Results and Status of KamLAND-Zen

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August 5, 2016
Neutrino Mass Opens Window to New Physics

• Does the neutrino have a Majorana type mass?
  • Would imply that lepton number is not a conserved quantity in nature
  • Could explain why the neutrino is so light
  • Would provide a link between matter and anti-matter and could help explain the matter/anti-matter asymmetry of the Universe.

\[ \nu_e \rightarrow m_{\beta\beta} \rightarrow \bar{\nu}_e \]

\[ \begin{align*}
\nu_e, \nu_H, \bar{\nu}_e & \quad (e.g. \, h) \\
\bar{\nu}_e & \quad (h) \\
\end{align*} \]

Matter
\[ u, c, t \quad d, s, b \quad e, \mu, \tau \]

Anti-Matter
\[ \bar{u}, \bar{c}, \bar{t} \quad \bar{d}, \bar{s}, \bar{b} \quad \bar{e}, \bar{\mu}, \bar{\tau} \]
Neutrinoless Double-Beta Decay

Exchange of light Majorana Neutrino

\[ (Z, A) \xrightarrow{W^-} (Z + 2, A) \]

Decay Rate:

\[ \Gamma_{0\nu} \propto G_{0\nu}^{2} |M_{0\nu}|^{2} \frac{m_{\beta\beta}^{2}}{m_{e}^{2}} \]

Kinematics  Nuclear  BSM Physics

Effective Majorana Mass

\[ m_{\beta\beta} \equiv \left| \sum_{i} U_{ei}^{2} m_{i} \right| \]

- \( m_{\beta\beta} \): Effective Majorana Mass
- \( U_{ei} \): PMNS Matrix
- \( m_{i} \): Neutrino Masses
Double-Beta Decay

- Detectors measure the kinetic energy of the emitted electrons
- $2\nu\beta\beta$ produces a broadened spectrum
- $0\nu\beta\beta$ has no neutrinos, thus no missing energy.

- $2\nu\beta\beta$ is the *slowest* process ever measured with $T_{1/2} \sim 10^{19} - 10^{24}$ yr
- $0\nu\beta\beta$ is slower still with $T_{1/2} > 10^{24} - 10^{26}$ yr (if it occurs at all)

- We combat this by making detectors very large and very low background!
$^{136}$Xe as a 0νββ Search Candidate

- Xenon is a noble gas
  - Easy to purify
  - Easy to enrich to high levels
  - Easy to dissolve into LS
- Natural isotopic abundance of 8.9%
- High Q-value: 2.458 MeV
- No long lived radioactive isotopes to act as background
- Safe for handling

\[\begin{align*}
\begin{array}{c}
\text{Isotope} \\
\text{Experiment}
\end{array}
\begin{array}{c}
{^{48}}\text{Ca} \\
{^{76}}\text{Ge} \\
{^{82}}\text{Se} \\
{^{100}}\text{Mo} \\
{^{116}}\text{Cd} \\
{^{130}}\text{Te} \\
{^{136}}\text{Xe}
\end{array}
\begin{array}{c}
\text{Candles} \\
\text{Gerda, Majorana} \\
\text{SuperNemo} \\
\text{Moon} \\
\text{Cobra} \\
\text{CUORE, Cobra, SNO+} \\
\text{EXO, NEXT, KamLAND-Zen}
\end{array}
\end{align*}\]
The KamLAND Detector

• Located in Kamioka mine with 2,700 m.w.e. overburden.
• Originally designed to detect neutrino oscillations from nuclear reactors around Japan, has been in operation since 2002.
• Detector performance is well characterized
• 1 kton of ultra-pure LS (80% Dodecane, 20% Pseudocumene + PPO)
• Inner detector instrumented with 1879 PMTs with 34% coverage
The KamLAND-Zen Detector

