Moriond 2015 EW session
Mar. 15, 2015

Recent results from KamLAND-Zen

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KamLAND-Zen Collaboration

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KamLAND-Zen experiment (1)

- KamLAND-Zen searches for zero neutrino double beta decay.

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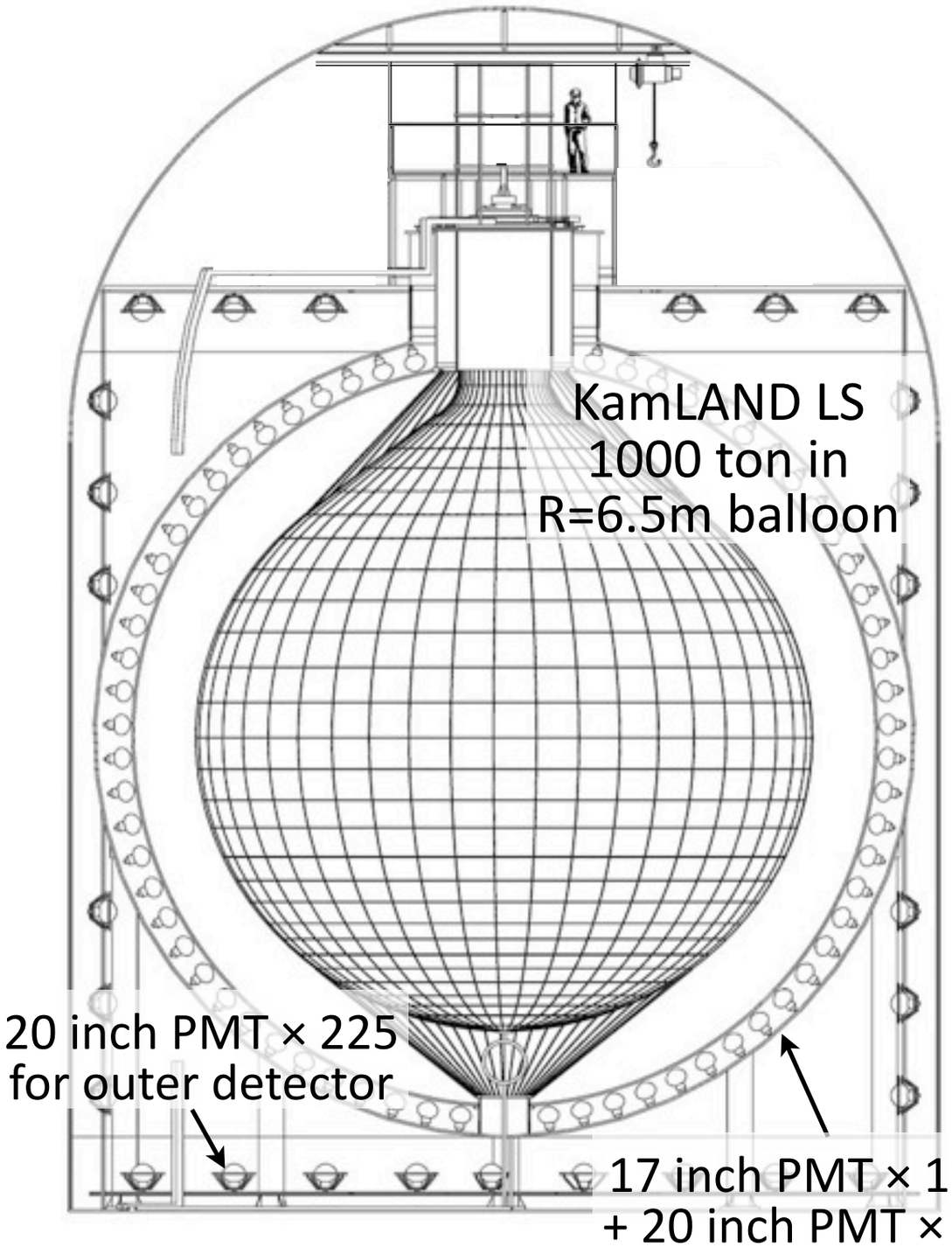
BIG & low BG

Modification of KamLAND (ν detector).



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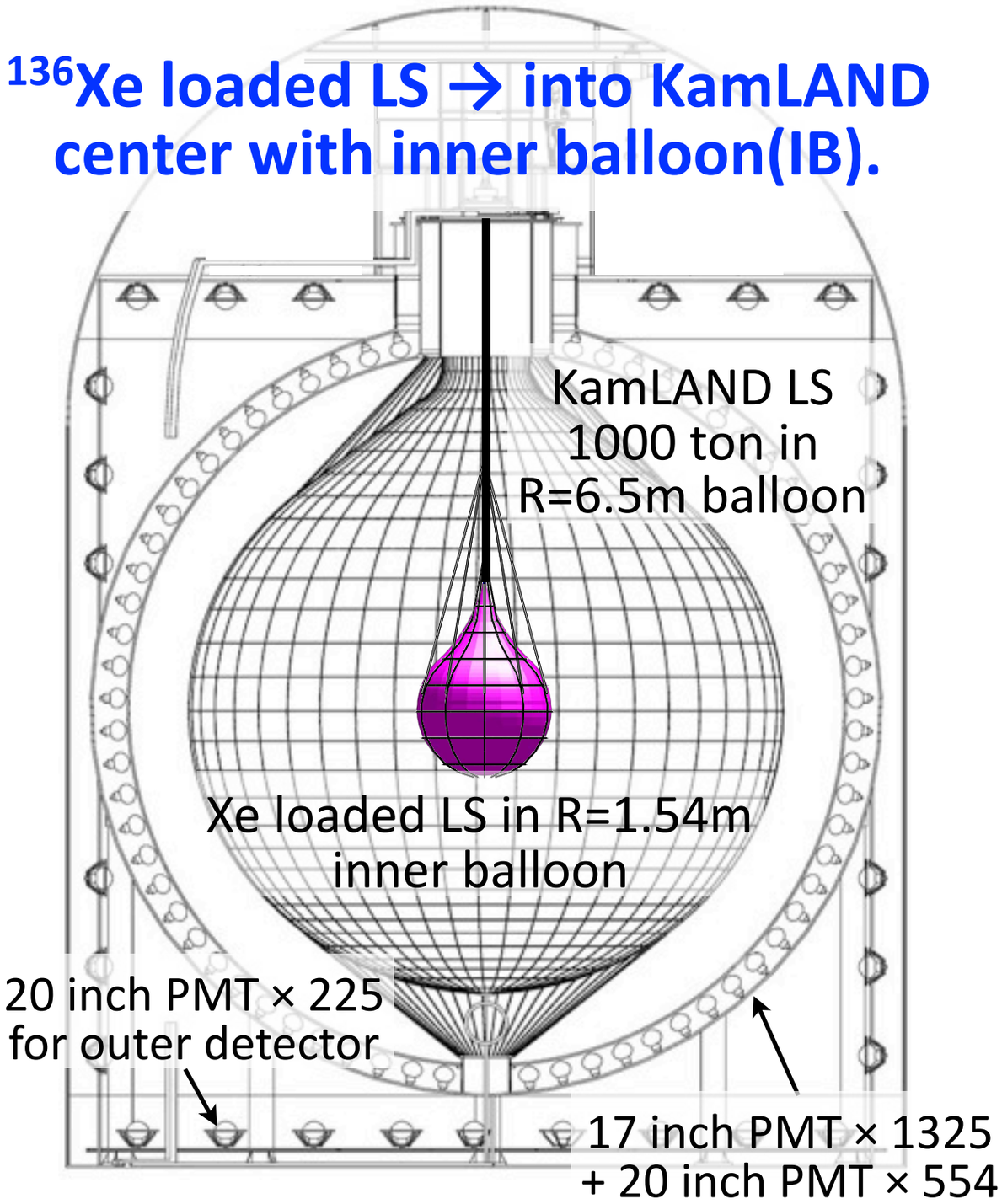
^{136}Xe loaded LS → into KamLAND center with inner balloon(IB).



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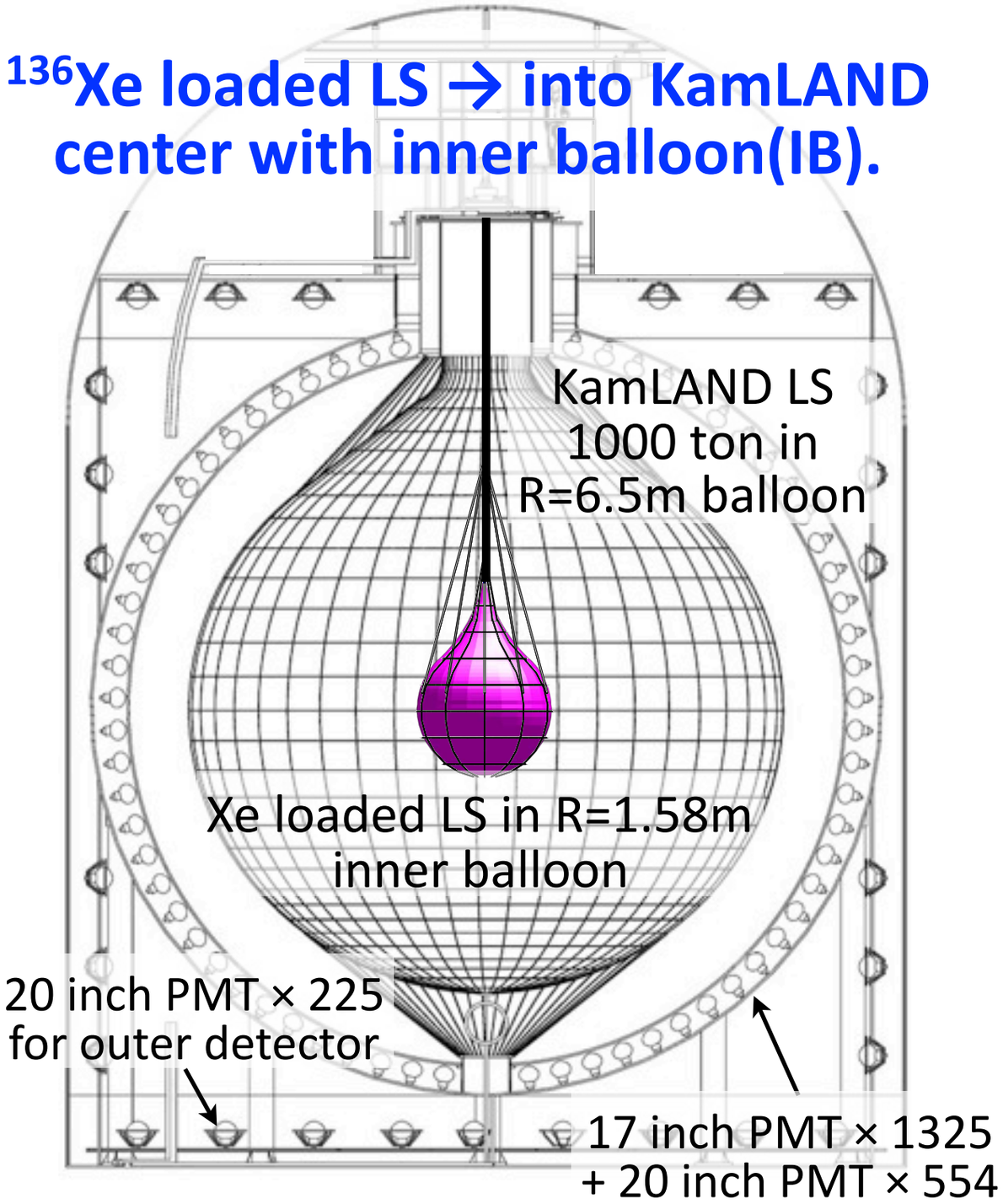
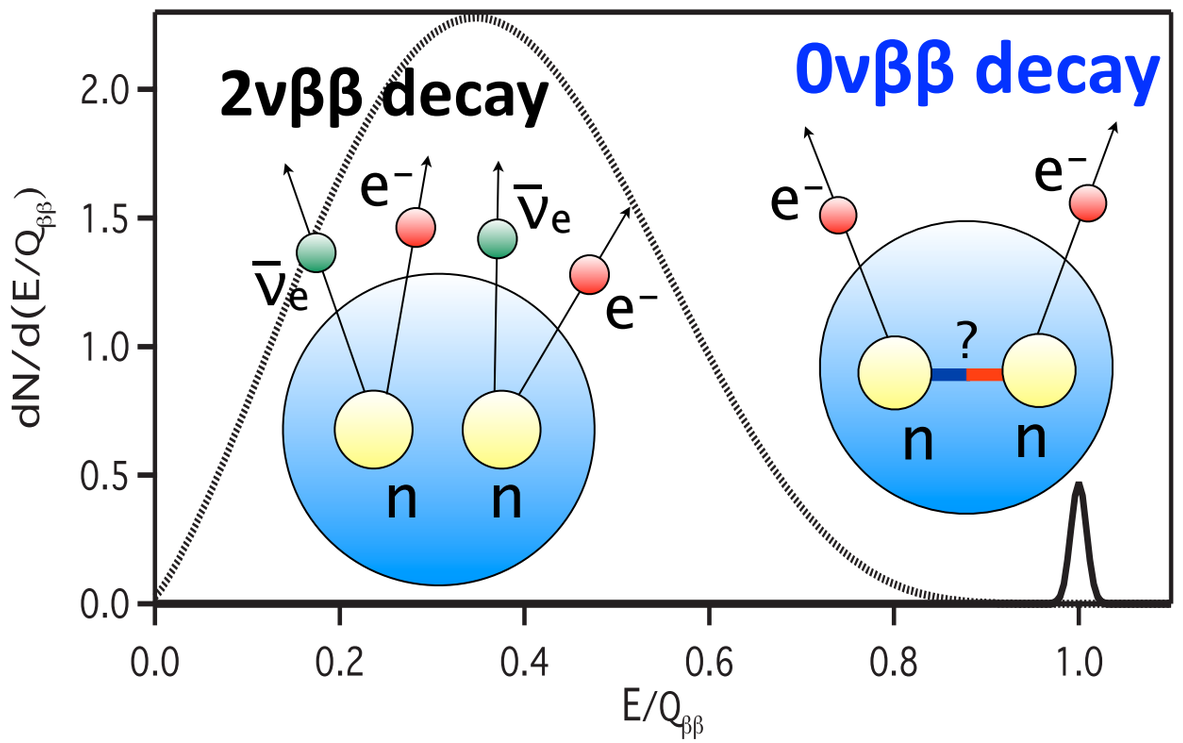




Observation of 0νββ decay:

- lepton number violation
- massive Majorana neutrinos
- hint for neutrino absolute mass

effective neutrino mass from decay rate

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

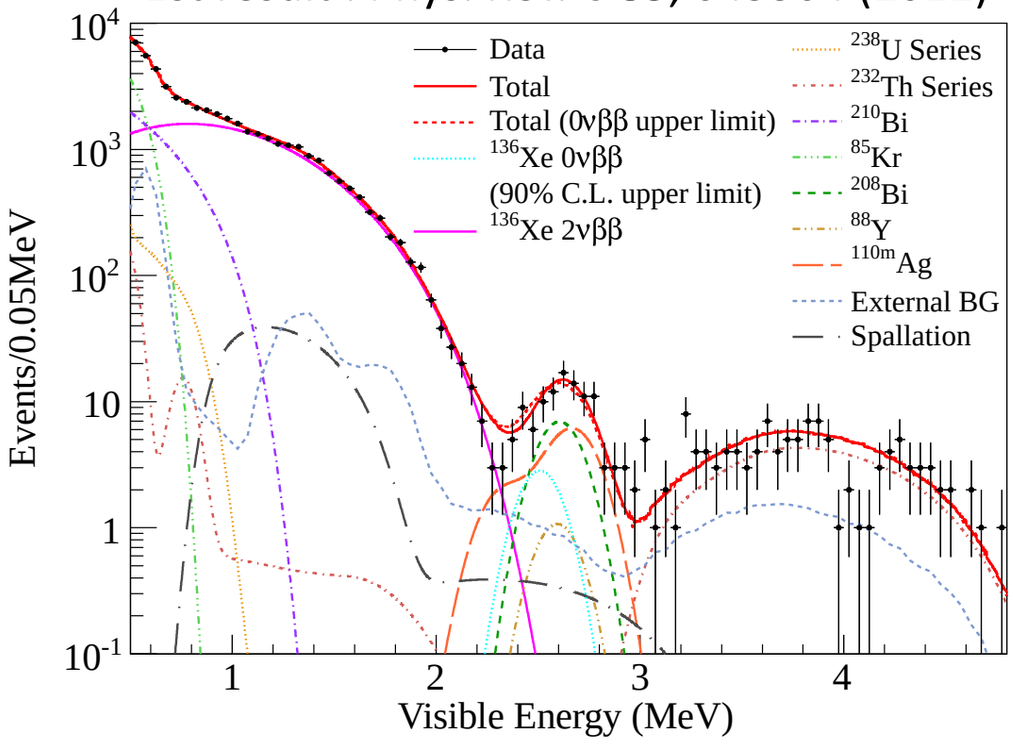
$$\langle m_\nu\rangle \equiv \left||U_{e1}^L|^2 m_1 + |U_{e2}^L|^2 m_2 e^{i\phi_2} + |U_{e3}^L|^2 m_3 e^{i\phi_3}\right|$$

$G^{0\nu}$: phase space factor

$M^{0\nu}$: nuclear matrix element

KamLAND-Zen experiment (2)

1st result : Phys. Rev. C **85**, 045504 (2012)



Backgrounds in 0νββ region:

(1) Unexpected peak around 2.6MeV

→ All nuclei are checked.

