KamLAND-Zen 800

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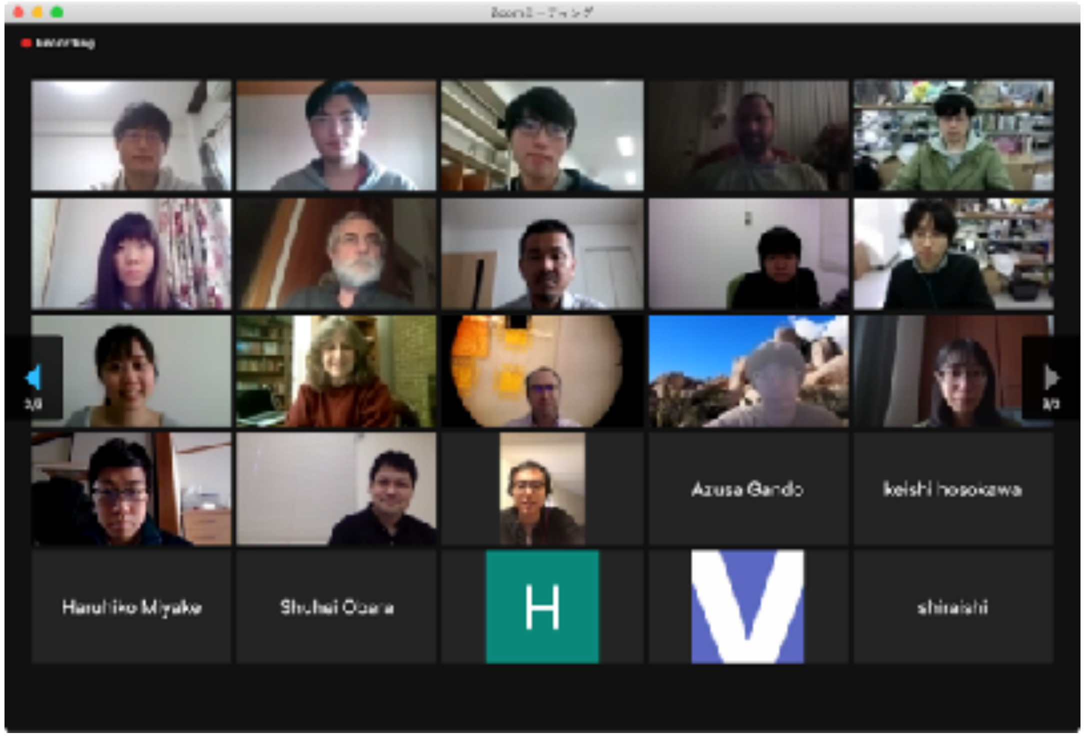
for the KamLAND-Zen Collaboration

XIX International Workshop on Neutrino Telescopes, 2021/02/23

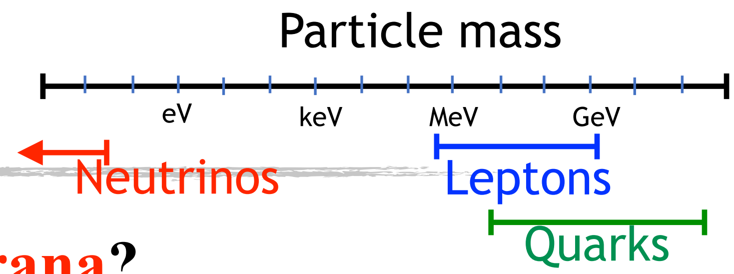
KamLAND-Zen Collaboration

KamLAND collaboration meeting in October 2020



KamLAND-Zen collaboration
~60 researchers
~20 institutions

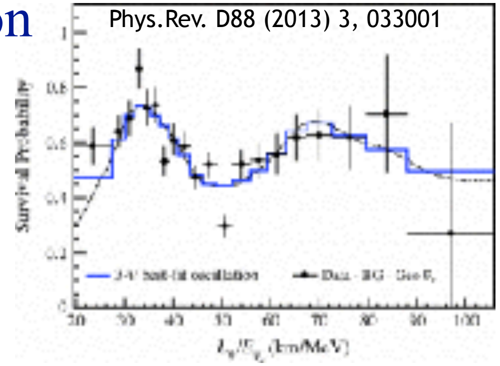
Majorana neutrinos



Neutrino oscillation

$m\nu \neq 0$

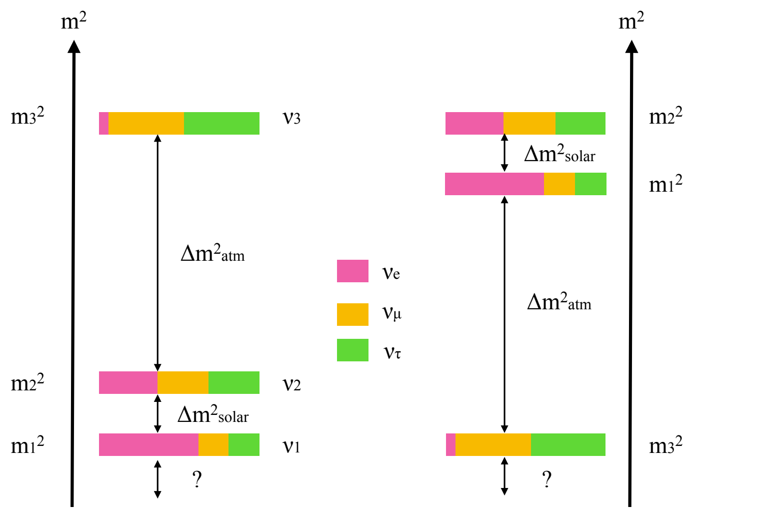
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{\rm PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Δm^2 ,θ SK, SNO, KamLAND, etc **δCP T2K, NOνA**

Neutrino mass hierarchy

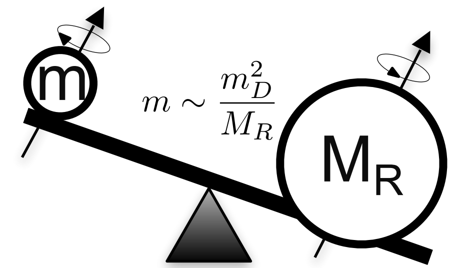
$\Delta m^2_{atm} \sim 2.5\times10^{-3} eV^2$, $\Delta m^2_{solar} \sim 7.4\times10^{-5} eV^2$



Normal hierarchy Inverted hierarchy

Dirac or Majorana?

If Majorana neutrinos exist

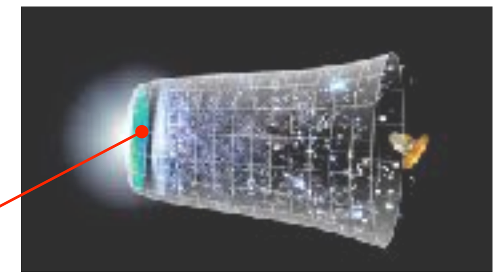


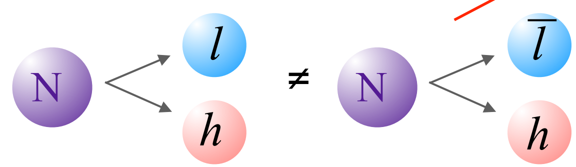
Seesaw mechanism

Extremely small neutrino mass

Leptogenesis

Matter dominant universe



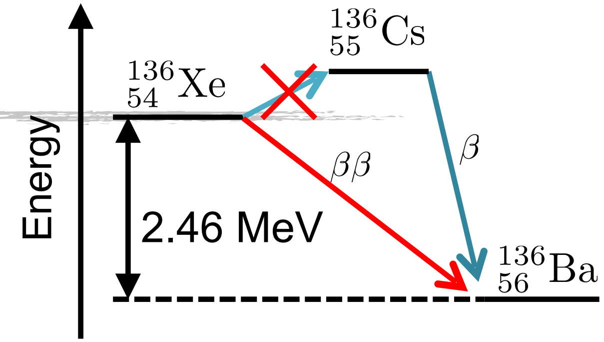


ΔL≠0

How to find Majorana nature of neutrinos

-> Neutrinoless Double-Beta Decay(0νββ)

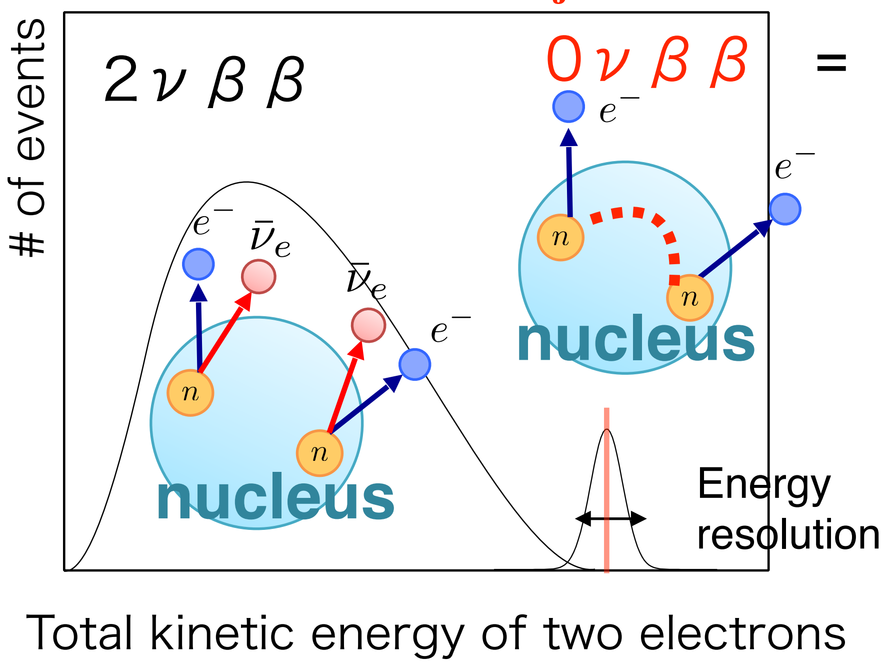
Neutrinoless Double-Beta Decay



Double-Beta Decay

Half-life O($10^{18\text{-}24}$) years (^{48}Ca, ^{76}Ge, ^{130}Te, ^{136}Xe etc.)