- 3m diameter balloon lowered into the center of the KL detector
- Filled with LS loaded with 383 kg of Xe, enriched to 91% $^{136}$Xe
- KamLAND can search for $0\nu\beta\beta$!
- Other physics searches on-going in parallel: geo-neutrinos, SN neutrinos, GW-coincidence, etc…

arXiv:1606.07155
The KamLAND-Zen Detector

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• Filled with LS loaded with 383 kg of Xe, enriched to 91% $^{136}$Xe
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• Other physics searches on-going in parallel: geo-neutrinos, SN neutrinos, GW-coincidence, etc…

arXiv:1606.07155
KamLAND-Zen Time Line

- Balloon fabrication in Sendai in Spring 2011
- (Great Eastern Japan Earthquake March 11, 2011)
- Installation and filled in August 2011
- **KamLAND-Zen Phase 1** (October 2011 - June 2012)
  - 89.5 kg·yr of $^{136}$Xe exposure
  - $T_{1/2}(0\nu) > 1.9 \times 10^{25}$ yr (90% C.L.)
- Xe-LS Purification (July 2012 - October 2013)
  - Three full purification cycles
- **KamLAND-Zen Phase 2** (November 2013 - October 2015)
  - 504 kg·yr of $^{136}$Xe exposure
  - (These results)
- Current:
  - Preparation for a new phase of data taking!

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**KamLAND-Zen Phase 1**

![Energy Spectrum Diagram](image)

- **Figure 3.13**: A diagram of IB and supporting structure (left) and a picture of real scale.
- **Figure 3.14**: Shows parts of the IB supporting structure written below.

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**CHAPTER 3. DOUBLE BETA DECAY WITH KAMLAND-ZEN**

To place the IB at the center of the detector, the length of the connection with the IB and the top flange becomes almost 7 m. It may be desirable to make a whole window on top of the IB position.

Connection part with a clean nylon film to reduce backgrounds, but it is unrealistic...
Results and Status of KamLAND-Zen

KamLAND-Zen Phase 1

- Saw unexpected peak! Consistent with contamination from $^{110m}_{\text{Ag}}$ ($Q = 3.01$ MeV, $\tau = 260$ d).
- Suspected contamination from Fukushima reactor incident during transportation from Tohoku to Kamioka.
- Also saw excess contamination of $^{134}_{\text{Cs}}$ & $^{137}_{\text{Cs}}$.

KamLAND-Zen Phase 1 89.5 kg·yr

(a) DS-1 + DS-2
Saw unexpected peak! Consistent with contamination from $^{110m}\text{Ag}$ ($Q = 3.01$ MeV, $\tau = 260$ d).

Suspected contamination from Fukushima reactor incident during transportation from Tohoku to Kamioka.

Also saw excess contamination of $^{134}\text{Cs}$ & $^{137}\text{Cs}$.

KamLAND-Zen Phase 1 89.5 kg·yr
Xe-LS Purification Procedure

- Xe was extracted from LS and purified
- Performed a Xe depleted run and background in the ROI remained
- LS was circulated through filtration system and new LS was added
  - Three full volume exchanges of the mini-balloon LS
- Xe was reintroduced into LS

![Diagram of Xe-LS Purification Procedure]

KamLAND-Zen Xe depleted run (June 2012)
Results and Status of KamLAND-Zen

Results of Xe-LS Purification

Phase 1: First 112 days

Phase 2: First 114 days

Events

Visible Energy (MeV)

Date


Events/Day

0

0.5

1

2.2 < E < 3.0 MeV, R < 1 m

Phase 2: First 114 days

Phase 1: First 112 days

2\nu\beta\beta \quad 0\nu\beta\beta

Events

Visible Energy (MeV)

(R/1.54m)^3

(R/1.54m)^3

137Cs 134Cs 214Bi 208Tl

137Cs 134Cs 214Bi 208Tl

preliminary

Balloon film

R = 1 m

Balloon film

R = 1 m

Events

Visible Energy (MeV)

