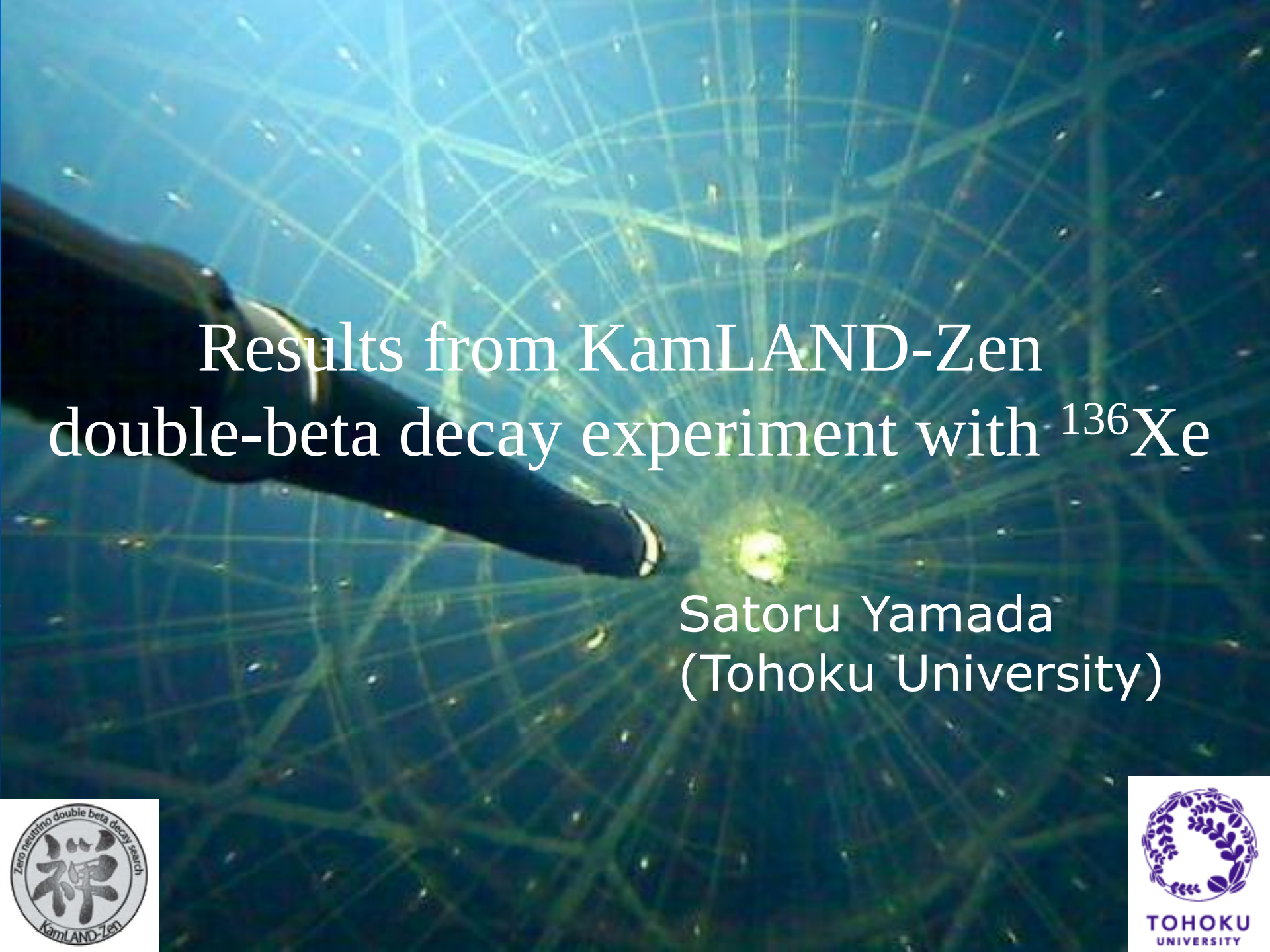
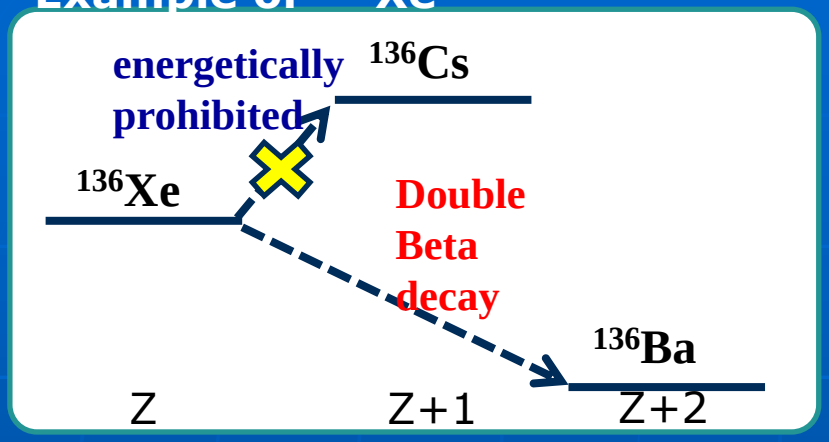


Results from KamLAND-Zen double-beta decay experiment with ^{136}Xe

Satoru Yamada
(Tohoku University)

Double beta decay

Example of ^{136}Xe



Possible two decay modes :

- 2 neutrino double beta decay:

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

- neutrinoless double beta decay:

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

If neutrinoless double beta decay occurs,

- Neutrino is a Majorana particle
  - Hint for See-saw mechanism, leptogenesis
- Lepton number violation
- Absolute mass of neutrino and neutrino mass hierarchy

