The Status of KamLAND-Zen for Neutrinoless Double Beta Decay of ^{136}Xe

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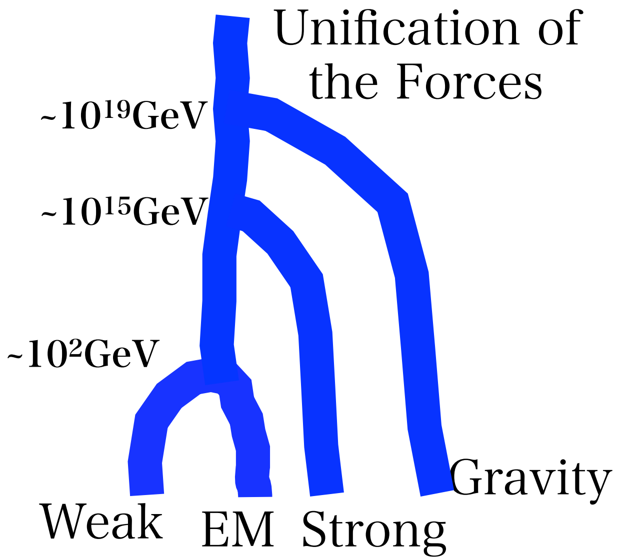
Moscow State University, Aug.22-28, 2013.

$M_\nu \neq 0$ Beyond the SM

$\Leftrightarrow$ $\nu = \bar{\nu}$ (Majorana) or $\nu \neq \bar{\nu}$ (Dirac)

Physics of super-high energies,
Cosmology, etc.



$0\nu\beta\beta$ unique and feasible way to check the Majorana nature of ν s.

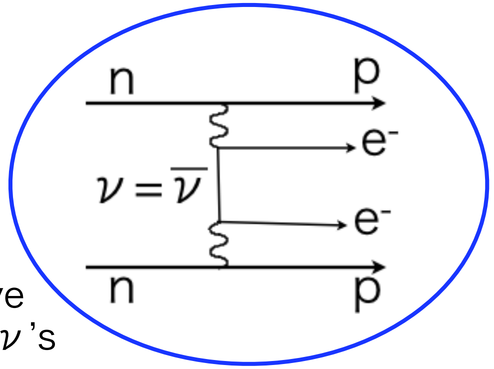
- Total lepton number non-conservation

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

  Phase space factor ($G^{0\nu}$), Nuclear Matrix Element ($M^{0\nu}$)

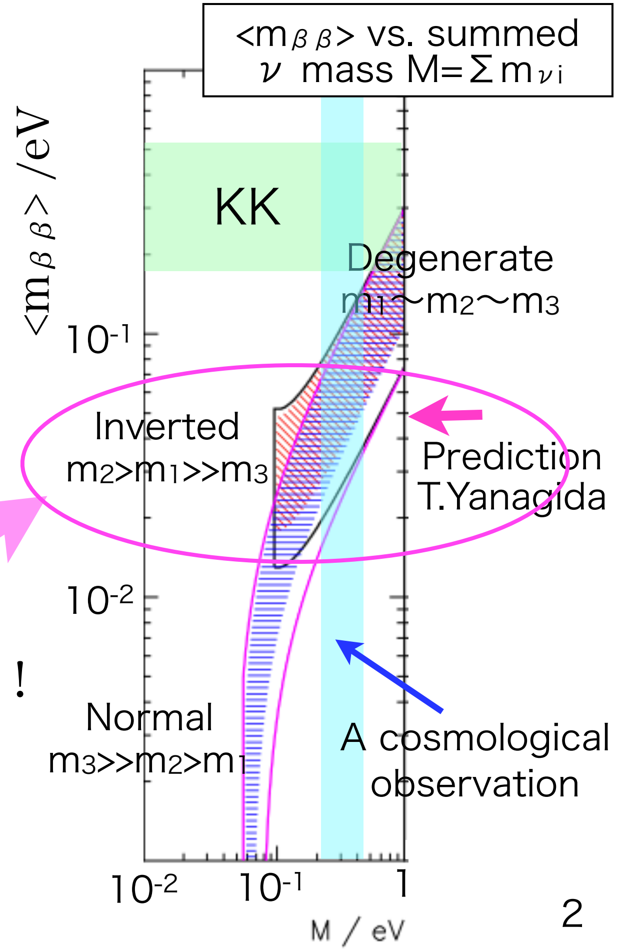
  $$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$

  Effective mass of ν's



Absolute ν mass scale.
ν mass hierarchy.

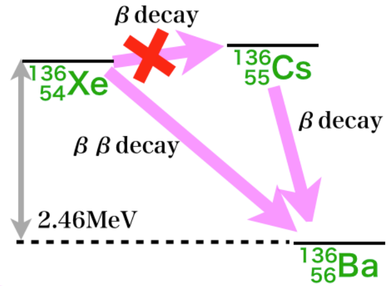
To reach the inverted region is very important !



No positive results except for a claim for ^{76}Ge.

Planned or ongoing experiments : **Large mass > O(100) kg in ultra-clean environment.**

^{136}Xe is attractive for $0\nu\beta\beta$ search



↔ ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{150}Nd
($Q_{\beta\beta}$>2MeV)

^{136}Xe

$Q_{\beta\beta}$=2.458MeV
Nat.ab.=8.9%
$T_{1/2}^{2\nu} = 2.2\times10^{21}$ y **(EXO, KL-Zen)**

Relatively high $Q_{\beta\beta}$,
High natural abundance,
Longest $2\nu\beta\beta$ half life among the known $\beta\beta$ nuclei.

Noble gas

Chemically stable.
Highly safe (Non-toxic, Non-flammable) and easy to handle.

Very friendly to human!

Large solubility to LS (>3 wt%) to make scale-up to O(1)ton.
Easily separated by N_2 flashing to retry measurement and do blank run.

Very friendly to us!

Established techniques for Isotopic separation & Purification.

Very friendly to physicists!

^{136}Xe is highly flexible, and a combination with a large volume LS detector like KamLAND is a good strategy!

KamLAND-Zen Collaboration

9 Institutes
~40 physicists

RCNS, Tohoku Univ. : A.Gando, Y.gando, H.Hanakago, H.Ikeda, K.Inoue, K.ishidoshiro, R.Kato, M.Koga, S.Matsuda, T.Mitsui, D.Motoki, T.Nakada, K.Nakamura, A.Obata, A.Oki, Y.Ono, M.Otani, I.Shimizu, J.Shirai, A.Suzuki, Y.Takemoto, K.Tamae, K.Ueshima, H.Watanabe, B.D.Xu, S.Yamada, H.Yoshida

Kavli IPMU, Univ. of Tokyo : A.Kozlov

Osaka University : S.Yoshida

Univ. of California, Berkeley : T.I.Banks, S.J.Freedman, B.K.Fujikawa, K.Han, T.O'Donnell

Colorado State Univ. : B.E.Berger

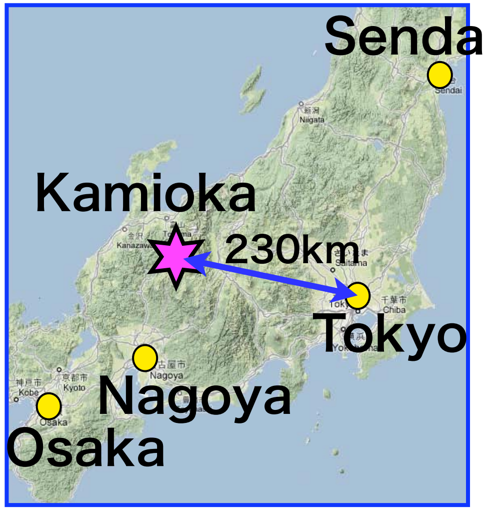
TUNL : H.J.Karwowski, D.M.Markoff, W.Tornow

