Latest result and future of neutrinoless double-beta decay search by KamLAND-Zen

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Workshop on Xenon Detector $0\nu\beta\beta$ Search: Steps Towards the Kilotonne Scale

Contents

- The KamLAND-Zen experiment
- Latest result of neutrinoless double-beta decay search
- Future of KamLAND-Zen

Contents

- The KamLAND-Zen experiment
- Latest result of neutrinoless double-beta decay search
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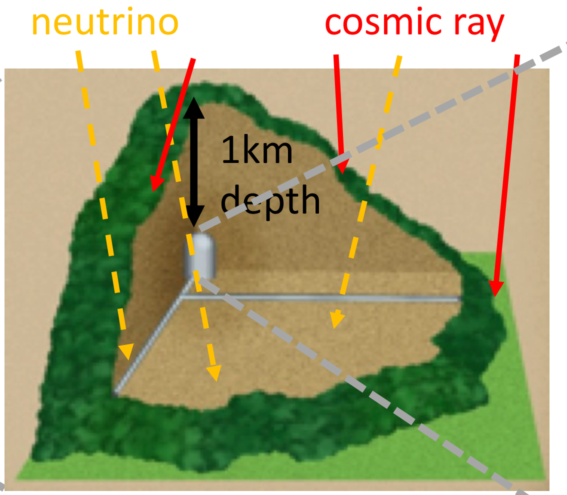
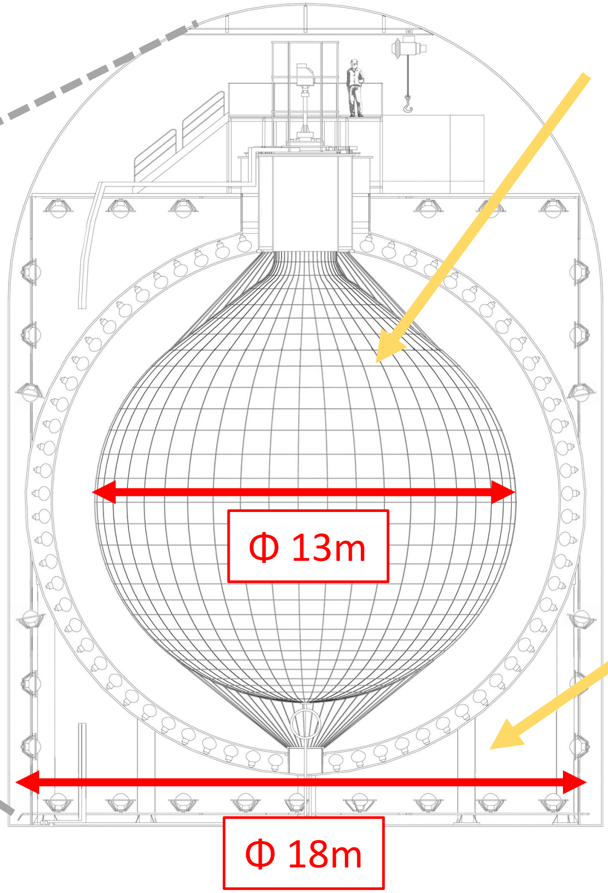
KamLAND detector

Detector site and components



1km depth rock = 2700 m.w.e.

The rock overburden effectively suppresses the cosmic-ray muons by a factor of 10^{-5}.



Scintillation inner detector

1kt purified liquid scintillator
(PC+Dodecane+PPO mixture)
1325 17” + 554 20” PMTs
photo coverage 34%
energy resolution 6.7%/√E[MeV]
Physics observation

Water Cherenkov outer detector

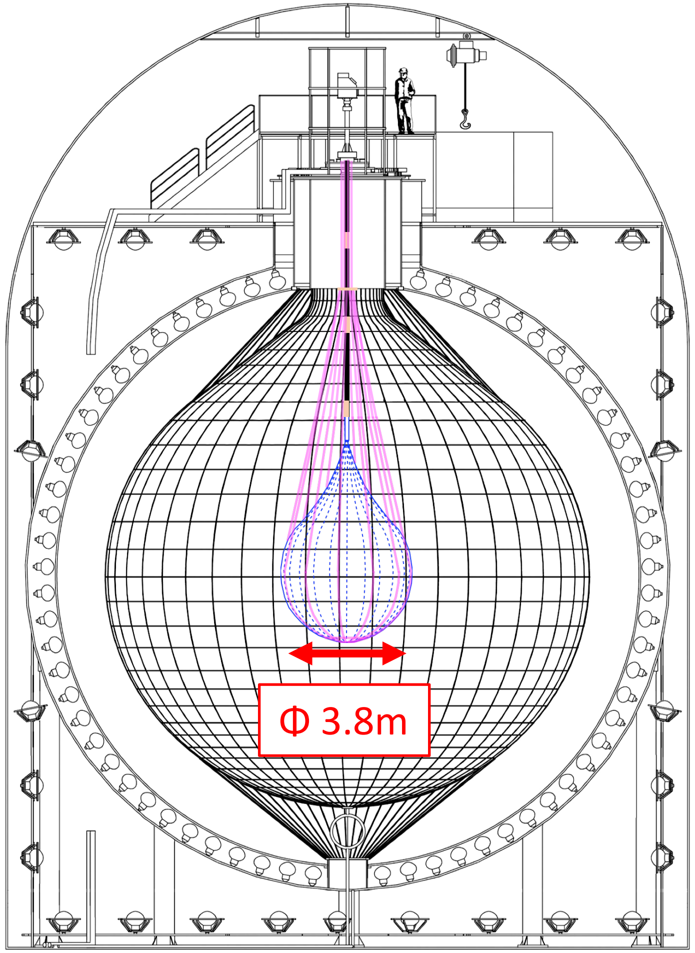
3.2 kt purified water
225(140) 20” PMTs
passive shielding
active veto to muon

Broad scientific objectives of KamLAND experiment

- Solar neutrinos https://journals.aps.org/prc/abstract/10.1103/PhysRevC.92.055808
- Reactor neutrinos https://doi.org/10.1103/PhysRevD.88.033001
- Geoneutrinos https://doi.org/10.1029/2022GL099566
- Atmospheric neutrinos https://doi.org/10.1103/PhysRevD.107.072006
- Astrophysical neutrinos https://doi.org/10.3847/1538-4357/ac7a3f
- Proton decay https://iopscience.iop.org/article/10.3847/0004-637X/818/1/91
- **Neutrinoless double-beta decay (This talk)**
  https://doi.org/10.1103/PhysRevLett.130.051801

and more !!

KamLAND-Zen experiment



Zero-**n**eutrino double-beta decay search with **KamLAND** detector

Advantage of using the KamLAND detector

- Ultra-low radioactive environment – U, Th ≤ 10^{-17} g/g
- Huge & scalable – 1kt liquid scintillator

→ **Ideal enviromnet for extremely rare decay search !!**

Double-beta decay source : ^{136}Xe

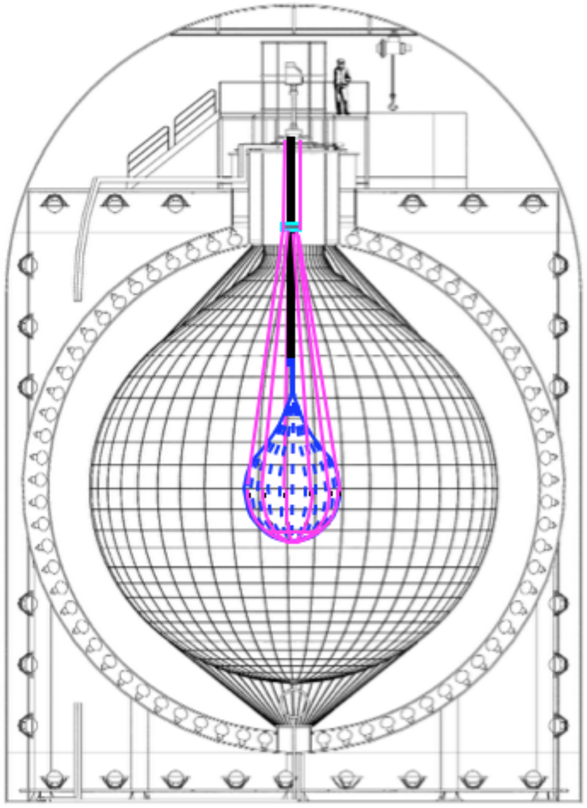
- 0νββ Q-value : 2.46 MeV — below ^{208}Tl γ BG
- Long 2νββ half life — fewer 2νββ BG
- **(Relatively)** easy to enrich/purify by distillation — ^{136}Xe is enriched to ~90%
- Dissolved into liquid scintillator (LS) at 3% — stable in room temperature and pressure

Mini-balloon installed to support xenon-loaded LS (XeLS)

- Outer LS provides passive shielding from external radioactive background.
- Concentrated target nuclei can suppress volume-proportional backgrounds.