Relation between $\langle m_{\beta\beta}\rangle$ and 0νββ decay half-life

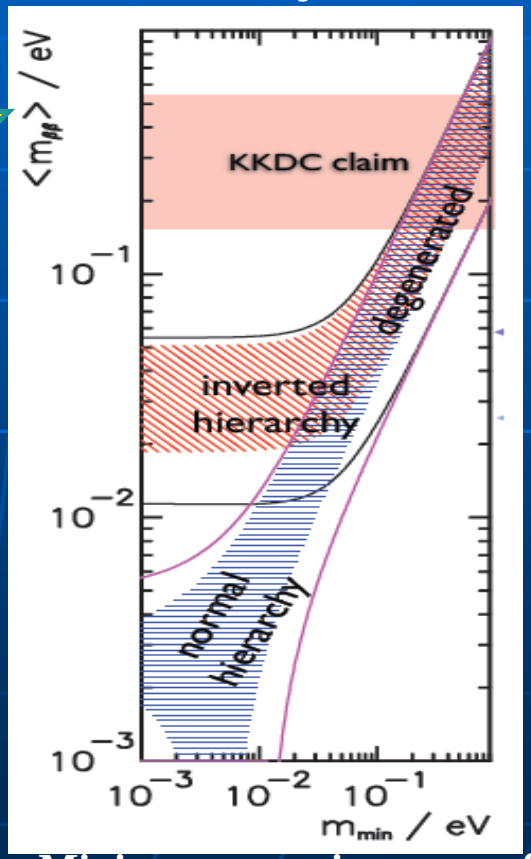
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M'^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

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

α_i Unknown Majorana phase

0νββ decay search

Mass hierarchy and effective Majorana mass

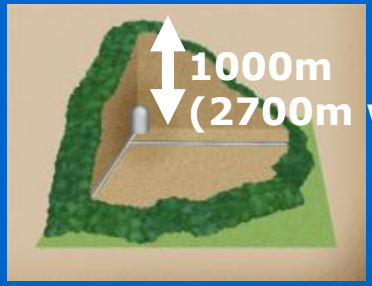


Minimum neutrino mass of the mass eigenstates

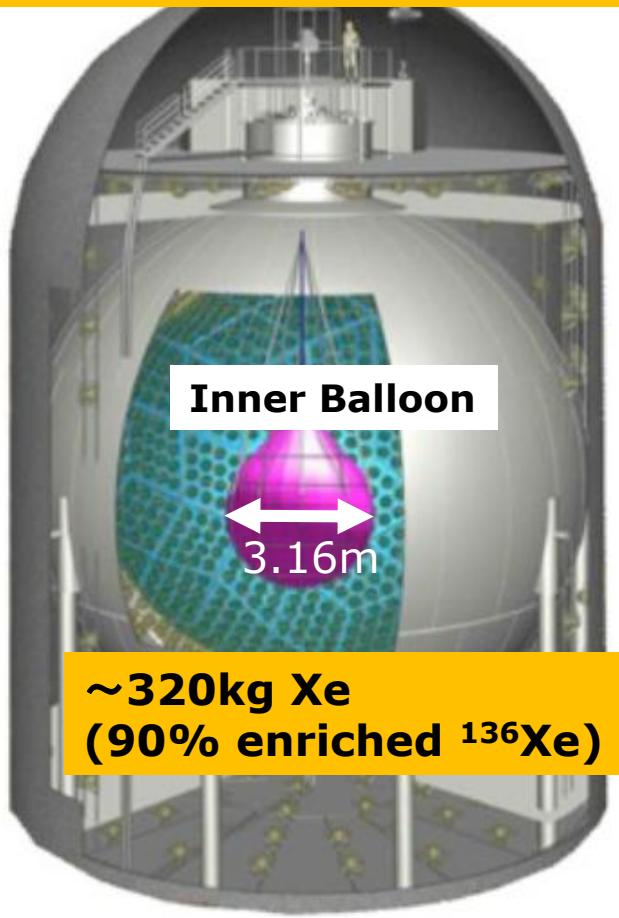
KamLAND-Zen detector

KamLAND-Zen experiment

KamLAND detector (1kton liquid scintillator(LS) and) and 1879 PMTs) + Xe-loaded liquid Scintillator



13 ton Xe loaded liquid Scintillator in an inner balloon(IB) was Installed in the current KamLAND detector



~320kg Xe (90% enriched ^{136}Xe)

0νββ search with KamLAND detector

Advantages

- Well-known detector response
- Surrounded by clean liquid scintillator as a good shield
- Large mass experiment, scalability

Demerits

- Not good energy resolution ($6.6\%/\sqrt{E}$ @ 2.6MeV)
- No particle identification for signal β and b.g. γ

^{136}Xe as a target ββ nucleus

- Soluble to liquid scintillator (up to 3wt%)
- Established enrichment method
- Relatively slow 2νββ decay

Target of 1st phase : $\langle m_{\beta\beta} \rangle$ ~80meV (KKDC claim, degenerated)
Future upgrade plan : $\langle m_{\beta\beta} \rangle$ ~20meV

KamLAND-Zen collaboration

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B.E. Berger (Colorado State university), Y. Efremenko (University of Tennessee),
S. Enomoto (University of Washington), and M.P. Decowski (NIKHEF)

Construction of inner-balloon

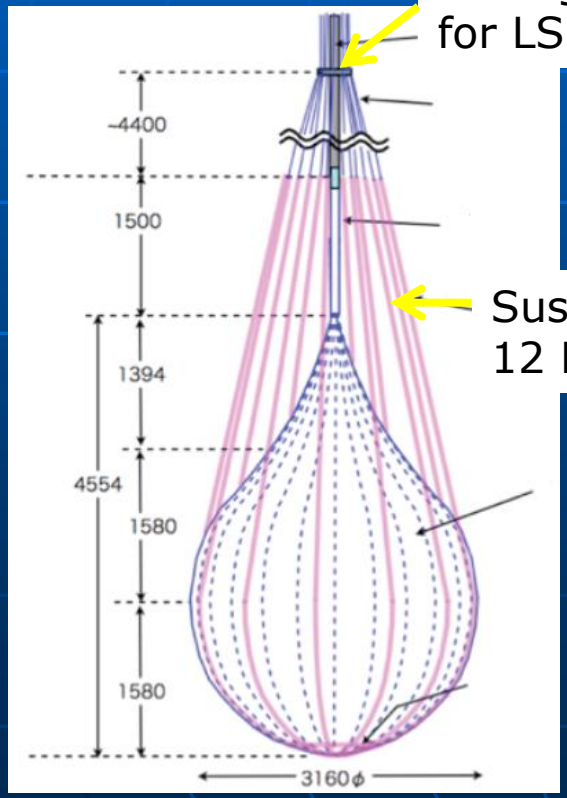
Balloon film

- **25um Nylon film (c.f. KamLAND balloon film = 135um)**
- **Low radioactivity (specially made without filler)**