(R/1.54m)^3

(R/1.54m)^3

0

1

2

3

4

1

10

100

1000

0

1

2

3

4
High Rn Studies

- During circulation of the LS, radon is introduced to the detector ($^{220}\text{Rn}$: $\tau \sim 55$ s, $^{222}\text{Rn}$: $\tau \sim 4$ d)
- Performed studies with $^{214}\text{Bi}$-$^{214}\text{Po}$
  - Delayed coincidence tagging efficiency of 99.95%
  - Vertex reconstruction efficiency
  - Detector effects on the tail of a $\beta$-distribution
Event Tagging and Background Removal

\[ \text{\( ^{10}\text{C} \) removed with triple coincidence} \]

\[ \mu \rightarrow 1 \]

\[ \text{\( ^{12}\text{C} \)} \rightarrow 2 \]

\[ \text{\( ^{10}\text{C} \)} \rightarrow 3 \]

\[ \tau = 208 \, \mu s \]

\[ \tau = 27.8 \, s \]

New dead-time free “Mogura” electronics

**\(^{10}\text{C} \) background:**
- \( Q = 3.65 \, \text{MeV} \)
- \( \tau \approx 27.8 \, s \)

**Cut:**
- \( \Delta T < 180 \, s \) & \( \Delta x < 1.6 \, m \)
- Removes 64 ± 4% of \(^{10}\text{C} \)
- Signal Efficiency of 93%
Double-Beta Decay Event Selection

- $R < 2 \text{ m}$
- Remove muons and 2ms after muons
- Delayed coincidence cuts:
  - $^{214}\text{Bi} - ^{214}\text{Po}$: $\Delta T < 1.9 \text{ ms} \& \Delta x < 1.7 \text{ m}$
  - $^{212}\text{Bi} - ^{212}\text{Po}$: Pulse shape
- Reactor $\bar{\nu}_e$: (e$^+$ and neutron capture $\gamma$)
- Vertex quality cut

- **Dominant external background from $^{214}\text{Bi}$ on the balloon surface.**
  - Non-uniform in $Z$
  - Likely dust on the balloon

- **Ratio of $^{134}\text{Cs}/^{137}\text{Cs}$ is consistent with fallout from Fukushima!**
KamLAND-Zen Phase 2 Fitting Approach

- Split the volume into 40 equal volume bins
  - 20 with \( z > 0 \), 20 with \( z < 0 \)
- Split the exposure into 2 data taking periods of 270.7 days and 263.8 days
- The \( 0\nu\beta\beta \) analysis uses a fiducial volume cut of \( R < 2 \) m
- The \( 2\nu\beta\beta \) analysis uses a more restrictive cut of \( R < 1 \) m

\[ 2.3 < E < 2.7 \text{ MeV, } R < 1 \text{ m} \]

Possible that the background sources sank?
Or, only a 2\( \sigma \) disagreement with a decay hypothesis
• Phase 2 $^{136}$Xe $2\nu\beta\beta$ half-life measurement based on 126 kg·yr exposure:
  • $T_{1/2}(2\nu) = 2.21 \pm 0.02 \pm 0.07 \times 10^{21}$ yr
• Consistent with previous measurements
• Systematic uncertainty of 3.1% dominated by uncertainty in fiducial volume.

**Systematics**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial Volume</td>
<td>3.0%</td>
</tr>
<tr>
<td>Xe-mass</td>
<td>0.8%</td>
</tr>
<tr>
<td>Energy Scale</td>
<td>0.3%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.2%</td>
</tr>
<tr>
<td>$^{136}$Xe enrichment</td>
<td>0.09%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.1%</td>
</tr>
</tbody>
</table>

**$T_{1/2}(2\nu)$ ($10^{21}$ yr)**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Result</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLZ Phase 2</td>
<td>$2.21 \pm 0.02 \pm 0.07$</td>
<td>This Result</td>
</tr>
<tr>
<td>KLZ Phase 1</td>
<td>$2.30 \pm 0.02 \pm 0.12$</td>
<td>PRC86, 012601 (2012)</td>
</tr>
<tr>
<td>EXO-200</td>
<td>$2.165 \pm 0.016 \pm 0.059$</td>
<td>PRC89 015502 (2014)</td>
</tr>
</tbody>
</table>
\( ^{136}\text{Xe} \, 0\nu\beta\beta \) Decay Half-life

