First results from KamLAND-Zen double beta decay with ^{136}Xe

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Rencontres de Moriond, EW session, 2012

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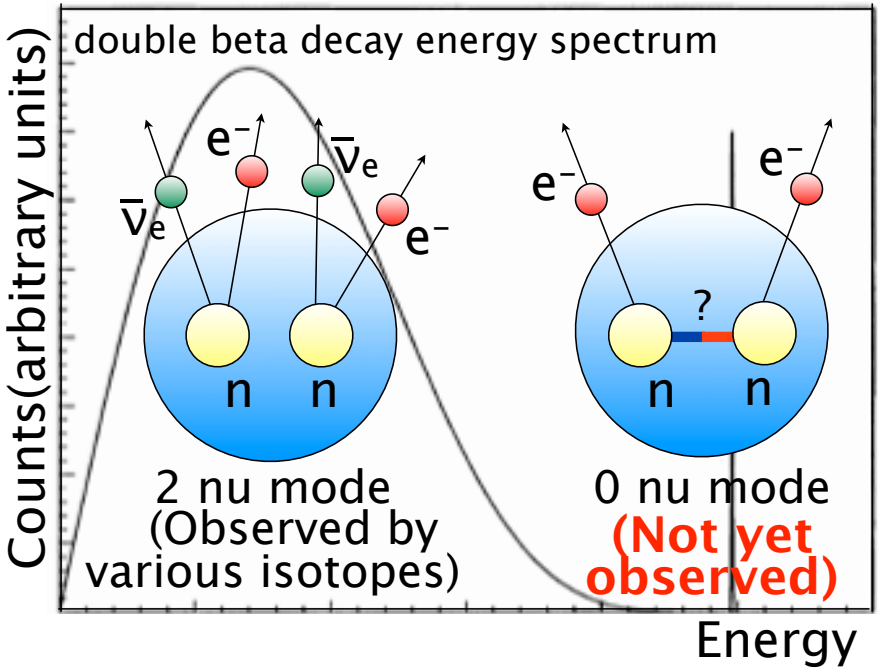
Contents

Motivation : Double beta decay

Double beta decay→2 decay mode



What we measure : decay rate

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

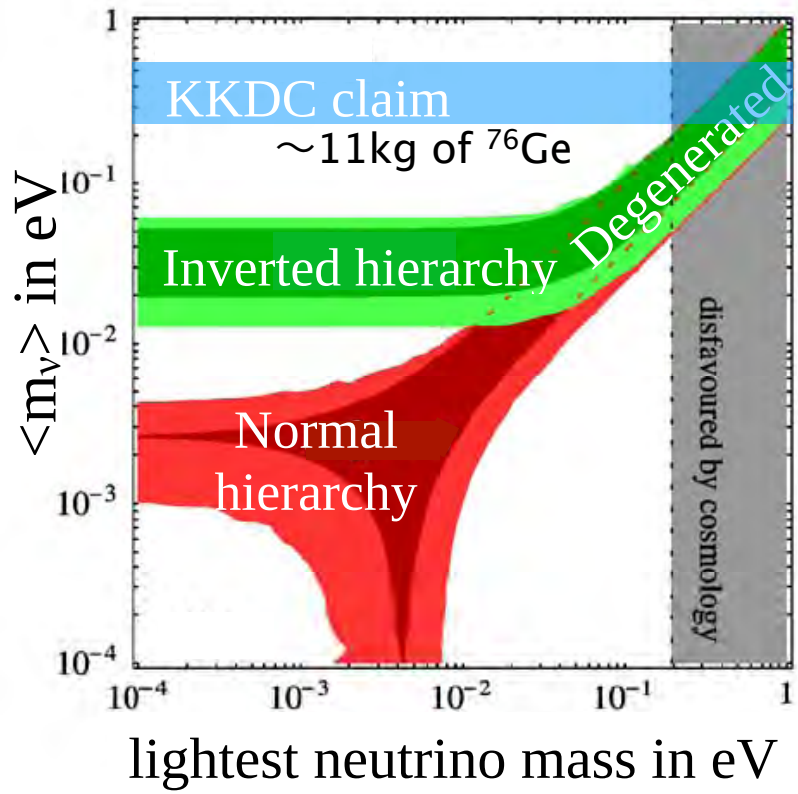
0nu mode $\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2$

G: phase space factor, M: nuclear matrix element
<mν>: effective neutrino mass

$$\langle m_\nu\rangle \equiv \left||U^L_{e1}|^2 m_1 + |U^L_{e2}|^2 m_2 e^{i\phi_2} + |U^L_{e3}|^2 m_3 e^{i\phi_3}\right|$$

If 0nu mode observed

→lepton number violation
→Majorana particle
→see-saw mechanism？, leptogenesis？
→Neutrino mass hierarchy
→Neutrino effective mass
→hint for neutrino (absolute) mass



Double beta decay→ Very long half-life (> 10^{18} yr), a few MeV Q-value.
→Need large amount of isotopes & low B.G. environment.

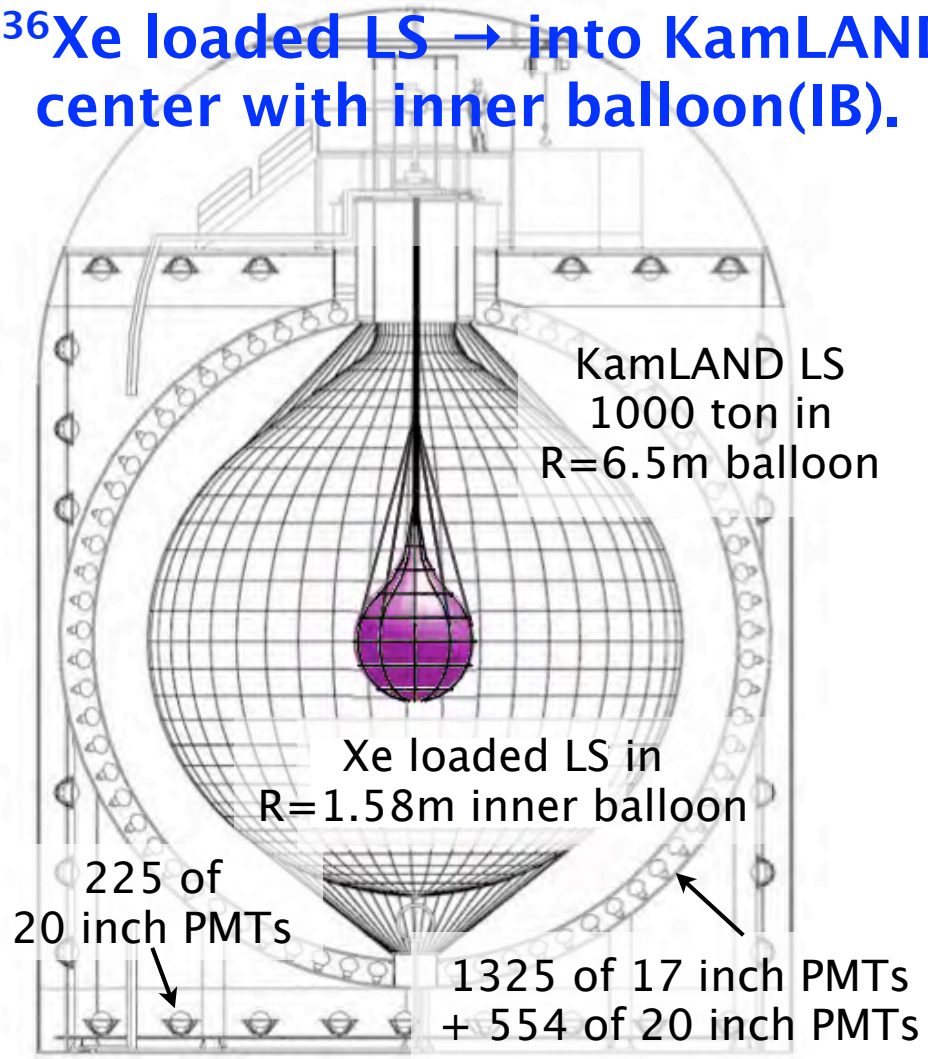
KamLAND-Zen(Zero neutrino double beta decay)

KamLAND-Zen :

Modification of KamLAND.
1,000 tons of
highly purified liquid scintillator.

BIG & Low BG

^{136}Xe loaded LS → into KamLAND center with inner balloon(IB).



Double beta decay isotope

~300 kg of ^{136}Xe (91% enriched)
Largest amount for DBD experiment.
Already have another 200kg for next phase.
Q-value : 2.476MeV

Target for 1st phase

Search for KKDC claim and
Degenerated hierarchy.

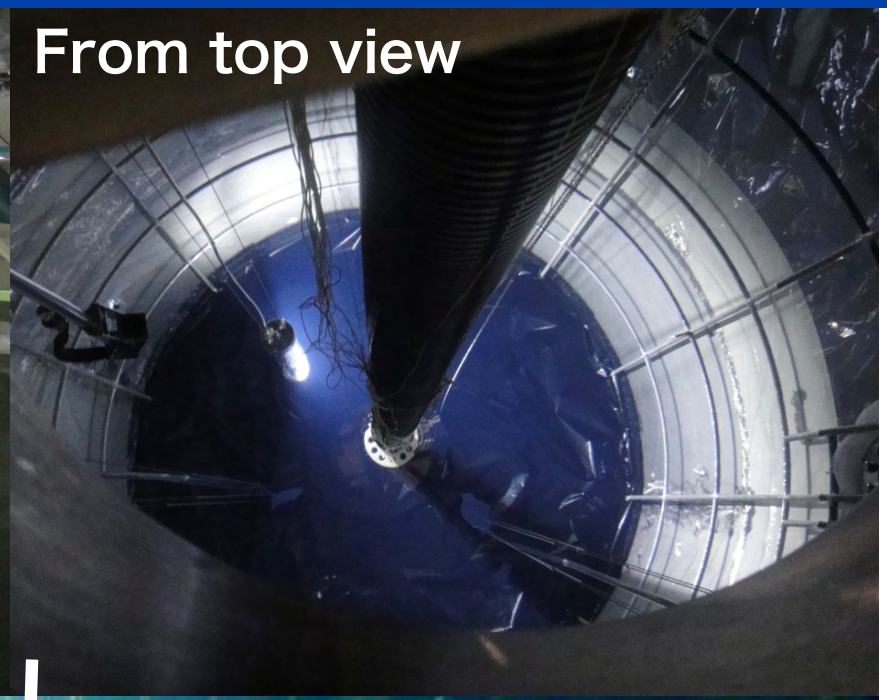
Why Xe?

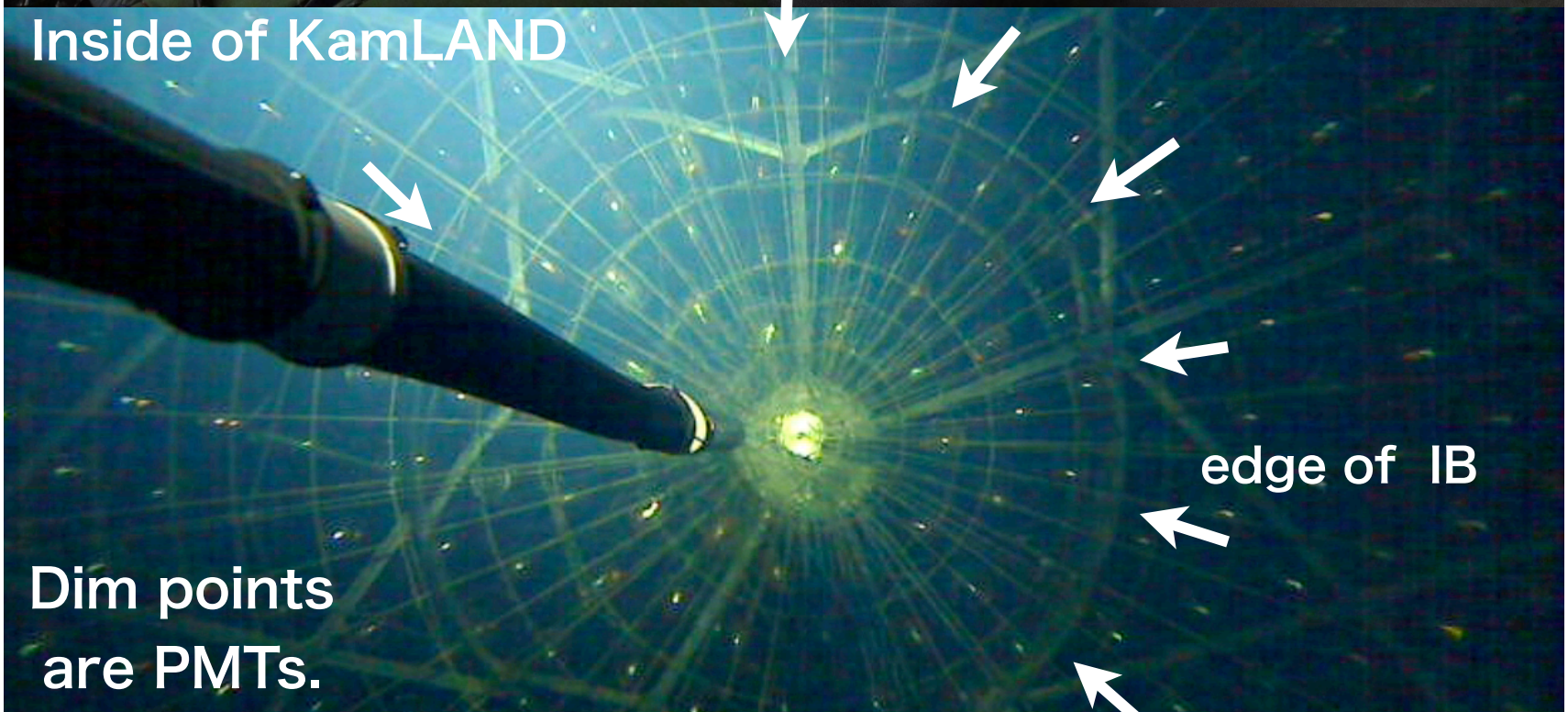
- Soluble to LS ~3% by weight.
- easily extracted.
- Isotopic enrichment, purification established.

