# KamLAND-Zen 800 status and future prospects

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KAVLI IPMU

2017 ICNFP @AOC

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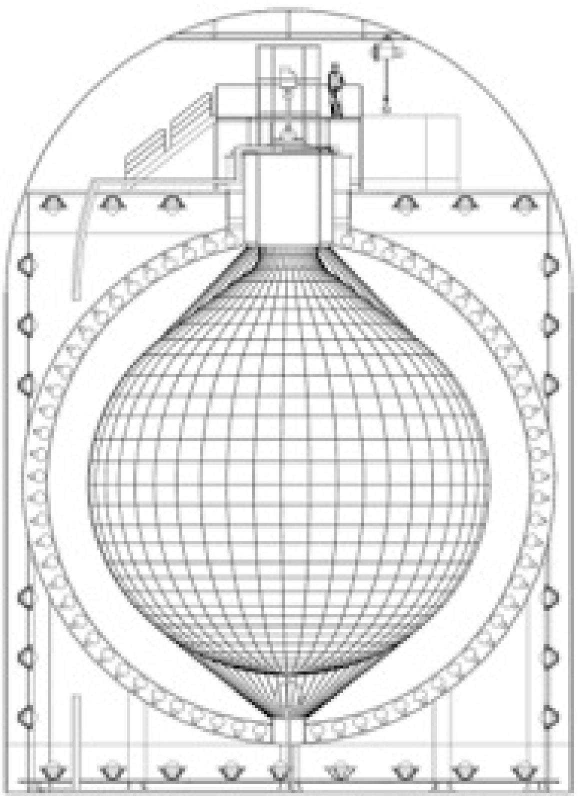
# KamLAND experiment on $\bar{\nu}_e$

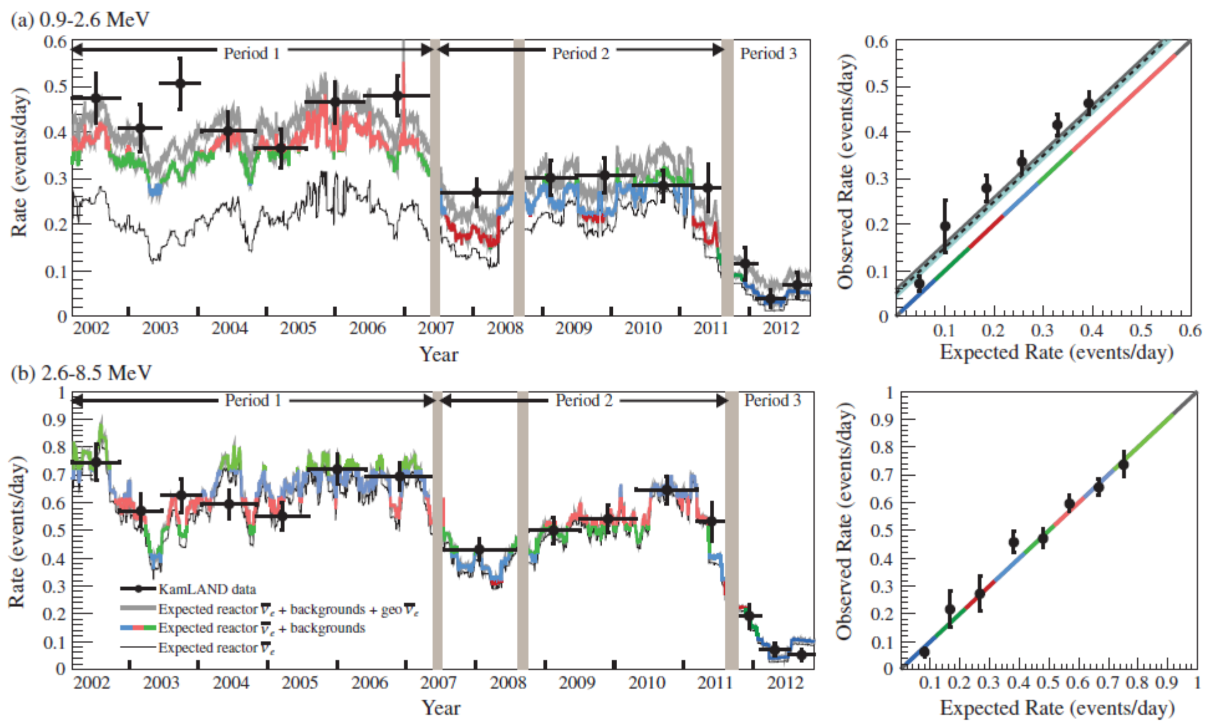
- Detector running over 15 years (from 2002)

- Large volume: 1,200m$^3$ Liquid Scintillator
  Ultra low radioactivity: U: <$3.5\times10^{-18}$g/g,
  Th: <$5.2\times10^{-17}$g/g (from2007)
- KamLAND Energy Resolution:

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



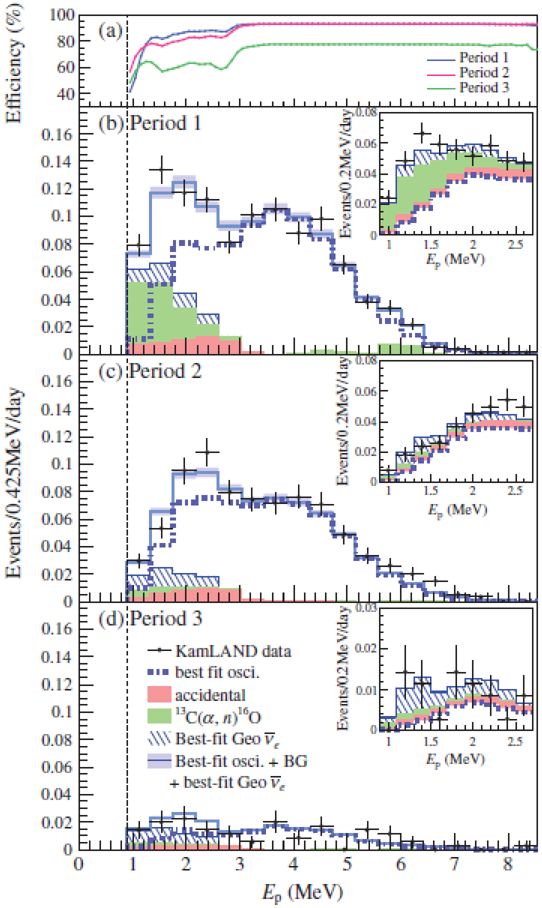
Depth: 2,700 m.w.e.
t =2.5m paraffin shield
Acrylic plate for Rn
3.8kL pure-water OD veto




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

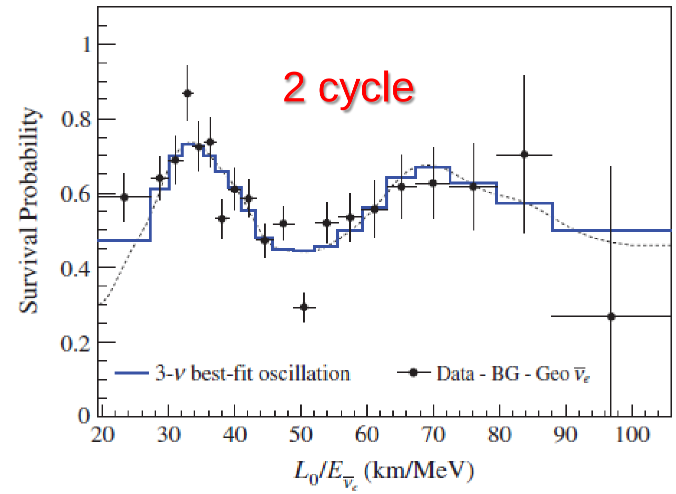
# KamLAND reactor $\overline{\nu}_e$ results

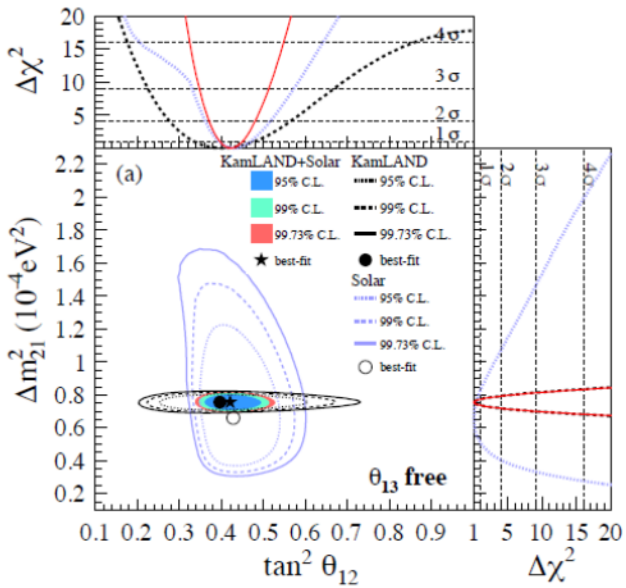
- energy spectrum

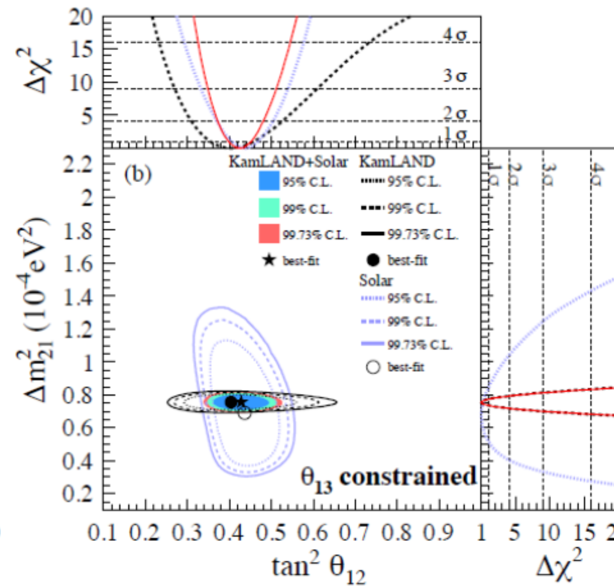



- Stable data-taking
- Low B.G.
  (ultra pure LS, low reactor ν flux)
- more precise measurement

- for Reactor neutrino



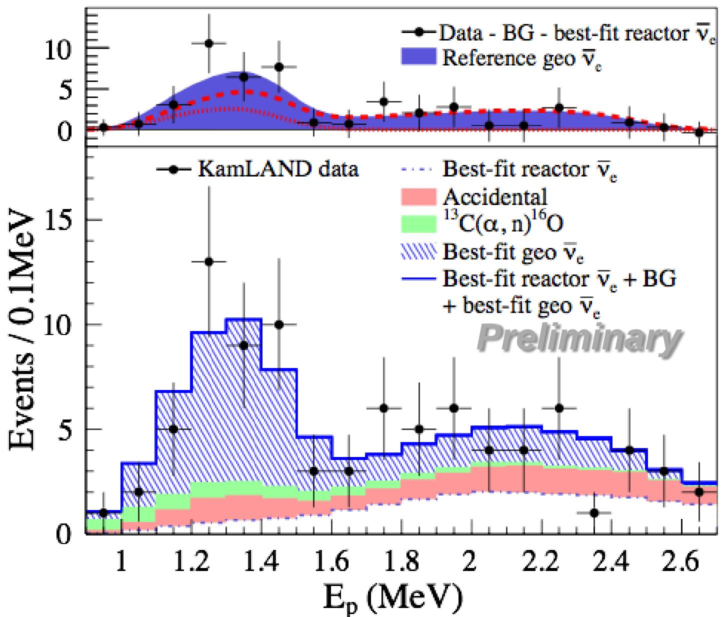




| | $\Delta m^2_{21}$ | $\tan^2\theta_{12}$ | $\sin^2\theta_{13}$ |
|---|---|---|---|
| KamLAND | $7.56^{+0.18}_{-0.19}$ | $0.396^{+0.082}_{-0.062}$ | $0.026^{+0.034}_{-0.038}$ |
| KamLAD+Solar+θ13 | $7.56^{+0.17}_{-0.20}$ | $0.428^{+0.024}_{-0.030}$ | $0.023^{+0.003}_{-0.002}$ |