If Majorana neutrinos

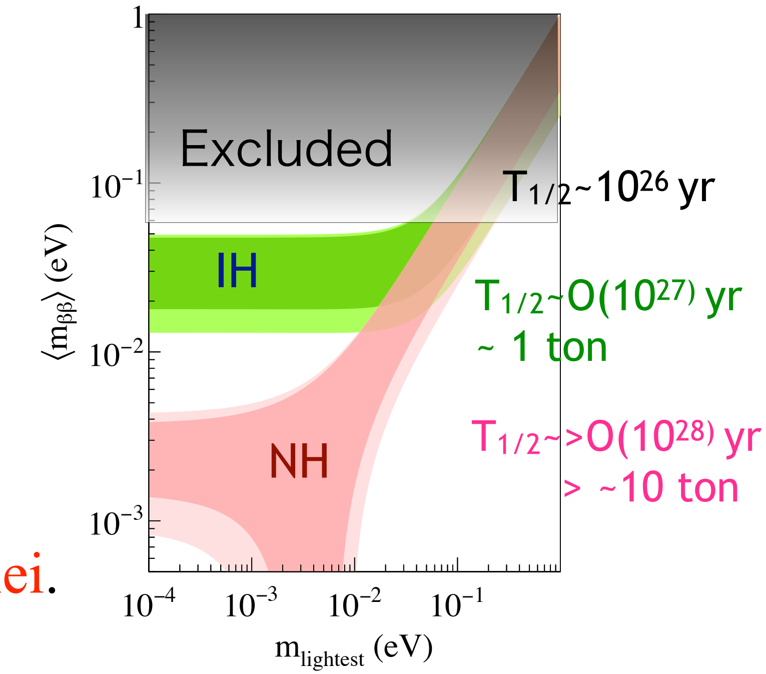


0νββ = Lepton number violating process

Effective Majorana mass

Observable -> $(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(g_{A,\mathrm{eff}}/g_A)^4|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$

$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

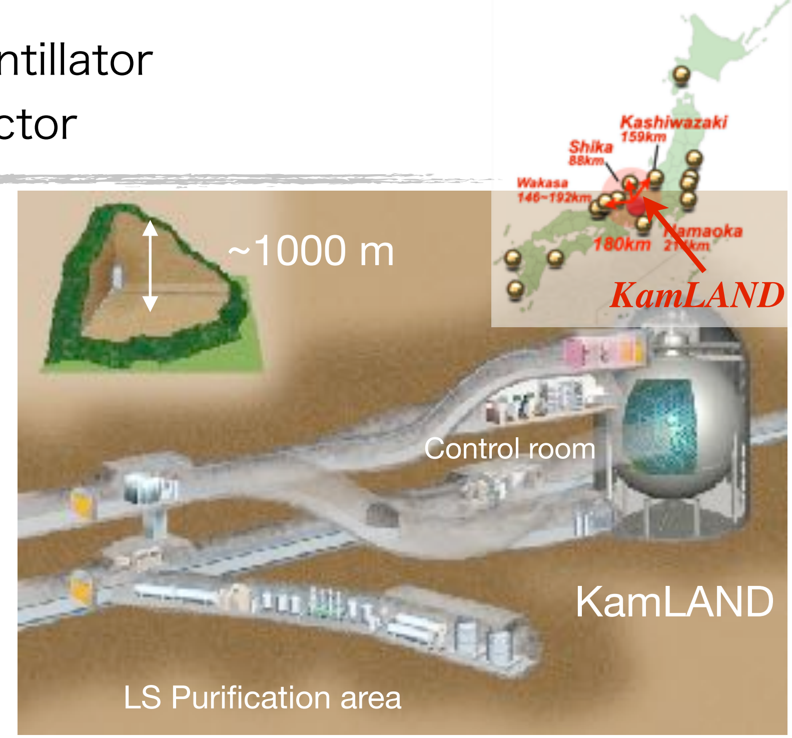


What is important is to construct an ultra-low background detector and to monitor a large number of 0νββ decaying nuclei.

KamLAND

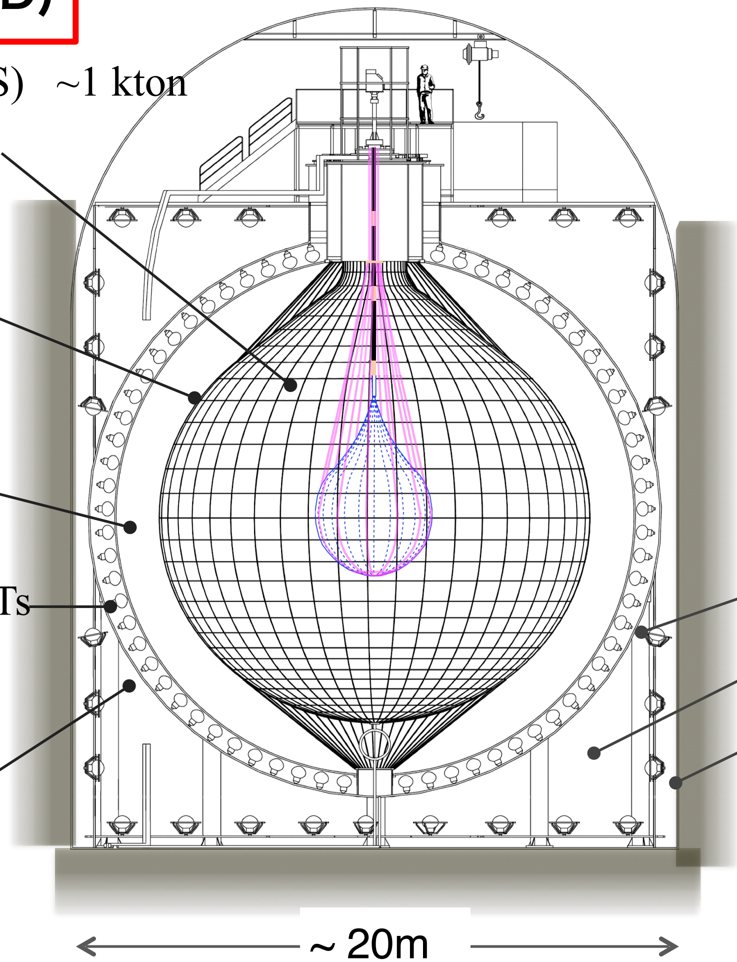
Kamioka Liquid Scintillator
Anti-Neutrino Detector

Located underground near Kamioka in Japan ~1,000 m (2,700 m w.e.)



Inner detector (ID)

- Liquid scintillator (LS) ~1 kton
  - Decane ~ 80%
  - Pseudo-cumene ~20%
  - PPO 1.36 g/l
- 13 m-diameter outer balloon
- Non-scintillating buffer oil
- 1325 B&L17-inch PMTs
  554 SK(Kamiokande) 20-inch PMTs
- 18 m-diameter stainless tank



Water Cherenkov Outer Detector(OD)

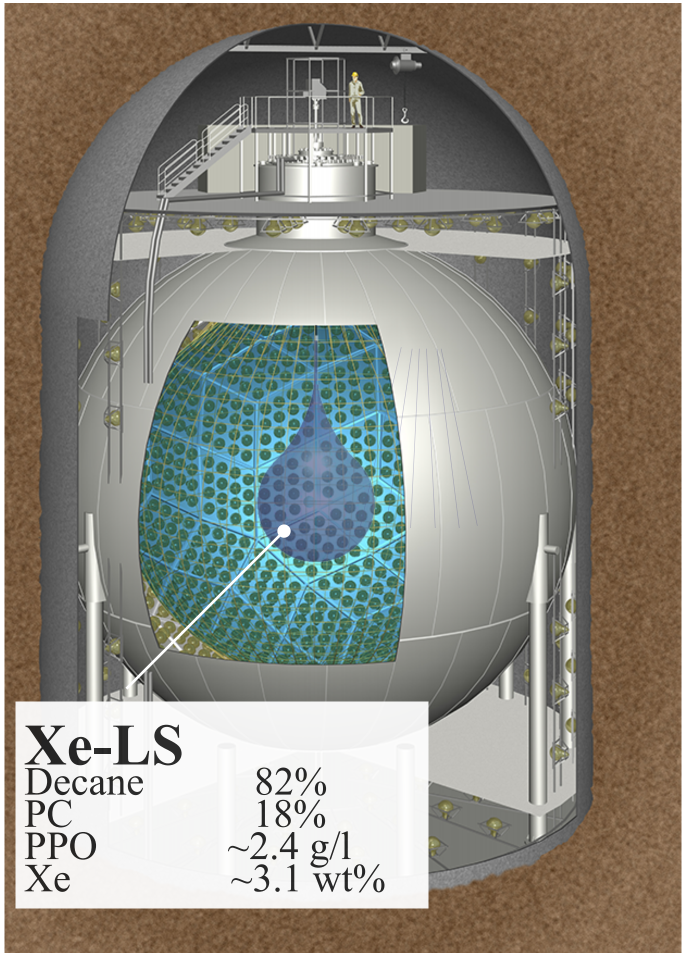
Refurbished in 2016

- 140 SK type 20-inch PMTs
- ~ 3.2 kton pure water
- Tyvek sheets for high reflectivity