History and future of KamLAND-Zen

Past: 2011 – 2015

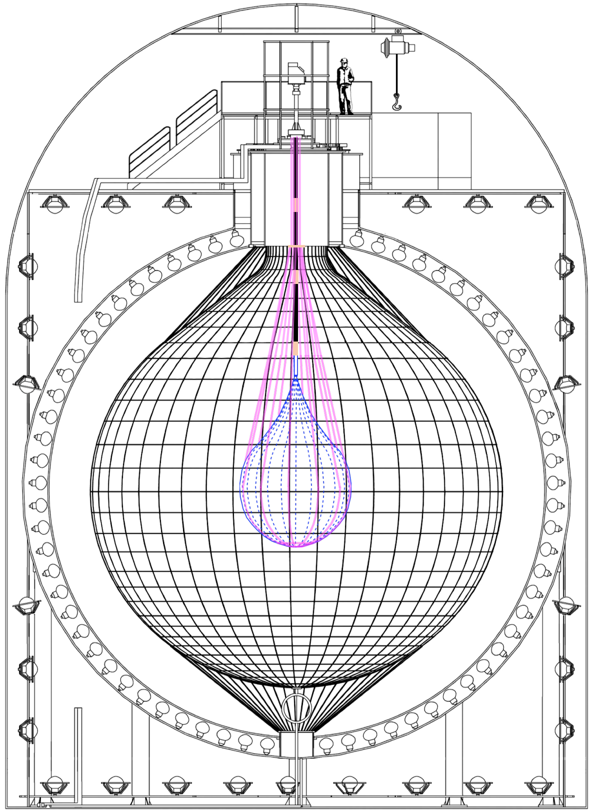


KamLAND-Zen 400

- Mini-balloon radius = 1.54 m
- 320–380 kg of enriched xenon
- $\langle m_{\beta\beta} \rangle < 61\text{–}165\ \mathrm{meV}$

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

Present: 2019 –



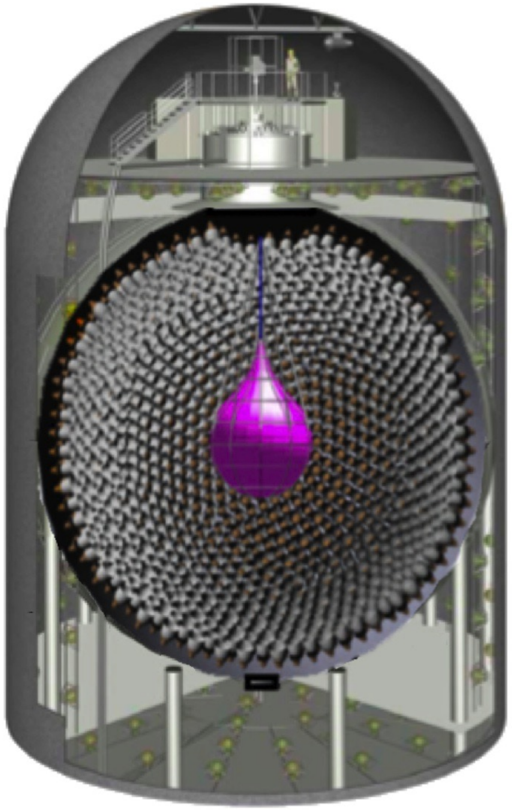
KamLAND-Zen 800

- Mini-balloon radius = 1.90 m
- 745±3 kg of enriched xenon

Phys. Rev. Lett. 130, 051801 (2023)

Cleaner mini-ballon, more xenon for better sensitivity (this talk)

(Near?) Future:



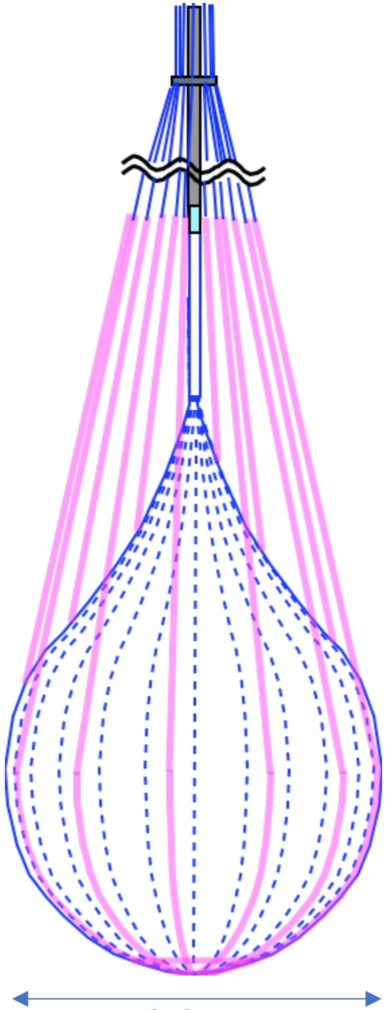
KamLAND2-Zen

- Detector upgrade for better energy resolution
- ~1 ton of enriched xenon

Toward $\langle m_{\beta\beta} \rangle = 20\ \mathrm{meV}$ **!!**

Hand-made mini-balloon production in 2017

Geometry



Procedure

1. wash the film

2. cut the film

3. weld the film to balloon shape

4. leak hunt and repair holes

5. Install !!

It took more than 1.5 year with 20+ researchers.

published as JINST 16 P08023(2021)

Low-radiactivity technique

Class-1 super clean room in Sendai

- Particle with 0.5+ μm-radius is less than 1 per cubic foot.
- All items in the room is also cleaned well with ethanol and pure water.

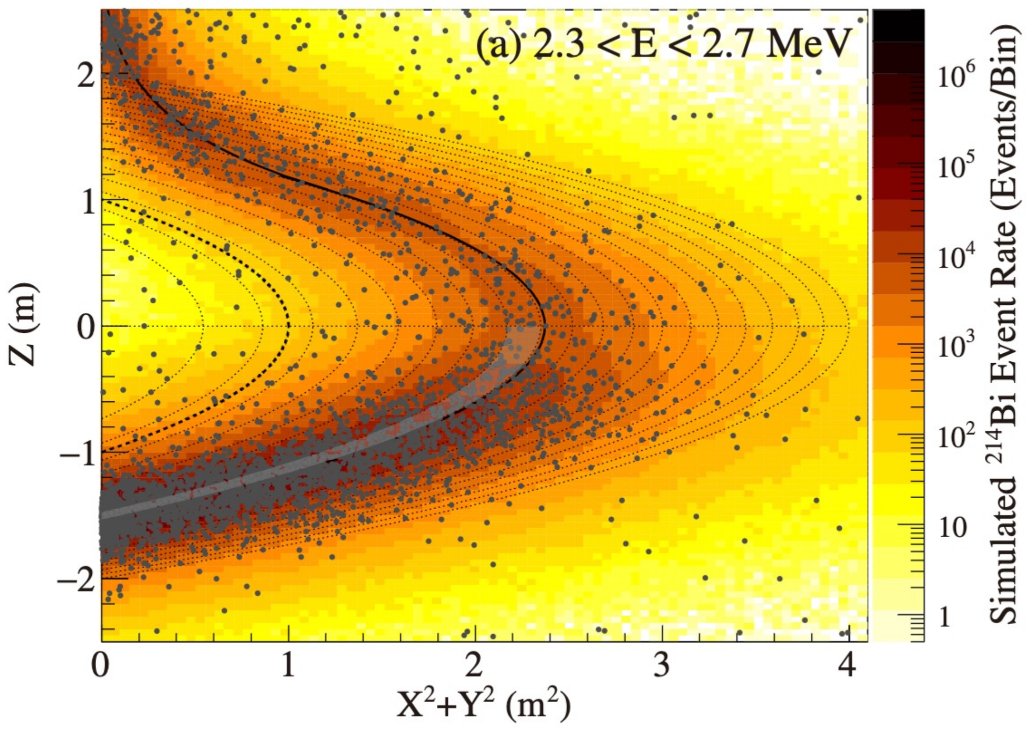
Clean suit

- Full-body suit, goggle and double gloves.
- Suits goes to laundry after one-time-use.

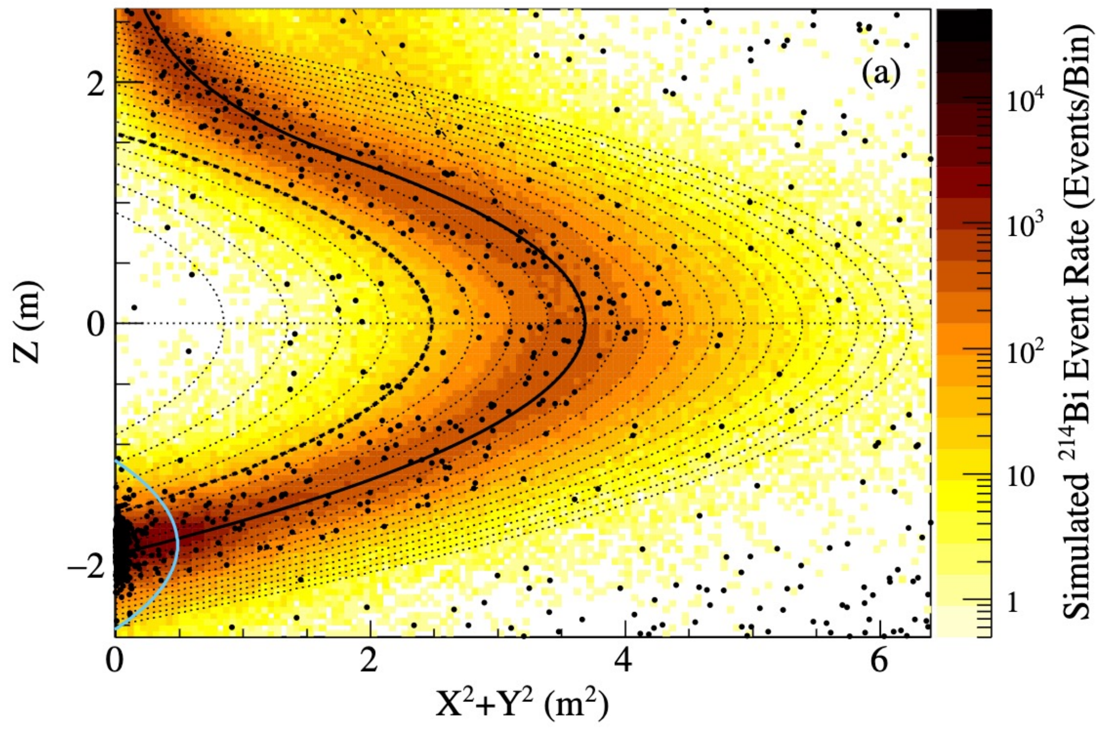
Contamination comes from human bodies and clothes.