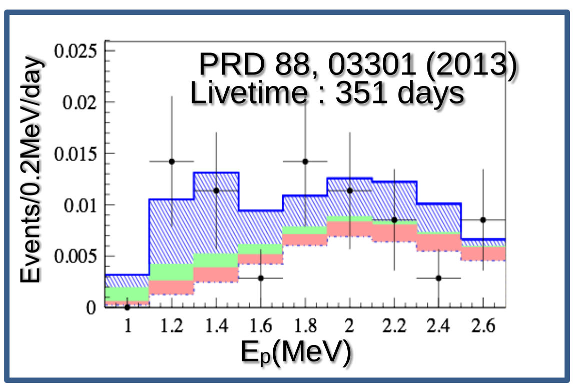
## • for Geo neutrino

Livetime : 1259.8 days   <u>2016 Preliminary Result</u>

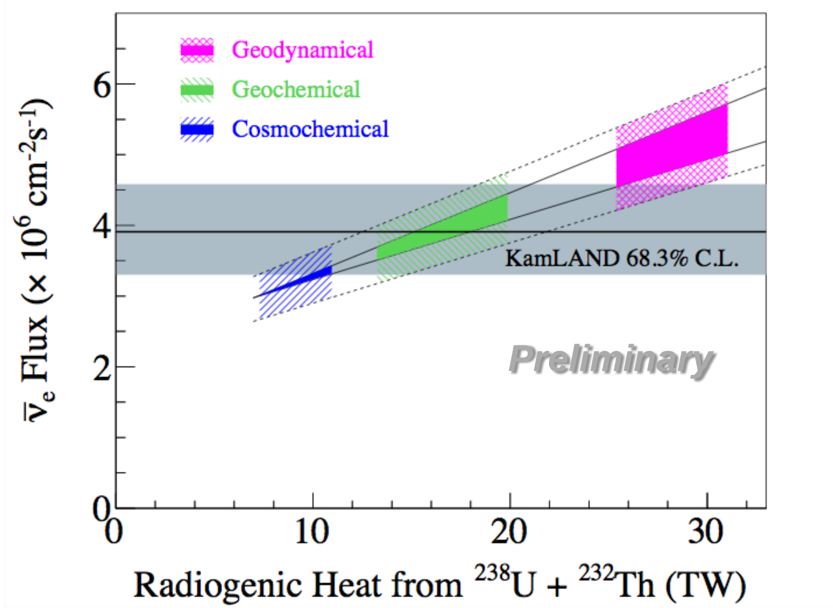
model prediction : Enomoto et al. EPSL 258, 147 (2007)




<u>best-fit : Period 3 analysis</u>




We measured clear distribution of geo-neutrino events!

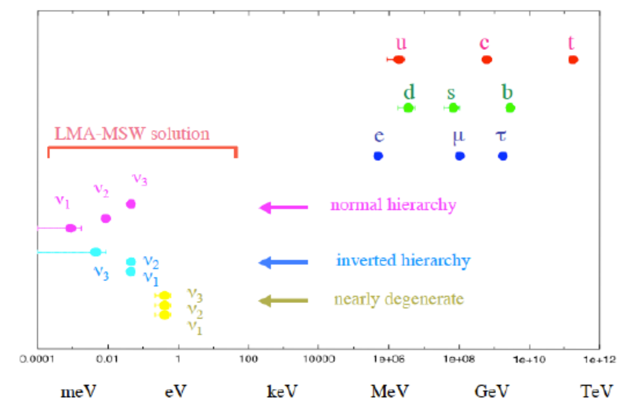



<u>Rate+Shape+time analysis (ratio fixed)</u>

| | [event] | [TNU] | Flux [$\times 10^6$ cm$^{-2}$s$^{-1}$] | | 0 signal rejection |
|---|---|---|---|---|---|
| | | | best-fit | model | |
| U+Th | **164 +28/-25 (17%)** | 34.9 +6.0/-5.4 | 3.9 +0.7/-0.6 | 4.1 | **7.92σ** |

# Why neutrino less double beta decay?

$m_\nu \ll m_{e,\,u,\,d}$




- Neutrino
  - 3 generation
  - Oscillation: $m_\nu \neq 0$, so small (why?)
  - Only Left-handed Neutrino (right-handed anti-neutrino) .

  where is right-handed ?

- Majorana Mass : Neutrino don't have charge

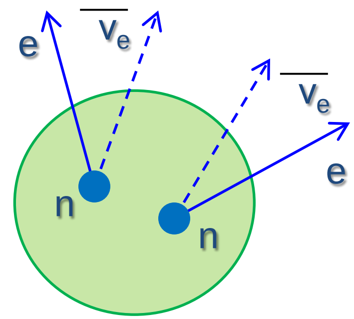
$$\mathcal{L}_{\mathrm{M}} = m_D(\bar{\psi}_L^c \psi_R^c + \bar{\psi}_R^c \psi_L^c) + m_L(\bar{\psi}_L (\psi_L)^c + (\bar{\psi}_L)^c \psi_L) + m_R\left((\bar{\psi}_R)^c \psi_R + \bar{\psi}_R (\psi_R)^c\right)$$

$$\mathcal{L}_{mass} = \mathcal{L}_D + \mathcal{L}_M = \mathcal{L}_D + \mathcal{L}_L + \mathcal{L}_R$$

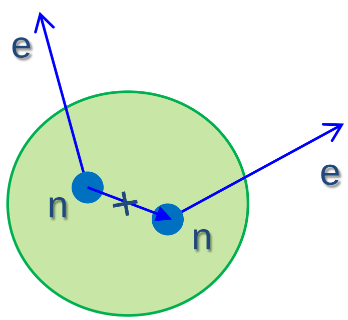
Violates lepton number !

- Heavy right-handed neutrino ? See-saw: (Yanagida, Gell-Mann…)

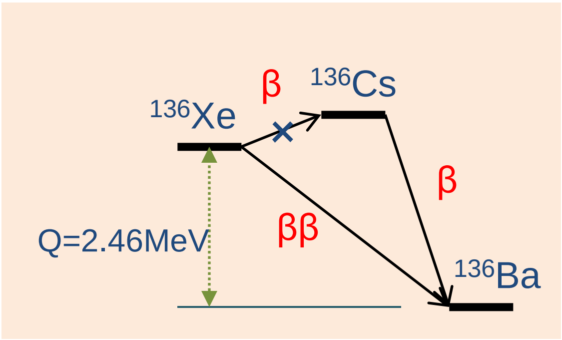
# Double beta decay isotope and 0νββ




2νββ




$\bar{\nu}_e = \nu_e$
0νββ




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

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

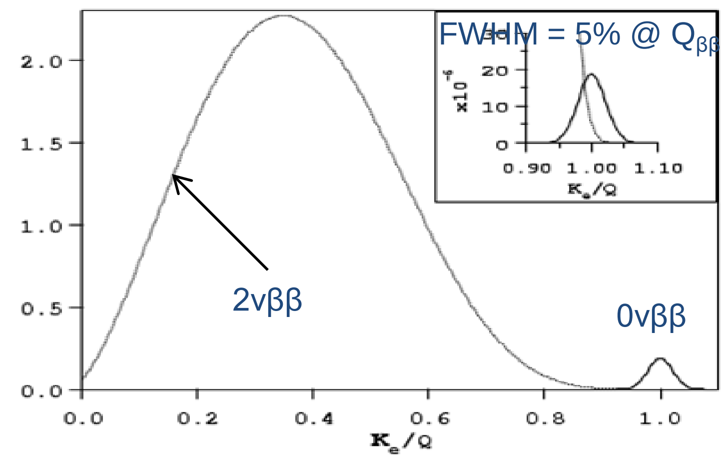
G: phase space factor,
M: nuclear matrix element
$\langle m_\nu \rangle$: effective neutrino mass

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

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

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

* Q>2MeV isotope



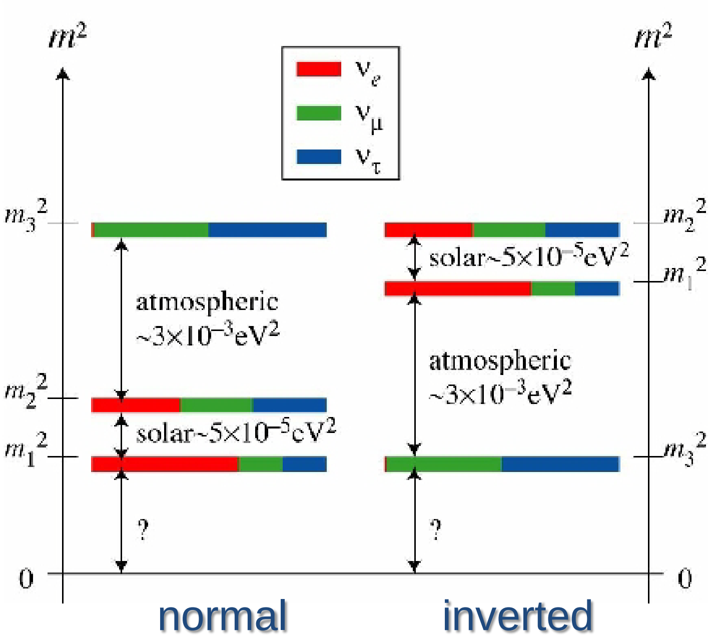

S.R.Elliot and P.Vogel, Ann. Rev.Nucl.Part.Sci.52(2002)115.

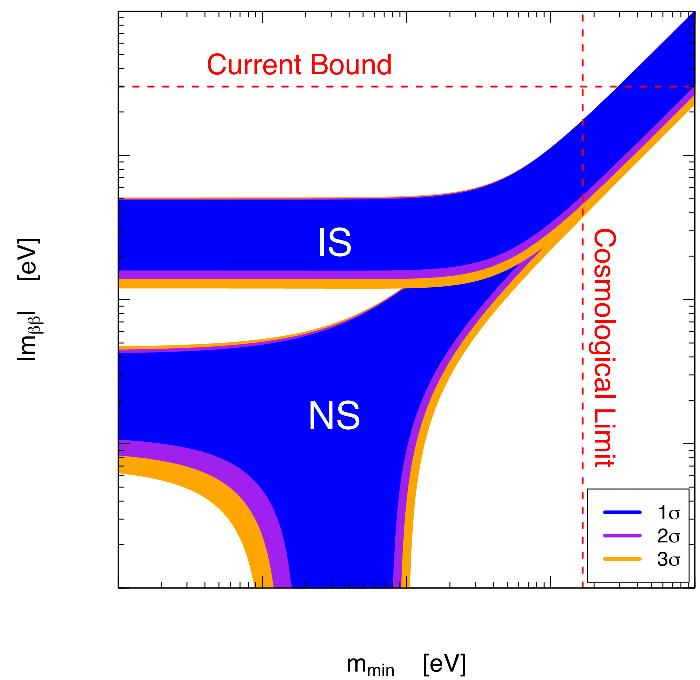
# Effective Majorana neutrino mass and hierarchy

