Experimental review of DBD and KamLAND-Zen experiment

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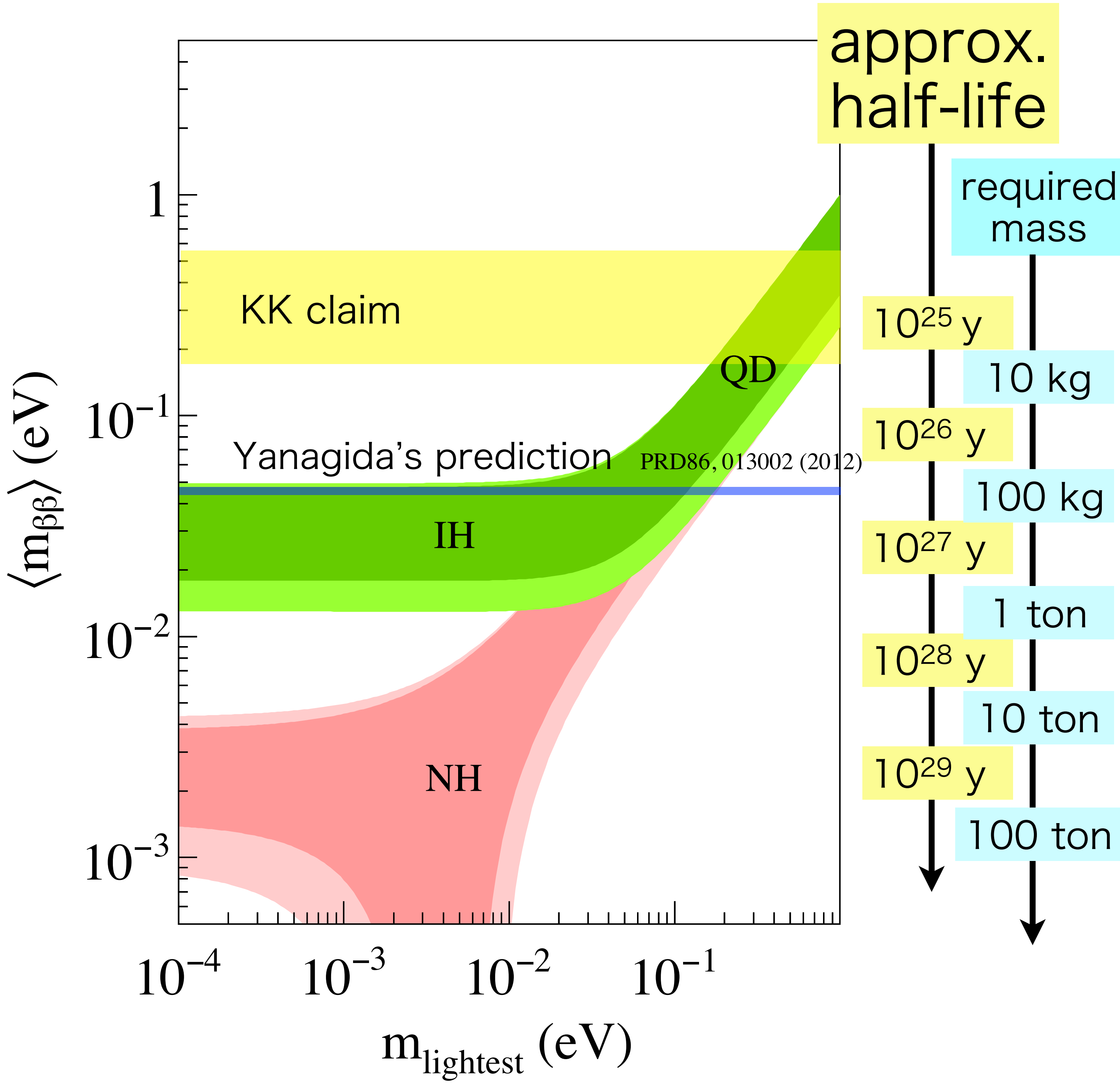
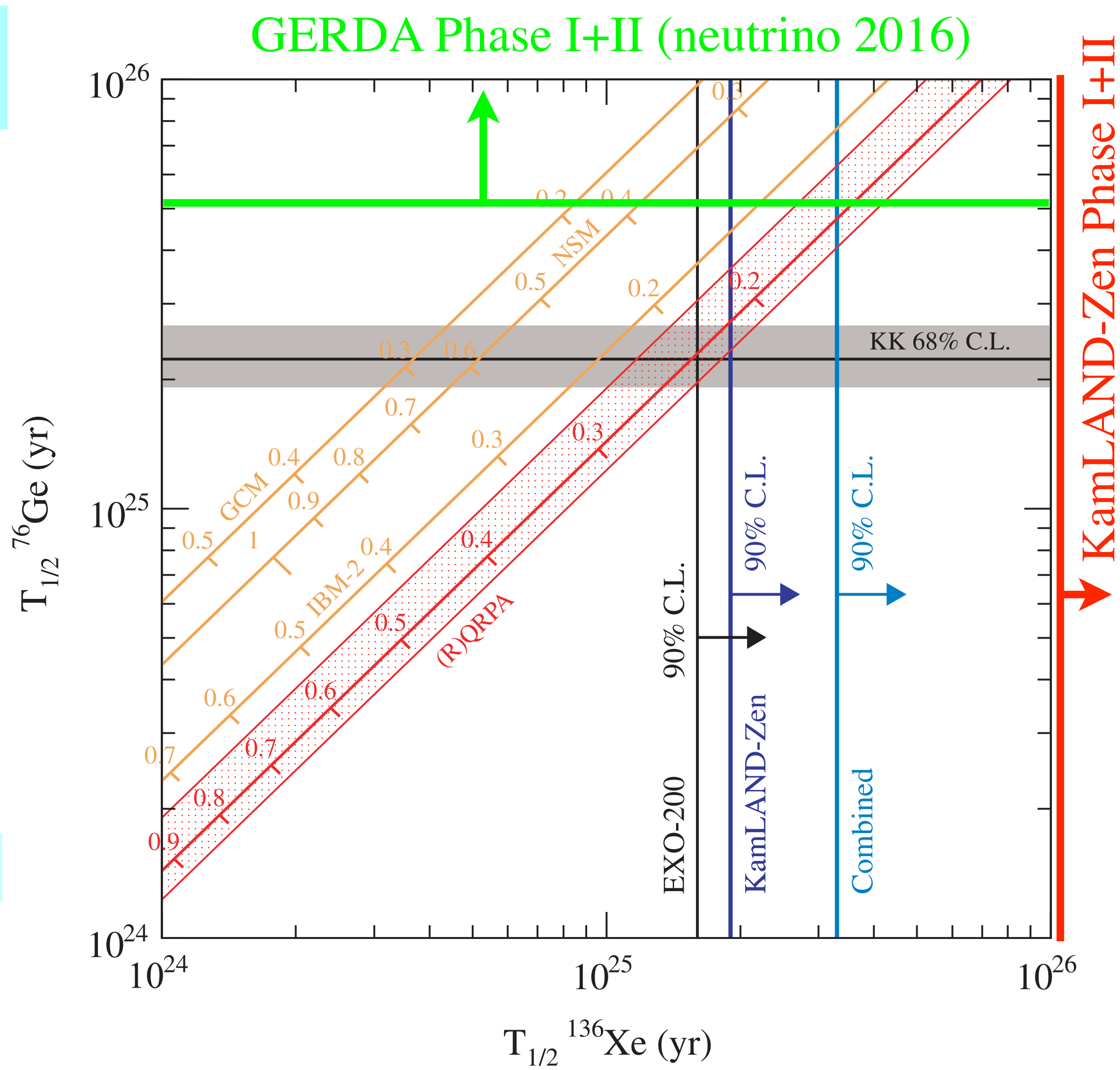
Double Beta Decay and Underground Science,
Hankyu Sanwa Hall, 8 November 2016

Milestone





Experimental milestone has been a verification of KK-claim.

KL-Zen+EXO-200 refuted it with fairly robust NME assumption.

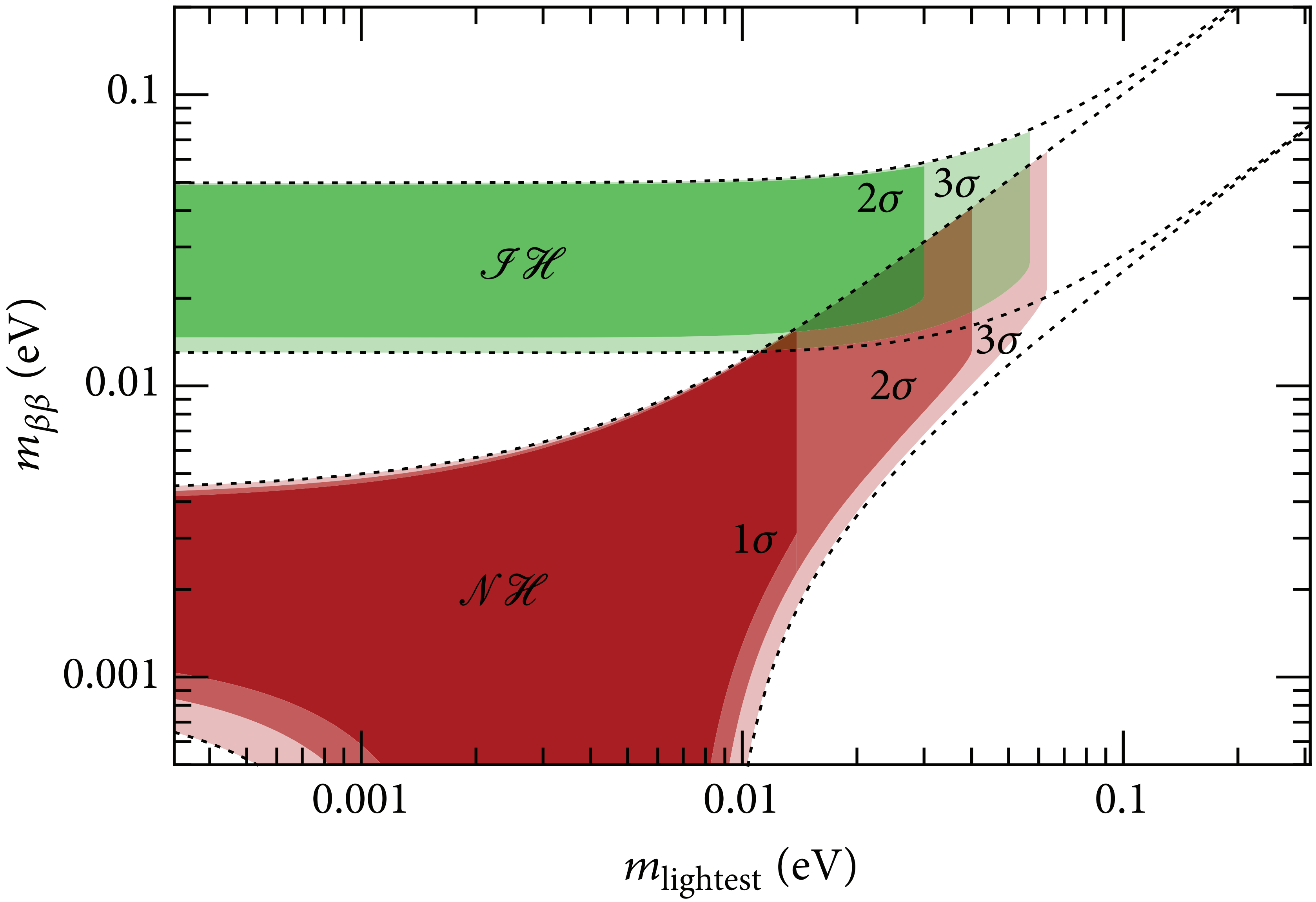
GERDA then clearly rejected it using the same ^{76}Ge.

What's next?

full coverage of Quasi Degenerate → next milestone
full coverage of Inverted Hierarchy → next gen. exp.
full coverage of $m_{lightest}$~0 (below 1 meV) → very difficult

Allowed region from Oscillation and Cosmology

Dell'Oro et al., Advances in High Energy Physics 2016, 2162659



We need to propose a future plan seeking below 10 meV.

comparison of double beta decay nuclei

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

Nucleas	$T^{0\nu}_{1/2}(50\,\mathrm{meV})$	$T^{2\nu}_{1/2}$ measured (year)	Nat. 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}	$(1.5 \pm 0.1) \times 10^{21}$	7.8	2039	semiconductor
$^{82}Se \rightarrow {}^{82}Kr$	2.44×10^{26}	$(0.92 \pm 0.07) \times 10^{20}$	9.2	2995	
$^{96}Zr \rightarrow {}^{96}Mo$	0.98×10^{27}	$(2.0 \pm 0.3) \times 10^{19}$	2.8	3351	
$^{100}Mo \rightarrow {}^{100}Ru$	2.37×10^{26}	$(7.1 \pm 0.4) \times 10^{18}$	9.6	3034	fast 2ν
$^{116}Cd \rightarrow {}^{116}Sn$	2.86×10^{26}	$(3.0 \pm 0.2) \times 10^{19}$	7.5	2805	
$^{128}Te \rightarrow {}^{128}Xe$	4.53×10^{27}	$(2.5 \pm 0.3) \times 10^{24}$	31.7	867	
$^{130}Te \rightarrow {}^{130}Xe$	2.16×10^{26}	$(0.9 \pm 0.1) \times 10^{21}$	34.5	2529	large nat. abundance
$^{136}Xe \rightarrow {}^{136}Ba$	4.55×10^{26}	$(2.3 \pm 0.1) \times 10^{21}$	8.9	2476	slow 2ν, rare gas
$^{150}Nd \rightarrow {}^{150}Sm$	2.23×10^{25}	$(7.8 \pm 0.6) \times 10^{18}$	5.6	3367	0ν, fast 2ν

Notable nuclei

^{48}Ca highest Q, isotope enrichment is an issue → Iida's talk

^{76}Ge semiconductor

^{136}Xe easy enrichment / purification, various detector technology

^{130}Te high natural abundance

^{150}Nd fast 0ν

So far, leading experiments are using technologies;

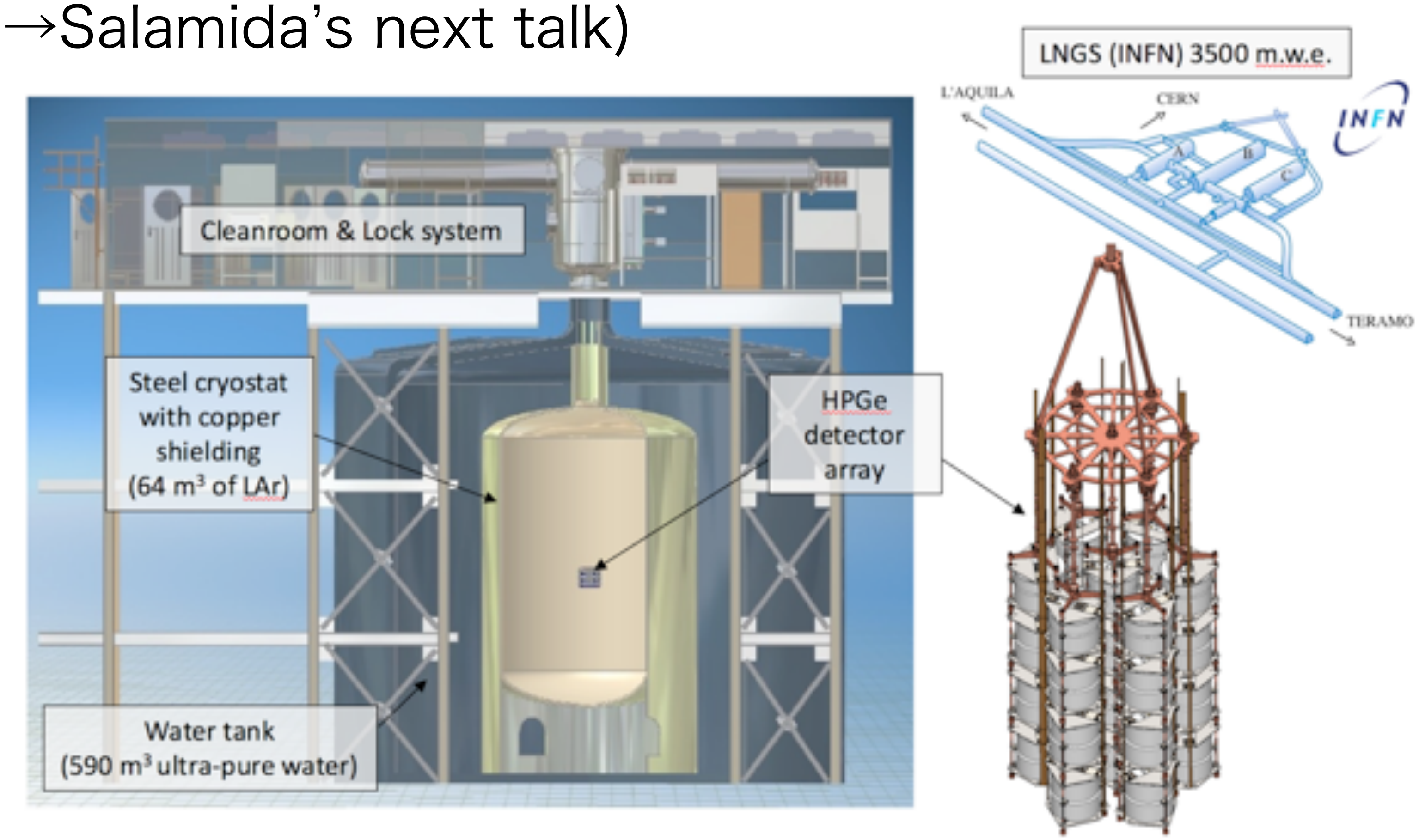
- Ge semiconductor (GERDA/Majorana)
- Tracking (NEMO-3)
- bolometer (CUORE)
- liquid xenon TPC (EXO-200)
- LS with xenon (KamLAND-Zen)

In addition to the above, next generation uses;

- doped LS (SNO+)
- hybrid bolometer (CUPID, AMoRE, CANDLES)
- high pressure gas TPC (NEXT, PandaX-III, AXEL)

Let me explain my view of their pros and cons, briefly.

GERDA (→Salamida's next talk)



pros

high resolution (no 2ν BG)

active shielding

PSD

easier cooling (in comparison with bolometers)

cons

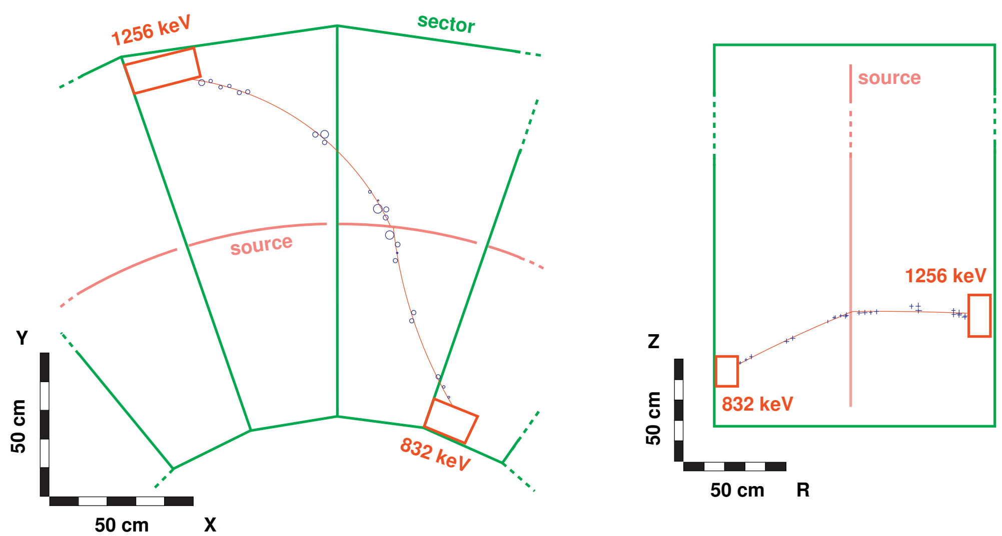
costly enrichment

~~external gamma/neutron~~

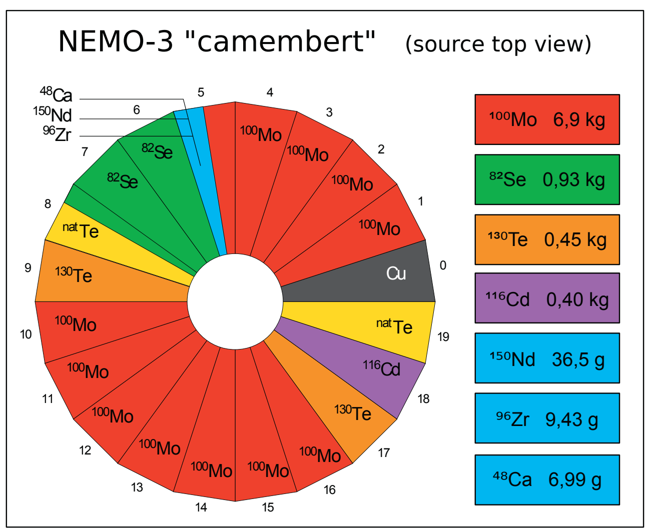
~~surface BG~~

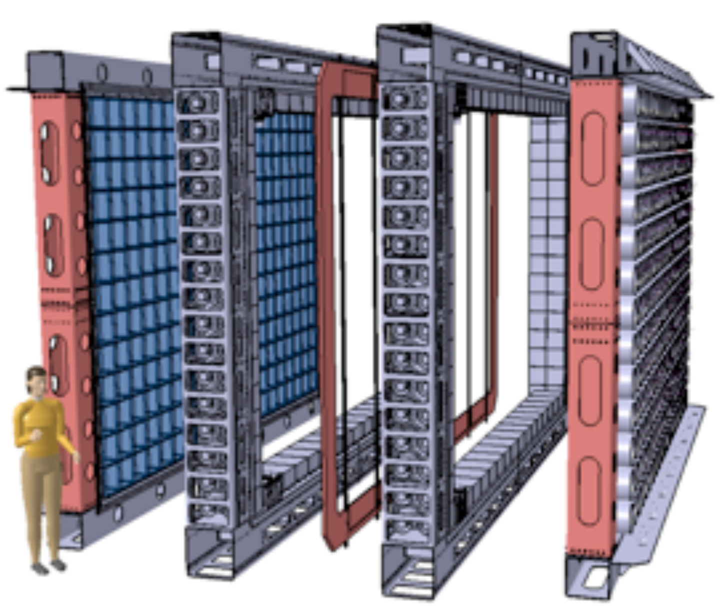
$T_{1/2}>5.2\times10^{25}$yr (90%CL) neutrino 2016

