Current Status and Future Prospects of the KamLAND-Zen

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ISoNF, Jul. 16th—19th, 2018, Quy Nhon, Vietnam

KamLAND-Zen Collaboration

Mar. 2018, Toyama, Japan

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~50 physicists, 12 institutes. 🇯🇵🇺🇸🇳🇱

Majorana neutrino and Neutrino-less double-beta decay ($0\nu\beta\beta$)

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

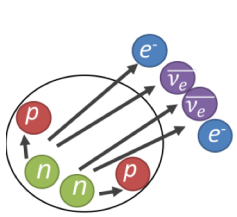
Majorana neutrino is a key to

- ✓ Tiny mass of neutrinos
  - See-saw mechanism*
- ✓ Matter/anti-matter asym.
  - Leptogenesis**

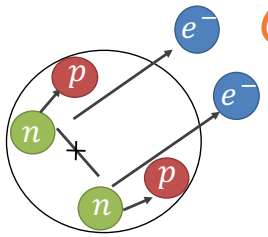
$0\nu\beta\beta$ decay

- Only happens if ν is Majorana
- Lepton# violation

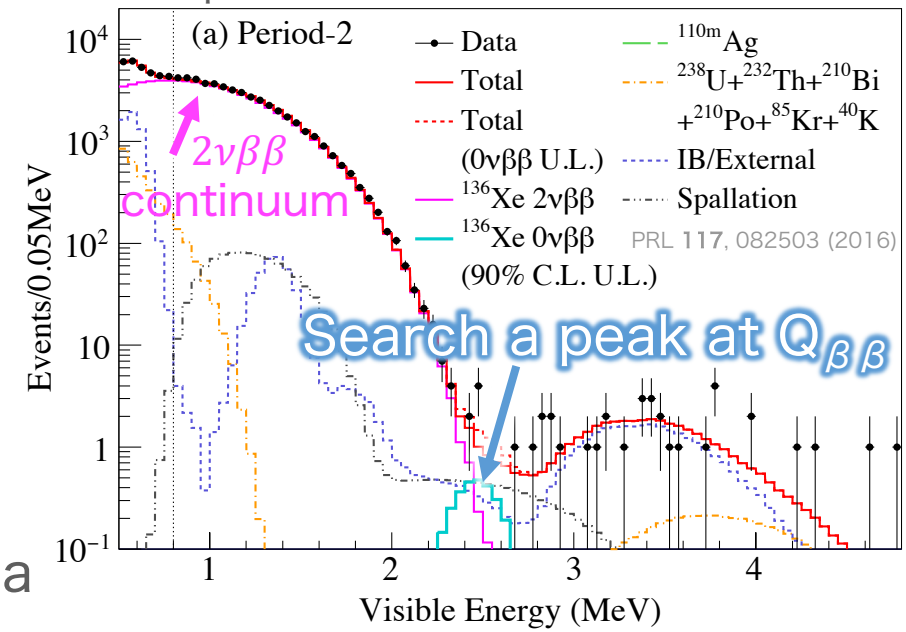
NOT Observed yet



$2\nu\beta\beta$



E spectrum from KamLAND-Zen result



~Summed e^- kinetic energy

Requirement for exp.

- O(100–1000) kg of isotope
- BG reduction at $Q_{\beta\beta}$
- Better energy resolution

*M. Gell-Mann, P. Ramond, R. Slansky ('79), T. Yanagida ('79),R. N. Mohapatra, G. Senjanovic ('80), **M. Fukugita, T. Yanagida ('86)

Effective Majorana mass

Convert half life
to effective Majorana mass

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

Current limit
$>10^{26}$ yr

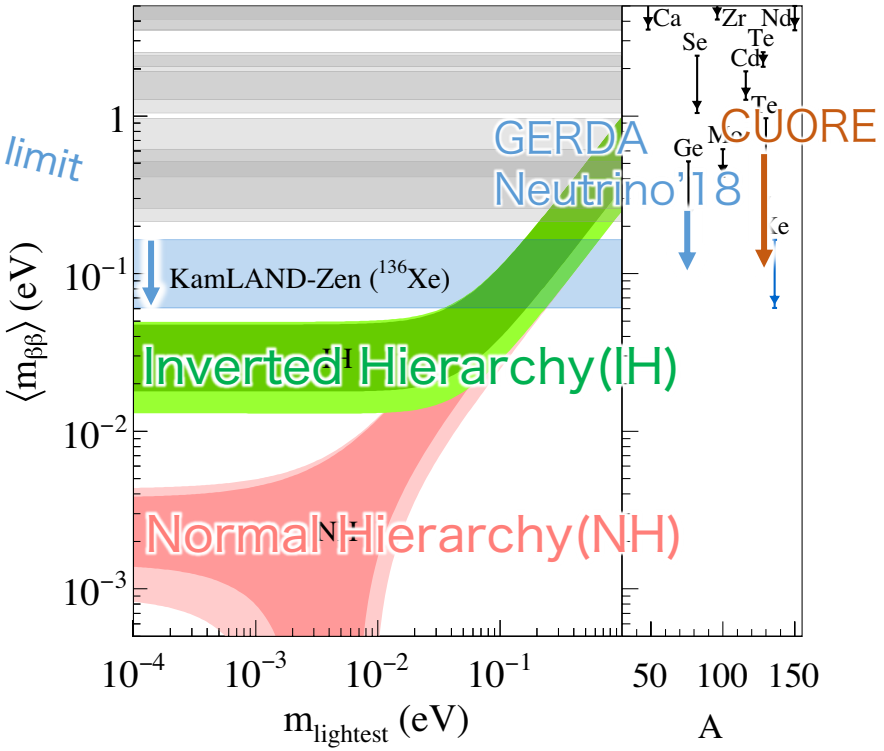
G : Phase space factor
M : Nuclear matrix element

$$\langle m_{\beta\beta}\rangle \equiv \left|\sum_i U_{ei}^2\, m_i\right|$$

U : PMNS matrix
m_i : neutrino mass eigenvalue

Hint of absolute mass scale

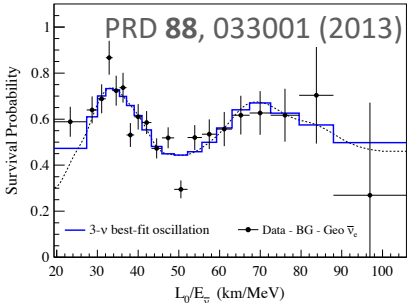
Allowed region limited by
oscillation parameters

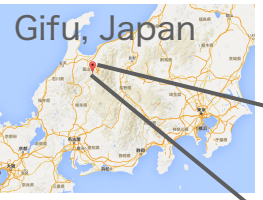


PRL 117, 082503 (2016)
PRL 120, 132501 (2018)