4 possible isotopes (lifetime longer than 30 days)

^{110m}Ag (250d), ^{208}Bi (3.7×10^5y), ^{60}Co (5.27y), ^{88}Y (107d)

↖ detected in Fukushima fallout

(2) ^{214}Bi from inner balloon

(3) Spallation product ^{10}C

(4) ^{136}Xe 2νββ decay

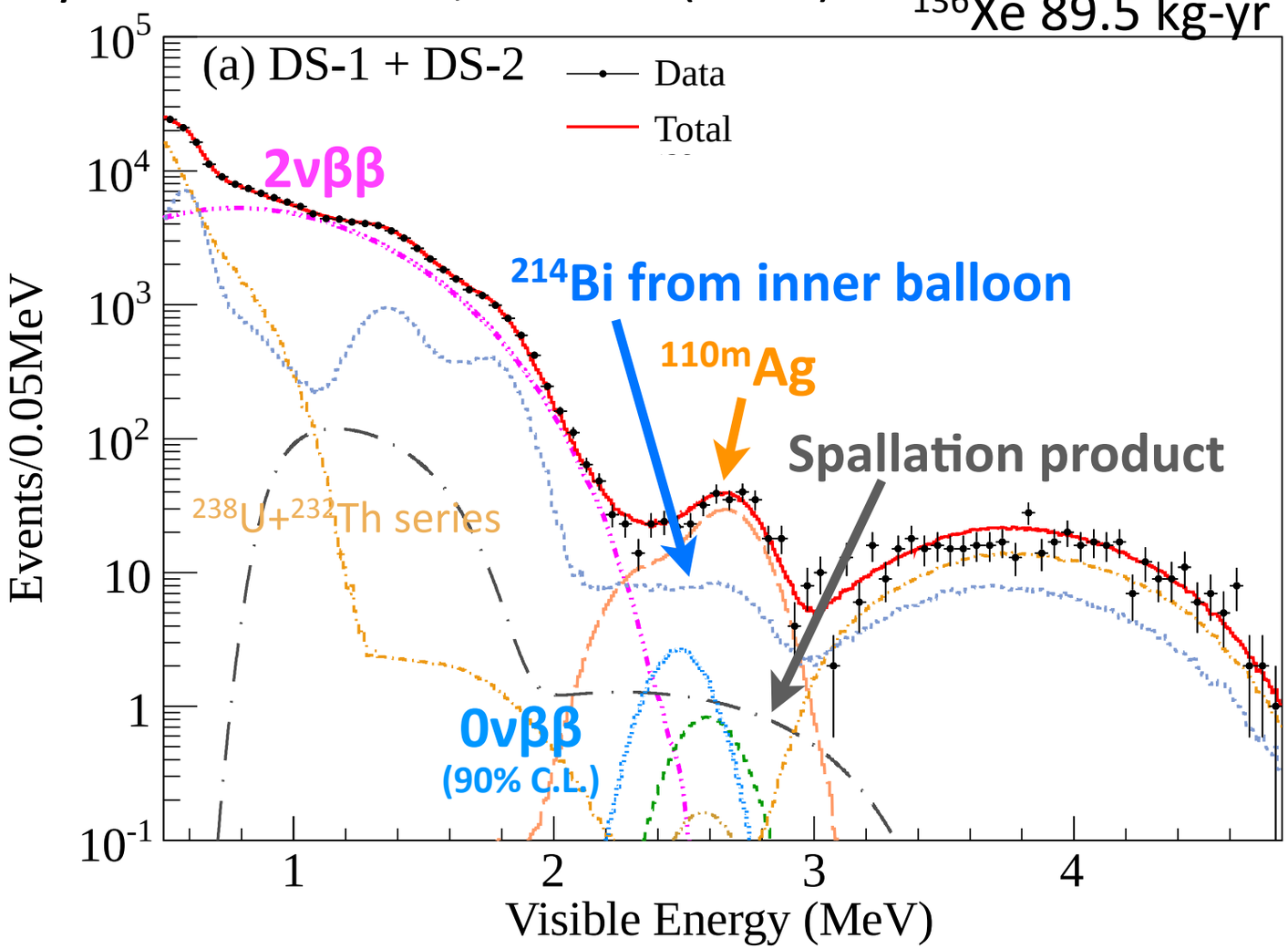
Large amount

Small amount

Result of Phase 1 (2011-2012)

Phys. Rev. Lett. 110, 062502 (2013)

^{136}Xe 89.5 kg-yr



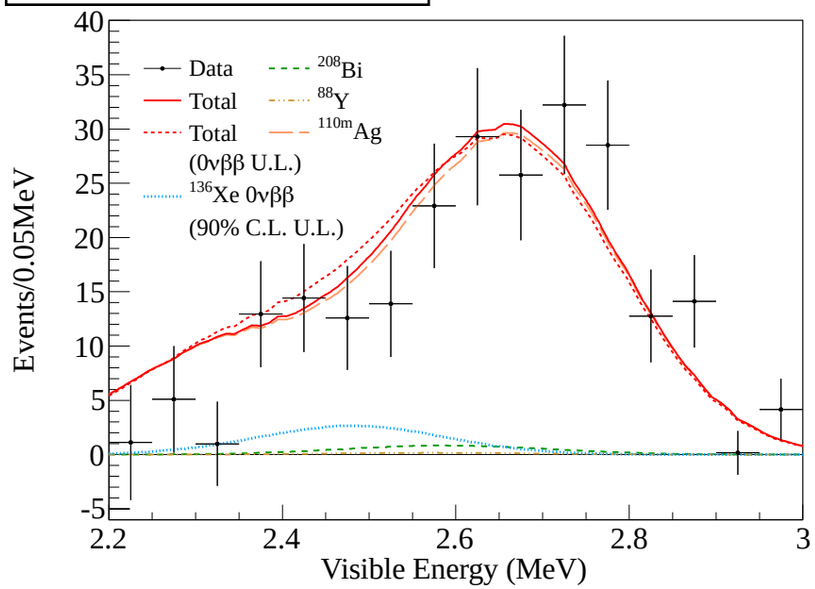
Lower limit of 0νββ decay half-life

$T^{1/2} > 1.9\times10^{25}$ yr (90% C.L.)

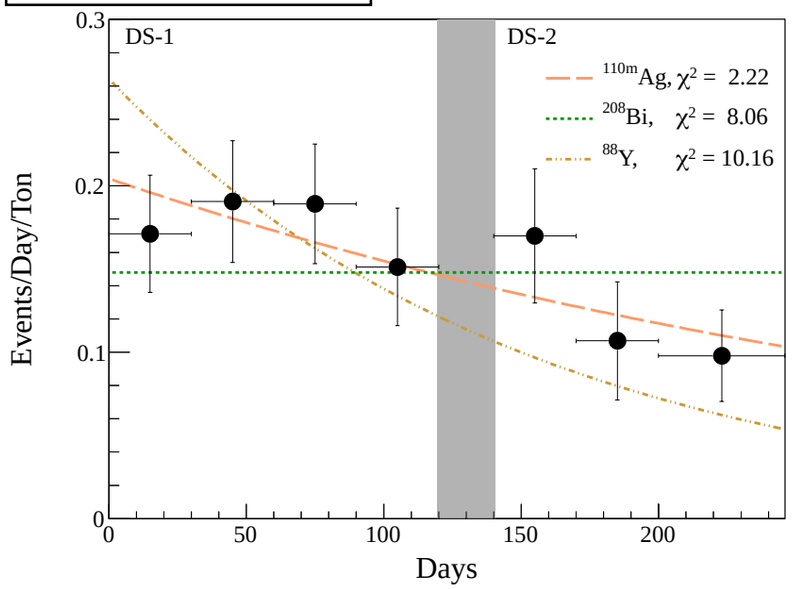
- Most stringent limit at that time.
- But many background at ROI. It is ^{110m}Ag.
  (Q value of ^{136}Xe : 2.458 MeV)

Event in 2.2<E<3.0 MeV

Energy spectrum (linear, known BG subtracted)



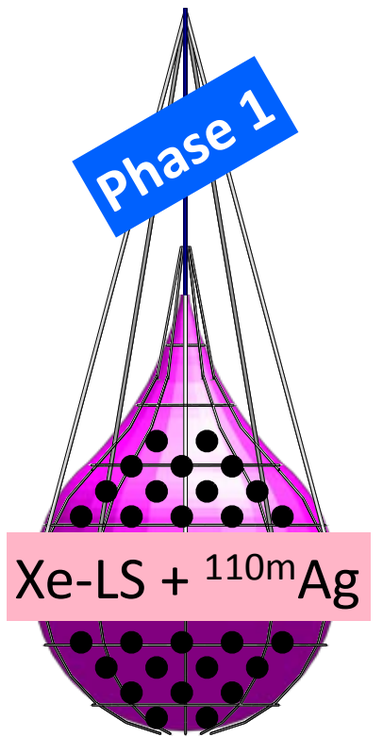
Time variation



Unexpected peak → ^{110m}Ag

→ We need improvements for phase 2.

Phase1 → Phase 2 : Purification of LS and Xe



Xe concentration
(2.44 ± 0.01)%
by weight

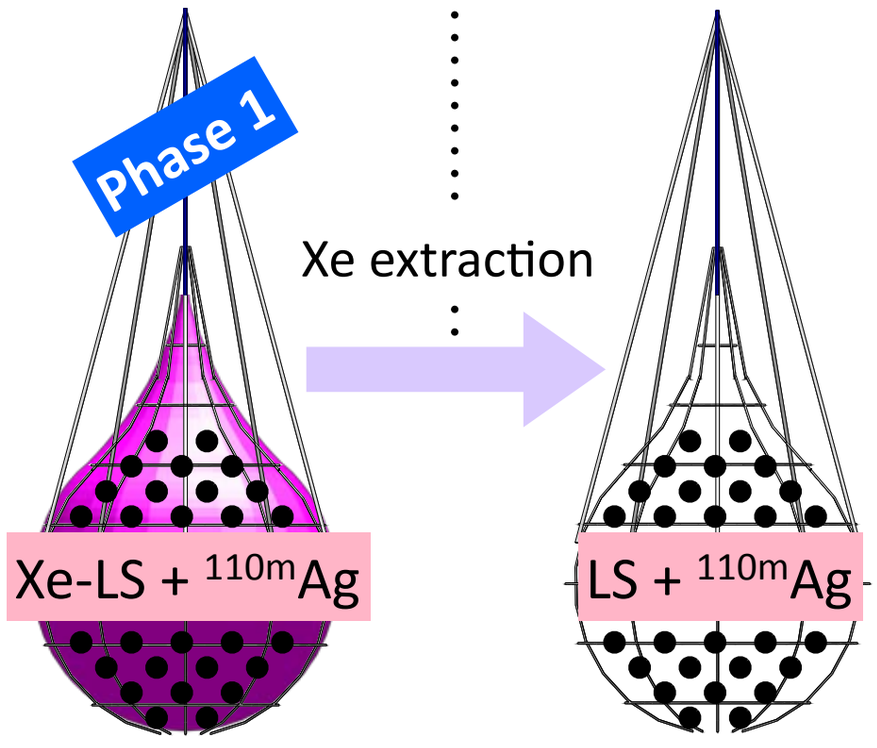
Phase1 → Phase 2 : Purification of LS and Xe

Xe collection

Phase 1

Xe extraction

:



Xe concentration
(2.44 ± 0.01)%
by weight

Confirm ^{110m}Ag
remains in LS.

Phase1 → Phase 2 : Purification of LS and Xe

Xe collection

Phase 1

Xe-LS + ^{110m}Ag

Xe concentration
(2.44 ± 0.01)%
by weight

Xe extraction

LS + ^{110m}Ag

Confirm ^{110m}Ag remains in LS.

Replace with new purified LS
Water extraction &distillation

new LS

Replace with new purified LS again

new LS

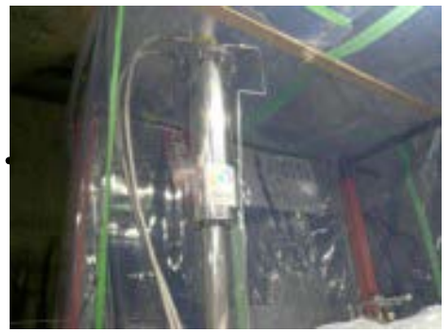
3 times purification and circulation

distillation system

Phase1 → Phase 2 : Purification of LS and Xe

Xe collection

Xe purification



(distillation & getter)

Phase 1

Xe extraction

Xe-LS + ^{110m}Ag

Xe concentration
(2.44 ± 0.01)%
by weight

LS + ^{110m}Ag

Confirm ^{110m}Ag remains in LS.

Replace with new purified LS
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3 times purification and circulation

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Phase1 → Phase 2 : Purification of LS and Xe

Xe collection

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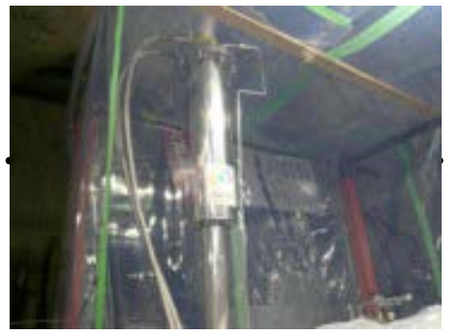


(distillation & getter)

Dissolving Xe into LS

Phase 1

Xe extraction

Xe-LS + ^{110m}Ag

Xe concentration
(2.44 ± 0.01)%
by weight

LS + ^{110m}Ag

Confirm ^{110m}Ag remains in LS.