Mini-balloon radioactivity reduction

KamLAND-Zen 400 (530 days)



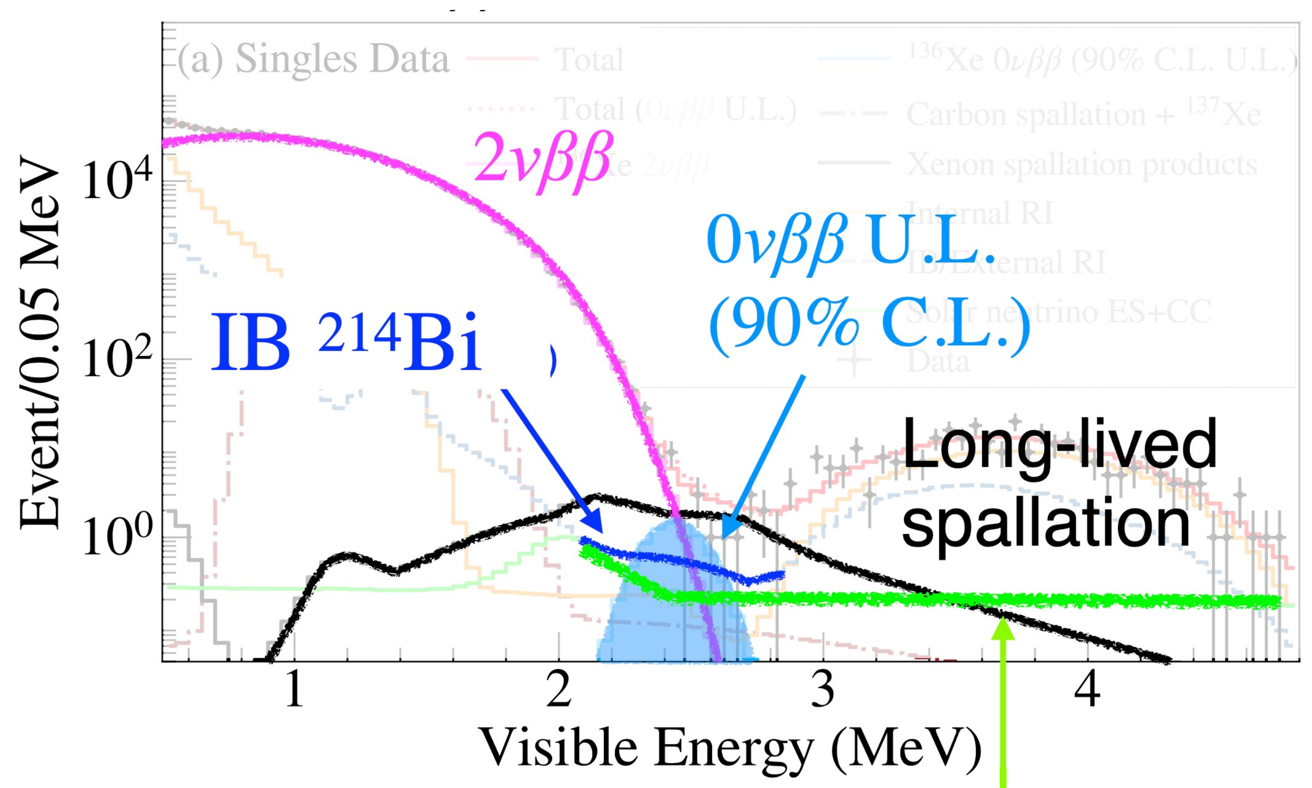
KamLAND-Zen 800 (520 days)



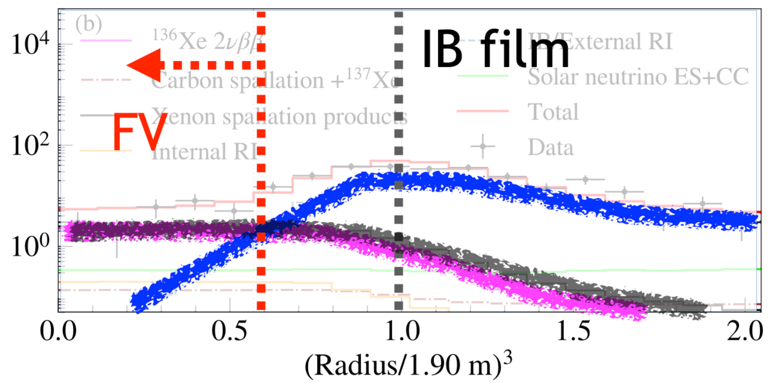
	KamLAND-Zen 400	KamLAND-Zen 800
^{238}U (g/g)	~ 5×10^{-11}	~ 3×10^{-12}
^{232}Th (g/g)	~ 3×10^{-10}	~ 4×10^{-11}
Sensitive volume (m^3)	5.7	16.2

- **radioactivity reduction by factor of 10**
- **2.8x sensitive volume achieved !!**

Backgrounds in KamLAND-Zen



Electron scattering
+ ^{136}Xe CC
by solar neutrinos



Double-beta decay of ^{136}Xe ($2\nu\beta\beta$)

– The only way to suppress this background is separation by energy.

Cosmic-ray muon spallation products

- ^{12}C spallation (short-lived spallation)
  – effectively tagged by muon-neutron-spallation triple coincidence and showering tag method
- ^{136}Xe spallation (long-lived spallation)

Major backgrounds (details on the next page)

Radioactive impurities

- Contamination in/on mini balloon
  – well studied with radius distribution

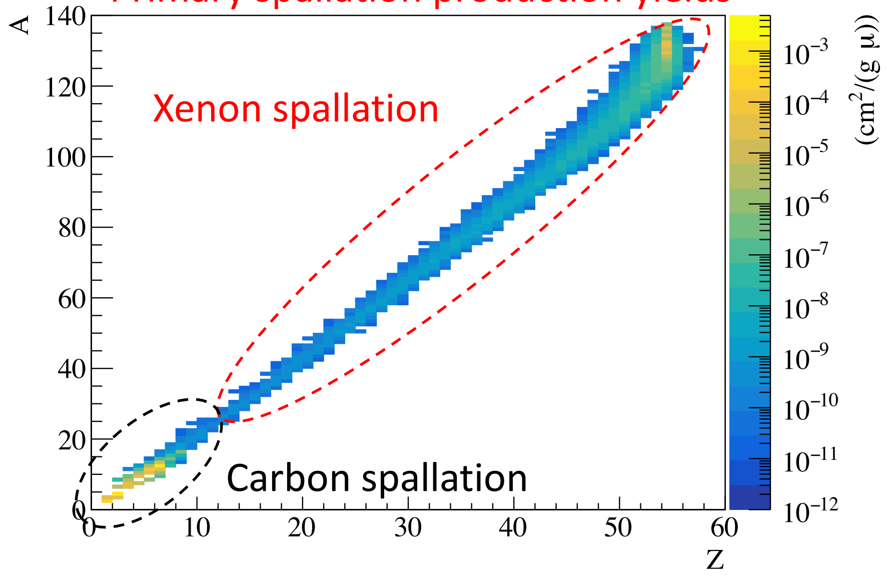
Neutrinos

- Interactions by solar neutrinos
  – Negligible for now. In the future, it might be serious background.

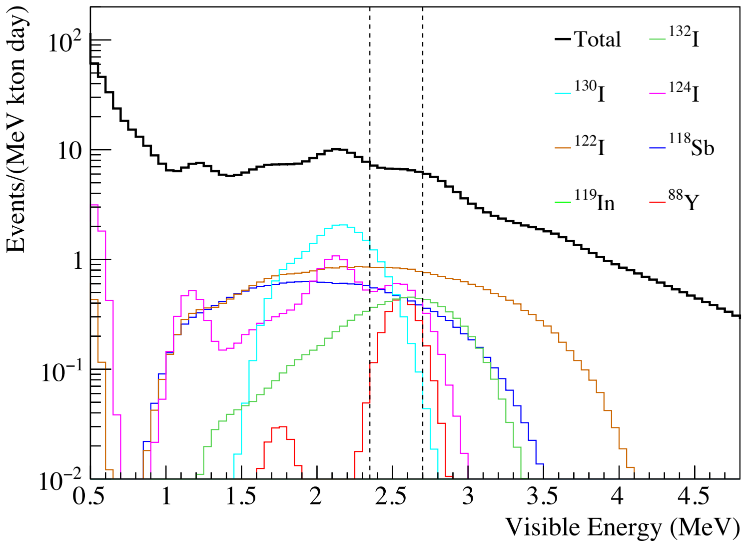
Long-lived spallation products

Figures from https://doi.org/10.1103/PhysRevC.107.054612

Primary spallation production yields

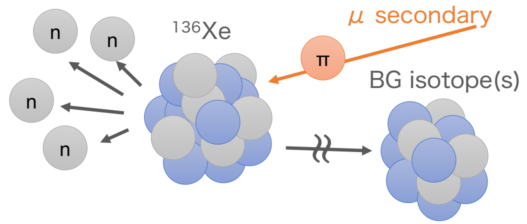


Energy spectrum of major ^{136}Xe daughters



Xenon spallation background

- Muon spallation on xenon nuclei yields a number of isotopes.
- Many isotopes have lifetimes of a few days or longer.
- Yields of each isotope are tiny.
- However the total yield is not negligible.



Production yield estimation

- FLUKA simulation for primary spallation product yields
- GEANT4 + ENSDF for daughters yields
- Expected event rate : 0.082 event/day/Xe-ton/ROI

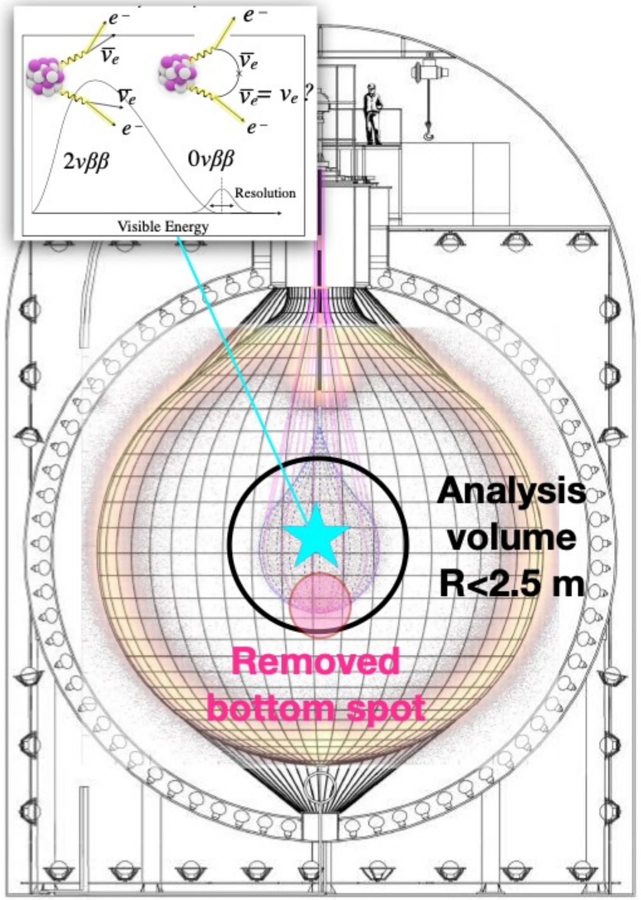
Background reduction technique

- Xenon spallation is accompanied by many neutrons (n-cluster).
- (Muon)–(n-cluster)–(spallation product) tagging is effective.
- We achieved 42±8.8% rejection with 8.6% signal sacrifice.