KamLAND

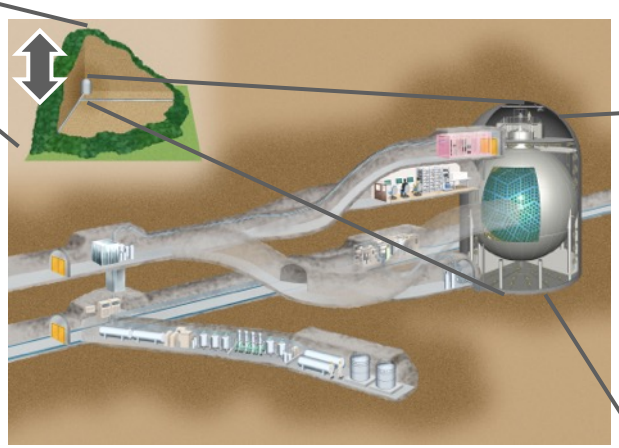
Kamioka Liquid scintillator Anti-Neutrino Detector Since 2002





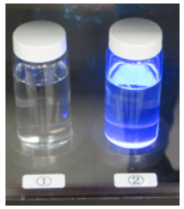
2700 m.w.e
μ flux 1/100k of surface level

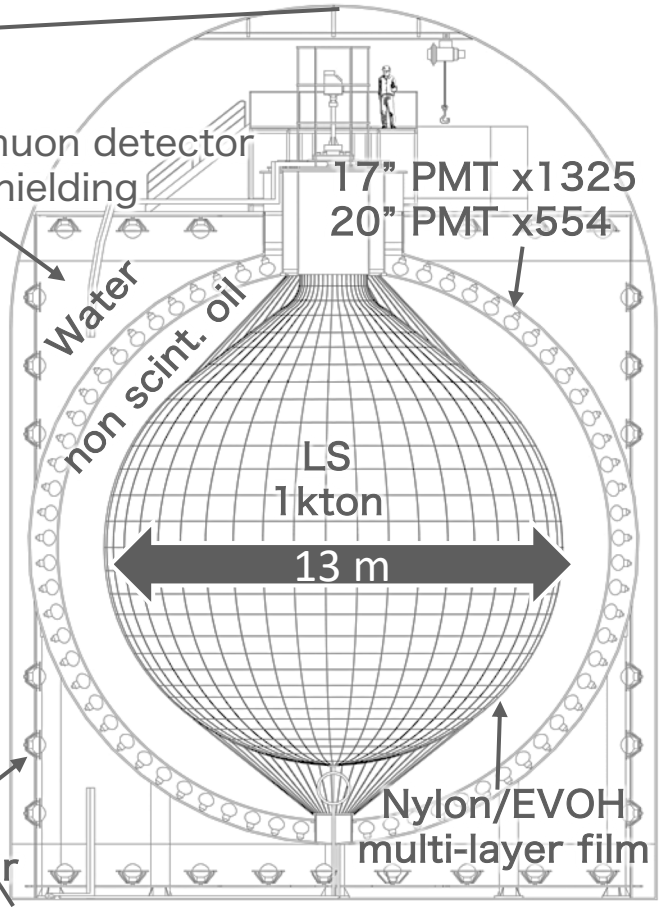
~180 km from reactors



20 m

Outer detector
- Cherenkov muon detector
- external γ shielding

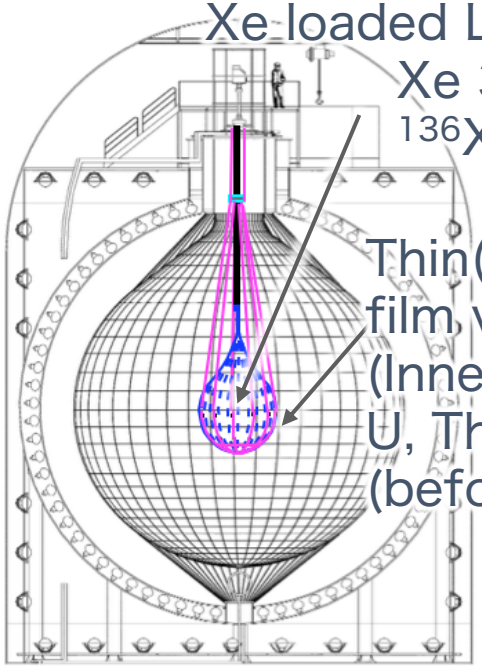




- Ultra pure liquid scintillator(LS)
  ^{238}U: O(10^{-18}) g/g, ^{232}Th: O(10^{-17}) g/g
- Energy res.: $\sigma = 6.4\%/\sqrt{E(MeV)}$
- Vertex res.: $\sigma = 12\ cm/\sqrt{E(MeV)}$

KamLAND-Zen

Zero-neutrino double-beta decay search



Isotope:^{136}Xe

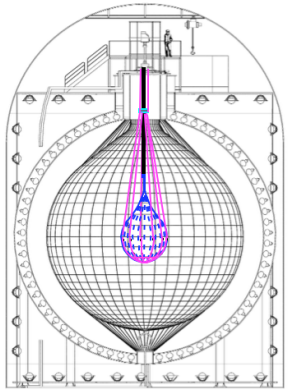
- Dissolve into LS (3 w%).
- On/off measurement.
- Easy to purify.

$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2e^{-}$$

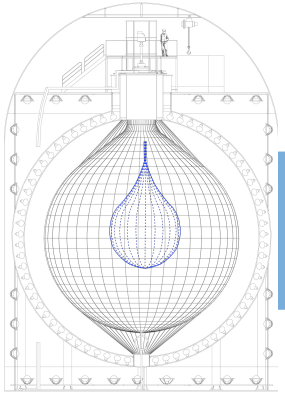
$$\mathrm{Q} = 2.46\ \mathrm{MeV}$$

Pros of using KamLAND

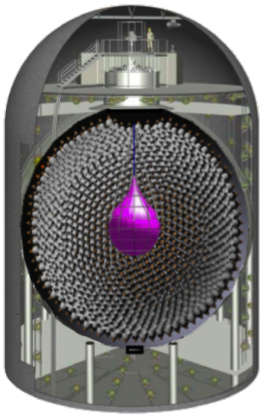
- Already running, quick start.
- Large mass & Scalable
- Low BG
- Active veto with Outer-LS



Zen400
380 kg_{Xe}
'11—'15



Zen800
750 kg_{Xe}
NOW



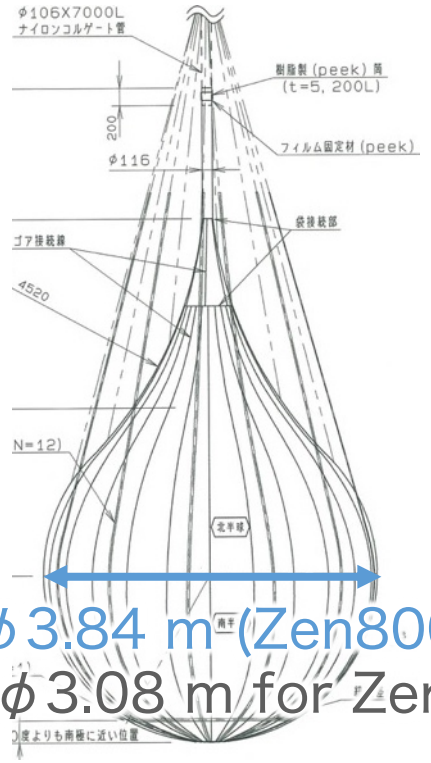
2-Zen
1000 kg_{Xe}
Future

KamLAND-Zen 400 KamLAND-Zen 800 KamLAND2-Zen

Inner Balloon (IB)

