Results and Future plans for the KamLAND-Zen

Junpei Shirai
(Tohoku University)
for the
KamLAND-Zen Collaboration

XXVII International Conference on Neutrino Physics and Astrophysics, Jul.8, 2016, London

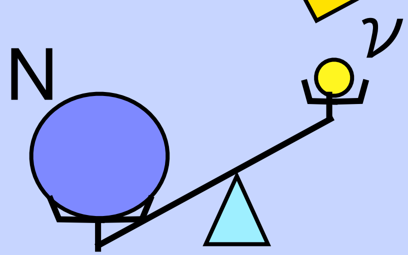
$M_\nu \neq 0$

$\nu = \overline{\nu}$?

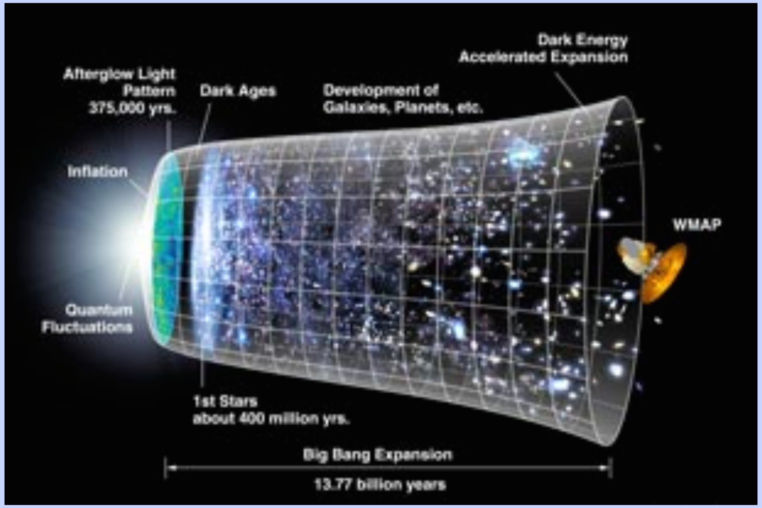
2 mass eigenstates

GUT

N



Seesaw



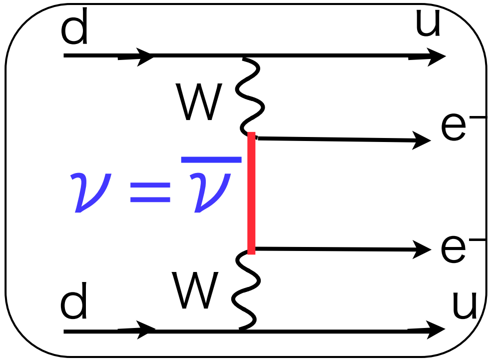
Big Bang

Matter dominance

0νββ

Key process to test $\nu=\overline{\nu}$

$\Delta L=2$ (beyond the SM)



$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$

(Phase space factor)

(Nuclear matrix element)

(Effective Majorana ν mass)

$>10^{26}$yr

Very challenging!

$\lesssim 0.1$eV

Absolute ν mass scale

ν mass hierarchy

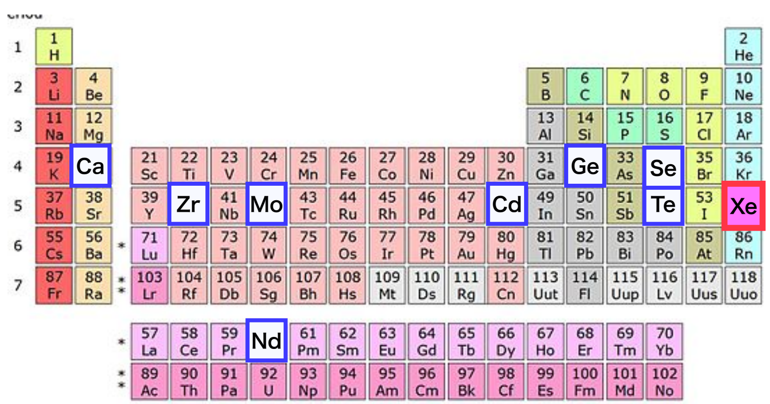
Oscillation parameters, CP-phase

0νββ : Large Mass + Low B.G. + Technique

^{136}Xe is excellent !

	^{48}Ca	^{76}Ge	^{82}Se	^{96}Zr	^{100}Mo	^{116}Cd	^{130}Te	^{136}Xe	^{150}Nd
Q-val.(MeV)	4.271	2.04	2.995	3.35	3.03	2.80	2.53	2.458	3.367
Nat.Ab.(%)	0.189	7.44	8.73	2.80	9.67	7.49	34.1	8.9%	5.6

Longest $T^{2\nu}_{\beta\beta}$
2.2×10^{21}yr



Xe: Noble gas

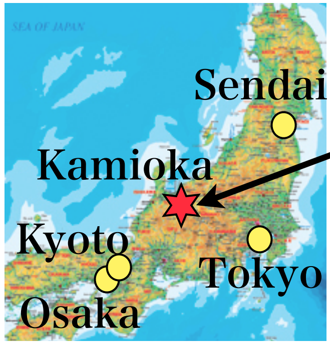
Isotope Enrichment
Purification
High chemical stability

Safety
handling
Repeated purification

High solubility to LS (~3.5wt%) easily purged out by flushing.

Excellent scalability !

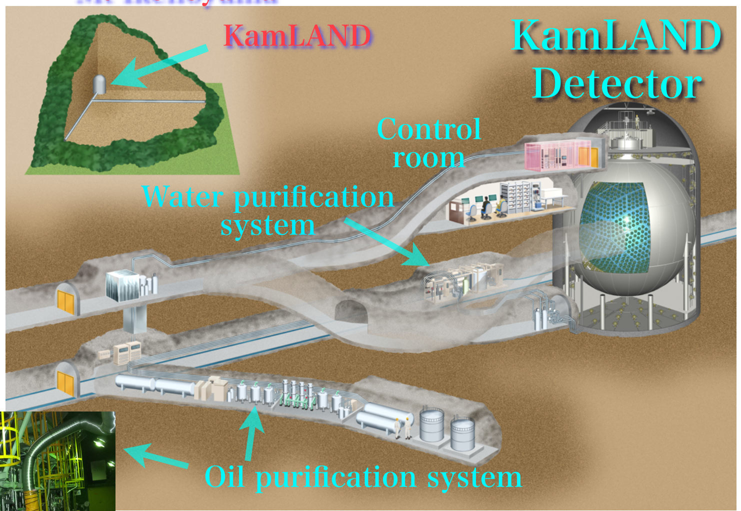
Xe + Large volume LS
Unique strategy for the search !

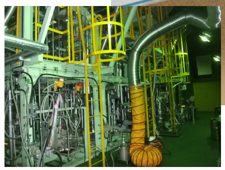


Location :

2,700m w.e. underground in Kamioka mine in Gifu prefecture
Cosmic ray flux : 1/100,000 of the above ground

Mt Ikenoyama

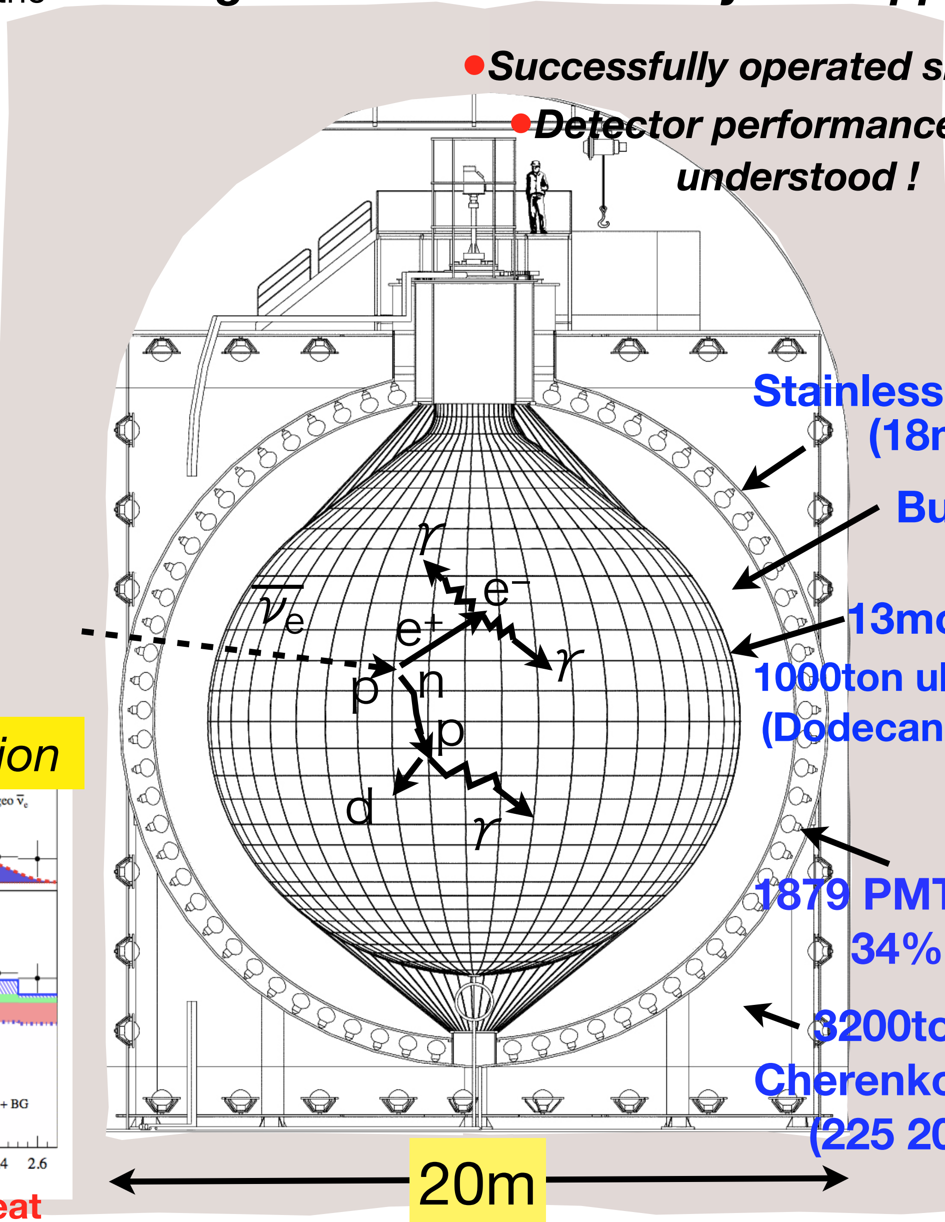




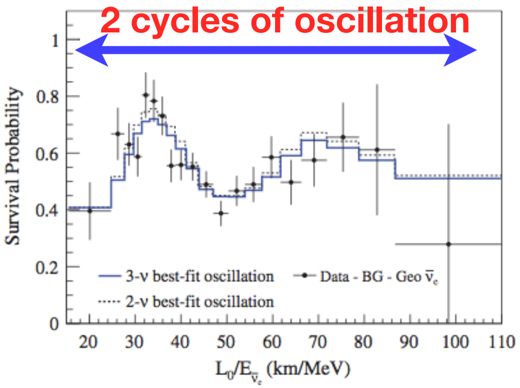
KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector

- ***Huge & ultra-clean facility for $0\nu\beta\beta$ search !***
- ***Successfully operated since 2002.***
- ***Detector performance is well understood !***

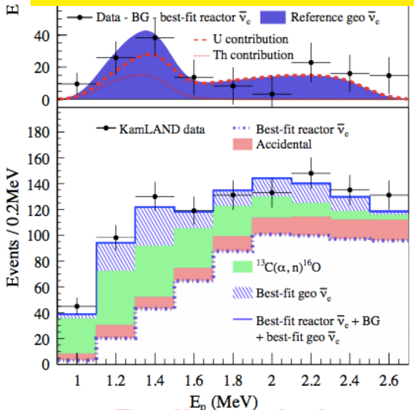


Reactor $\overline{\nu}_e$ oscillation



Precise determination of oscillation parameters !