Photo coverage ~34%
~ 400 p.e. / MeV
ΔE ~7%/√MeV @2020

KamLAND-Zen

Zero neutrino double beta decay search, Xenon



Inner-balloon (IB)

Zen 400 ~3.0 m-diameter V=16.7 m^3

Zen 800 ~3.8 m-diameter V=30.5 m^3

×2 larger

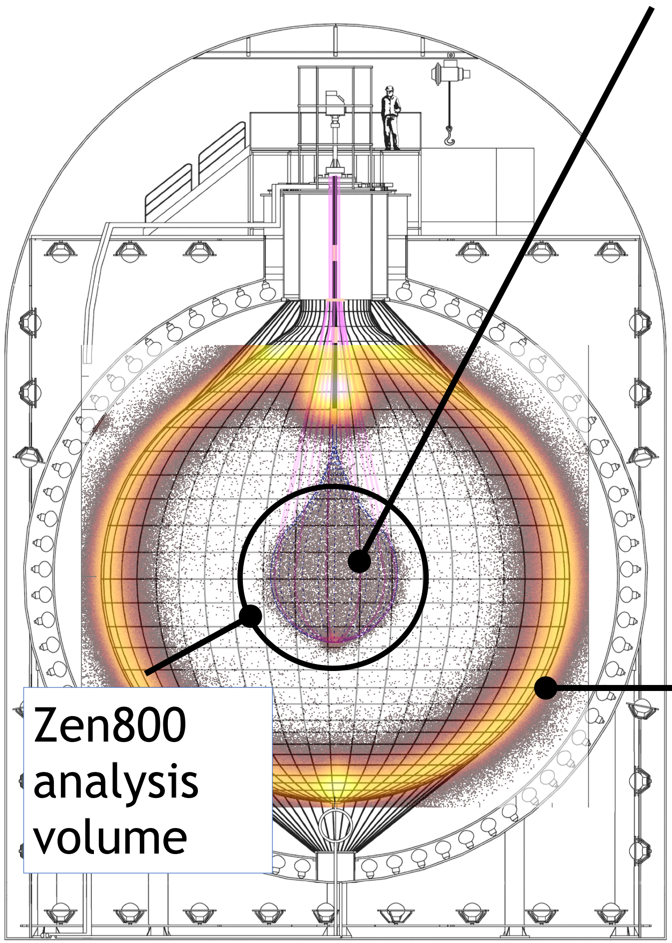
KamLAND + Xe

- KamLAND **Ultra-low BG detector**
  - Low radioactivity $^{238}U \sim 5.0\times10^{-18}$ g/g, $^{232}Th \sim 1.3\times10^{-17}$ g/g
  - Cosmic-ray muon ~ 0.2 Hz
  - Active shielding

- **Xenon**
  - Chemically stable noble gas
  - Solubility: Xe-LS ~3 wt%
  - Large mass&enrichment 745±3 kg of ^{136}Xe ~91wt% enriched Xe
  - High Q-value: 2.458MeV (Low BG in KamLAND)
  - Slow ^{136}Xe $2\nu\beta\beta$ decay -> less $2\nu\beta\beta$ tail due to energy resolution

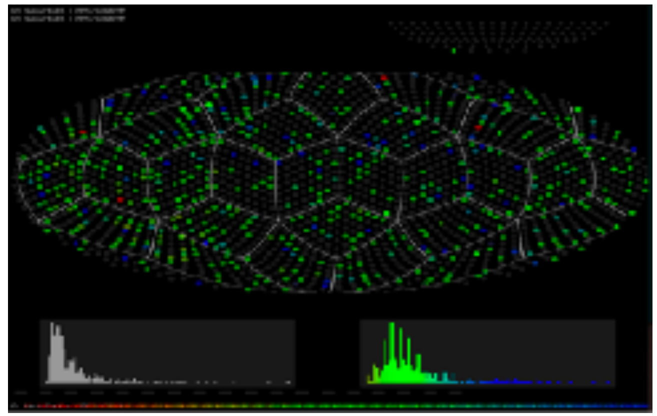
- KamLAND-Zen
  - Scalability
  - ^{136}Xe On-off

Event reconstruction

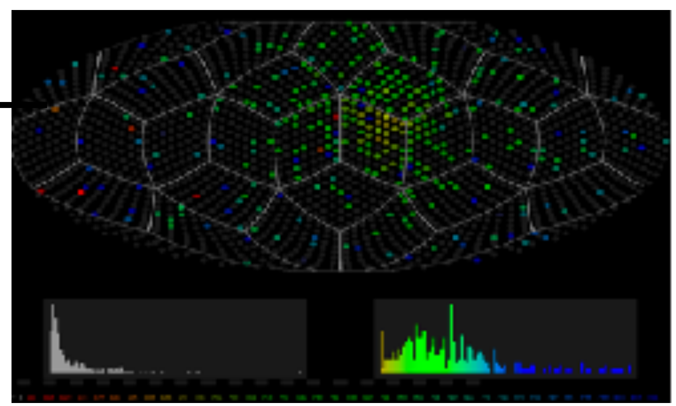


Reconstructed single event positions (1.0 MeV-3.0 MeV)

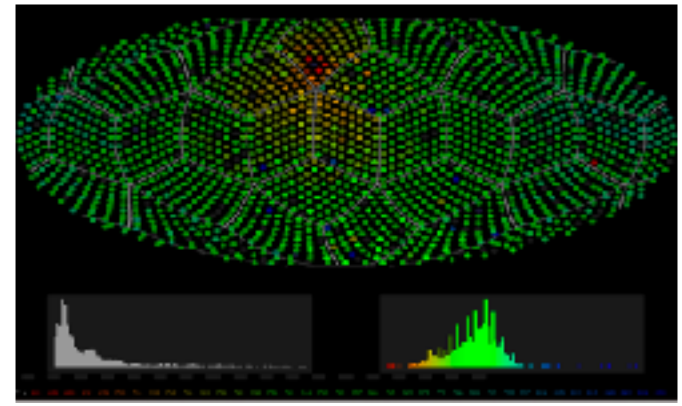
Events in Xe-LS (~2.45 MeV)



Outer-balloon events



Cosmic-ray muon



PMT waveforms

PMT Time&Charge(TQ)

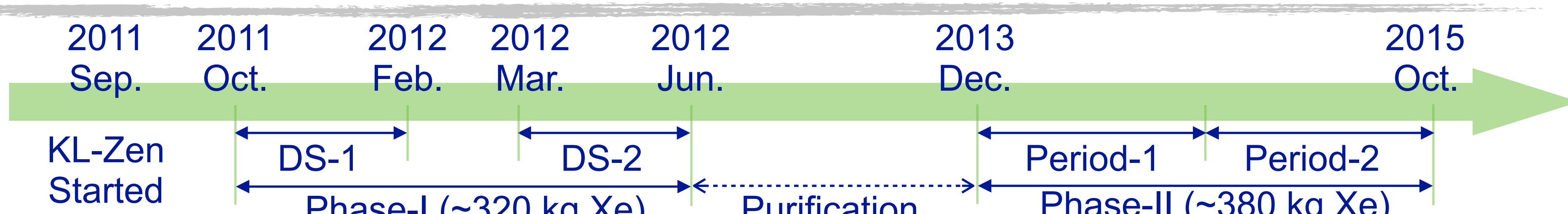
Event vertex&Energy

Calibration sources

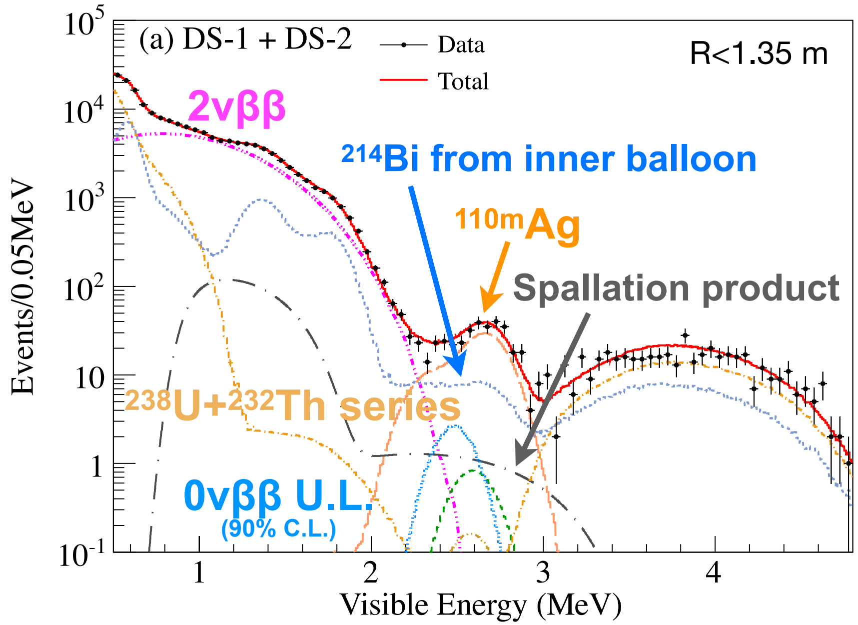
KamLAND: ^{137}Cs ^{68}Ge ^{60}Co composite source, (n,p)γ 2.22 MeV