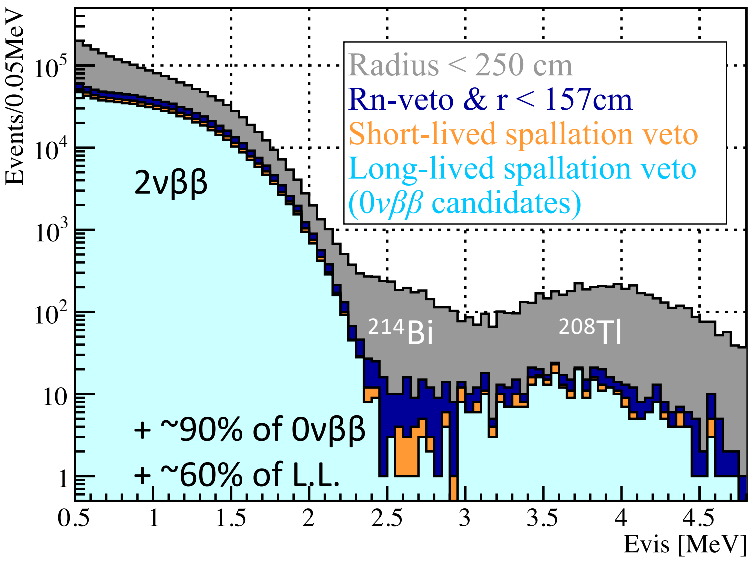
Contents

Double-beta decay analysis

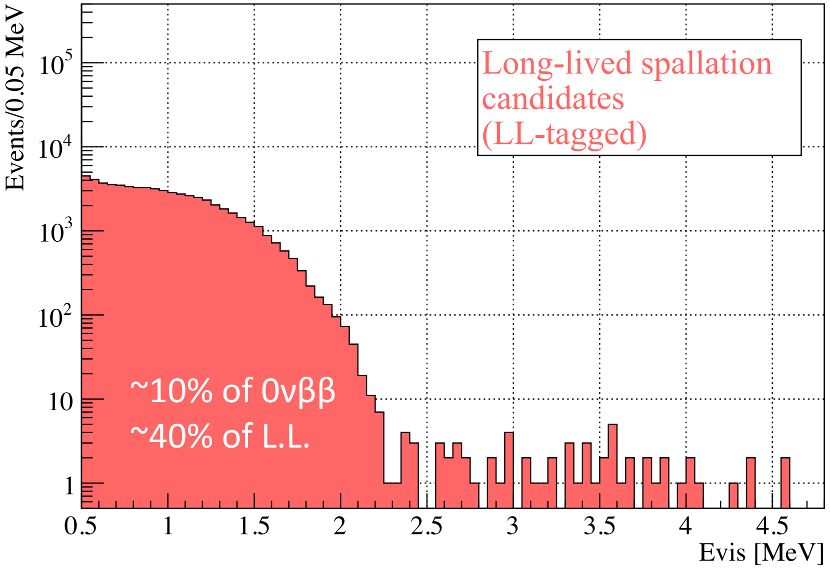
Analysis volume selection



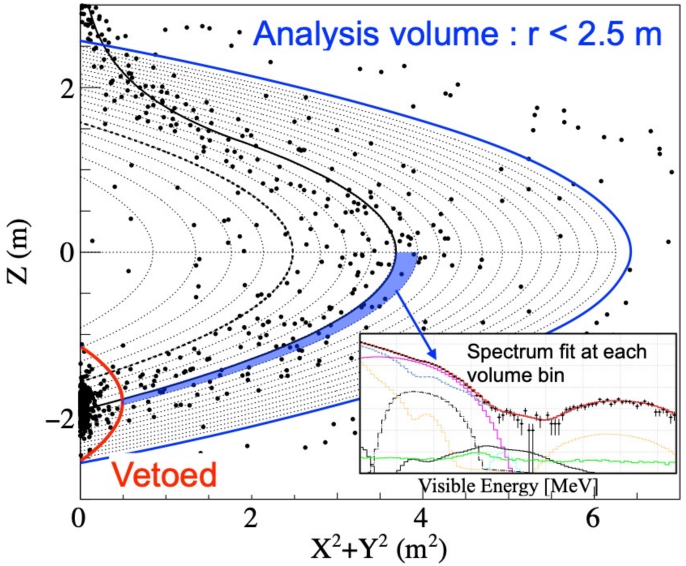
Single (0νββ candidate) dataset



Long-lived spallation (L.L.) tagged dataset



Equal-volume binning



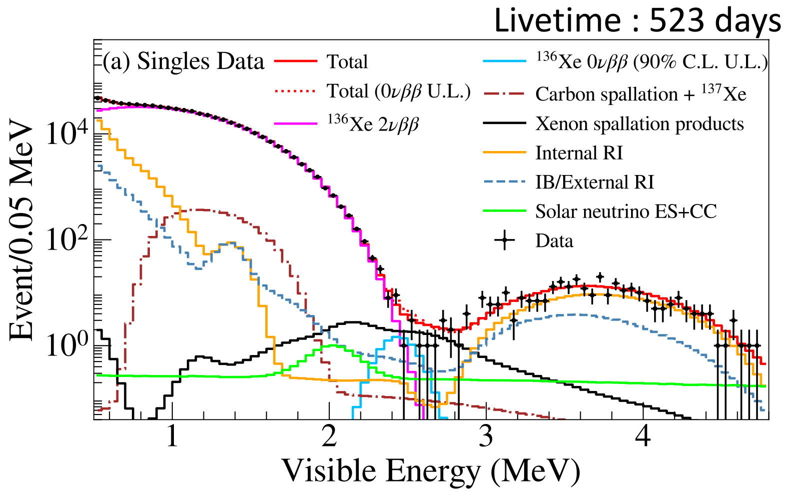
Analysis Method

- **2D scan of 0νββ rate and L.L. rate**
- Simultaneous fit of 2 datasets with:
  - 86 energy bins
  - 40 equal-volume bins
  - 3 time bins

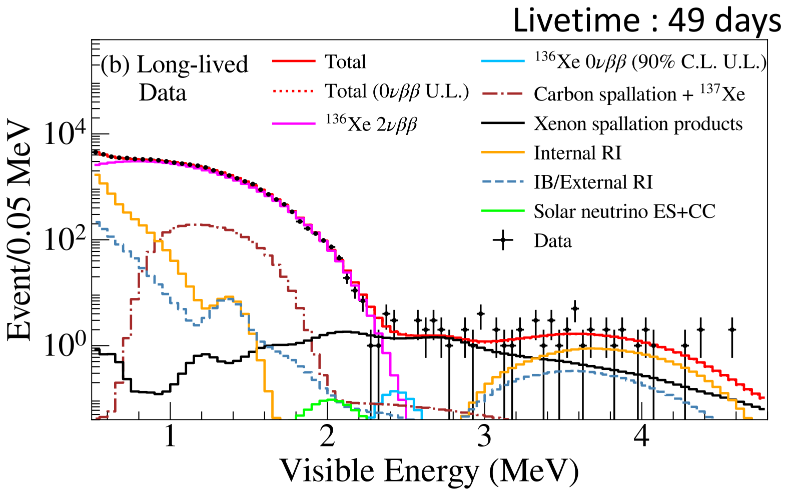
Best-fit energy spectra in KamLAND-Zen 800

Figures and numbers from https://doi.org/10.1103/PhysRevLett.130.051801

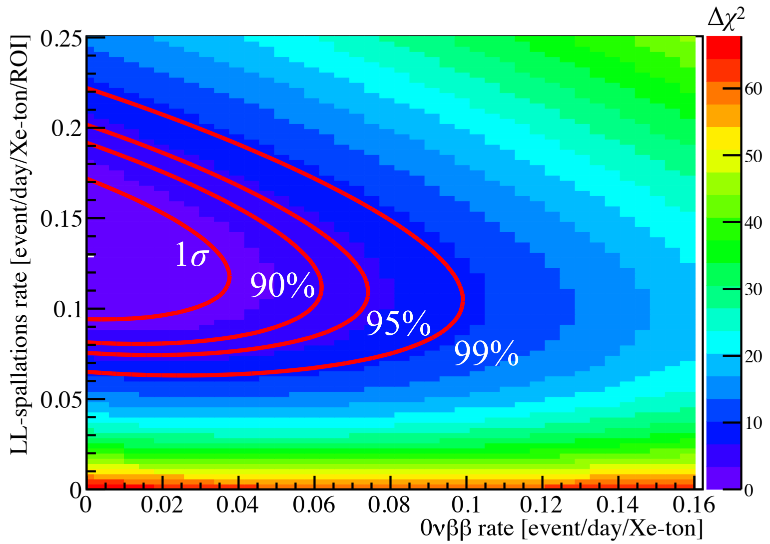
Single (0νββ candidate) dataset (R < 1.57)



Long-lived spallation (L.L.) tagged dataset (R < 1.57)



