Search for 0νββ at KamLAND

Kengo Nakamura (Tohoku University, Japan)

2018.1.11 @Gran Sasso

INSTRUCTIONS FOR SPEAKERS

Information for speakers to understand the setup of the seminar series of the National Laboratories of Gran Sasso.

The seminar of the National Laboratories of Gran Sasso (LNGS) usually takes place on **Thursday at 14h30** in the **Pontecorvo room**. Each seminar lasts approximately one hour including questions. The audience consists of researchers of the LNGS, professors of the University of L'Aquila, postdocs, Ph.D. students and undergraduate students. Most of them are working on topics related to neutrino physics, dark matter, rare events, cosmic rays and nuclear astrophysics.

Accessibility of the talks and background

Since we put together experimentalists and theoreticians from different fields the audience is rather heterogeneous. For this reason, we would like to ask you if you could please make sure that your talk is understandable to an audience with mixed background. The title of your talk and abstract should be as clear as possible; please avoid acronyms and technical jargon. It would be nice if you could start by giving enough background material. This should be slow and accessible to everyone. The aim should certainly be that the first part (e.g. 1/3 or 1/2 according to what you need) explains to a diverse audience the background in which your subject is important. Do not overestimate the knowledge of the audience, and consider whether you should define some concepts, terminology or symbols that appear in your presentation.

Thanks to this longer introduction, we will then be able to enjoy the second part of the seminar, dedicated to your recent work.

In presenting the results of your work please make sure you put them into a broader context considering the scientific focus of LNGS.

If technicalities are an important part of your talk please explain the technical tools and motivate them clearly. Avoid slides with just formulas or technical drawings that are difficult to grasp for non-experts.

Technical information

Please give us a title for your talk and an abstract at least one week before your seminar takes place. At the end of your seminar please give us a pdf copy of your seminar, which will appear on the web-page of the LNGS. You might also give us some links to related papers. All the material should be sent to:

Fausto Chiarizia fausto.chiarizia@lngs.infn.it

For your presentation you may use your laptop, in case you need a computer let us know in advance.

Thanks for your efforts. We are aware that this takes a lot of your time. We look forward to an interesting day.

The Organizing Committee

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  → My apology if I underestimate your knowledge.
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INFN
Istituto Nazionale
di Fisica Nucleare
National Laboratory of Gran Sasso (LNGS)

Via Acitelli, 22 - Assergi
67100 L'Aquila (AQ) Italy
Tel. 0862/4371 – Telefax 0862/27774

To:
Dr. Nakamura Kengo
Department of Physics,
Tohoku University
Sendai 980-8578, Japan
Tel: (+81) 22-795-6494

Subject: Invitation for a seminar on the results and perspectives of KamLAND-Zen project.

Dear Dr. Kengo,
the INFN-National Laboratory of Gran Sasso (LNGS) hosts a series of seminars and lectures of special interest to particle and astroparticle physics, nuclear physics, theoretical physics and technological physics.

It is my pleasure to invite you to give a seminar regarding the last results of KamLAND-Zen400 and the perspectives of KamLAND-Zen800 concerning rare events investigation, especially the Neutrinoless Double Beta Decay search and the so-called "geo-neutrino" studies.

We can schedule this seminar on January 11th 2018.

We will organize a tour to the Under Ground laboratory in January 12th.
The LNGS-Seminar committee will take care of your accommodation in L'Aquila.

You can find attached our instructions for speakers.

Yours sincerely,

Massimo Mannarelli, Ph. D.
Research Division of INFN Gran Sasso National Laboratory
Chairperson of the LNGS Seminars Committee
massimo.mannarelli@lngs.infn.it
Tel.: (+39) 0862-437-743

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- rare events investigation especially the Neutrino-less Double Beta Decay search and the so-called "geo-neutrino" studies.

not rare event anymore

You can find attached our instructions for speakers.

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KamLAND

Physics programs

- Neutrino oscillation of anti-neutrinos from nuclear reactors
- Geo-neutrino measurement
- ^{136}Xe 0νββ
    - KamLAND-Zen400 (completed)
    - KamLAND-Zen800 (coming soon)

Future Plans

- IsoDAR@KamLAND

KamLAND

Physics programs

- Neutrino oscillation of anti-neutrinos from nuclear reactors
- Geo-neutrino measurement
- ^{136}Xe $0\nu\beta\beta$
    - KamLAND-Zen400 (completed!)
    - KamLAND-Z[illegible] (coming soon)

Less Focus (not rare event)

Main Focus (rare event)

Future Plans

- IsoDAR@KamLAND

Slightly

Neutrino Oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2}\\ U_{\mu1} & U_{\mu2}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$$\Delta m^2 = m^2_2 - m^2_1$$

Neutrino oscillation parameters (physics)

Fixed

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]\mathrm{L[m]}}{E_\nu[\mathrm{MeV}]}\right)$$

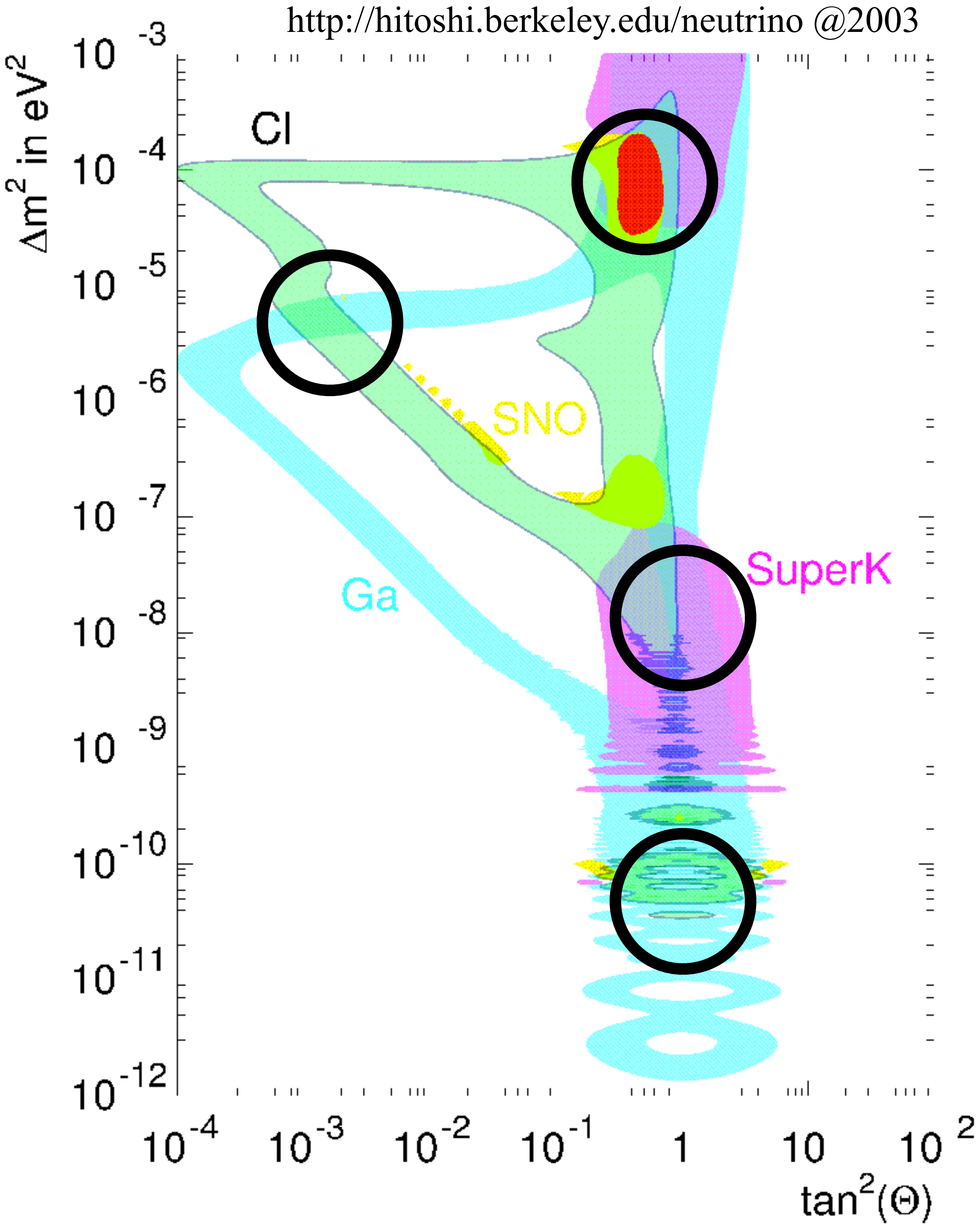
Appearance probability to be measured

Spectrum to be measured

$$P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_e)$$

Disappearance probability to be measured

Solar Neutrino Oscillations



Do you remember?
Four candidate solutions at 1990's.

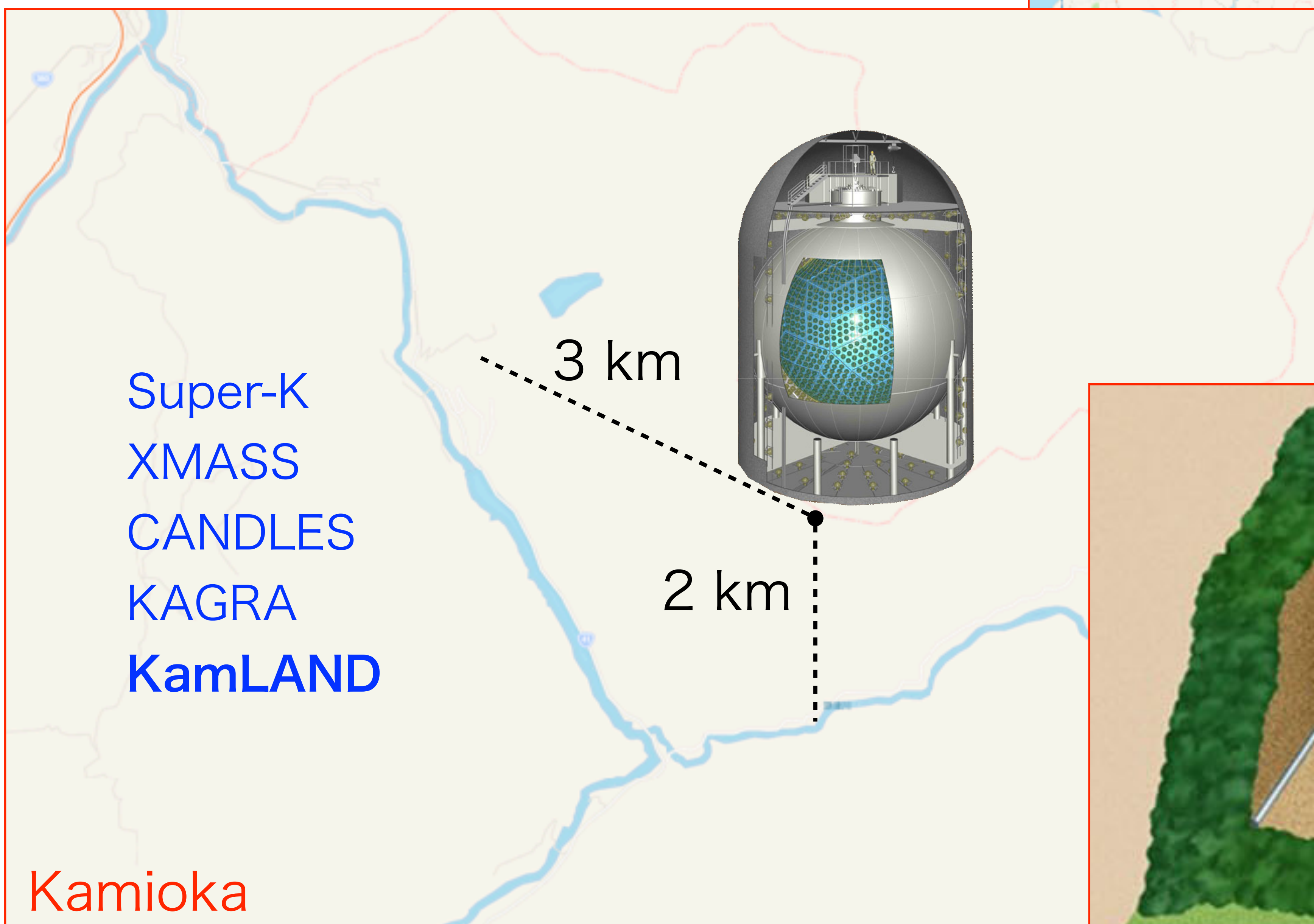
Let's check with man made neutrinos.

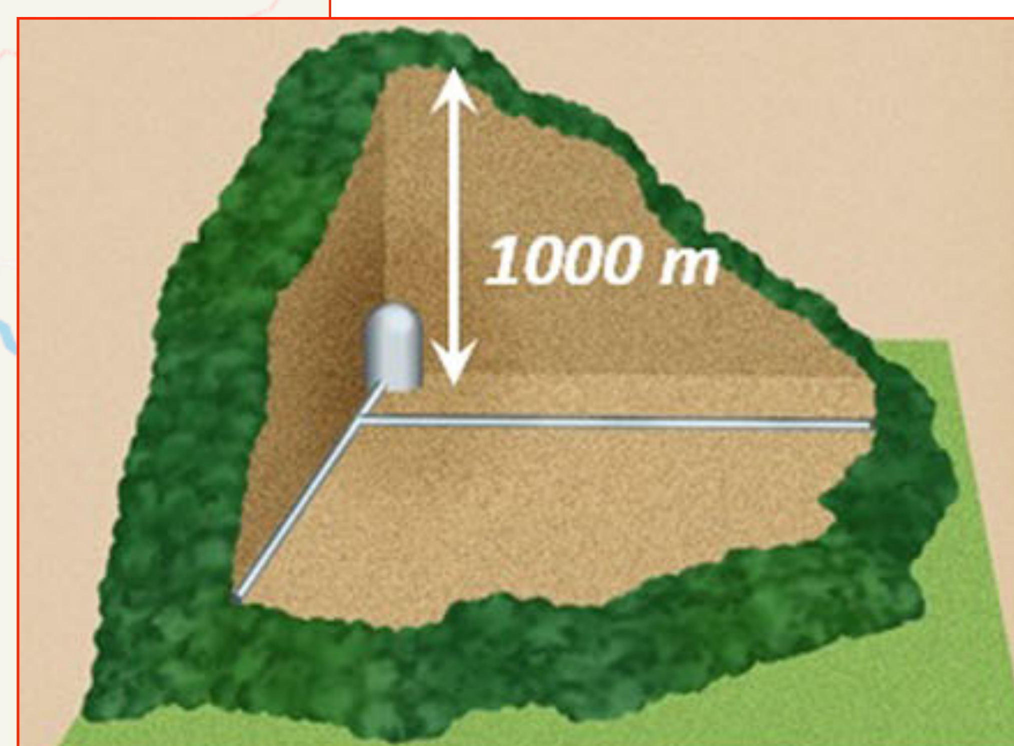
Reactor $\overline{\nu}e$ @KamLAND
L ~ 180 km
E ~ several MeV

KamLAND

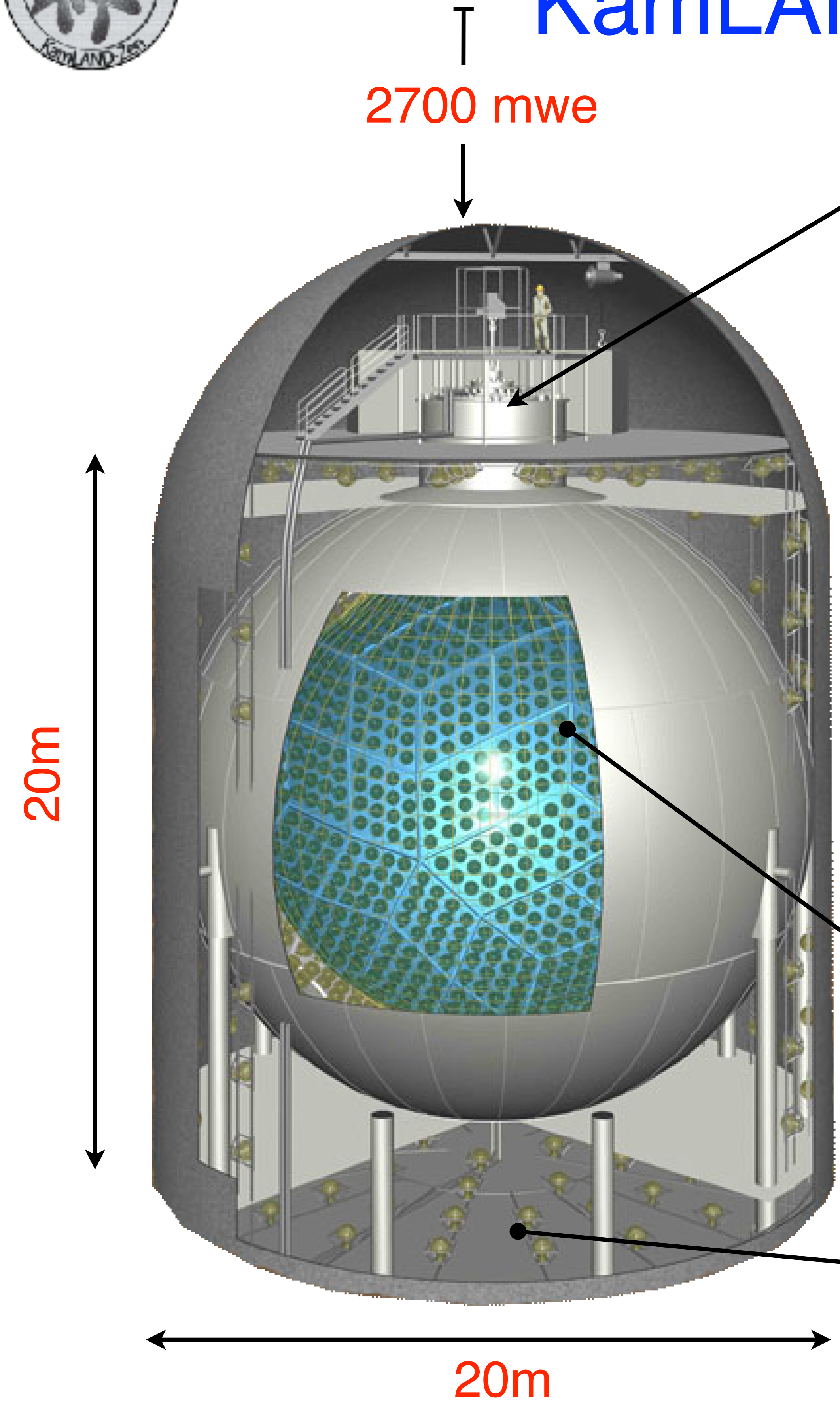
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]\mathrm{L}[\mathrm{m}]}{E_\nu[\mathrm{MeV}]}\right)$$

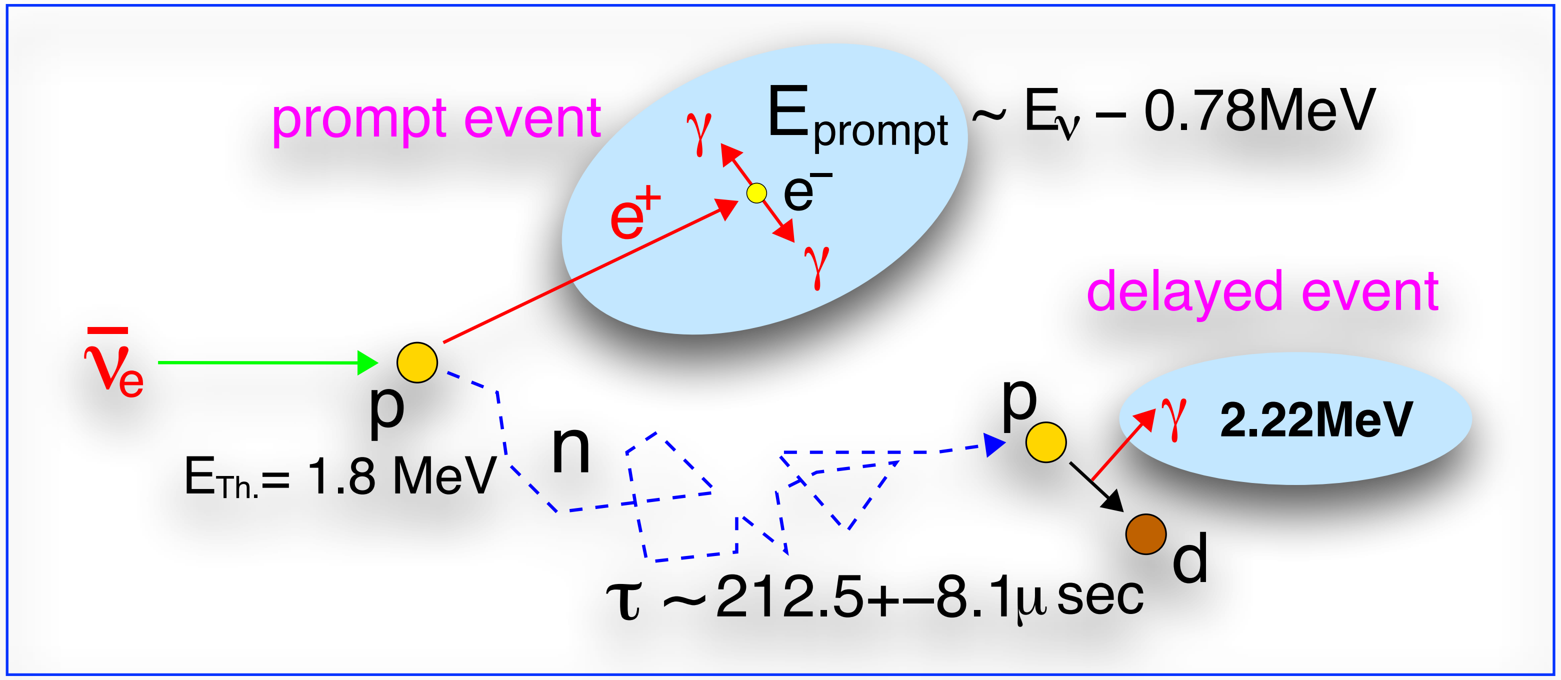
L ~ 180 km
E ~ several MeV



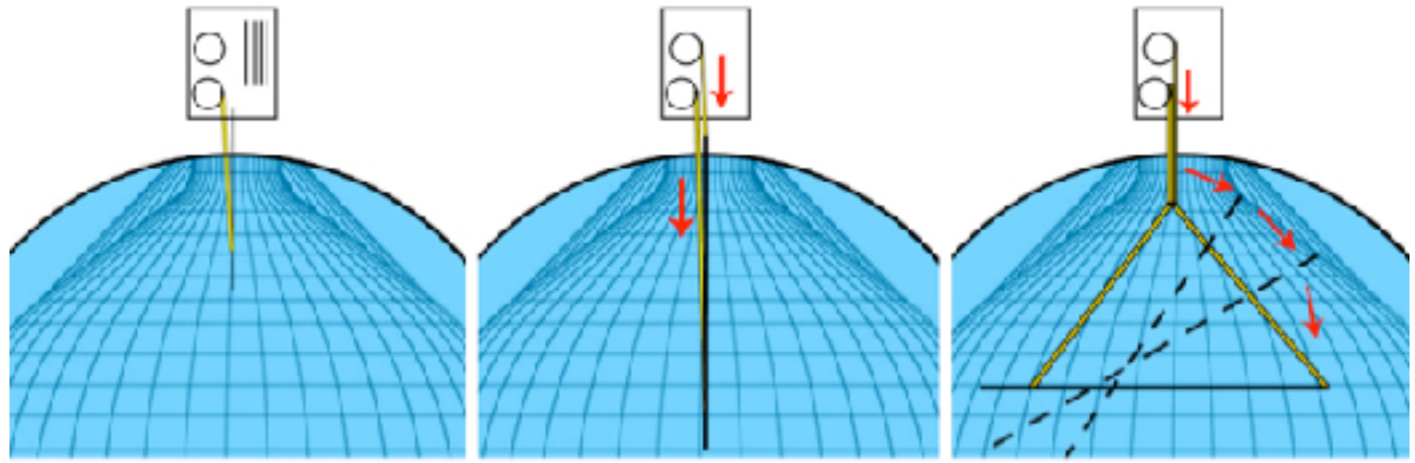


KamLAND

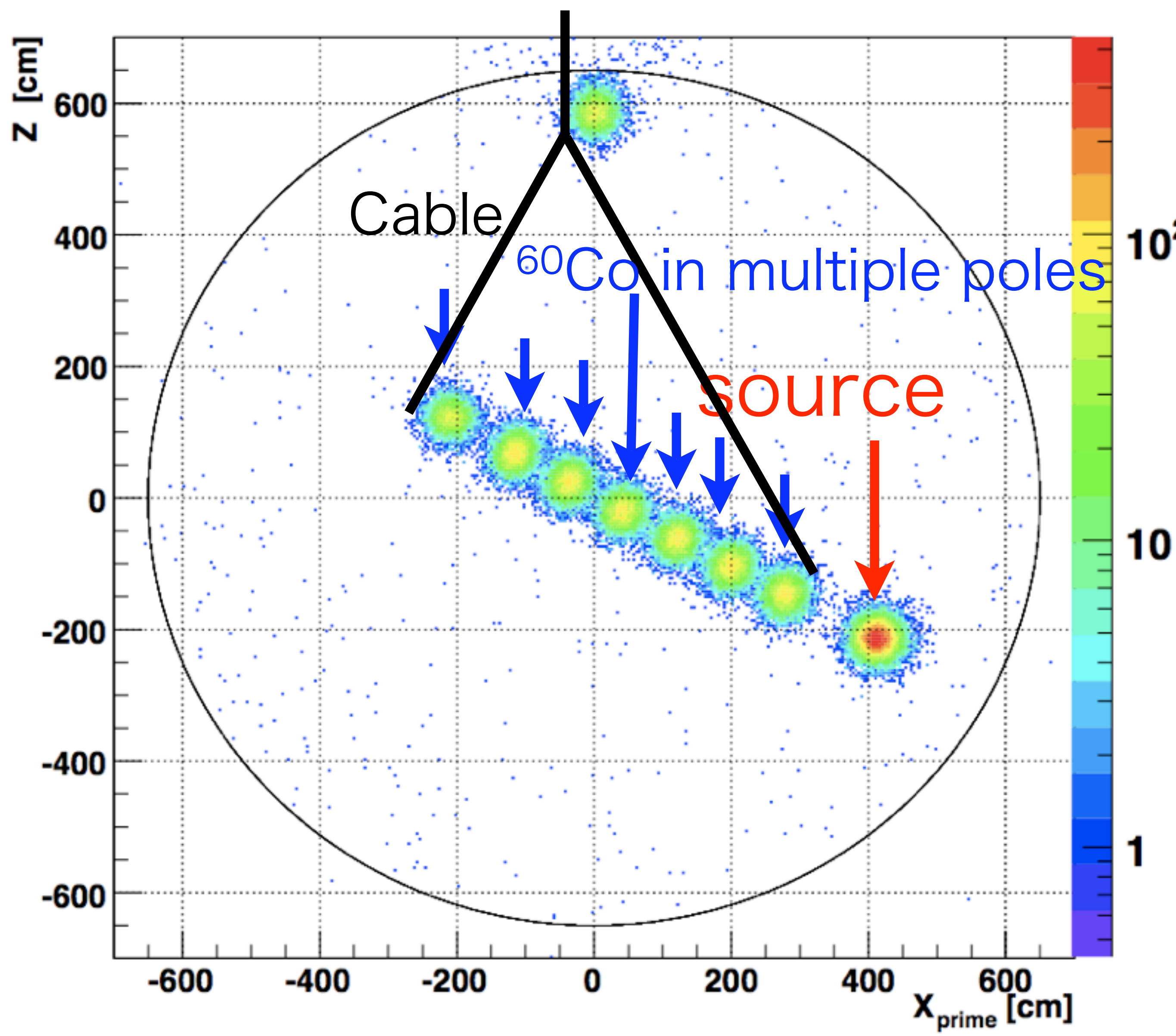

2700 mwe
Calibration access
20m
20m
1200 m³ LS in the KamLAND balloon
suspended in 1800m³ Buffer oil
Water Cherenkov Outer Detector
225 20" PMTs


prompt event
E_prompt ~ E_ν – 0.78MeV
γ
e⁺
e⁻
γ
delayed event
ν̄_e
p
E_Th.= 1.8 MeV
n
p
γ 2.22MeV
d
τ ~212.5+–8.1μ sec

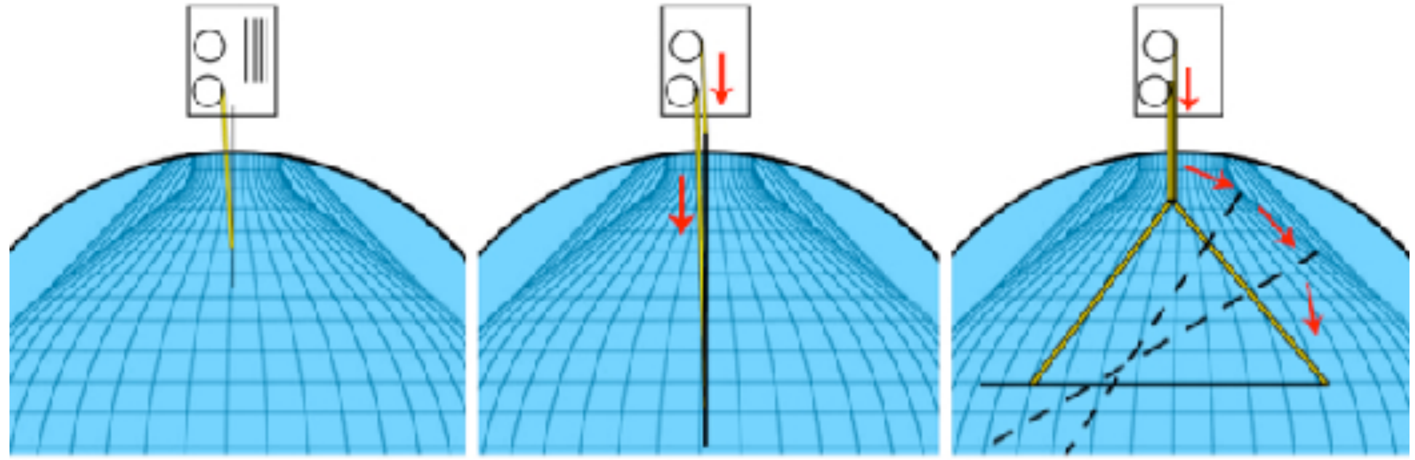
KamLAND



^{60}Co in multiple poles



KamLAND



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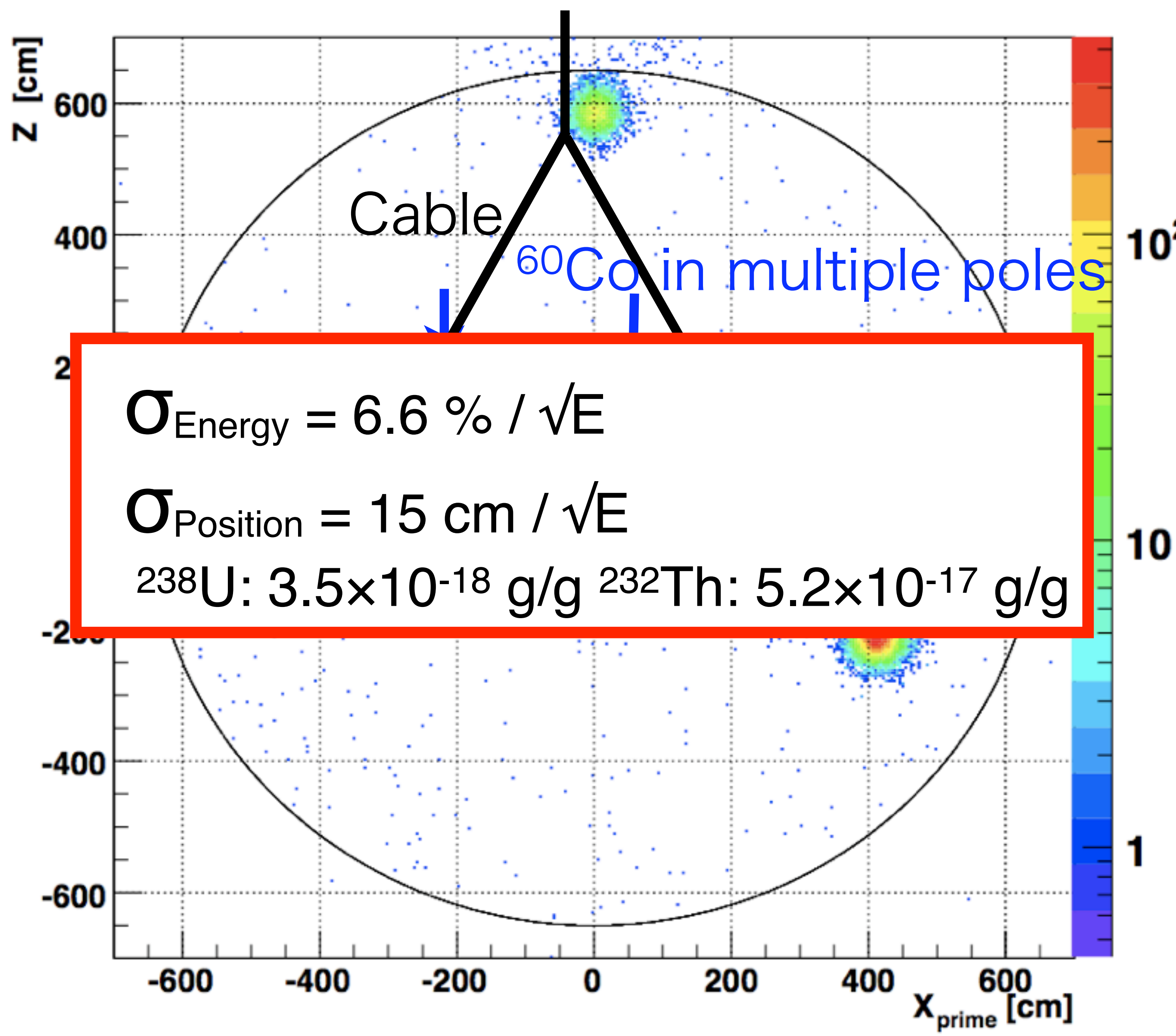


