

Neutrinoless double beta decay in KamLAND-Zen

3 Neutrinos and beyond

At ICISE Quy Nhon Vietnam

Aug.8th 2019

Kota Ueshima

Tohoku University RCNS

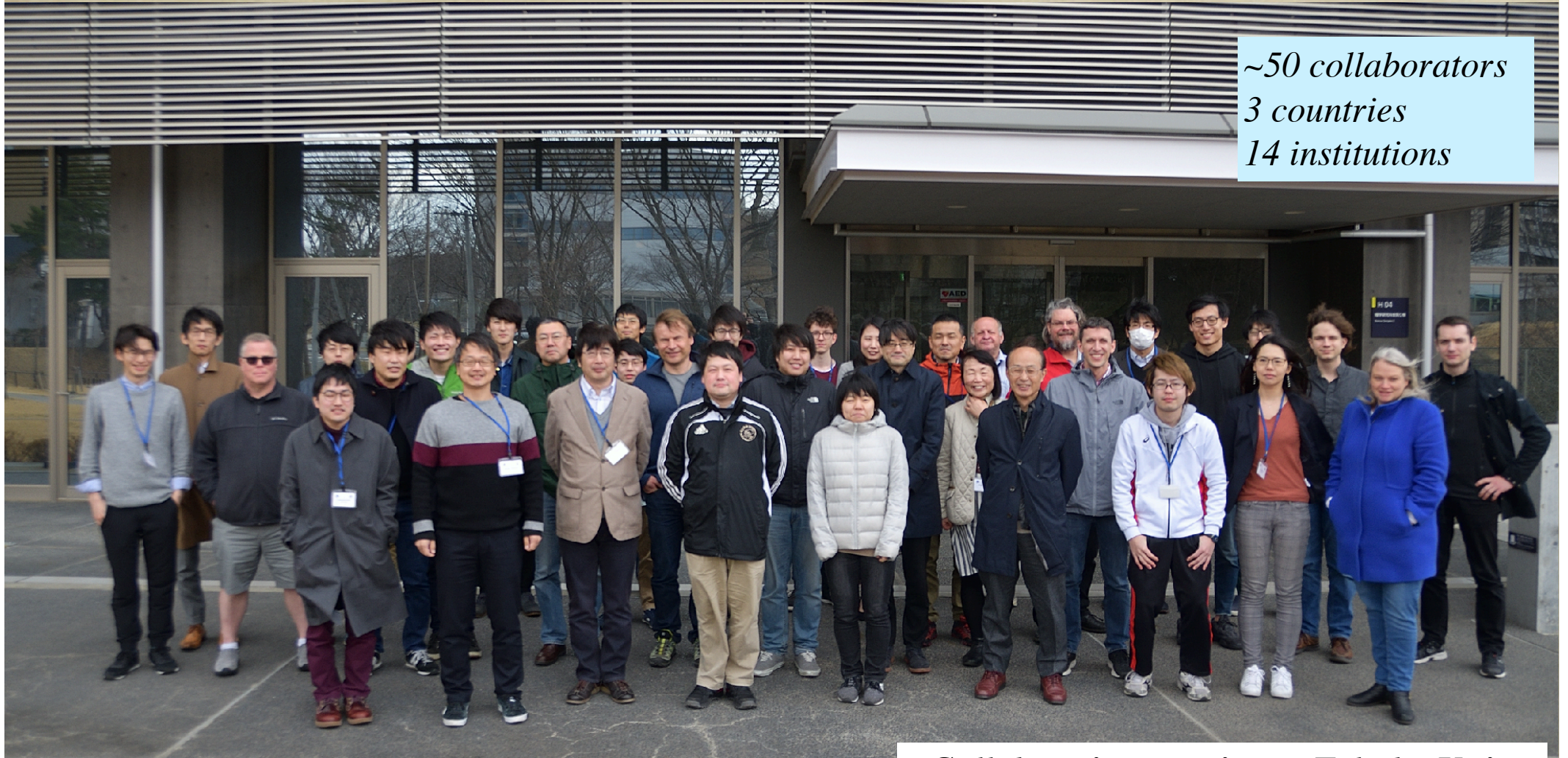
for the KamLAND-Zen collaboration



KamLAND-Zen Collaboration



*~50 collaborators
3 countries
14 institutions*



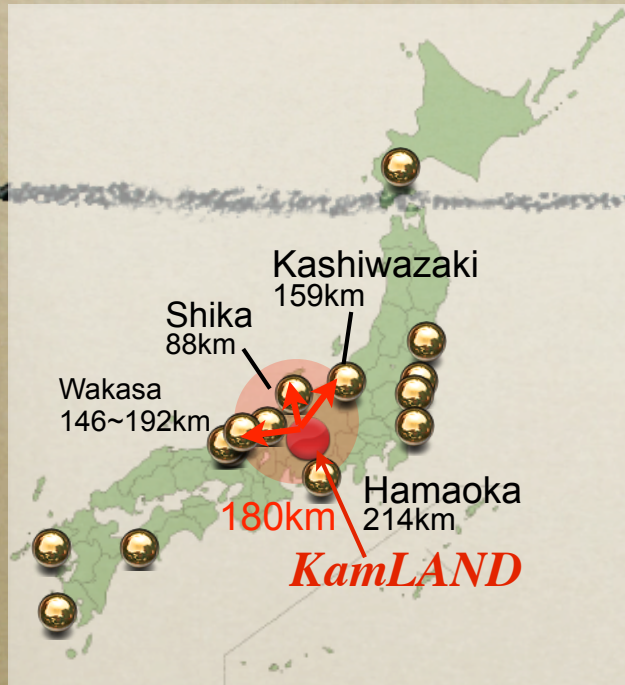
*Collaboration meeting at Tohoku Univ.
March 2019*



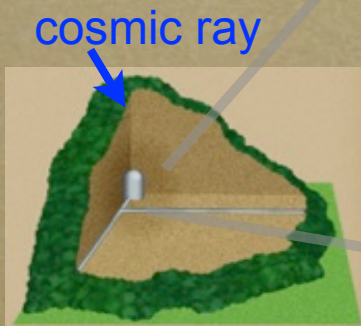
KamLAND

KamLAND

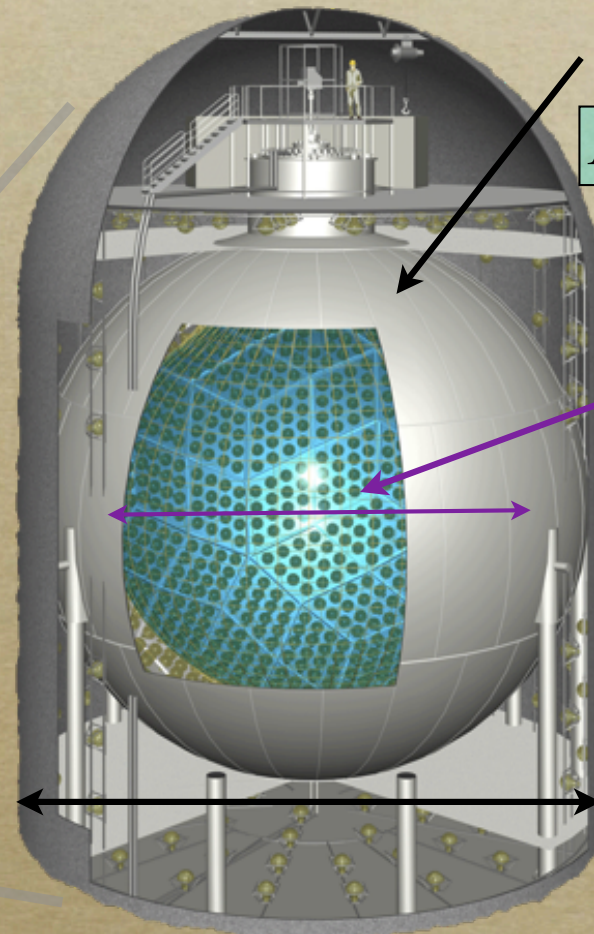
Kamioka Liquid Scintillator Anti-Neutrino Detector



Kamioka Mine



1000m depth



inner detector

1,325 17inch + 554 20inch PMTs

** Photo coverage 34%*

balloon

$\phi 13m, 135\mu m$ thick.

1 kton LS

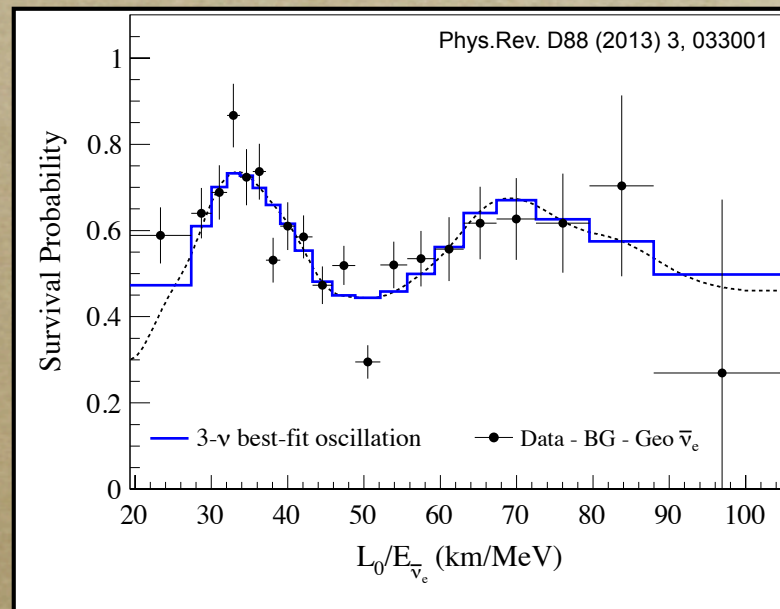
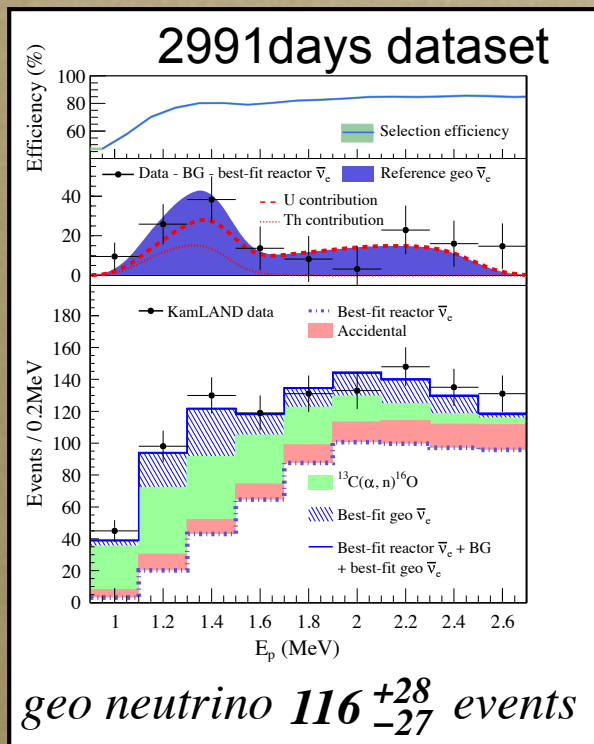
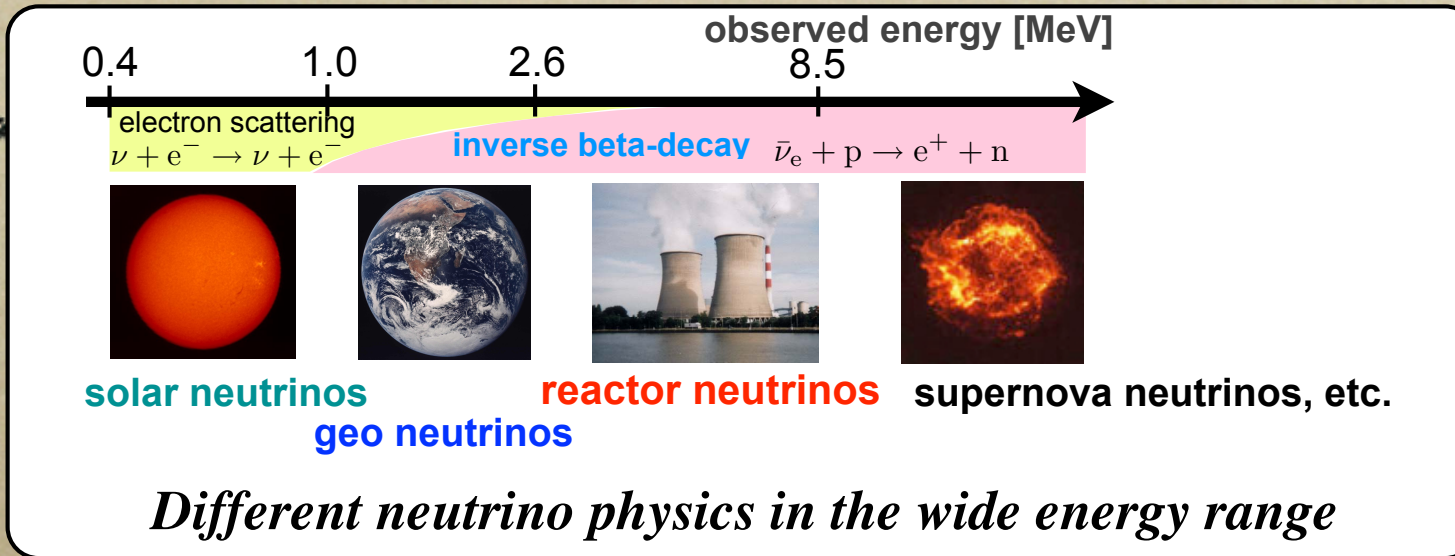
*Water Cherenkov outer detector
 $\phi 18m, 3.2$ kton pure water*