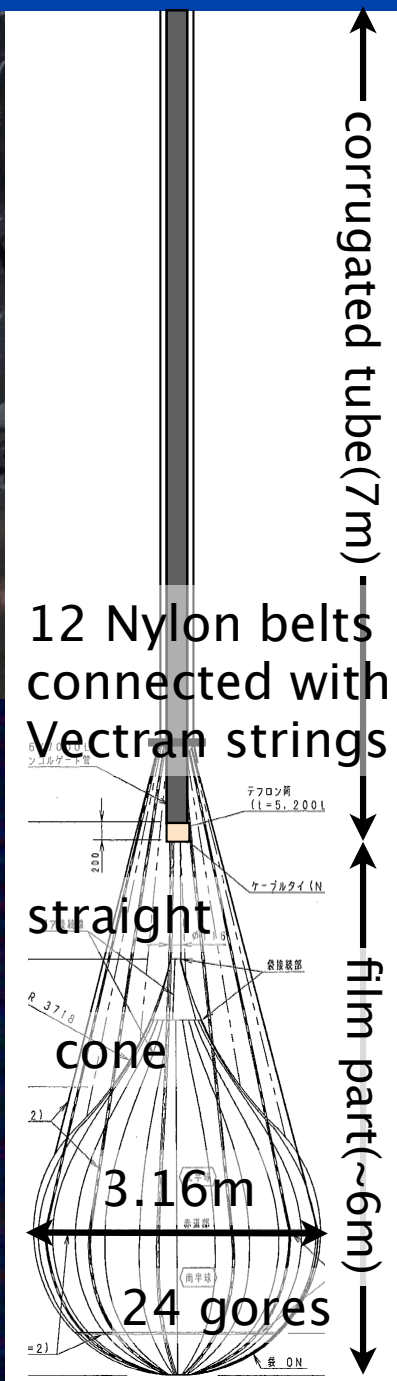
Schedule

2011 Aug. Modification
Sep. 24th, 2011 data taking start
Oct. 12th, 2011 –Jan 2nd, 2012.
77.6 days data for 1st result.

Hardware pictures



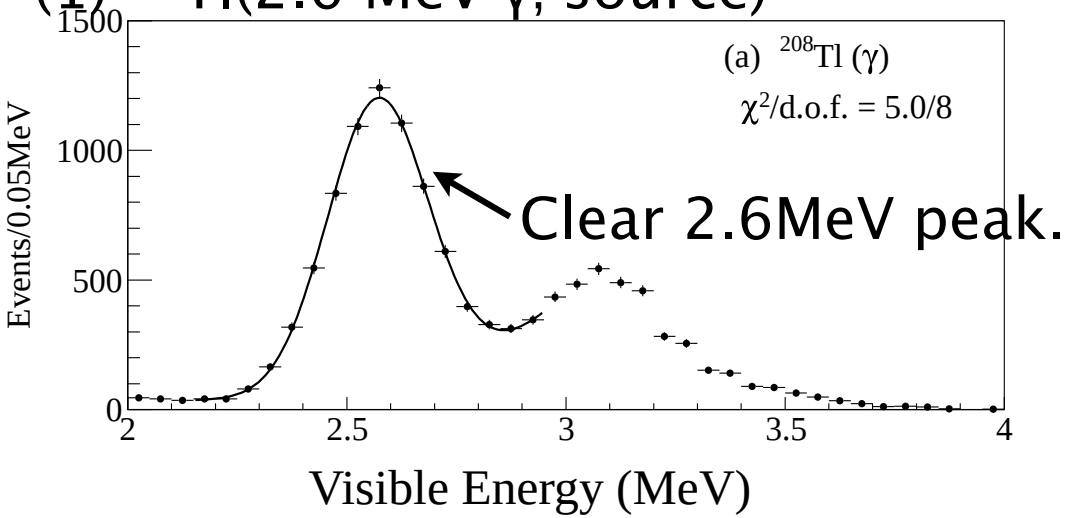


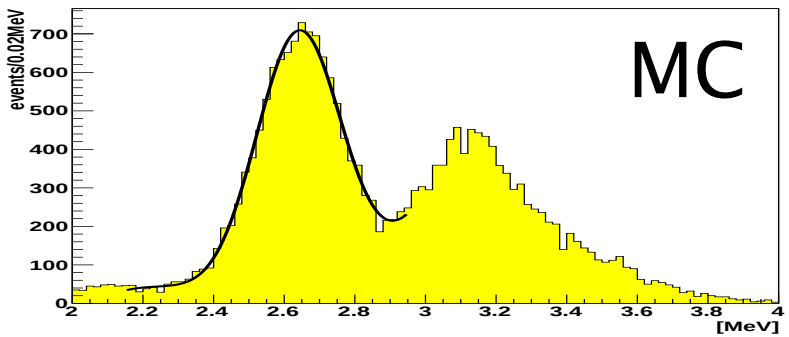


Calibration

3 Energy Calibration

(1) ^{208}Tl(2.6 MeV γ, source)

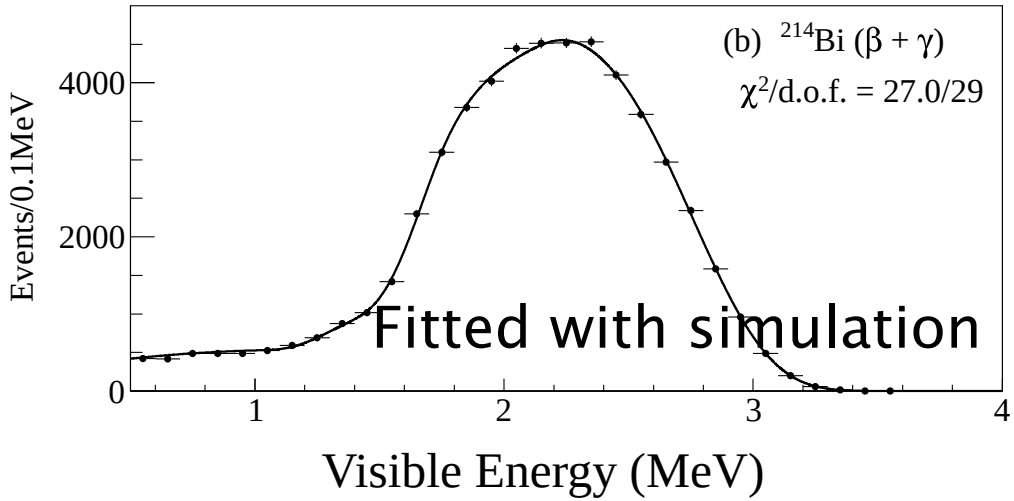




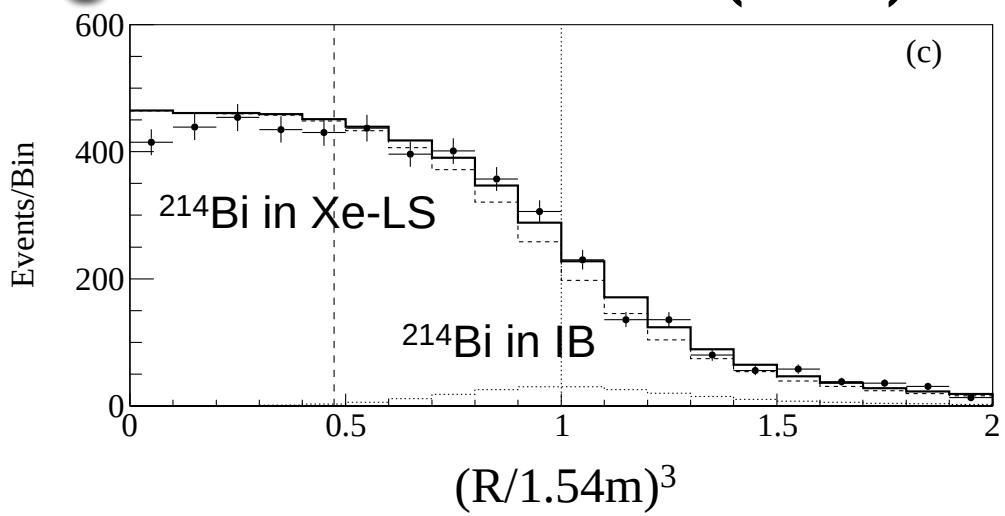
$\sigma_E = 6.6\%/\sqrt{E}$

(2) 2.225 MeV 's from spallation neutrons capture on protons.

(3) ^{214}Bi (β+γ's)



Vertex calibration (^{214}Bi)



Vertex resolution from balloon events(next page) ~15cm/$\sqrt{E}$

Fiducial volume

R<1.2 m, LS = 7.24 m^3
→ 129.4 kg ^{136}Xe in the FV
(^{136}Xe 90.93% enrichment,
2.52% by weight)

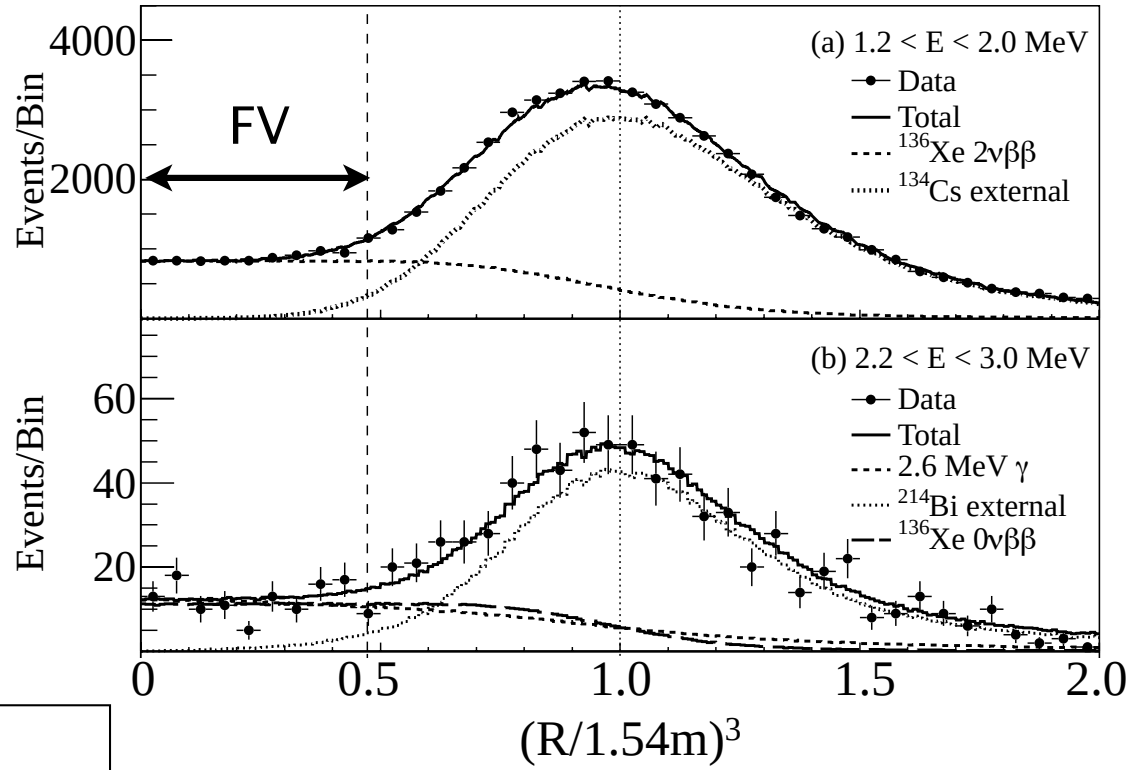
Volume ratio=0.438 ± 0.005
((R<1.2m)/Total 16.51 ± 0.17 m^3)