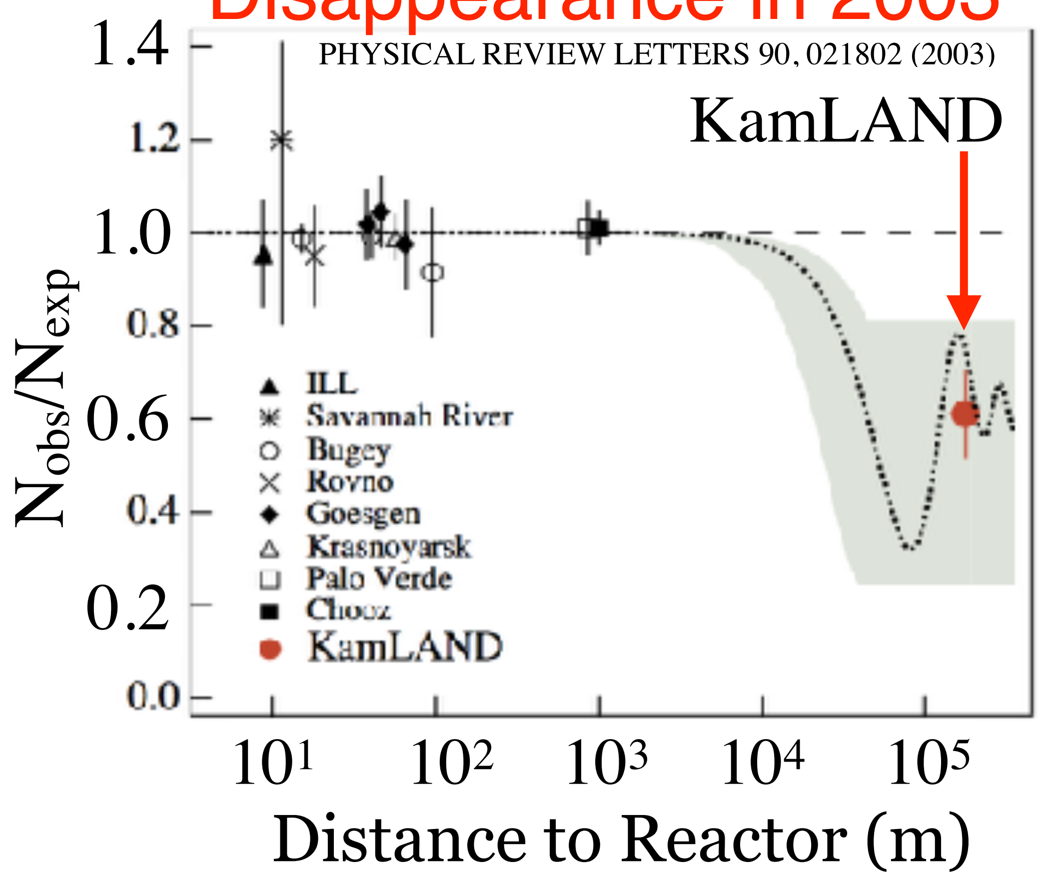
σ_{Energy} = 6.6 % / $\sqrt{E}$

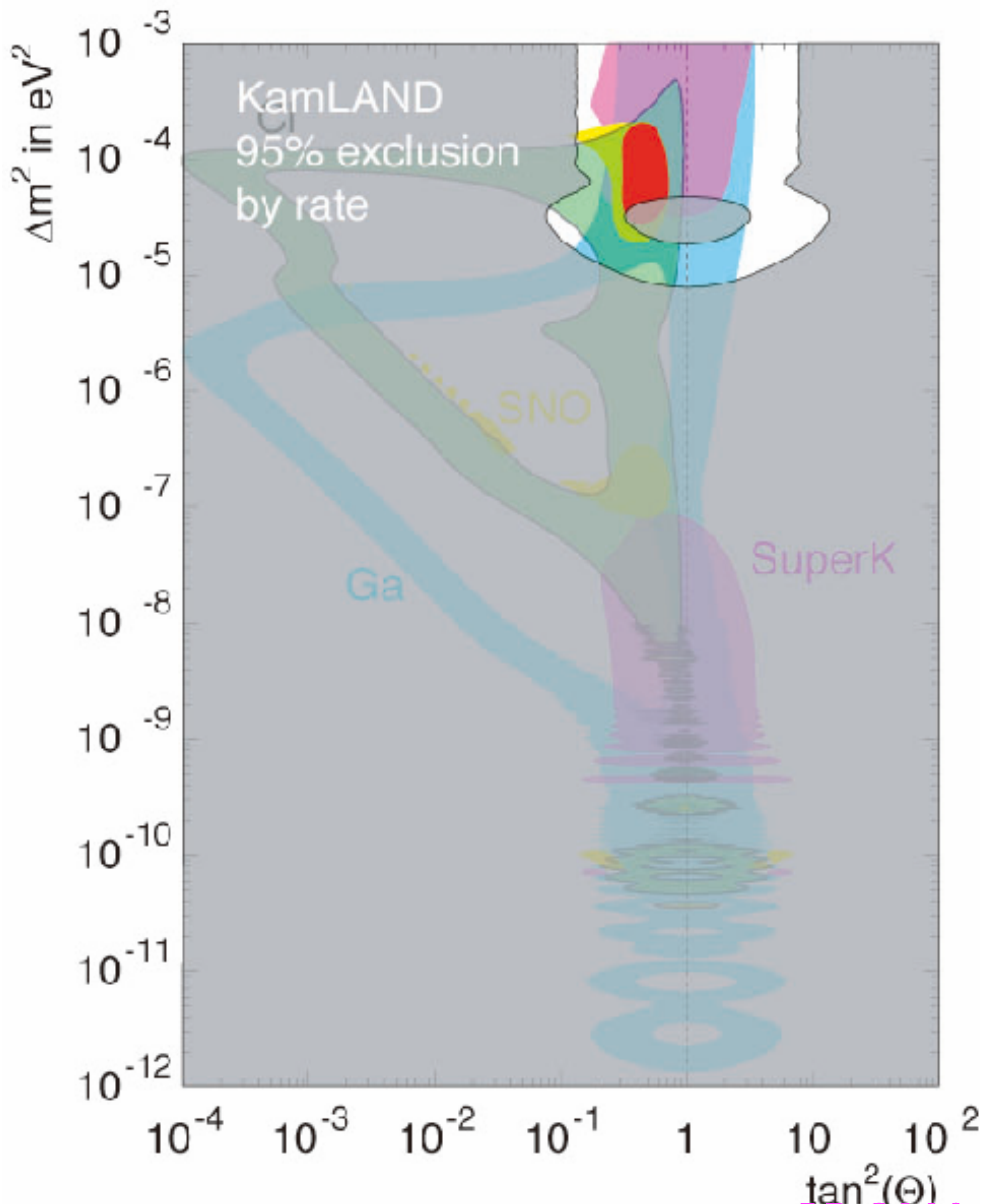
$\sigma_{Position}$ = 15 cm / $\sqrt{E}$

^{238}U: 3.5×10^{-18} g/g ^{232}Th: 5.2×10^{-17} g/g

KamLAND

Disappearance in 2003

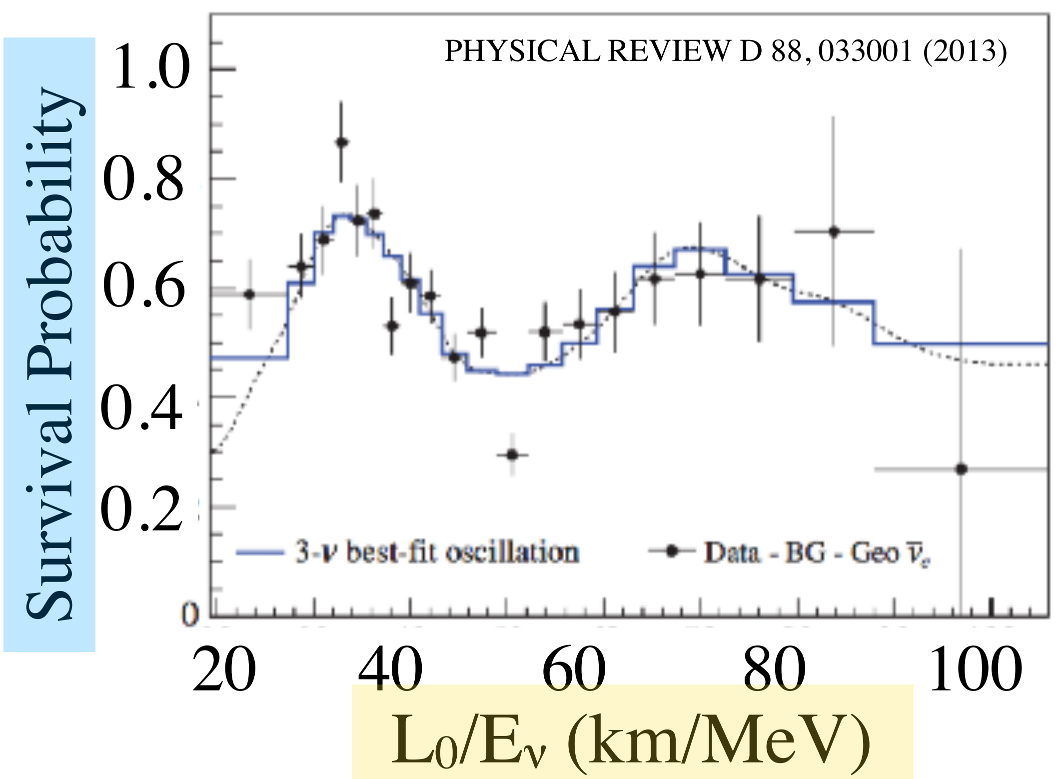


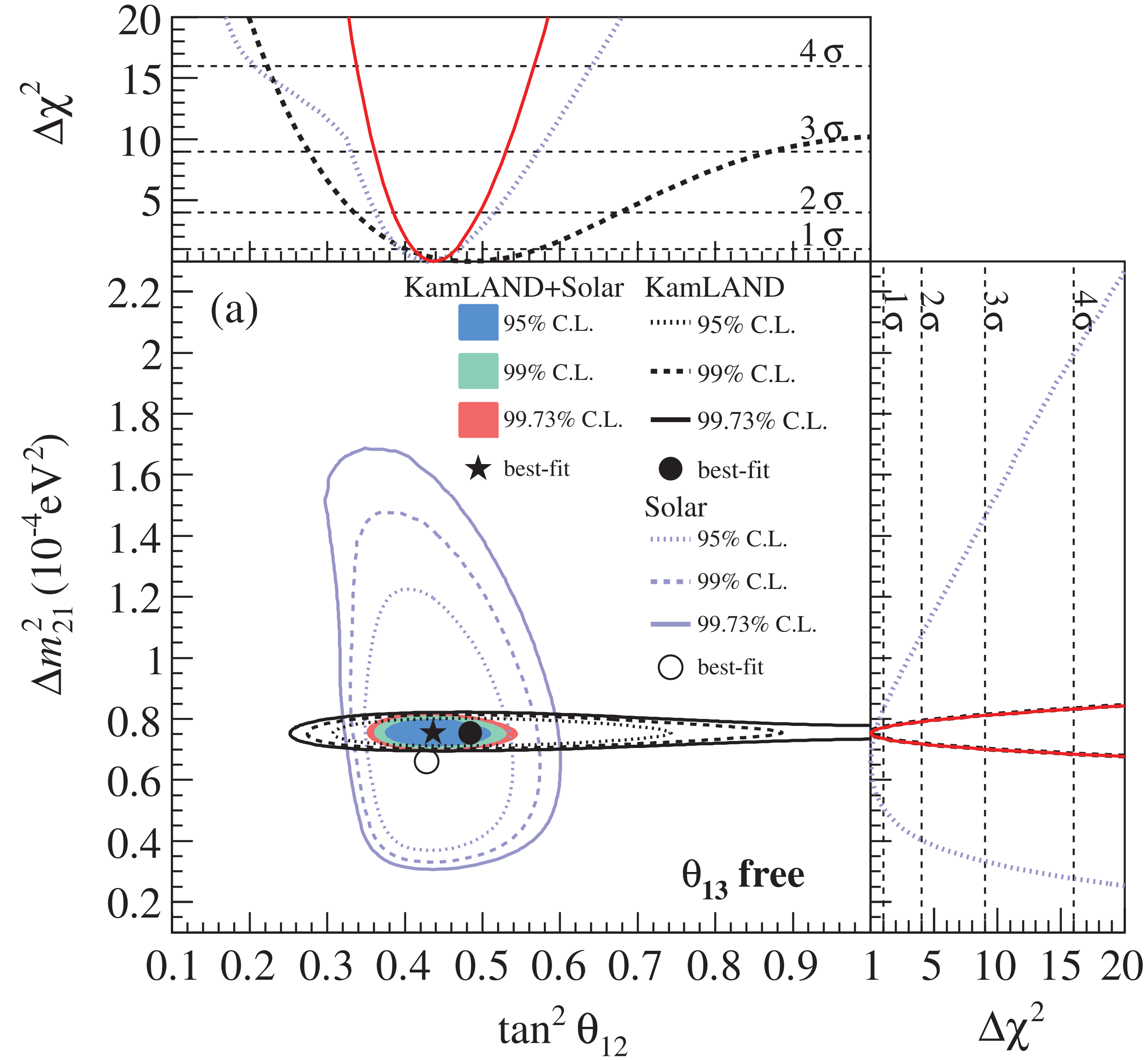


PDG2004

KamLAND

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{m}]}{E_\nu[\mathrm{MeV}]}\right)$$

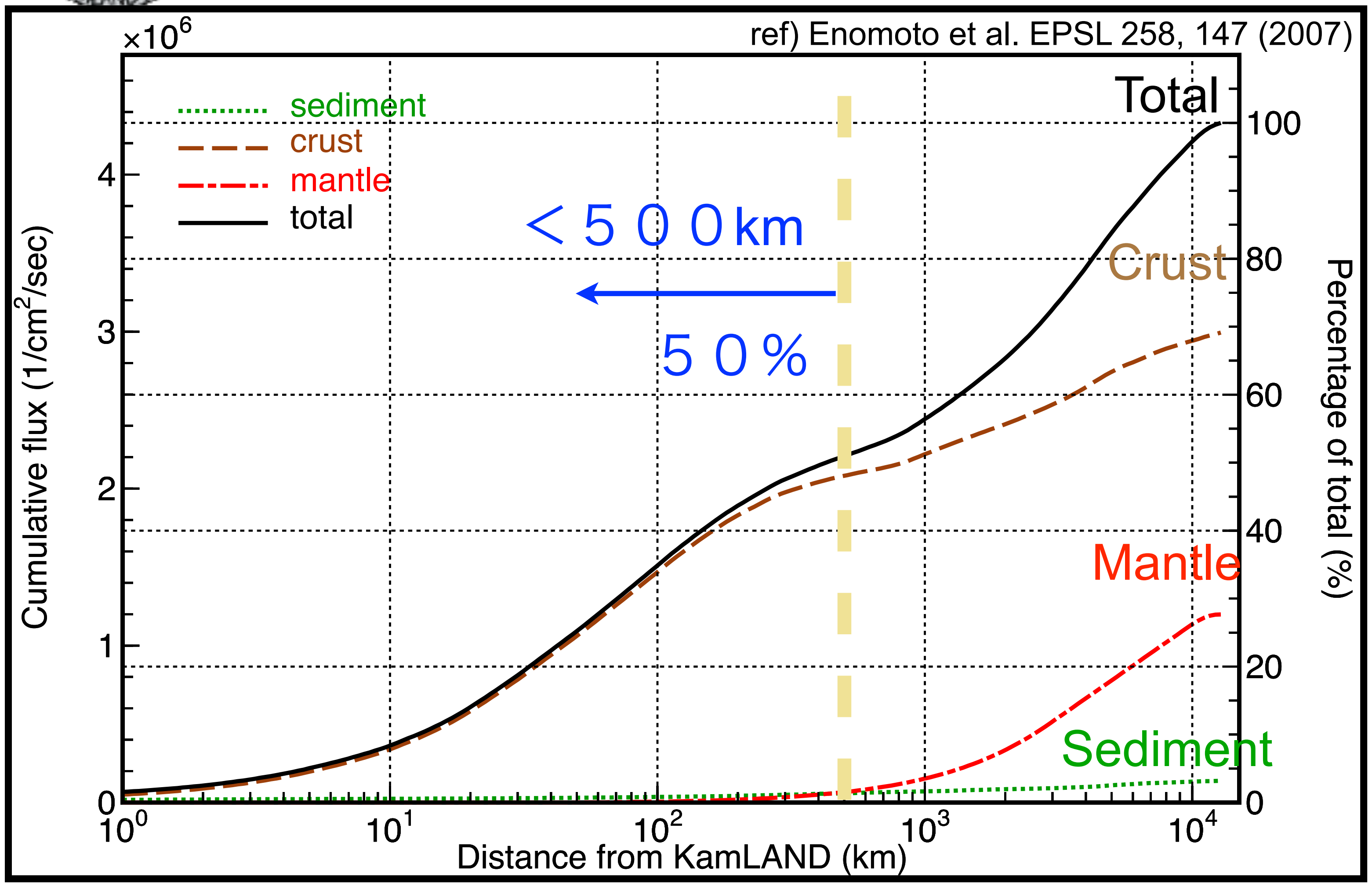




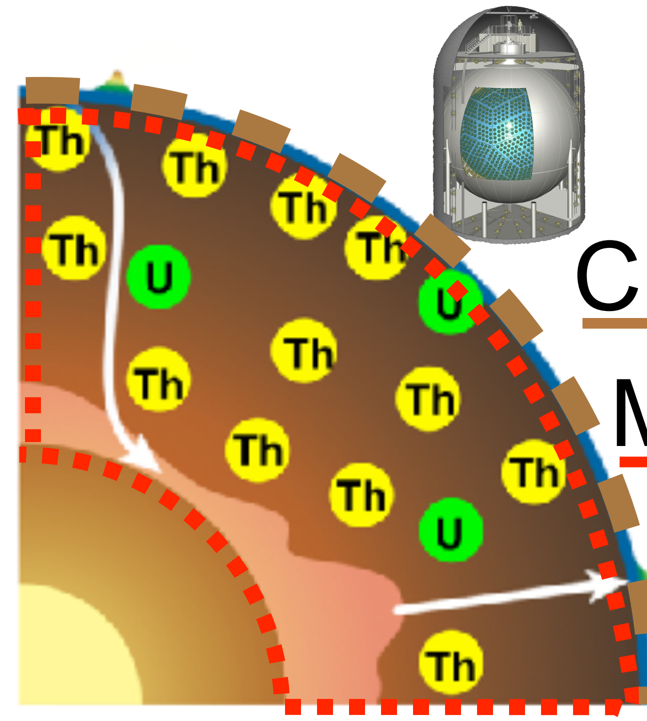
Precise measurement in 2013

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ [eV²] $\tan^2\theta_{12} = 0.437^{+0.029}_{-0.025} \times 10^{-5}$ $\sin^2\theta_{13} = 0.023 \pm 0.002$

Geo-neutrinos



Contributions from each part



Crust : 70%

Mantle : 27%

Core : 0%

Sediment etc. : 3%

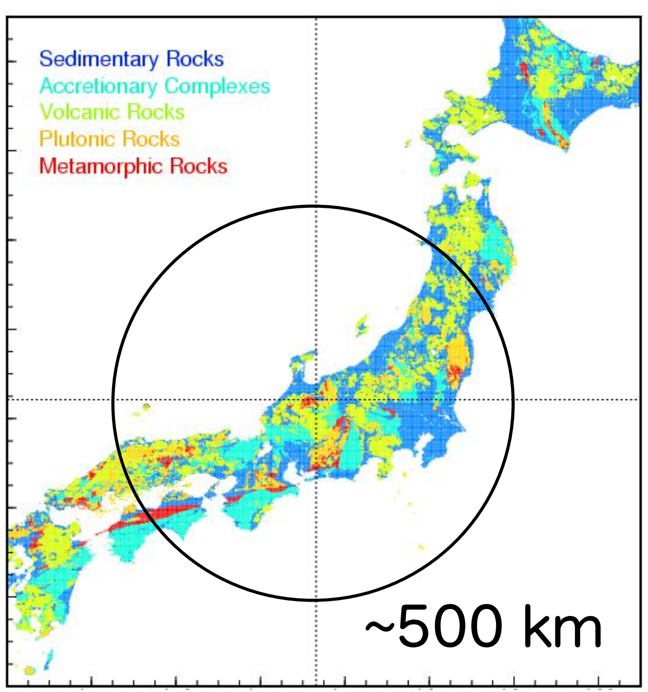
$$^{238}U \rightarrow ^{206}Pb + 8\,^{4}He + 6e^{-} + 6\bar{\nu}_e + 51.7MeV$$

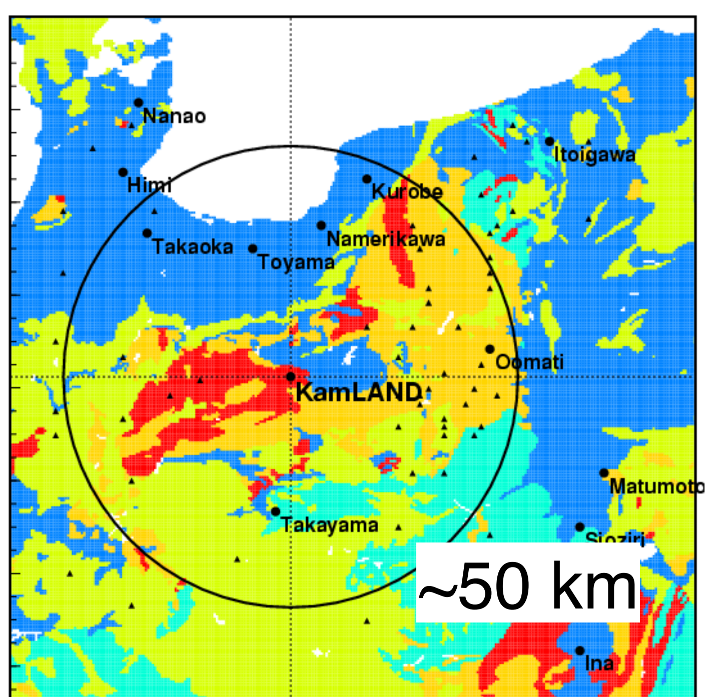
$$^{235}U \rightarrow ^{207}Pb + 7\,^{4}He + 4e^{-} + 4\bar{\nu}_e + 46.0MeV$$

$$^{232}Th \rightarrow ^{208}Pb + 6\,^{4}He + 4e^{-} + 4\bar{\nu}_e + 42.7MeV$$

$$^{40}K \rightarrow ^{40}Ca + e^{-} + \bar{\nu}_e + 1.31MeV$$

$$^{40}K + e \rightarrow ^{40}Ar + \nu_e + 1.51MeV$$





What we can tell ?

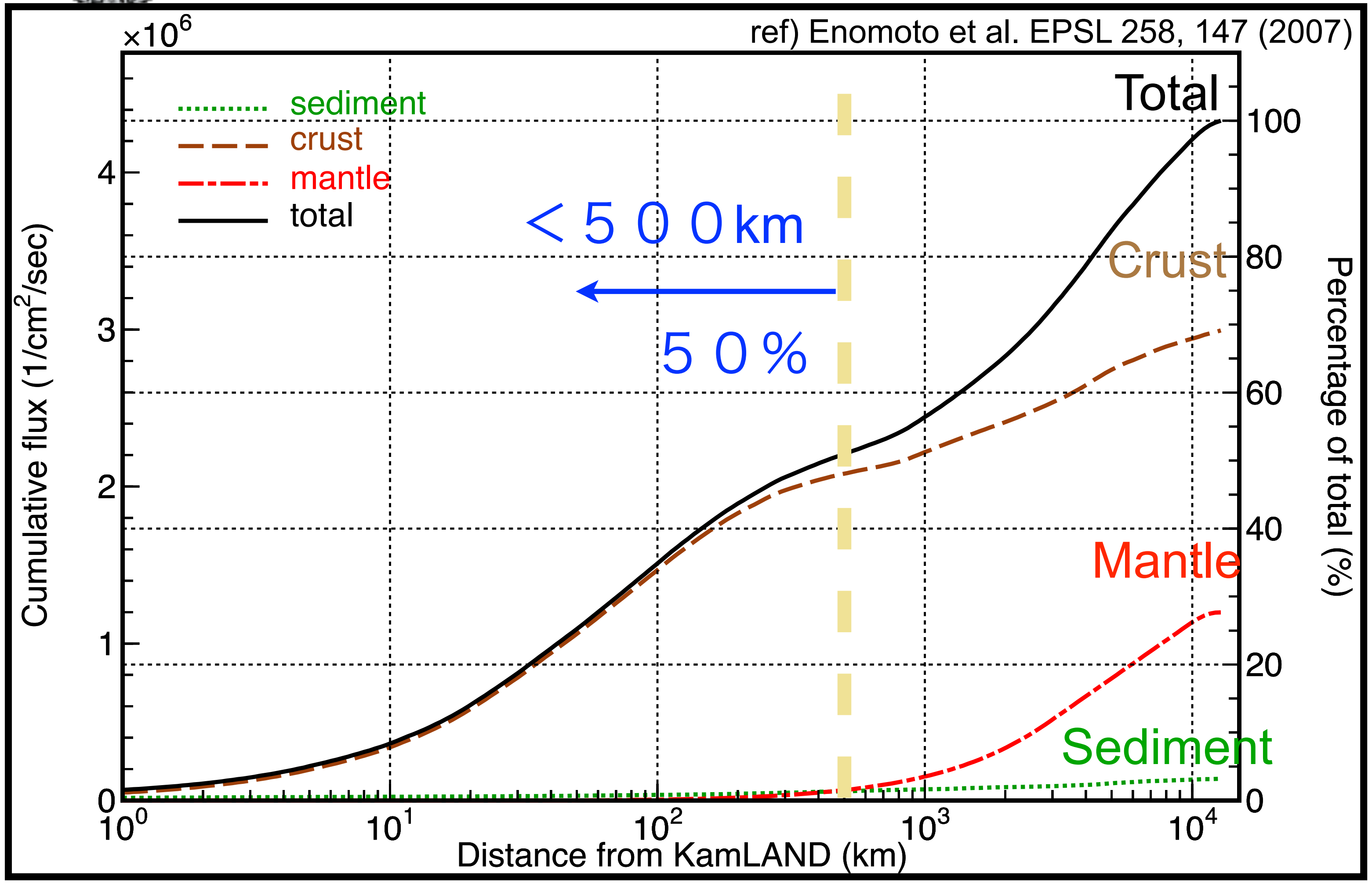
Geo-neutrino flux from U and Th.

→ Radiogenic heat.

→ U/Th ratio

→ Comparison with Models

Geo-neutrinos



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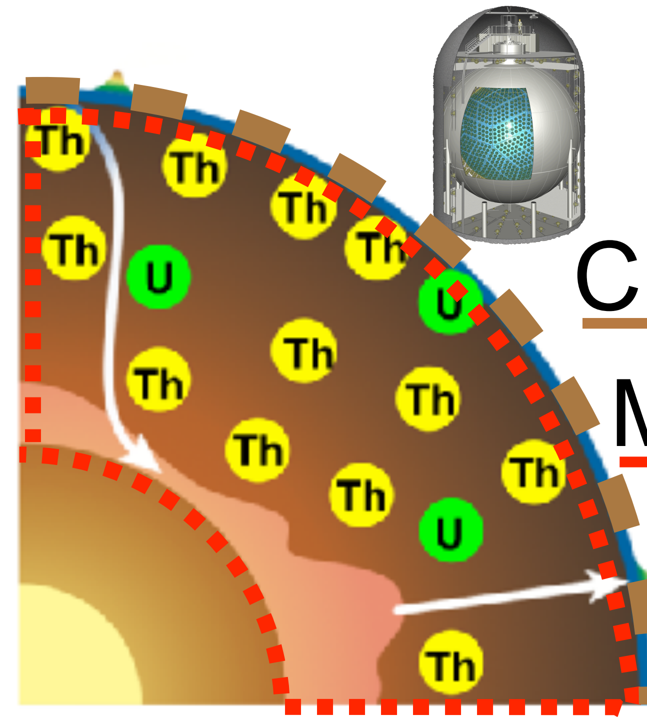

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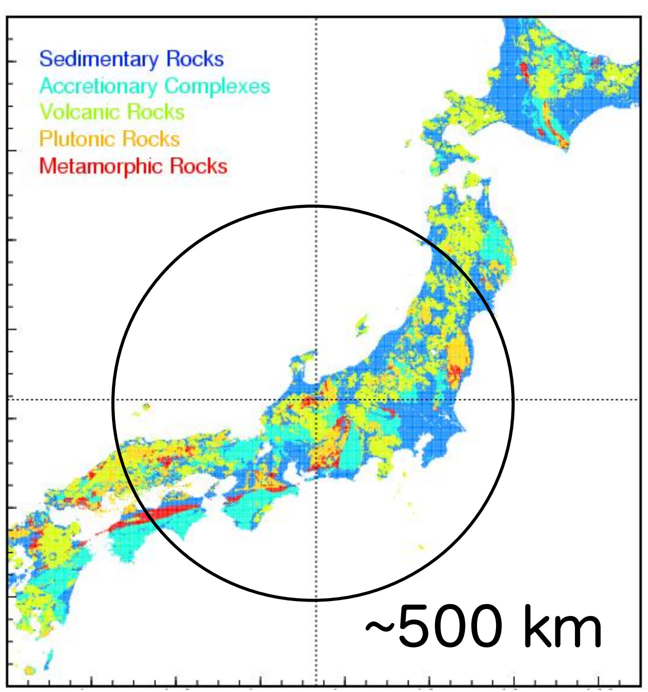
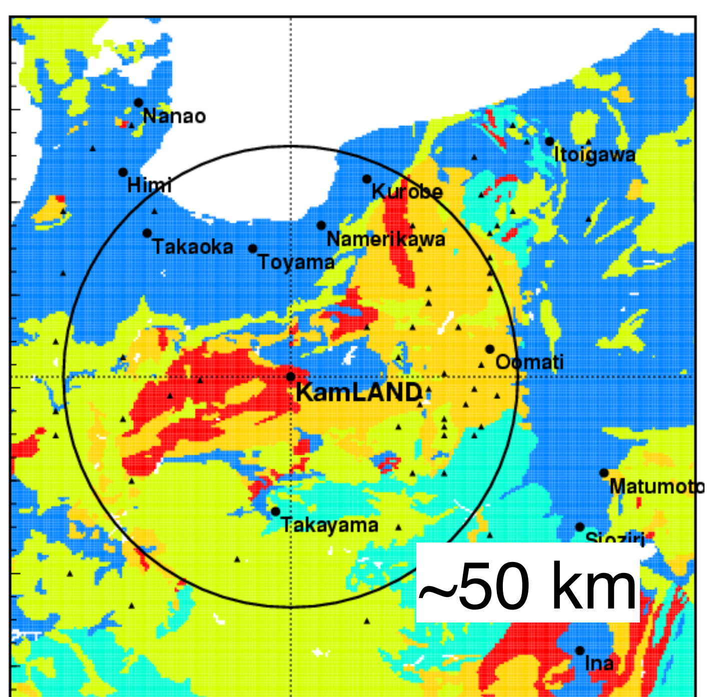
Below KamLAND threshold