Refurbished in 2016

140 20inch PMTs

** Muon veto*

Physics



※ $L_0=180\text{km}$ fixed
(flux-weighted average)

best-fit parameters
(KamLAND only)

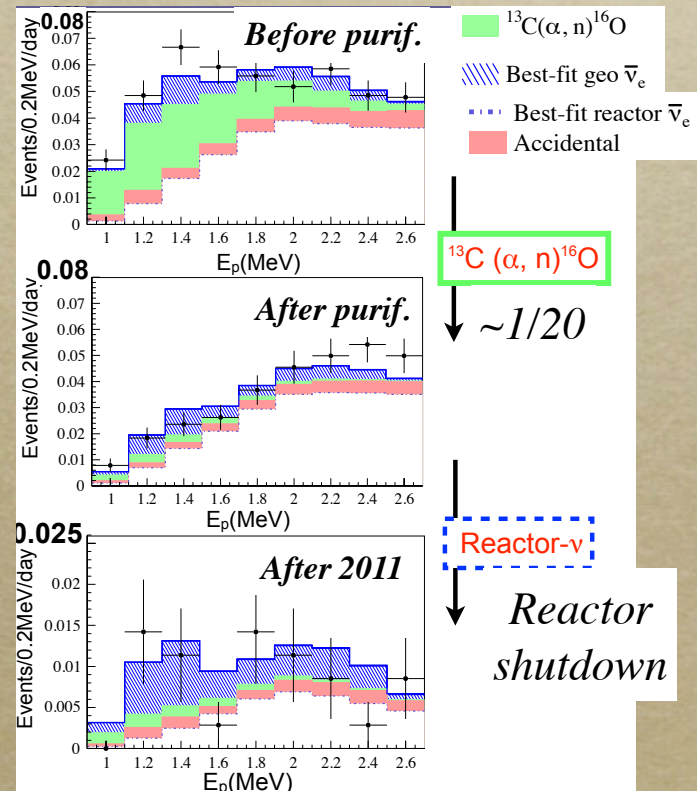
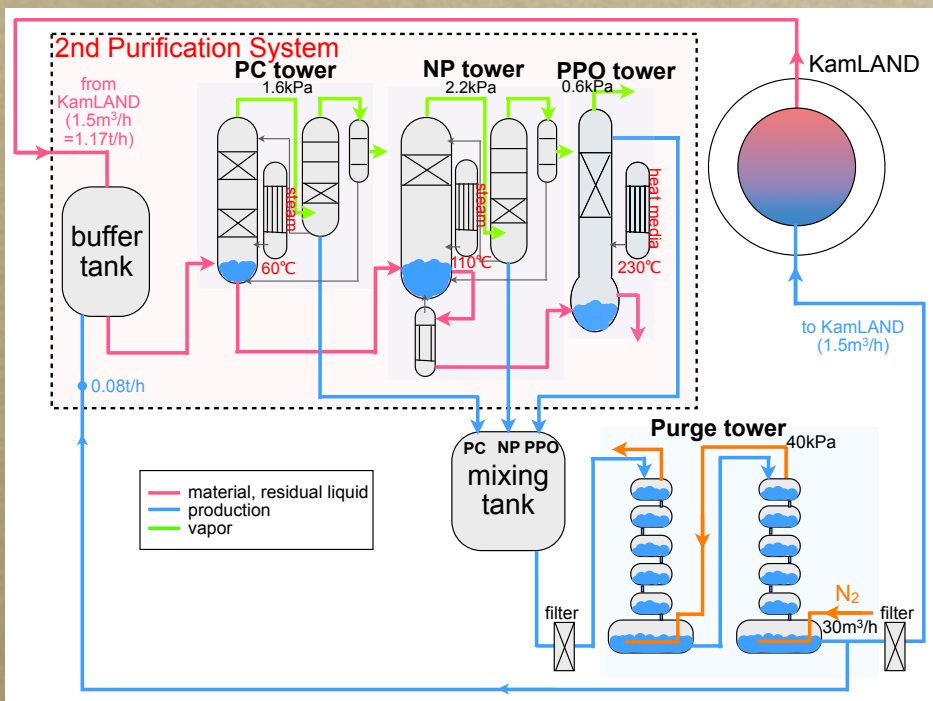
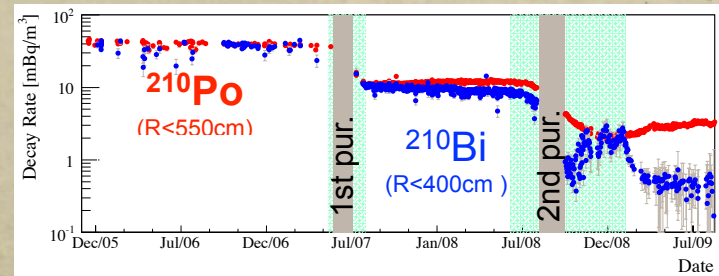
$$\Delta m_{21}^2 = 7.54^{+0.19}_{-0.18} \times 10^{-5} \text{eV}^2$$

$$\tan^2 \theta_{12} = 0.481^{+0.092}_{-0.080}$$

$$\sin^2 \theta_{13} = 0.010^{+0.033}_{-0.034}$$

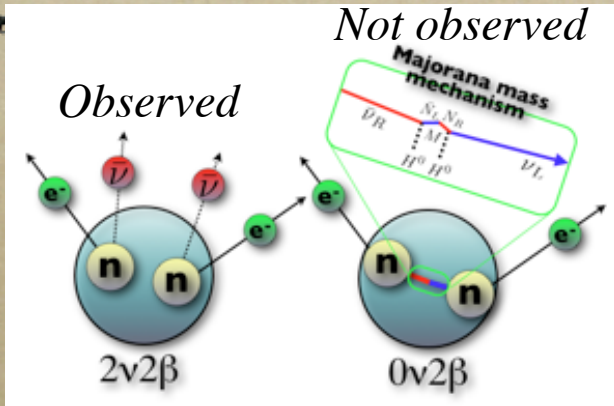
2 cycles of oscillation were measured precisely

1k ton LS purification system



Achieved ultra low impurity ($^{238}\text{U}:3.5 \times 10^{-18}\text{g/g}$, $^{232}\text{Th}:5.2 \times 10^{-17}\text{g/g}$)

Neutrinoless double beta decay



If neutrinos are Majorana particle, $0\nu 2\beta$ may occur.

- * effective neutrino mass
- * mass hierarchy
- * lepton number violation
- * evidence of Majorana particle

Big impact on particle physics!!

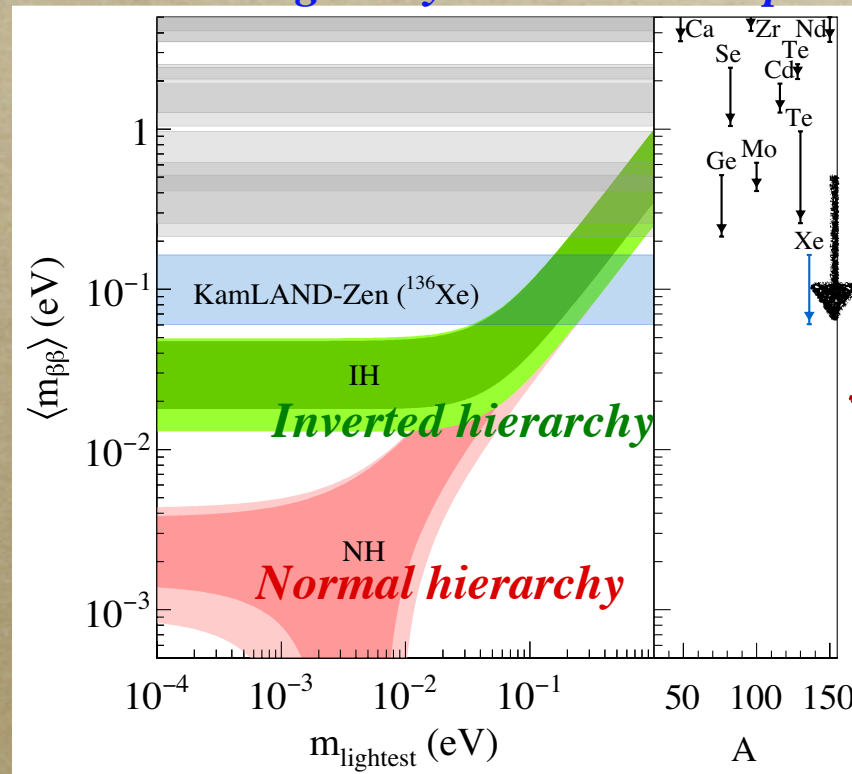
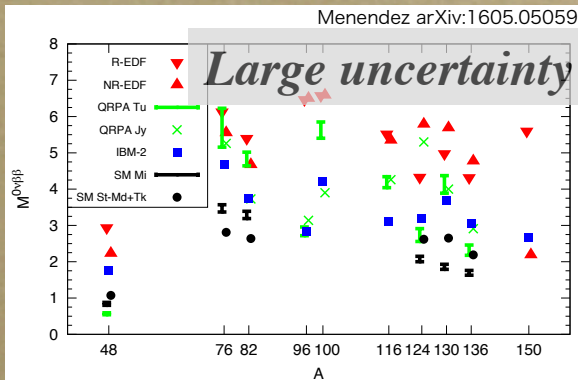
Allowed region by ν oscillation exp.