NEMO-3 (→Vilela's talk)



Isotope	Mass [g]	$Q_{\beta\beta}$ [keV]	Sig/Bkg	$T_{1/2}$ [years]
^{100}Mo	6914	3034	76	7.16 ± 0.01 (stat) ± 0.54 (syst) 10^{18}
^{82}Se	932	2995	4	9.6 ± 0.1 (stat) ± 1.0 (syst) 10^{19}
^{130}Te	454	2529	0.25	$7.0 \pm 1.4\ 10^{20}$
^{116}Cd	405	2805	10.3	$2.9 \pm 0.3\ 10^{19}$
^{150}Nd	37.0	3368	2.8	$9.1 \pm 0.7\ 10^{18}$
^{96}Zr	9.43	3350	1.0	$2.35 \pm 0.21\ 10^{19}$
^{48}Ca	6.99	4274	6.8	$4.4 \pm 0.6\ 10^{19}$





pros

tracking

various nuclei

- helpful for reducing uncorrelated NME uncertainty
- provides additional sensitivity to resolve underlying physics
- clear signature when found

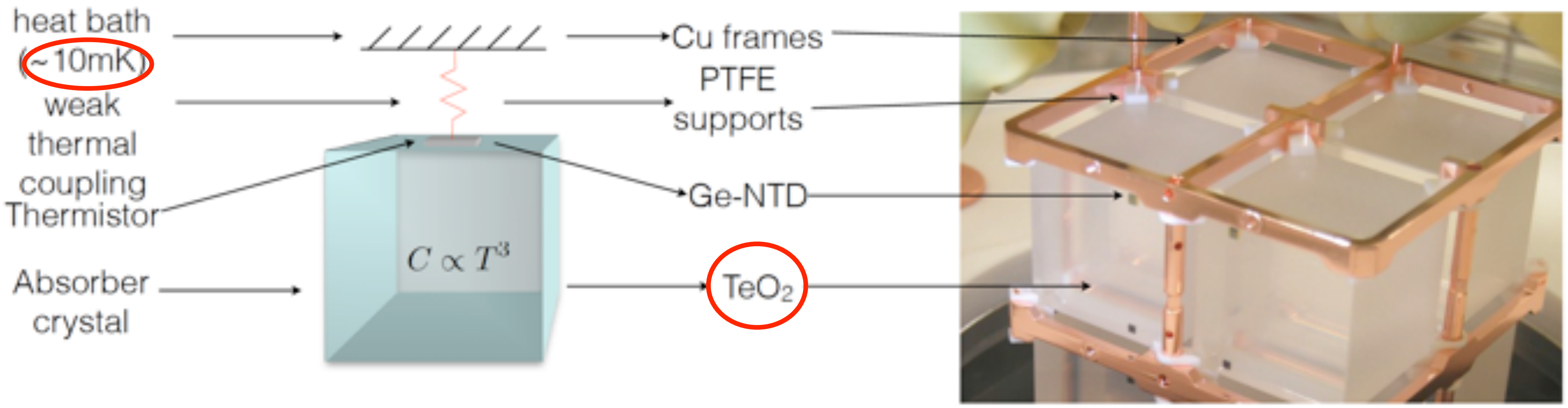
cons

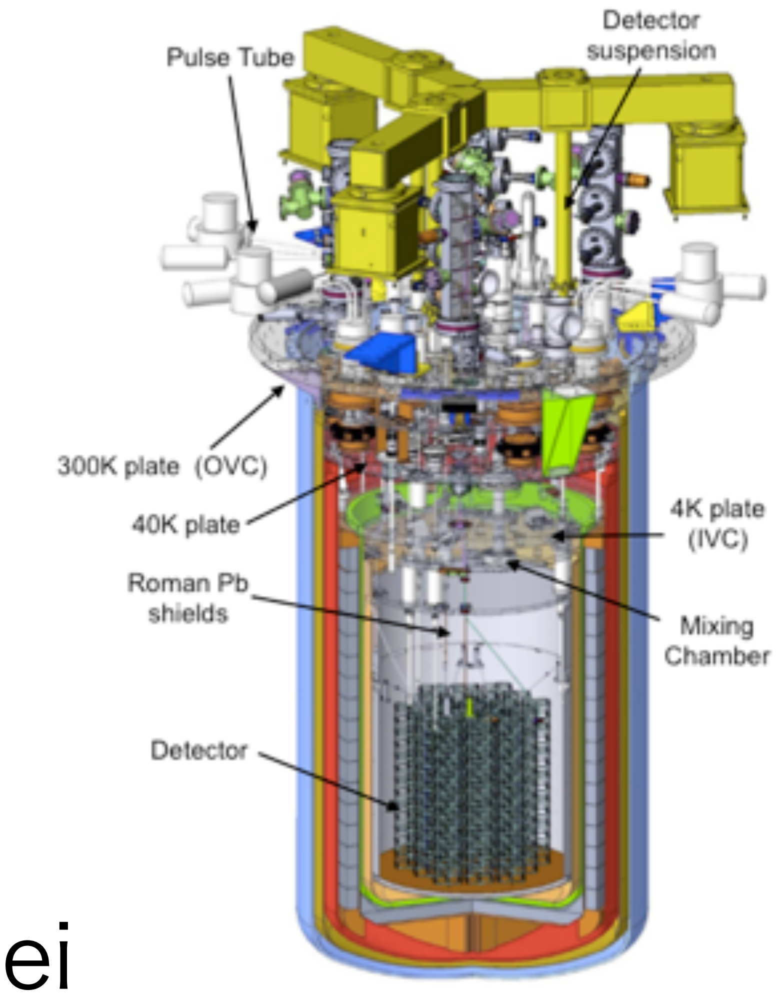
relatively poor energy resolution

limited scalability

Super NEMO is aiming at 50~100meV sensitivity (with 500kg・yr)

CUORE (→O'Donnell's talk)





pros

high resolution ideally with various nuclei

scintillation / phonon hybrid detection possible

cons

costly low T cavity (makes active shielding expensive or difficult)

(Vignati's talk)

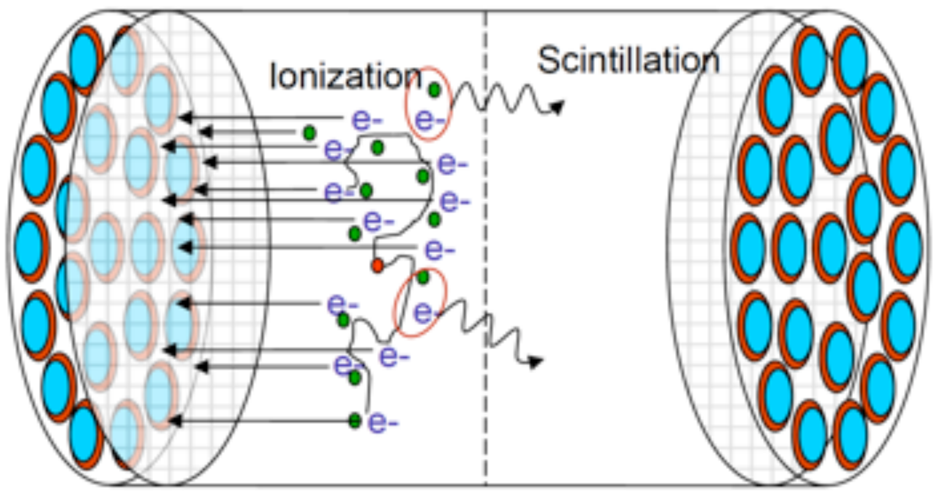
CUORE/CUPID are aiming at 50~130, O(10) meV sensitivity

(CUORE Upgrade with Particle IDentification ← scintillation hybrid)

AMoRE, CANDLES are also pursuing Hybrid concept.

(Park's talk) (Iida's talk)

EXO-200 (→Sinclair's talk)

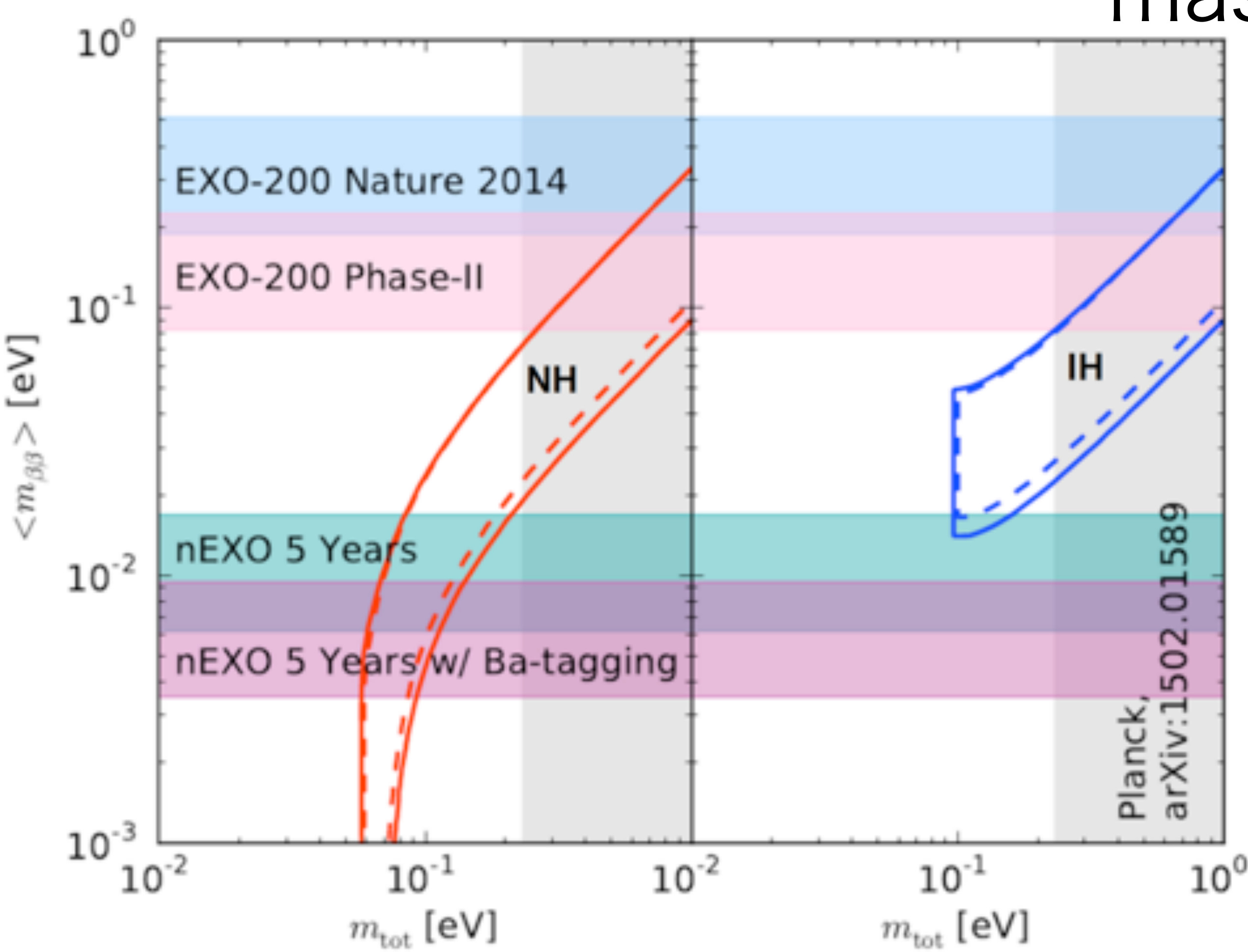


pros

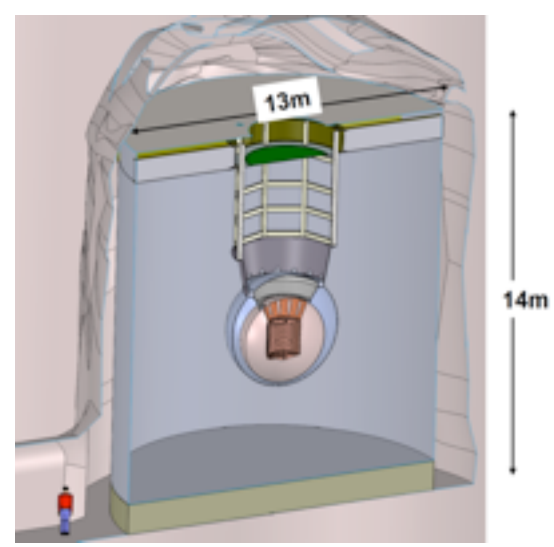
- compact monolithic detector (scalability)
- 3D reconstruction (BG rejection)
- sufficient energy resolution
- purification possible

cons

- Radon emanation
- massive structure

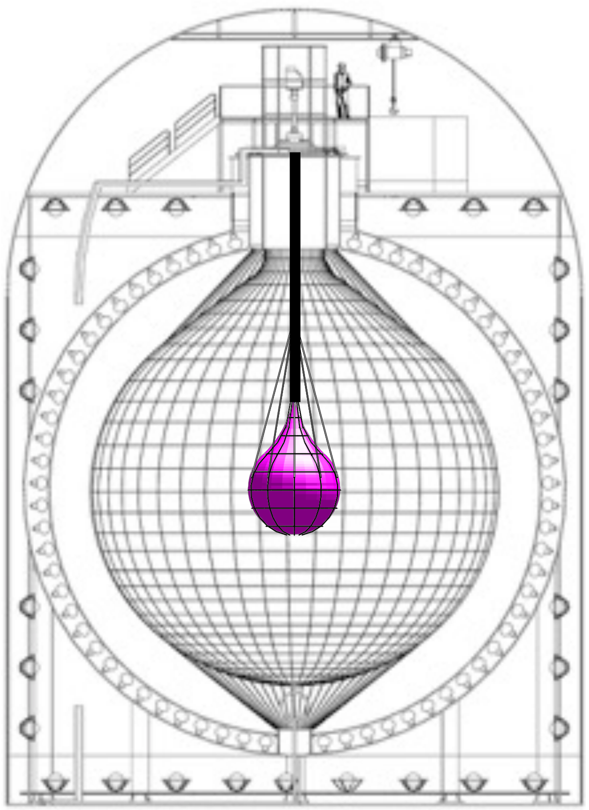


nEXO (5 ton Xe)



nEXO target sensitivity below 10 meV widely covers NH.

KamLAND-Zen



pros

- scalability (380kg→750kg planned)
- all active detector (^{208}Tl is above ROI)
- large active shielding
- minimum detector material (all β & γ detectable)
- on/off measurement
- in-situ purification

cons

- low resolution (2ν BG)
- low concentration
- high muon rate (spallation BG)

So far providing the world best limit

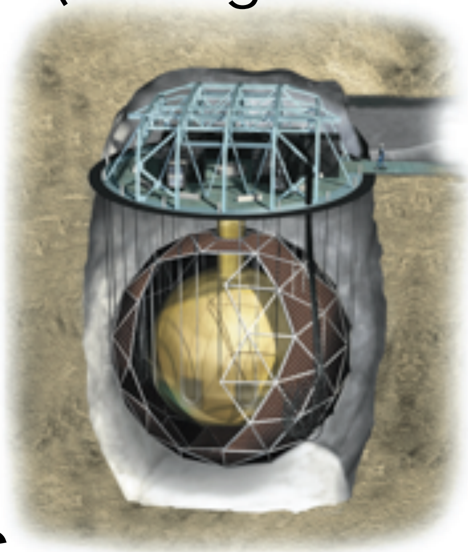
$$T_{1/2} > 1.07 \times 10^{26} \text{yr (90\%CL)}$$

$$m_{ee} < 61 \sim 165 \text{ meV}$$

future target KL-Zen 800 → KL2-Zen → SuperKL-Zen?
50meV 20meV 8meV?

SNO+ (→Singh's talk)

SNO+ Phase I 0.5wt% Te → 1333kg ^{130}Te (260kg FV)
expected to start in early 2018



5 yr expected sensitivity 1.96×10^{26}yr
(similar to KL-Zen 800)

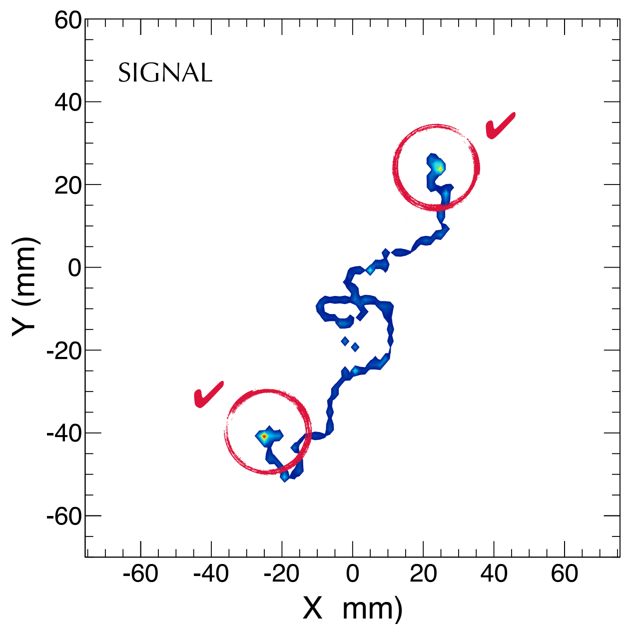
Phase II aiming at 10^{27}yr sensitivity

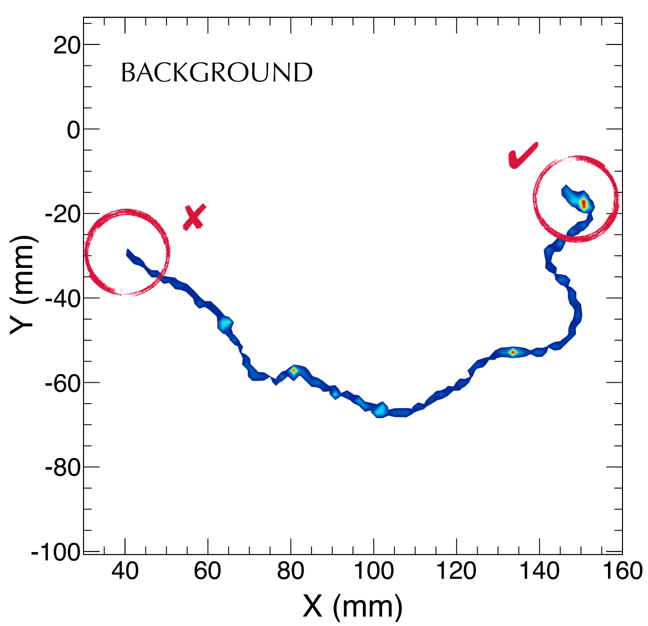
pros
- negligible spallation BG
- huge target mass
- all active

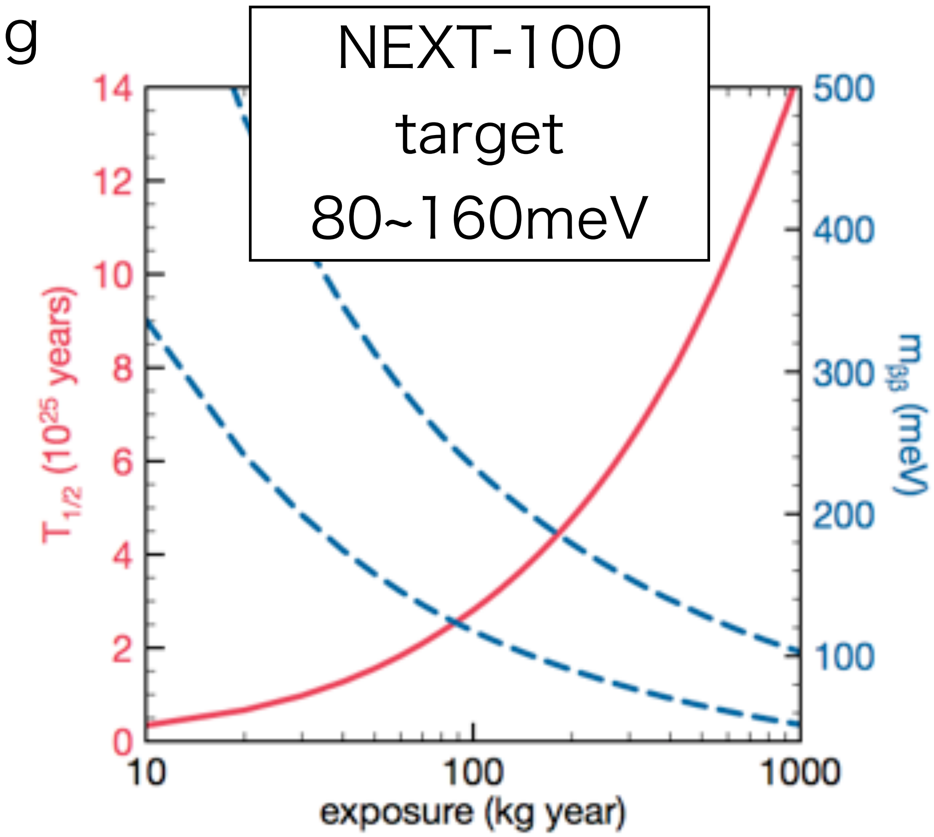
cons
- low concentration (tough after-purification)
- moderated energy resolution

NEXT (→JJ's talk)

(Ichikawa/Han's talks)
(AXEL/PandaX-III are developing with a similar concept.)