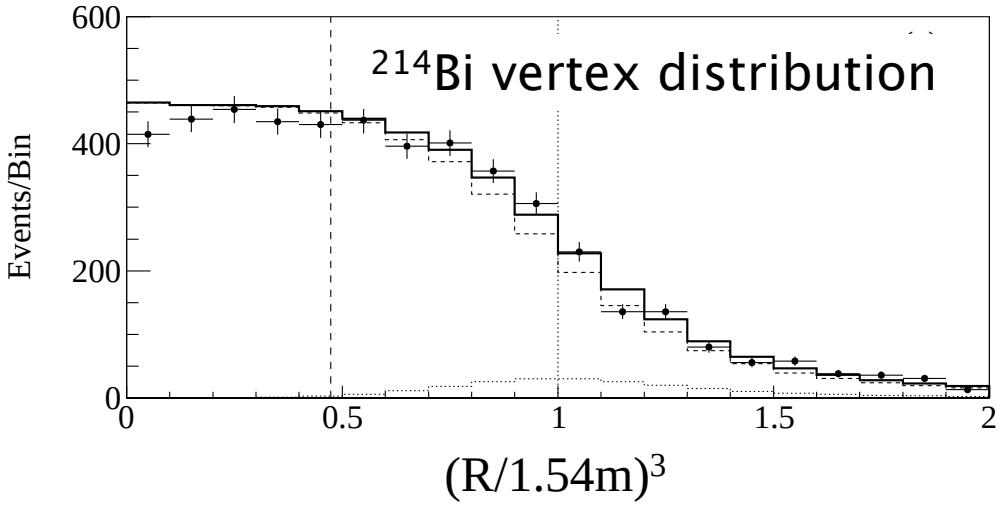
↑

Total fiducial volume error 5.2%

↓

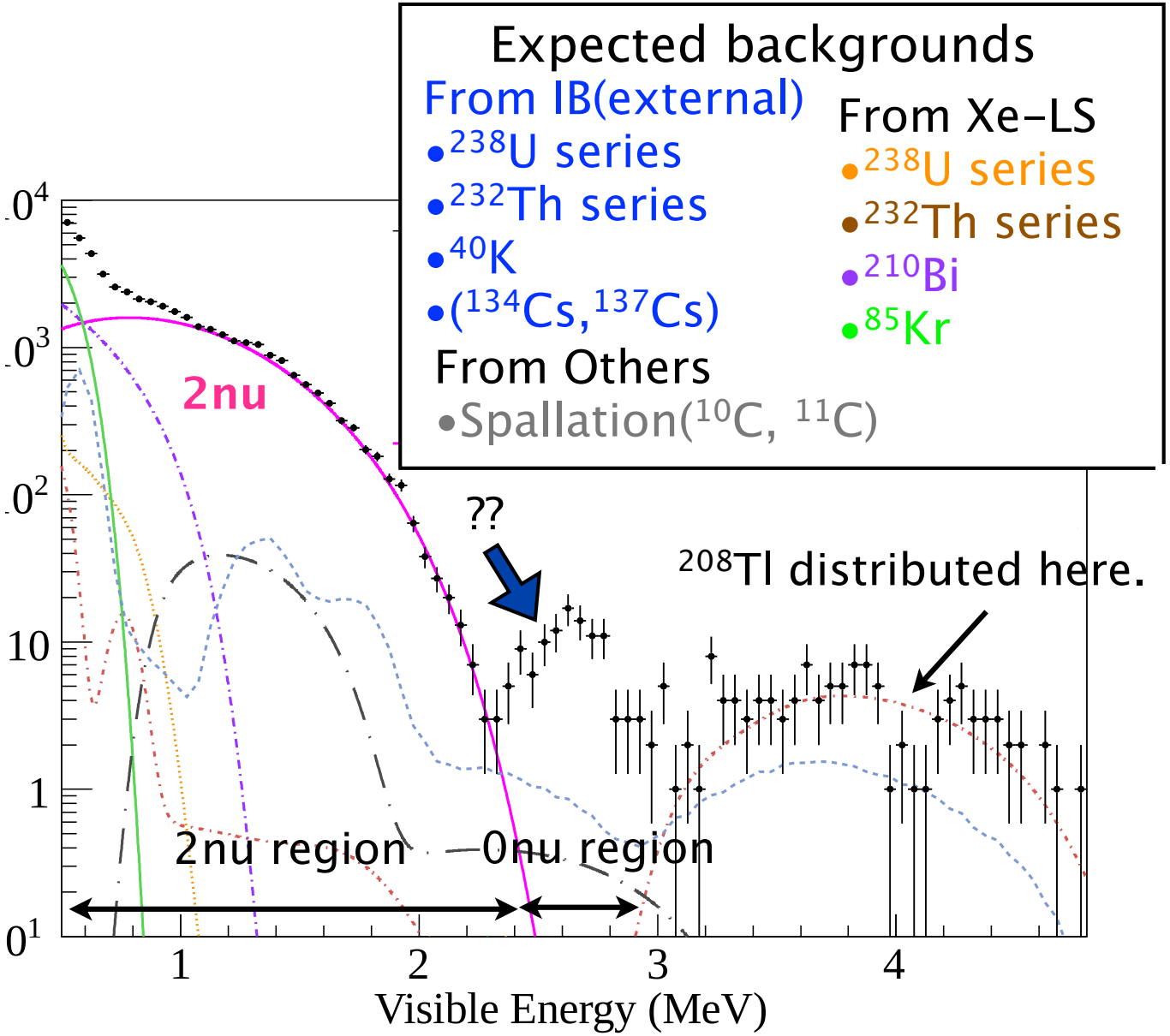
^{214}Bi rate (from vertex distribution)
ratio = 0.423 ± 0.007(stat.) ± 0.004(syst.)
(R<1.2 / Total ^{214}Bi events)

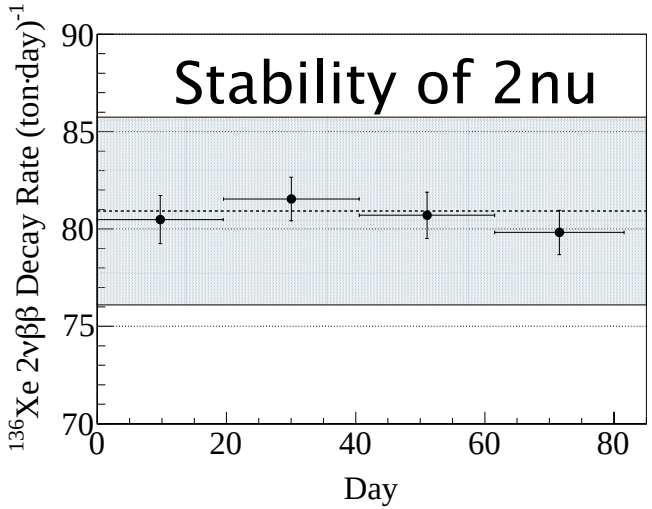


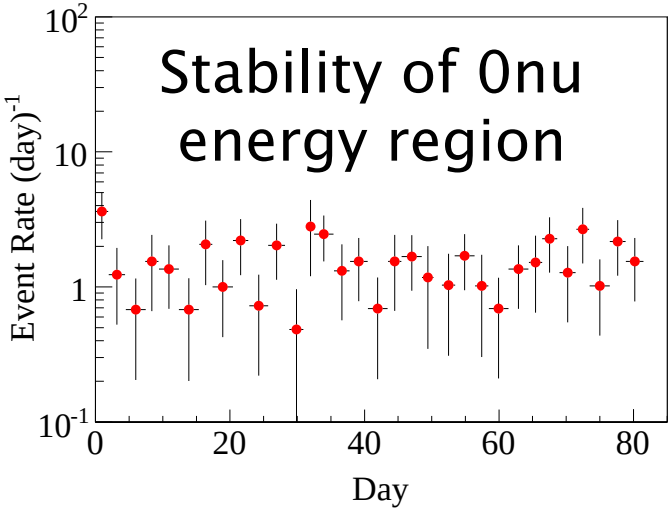


systematic uncertainty	error
fiducial volume	5.2%
enrichment of Xe	0.05%
Xe amount 2.5±0.07wt%	2.8%
energy scale	0.3%
Xe-LS edge effect	0.06%
total	5.9%

Energy spectrum for 77.6 days data







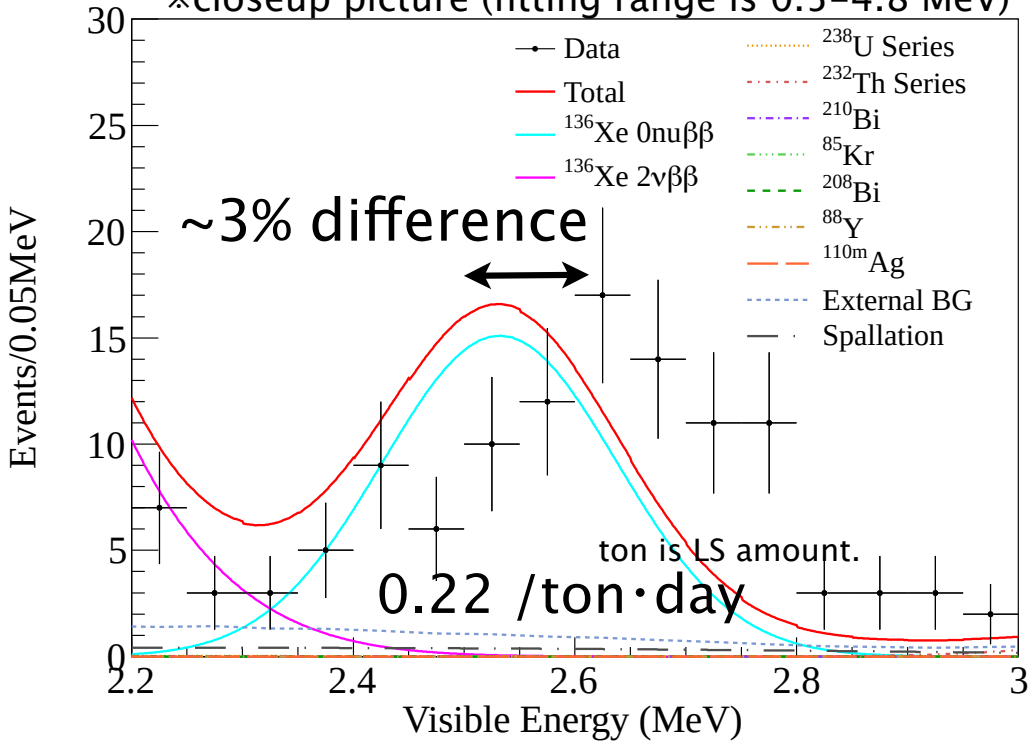
(2.2 < E < 3.0 MeV, R< 1.2m)

High statistics for 2nu region.
Peak at the 0nu region. Signal or background?

Unexpected background for ^{136}Xe 0νββ

Fit the peak with 0nu spectrum

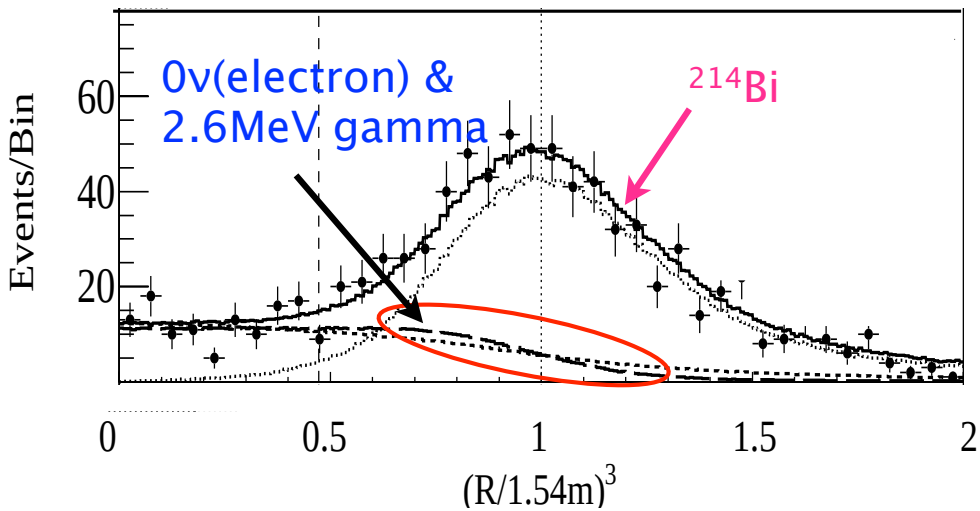
※closeup picture (fitting range is 0.5-4.8 MeV)



No background hypothesis excluded more than 5 sigmas.

Feature of peak

- Rate is stable.
- Uniformly distributed in Xe-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

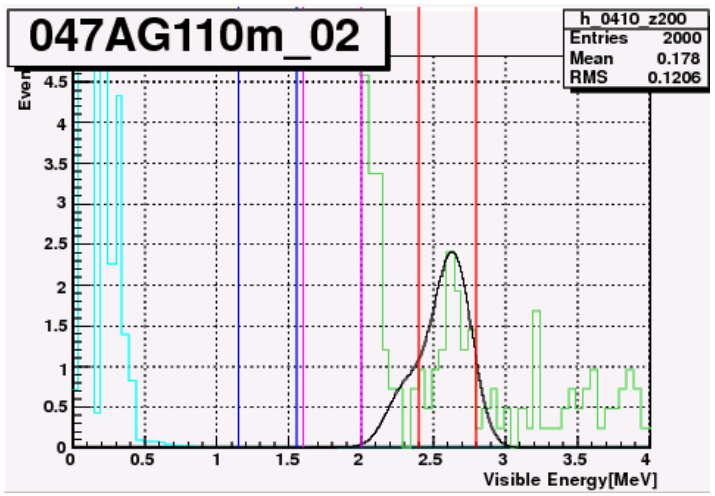
ENSDF search

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 $\beta^-(+\gamma)$, $\beta^+(+\gamma)$ 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.

4 nuclei remained.

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 limits nuclei w/ <100 sec lifetime should be <0.02 / ton·day (90% CL). → small

cont'd

4 Candidates → Free parameters in fitting.

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

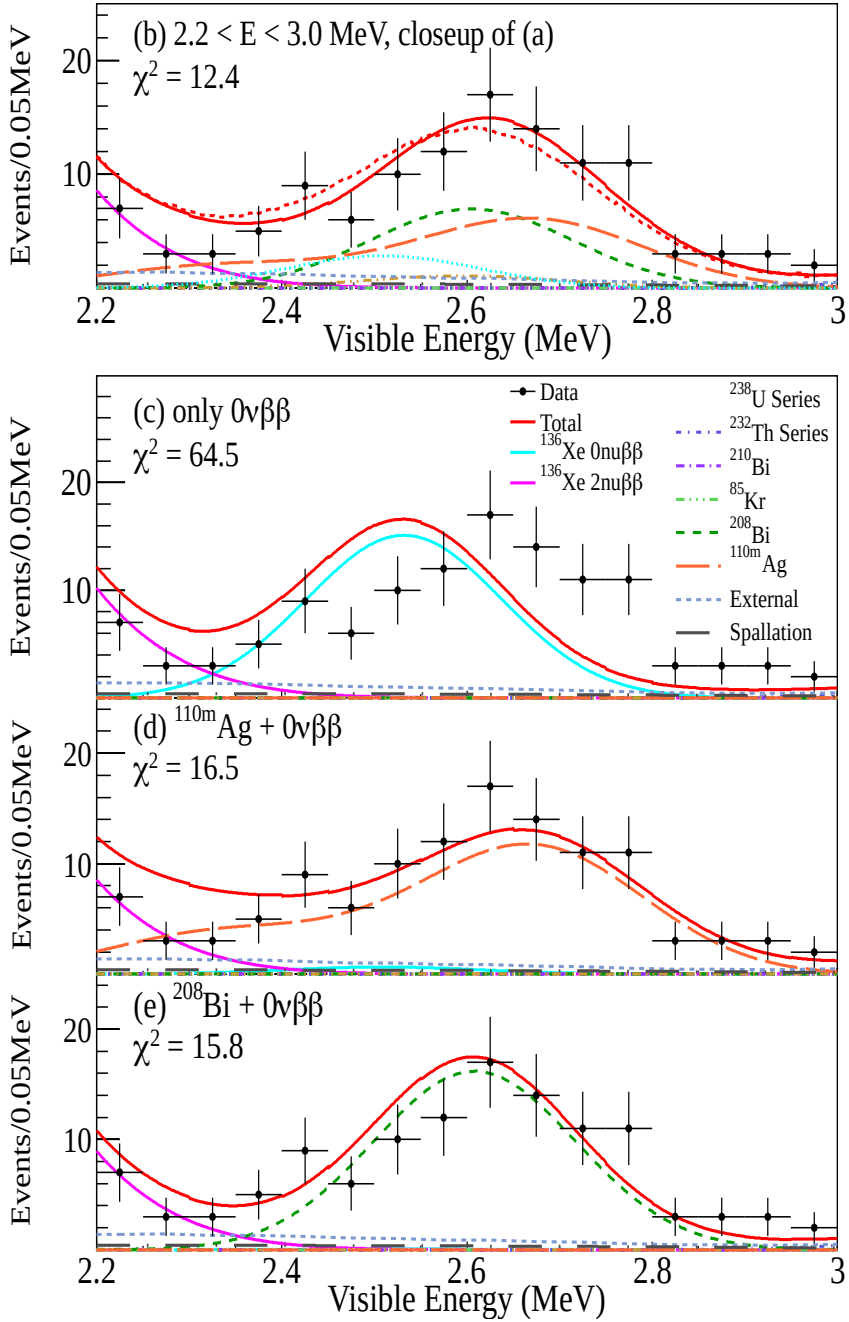
^{88}Y and ^{60}Co -> constrained by its half life and shape.