- Based on 504 kg·yr \(^{136}\text{Xe} \) exposure
- No excess found over the background rate.
- Upper limit on the \(^{136}\text{Xe} \) decay rate of < 5.5 cnts/(kton·day) for Period 1 and < 3.4 cnts/(kton·day) for Period 2 at 90% C.L.
- Combined limit of < 2.4 cnts/(kton·day) at 90% C.L.
- Yields a new limit on the \(^{136}\text{Xe} \, 0\nu\beta\beta \) half-life of

KamLAND-Zen Phase 2 Limit:
\[ T_{1/2}(0\nu) > 9.2 \times 10^{25} \text{ yr} \, (90\% \text{ C.L.}) \]

- Median sensitivity of \( 5.6 \times 10^{25} \text{ yr} \)
136Xe 0νββ Decay Half-life

KamLAND-Zen $^{136}$Xe Limits (90% C.L.)

Phase 1 $T_{1/2}(0\nu) > 1.9 \times 10^{25}$ yr

Phase 2 $T_{1/2}(0\nu) > 9.2 \times 10^{25}$ yr

Combined $T_{1/2}(0\nu) > 1.07 \times 10^{26}$ yr

$\langle m_{\beta\beta} \rangle < 61 - 165$ meV
## Remaining Backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Period-1 (270.7 days)</th>
<th>Period-2 (263.8 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{136}$Xe $2\nu\beta\beta$</td>
<td>-</td>
<td>5.48</td>
</tr>
</tbody>
</table>

**Residual radioactivity in Xe-LS**

<table>
<thead>
<tr>
<th>Background</th>
<th>Estimated</th>
<th>Best-fit</th>
<th>Estimated</th>
<th>Best-fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{214}$Bi ($^{238}$U series)</td>
<td>0.23 ± 0.04</td>
<td>0.25</td>
<td>0.028 ± 0.005</td>
<td>0.03</td>
</tr>
<tr>
<td>$^{208}$Tl ($^{232}$Th series)</td>
<td>-</td>
<td>0.001</td>
<td>-</td>
<td>0.001</td>
</tr>
<tr>
<td>$^{110m}$Ag</td>
<td>-</td>
<td>8.5</td>
<td>-</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**External (Radioactivity in IB)**

<table>
<thead>
<tr>
<th>Background</th>
<th>Estimated</th>
<th>Best-fit</th>
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<th>Best-fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{214}$Bi ($^{238}$U series)</td>
<td>-</td>
<td>2.56</td>
<td>-</td>
<td>2.45</td>
</tr>
<tr>
<td>$^{208}$Tl ($^{232}$Th series)</td>
<td>-</td>
<td>0.02</td>
<td>-</td>
<td>0.03</td>
</tr>
<tr>
<td>$^{110m}$Ag</td>
<td>-</td>
<td>0.003</td>
<td>-</td>
<td>0.002</td>
</tr>
</tbody>
</table>

**Spallation products**

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Estimated</th>
<th>Best-fit</th>
<th>Estimated</th>
<th>Best-fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}$C</td>
<td>2.7 ± 0.7</td>
<td>3.3</td>
<td>2.6 ± 0.7</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{6}$He</td>
<td>0.07 ± 0.18</td>
<td>0.08</td>
<td>0.07 ± 0.18</td>
<td>0.08</td>
</tr>
<tr>
<td>$^{12}$B</td>
<td>0.15 ± 0.04</td>
<td>0.16</td>
<td>0.14 ± 0.04</td>
<td>0.15</td>
</tr>
<tr>
<td>$^{137}$Xe</td>
<td>0.5 ± 0.2</td>
<td>0.5</td>
<td>0.5 ± 0.2</td>
<td>0.4</td>
</tr>
</tbody>
</table>
## Remaining Backgrounds

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<tr>
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<td>8.5</td>
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<tr>
<td>External (Radioactivity in IB)</td>
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<td></td>
</tr>
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<td>2.56</td>
</tr>
<tr>
<td>$^{208}$Tl ($^{232}$Th series)</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td>$^{110m}$Ag</td>
<td>-</td>
<td>0.003</td>
</tr>
<tr>
<td><strong>Spallation products</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{10}$C</td>
<td>2.7 ± 0.7</td>
<td>3.3</td>
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</tr>
<tr>
<td>$^{12}$B</td>
<td>0.15 ± 0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>$^{137}$Xe</td>
<td>0.5 ± 0.2</td>
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</tr>
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</table>