Geo $\overline{\nu}_e$ detection

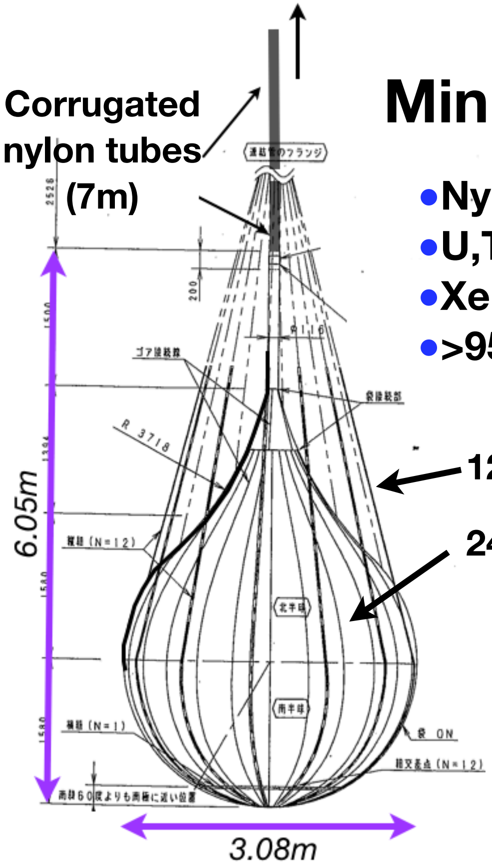


Radiogenic heat measurement and constrain earth models.

KamLAND-Zen

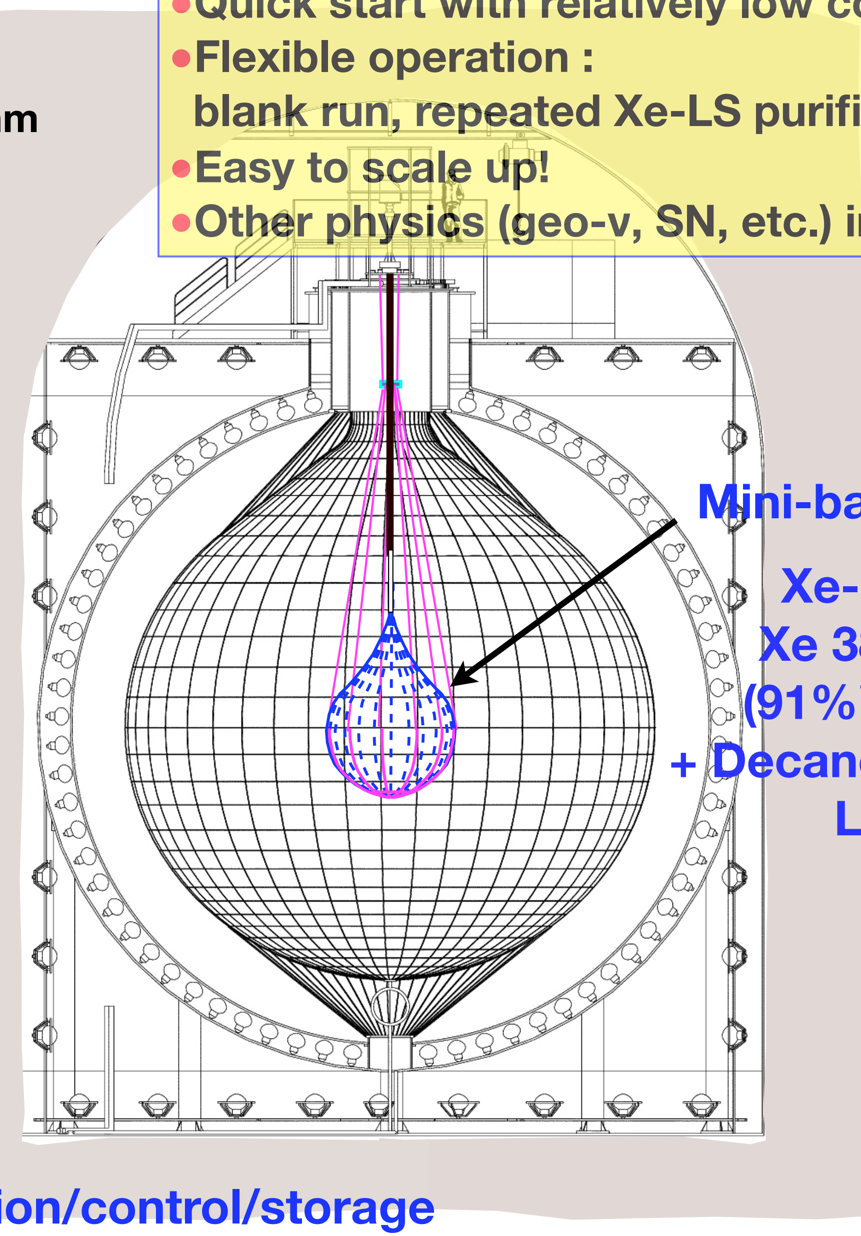
Zero neutrino
double beta decay
experiment

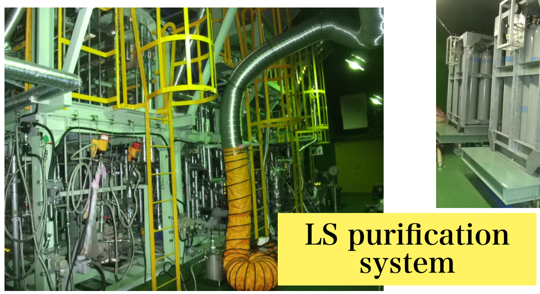
Mini-balloon



- Nylon film: 25μ-thick
- U,Th~10^{-12}, ^{40}K~10^{-11}g/g
- Xe tightness
- >95% transparent @400nm

- Quick start with relatively low cost !
- Flexible operation :
  blank run, repeated Xe-LS purification
- Easy to scale up!
- Other physics (geo-ν, SN, etc.) in parallel !





Xe distillation/control/storage
+LS purification plant

KamLAND-Zen Collaboration

March,2016

48 physicists from 11 institutes

Tohoku Univ : A.Gando, Y.Gando, T.Hachiya, A.Hayashi, S.Hayashida, Y.Honda, K.Hosokawa, H.Ikeda, K.Inoue, K.Ishidoshiro, K.Kamisawa, Y.Karino, M.Koga, S.Matsuda, T.Mitsui, K.Nakamura, S.Obara, H.Ozaki, Y.Shibukawa, I.Shimizu, Y.Shirahata, J.Shirai, K.Soma A.Suzuki, T.Takai, K.Tamae, Y.Teraoka, K.Ueshima, H.Watanabe **Tokyo Univ. IPMU :** A.Kozlov, Y.Takemoto, B.E.Berger, D.Chernyak

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

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 **North Carolina Univ :** H.J.Karwowski, D.M.Markoff

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

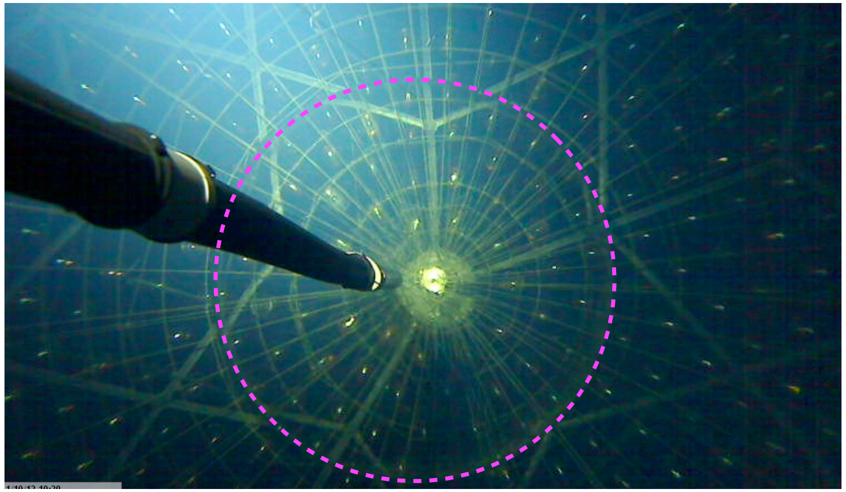
Univ. of Amsterdam : M.P.Decowski

KamLAND-Zen history

May-Aug. 2011

Mini-balloon construction, installed into the detector.

Mini-balloon in KamLAND



Oct.2011 ~ Jun. 2012

Phase1 (320kg enriched Xe)

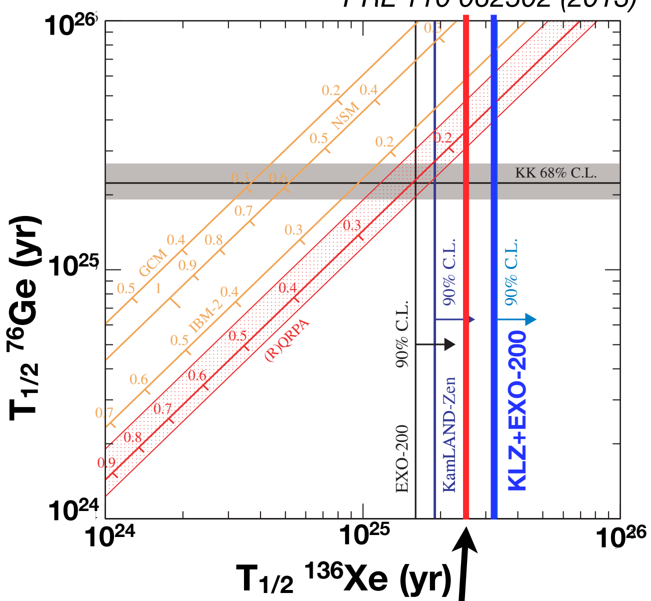
89.5kg yr ^{136}Xe

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

> 3.4×10^{25} yr (90%C.L.) (KLZ+EXO-200)

KK claim on ^{76}Ge was refuted (97.5%C.L.).

PRL 110 062502 (2013)



*KamLAND-Zen (v2014)

Limits from Phase1+Early Phase2(115d)

$T^{0\nu}_{1/2}$> 2.6×10^{25} yr (90%C.L.)

⟨$m_{\beta\beta}$⟩ <140~280meV (QRPA)

Jul. 2012 ~Oct.2013

Xe-LS Purification

Nov.2013 ~ Oct.2015

Phase2 (383kg enriched Xe)

504kg yr ^{136}Xe

Calibration

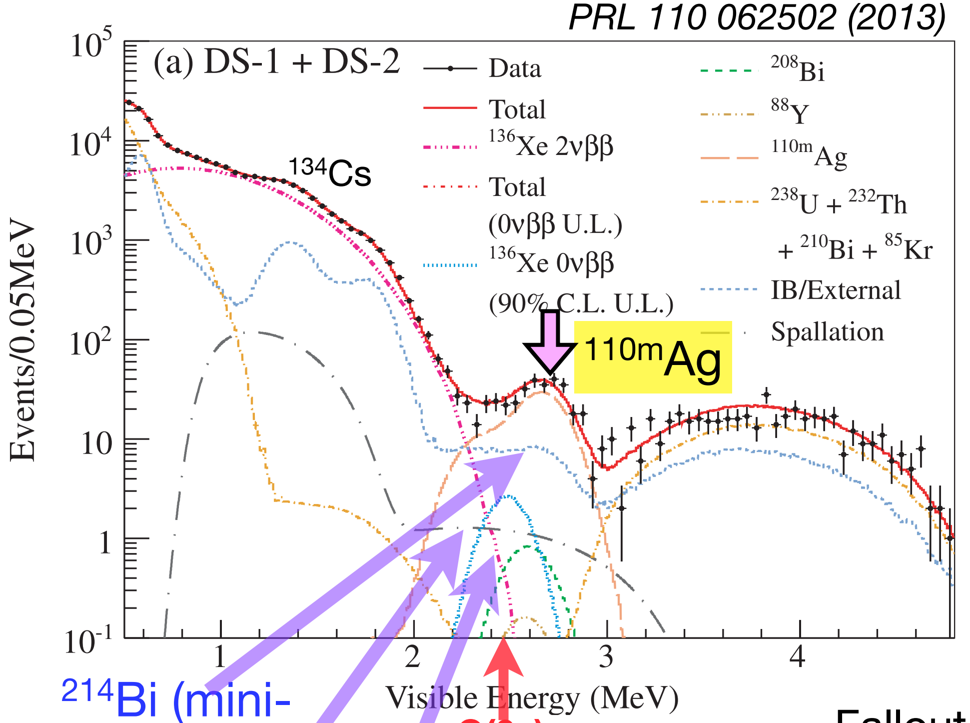
New !