Univ. of Washington : S.Enomoto

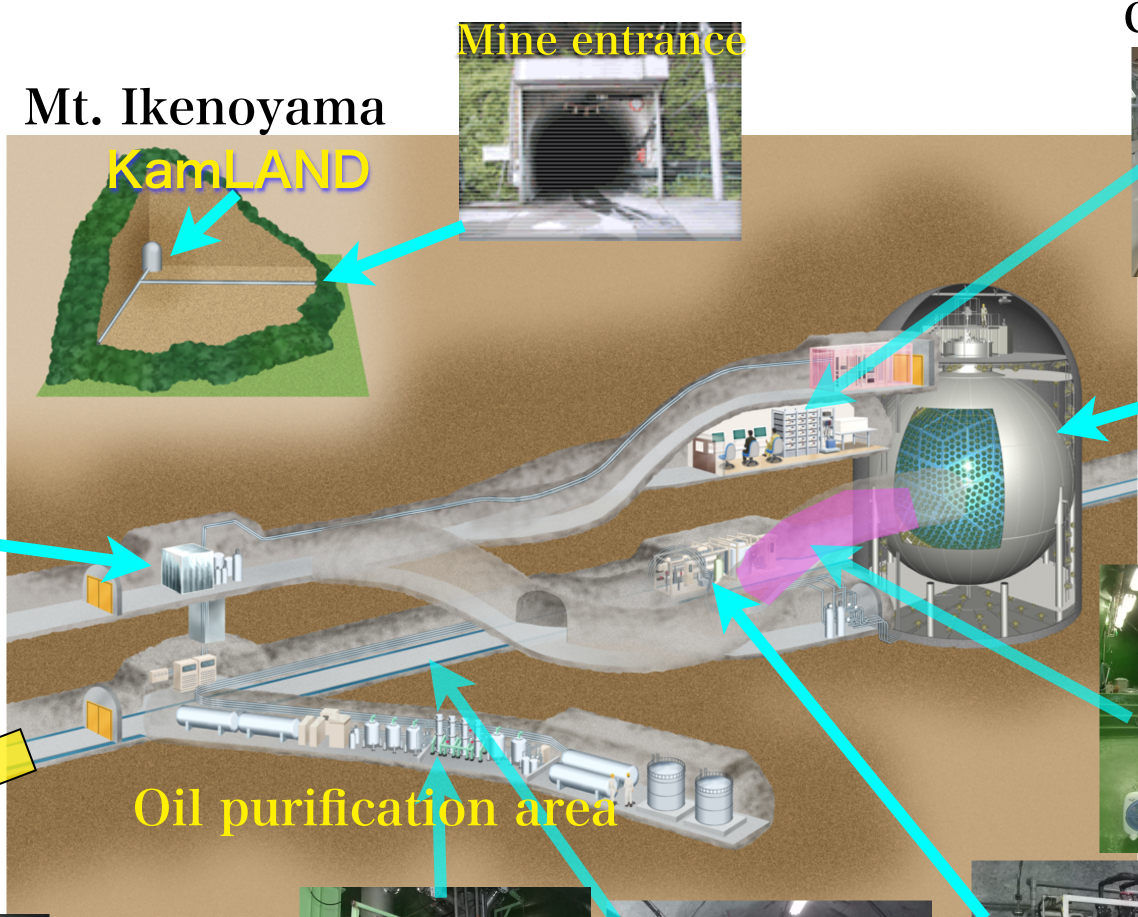
Univ. of Tennessee : Y.Efremenko

NIKHEF, Univ. of Amsterdam : M.P.Decowski

Location of the KamLAND

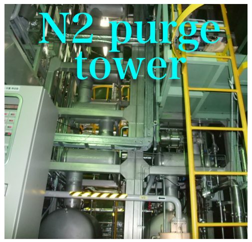


Location : 1000m (2,700m w.e.) deep underground in Kamioka mine, Gifu prefecture. The former Kamiokande cite. Cosmic ray flux : 100,000 times less than the ground level.



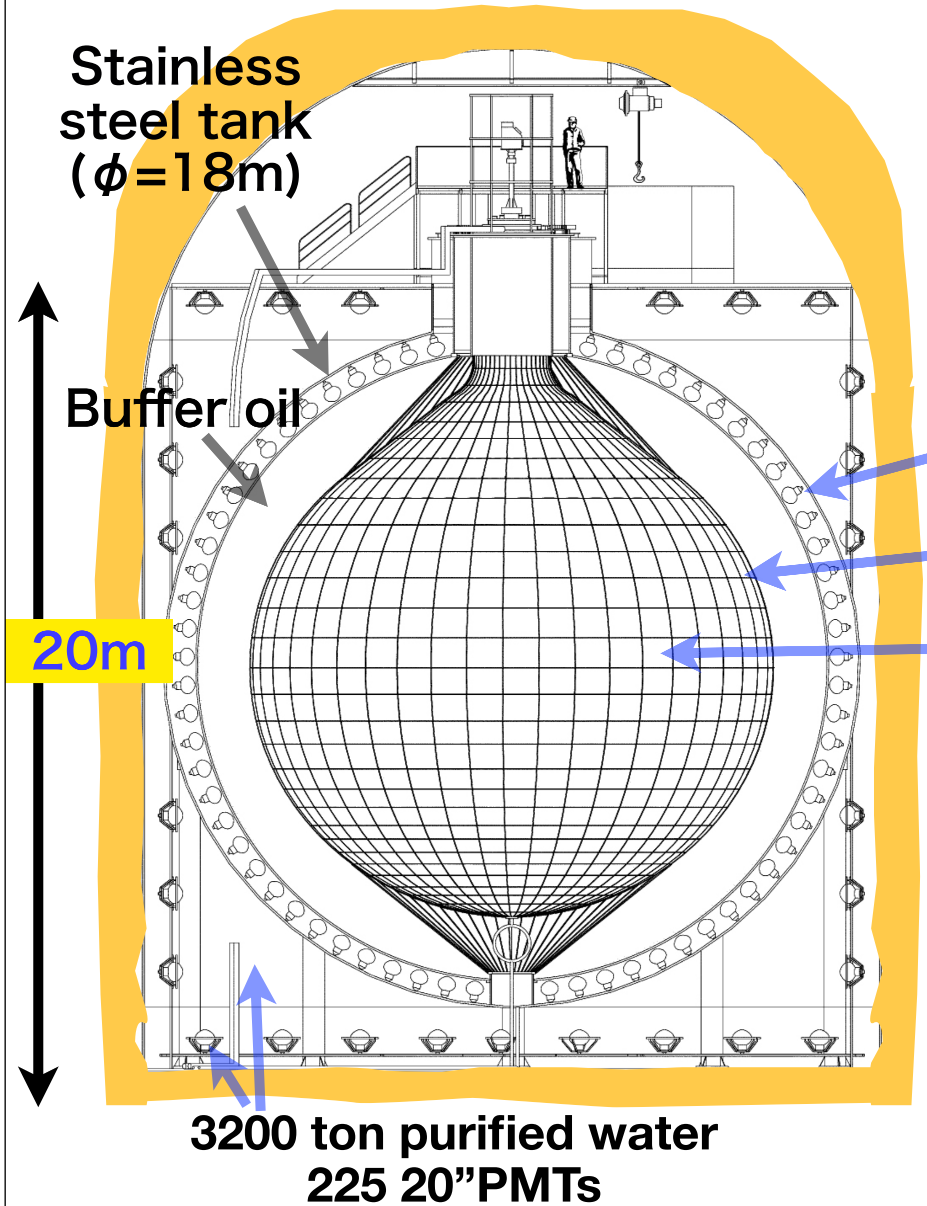
Control room

KamLAND Detector

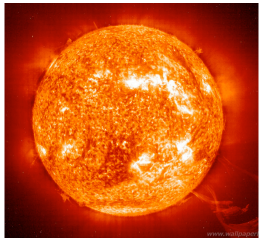


KamLAND detector

Kamioka Liquid scintillator Anti-Neutrino Detector



World’s largest (1,000ton) LS detector successfully operated since 2001 to explore the low energy neutrino physics !


Solar ν detection


1st challenge of Geoneutrino detection


1st observation of reactor neutrino oscillation

PMTs (1325 17”+554 20”), 34% of 4π

Balloon(ϕ=13m)