Replace with new purified LS

Water extraction &distillation

new LS

Replace with new purified LS again

new LS

3 times purification and circulation

distillation system

Phase 2

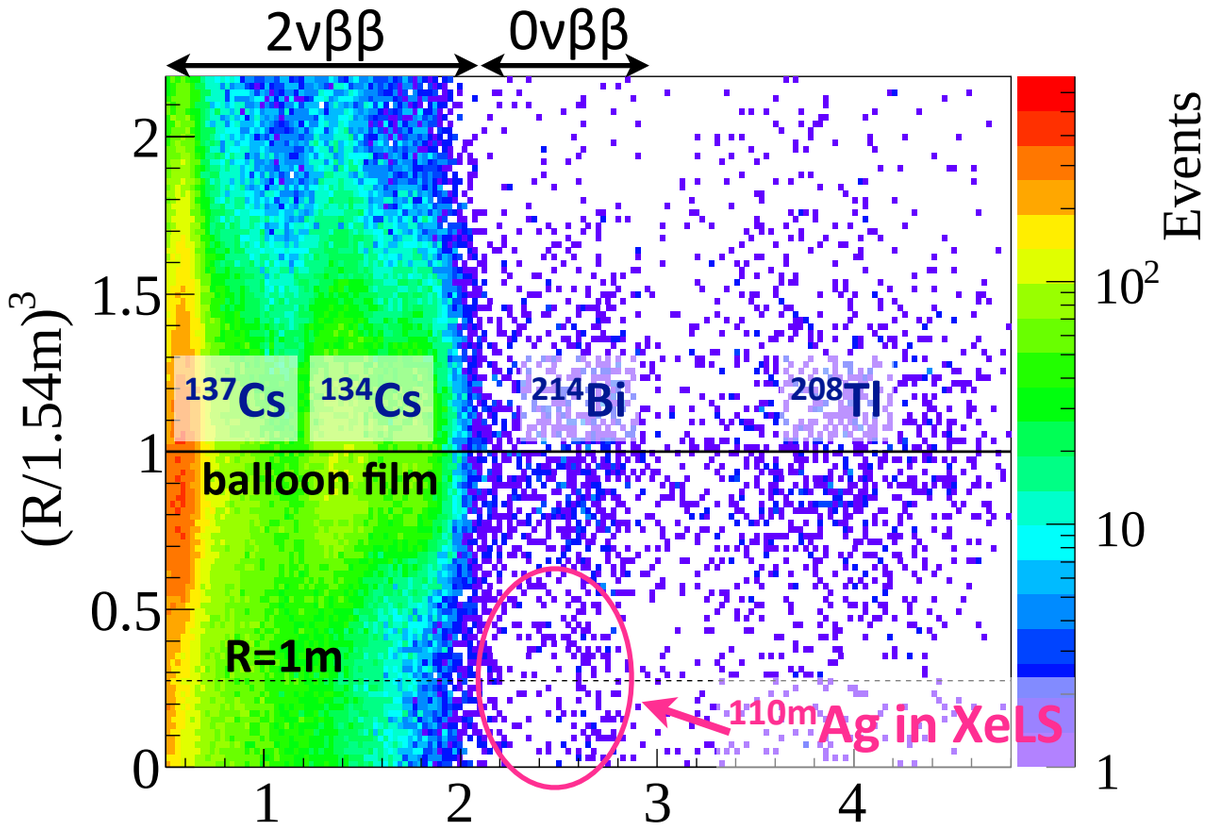
new Xe-LS

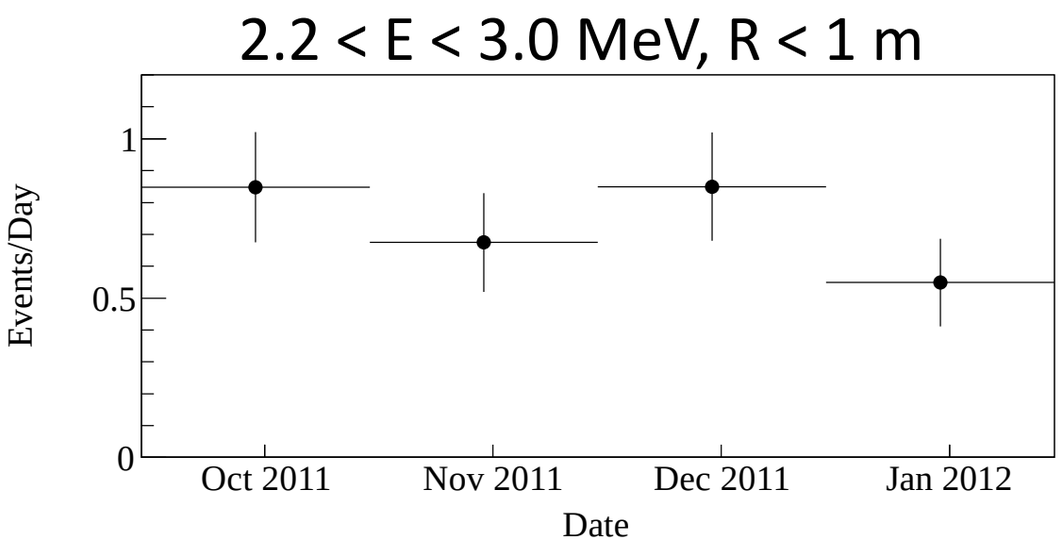
Xe concentration increased to
(2.96 ± 0.01)%
by weight

^{110m}Ag reduction to < 1/10 (next page)

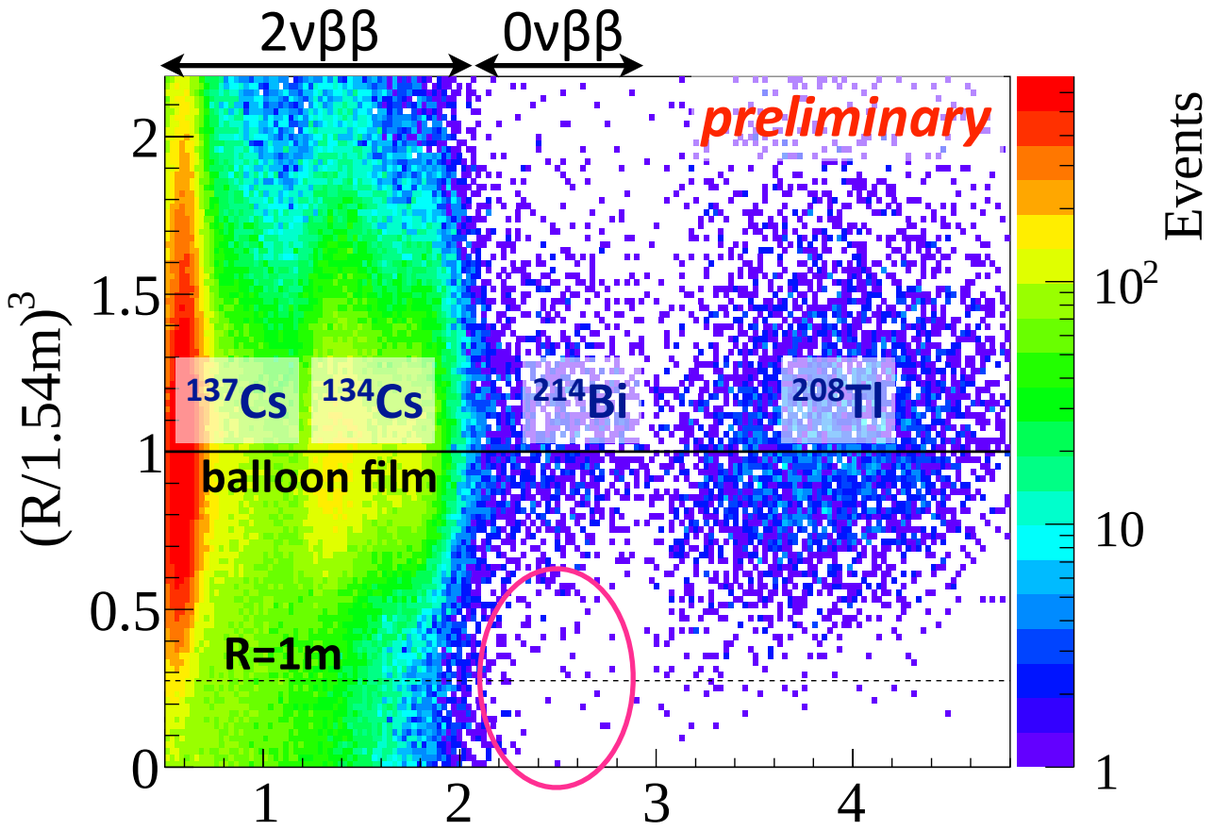
^{110m}Ag background reduction

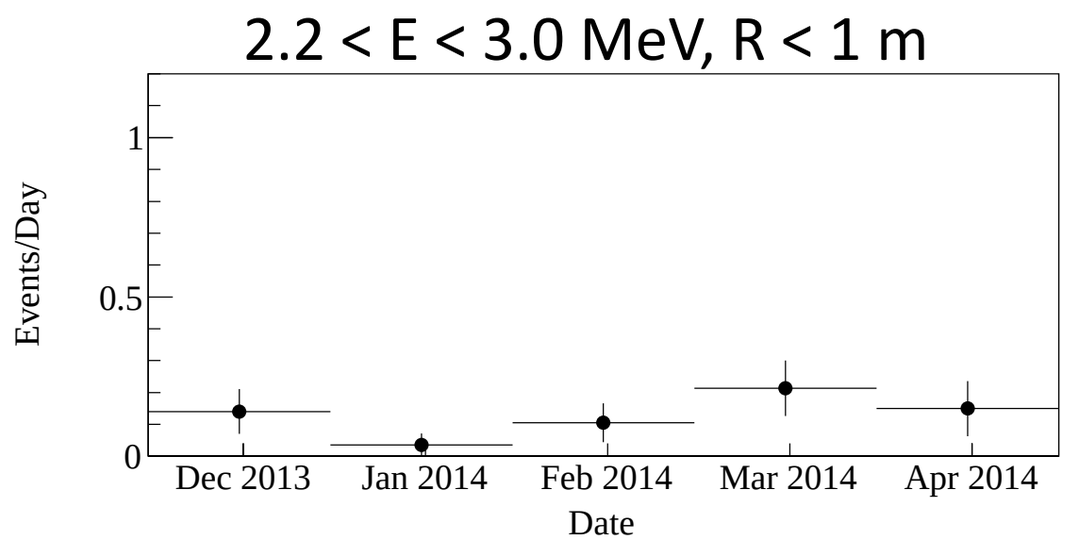
Phase 1 (first 112.3 days)





Phase 2 (first 114.8 days)

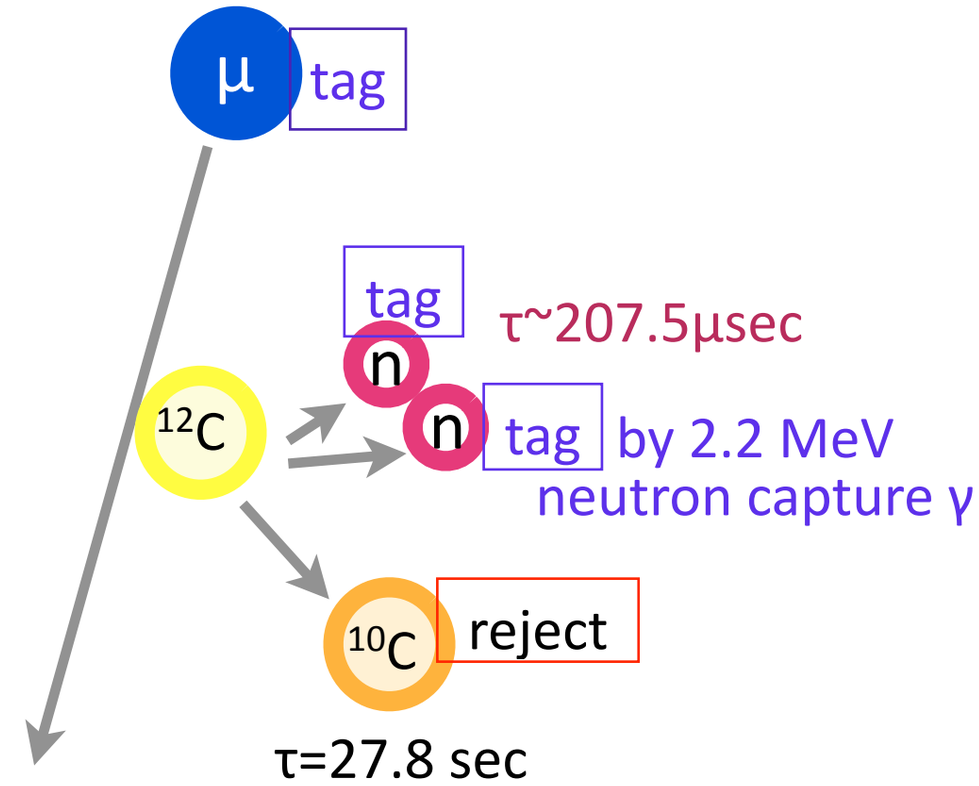




^{110m}Ag BG reduction to < 1/10

Other improvement 1 : Spallation cut

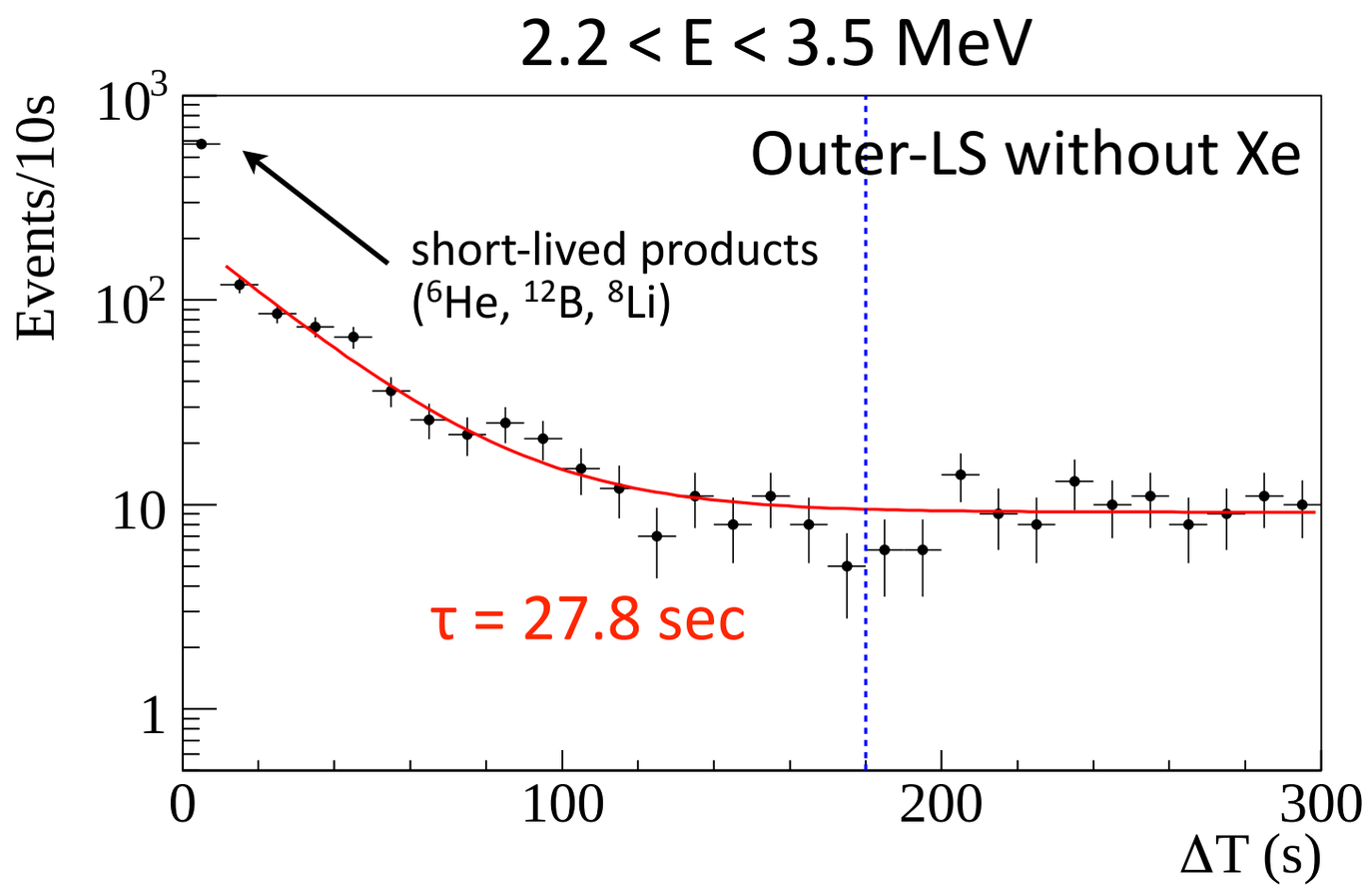
- Main target is ^{10}C
- Triple coincidence with muon, neutron and ^{10}C

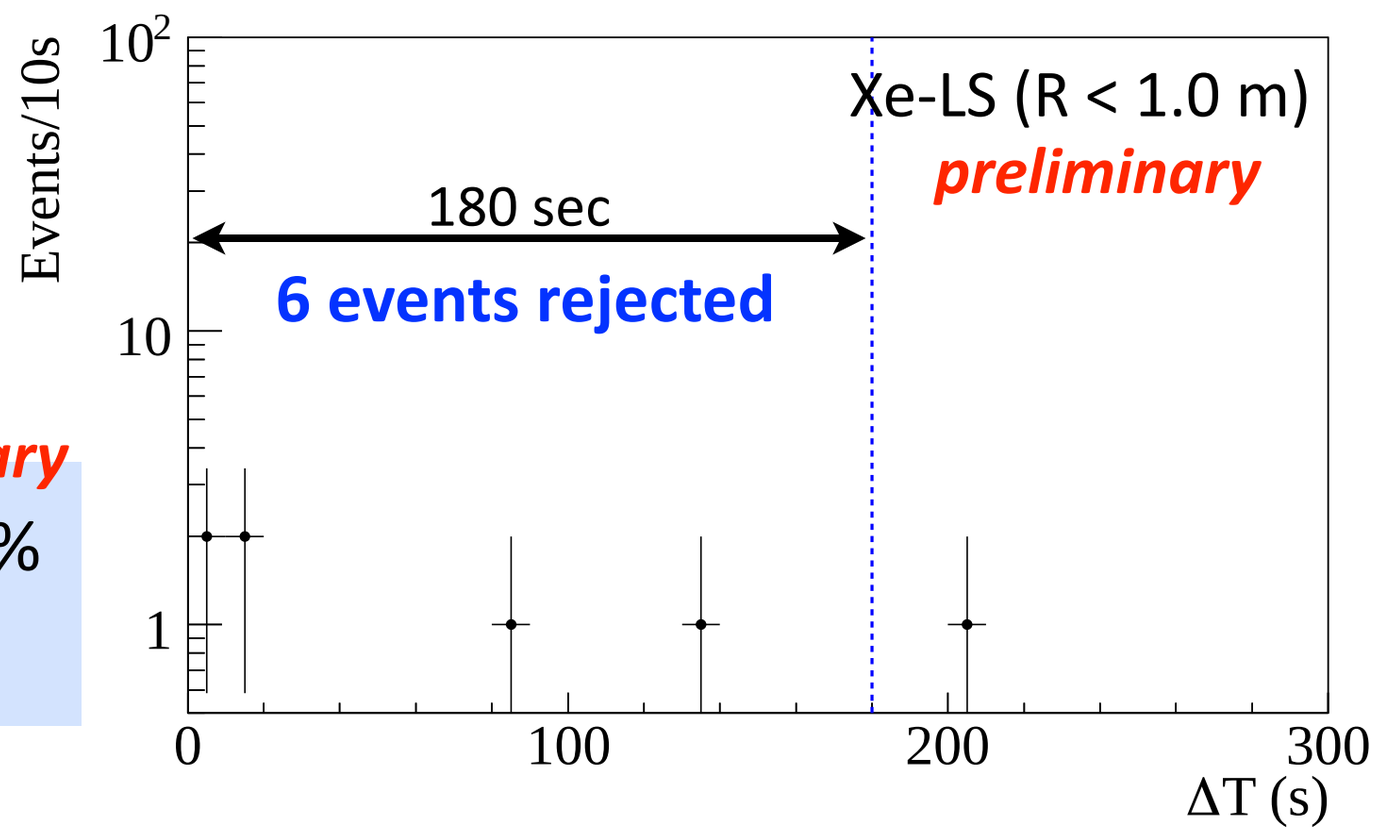


Thanks to dead time free electronics , neutron tagging efficiency is improved.