*production details
to be explained later

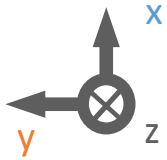
Tube
Cone
Gore
Polar



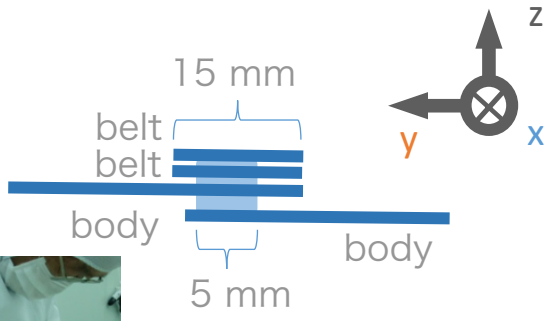
φ 3.84 m (Zen800)
(φ 3.08 m for Zen400)

Weld 24 gores

…



- Tension of stable running ~1 N/cm
- Strength requirement 10 N/cm (safety factor of 10)



4-layer welding

KamLAND-Zen 400 (completed)

Zen400 history

IB installation to KamLAND

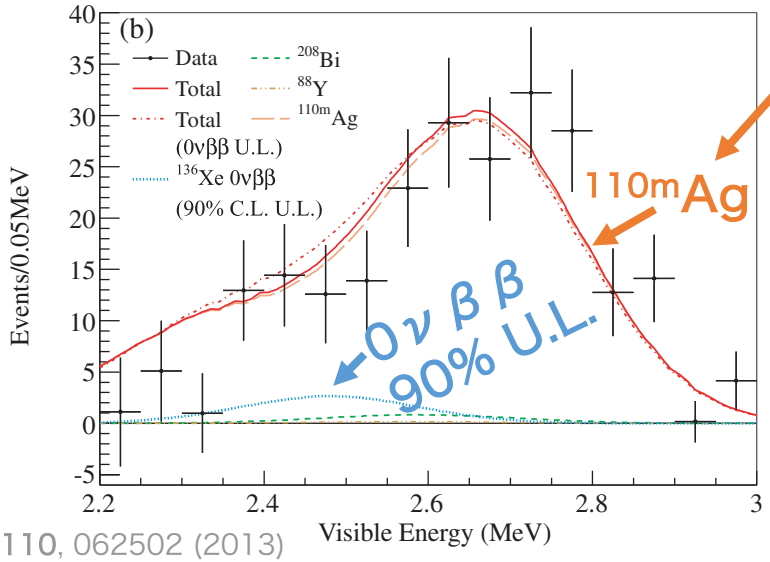
Purification

IB withdrawal

1st phase

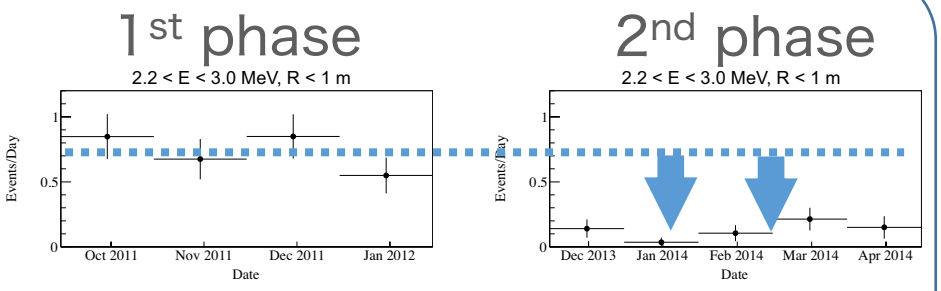
2nd phase

Source calibration



PRL 110, 062502 (2013)

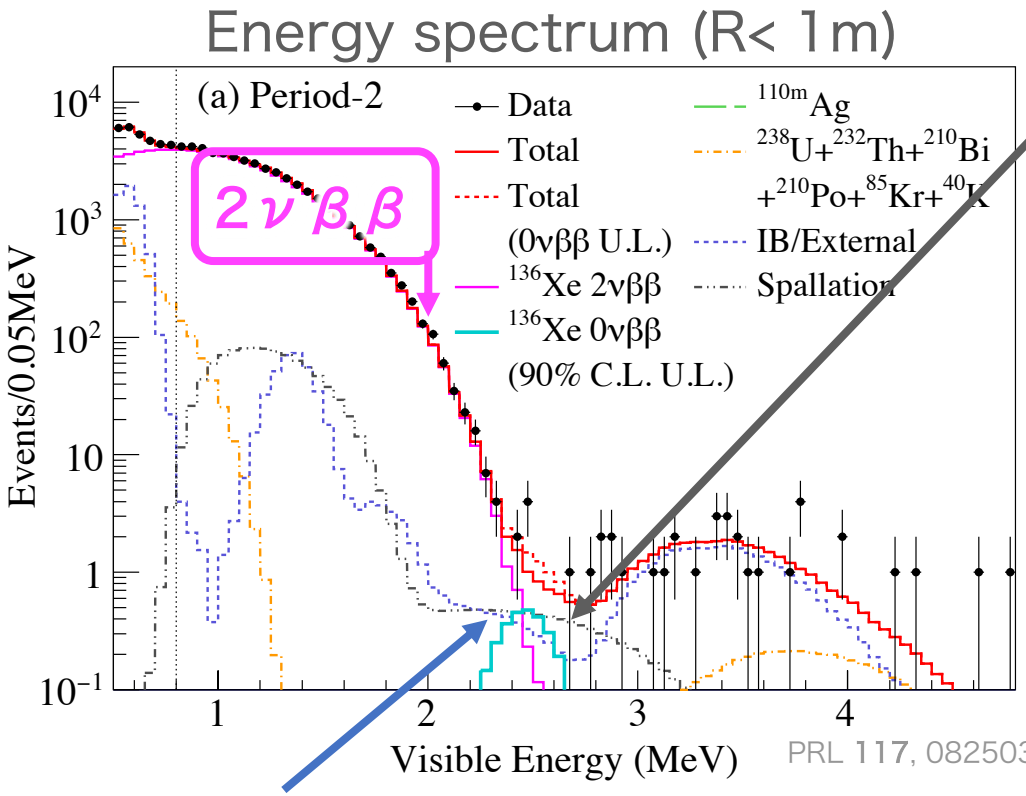
In the 1st phase, ROI was dominated by ^{110m}Ag



