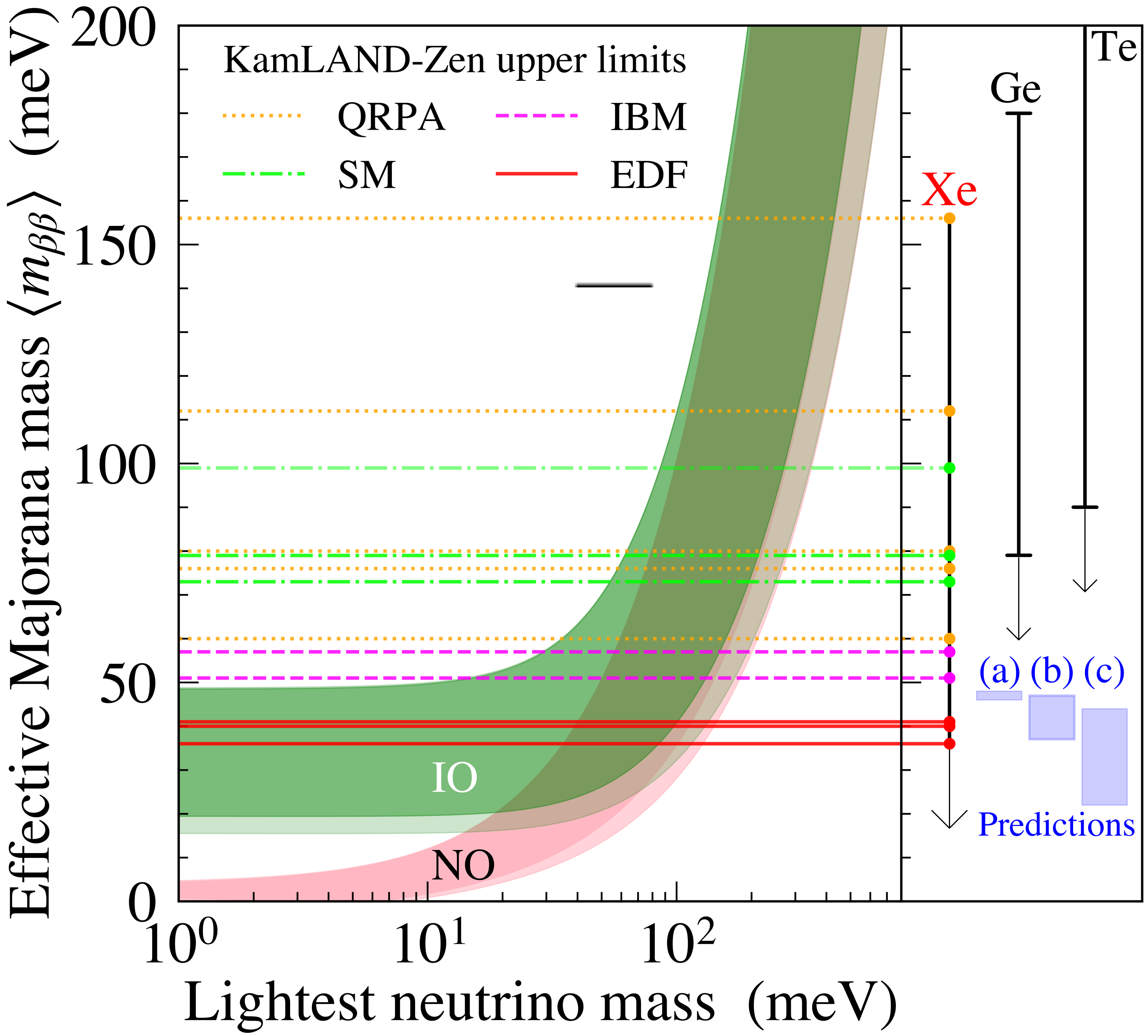
$T^{1/2} > 2.3\times10^{26}$ yr

Sensitivity (90% C.L.)

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

The probability of obtaining a stronger limit : 23%

Limit on the effective neutrino mass



$T^{1/2}$ > 2.3×10^{26} yr

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

NME (M^{0v}) : 1.11–4.77

(gA ~ 1.27)

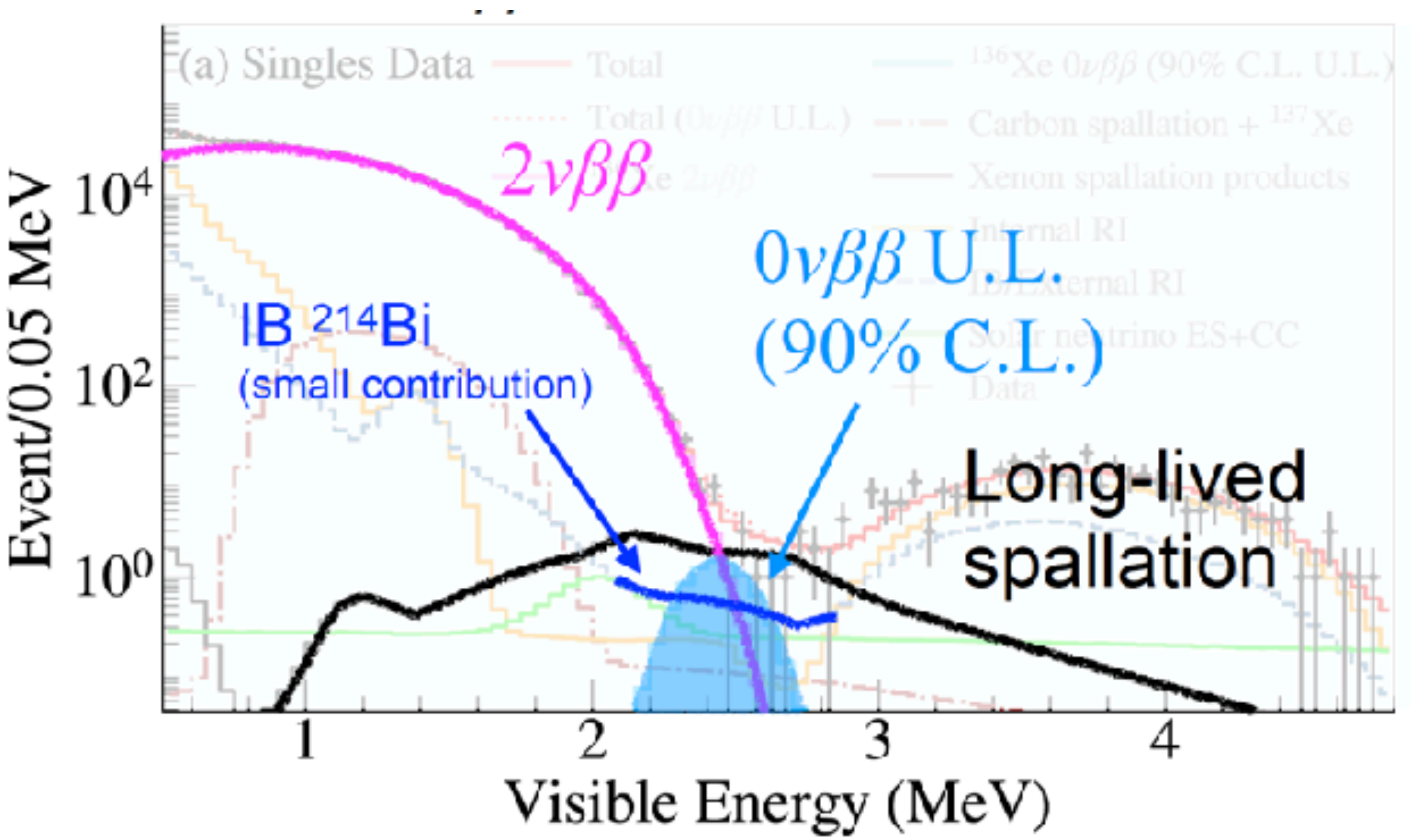
$\langle m_{\beta\beta}\rangle$ < 36-156 meV