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

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

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




S. M. Bilenky, arXiv:1203.5250

# Motivation of KamLAND-Zen for ββ

- KamLAND

  Large volume: 1,200$m^3$ Liquid Scintillator as a 4pi veto

  Ultra low radioactivity: U:<$3.5\times10^{-18}$g/g, Th<$5.2\times10^{-17}$g/g

  Distillation technique

  Experience of balloon development

  New electronics MoGRA (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

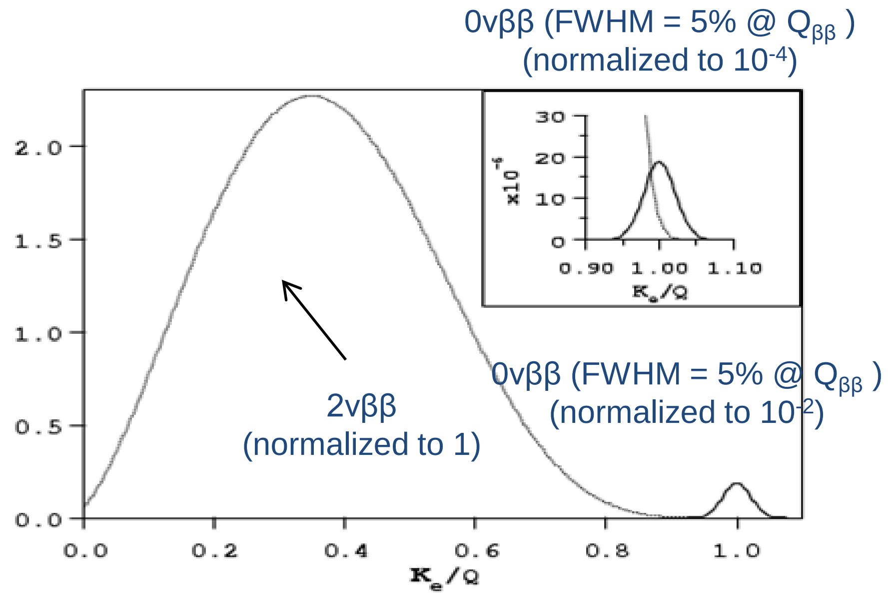
Before EXO-200 and KamLAND-Zen start

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

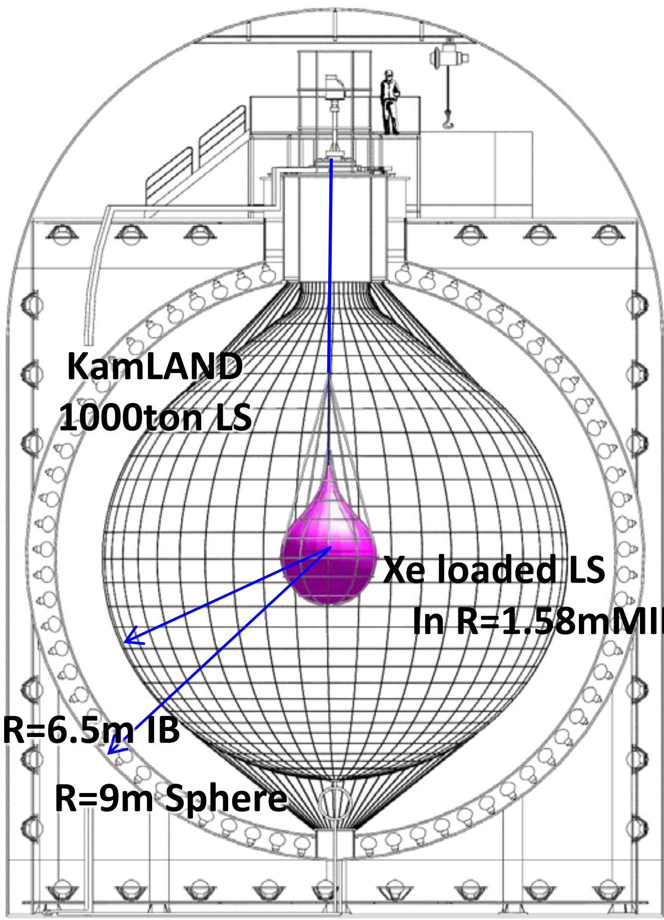
Rodin et al., Nucl. Phys. A793 (2007)213-215

Merits on KamLAND

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



# KamLAND-Zen project




**1325 17inch PMT**
**+554 20inch PMT**

## KamLAND-Zen collaboration

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

Zero neutrino double beta decay search
KamLAND-Zen

## 1st phase

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

R=1.54m balloon

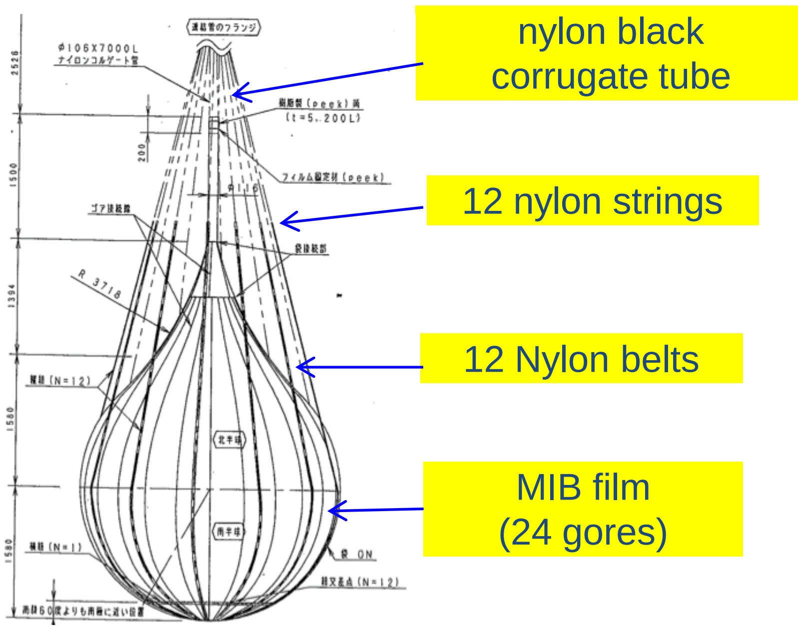
V=16.5m$^3$

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 | $2x10^{-12}$g/g |
| Th contamination | $3x10^{-12}$g/g |
| $^{40}$K contamination | $2x10^{-12}$g/g |

**filling test by water**

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

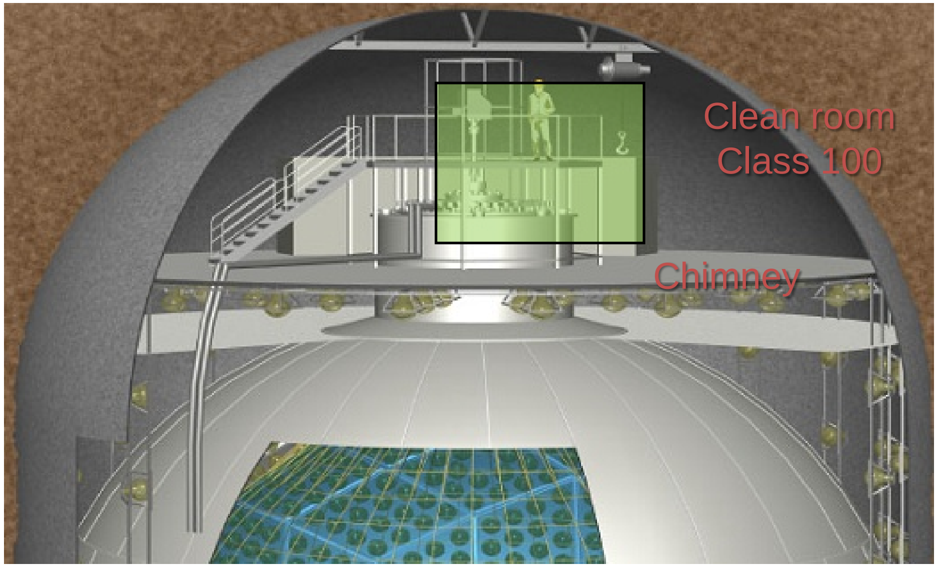
Ultra-sonic cleaning
using pure water

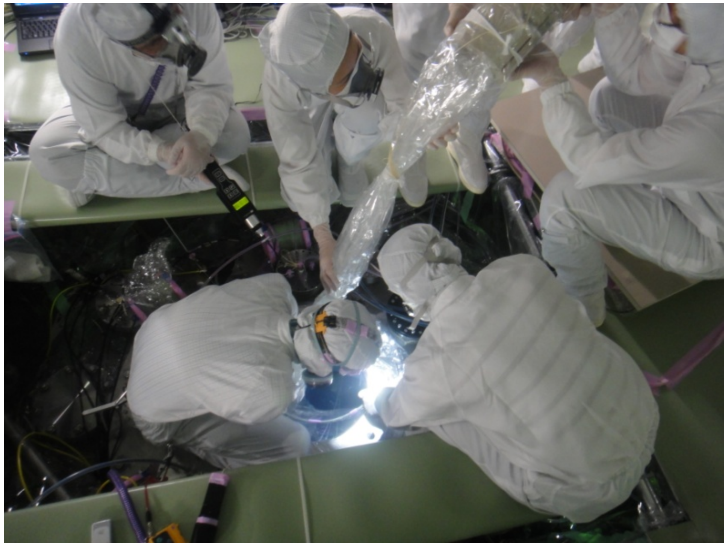
heat welding

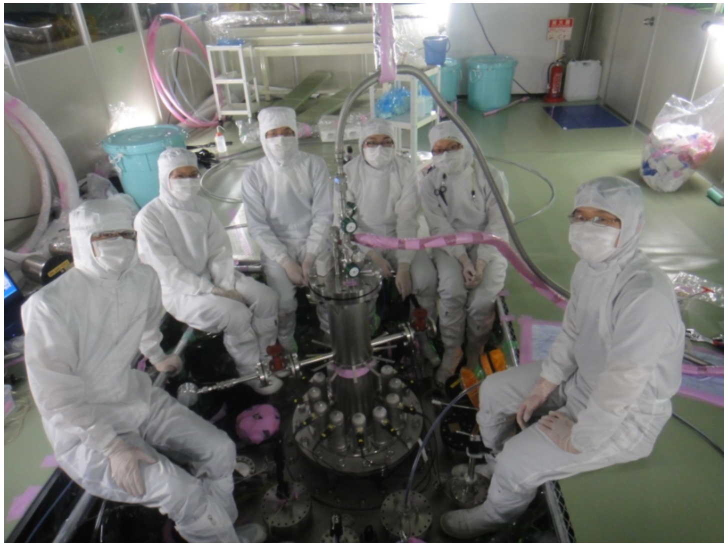
He leak test &
Repair work

Before shipping

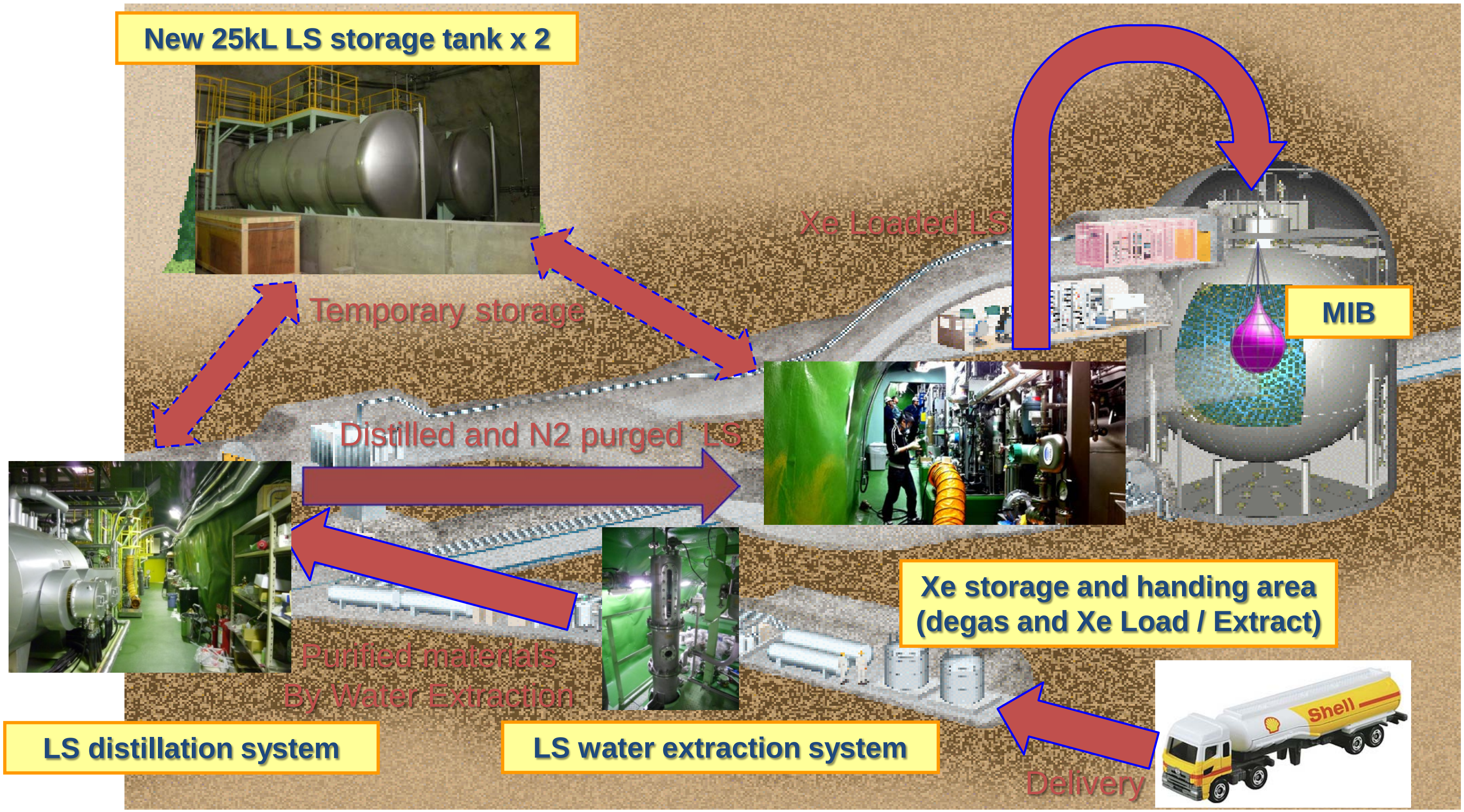
# Installation of KamLAND-Zen mini balloon