preliminary

BG rejection efficiency (^{10}C) 72 ± 5%
signal inefficiency 7%

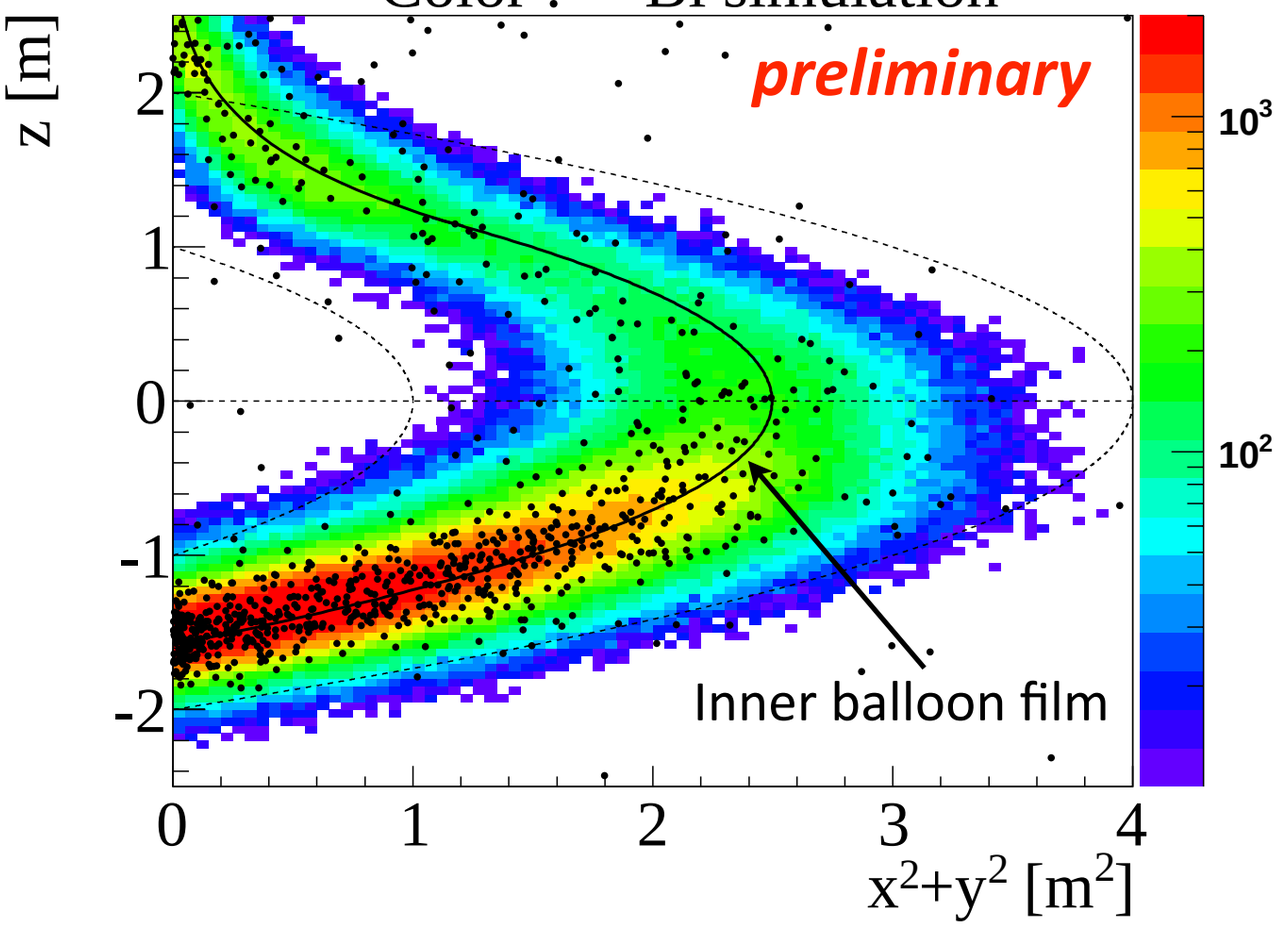




Other improvement 2 : ^{214}Bi distribution

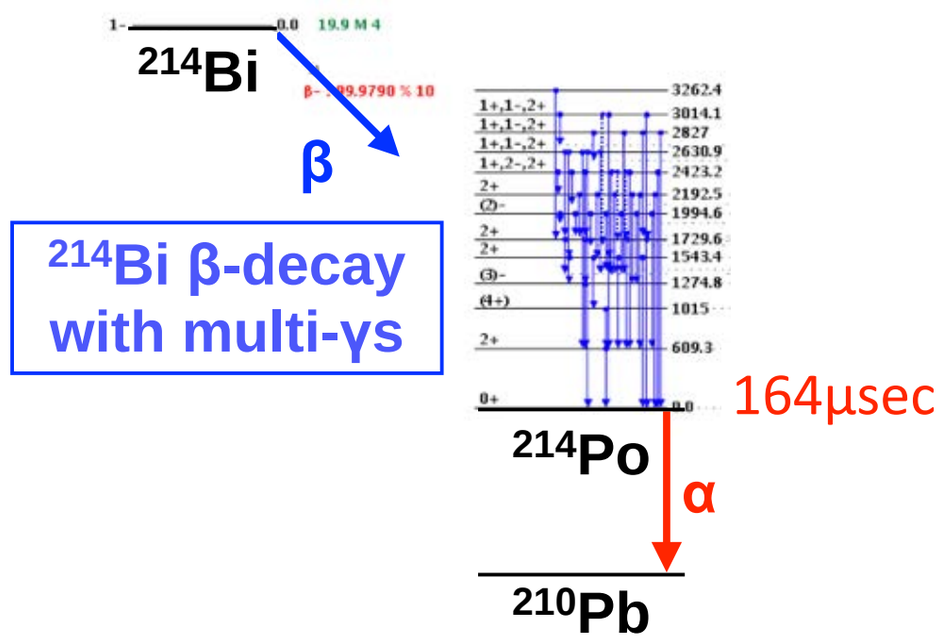
- ^{214}Bi distribution on the IB is not uniform.
  → Effected to fiducial volume selection.

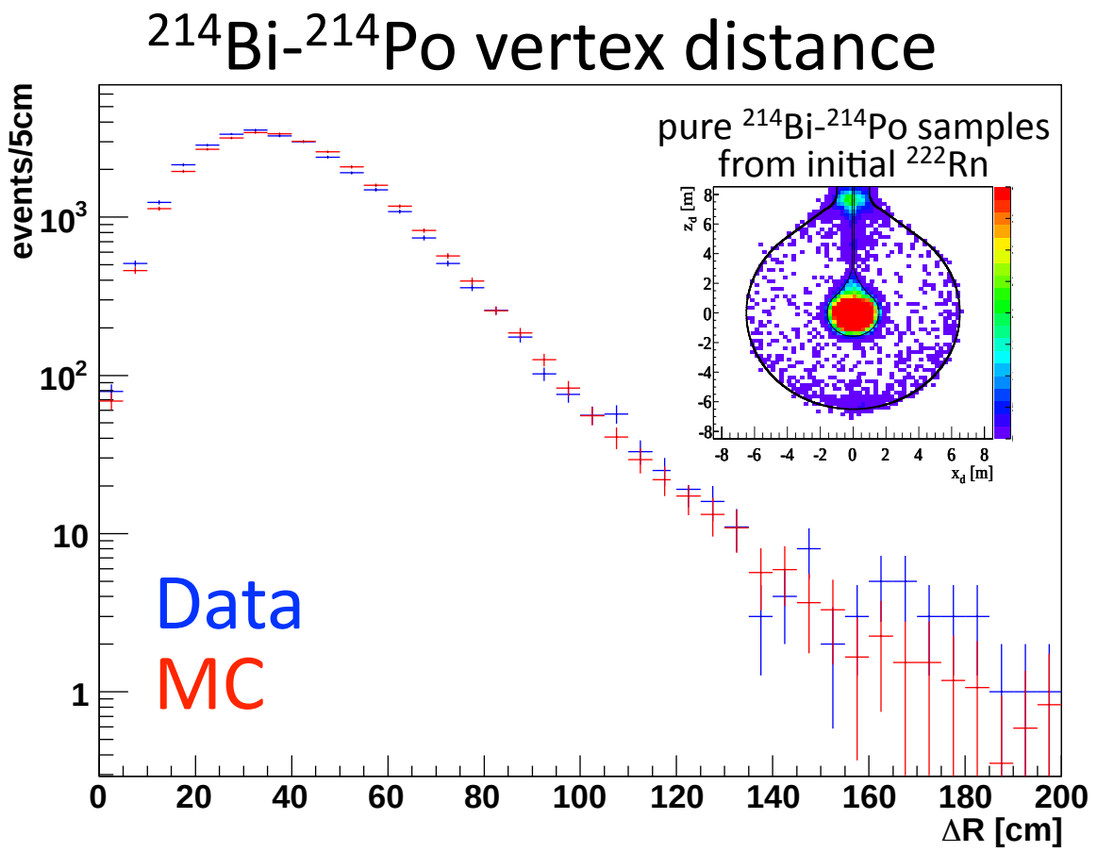
Black dot : Data (2.3-2.7MeV)
Color : ^{214}Bi simulation



Vertex distribution was evaluated by detector full MC simulation

Geant4 detector simulation tuned for KamLAND





Vertex distribution is well reproduced

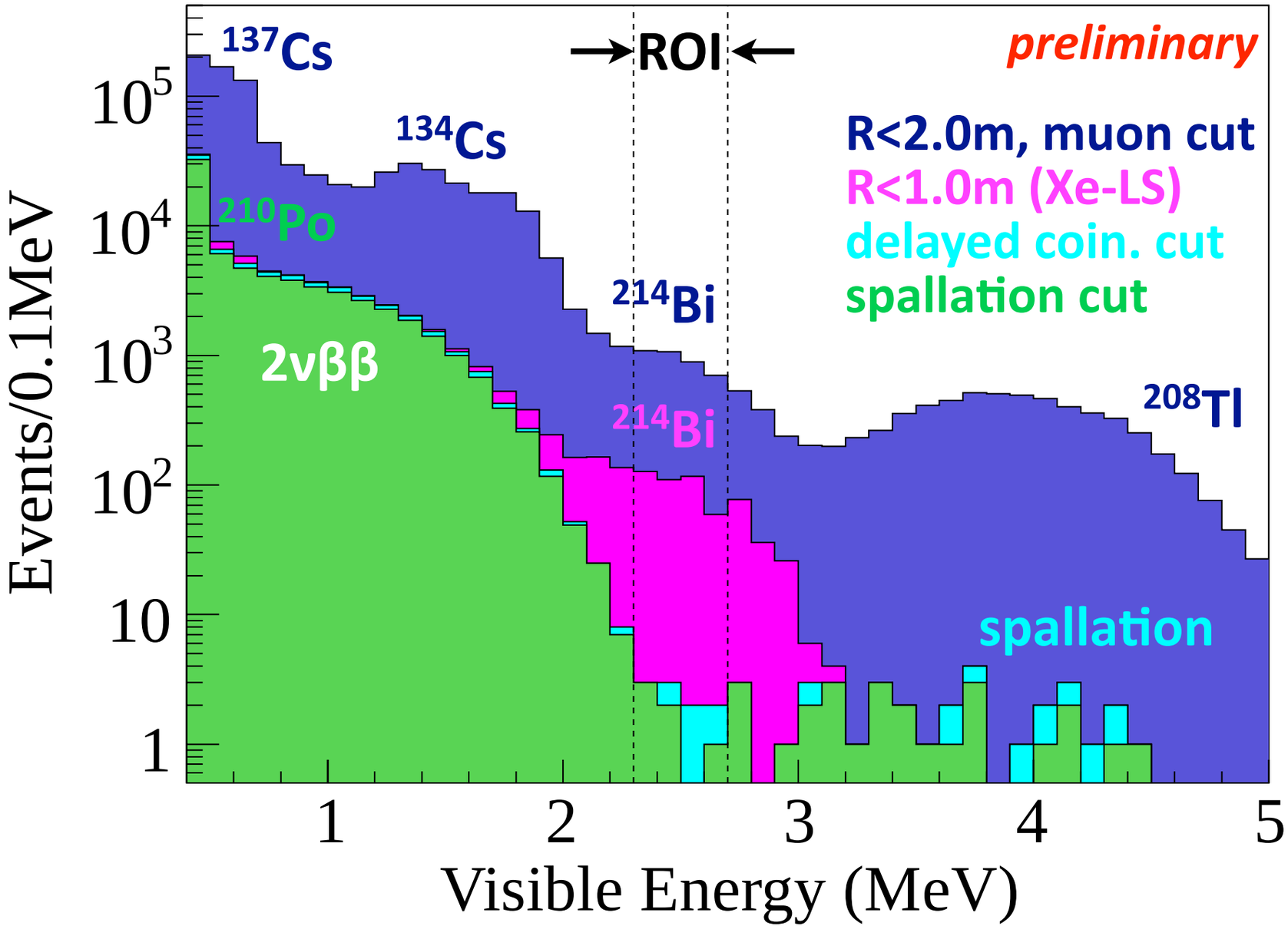
Event reduction

KamLAND-Zen Phase 2

Isotope of double beta decay : ^{136}Xe, Q value = 2.458MeV

90.77 % enriched, 348 kg ^{136}Xe in whole volume

Livetime = 114.8 days (Dec. 11, 2013 - May 1, 2014)



Number of event in ROI (2.3<E<2.7MeV)

R<2.0m
(around inner balloon)
&
muon veto

3756 events

R<1.0m (volume cut)

