# KamLAND-Zen double beta decay experiment

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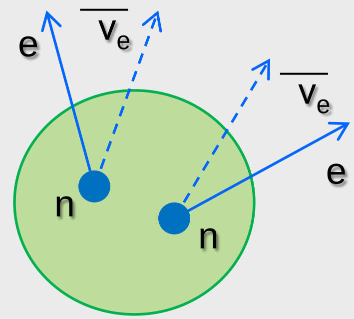
KAVLI IPMU

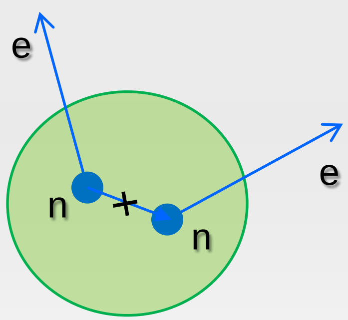
Windows on the Universe 2013

Qui Nhon, Vietnam

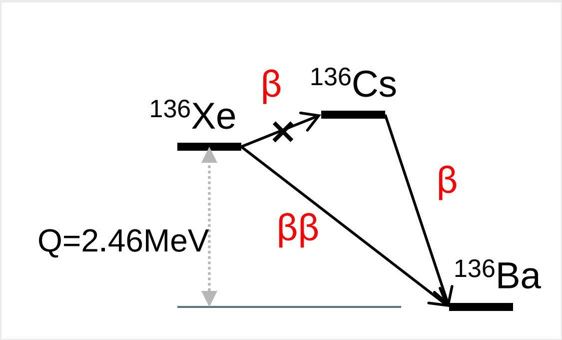
# Double beta decay isotope and 0νββ




2νββ




$\bar{\nu}_e = \nu_e$
0νββ




| isotope | Q-Value(MeV) | abundance(%) |
|---|---|---|
| $^{48}Ca \rightarrow {}^{48}Ti$ | 4.271 | 0.187 |
| $^{76}Ge \rightarrow {}^{76}Se$ | 2.040 | 7.8 |
| $^{82}Se \rightarrow {}^{82}Kr$ | 2.995 | 9.6 |
| $^{96}Zr \rightarrow {}^{96}Mo$ | 3.350 | 2.8 |
| $^{100}Mo \rightarrow {}^{100}Ru$ | 3.034 | 11.8 |
| $^{116}Cd \rightarrow {}^{116}Sn$ | 2.802 | 7.5 |
| $^{124}Sn \rightarrow {}^{124}Te$ | 2.228 | 5.64 |
| $^{130}Te \rightarrow {}^{130}Xe$ | 2.533 | 34.5 |
| $^{136}Xe \rightarrow {}^{136}Ba$ | 2.479 | 8.9 |
| $^{150}Nd \rightarrow {}^{150}Sm$ | 3.367 | 5.6 |

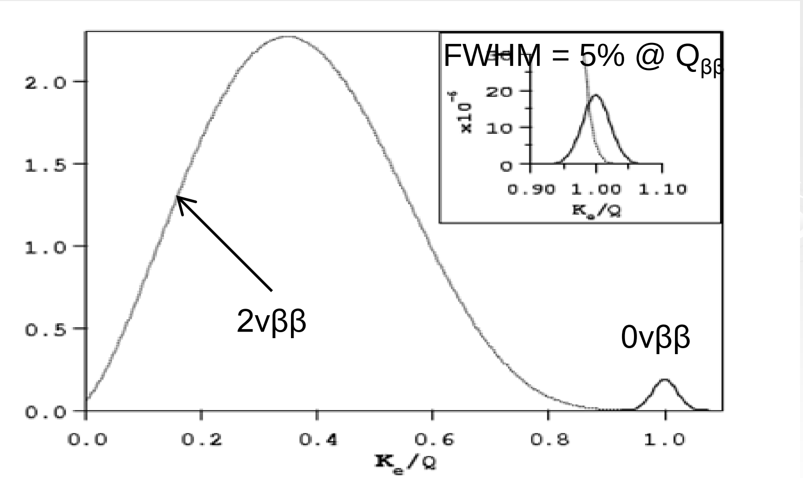
* Q>2MeV isotope

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G^{2\nu}|M^{2\nu}|^2$$

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

G: phase space factor,
M: nuclear matrix element
$\langle m_\nu \rangle$: effective neutrino mass

Double beta decay
→ very long life >$10^{18}$ yr
→ Large amount isotope
High ΔE



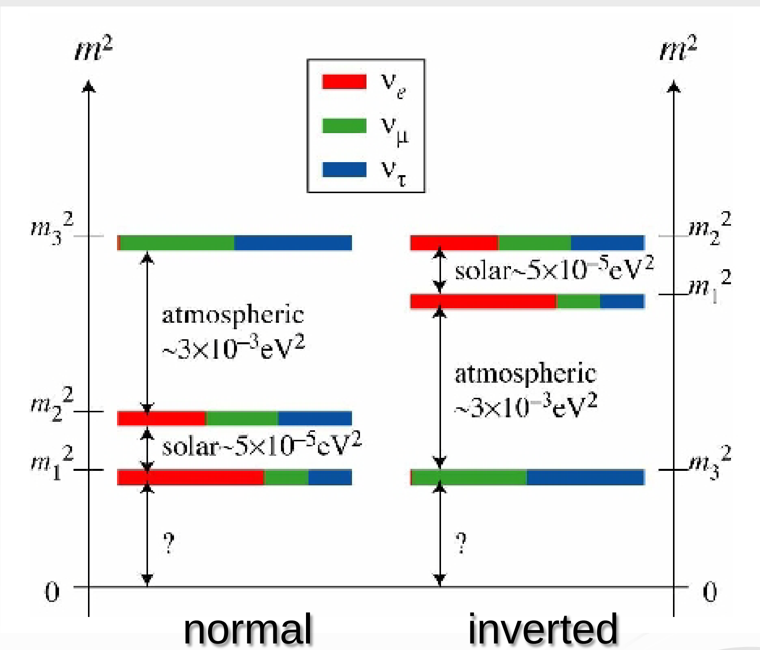

S.R.Elliot and P.Vogel, Ann. Rev.Nucl.Part.Sci.52(2002)115.

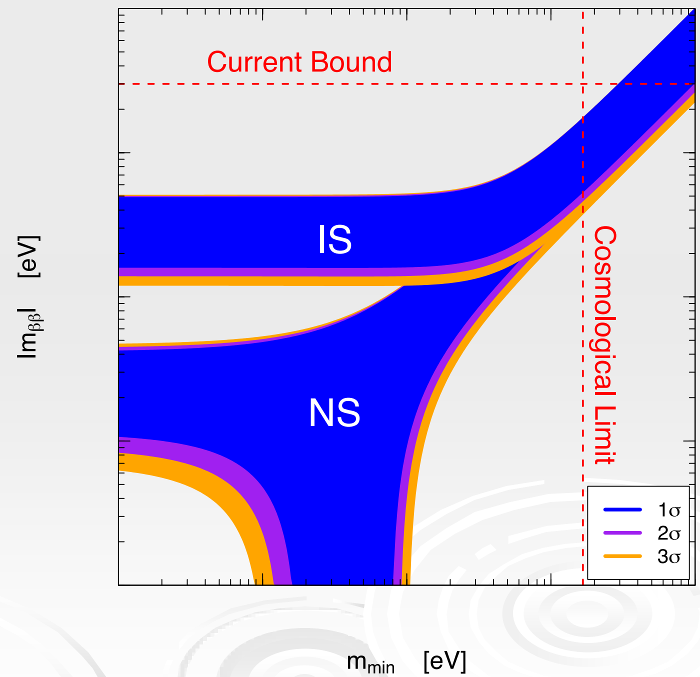
# Effective Majorana neutrino mass and hierarchy

$$|\langle m_\nu \rangle| = |\sum U_{e_i}^2 m_i| = |\cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}|$$

$$\langle m_{ee} \rangle^{\rm nor} = \left| m_1\, c_{12}^2\, c_{13}^2 + \sqrt{m_1^2 + \Delta m_\odot^2}\; s_{12}^2\, c_{13}^2\, e^{2i\alpha} + \sqrt{m_1^2 + \Delta m_{\rm A}^2}\; s_{13}^2\, e^{2i\beta} \right|$$

$$\langle m_{ee} \rangle^{\rm inv} = \left| \sqrt{m_3^2 + \Delta m_{\rm A}^2}\; c_{12}^2\, c_{13}^2 + \sqrt{m_3^2 + \Delta m_\odot^2 + \Delta m_{\rm A}^2}\; s_{12}^2\, c_{13}^2\, e^{2i\alpha} + m_3\, s_{13}^2\, e^{2i\beta} \right|$$