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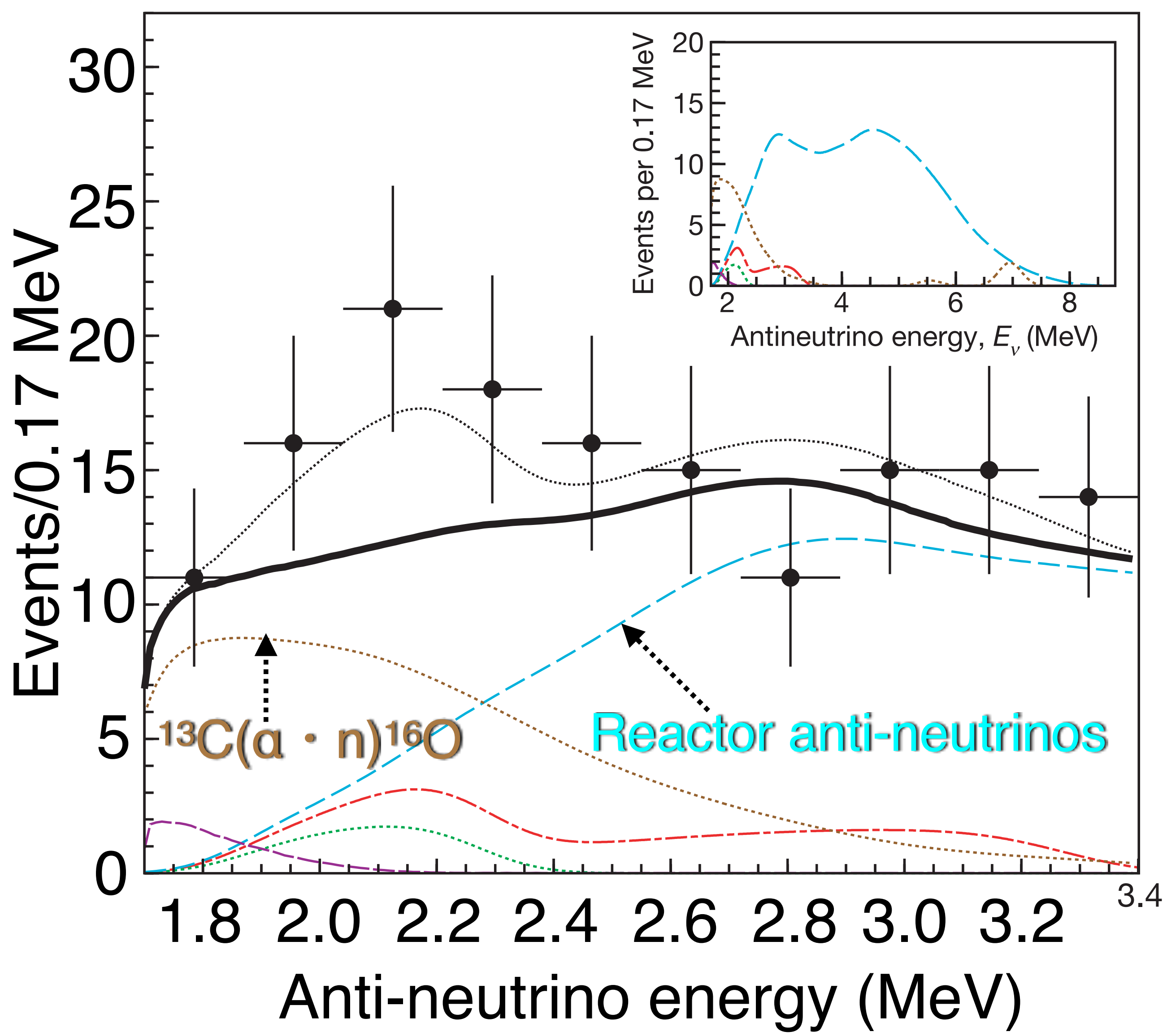
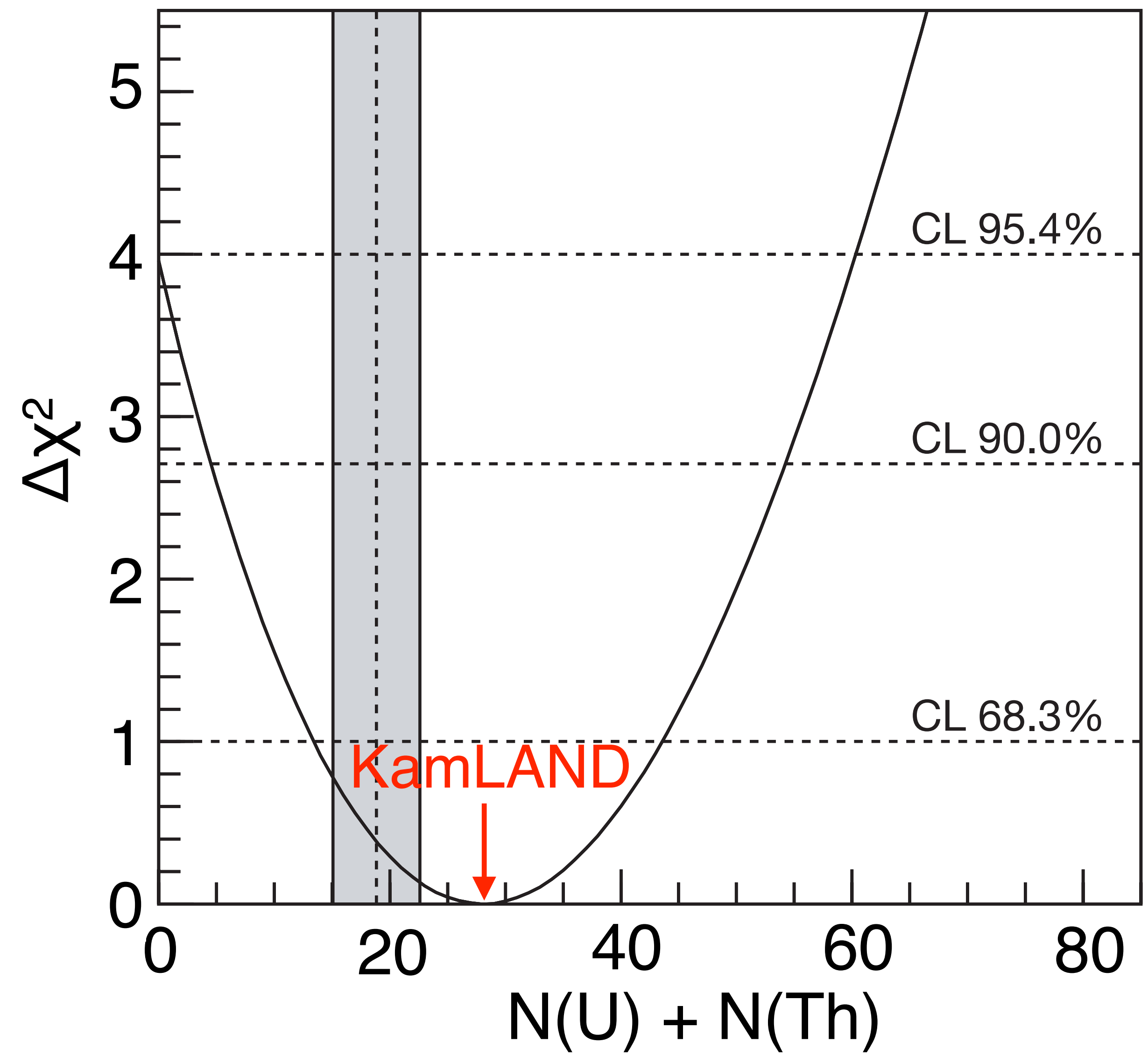
Geo-neutrinos

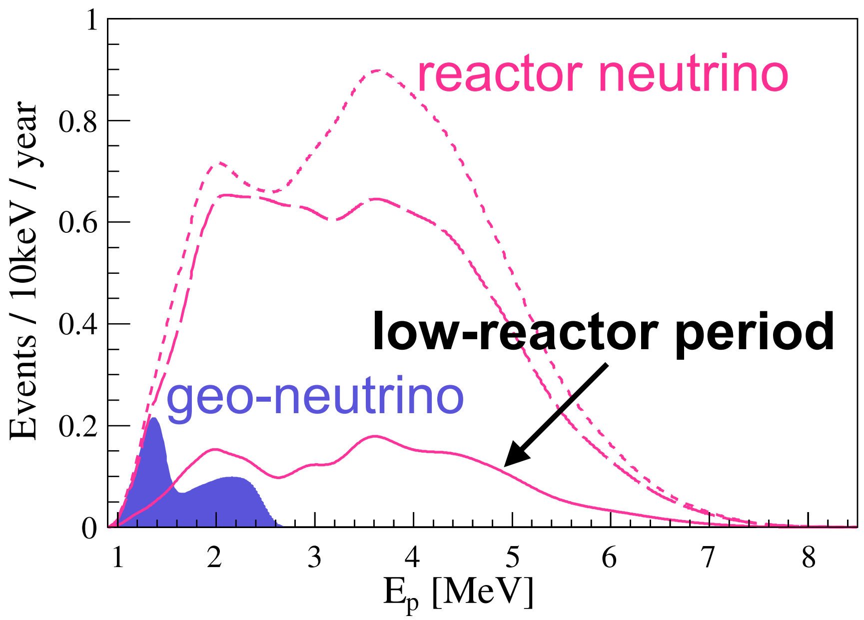
Geo-neutrinos in 2005

N(U) + N(Th) = 4.5 to 54.2 @90 % C.L.



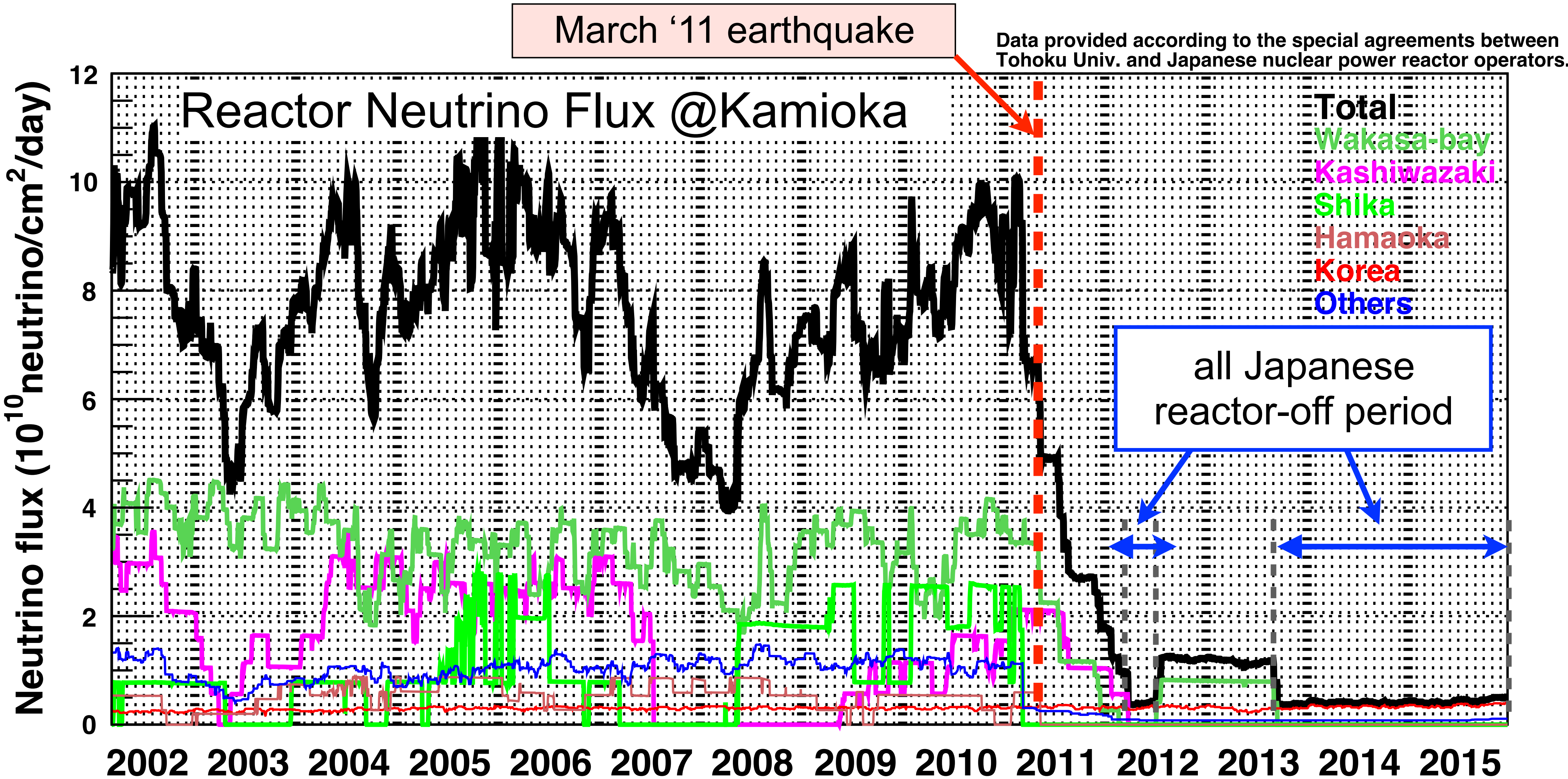


Geo-neutrinos



advantages

- low-reactor operation period : **~3.5 years** live time
- **all Japanese reactor-off period : ~2.0 years** live time

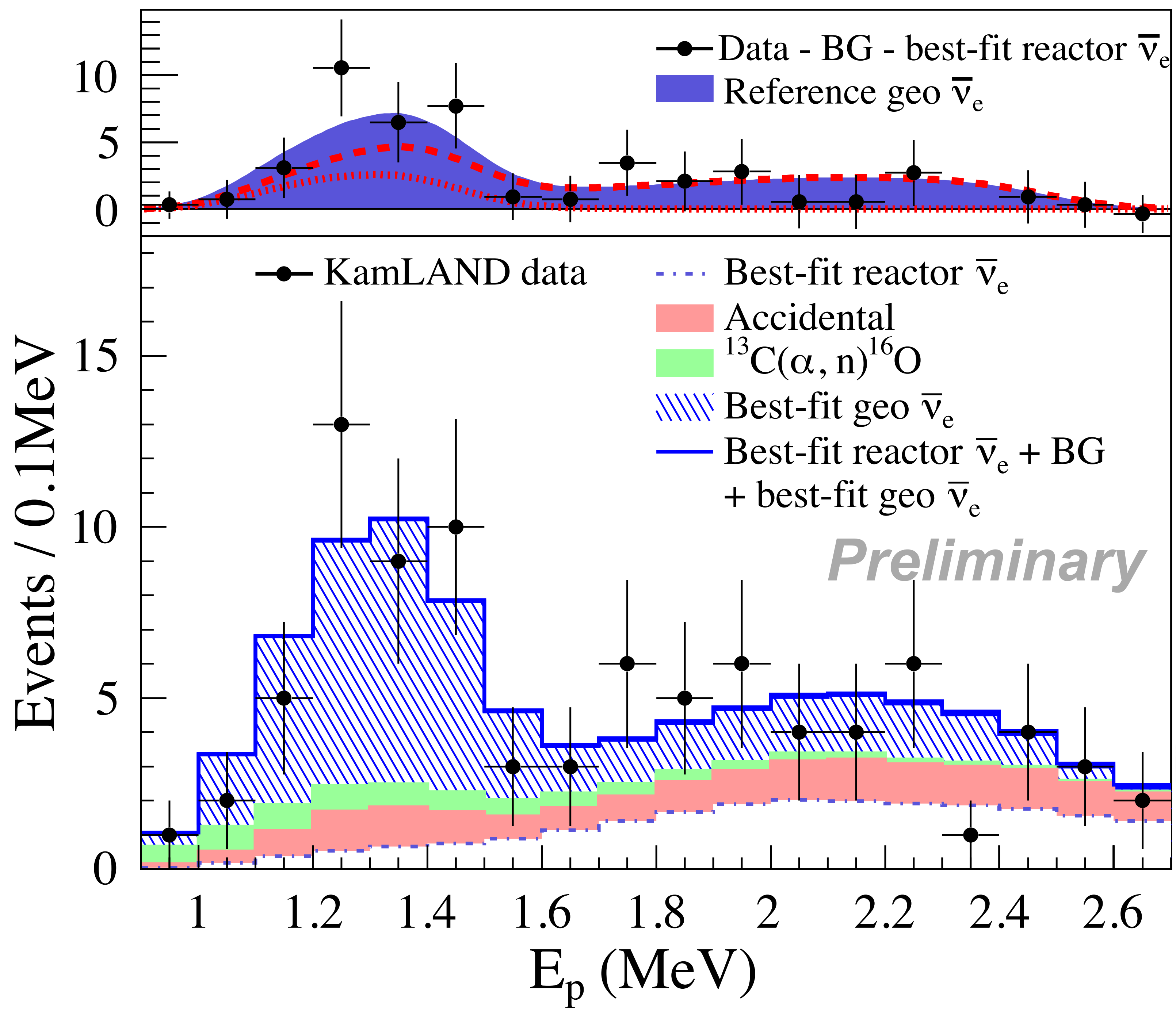


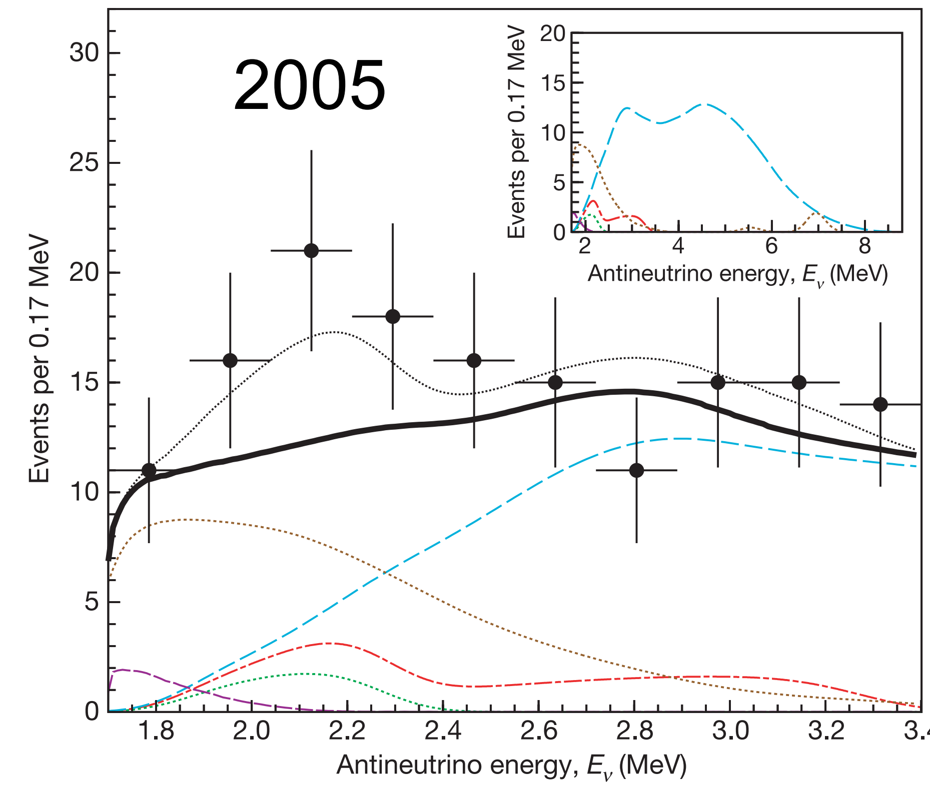
Geo-neutrinos

2016 Preliminary Result

best-fit : Period 3 analysis (live time: 1260 days)

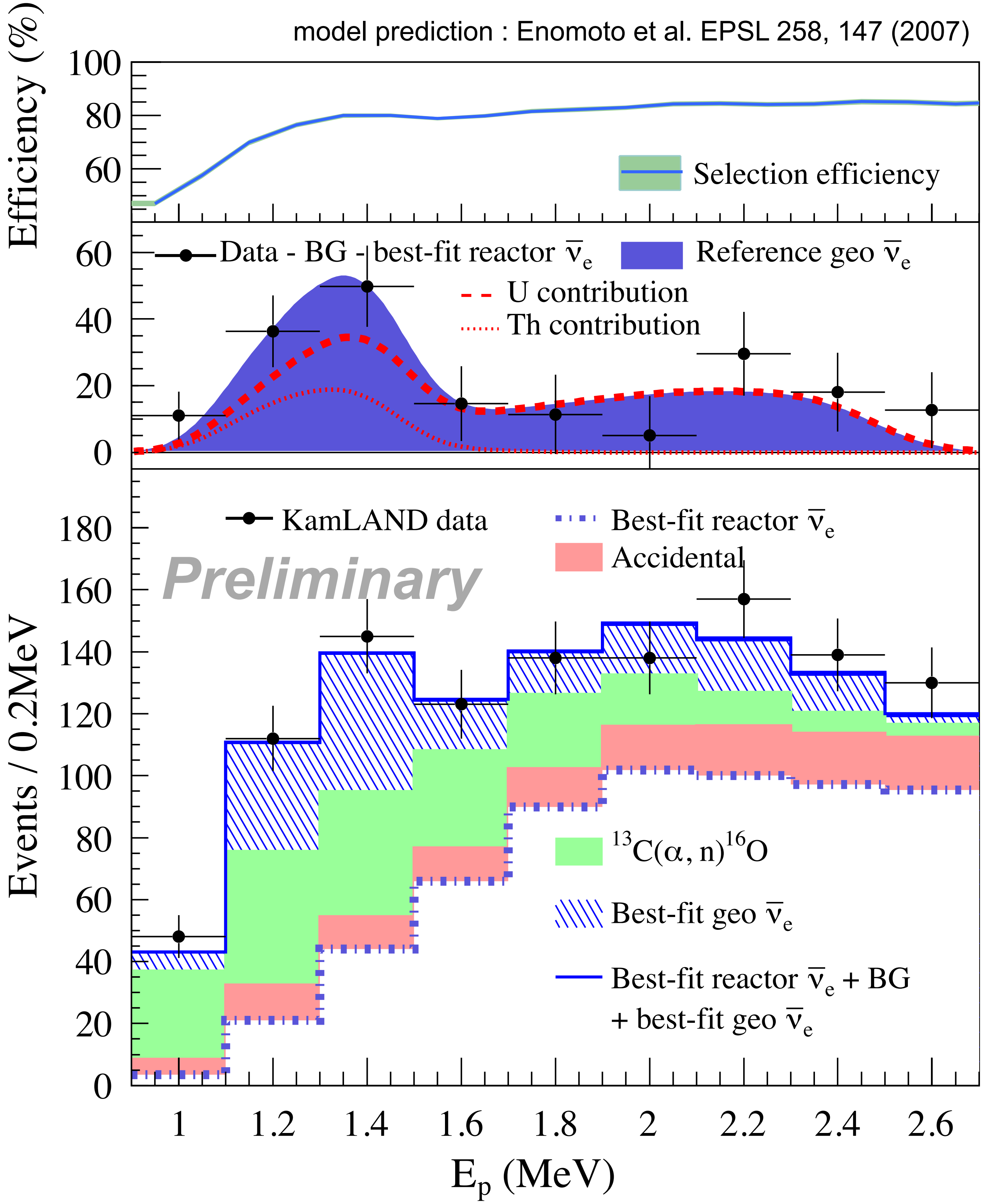
model prediction : Enomoto et al. EPSL 258, 147 (2007)

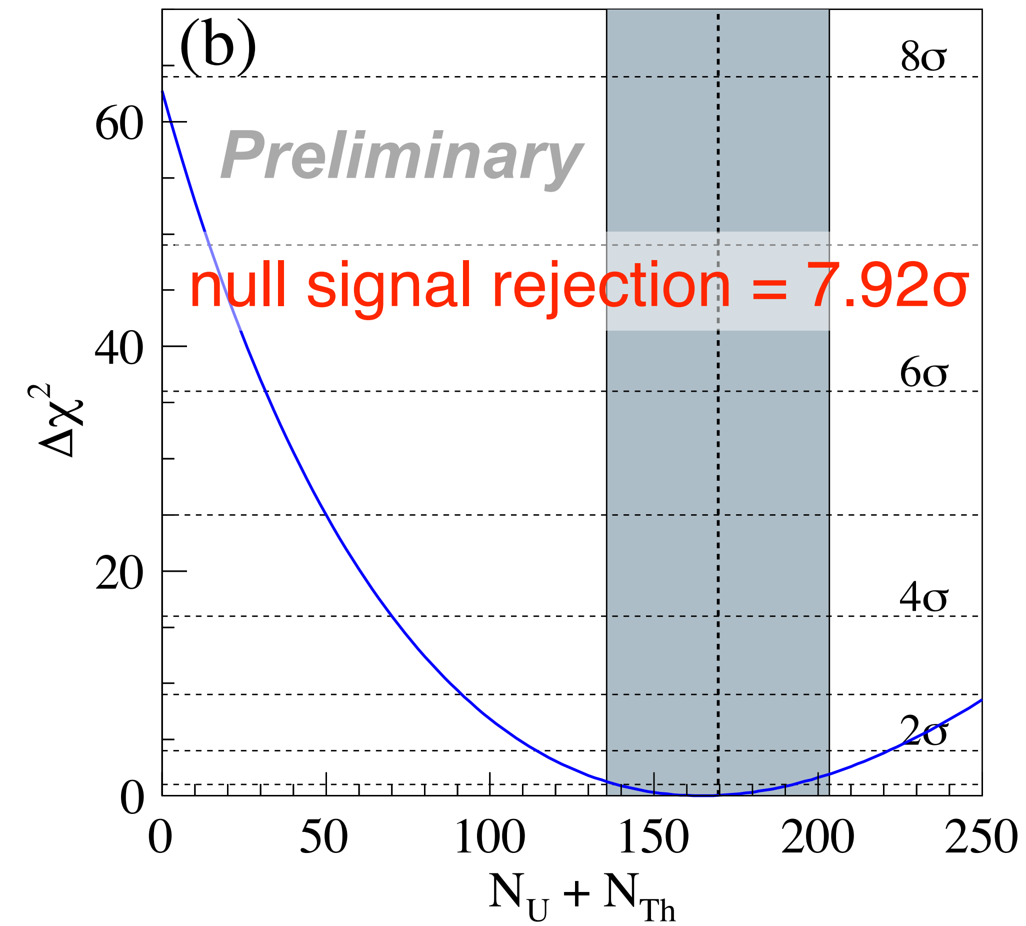




☑ We measured clear distribution of geo-neutrino events.

Geo-neutrinos





2016 Preliminary Result

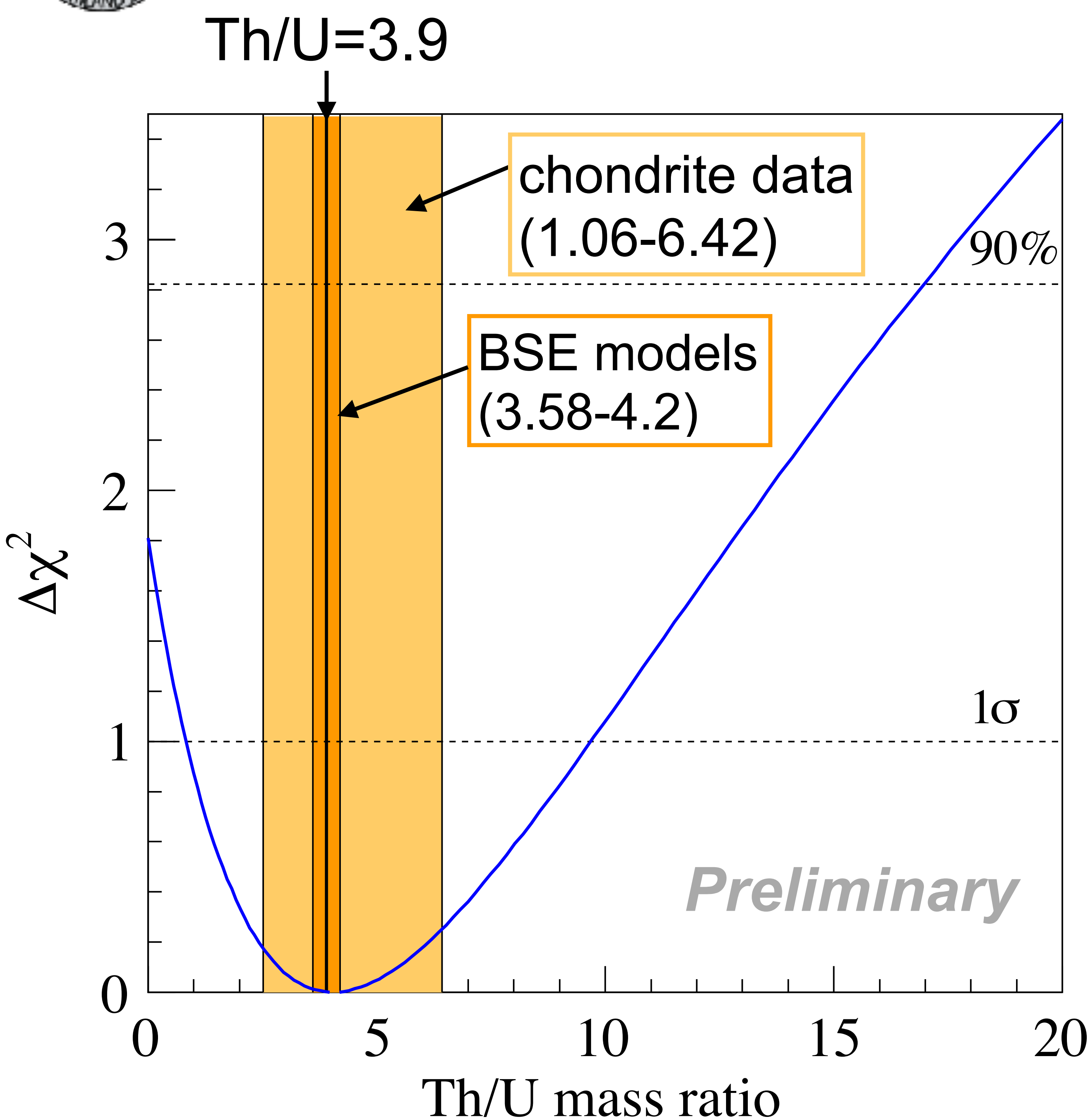
Live time : 3900.9 days

Candidate : 1130 ev

Background Summary

^9Li	3.4 ± 0.1
Accidental	114.0 ± 0.1
Fast neutron	< 4.0
$^{13}C(\alpha, n)^{16}O$	205.5 ± 22.6
Reactor $\bar{\nu}_e$	**618.9 ± 33.8**
Total	941.8 ± 40.9

Geo-neutrinos



<u>2016 Preliminary Result</u>

Best fit

$Th/U = 4.1^{+5.5}_{-3.3}$

Th/U < 17.0 (90% C.L.)

ref) 2013 paper Th/U < 19 (90% C.L.)

- ☑ **KamLAND best-fit is consistent with chondrite data and BSE models.**

ref) chondrite data

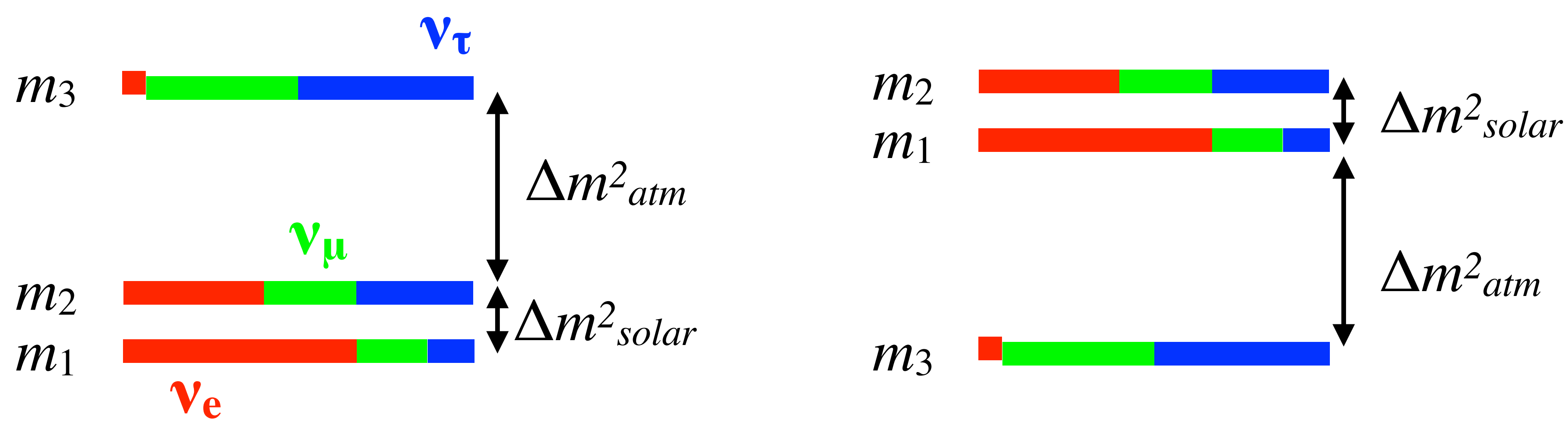
Ordinary Chondrites : J. S. Goreva & D. S. Burnett, Meteoritics & Planetary Science 36, 63-74 (2001)

Carbonaceous Chondrites : A. Rocholl & K. P. Jochum, EPSL 117, 265-278 (1993)

Enstatite Chondrites : M. Javoy & E. Kaminski, EPSL 407, 1-8 (2014)

Now we know neutrinos have mass

- We do not know their absolute mass scale.
- We do not know mass hierarchy.



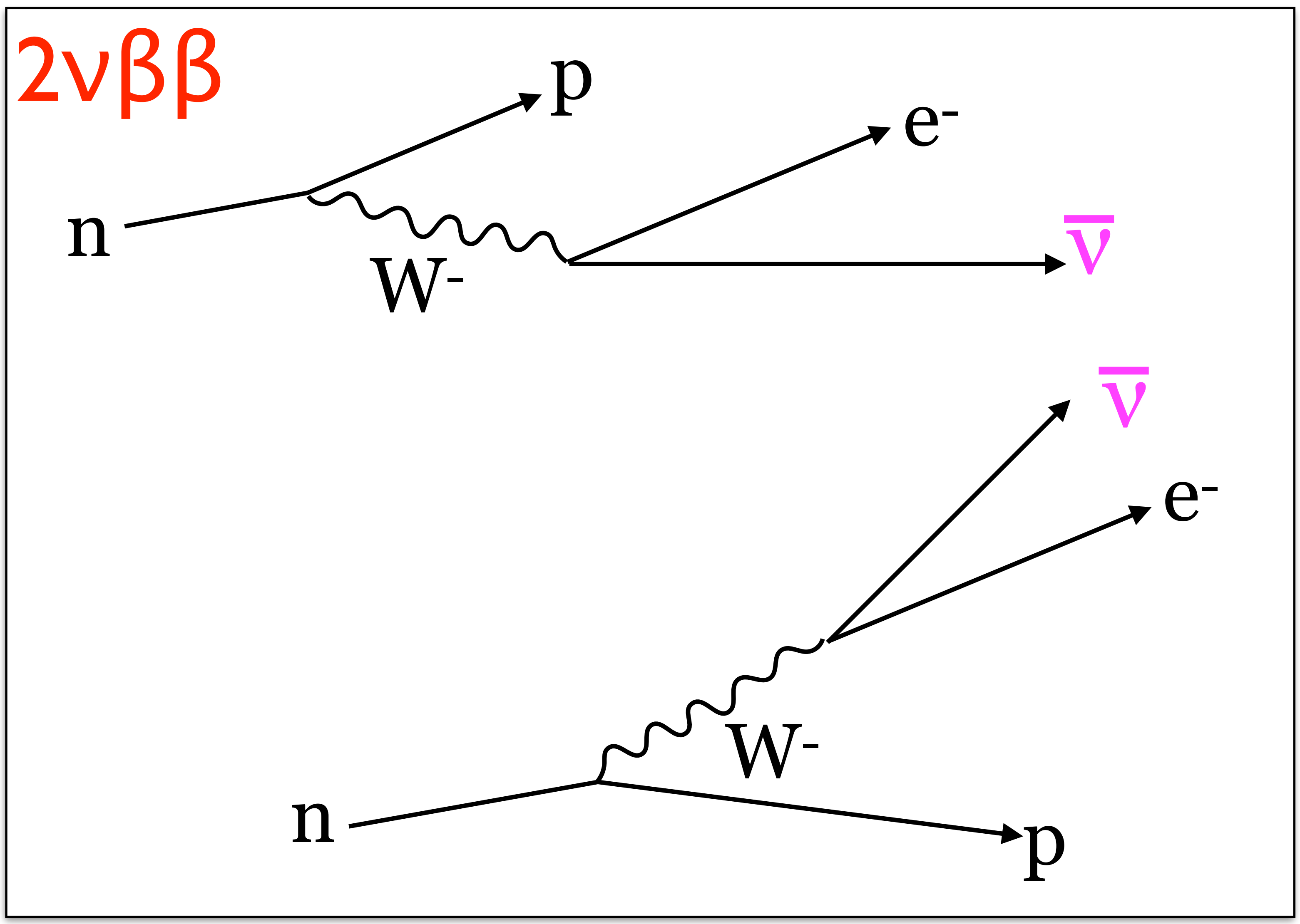
- Anti-neutrinos = Neutrinos? can happen to neutrinos because they are electrically neutral.