$\sigma_E = 6.4\% \times \sqrt{E_{[MeV]}}$

$\sigma_{position} = 12cm/\sqrt{E_{[MeV]}}$

1000ton Ultra-pure LS

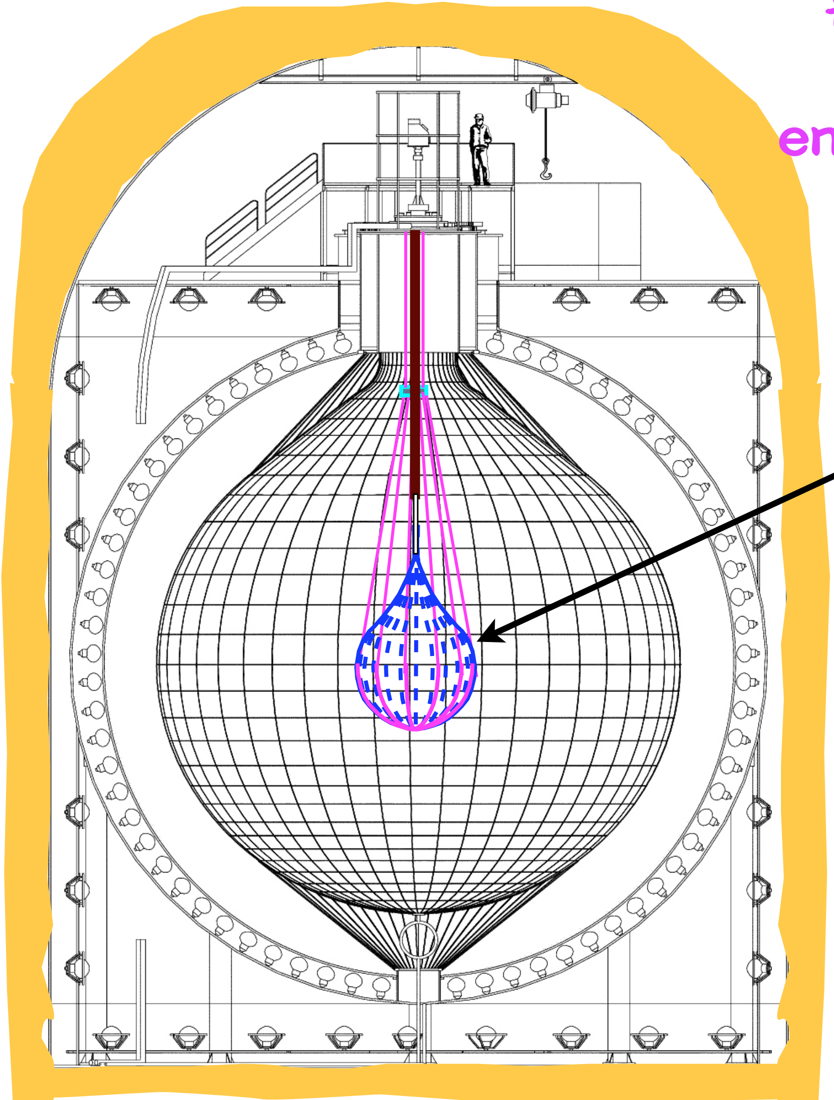
$^{238}U \sim 3.5\times10^{-18}$ g/g, $^{232}Th \sim 5.2\times10^{-17}$ g/g

The huge volume ultra-clean environment !
The detector has been well understood !

Excellent facility for $\beta\beta$ experiment !

KamLAND-Zen (禅)

Zero neutrino double beta decay experiment



禅= Spiritual practice in Buddhism to get the enlightenment ("悟り") in pure mind !
=> KamLAND-Zen is also to get the enlightenment (0ν signal) in ultra-pure quiet environment.

A mini-balloon (ϕ=3.1m) of 25μm-thick nylon film filled with 330kg-Xe (91% ^{136}Xe) loaded liquid scintillator.

The $\beta\beta$ experiment with world's largest amount of ^{136}Xe.

The minor modification made the construction period and the cost minimized.

Other physics can be run in parallel ;
Geo-neutrinos, Reactor neutrinos,
New challenges (ex. 4-th ν search(CeLAND)).

T.Lasserre's talk

Phys.Rev.D88, 033001(2013)

R&D and construction of the Mini-balloon

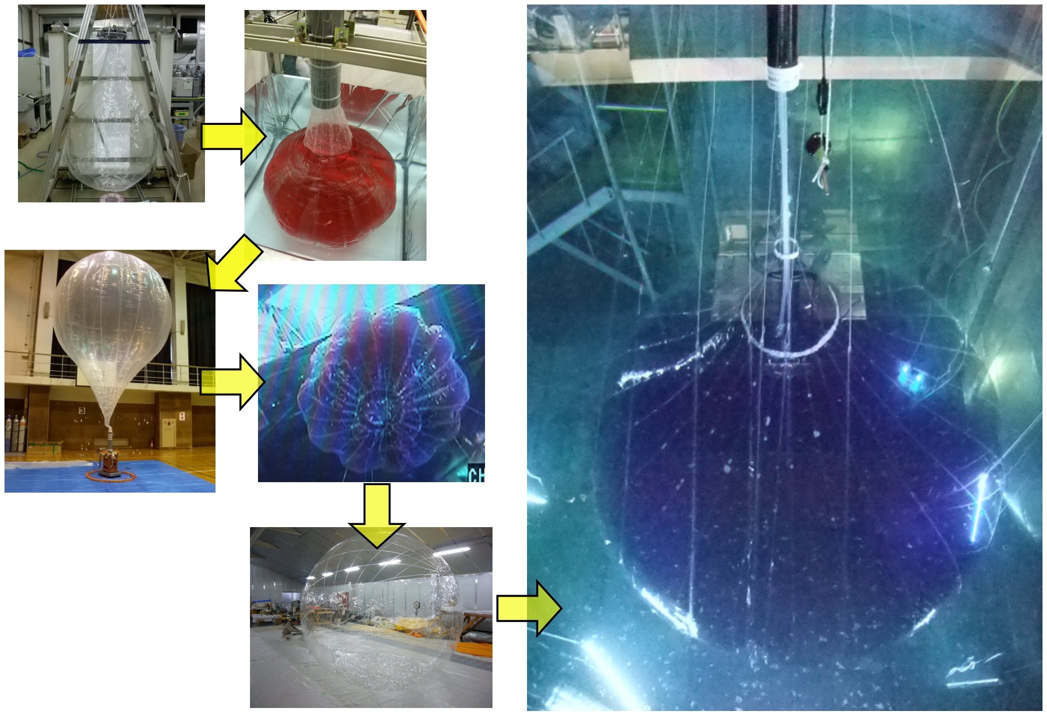
(2009~2011)

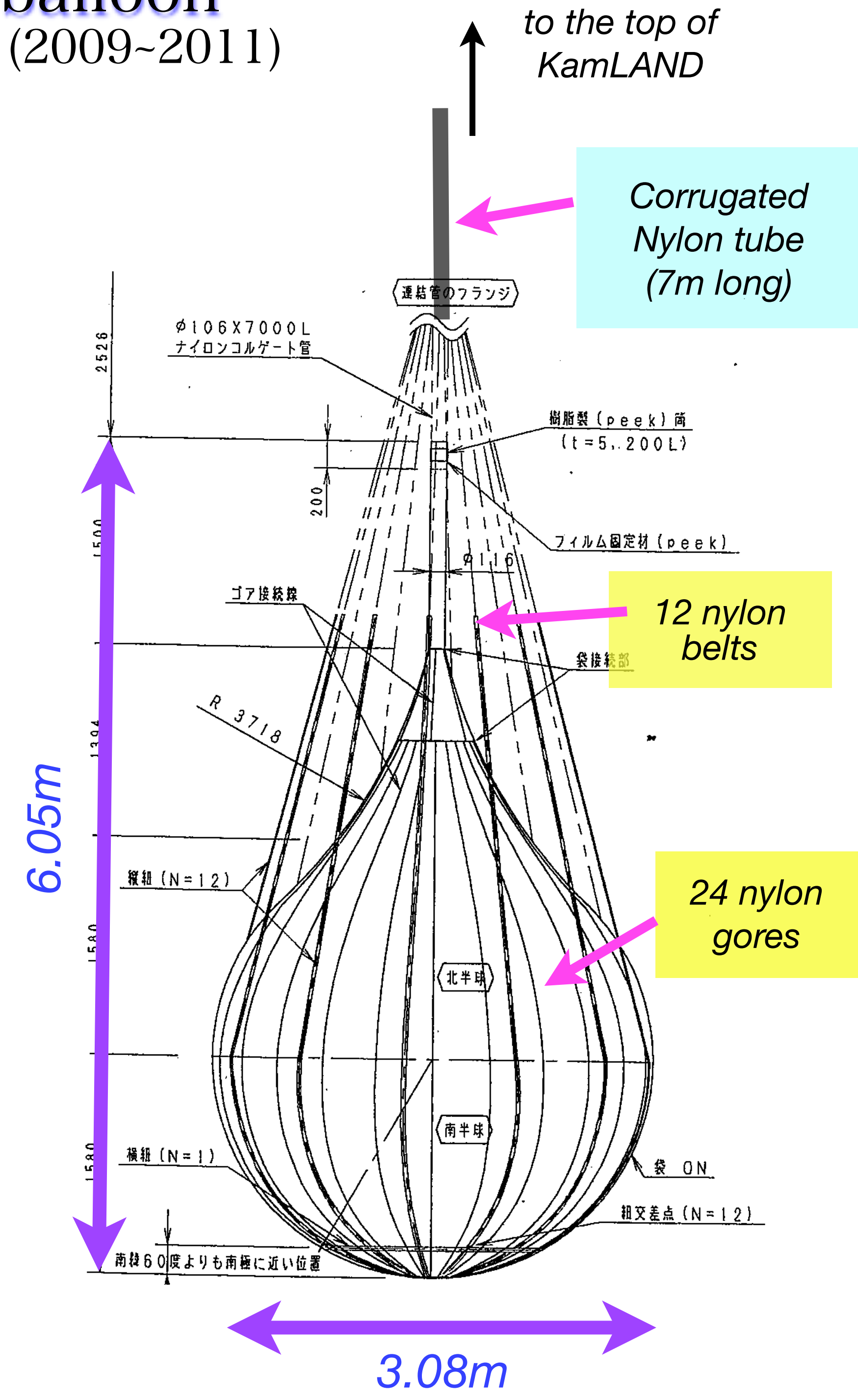
Film characteristics and sealing technique

Film material	Nylon, 25 μm thick
Radio-purity (g/g)	U,Th~10^{-12}, ^{40}K ~10^{-11}
Mechanical strength	>10N/cm
Xe tightness	<1kg/5yr
Light transparency	>95% (400nm)
LS compatibility	Long term stability
Sealing technique	Impulse welding*

*Direct heating with well-controlled temp. & time.