Product analysis of the film

- ^{232}U : 2×10^{-12}g/g
- ^{226}Th: 3×10^{-12}g/g
- ^{40}K : 2×10^{-12}g/g

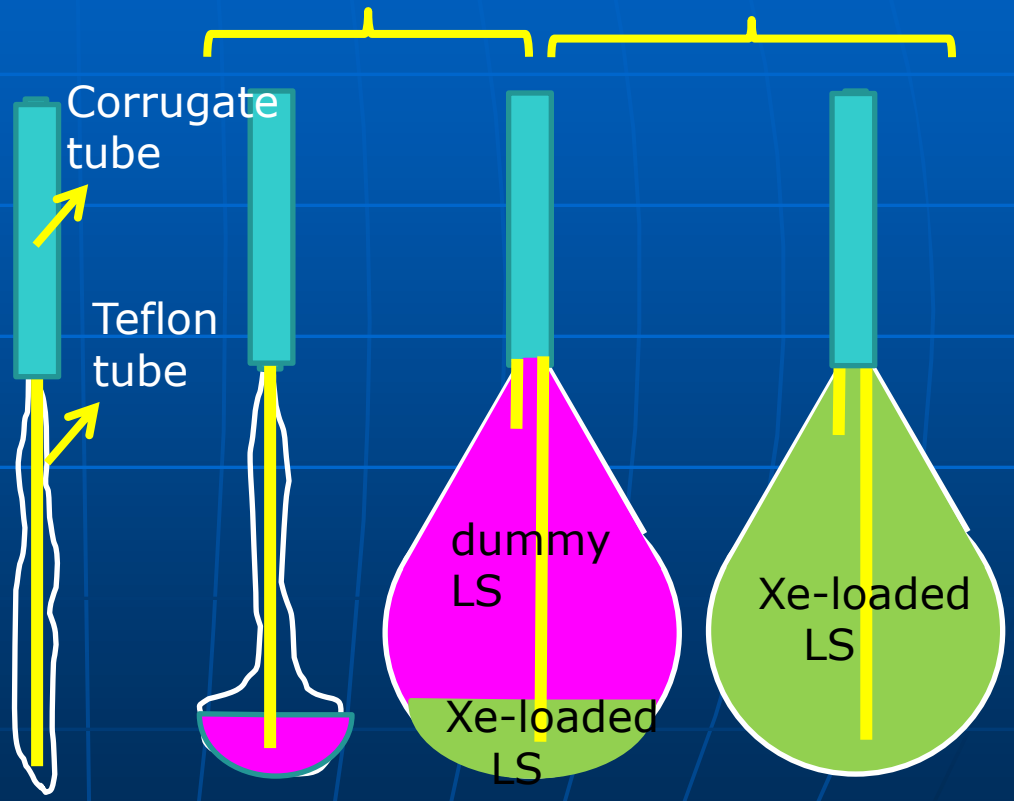
Fabricated in a super clean room (class1)



Installation of inner-balloon

- Dummy-LS(w/o Xe) was filled to inflate the inner-balloon and check there was no problem.

- Dummy-LS was replaced with Xe-LS.



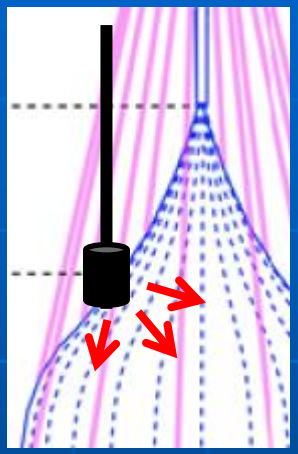
KamLAND-Zen data and 2vββ decay

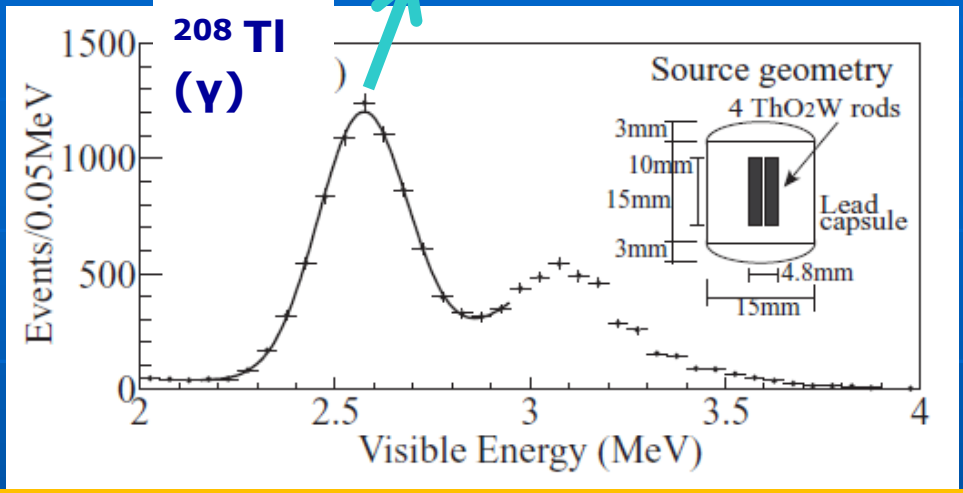
Energy Calibration

Three types of calibration data were used.

1, calibration source

^{208}Tl gamma ray from ThO_2W source installed on the inner balloon surface.