Entering the IO region

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

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

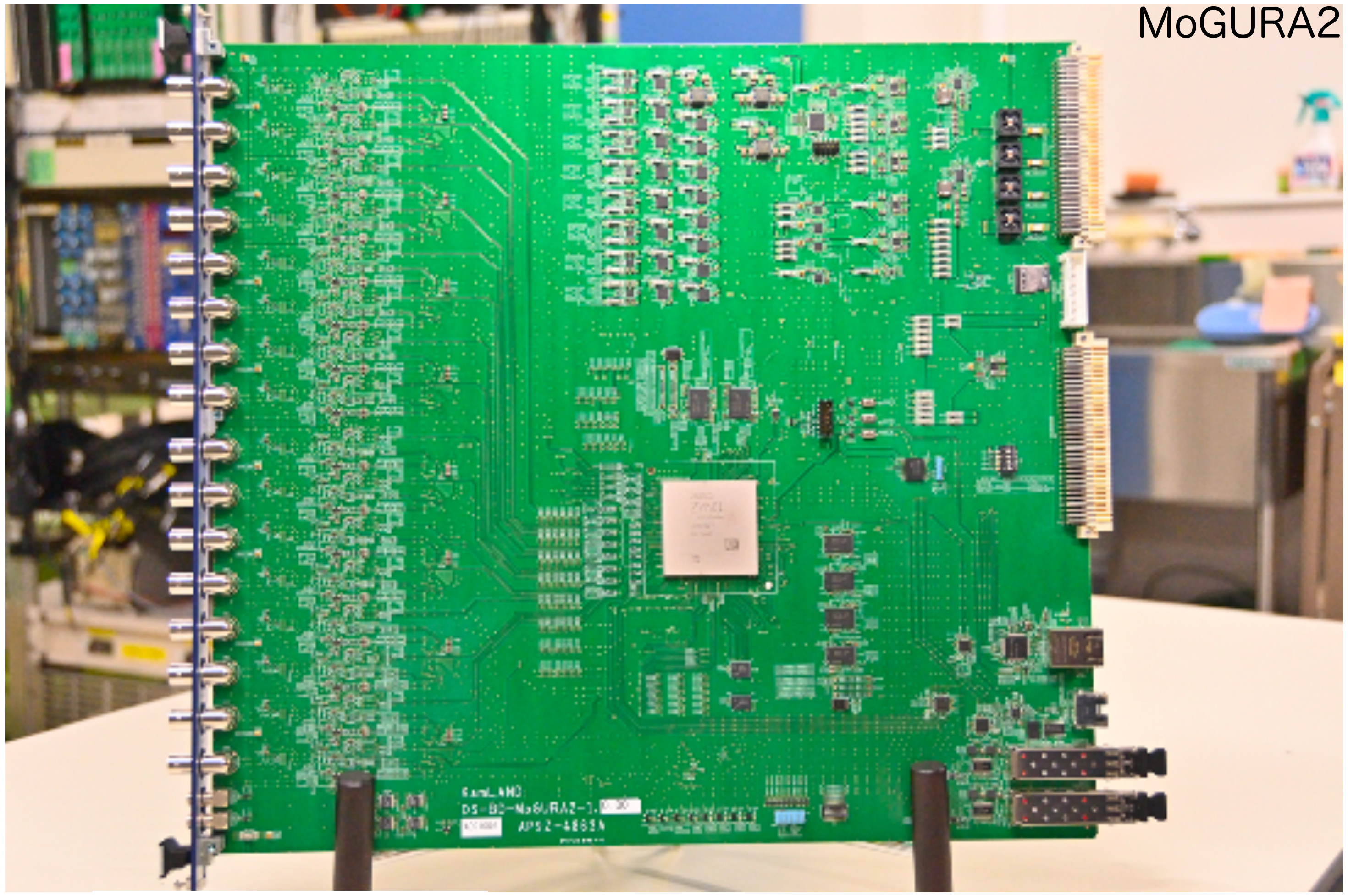
^{214}Bi → scintillation balloon, neural net (enlarging FV)

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

Improvement of neutron tagging efficiency (new front-end electronics)

Full-size prototype delivered in September 2020

MoGURA2



H-gain for 1p.e.
- 1GS/s, 12bit
(2GS/s and averaging)
- Vin: -150mV - +50mV
- Vnoise: <0.12mVrms
- BW: < 65-100MHz

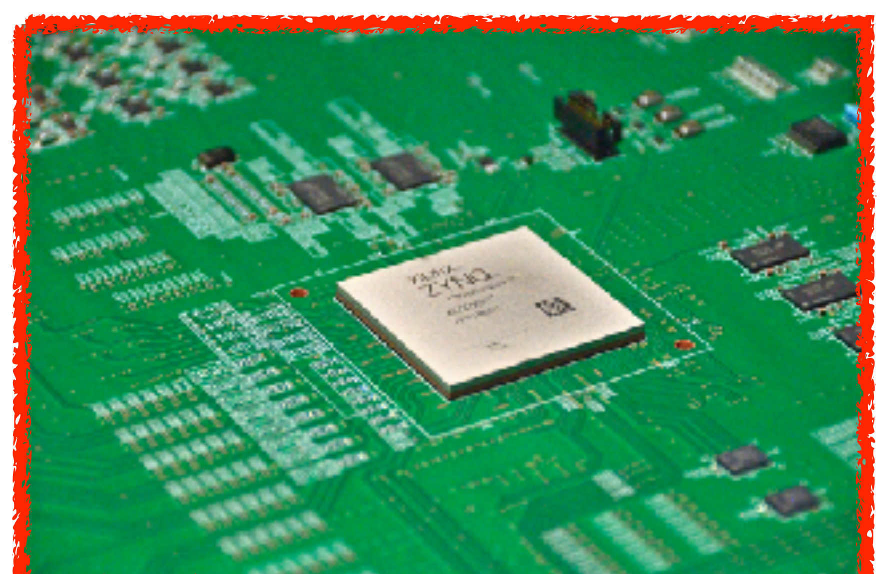
L-gain for muon
- 250MS/s, 16bit
- Vin: -7.5V - +0.5V
- Vnoise: <1.2mVrms
- BW: < 65-100MHz