Event rate reduced

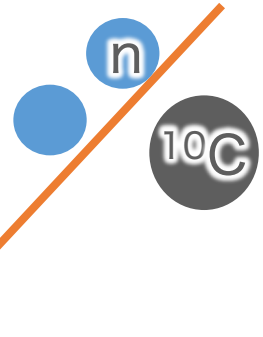
S. Matsuda, Ph. D thesis (2016)

Phase II spectrum and BGs



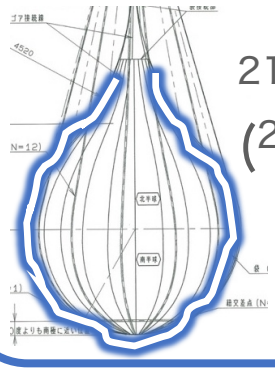
PRL 117, 082503 (2016)

Muon spallation



τ = 28 s
Q = 3.7 MeV

- (μ,n,^{10}C) 3-fold tag.
  - Eff. 64+/-4%
  - Livetime loss 7%



^{214}Bi from film
(^{238}U daughter)

$2\nu\beta\beta$ measurement result

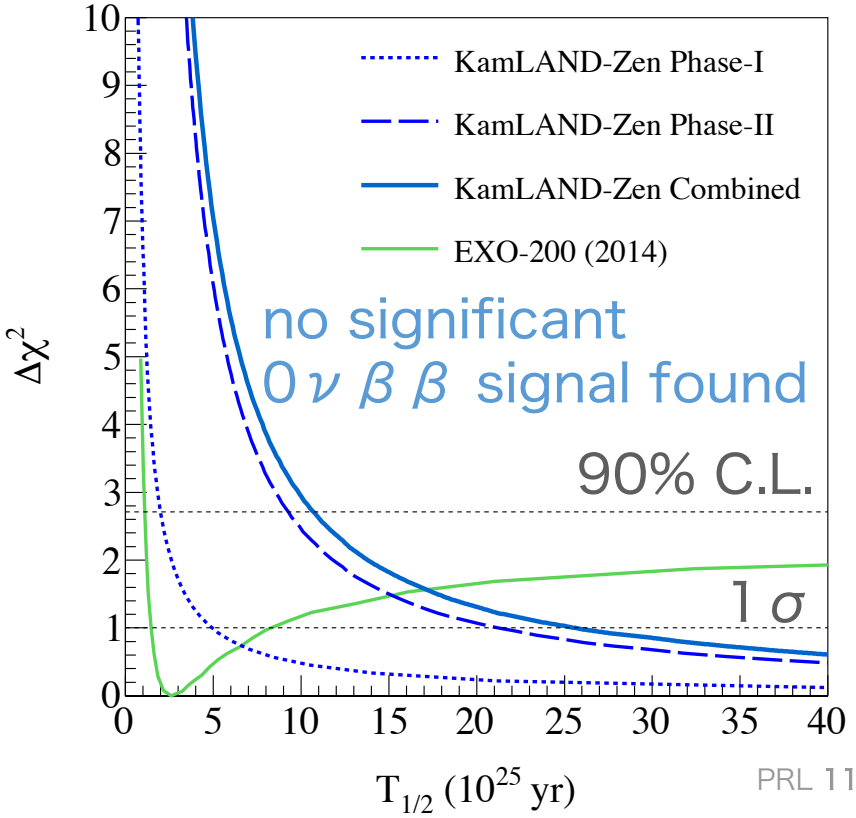
$$T_{2\nu}^{1/2} = 2.21 \pm 0.02(\text{stat.}) \pm 0.07(\text{syst.})(10^{21}\text{yr})$$

- ^{136}Xe exposure = 126 kg*yr
- Consistent with EXO-200 results*

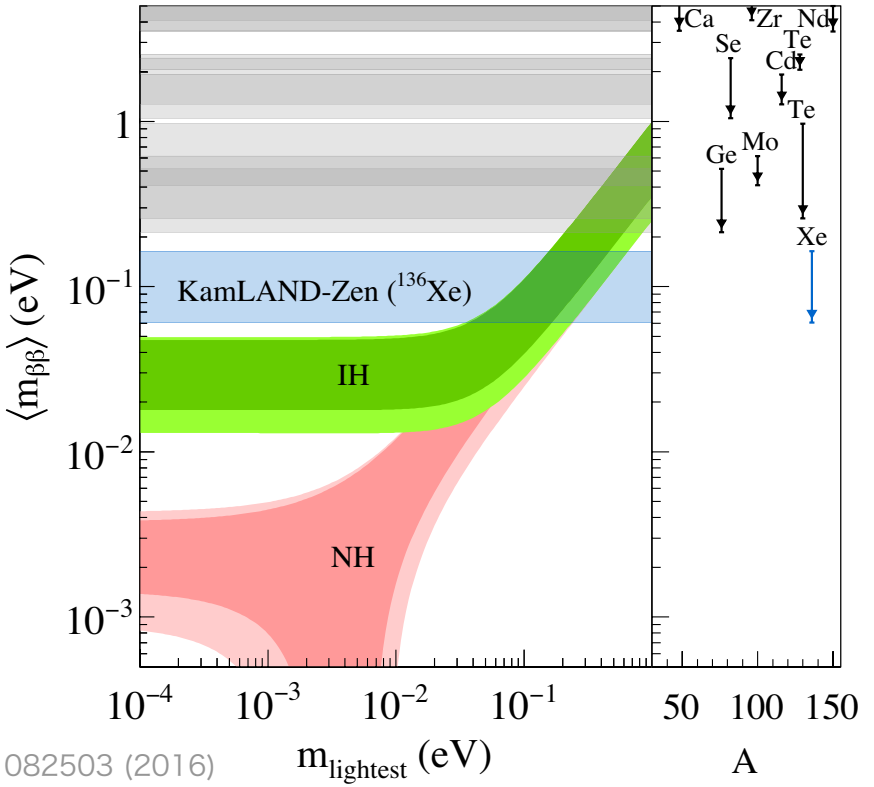
*PRC **89**, 015502 (2014)

$0\nu\beta\beta$ search results

Half-life limit



Limit on Majorana eff. mass



PRL 117, 082503 (2016)

Phase-I: $T_{1/2} > 1.9\times10^{25}$ yr

Phase-II: $T_{1/2} > 9.2\times10^{25}$ yr

Combined: $T_{1/2} > 1.07\times10^{26}$ yr

*90% C.L.