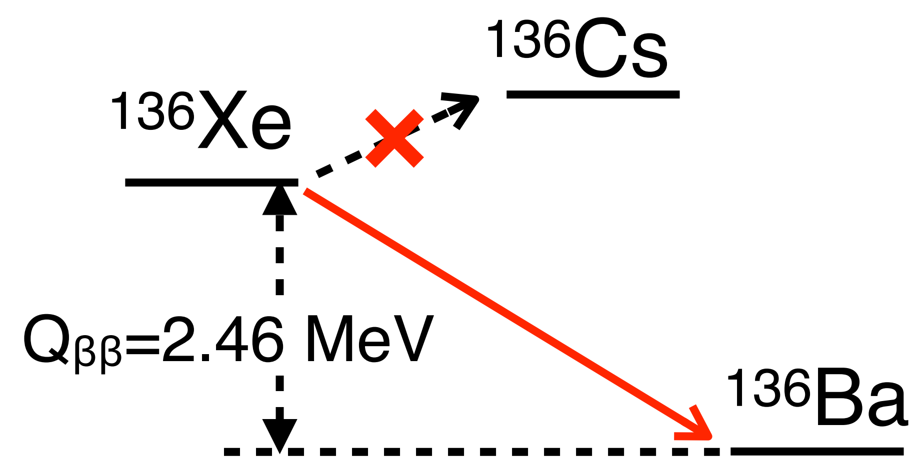
Majorana Neutrinos: $\nu = \nu_L, \nu_R$ → ν, $\bar{\nu}$

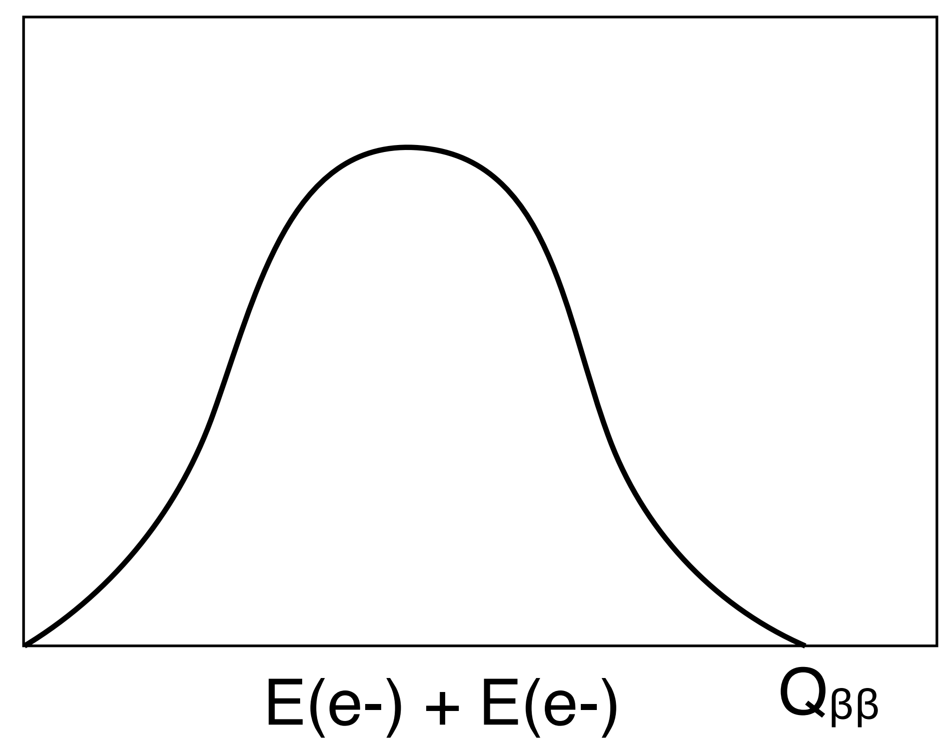
$0\nu\beta\beta$ → Neutrino mass hierarchy

Leptogenesis → Matter dominant universe

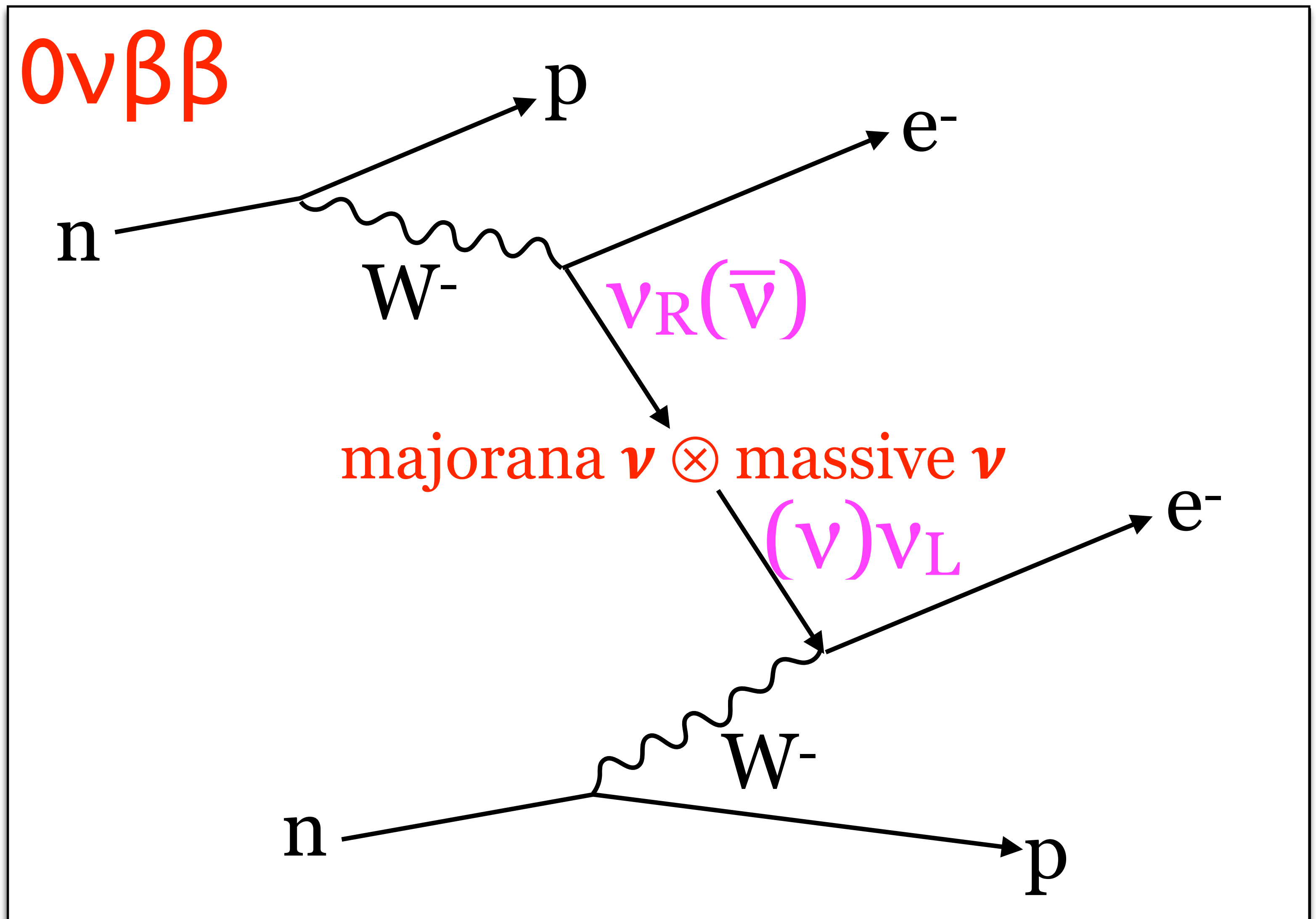
Double beta decay

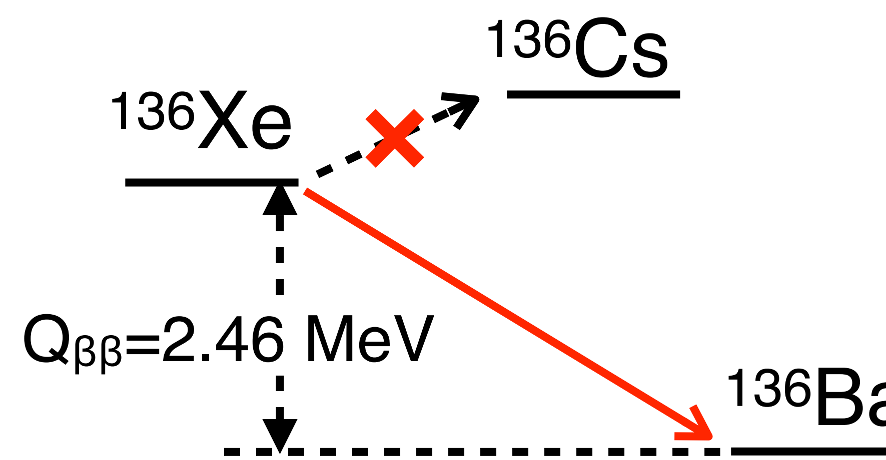


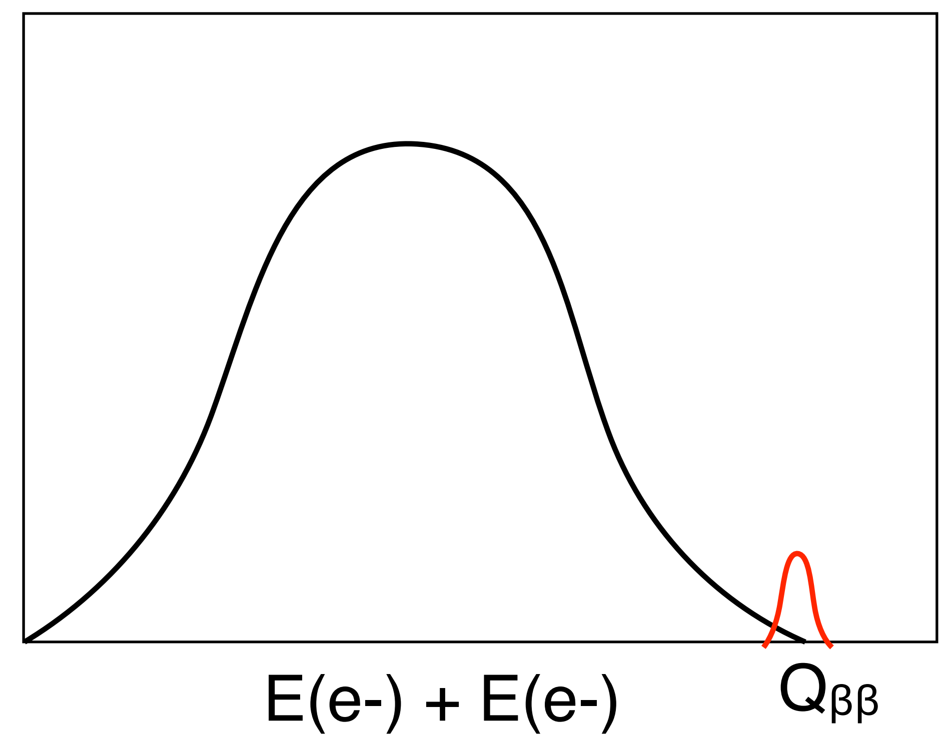




Neutrino-less double beta decay







Neutrino-less double beta decay

Exposure

Sensitivity (Observable) $$T_{1/2}^{0\nu} \propto \sqrt{\frac{M[\mathrm{kg}]\,t[\mathrm{yr}]}{b[/\mathrm{keV/kg/yr}]\;\Delta(E)[\mathrm{keV}]}} \times 10^{26}\ [\mathrm{years}]$$

Background Energy resolution

Matrix element (calculable, but hard)

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

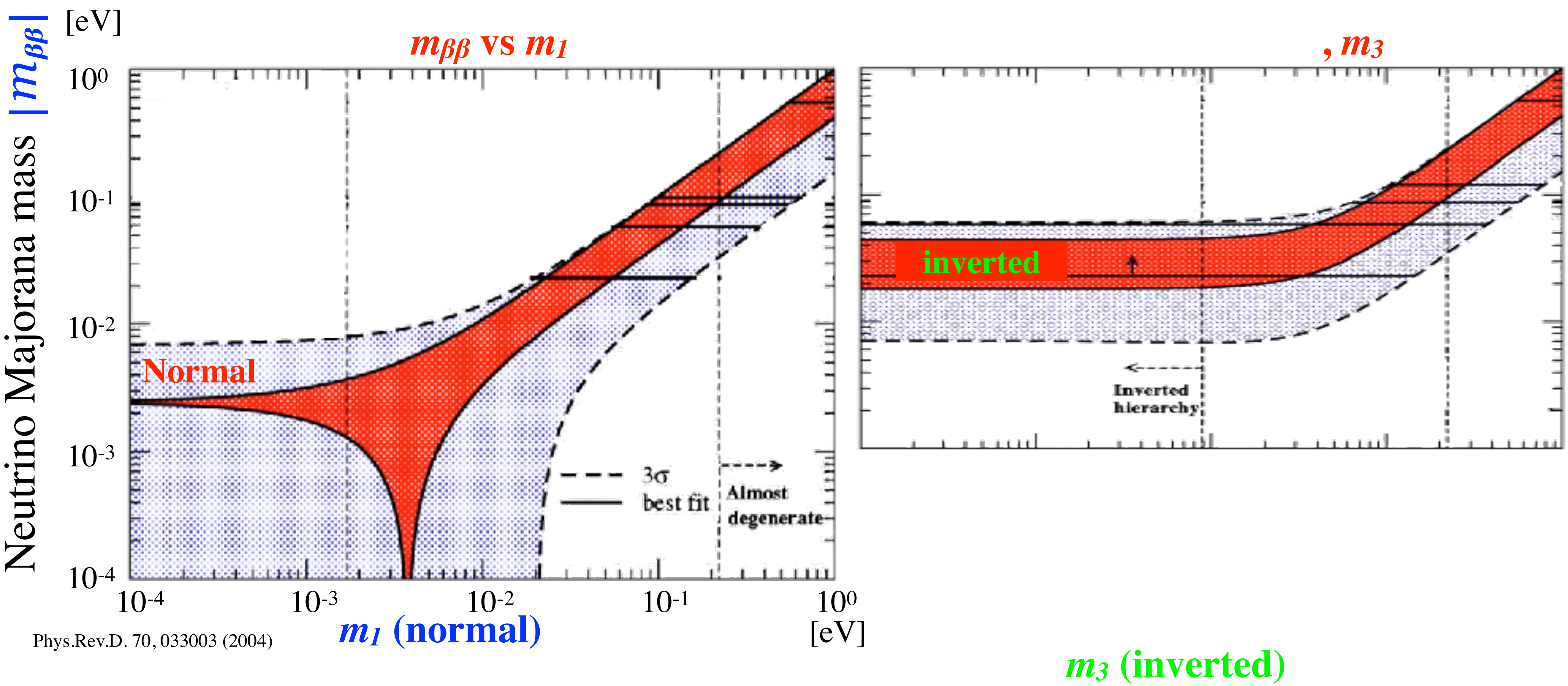
Phase space factor (calculable)

Neutrino majorana mass (Isotope independent)

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

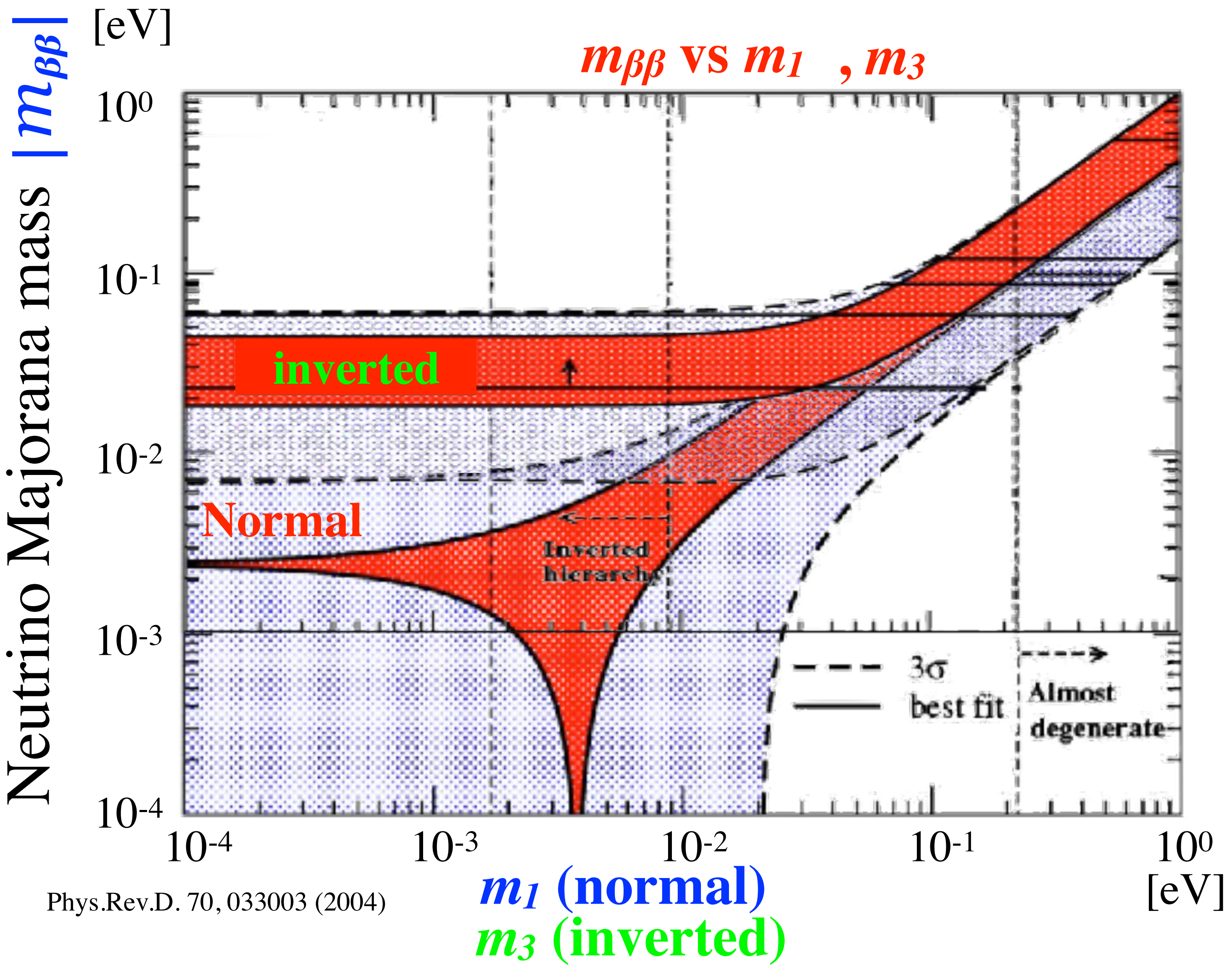
Neutrino oscillation Matrix

Neutrino-less double beta decay



Phys.Rev.D. 70, 033003 (2004)

Neutrino-less double beta decay



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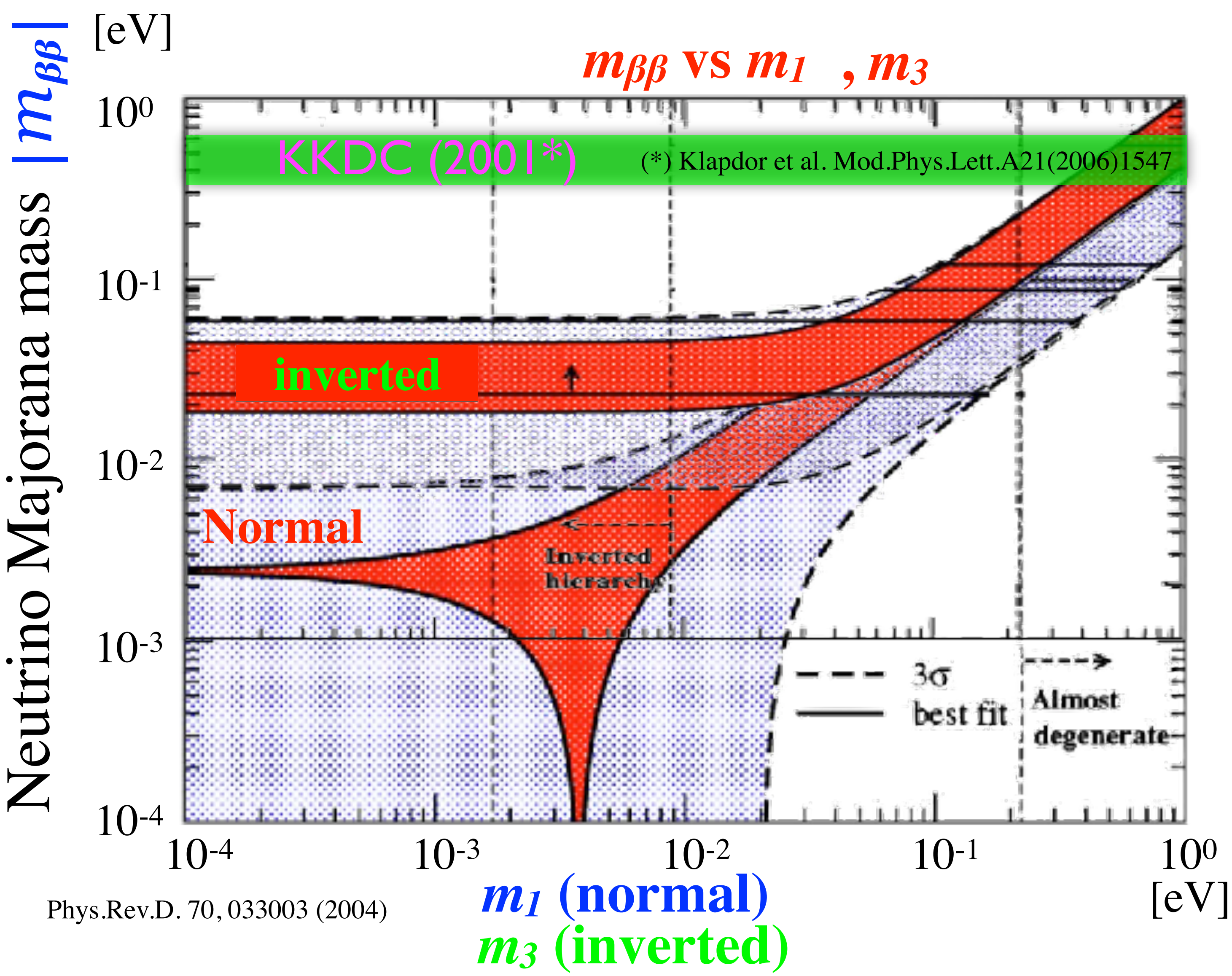
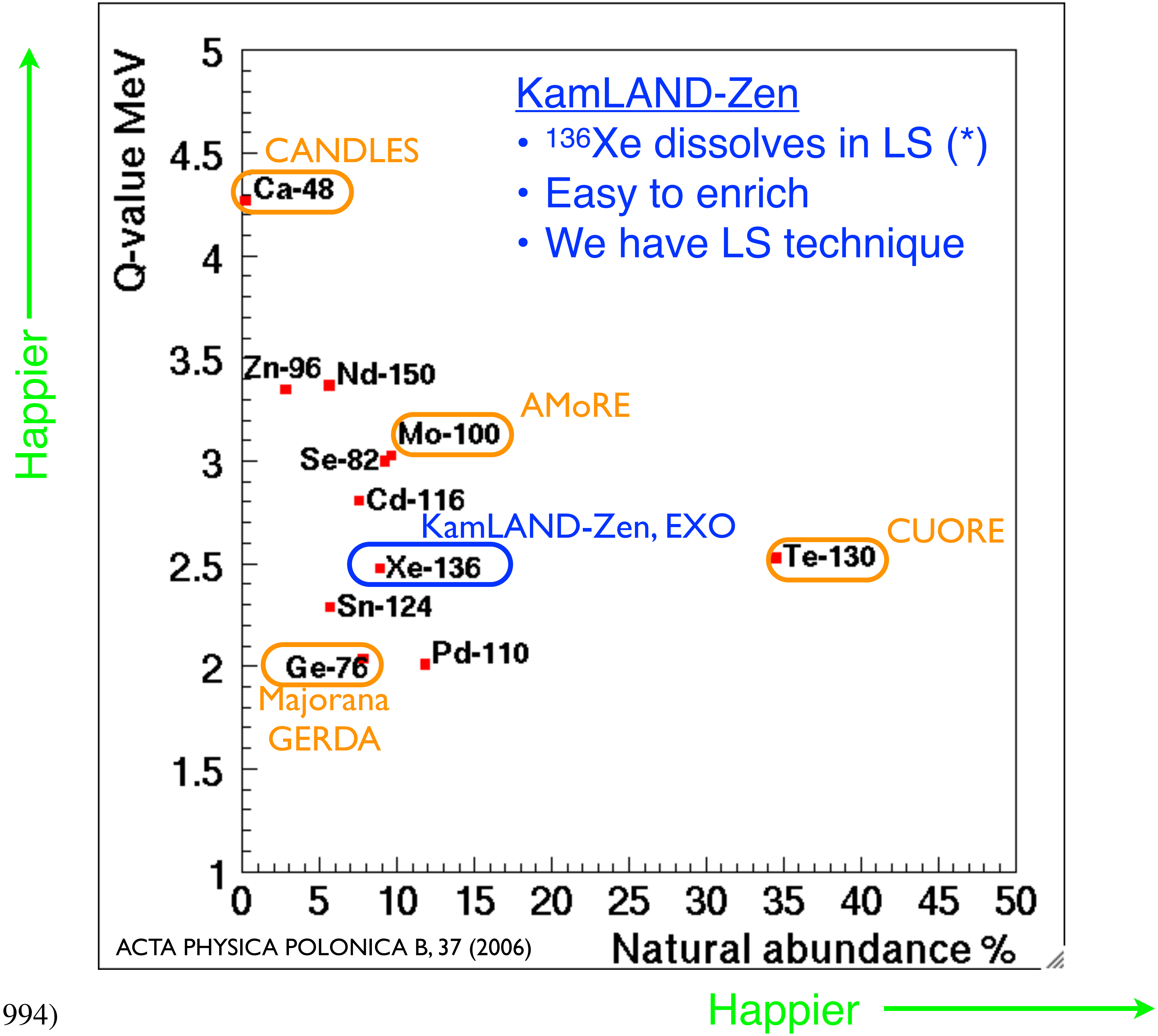


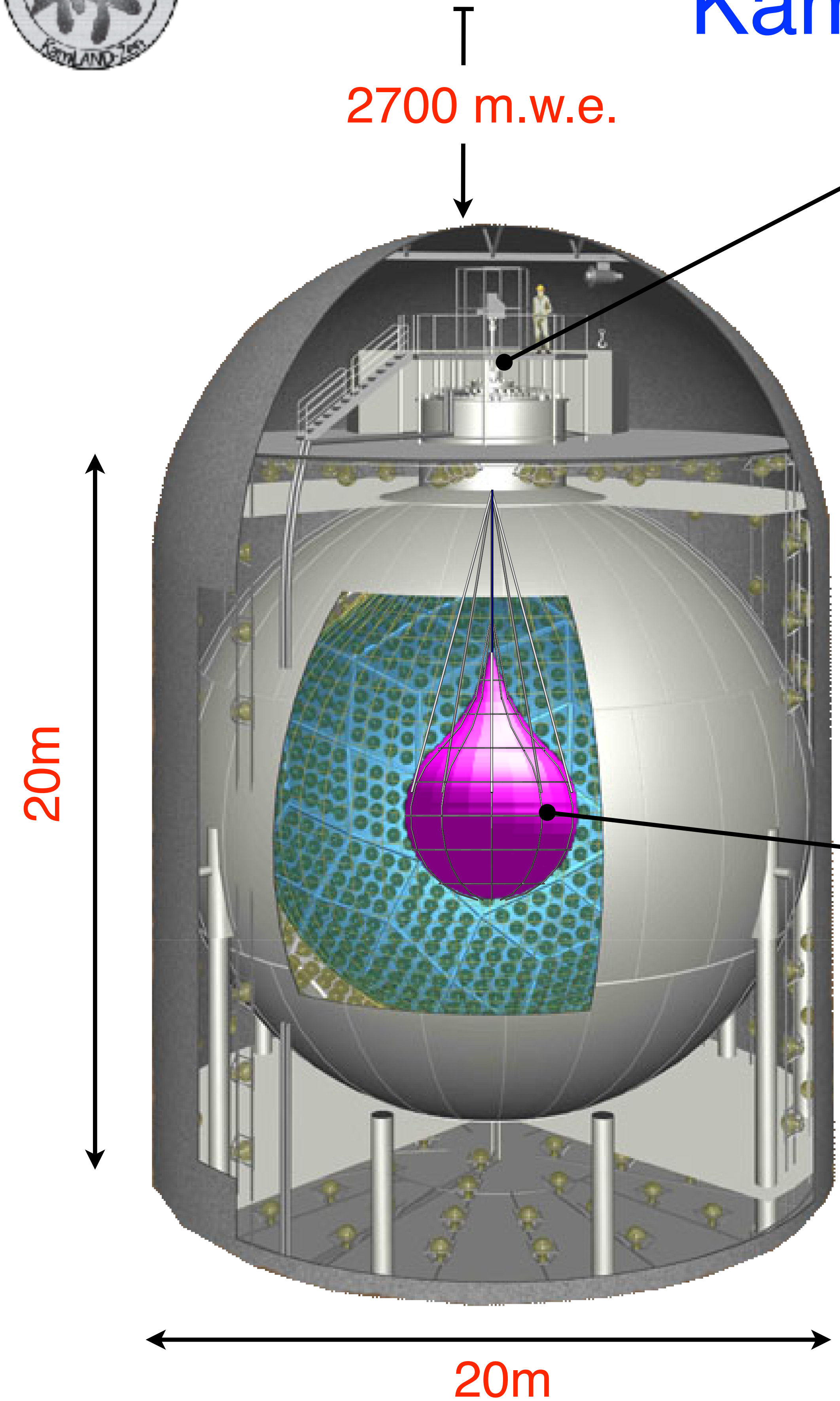
Phys.Rev.D. 70, 033003 (2004)

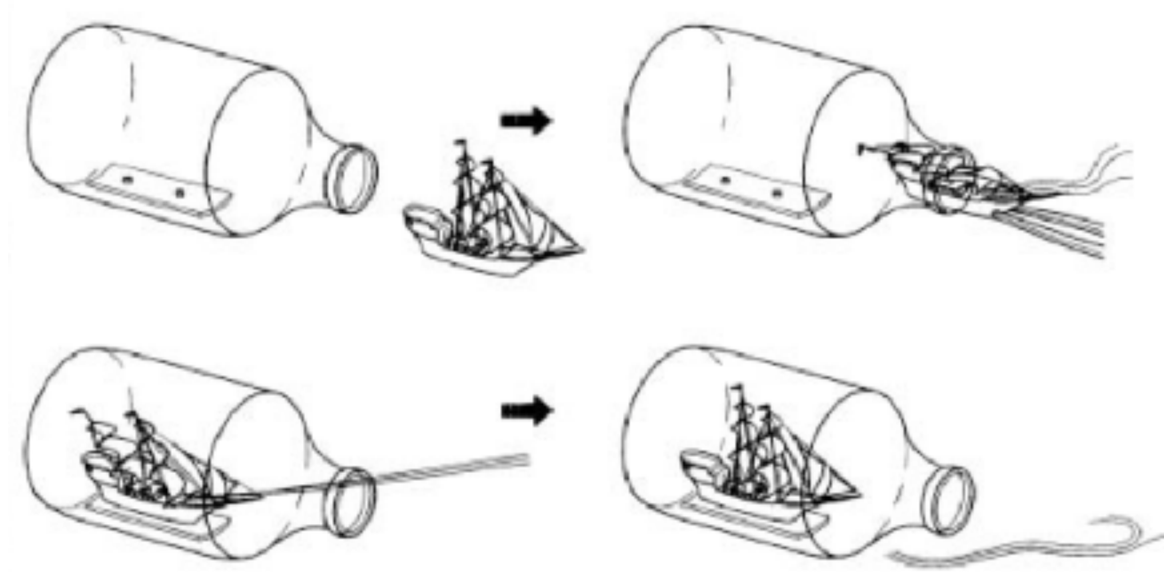
KamLAND-Zen400



(*) PRL72,1411(1994)