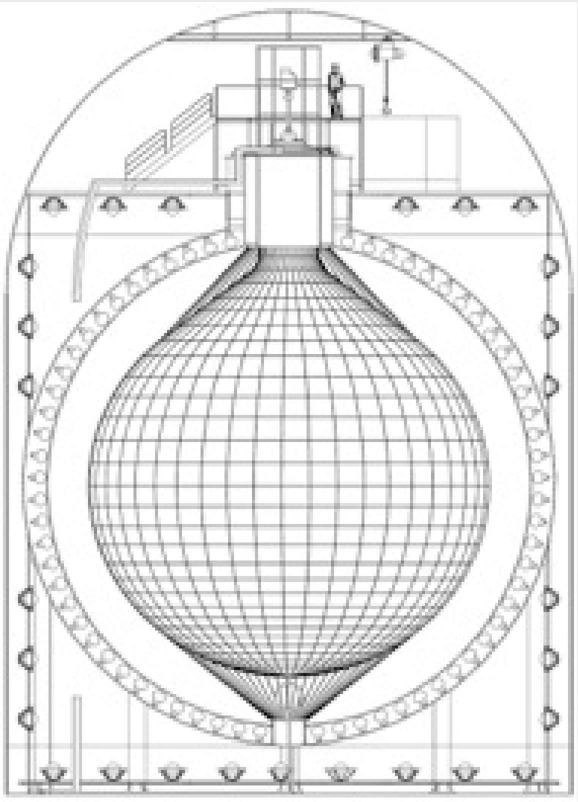

S. M. Bilenky, arXiv:1203.5250

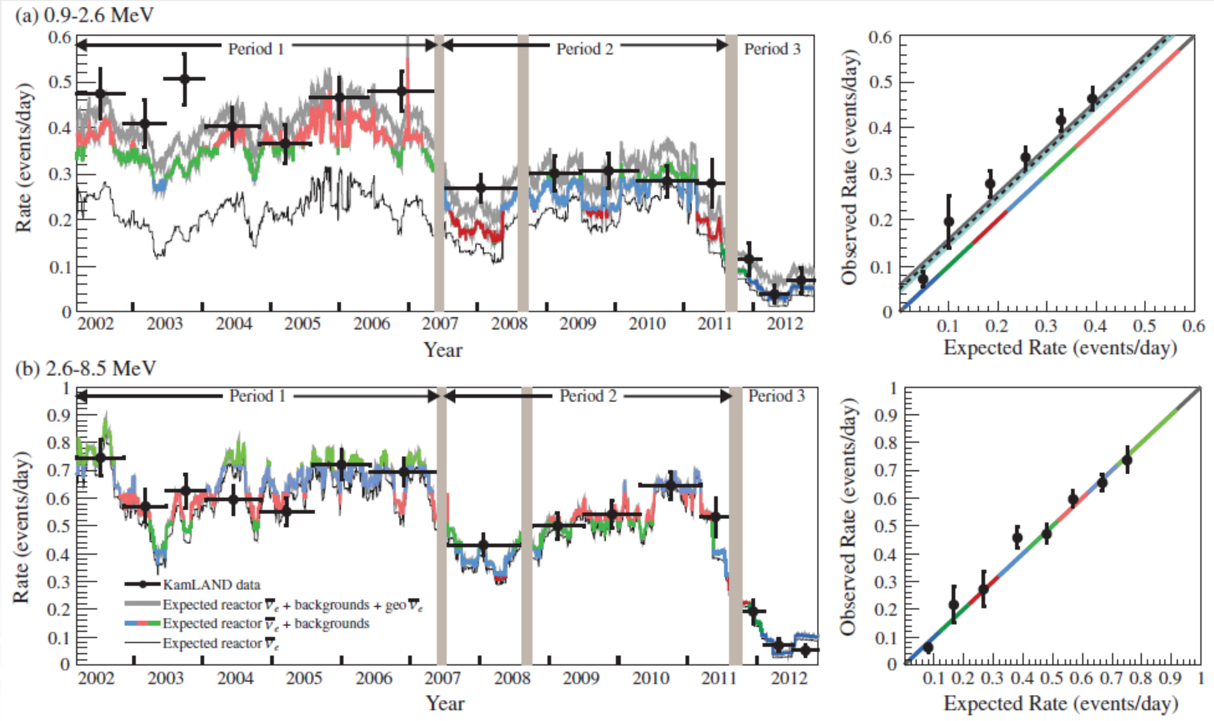
# KamLAND experiment on $\bar{\nu}_e$

- Detector running over 11 years (from 2002)

- Large volume: 1,200m$^3$ Liquid Scintillator
  Ultra low radioactivity: U: <3.5x10$^{-18}$g/g,
  Th: <5.2x10$^{-17}$g/g (from2007)
- KamLAND Energy Resolution:

$$\Delta E = \frac{6.2\%}{\sqrt{\mathbf{E(MeV)}}}$$ (34% photo coverage)



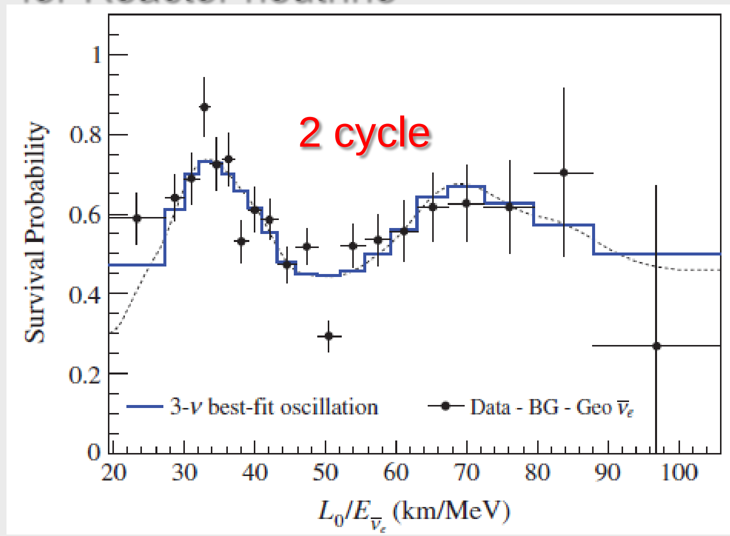



Depth: 2,700 m.w.e.
t =2.5m paraffin shield
Acrylic plate for Rn
3.8kL pure-water OD veto

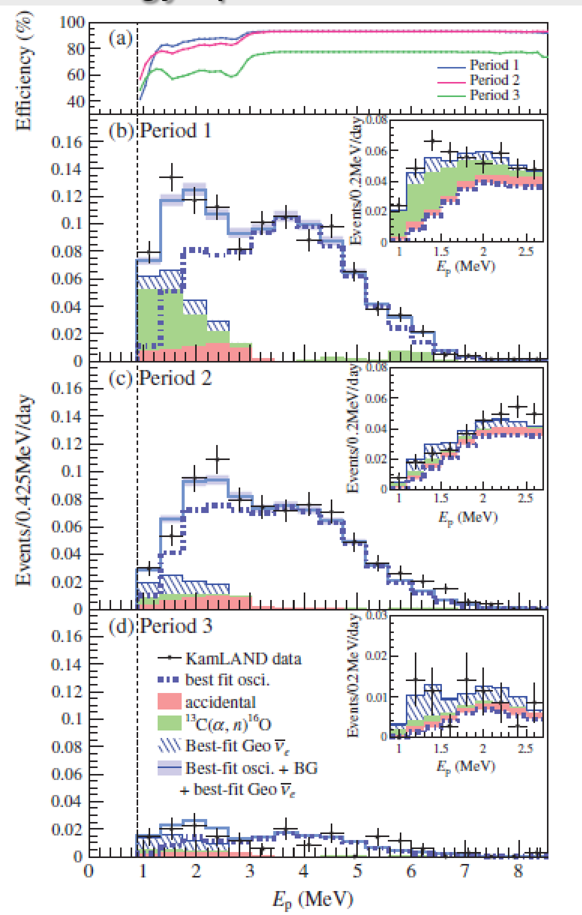
PHYSICAL REVIEW D **88,** 033001 (2013)

# KamLAND $\overline{\nu}_e$ results

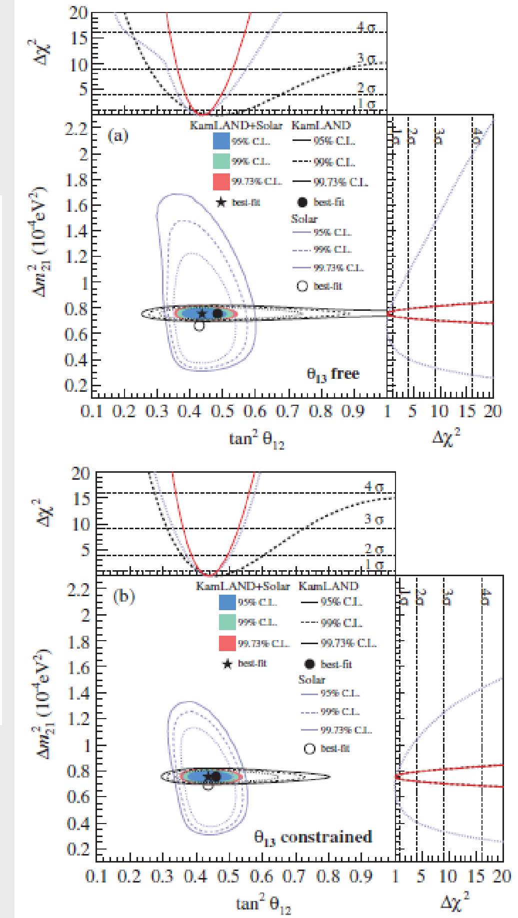
- for Reactor neutrino



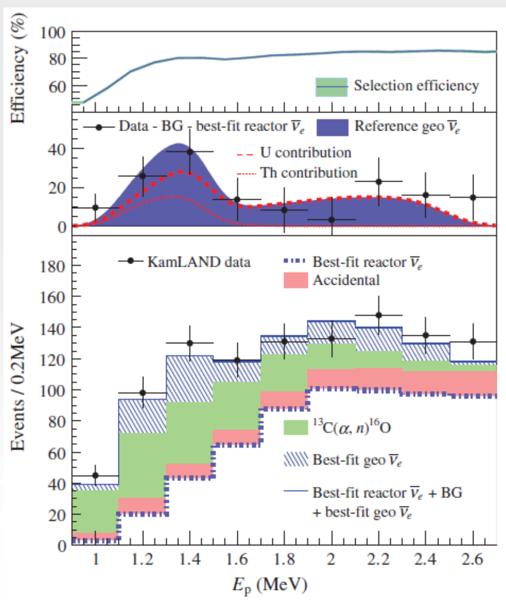

- energy spectrum

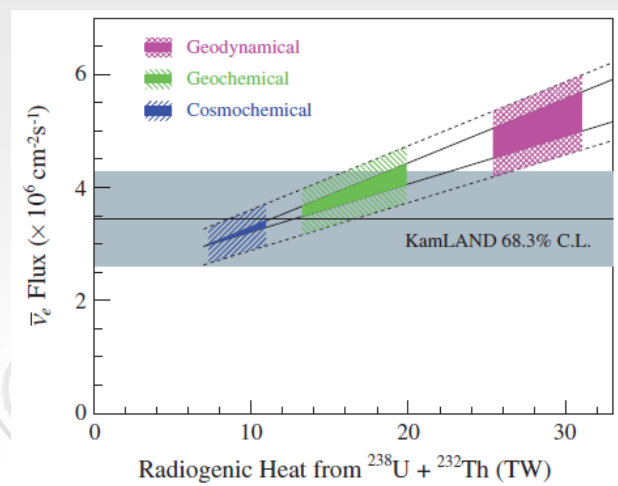



- Stable data-taking
- Low B.G.
  (ultra pure LS, low reactor ν flux)
- more precise measurement




- for Geo neutrino



# Motivation of KamLAND-Zen for ββ

- KamLAND
  - Large volume: 1,200$m^3$ Liquid Scintillator as a 4pi veto
  - Ultra low radioactivity: U:<3.5x10-18g/g, Th<5.2x10-17g/g
  - Distillation technique
  - Experience of balloon development
  - New electronics (available $^{10}C$,$^{11}C$ tagging)
  - Detector is running. => quick start by low cost.