413 events

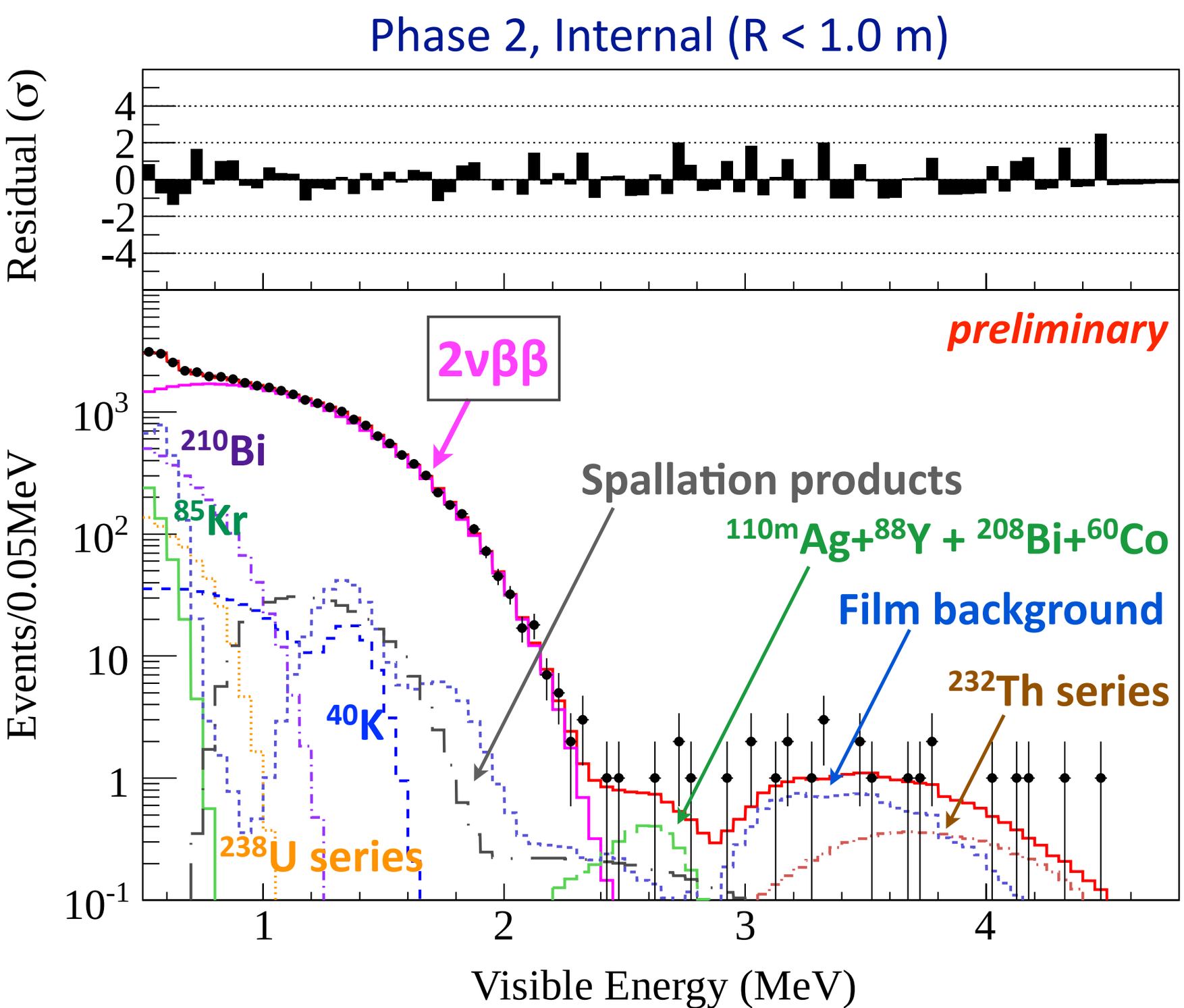
delayed coincidence cut
(^{214}Bi-Po, ^{212}Bi-Po, anti-ν)

10 events

spallation cut

6 events

Result of 2νββ decay



preliminary

$$T^{1/2}(2\nu) = 2.32 \pm 0.05(\text{stat}) \pm 0.08(\text{syst}) \times 10^{21}\ \text{yr}$$

Consistent with previous KamLAND-Zen results and EXO-200 results

Energy spectra of 0νββ decay

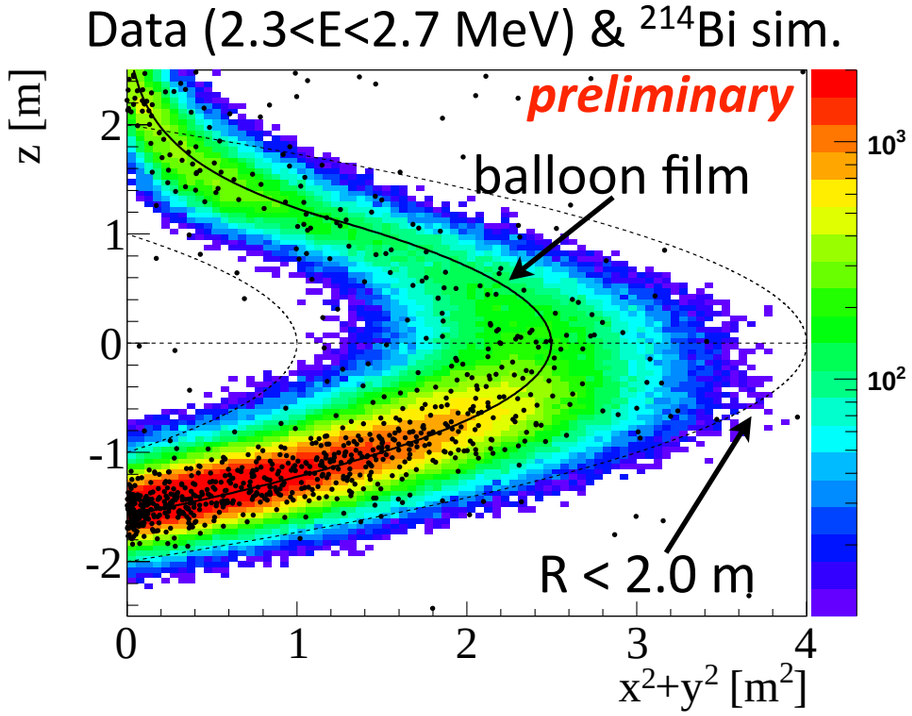
Multi-volume selection for analysis optimization

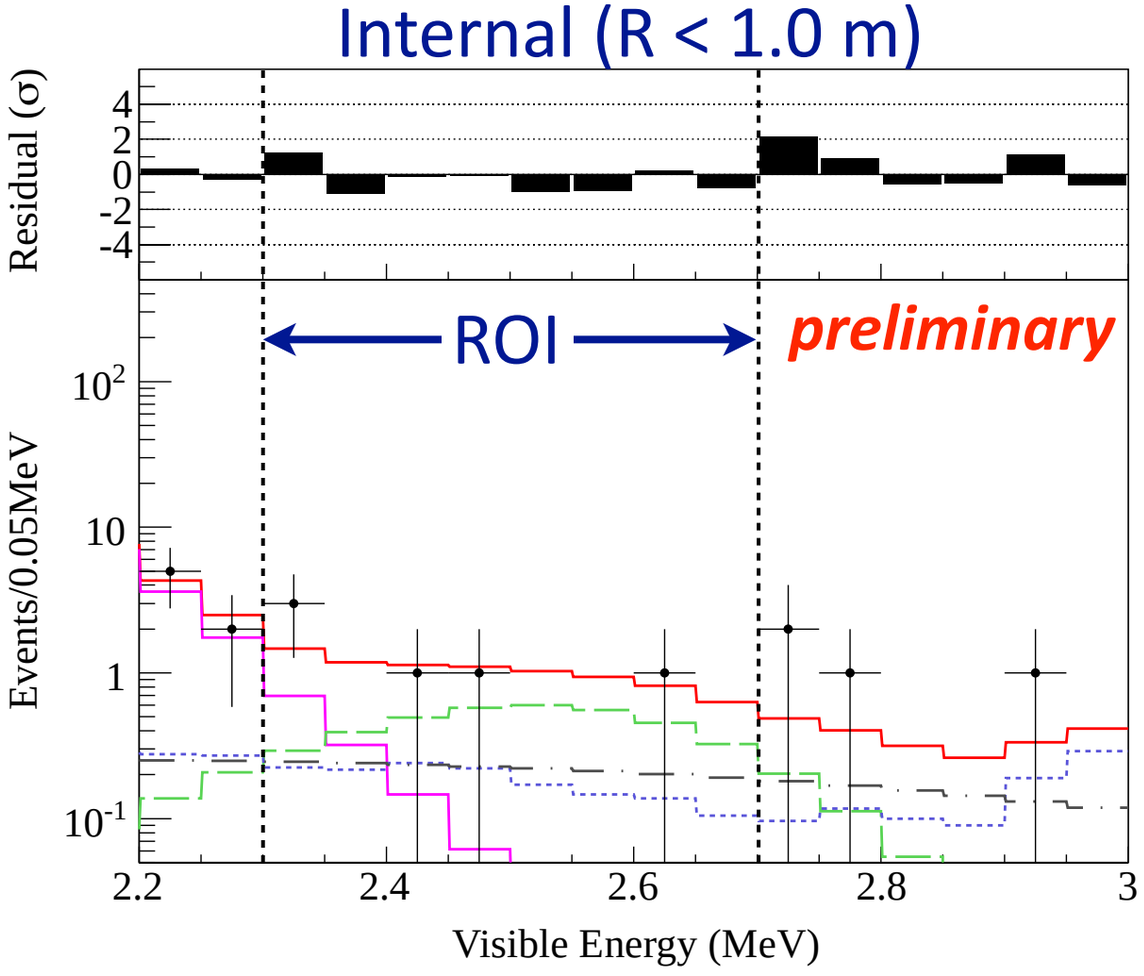
Target volume for spectral fit : R < 2.0 m

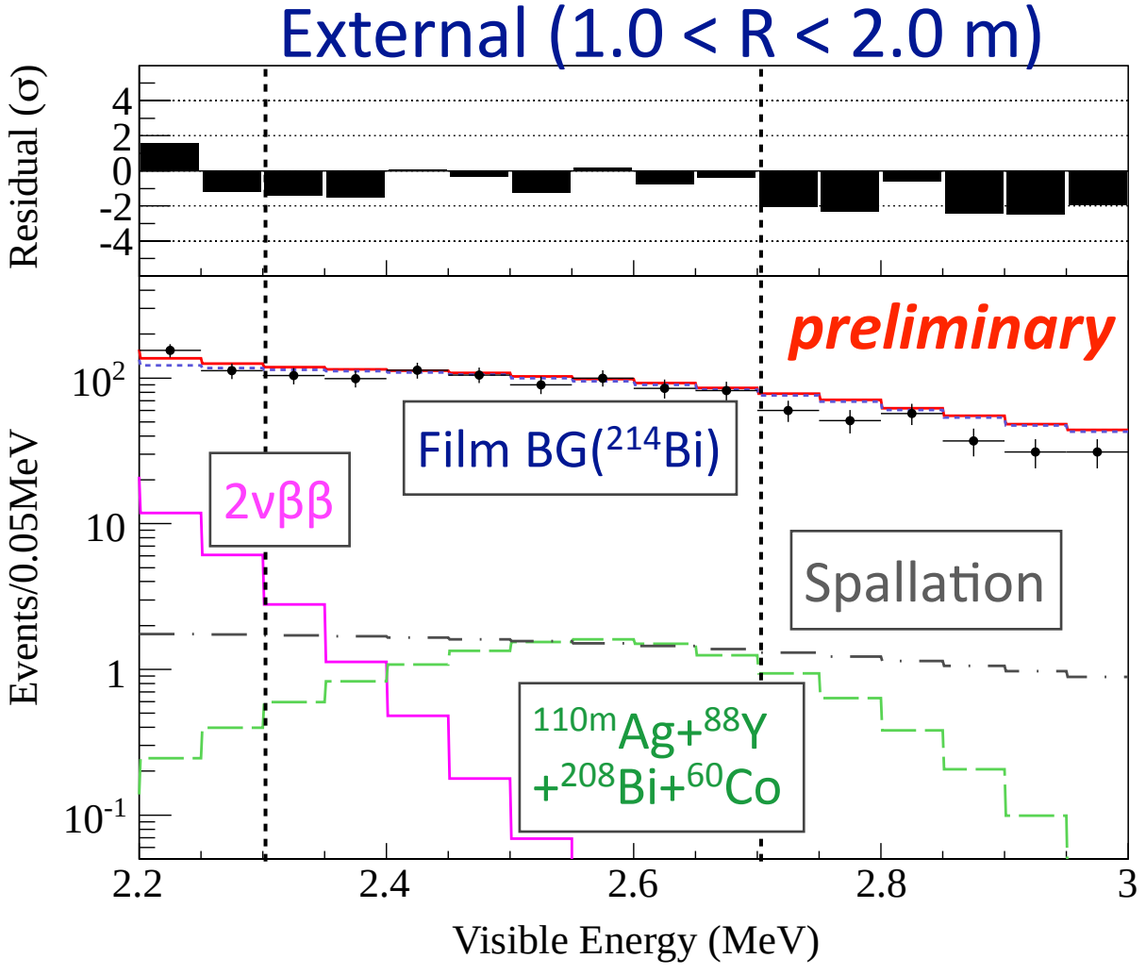
- Distribution of ^{214}Bi background from IB film is asymmetry.
  Larger background at the bottom.

R 20bin (same volume in each radius bin)
× Theta 2bin (-1<cosθ<0, 0<cosθ<1)

lower / upper hemisphere

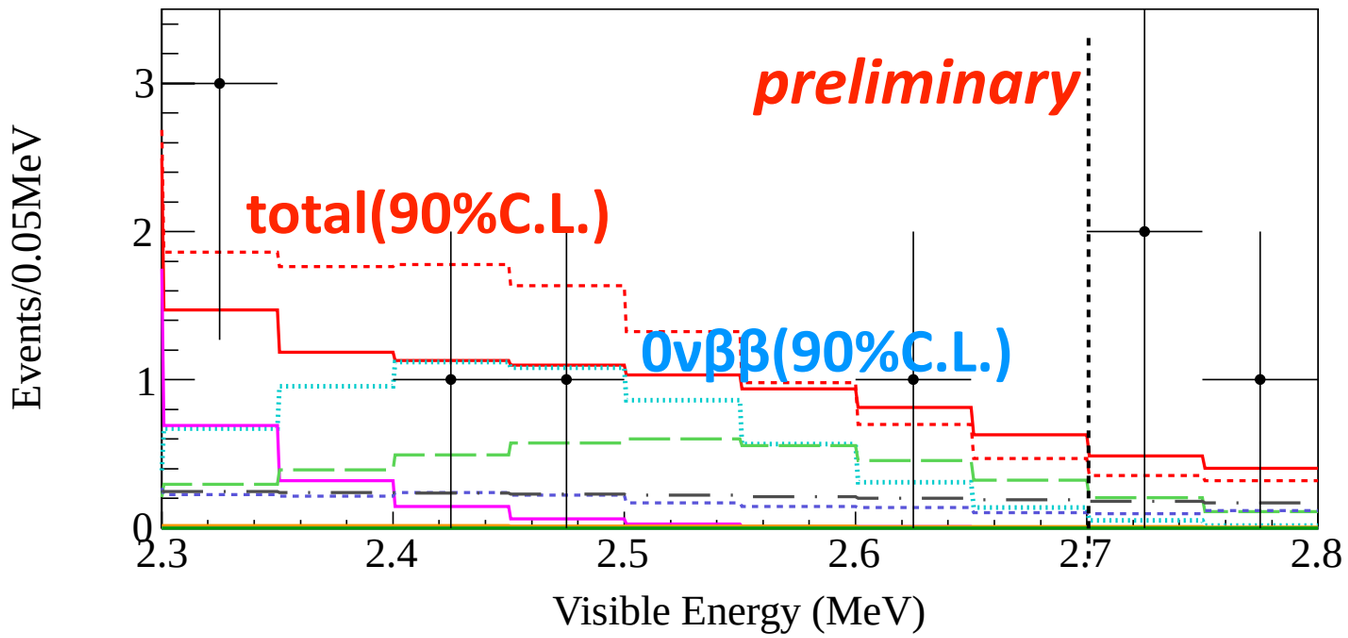






Result of 0νββ decay

2.3 < E < 2.8 MeV (R < 1.0 m)



0nu limit of Phase 2

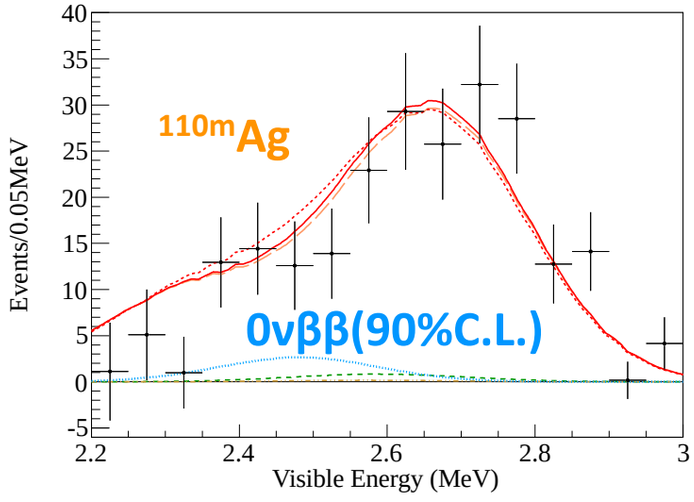
< 17.0 events/day/kton-LS (90%C.L.)

preliminary

$T^{1/2} > 1.3\times10^{25}$ yr (90% C.L.)