There is no clear evidence for existing BG.

difficult to determine each contribution separately by an ex-situ measurement.

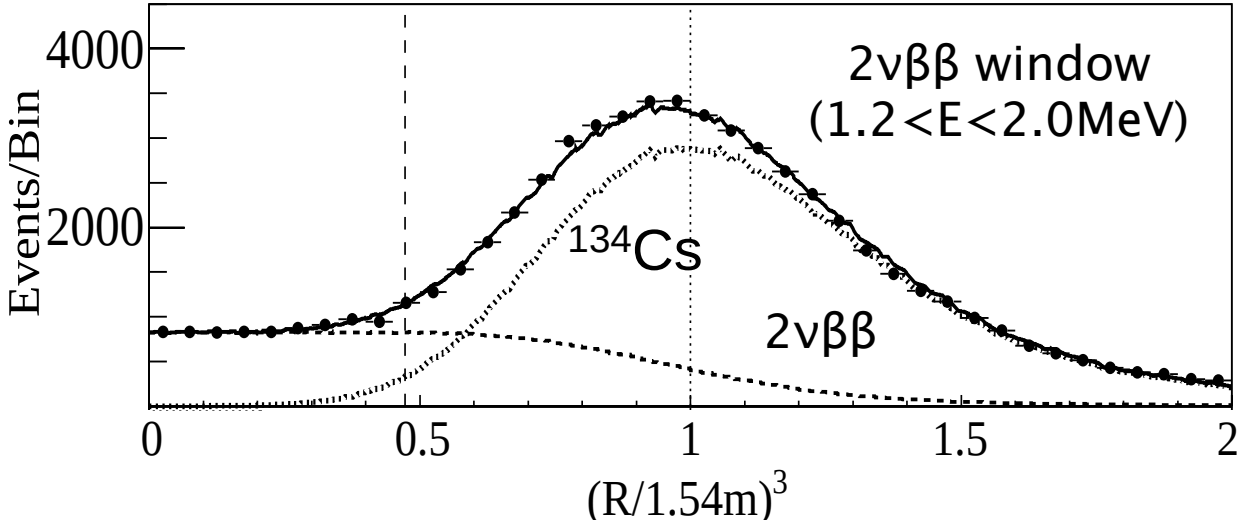
Possibility of Ag
- Spallation (gas made in Russia sent by airplane.).
- Included in the solder for Xe system.
  but no detection in Ge detector.
- Fukushima fallout contains Ag.
  Observed in the soil in Sendai(IB fabrication)
  with Ge detector.

Possibility of Bi
- Included in the solder for Xe system(same as Ag).
- ^{207}Bi/^{208}Bi ratio is small than expected.

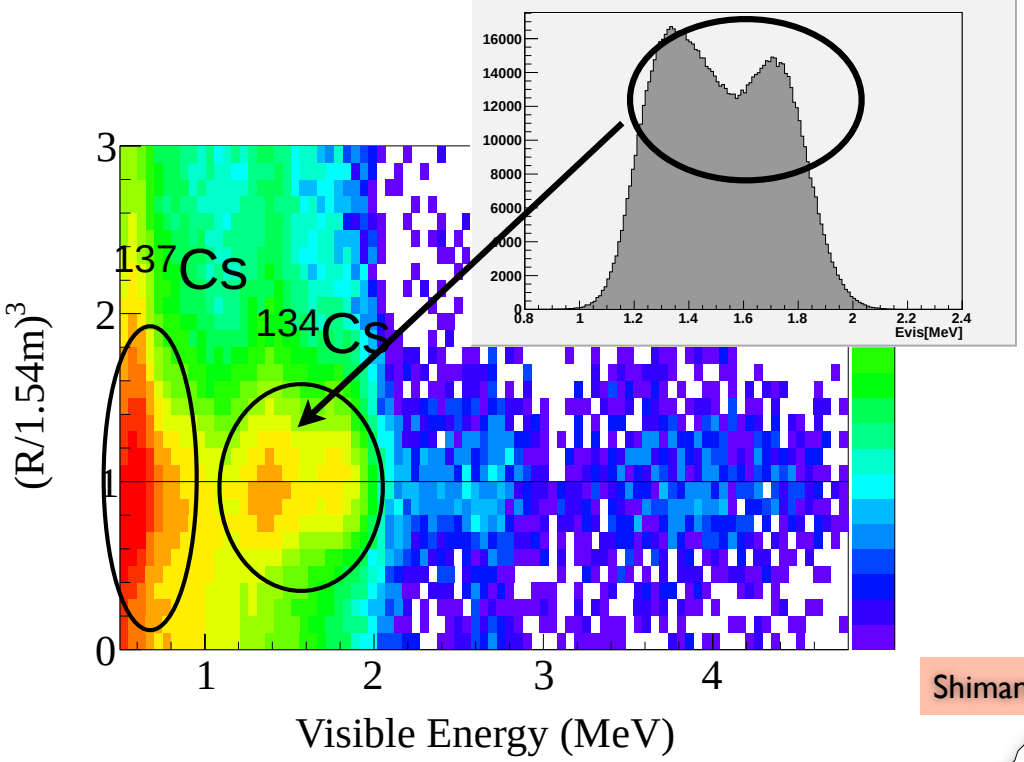


Unexpected background for ^{136}Xe 2νββ

^{134}Cs distribute on the IB. Origin → Fukushima reactor accident



simulation data of ^{134}Cs

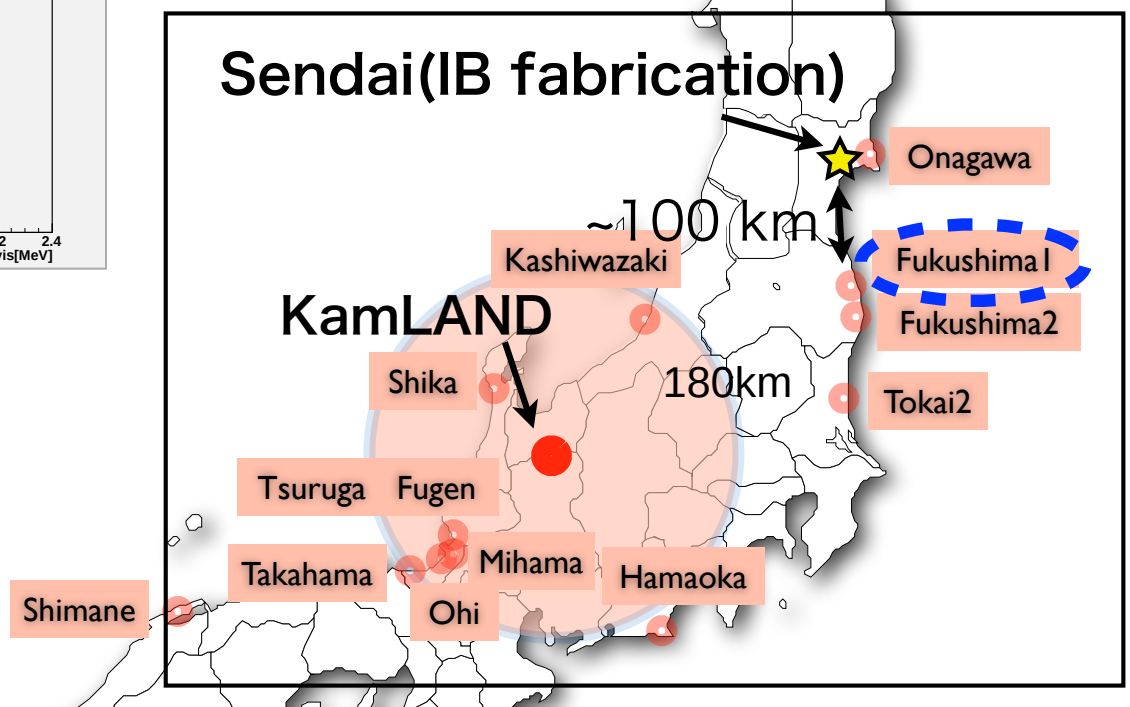


Why Fukushima?

- Cs don't exist in nature.
- Ratio of ^{134}Cs/^{137}Cs data & soil sample almost consistent. Possibility Spallation of ^{136}Xe?
- Amount of ^{137}Cs can't explain.

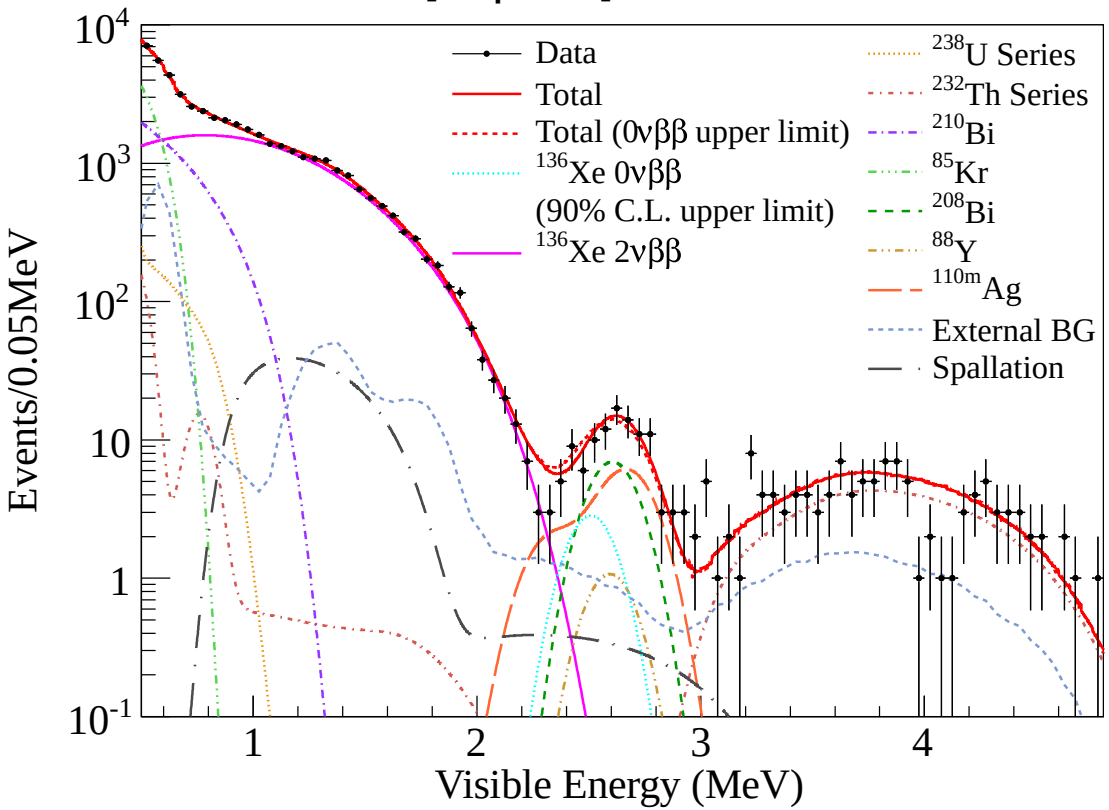
Why on IB?

- IB made in Sendai
- Fit well with data.
- Cs don't dissolve to LS.

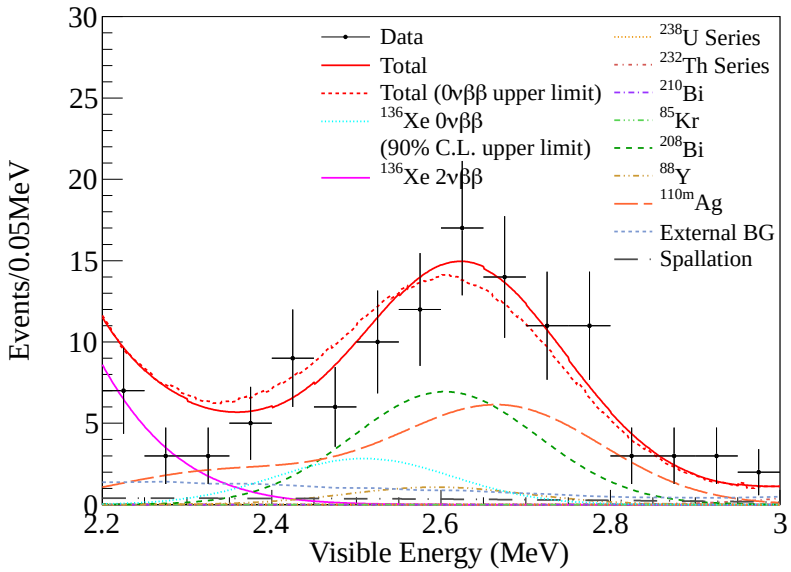


^{136}Xe 2νββ & 0νββ Half life

arXiv:1201.4664v1 [hep-ex]



- livetime 77.6 days.
- 129 kg of ^{136}Xe



$T^{2\nu}_{1/2}$=2.38±0.02(stat)±0.14(syst) ×10^{21} years

- high precision measurement.
- consistent with EXO result. $T^{2\nu}_{1/2}$=2.11±0.04(stat)±0.21(syst) ×10^{21} yr
- verification of discrepancy of $T^{2\nu}_{1/2}$. (DAMA result $T^{2\nu}_{1/2}$>1.0 × 10^{22} yr)

$T^{0\nu}_{1/2}$ > 5.7×10^{24} years at 90% C.L.

$\langle m_{\beta\beta} \rangle$ <0.3~0.6 eV QRPA, shell model

- Top class measurement.

Near future plan

Expectation of reducing BG to improve limit.

- Filtration (with 50 nm filter) of LS.
- Done on middle of Feb. Waiting for Rn decay.