  **mach advantage for ββ experiment !**

- Disadvantage
  - KamLAND Energy Resolution:

$$\Delta E = \frac{6.2\%}{\sqrt{\mathbf{E(MeV)}}}$$

(34% photo coverage)

# Merits of $^{136}$Xe on KamLAND

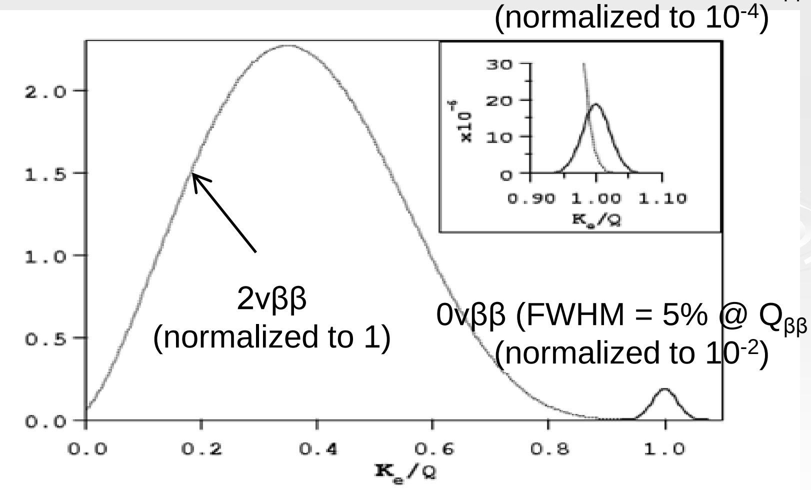
Before EXO-200 and KamLAND-Zen start

| isotope | $T^{0v}_{1/2}$(50 meV) | $T^{2v}_{1/2}$ measured (year) | Nat.Abundane (%) | Q-value (keV) |
|---|---|---|---|---|
| $^{136}Xe \rightarrow ^{136}Ba$ | $4.55 \times 10^{26}$ | $>10^{22}$ | 8.9 | 2476 |

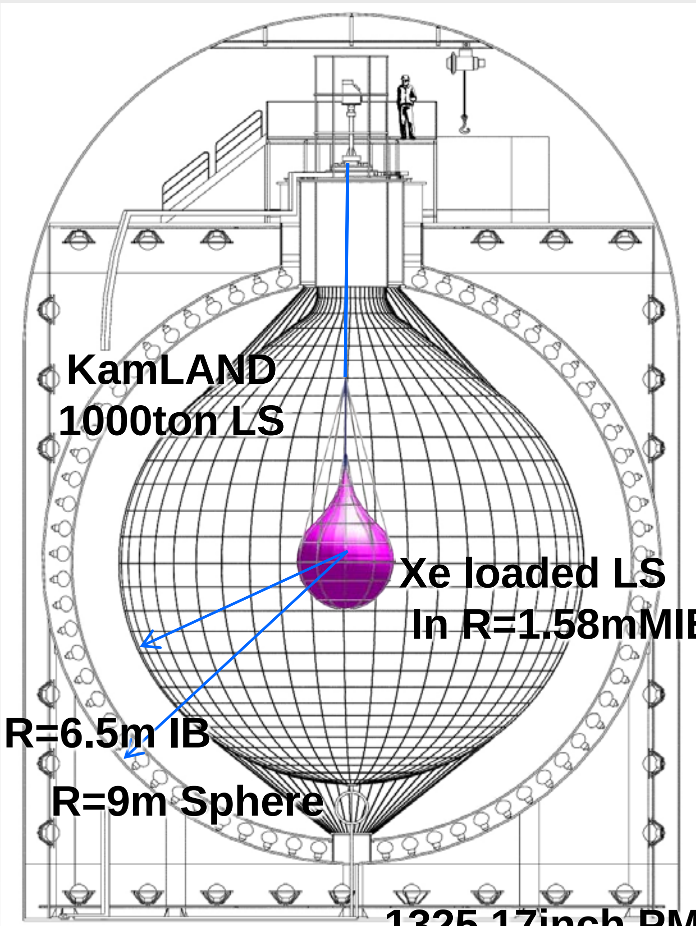
Rodin et al., Nucl. Phys. A793 (2007)213-215

Merits on KamLAND

- Isotopic enrichment
- purification established
- solubility to LS > 3%, easy extracted
- slow $2v\beta\beta$ ($T^{2v}_{1/2}$ >$10^{22}$ years)
  small $T^{0v}$/ $T^{2v}$ ratio



# KamLAND-Zen project




KamLAND-Zen collaboration

- Tohoku University
- Kavli IPMU Tokyo University
- Osaka University
- University of California Berkeley
- LBNL
- Colorado State University
- University of Tennessee
- TUNL
- University of Washington
- NIKHEF and University of Amsterdam

1st phase

$^{136}Xe$ ~320kg (91% enriched)

R=1.58m balloon

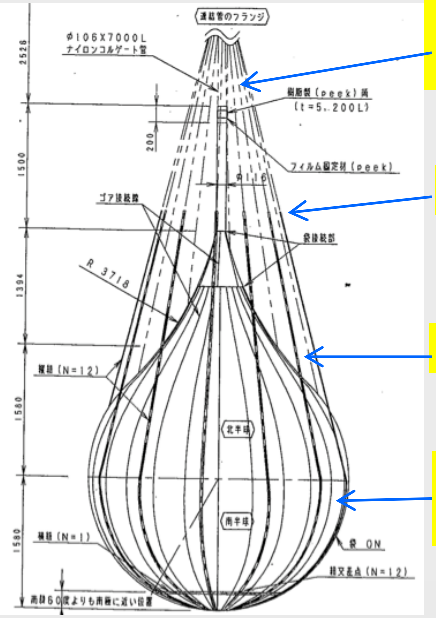
V=16.5m$^3$

LS : C10H22(81.8%) + PC(18%) + PPO + Xe(～3wt%)

ρLS : 0.78kg／ℓ

target : ～60meV / 2years for 0νββ

# KamLAND-Zen MIB (Zen Balloon)



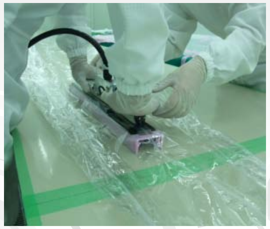

| | |
|---|---|
| Sphere diameter | 3.16m |
| volume | 17m$^3$ |
| Film thickness | 25μm |
| Film strength | 3kg/cm |
| Connection part strength | 2kg/cm |
| Xe leakage | <1.3kg/5years |
| Transparency (@400nm) | 99% |
| U contamination | 2E-12g/g |
| Th contamination | 3E-12g/g |
| 40K contamination | 2E-12g/g |