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

G: phase space factor

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^3 U_{ei}^2 m_i \right|$$

Nuclear matrix element



Amount of target nucleus

$\sim 100\text{kg}$

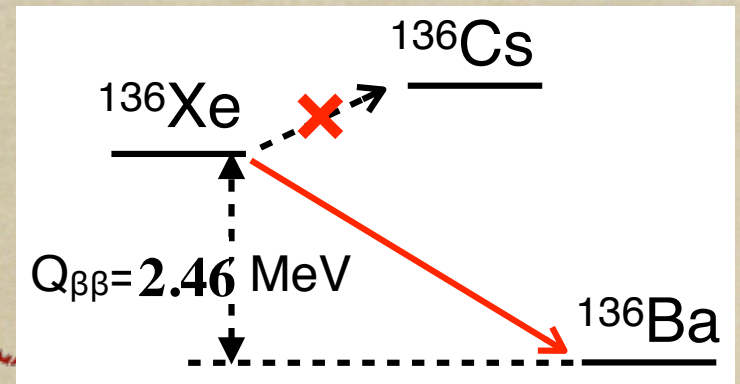
$\sim 1\text{ton}$

$\sim 100\text{ton}$



KamLAND-Zen

Zero Neutrino Double Beta Decay Search



Detector features

Mini-balloon was installed at center of KamLAND (ultra clean)

Xe loaded LS was installed in Sep. 2011.

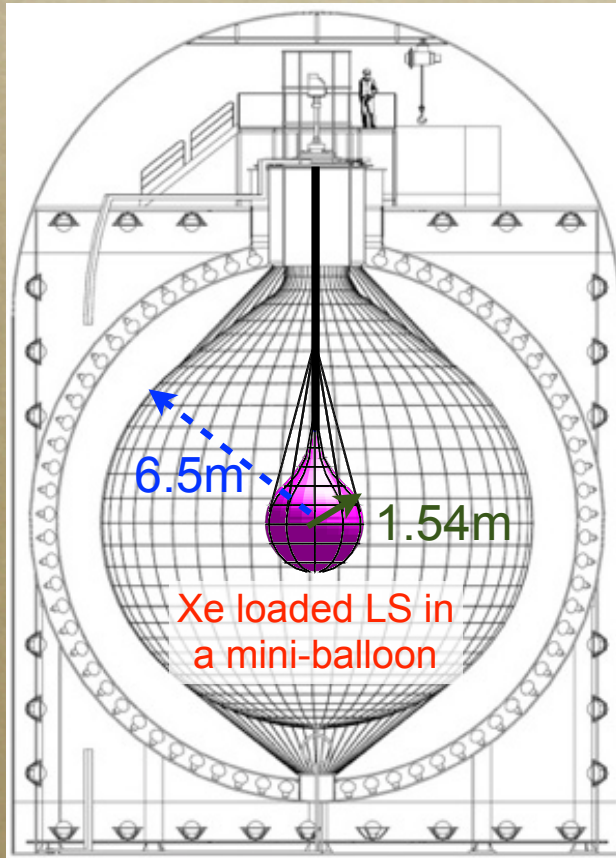
↳ **320kg 91% enriched ^{136}Xe** DAQ was started in Oct. 2011.
(The project was started in 2009)

^{136}Xe merit

enrichment is available **~91%**

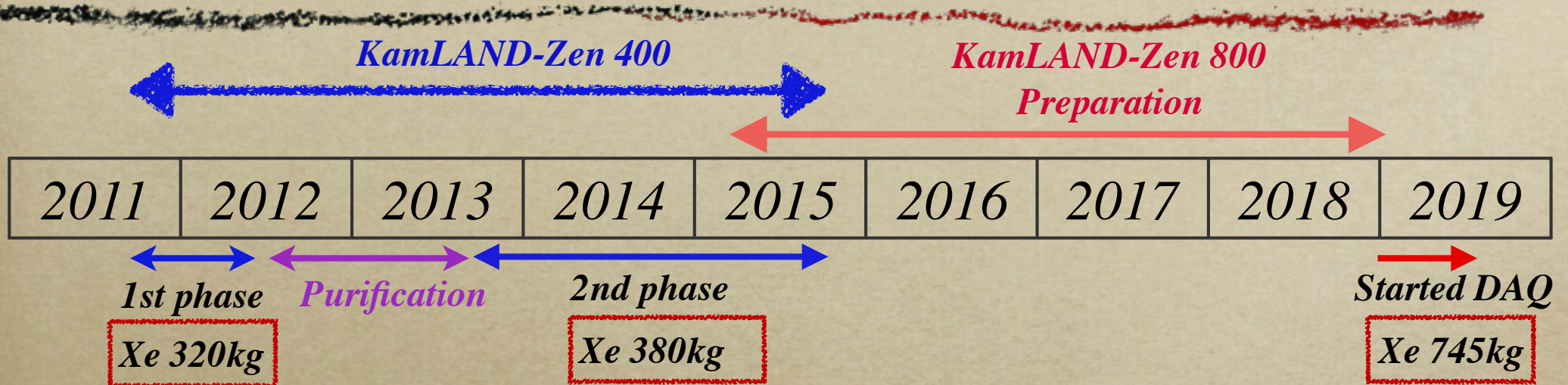
High solubility: Xe is dissolved in LS **3wt%** at 1 atm.
collect Xe from Xe loaded LS by degassing **easily**.
purification method is established (LS, Xe)

High scalability: replace with big balloon
and dissolve ton scale ^{136}Xe .



If $0\nu 2\beta$ signal was observed, it can be verified
using same detector with ^{136}Xe removed.

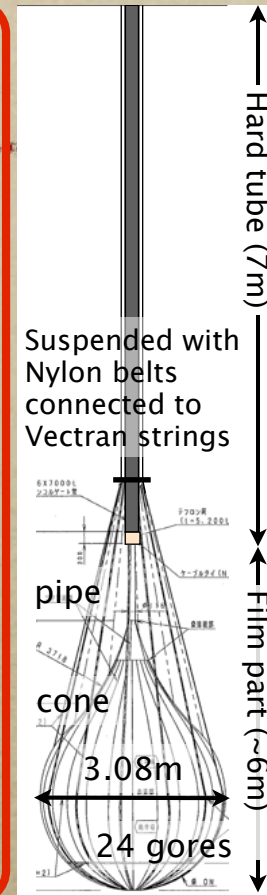
History



- 1st phase (Oct.2011- Jun.2012) *PRL 110, 062502(2013)*
- Purification (Jun.2012-Nov.2013) Xe extraction, Xe purification, LS purification.
- 2nd phase (Dec.2013- Oct.2015)
Latest $0\nu 2\beta$ result was released in 2016. *PRL 117, 082503(2016)*
- Preparation for KamLAND-Zen 800 phase was started in 2015
(Zen 400 mini-balloon extraction, new mini-balloon production, extracted xenon & new xenon purification)
- KamLAND-Zen 800 phase was started. Jan.2019 -

Mini-balloon production and installation

at Sendai in June 2011



Mini-balloon was made in Sendai.

Deflated Mini-balloon was delivered to Kamioka.

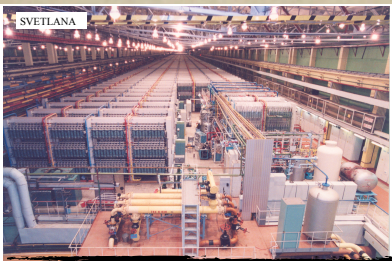
After the Mini-balloon was installed in KamLAND, the Mini-balloon was inflated using normal LS.

Finally the normal LS was replaced with the Xe loaded LS.

at Kamioka mine in Aug 2011

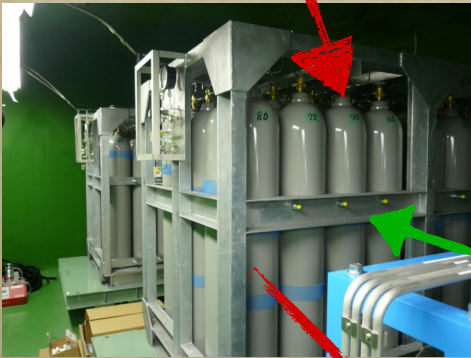


Xe handling system



^{136}Xe made in Russia

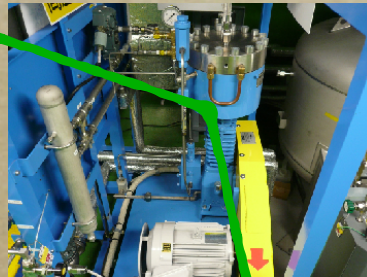
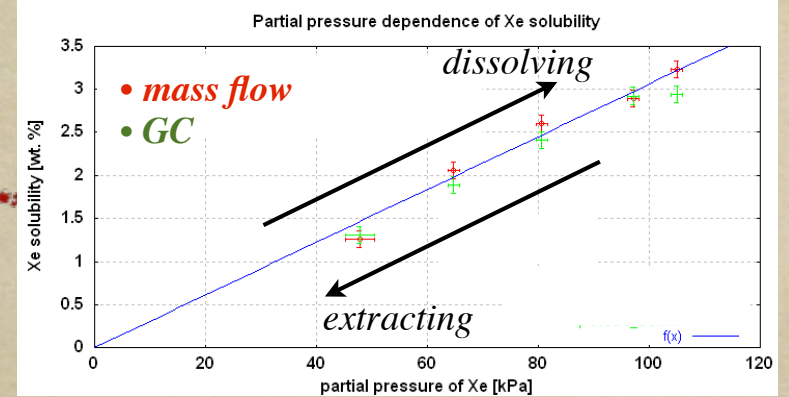
Kamioka mine



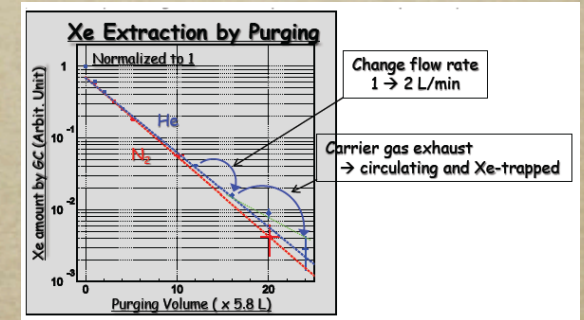
Xe solubility follows Henry's law.