Prototypes were made and tested. ⇒Structure and handling, deployment (liquid handling, monitoring, etc.)





Construction in a class1 super clean room in Tohoku University. *(=1 particle(>0.1μm) /feet^3)*

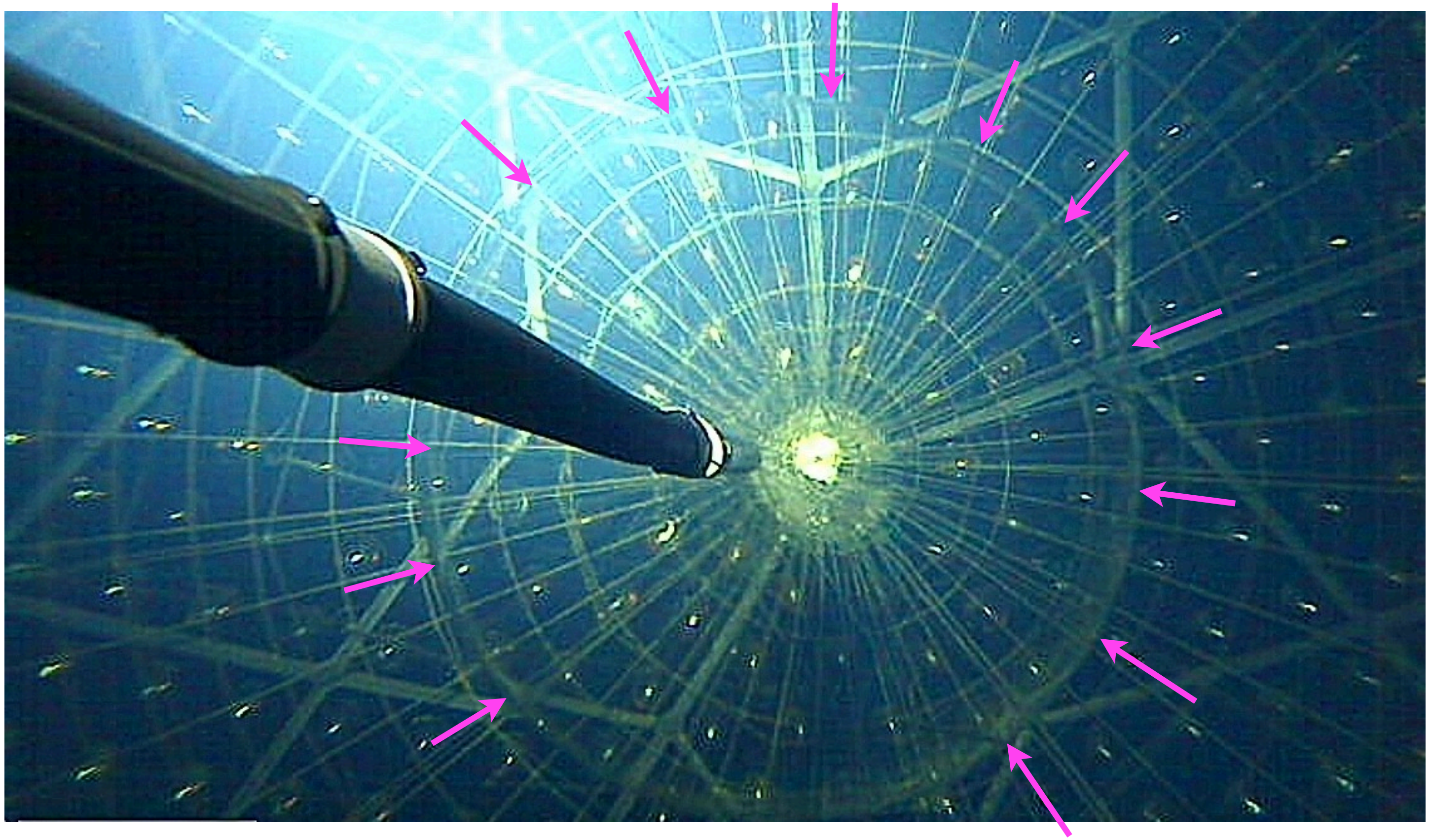
(May-July, 2011)

to KamLAND

Dome

Installation into the detector

Successfully Installed in the KamLAND, *(Aug.23,2011)*

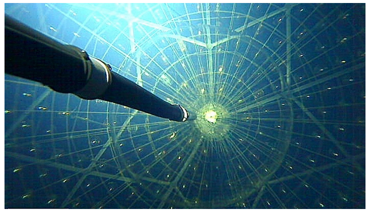


KamLAND-Zen activities & outputs

2011 | 2012 | 2013

May — Aug.

Mini-balloon construction



Installation

KamLAND-Zen 1st phase

Oct.12-Jan.2 — 1st results (Apr.19)

Feb.9 — 2nd results (Aug.6)

Jun.14 — 3rd results (Feb.7)

Filtration of Xe-LS (Feb)

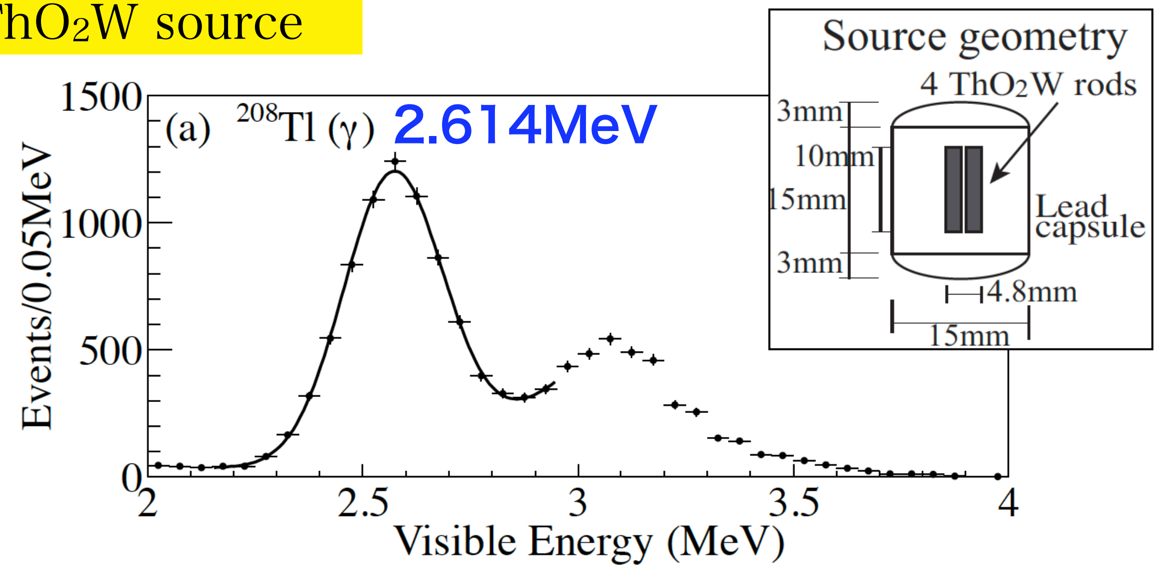
Purification & others

Now!

	Live time (days)	^{136}Xe exposure (kg yr)	$T^{0\nu}_{1/2}$ ($10^{24}y$, 90%CL)	$T^{2\nu}_{1/2}$ ($10^{21}y$)	
1st	77.6	27.4	> 5.7	2.38±0.02(st) ±0.14(sys)	**Phys.Rev.C85, 045504(2012)**
2nd	112.3	38.6	$T^{0\nu}$ > 6.2 $T^{0\nu\chi}$ > 2.6	2.30±0.02(st) ±0.12(sys)	**Phys.Rev.C86, 021601(R) (2012)**
3rd	213.4	89.5	> 19	consistent 2νββ rates with 1st and 2nd results.	**Phys.Rev.Lett.110, 062502 (2013)**