**filling test by water**

**Real balloon construction in the ultra clean room (crass 1)**

Ultra-sonic cleaning using pure water

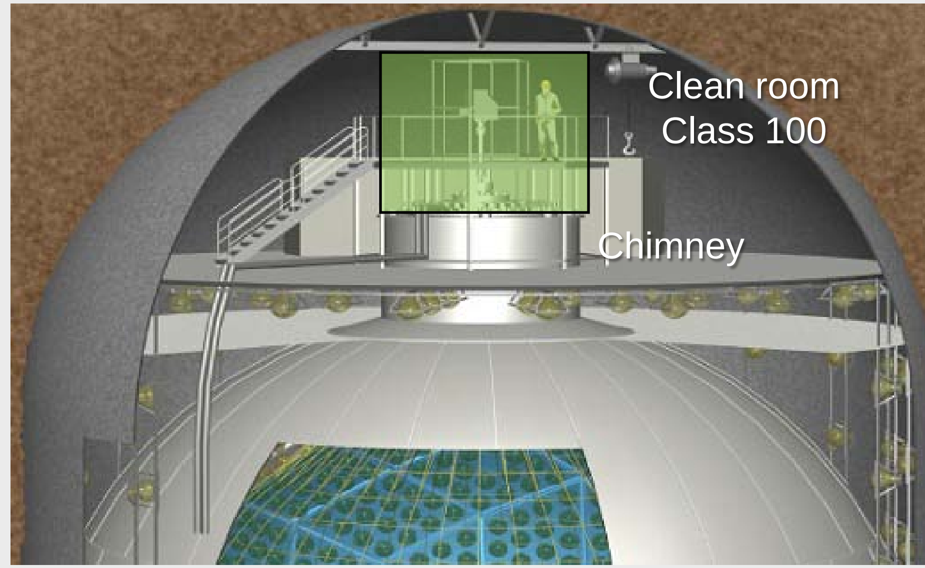
heat welding



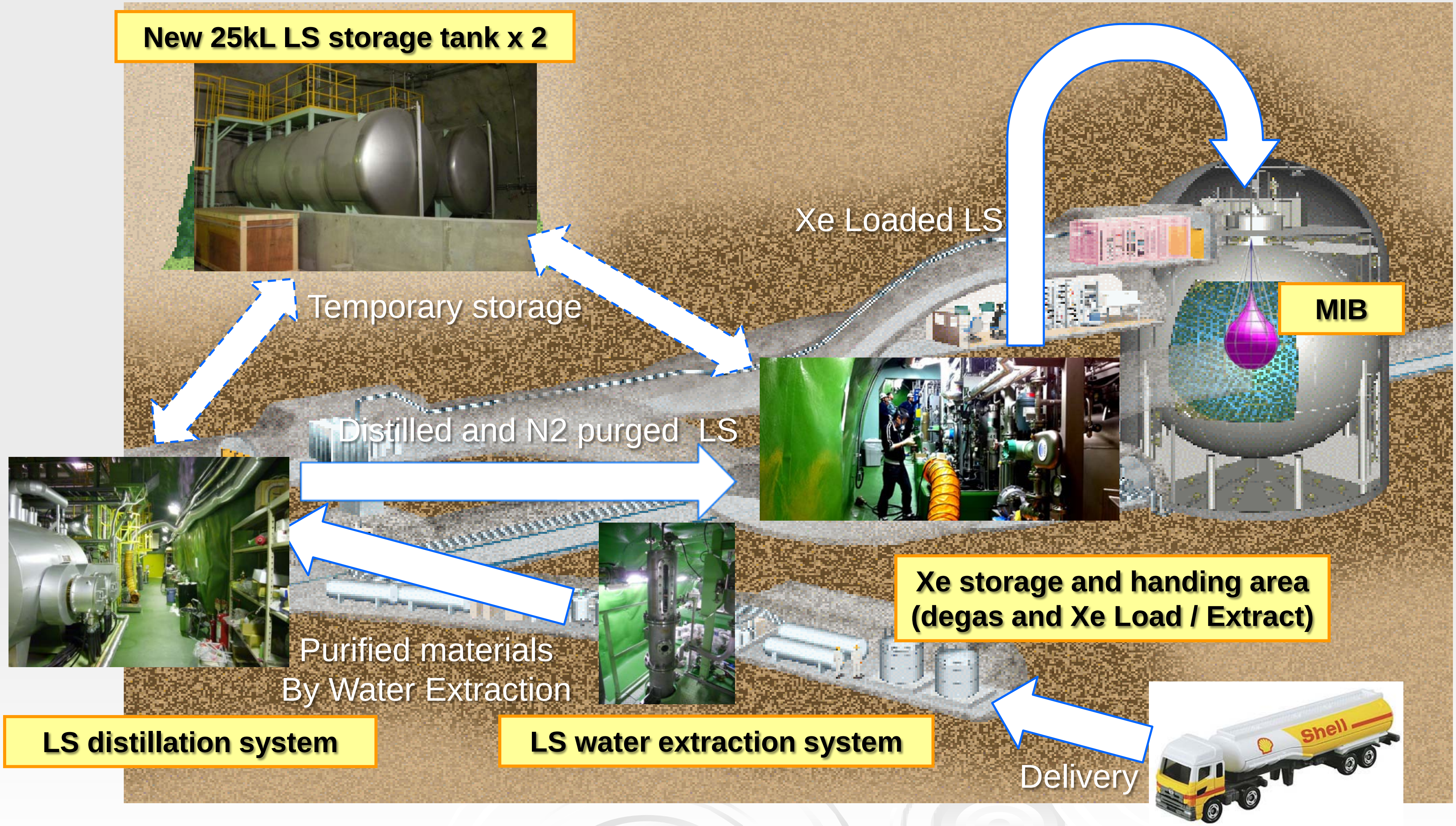
He leak test & Repair work

Before shipping

# Installation of KamLAND-Zen mini balloon




# Making Xe loaded LS



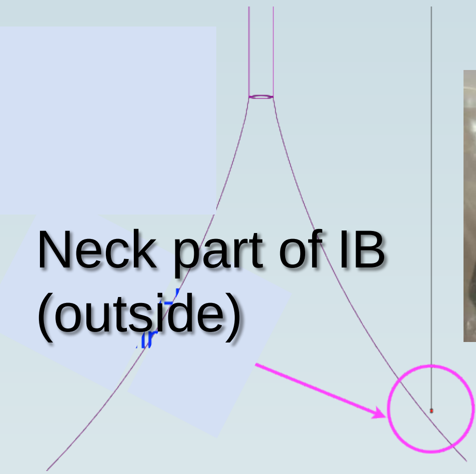


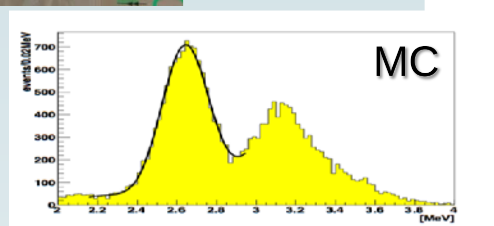

Normal data taking has been started on 24 September 2011

# Energy Calibration

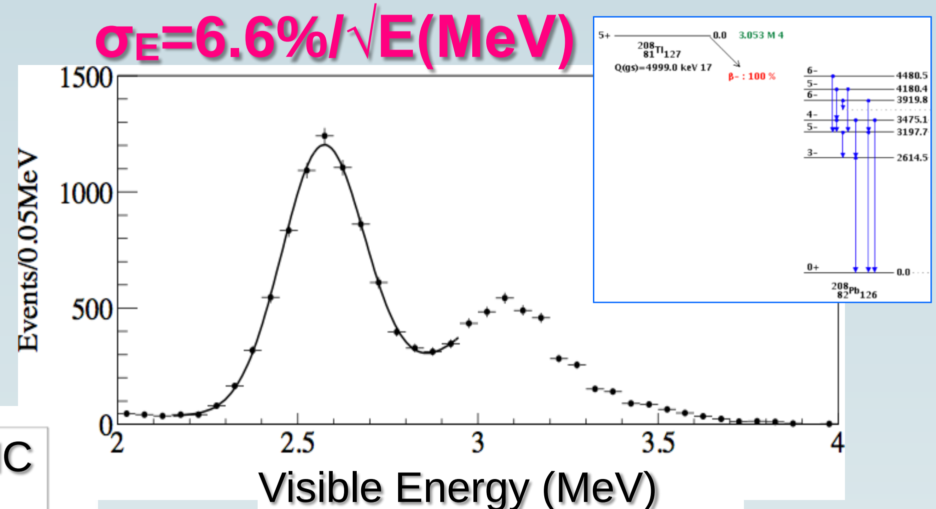
## 1. Calibration source

$^{208}$Tl(2.6 MeV γ, source)




$\sigma_E = 6.6\% / \sqrt{E(\text{MeV})}$




## 2. **2.225 MeV gamma's** from spallation neutrons capture on protons.

## 3. Radioactivity in Xe-LS

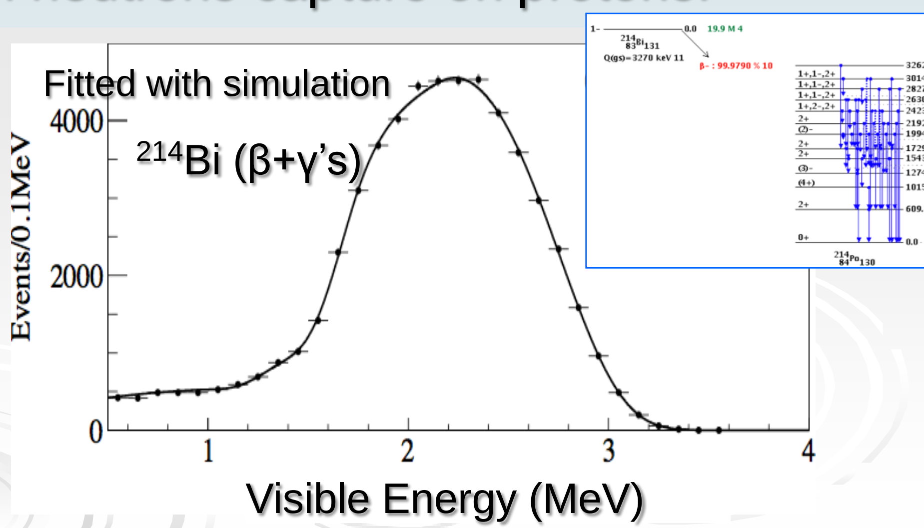
from initial contamination

Prompt delayed

$^{222}$Rn 3.824 day ···→ $^{214}$Bi 19.9 m → $^{214}$Po 164.3 μs → $^{210}$Pb 22.3 yr

$Q_\beta$ = 3.272 MeV

$Q_\alpha$ = 7.687 MeV



# Fiducial Volume

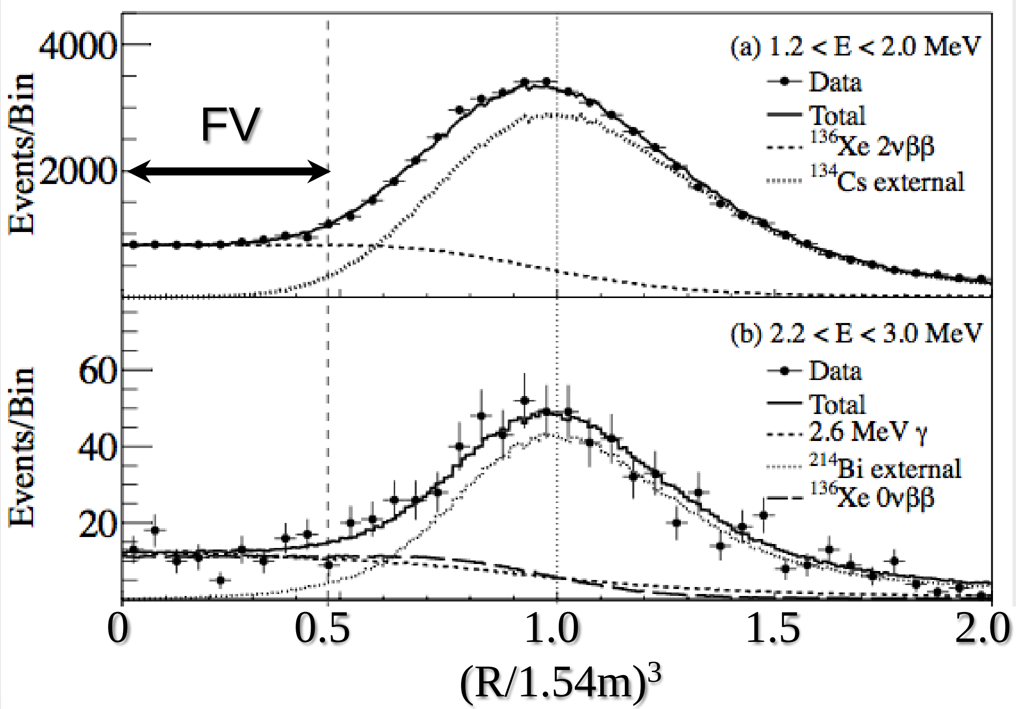
Vertex resolution $\sigma = \sim 15 cm/\sqrt{E}$

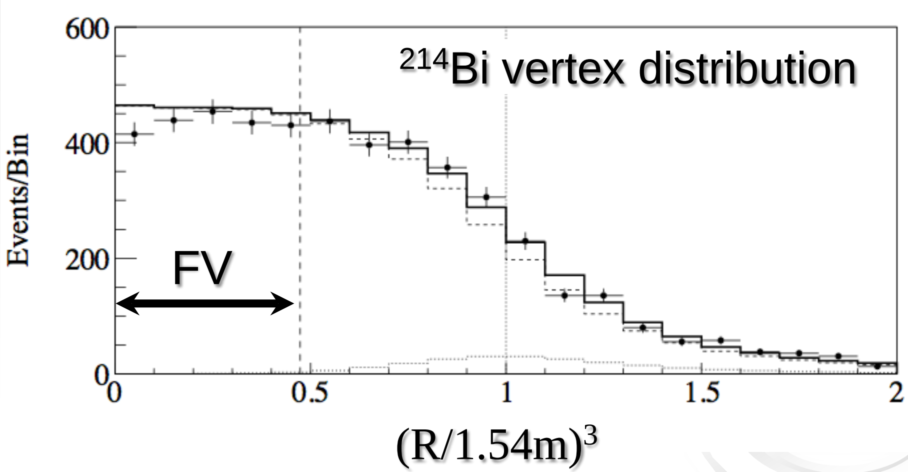
R<1.2 m, LS = 7.24 $m^3$
→ 125 kg $^{136}Xe$ in the FV
($^{136}Xe$ 90.93% enrichment,
2.44% by weight)

Volume ratio=0.438 ± 0.005
((R<1.2m)/Total 16.51 ± 0.17 $m^3$)

Total fiducial volume error 5.2%

$^{214}Bi$ rate (from vertex distribution)
ratio = 0.423 ± 0.007(stat.) ± 0.004(syst.)
(R<1.2 / Total $^{214}Bi$ events)