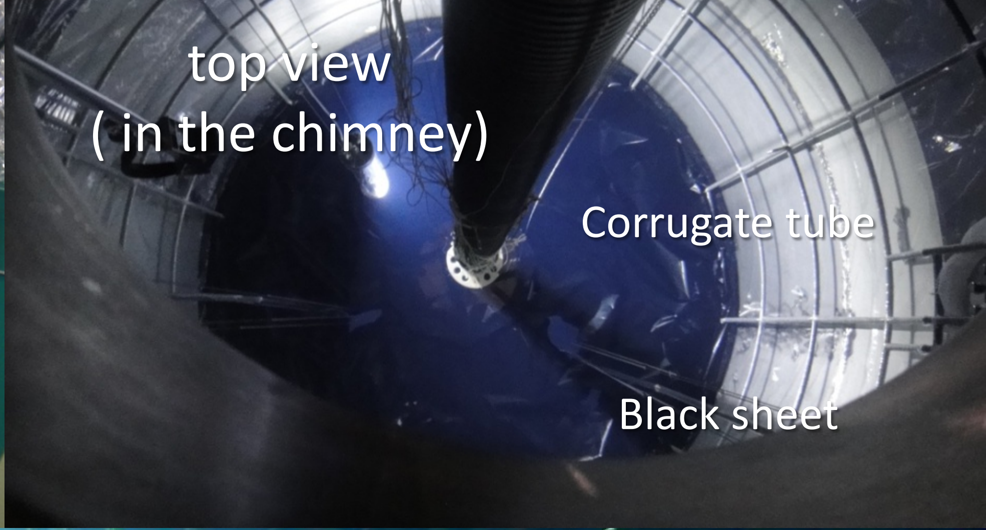




# Making Xe loaded LS



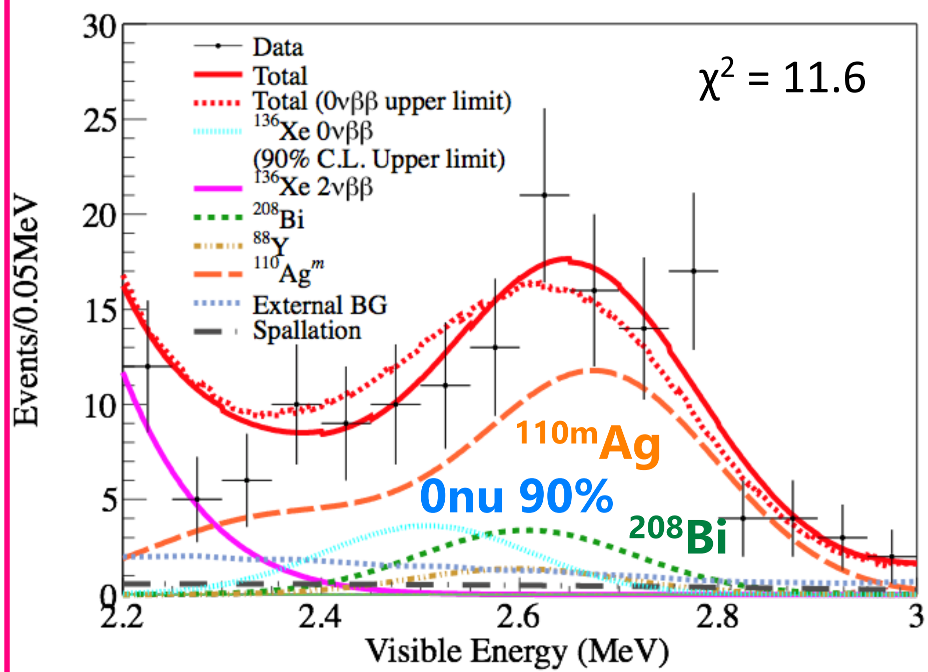


Normal data taking has been started on 24 September 2011

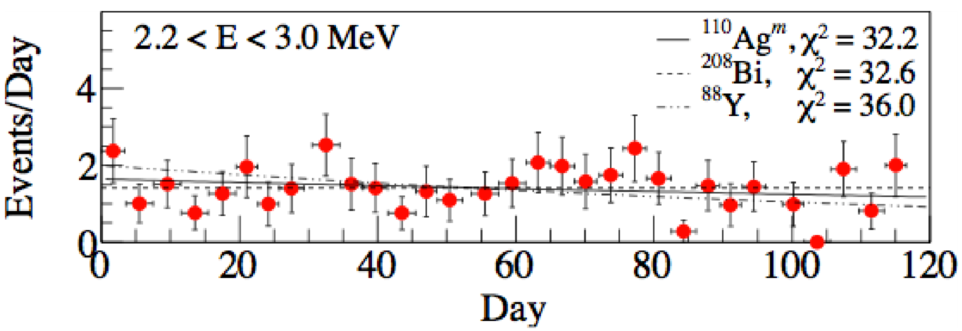
Masayuki Koga

# Background study around Q-value

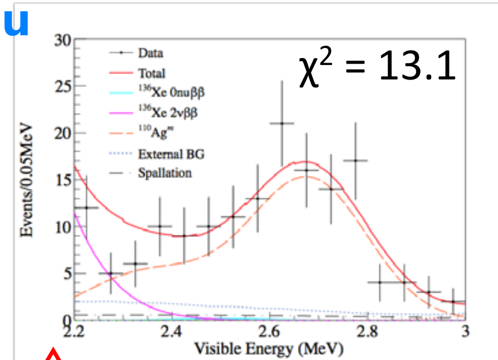
## Simultaneous fit
and 90% CL upper limit for 0νββ