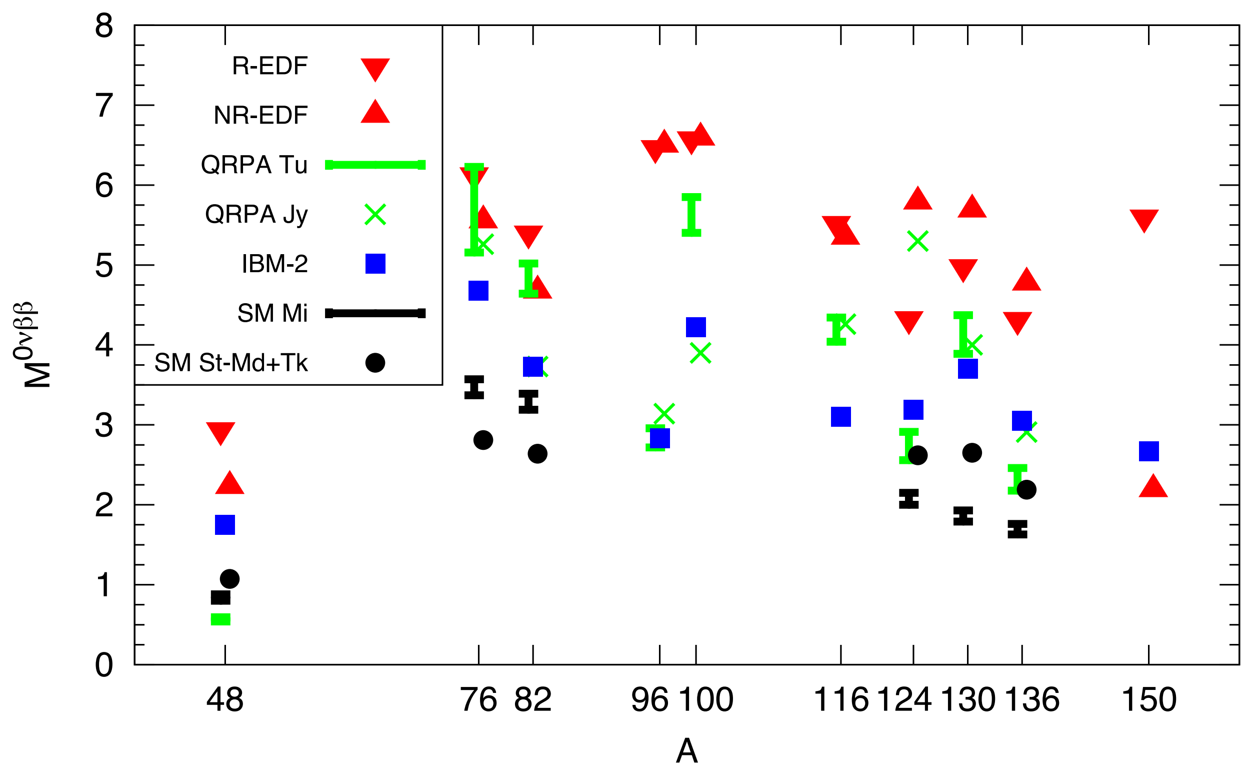
- Size and active shielding are the issues for higher sensitivities.

There are only a few proposals those offer NH sensitivity, but they seem to be very expensive.

Integration of complementary technologies and multiple collaborations may be necessary. Let’s think big!!

More to concern

Menendez arXiv:1605.05059



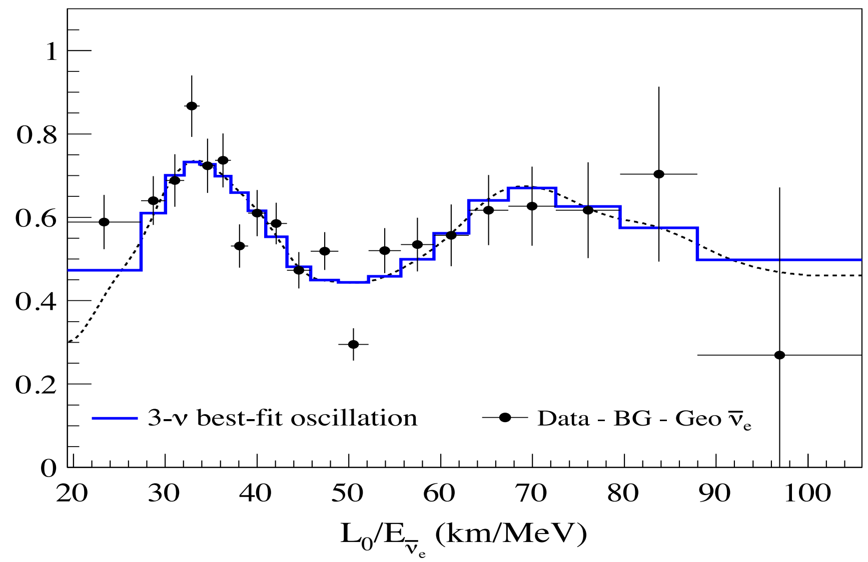
factor 3 uncertainty of NME ---> requires 10(BG free)~100 times more exposure

Experimental / theoretical efforts to reduce NME uncertainty are very important.

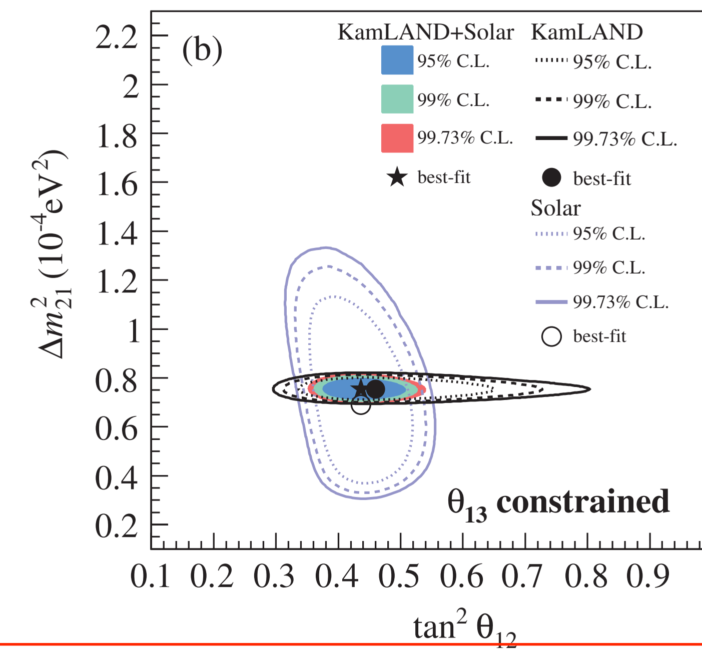
Ultra-low BG underground (& huge) experiment is necessary

It is KamLAND !!

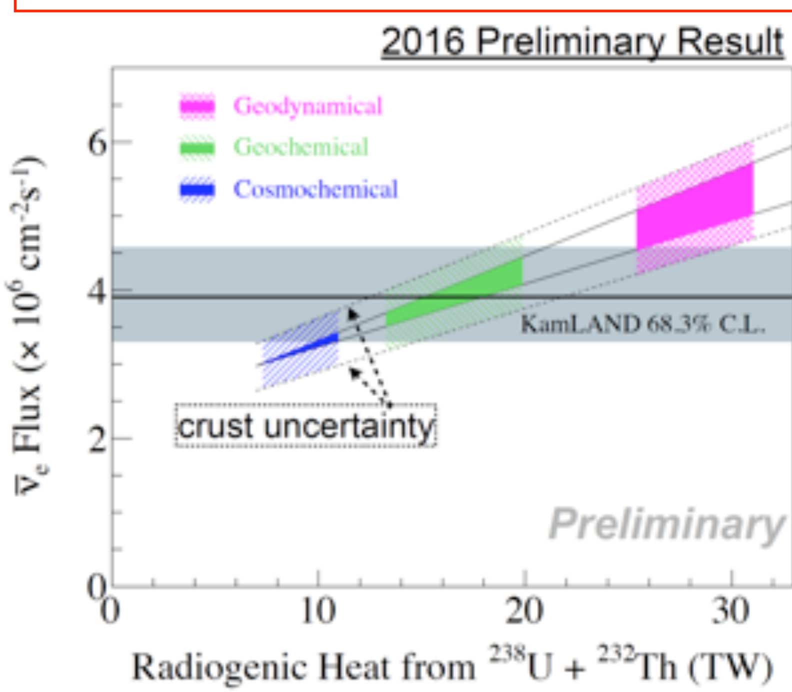
2 cycles of oscillations



Precision measurement

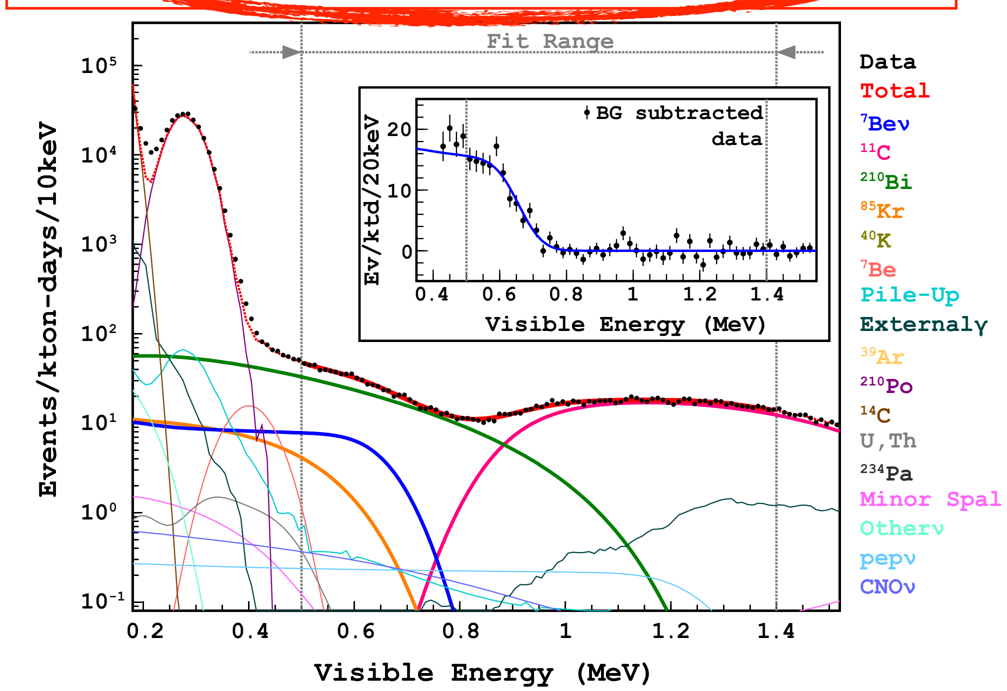


Radiogenic heat measured,
Model discrimination started



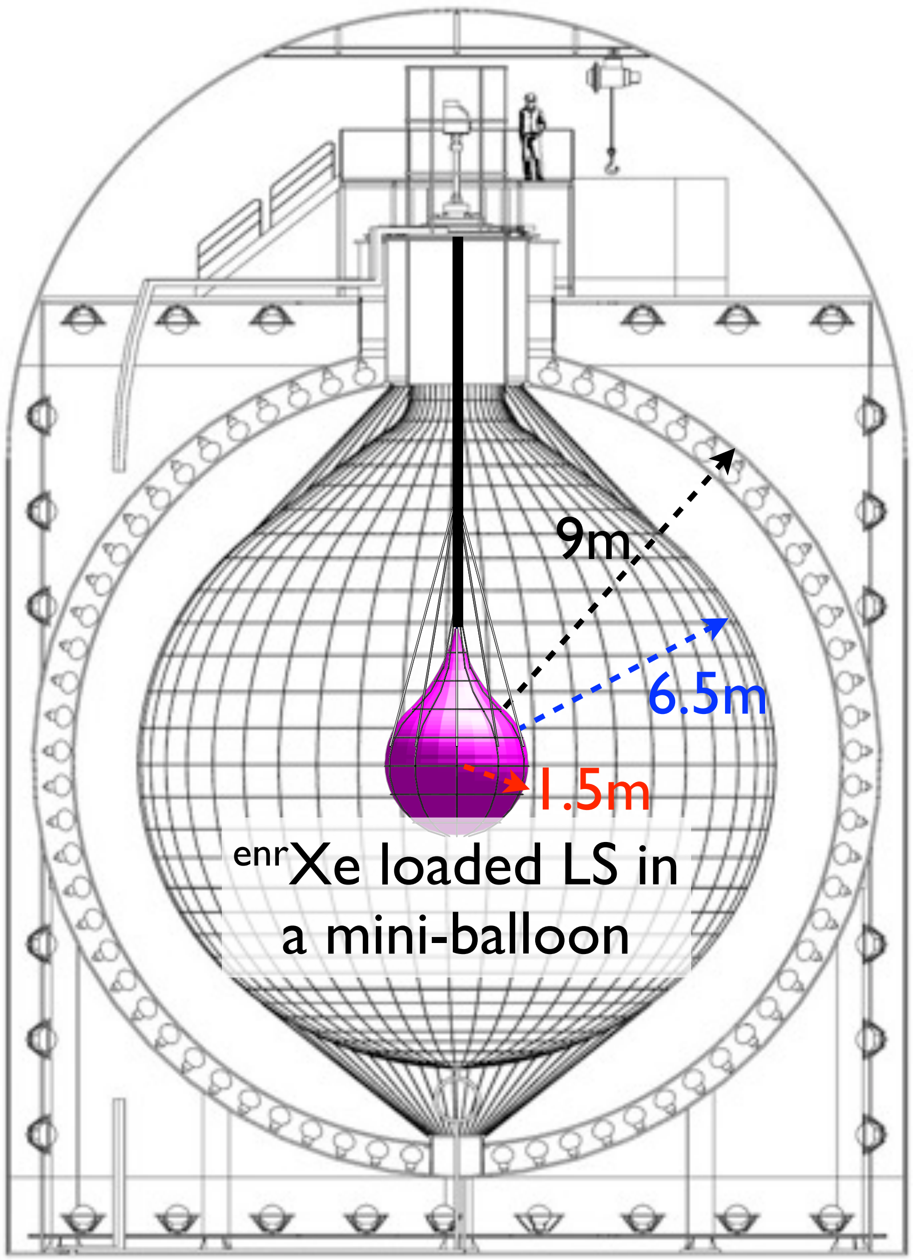
New preriminary result is here; http://www.tfc.tohoku.ac.jp/wp-content/uploads/2016/10/04_Hiroko_Watanabe_TFC2016.pdf

^{7}Be solar ν measured,
BG well-understood



KamLAND-Zen

Zero Neutrino
double beta decay search

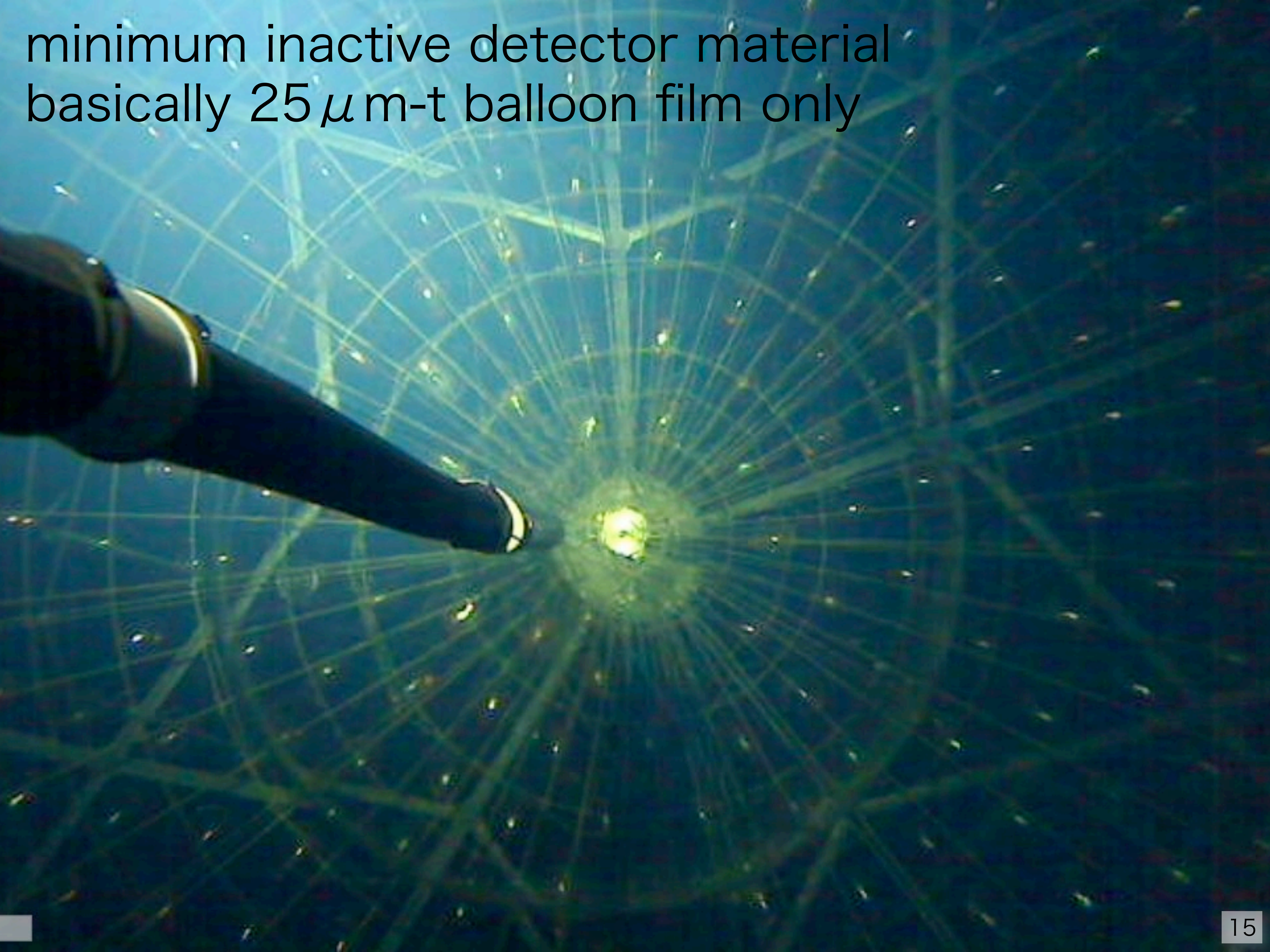


320kg 90% enriched ^{136}Xe installed for phase-I
and 380kg for phase-II

Advantages of using KamLAND

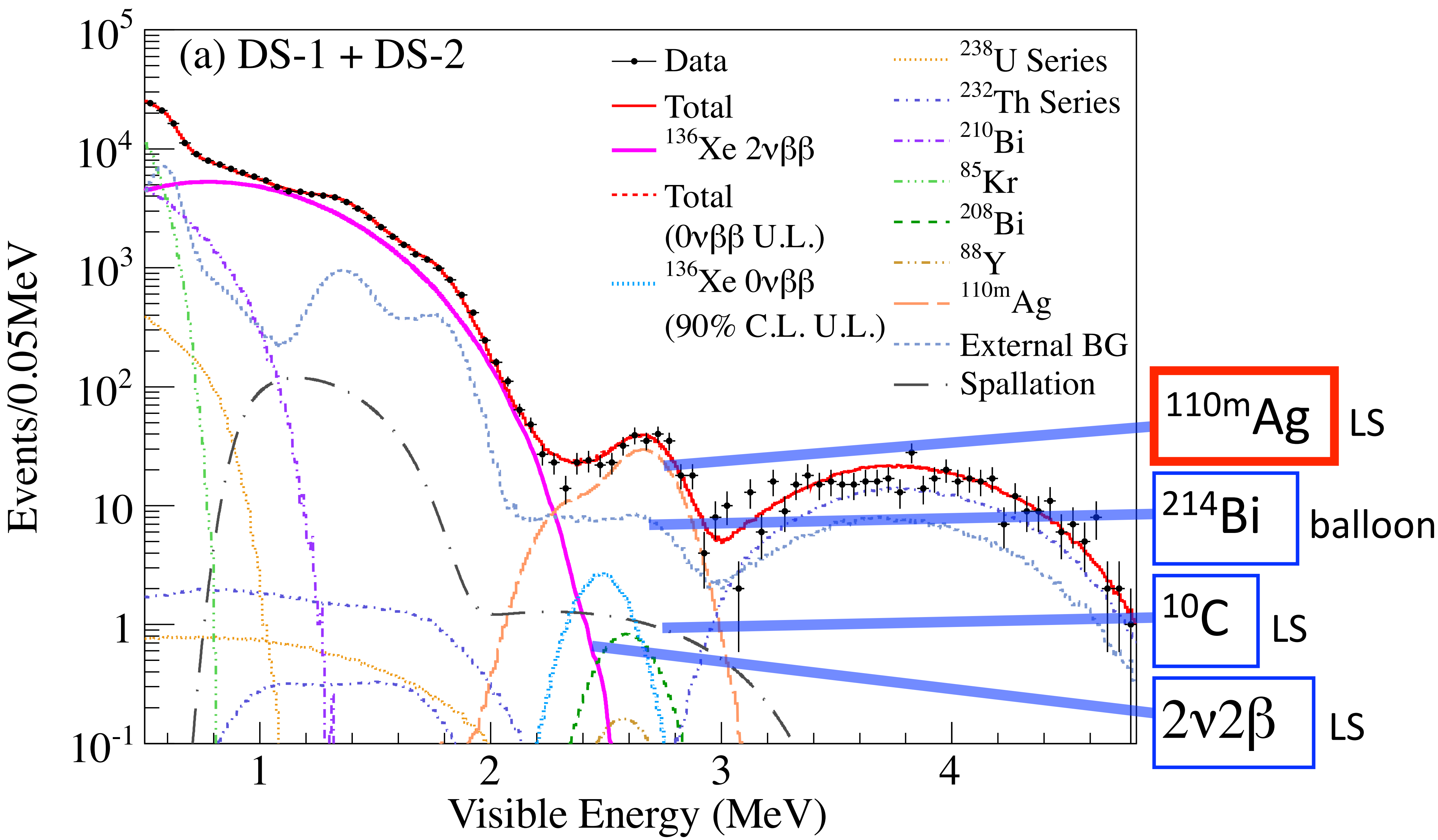
- running detector
  → relatively low cost and quick start
- huge and clean (1200m^3, U: 3.5x10^{-18} g/g, Th: 5.2x10^{-17})
  → negligible external gamma
  (Xe and mini-balloon need to be clean)
- Xe-LS can be purified, mini-balloon replaceable if necessary, with relatively low cost
  → highly scalable (up to several tons of Xe)
- No escape or invisible energy from β, γ
  → BG identification relatively easy
- **anti-neutrino observation continues**
  → geo-neutrino w/o Japanese reactors