Oct.2015～

Preparation for a new phase

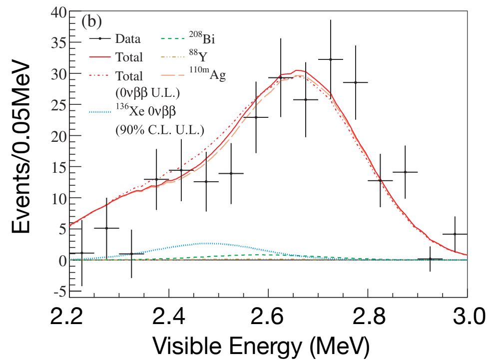
Phase1 (before purification)

PRL 110 062502 (2013)

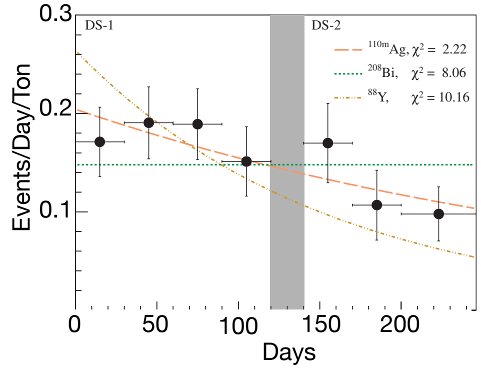


0ν region (2.3-2.7MeV) is dominated by ^{110m}Ag (Q=3.01MeV, $T_{1/2}$=260d)

spectrum shape



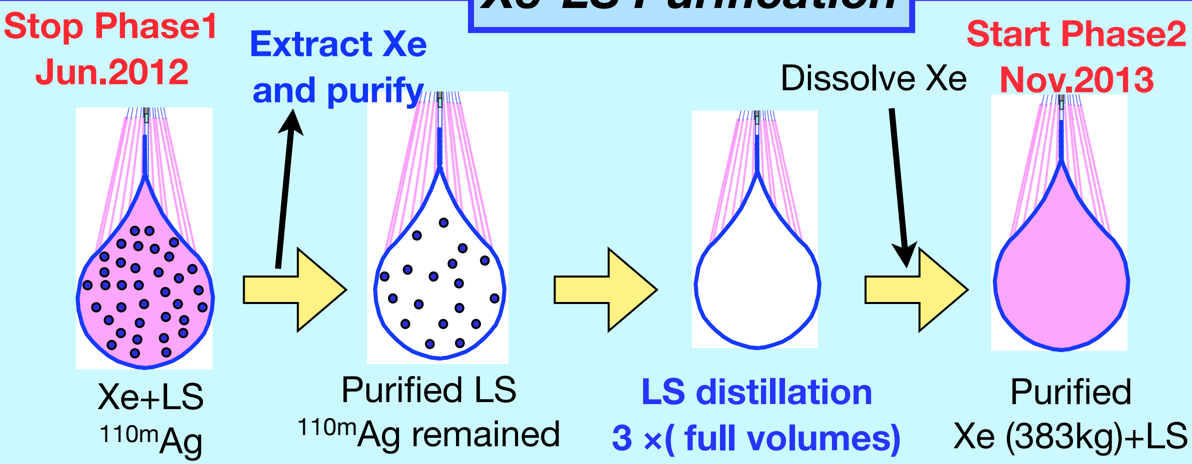
time variation



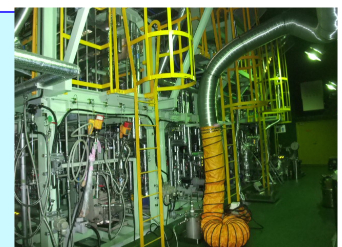
Fallout from the Fukushima reactor accident in Mar.2011 when mini-balloon was constructed in Tohoku Univ.

2ν region (1.2~2.0MeV) : ^{134}Cs (τ=2.06yr, 2.06MeV)

Xe-LS Purification



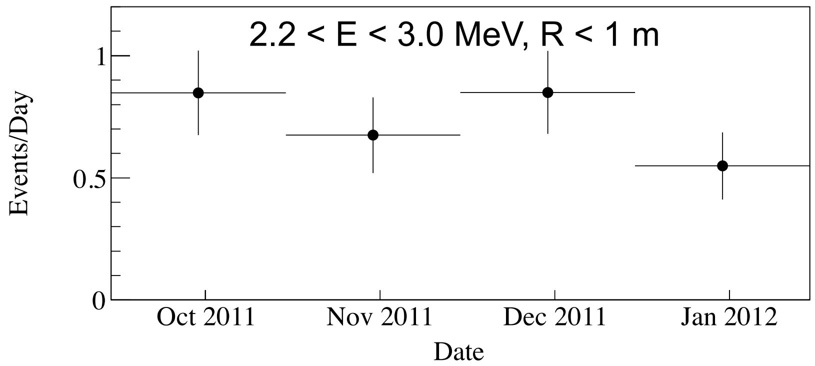
LS vac. distillation (+Water extraction, N_2 purge)



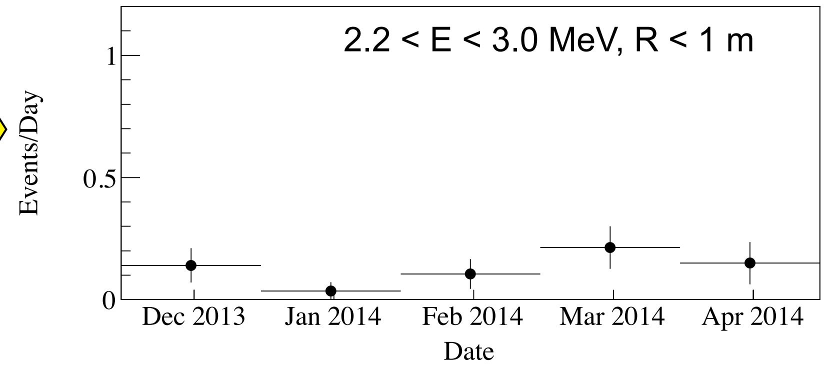
Xe distillation + filtration (charcoal, sintered metal, 3nm PTFE)+ getter

Before **Purification** After

Phase 1 (first 112.3 days)



Phase 2 (first 114.8 days)



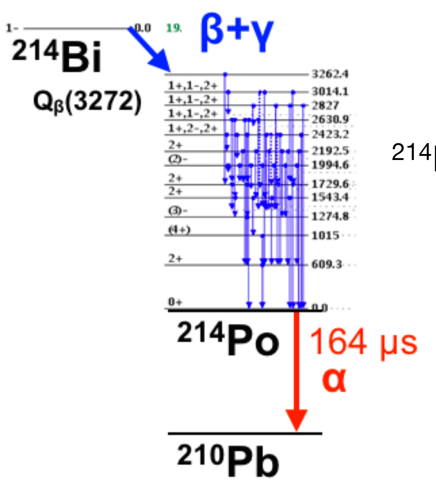
^{110m}Ag was removed by ~10 !
Purification method was found effective.

BG: ^{214}Bi, ^{10}C, 2ν, and possibly remaining ^{110m}Ag

^{214}Bi studies

MC study of ^{214}Bi→^{214}Po decay vertex distribution by using Geant4 full detector simulation tuned for KamLAND.

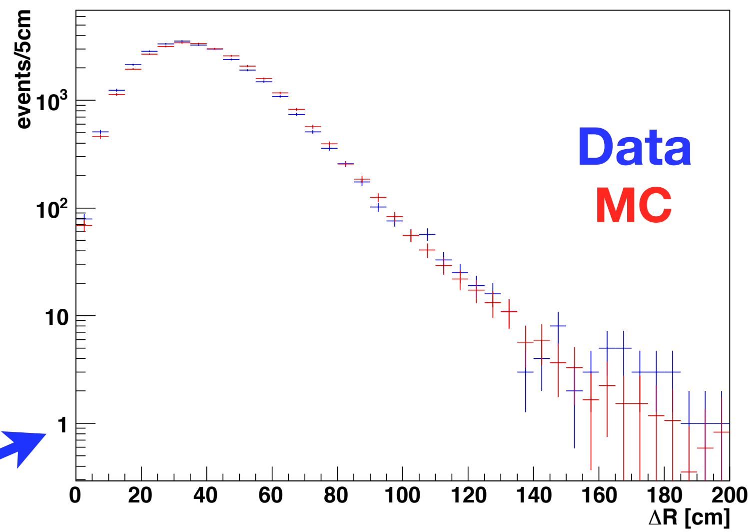
(Particle tracking, scintillation photons, PMT timings)



^{214}Bi β^- decays with multi-γs

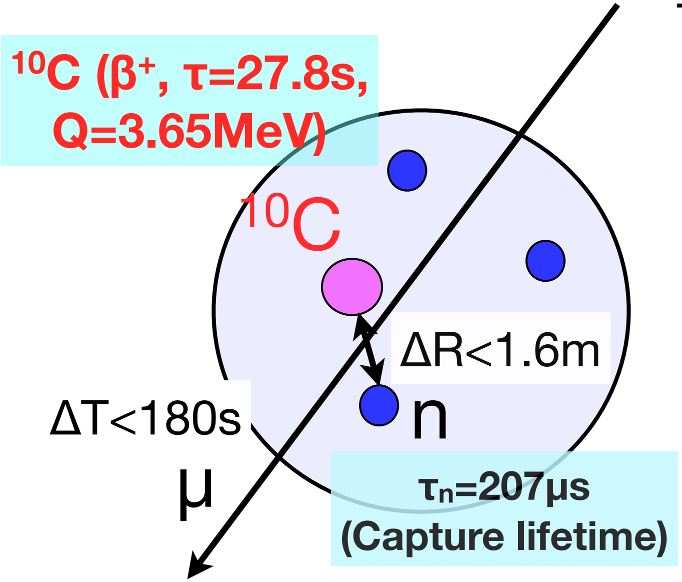
Data of pure ^{214}Bi→^{214}Po samples from initial ^{222}Rn rich period

Distance of ^{214}Bi-^{214}Po vertex



Vertex distribution is well reproduced !