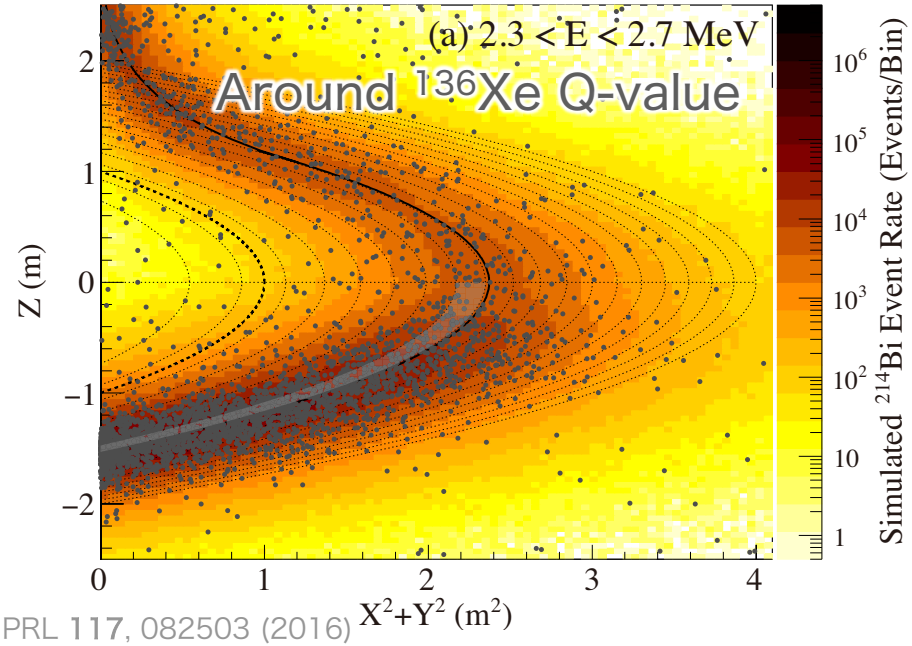
g_A~1.27 assumed

$\langle m_{\beta\beta}\rangle < 61—165$ meV

most stringent limit so far

KamLAND-Zen 800 (in preparation)

Problem of Zen400



PRL 117, 082503 (2016)

Comparison btw. Zen400 2nd phase data and ^{214}Bi(MC) vertex distribution

RI in/on film

	^{238}U (10^{-12}g/g_{film})	^{232}Th (10^{-12}g/g_{film})
Initial	2	6
Zen 400 1st	14+-1	79+-3
Zen 400 2nd	46.1+-4	336+-2

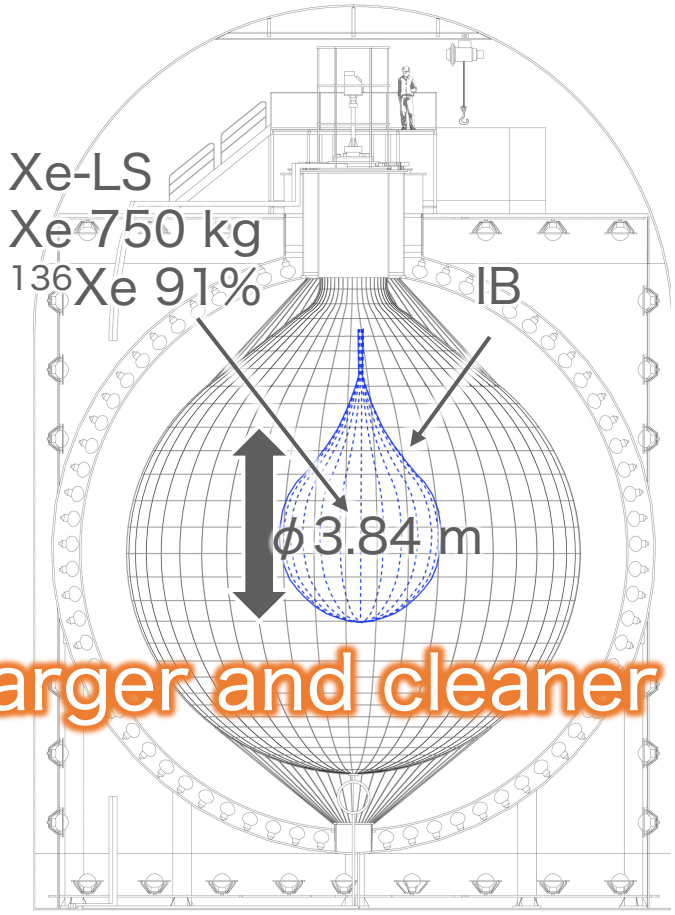
x7

Pump failure

- **IB was contaminated.**
- Fiducial vol. ratio at 2nd phase ~43%* (150 kg_{Xe})

*S. Matsuda, Tohoku U., Ph. D thesis (2016). Whole volume was binned and simultaneously analyzed at final result of 2nd phase.

KamLAND-Zen 800

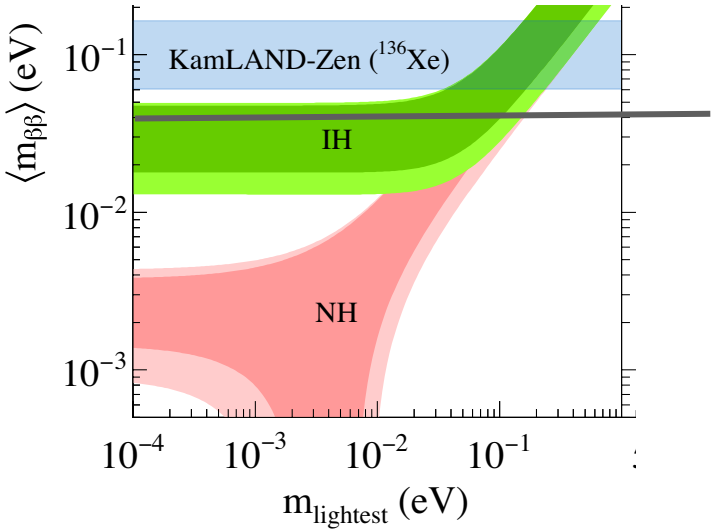


Larger and cleaner IB

- Double Xe amount.
- Triple the fiducial volume of 2nd phase of Zen400

RI in/on film

	^{238}U (10^{-12}g/g$_{film}$)	^{232}Th (10^{-12}g/g$_{film}$)
Initial	2 (Target!!)	6
Zen 400 1st	14+-1	79+-3
Zen 400 2nd	46.1+-4	336+-2



Enter into IH region
Aiming $\langle m_{\beta\beta} \rangle$ ~ 40 meV

Toward a Cleaner IB Production

- **Clean wears**

Clean inners adopted

Change-room shared with other labs (changing done only here at Zen400)

Change again in change-room in clean room

Goggle

Wash hands frequently

Suits go to laundry after one-time-use

laundry twice a day

- **Covering film**

Cut with covers.
Strip edge when welding.

Misc.