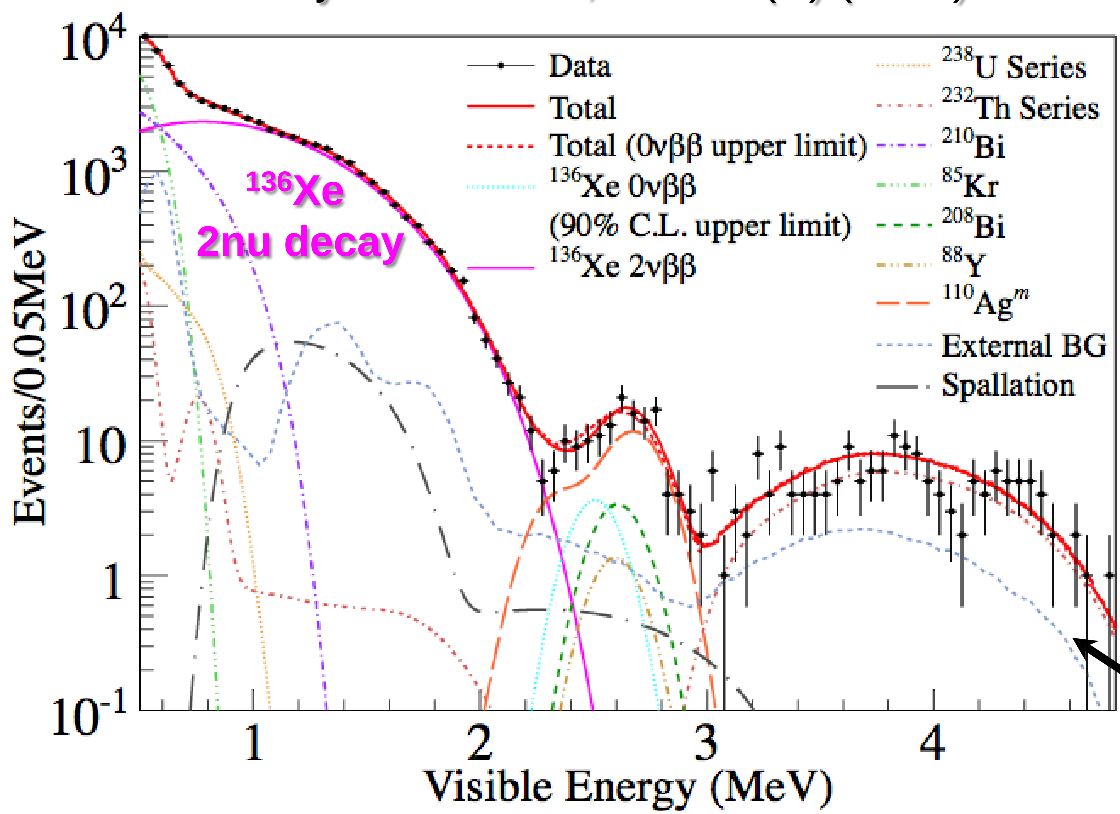



| systematic uncertainty | error |
|---|---|
| fiducial volume | 5.2% |
| enrichment of Xe | 0.05% |
| Xe amount 2.44±0.01wt% | 0.34% |
| energy scale | 0.3% |
| Xe-LS edge effect | 0.06% |
| total | 5.2% |

# result of $^{136}$Xe 2νββ half life

Phys. Rev. C 86, 021601(R) (2012)




- Livetime 112.3 days.
- $^{136}$Xe 125 kg.

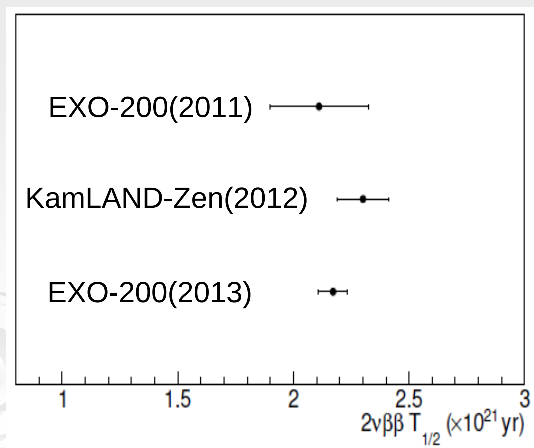
Event selection:
1. 1.2-m-radius FV.
2. 2msec veto after muon.
3. Sequential Bi-Po decay tagged.
4. Anti-neutrino (from reactor) tagged.
5. Vertex-time-charge test.

$^{208}$Tl distributed here.

**KamLAND-Zen $T^{2\nu}_{1/2}$=2.30±0.02(stat)±0.12(syst) ×$10^{21}$ yr**

**EXO-200 $T^{2\nu}_{1/2}$=2.172±0.017(stat)±0.060(syst) ×$10^{21}$ yr**

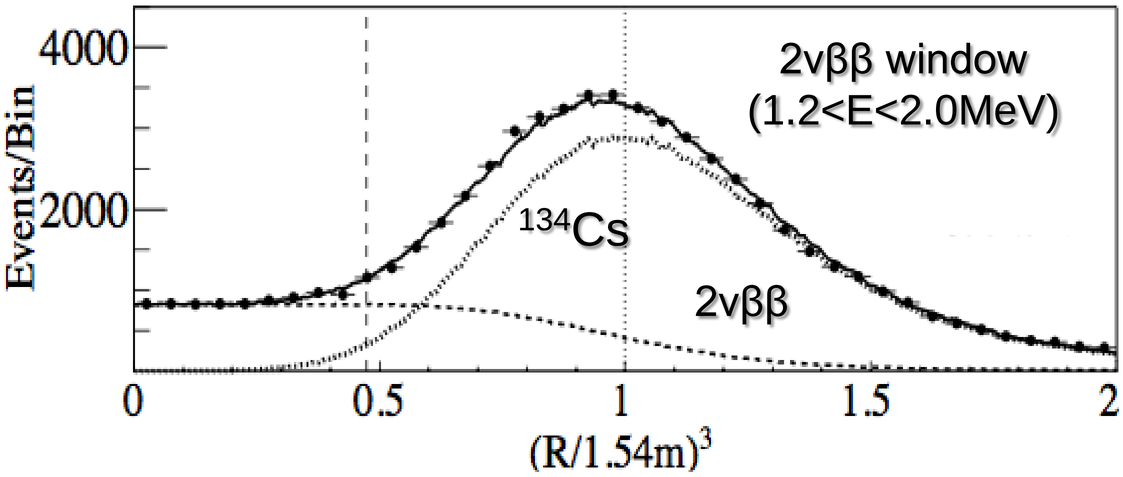
**arXiv:1306.6106 (2013)**




**consistent with EXO-200 results !**

# Unexpected background for $^{136}$Xe 0νββ

$^{134}$Cs distribute on the MIB.  Origin → Fallout of Fukushima reactor accident

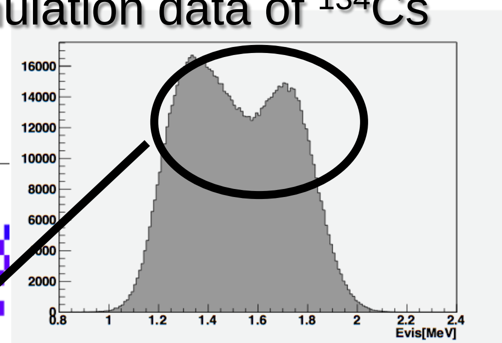


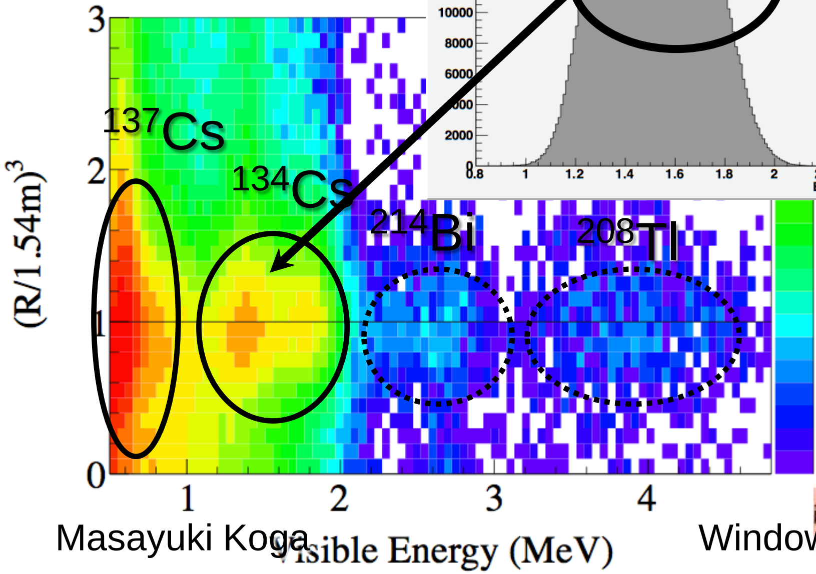

Why Fukushima?
- Cs doesn't exist in nature.
- Ratio of $^{134}$Cs/$^{137}$Cs data (~0.8)& soil sample almost consistent.

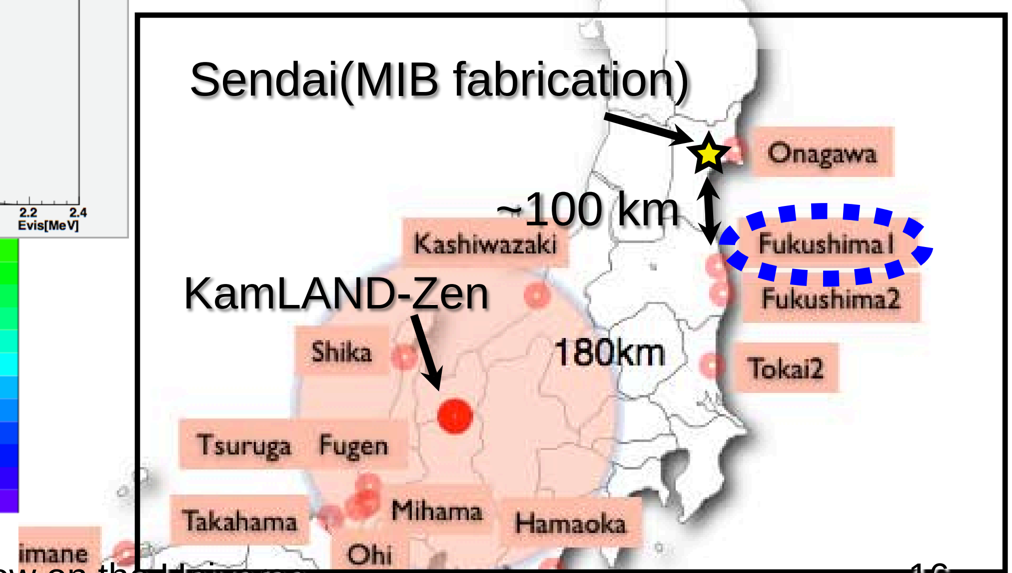
Possibility Spallation of $^{136}$Xe?
- Amount of $^{137}$Cs can't explain.