Peak remained →

- Other purification (distillation for LS & Xe)
- We already have distillation system, experience and technique.

NO Peak →

- Measurement going. Will present new limit.

If peak remained →

- Extraction of Xe from LS.
- Measure the left LS and its background.

Peak remained →

- Return Xe to LS (after purified).
- Options:
  Fabrication of new IB.
  – cleaner film.
  – larger radius.
  Pressurized Xenon
  – higher concentration.

NO peak →

- ...Peak is 0nu?

Summary

- Double beta decay
  - Interesting & important experiment.

- KamLAND-Zen 1st phase started.
  - Data taking start on Sep. 2011
  - 1st results with initial 3 month reported.

  $T^{2\nu}_{1/2}$=2.38±0.02(stat)±0.14(syst) ×10^{21} years

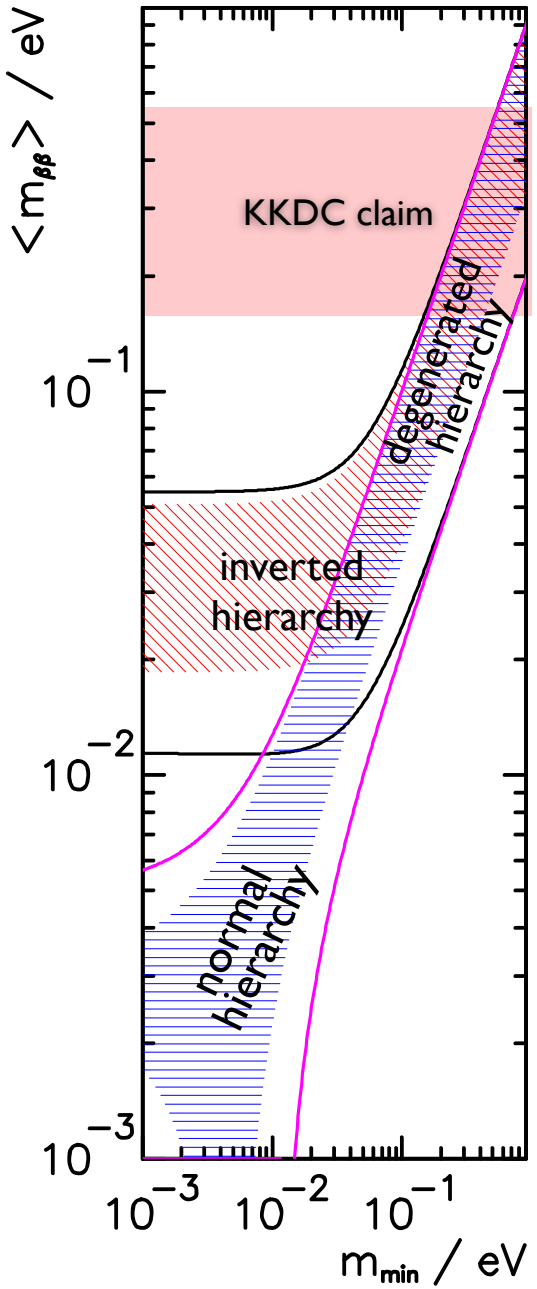
  $T^{0\nu}_{1/2}$ > 5.7×10^{24} years at 90% CL

- To reduce background around 0nu region,
  - Filtration done on middle of Feb.
  - Another purification method.

- KamLAND also working - for reactor and geo neutrinos.

Backup

Milestone

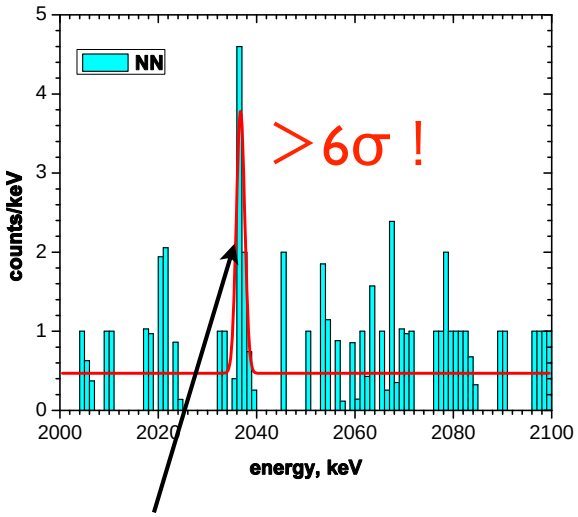


hatch:
unknown CP phase only
Solid:
w/ uncertainty from oscillation parameters

GCOE inoue

KKDC claim part of Heidelberg Moscow group

Klapdor et al. Mod.Phys.Lett.A21(2006)1547



evidence of 0ν2β ?

11 kg ^{76}Ge

exposure 71 kg・yr

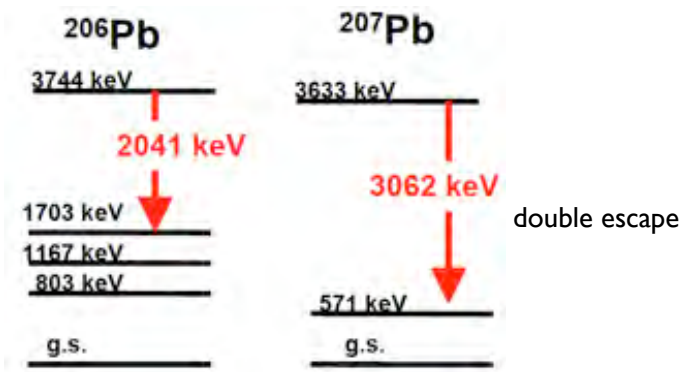
$T_{1/2}=2.23^{+0.44}_{-0.31}\times10^{25}$ yrs

m_ν =320±30 meV

no theoretical error

Despite of the high statistical significance, it is still controversial.
High energy resolution alone is not satisfactory.

background candidates

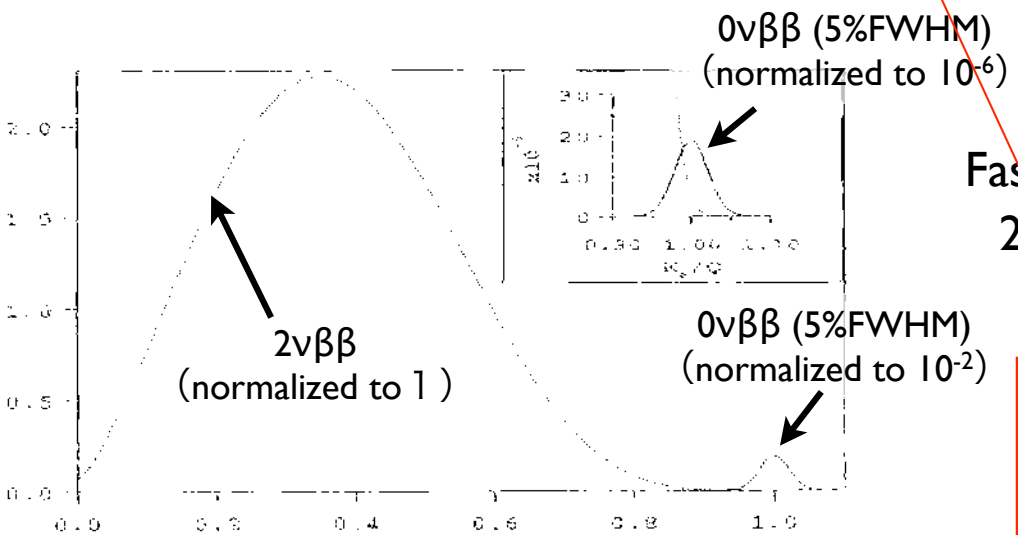


Huge and low-background instrument is necessary!

		half lives	mass
~100meV KKDC claim	→	10^{25}~10^{26}y	10~100kg
~60meV degenerated	→	10^{26}~10^{27}y	100~1000kg
~20meV inverted	→	10^{27}~10^{28}y	1000~ kg

Various double beta decay nuclei

nucleous	$T^{0\nu}_{1/2}(50\,\mathrm{meV})$	$T^{2\nu}_{1/2}$ measured (year)	natural abundance (%)	Q-value (keV)	
$^{48}Ca \rightarrow ^{48}Ti$		$(4.2^{+2.1}_{-1.0}) \times 10^{19}$	0.19	4271	max. Q, fast 2ν
$^{76}Ge \rightarrow ^{76}Se$	0.86×10^{27}	$(1.5\pm0.1) \times 10^{21}$	7.8	2039	semiconductor
$^{82}Se \rightarrow ^{82}Kr$	2.44×10^{26}	$(0.92\pm0.07) \times 10^{20}$	9.2	2995	
$^{96}Zr \rightarrow ^{96}Mo$	0.98×10^{27}	$(2.0\pm0.3) \times 10^{19}$	2.8	3351	
$^{100}Mo \rightarrow ^{100}Ru$	2.37×10^{26}	$(7.1\pm0.4) \times 10^{18}$	9.6	3034	fast 2ν
$^{116}Cd \rightarrow ^{116}Sn$	2.86×10^{26}	$(3.0\pm0.2) \times 10^{19}$	7.5	2805	
$^{130}Te \rightarrow ^{130}Xe$	2.16×10^{26}	$(0.9\pm0.1) \times 10^{21}$	34.5	2529	high abundance
$^{136}Xe \rightarrow ^{136}Ba$	4.55×10^{26}	$(2.11\pm0.21)\times10^{21}$	8.9	2476	slow 2ν, noble gas
$^{150}Nd \rightarrow ^{150}Sm$	2.23×10^{25}	$(7.8\pm0.6) \times 10^{18}$	5.6	3367	fast 0ν, 2ν



Fast 2ν requires high energy resolution.
2ν BG is proportional to ~5.8th powers of the energy resolution.

Small $T^{0\nu}/T^{2\nu}$ requires modest energy resolution.

About KamLAND

● Targets

Visible energy [MeV]

0.4 | 1.0 | 2.6 | 8.5

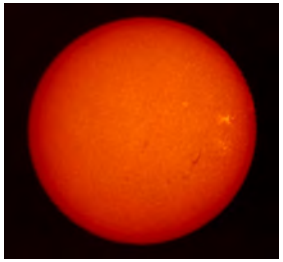
neutrino electron elastic scattering

$$\nu + e^- \rightarrow \nu + e^-$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

inverse beta decay

^{7}Be solar neutrino



Neutrino Astrophysics

Geo-neutrino

First detection!

Neutrino Geophysics

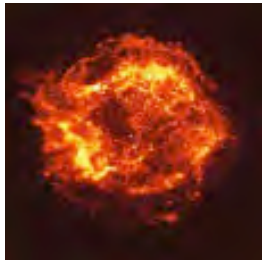
Reactor neutrino

Precise measurement of Δm^2_{21}

Neutrino Physics

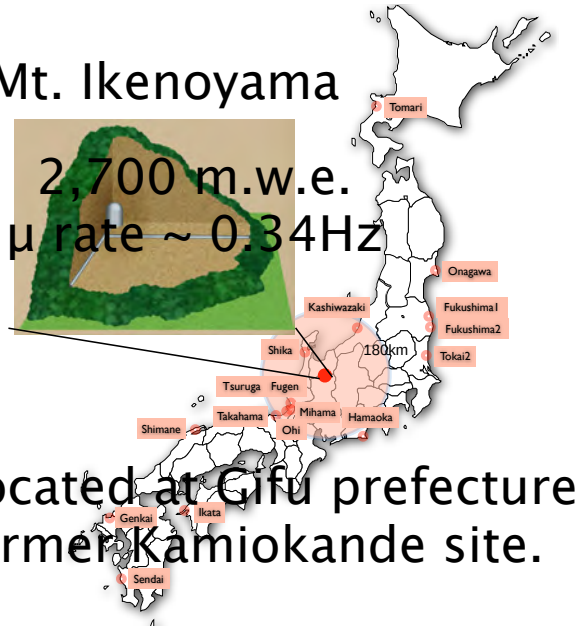
supernova relic neutrino

GRB neutrino etc.

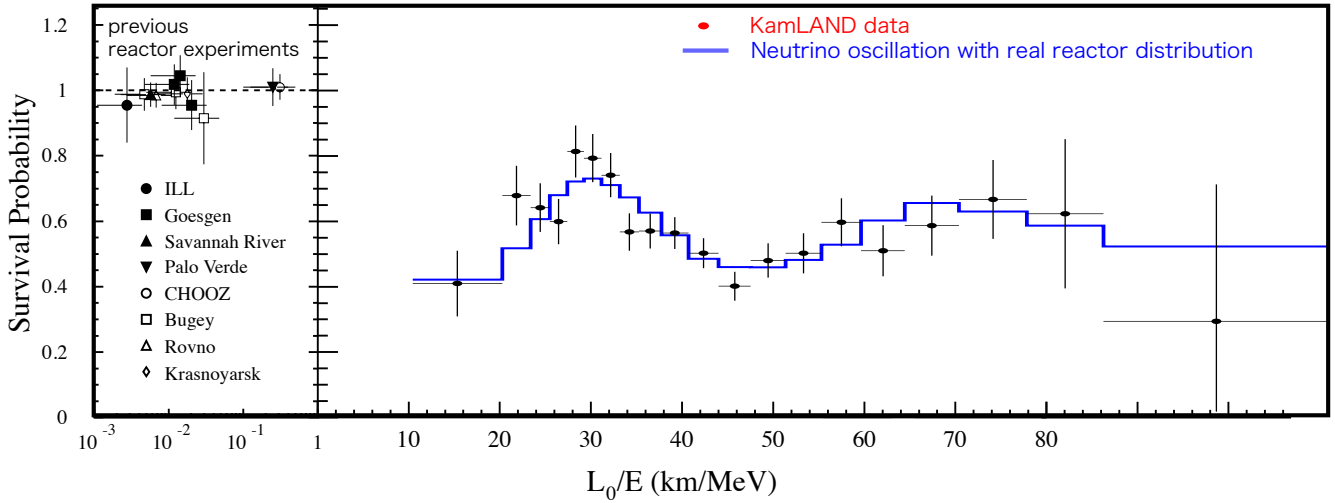


Neutrino Astrophysics
Cosmology

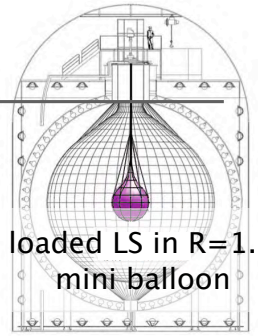
Mt. Ikenoyama



Located at Gifu prefecture, former Kamiokande site.