- Clean clean-room
- Clean tools
- More neutralizers
- **Semi-auto welding**

Semi-auto welding

Zen400

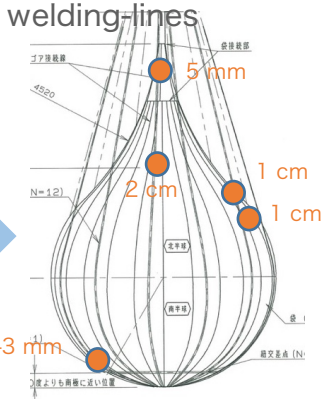
Zen800

- Hand-welding by a professional from a company

- Semi-auto welding
  - speed up
  - stay away, less dust.

Zen800 history & schedule

*all at the edges of welding-lines



’15Q2 | ’15Q3 | ’15Q4 | ’16Q1 | ’16Q2 | ’16Q3 | ’16Q4

IB production.

Suspension due to low humidity

Continued.

Failed800

suspected cause: mistakenly applied pressure during installation work.

Zen400 IB removal.

Xe purification.

IB installation to KamLAND.

Leakage from IB confirmed. Removal.

*before Xe-loading.

’17Q1 | ’17Q2 | ’17Q3 | ’17Q4 | ’18Q1 | ’18Q2 | ’18Q3 | ’18Q4

IB re-production.

NOW

IB installation to KamLAND.

Start phys. run

LS purification. Xe dissolving.

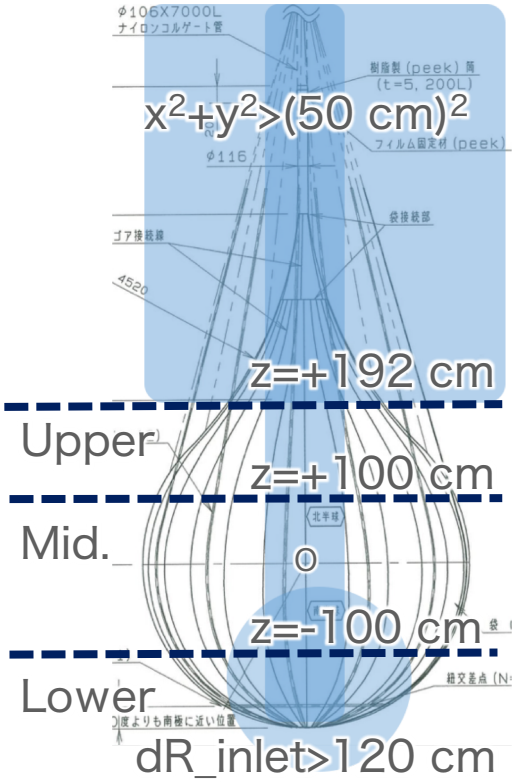
Results from Failed800

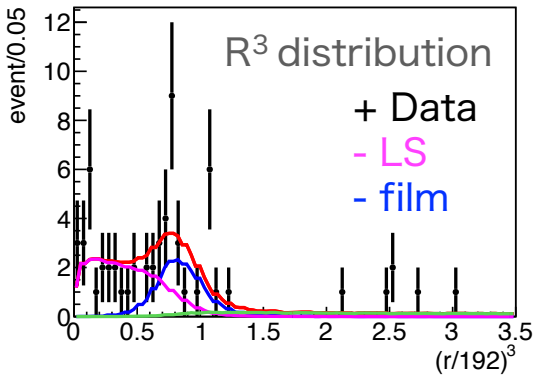
PRELIMINARY

	$^{232}Th(10^{-12}g/g_{film})$	$^{238}U(10^{-12}g/g_{film})$
Upper	49+-11	9.3+-1.9
Mid.	18+-9.4	3.1+-0.8
Lower	52+-14	7.7+-2.5

	$^{232}Th(10^{-12}g/g_{film})$	$^{238}U(10^{-12}g/g_{film})$
Initial	6	2 Target
This time*	31+-7	5.3+-0.8
Zen 400 1st	79+-3	14+-1
Zen 400 2nd	336+-2	46.1+-4

*Weighted average by film mass





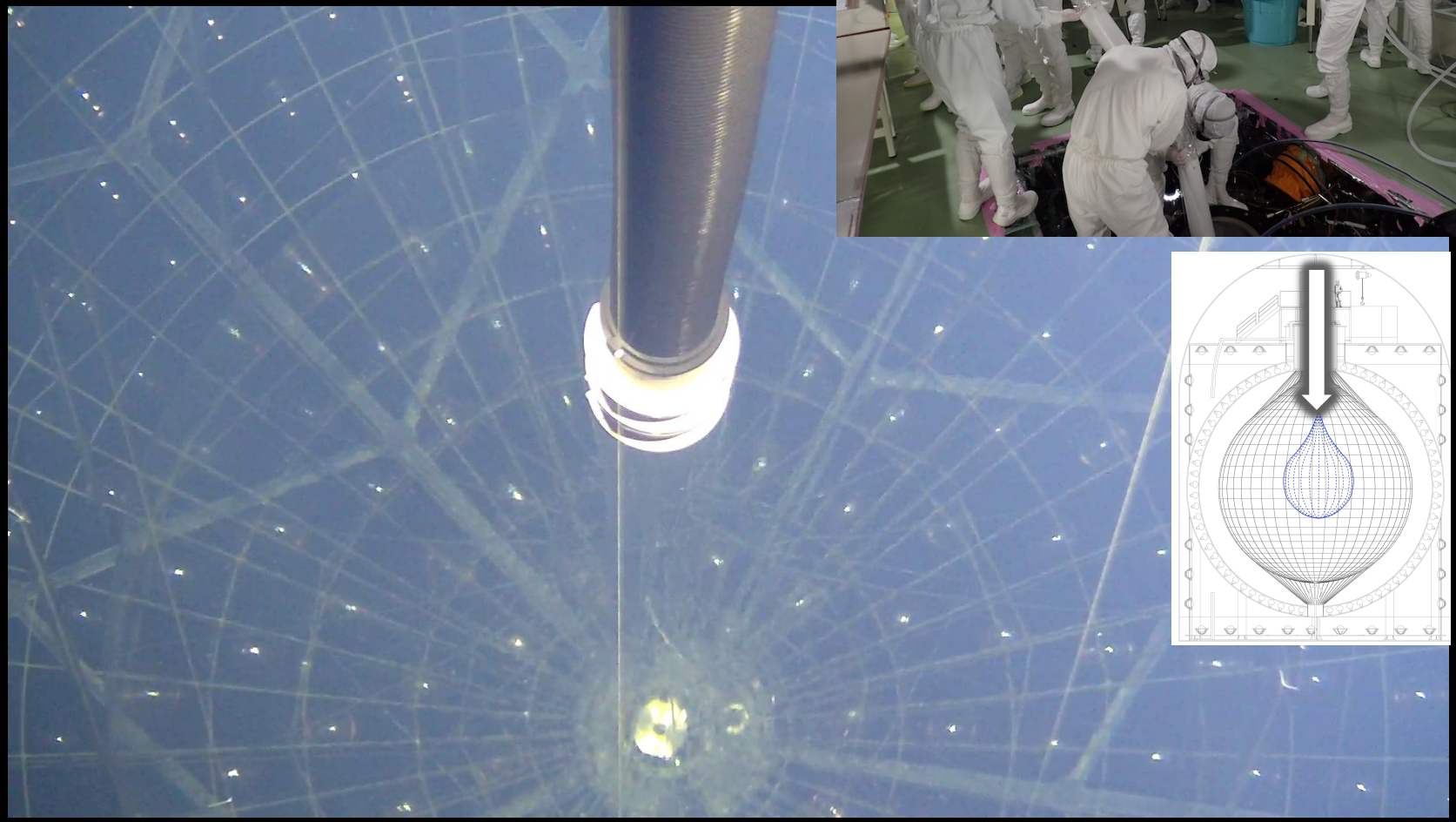
✓ BG reduction was confirmed!!