Zen 800: ^{214}Bi-^{214}Po, (n,p)γ 2.22 MeV 2νββ

History of KamLAND-Zen 400



Phys. Rev. Lett. 110, 062502 (2013) ^{136}Xe 89.5 kg-yr



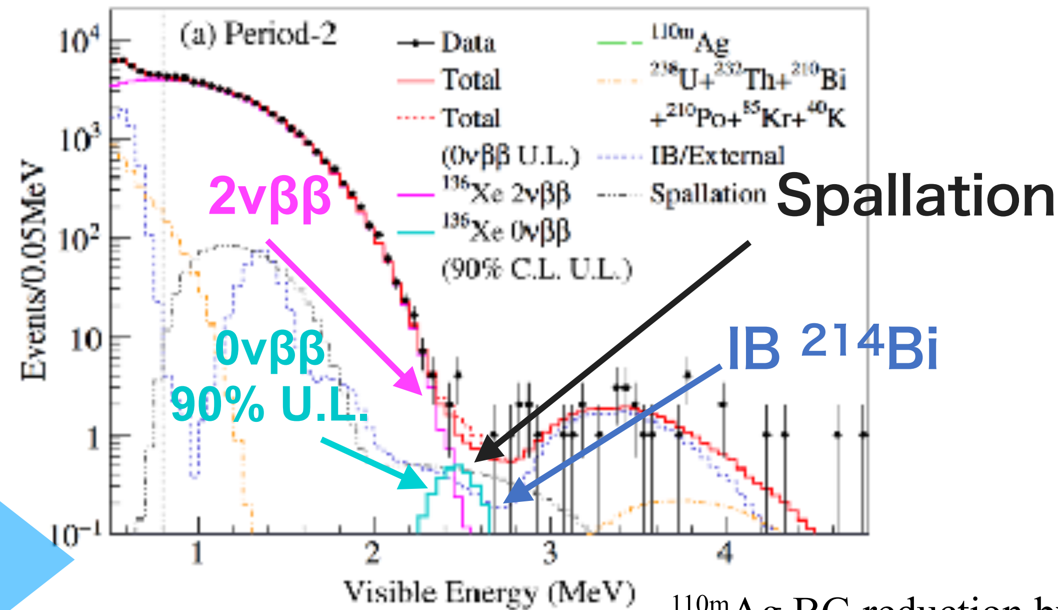
Lower limit for 0νββ in phase I

$T^{1/2} > 1.9\times10^{25}$ yr (90% C.L.)

Unexpected ^{110m}Ag BG

LS and Xe gas purification

Energy spectrum (R < 1m)



0νββ result (only Phase II)

$T^{1/2} > 9.2\times10^{25}$ yr

0νββ result (Phase I+II)

$T^{1/2} > 1.07\times10^{26}$ yr

^{110m}Ag BG reduction by LS and Xe gas purifications.
Very stringent limit

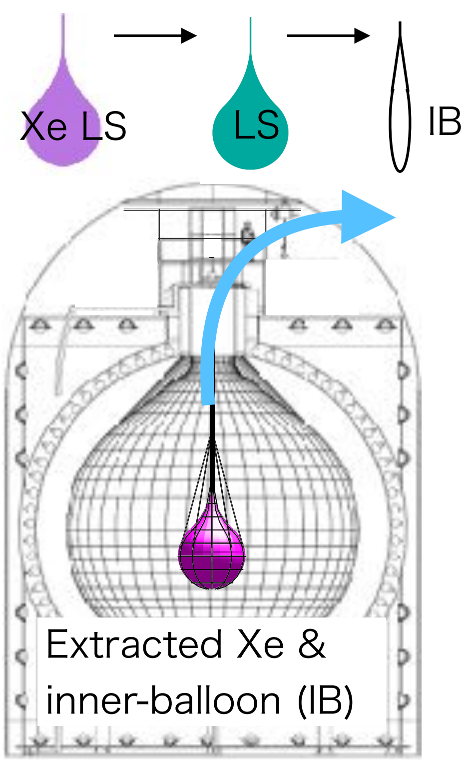
Phys- RevLett.117.082503 (August 2016) pp.1–6.

KamLAND-Zen 800 construction

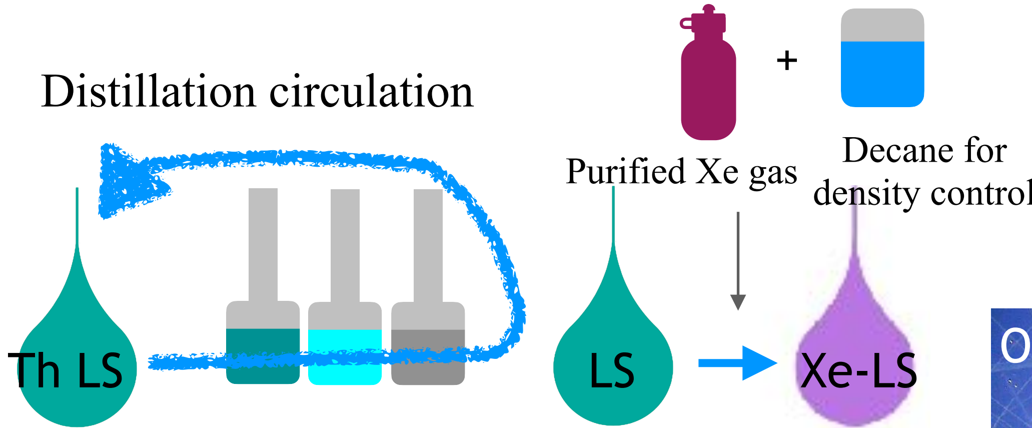
Target:
Doubling Xe amount
Reducing ^{214}Bi from IB

- 2015 Oct.: Zen 400 Xe extraction
- 2015 Dec. – 2016 Apr.: Outer Detector refurbishment, ID tank inspection
- 2016 Aug. – 2016 Nov.: Failed Inner-balloon
- 2016 Nov. – 2018 May.: New inner-balloon production
- 2018 May. – 2018 Nov.: LS purification
- 2018 Nov. – 2019 Jan.: Xe dissolving
- 2019 Jan. – 2021 Feb.: Zen-physics data taking

Leak found 1st Zen800 IB
2nd Zen800 IB was installed in 2018.

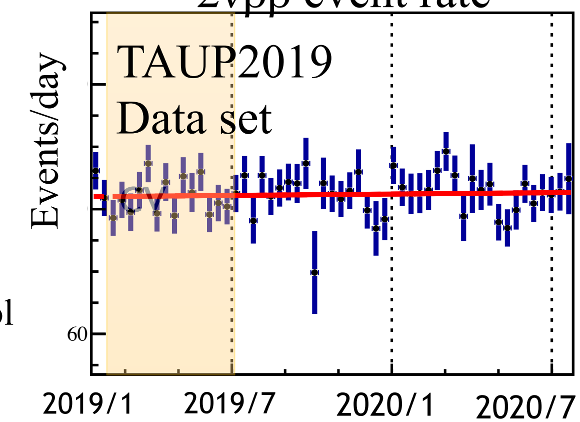


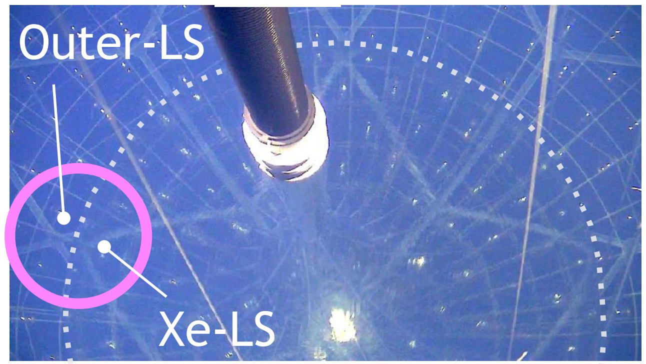
Distillation circulation



Installed
30.5 m3 new LS
@May 2018

Removed Th contamination in LS
by distillation circulation
to reduce "pileup" background





Ultra-low BG Inner-balloon(IB)

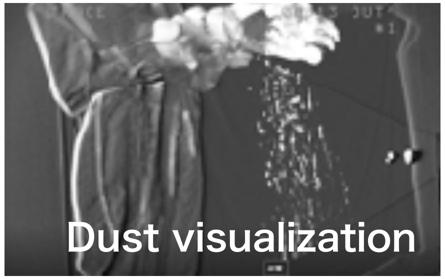
Fabricated in class-1 cleanroom in Sendai

25 µm-thick nylon film

↓

3.8 m diameter inner-balloon

Dust from workers is the main source of contamination.