Dissolving: increase partial pressure of Xe

Extracting: degassing + nitrogen purge passing through Xe cold trap



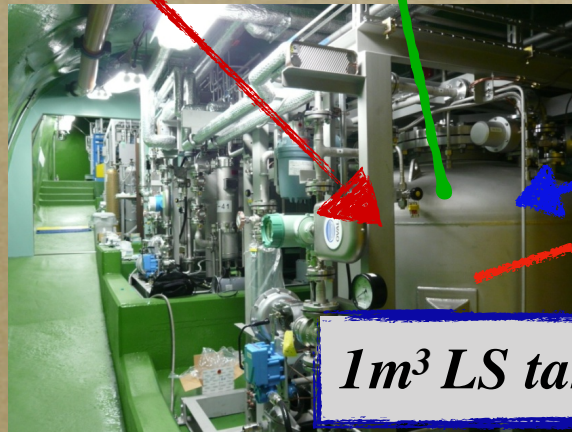
*Compressor
~6MPa*



Xe dissolving

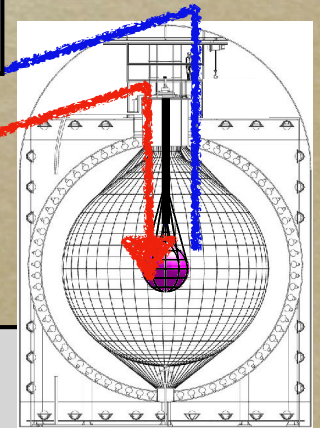
Xe extraction

Xe-LS extraction



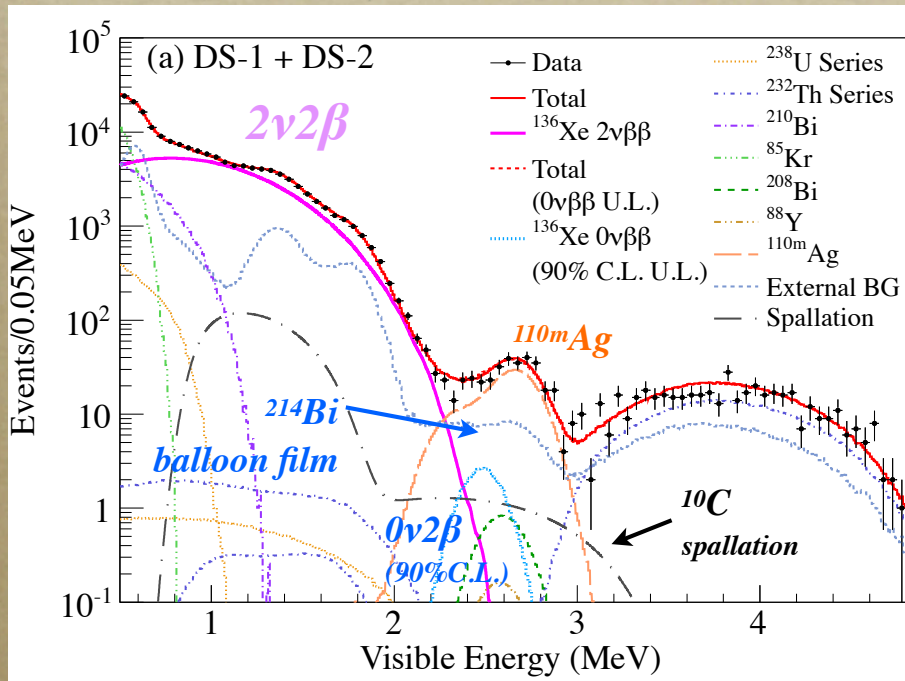
1m³ LS tank

*Filling Xe-LS
Density ~ ±0.01%
Temperature < ±0.3°C*



1st Phase result

PRL 110, 062502 (2013)



Unexpected ^{110m}Ag is dominant BG.

Fallout product from Fukushima reactor accident

FV is optimized to 1.35m radius for $0\nu 2\beta$ analysis.

lifetime 213.4 days

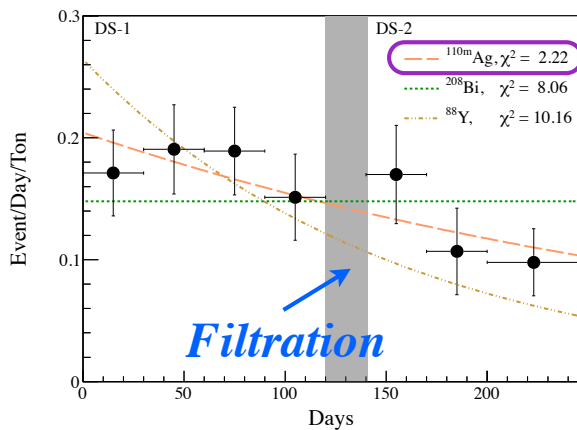
*exposure: 89.5 kg*yr*

$0\nu 2\beta$ result

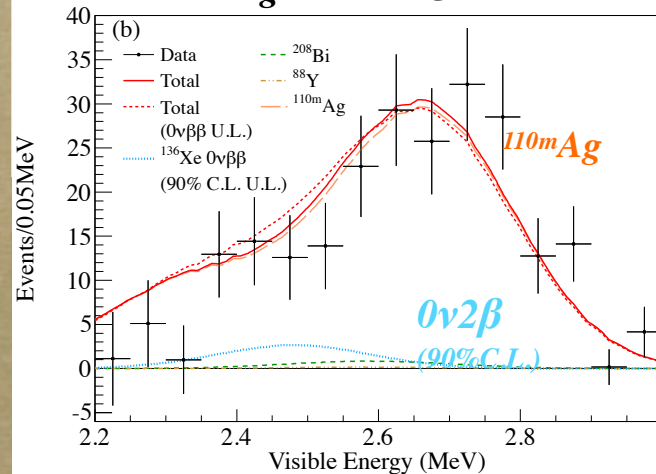
$$T_{1/2}^{0\nu 2\beta} > 1.9 \times 10^{25} \text{ yr (90\% C.L.)}$$

$$\langle m_{\beta\beta} \rangle < 0.16 - 0.33 \text{ eV (90\% C.L.)}$$

Time variation at 0ν region

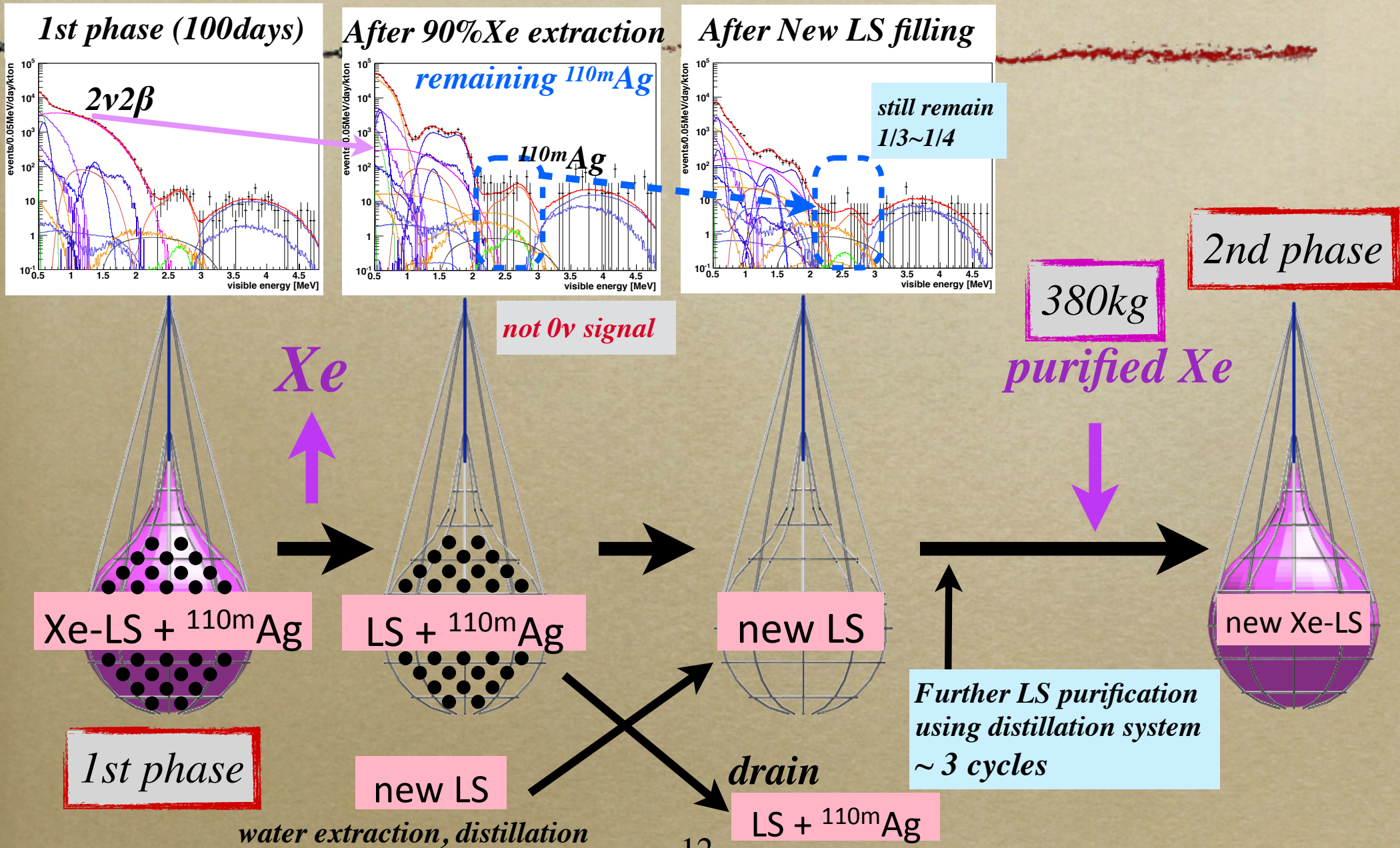


subtracting known BG contribution



**Remove BG
→ Purification**

Purification methods



Xe purification system

Xe was collected passing through LS cold trap.