minimum inactive detector material
basically 25μm-t balloon film only



KamLAND-Zen started in 2011

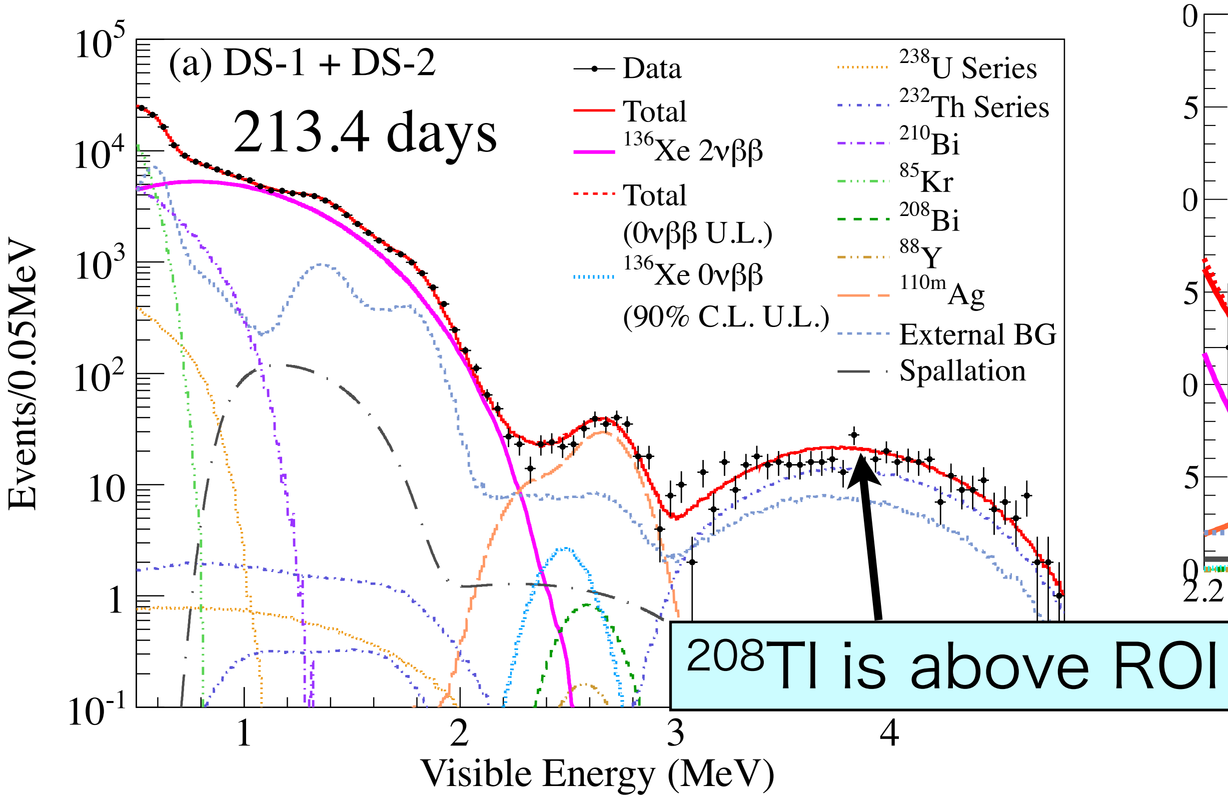
only 2 years from initial funding (very quick!)



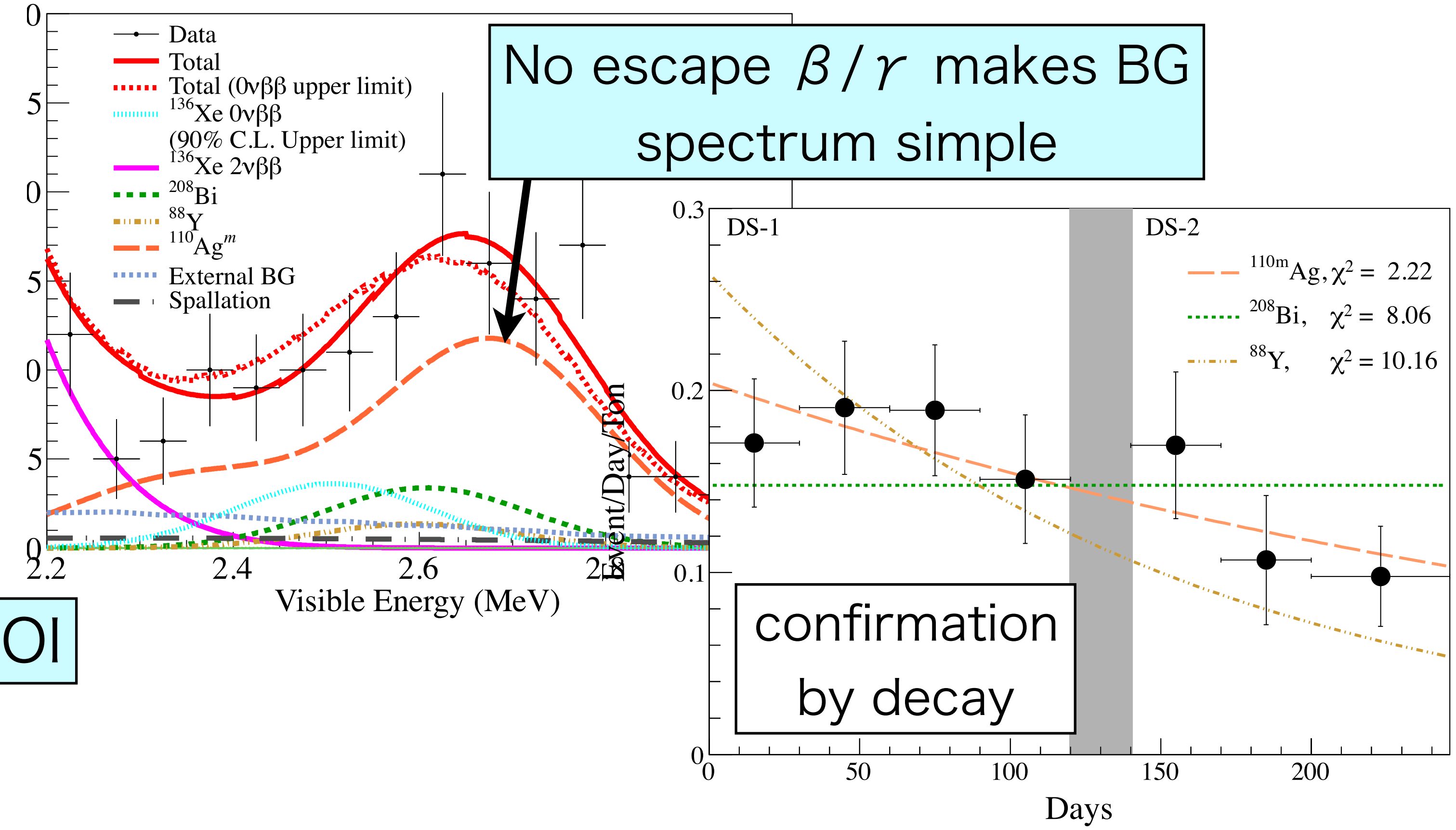
Unexpected BG has found

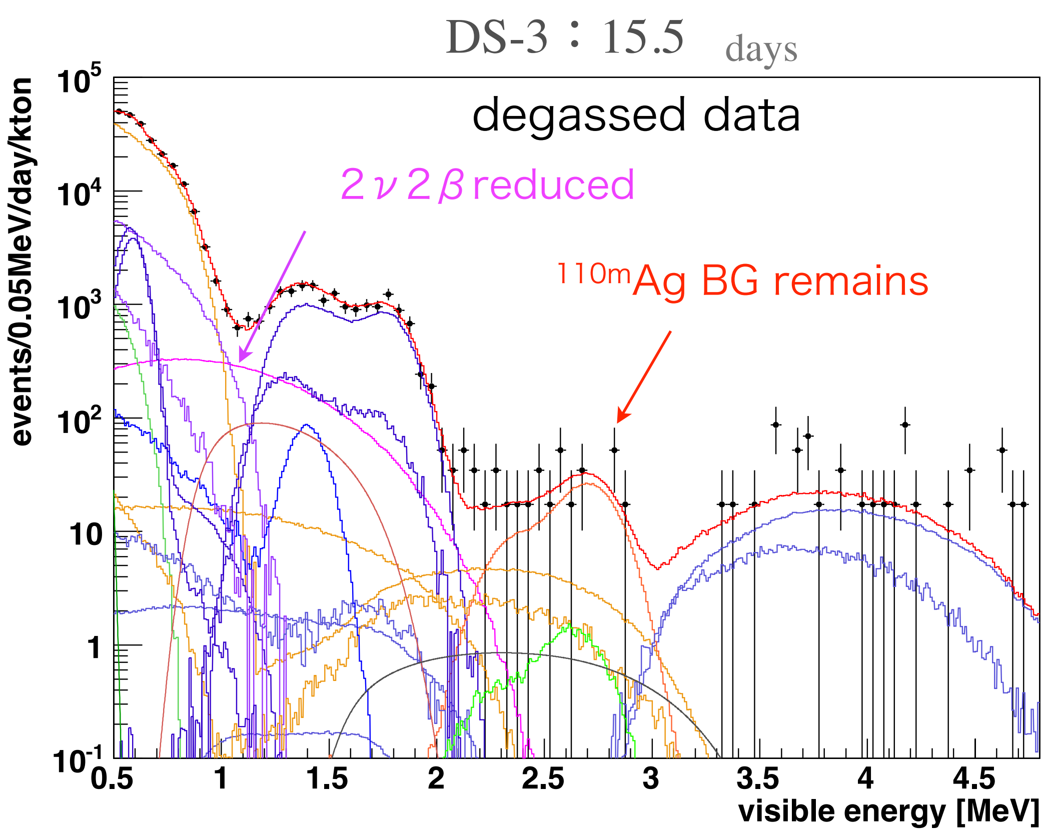
KamLAND-Zen Phase I (320kg xenon loading)

Thanks to full active apparatus,



Dominant BG identified as ^{110m}Ag



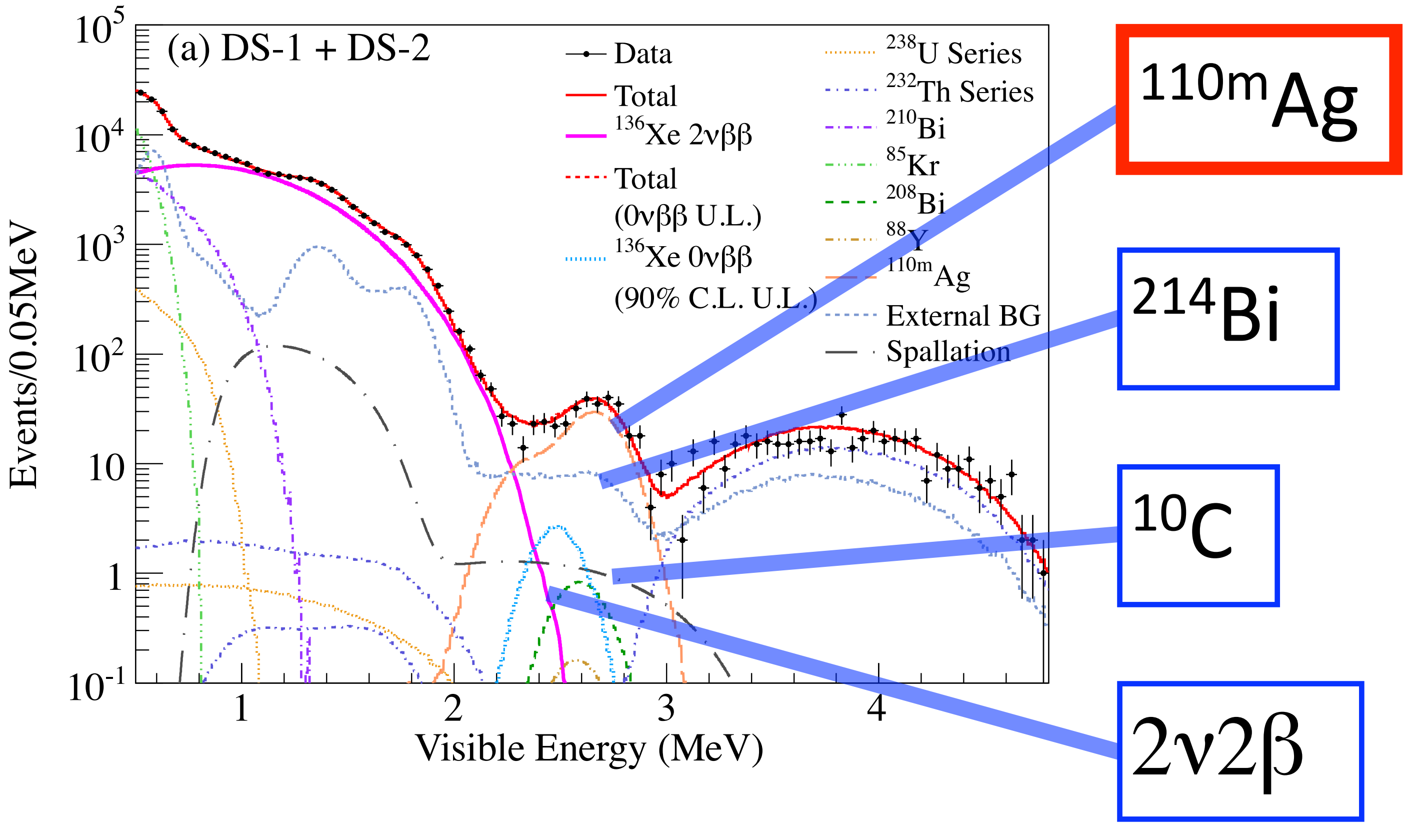


Xenon can be degassed from Xe-LS.

And ^{136}Xe on/off measurement has been demonstrated.

(useful for signal confirmation)

What can we do?



purification !!