Technology innovation from spread of 5G

2002- KAMFEE

2010- MoGURA

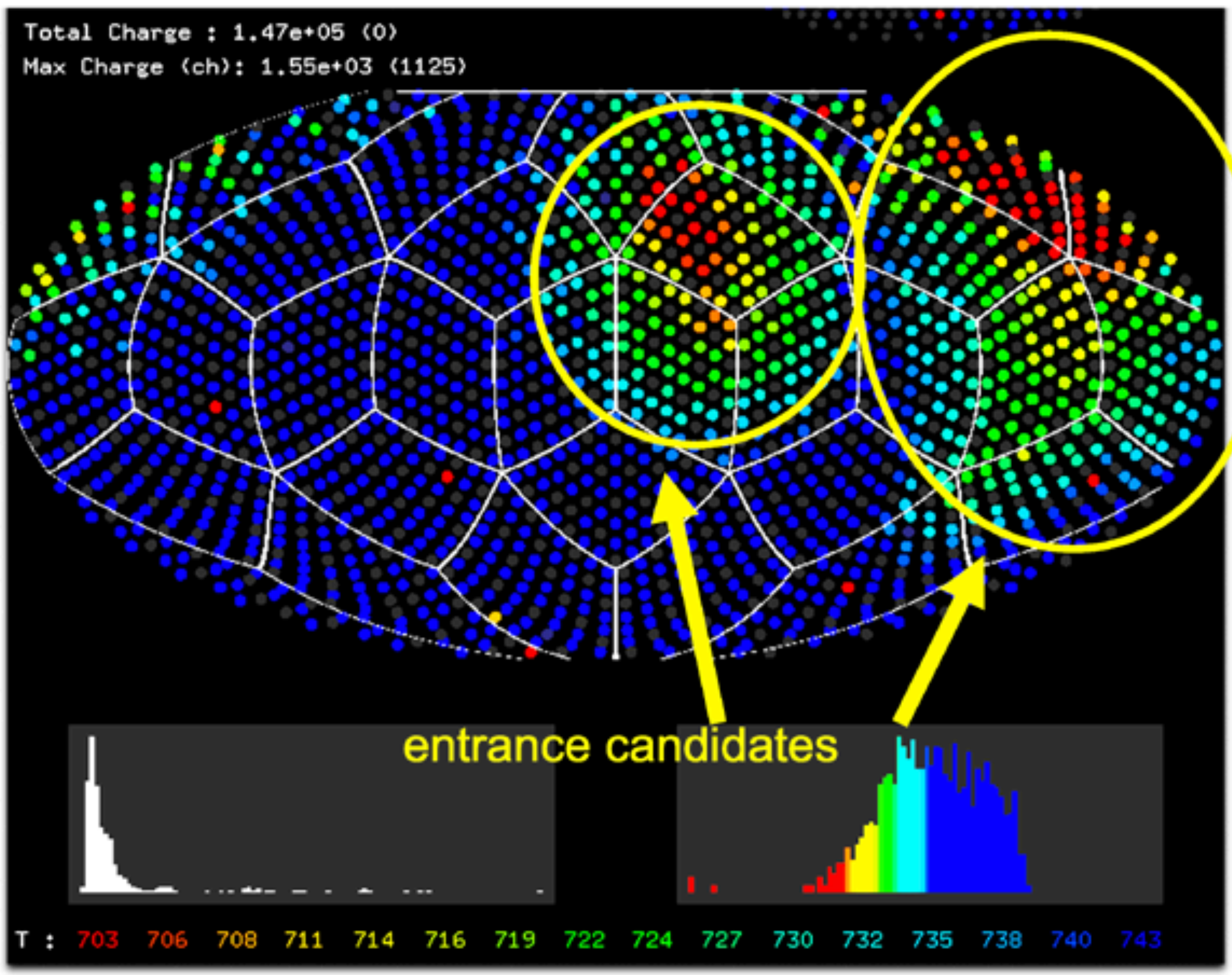
Xilinx Zynq®Ultrascale+™ RFSoC



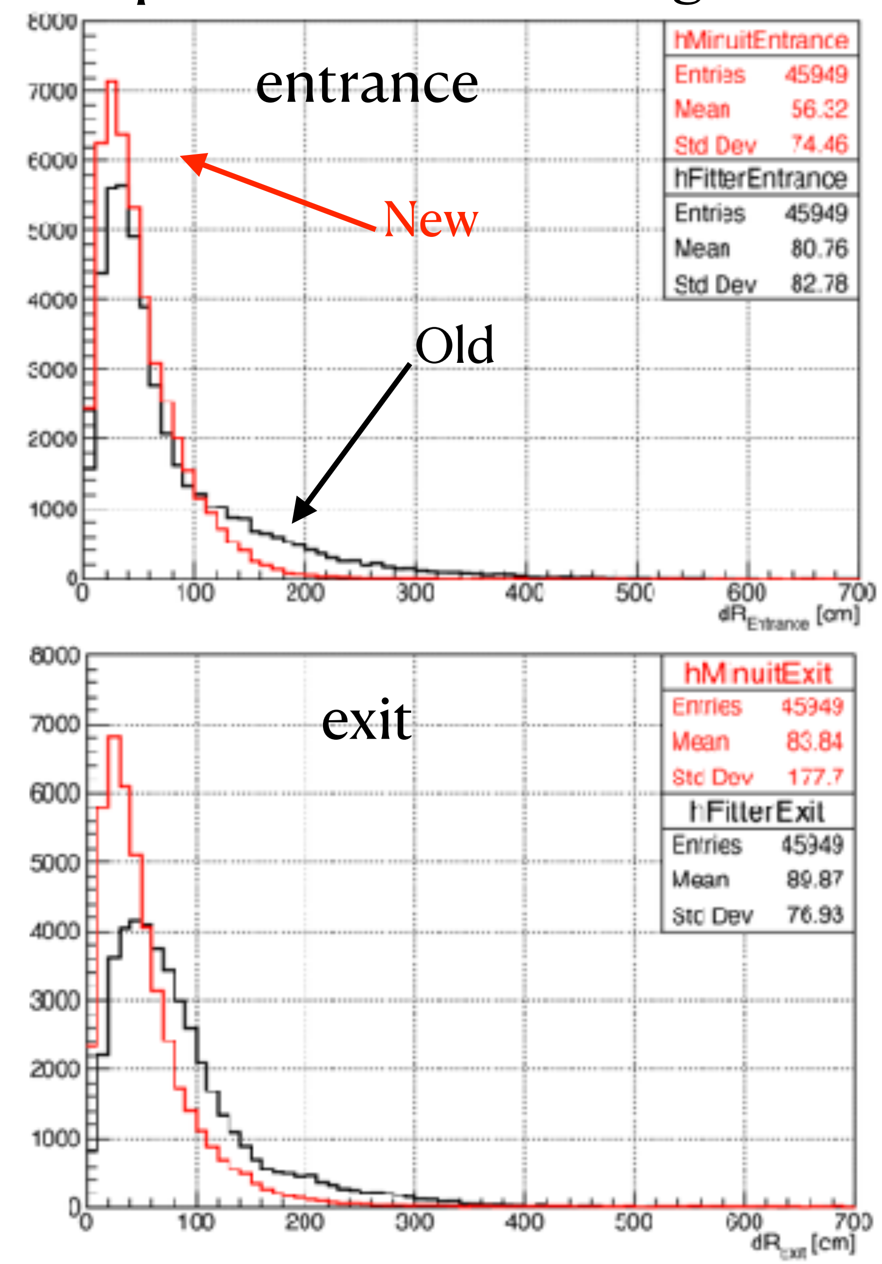
16ch×1GS/s×12bit

New muon tracking

muon bundle @ KamLAND ~4%



performance with singles

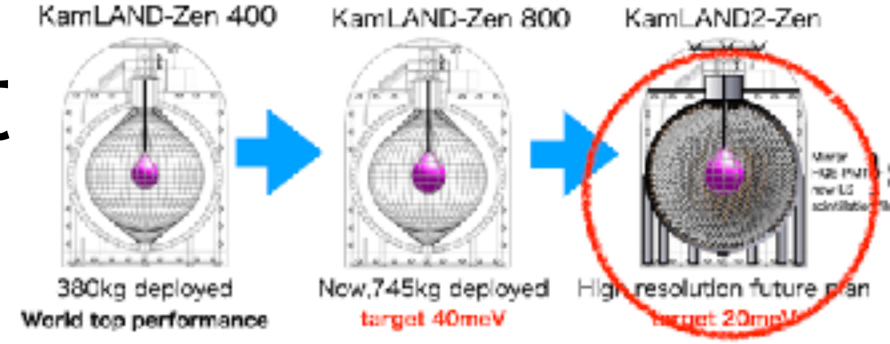


entrance	<1.5m	<1m
old single	85%	66%
multi new	90%	76%

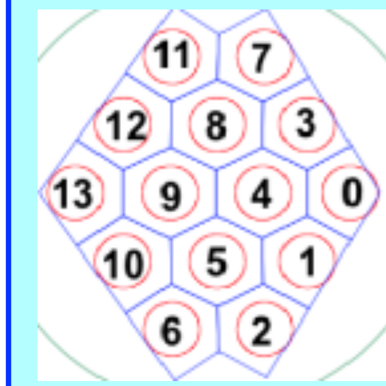
Muon bundle identification is ~90% efficiency,
and better track reconstruction than the current single muon fitter.

KamLAND2-Zen project

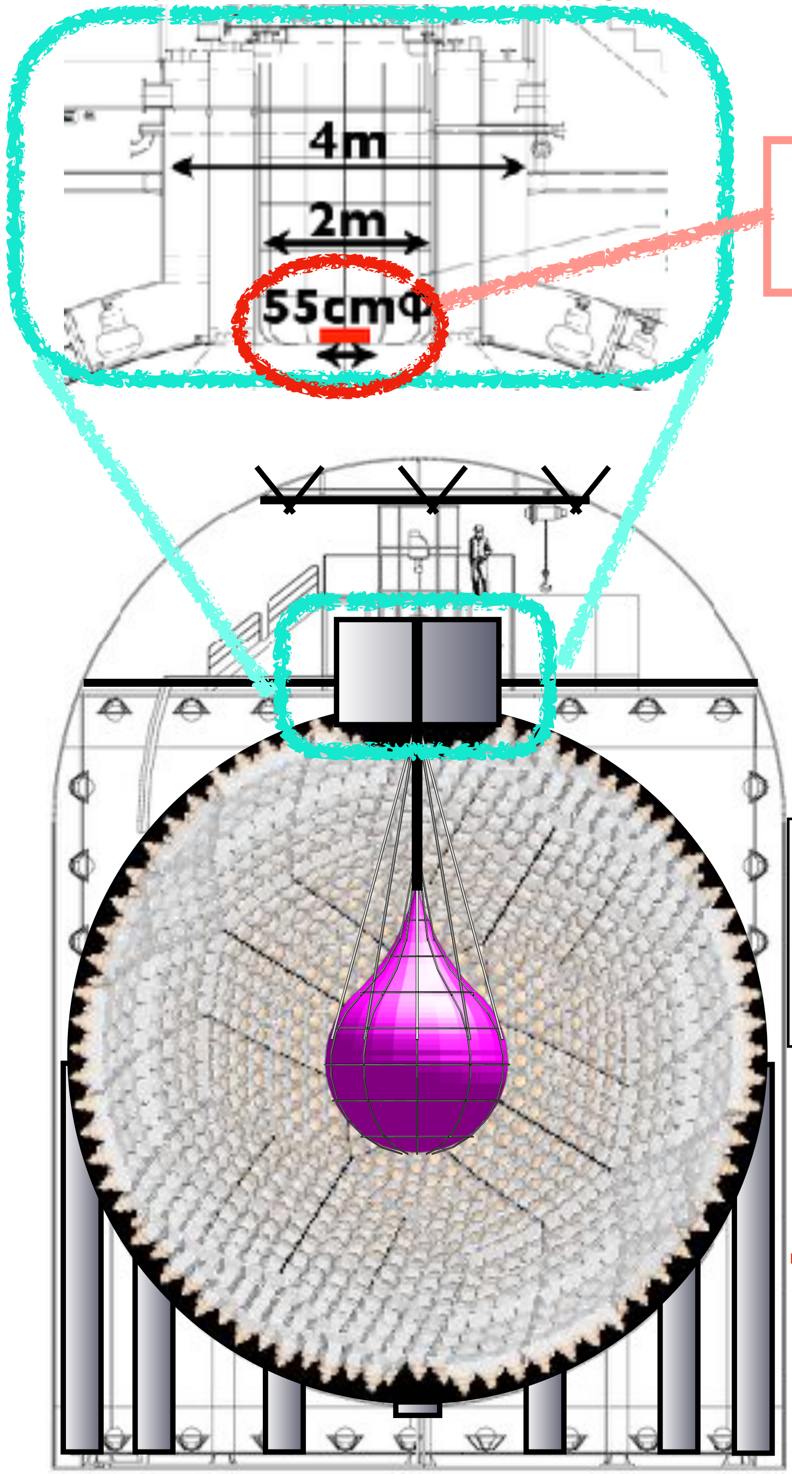
Ranked as "highest priority" in cosmic ray community