Energy calibration

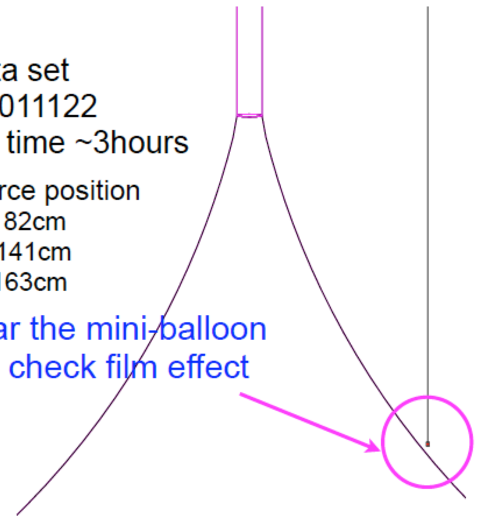
ThO_2W source



Data set
run011122
run time ~3hours

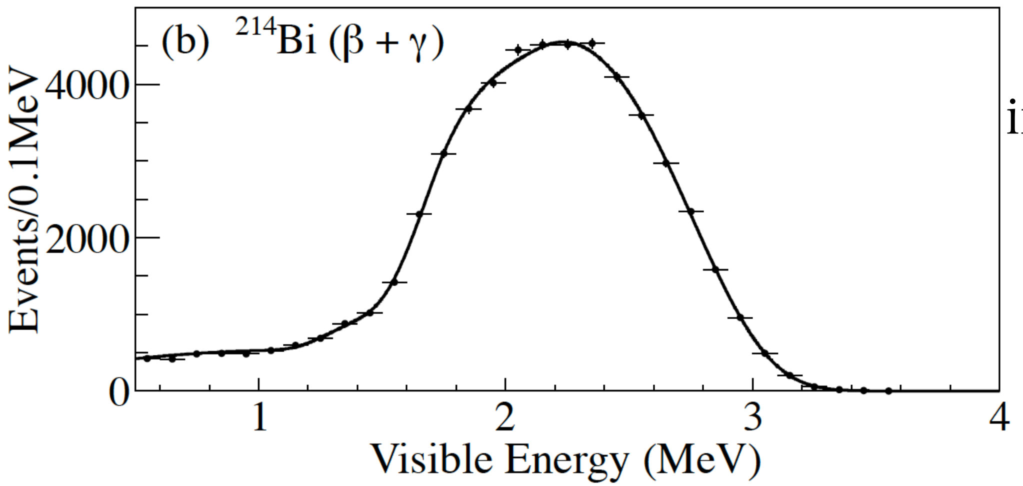
source position
ρ ~ 82cm
z ~ 141cm
r ~ 163cm

near the mini-balloon
to check film effect

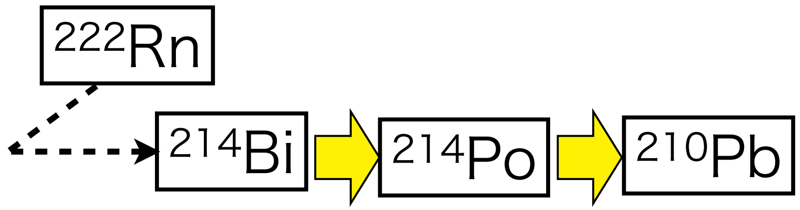


$\Delta E/E = (6.6 \pm 0.3)\% / \sqrt{E_{[MeV]}}$ (@2.614MeV)

$^{214}Bi \Rightarrow {}^{214}Po$ events



Using the delayed coincidence of $^{214}Bi \Rightarrow {}^{214}Po$ from residual ^{222}Rn in the initial stage, the energy scale parameters are tuned to reproduce the spectrum.



$T_{1/2}$=19.9 min Q_β(3272keV)

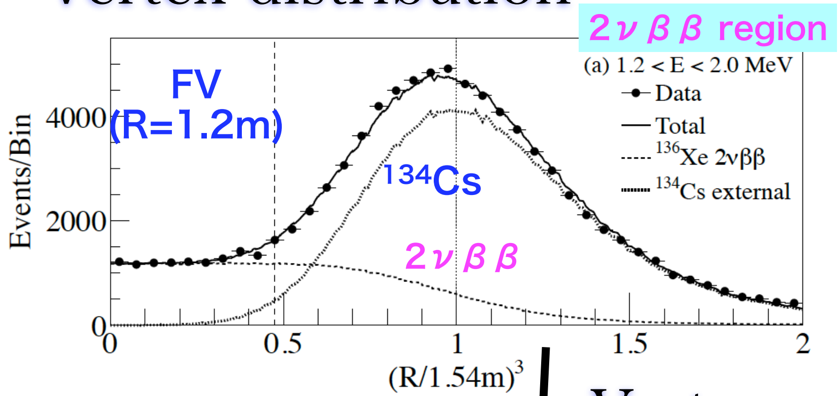
$T_{1/2}$=164 μs α(7687keV)

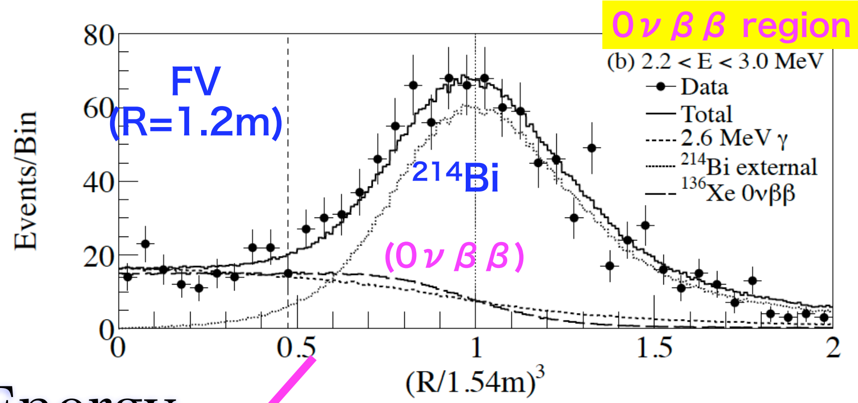
2.225MeV γ's from spallation neutron captures

(Systematic variation of the reconstructed energies over the Xe-LS volume <1.0%)