No longer an issue!
Results and Status of KamLAND-Zen

**Remaining Backgrounds**

<table>
<thead>
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<th>Background</th>
<th>Period-1 (270.7 days)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>136Xe 2νββ</td>
<td>Estimated: 5.48</td>
<td>Estimated: 5.29</td>
</tr>
</tbody>
</table>

**Residual radioactivity in Xe-LS**

- 214Bi (238U series): 0.23 ± 0.04
- 208Tl (232Th series): 0.001
- 110mAg: 8.5

**External (Radioactivity in IB)**

- 214Bi (238U series): 2.56
- 208Tl (232Th series): 0.02
- 110mAg: 0.003

**Spallation products**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Period-1</th>
<th>Period-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>10C</td>
<td>2.7 ± 0.7</td>
<td>2.6 ± 0.7</td>
</tr>
<tr>
<td>6He</td>
<td>0.07 ± 0.18</td>
<td>0.07 ± 0.18</td>
</tr>
<tr>
<td>12B</td>
<td>0.15 ± 0.04</td>
<td>0.14 ± 0.04</td>
</tr>
<tr>
<td>137Xe</td>
<td>0.4</td>
<td>0.5 ± 0.2</td>
</tr>
</tbody>
</table>

**Remarks**

- Improve energy resolution
- No longer an issue!
- New (cleaner) mini-balloon
- Improve neutron detection
KamLAND-Zen 800

- Replacing mini-balloon with a new, cleaner balloon with twice the volume.
- Loading with 750 kg of enriched Xe
- Balloon construction took place in a class 1 clean room in Tohoku University with strict cleanliness procedures and dust control measures
  - Goal of reducing the $^{214}$Bi contamination
- Ultimate sensitivity of $\langle m_{\beta\beta} \rangle \approx 40$ meV.

Washing  Leak checking  Ready to ship!

Packaging
KamLAND-Zen 800

- October 2015: Source calibration & close Phase 2
- December 2015: Mini-balloon extraction
- January - March 2016: Outer detector refurbishment
- May 2016: Xe-distillation, LS-distillation
- April - July 2016: New mini-balloon completion
- August 2016: New mini-balloon installation
- September 2016: Xe dissolving and Xe-LS filling
- October 2016: Start KamLAND-Zen 800

See poster #1177 by Hideyoshi Ozaki (Aug 8)
Mini-Balloon Installation

Packing in gas tight box

Carrying in to the clean room

Ready to ship!
Results and Status of KamLAND-Zen

Future: KamLAND2-Zen

- **Goal**: to cover the full inverted hierarchy $\Rightarrow \langle m_{\beta\beta} \rangle \sim 20\,\text{meV}$
- 1000 kg of enriched Xe
- Ongoing R&D:
  - **Background Rejection**
    - Scintillating Balloon for $^{214}\text{Bi}$ tagging
    - Improved LS purification: Molecular Sieve, Metal scavenger
    - Imaging sensor
    - Pressurized Xe-LS
  - Better light collection for improved $\sigma_E$
    - LAB based LS (L.Y. increased by 40%)
    - New High Q.E. PMT (L.Y. increased by 90%)
    - Light collectors for PMTs (L.Y. increased by 80%)
KamLAND-Zen Sensitivity

Current

KamLAND-Zen 800

KamLAND2-Zen

Close to IH

Into to IH

Covering most of IH
In Summary …

- Based on a 126 kg·yr $^{136}$Xe Phase 2 exposure, KamLAND-Zen has measured the $^{136}$Xe $2\nu\beta\beta$ half-life to be $T_{1/2}(2\nu) = 2.21 \pm 0.02\, \text{(stat.)} \pm 0.07\, \text{(syst.)} \times 10^{25}\, \text{yr}$.