Why on MIB?
- MIB made in Sendai (Cs detected in soil sample by Ge detector).
- Fit well with data.
- Cs don't dissolve to LS.

simulation data of $^{134}$Cs



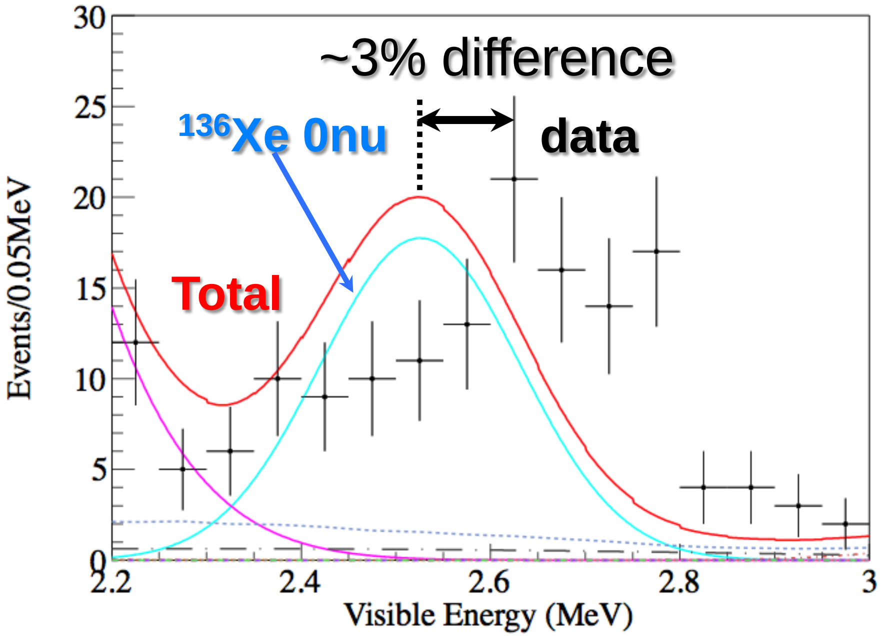



# Unexpected background for $^{136}$Xe 0νββ

Fit the peak with 0nu spectrum

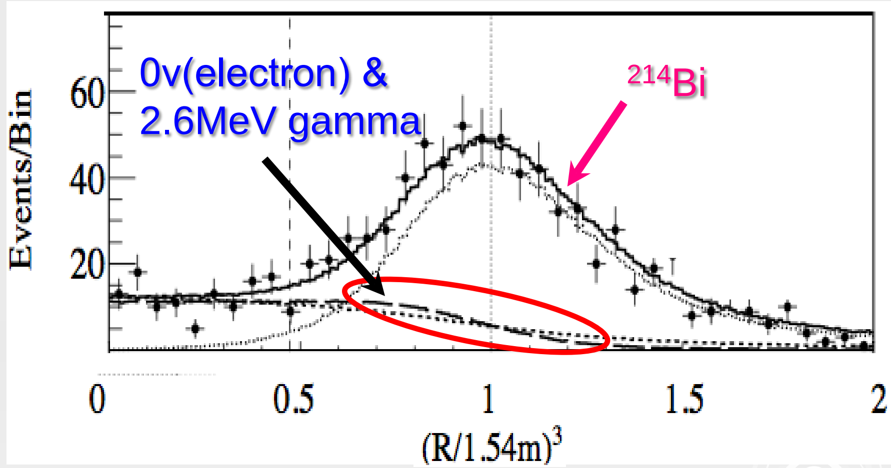
※close-up picture (fitting range is 0.5-4.8 MeV)




**No background hypothesis excluded more than 5 sigmas.**

Features of peak

- Rate is stable.
- Uniformly distributed in Xe-LS.
- No signal in KamLAND-LS
- beta or gamma : difficult to distinguish




**What is this background?**

Long-lived radioactive impurities ?

Cosmogenic spallation nuclei ?

- ex-situ measurement didn't determine BG. Amount of BG is too small to measure.

**Search all nuclei and decay path in the ENSDF**

database of nuclei

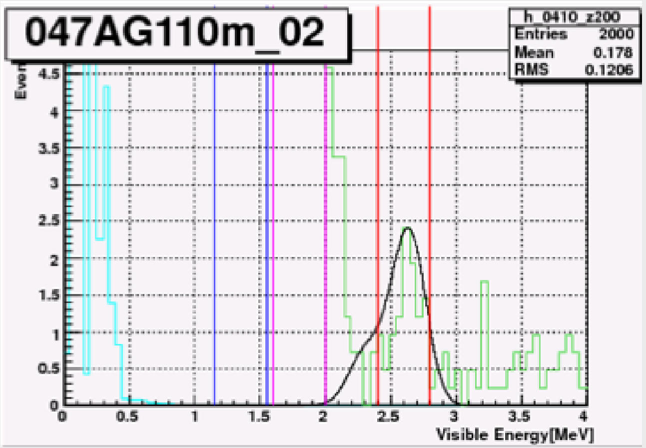
# ENSDF search

- We search all of isotopes, all of decays in ENSDF

## Procedure

- Follow every ENSDF cascade info and check lifetime, Q-value and so on.
- Make energy spectrum of $\beta^-$(+γ), $\beta^+$ (+γ) and EC(+γ) decays expected in KamLAND (considered alpha quenching, energy resolution, the time structure of the chain and pile-up in DAQ etc.)
- Check its peak and shape (it is in 2.4-2.8 MeV?).
- Check long lived parent (> 30days) for each candidates.

example of spectrum




- Nuclei w/ 100sec~30days are rejected from the study of energy spectrum w/ close A,Z nuclei.
→ negligible

- Study on time-correlation event with muon w/ <100 sec lifetime is estimated to be $<6.7\times10^{-3}$ /ton·day (90% CL).
→ small

## 4 nuclei remains.

| | decay | τ | Q-value[MeV] |
|---|---|---|---|
| $^{110m}$Ag | $\beta^-$ + γ | 360 days | 3.01 |
| $^{88}$Y | EC + γ | 154 days | 3.62 |
| $^{208}$Bi | EC + γ | $5.31\times10^5$ yr | 2.88 |
| $^{60}$Co | $\beta^-$+γ | 7.61 yr | 2.82 |

※ $^{110m}$Ag is one of reactor fallout, too.

# Cosmogenic spallation at aboveground?

## Possibility of cosmogenic spallation in Xe?

- Xe enriched in Russia and sent to mine by airplane (high cosmic ray flux).

**$^{136}Xe + p(1\ GeV)$ cross section**

P.Napolitiani et. al.
Phys. Rev. C **76,** 064609 (2007)

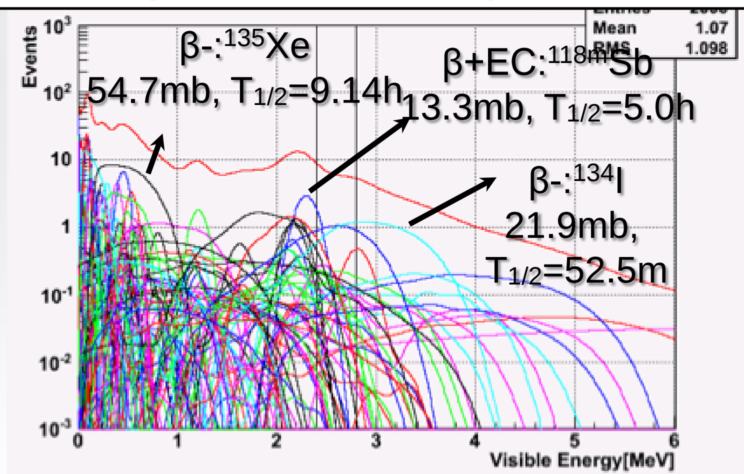
quantitative background estimation is difficult due to transportation loss in the gas system.

$^{136}Xe$ → surface → mine → Radioactivities after X + Y days → energy spectrum

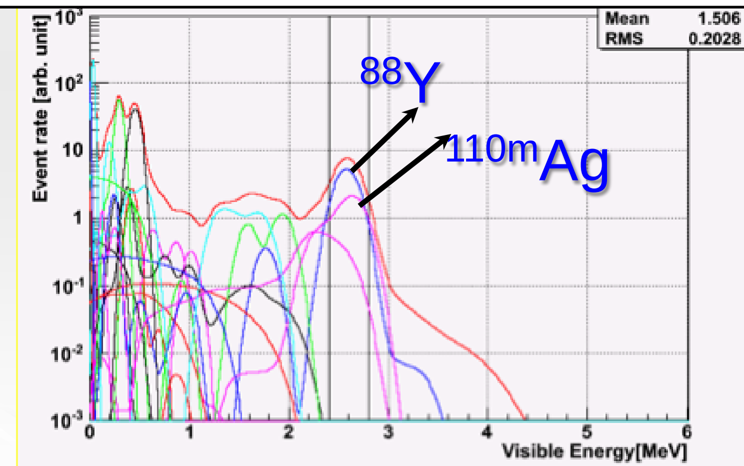
surface: X = 100 days

mine: Y = 0, 100, 300, 600days

100 days on surface, 0 days in the mine




100 days on surface, 300 days in the mine

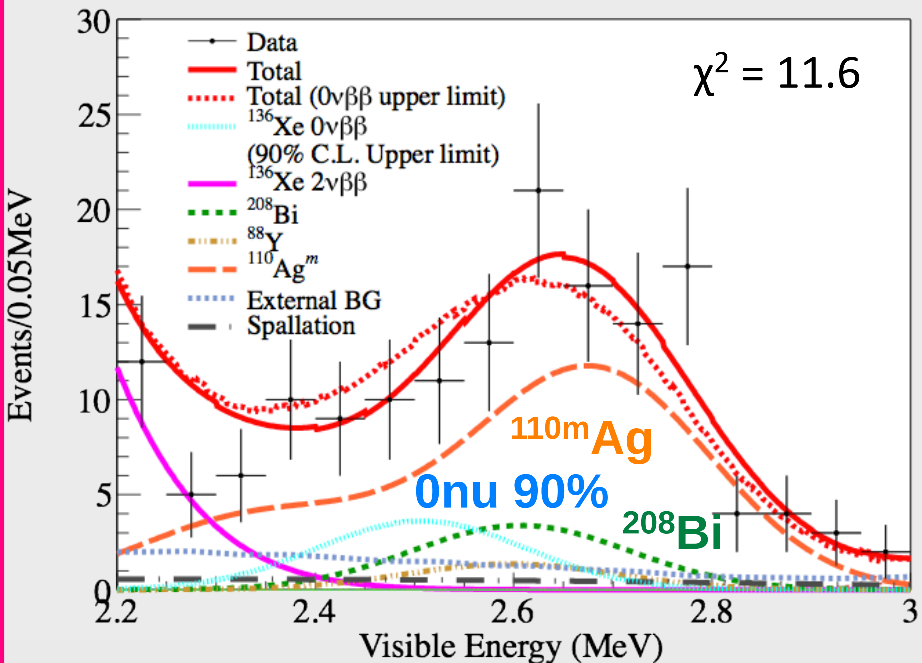



→ $^{110m}Ag$ and $^{88}Y$ remains.