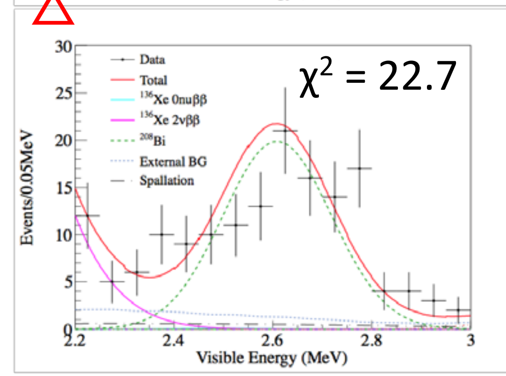

## Time distribution of events




$^{110m}$Ag + 0nu




$^{208}$Bi + 0nu △



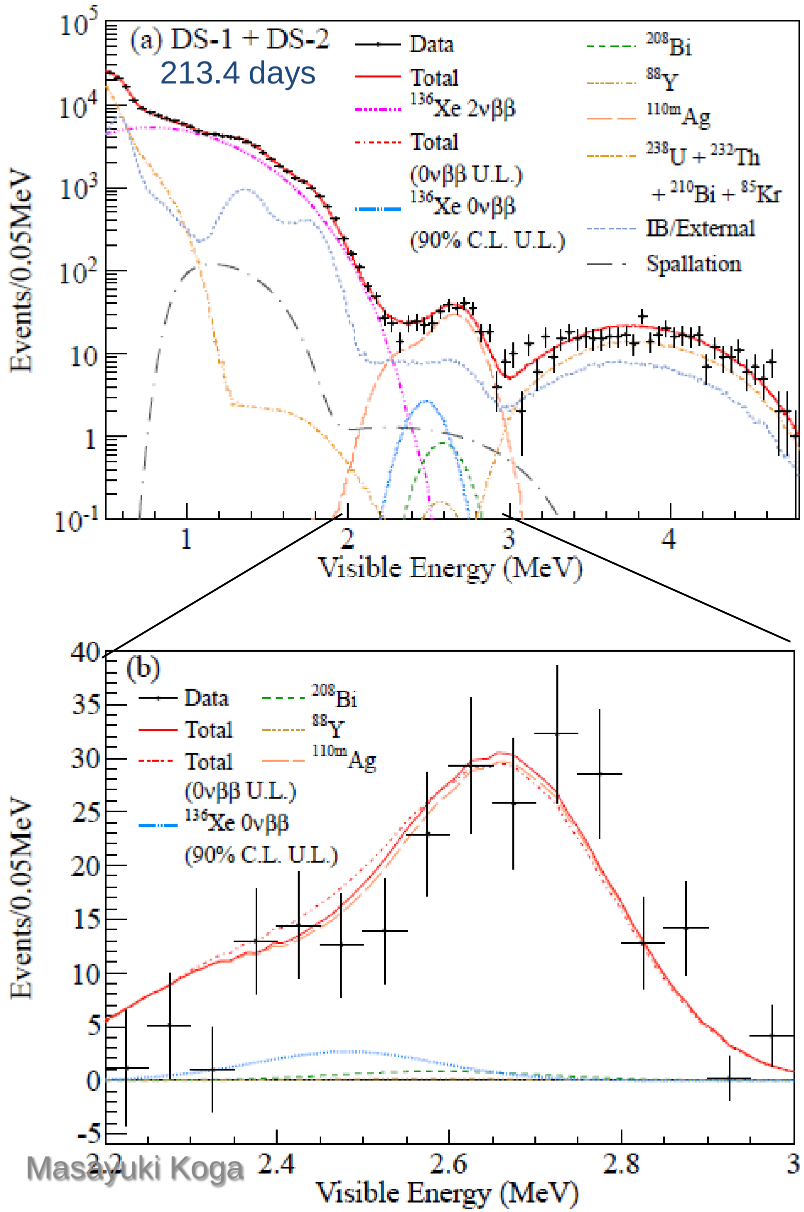

$^{88}$Y + 0nu → $\chi^2 = 22.2$ △

$^{60}$Co + 0nu → $\chi^2 = 82.9$ ×

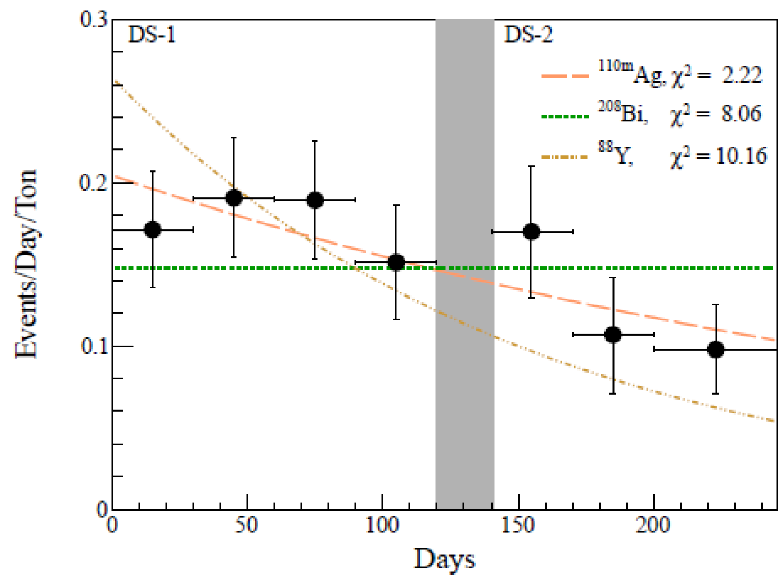
0nu only → $\chi^2 = 85.0$ ×

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

# KamLAND-Zen phase-1 result




2.2MeV < E < 3.0MeV

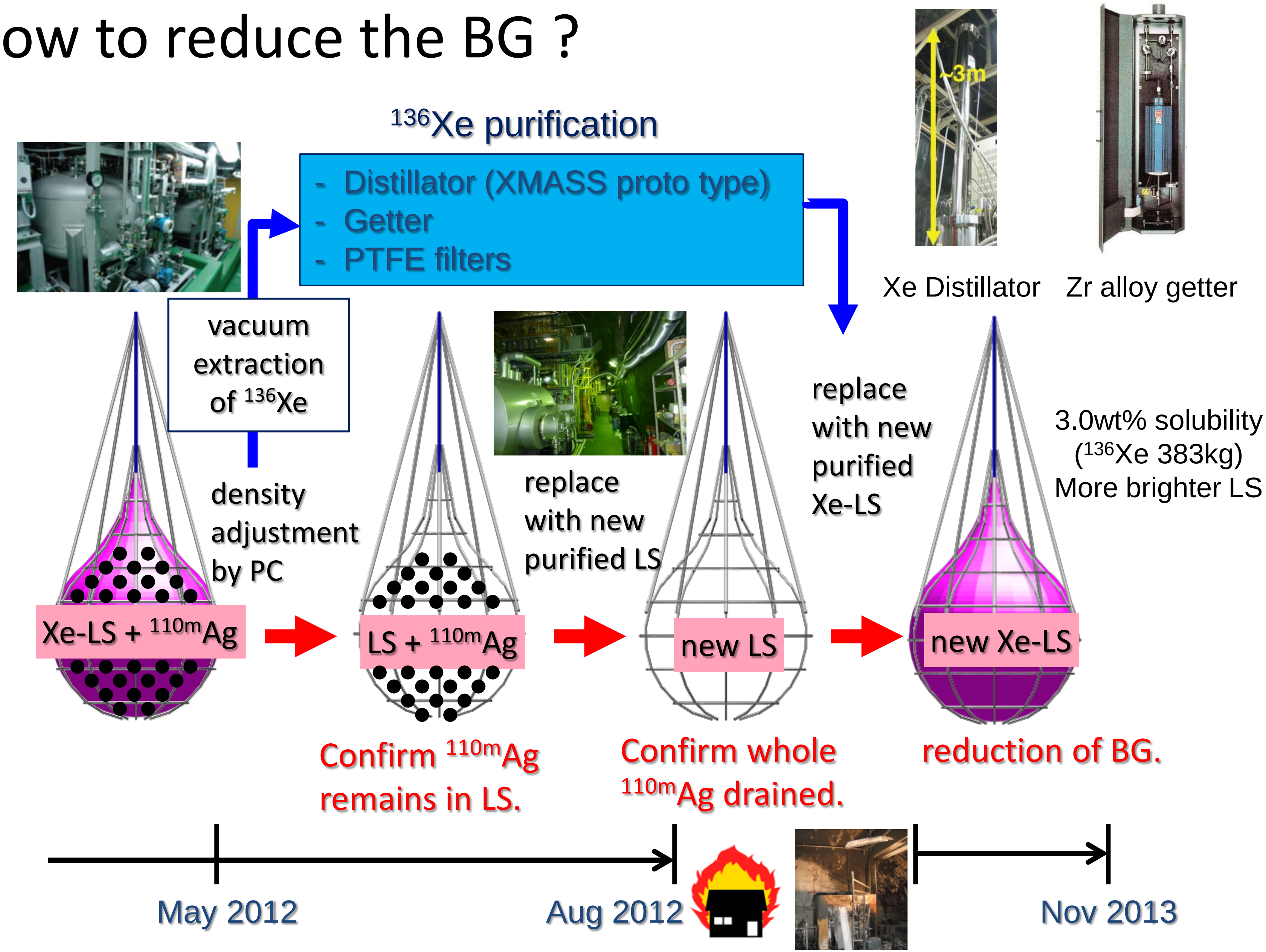



KamLAND-Zen

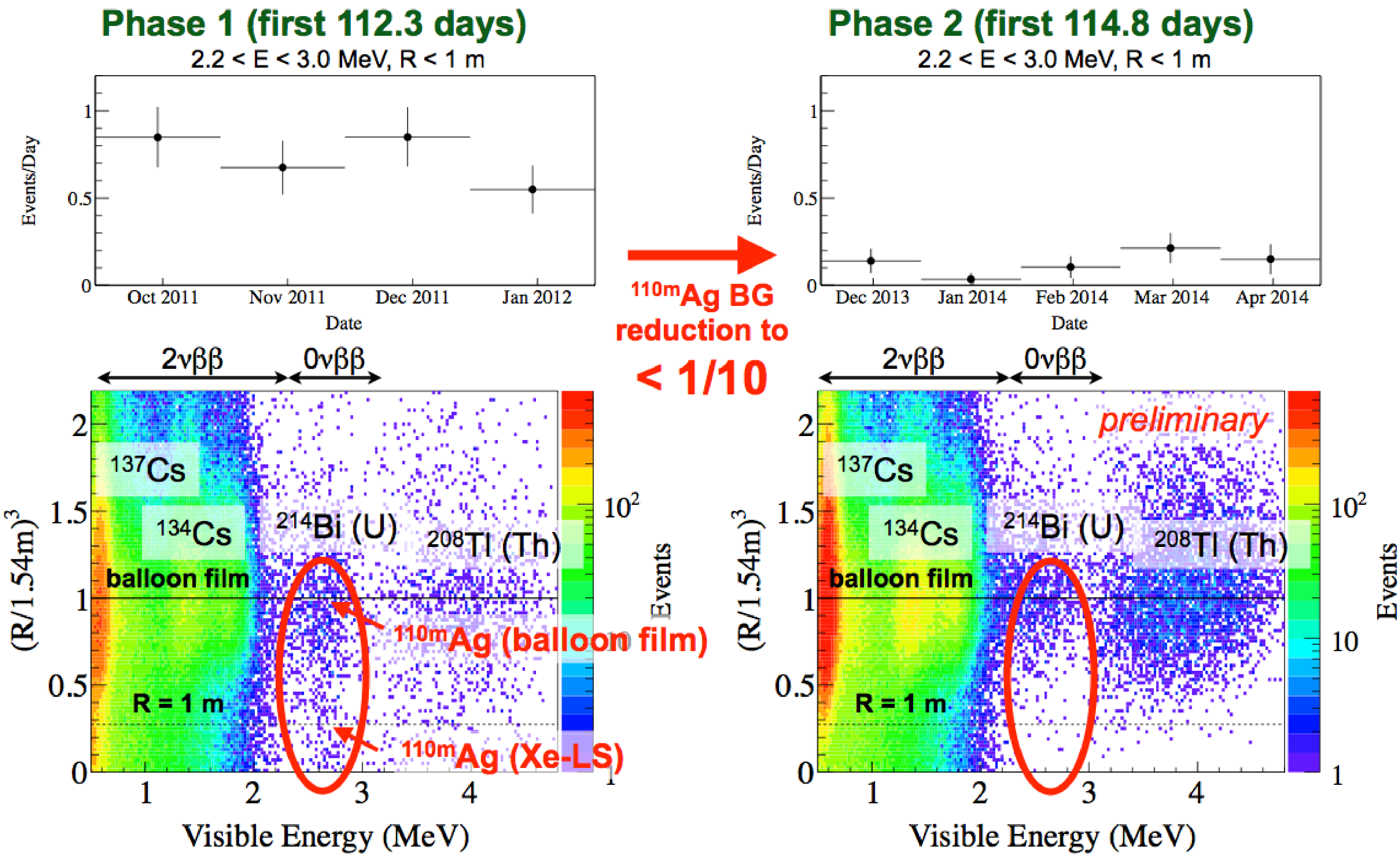
$T^{0v}_{1/2}$ > 1.9x10$^{-25}$ yr @90%CL

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

# How to reduce the BG ?

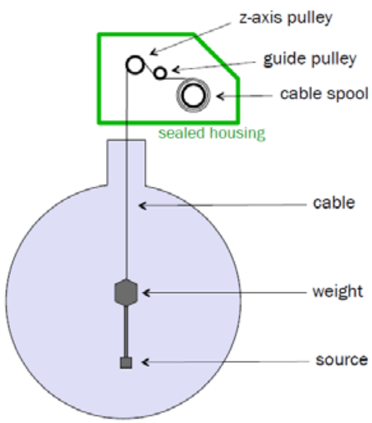


# $^{110m}$Ag BG reduction



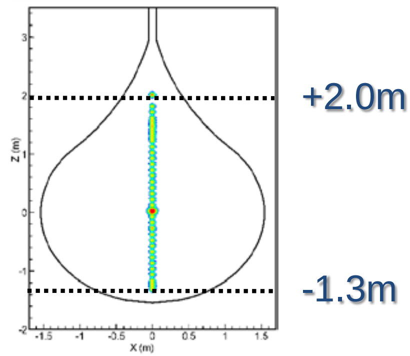
# KamLAND-Zen 400 phase-2 calibration

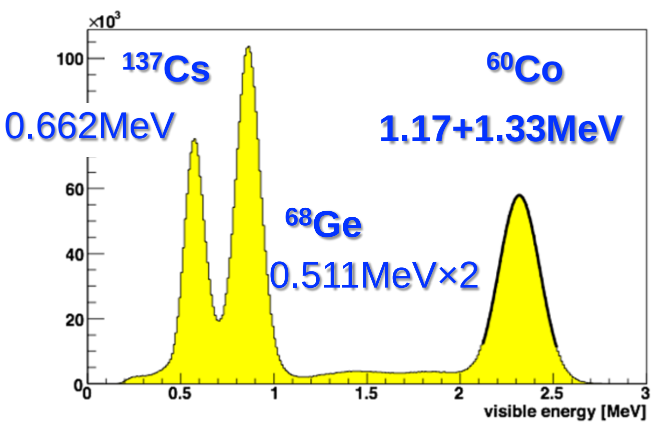
## Z-axis calibration with composite source ($^{137}$Cs $^{68}$Ge $^{60}$Co)




miniCAL

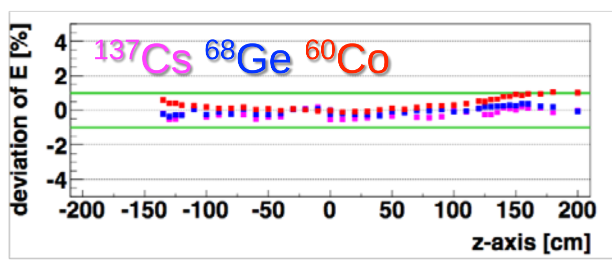
Deploy in MIB



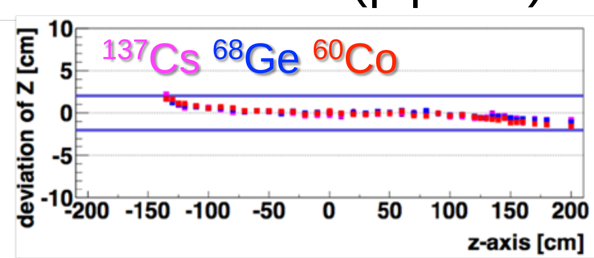

**energy**

bias <1% (IB)



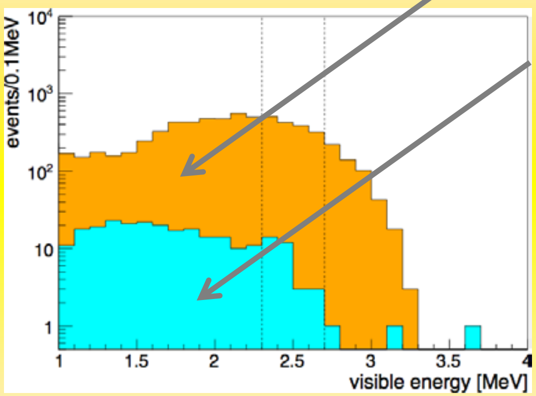

**vertex**

bias <2cm (IB)
<1cm (|z|<1m)

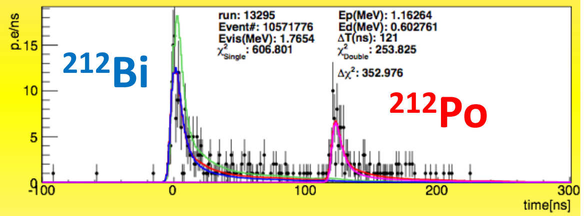


# KamLAND-Zen 400 phase-2 BG

## $^{214}$Bi/$^{212}$Bi Tagging



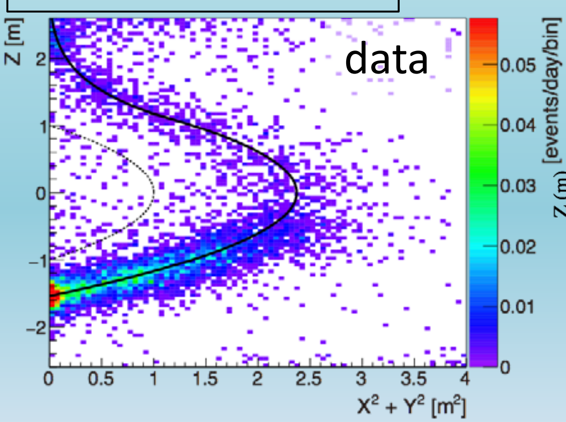

- delayed coincidence
  $^{214}$Bi-$^{214}$Po
- pileup event search

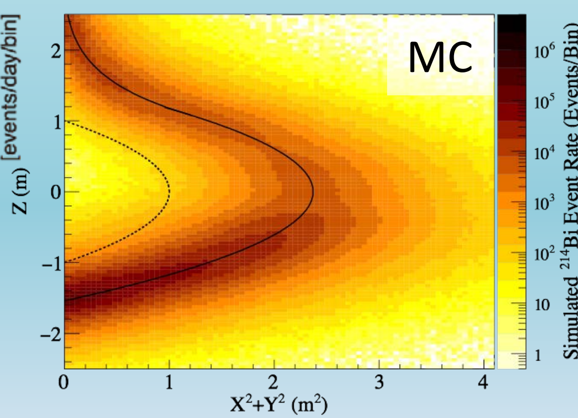



***LS purification cycle did not remove Bi on surface***

(Some Po signal extinction by film)