Anti-stat

Backgrounds (R<157 cm)

Zen 800 ROI: 2.35 MeV < E < 2.70 MeV,
$0\nu\beta\beta$ efficiency ~90%

(Gando @TAUP2019)

Source: $2\nu\beta\beta$
Radioactive impurities: Xe-LS, IB and outer-LS
Cosmogenic: muon-spallation Solar neutrino ES

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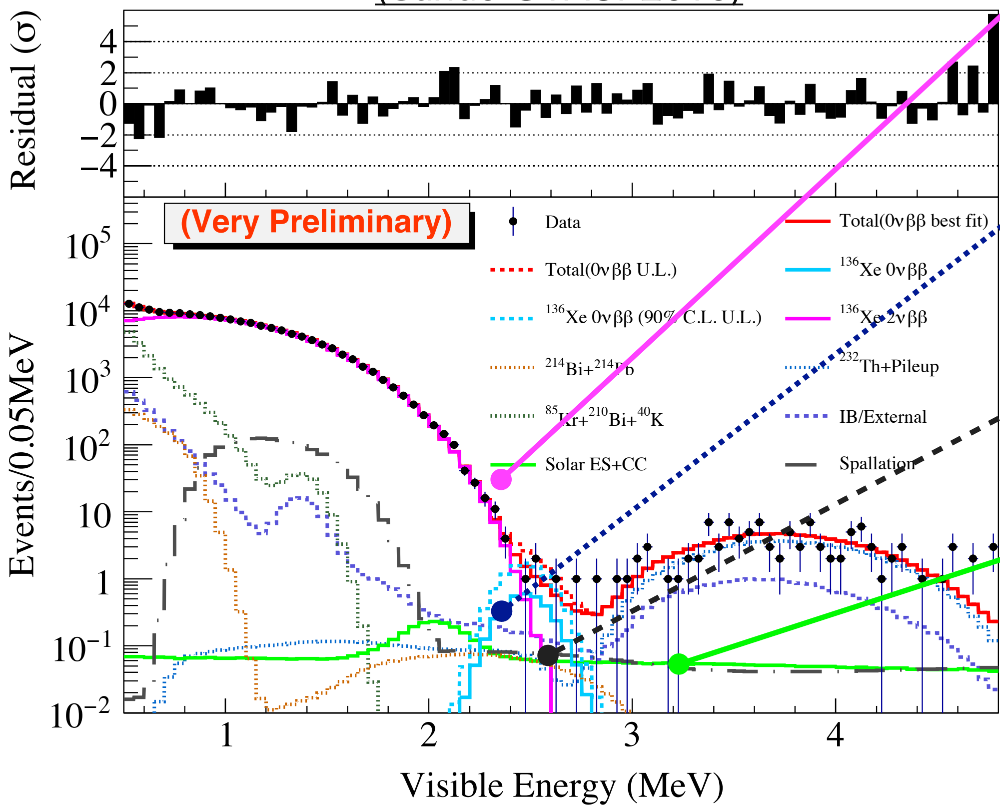

$2\nu\beta\beta$ tail due to energy resolution
Most dominant & inevitable BG
ΔE~4.5%@2.45 MeV ~ 5.1 events/ROI

^{214}Bi from IB film
Vertex resolution ~15 cm/$\sqrt{E(\mathrm{MeV})}$
Limit sensitive region to $0\nu\beta\beta$ decay.
~ 0.9 events/ROI

^{12}C spallation products
Significantly reduced by new analysis methods
~ 0.2 events/ROI

Solar neutrino electron scattering + C.C. (^{136}Cs)
Inevitable BG
~ 0.4 events/ROI

Very preliminary

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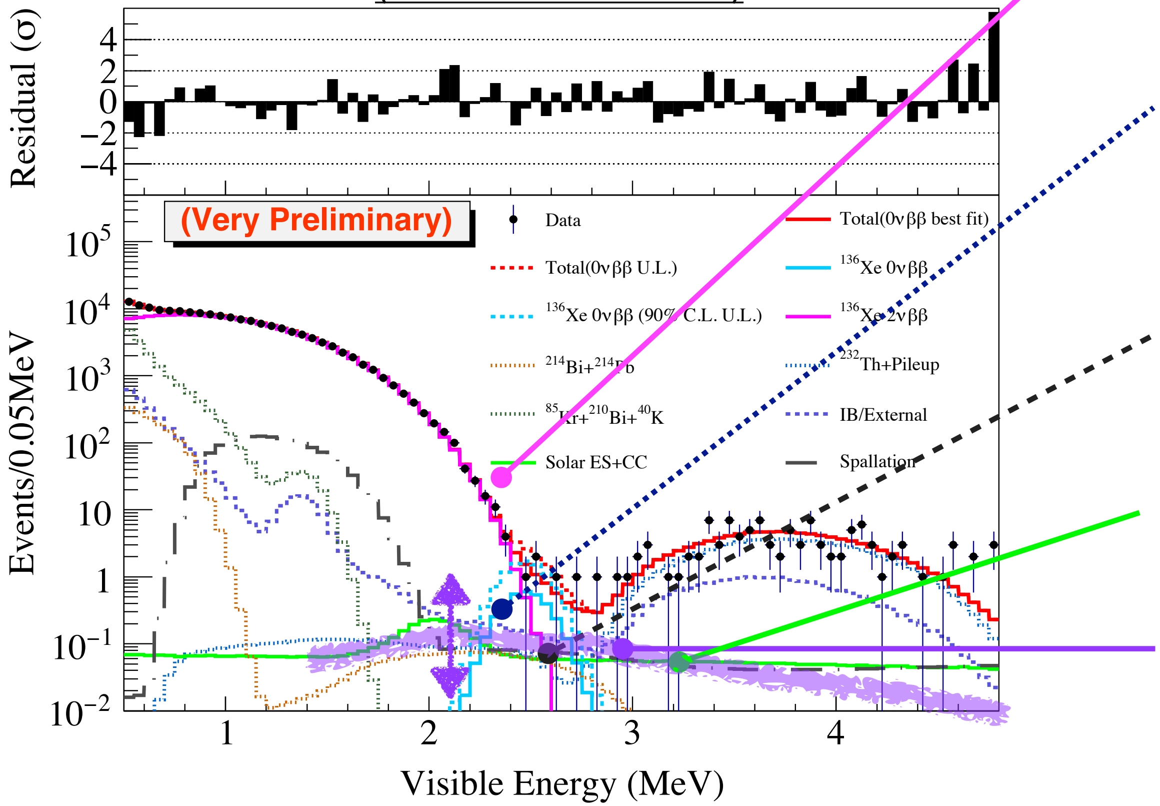

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Solar neutrino electron scattering + C.C. (^{136}Cs)
Inevitable BG
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^{136}Xe spallation products
Nuisance BG in Zen800
Hard to reject because of their long-lives

Very preliminary

Radioactive impurity (Xe-LS)

BGs ^{238}U series … ^{214}Bi
^{232}Th series … Pileup(^{212}Bi+^{212}Po)

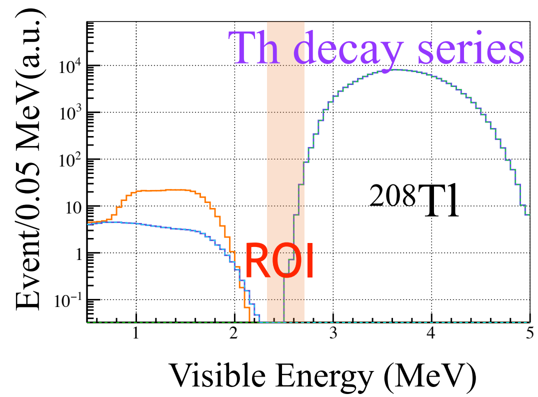
U and Th contamination in Xe-LS measured using delayed coincidence (1.β + 2.α)

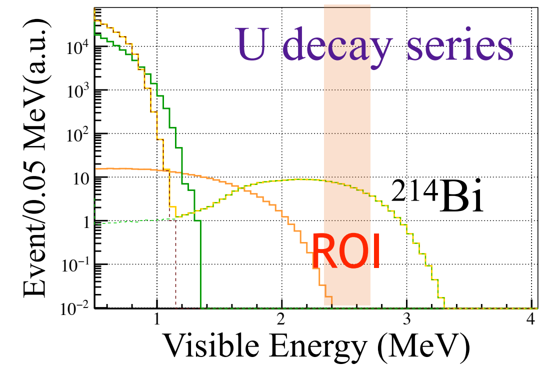
^{232}Th daughters ~70% eff.

^{212}Bi →(β) ^{212}Po →(α) ^{208}Pb $T_{1/2}$: 299 ns

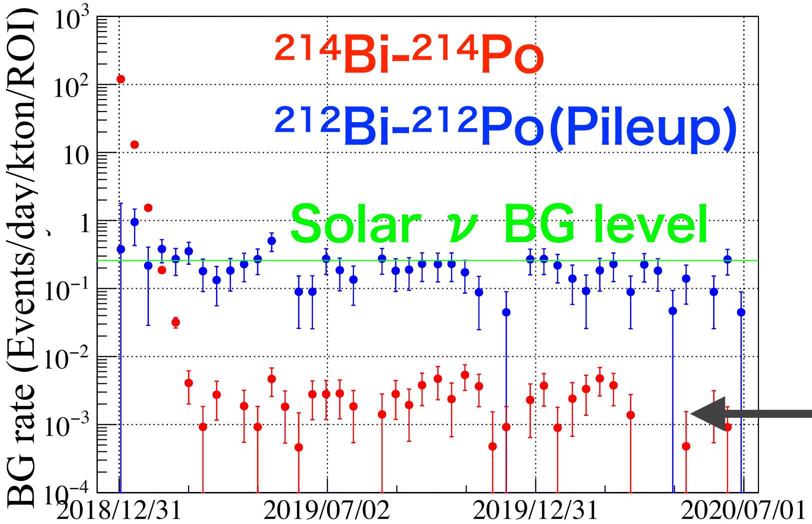
^{238}U daughters > 99.9% eff.