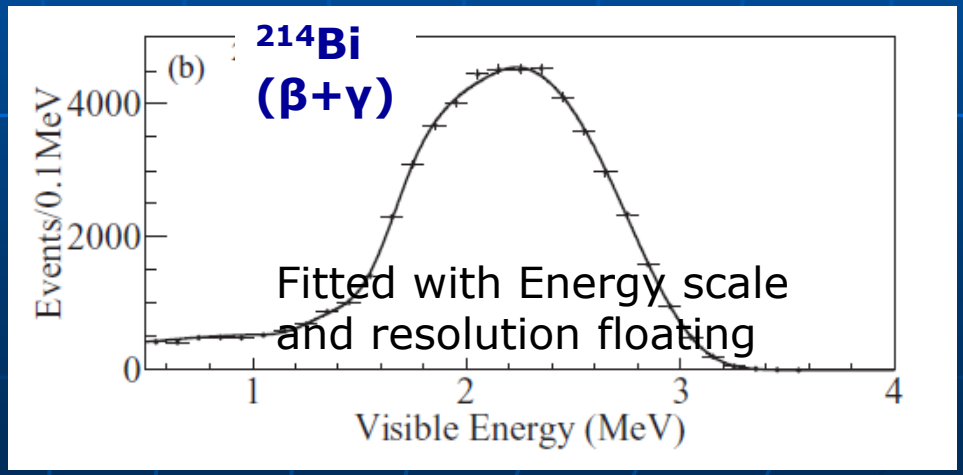
Energy resolution : (6.6 ± 0.3)%/ √E(MeV)
@ 2.614MeV

2, radio impurities in Xe-LS

^{214}Bi beta and gamma ray : From ^{222}Rn inside Xe-LS

3, muon-spallation product

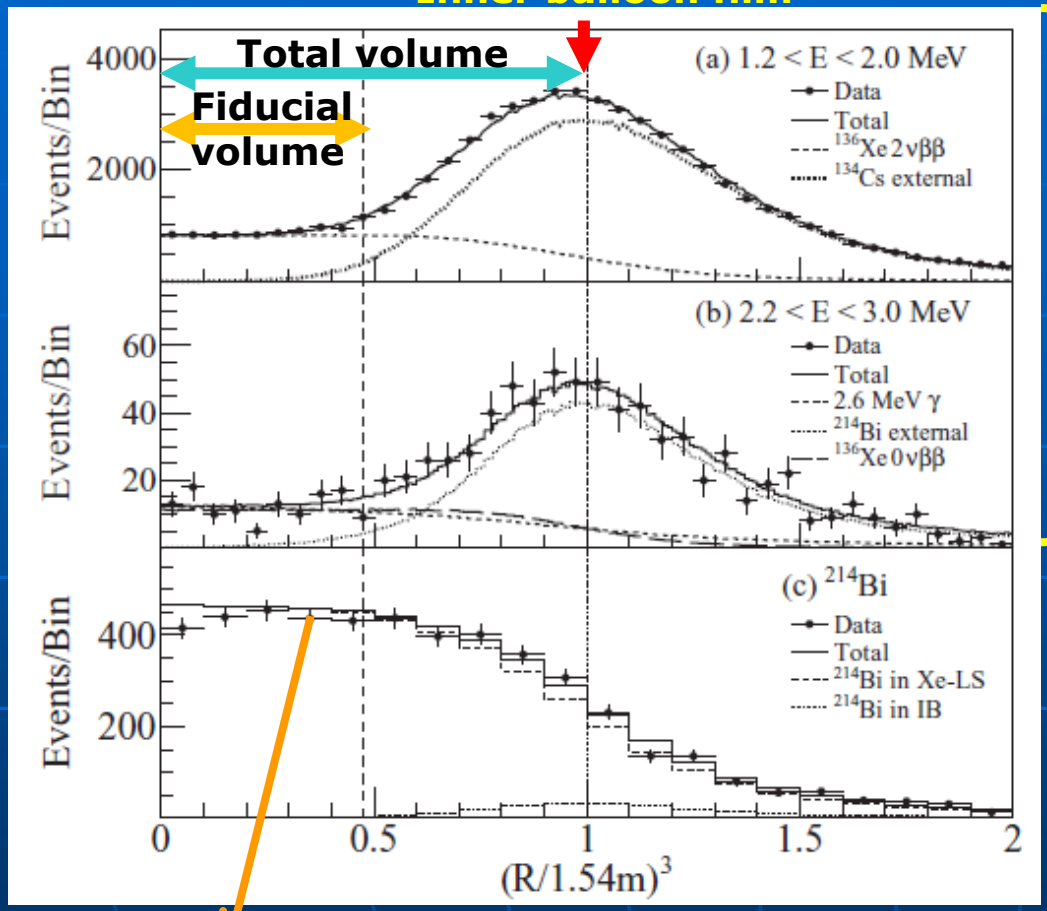
Neutron captured gamma (2.225MeV)



Systematic error of ββ halflife due to detector energy scale = 0.3%

Fiducial volume

R-cubic distribution of events



Size

Fiducial volume R < 1.2m

^{214}Bi from inner-balloon limited the fiducial volume.

The amount of ^{214}Bi is about 8 times larger than expected from the product analysis of the balloon film.

From the energy spectrum of tagged ^{214}Po,
The impurities are likely on the balloon film surface, not inside the film.

Systematic error for ββ decay half-life measurement

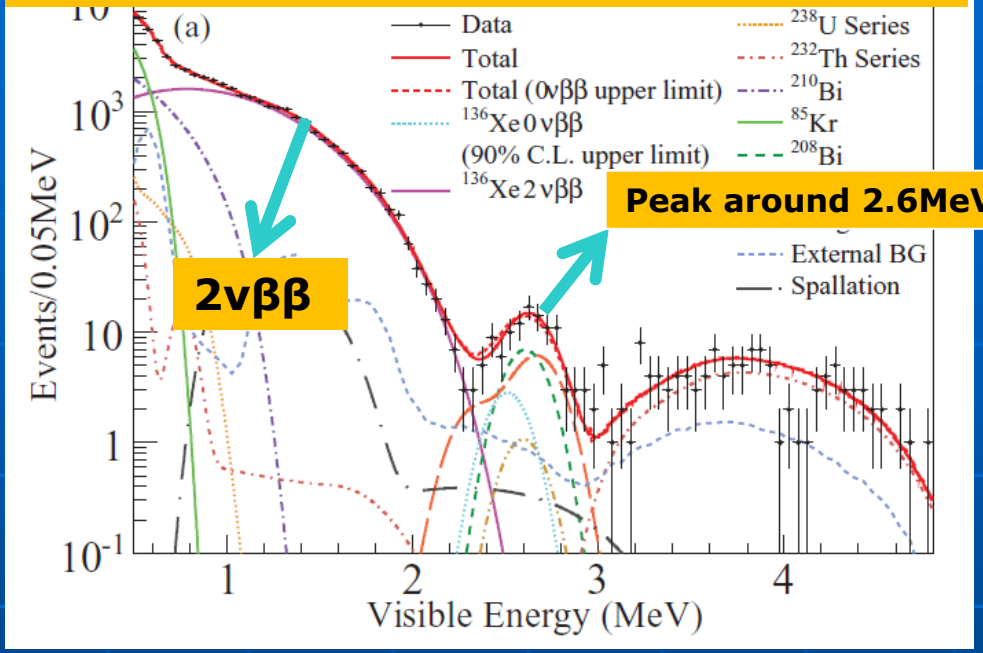
Systematic error of fid. Volume was estimated by checking ^{214}Bi event rate inside the inner-balloon.
=> **5.2%** (dominant in total systematic error : total = 5.2%)