## $^{214}$Bi on IB surface

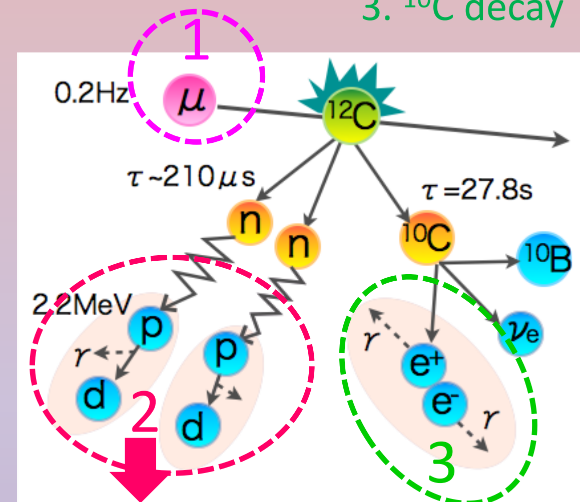


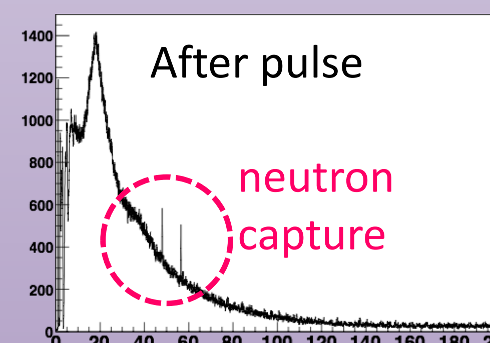




**Reconstruction of non-uniform $^{214}$Bi distribution**

## $^{10}$C tagging

Triple coincidence
1. muon
2. neutron capture
3. $^{10}$C decay



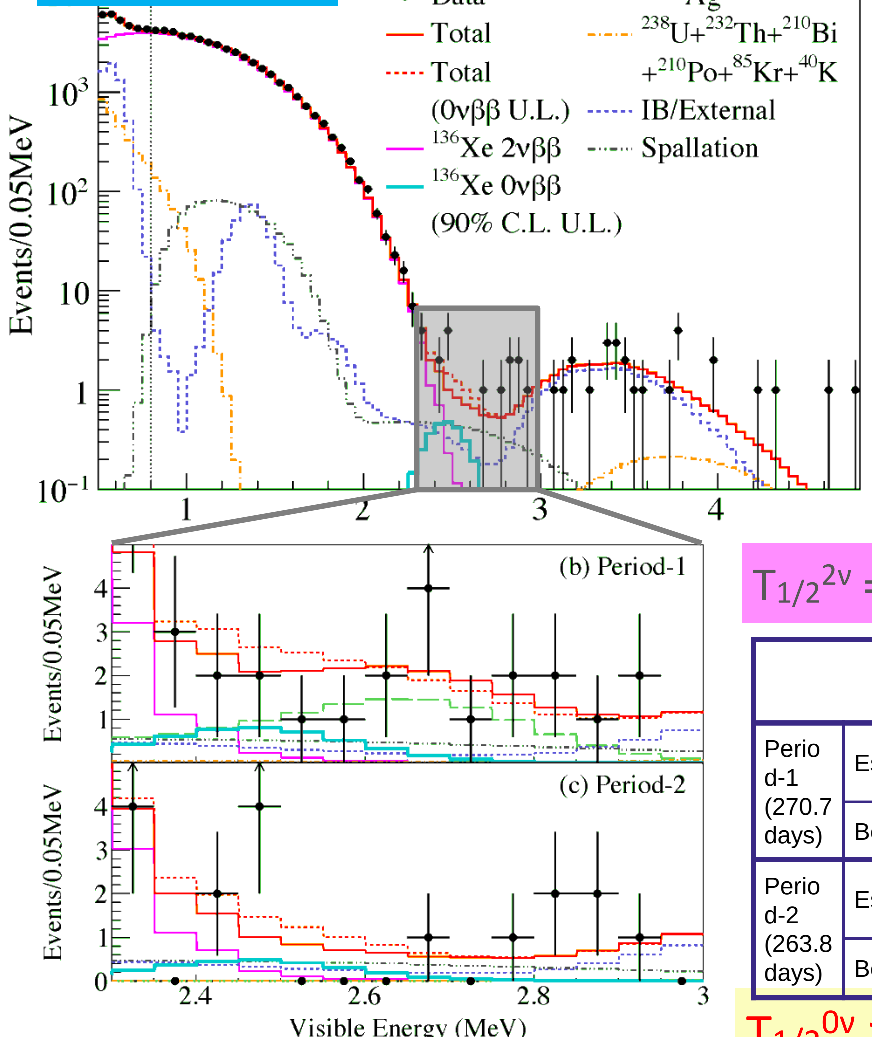

**$^{10}$C detection efficiency: 64±4 %**

# KamLAND-Zen 400 phase-2

Phys.Rev.Lett. 117 (2016)

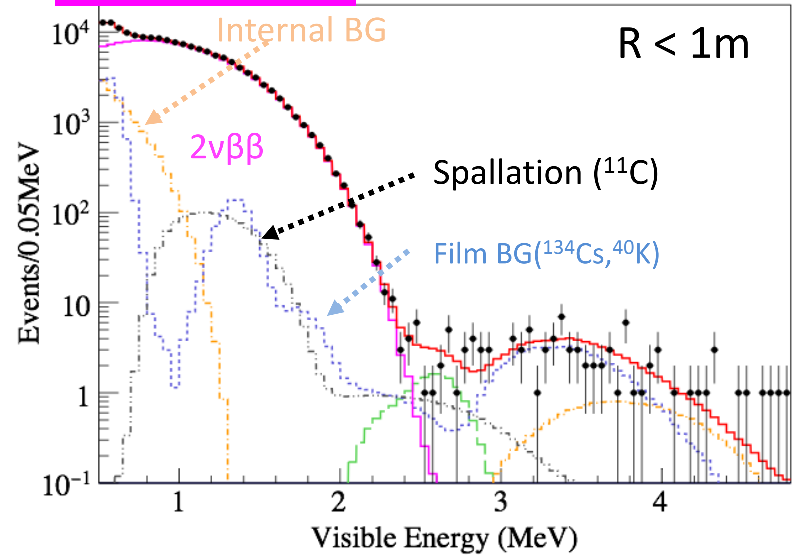
## 0νββ analysis

systematic uncertainty 3.1 %




## 2νββ analysis

Small Film BG area



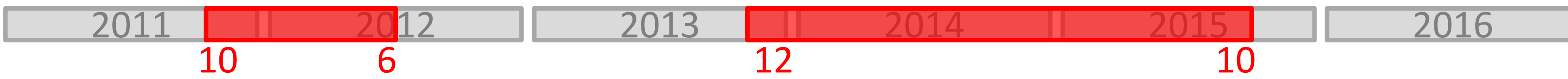

$T_{1/2}^{2\nu}$ =2.21±0.02(stat)±0.07(syst) × $10^{21}$ year (90%C.L.)

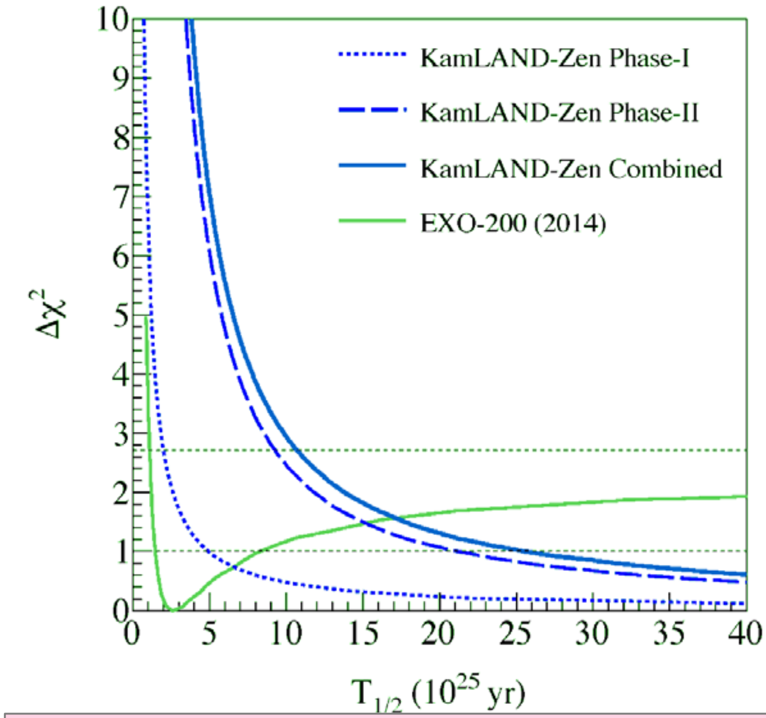
| | | 0νββ | 2νββ | $^{214}$Bi LS | $^{110m}$Ag | $^{214}$Bi film | spallation | Total BG | Observed |
|---|---|---|---|---|---|---|---|---|---|
| Period-1 (270.7 days) | Estimated | - | - | 0.23 ± 0.04 | - | - | 3.4 ± 0.8 | - | 22 |
| | Best-fit | 0 | 5.48 | 0.25 | 8.5 | 2.56 | 4.04 | 20.8 | |
| Period-2 (263.8 days) | Estimated | - | - | 0.03 ± 0.01 | - | - | 3.3 ± 0.8 | - | 11 |
| | Best-fit | 0 | 5.29 | 0.03 | 0.0 | 2.45 | 3.43 | 11.3 | |

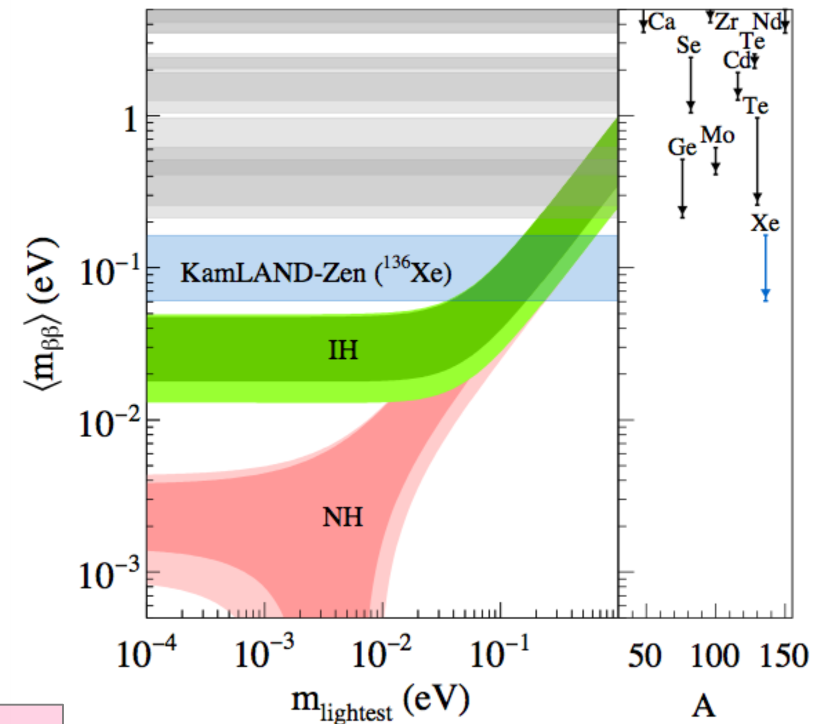
$T_{1/2}^{0\nu}$ > 9.2 × $10^{25}$ year (90% C.L.)

# KamLAND-Zen 400 phase 1+2

Phys.Rev.Lett. 117 (2016)




Upper limit of $^{136}$Xe 0νββ half life (90%C.L.)