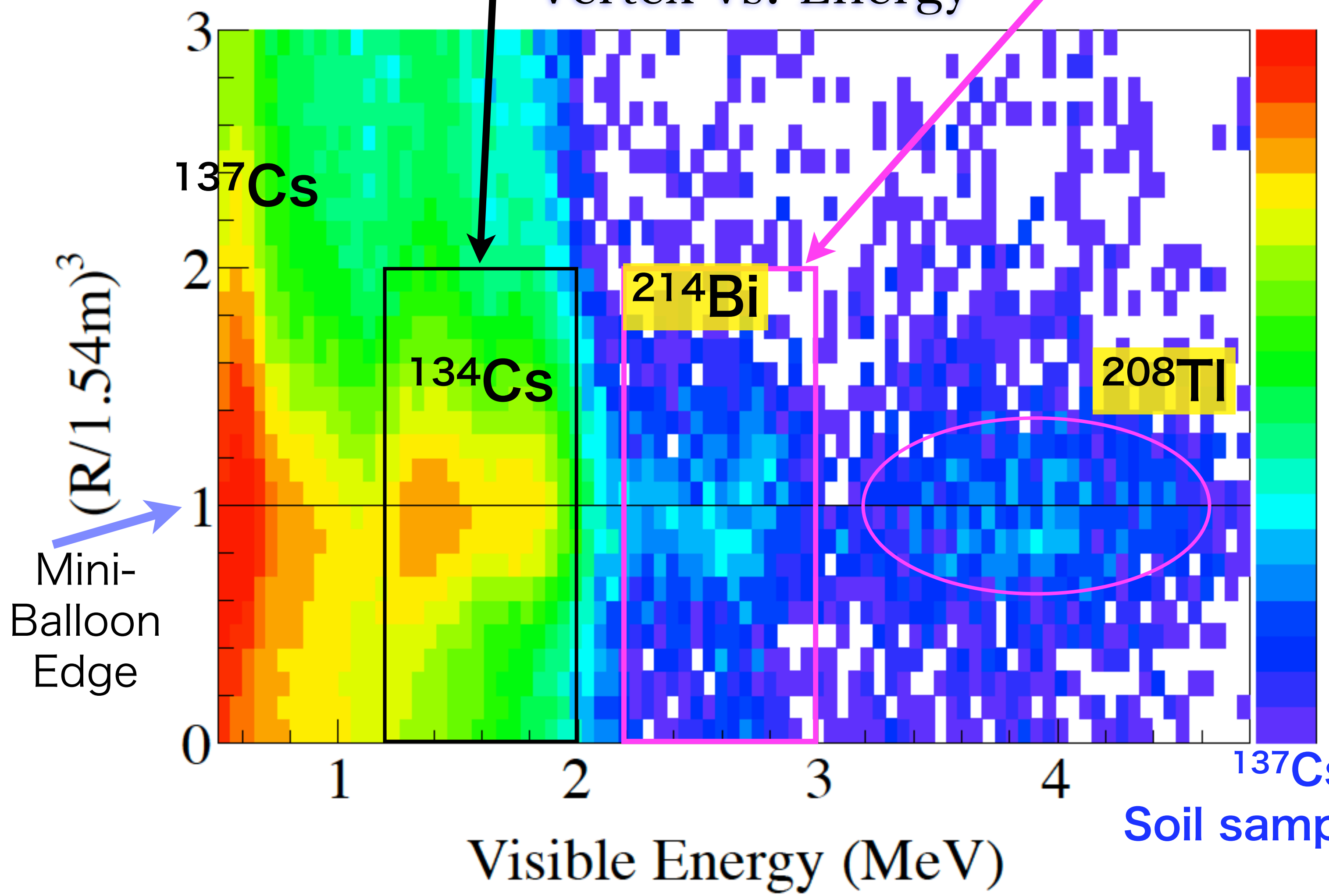
2nd results

Vertex distribution

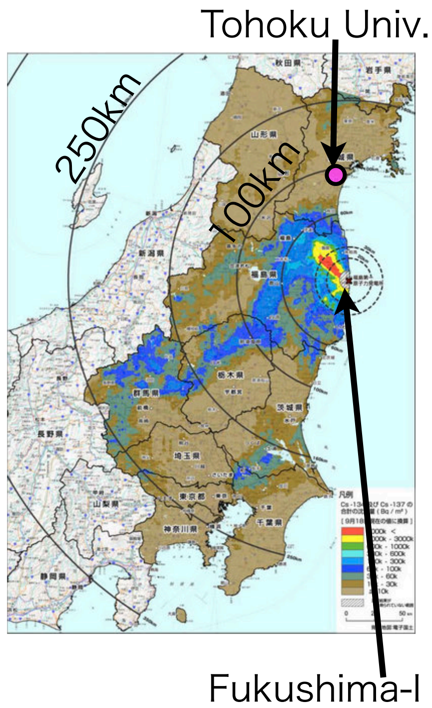




Vertex vs. Energy



^{134}Cs, ^{137}Cs



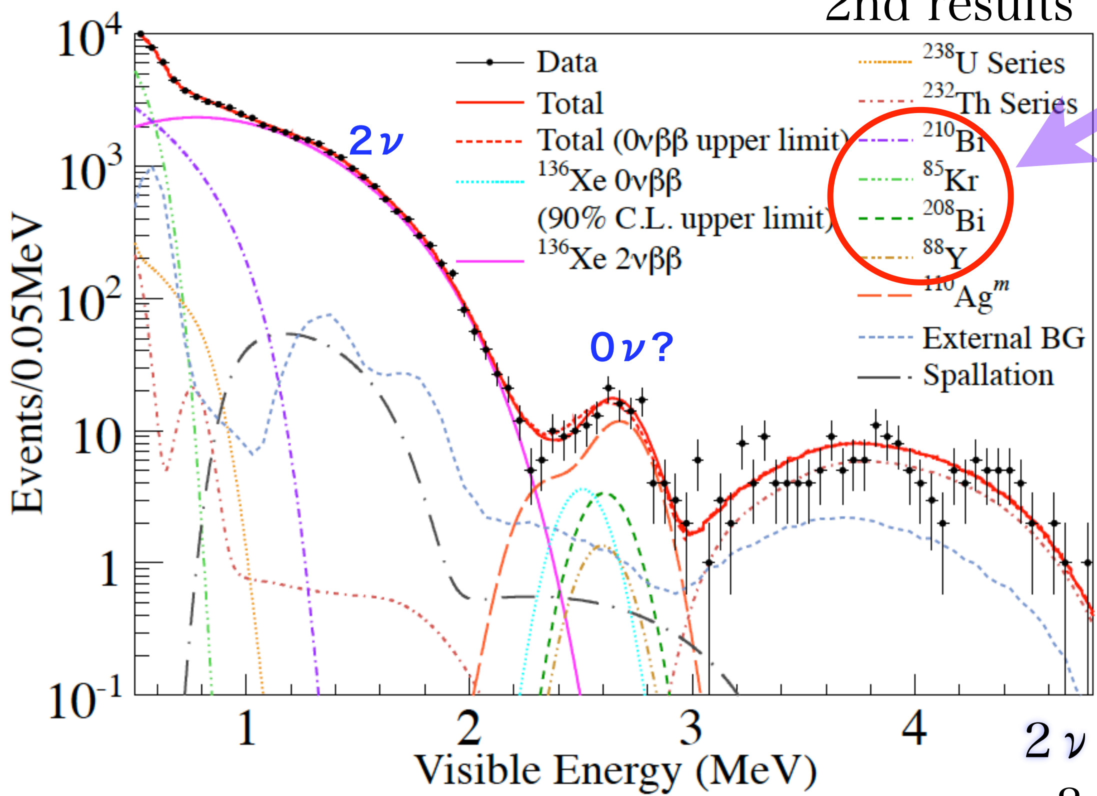
$^{137}Cs/^{134}Cs \sim 0.8$

Soil samples around RCNS.

Event selection

- Fiducial volume : R<1.2m
- Cosmic ray muons and events within 2ms are rejected.
- Reject sequential events within 3ms and 200ns daq time window.
  (^{214}Bi→^{214}Po(τ =237 μs), ^{212}Bi →^{212}Po(τ =0.4 μs) decays)
- Reject inverse beta decay events ($\overline{\nu}_e p \rightarrow e^+ n$) (from reactor $\overline{\nu}_e$ s) by requiring event time separation >1ms.

Energy spectrum



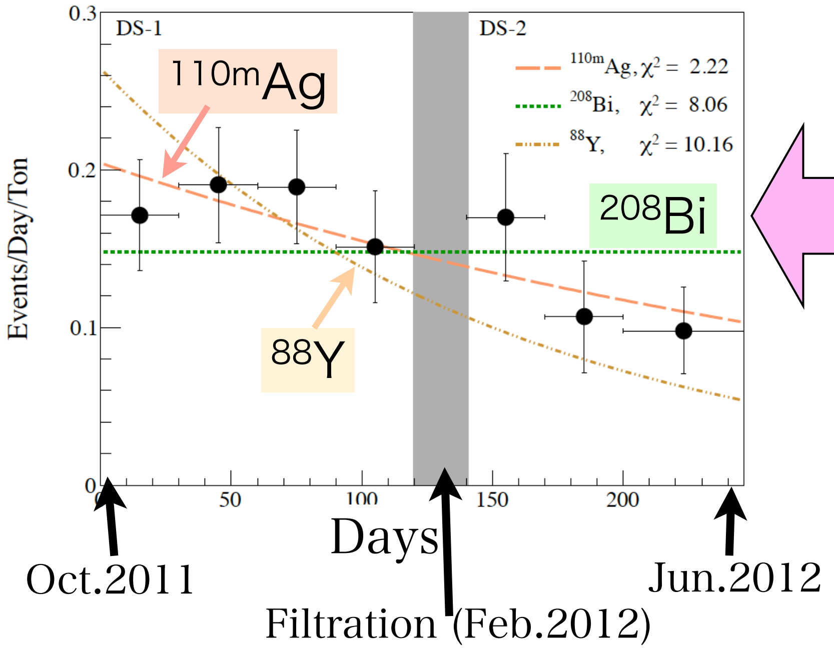
0 ν region (2.2〜3.0MeV) :
A peak around $Q_{\beta\beta}$ was fit with 4 candidate nuclei which were found by thorough investigation of the ENSDF data file.

Candidates (τ)	χ^2
0 ν +^{110m}Ag (360d)	13.1
0 ν +^{208}Bi (5.3e5 y)	22.7
0 ν +^{88}Y (154d)	22.2
0 ν +^{60}Co (7.61y)	82.9
0 ν only	85.01
0 ν +^{110m}Ag+^{208}Bi+^{88}Y+^{60}Co	11.6

^{110m}Ag best reproduces the data.

2 ν region (1.2-2.0MeV) : T(2 ν β β) =2.30±0.02(st)±0.12(sys) ×10^{21}yr: Systematic error is dominated by FV uncertainty (5.2%)