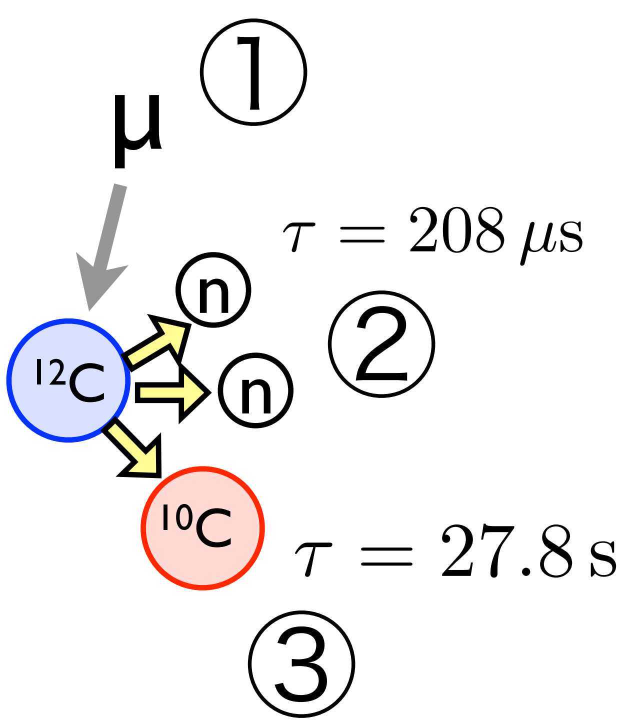
fine binning of volume

triple fold coincidence

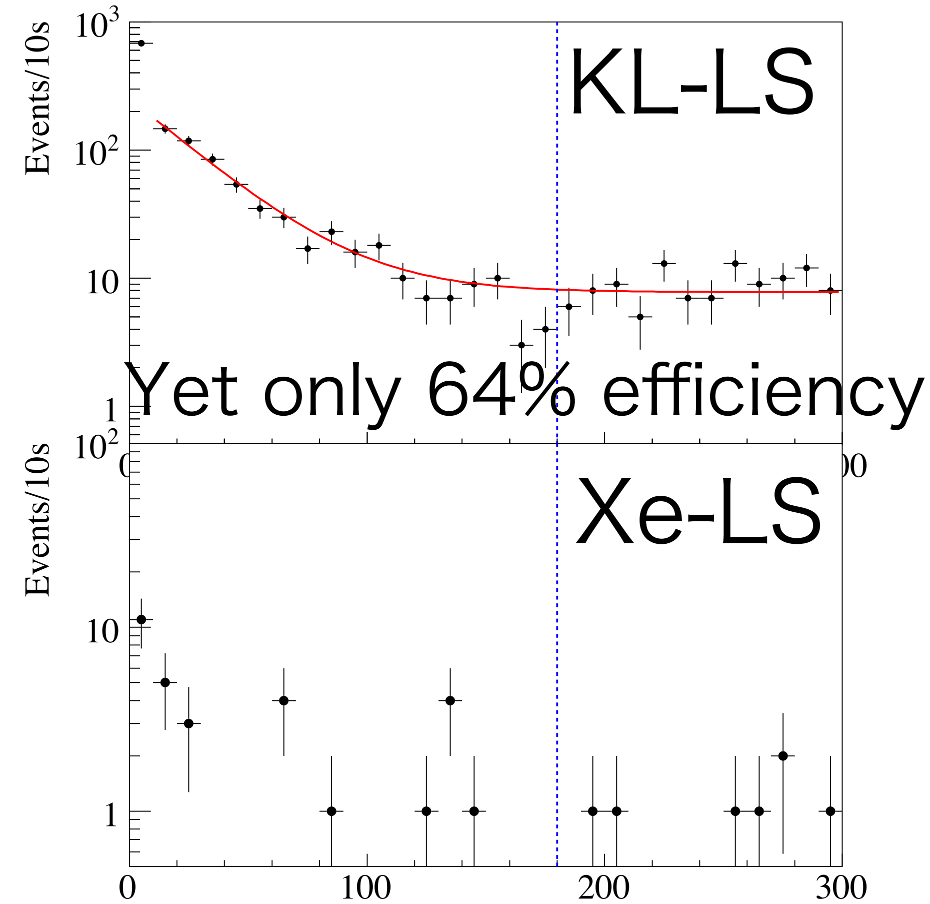
future task

tripe fold coincidence

for ^{10}C rejection



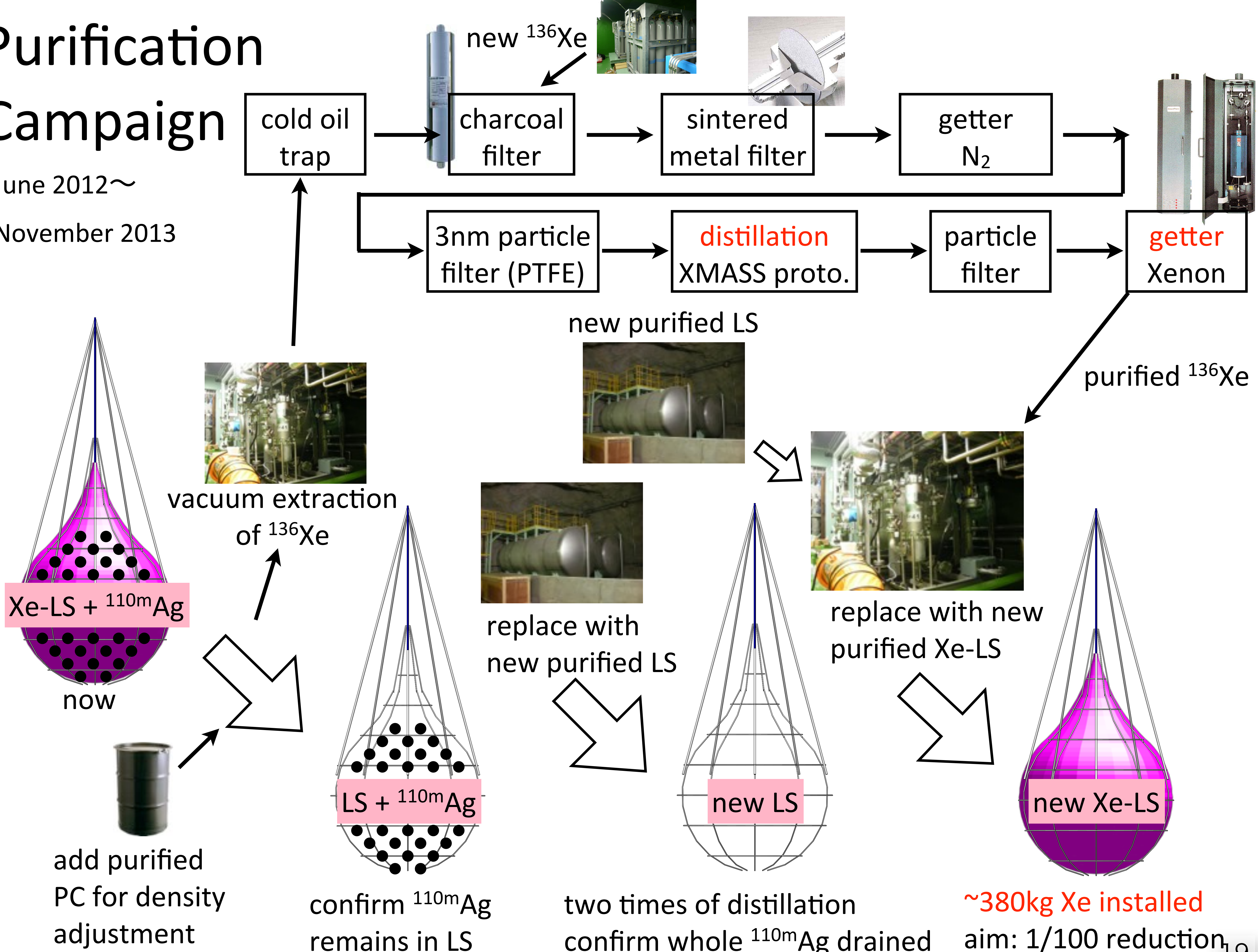
dead time free electronics MoGURA



Purification Campaign

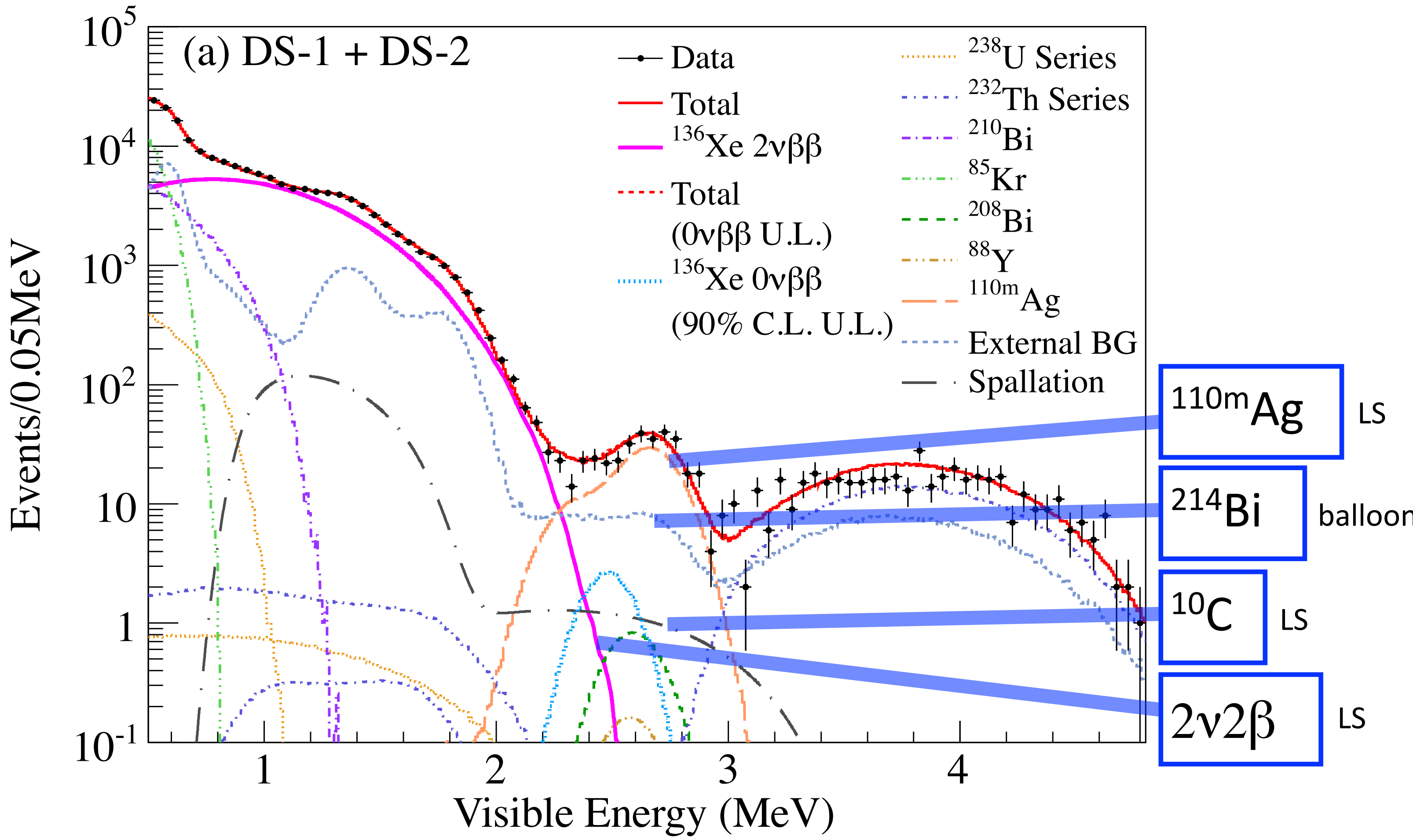
June 2012〜

November 2013



Phase-1 320kg

before purification

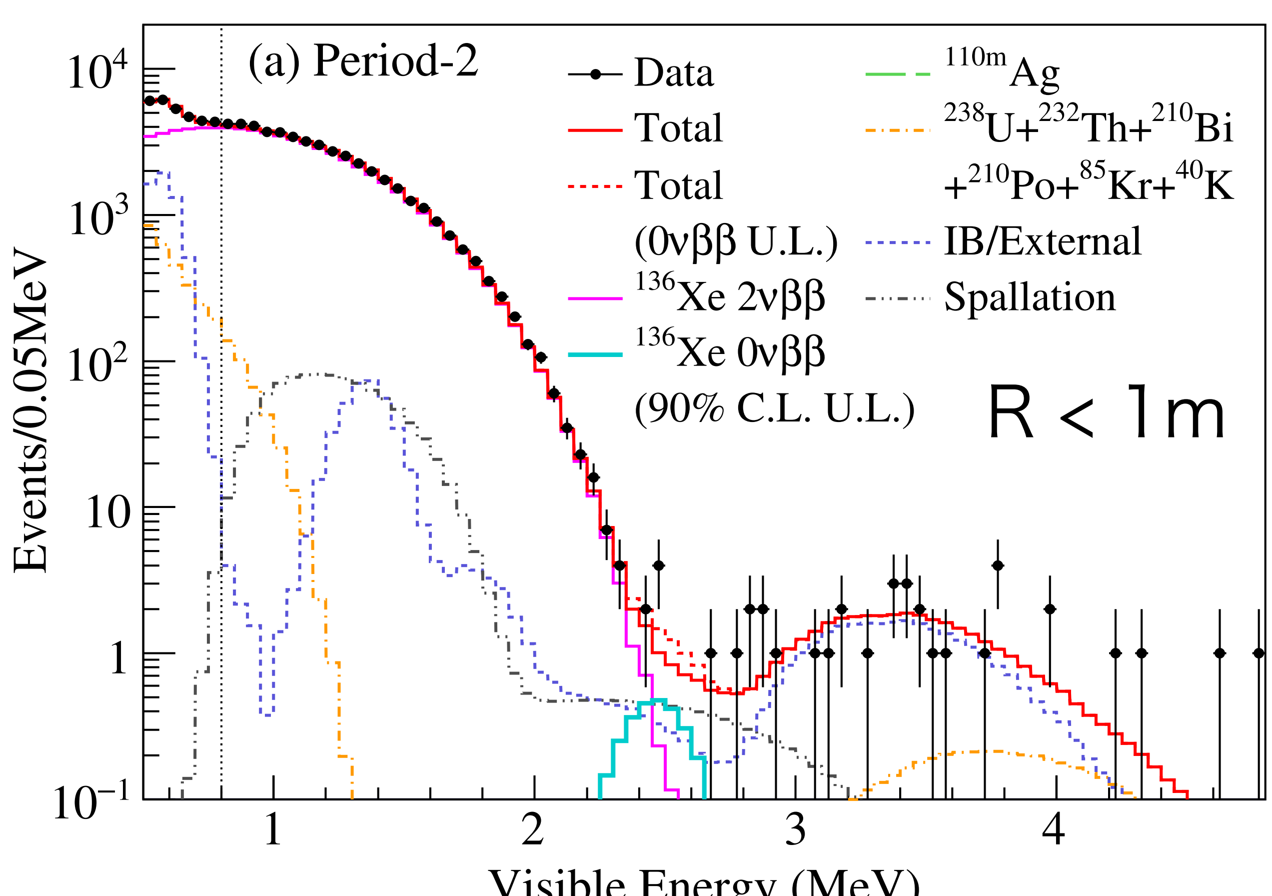


$>1.9\times10^{25}$y

Phase-2 380kg

after purification

^{110m}Ag reduction <1/10

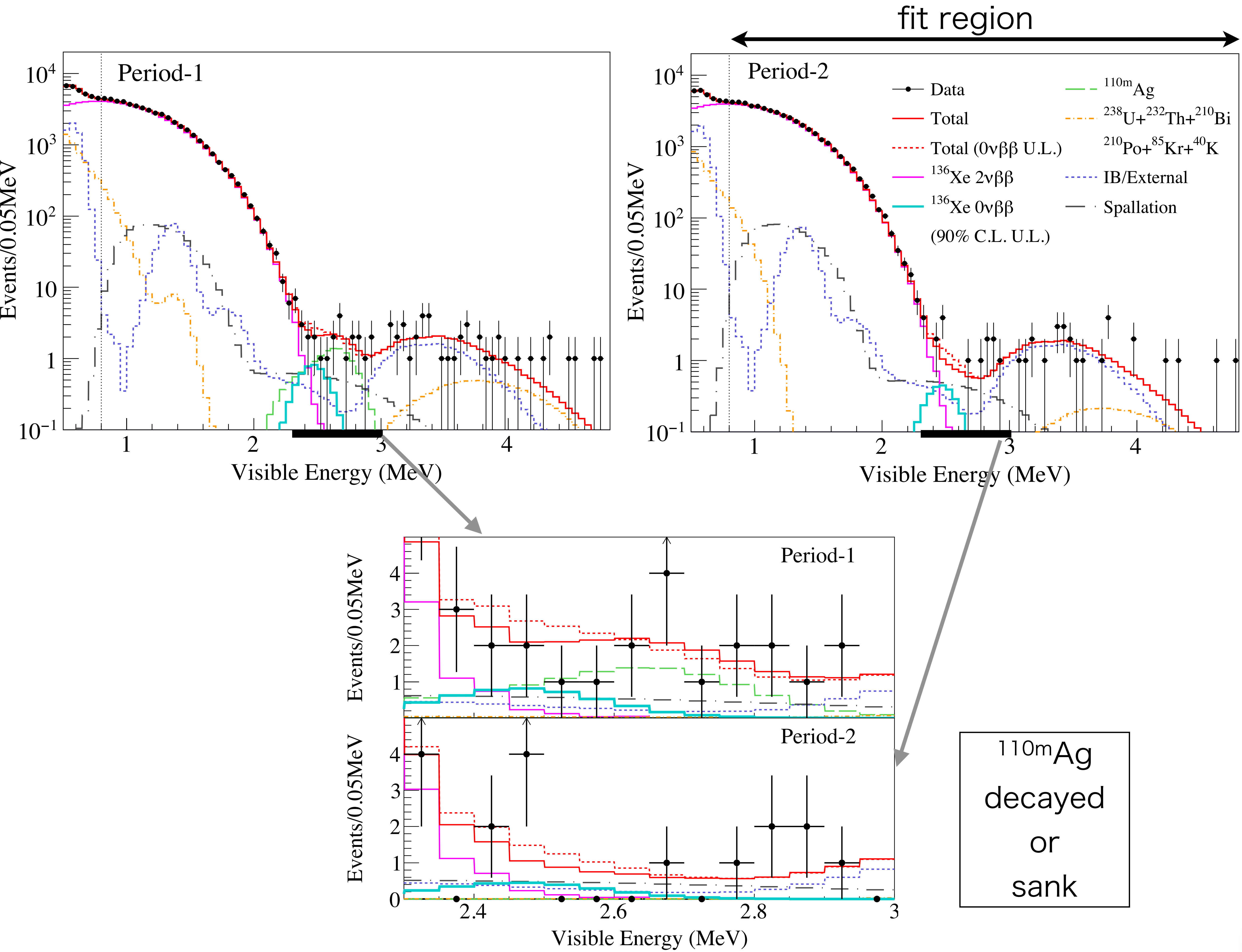


2013/12/11 - 2014/10/27

534.5 days (504 kg-yr)

(cf. $T_{1/2}$(^{110m}Ag)=250 days)

in-situ purification possible!!

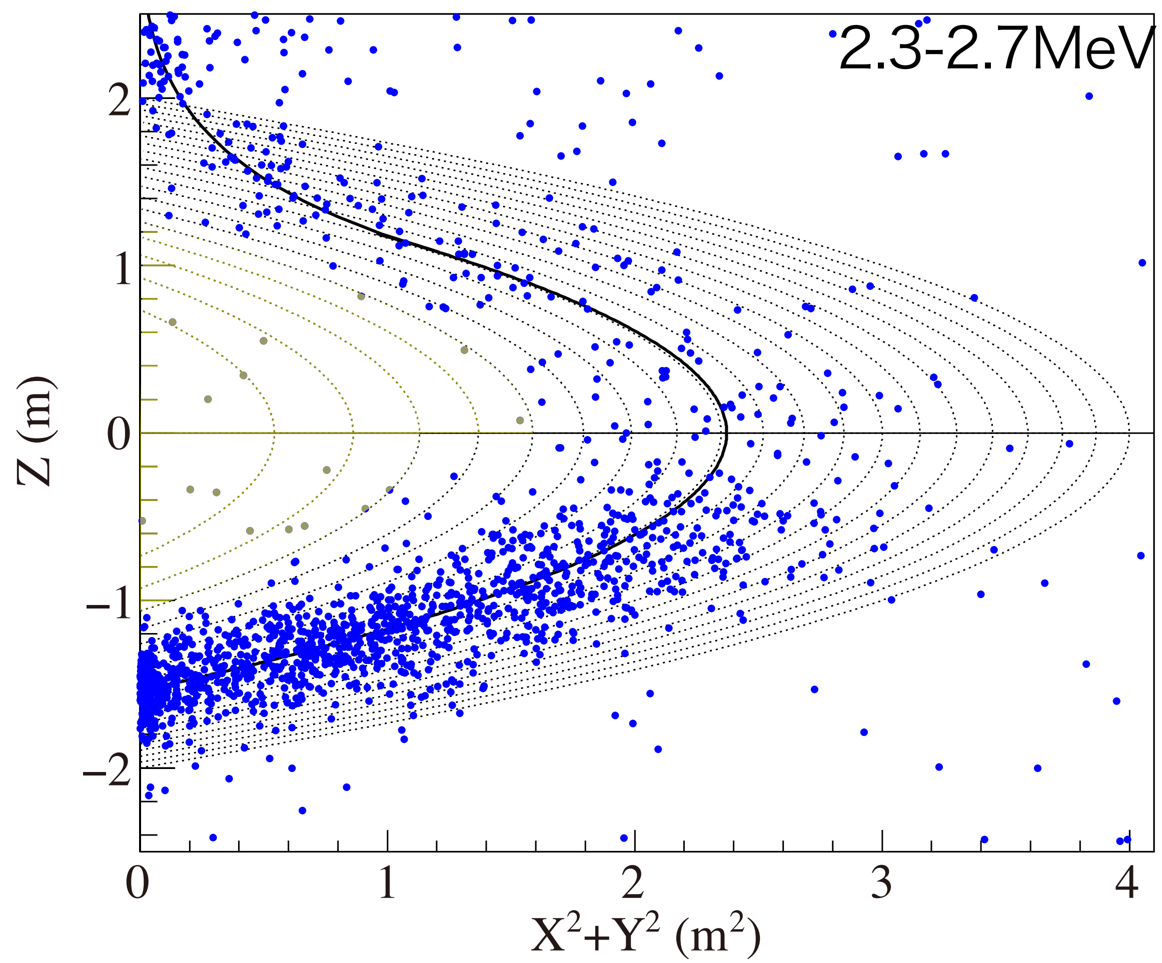

fit region
Period-1
Period-2
Data
Total
Total (0νββ U.L.)
136Xe 2νββ
136Xe 0νββ
(90% C.L. U.L.)
110mAg
238U+232Th+210Bi
210Po+85Kr+40K
IB/External
Spallation
Events/0.05MeV
Visible Energy (MeV)
110mAg
decayed
or
sank

We have acquired phase-2 data (after purification)

from December 11 2013 to October 27, 2015;

total livetime of 534.5 days (cf. $T_{1/2}(^{110m}Ag)$=250 days)

and exposure of 504 kg-yr.

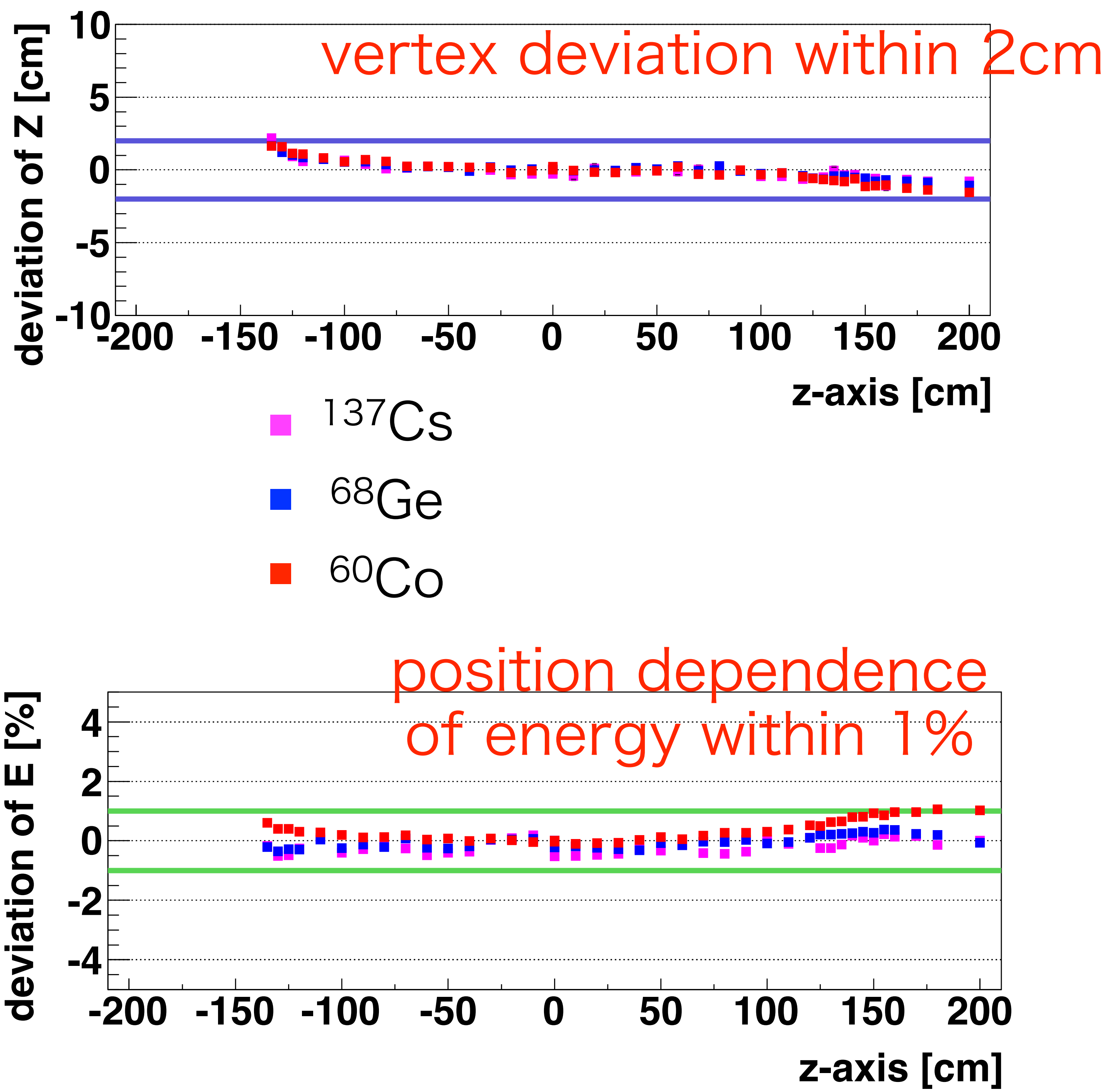


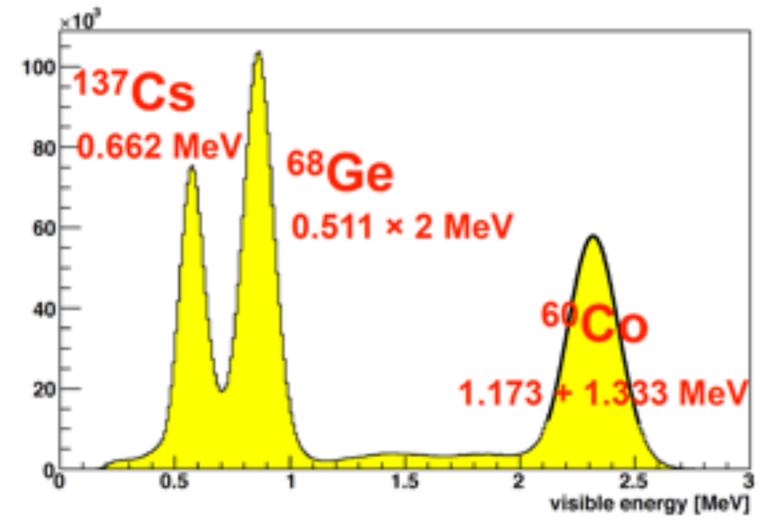
Balloon surface has higher BG rate but still provides some sensitivity.