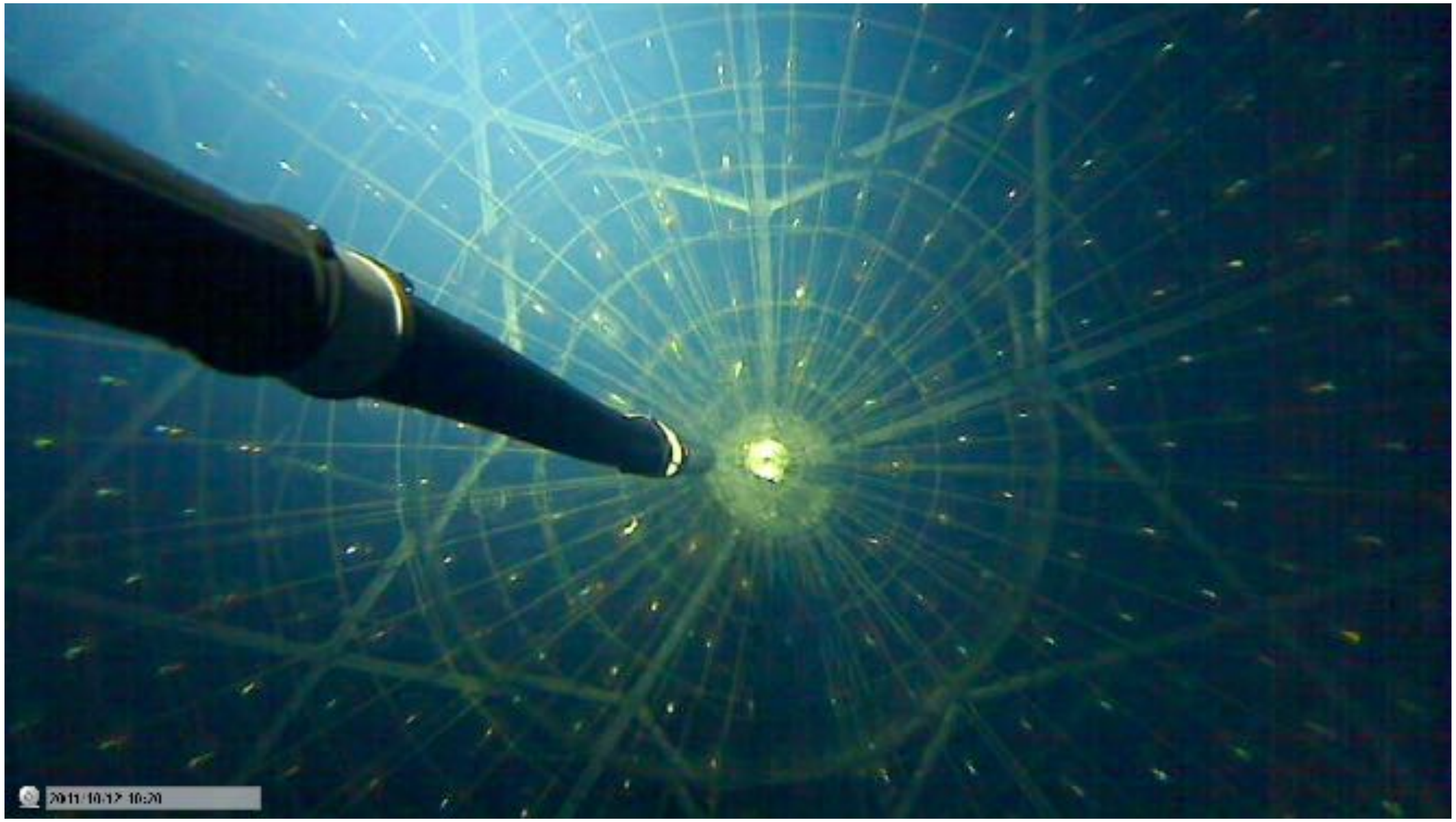
KamLAND-Zen400

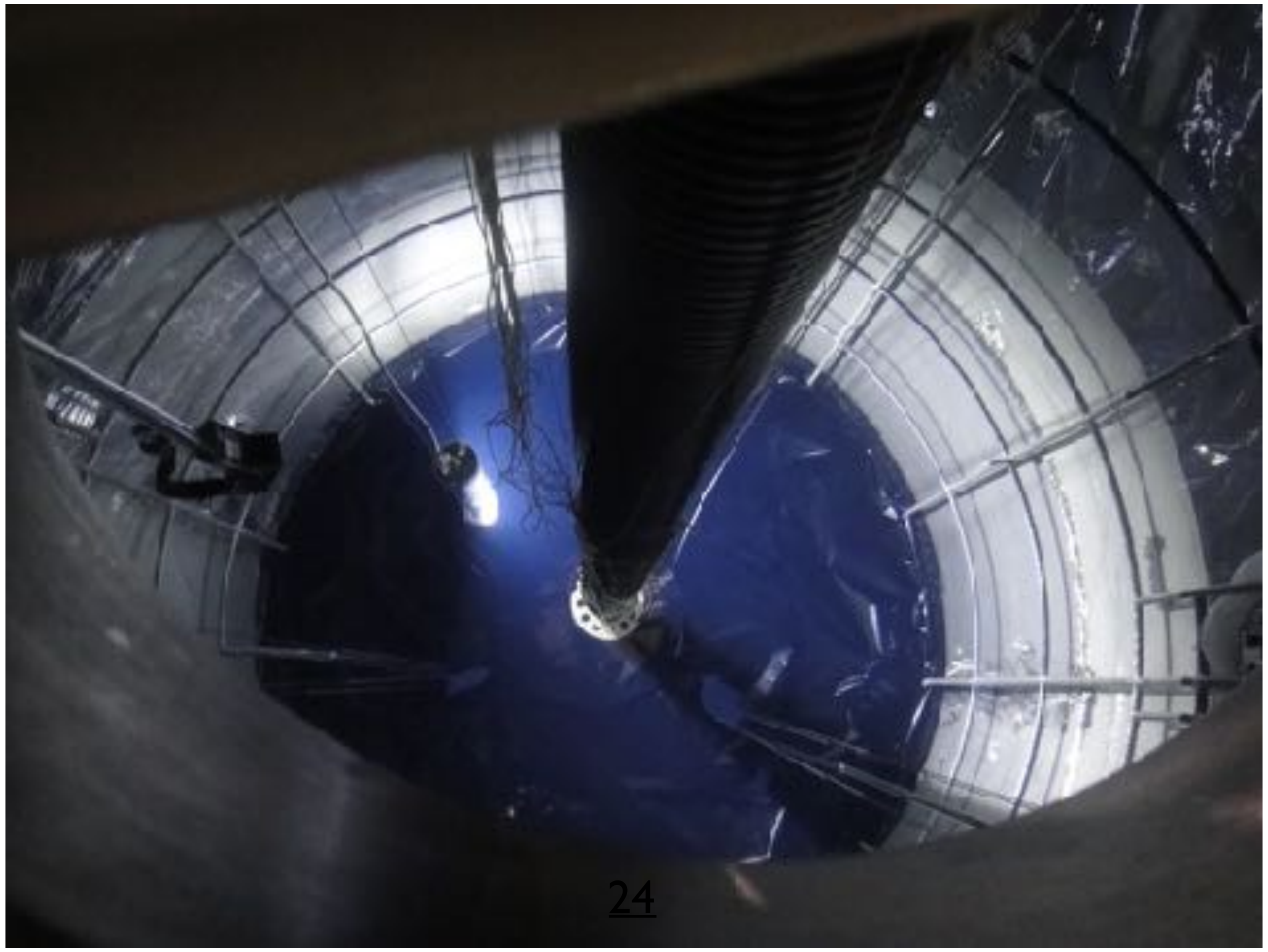


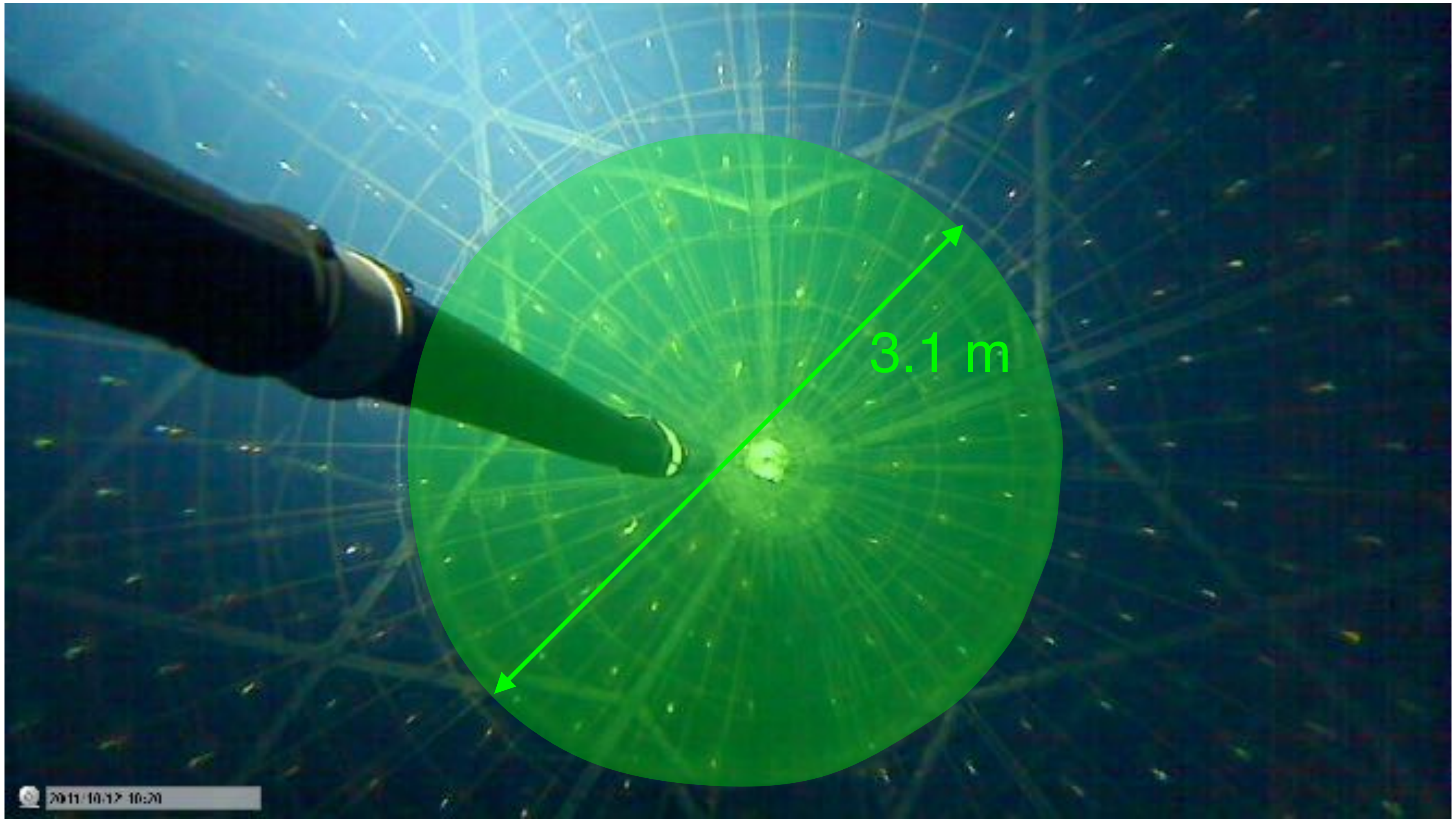


^{136}Xe loaded LS in **mini-balloon**

~3 % of ^{136}Xe in LS by weight
90 % enriched,
~400 kg of Xe dissolved in ~17 m^3 LS


2011/10/12 10:20




3.1 m

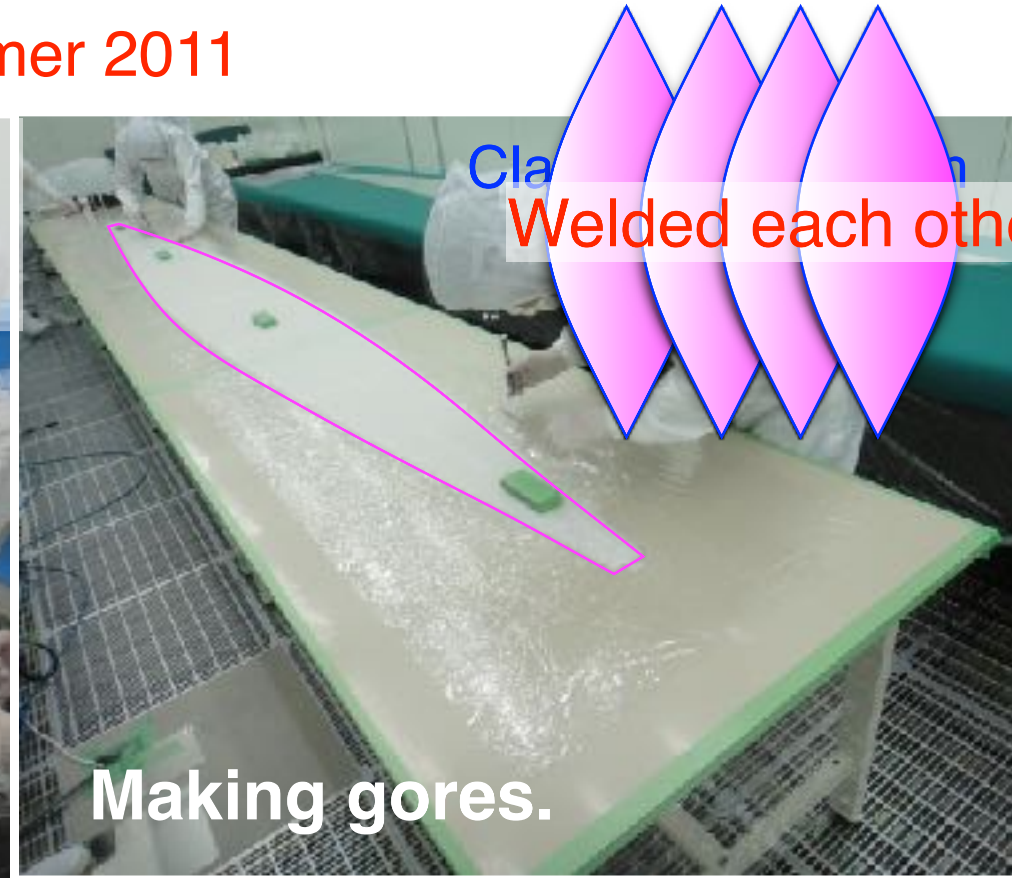

Do you believe ?
Φ 40 cm opening

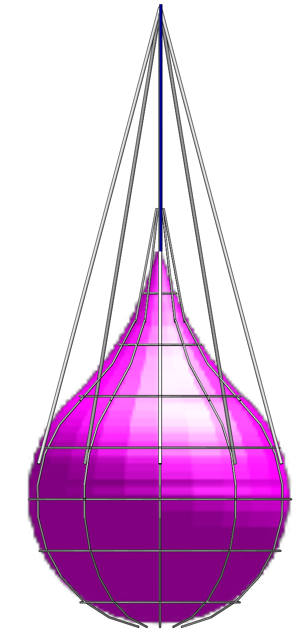
mini-Balloon factory

Fabrication at Sendai in Spring 2011
Installation into KamLAND in Summer 2011

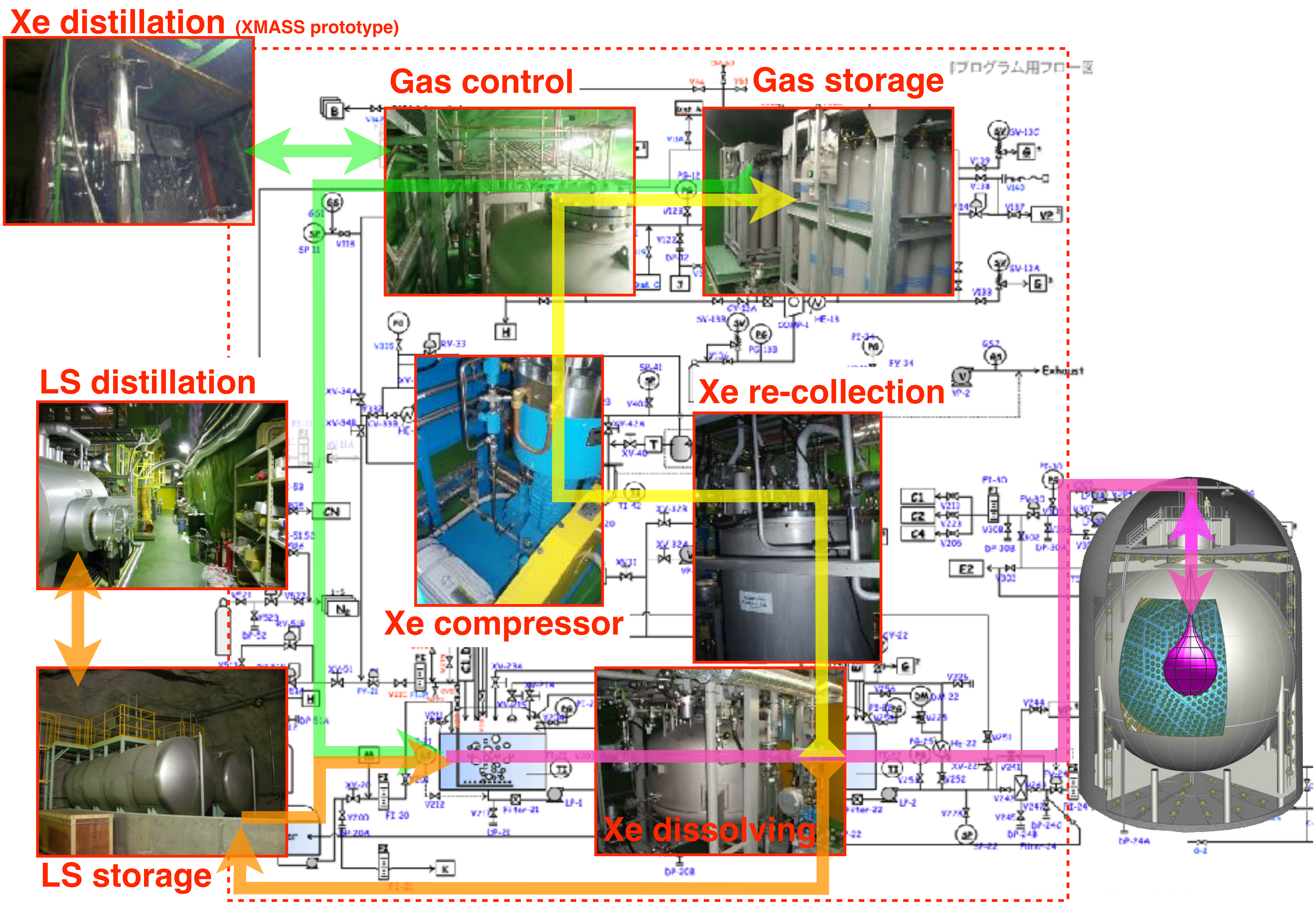
mini-Balloon factory

Fabrication at Sendai in Spring 2011
Installation into KamLAND in Summer 2011

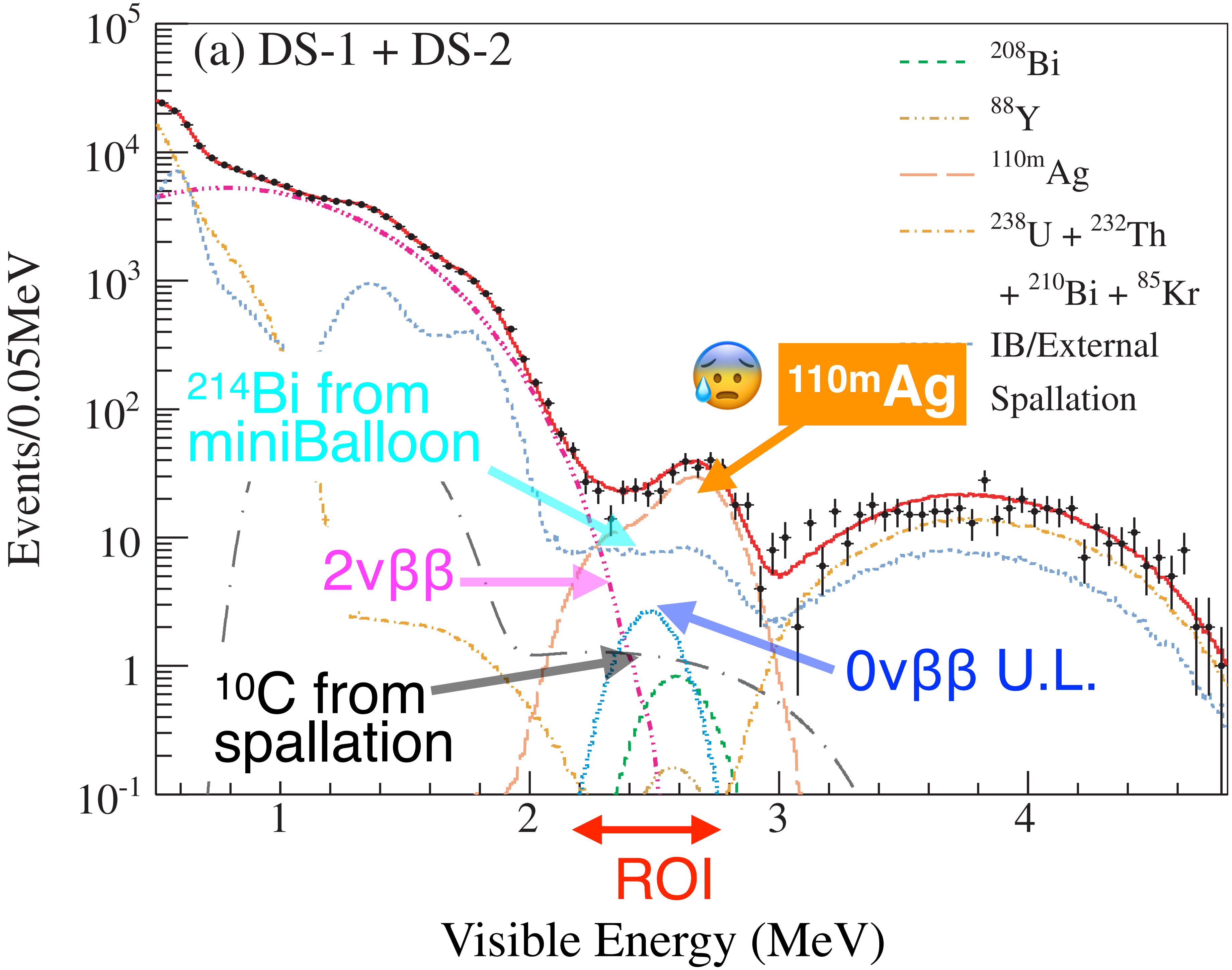




Xe-LS facility



KamLAND-Zen400 (phase 1)



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

\+ EXO-200 (*)

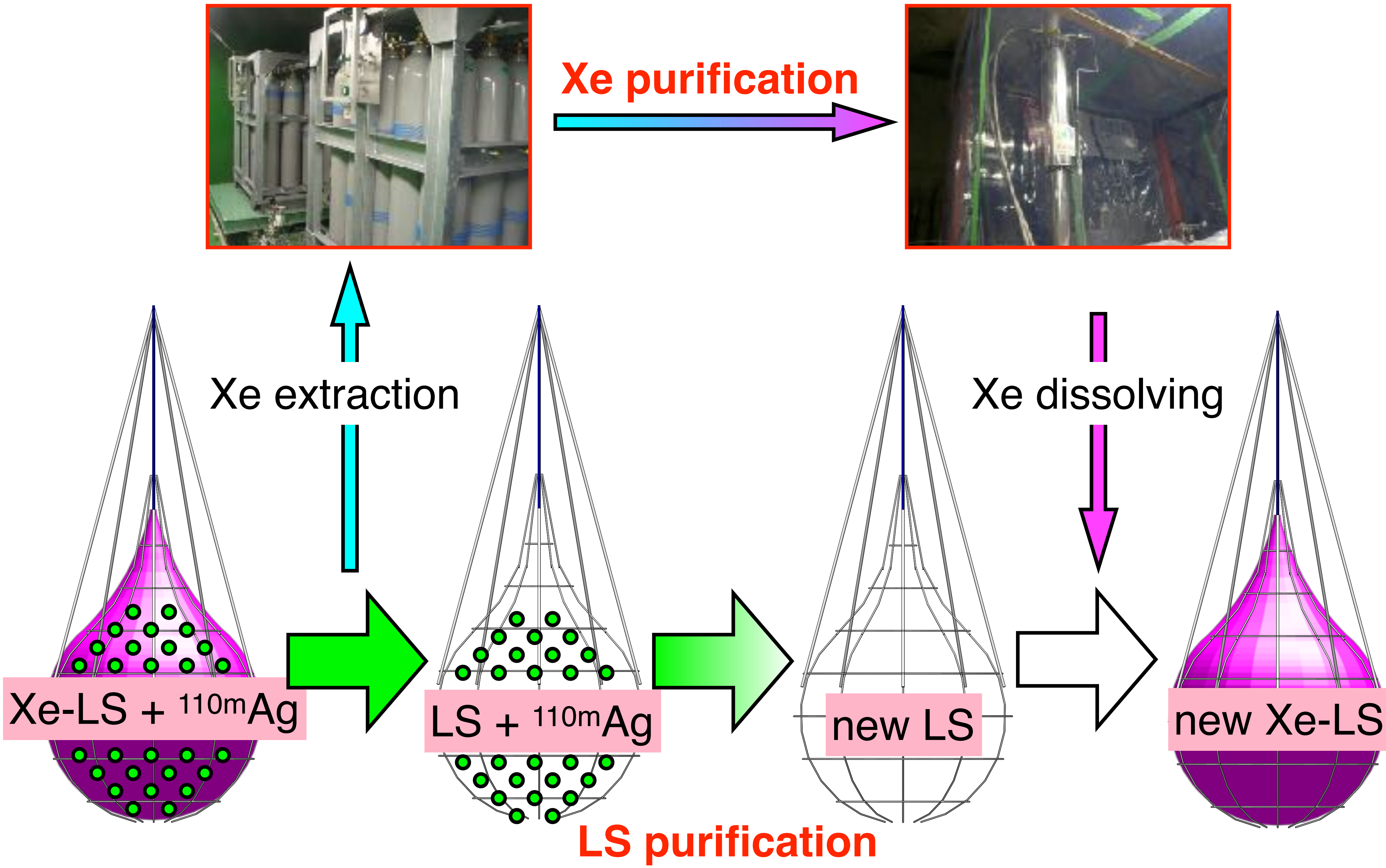
$T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ years (90% C.L.)

$\langle m_{\beta\beta} \rangle$ < (120–250) meV (90% C.L.)

KKDC excluded

(*) PRL **109**, 032505 (2012)

Strategy for ^{111m}Ag removal



Filling completed @2011
Filtration @2012 Feb.

It was confirmed
^{110m}Ag remains in LS.
@2012 Summer

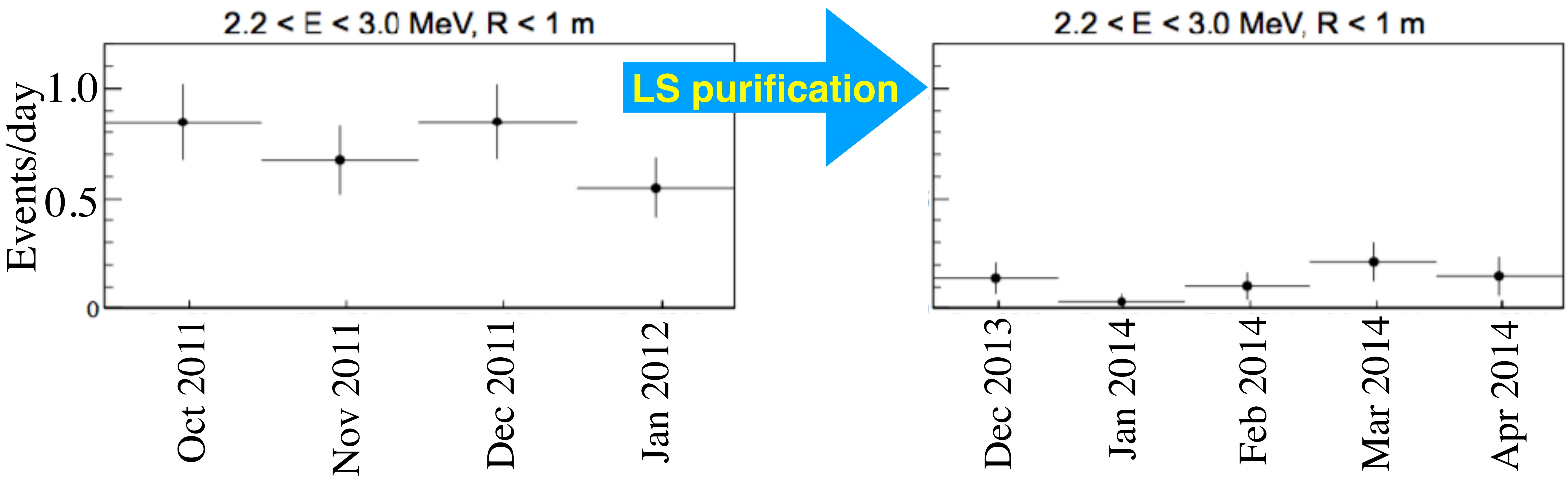
replaced with new
purified LS

× 0.1 Ag

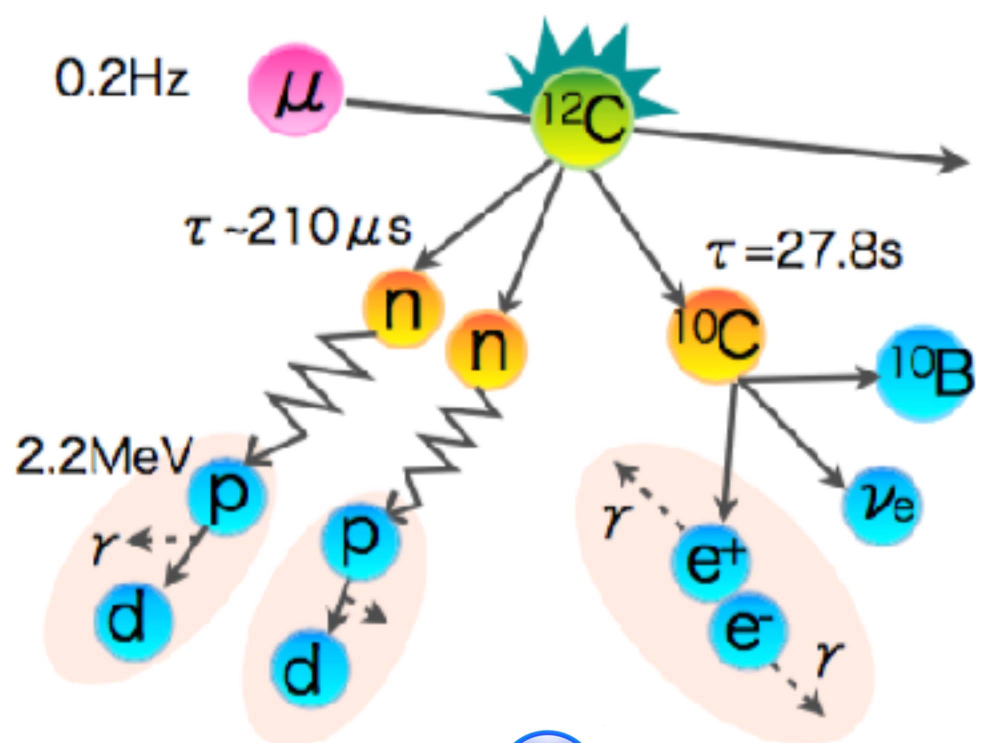
KamLAND-Zen400 (phase 2)

- **LS purification**
- Better understanding and rejection of BG
- Fit Volume binning (non-uniform BG distribution)
- Calibration in the mini-Balloon

KamLAND-Zen400 (phase 2)



B.G. Rejection



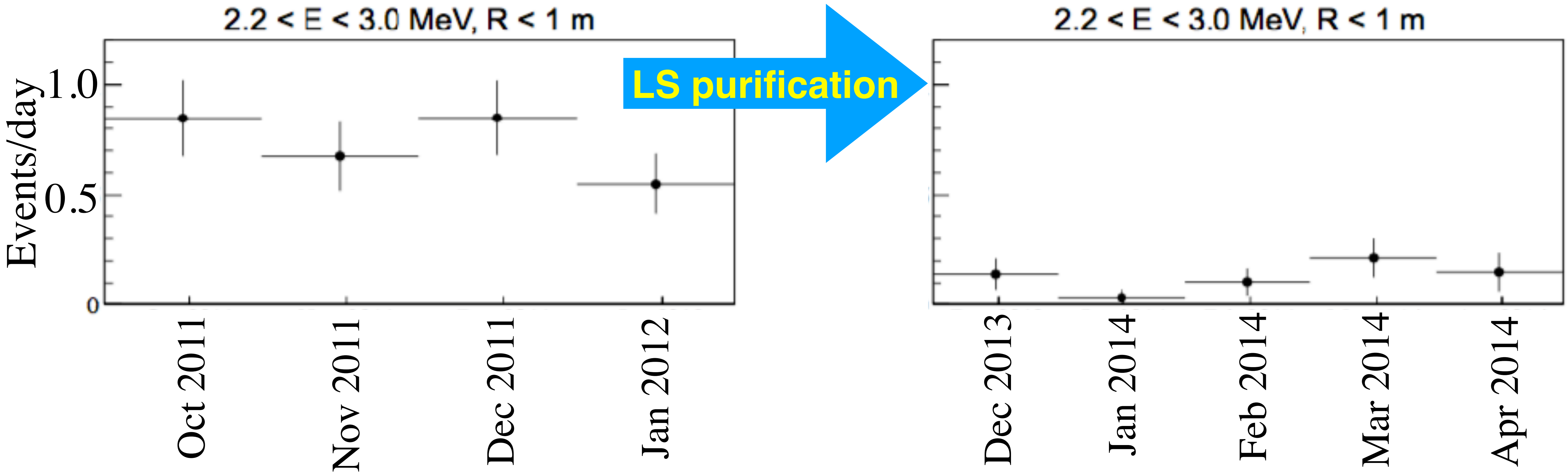
Q=3.65 MeV

Triple coincidence

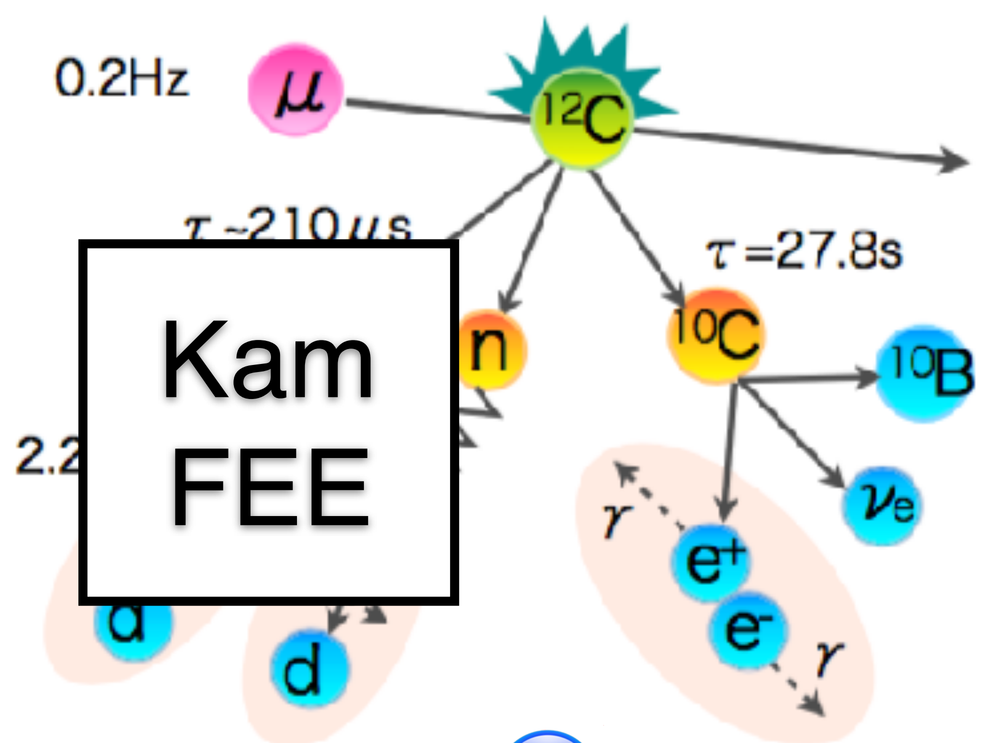
- Muon
- Thermal neutron
- ^{10}C

~65% rejection eff.

