The KamLAND-Zen Double Beta Decay Experiment with ^{136}Xe

Research Progress Meetings at LBNL

Sep. 9, 2014

Itaru Shimizu (Tohoku Univ.)

Majorana Neutrino Mass

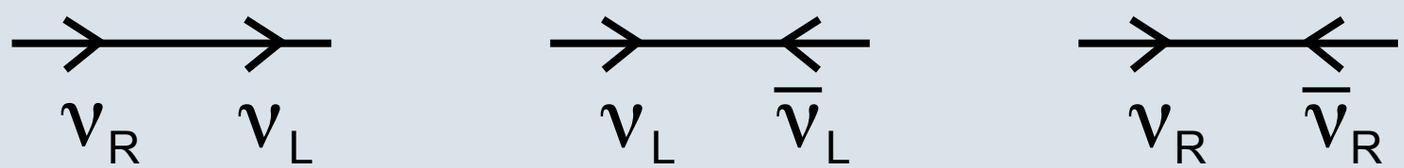
Neutrino oscillation $\longrightarrow$ finite small masses and mixing

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle \qquad (\alpha = e, \mu, \tau) \qquad m_i > 0$$

Possible mass terms

neutrino has no electric charge

$$L_{mass} = \overline{\psi_R} m_D \psi_L + \frac{1}{2}\overline{(\psi_L)^C} m_L \psi_L + \frac{1}{2}\overline{\psi_R} m_R (\psi_R)^C$$



$\Delta L = 0$ $\qquad$ $\Delta L = 2$ $\qquad$ $\Delta L = 2$

lepton number violation

Majorana particle $\nu = \bar{\nu}$

- Heavy neutrino (just below GUT scale) naturally explains
  "finite but light neutrino mass" $\quad m \sim \frac{m_D^2}{M_R}$ (Seesaw mechanism)
- CP violating decay of heavy neutrino explains
  "matter dominance in the universe" (Leptogenesis theory)