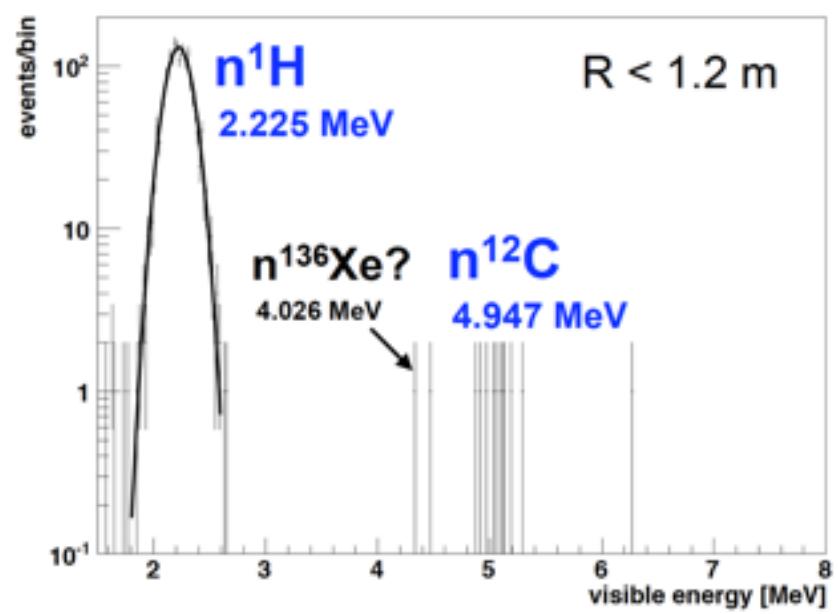
In order to improve the sensitivity, we have performed all volume and time-binned analysis.

Source calibration

(Oct. 2015)



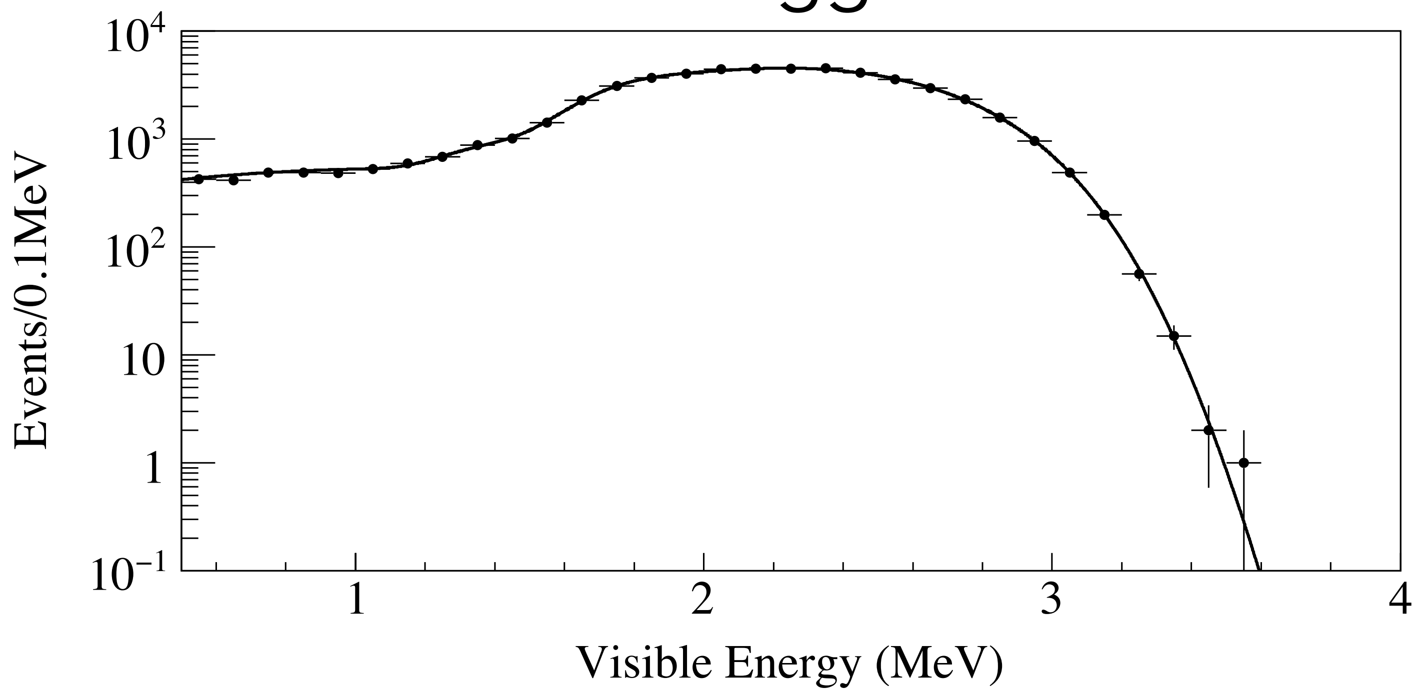




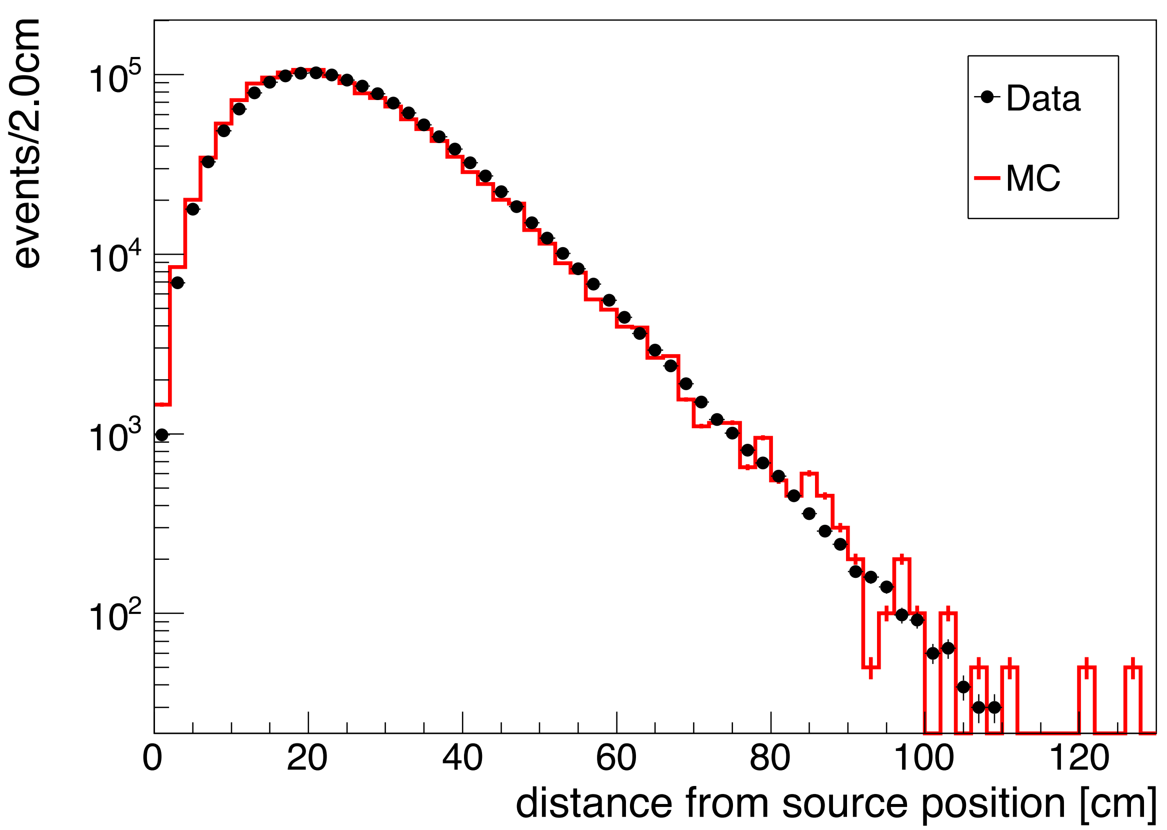
also in-situ calibration with n-capture on ^{1}H/^{12}C and ^{214}Bi

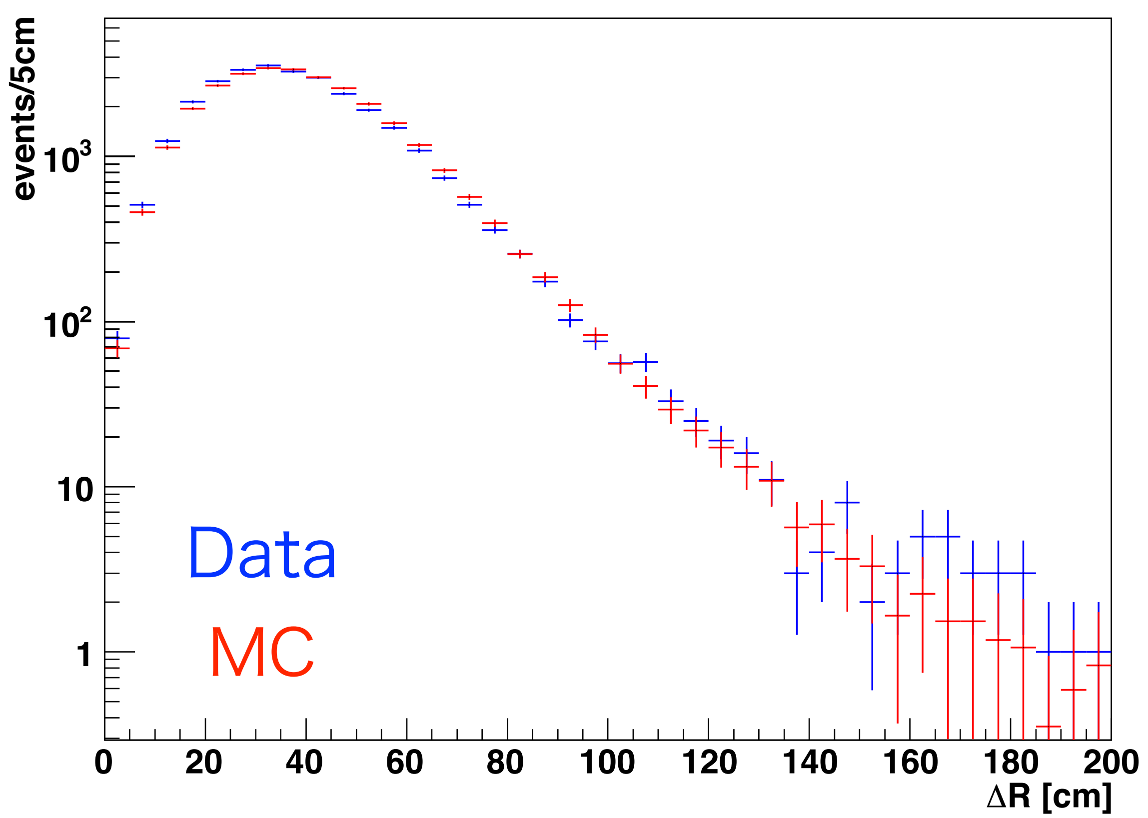
Energy resolution in phase-2: ~7.3%/√E

investigation of energy resolution tail with tagged ^{214}Bi

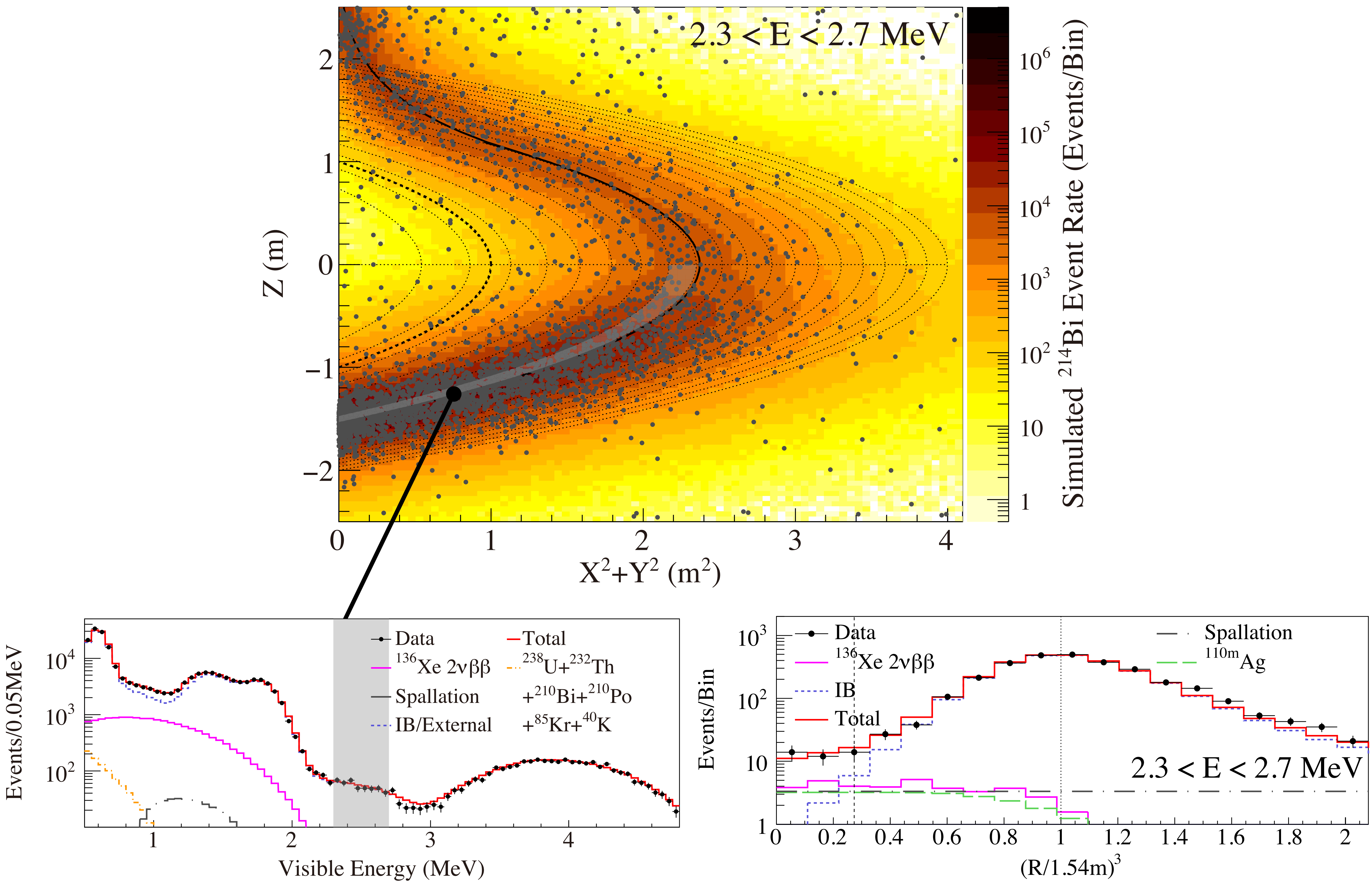


investigation of vertex resolution tail with ^{60}Co source and tagged ^{214}Bi-Po





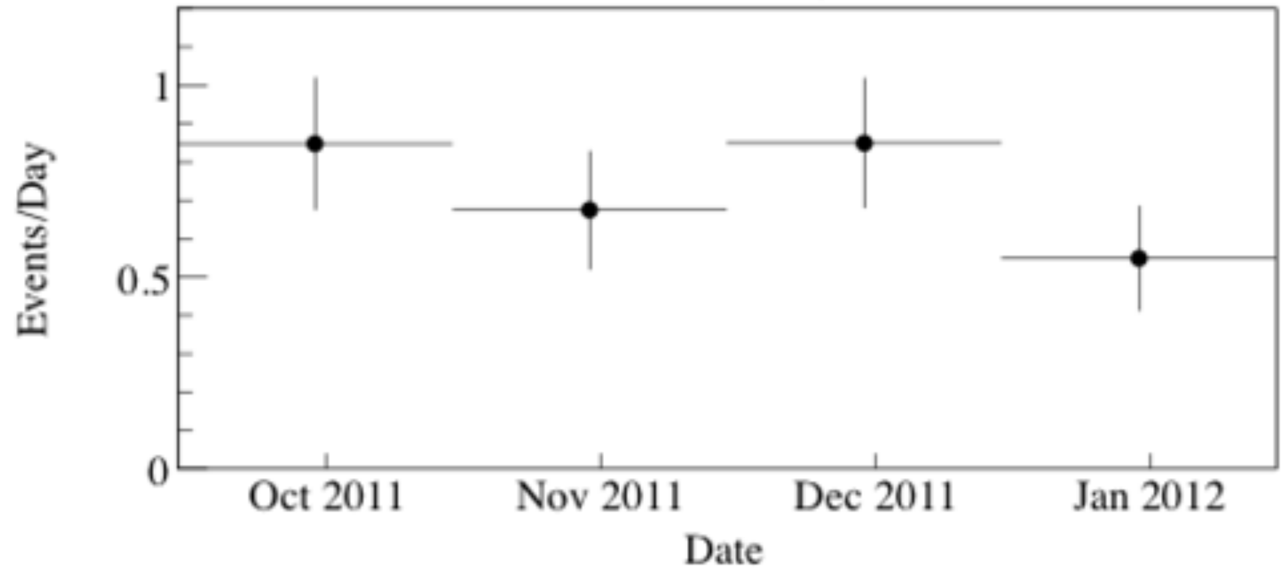
40 equal-volume bins



Energy and radial distributions are well-reproduced by known BGs.

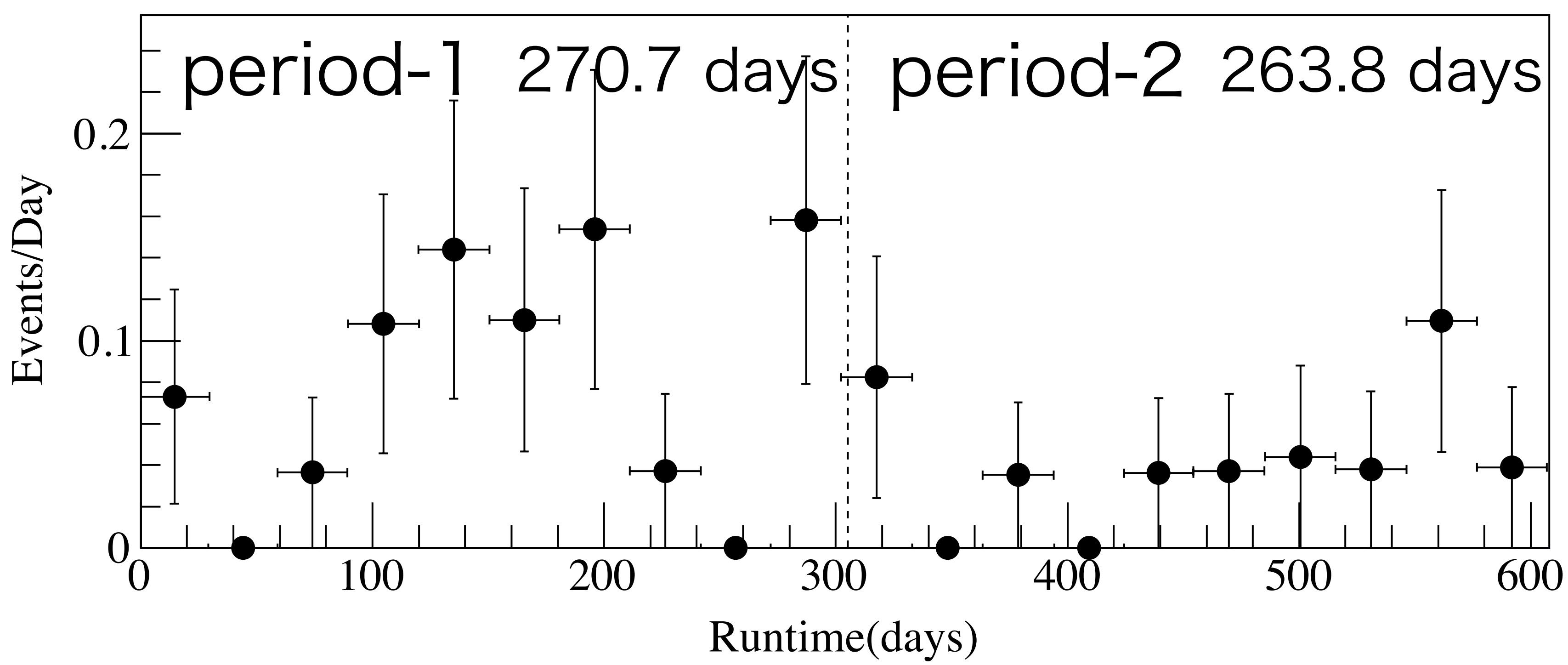
Phase 1 (first 112.3 days)

2.2 < E < 3.0 MeV, R < 1 m



Phase 2 534.5 days

2.3 < E < 2.7 MeV, R < 1 m



22 events   11 events

A hypothesis: "Dust" sank !?