Xe distillation system

borrowed from XMASS

design goal: reducing Kr by more than 3 orders of magnitude. (achieved)



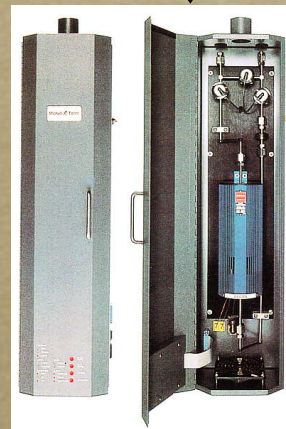
charcoal filter

LS vapor < 1ppb

adsorption type filter



sintered metal filter (SUS)



getter

H₂O, N₂, O₂, CH₄, CO, CO₂ < 1ppb

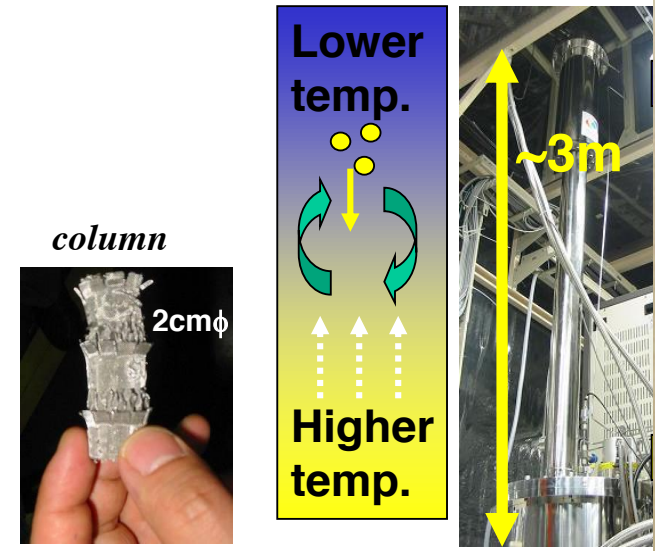


PTFE filter

pore size 3nm

Zr alloy

350~400°C



column

Lower temp.

Higher temp.

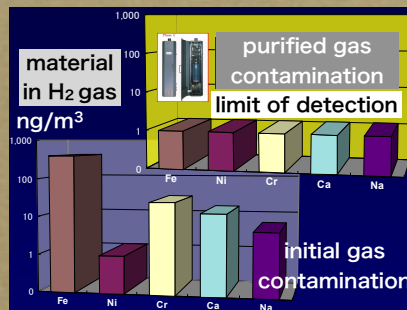
Nitrogen concentration in Xe was reduced from 2% to less than 100ppm. Metal might be removed.

SAES

Metal	Metal Generation (ppmw)	Metal after SST (ppmw)	Trap Efficiency
Fe	1.3	0.03	98%
	1.2	0.02	98%
	1.3	0.01	99%
	1.4	0.03	98%
	3.1	0.03	99%
Cr	3.3	0.02	99%
	1.2	0.03	98%
Cu	6.54	0.03	100%
	0.08	0.005	94%
Ni	0.03	0.003	91%
	0.05	0.005	91%
Ni	0.18	0.018	91%
	0.5	0.01	98%

Metal also trapped in charcoal.

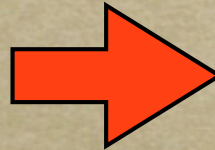
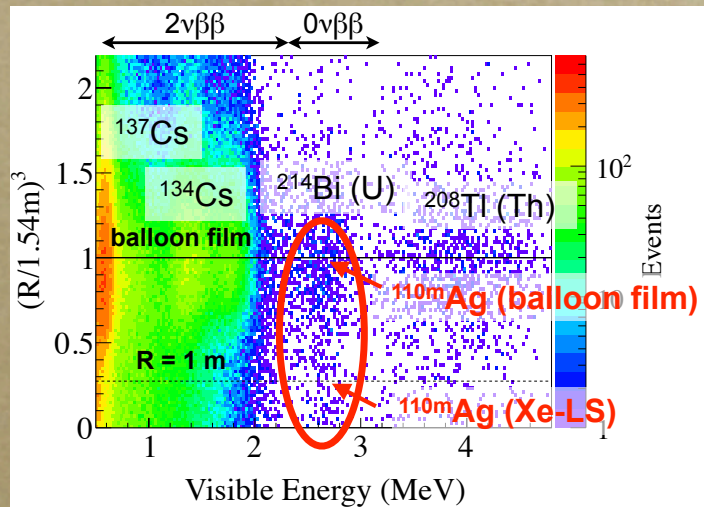
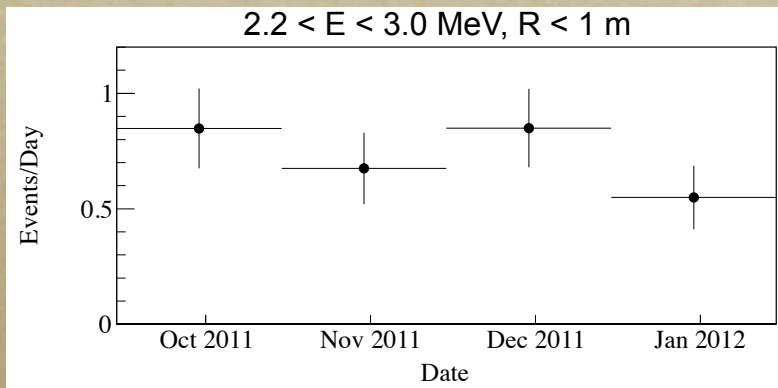
SAES



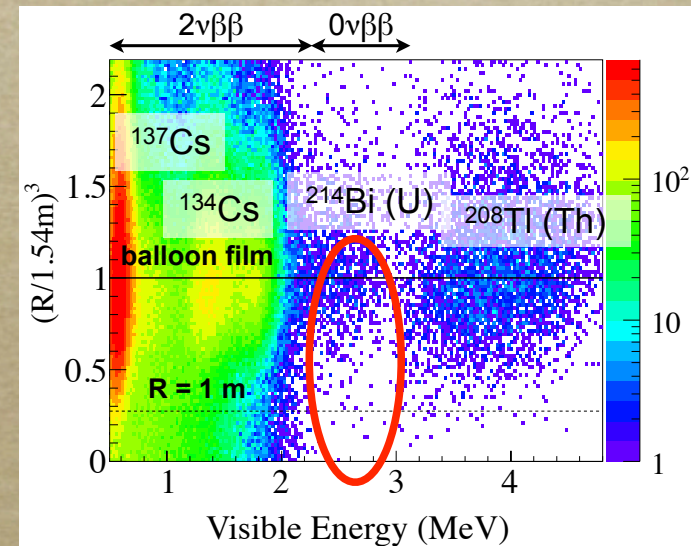
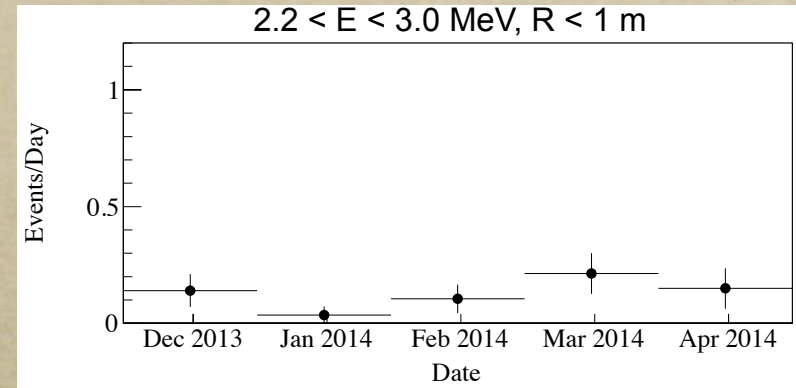
~410kg Xe was purified.

Ag BG reduction results

1st Phase (first 112.3 days)



2nd Phase (first 114.8 days)



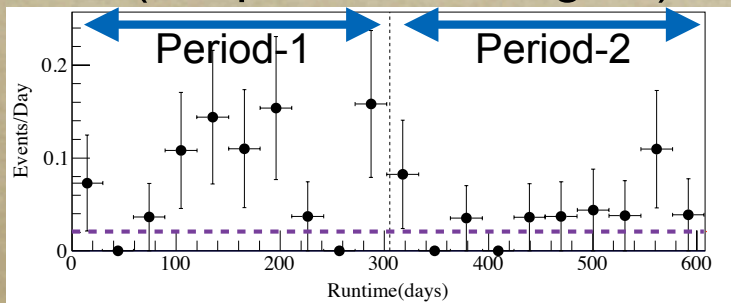
*^{110m}Ag BG was reduced by a factor of more than **10**.*

KamLAND-Zen 400 result

PRL 117, 082503(2016)

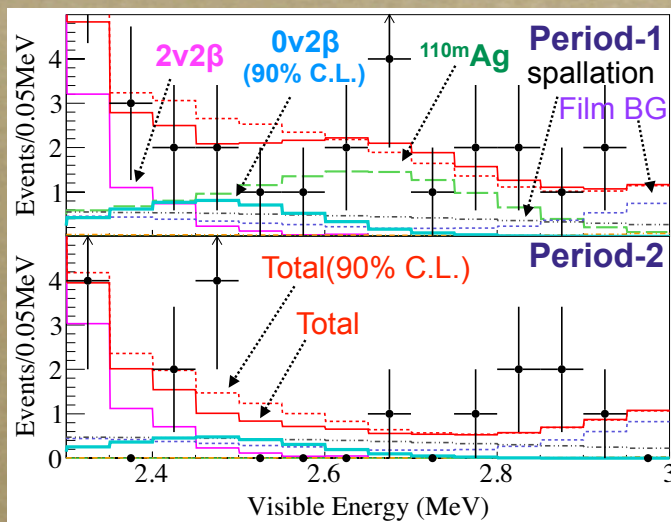
2nd Phase Result

$R < 1.0\text{m}$ $2.3 < E < 2.7\text{ MeV}$
($0\nu 2\beta$ sensitive region)

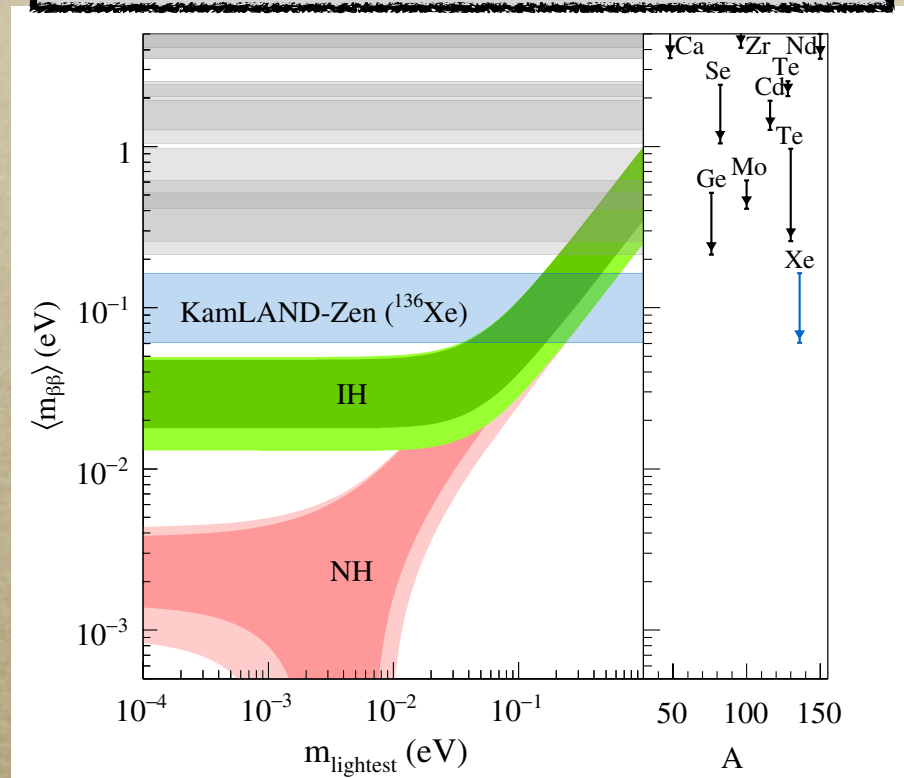


22 events

11 events



Combined Result (1st & 2nd Phase)