Even **x2.4** is possible with an optimization



Higher energy resolution for reducing 2ν BG

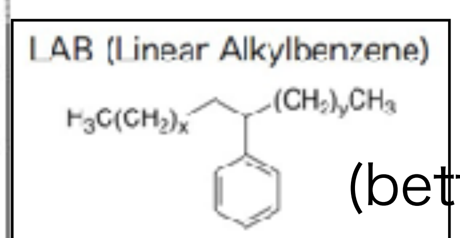


Expansion of entrance

Winston cone — light collection ×1.8

high q.e. PMT — light collection ×1.9

17"ϕ→20"ϕ ε=22→30+%



LAB LS — light collection ×1.4

(better transparency)

expected σ(2.6MeV)= 4% → ~2%

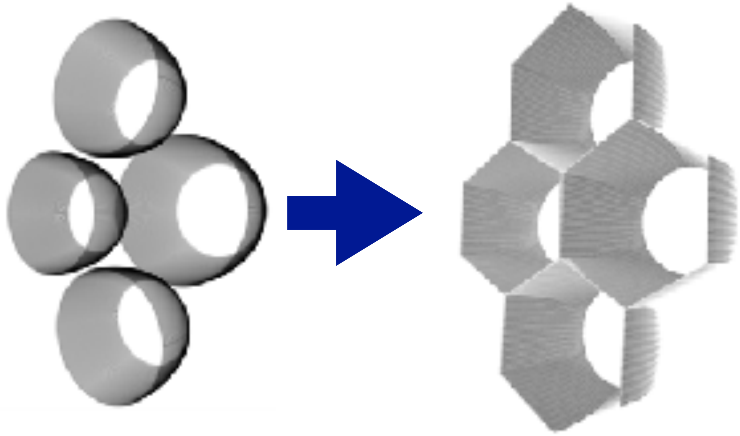
target sensitivity 20 meV (2×10^{27} yrs)

20meV	**95% of IO**
	50% of NO

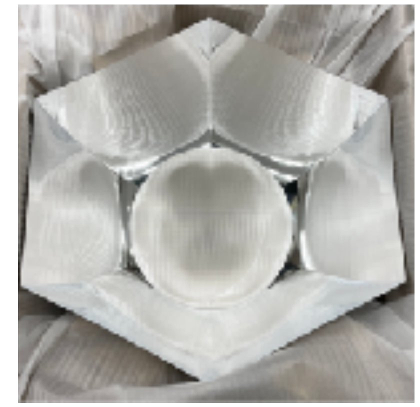
1000+ kg xenon

Improvement of energy resolution

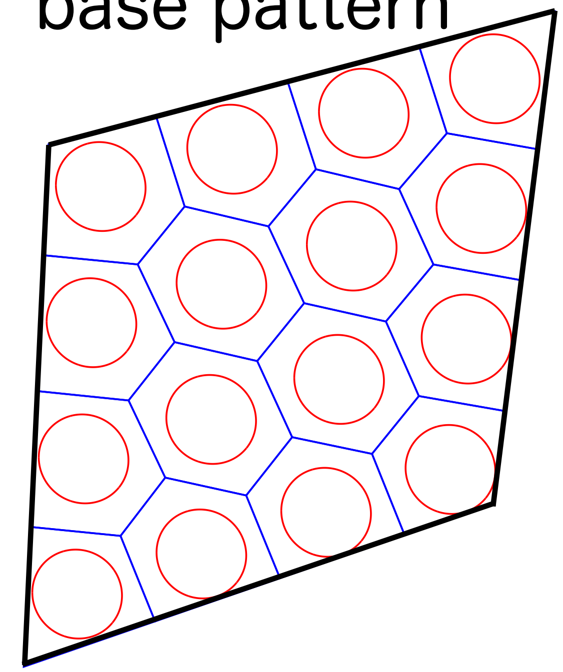
circle to polygon shape
for eliminating gaps