^{214}Bi →(β) ^{214}Po →(α) ^{210}Pb $T_{1/2}$: 164 μs

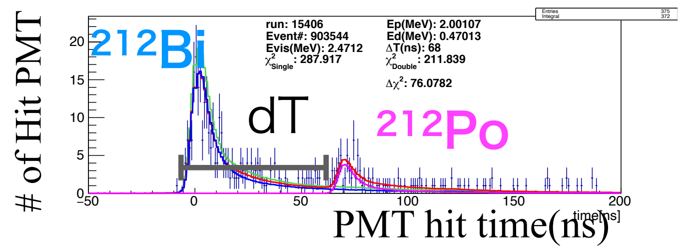




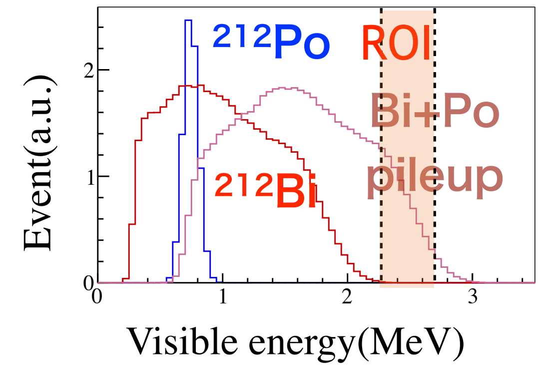
Trends of DC events



Pileup BG from Th daughters



Pileup if dT <~10 nsec **(~2%)**



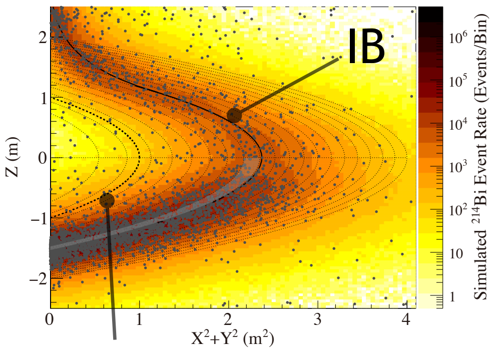
BG from RI in Xe-LS is negligibly small!!

Radioactive impurity in Xe-LS
^{238}U ~ O(10^{-17}) g/g Xe-LS
^{232}Th ~ 3×10^{-16} g/g Xe-LS

Radioactive impurity (IB film)

^{214}Bi distribution from IB

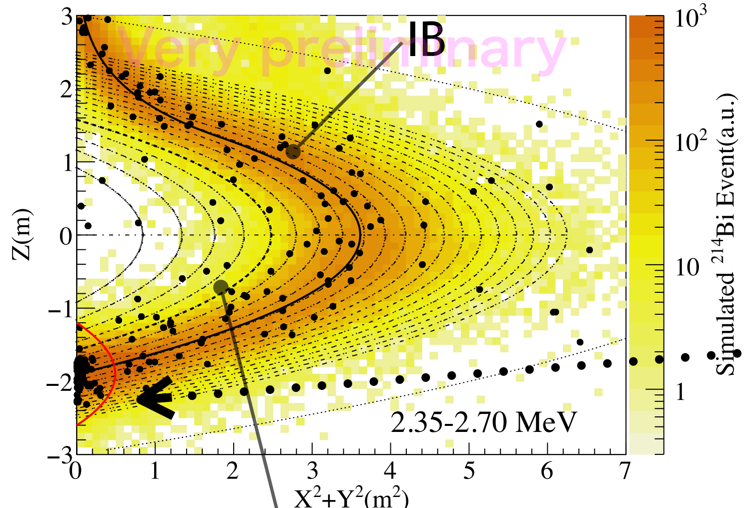
Zen 400 Phase-II



Sensitive region
r<1.06 m z<0
r<1.26 m z>0

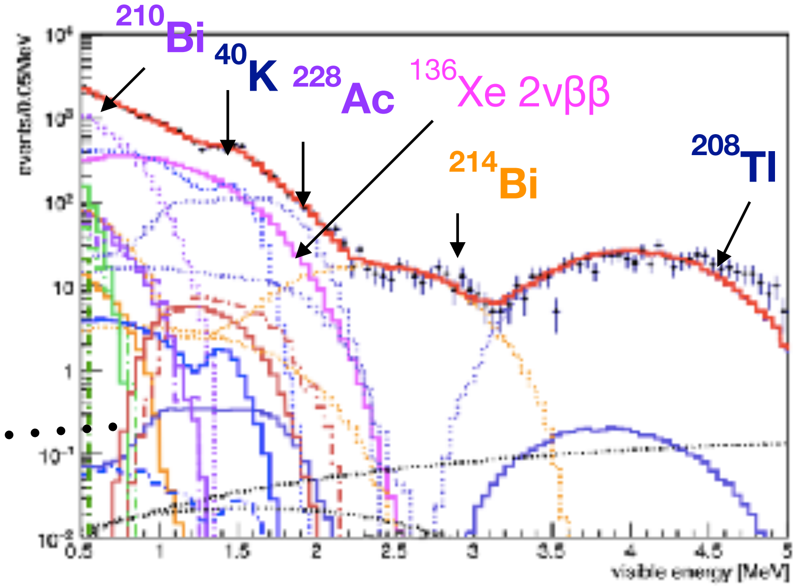
× >3 scale-up

Zen 800(Gando @TAUP2019)

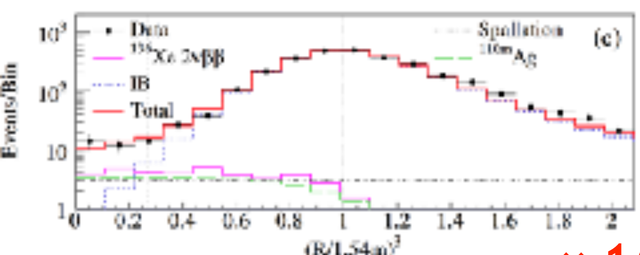


Sensitive region r<1.57 m

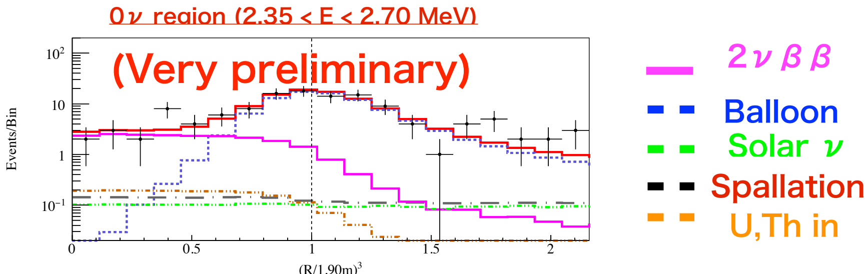
Bottom Hot Spot



Sinking dusts?
Will be removed from analysis volume.



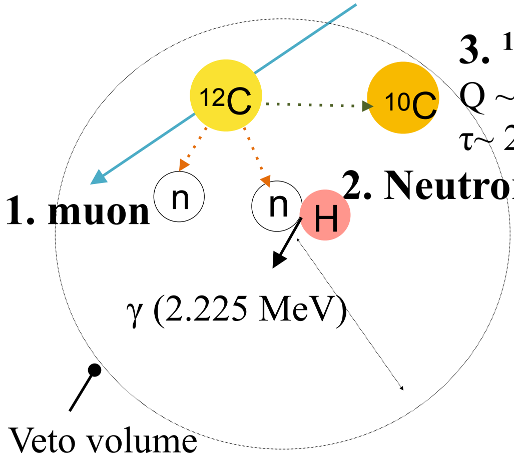
× 1/10 BG



Radioactive impurity in IB
^{238}U ~ 3×10^{-12} g/g IB
^{232}Th ~ 4×10^{-11} g/g IB