$$T_{1/2}^{0\nu 2\beta} > 1.07 \times 10^{26} \text{ yr} \quad (90\% \text{ C.L.})$$

best upper limit

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

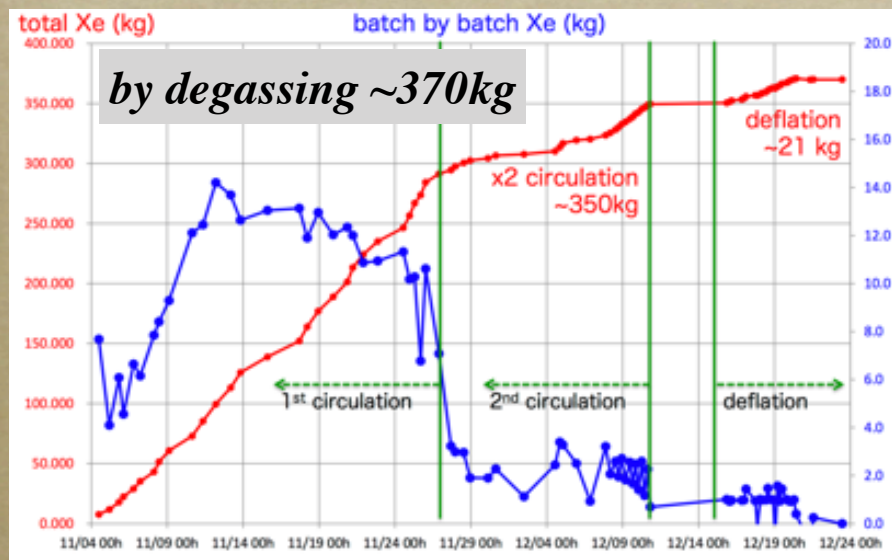
$\langle m_{\beta\beta} \rangle$ limit reached near IH region below 100meV

Toward KamLAND-Zen 800 phase

increase ^{136}Xe & ultra clean mini-balloon production

Zen-400 mini-balloon extraction

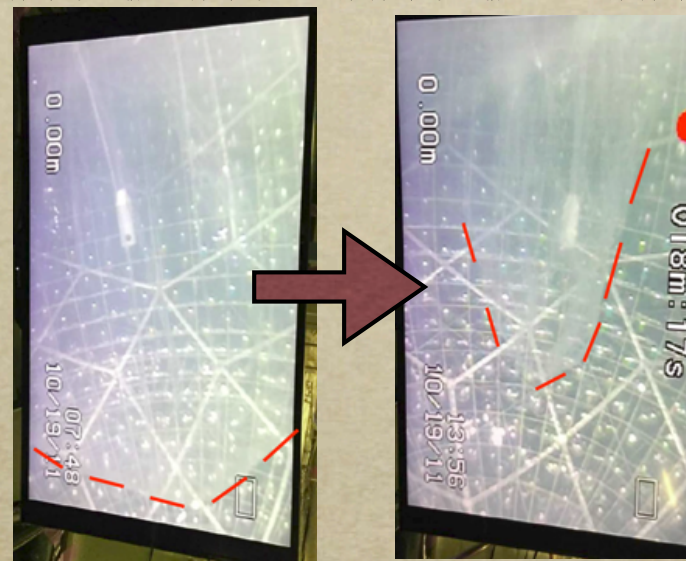
Xe collection from mini-balloon



*remaining Xe in LS was collected
by N₂ purge ~10kg*

*Purified collected Xe and new Xe
using distillation system.*

**770kg Xe was purified
for KamLAND-Zen 800 phase.**

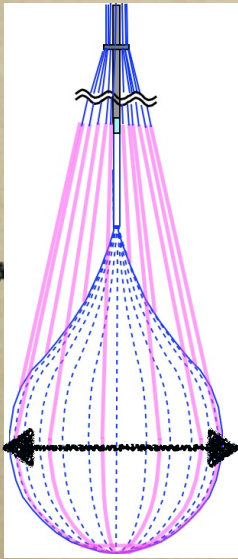


deflation



Zen 800 mini-balloon production

Toward ultra clean mini-balloon production



$\phi 3.84m$
(Zen400 $\phi 3.08m$)