KamLAND-Zen 1st phase



- Procedure
  inner balloon installation → dummy LS filling → Xe-LS filling
  (inflation) (replace)
- items for KamLAND-Zen

- **^{136}Xe**

- **Xe handling system**

- **Xe-LS($\Delta\rho$<0.1%)**
  Decane (distillation), PC(water extraction, distillation), PPO(distillation), Xe

- **Dummy LS**
  Decane, PC, PPO(same as Xe-LS)

- **mini balloon**(Nylon)
  R=1.58m, 25μm
  measured radio-purity
  ^{238}U: 2×10^{-12}g/g
  ^{232}Th: 3×10^{-12} g/g
  ^{40}K: 2×10^{-12} g/g

- **Dead time free electronics**
  ^{10}C tagging

Inner balloon fabrication

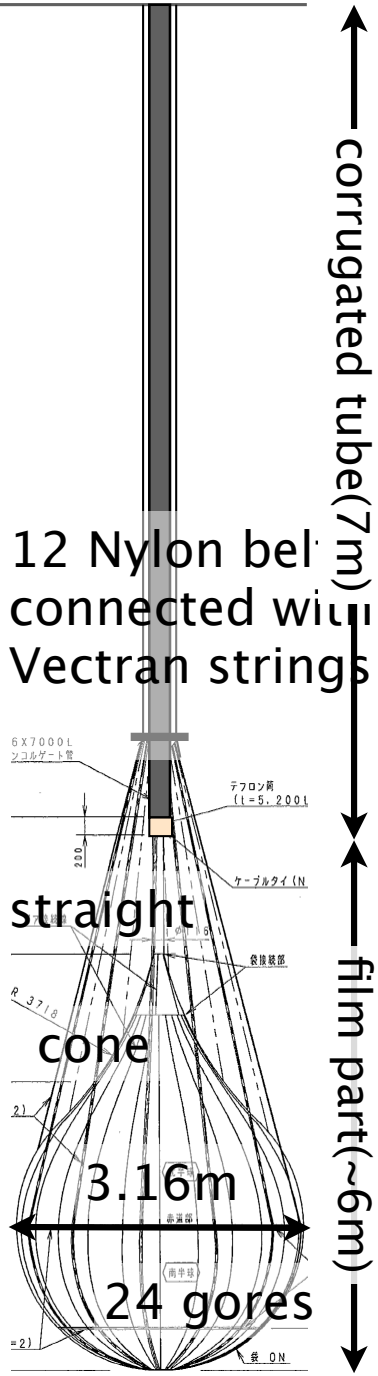
- Produced in a class 1 super-clean-room in Sendai.
  (class 1 = less than 1 0.5-micron-particle in cubic feet


Ultrasonic cleaning
with pure water.


Making gores.


Heat welding.

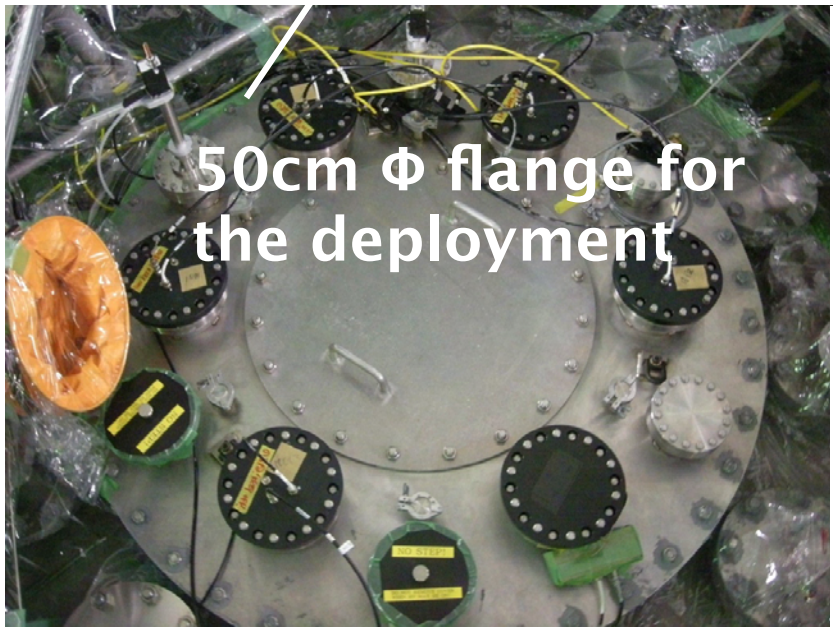

Packed and N2 purged.
Transferred to Kamioka.



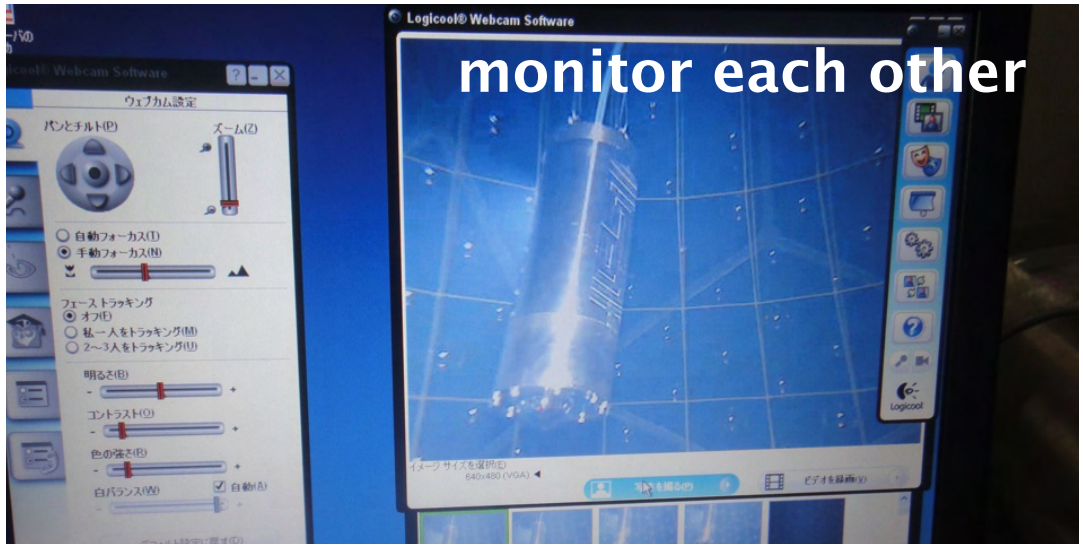
- All tools and parts to be used for the installation have been cleaned here.

mini balloon installation

- Clean room in the dome(Kamioka) (class 10~100 achieved)

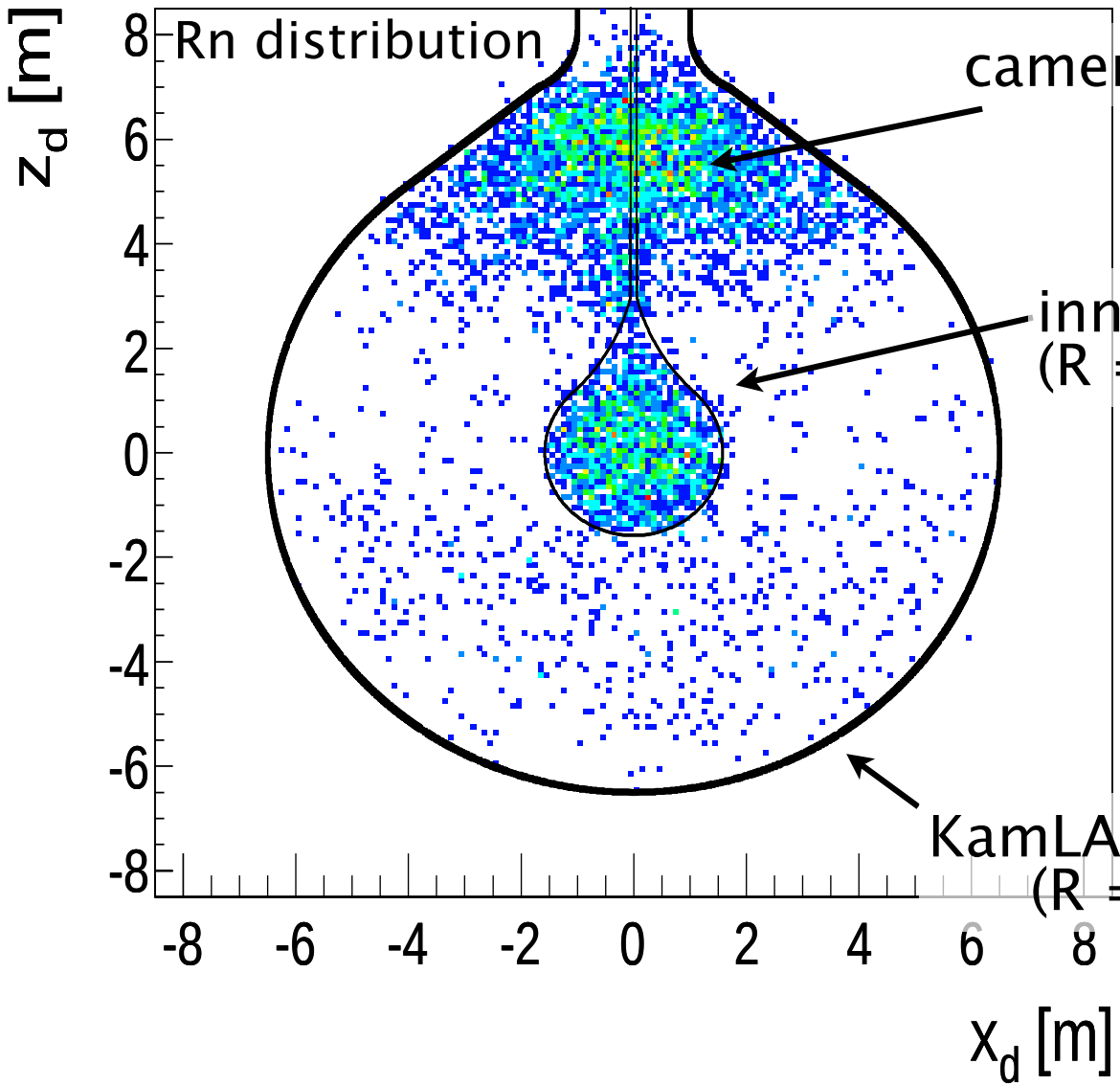


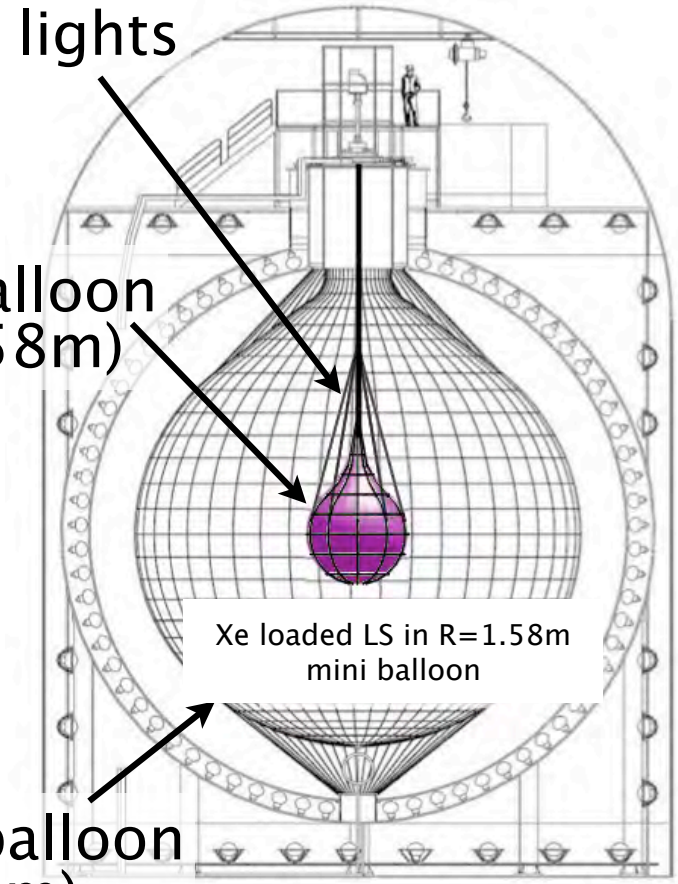
- Balloon shape below the black sheet was monitored by two sets of cameras.



dummy LS filling

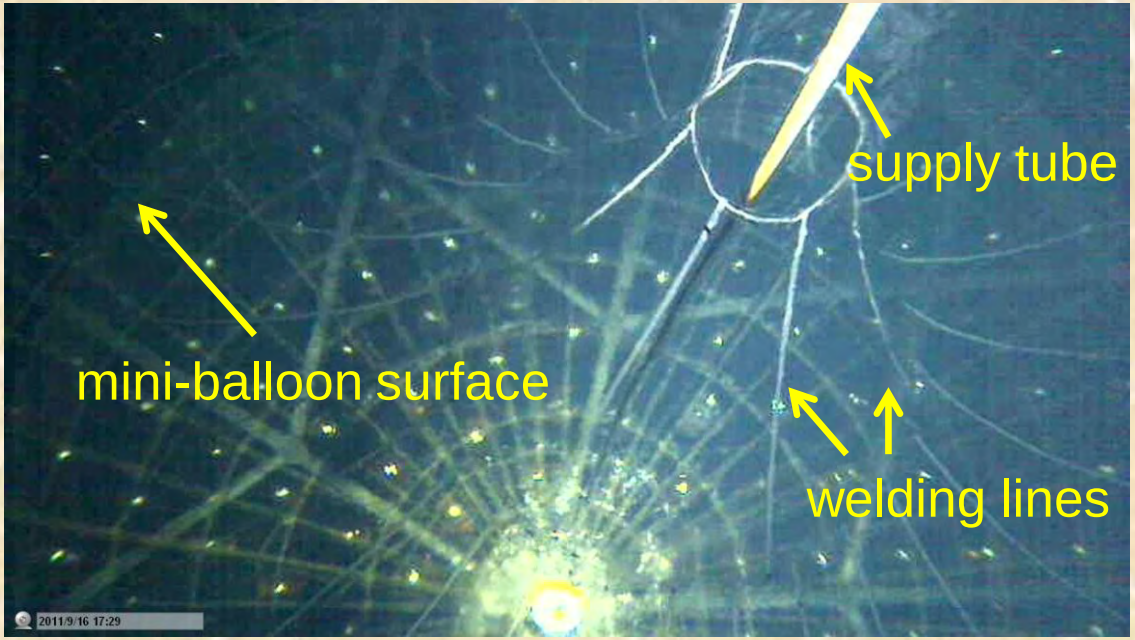
- Filling form top with checking camera, load-cell, amount of liquid measured by Xe system.
- Density difference is +0.05wt% compared to KamLAND LS.
- Check the shape of balloon with Rn events. Well finished.