Yet only ~2σ discrepancy from the simple decay

Kown BG other than ^{110m}Ag are ~11 events in each periods

Event summary 2.3 < E < 2.7 MeV, R < 1 m

	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

Results on $0\nu2\beta$

	period-1	period-2
livetime	270.7 days	263.8 days
^{136}Xe $0\nu2\beta$ decay rate	< 5.5 /kton/day	< 3.4 /kton/day

combined < 2.4 /kton/day (90%C.L.)

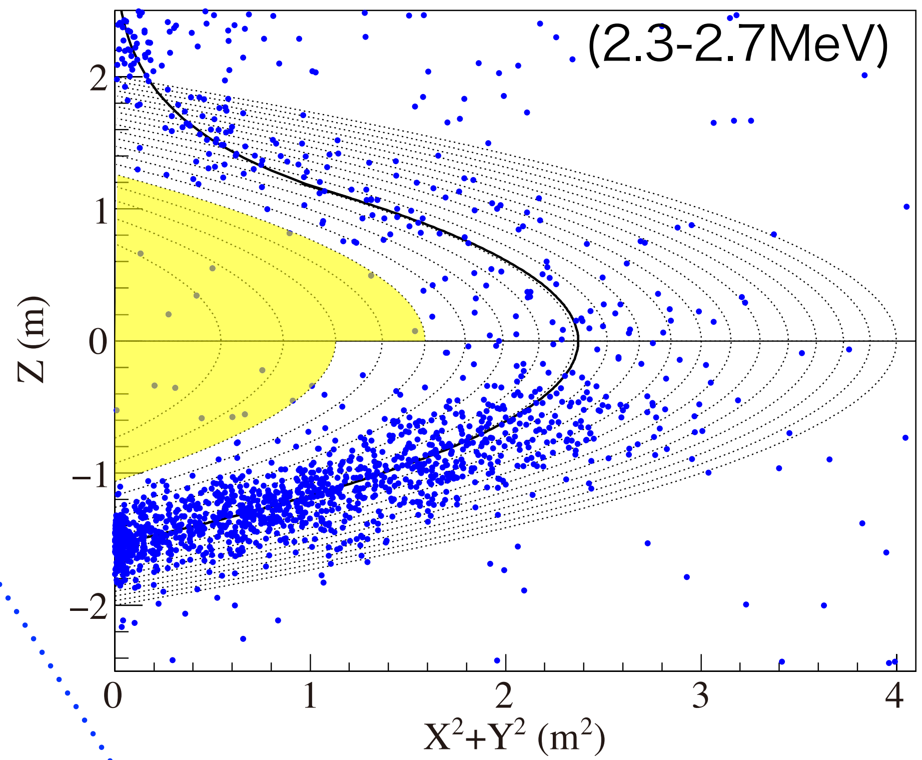
^{136}Xe $0\nu2\beta$ half-life > 9.2×10^{25} yr (90%C.L.)

sensitivity > 4.9×10^{25} yr

(11% probability)

Lucky (11%) comes from R >1m region

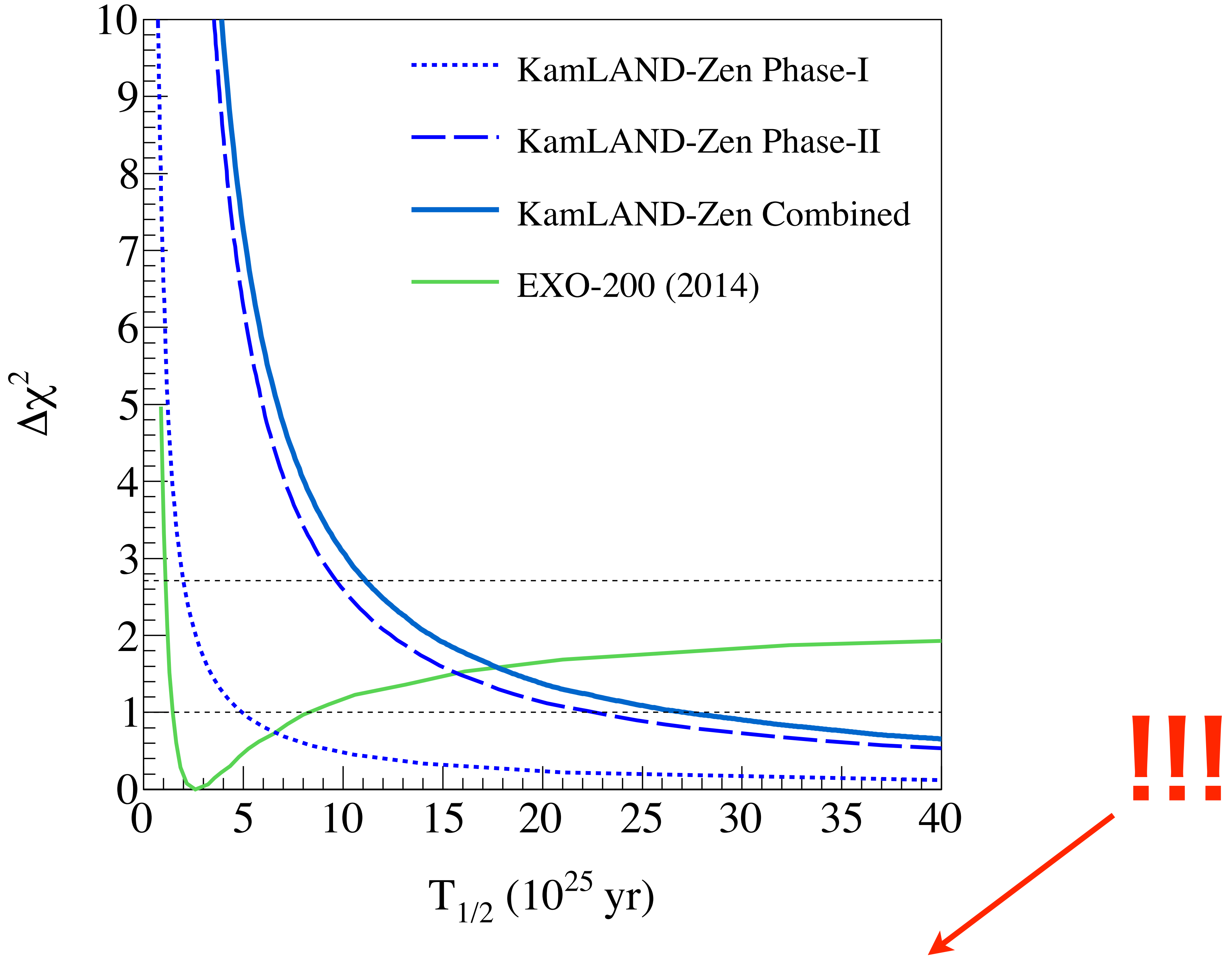
use FV for period-2 data
upper hemisphere R<1.26 m (5 bins)
lower hemisphere R<1.06 m (3 bins)



provides better limit of

< 3.25 /day/kton

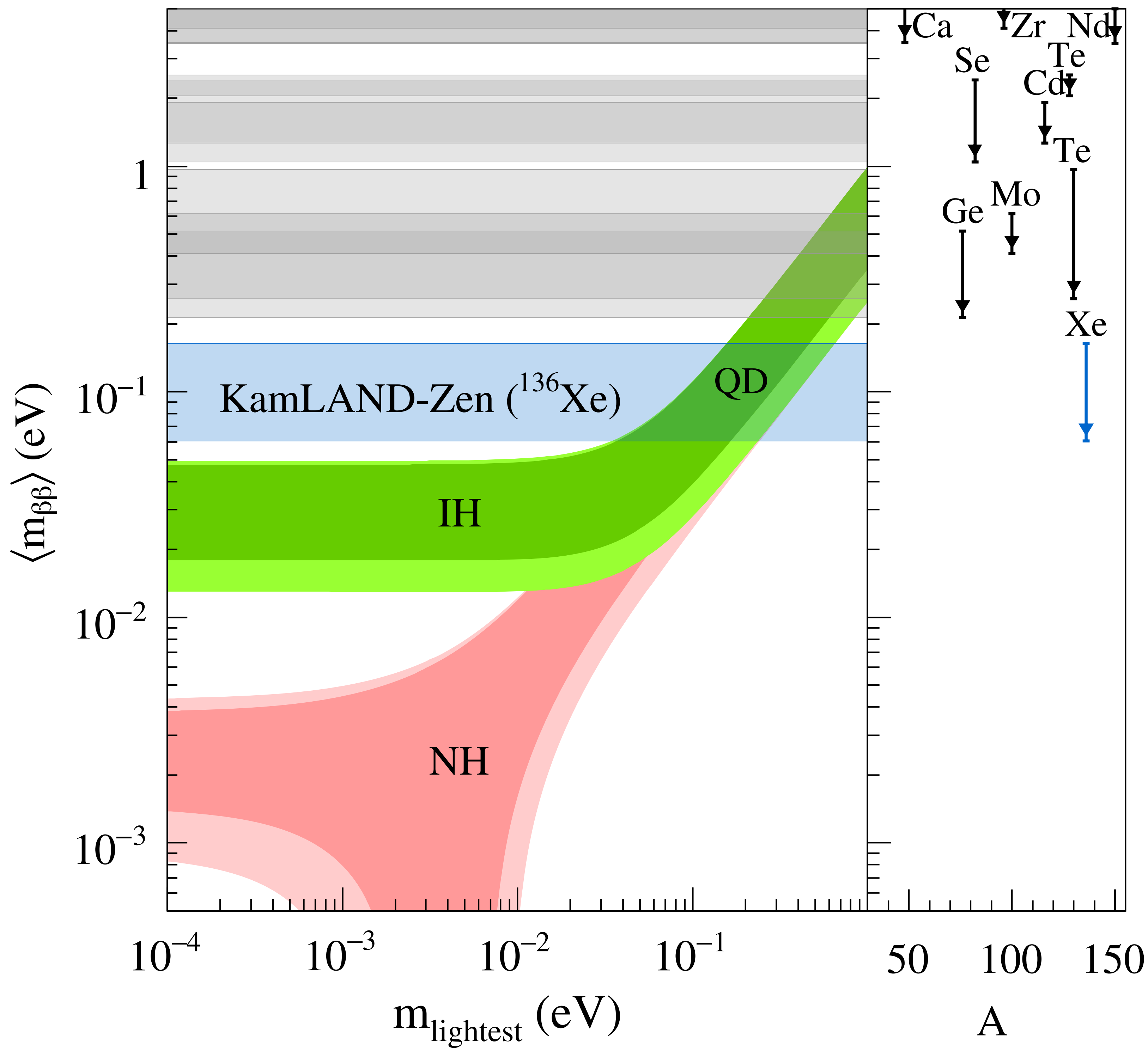
Phase-1 & 2 combined limit



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

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

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



It also provides upper limit of $m_{lightest}$ at 180-480 meV.

Big leap toward IH !!

Our challenge continues!

Three dominant BGs; 2ν, "^{214}Bi on the film" and ^{10}C.

next target

further optimization of triple-fold coincidence

We have purchased 800 kg of enriched xenon in total.

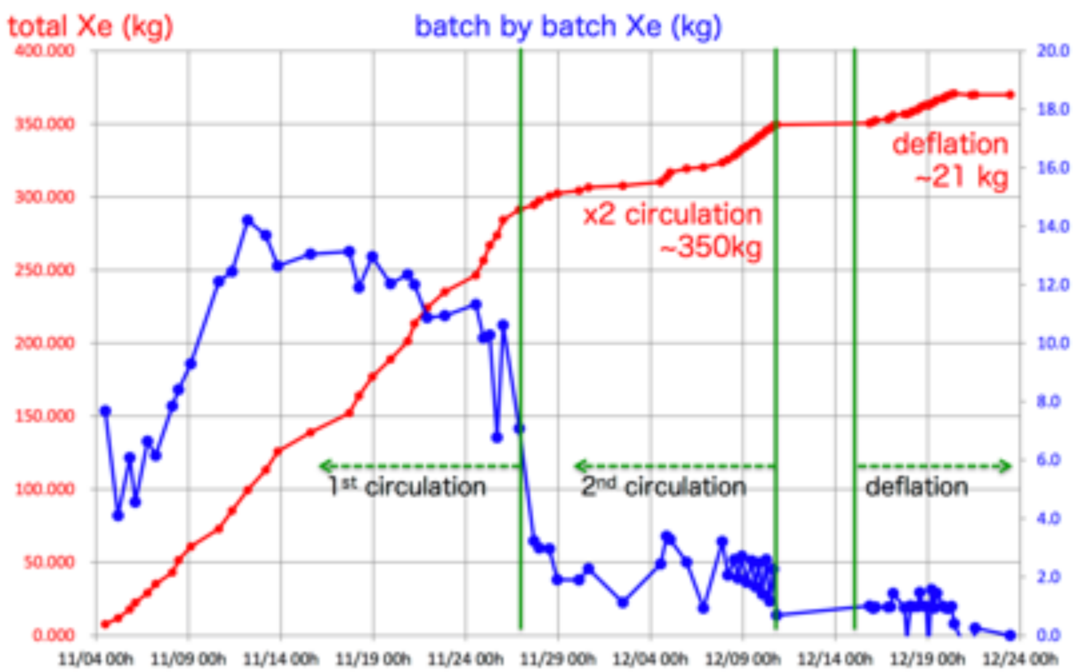
We have fabricated a larger mini-balloon with better measures against dusts.

We will resume the search with 750 kg of xenon.
To be called as "KamLAND-Zen 800".

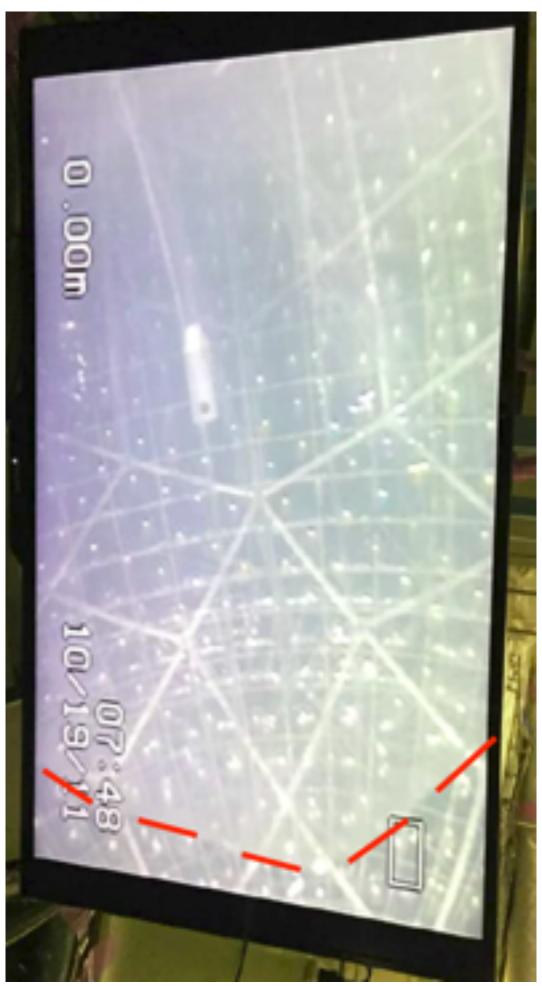
(Expected sensitivity is below 50 meV hoping to cover Yanagida's prediction.)

Mini-balloon has been extracted. (Dec. 2015)

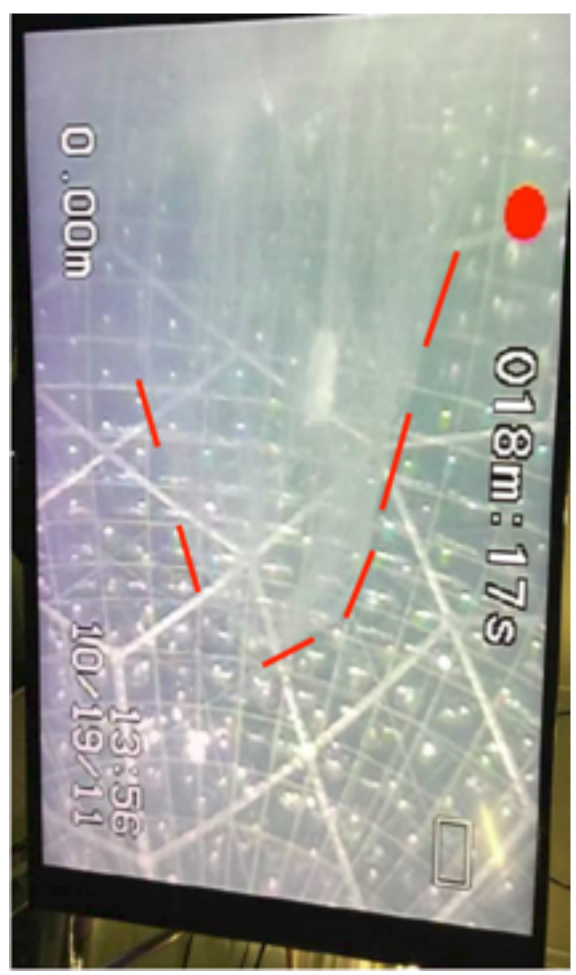
for tank investigation required by law



Xenon has been recovered during recirculation and deflation of the mini-balloon.



deflation



2nd mini-balloon fabrication

cleaning, cleaning and cleaning as usual

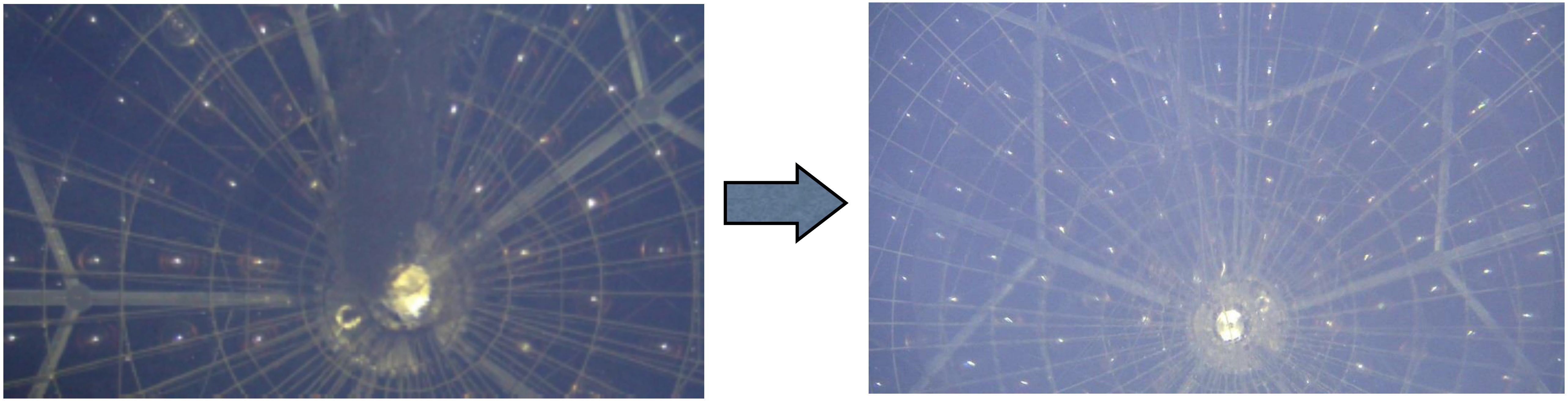
Example of improvements

before

after

keep staying away
goggle
welding machine
cover sheet .
glove on glove
laundry twice a day .
clean underwear .
changing room in a clean room .
dust visualization
more neutralizer
. . .