Clean underwear

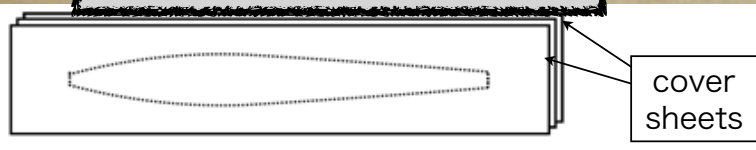


goggle
Double gloves



laundry
twice a day

Balloon film protection



cover
sheets

2 class 1 clean rooms

~\$6000/month

Room1: mini-balloon production

*Room2: changing clean suits
cleaning all equipments*

Static-electricity control

Mistgeneration system



Humidity control



Ion generation system

Semi-automatic welding machine

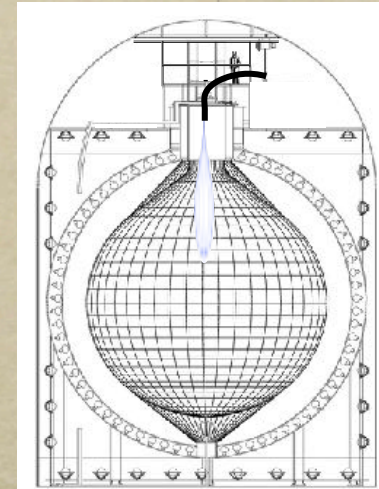


Zen 400



Zen 800

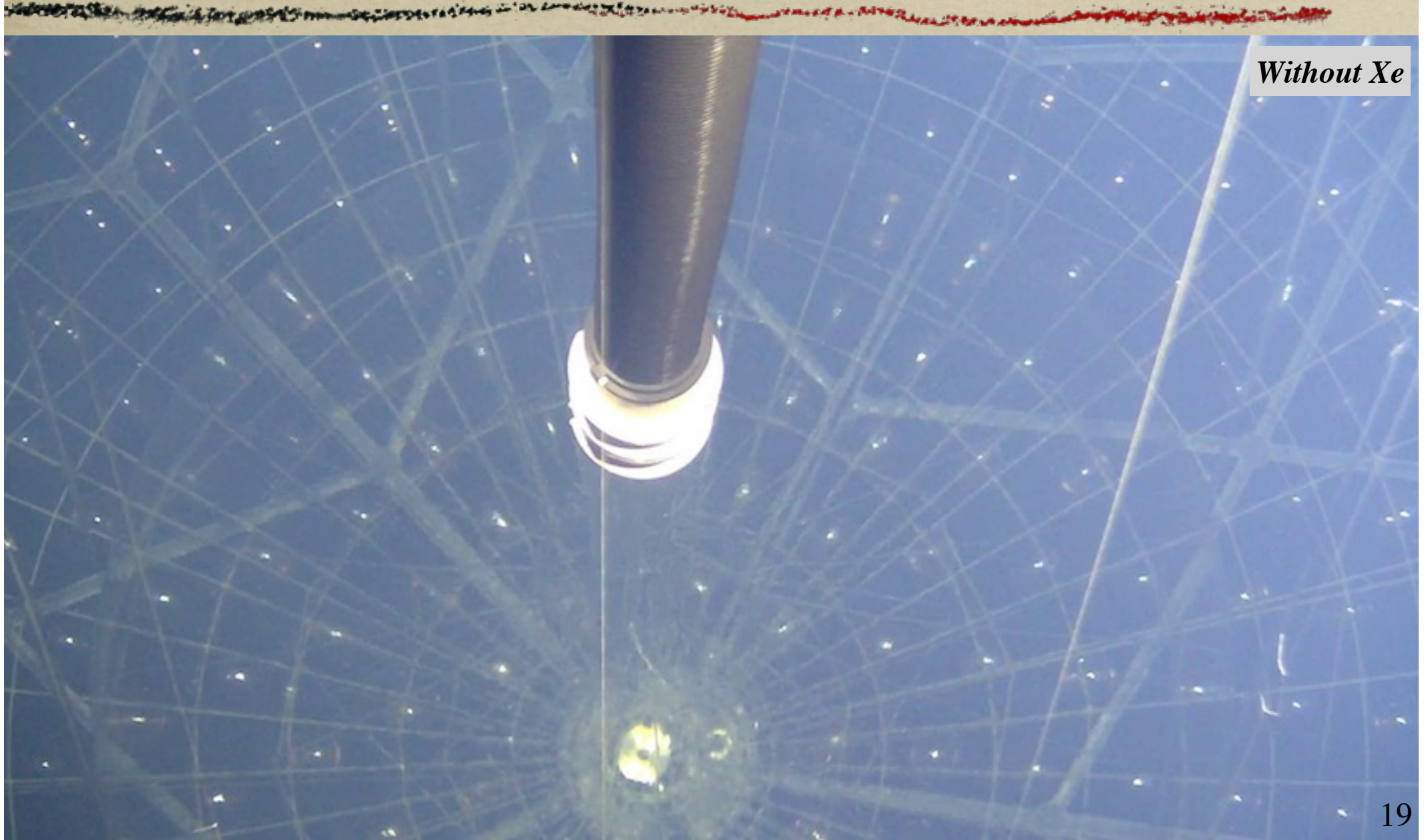
Zen 800 mini-balloon installation



*Zen 800 mini-balloon was installed
in May 2018*

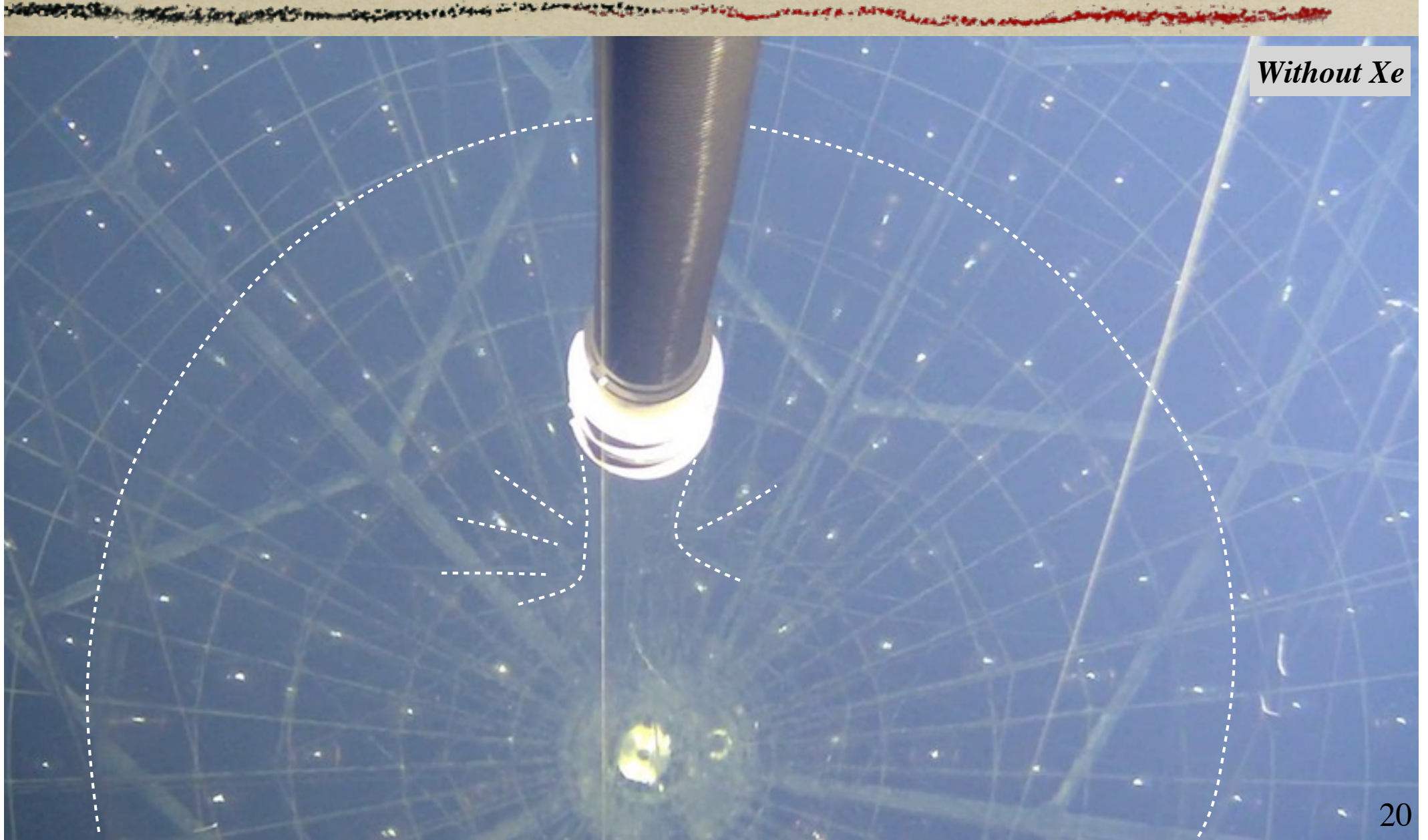


30.5m³ normal LS filling



Without Xe

30.5m³ normal LS filling



Without Xe



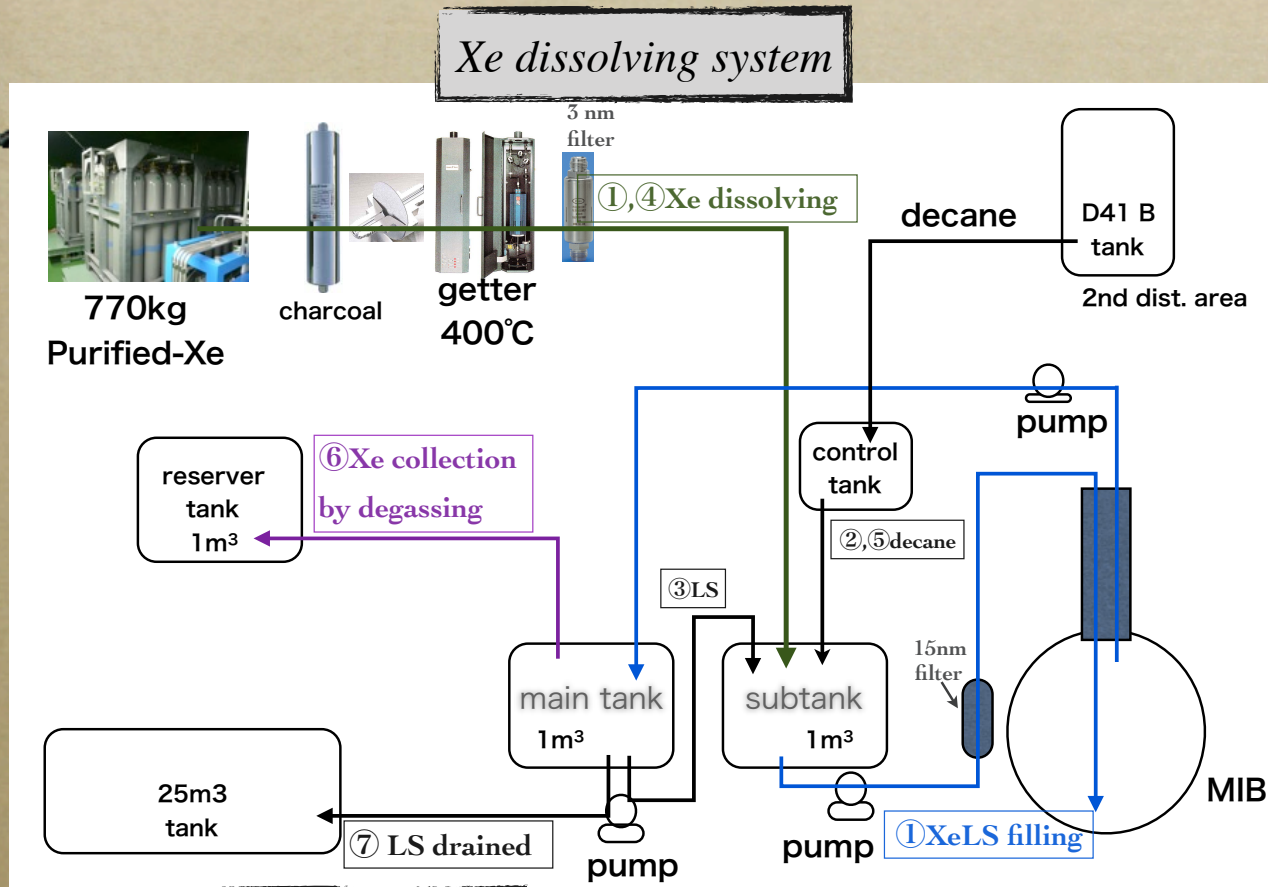
Zen 800 vs Zen 400

30.5m³

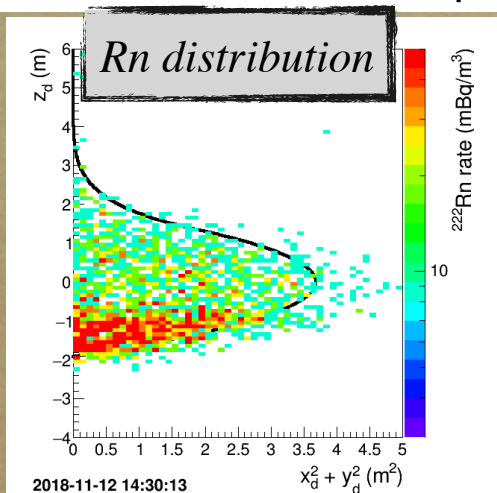
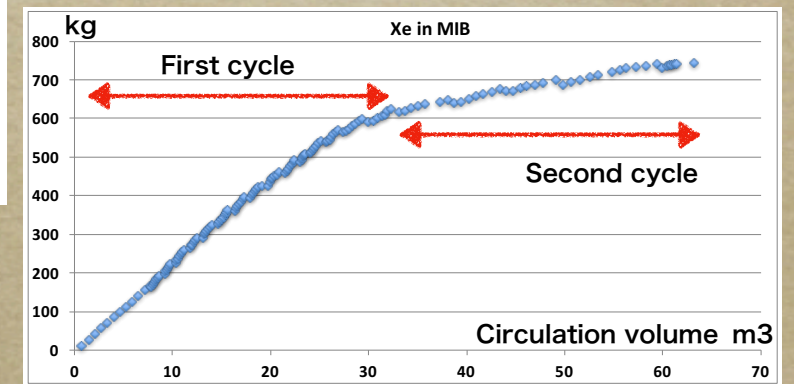
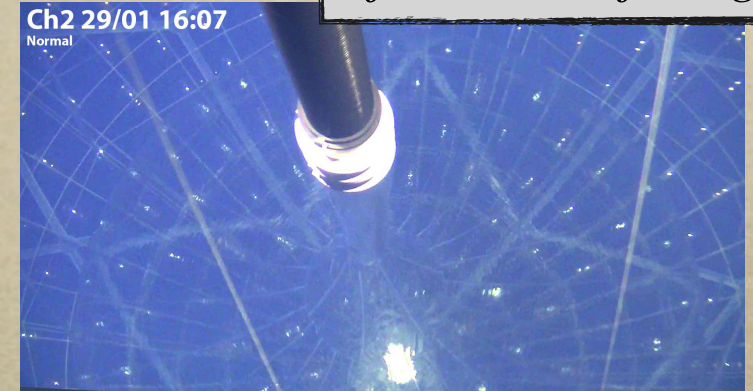
16.5m³

Xe dissolving

Nov. 2018~ Jan. 2019



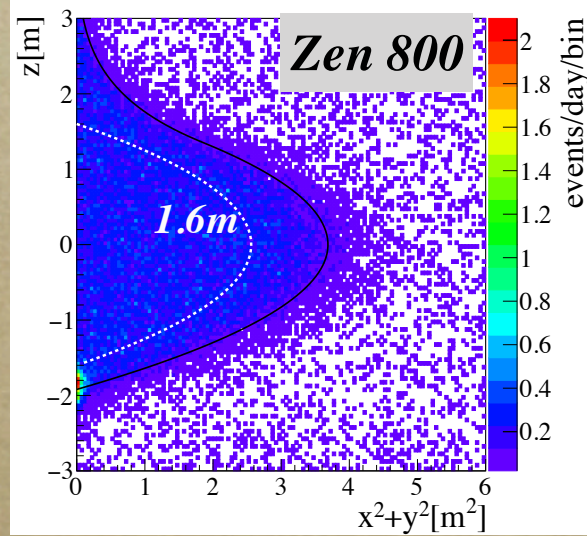
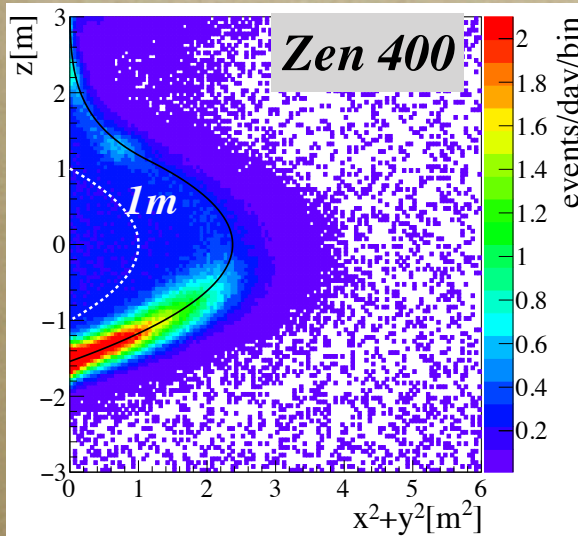
After Xe-LS filling