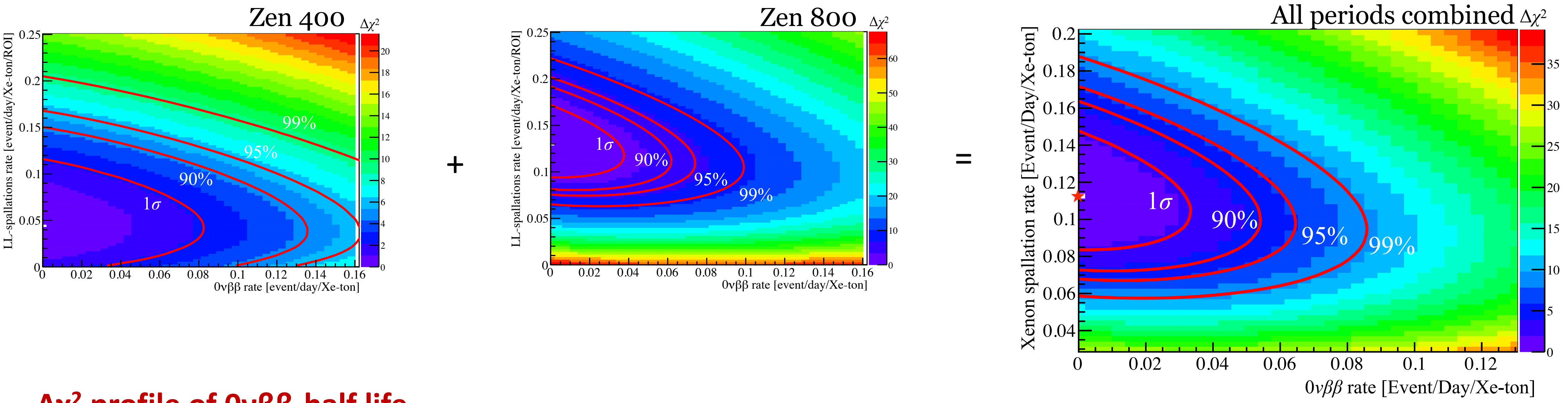
$\Delta\chi^2$ map of 0νββ rate and L.L. rate in ROI



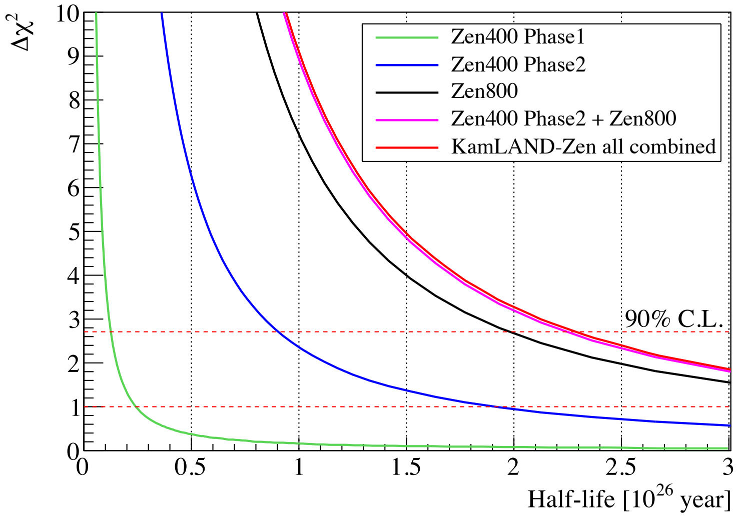
- Dominant background : 2νββ & **long-lived spallation**
- Best-fit 0νββ rate : **0 [event/day/Xe-ton]**
- 90% U.L. on the number of 0νββ event : **7.9**
- Corresponding 0νββ half-life 90% lower limit : **2.0×10^{26} years**

Combined analysis of KamLAND-Zen 400 and 800

$\Delta\chi^2$ map of 0νββ rate and L.L. rate in ROI

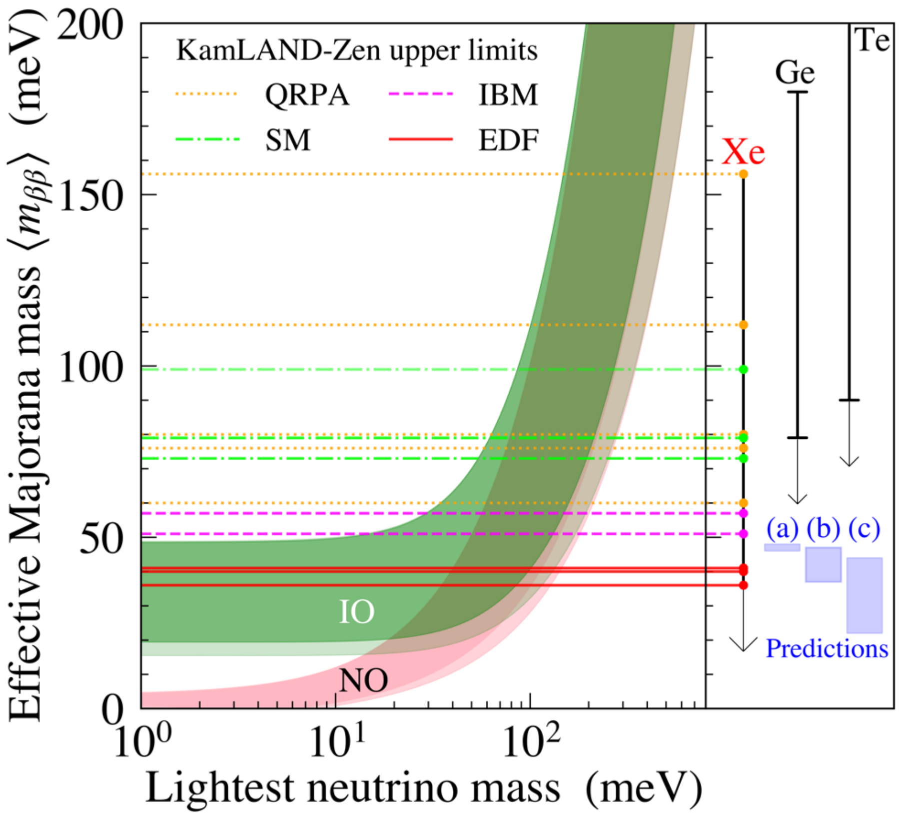


$\Delta\chi^2$ profile of 0νββ-half life



- KamLAND-Zen 400 dataset was re-analyzed with the new strategy.
- Zen400 and Zen800 datasets were combined in $\Delta\chi^2$ map.
- 0νββ half-life lower limit (90% C.L.):
  - Zen400 : 0.9×10^{26} years
  - Zen800 : 2.0×10^{26} years
  - Combined : **2.3×10^{26} years — >2x better half-life limit !!**
- This analysis also gave **the most precise measurement of Xe spallation.**

Upper limit on effective Majorana mass



Theoretical predictions
(a) Phys. Rev. D 86, 013002 (2012)
(b) Phys. Lett. B 811, 135956 (2020)
(c) Eur. Phys. J. C 80, 76 (2020)

- 0νββ half-life is translated to effective Majorana mass as

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

$G^{0\nu}$: Phase space factor

$|M^{0\nu}|^2$: Nuclear matric element (NME)

- Combined $(T^{0\nu}_{1/2})^{-1}$ lower limit (**2.3 × 10^{26} years**) is translated to

$$\langle m_{\beta\beta}\rangle < 36 - 156 \text{ meV}$$ with different NMEs.

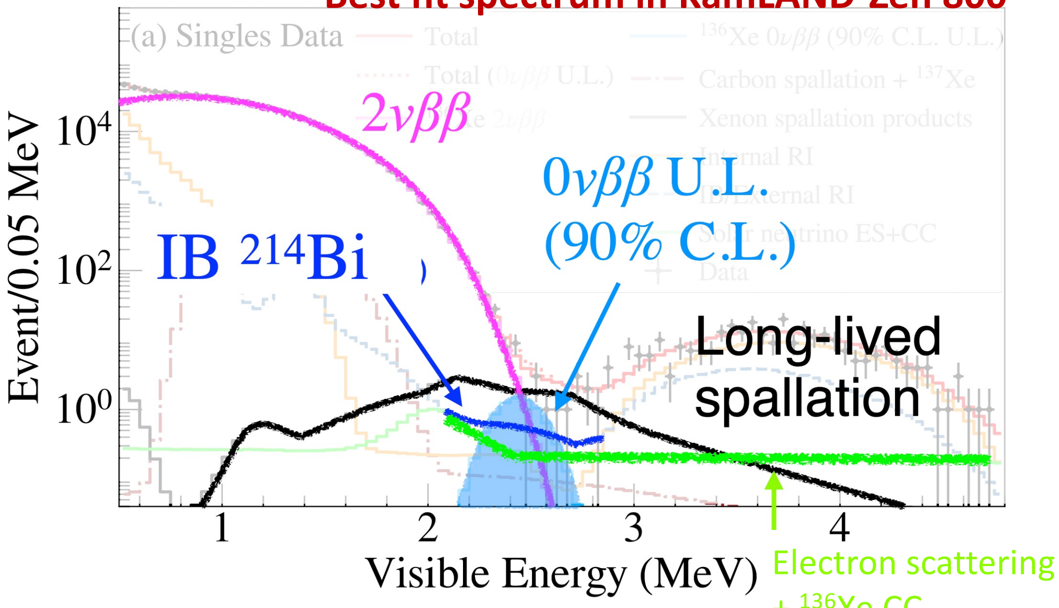
KamLAND-Zen achieved the first search for neutrinoless double-beta decay in the inverted mass ordering region below 50 meV.