- $^{238}U_{Mid}$ close to initial.
- 1/3 reduction from Zen400**

**1/9 from 2nd phase

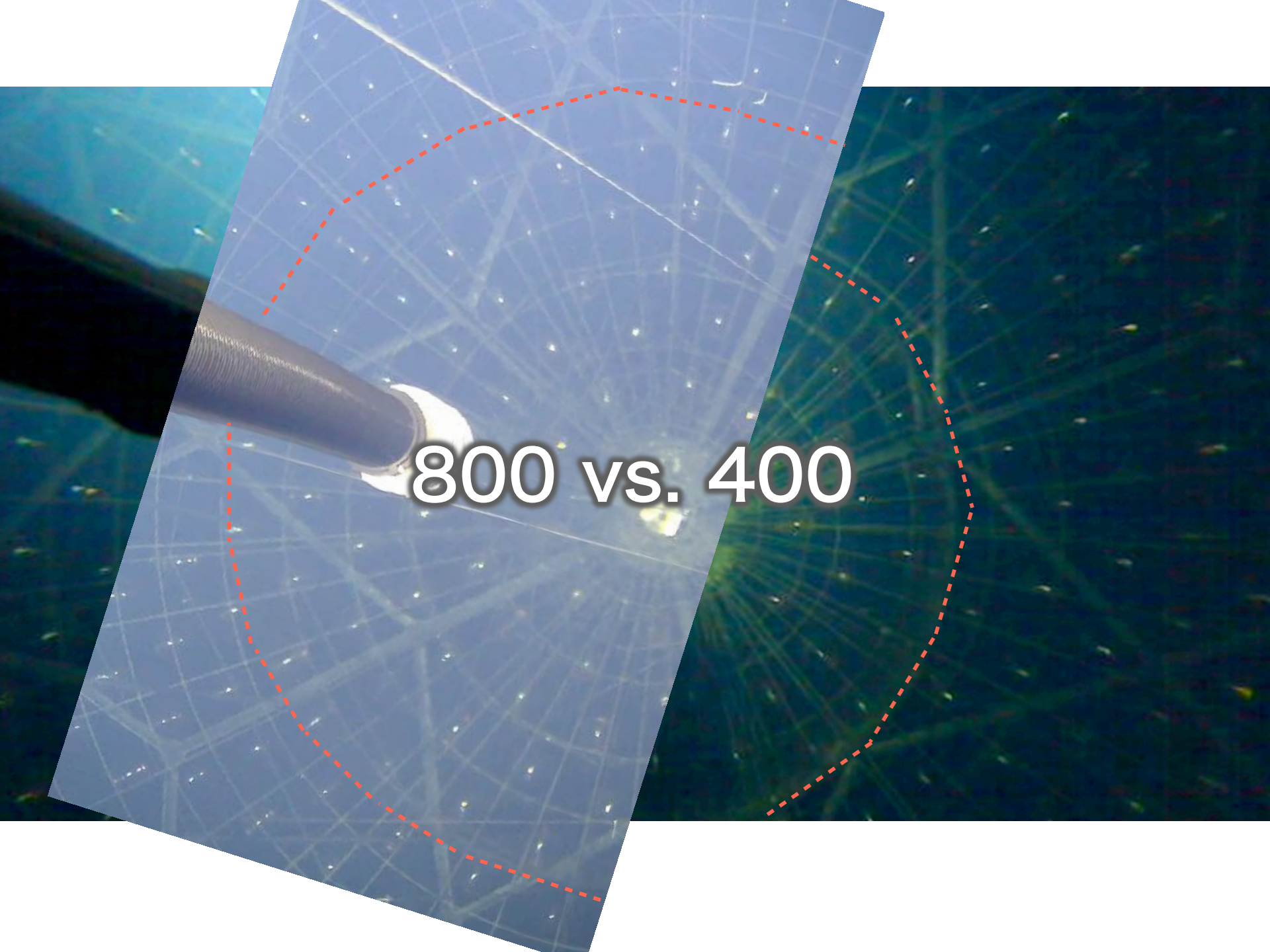
IB re-production 2017—2018

New Zen800 IB

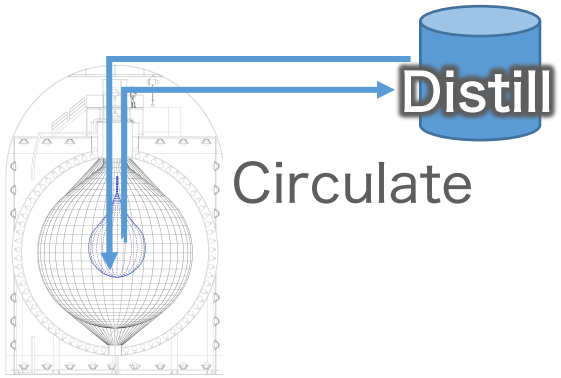


Finished expansion by filling Xe-less LS on May 19th

Simulation


800 vs. 400

Now purifying LS



^{232}Th daughters

^{212}Bi ➡ ^{212}Po ➡ ^{208}Pb

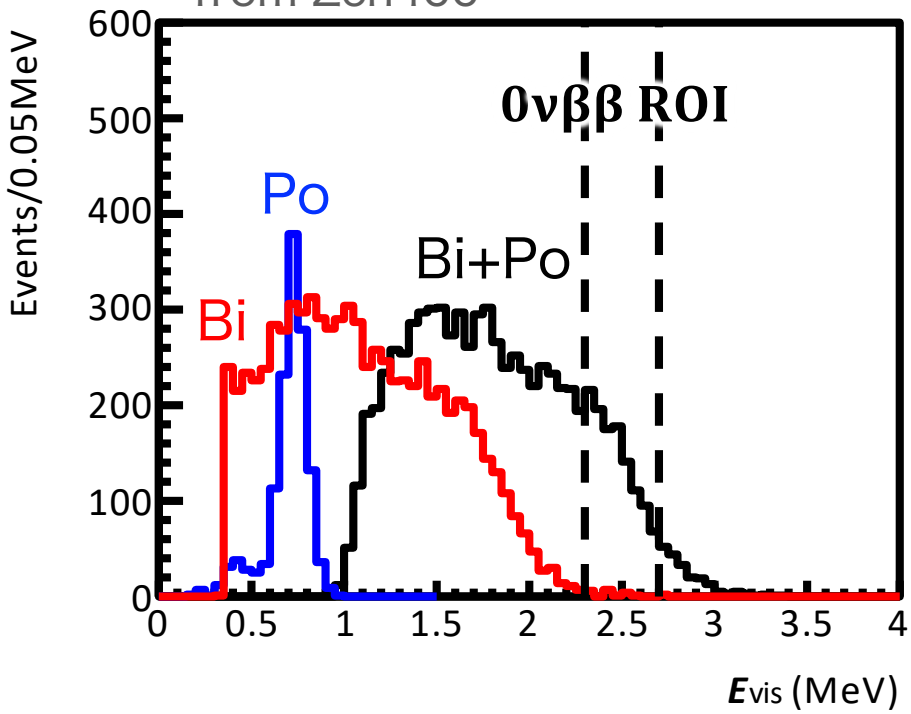
β α

τ 430 ns

~event window

→ Pileup

Energy spectra of tagged Bi&Po from Zen400



^{232}Th in LS

After IB inst. : O(10^{-15})g/g

Aim : O(10^{-16})g/g

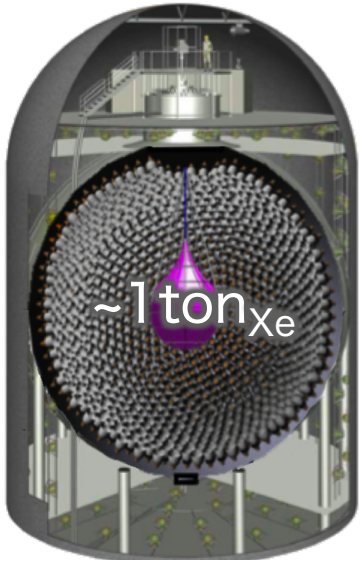
Zen400 2nd : 5.9x10^{-17} g/g

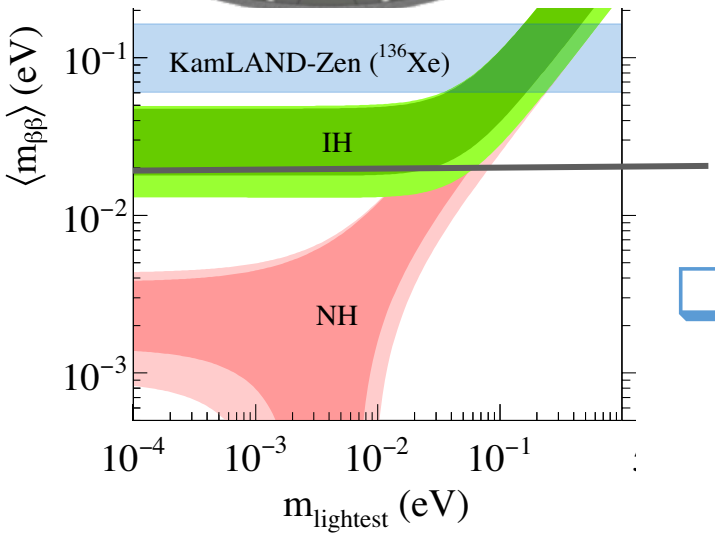
After purification, continue to

- Xe loading
- Physics run starts in this year

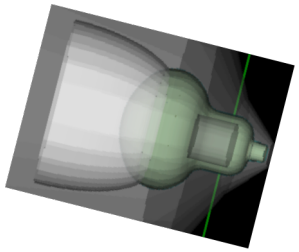
KamLAND2-Zen (future)

KamLAND2-Zen





- Improve energy resolution to reduce $2\nu\beta\beta$ BG.
  - Target $\sigma = 2.5\%$ at 2.5 MeV
- >x5 light yield than now
  - (x1.4) New LS
    - brighter
    - more transparent
  - (x1.8) Light collecting mirror
  - (x2.1) High Q.E. 20" PMT
- Cover IH region