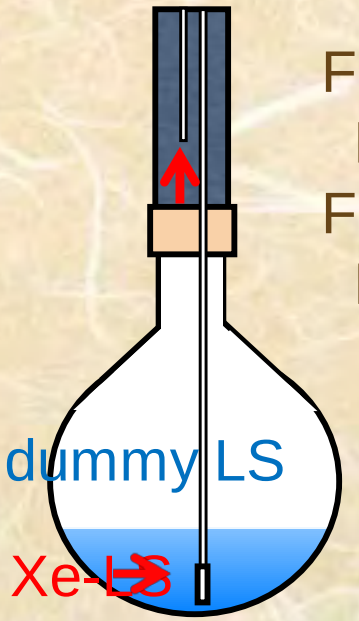


Xe-LS filling

Aug.~Sep., 2011



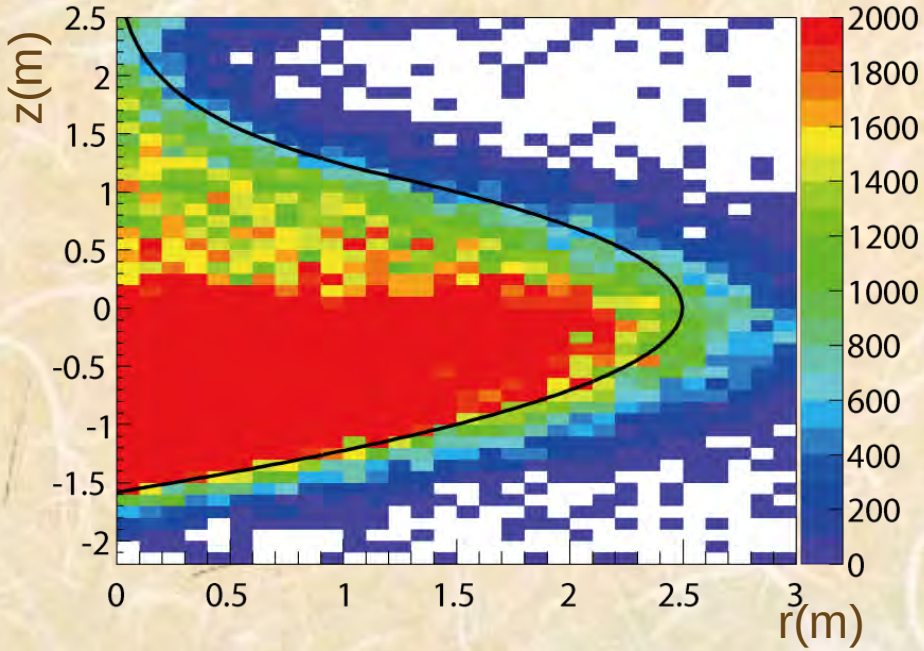
- Dummy-LS was replaced with Xe-loaded LS (0.02% density difference made layer of LS)
- LS replacement was monitored by DAQ using ^{222}Rn events as a tracer



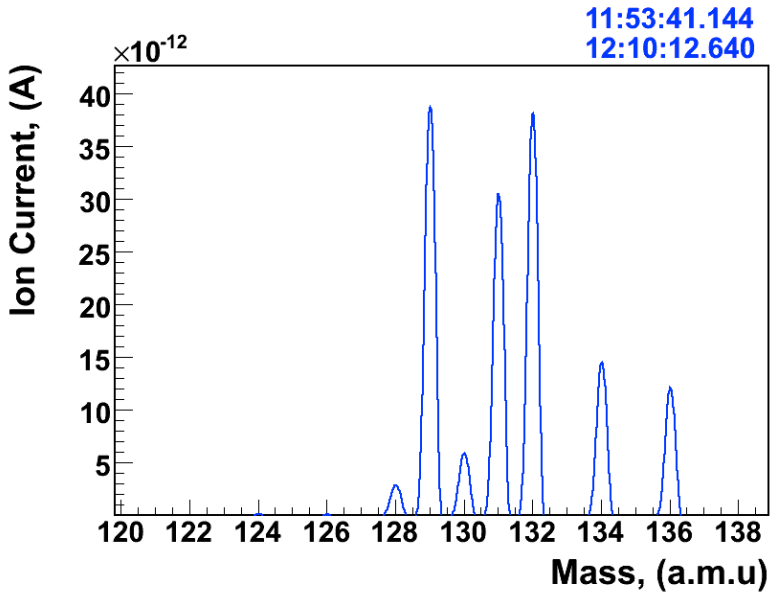
From top :
Draining dummy-LS
From bottom :
Filling Xe-LS

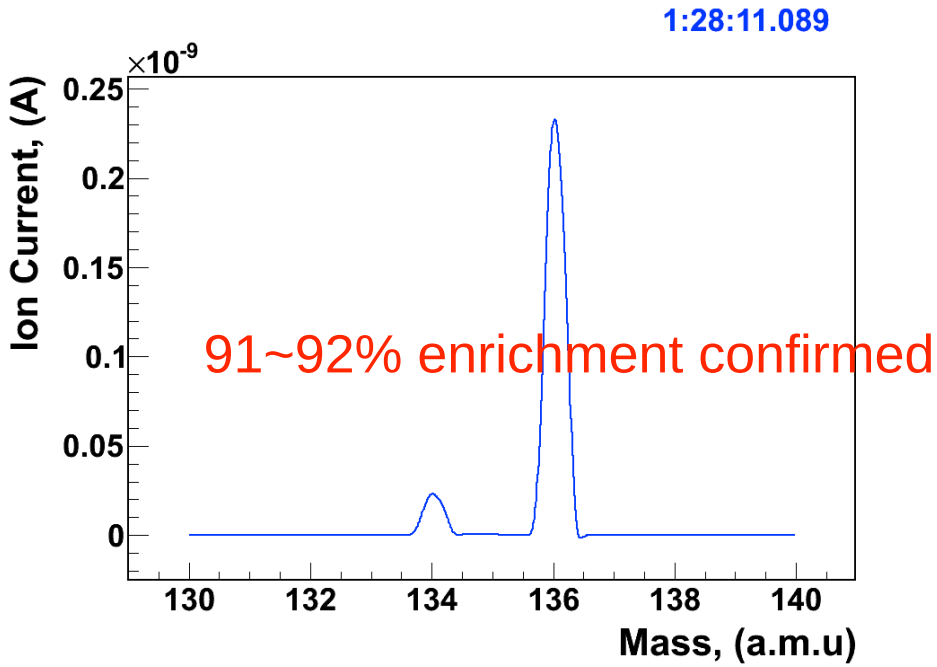
+0.015% density
+0.035% density

Vertex of ^{222}Rn events



enriched Xenon





410 kg in hand

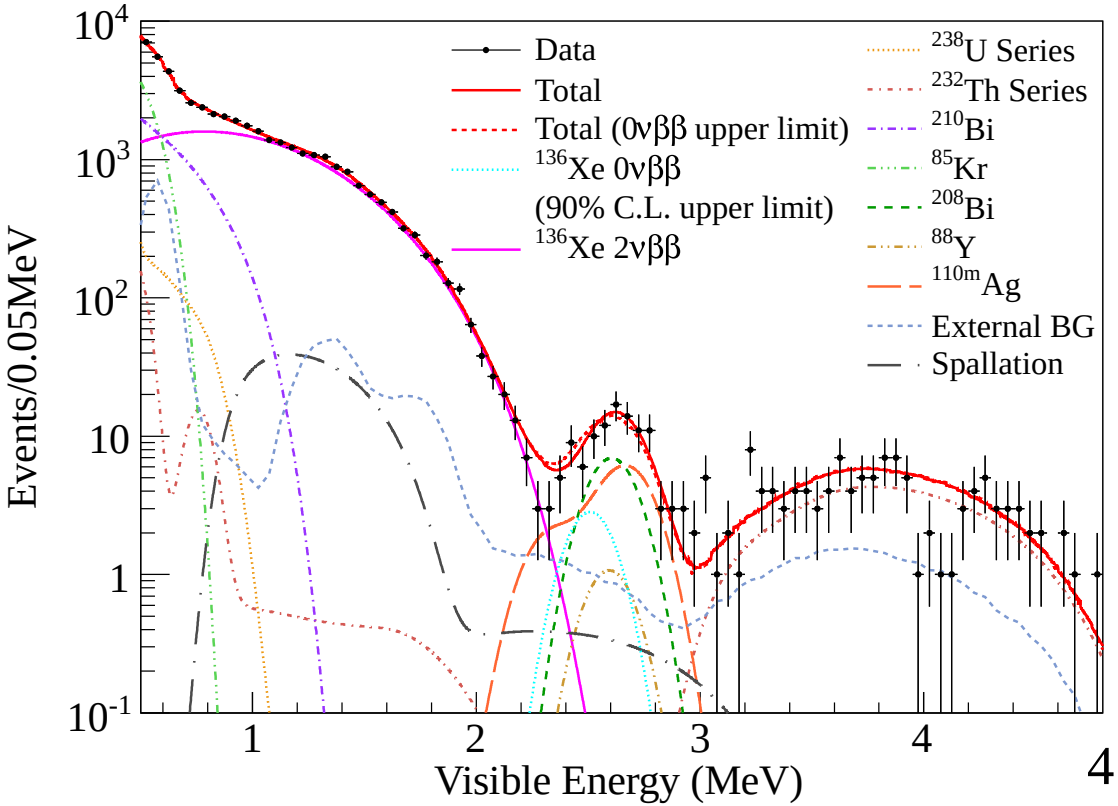
procurement up to 800 kg going on (until 2013)