Phase 1 :

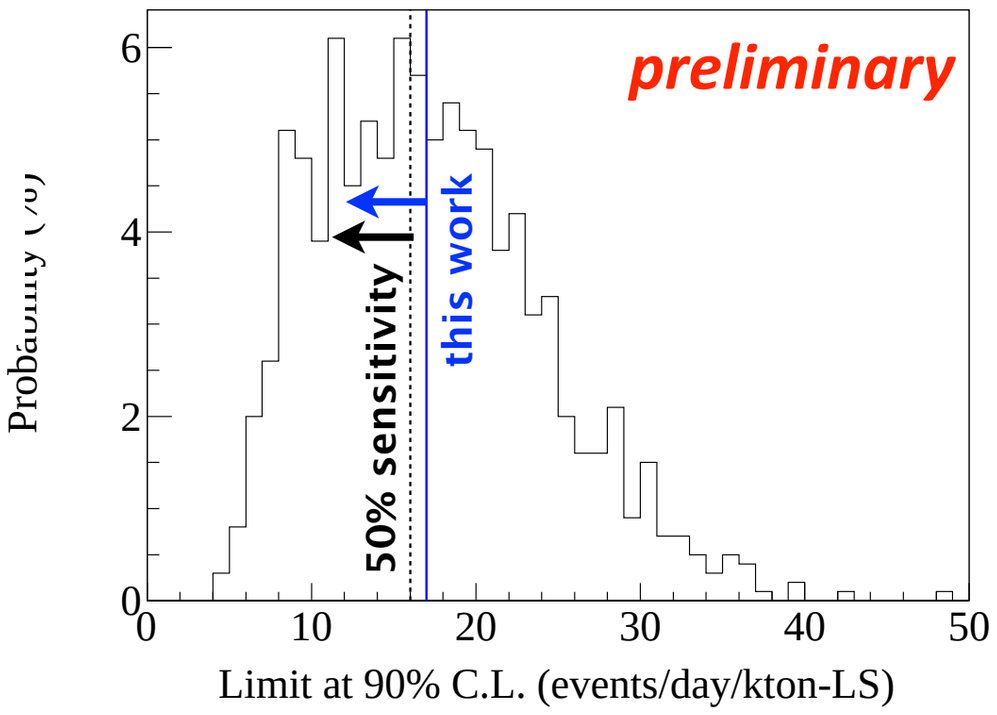
$T^{1/2} > 1.9\times10^{25}$ yr
(90% C.L.)



Upper Limits from Toy MC

Distribution of 0νββ limits
from Toy MC

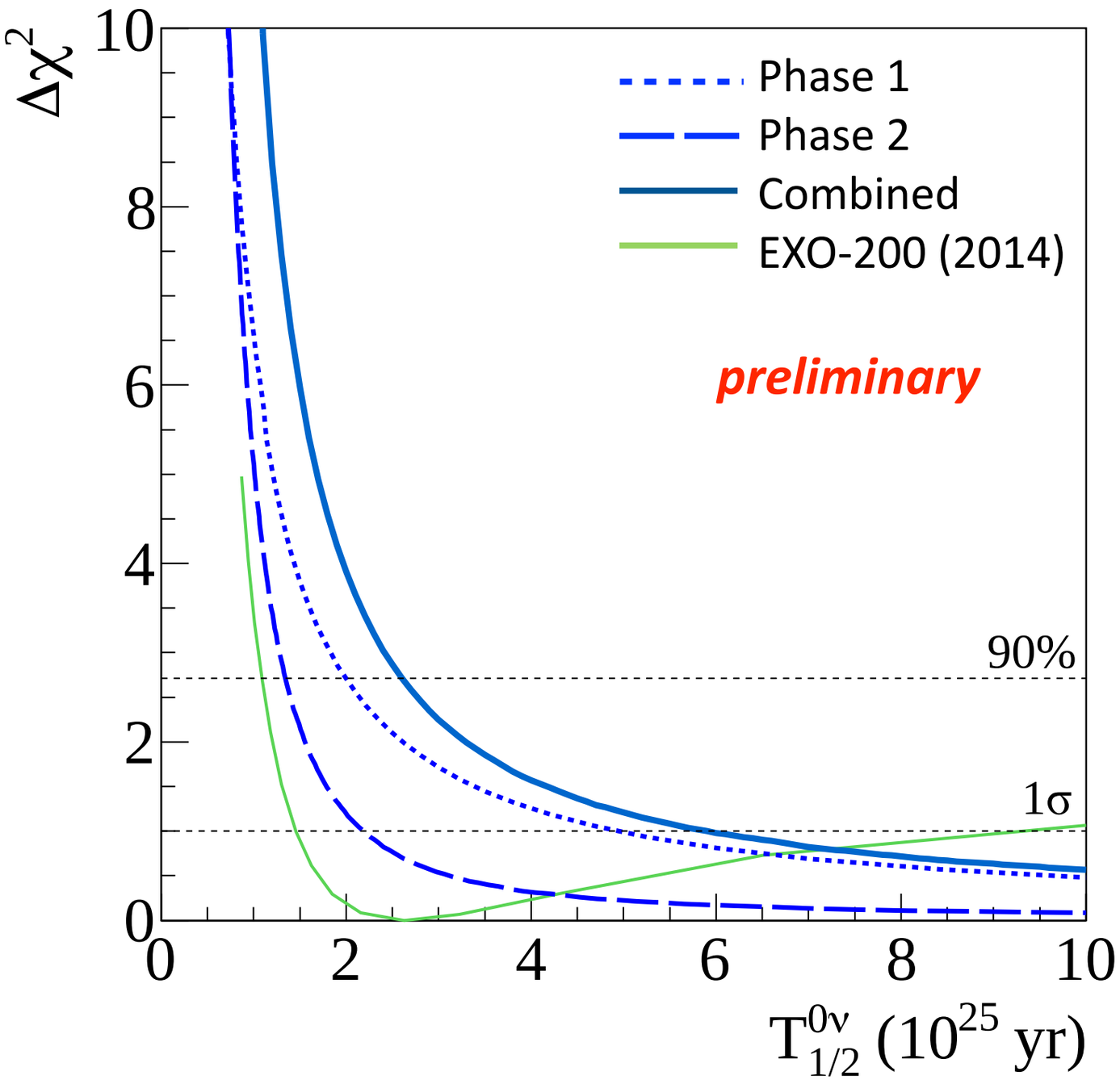
(no 0νββ signal, best-fit BG rate)



MC : < 16 events/day/kton-LS
(50% of the time)

this work :
< 17 events/day/kton-LS
(52% of the time)

Combined result



KamLAND-Zen

^{136}Xe Half-life limit (90% C.L.)

Phase 1 : $T^{1/2} > 1.9\times10^{25}$ yr

Phase 2 : $T^{1/2} > 1.3\times10^{25}$ yr

KamLAND-Zen Combined

preliminary

$T^{1/2} > 2.6\times10^{25}$ yr (90% C.L.)

Limit of effective mass

preliminary

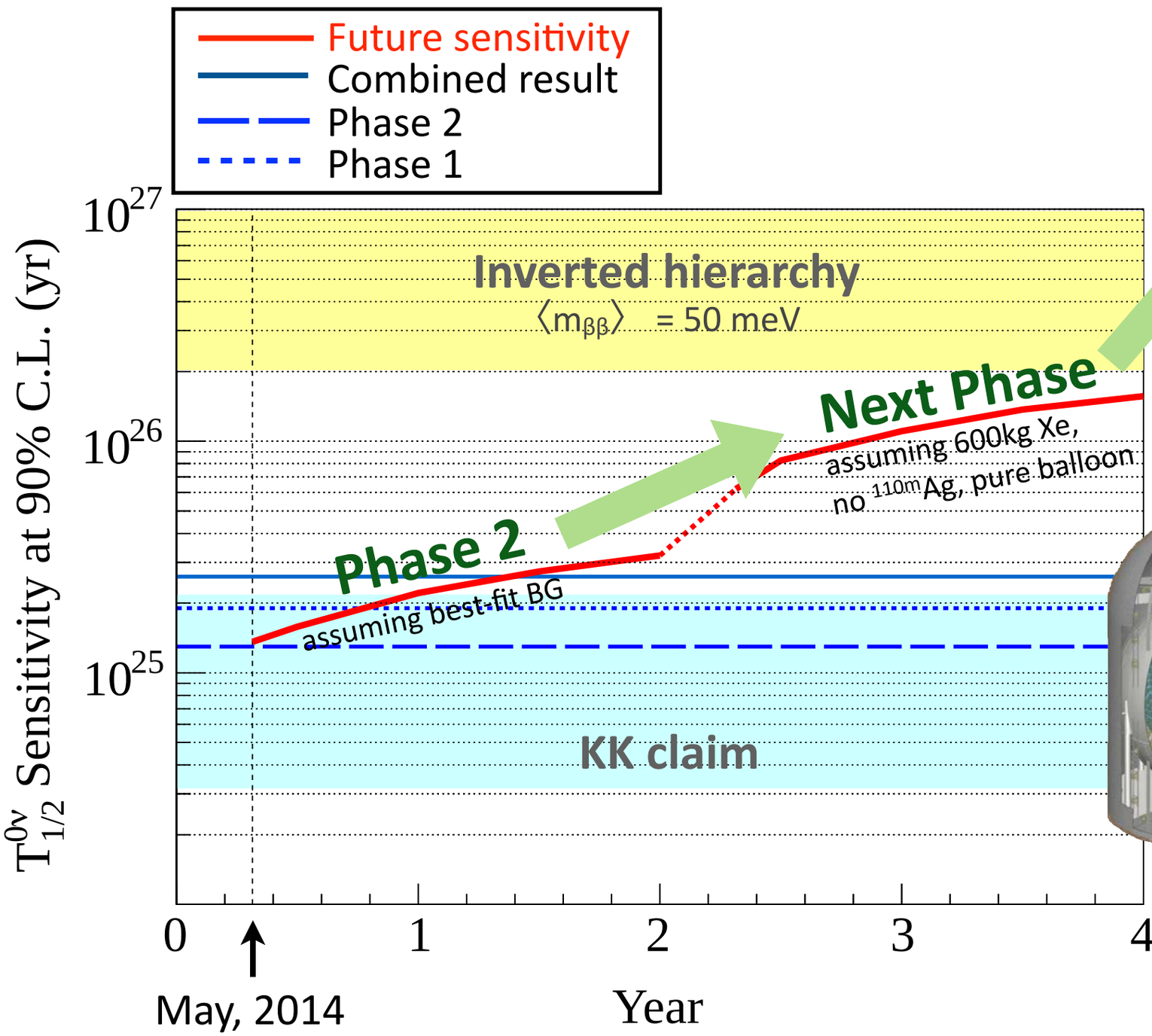
$\langle m_{\beta\beta}\rangle$ < 0.14-0.28 eV

QRPA NME model

J. Phys. G 39 124006 (2012)

Limits on ^{136}Xe half-life and effective neutrino mass are improved.

Future prospect



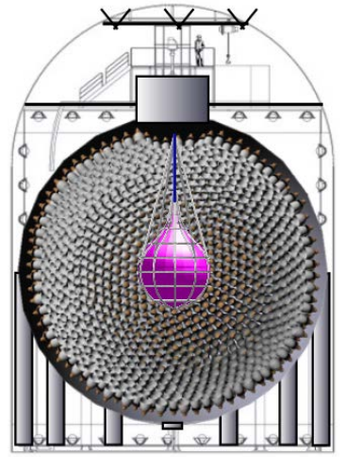
plan

KamLAND2-Zen

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

1,000 kg Xe

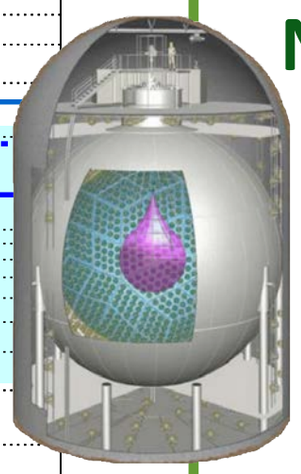
- High energy resolution
- Various R&D is going on.



funded

Next Phase

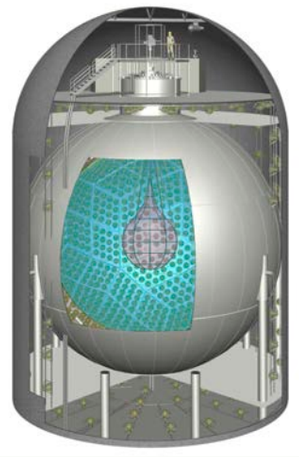
- Start in 2016.
- New inner balloon with about 600 kg Xe.
- Cover degenerated hierarchy.



running

Phase 2

- 383 kg Xe
- Data taking will finish at the end of this year.



Summary

- KamLAND-Zen searches for zero neutrino double beta decay with ^{136}Xe. Data taking started on Sep. 2011.
- KamLAND-Zen phase 2 started on Dec. 2013 with purified liquid scintillator and Xe.
- Reduction factor of ^{110m}Ag is more than 10.

- New preliminary results for ^{136}Xe 0νββ at 90% C.L.

  Lower limit of half-life

  Phase 1 : $T^{1/2} > 1.9\times10^{25}$ yr
  Phase 2 : $T^{1/2} > 1.3\times10^{25}$ yr
  ⌉ Combine 1+2 : **$T^{1/2} > 2.6\times10^{25}$ yr**

  Effective neutrino mass $\langle m_{\beta\beta} \rangle$ **< 0.14-0.28 eV** (QRPA)

  Proceedings of Neutrino2014 found at **arXiv:1409.0077**

- Phase 2 will finish at the end of 2015 and next phase (600kg Xe) will start in 2016.
- Target of KamLAND2-Zen is inverted neutrino mass hierarchy.
  It requires several detector improvements. R&D is going on.