^{10}C rejection by neutron tagging



Triple coincidence : μ-on + neutrons + ^{10}C

τ_n=207μs

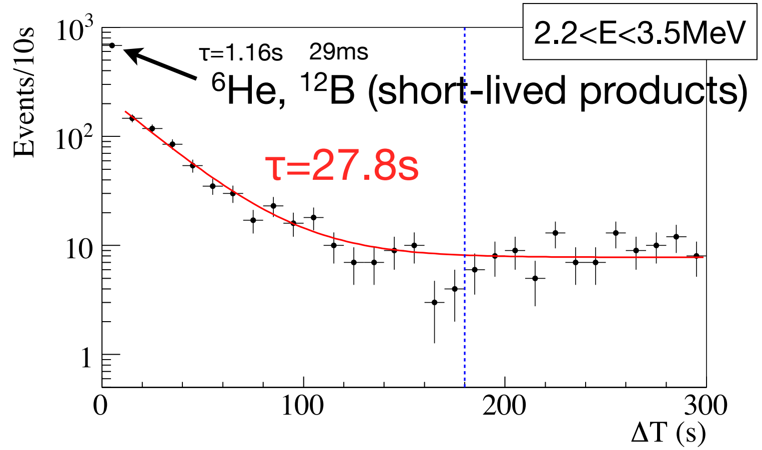
n+p→d+γ(2.2MeV)

Cut conditions

ΔT<180s

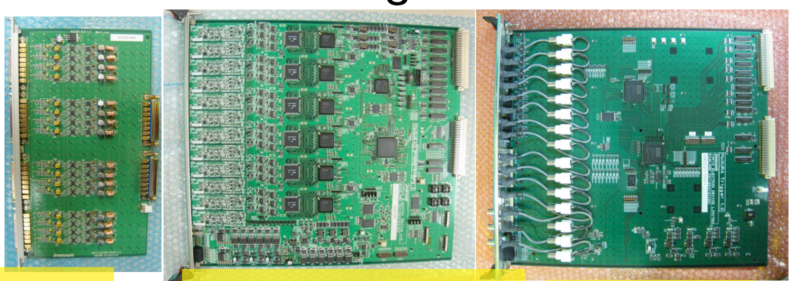
ΔR<1.6m

Study ^{10}C events in outer LS (R<3.5m)



New dead-time free electronics

"Mogura" for n-detection

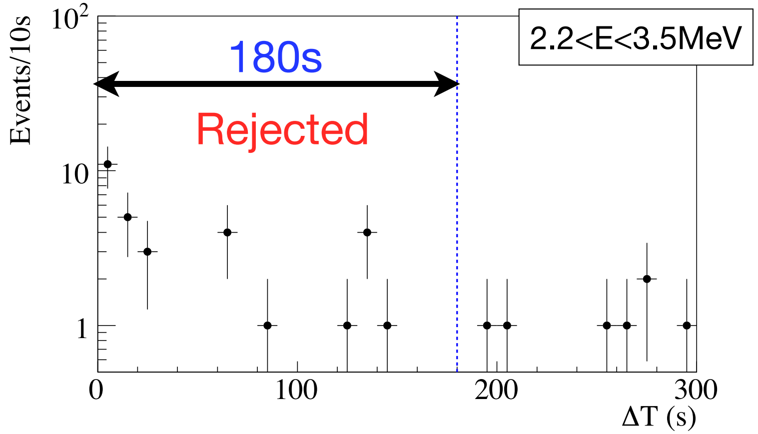


Baseline restorer

1GHz & 3-range 200MHz FADC for each channels

Trigger module

^{10}C decay events in Xe-LS (R<1.0m)



^{10}C detection efficiency: 64±4 %

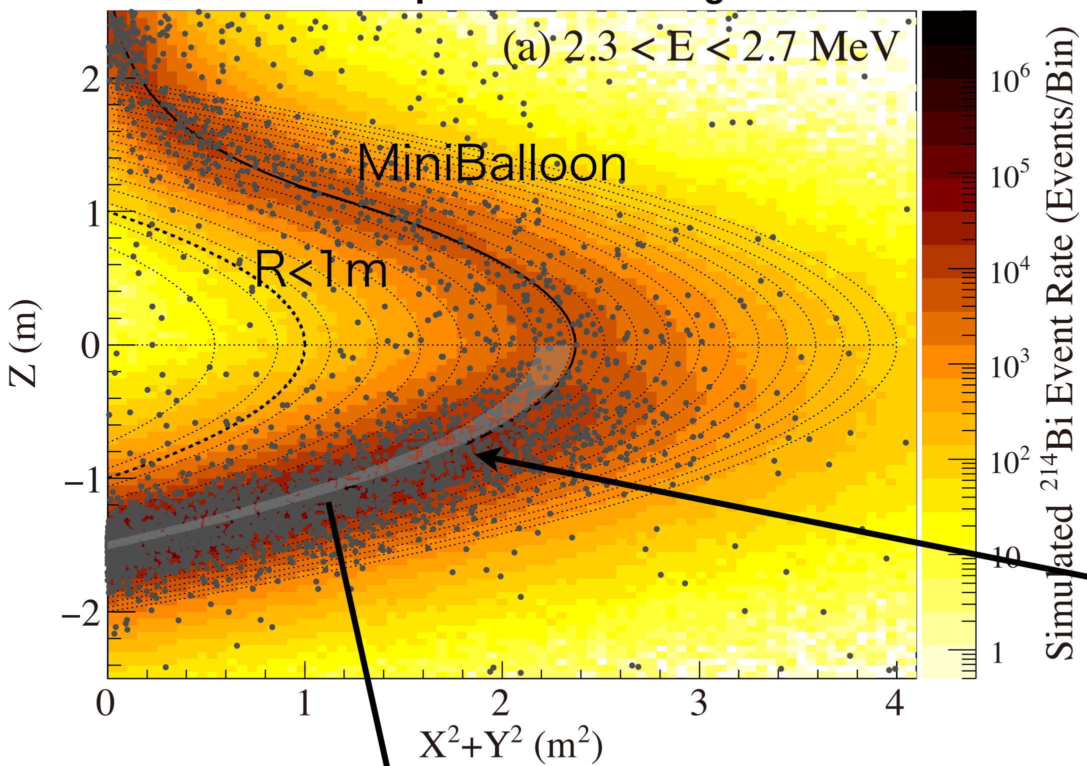
Signal inefficiency: 7%

* ^{137}Xe (β^-, τ=5.5min, Q=4.17MeV) production is dominated by n+^{136}Xe.
(Estimated by spallation neutron rate & capture cross section)

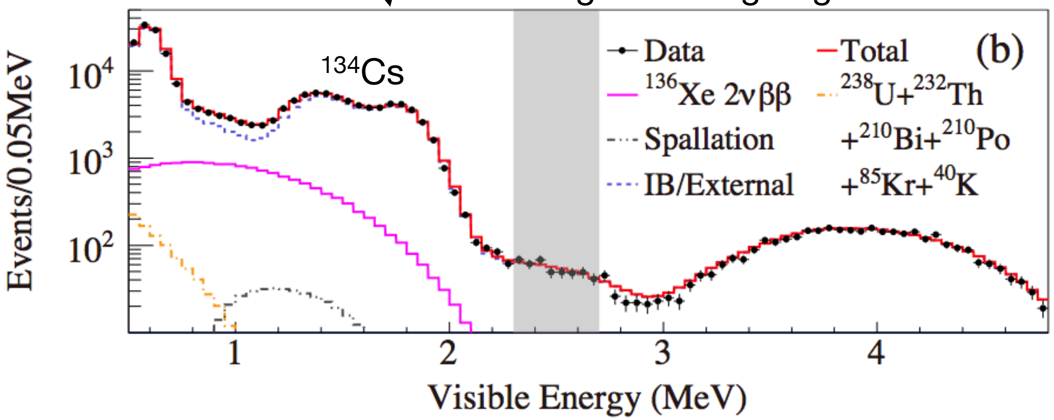
Post-purification data (Phase2)

Exposure of 504 kg yr ^{136}Xe

Dots : Selected events in 0ν window
Color: MC-reproduced ^{214}Bi b.g. events



High ^{214}Bi b.g. region near the IB



Event selection

i) R<2m.

ii) Cut μ-ons +2ms events after μ-ons.

iii) Delayed Coincidence cut for

- ^{214}Bi-^{214}Po(τ=237μs) with ΔT<1.9ms, ΔR<1.7m
- ^{212}Bi-^{212}Po(τ=0.4μs) + Pulse shape
- Reactor $\overline{\nu_e}$ cut (e^+, n capture γ)

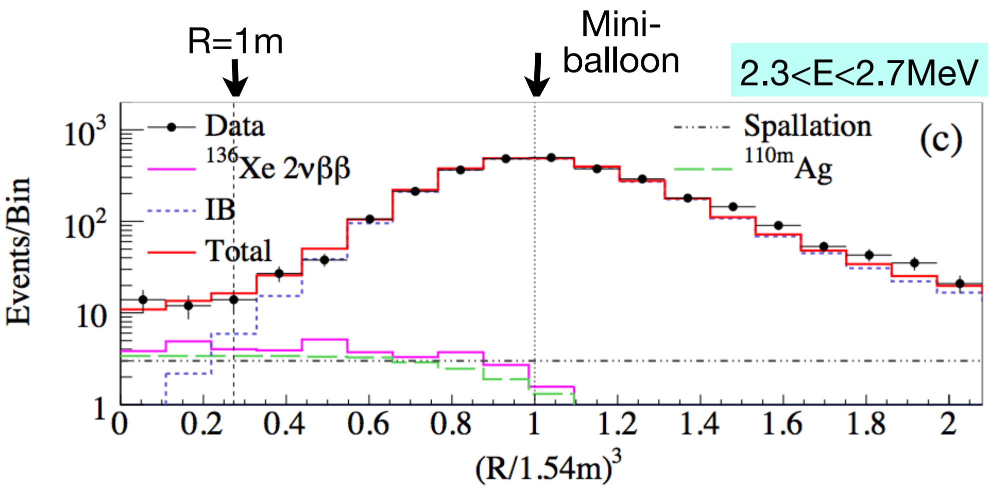
iv) Vertex quality cut (PMT time-charge)

^{214}Bi on the film: Dominant external B.G.!

^{238}U: 160ppt ⇔ 2ppt (ICP-MS)
Not uniform (Upper<Lower)

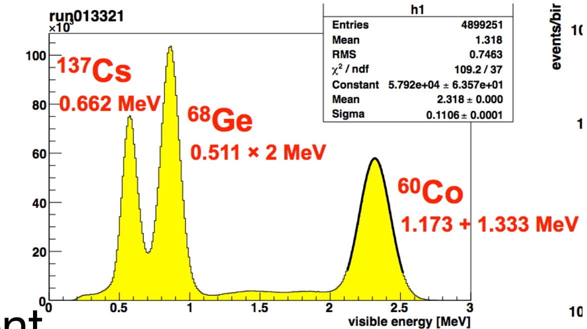
Dusts during mini-balloon construction and diaphragm pump trouble

Analysis optimization by multi-volume selection: Spectra of 20 + 20 equal-volume regions in upper and lower hemisphere for simultaneous fitting.

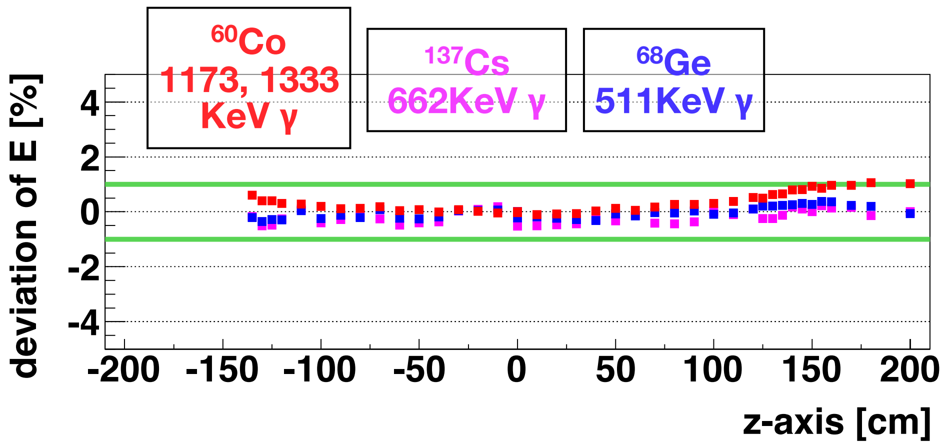


Radial distribution of the candidate events in $0\nu\beta\beta$ region.

^{214}Bi is dominant at the mini-balloon but rapidly decreases in the central part where ^{110m}Ag is remained.