Backgrounds from cosmic-ray muons

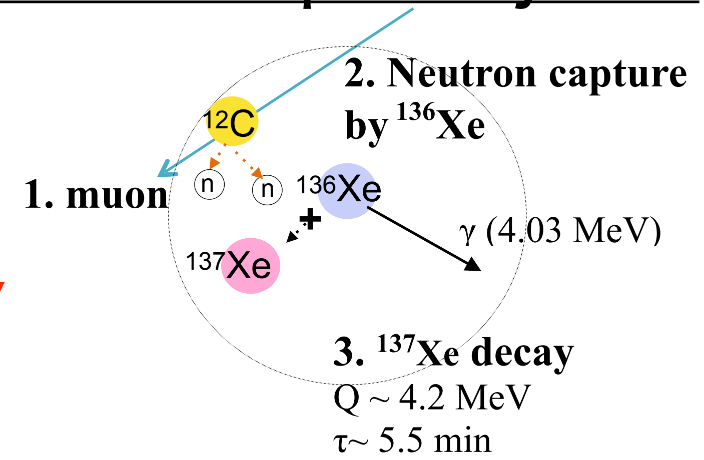
^{12}C spallation



$T_{1/2}$<~30 sec
Measurable with KamLAND LS
~8 events/day/kton/ROI

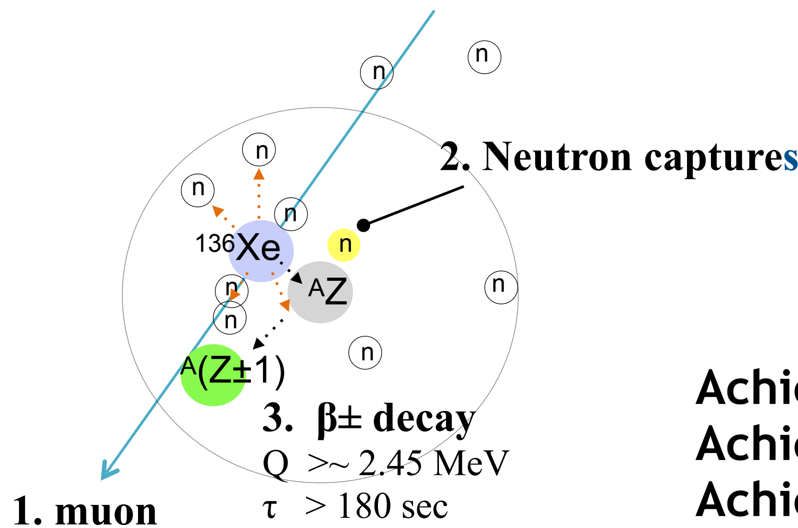
^{137}Xe decay from neutron capture by ^{136}Xe

~ 0.5±0.2 events/day/ton/ROI
Long-life τ~ 5.5 min
Tagged by high energy γ ~4 MeV



^{136}Xe spallation

More than 30 main nuclei
Long-life $T_{1/2}$ ~ O(hours)
High neutron multiplicity



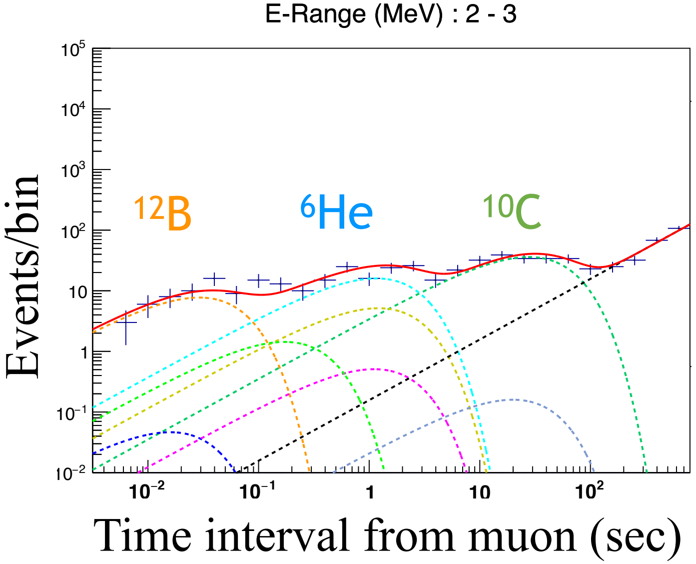
Background rejection methods
1. After-muon full volume veto
2. Muon-neutron tagging
3. Muon-shower tagging (New)

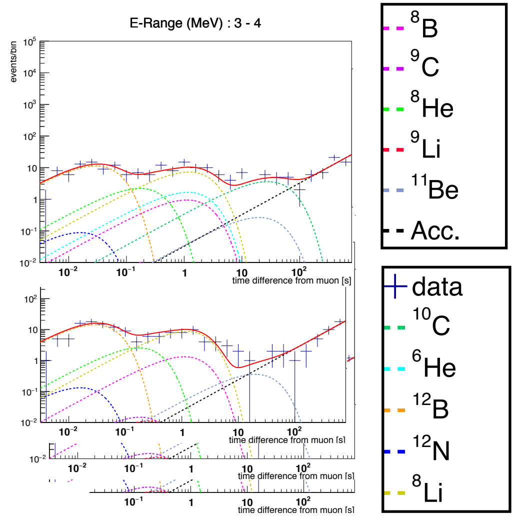
Achieved more than 90% ^{10}C rejection
Achieved ~80% ^{137}Xe rejection
Achieved ~40% ^{136}Xe spallation rejection with ~10% 0νββ inefficiency

^{12}C-spallation

After muon 150 ms veto
+ muon-neutron-spallation
+ muon-shower-spallation

Simultaneous fit with energy and dT spectra

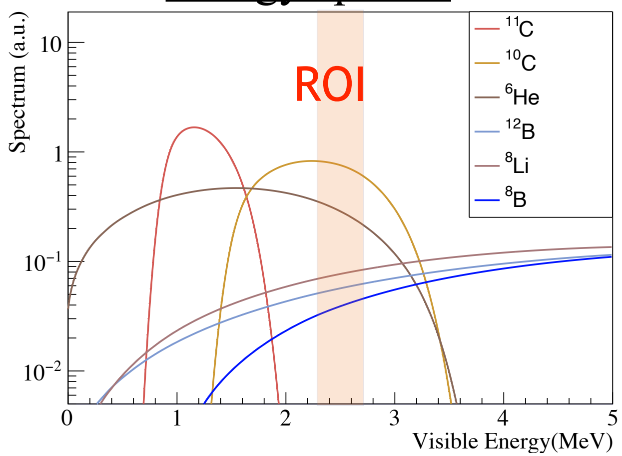




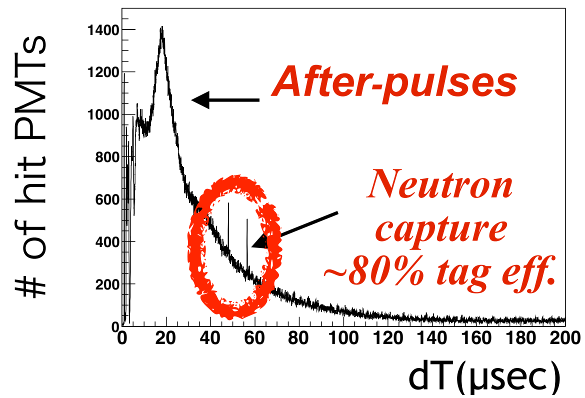
	Production rate [/day/kton]
^{6}He	15±2
^{8}Li	12±3
^{10}C	20±1
^{12}B	51±2

Remaining
~<0.1 /day/kton/ROI
> 90% rejection
Less than solar ν BGs
(~0.3 /day/kton/ROI)

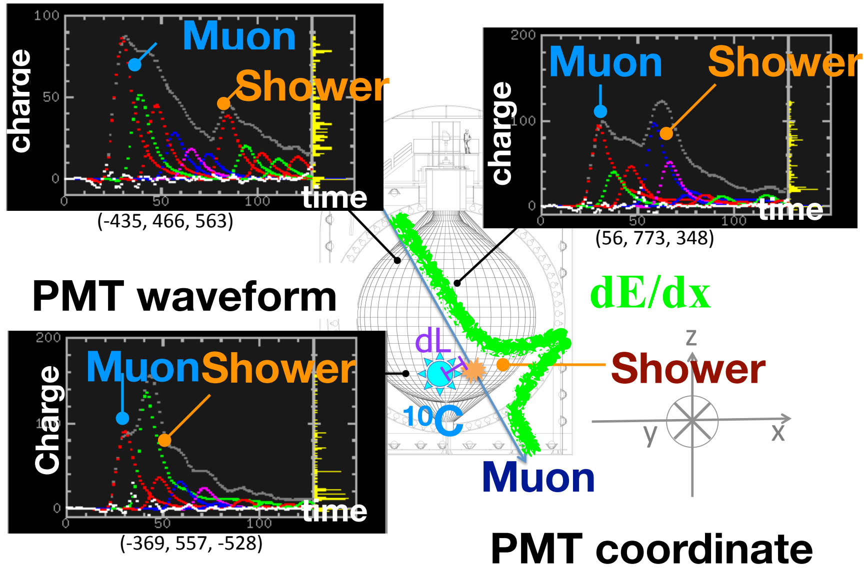
Energy spectra



PMT hit timing after muon



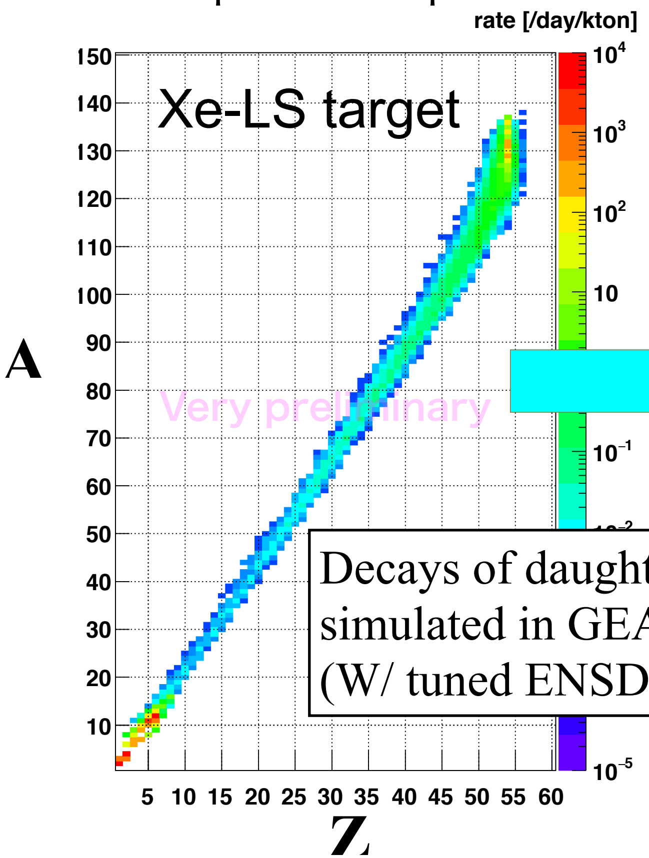
Spallation veto with shower correlation (dE/dx and dL)