Time variation of the event rate in the 0ν region

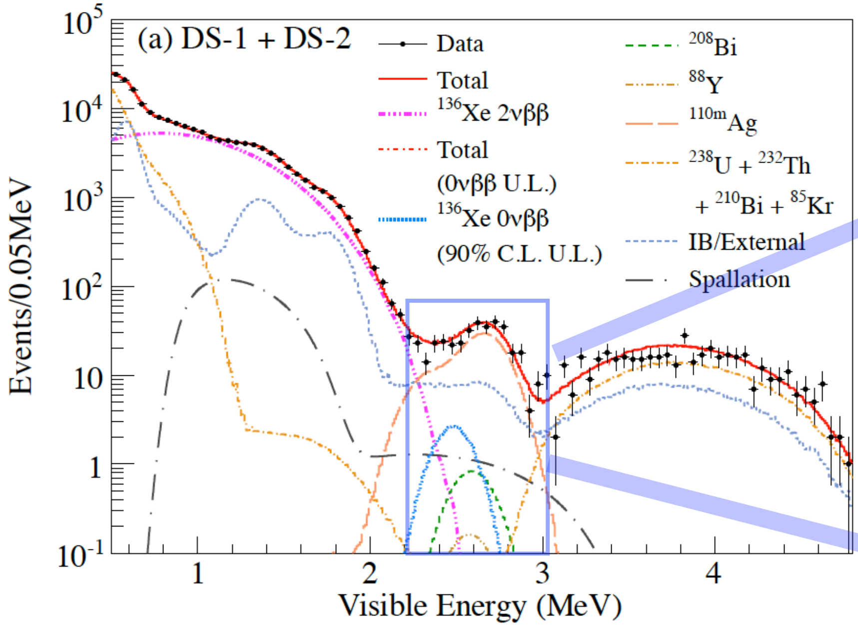


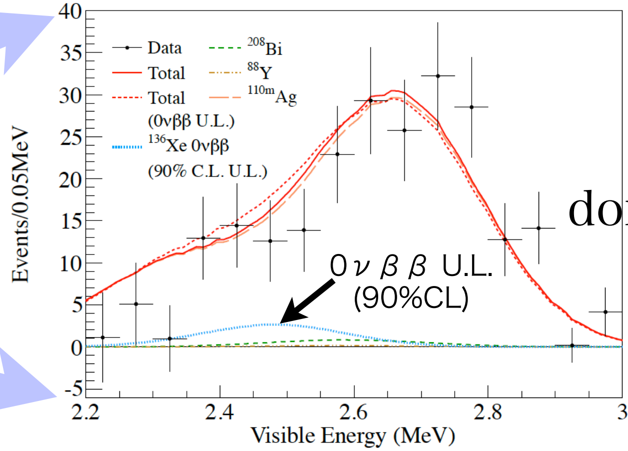
We carried out purification with 50nm PTFE-based filter in Feb.2012.

The event rate in the 0ν region before and after the filtration is well reproduced by the decay of ^{110m}Ag. The filtration was not effective. The Xe run was stopped and purification of Xe and LS was started.

The 3rd results (**Phys.Rev.Lett.110, 062502 (2013)**)

Use all the data samples (Oct.'11~Jun.'12, 213.4days of live time) and the Fid Vol. is enlarged (R=1.2m→1.35m) to optimize the 0ν search (89.5kg yr of ^{136}Xe).





0ν region is dominated by ^{110m}Ag.

< 0.19±0.02 events/day/ton

Number of ^{110m}Ag nucleus < 1000 !

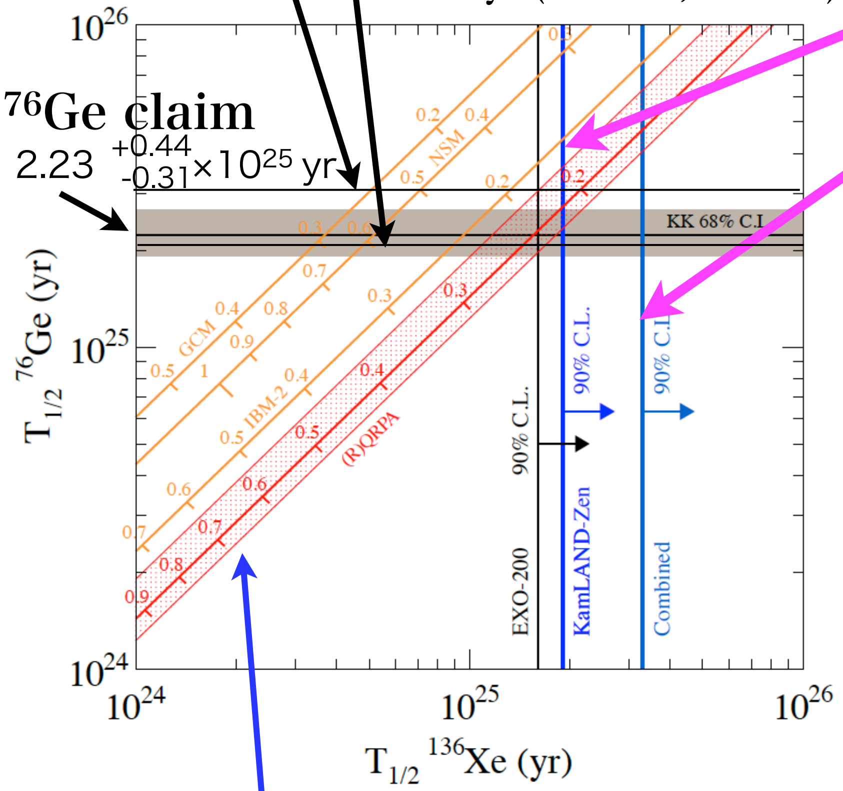
Comparison of ^{76}Ge vs. ^{136}Xe

3.0×10^{25}yr(GERDA+previous Ge, 90%CL)

2.1×10^{25}yr (GERDA, 90%CL)

^{76}Ge claim

$2.23^{+0.44}_{-0.31}\times10^{25}$ yr



NME ($M^{0\nu}$) predictions

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

$T_{1/2}^{0\nu} > 1.9\times10^{25}$ yr (90%CL) KamLAND-Zen

$T_{1/2}^{0\nu} > 3.4\times10^{25}$ yr (90%CL) KamLAND-Zen +EXO-200

PRL109, 032505 (2012)

$\langle m_{\beta\beta}\rangle <$ (120～250) meV

The results provide the stringent limit on the 0ν nucleus other than ^{76}Ge !

The longstanding positive claim for 0νββ decay of the ^{76}Ge has been excluded (> 97.5%CL). (Mod.Phys.Lett.A21,(2006)1547)

Recent results from GERDA provides the most stringent limit on ^{76}Ge and disfavors the claim.

We understand well the B.G. components !

^{110m}Ag (dominant in the Xe-LS), ^{214}Bi (mini-balloon), ^{10}C (μ-spallation), 2ν decays.

We stopped Xe run in Jun.'12 and started purification of Xe and LS to remove ^{110m}Ag.

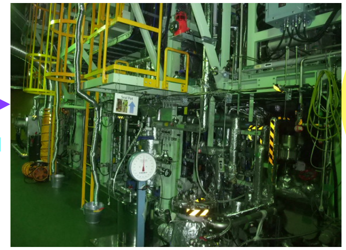
Efforts to remove ^{110m}Ag nuclei in the mini-balloon.

Xe purification (distillation, filtration (by charcoal, sintered metal, particle filter (3nm)) and storage.

Xe

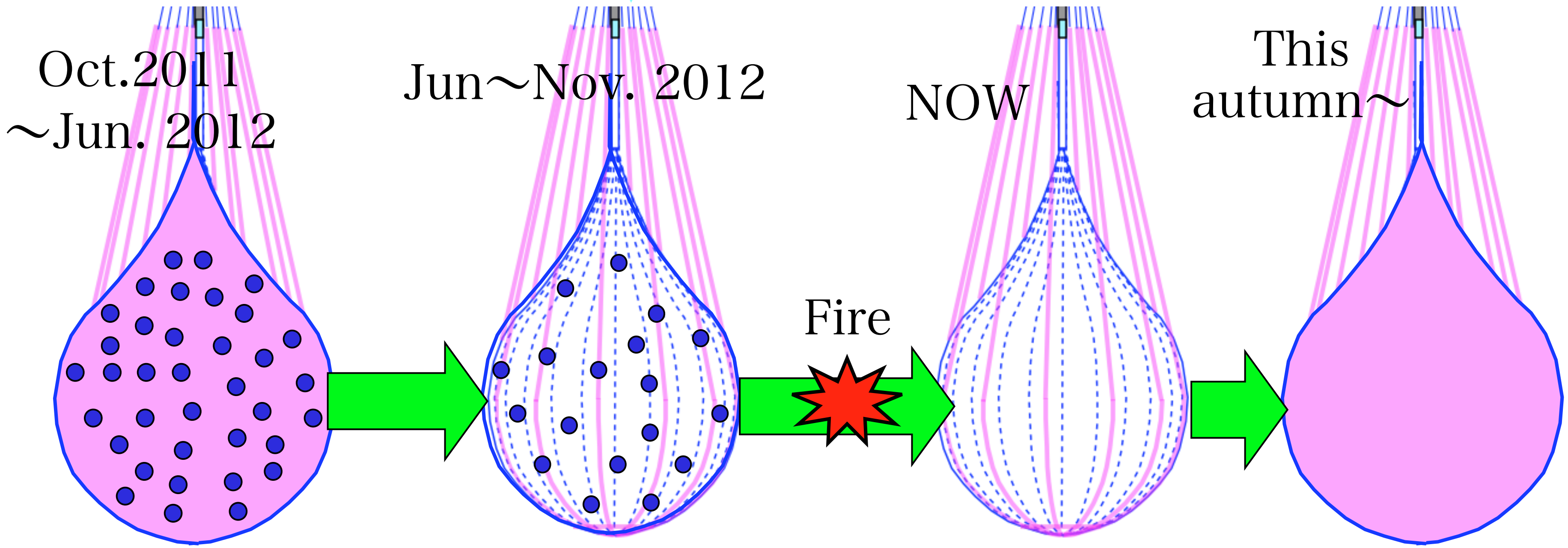
Xe system

LS



LS purification plant

LS distillation & nitrogen purging



Xe-LS+^{110m}Ag

Filtration by 50nm PTFE-based filter (in Feb.2012) was found not effective.