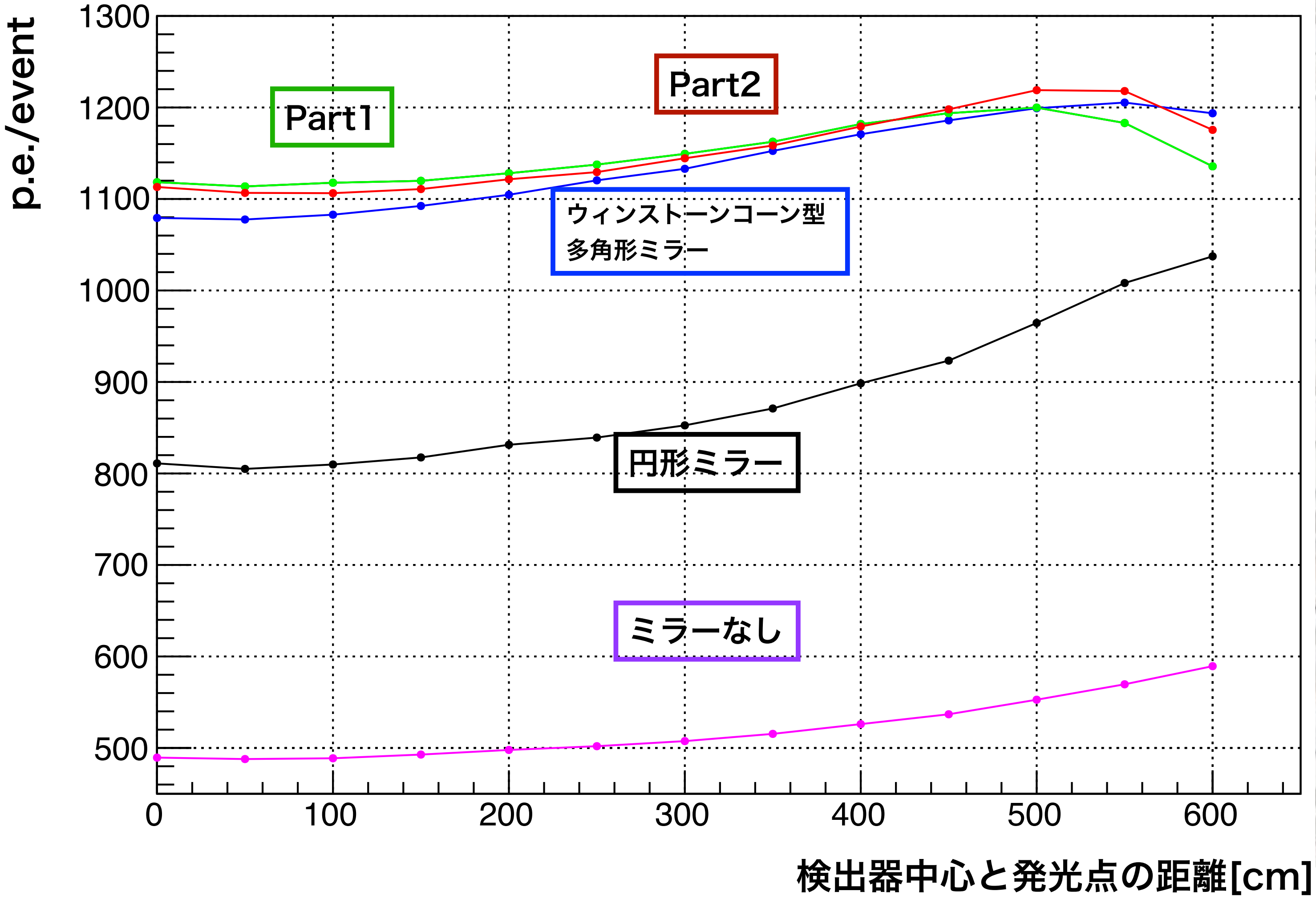


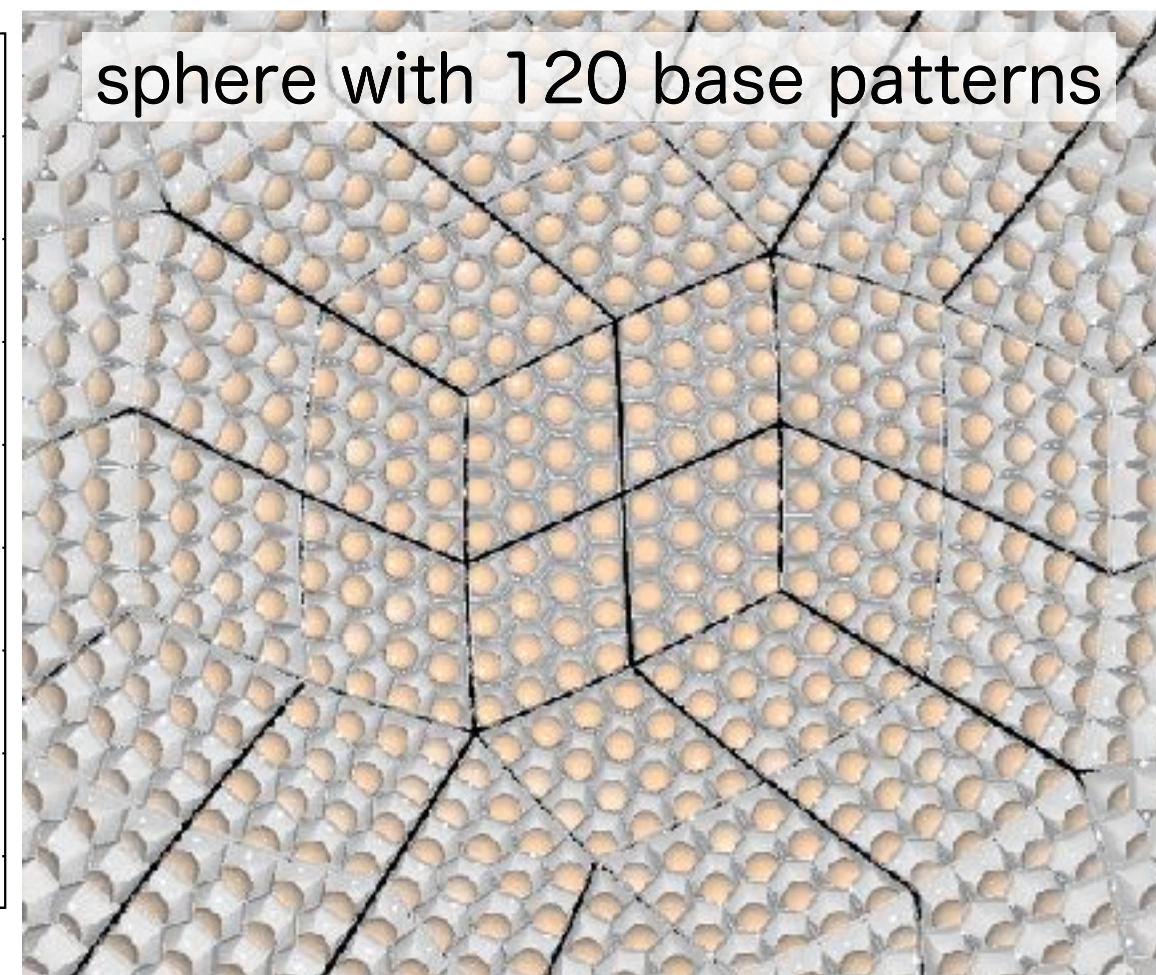
trial product



base pattern



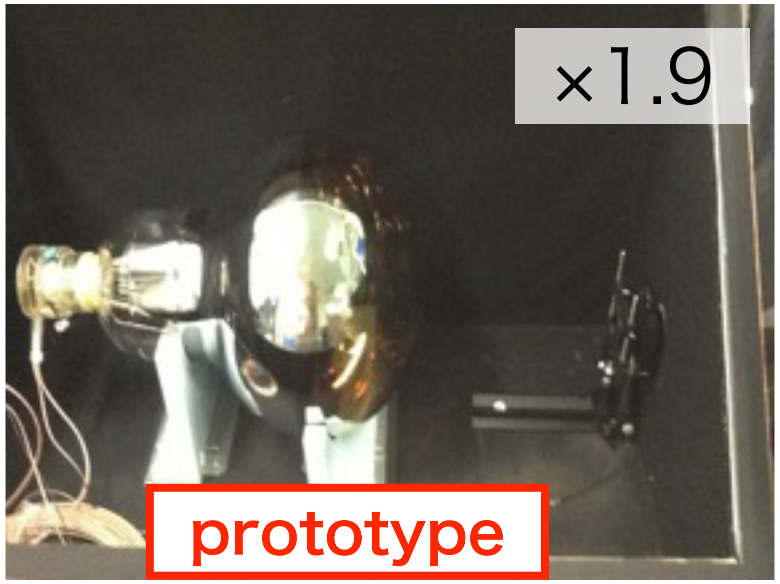




x2.2~2.3 light collection w.r.t. no mirror

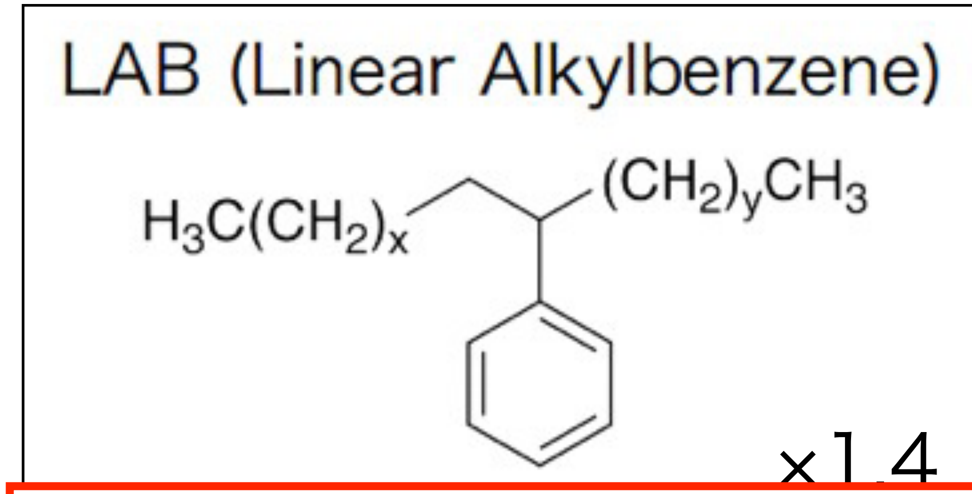
The other R&Ds for KamLAND2-Zen

○ high QE PMT



prototype

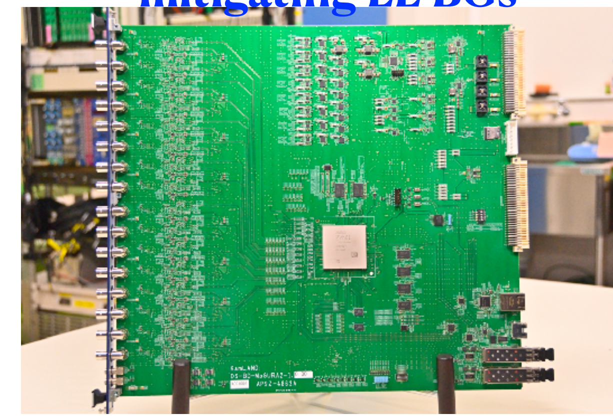
○ New LS



high transparency confirmed

○ New electronics

mitigating LL BGs

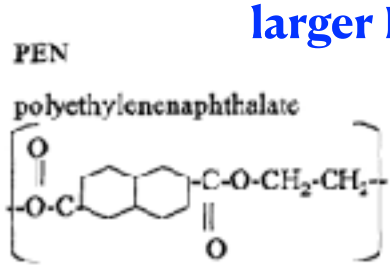


16ch×1GS/s×12bit

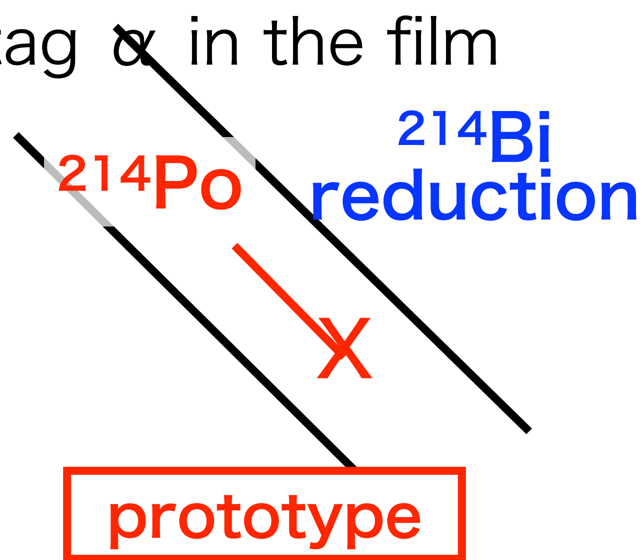
prototype

○ Scintillator film

larger FV

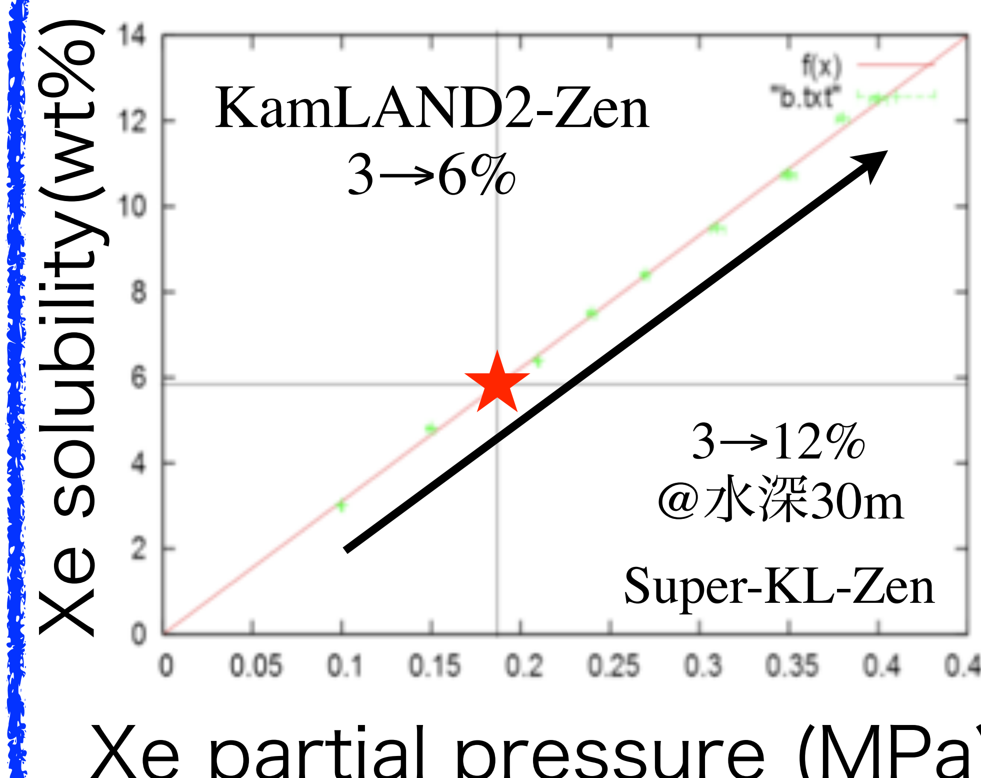


tag α in the film



prototype

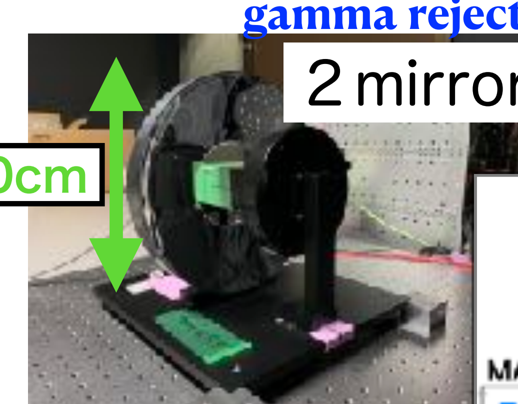
○ high concentration