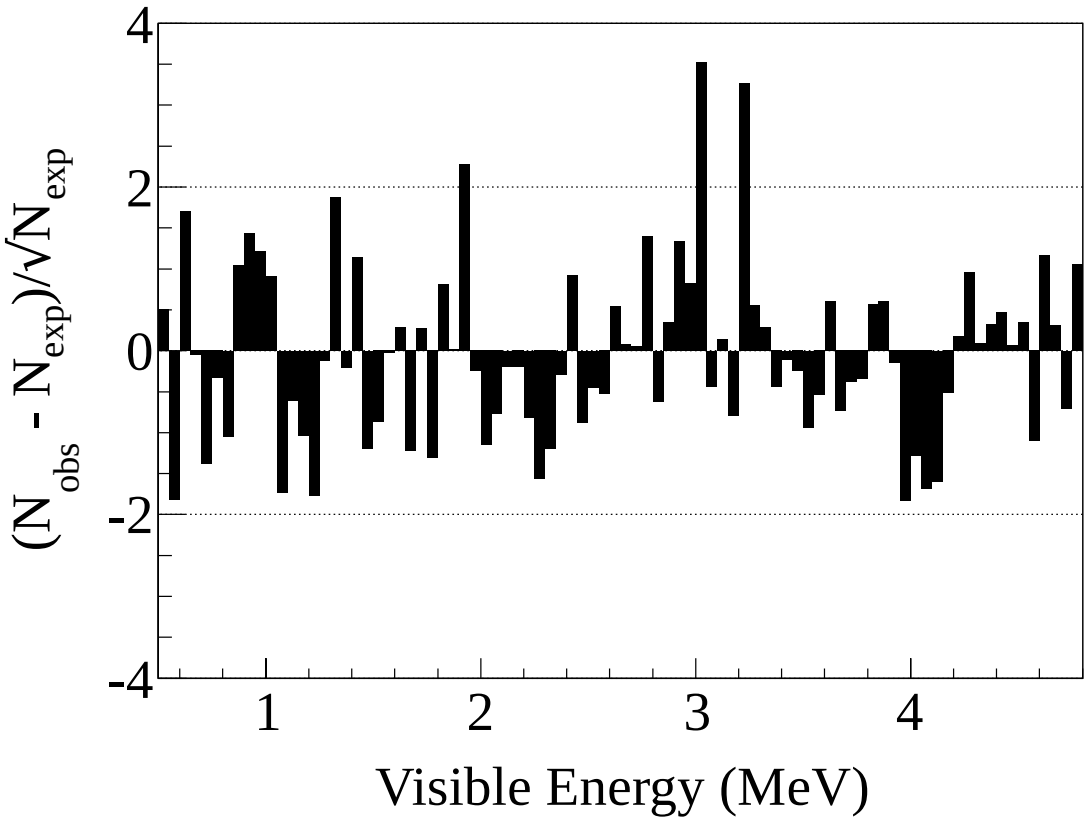
Xenon loaded LS recipe

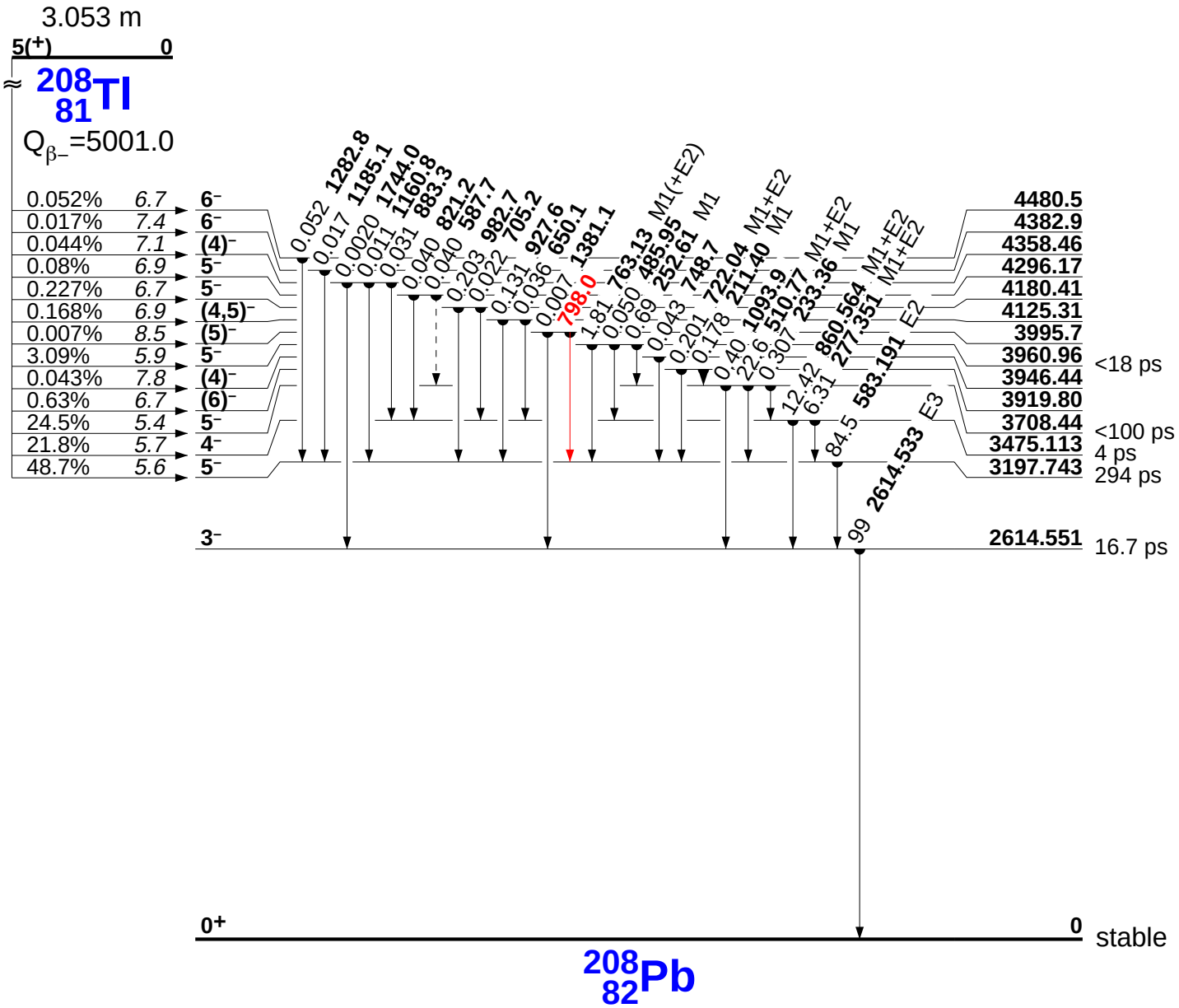
- Xenon loaded LS with the same density, luminosity, transparency

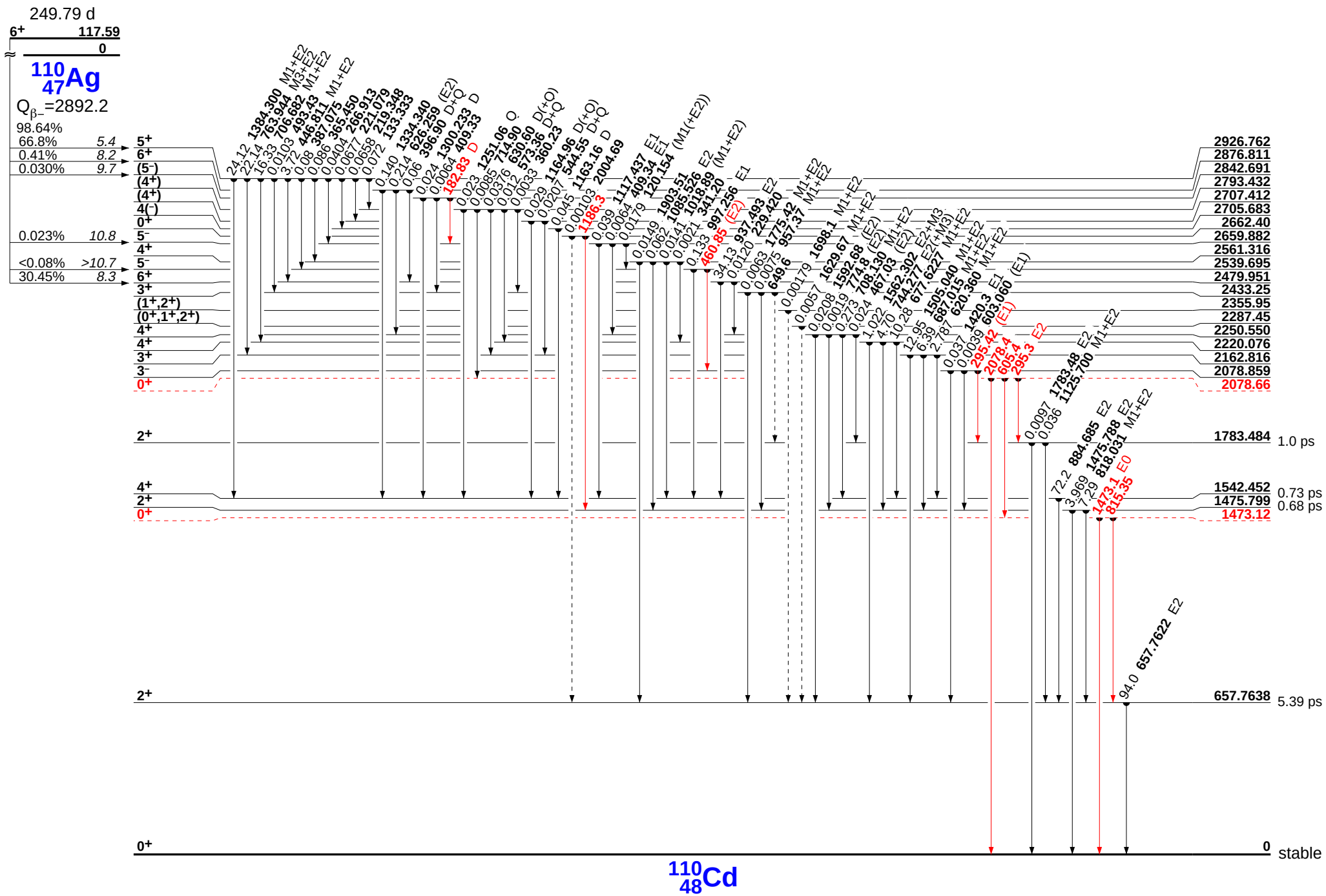
KamLAND LS	
dodecane	80%
pseudo-cumene	20%
PPO	1.36 g/liter

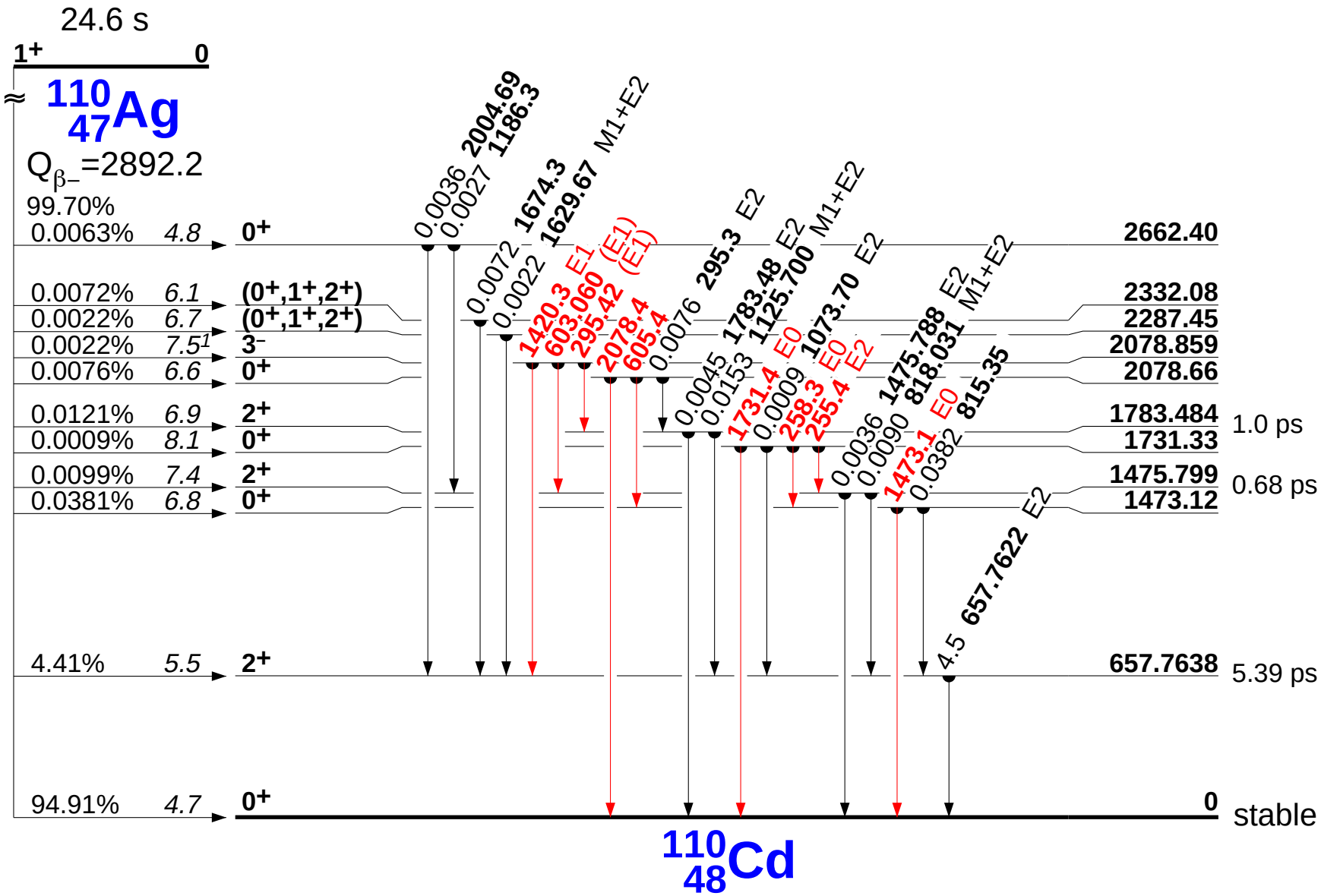
Xenon loaded LS	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
Xenon	2.6 wt% → soluble up to 3.1 wt%


Data
Total
Total (0νββ upper limit)
136Xe 0νββ
(90% C.L. upper limit)
136Xe 2νββ
238U Series
232Th Series
210Bi
85Kr
208Bi
88Y
110mAg
External BG
Spallation
Events/0.05MeV
Visible Energy (MeV)


(N_obs - N_exp)/√N_exp
Visible Energy (MeV)


3.053 m
5(+) 0
208 81 Tl
Qβ−=5001.0
0.052% 6.7 6−
0.017% 7.4 6−
0.044% 7.1 (4)−
0.08% 6.9 5−
0.227% 6.7 5−
0.168% 6.9 (4,5)−
0.007% 8.5 (5)−
3.09% 5.9 5−
0.043% 7.8 (4)−
0.63% 6.7 (6)−
24.5% 5.4 5−
21.8% 5.7 4−
48.7% 5.6 5−
3− 2614.551 16.7 ps
0+ 0 stable
4480.5
4382.9
4358.46
4296.17
4180.41
4125.31
3995.7
3960.96 <18 ps
3946.44
3919.80
3708.44 <100 ps
3475.113 4 ps
3197.743 294 ps
0.052 1282.8
0.017 1185.1
0.0020 1744.0
0.011 1160.8
0.031 883.3
0.040 821.2
0.040 587.7
0.203 982.7
0.022 705.2
0.131 927.6
0.036 650.1
0.007 1381.1
798.0
1.81 763.13 M1(+E2)
0.050 485.95
0.69 252.61 M1
0.043 748.7
0.201 722.04 M1+E2
0.178 211.40 M1
0.40 1093.9
22.6 510.77 M1+E2
0.307 233.36 M1
12.42 860.564 M1+E2
6.31 277.351 M1+E2
84.5 583.191 E2
99 2614.533 E3
208 82 Pb


249.79 d
6+ 117.59
0
110 47 Ag
Qβ−=2892.2
98.64%
66.8% 5.4
0.41% 8.2
0.030% 9.7
0.023% 10.8
<0.08% >10.7
30.45% 8.3
5+
6+
(5−)
(4+)
(4+)
4(−)
0+
5−
4+
5−
6+
3+
(1+,2+)
(0+,1+,2+)
4+
4+
3+
3−
0+
2+
4+
2+
0+
2+
0+
2926.762
2876.811
2842.691
2793.432
2707.412
2705.683
2662.40
2659.882
2561.316
2539.695
2479.951
2433.25
2355.95
2287.45
2250.550
2220.076
2162.816
2078.859
2078.66
1783.484 1.0 ps
1542.452 0.73 ps
1475.799 0.68 ps
1473.12
657.7638 5.39 ps
0 stable
110 48 Cd


24.6 s
1+
0
110 47 Ag
Qβ−=2892.2
99.70%
0.0063% 4.8 0+
0.0072% 6.1 (0+,1+,2+)
0.0022% 6.7 (0+,1+,2+)
0.0022% 7.51 3−
0.0076% 6.6 0+
0.0121% 6.9 2+
0.0009% 8.1 0+
0.0099% 7.4 2+
0.0381% 6.8 0+
4.41% 5.5 2+
94.91% 4.7 0+
0.0036 2004.69
0.0027 1186.3
1674.3
1629.67 M1+E2
0.0072
0.0022
1420.3 E1
603.060 (E1)
295.42 (E1)
2078.4
605.4
0.0076 295.3 E2
1783.48 E2
1125.700 M1+E2
1073.70 E2
0.0045
0.0153
1731.4 E0
0.0009
258.3 E0
255.4 E2
1475.788 E2
818.031 M1+E2
815.35
0.0036
0.0090
1473.1 E0
0.0382 E2
4.5 657.7622
2662.40
2332.08
2287.45
2078.859
2078.66
1783.484
1731.33
1475.799
1473.12
657.7638
0
1.0 ps
0.68 ps
5.39 ps
stable
110 48 Cd