Contents

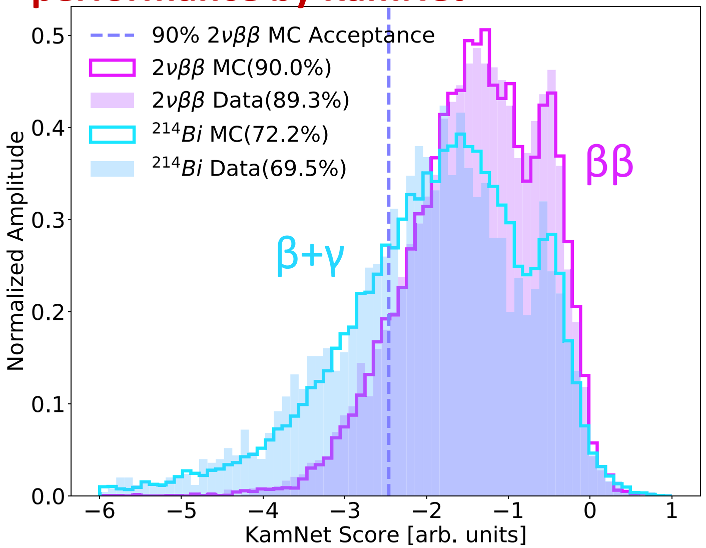
Towards higher sensitivity

numbers from https://doi.org/10.1103/PhysRevLett.130.051801

Best fit spectrum in KamLAND-Zen 800



β/γ discrimination performance by KamNet



Background summary

	# of event in ROI
(a) 2νββ	12.0
(b) Long-lived spallation	12.5
(c) IB ^{214}Bi	3.0

PID with neural network

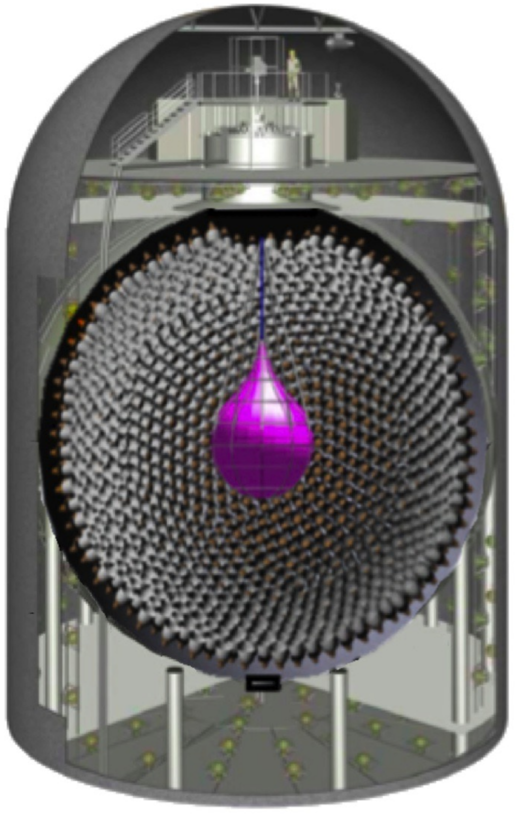
- (b) and (c) are accompanied by γ-ray, while 0νββ is pure β.
- Finding γ-cascade resulting in non-isotropic event topology would be a key technique.
- KamNet (Phys. Rev. C 107, 014323) was developed and has achieved **27% L.L. rejection accepting 90% of 0νββ signal**.

What we can do for 2νββ background reduction?

- Separation by observed energy is the only way.
- **Energy resolution is definitive.**

$$N_{\rm BG}^{2\nu2\beta} \propto \left(\frac{\Delta \rm E}{\rm E}\right)^{5.8}$$ (very rough estimation)

KamLAND2-Zen — Next-generation KamLAND-Zen



KamLAND2-Zen

Detector upgrade plan

- Light yield increase by
  - ➢ High light-yield scintillator (x1.4)
  - ➢ Light-correcting Winston cone on PMTs (x1.8)
  - ➢ High quantum efficiency PMT (x1.9)

✓ **5x increased effective light yield**
✓ **Twice better energy resolution@Q-value**
✓ **2νββ background reduction by order of 2.**

- New mini-balloon of scintillating material

✓ **Film-^{214}Bi rejection by α-tagging**
✓ **Expanding effective volume**

- State-of-the-art read-out electronics: MoGURA2
  - ➢ RFSoC powered data acquisition
  - ➢ Huge buffer for SN-burst detection

✓ **~100% spallation neutron detection**
✓ **More efficient L.L. tagging**

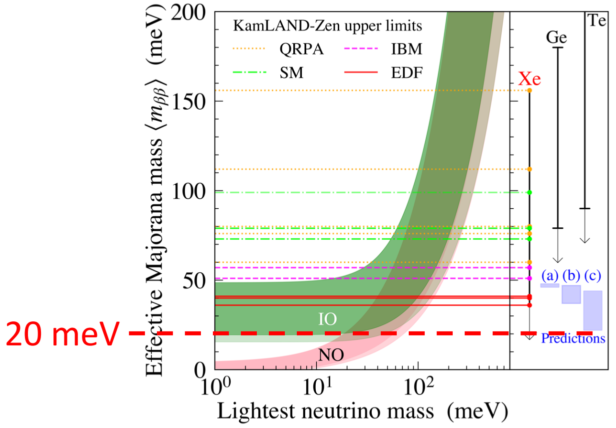
- Increased xenon: 745 kg → 1,000 kg

✓ **More xenon, more exposure.**

Target sensitivity

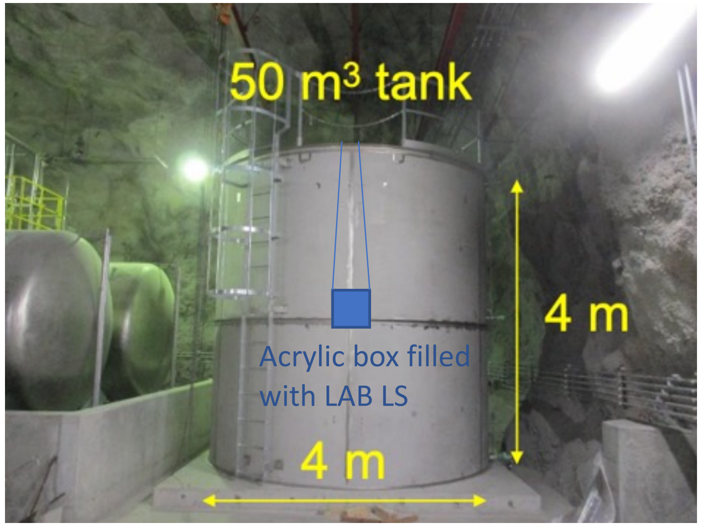
- The half-life : 2.0 × 10^{27} year
- $\langle m_{\beta\beta} \rangle \sim 20$ meV (in 10 years)

KamLAND2-Zen will be the first search to cover the inverted mass ordering region !!



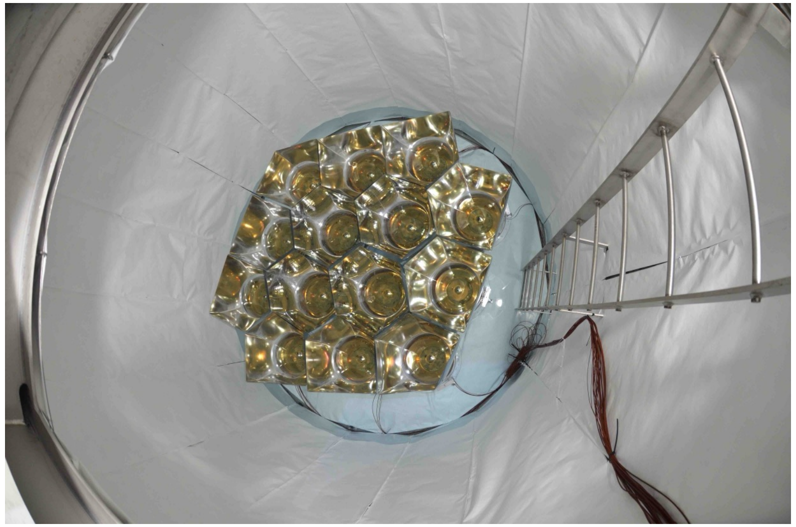
KamLAND2-Zen R&D in prototype detector

Tank overview



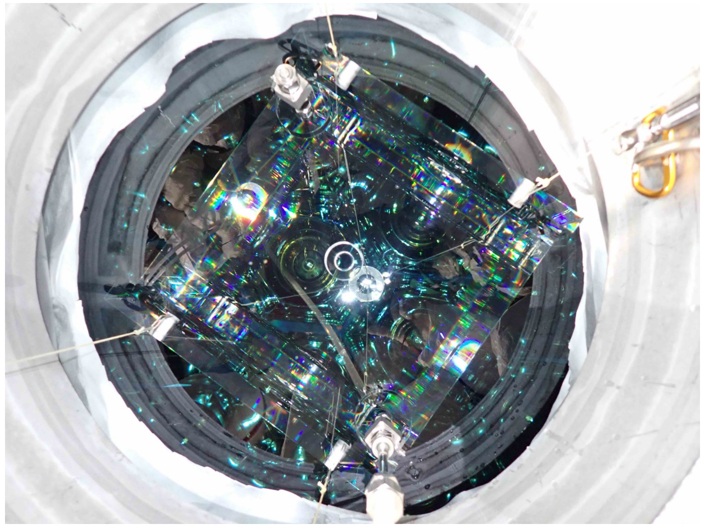
50 m^3 tank was built for benchmark of light-yield increase.

Tank inside view



14 High-QE PMTs were installed at the bottom of the tank with Winston cones. The tank is filled with filtered water.

LS-filled Acrylic box



LAB LS is filled into 30 cm x 30 cm x 30 cm acrylic box and installed at the center.

New read-out electronics is also tested in this detector.

The light-yield increase performance is under demonstration !!