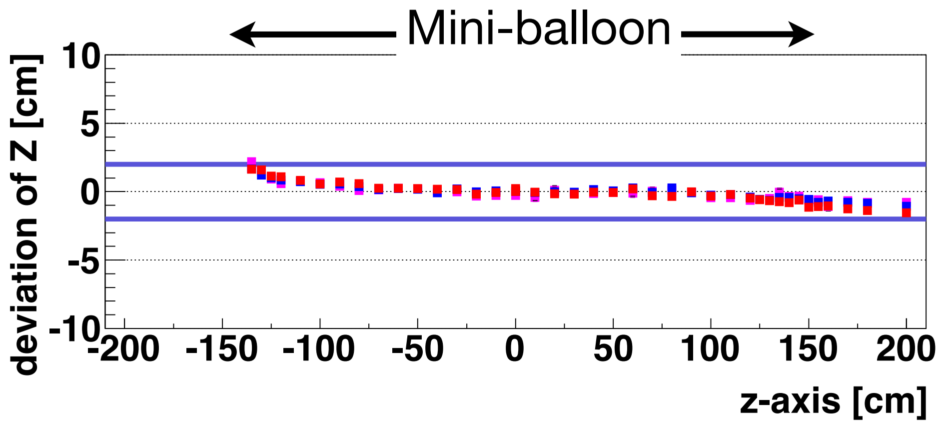


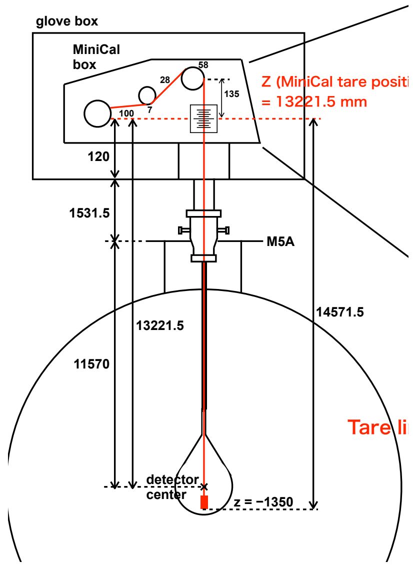
Calibration (Oct.2015, after Phase2)



Position dependent energy bias **< 1%**

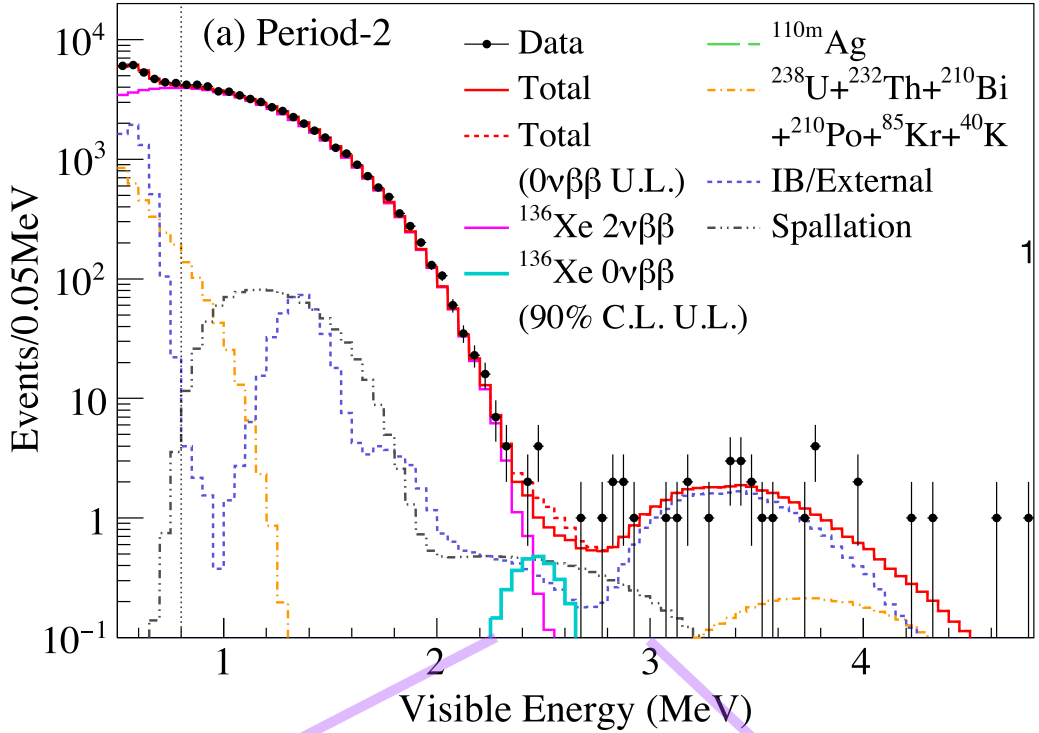
Energy resolution $\sigma/E=(7.3\pm0.4)\%/\sqrt{E_{[MeV]}}$





Position dependent vertex bias **< 1.0cm for |z| <1.0m**

* Energy response at off-axis region (studied by spallation neutron capture on protons) **<1%**



Energy spectrum of the central region (R<1m)

Considering the time dependence of the ^{110m}Ag rate, data is divided into equal periods: Period-1 (270.7d) & Period-2(263.8d).

Fits are performed in 0.8<E<4.8MeV independently for the two periods.

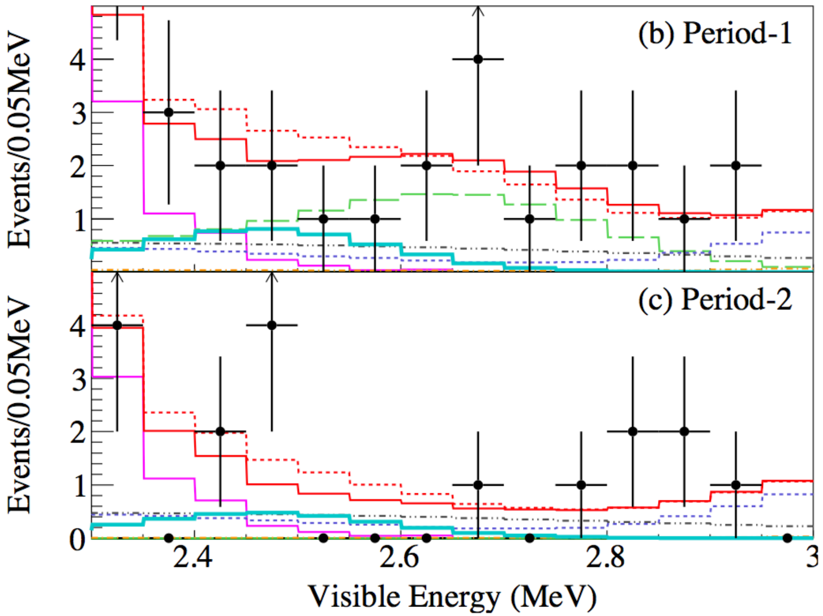
No excess is found over the B.G.

90%C.L. upper limits on ^{136}Xe 0νββ rate [1/(kton-day)]:

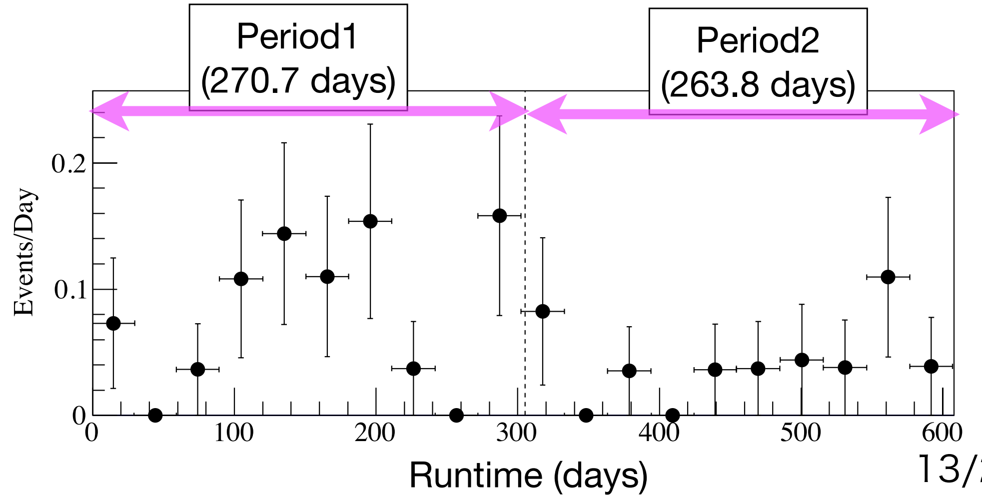
< 5.5 (period-1), <3.4 (period-2)

Combined <2.4 ⇒ **$T^{0\nu}_{1/2}$>9.2×10^{25} yr**

Visible energies in 2.3~3.0MeV



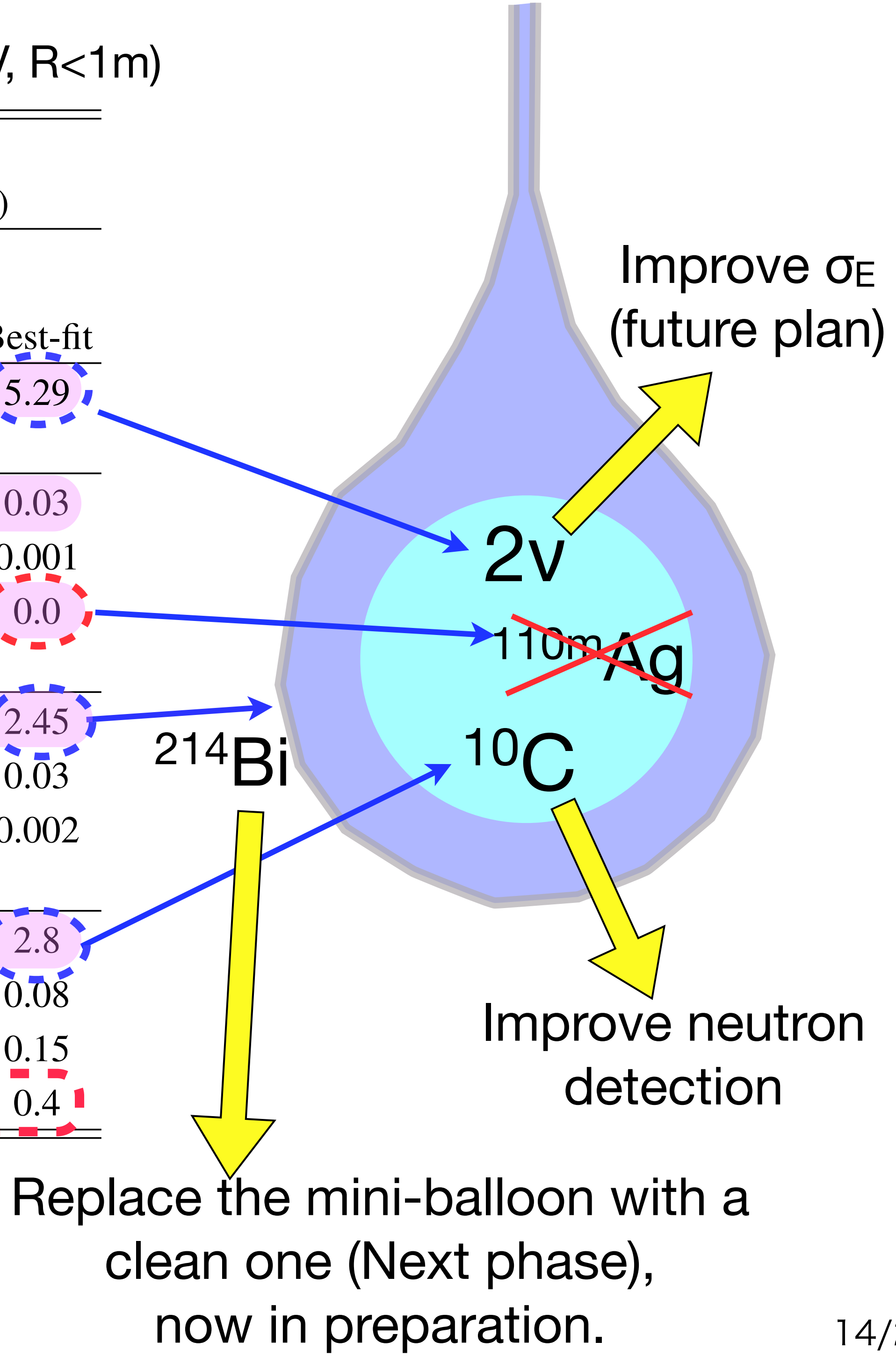
Variance of events/day (2.3-2.7MeV, R<1m)



Summary of the B.G. (2.3<E<2.7MeV, R<1m)

	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.5	-	0.0
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.56	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.003	-	0.002
Spallation products				
^{10}C	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4

*** ^{137}Xe production rate was overestimated in the e-print (arXiv:1605.02889v1[hep-ex]10 May 2016). The correct numbers and figures are slightly changed and presented here, and is appeared in arXiv:1605.02889v2. today.**



* ^{137}Xe production rate was overestimated by ~2 in the e-print (arXiv:1605.02889v1[hep-ex]10 May 2016). ^{137}Xe production is almost from neutron captures, but we misunderstood part of the calculations in FLUKA. Corrected numbers and figures are presented which are slightly changed as follows.*

Old version

Table I, arXiv:1605.02889v1[hep-ex]10 May 2016)

	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.0	-	0.002
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.55	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.002	-	0.001
Spallation products				
^{10}C	2.7 ± 0.7	3.2	2.6 ± 0.7	2.7
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.9 ± 0.5	1.1	0.9 ± 0.5	0.8

Limits (90%C.L.)