  - aiming $\langle m_{\beta\beta} \rangle \sim 20$ meV



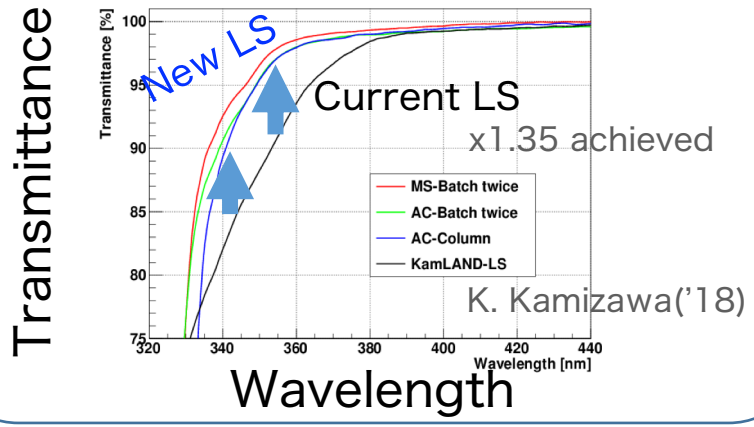
R&Ds

New LS

Linear AlkylBenzene(LAB) base

Purification studies are ongoing.

- For optical: Activated charcoal
- For RI: Metal-scavenger



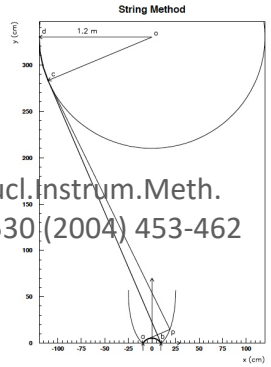
K. Kamizawa('18)

High Q.E. PMT

- Testing
  - Tolerance against high light yield
  - Overshoot and after-pulse

Light collecting mirror

- Design: "String method"
- Material: PET+Al deposition



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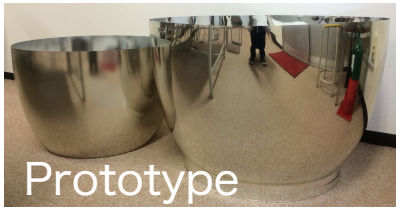

H. Tachibana('15)
A. Hayashi('17)

- Simulation for optimizing arrangement is ongoing.

New electronics (MoGURA2)

- On-board logic for improving neutron tag.
- Developing prototype.

Other options

- Scintillating balloon
- Pressurize by density diff.

Summary

- KamLAND-Zen searches for Majorana neutrino with ^{136}Xe-loaded liquid scintillator.
- Limit on Majorana effective mass from KamLAND-Zen 400 result is the most stringent so far.
- KamLAND-Zen 800 starts this year and expected to enter into IH region.
- KamLAND2-Zen is now in R&D stage aiming to cover IH region.