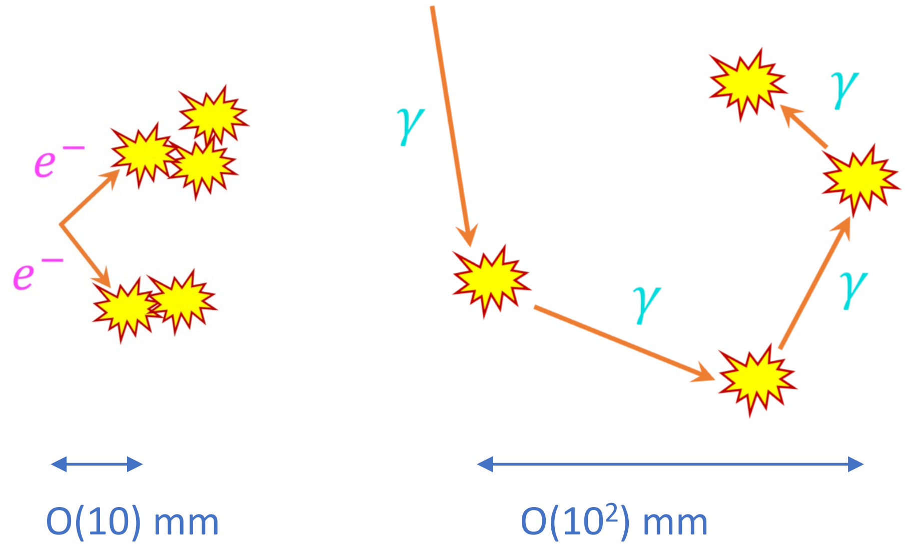
- radioactive source calibration
- long-term DAQ test

Me installing radioactive source very very very carefully

Imaging detector R&D: concept

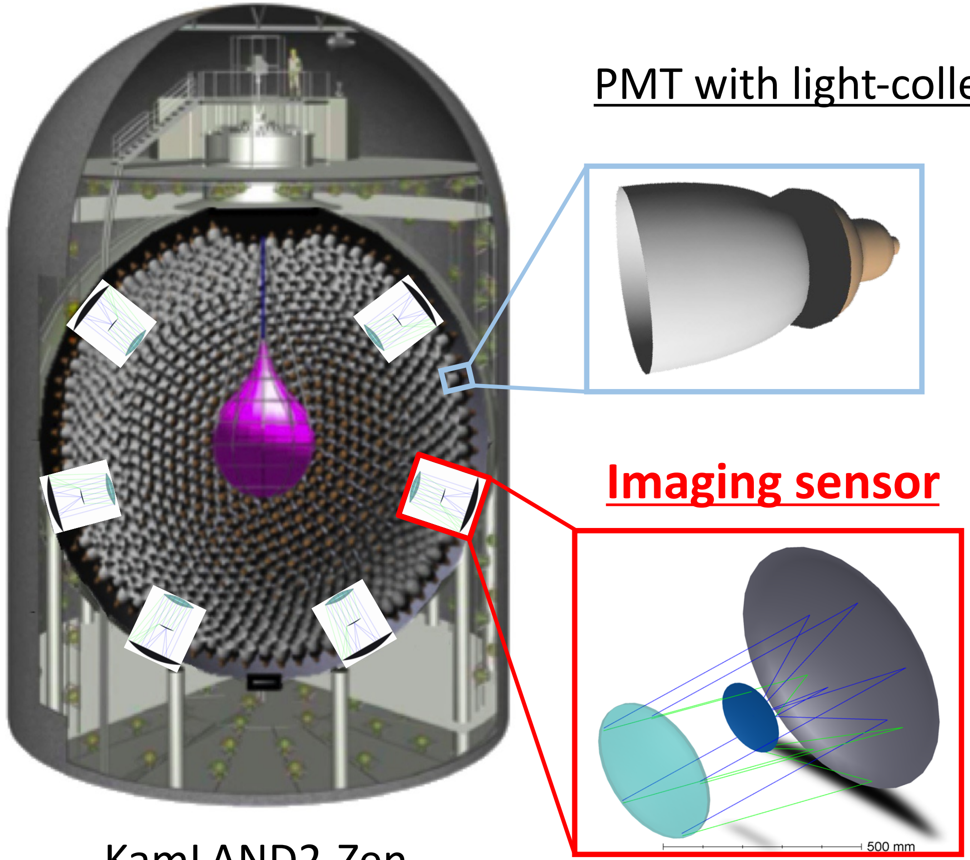
Difference in scintillation topology

pure β (0νββ, 2νββ)   β+γ (long-lived spallation)



Imaging "scintillation topology" is useful to separate pure β signal from γ-accompanied background.

KamLAND2-Zen design with imaging sensor



PMT with light-collecting winston cone

x1800
Event reconstruction
(vertex, energy)

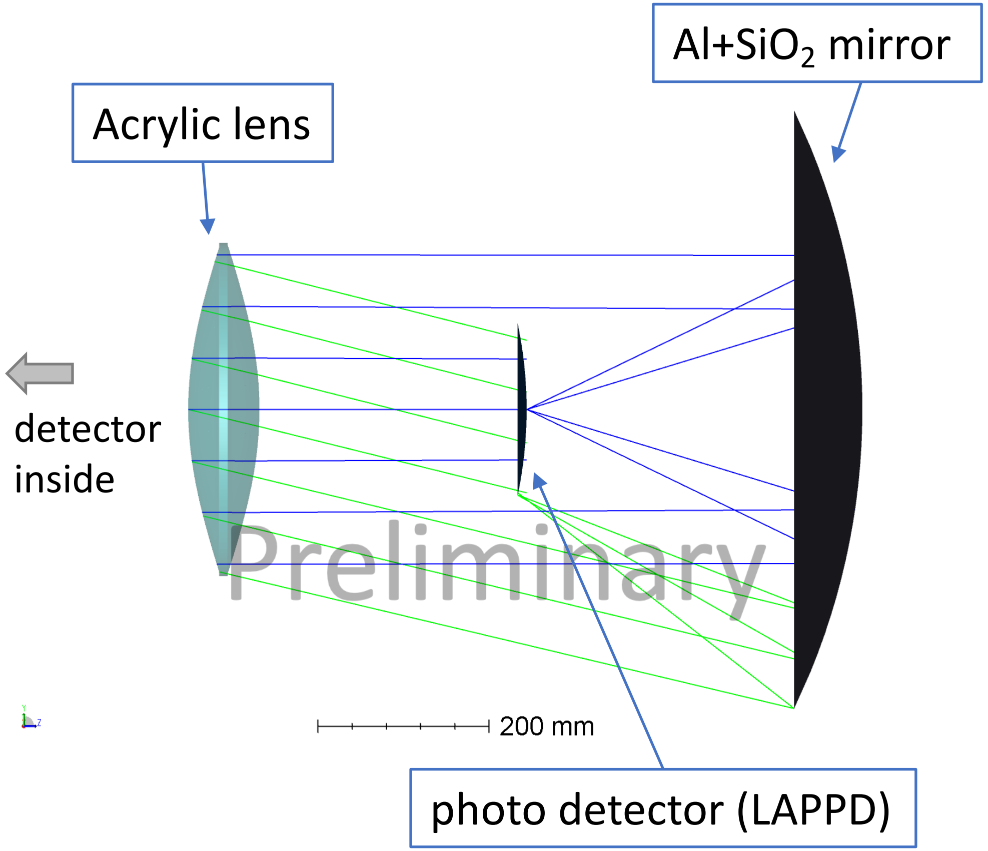
Imaging sensor

x100
PID

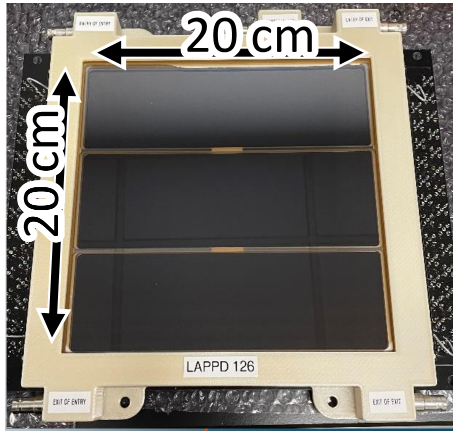
KamLAND2-Zen

Imaging detector R&D: sensor design

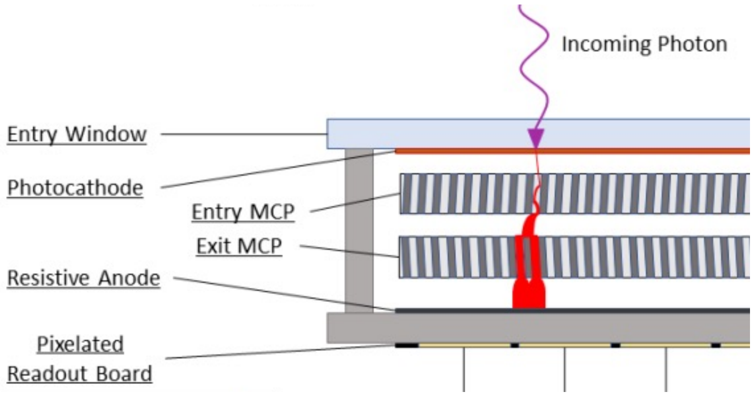
Components



Large-Area Picosecond Photo Detector (LAPPD)