Result of 2νββ decay halflife

Event selection

- Fiducial cut : R<1.2m
- 2ms veto after muon
- remove consecutive events within 3ms for Bi-Po rejection(99.97% rejection for ^{214}Bi)
- Anti-nu CC reaction cut
- vertex-time-charge test to cut noise events

Energy spectrum after event selection



2νββ life

	exposure	2νββ life
1st result Phys.Rev.C85,045504(2012)	77.6days 129kg of ^{136}Xe	2.38±0.02(stat.)±0.14(sys.) ×10^{21} yrs.
Updated Result arXiv:1205.6372	112.3days 125kg of ^{136}Xe	2.30±0.02(stat.)±0.12(sys.) ×10^{21} yrs.

Consistent with the EXO-200 results arXiv:1205.5608
($T_{1/2}$=2.23±0.017(stat)±0.22(syst) ×10^{21} years)

0νββ decay and its background

Peak around 2.6MeV region

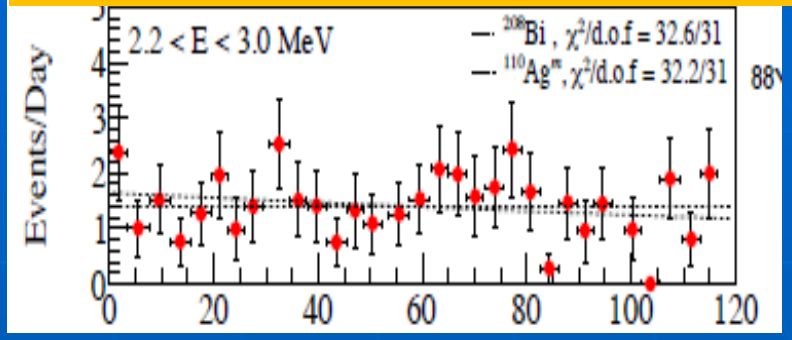
Features

- ◆ No significant decrease during 112days

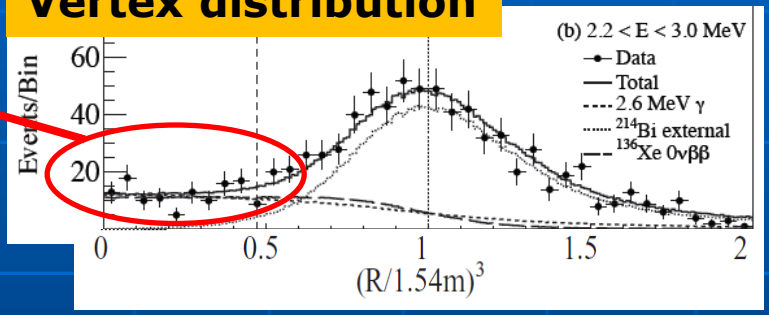
-> Long-lived radioactivity
or muon spallation product in the detector

- ◆ Uniformly distributed over Xe-LS

Time dependence over 112days



Vertex distribution



Short-lived nuclei due to muon-spallation in the detector

- ➢ Up to 100s from Muon events
- Check coincident events with muon in KamLAND-Zen data

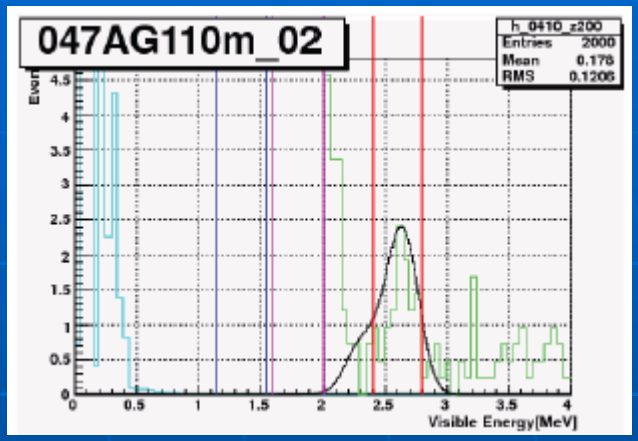
-> negligible

- ➢ Lifetime from 100s to 30days :
- Using ENSDF(Evaluated Nuclear Structure Data File) database and cross-section data, we found no unstable nuclei to reproduce the observed energy spectrum.

long-lived radioactive impurities (life > 30days)

- Use decay information from ENSDF (http://ie.lbl.gov/databases/ensdfserve.html)
- We traced the paths from beta-, beta+ and EC decays and cascade gammas, and made expected visible energy spectra in KamLAND
- Search a peak within 2.4-2.8MeV by eye.
- Apply short lifetime cut (life < 30days).
- Exclude spectra with a higher energy peak (E>2.6MeV) , which cannot reproduce the KamLAND-Zen measured spectrum.