KamLAND-Zen400 (phase 2)



B.G. Rejection

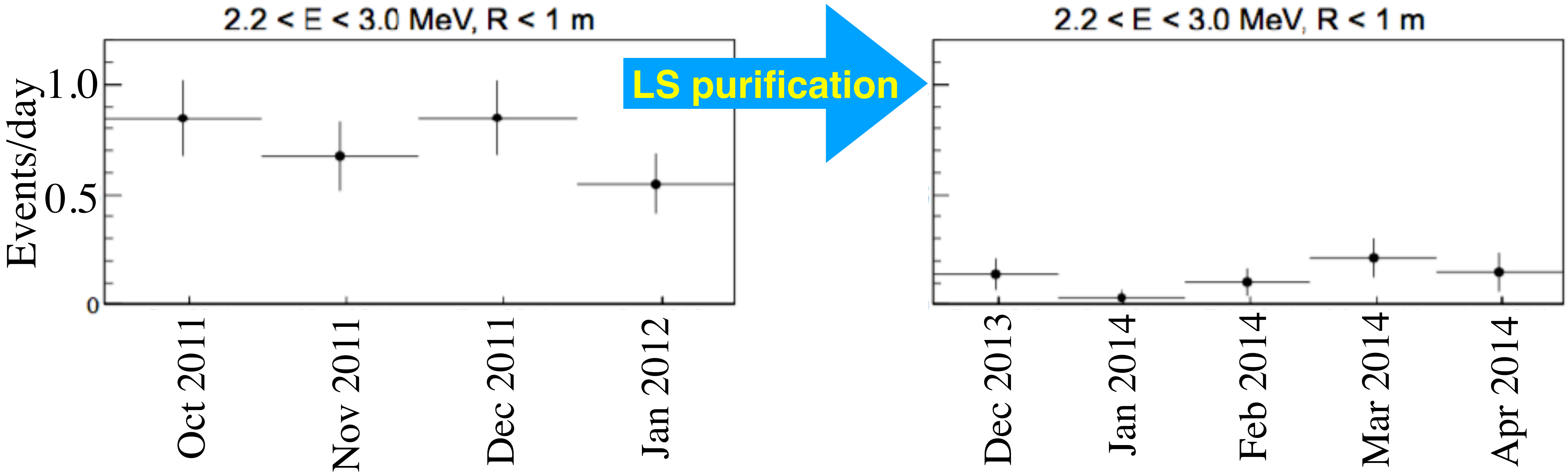


Q=3.65 MeV

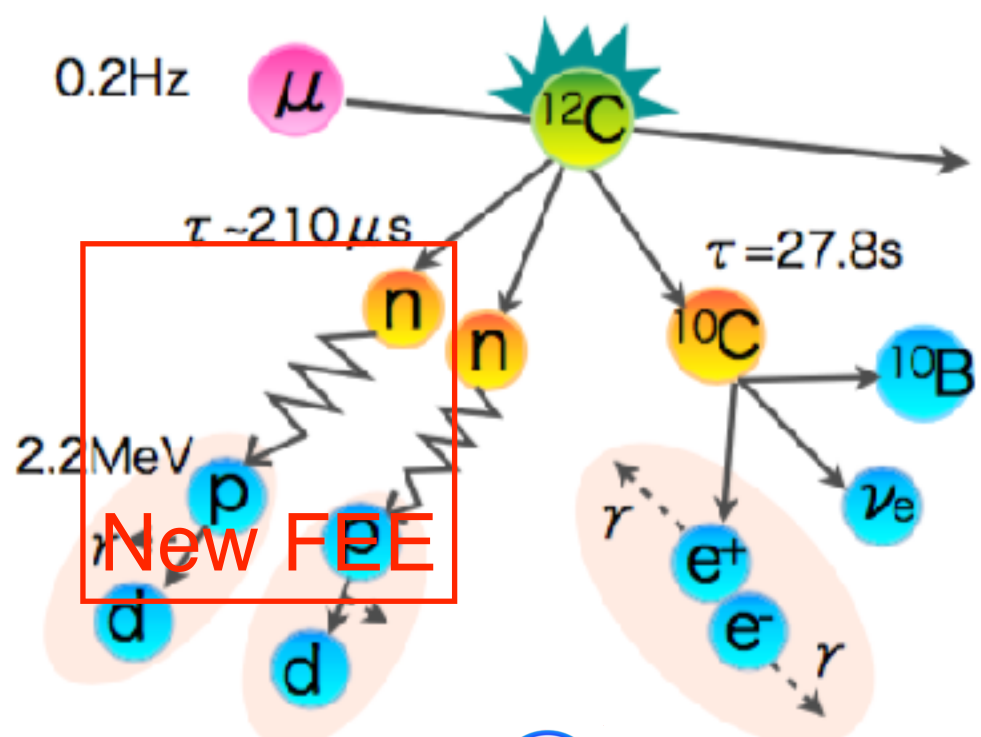
Triple coincidence
- Muon
- Thermal neutron
- ^{10}C

~65% rejection eff.

KamLAND-Zen400 (phase 2)



B.G. Rejection



Q=3.65 MeV

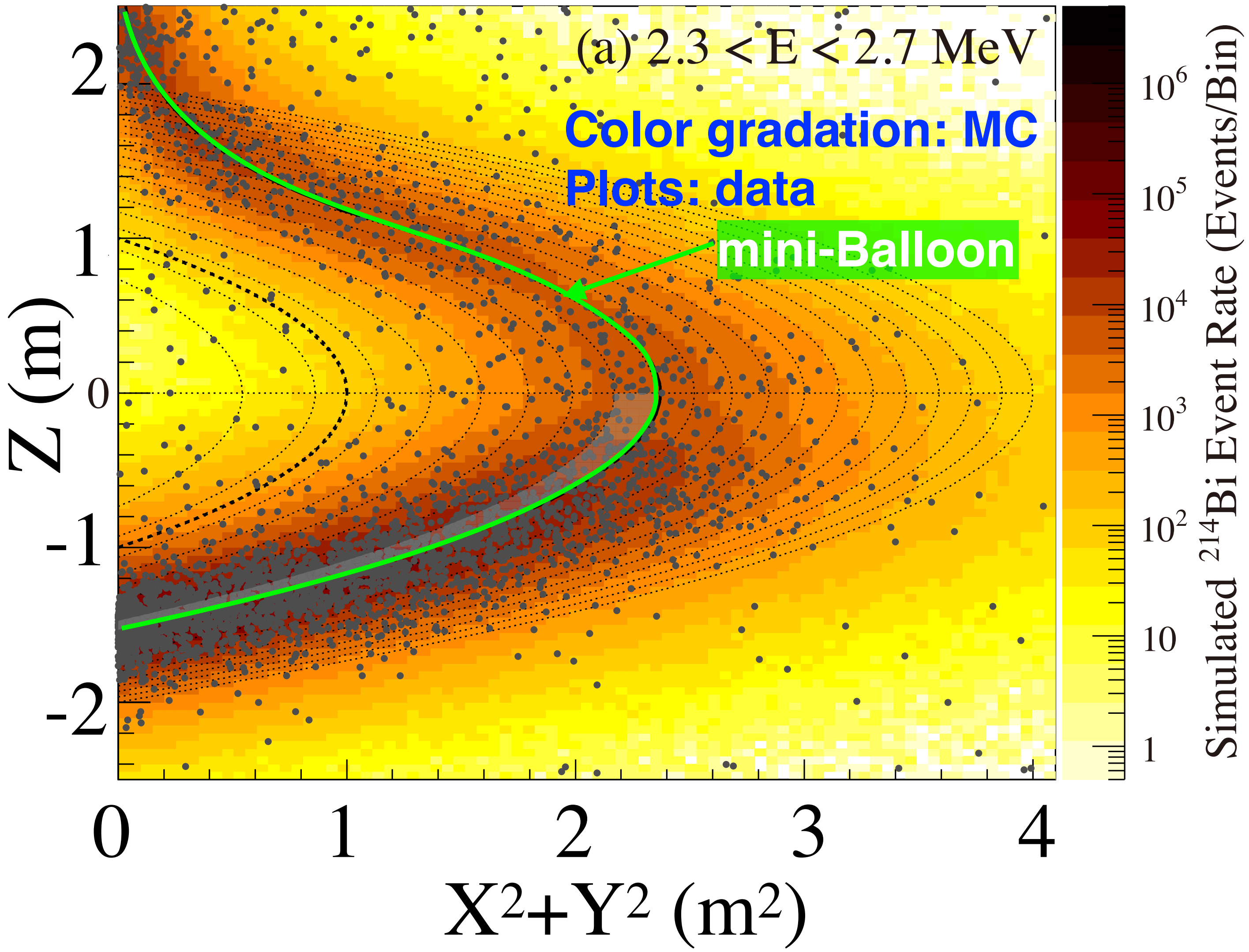
Triple coincidence

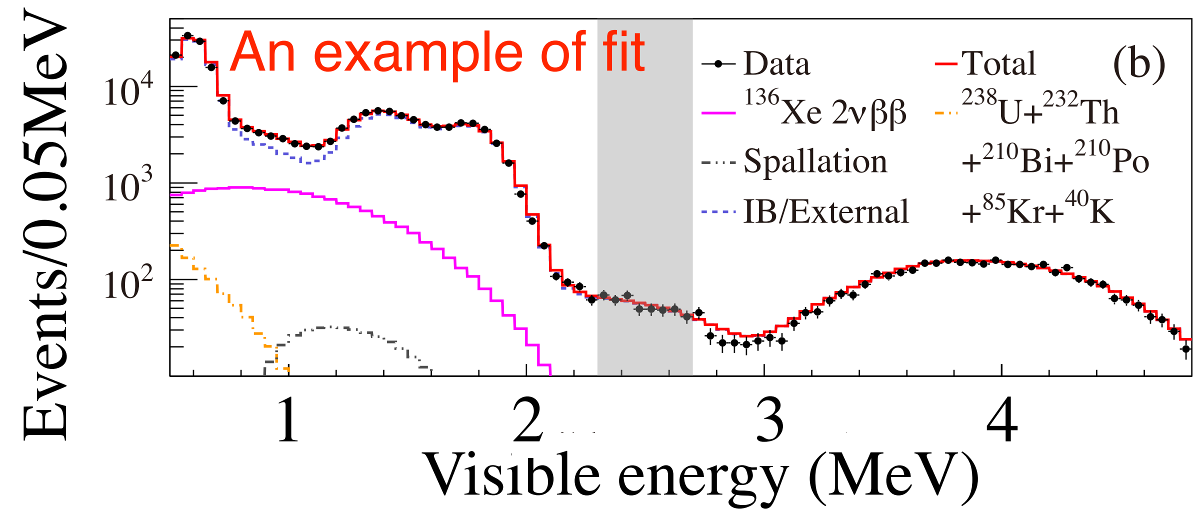
- Muon
- Thermal neutron
- ^{10}C

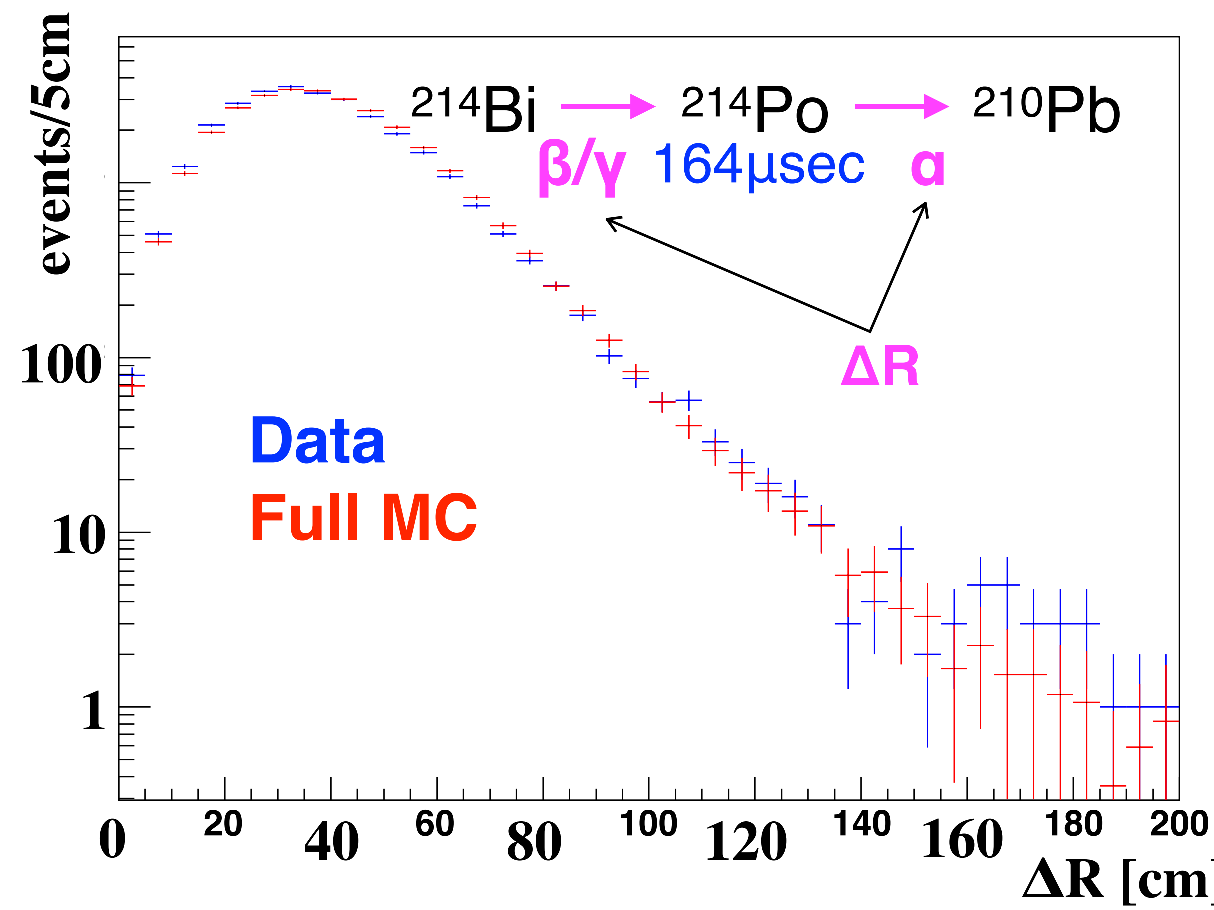
~65% rejection eff.

KamLAND-Zen400 (phase 2)

B.G. understanding and volume binning





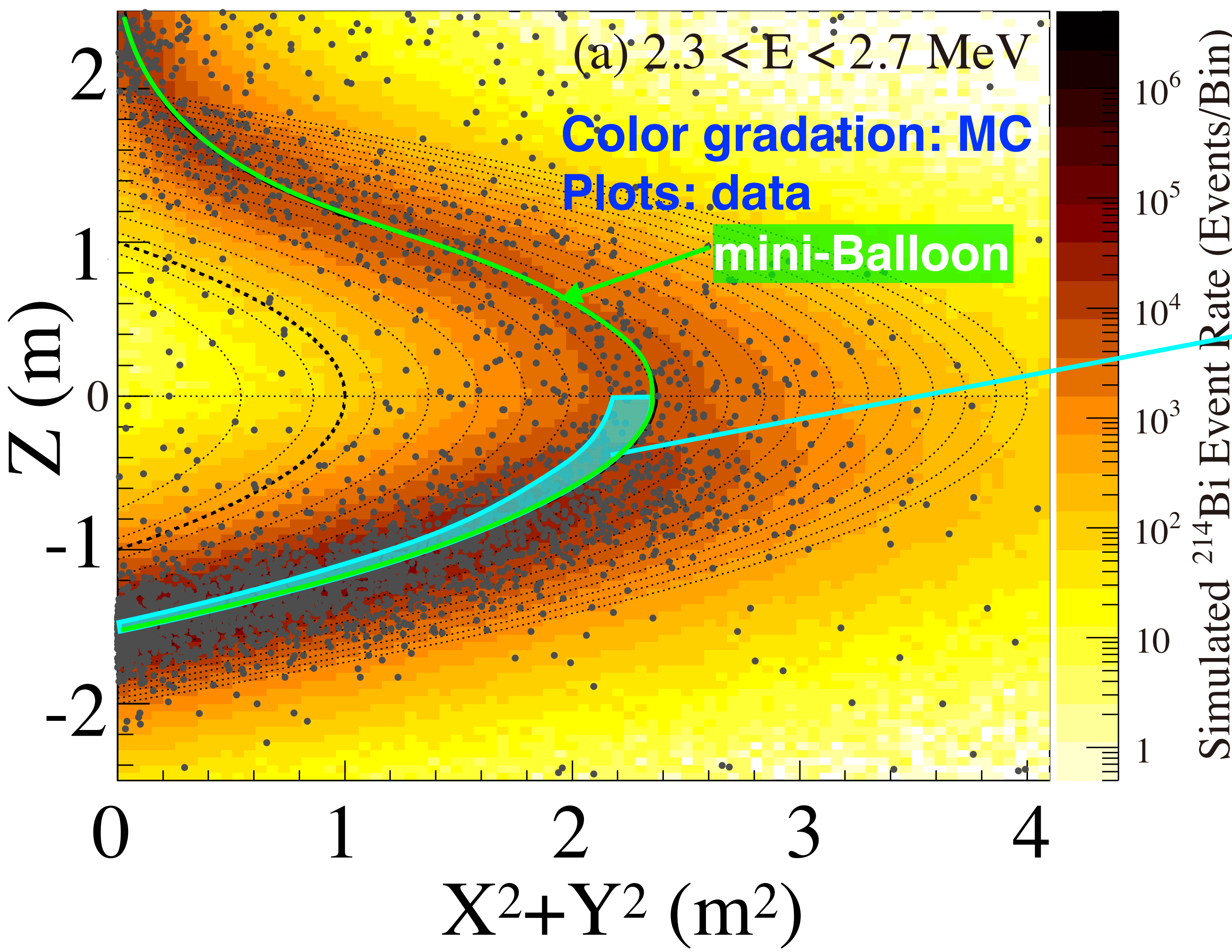


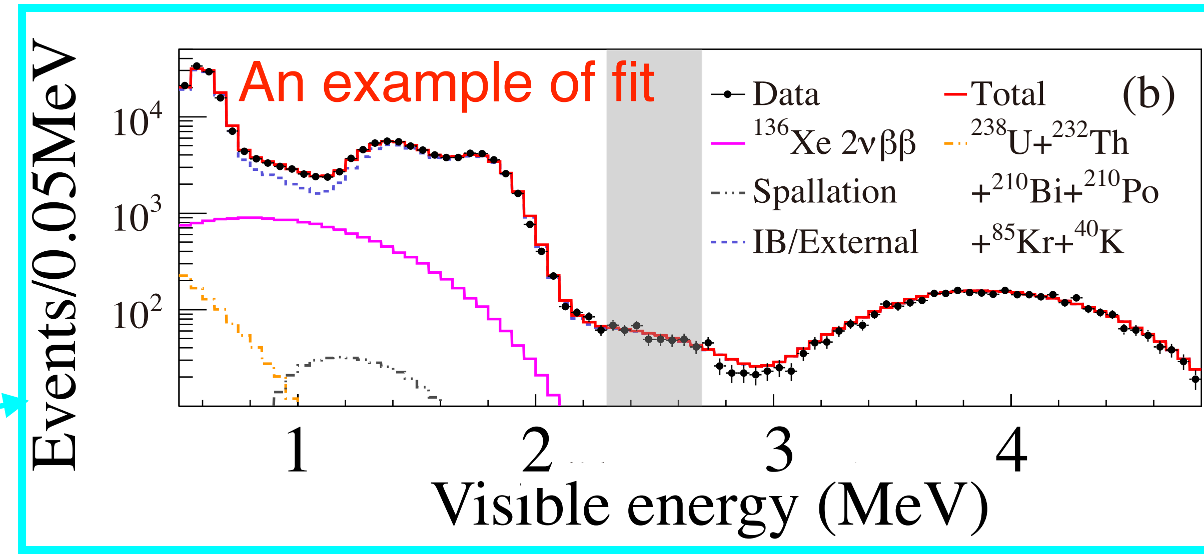
✓Non uniform distribution of ^{214}Bi is well understood and reproduced by MC.

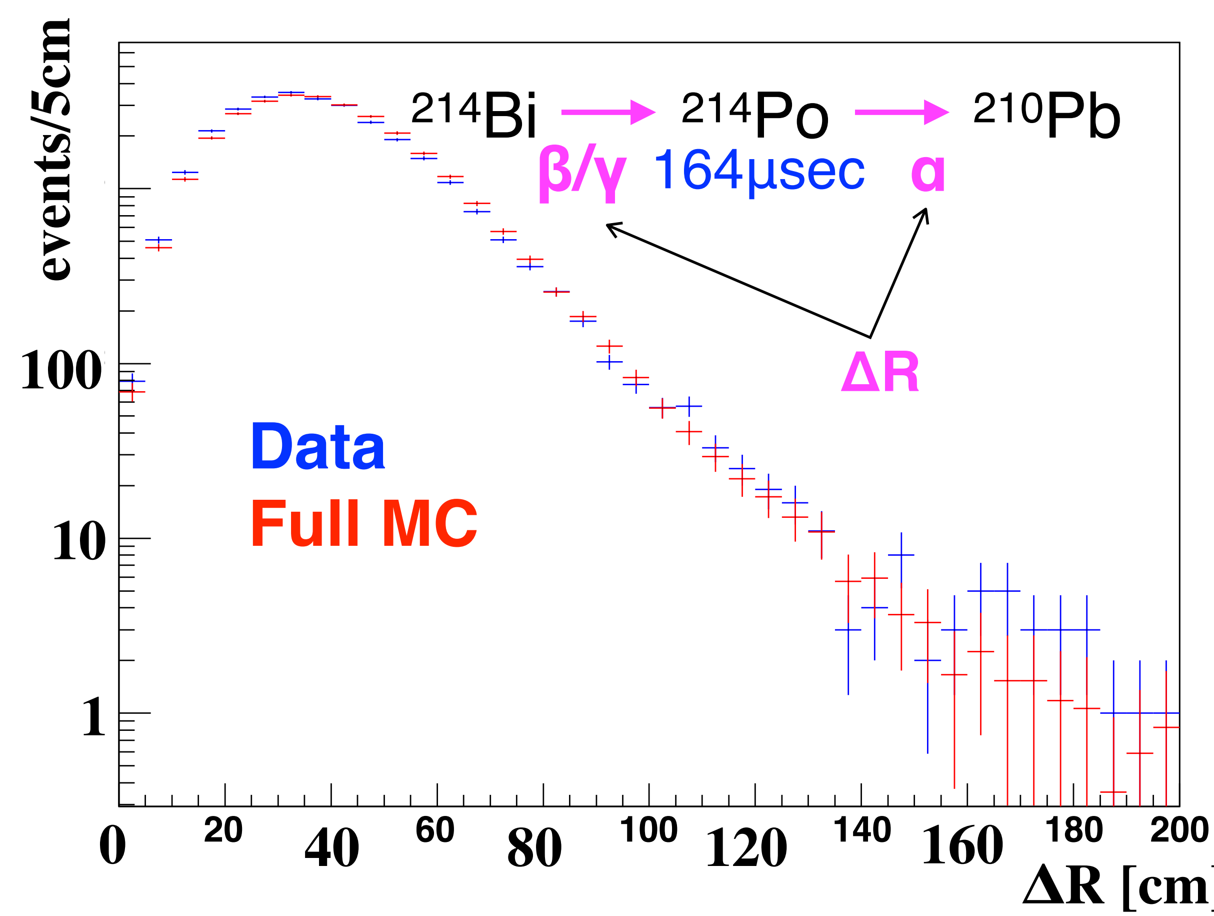
✓Fit volume is divided into 40 equal volume bins and fits are performed for each bin.

KamLAND-Zen400 (phase 2)

B.G. understanding and volume binning





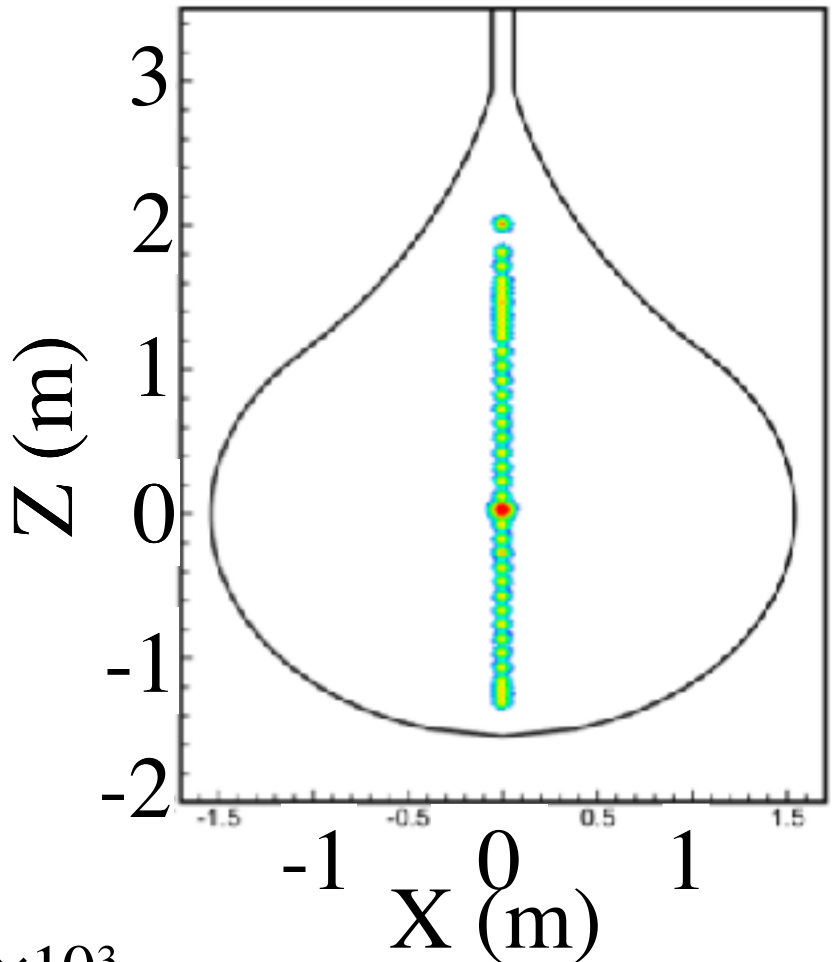


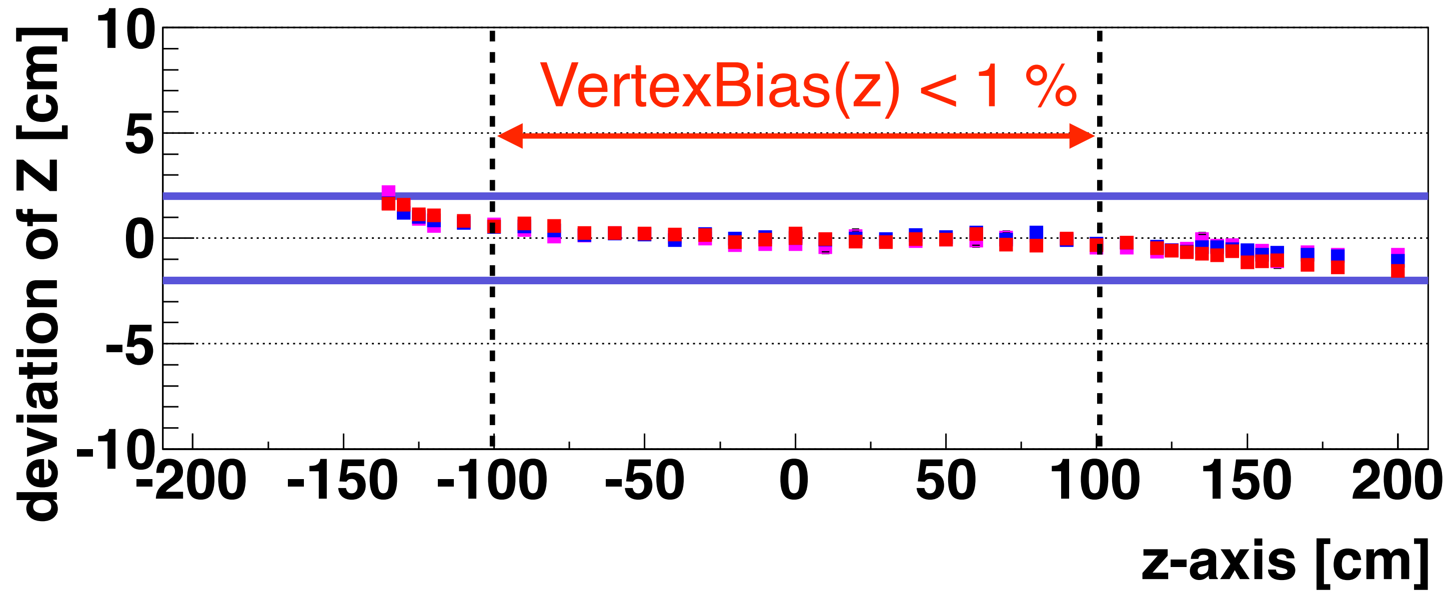
✓Non uniform distribution of ^{214}Bi is well understood and reproduced by MC.

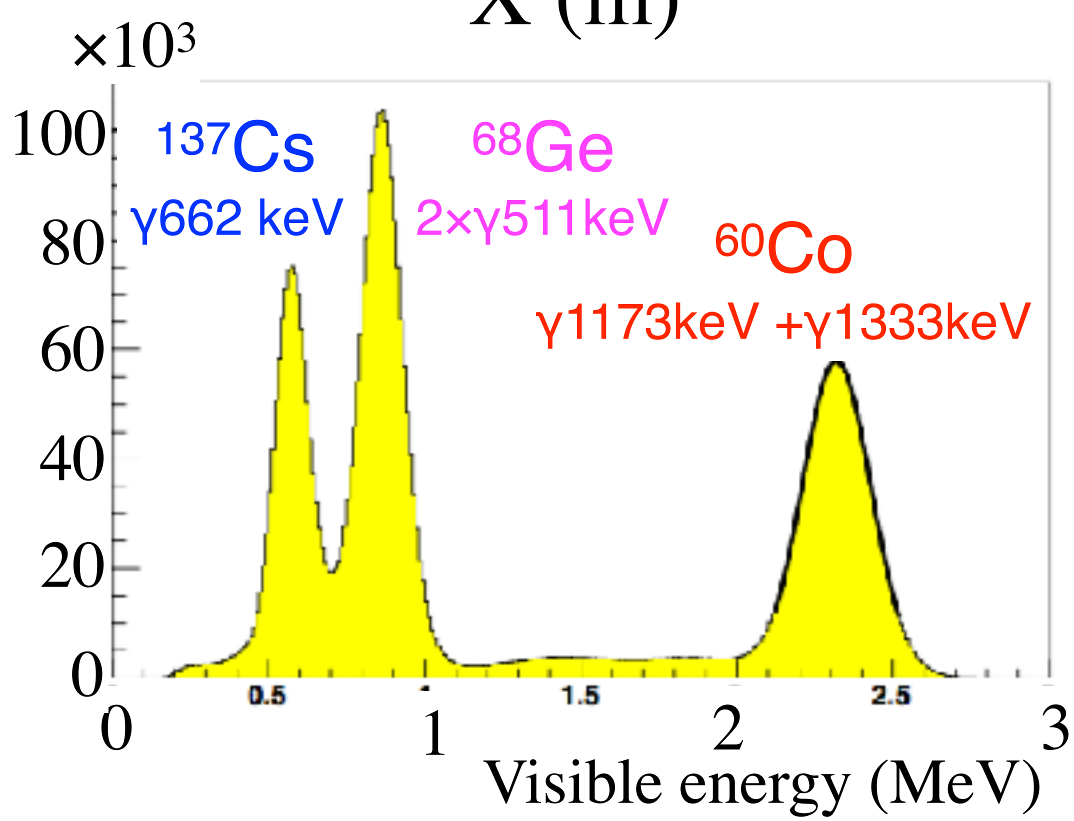
✓Fit volume is divided into 40 equal volume bins and fits are performed for each bin.