8x8 pixelized



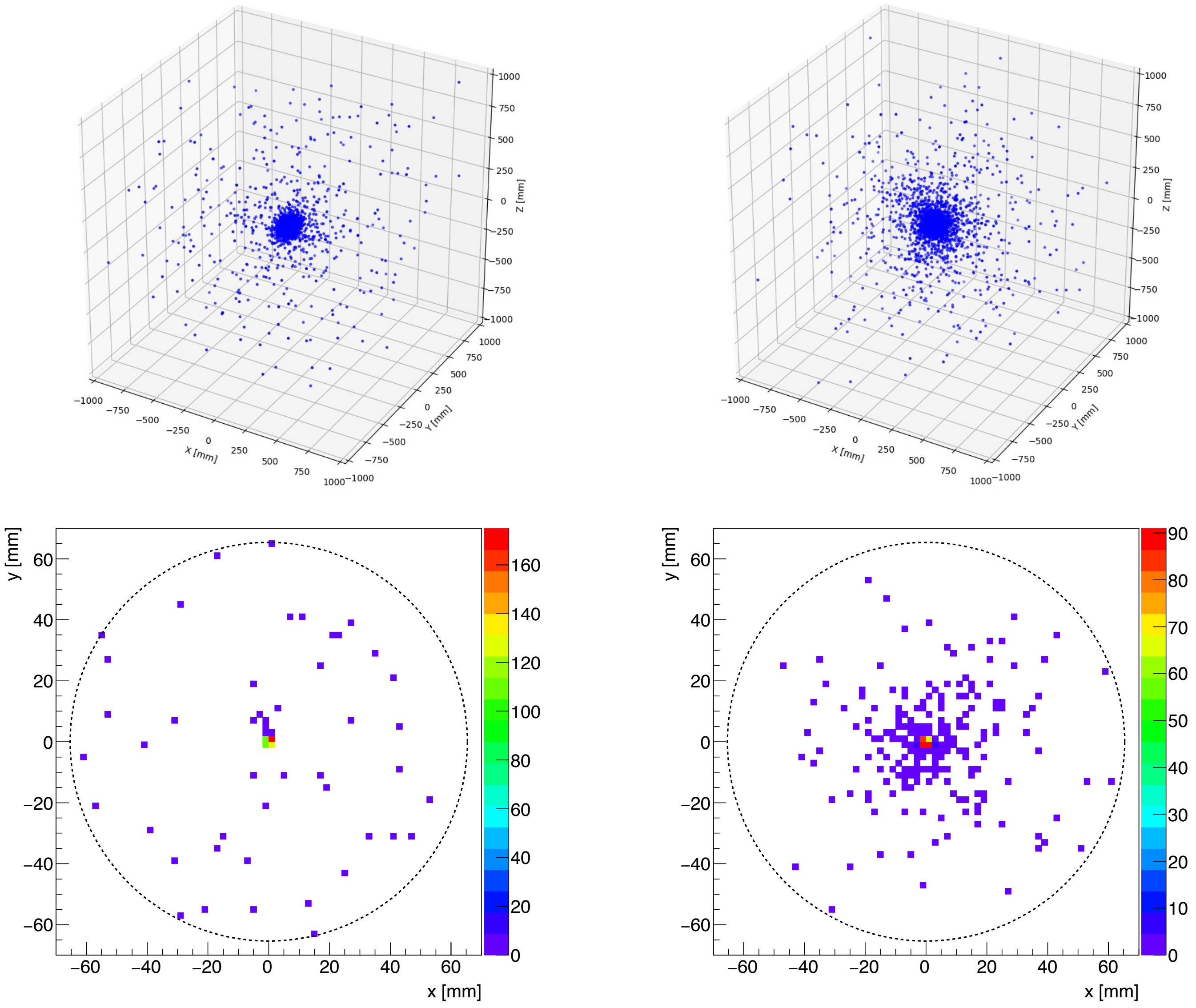
MCP = **M**ulti-**C**hannel **P**late

- High quantum efficiency@365 nm > 30%
- High position resolution ~1.3 mm
- High time resolution ~50 ns
- High gain ~10^7

Single photon detection with high time&position resolution is possible.

Imaging detector R&D: simulation study

pure β (e^- 2.5 MeV) β+γ (^{118}Sb)



Simulator

- GEANT4
  - https://geant4.web.cern.ch/
  - For KamLAND response
- ROBAST
  - https://robast.github.io/
  - Photon transport in image sensor

Result

Imaging sensor can find spread of photon-emission points in γ-accompanied event.

An detailed study revealed that

^{118}Sb 90% rejection would be achieved with only ~20% signal sacrifice.

Summary

- The latest result of the $0\nu\beta\beta$ search by KamLAND-Zen were reported.
  - $0\nu\beta\beta$ half-life lower limit (90% C.L.):
    - ➢ Zen400 : 0.9×10^{26} year
    - ➢ Zen800 : 2.0×10^{26} year
    - ➢ Combined : **2.3×10^{26} year**
  - **Effective Majorana mass limit (90% C.L.)**
    - ➢ $\langle m_{\beta\beta} \rangle < 36 - 156\ \mathrm{meV}$
- New analytical techniques are being developed for increased sensitivity.
- R&D for the future of KamLAND-Zen, "KamLAND2-Zen", is on-going !!

We are the KamLAND-Zen collaboration !!

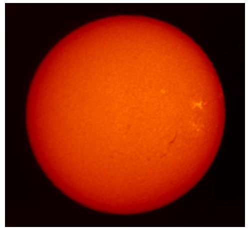
>50 researchers from US, Netherlands and Japan

TOHOKU UNIVERSITY
東京大学 THE UNIVERSITY OF TOKYO
大阪大学 OSAKA UNIVERSITY
VIRGINIA TECH.
BERKELEY LAB
THE UNIVERSITY OF TENNESSEE KNOXVILLE
BOSTON UNIVERSITY
Nikhef
TUNL
UNIVERSITY of HAWAI'I
TOKUSHIMA UNIVERSITY

Broad science objectives of KamLAND experiment

10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} Neurino energy [MeV]

Solar neutrinos



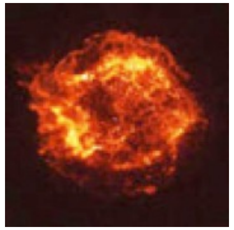
Solar mechanism
Evolution of slars
Neutrino astronomy

Reactor neutrinos

Neutrino oscillation

Nature of neutrinos

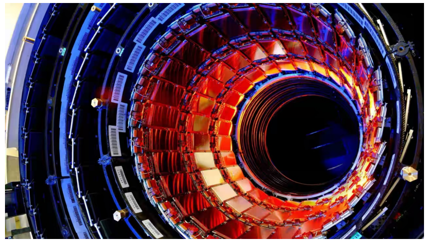
Astrophysical burst neutrinos



Supernova
GRB
Solar flare etc..

Neutrino astronomy

Accelerator neutrinos



CP violation in lepton sector

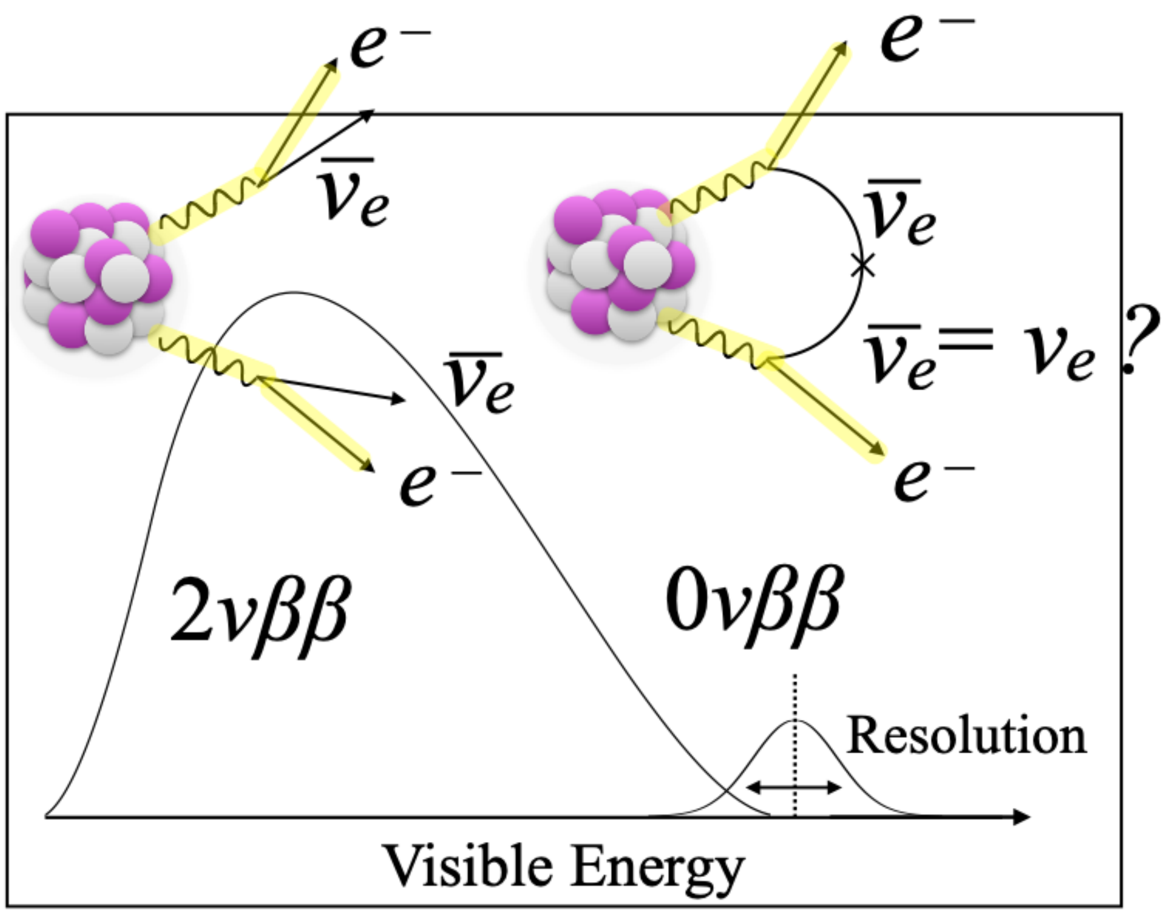
Geoneutrinos

Radioactivity and heat inside the Earth

Neutrino geoscience

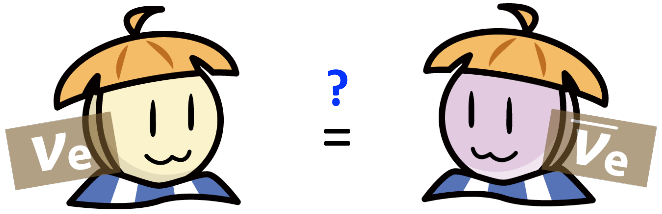
Neutrinos provide unique probe of particle physics, astronomy and geoscience.

Neutrinoless double-beta decay



Majorana neutrino

- Neutrino can be Majorana particle.



https://higgstan.com/

- Majorana neutrino is key componet of
  - Tiny neutrino mass (via SeeSaw mechanism)
  - Matter dominant universe (via Leptogenesis)

Neutrinoless double-beta decay (0νββ)

- It happens only if ν is Majorana particle.

  Proof of Majorana neutrino

- Experiment: peak search around the Q-value
- Requirements: large exposure, background reduction

  KamLAND is a suitable detector