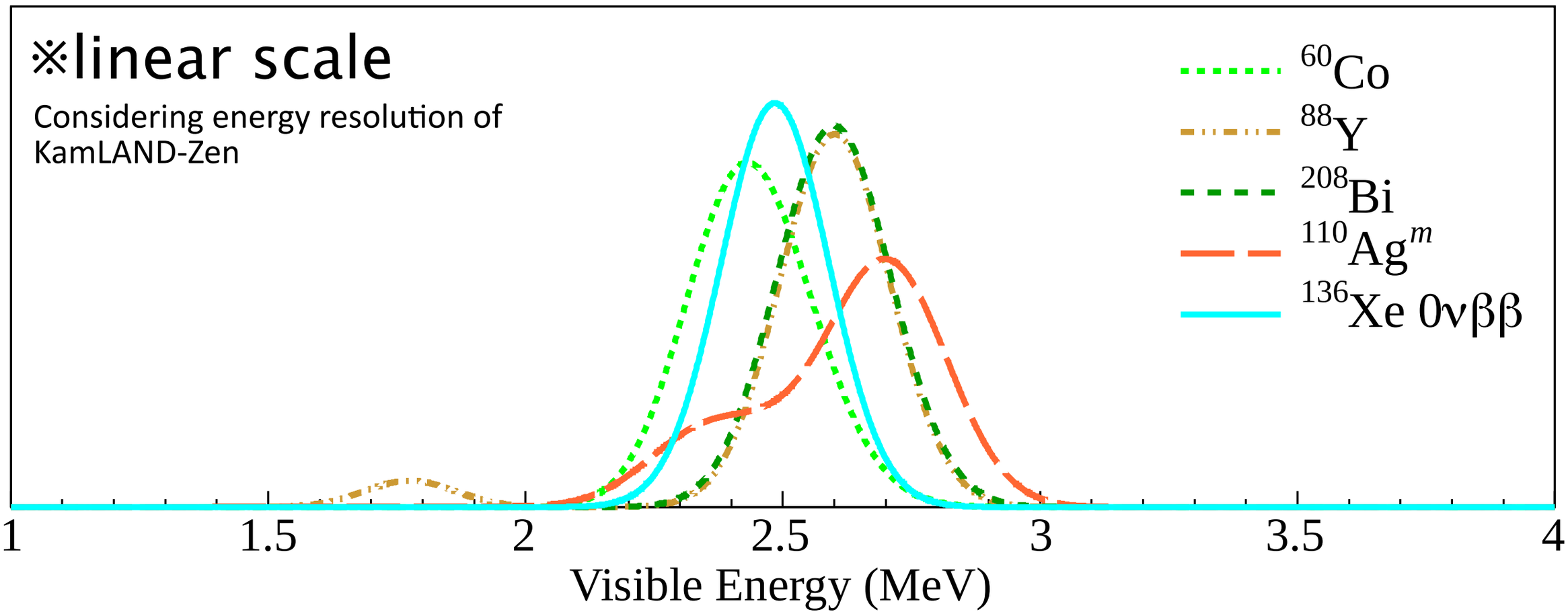
Backup

About unexpected peak around 2.6 MeV

Energy spectra of 4 nuclei and ^{136}Xe 0νββ

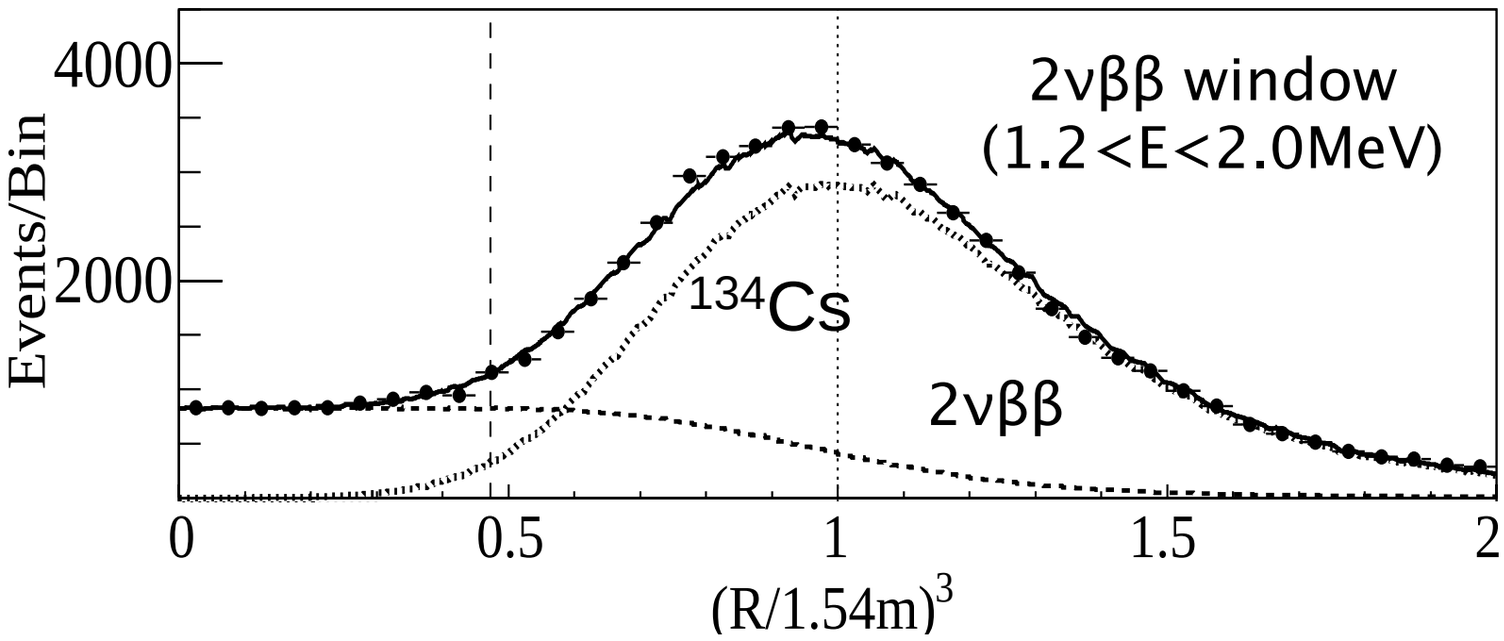
※linear scale

Considering energy resolution of KamLAND-Zen

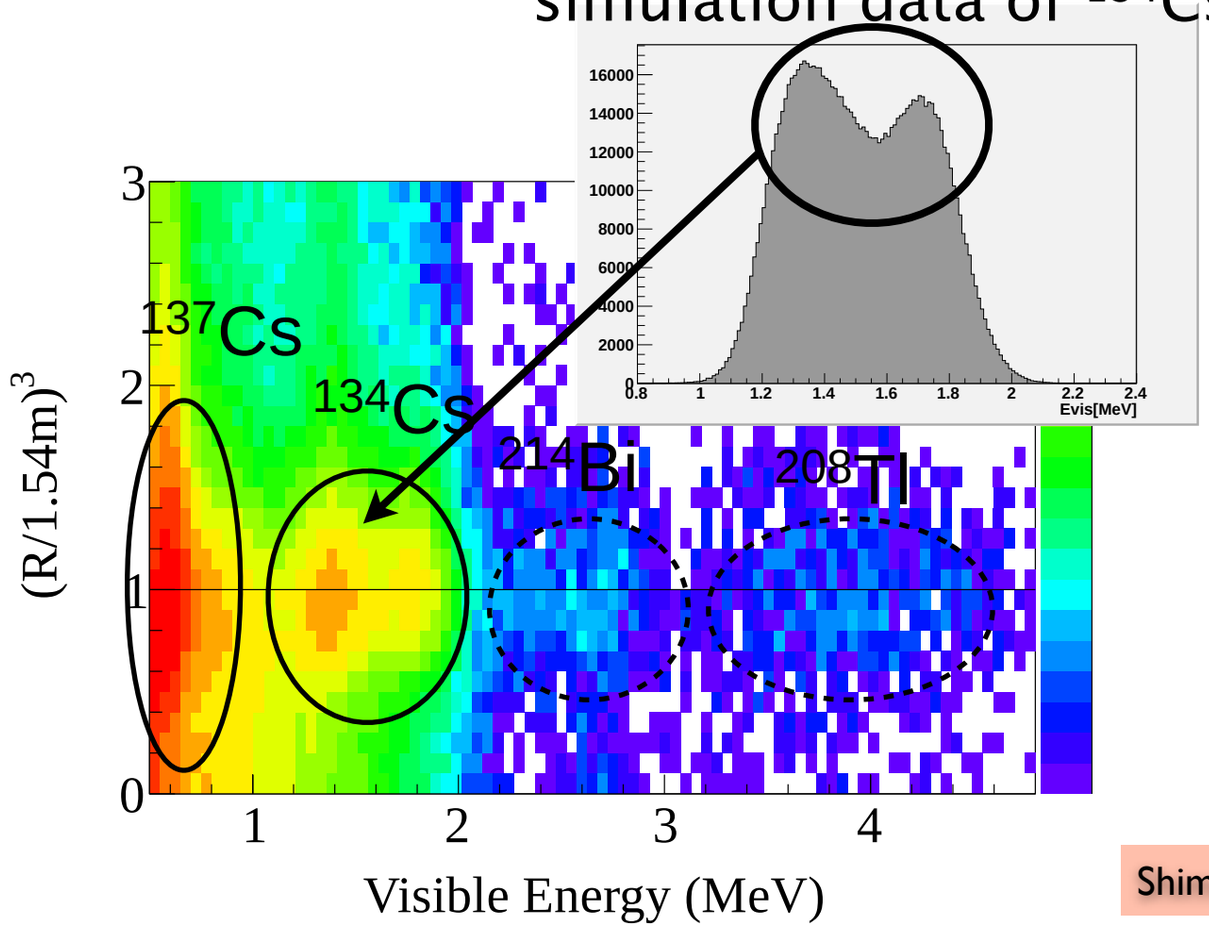


Unexpected background for ^{136}Xe 2νββ

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



simulation data of ^{134}Cs



Why Fukushima?

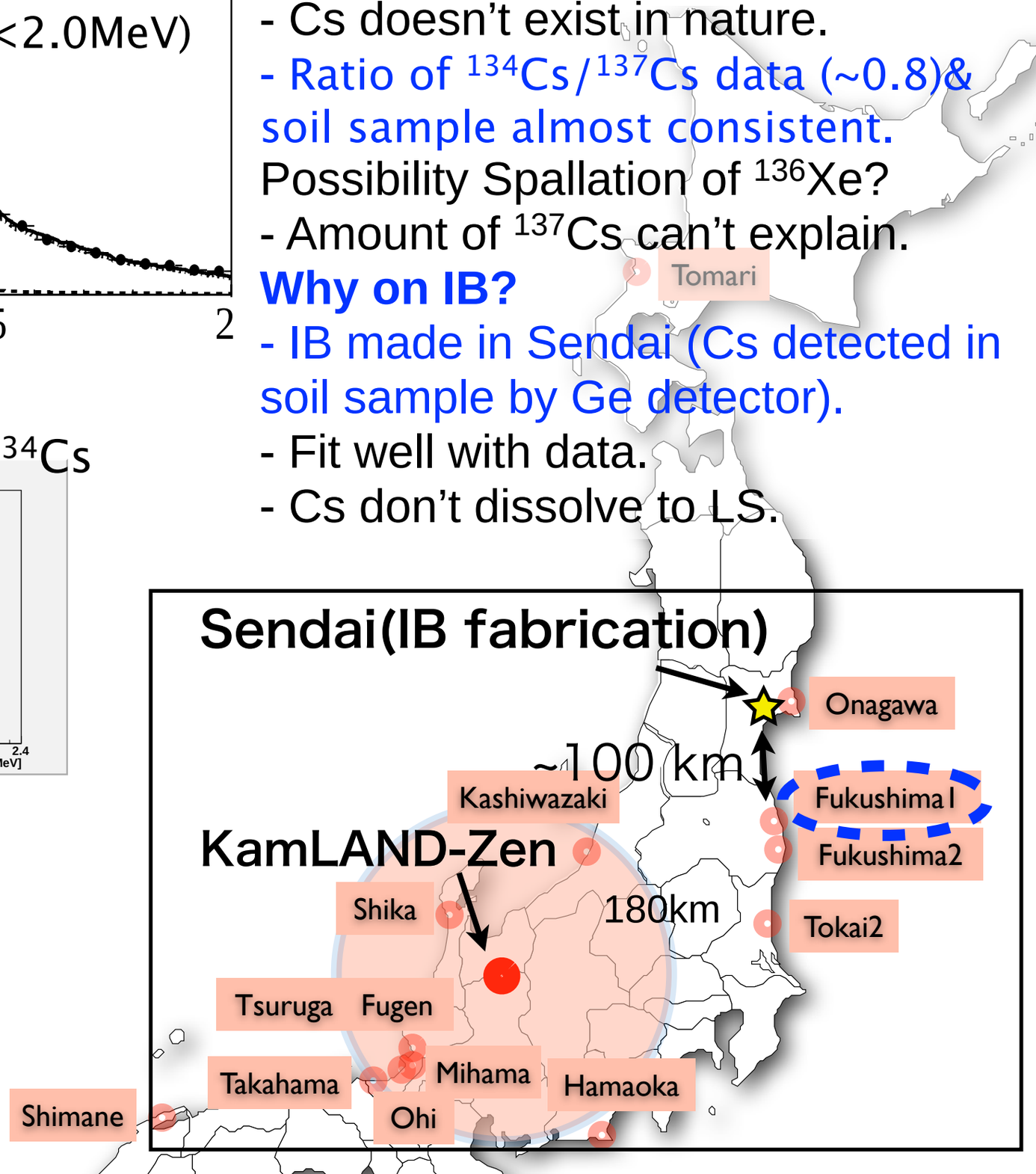
- Cs doesn't exist in nature.
- Ratio of ^{134}Cs/^{137}Cs data (~0.8)& soil sample almost consistent.

Possibility Spallation of ^{136}Xe?

- Amount of ^{137}Cs can't explain.

Why on IB?

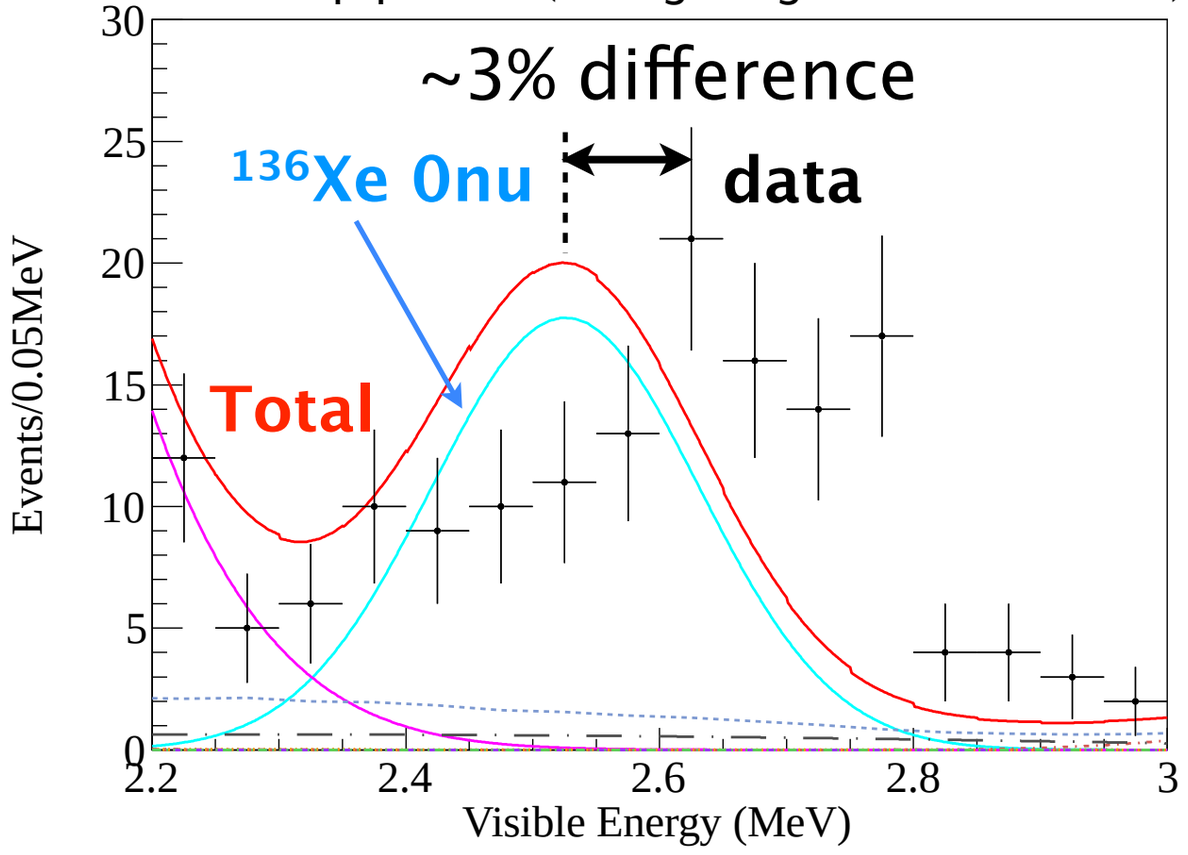
- IB made in Sendai (Cs detected in soil sample by Ge detector).
- Fit well with data.
- Cs don't dissolve to LS.



Unexpected background for ^{136}Xe 0νββ

Fit the peak with 0nu spectrum

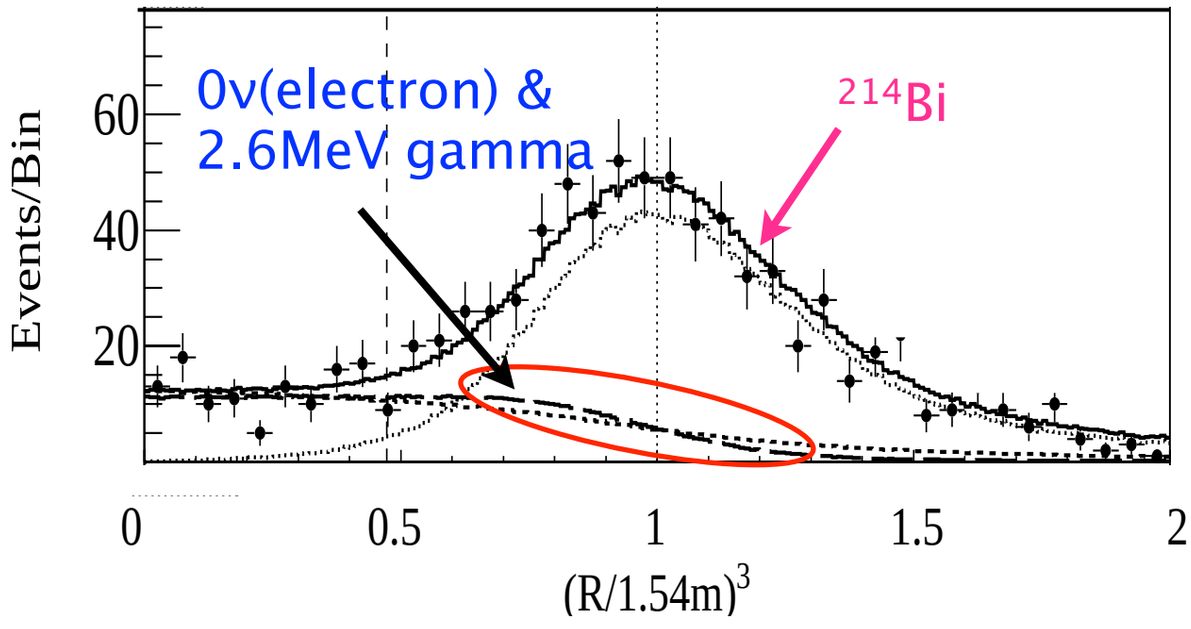
※closeup picture (fitting range is 0.5-4.8 MeV)



No background hypothesis excluded more than 5 sigmas.