$T^{0\nu}_{1/2} > 1.1 \times 10^{26}$ yr

$\langle m_{\beta\beta} \rangle < (60\text{-}\ 161)$ meV

$m_{\text{lightest}} < (180\sim470)$meV

Corrected version

	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.5	-	0.0
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.56	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.003	-	0.002
Spallation products				
^{10}C	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4

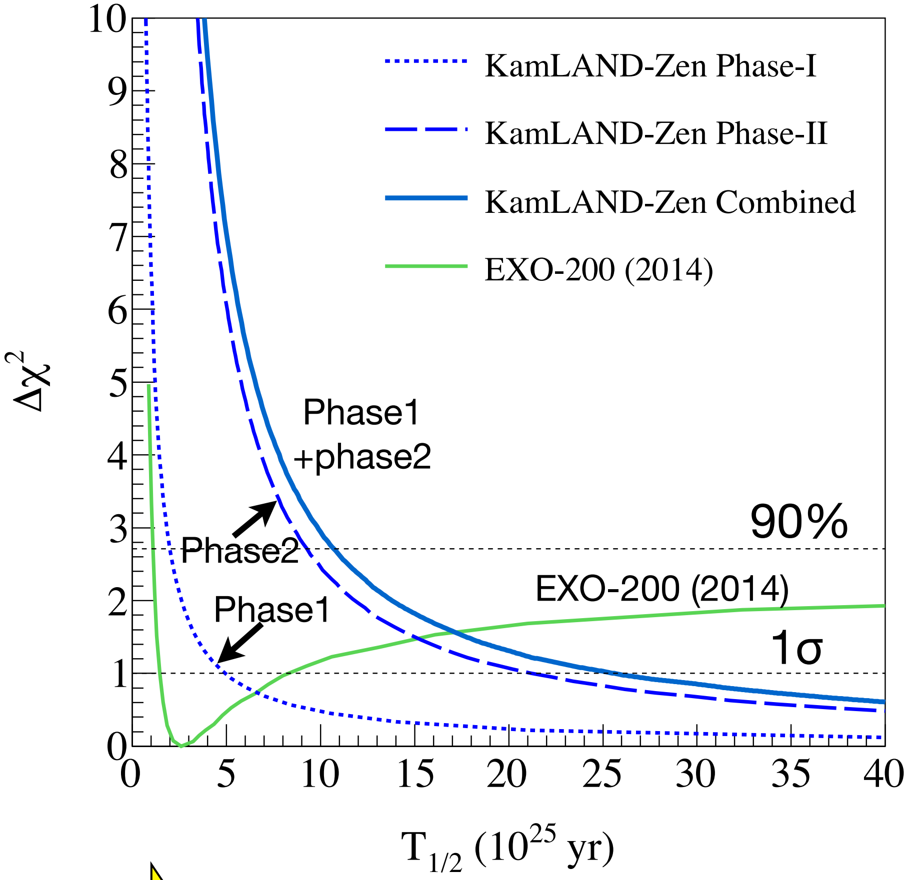
Limits (90%C.L.)

$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr

$\langle m_{\beta\beta} \rangle < (61\text{-}\ 165)$ meV

$m_{\text{lightest}} < (180\sim480)$meV

^{136}Xe 0νββ Decay Half-life



KamLAND-Zen

Half-life limit (@90%C.L.)

Phase1 $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr

Phase2 $T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr ×6!

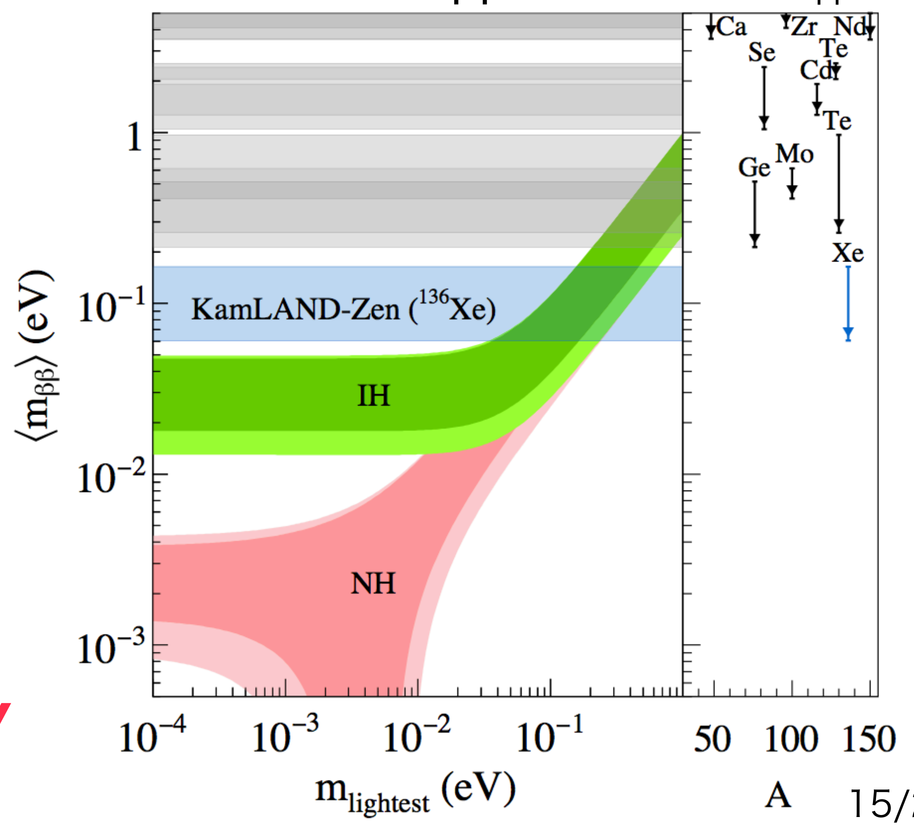
Combined $\mathbf{T^{0\nu}_{1/2} > 1.07{\times}10^{26}}$ **yr**

$\langle m_{\beta\beta}\rangle$ < (61- 165) meV

Commonly used NME with g_A~1.27,
Improved phase space calculations.

$m_{lightest}$ < (180~480)meV

90%C.L. upper limits on $\langle m_{\beta\beta}\rangle$



$\langle m_{\beta\beta}\rangle$ limit reaches below 100meV
and getting close to the IH region !

$2\nu\beta\beta$ decay rate

Fiducial vol. R<1m (126 kg-yr ^{136}Xe exposure)
Likelihood fit to 0.5<E<4.8 MeV

Results on $T^{2\nu}_{1/2}$=

2.21±0.02(stat)±0.07(sys) ×10^{21}yr (Phase2)

2.30±0.02(stat)±0.12(sys) ×10^{21}yr (Phase1) *PRC86, 021601 (2012)*

2.165±0.016(stat)±0.059(sys) ×10^{21}yr (EXO-200) *PRC89, 015502 (2014)*

Systematic uncertainty	(%)
Fiducial vol.	3.0*
Xe-mass	0.8
Detector energy scale	0.3
Efficiency	0.2
^{136}Xe enrichment	0.09

⇒ **Total 3.1%**

*from initial radon-rich data of uniform ^{214}Bi in Xe-LS ⇔ consistent with radial vtx. resolution=1cm.

Recent activity & schedule

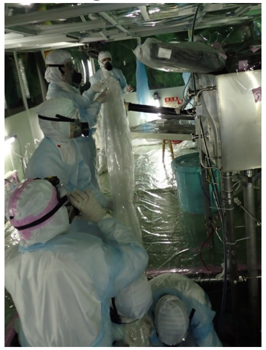
2015
- Oct Source calibration, Phase 2 terminated.
- Dec Mini-balloon extraction

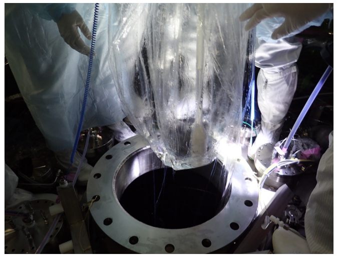
Phase1&2: KamLAND-Zen 400

Kamioka

2016
- Jan~Mar Outer detector refurbishment — Kamioka
- May~ Xe-distillation, LS-distillation
- Apr-Jul **New Mini-balloon construction finalized (⇒next slide)** — Sendai
- Aug New mini-Balloon installation
- Sep~ Xe dissolving and Xe-LS filling, — Kamioka
- Oct **Start new phase : KamLAND-Zen 800.**

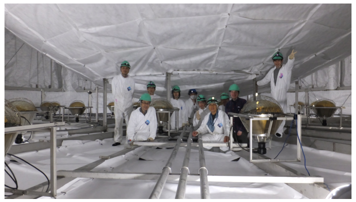
Taking out the mini-balloon (Dec.2015)





Last drip of the LS in the mini-balloon

OD refurbishment (225 PMTs were replaced with new 140 PMTs)



Towards higher sensitivity (1)

^{214}**Bi removal**
$\langle m_{\beta\beta}\rangle \sim$ 40meV

"KamLAND-Zen 800" (now in preparation !)

(P1.064 S.Hayashida)

A new, clean & double-volume mini-balloon construction
(750kg enriched Xe)

Construction of the main body was finished (2015) in a class1 super-clean room in Tohoku Univ. with much better cleanliness and improved dust control.

2015

Washing nylon films (Ultra-pure water + ultrasonic machine)

Two-stage clean wears including shoes and gloves. Wear changing in one of the clean rooms.

Clean wears and goggles are washed every after the shift.

Gore welding

A new large welding machine
Protection films on the balloon film.
A new storage bag for the mini-balloon
A new particle counter.
More electrostatic eliminators

2016

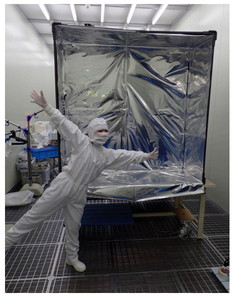
Washing parts

Leak hunting with helium detector

Repair

Air-tight bag

Container



Miniballoon assembly for deployment is underway. It is sent to Kamioka very soon.

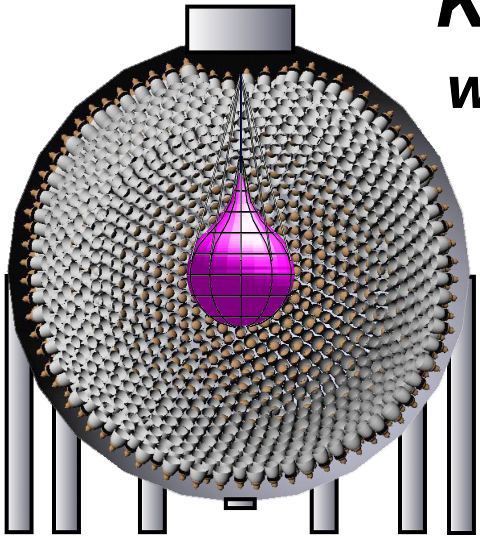
The new mini-balloon is deployed in KamLAND in the next month !