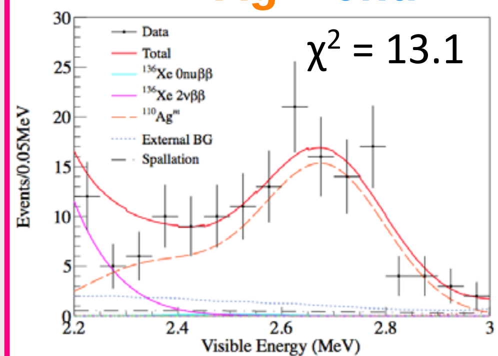
# Background study around Q-value

## Simultaneous fit

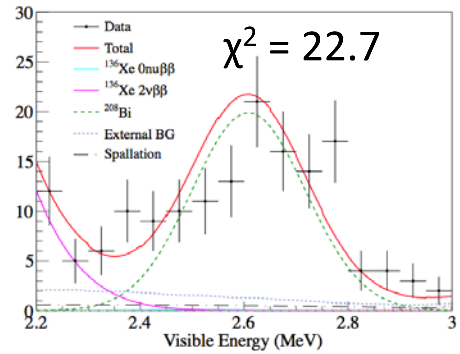
and 90% CL upper limit for 0vββ




$^{110m}$Ag + 0nu




$^{208}$Bi + 0nu △



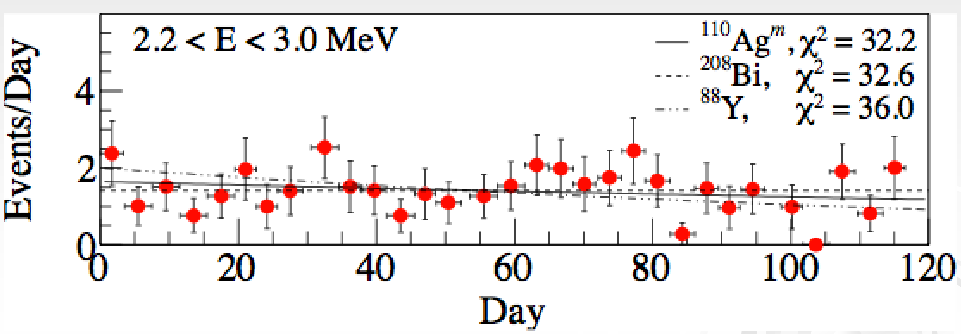

$^{88}$Y + 0nu → $\chi^2$ = 22.2 △

$^{60}$Co + 0nu → $\chi^2$ = 82.9 ✕

0nu only → $\chi^2$ = 85.0 ✕

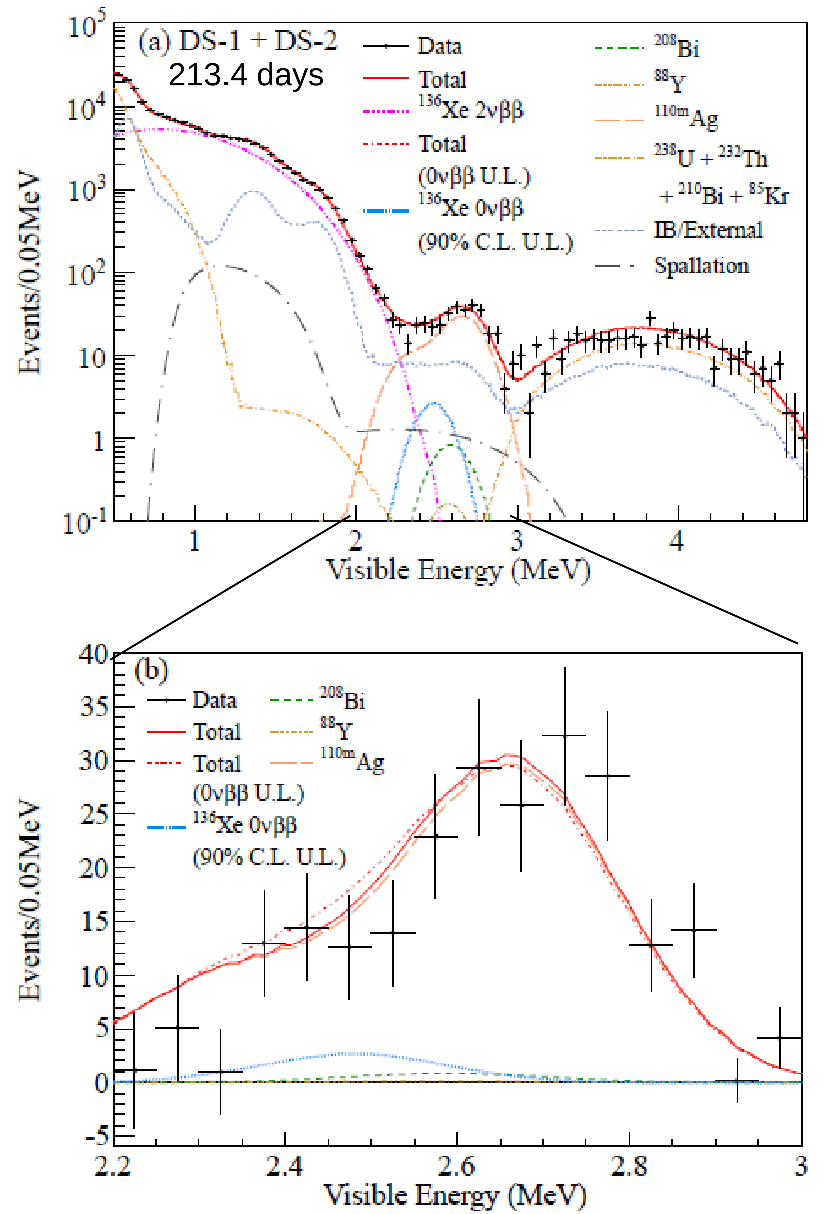
BG is likely to be $^{110m}$Ag.

## Time distribution of events

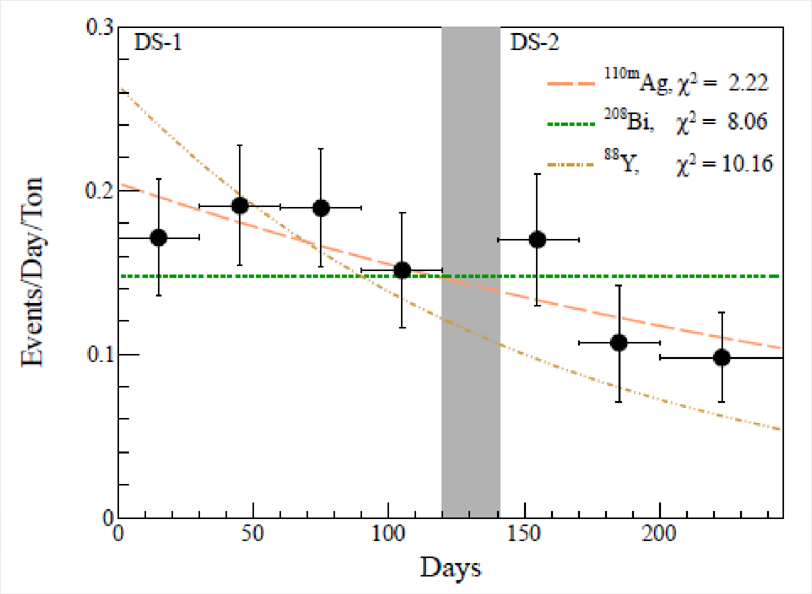



Stable. No strong discrimination.

# KamLAND-Zen phese-1 result




2.2MeV < E < 3.0MeV

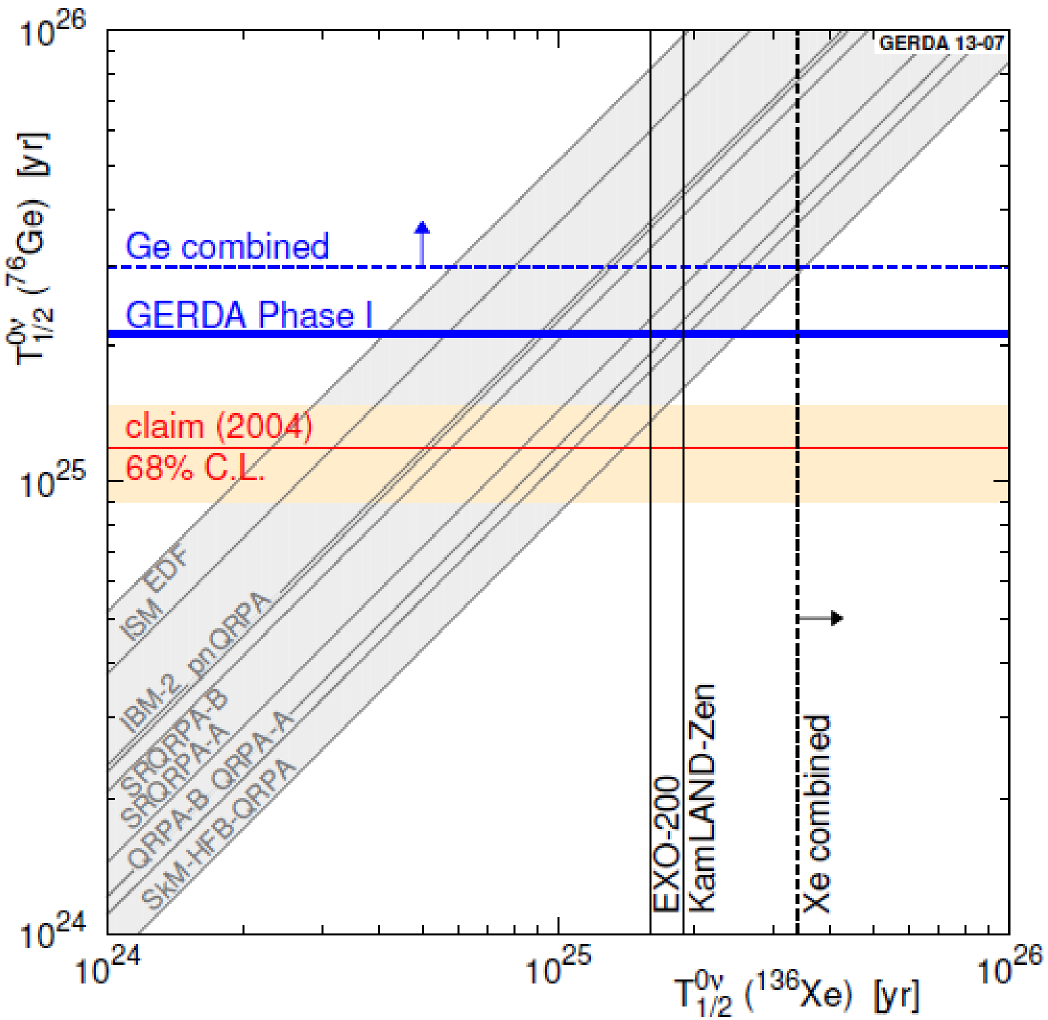



KamLAND-Zen

$T^{0\nu}_{1/2}$ > 2.1x10$^{-25}$ yr @90%CL

**Phys.Rev.Lett.110:062502,2013.**

# 0ν2β half-life limit on $^{136}$Xe .vs. $^{76}$Ge




- $^{136}$Xe

  KamLAND-Zen PRL. 110, 062502 (2013)

  $T^{0v}_{1/2} > 1.9 \times 10^{25}$ yr (90%C.L.)