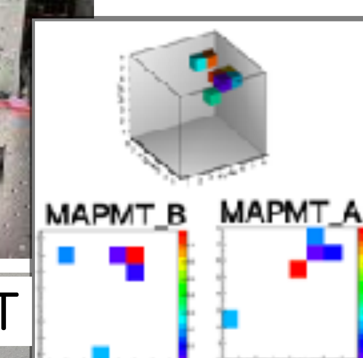


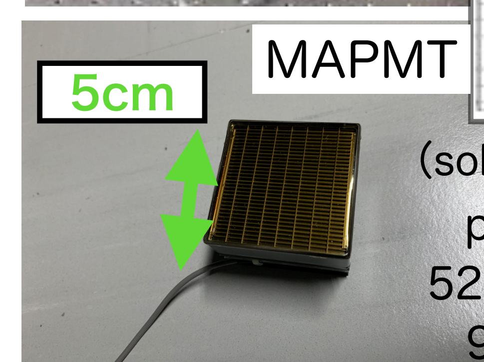
principle verification

○ imaging

gamma rejection



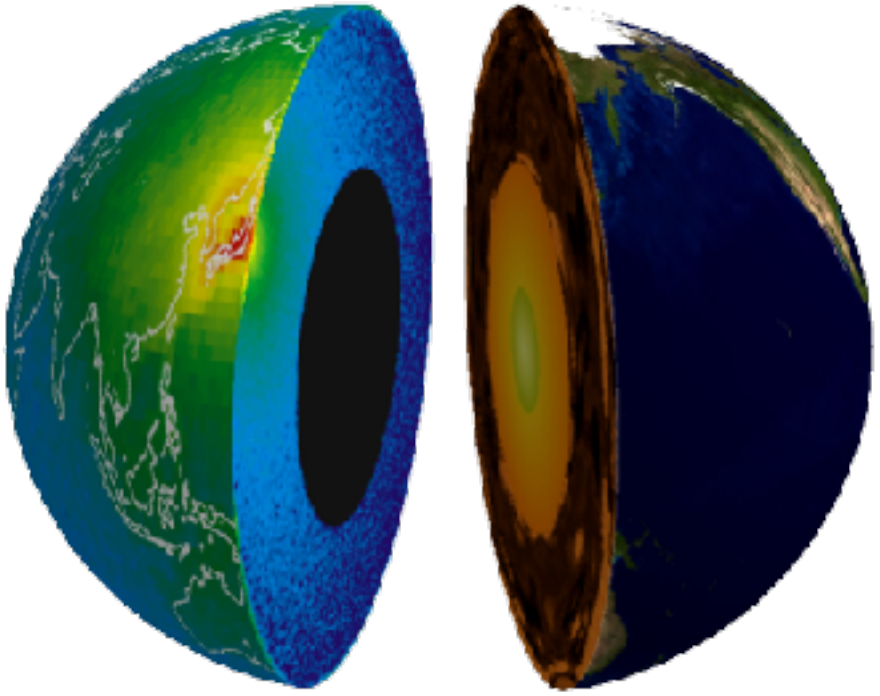




(solid angle 0.4%×2)
pos. res.1.4cm
52% γ rejection @ 90% efficiency

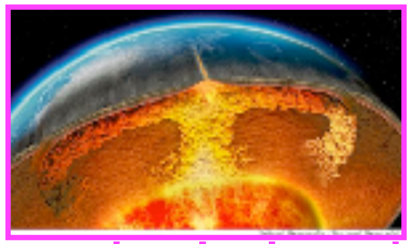
principle verification

geoneutrino



Big arguments

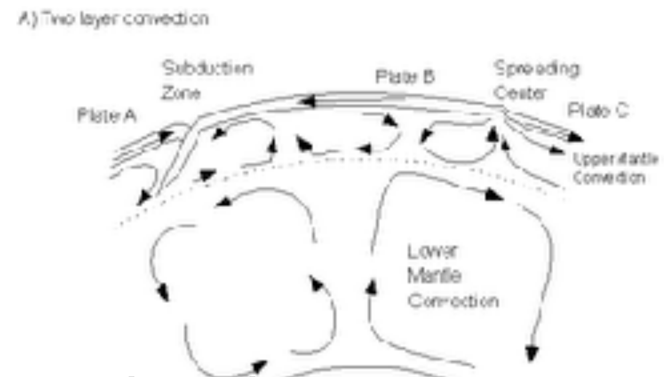
Mantle convection



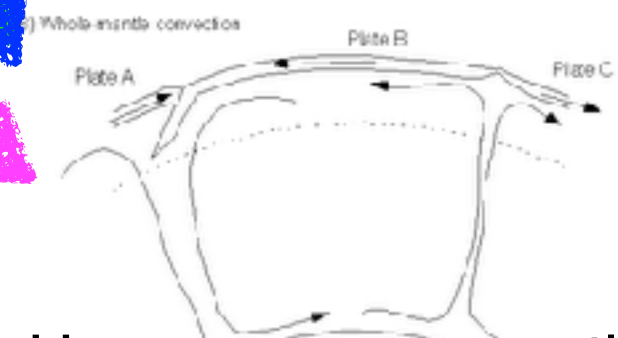
geophysical model predicts **single convection**

geochemical model predicts **multi-layer convection**

High-Q



U/Th rich lower mantle



Homogeneous mantle

Middle-Q

Primordial meteorite

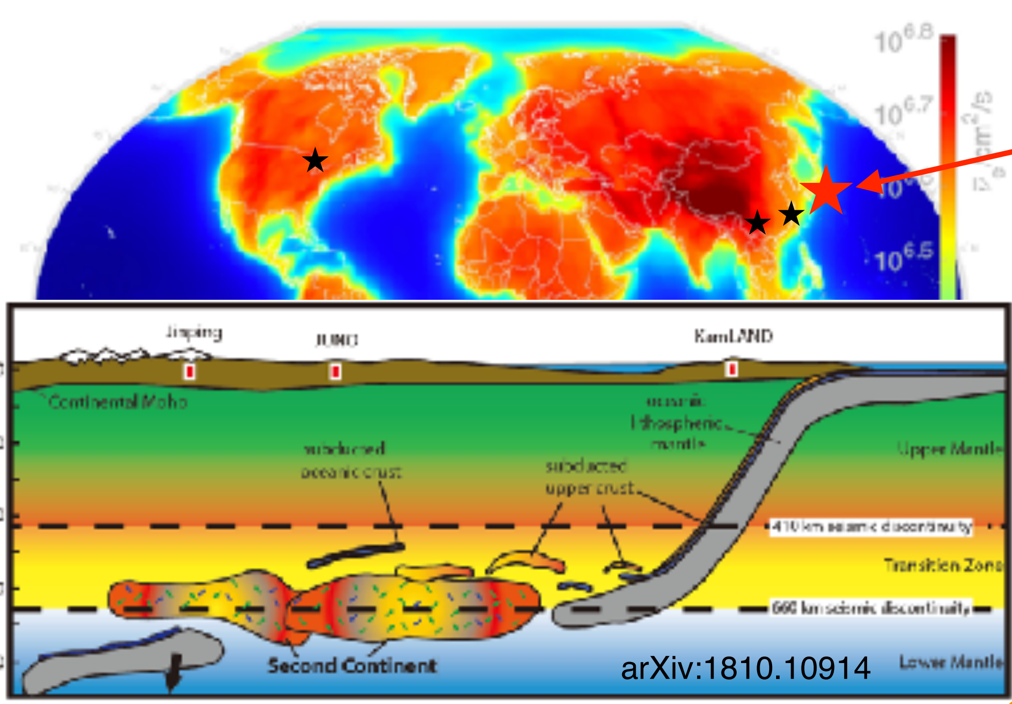
chemical abundance implies **"C1 chondrite"** (geochemical model)