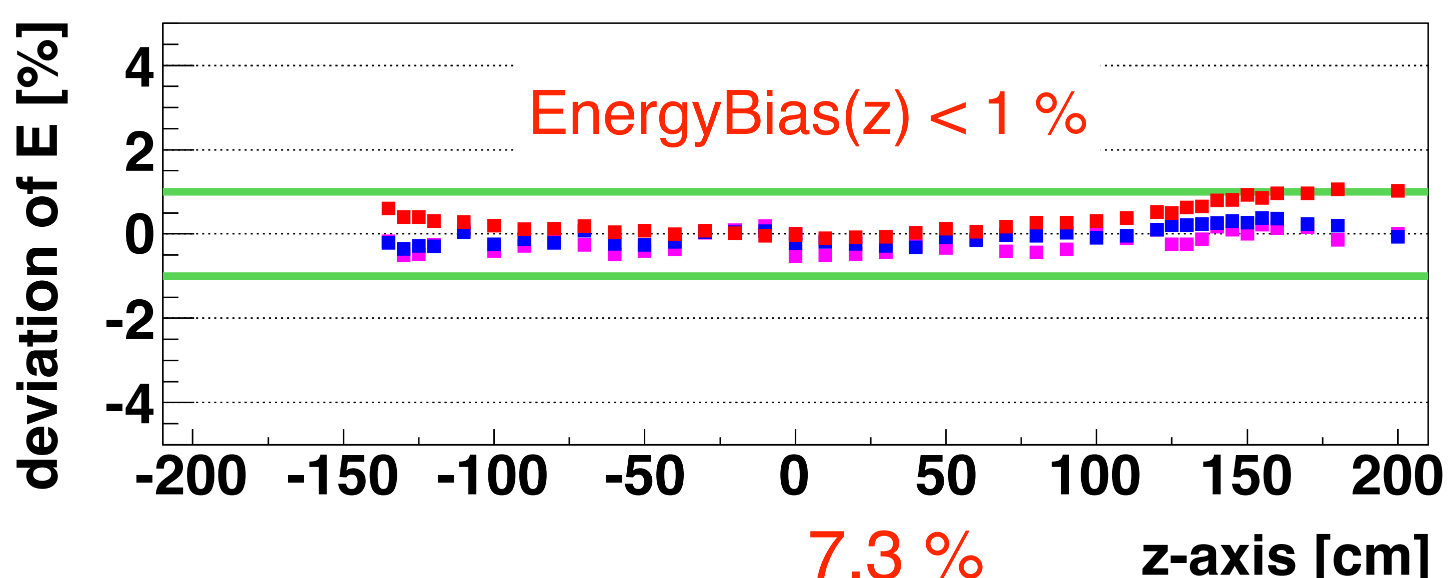
KamLAND-Zen400 (phase 2)

Calibration



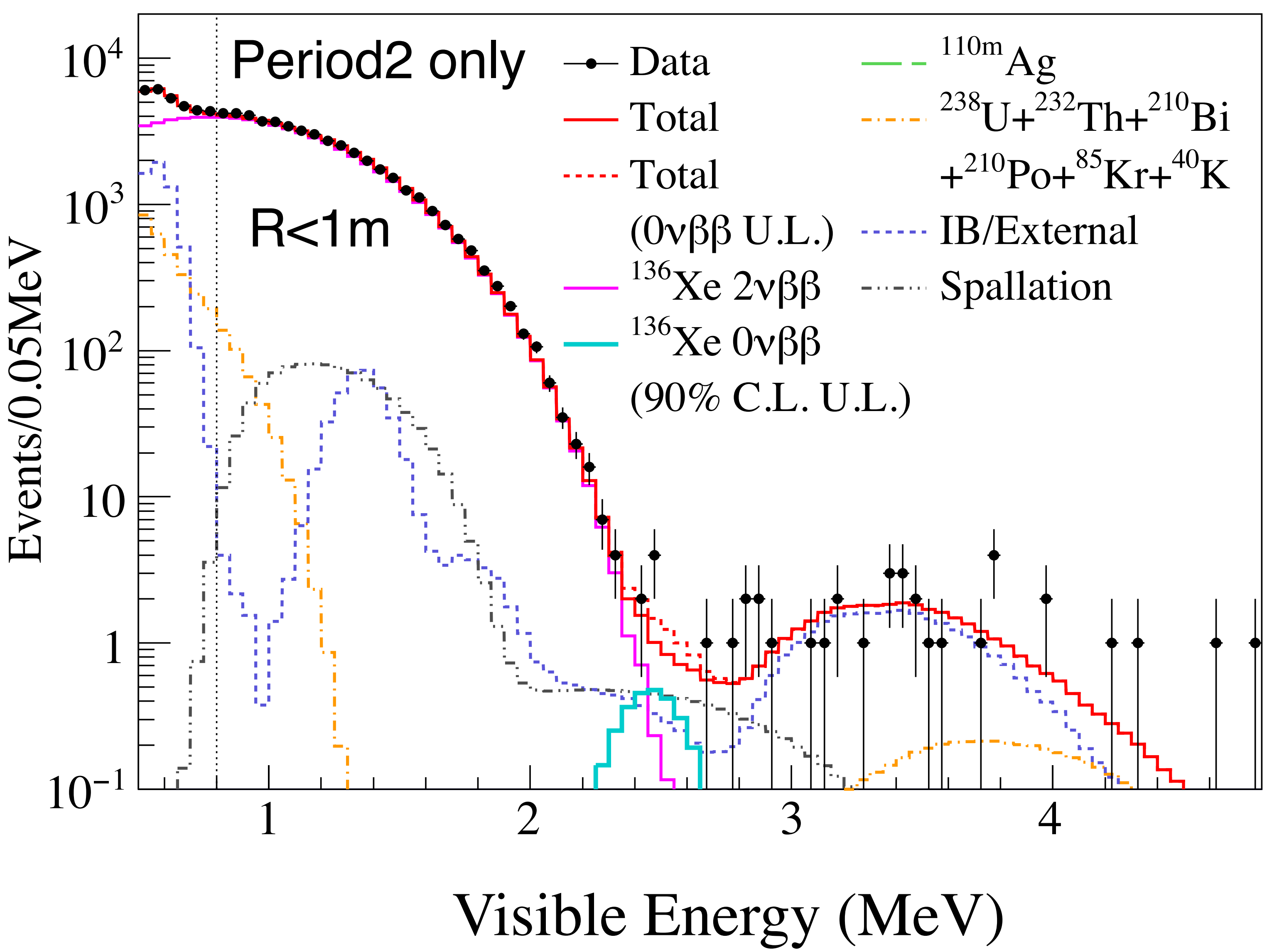






$$\sigma/E = \frac{7.3\ \%}{\sqrt{E}}$$

KamLAND-Zen400 (phase 2)

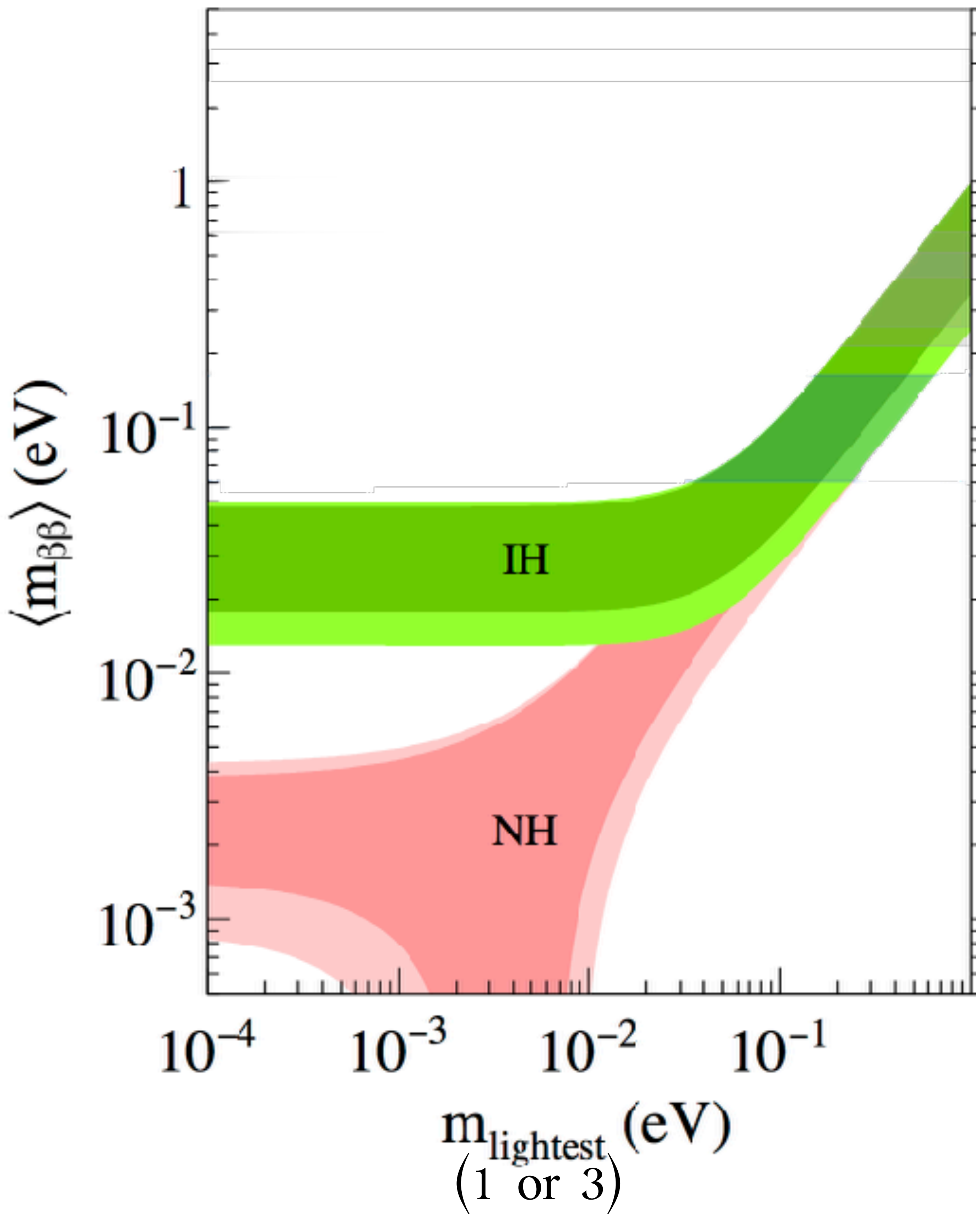


2.3 < E < 2.7 MeV, R < 1m

	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

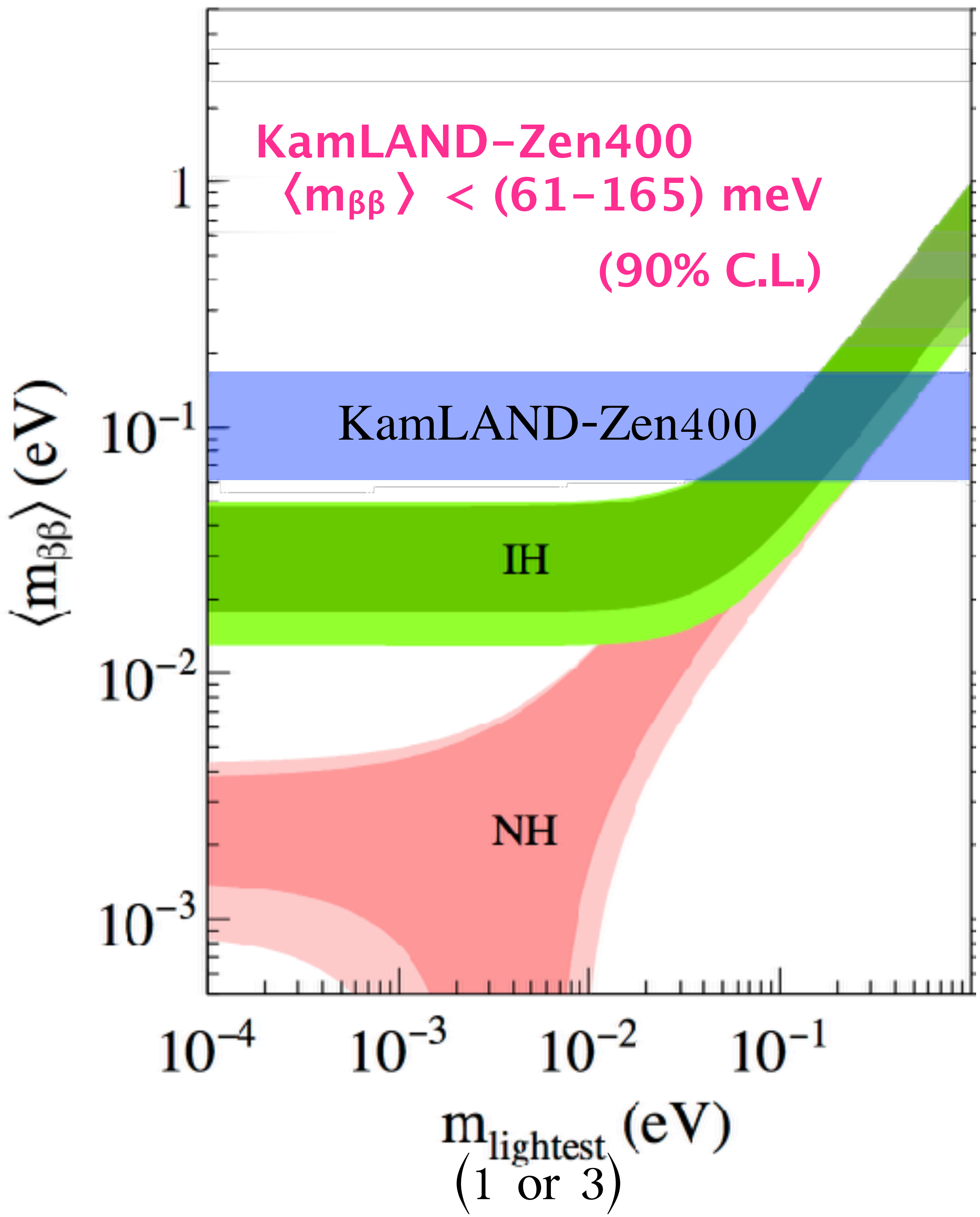
Phase 2:
$T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ years (90% C.L.) ⊗ **Phase 1** → **$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ years (90% C.L.)**

KamLAND-Zen400



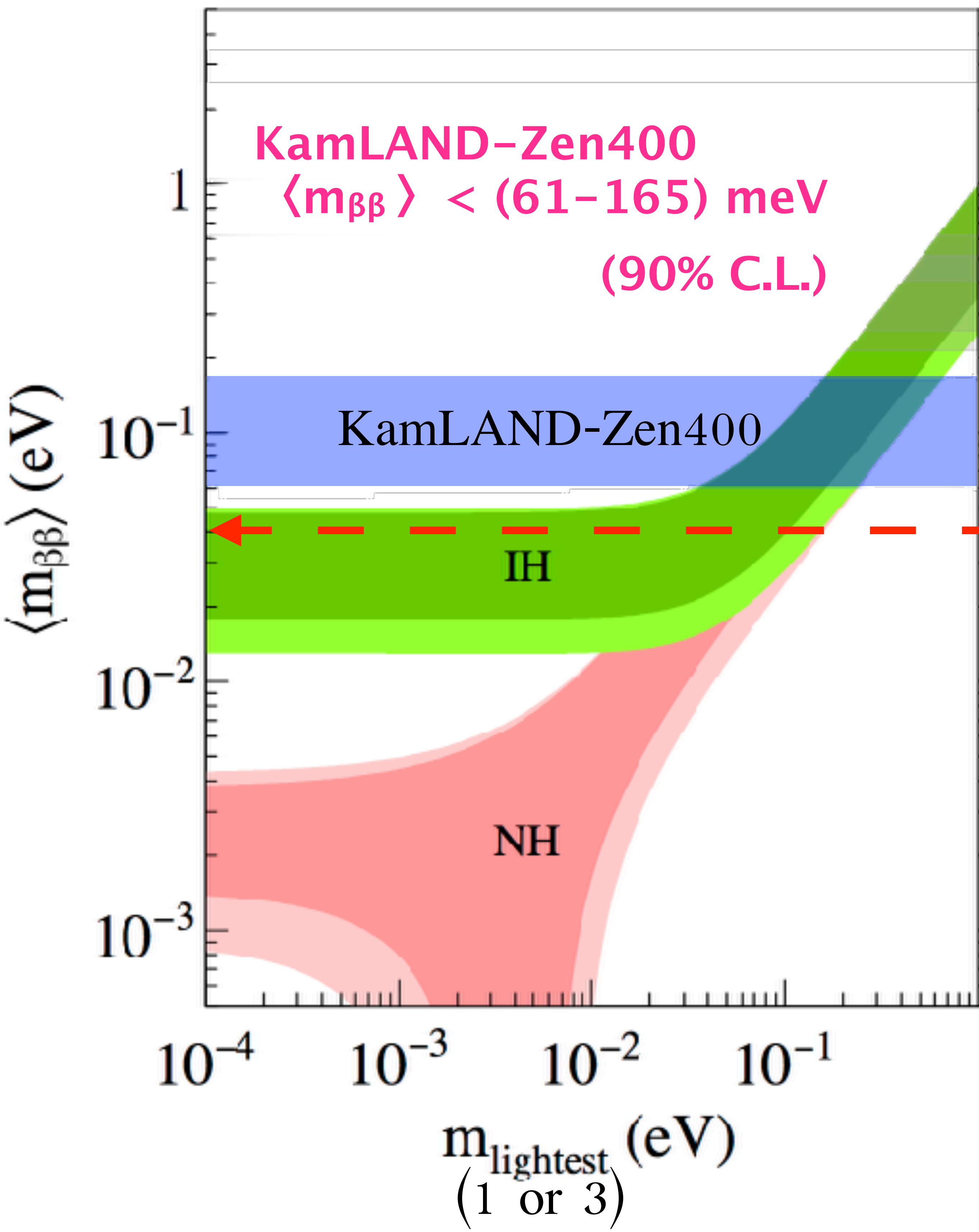
PRL 117, 082503 (2016)

KamLAND-Zen400



PRL 117, 082503 (2016)

KamLAND-Zen800



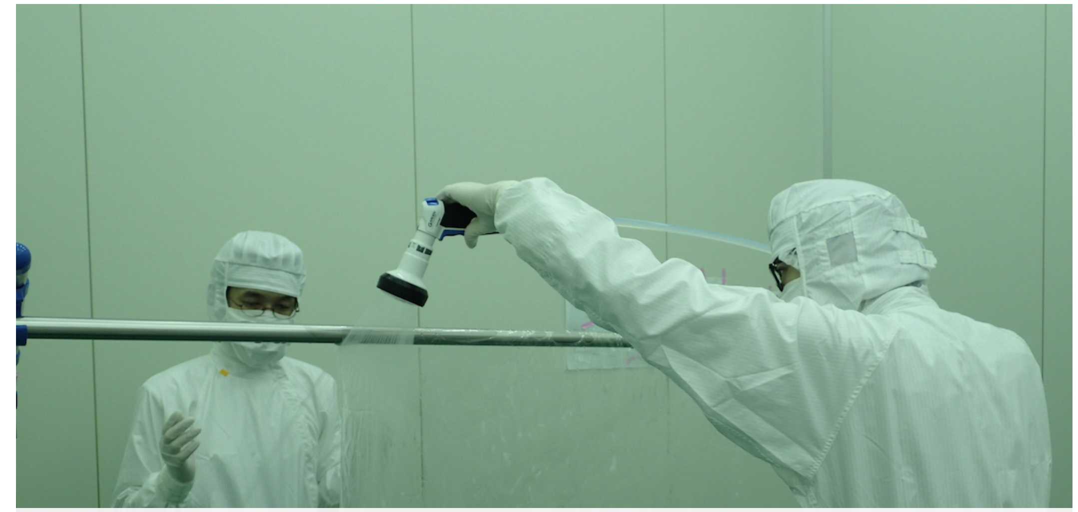
800 kg ^{136}Xe

40 meV

- Upgrade the mini-Balloon
- OD refurbishment

PRL 117, 082503 (2016)

mini-Balloon upgrade



BEFORE

Balloon film washing procedure was human control.

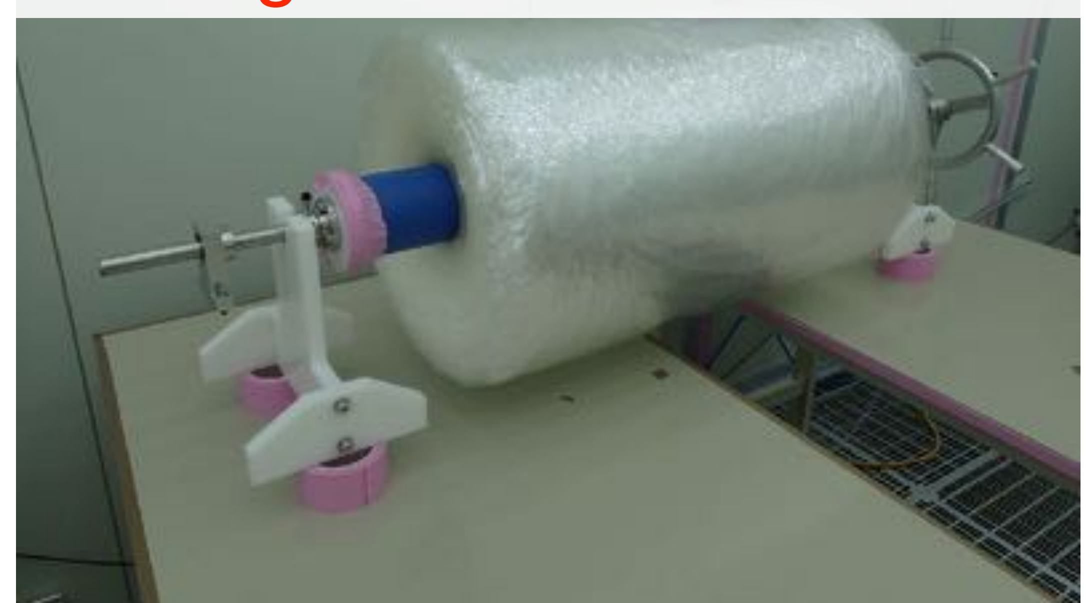
Long exposure in the air can collect dusts by electro statics.

mini-Balloon upgrade

New Procedure

Balloon film washing machine is implemented.

Less exposure reduces dusts attaching to the surface.

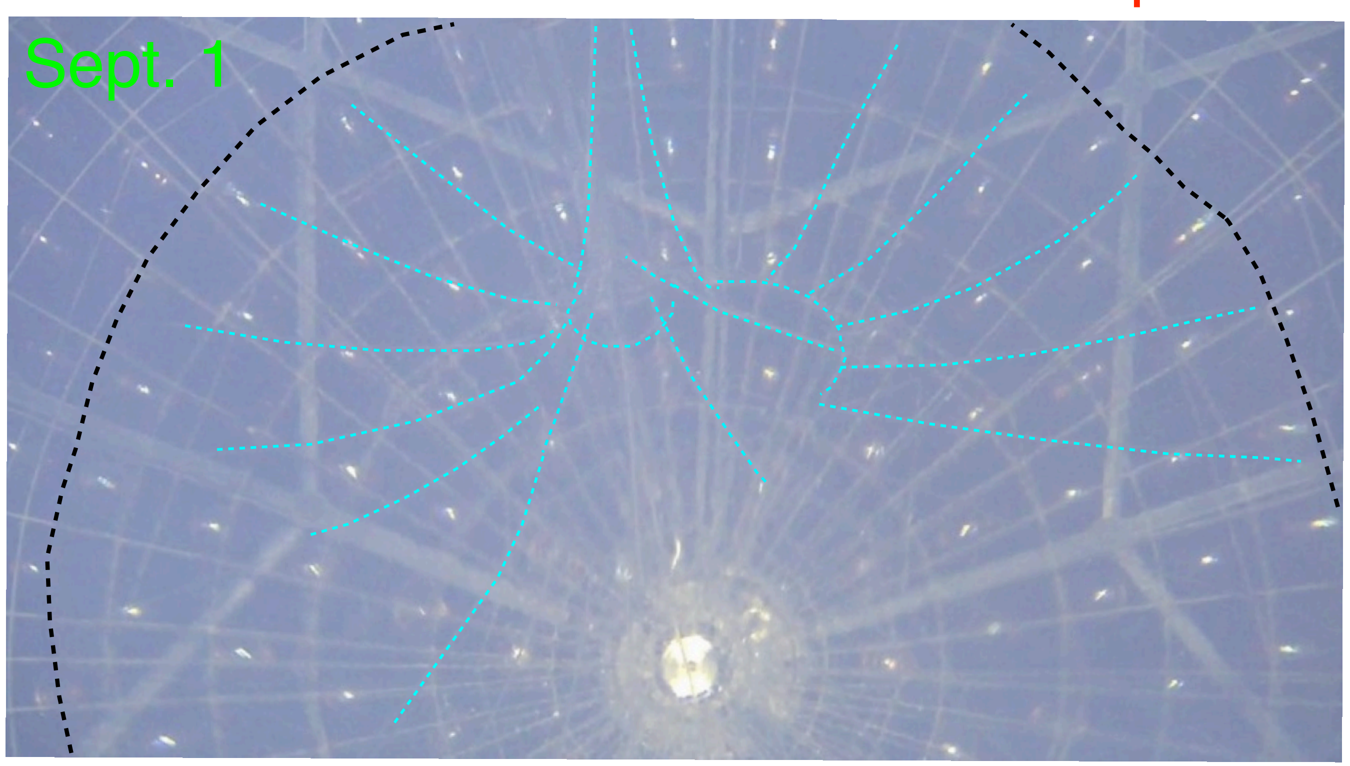


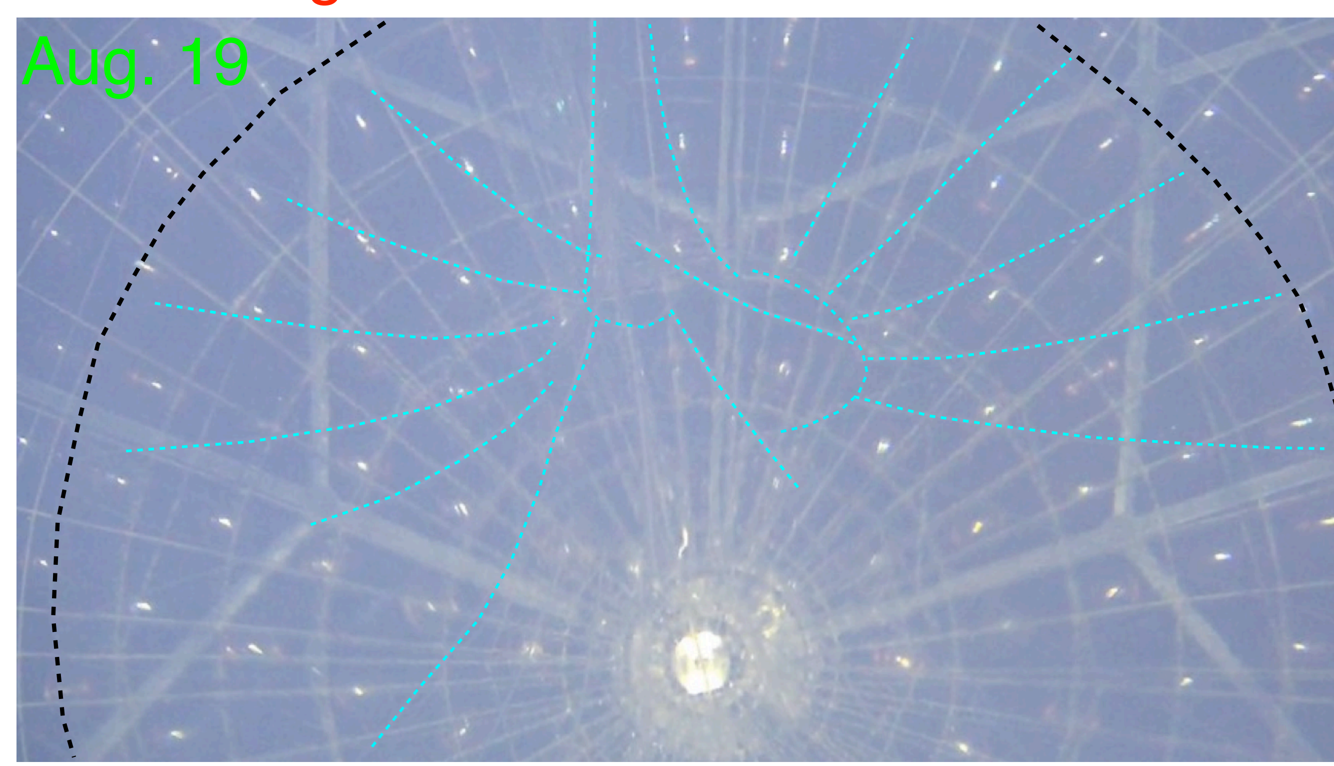
mini-Balloon upgrade in 2016

- mini-Balloon installation with Xe-less LS filling in 2016 summer.
- Leak detected.
  - Camera image analysis
  - Load cell analysis
  - Balloon shape reconstruction with ^{210}Po events
  - mixture of mini-Balloon LS and KamLAND-balloon LS
- mini-Balloon removal in 2016 December.

	^{238}U (10^{-12} g/g)	^{232}Th (10^{-12} g/g)
Zen400	46±4	336±2
New	5.3±0.8	31±7
	No ^{110}Ag, ^{137}Cs, ^{134}Cs	

Example of camera images

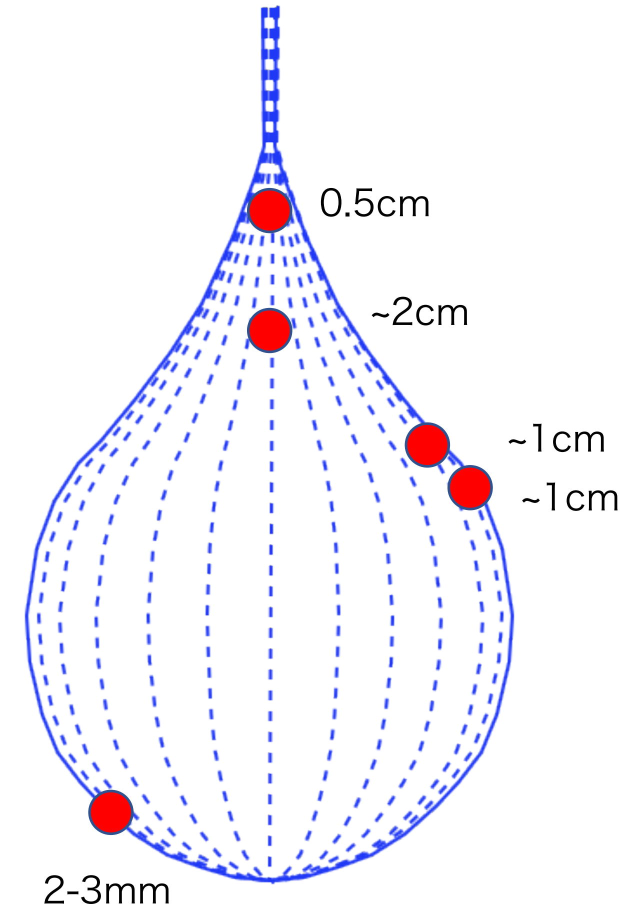


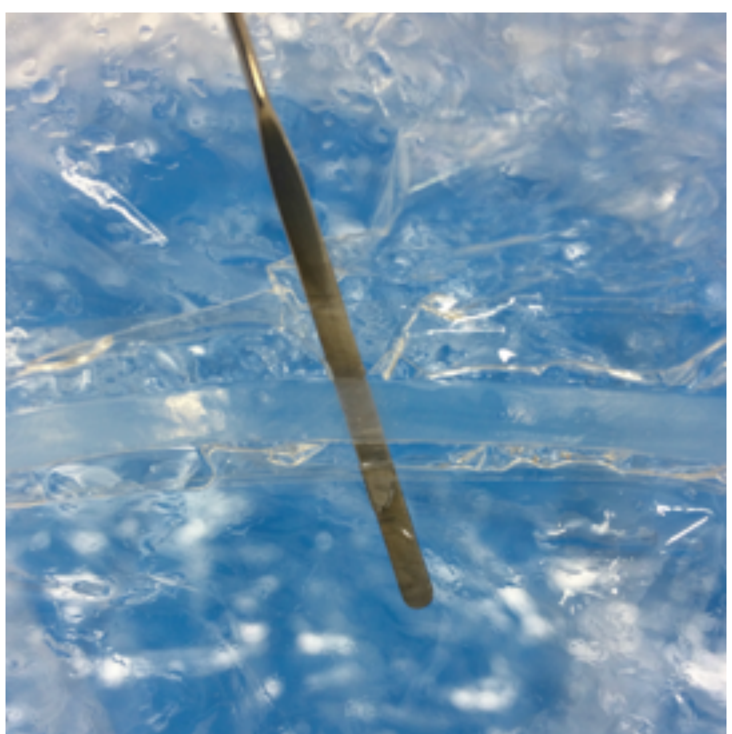


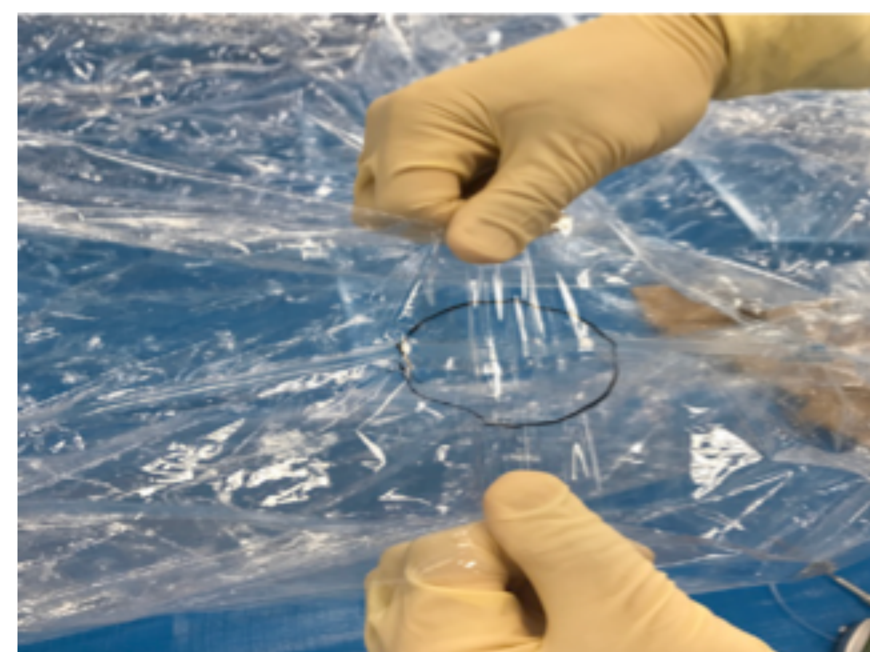
mini-Balloon upgrade in 2016

We learned …

Which part of welding is weak.