Phase 1 : $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ year

Phase 2 : $\mathbf{T_{1/2}^{0\nu} > 9.2 \times 10^{25}}$ **year**

Phase 1+2 : $\mathbf{T_{1/2}^{0\nu} > 1.07 \times 10^{26}}$ **year**

**Effective Majorana mass**

**$\langle m_{\beta\beta}\rangle$ < 61 ~ 165 meV**

**$m_{lightest}$ < 180 ~ 480 meV**

# Recent 0νββ Summary (form TAUP2017)

- EXO : $^{136}Xe$
  - New EXO-200 data results show no statistically significant 0νββ excess
  - $T_{1/2} > 1.8 \times 10^{25}$ yr (90% CL), $\langle m_{\beta\beta} \rangle < 147 – 398$ meV

  On-going EXO-200 Phase-II running will continue to improve sensitivity
- GERDA: $^{76}Ge$ Preliminary 11:30 24th Aug GUSEV, Konstantin

  Unblinding of 12.4 kg･yr of best-quality data
  - $T_{1/2} > 8.0 \times 10^{25}$ yr @ 90% CL , $m_{\beta\beta} < 0.12\text{-}0.27$ eV
  - For full 100 kg･yr exposure: sensitivity to a signal up to $T_{1/2} > 8.0 \times 10^{25}$ yr (or limit $T_{1/2} > 1.3 \times 10^{26}$ yr at 90%CL )

# Recent 0νββ Summary (form TAUP2017)

- CUORE : $^{130}$Te Bolometers
  - combined result with
    19.75kg･yr of Cuoricino and 9.8kg･yr of CUORE-0
  - The combined 90% C.L. limit is
    $T_{0\nu} > 6.6 \times 10^{24}$ yr, $m_{\beta\beta} < 210–590$ meV
- SNO+: $^{130}$Te Loaded LS
  - LAB+PPO+Te-ButaneDiol Cocktail : 0.5% Te (~1300 kg $^{130}$Te)
  - Commissioning Ongoing, Filling with Scintillator later this year
  - Sensitivity: $T_{1/2} > 2 \times 10^{26}$ y, 90% CL, $m_{\beta\beta} \approx 40 – 90$ meV
    (after 5 yrs, 0.5% loading)
- Others: Se (SuperNEMO, CUPID-0), Mo (CUPID-Mo, AMoRE
  Ge (MJD, LEGEND), gas-Xe (NEXT, PandaX-III), Ca (CANDLES), ….

# KamLAND-Zen 400 removal

2011 | 2012 | 2013 | 2014 | 2015 | 2016

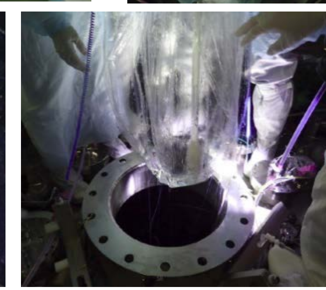
10 12

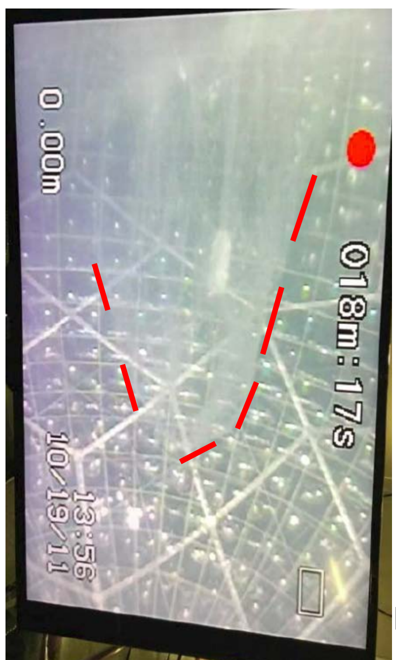
Smooth work !!

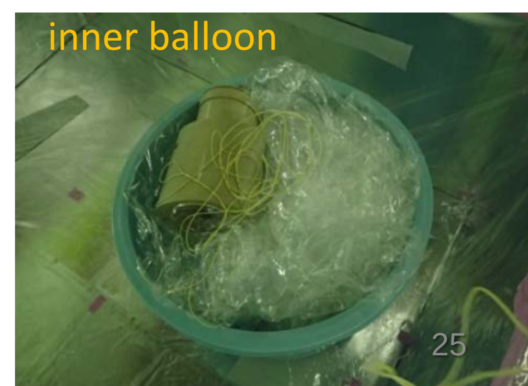
1. Xe extraction from LS
2. LS draining from inner balloon
3. Inner balloon  removal
4. Close top flange









# KamLAND-Zen 800

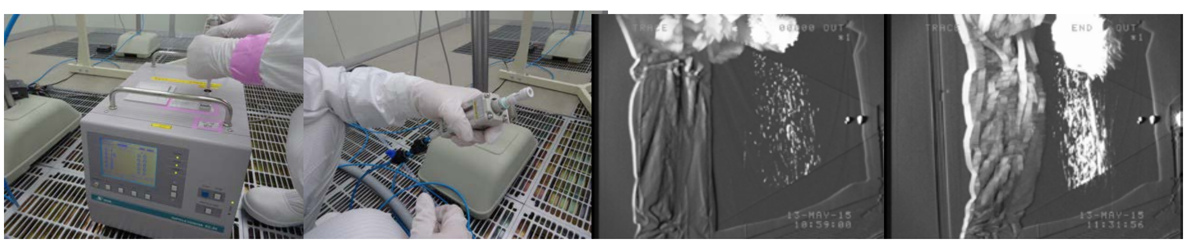
Motivation:

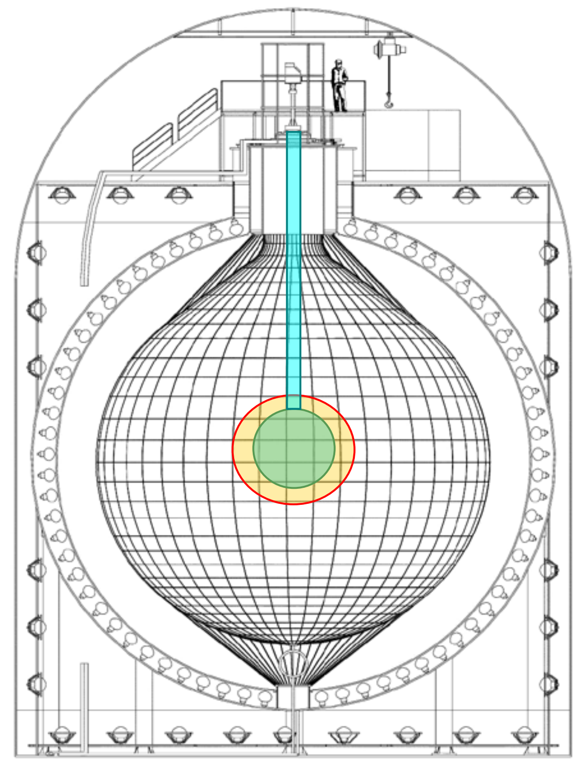
KamLAND need spherical tank inspection under the flammable liquid law.
(∼May 2016, every 16 years) So, we need to drain OD water.

- Good chance to improve Zen mini-balloon and OD!
- We kept extra $^{136}$Xe in the mine. (>2years)

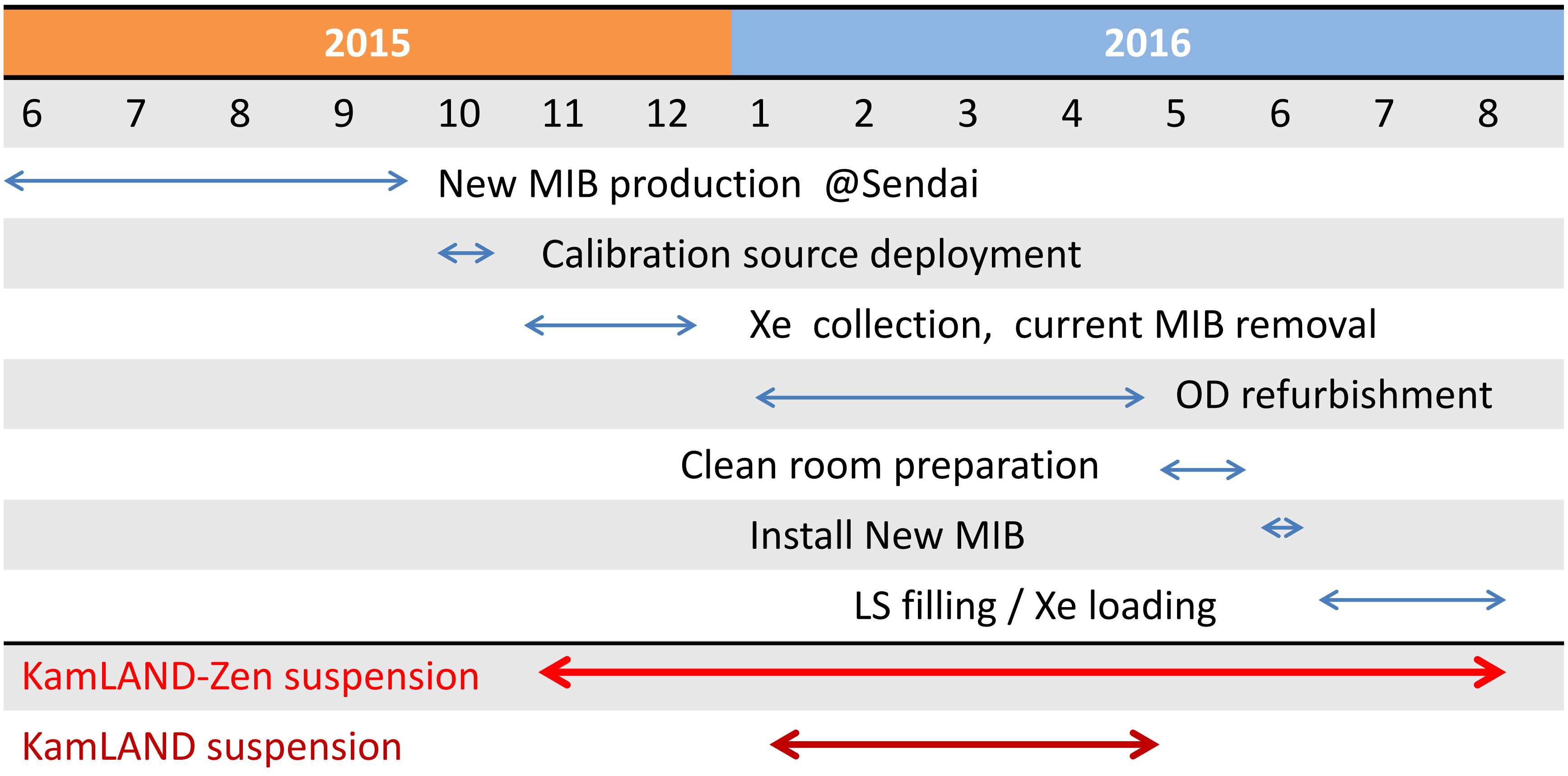
| | KL-zen 400 | | KL-zen 800 |
|---|---|---|---|
| balloon size : | 3.16mφ | => | ∼4mφ |
| $^{136}$Xe amount : | 383kg | => | 756kg |
| enlarge FV using ultra clean balloon | | | |

=> establish more cleaner production technique
(particle and electro static Ctrl., screening, etc….)





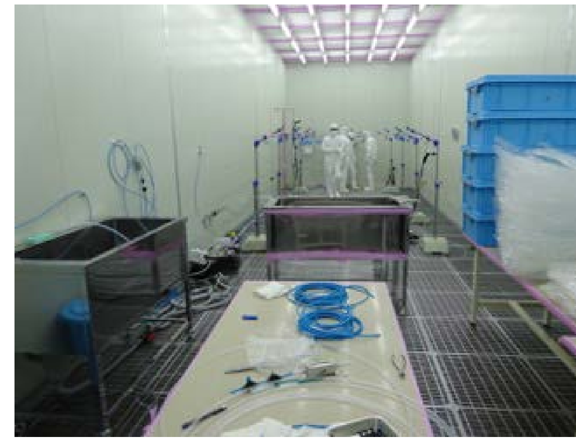
# Original Schedule for KamLAND-Zen 800




## Deployed MIB with LS from September 2016

# new mini-balloon production (June 2015～2016) in class-1 ultra clean room, Sendai

film cut



washing

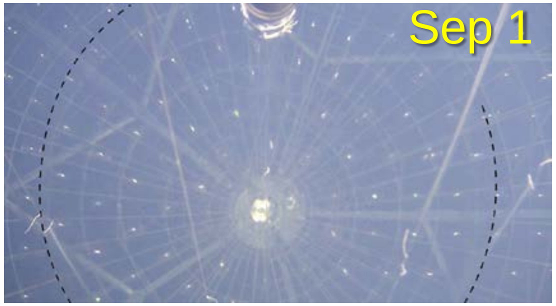
drying

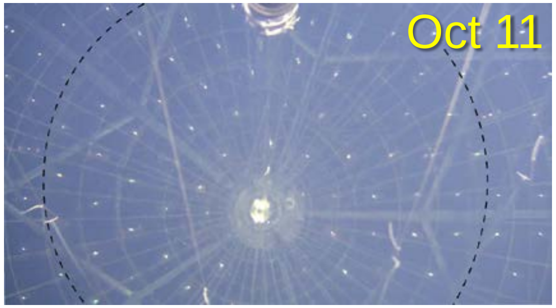
# KamLAND-Zen 800 status

- New MIB was installed in August, and LS was filled.
- lower Th/U concentration

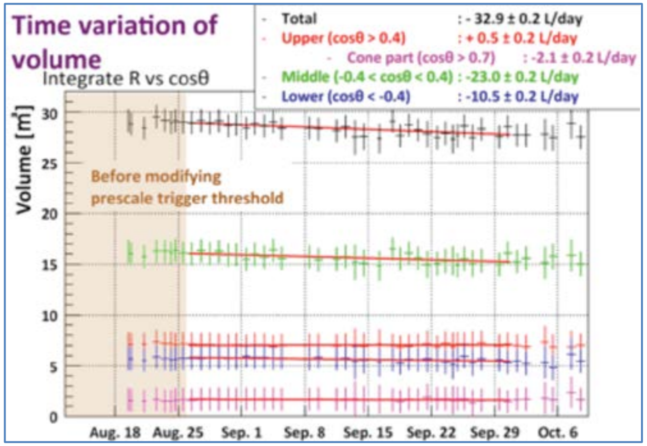
But,….