V U,Th amount

isotope ratio implies **"enstatite chondrite"** (geochemical model)

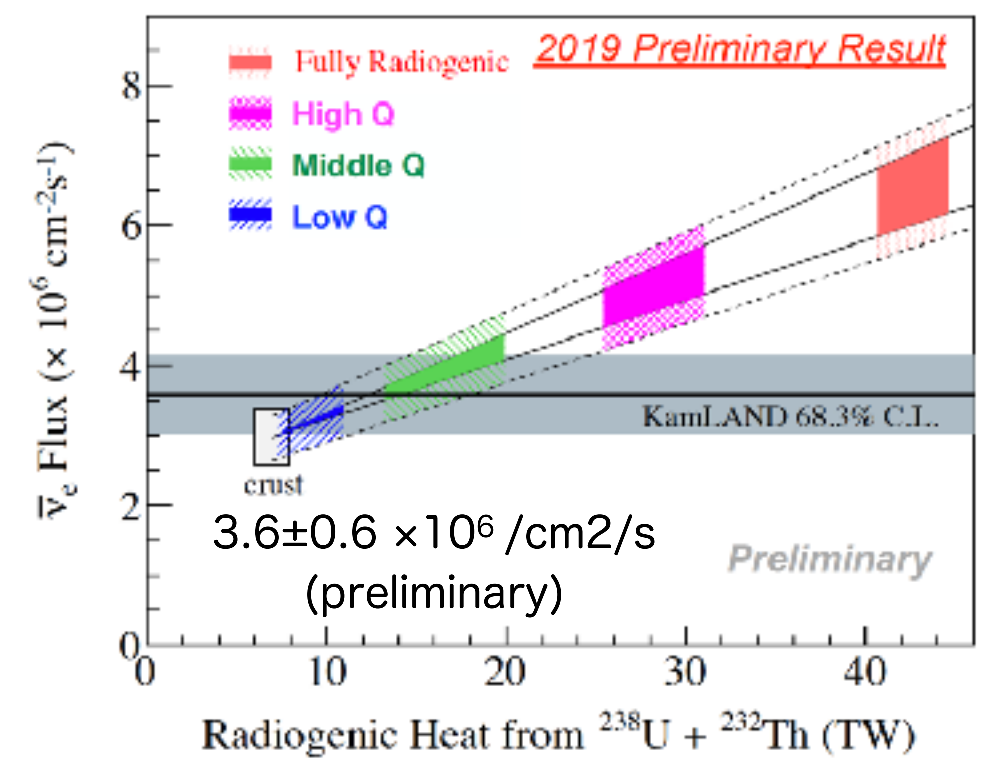
Low-Q

Destination of subducted crust



arXiv:1810.10914

Unique location (edge of continent)

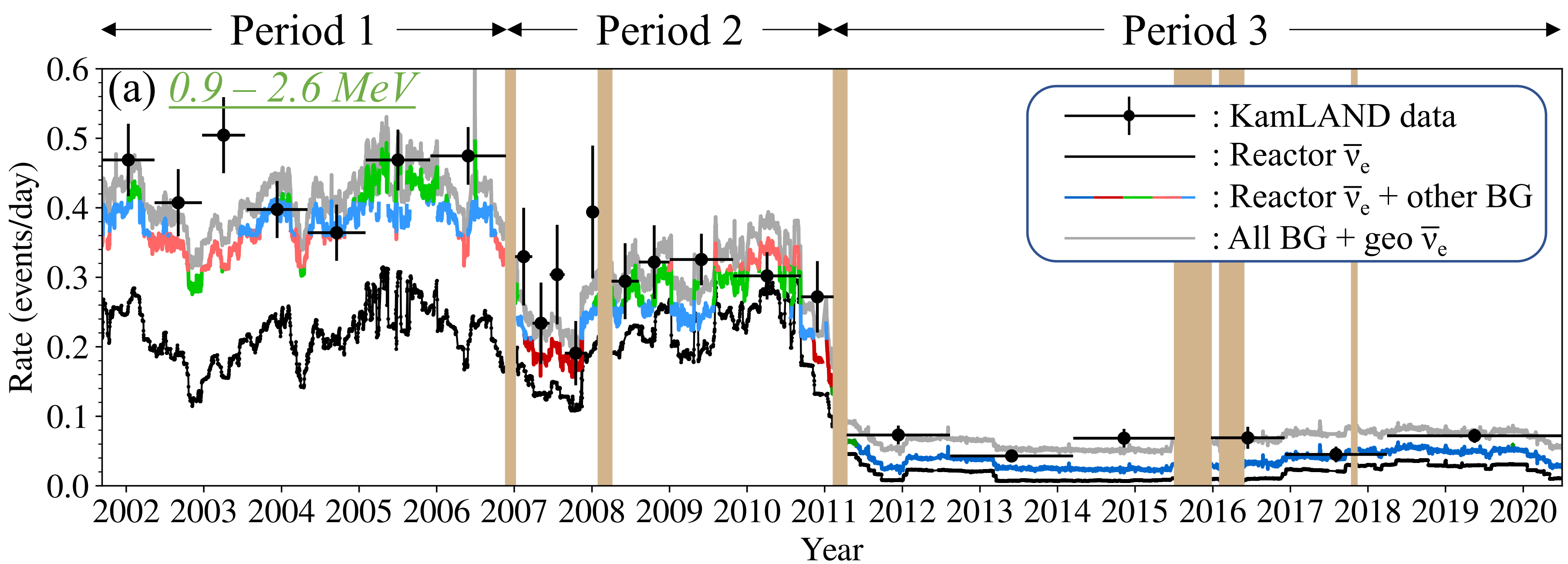


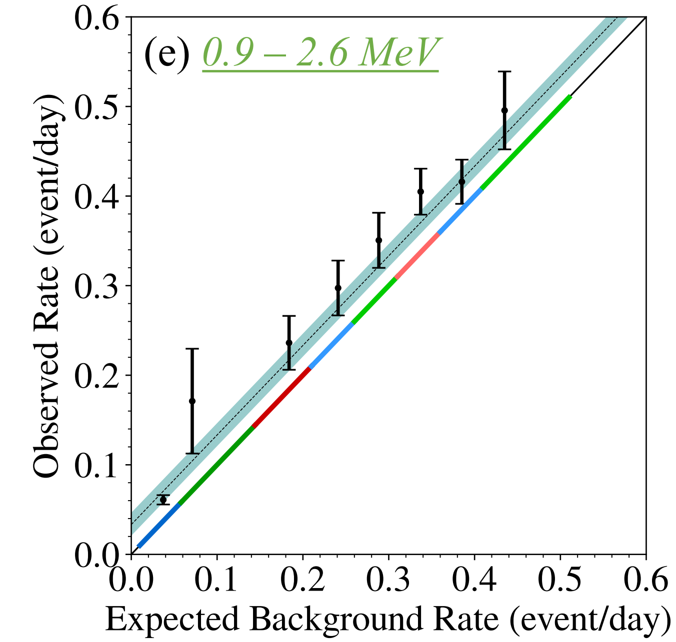
$3.6 \pm 0.6 \times 10^6$ /cm2/s (preliminary)

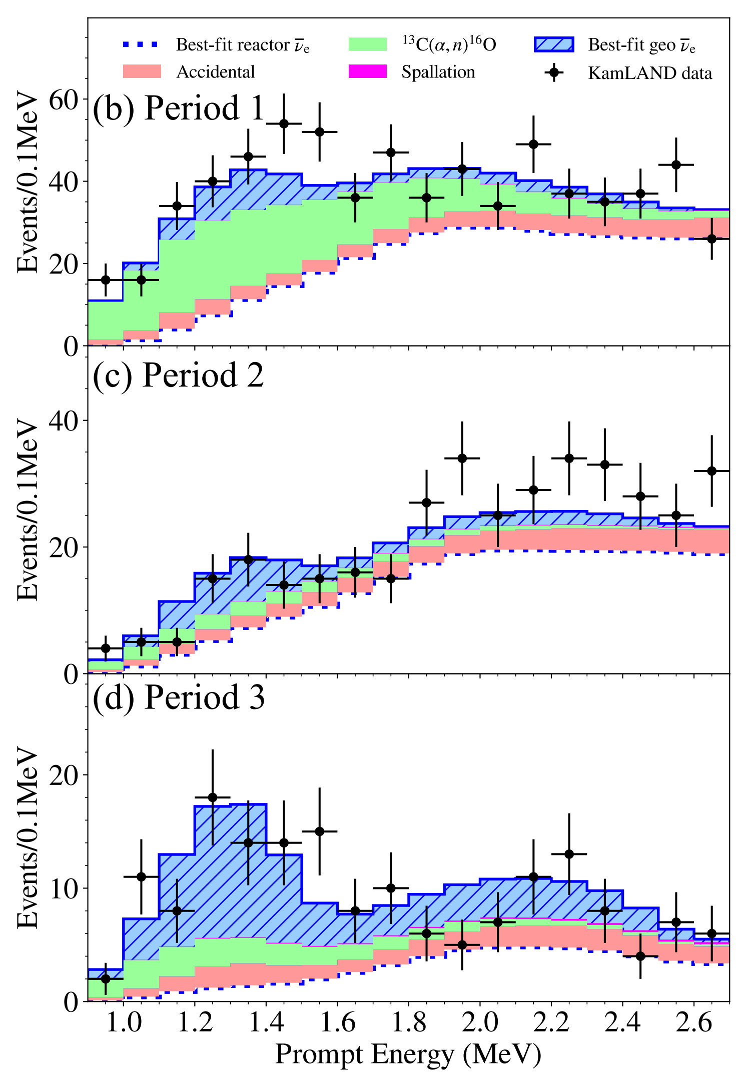
In the past publications, standard mass ratio Th/U=3.9 has been assumed.