Example of expected spectrum



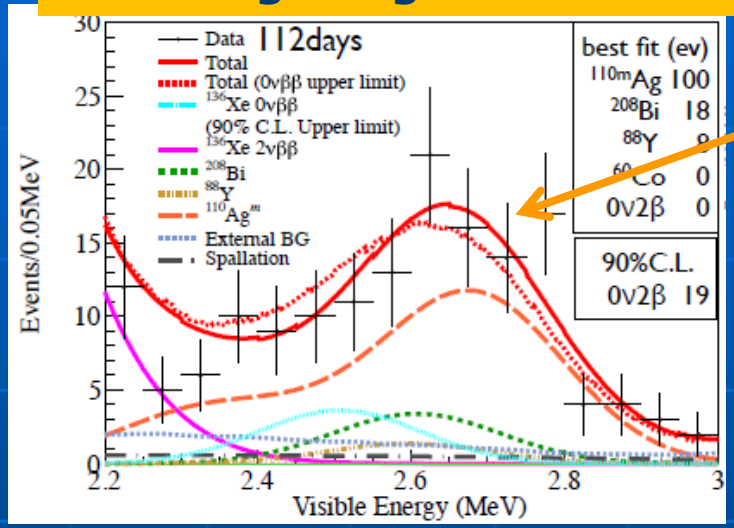
Remaining 4 candidates

	Decay	life	Q[MeV]
^{110m}Ag	$\beta^- + \gamma$	360days	3.01
^{88}Y	EC + γ	154days	3.62
^{208}Bi	EC + γ	5.31×10^5 yrs.	2.88
^{60}Co	$\beta^- + \gamma$	7.61 yrs.	2.82

Limit on 0νββ decay

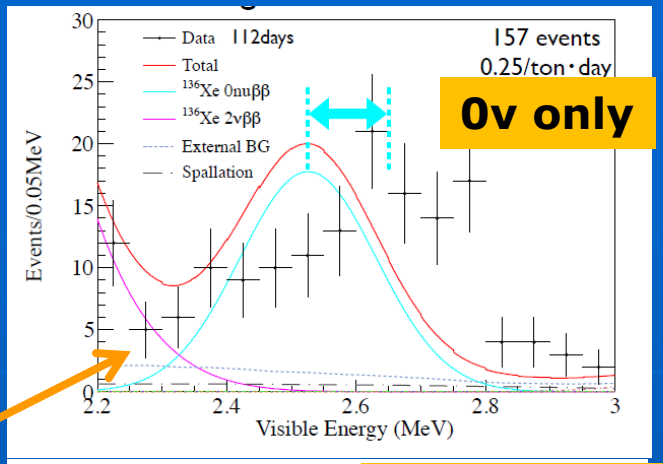
112.3days measurement

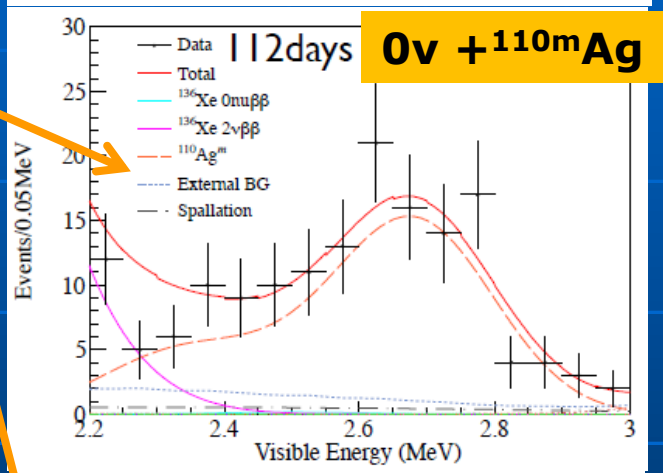
Including 4 b.g. candidates

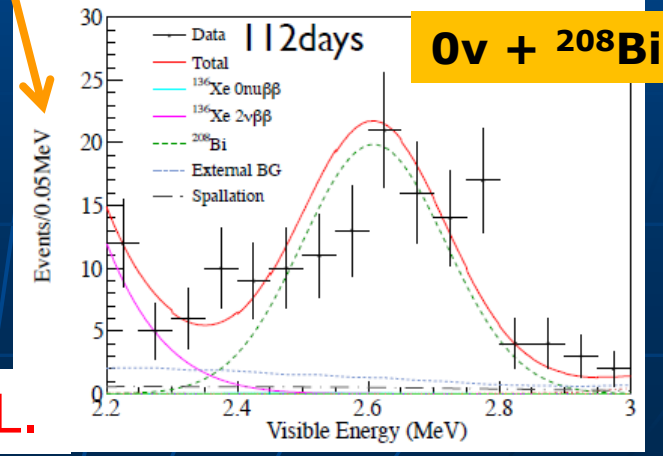


E=2.2-3.0MeV

	χ^2
0ν + 4b.g. candidates	11.6
0ν only	85
0ν + ^{110m}Ag	13.1
0ν + ^{208}Bi	22.7
0ν + ^{88}Y	22.2
0ν + ^{60}Co	82.9







^{110m}Ag is favored to explain the 2.6MeV peak.

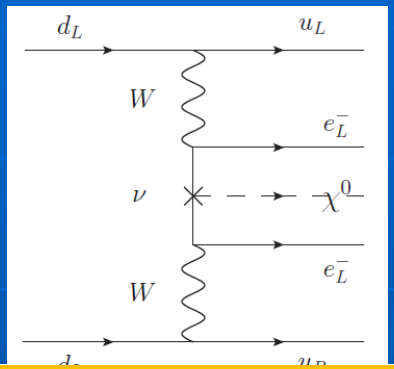
Lower limit for ^{136}Xe 0νββ decay half life

	exposure	0νββ limit
Updated Result arXiv:1205.6372	**112.3days 125kg of 136Xe**	**> 6.2×10^{24} yrs. (90% C.L.)**

Upper limit $\langle m_{\beta\beta}\rangle$<0.26~0.54 eV @90% C.L.