  EXO-200 PRL.109,032505 (2012)

  $T^{0v}_{1/2} > 1.6 \times 10^{25}$ yr (90%C.L.)

  $^{136}$Xe combined

  $T^{0v}_{1/2} > 3.4 \times 10^{25}$ yr (90%C.L.)

  $\langle m_{\beta\beta} \rangle < 0.12 – 0.25$ eV

  By (R)QRPA Phys.Rev.C79,055501(2009)

  claim was excluded at >97.5%CL for a representative range of NME estimation

- $^{76}$Ge

  GERDA Phase1 arXiv:1307.4720 (2013)

  $T^{0v}_{1/2} > 2.1 \times 10^{25}$ yr (90%C.L.)

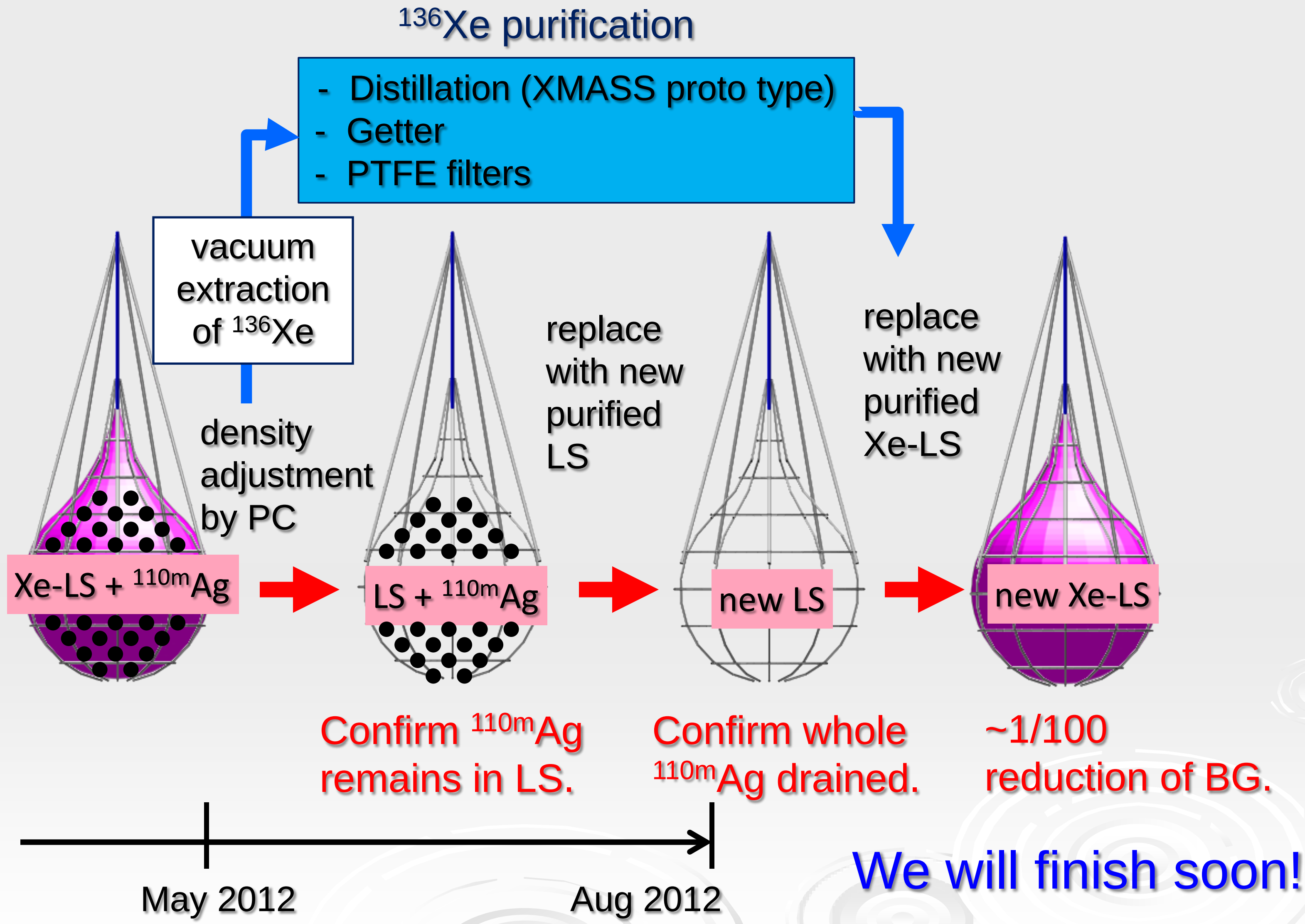
  $^{76}$Ge combined

  $T^{0v}_{1/2} > 3.0 \times 10^{25}$ yr (90%C.L.)

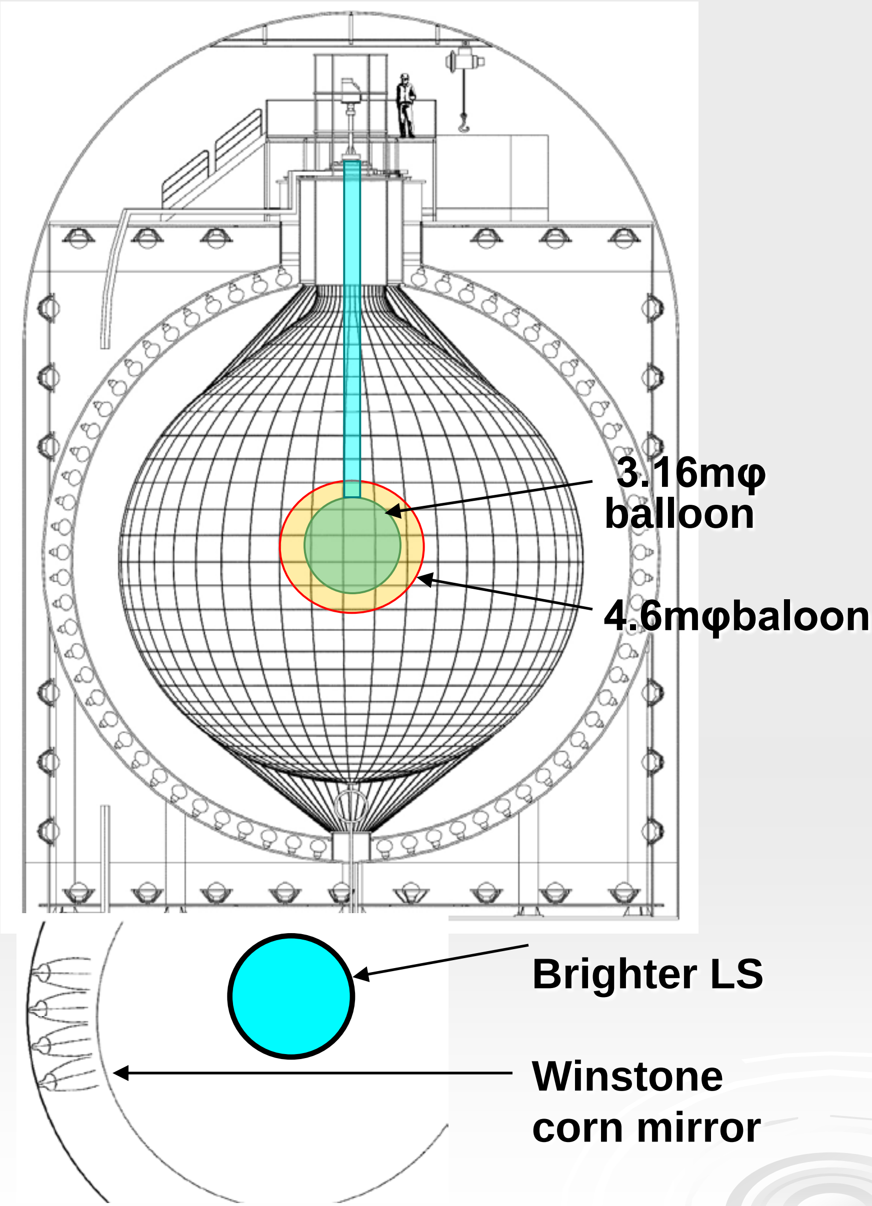
  $\langle m_{\beta\beta} \rangle < 0.2 - 0.4$ eV

The long-standing claim was strongly disfavored. Independent with NME .

# How to reduce the BG ?



# Future Plan




## Current phase

re-start (from Nov. 2013?)

## KamLAND-Zen2

- we will purchase 700~800kg enrich $^{136}$Xe to the end of 2013
- make bigger balloon
- same component XeLS (~3wt%)
- main tank inspection & OD repair (beginning of 2015?)

tank opening (201?)

## KamLAND2-Zen $^{136}$Xe 800~1000kg

- R=2.3m balloon, $V=51.3m^3$, $S=66.7m^2$
- Detector upgrade
  improvement of energy resolution
  (brighter LS, higher light concentrator )
  ~25meV with 5 years

# summary

- KamLAND-Zen started from September 2011

- Current result
  - 2νββ decay
    KamLAND-Zen $T^{2\nu}_{1/2}=2.30\pm0.02(stat)\pm0.12(syst)\times10^{21}$ yr
    EXO-200 $T^{2\nu}_{1/2}=2.172\pm0.017(stat)\pm0.060(syst)\times10^{21}$ yr
  - 0νββ decay
    KamLAND-Zen $T^{0\nu}_{1/2} > 1.9\times10^{25}$ yr (90%C.L.)
    $^{136}Xe$ combined (with EXO-200) $T^{0\nu}_{1/2} > 3.4\times10^{25}$ yr (90%C.L.)
    corresponding to $\langle m_{\beta\beta}\rangle < 0.12\text{-}0.25$ eV.

- Claim was excluded. 0νββ observation move to the next stage (<100meV).

- Under the BG reduction campaign from LS.
  We will restart soon (November 2013?)

- Considering to upgrade (KamLAND-Zen2 and KamLAND2-Zen)