Towards higher sensitivity (2)

"KamLAND2-Zen"

with 1000kg enriched Xe

Many R&Ds are ongoing !



Better σ_E/E~2%
to remove 2ν b.g.
⇒ ⟨$m_{\beta\beta}$⟩～20meV

Full coverage of IH !

More photons for better σ_E

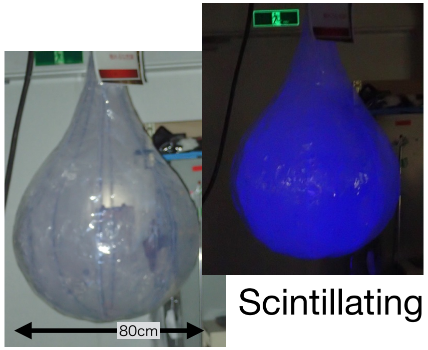
- New LAB-based LS (L.Y.×1.4),
- New High Q.E. PMT (×1.9),
- Light collector of PMT(×1.8)

New-type high Q.E. PMT

Light collector

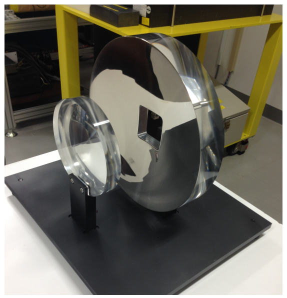
Background rejection

- Scintillating balloon (^{214}Bi tagging)
- New method for LS purification :
  Molecular sieve, Metal scavenger
- Imaging sensor
- Pressurized Xe-LS

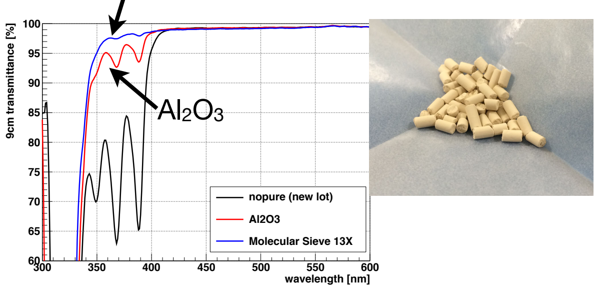


Scintillating balloon

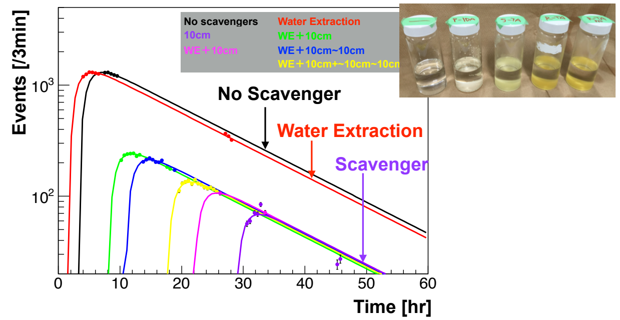
Imaging sensor



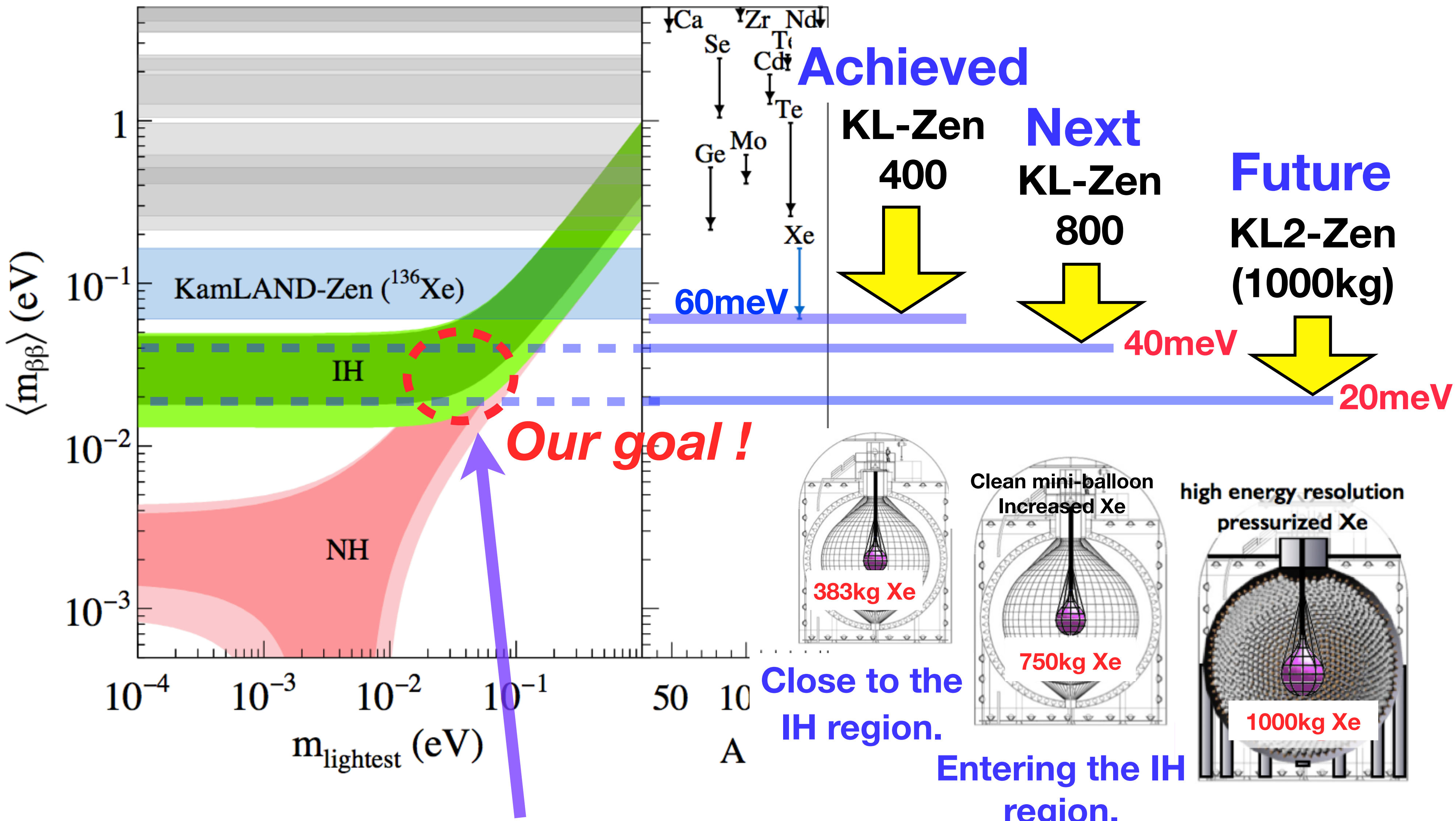
Molecular sieve 13X



Metal scavenger



KamLAND-Zen sensitivity



Covering most of the IH region !

Branch point of the IH and NH

Cosmological observation
Accelerator, reactor, atmospheric, solar ν experiments
Theoretical research

Summary

- KamLAND-Zen phase2 (post purification phase) data corresponding to 504kg-yr ^{136}Xe exposure showed successful reduction of ^{110m}Ag and higher sensitivity to the 0νββ search.
- Combined 90%C.L. limits on 0νββ of phase1+phase 2 (KamLAND-Zen 400) are

  $T^{0\nu}_{1/2} > 1.07\times10^{26}$ yr (90%CL) : ~6 times improvement of phase1

  $\langle m_{\beta\beta}\rangle < 61\text{-}165$meV : approaching to the IH region.

- Preparation is ongoing for the next phase of KmaLAND-Zen 800 ; a new mini-balloon is installed next month and data taking will be started in the autumn aiming to $\langle m_{\beta\beta}\rangle \sim 40$meV entering the IH region.
- Various R&Ds are ongoing for the future KamLAND2-Zen aiming to $\langle m_{\beta\beta}\rangle \sim 20$meV fully covering the IH region.

Announcement !

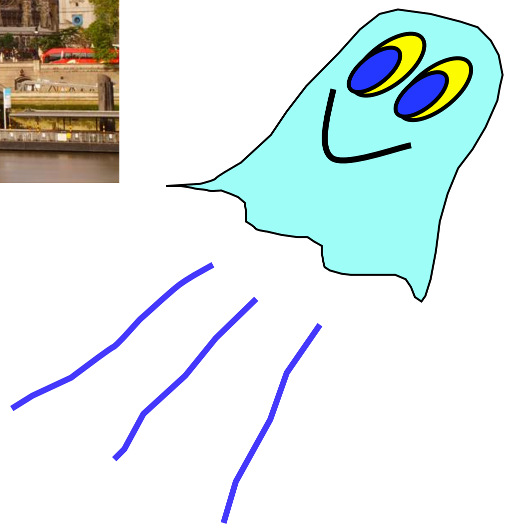
International Workshop on Double Beta Decay and Underground Science

Nov. 8-10, 2016, Osaka, Japan

http://www.rcnp.osaka-u.ac.jp/dbd16/index.html

Please join !

Thank you !



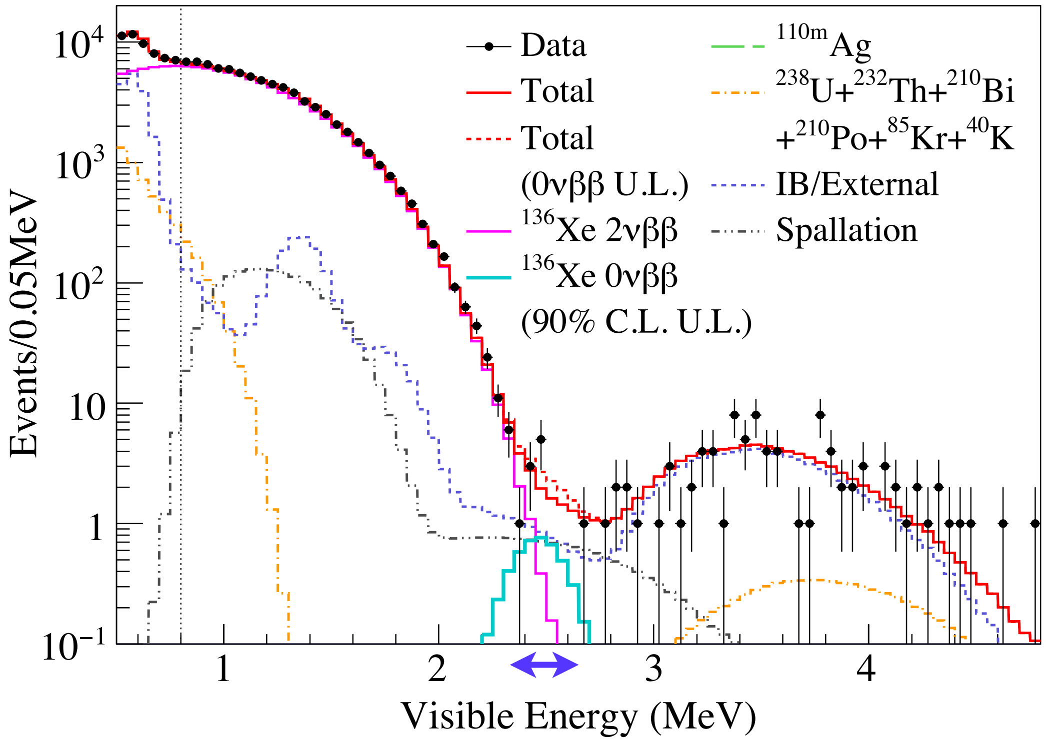
Backup slides

The obtained limit is better than the sensitivity

Optimized volume sensitive to 0nbb search:

R<1.063m in z<0, R>1.260m in z>0

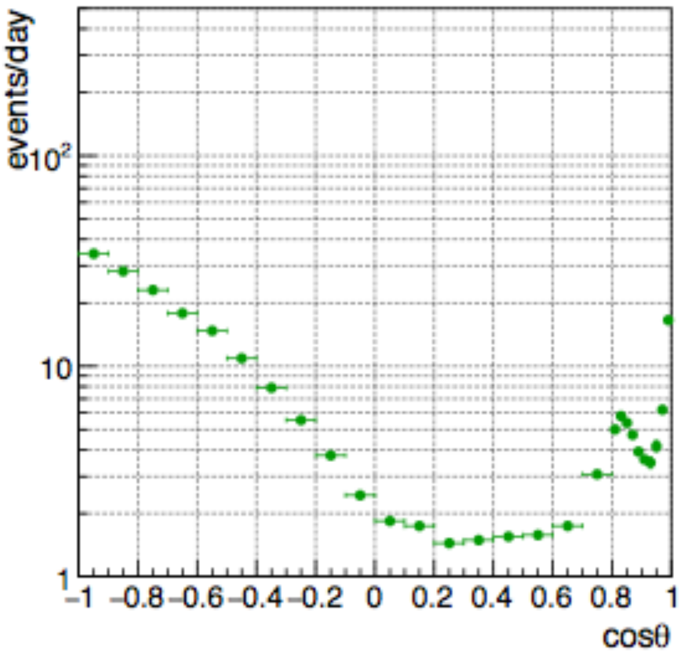
(3 volume bins in z<0 and 5 volume bins in z>0)



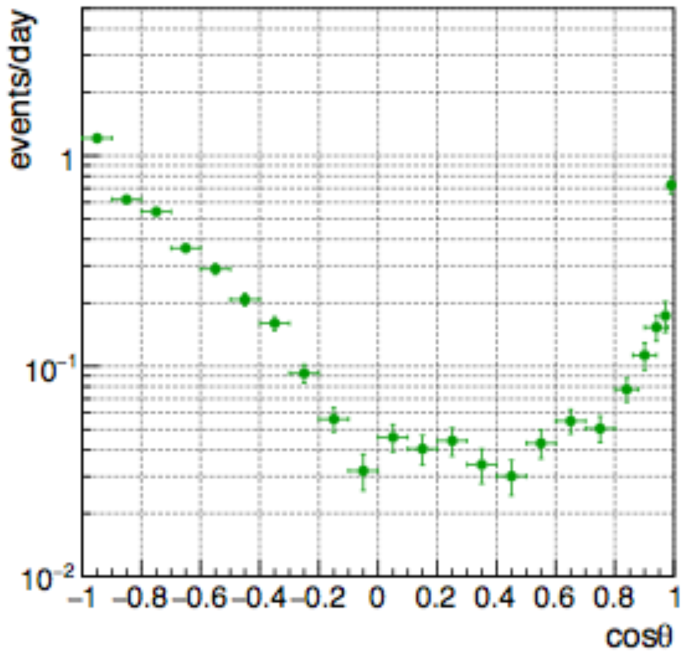
We find **9** events in 2.35-2.65 MeV region over the expected background of **12.9** providing 90%C.L. upper limit on 0nbb to <**3.3** events.

If we had found **13** events, the same as the B.G. expectation, the limit would increase to <**7.2** events, indicating the above limit (< 3.3) is ~2 times stronger than the sensitivity.

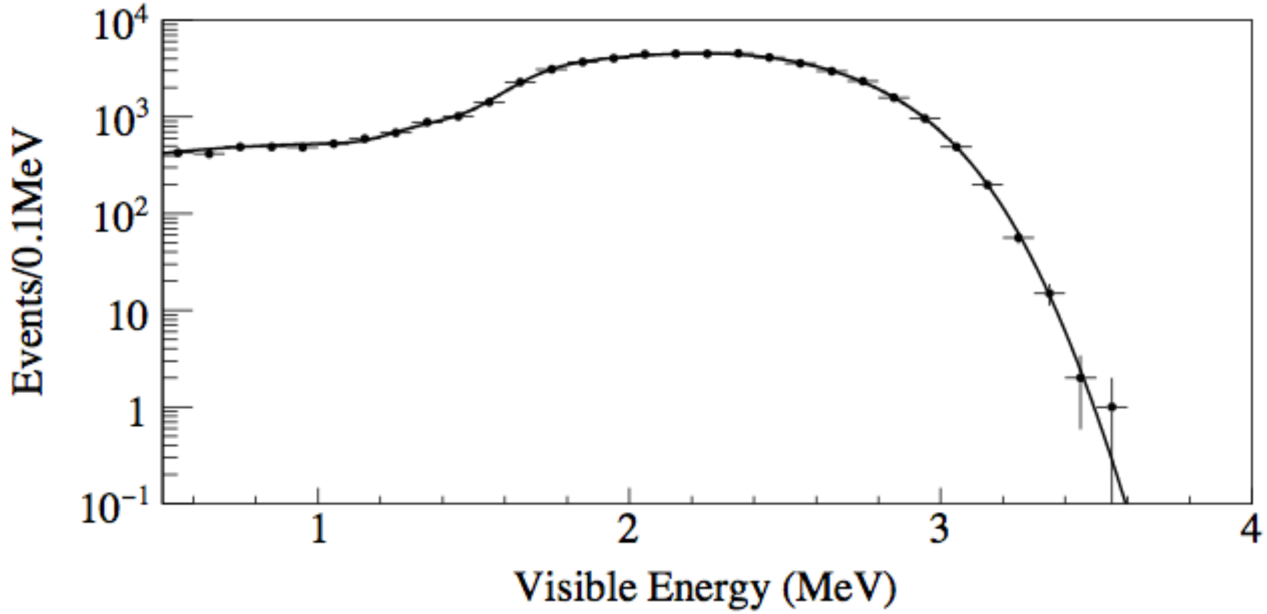
Cs



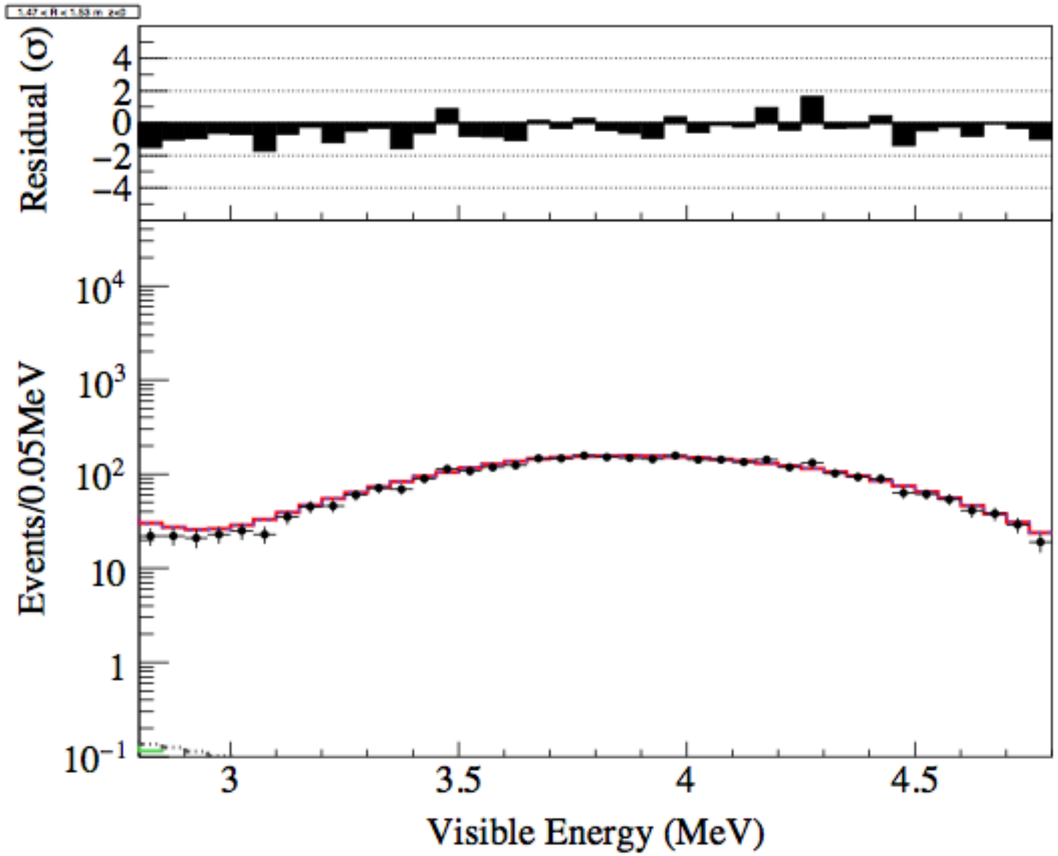
U



Cs and U show similar z-dependence indicating they are both from dust contamination.

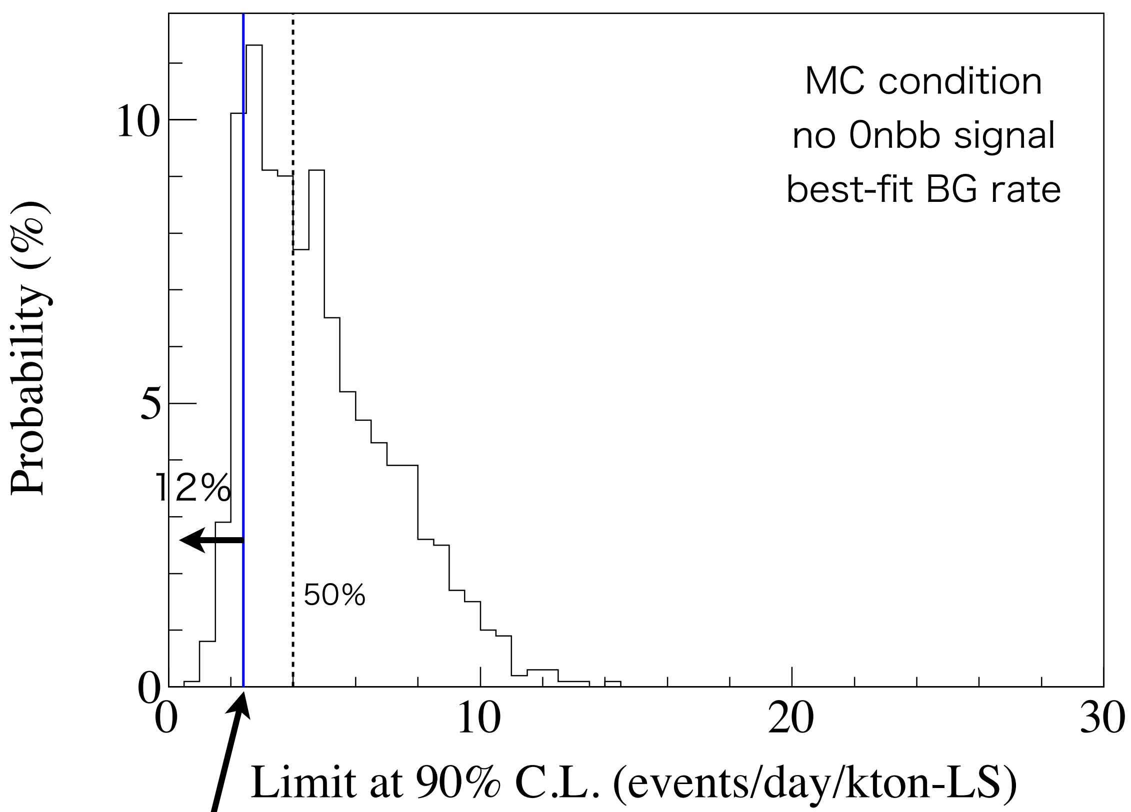


^{214}Bi events tagged with delayed coincidence in high ^{220}Rn data are well reproduced.



Pull histogram of 2.8-4.8MeV region.
No data points are outside of 2 sigma.

Upper limits from Toy MC



2.4

$T^{0\nu}_{1/2} > 9.2\times10^{25}$ yr

50% sensitivity 5.6×10^{25} yr

Sensitivity is checked by MC assuming best-fit BG rate.