Limits on Majoron-emitting 0νββ decay

Majoron-emitting 0νββ decay mode



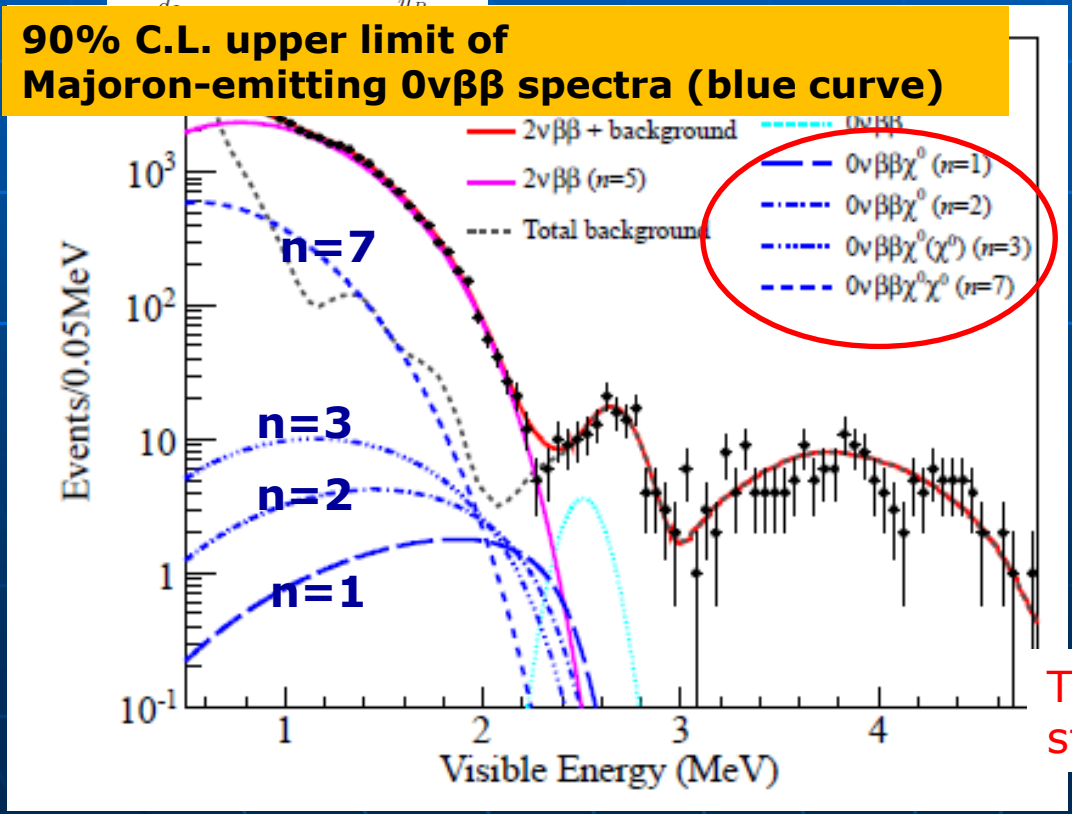
Spectral index n is model-dependent and the expected spectrum differs from the 2νββ spectrum.

Phase space factor

$$G = \pi \int (Q_{\beta\beta} - \varepsilon_1 - \varepsilon_2)^n \prod_k p_k \varepsilon_k f(\varepsilon_k) d\varepsilon_k$$

Using KamLAND-Zen spectrum of 2νββ energy region, we can limit the rate of Majoron-emitting 0νββ decay.

90% C.L. upper limit of Majoron-emitting 0νββ spectra (blue curve)



Ordinary (spectral index n = 1) Majoron-emitting decay of ^{136}Xe

$T_{1/2} > 2.6 \times 10^{24}$ years

for $0\nu2\beta\chi^0$ (one Majoron emission)

$$T_{1/2}^{-1} = |\langle g_{ee} \rangle|^2 \, |M|^2 G$$

$\langle g_{ee} \rangle$: effective coupling constant of the Majoron to the neutrino

$\langle g_{ee} \rangle < (0.8\text{-}1.6) \times 10^{-5}$

This result is a factor of five more stringent limit than the previous one.

Possible b.g. sources for the 2.6MeV peak

Fukushima fallout

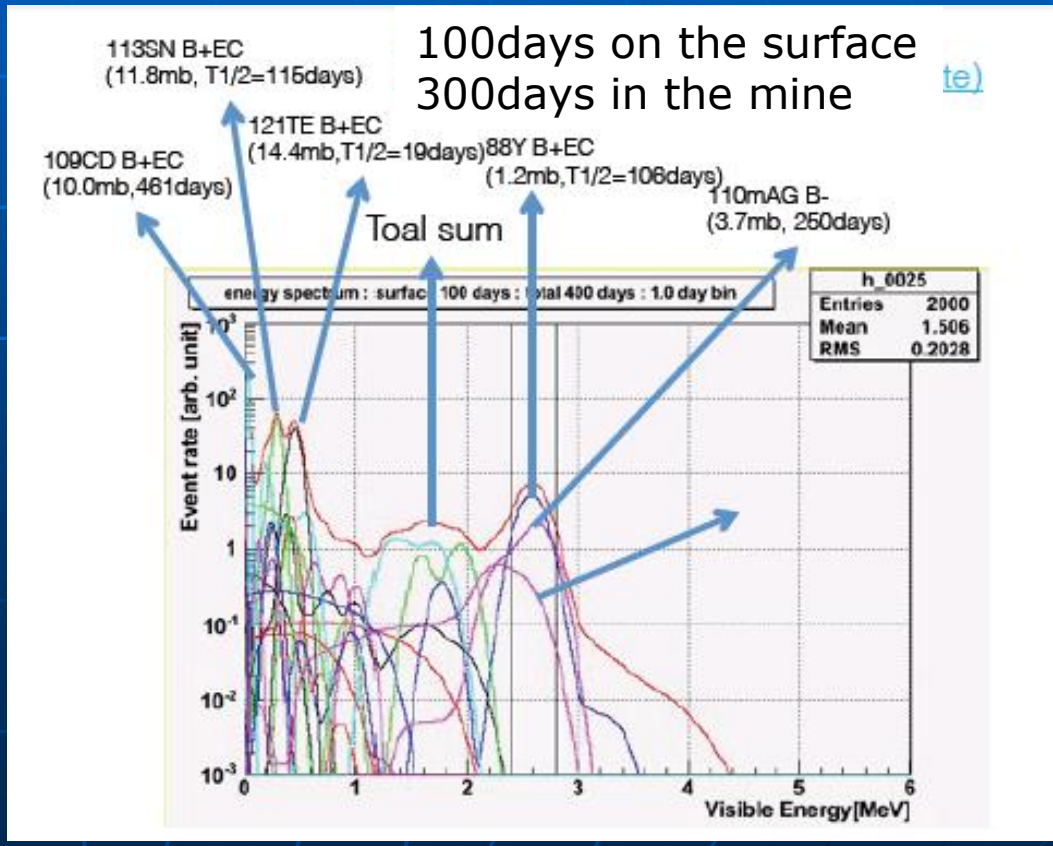
- ^{137}Cs, ^{134}Cs, ^{110m}Ag and ^{88}Y were found in soil sample near Fukushima.
- ^{137}Cs and ^{134}Cs were found on Balloon film.
  - The ratio of ^{134}Cs to ^{137}Cs (~0.8) is consistent with that measured in Fukushima soil sample.