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

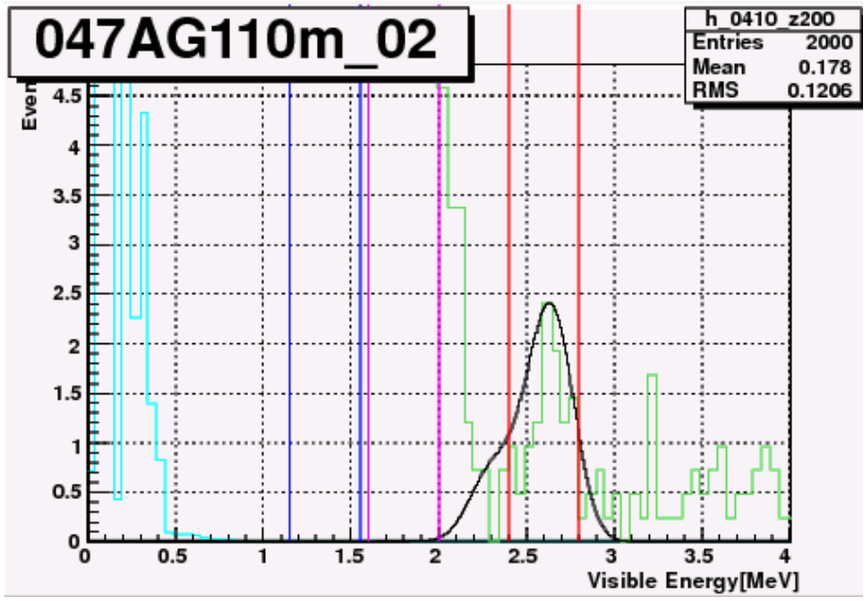
database of nuclei

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

example of spectrum



4 nuclei remains.

	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

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

- 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

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

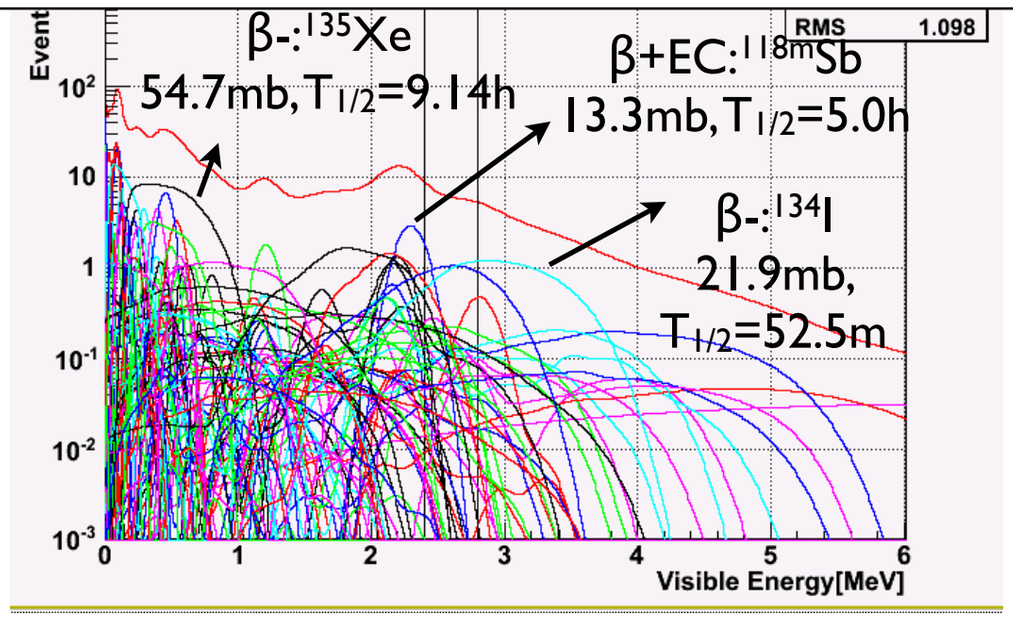
P.Napolitiani et. al.
Phys. Rev. C **76,** 064609 (2007)

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

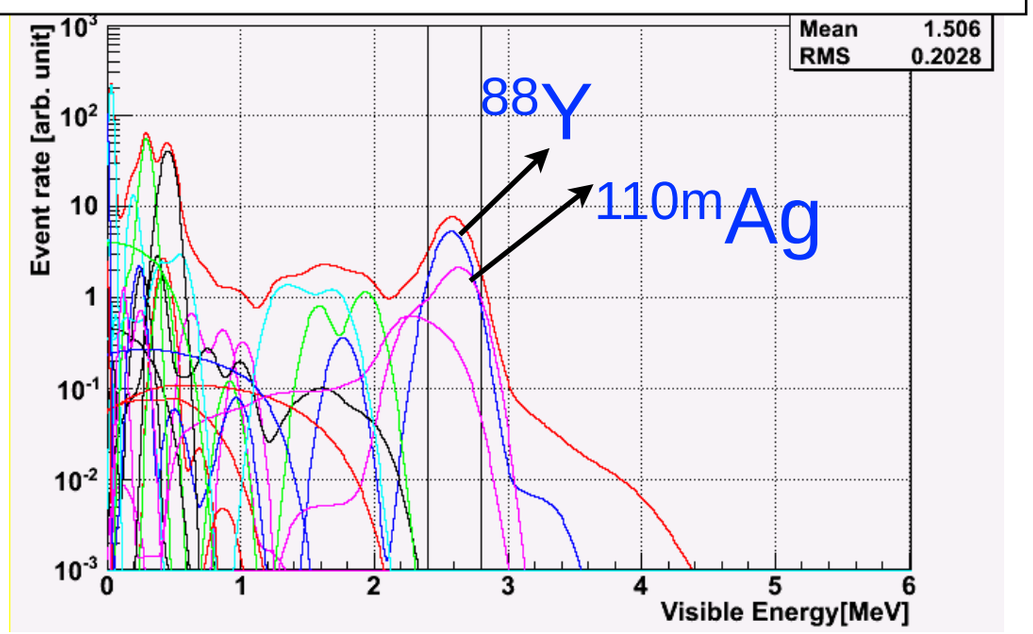
quantitative background estimation is difficult due to transportation loss in the gas system.

X = 100 days 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 remain.

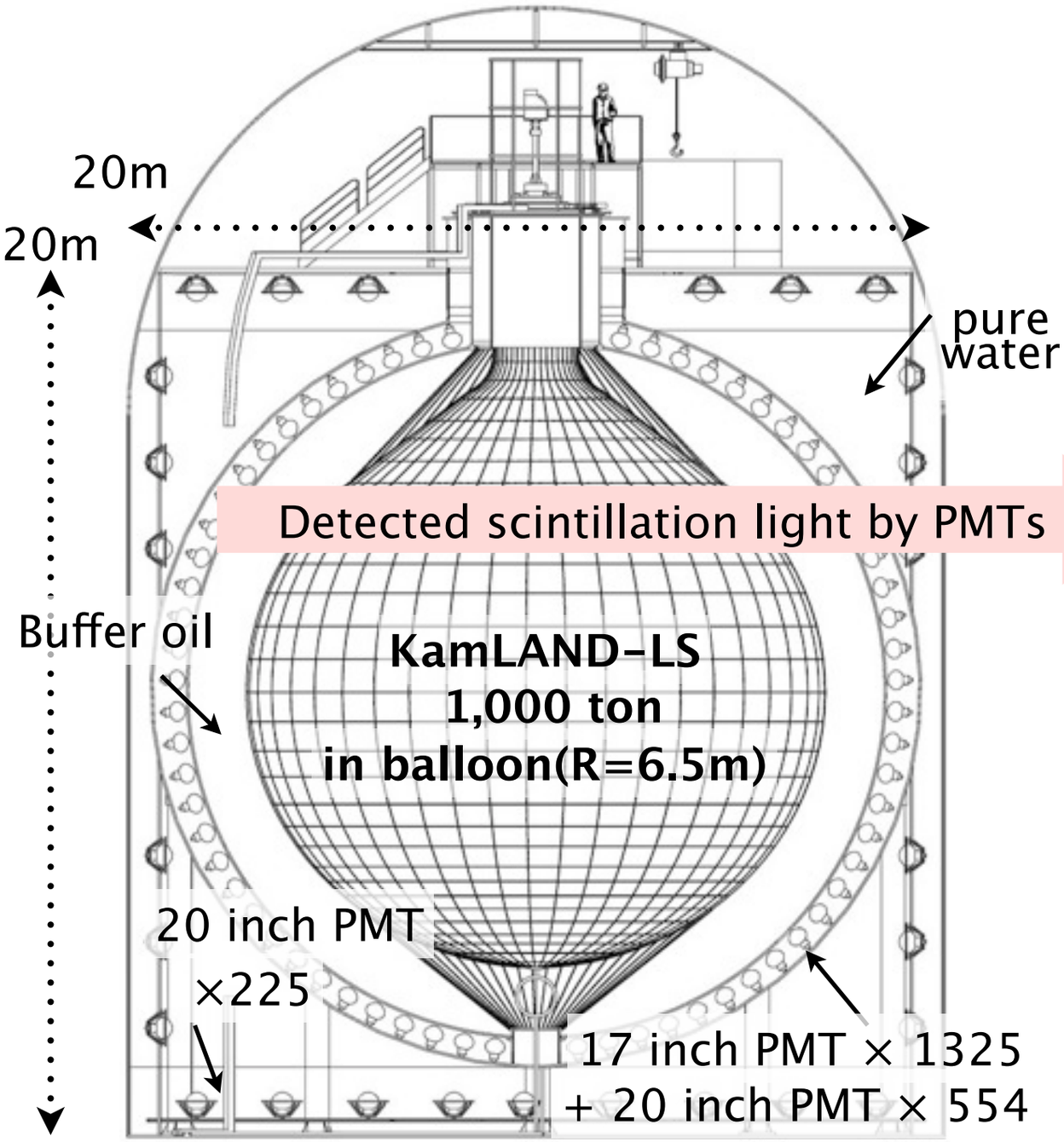
Backup

About KamLAND

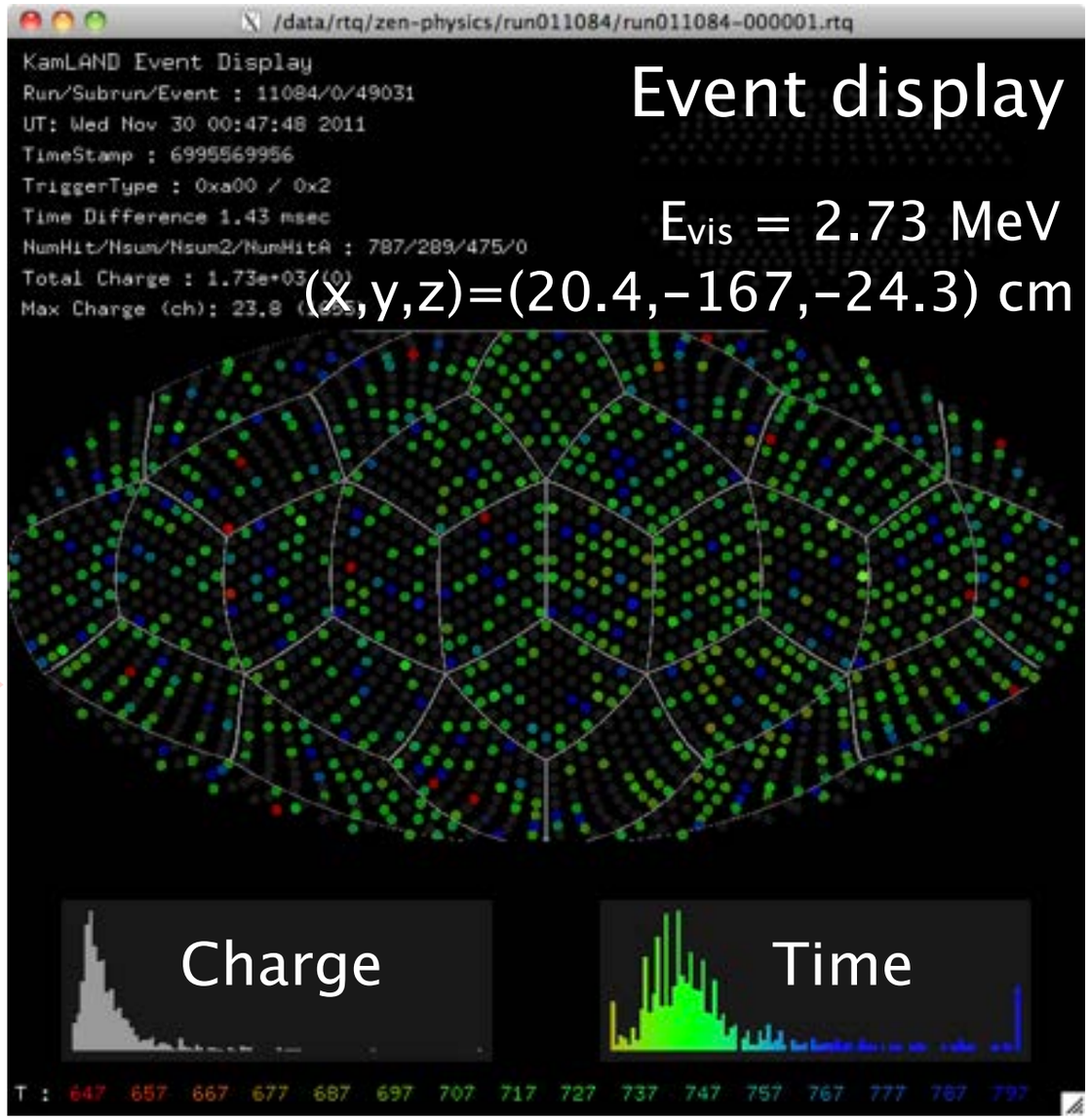
KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector)

- 1,000 ton of ultra pure liquid scintillator

  ^{238}U $(3.4 \pm 0.4) \times 10^{-18}$ [g/g]
  ^{232}Th $(5.7 \pm 0.8) \times 10^{-17}$ [g/g]
  ^{40}K 2.7×10^{-16} [g/g]



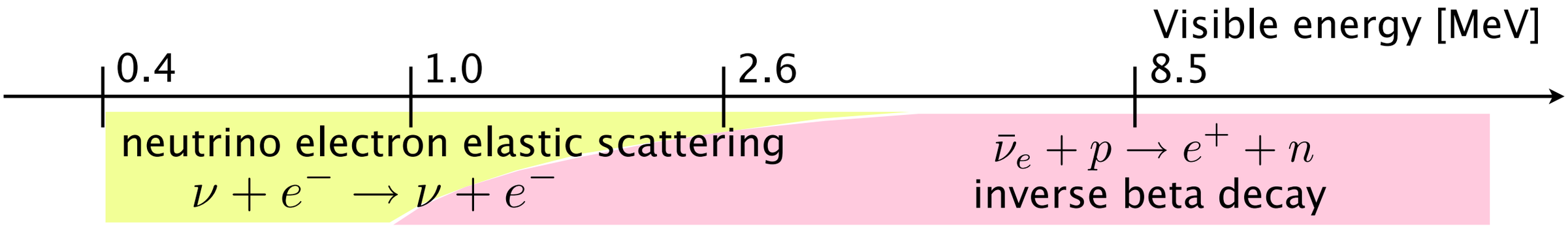
Detected scintillation light by PMTs

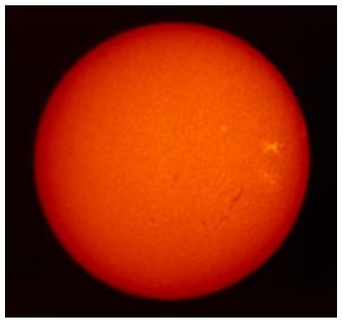
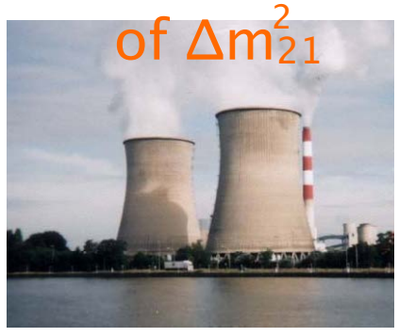
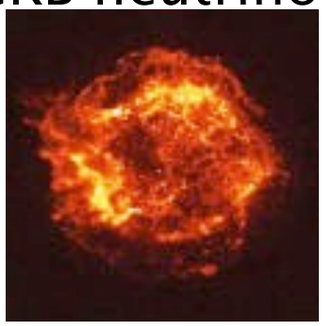


No directional information

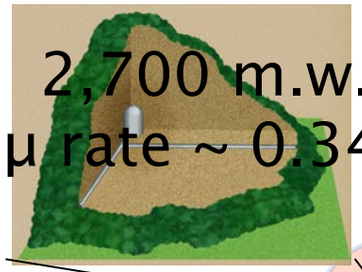
Energy resolution $\sigma = \sim 6.4\%/\sqrt{E(MeV)}$
Vertex resolution $\sigma = \sim 12cm/\sqrt{E(MeV)}$

Targets of KamLAND



^{7}Be solar neutrino	Geo-neutrino **First detection!**	Reactor neutrino Precise measurement of Δm^2_{21}	supernova relic neutrino, GRB neutrino etc.
			
Neutrino Astrophysics	Neutrino Geophysics	Neutrino Physics	Neutrino Astrophysics Cosmology

Mt. Ikenoyama



Located at Gifu prefecture, former Kamiokande site.

Clear cycle of neutrino oscillation