^{136}Xe-spallation

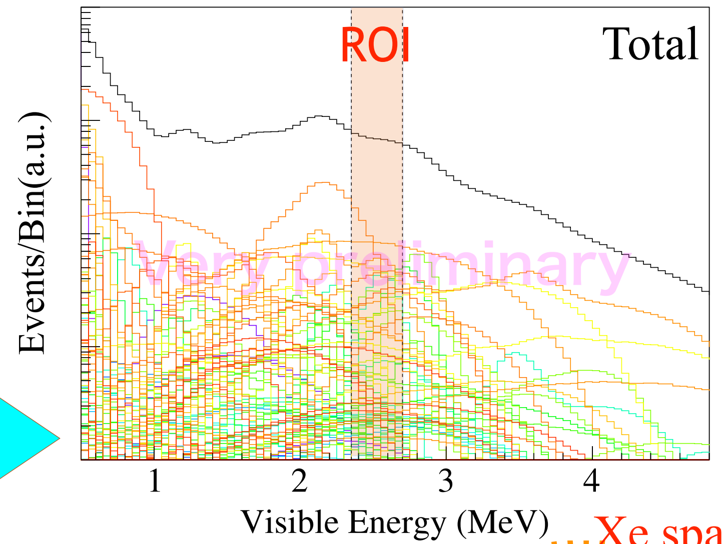
High neutron multiplicity
Long $T_{1/2}$
EC/β^+/β-γ decay

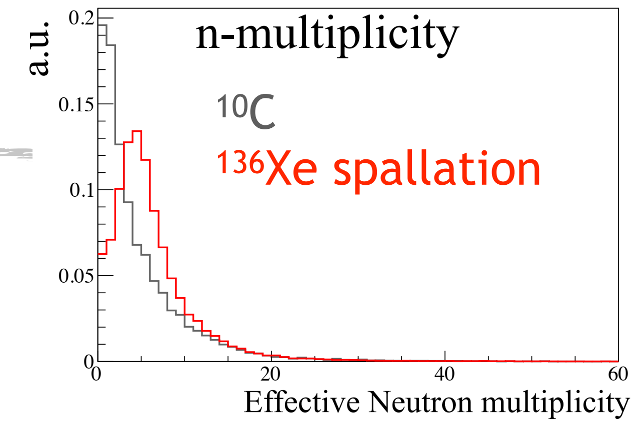
^{136}Xe spallation products

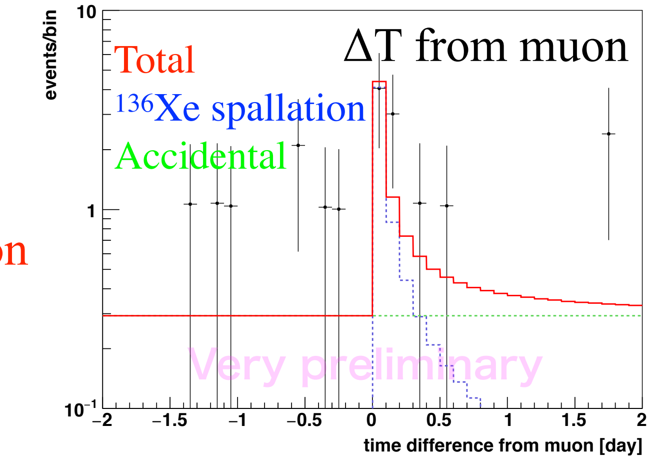


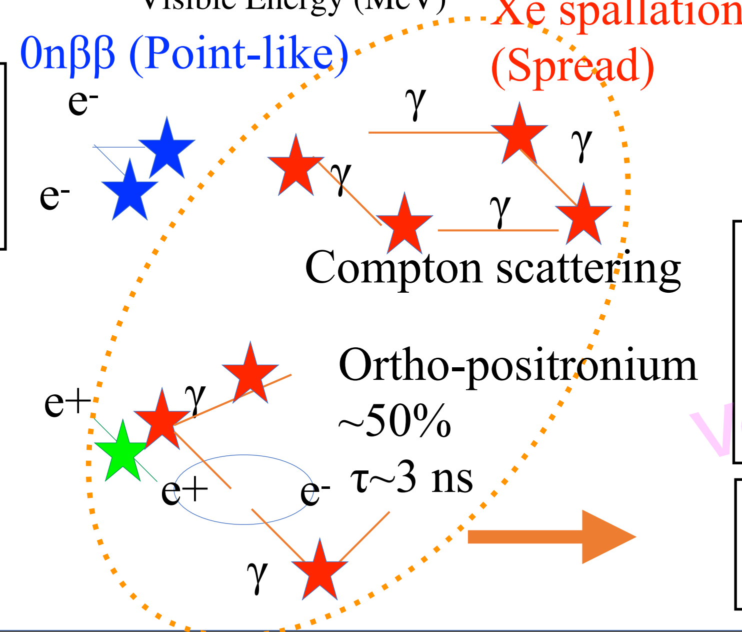
Decays of daughter nuclei simulated in GEANT4 (W/ tuned ENSDF)

Production rate was estimated by FLUKA.









Neutron tag with n-multiplicity, dR, dT
~40% rejection with ~10% 0νββ ineff.

Very preliminary

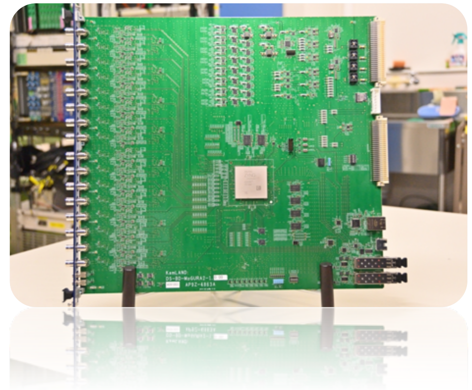
PID by neural network
Under development

Prospects for Improvements and future plans

Started Jan. 2019

KamLAND-Zen ~ 800 kg phase
with new larger and cleaner inner-balloon

- PMT AMP for better energy resolution
- New electronics to collect all neutron captures
- Source calibration



~5 years observation

Future plan

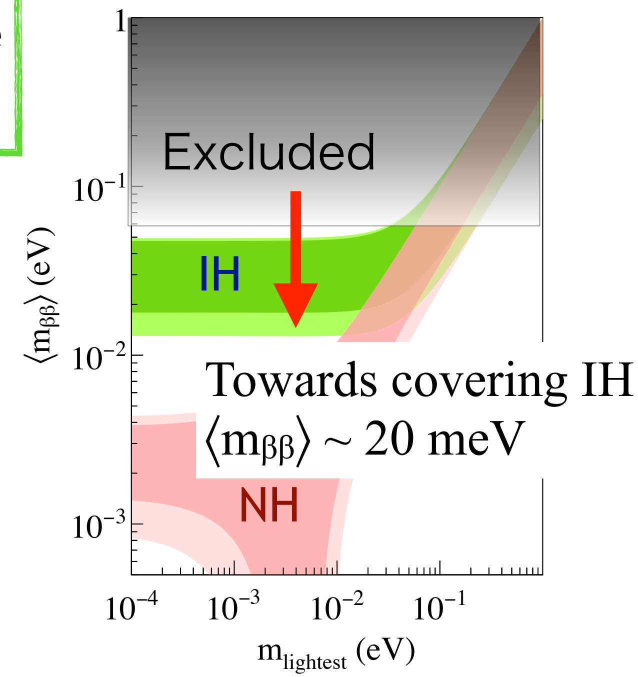
KamLAND2-Zen >1000 kg phase
with remodeled detector

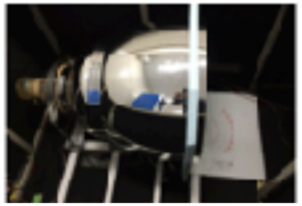
- HQE PMT
- LAB LS
- Mirror for PMT
- Scintillating inner balloon
- Imaging camera

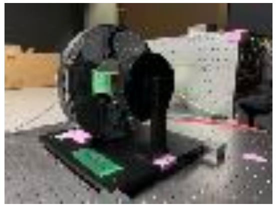
} > ×5 brighter

Energy resolution
~2%@2.45 MeV

> ×2 improvement







R&D
Ongoing

Summary

- KamLAND-Zen 800 is stably running with the goal of searching for $0\nu\beta\beta$ within the IH region.
- We successfully characterized and reduced backgrounds.
  - Constructed an ultra-low background IB
  - Strongly reduced ^{12}C-spallation by analysis
  - Successfully characterized ^{136}Xe-spallation
- The latest results will be published very soon.