- We found a leakage from MIB

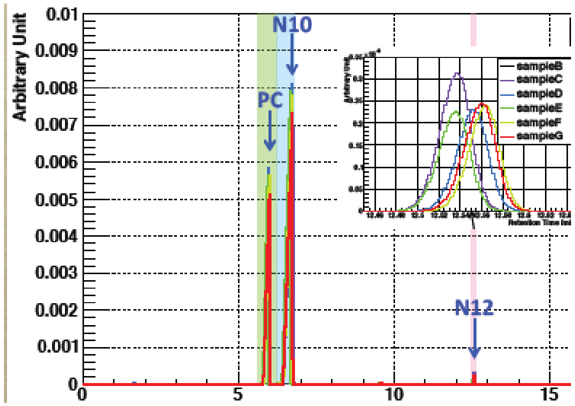



$^{210}$Po events




MIB looks shrink on upper hemisphere

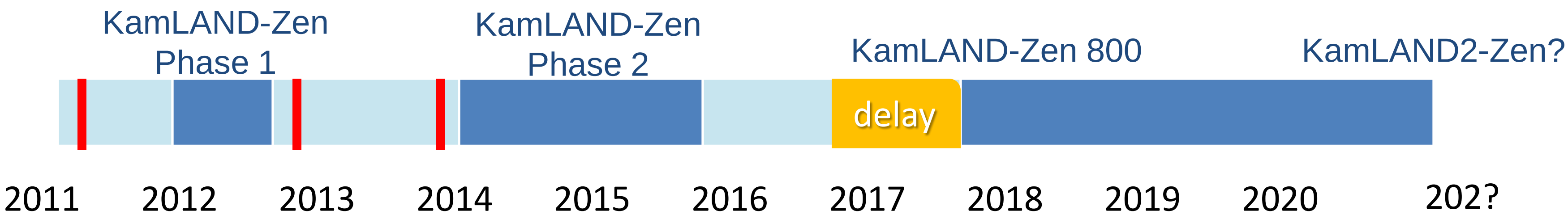


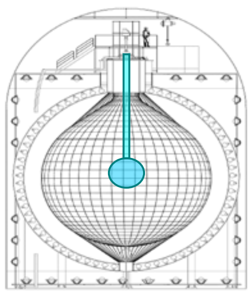

Detected Buffer oil component N12

# KamLAND-Zen 800 status

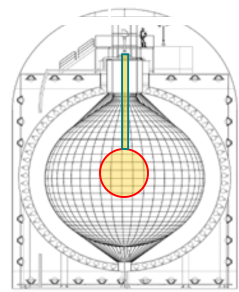
- Removed 800 MIB was checked carefully.
- Five small holes were found.
- Film didn’t break but welding line broke.
- Welding from top as done for the first 400 MIB which didn’t break.
  - 400 MIB: handy tool, from bottom
  - 800 MIB: machine , from top
- Welding parameter was scanned again.
- Review to JP and US balloon experts. (April 2017)
- Customize welding machine and method.
- New MIB production will be finished in September.
- Retrial for new MIB installation will be in October.

# KamLAND-Zen & KamLAND-Zen 800 sensitivity

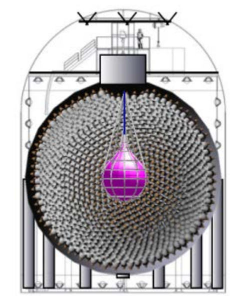


- LS & $^{136}$Xe Purification
- More $^{136}$Xe

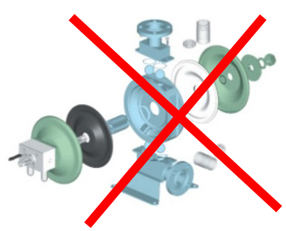


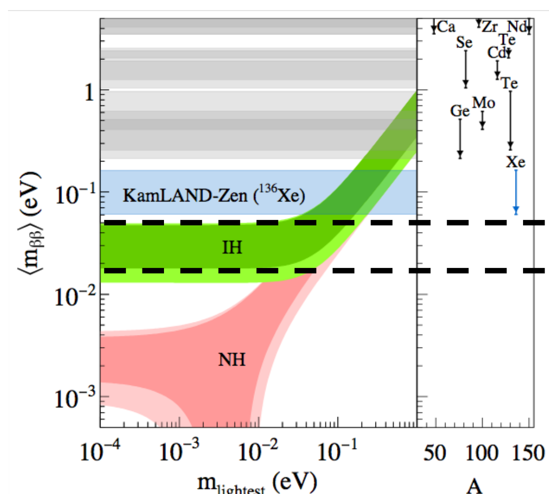
MIB: ~Φ4m
$^{136}$Xe ~756kg(91%)
5 years



MIB: ~Φ3.12m
Livetime 270.7 days.
$^{136}$Xe ~320kg(91%)
FV: $^{136}$Xe 125 kg.

Livetime 263.8 days.
$^{136}$Xe ~383kg(91%)

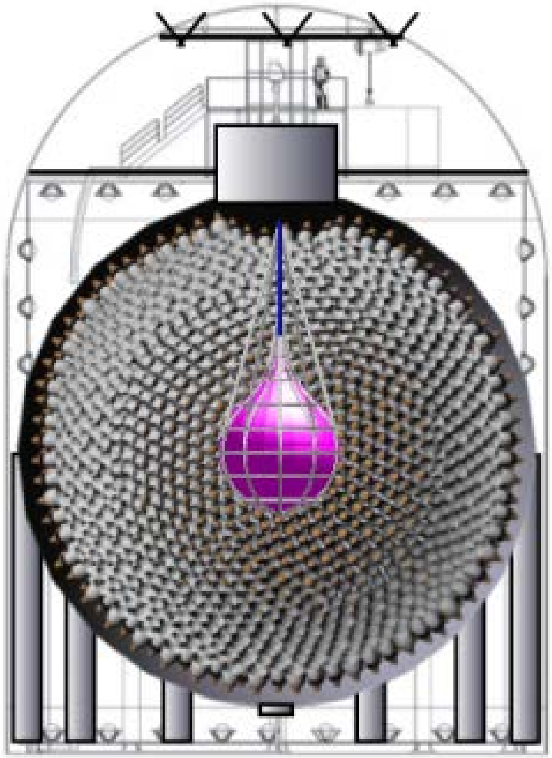






KL-Zen800 50meV?
KL2-Zen~20meV (5years)

# Future prospects on KamLAND

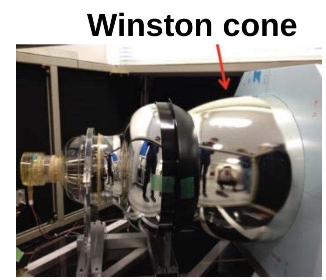
## KamLAND2-Zen
## 1000kg $^{136}$Xe phase



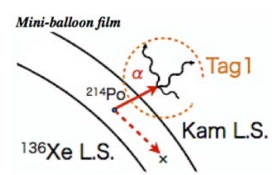
Energy resolution at 2.6MeV

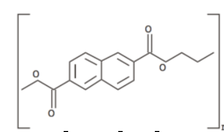
4% → 2%

- light correction by WC ×1.8
- High light emission LS ×1.4
- High Q.E. 20”PMT or HPD (QE ~22% →>30%, 17”→20”) ×1.9




Dead layer free scintillation film balloon



**Polyethylene naphthalate**

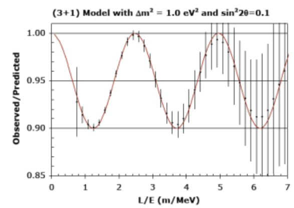
New electronics and trigger

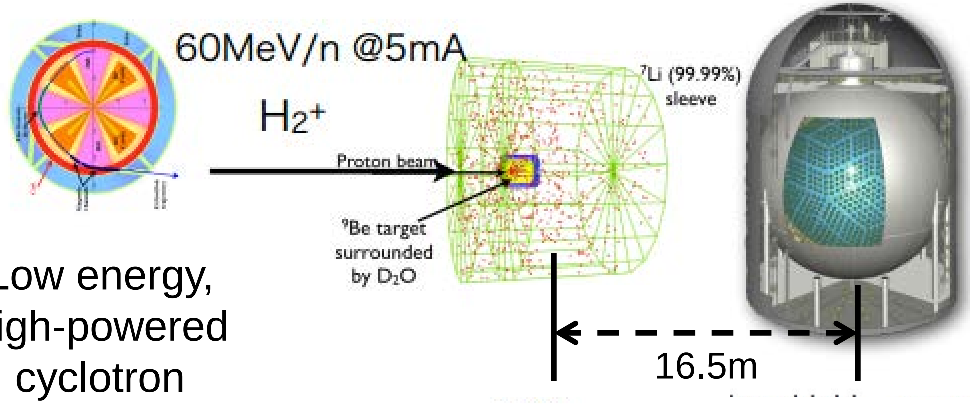
Target sensitivity ~20meV by 5years

Cover inverted hierarchy region !

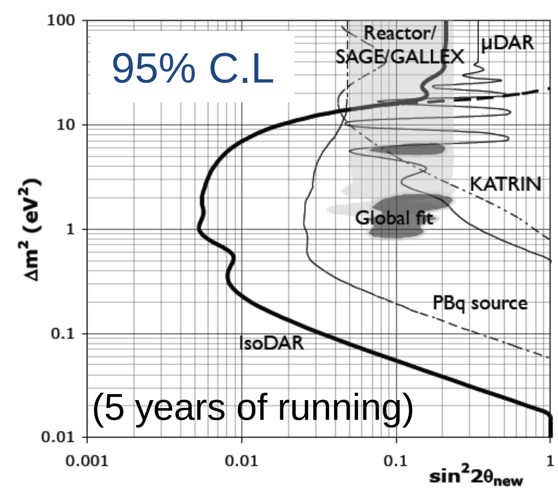
# Other future option on KamLAND

- Sterile neutrino
  IsoDAR + KamLAND



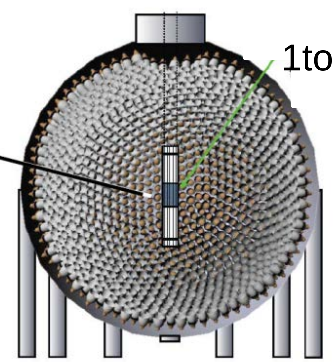

Low energy,
high-powered
cyclotron




IsoDAR + KamLAND:
PRL 109, 141802 (2012)

- Dark matter
  PICO-LON + KamLAND

KamLAND:
Ultra low BG
4pi active shield



1ton NaI

KamLAND-PICO

- other ββ source?
- super-KamLAND?

# summary

- KamLAND-Zen 400 phase-2 was ended.

- Recent 0νββ decay result

  KamLAND-Zen combined (phase-1 + phase-2)

  $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr (90%C.L.)

  corresponding to $\langle m_{\beta\beta} \rangle < 61\text{-}165$ meV.

- KamLAND-Zen 800 MIB was installed in August 2016 after inspection of KamLAND main tank. But , it was removed for leakage problem.

- New 800 MIB will be produced and deployed in end of this year.

- KamLAND2/KamLAND2-Zen will be future project. Some of other possibility.