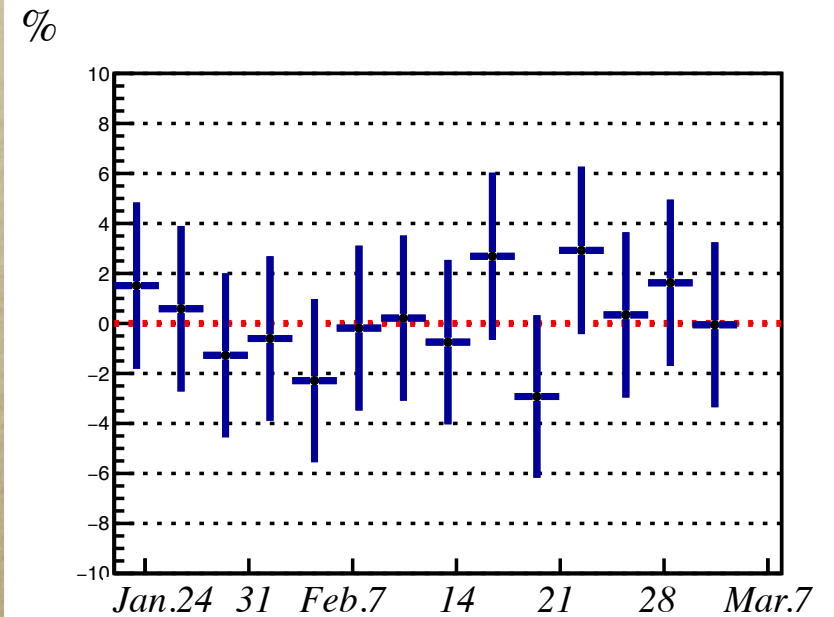
745kg Xe was installed.
Physics run was started in Jan. 2019.

$2\nu 2\beta$ event distribution

$2\nu 2\beta$ events distribution
($1.0 < E_{\text{vis}} < 2.3$)



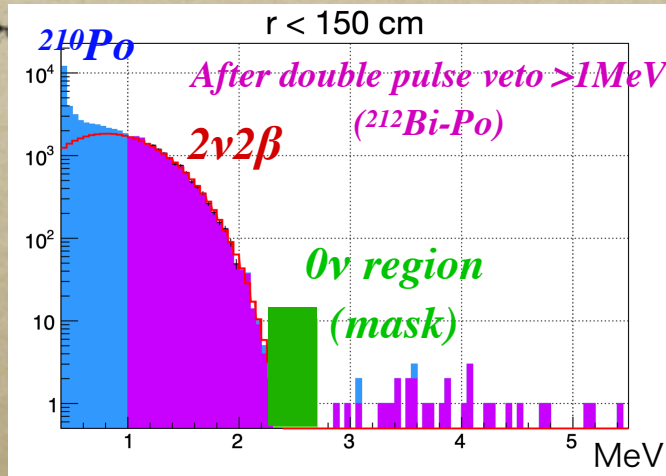
$2\nu 2\beta$ event rate time variation
 $r < 220$ cm



$2\nu 2\beta$ events dominant for all volume!! Stable $2\nu 2\beta$ event rate!!

$0\nu 2\beta$ search status

Energy spectrum after $^{214}\text{Bi-Po}$ veto

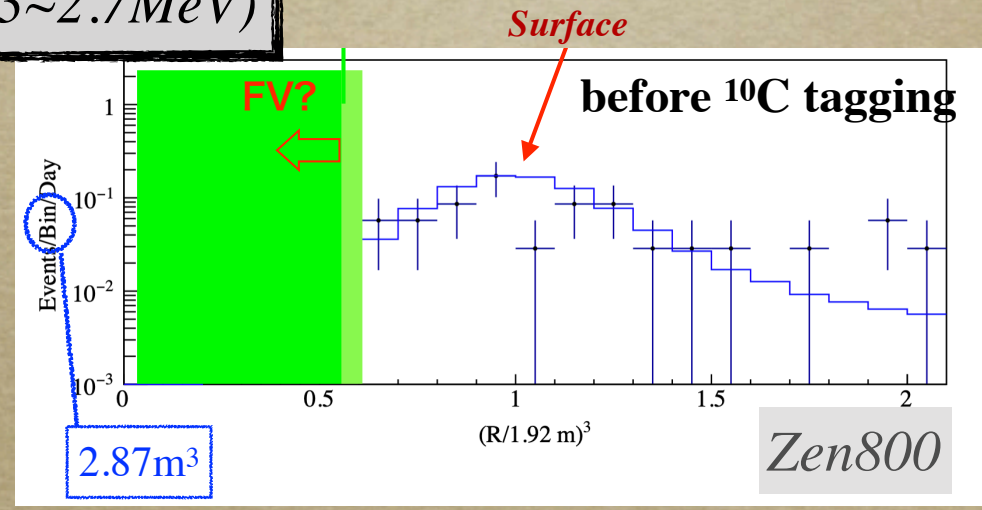
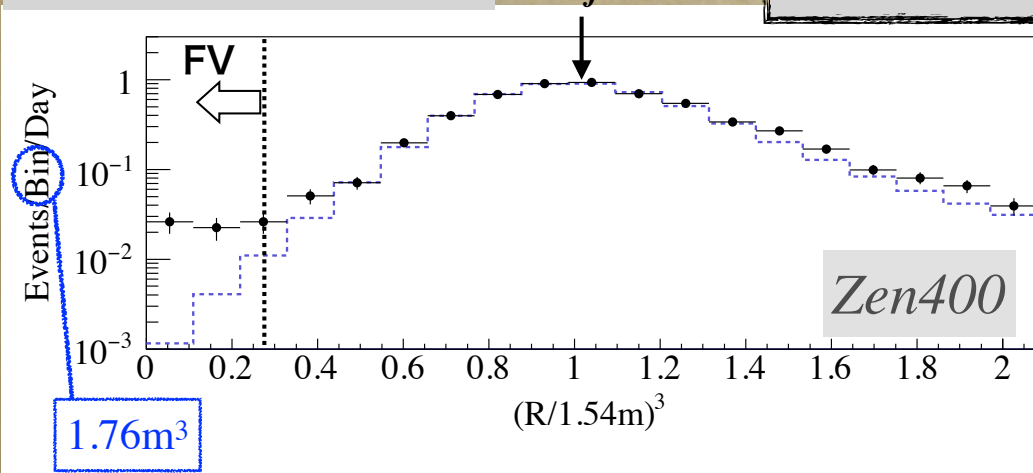


No strange BG!!

*Mini-balloon was clean!! ~1/10 low BG
 FV will be increased to 3~4 times of Zen400.*

r^3 event distribution

0ν region (2.3~2.7 MeV)



Target Sensitivity : $\langle m_{\beta\beta} \rangle \sim 40 \text{ meV}$ (5yr data taking)

XVI International Conference on Topics in Astroparticle and Underground Physics



The biennial TAUP series covers recent experimental and theoretical developments in astroparticle physics including Cosmology and particle physics, Dark matter and dark energy, Neutrino physics and astrophysics, Gravitational waves, High-energy astrophysics and cosmic rays

Sep. 9 (Mon.) - Sep. 13 (Fri.), 2019
Toyama International Conference Center, Toyama, Japan

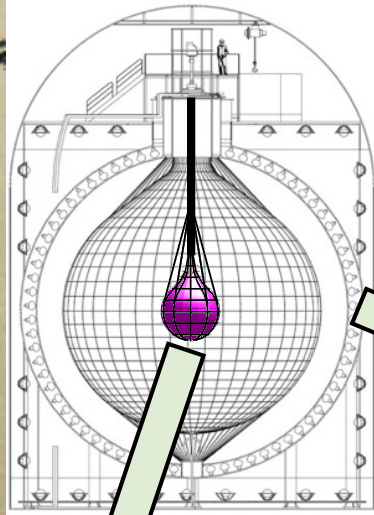
TATEYAMA
Tateyama Mountain Range

TOYAMA
Amazing City, TOYAMA

First result from KamLAND-Zen 800 will be released in Next Month.

Future prospects

Reduce $2\nu 2\beta$, ^{214}Bi



Scintillating Balloon

○ scintillator film

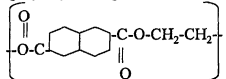
tag α in the film

^{214}Po ^{214}Bi
reduction



PEN

polyethylenephthalate

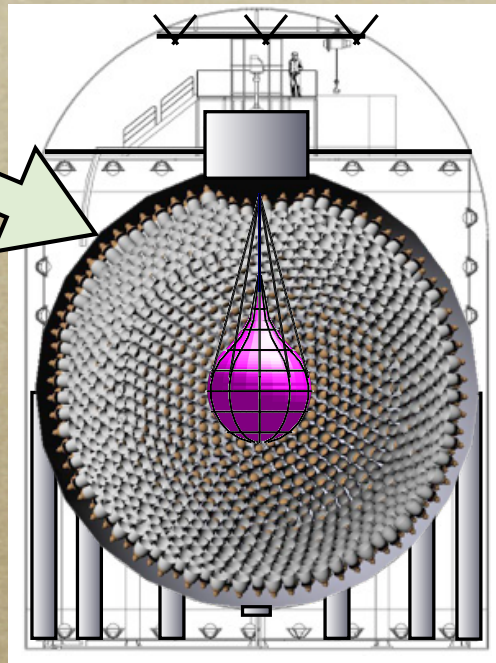


prototype succeeded

KamLAND2-Zen

>1000kg ^{136}Xe

Improve σ_E



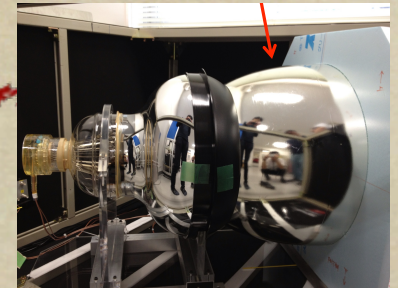
E resolution at 2.6MeV 4% \rightarrow < 2.5%

(simple calculation < 2%)

sensitivity $\sim 20\text{meV}$ ($2 \times 10^{27}\text{yr}$) 5 yr

cover inverted hierarchy region

Winston cone



*1. Winston cone
light yield $\times 1.8$*

*2. High Q.E. 20" PMT
QE $\sim 22\%$ \rightarrow $> 30\%$
light yield $\times 1.9$*

*3. High light yield LS
KL LS 8000ph/MeV
Standard 12000ph/MeV
 \rightarrow light yield $\times 1.4$*

Summary

- *The ^{110m}Ag BG was reduced by a factor of more than 10.*
- *KamLAND-Zen latest result:
the $0\nu 2\beta$ half life limited to more than 1.07×10^{26} yr (90% C.L.)*
$$\langle m_{\beta\beta} \rangle < 61 - 165 \text{ meV (90\% C.L.)} \quad \text{Near IH region}$$
- *The installed new mini-balloon was cleaner than Zen400 balloon.*
- *745kg Xe was installed. KamLAND-Zen 800 DAQ was started in January 2019. $\langle m_{\beta\beta} \rangle \sim 40 \text{ meV}$ (5yr data taking)*