Spallation on ^{136}Xe on surface

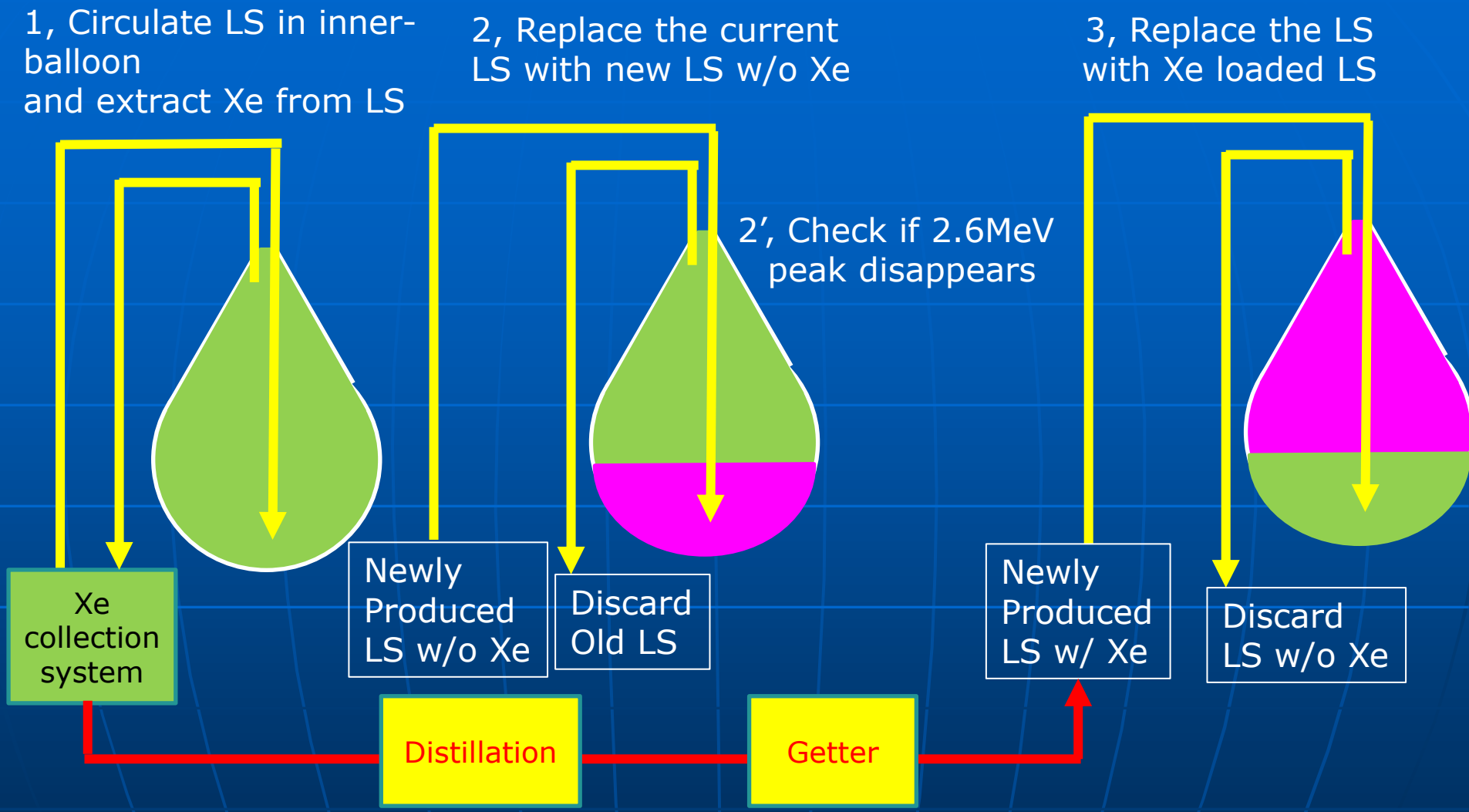
- After enrichment in Russia, ^{136}Xe gas cylinders were transported by air to Japan. They were placed on the surface for a few months.

-> Cosmic ray spallation may produce radioactive nuclei.

- It is easier to explain the uniform distribution in the inner-balloon, when considiering radio impurities of ^{136}Xe gas.
- Using the cross-section data of 1GeV proton + ^{136}Xe, energy spectra of spallation products were calculated (right figure)



Purification work is ongoing



TARGET:
More than factor 100 reduction of the 2.6MeV peak

Summary

- KamLAND-Zen is a neutrino-less double beta decay experiment using enriched ^{136}Xe loaded liquid scintillator. An inner-balloon was installed inside the current KamLAND detector and data-taking was started on September, 2011.

- With an exposure of 112.3days and 125kg of ^{136}Xe, the measured 2νββ decay half-life is $2.30 \pm 0.02(\text{stat.}) \pm 0.12(\text{sys.}) \times 10^{21}$ yrs, which is consistent with EXO-200's result.

- There is a peak near the 0νββ energy region.
The data were fitted with the spectra of 4 long-lived radioactive nuclei and the obtained lower limit of the 0νββ decay half-life (90% C.L.) is 6.2×10^{24} yr, which corresponds to $\langle m_{\beta\beta} \rangle < 0.26 \sim 0.54$ eV

- Set a new constraint on the Majoron emitting 0νββ decay.

- Purification of Xe-loaded liquid scintillator is on-going. We aim at the reduction to 1% for the 2.6MeV peak.