- Based on 504 kg·yr $^{136}$Xe Phase 2 exposure and in combination with the 89.5 kg·yr Phase 1 exposure KamLAND-Zen has placed a lower limit on the $^{136}$Xe $0\nu\beta\beta$ half-life of $T_{1/2}(0\nu) > 1.07 \times 10^{26}\, \text{yr}\, \text{(90\% C.L.)}$.

- This corresponds to an upper limit on the effective Majorana mass of $\langle m_{\beta\beta} \rangle < 61 - 165\, \text{meV}$, nearing the top of the inverted hierarchy.

- KamLAND-Zen 800 seeks to improve the sensitivity to $0\nu\beta\beta$ with a new, cleaner mini-balloon and almost twice the mass of Xe.

- Installation of the new mini-balloon is on-going, and we expect to begin this new phase of KamLAND-Zen in October 2016.

- R&D for future upgrades to KamLAND $\Rightarrow$ KamLAND2 are on-going (and promising).
International Workshop on Double Beta Decay and Underground Science
Nov. 8-10, 2016, Osaka, Japan
http://www.rcnp.osaka-u.ac.jp/dbd16/index.html

Please join!
Thank you for your attention!


**Tokyo Univ. IPMU**: A.Kozlov, Y.Takemoto, B.E.Berger, D.Chernyak

**Oska Univ**: S.Yoshida **Tokushima Univ**: K.Fushimi

**Lawrence Berkeley National Lab**: T.I.Banks, B.K.Fujikawa, T.O’Donnell

**Massachusetts Institute of Technology**: L.A.Winslow, J.Ouellet, E.Krupczak

**Univ. of Tennessee**: Y.Efremenko **Univ. of North Carolina**: H.J.Karwowski

**N.C. Central Univ**: D.M.Markoff

**Duke Univ**: W.Tornow **Univ. of Washington**: J. Detwiler, S.Enomoto

**Univ. of Amsterdam**: M.P.Decowski

48 physicists from 11 institutes
Back Up Slides
KamLAND-Zen Mini-Balloon

- Mini-balloon constructed from nylon film
- 25μm-thick
- 95% transparency at 400 nm
- Tight to Xe
- U & Th contaminations around $1 \times 10^{-12}$ g/g
- K contamination around $10 \times 10^{-12}$ g/g
- Observed U & Th contamination on mini-balloon dominated by dust on the surface.
Results and Status of KamLAND-Zen

Purification Scheme

- cold oil trap
- charcoal filter
- sintered metal filter
- getter N₂
- 3nm particle filter (PTFE)
- distillation XMASS proto.
- particle filter
- getter Xenon
- new purified LS

June 2012 ~ November 2013

- vacuum extraction of $^{136}$Xe
- new $^{136}$Xe
- replace with new purified Xe-LS
- replace with new purified LS
- new LS
- new Xe-LS
- purifed $^{136}$Xe

Xe-LS + $^{110m}$Ag

- add purified PC for density adjustment
- confirm $^{110m}$Ag remains in LS
- two times of distillation confirm whole $^{110m}$Ag drained
- $\sim$380kg Xe installed
- aim: 1/100 reduction

Now

ICHEP 2016
KamLAND-Zen
August 5, 2016
Xe Handling Facility

Gas Handling System

- The system is composed of 4 parts
- Storage
- Gas Buffer
- Compressor 1
- Compressor 2
- Cold Trap
- LS Condenser
- Filter
- Main tank
- Sub tank
- Vacuum pump
- Density Control Unit
- TEMP controller
- LS Buffer
Detector Calibration (October 2015)

- Lowered sources into the center of the mini-balloon to test energy response and vertex reconstruction vs position.

Position dependent energy bias < 1%

Energy resolution $\sigma/E = (7.3 \pm 0.4)\%/\sqrt{E_{[\text{MeV}}}$

Position dependent vertex bias < 1.0 cm for $|z| < 1.0$ m
Toy Monte Carlo

- Assuming best-fit background model
- 12% probability for a stronger limit
- Median 90% sensitivity of $5.6 \times 10^{25}$ yr

![Graph showing probability distribution for limit at 90% C.L. (events/day/kton-LS)]
Cs and U show similar z-dependence indicating they are likely both from dust contamination.