Which part of welding is strong.

mini-Balloon upgrade in 2017

We finished mini-balloon welding at Sep. 13, 2017

Current status of KamLAND-Zen800

- ☑ Improved welding technique
- ☑ Improved cutting technique to avoid shape distortion
- ☑ Finish manufacturing and cleaning sub-components
- ☑ Leak check, Leak repair
- ☐ Folding and packing
- ☐ Delivery to KamLAND site
- ☐ New LS purification (half done)
- ☐ Installing the miniBalloon filled with Xe-less LS
- ☐ Replacing the Xe-less LS with Xe-loaded LS

We finished mini-balloon welding at Sep. 13, 2017

Beyond KamLAND-Zen800

KamLAND2 ← Better energy resolution

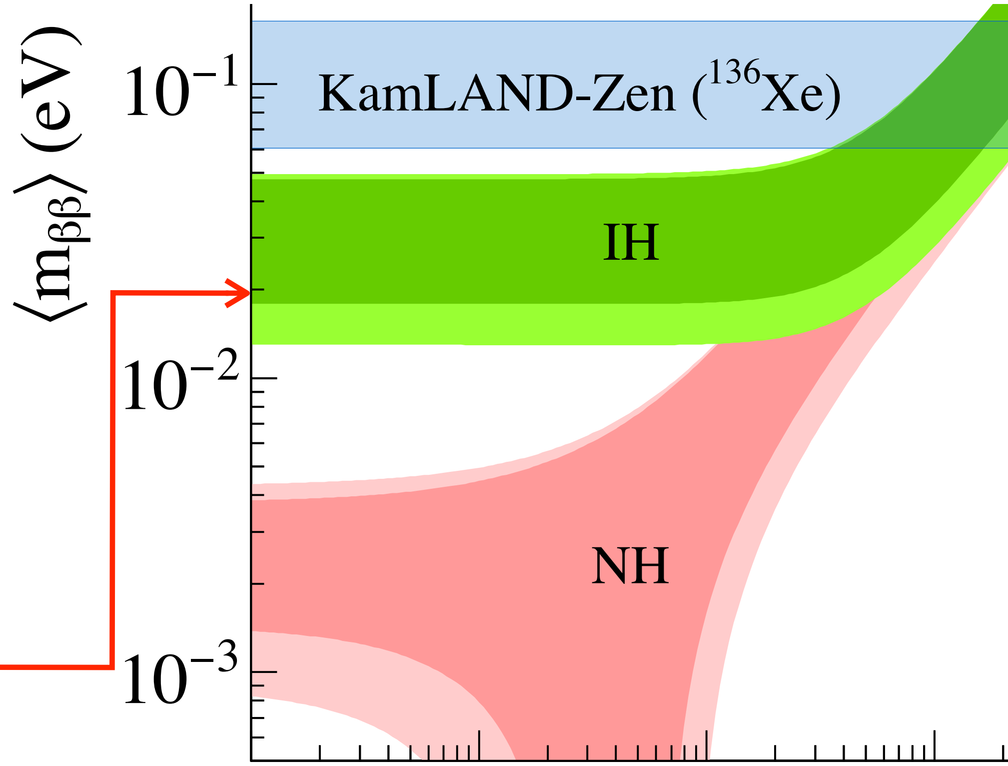
- Winston cone : light collection × 1.8 **Prototype**
- High Q.E. (~30%) and large photo cathode (20”) PMT: light collection × 1.8 **Prototype**
- More transparent LS (LAB): light collection × 1.4

→ σ = 2 % @E=2.6MeV (c.f. 4 % at KamLAND)

KamLAND2-Zen

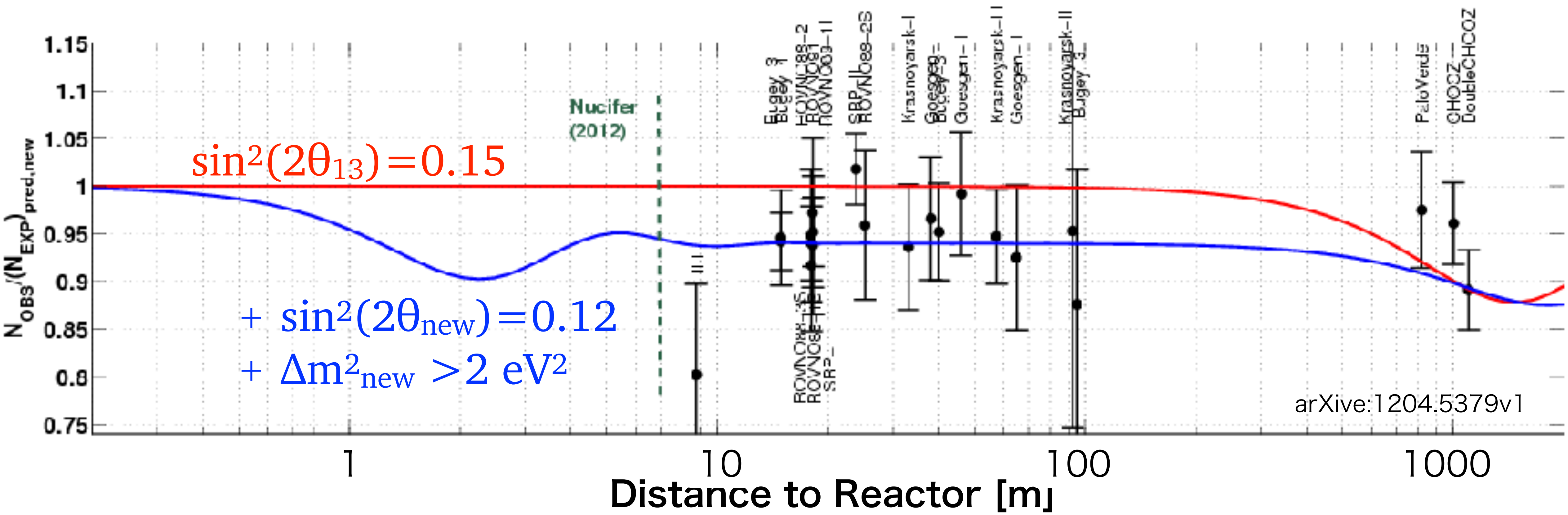
- Scintillation film for the mini-Balloon (^{214}Bi-^{210}Po)
- Imaging (β/γ discrimination)

→ 20 meV (cover Inverted hierarchy)

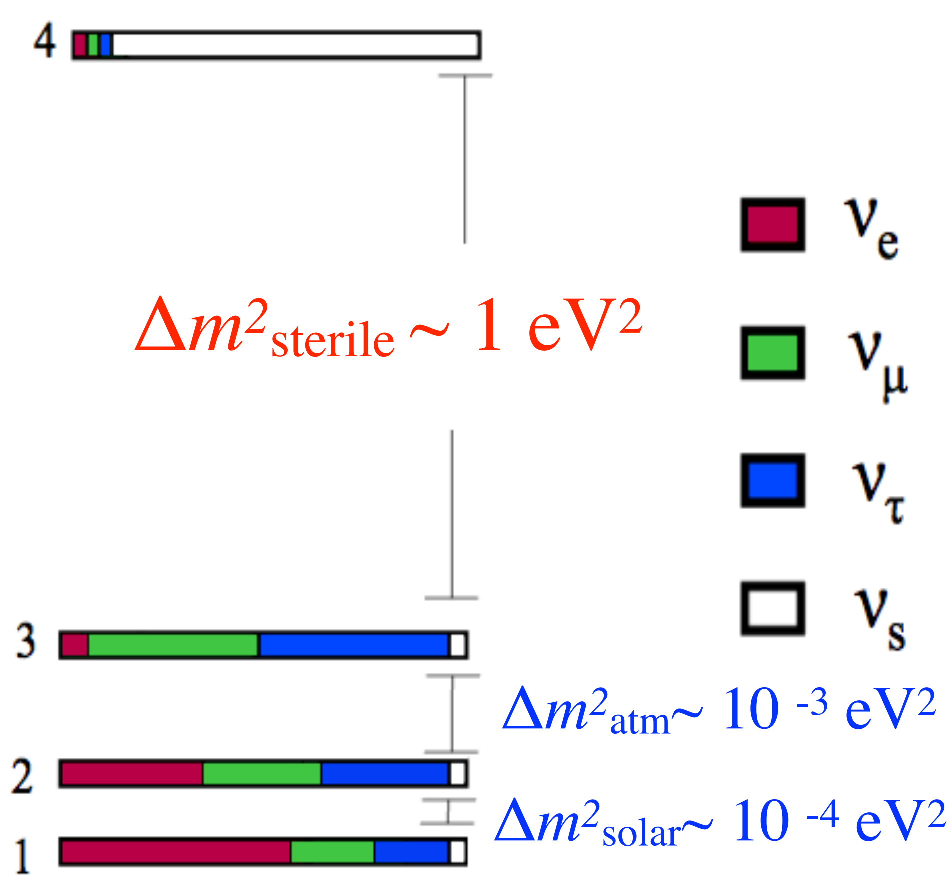


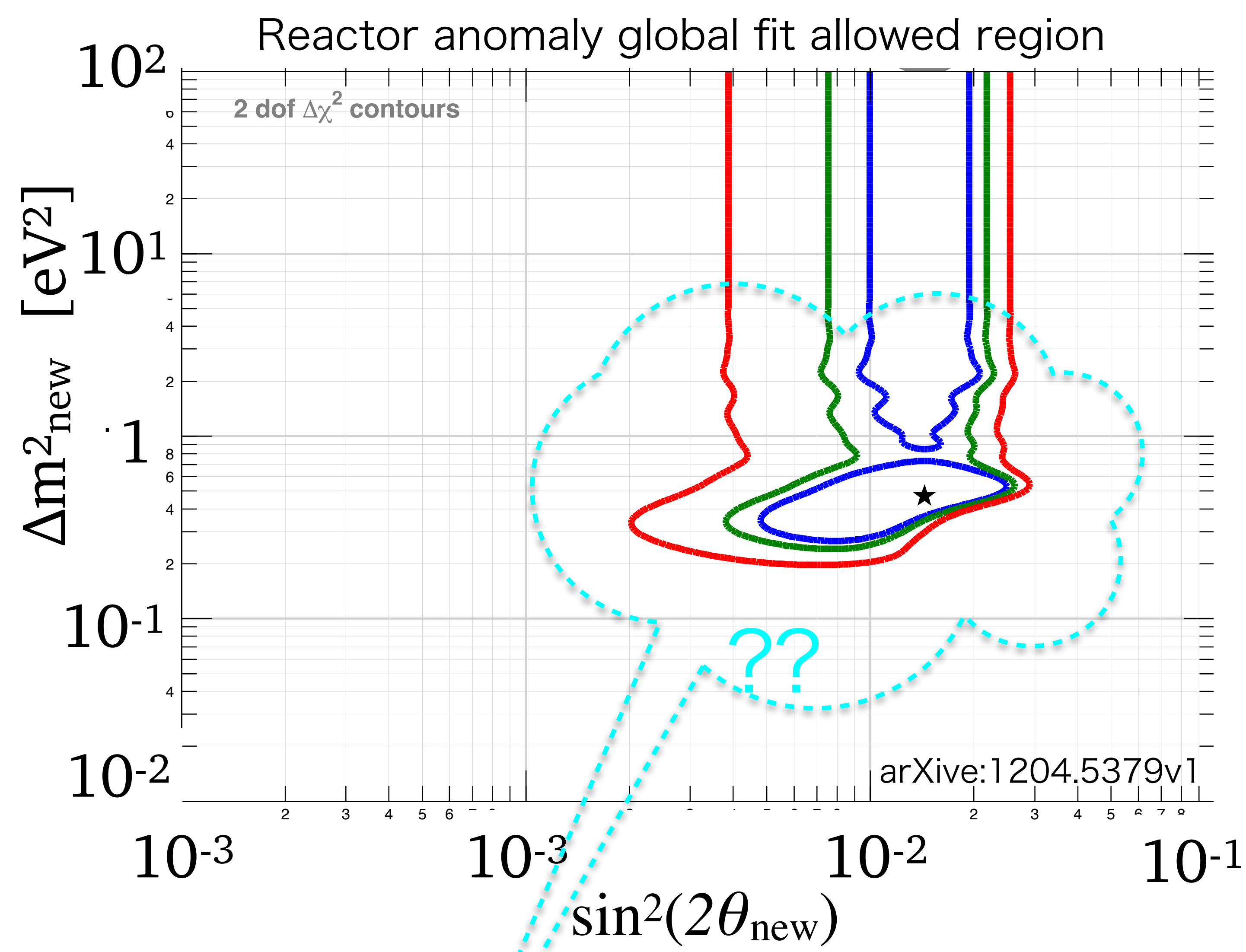
Future plan

Reactor neutrino oscillation anomaly



IsoDAR@KamLAND



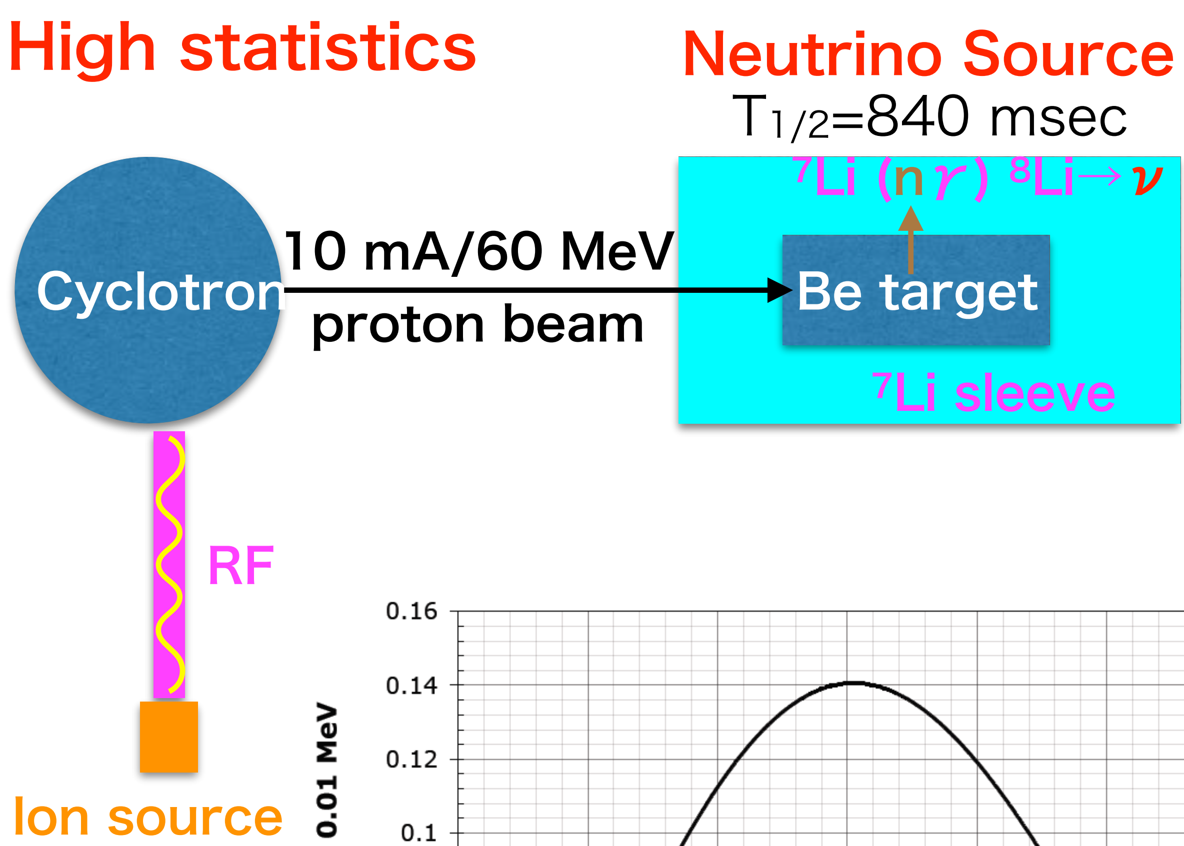


IsoDAR@KamLAND

a new definitive experiment to search ν_s

with more than 5 σ level (high statistics)

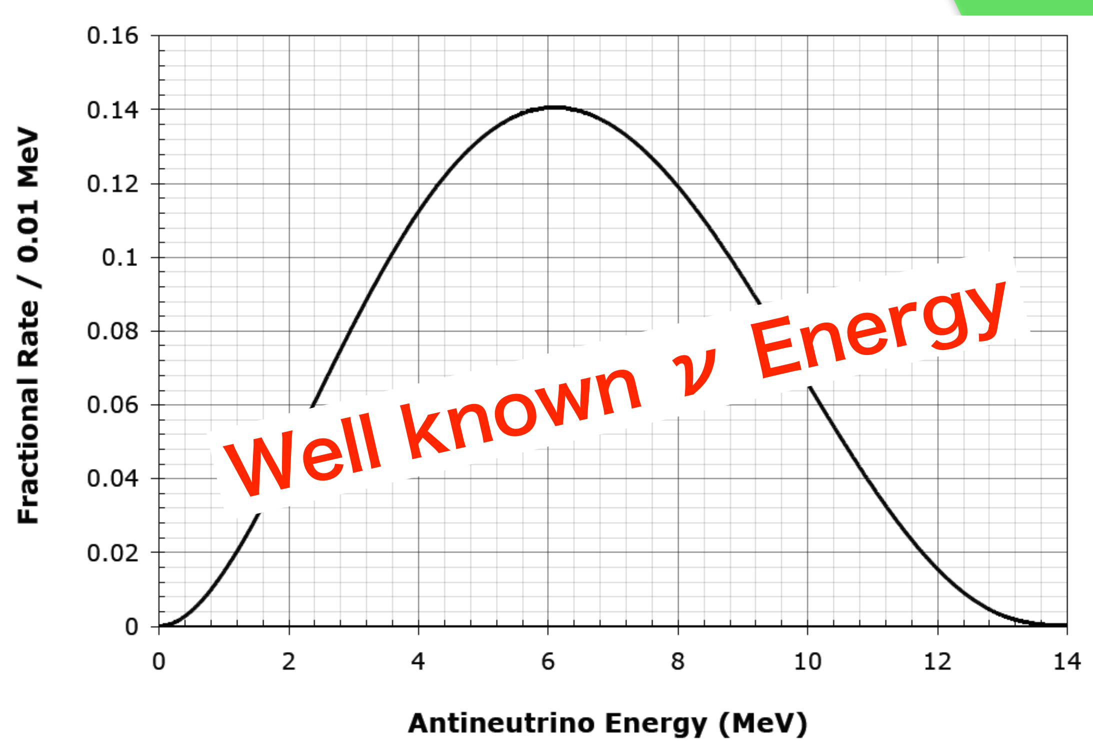
IsoDAR@KamLAND



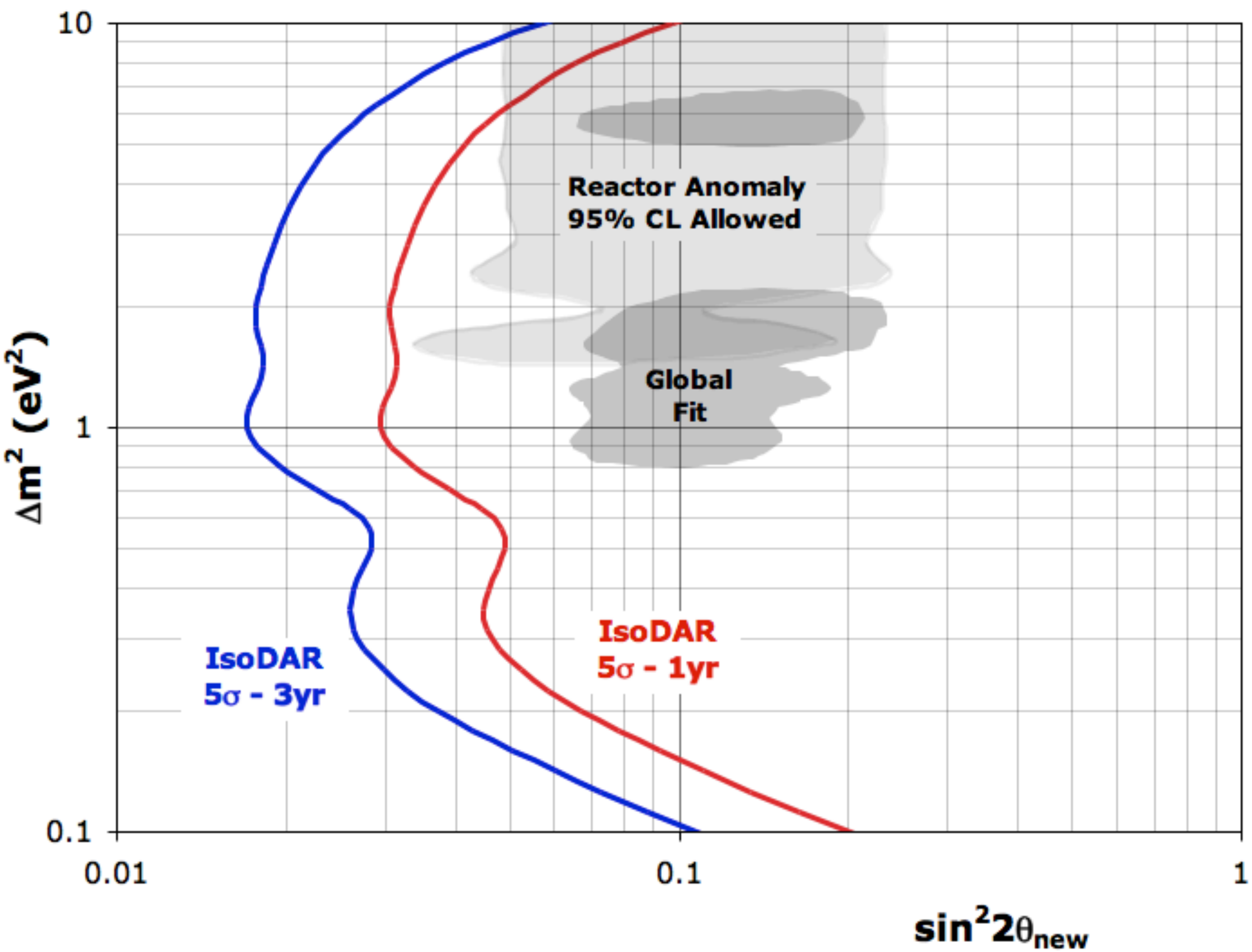
KamLAND

1 kton Liquid scintillator
Reactor neutrino oscillation
Geo-neutrinos
ν-less double beta decay
$\Delta E \sim 7\ \%/\sqrt{E(\mathrm{MeV})}$
$\Delta \mathrm{vertex} \sim 13\ \mathrm{cm}/\sqrt{E(\mathrm{MeV})}$

Neutrino Oscillation
($\bar{\nu}_e$ disappearance)

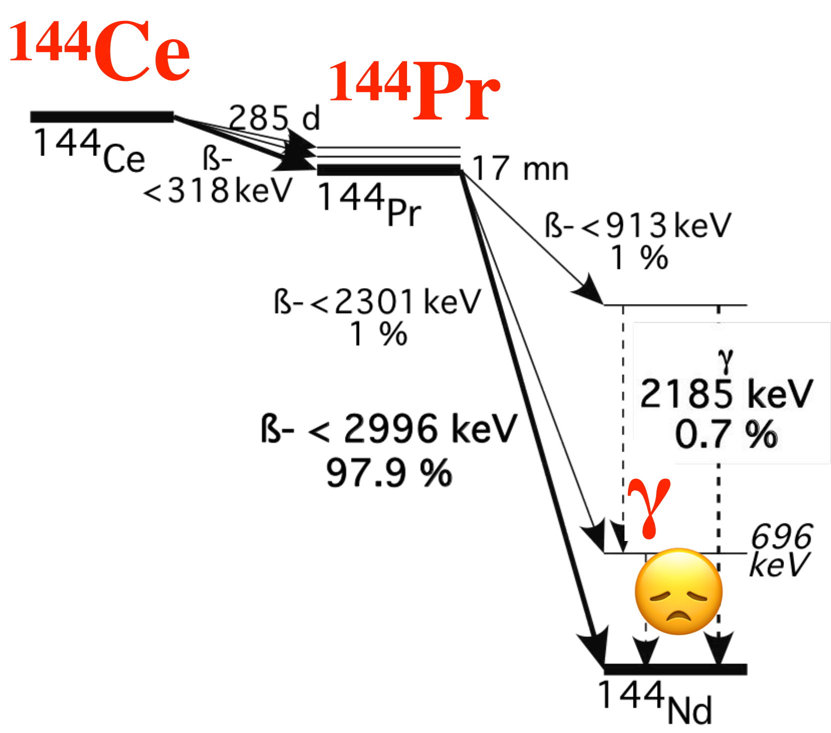


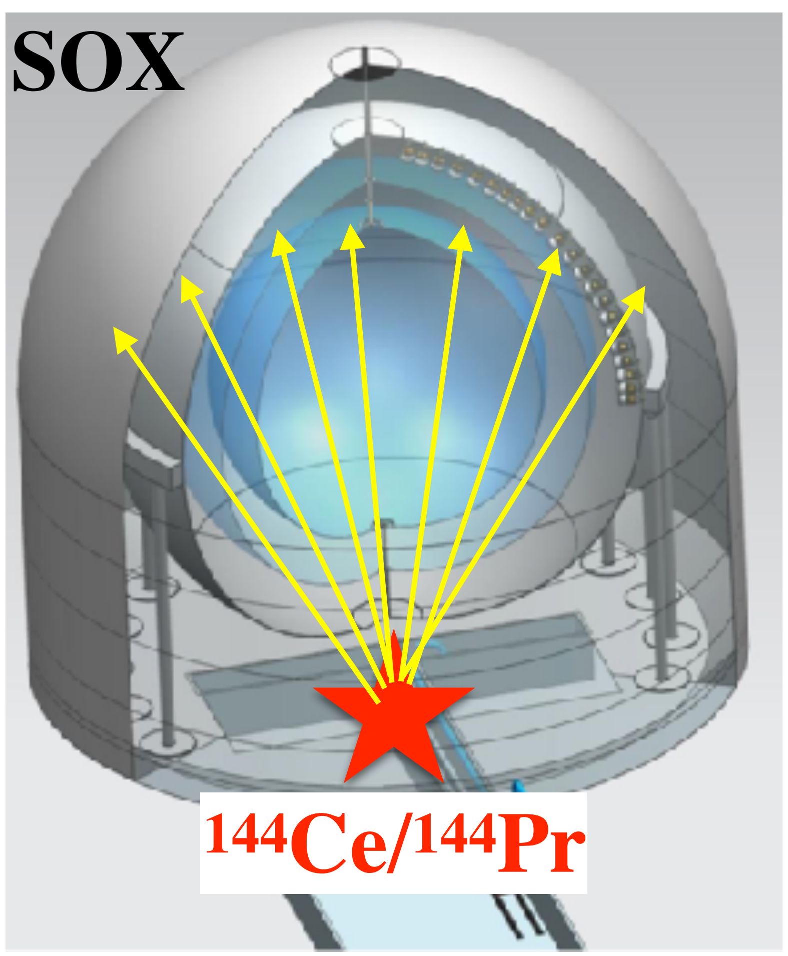
IsoDAR $\bar{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)



⇒ Global fit region can be ruled out at > 5σ in 4 months of running!

IsoDAR@KamLAND





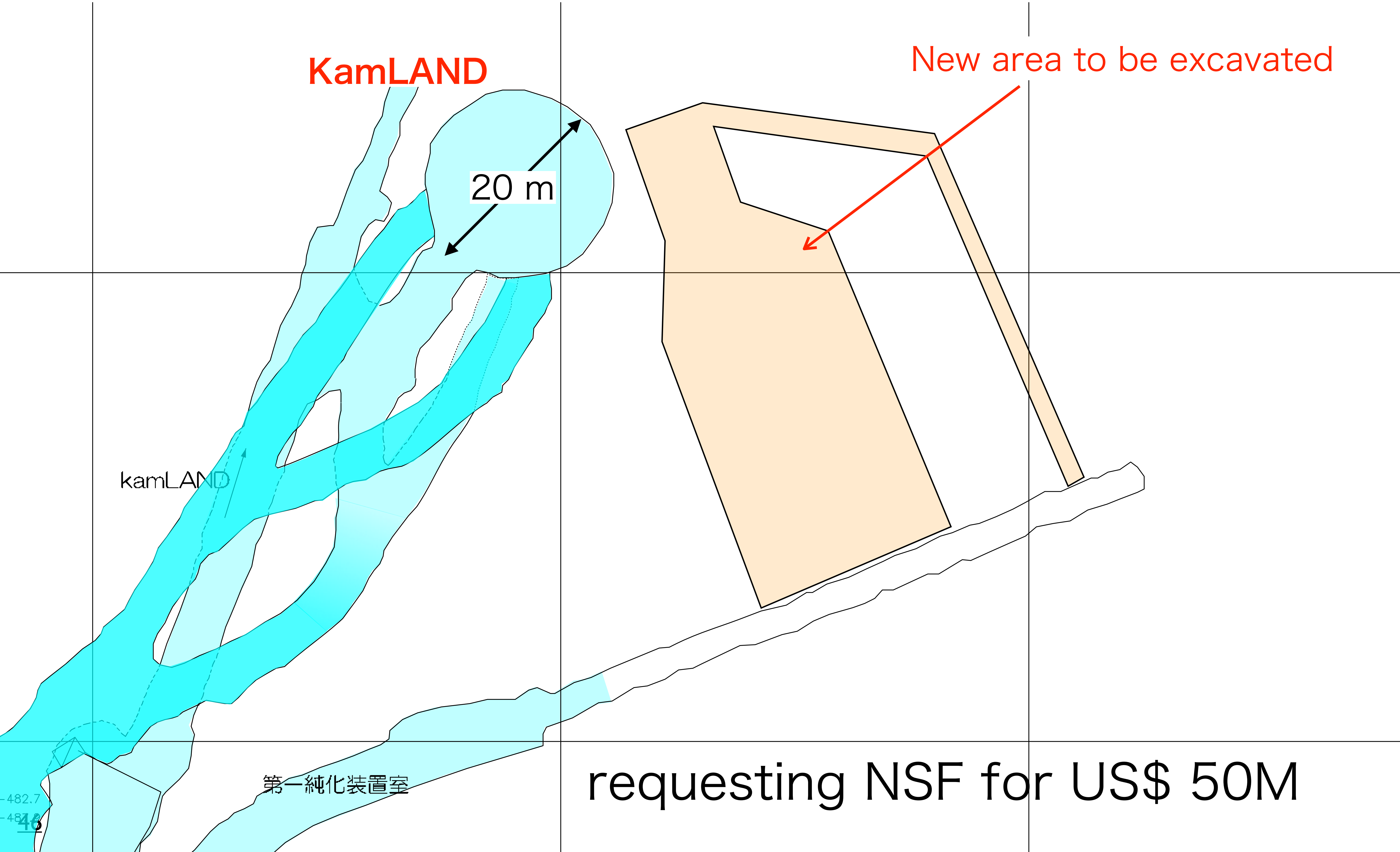
http://nuclphys.sinp.msu.ru/conf/epp10/Machulin.pdf

Comparison to other projects (an example)

	SOX*	IsoDAR
Source	^{144}Ce	^{8}Li
Strength	100 kCi	50 kCi
"Half-life"	285 days	Infinite
Peak energy of events	3.4 MeV	8.5 MeV
Detector	Borexino	KamLAND
Detection	IBD	IBD
Type	Liquid scint	Liquid scint
Fiducial volume	100 tons	900 tons
Length to ν Source	8.5 ± 4 m	16 ± 6.5 m
Total IBD events	$\sim 10^4$	$\sim 8 \times 10^5$
Osc Fit Method	Rate plus Shape	Shape only

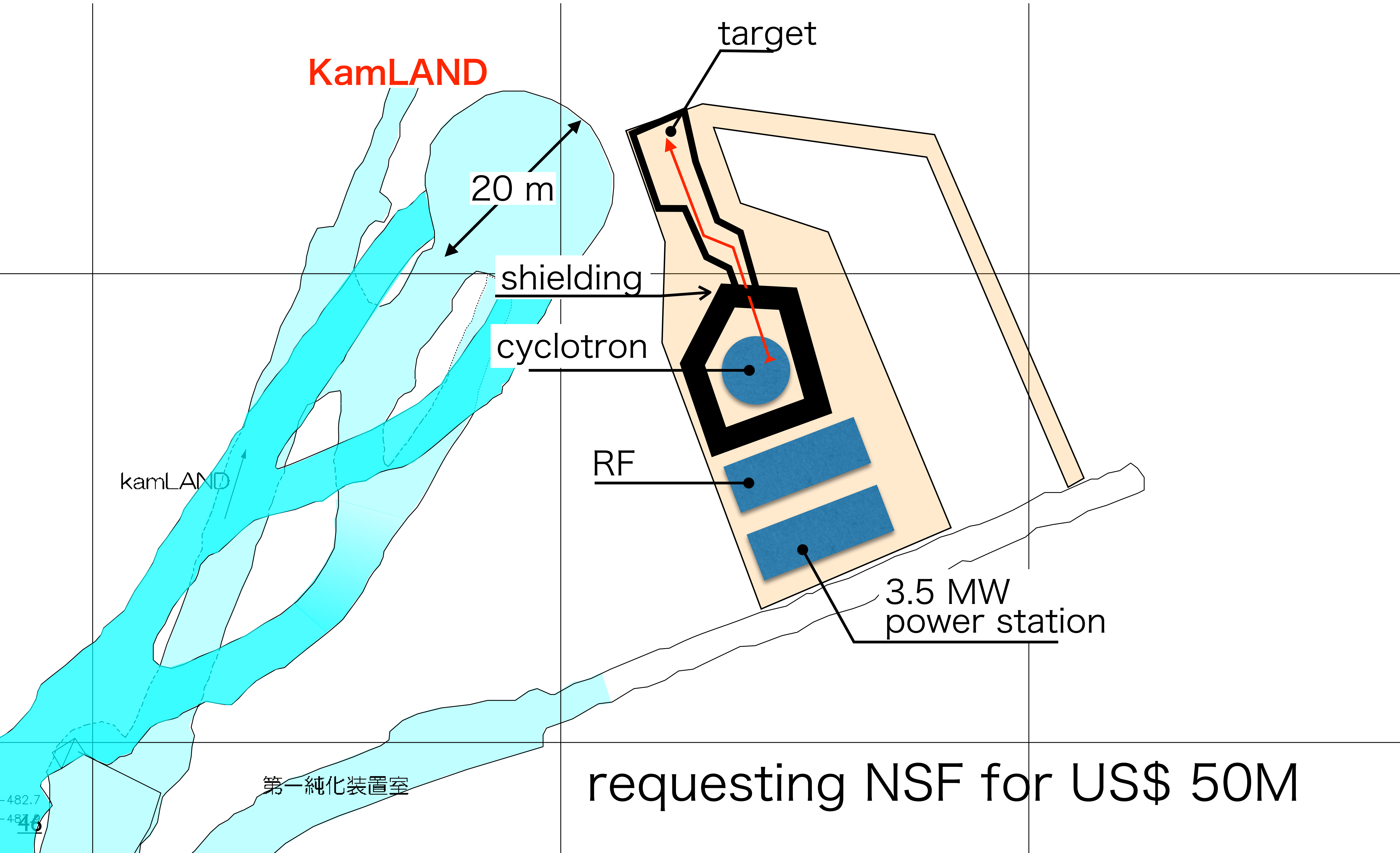
* M. Wurm, https://www.mpi-hd.mpg.de/WIN2015/talks/neutrino3_wurm.pdf

IsoDAR@KamLAND



requesting NSF for US$ 50M

IsoDAR@KamLAND



requesting NSF for US$ 50M

End of the talk

Physics programs

- Neutrino oscillation of anti-neutrinos from nuclear reactors
- Geo-neutrino measurement
- ^{136}Xe 0νββ
    - KamLAND-Zen400 (completed)
        - $T(^{136}Xe\ 0\nu\beta\beta)_{1/2} > 1.07\times10^{26}$ years @90 % C.L.
        - $m_{\beta\beta} < (61\text{-}165)$ meV @90 % C.L.
    - KamLAND-Zen800 (coming soon)
        - The first 800 balloon failed but the second one has been constructed with a lot of improvements.

Future Plans

- IsoDAR@KamLAND

KamLAND-Zen Collaboration

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