KL is accumulating low reactor data

arXiv: 2205.14934

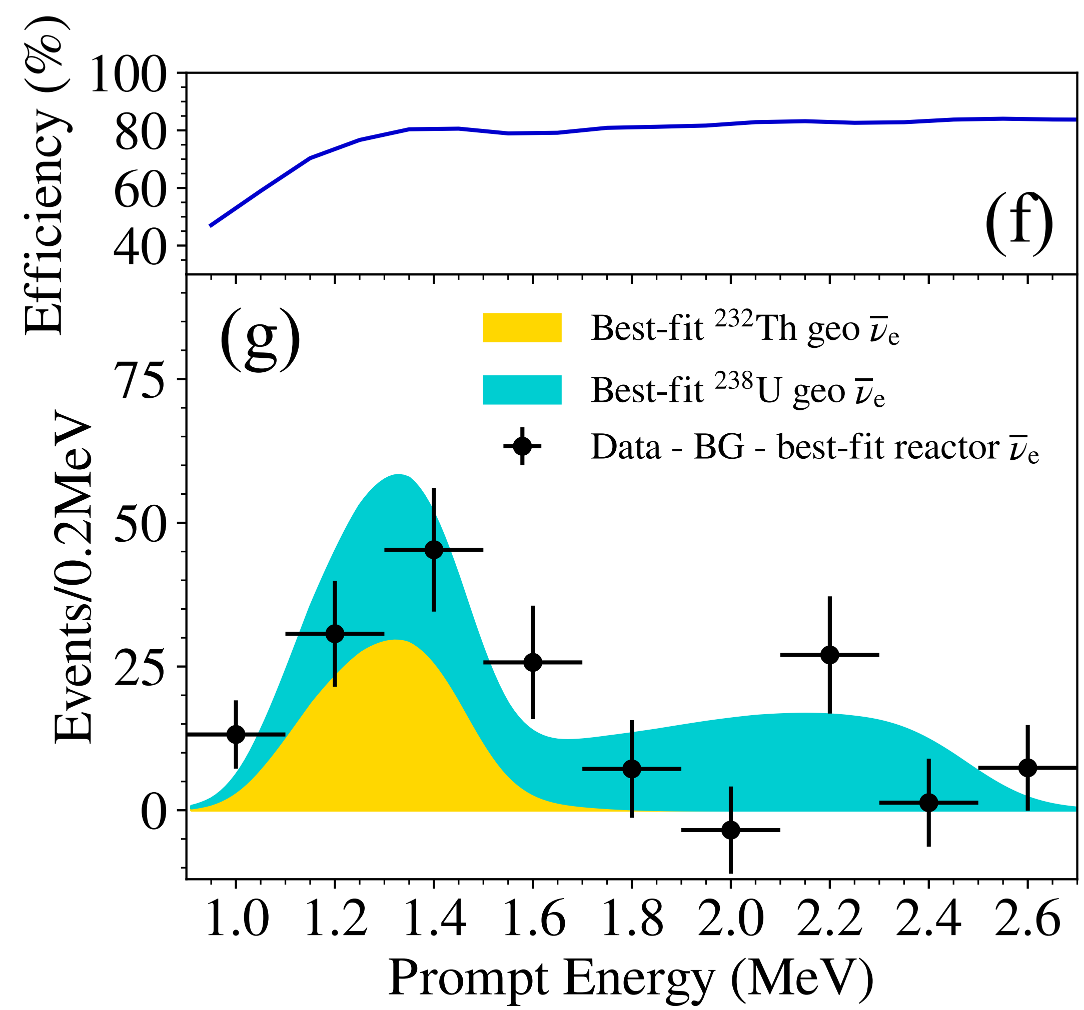






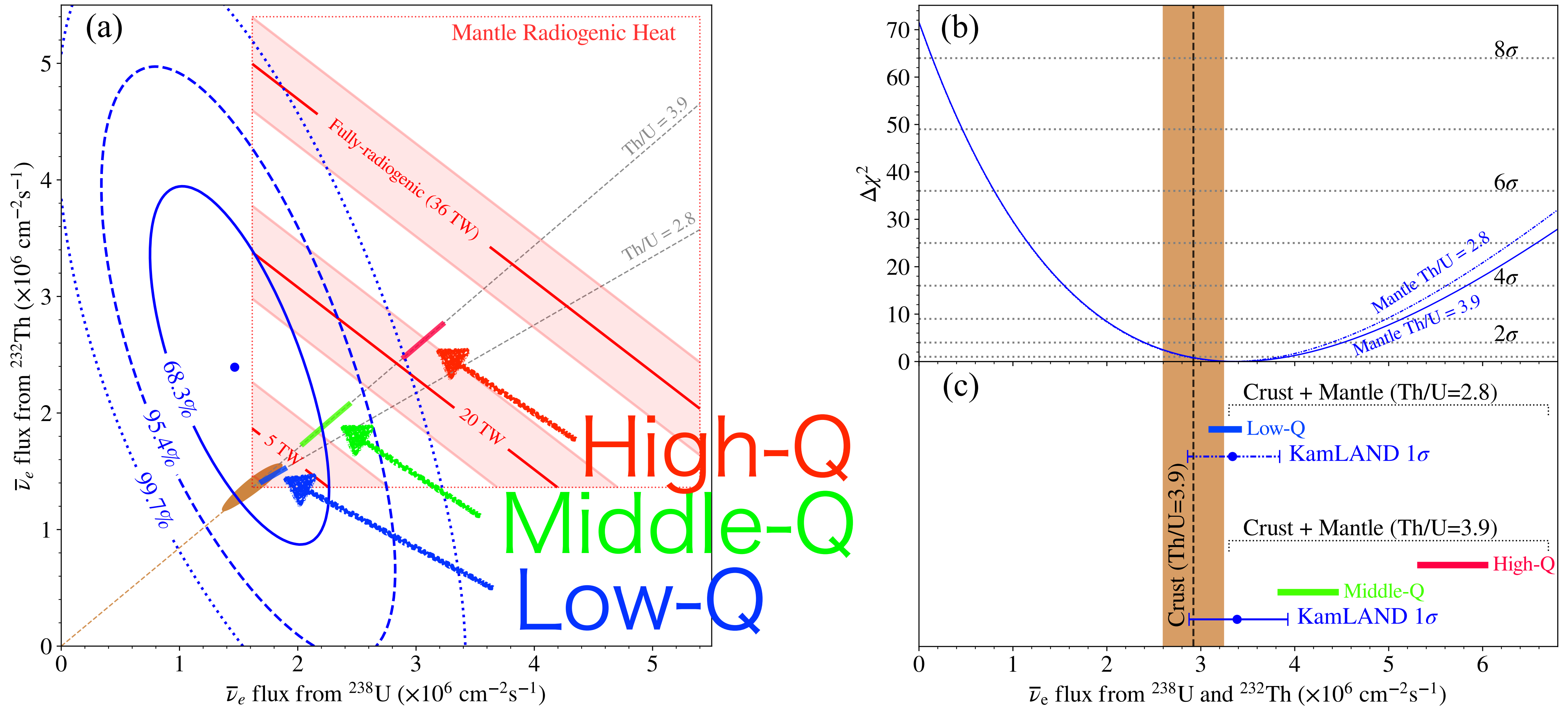
distillation

low reactor



Results from 18 years of observation

(8 years low reactor period)



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

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

Zero Uranium excluded at 3.3σ.

Fully radiogenic excluded at 5.2σ.

Assuming Th/U mass ratio of 3.9

183^{+29}_{-28} events observed 8.3σ

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

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

Model discrimination started!!

Summary

- KamLAND-Zen 800 started to explore the IO region.

$$T^{0\nu}_{1/2} > 2.3 \times 10^{26}\,\mathrm{yr}$$

arXiv: 2203.02139

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

The goal of the A01 program is achieved ahead of schedule.

- Geoneutrino measurement has been updated with 8 years of low reactor data.

183^{+29}_{-28} events observed with 8.3σ significance.

Model discrimination has started.

Fully radiogenic model excluded at 5.2σ.

High-Q model disfavored at 99.76% CL.

The progress is beyond the goal of the A01 program.

This work was supported by Grant-in-Aid for Scientific Research on Innovative Areas,
"Unraveling the History of the Universe and Matter Evolution with Underground Physics."

Thank you!