Dummy LS+^{110m}Ag

Xe-LS was replaced with purified LS. ^{110m}Ag still remained.

Purification of the dummy LS is continued.

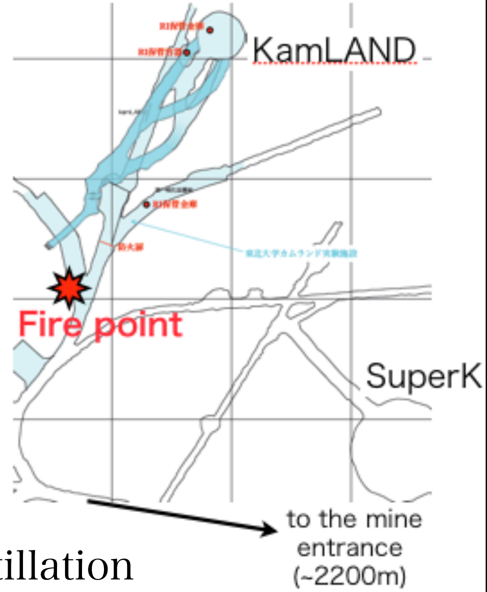
Data taking with purified Xe+LS.

Fire accident in KamLAND area (Nov.20, 2012)

(before the fire)

Rn-free air generator
(activated carbon
cooled by methanol)
covered by styrofoam.

LS distillation
plant



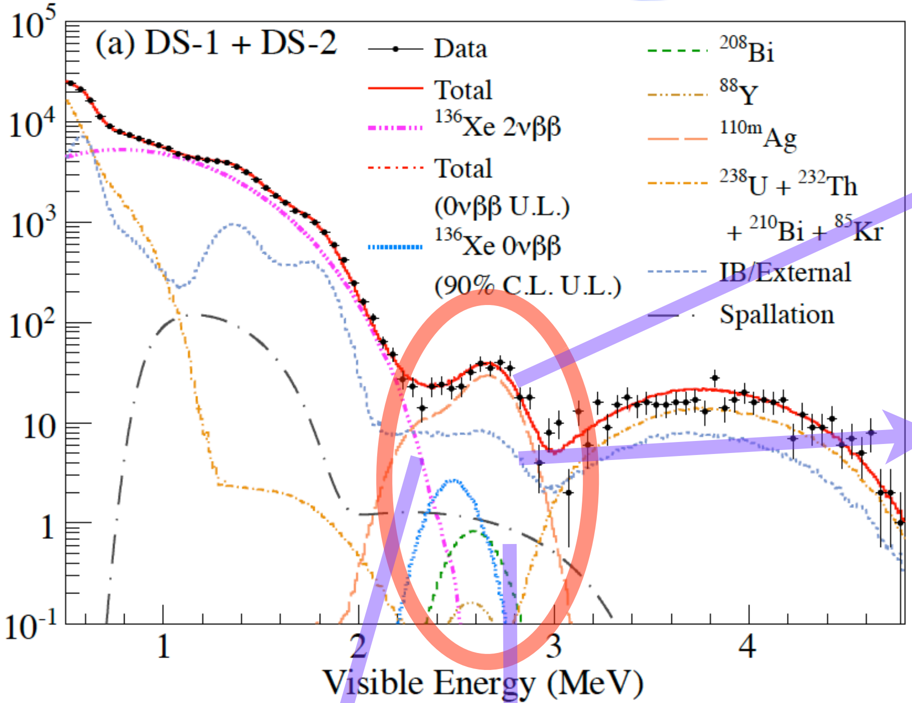
The fire broke out during a dismantle work of the old Rn-free generator.

All the people safely evacuated without seriously injured.
KamLAND detector and the nearby facilities were safe, but the power lines, signal wires, monitoring cables, fresh-air pipe around the fire point were heavily damaged.

Lots of efforts were made for recovery, taking safety measure, etc. The data taking was restarted in a month.
Now the whole system recovered, but the accident caused a big delay of the purification procedure.

Now
(Liq. Nitrogen CE inside.)

Towards the higher sensitivity



Now

$\langle m_{\beta\beta} \rangle$ < (120〜250) meV

^{110m}Ag : Ongoing purification work.

This year

$\langle m_{\beta\beta} \rangle$ <~80meV

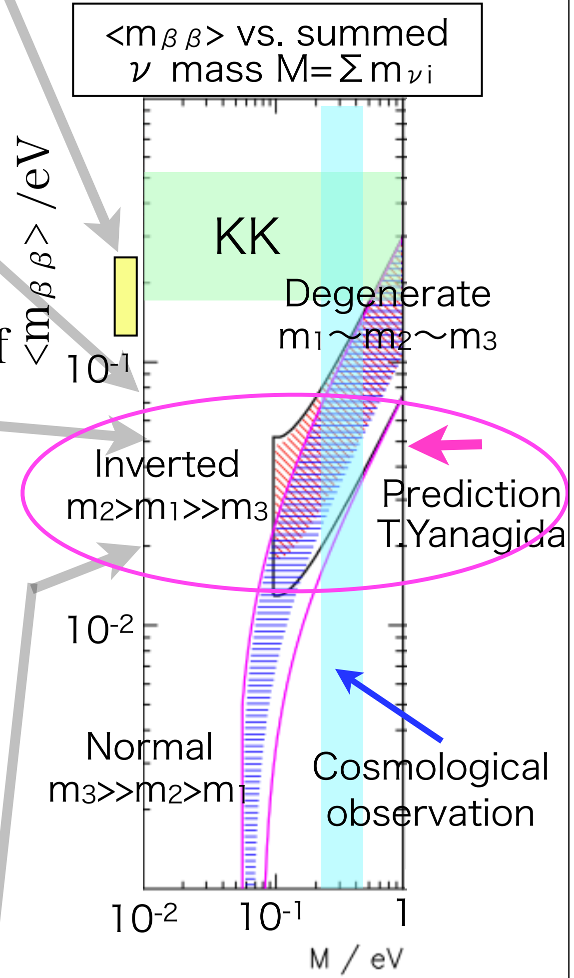
^{214}Bi : a cleaner and a larger mini-balloon of >600 kg Xe.

Next year

$\langle m_{\beta\beta} \rangle$ <~50meV

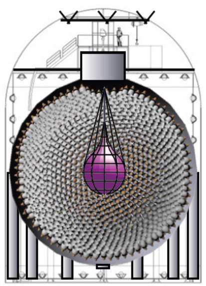
^{10}C : Spallation products of ^{12}C nucleus associated with neutrons (90%). They can be rejected by triple coincidence (μ-n-^{10}C). Special trigger logic has been developed for a new electronics system (Mogura).

R&D finished



2νββ :

KamLAND2-Zen



Planned KamLAND2-Zen
(1000kg Xe)

$\langle m_{\beta\beta} \rangle$ <~20meV

Improve ΔE/E =4%(Now) ⇒2.5% (@2.6MeV)

R&Ds for Light collector of the PMTs, New LS, Imaging detector for Single vs Multi vertex discrimination, Scintillating film for balloon.

Summary

- KamLAND-Zen is a unique detector of Xe+LS combination to search for ^{136}Xe $0\nu\beta\beta$ decays since 2011 and the 1st phase was finished.
- The limit on the half life of ^{136}Xe $0\nu\beta\beta$ is **$>1.9\times10^{25}$ yr (90%CL)**, and the $2\nu\beta\beta$ half life is measured as 2.30 ± 0.02(st) ±0.12(sys)$\times10^{21}$ yr which is consistent with EXO-200.
- Combined limits with the EXO-200 is $>$ **3.4×10^{25} yr (90%CL)** corresponding to $\langle m_{\beta\beta}\rangle$ **$<$(120-250)meV** for most of the NME calculations.
  The limit excludes the claimed observation of ^{76}Ge $0\nu\beta\beta$ decays at $>$ 97.5%CL.
- The backgrounds are understood and the measures are taken now by Xe-LS purification works to remove ^{110m}Ag. The next KamLAND-Zen data taking with the purified Xe-LS will start in this autumn aiming to $\langle m_{\beta\beta}\rangle$ ~80meV.
- A new clean mini-balloon with a larger volume for $>$ 600kg Xe will be made next year to reach the $\langle m_{\beta\beta}\rangle$ ~50meV, to enter the inverted mass hierarchy region.
- As a near-future plan KamLAND2-Zen is planned to cover the inverse hierarchy region. Many R&Ds are being done.

Thank you
for your attention !