after Leak check and repair



New mini-balloon has been deployed and inflated with "dummy" LS in last August

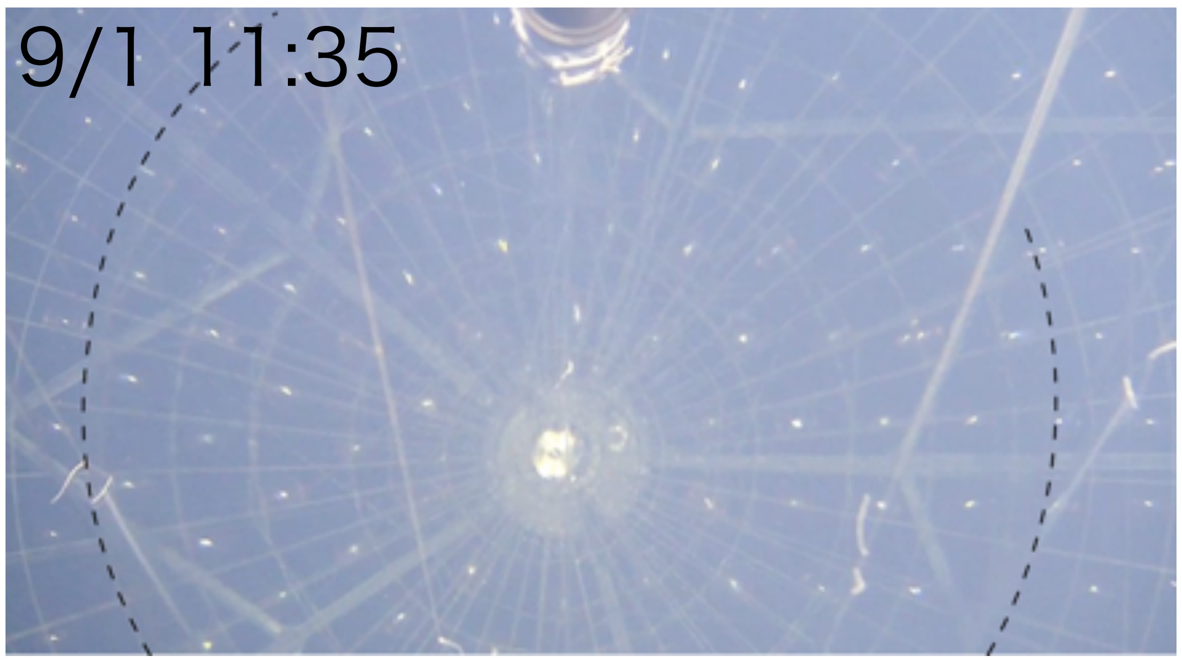
through characterization of mini-balloon

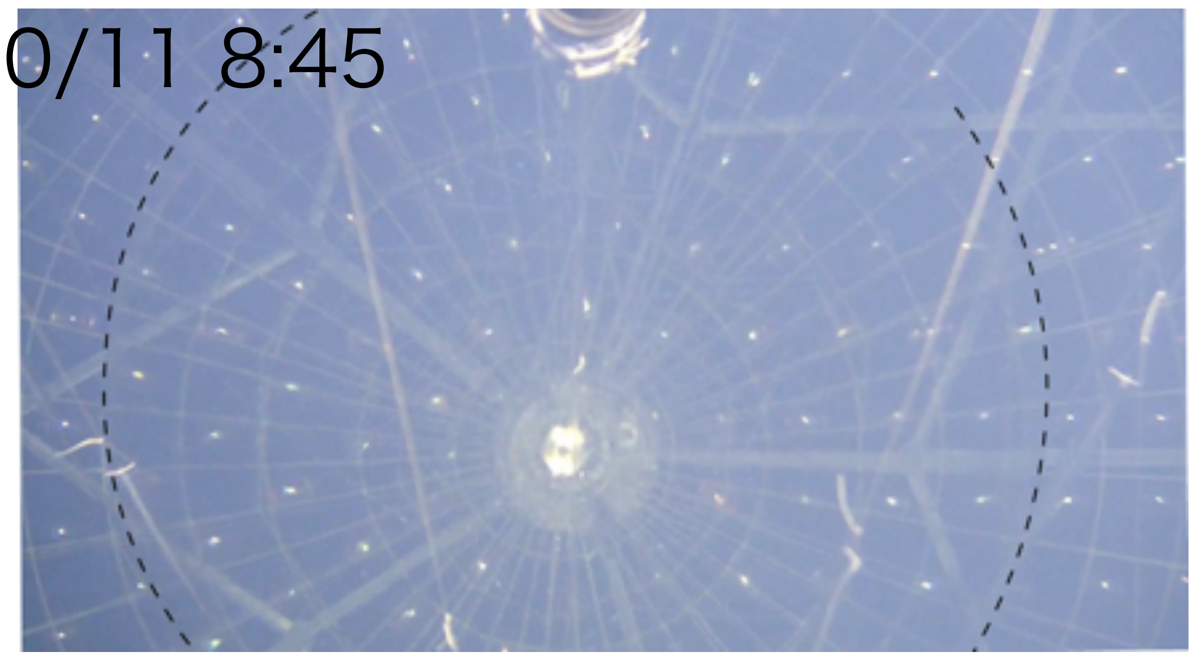
We confirmed that the mini-balloon is cleaner !!

Measures we took worked!

→ see Hachiya's poster

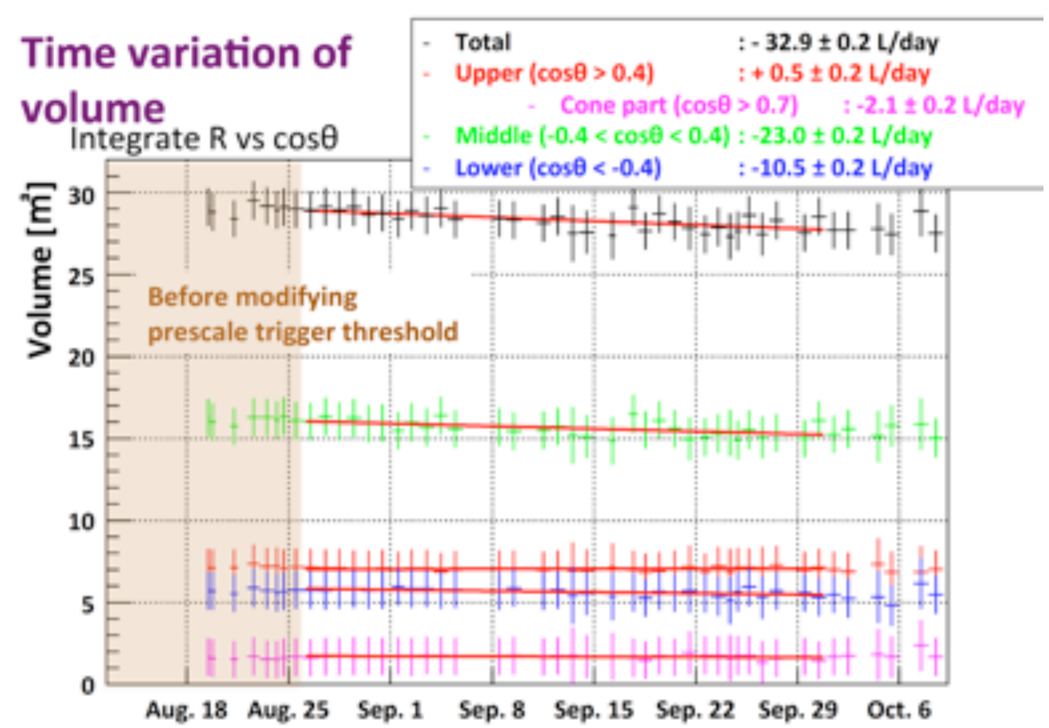
At the same time, we noticed; → further information Obara's poster





Indications of leak;

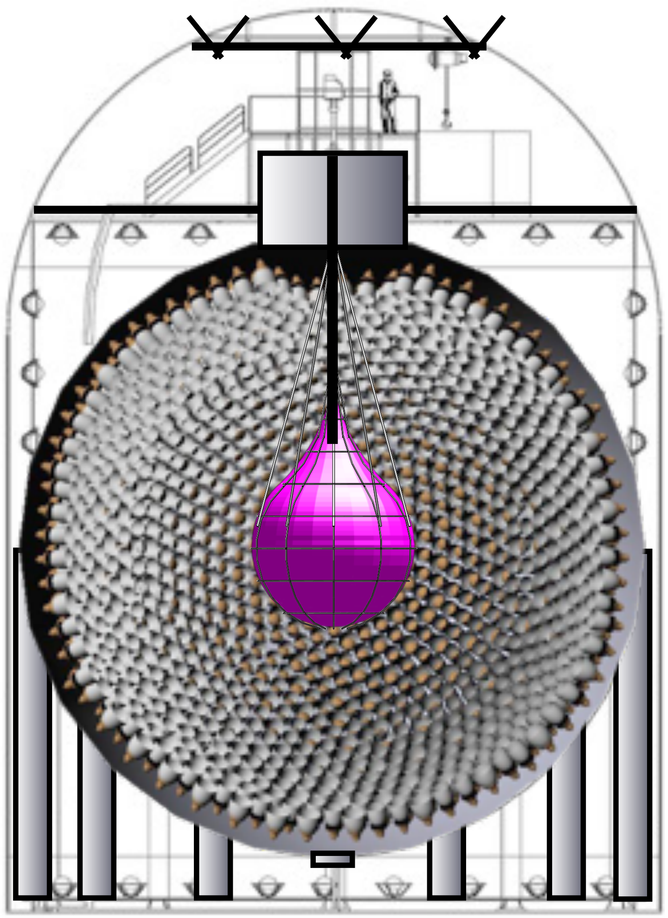
- camera image
- load cell
- balloon shape reconstruction with ^{210}Po events
- ^{222}Rn decay rate
- mixture of KL-LS and dummy-LS by gas-chromatography



And more future plans!

Higher energy resolution for reducing 2ν BG

⇨ KamLAND2-Zen



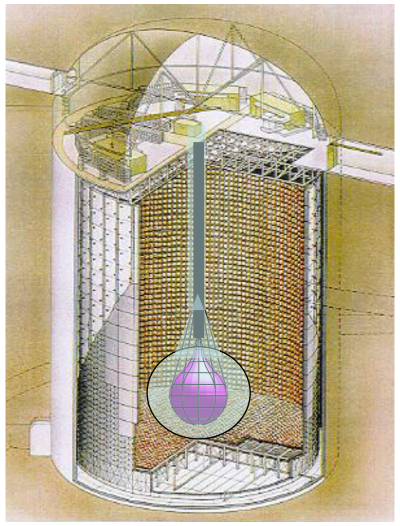
1000+ kg xenon

Winston cone	light collection ×1.8
high q.e. PMT 17"ϕ→20"ϕ ε=22→30+%	light collection ×1.9
New LAB LS (better transparency)	light collection ×1.4

expected σ(2.6MeV)= 4% → ~2%

target sensitivity 20 meV

And more?



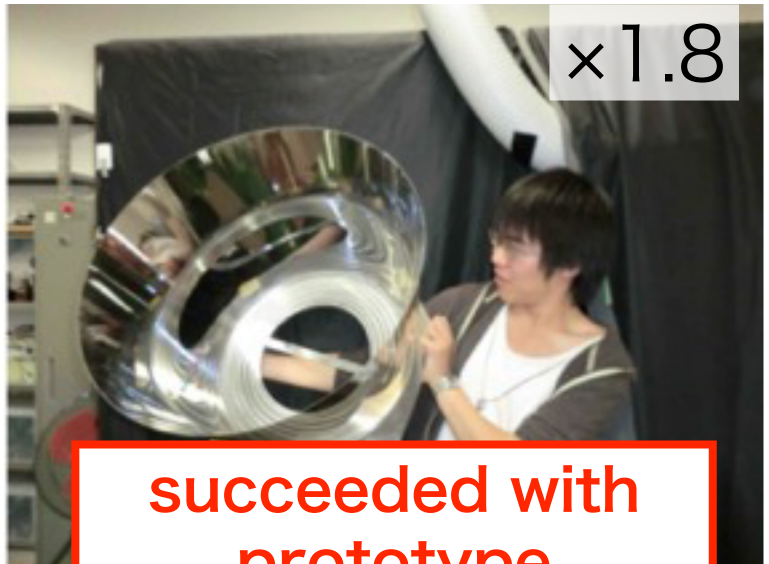
Super-KamLAND-Zen

in connection with Hyper-Kamiokande

target sensitivity 8 meV

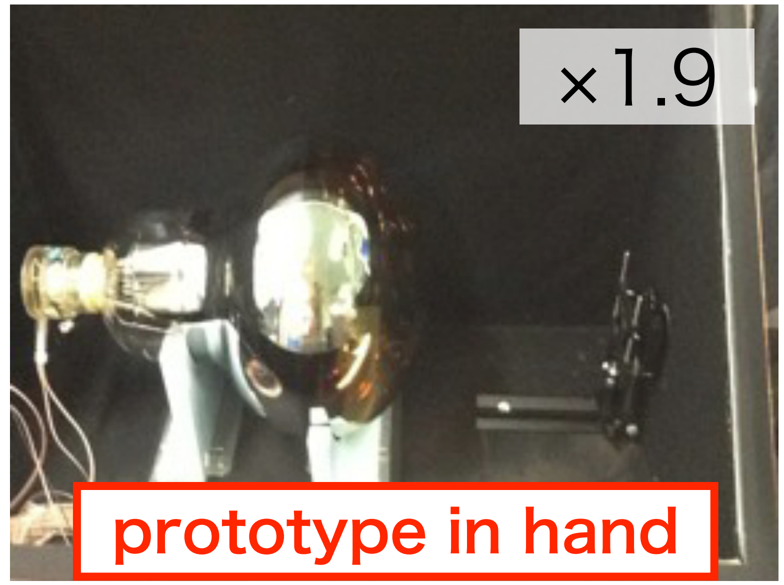
R&D for KamLAND2-Zen and future

○ winston cone



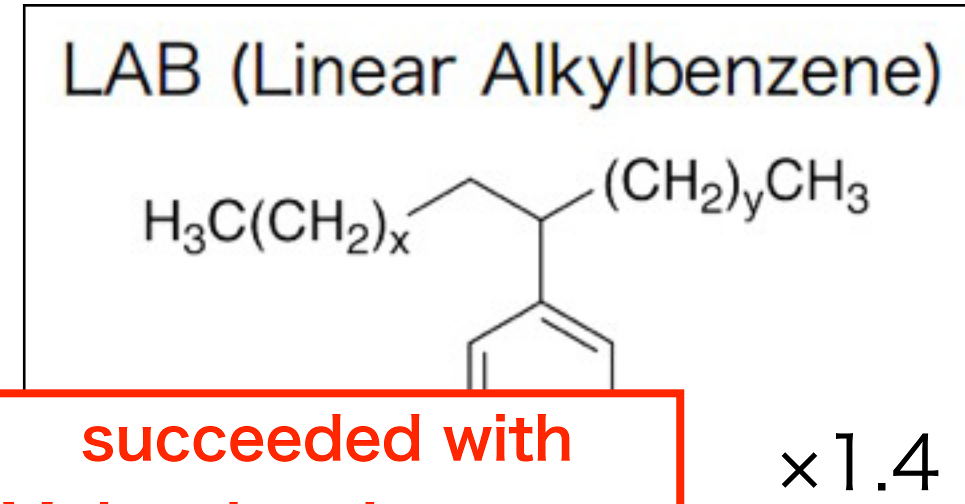
succeeded with prototype

○ HQE-PMT



prototype in hand

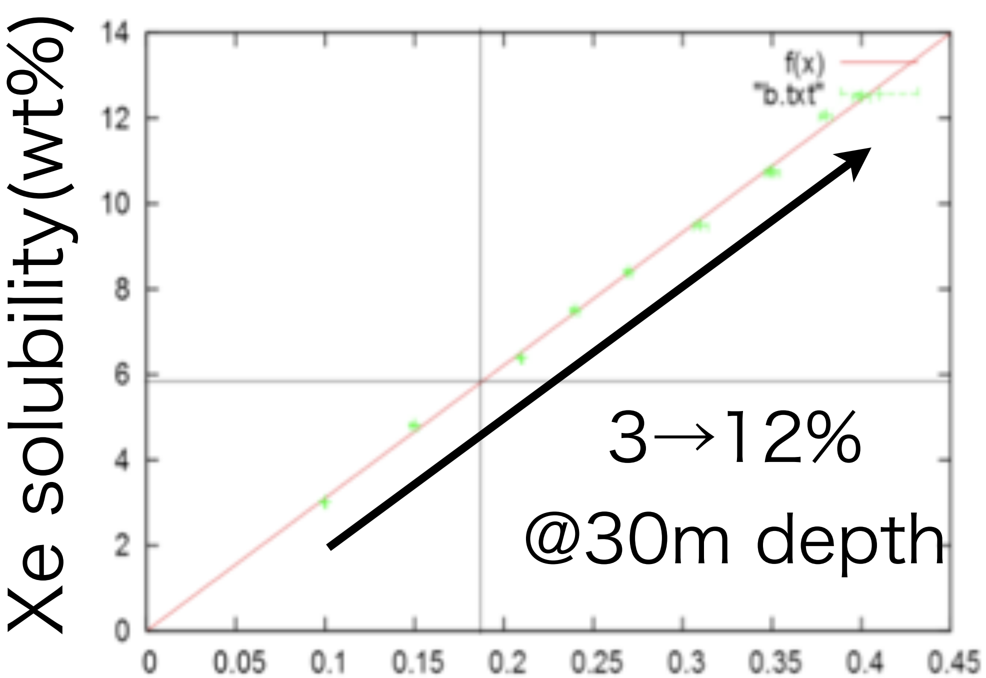
○ New LAB-LS



succeeded with Molecular sieve (13X)

×1.4

○ denser xenon

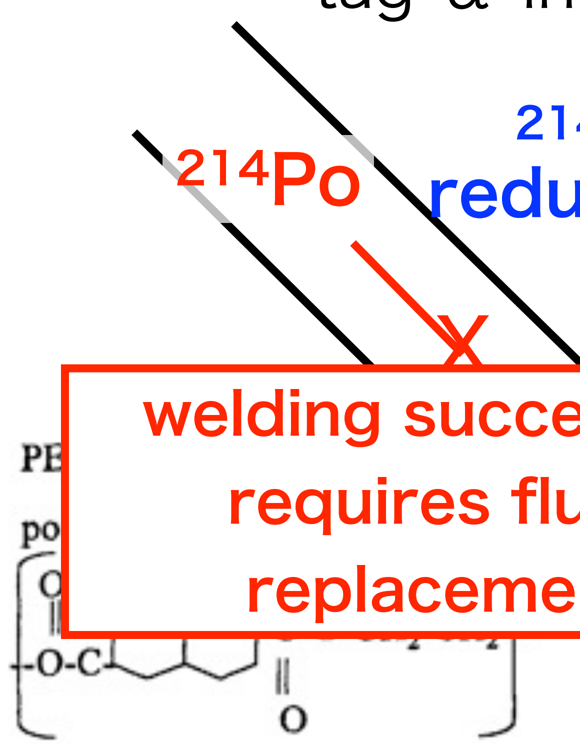


Xe partial pressure(MPa)

principle confirmed

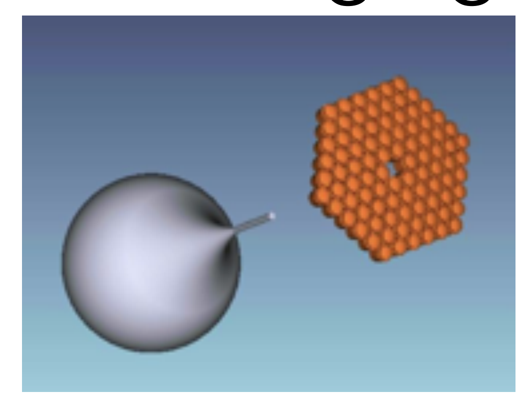
○ scintillator film

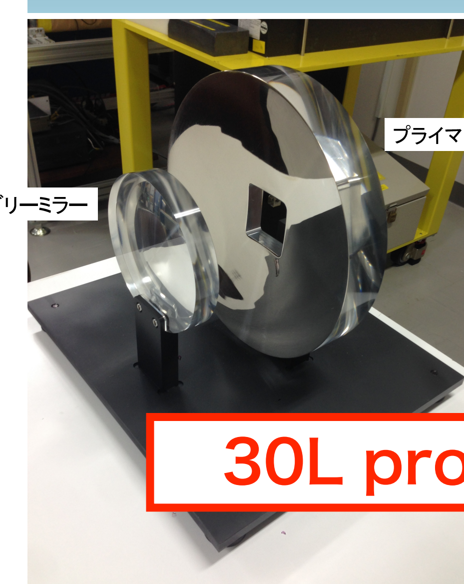
tag α in film



welding succeeded requires fluor replacement

○ imaging





***β / γ* id.**

30L prototype

Summary

- $0\nu 2\beta$ experiments very briefly reviewed
- Results from KL-Zen Phase-2 (534.5 days, 380 kg) presented

  ^{110m}Ag has been successfully reduced.

  improved analysis: 40 equal bins for volume, 2 time bins

- Phase-1 & 2 combined result for $0\nu 2\beta$ of ^{136}Xe

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

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

PRL117, 082503

- KamLAND-Zen 800 is planned

  Mini-balloon for 750kg once installed, but there was a leak. (→ Obara's poster)

  Balloon film was cleaner than previous installation. (→ Hachiya's poster)

  Target sensitivity is below 50 meV, and next deployment will be in autumn 2017.

- R&D for KamLAND2-Zen is going well.

  Target sensitivity is below 20 meV.

Thank you!