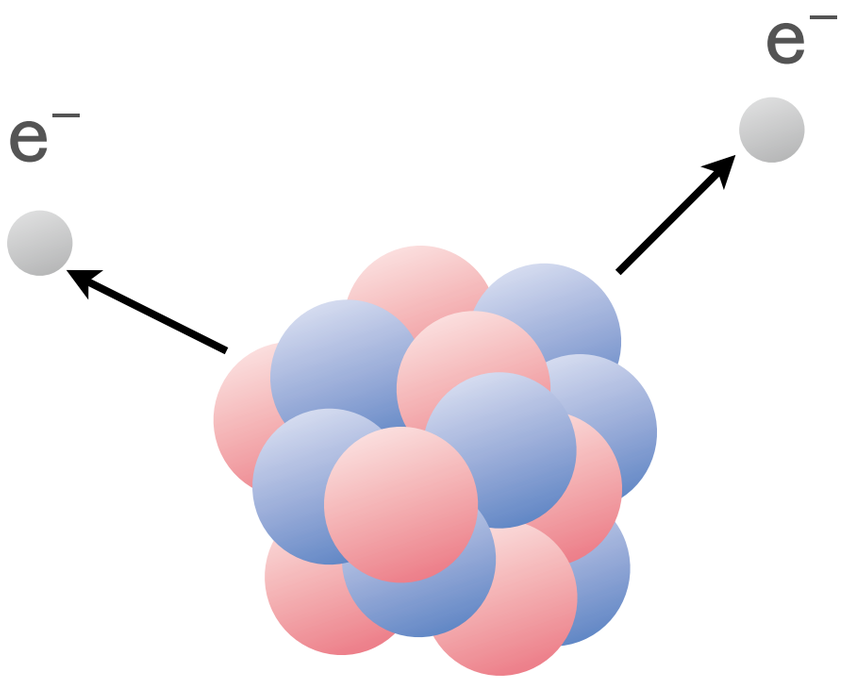
Neutrinoless Double-Beta Decay

Nucleus ββ-decay emitting two electrons

$$(Z, A) \rightarrow (Z + 2, A) + 2e^-$$

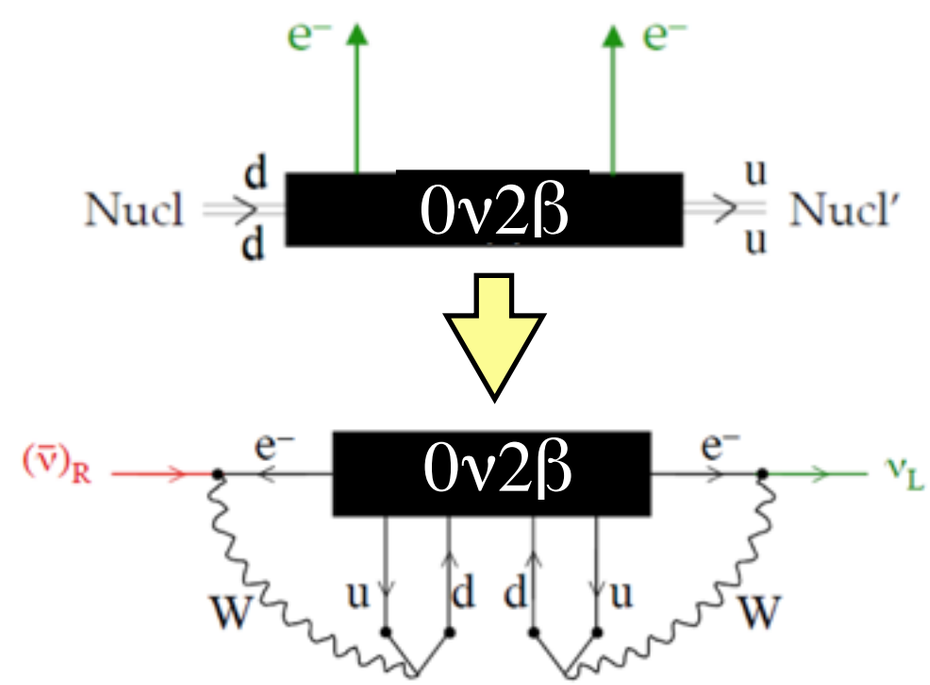
ΔL = 2

lepton number violation



0νββ

Schechter Valle theorem

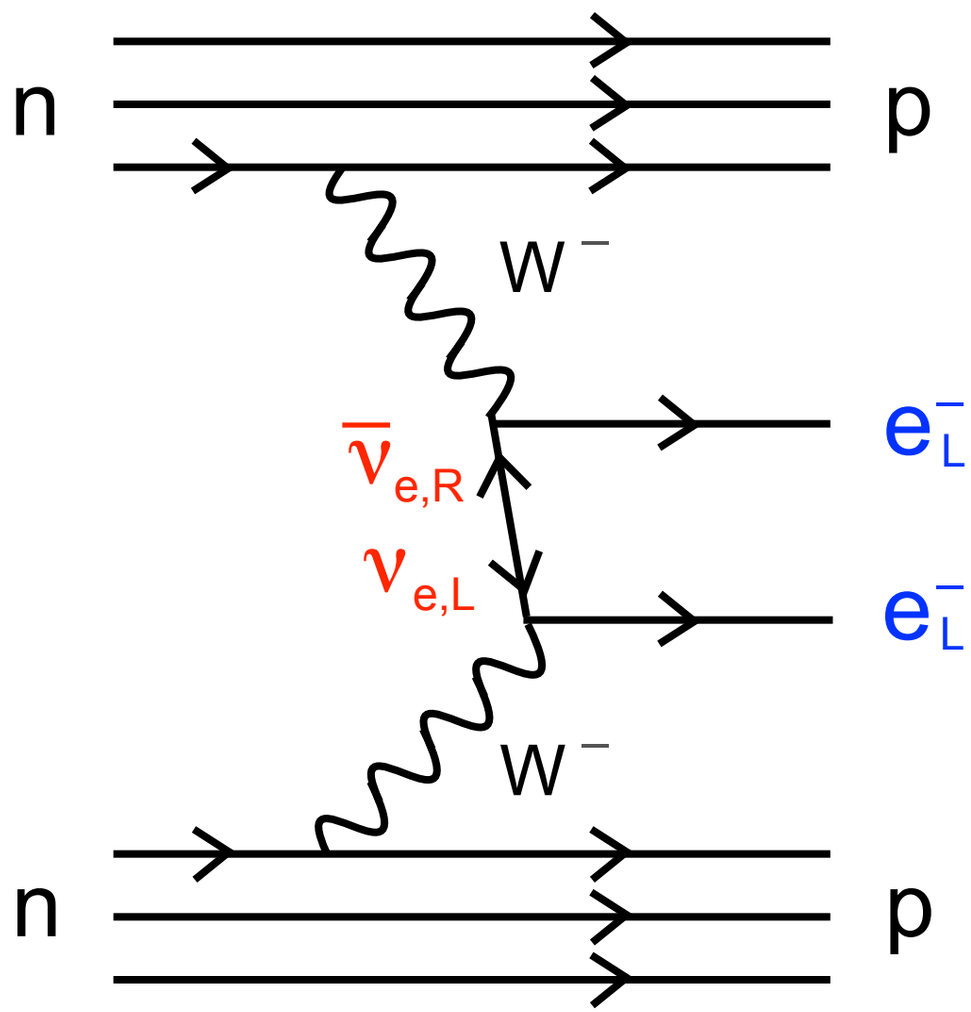


⟶ establish the neutrino Majorana nature

0νββ ⟺ Majorana ν

Light Majorana Neutrino Exchange

mass mechanism



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

effective neutrino mass

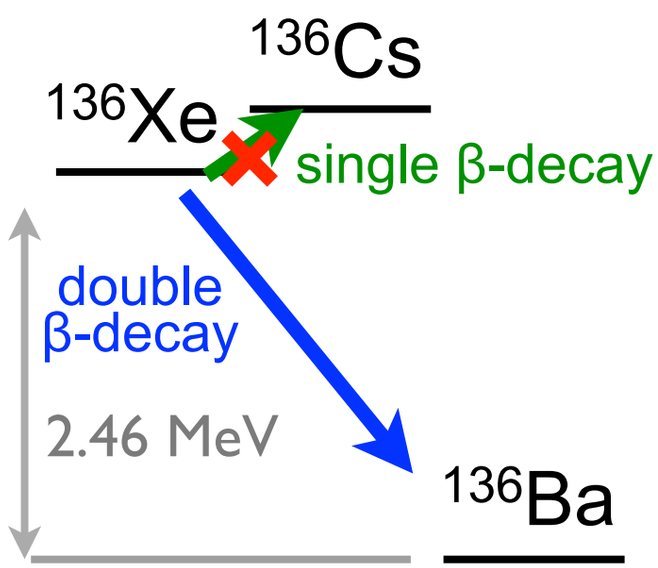
Possible contributions also from
Majoron, SUSY, right-handed current, ...

Effective neutrino mass <$m_{\beta\beta}$>

$$\langle m_{\beta\beta} \rangle = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_1} m_2 + |U_{e3}|^2 e^{i\alpha_1} m_3 \right|$$

- Unknown parameters : α_1, α_2, m_{min}
- Mass hierarchy is not determined
- Cancellations due to CP phases (α_1, α_2)

How to measure <$m_{\beta\beta}$>?



determine the decay rate using
large number of ββ-decay nuclei

Neutrino Mass Sensitivity

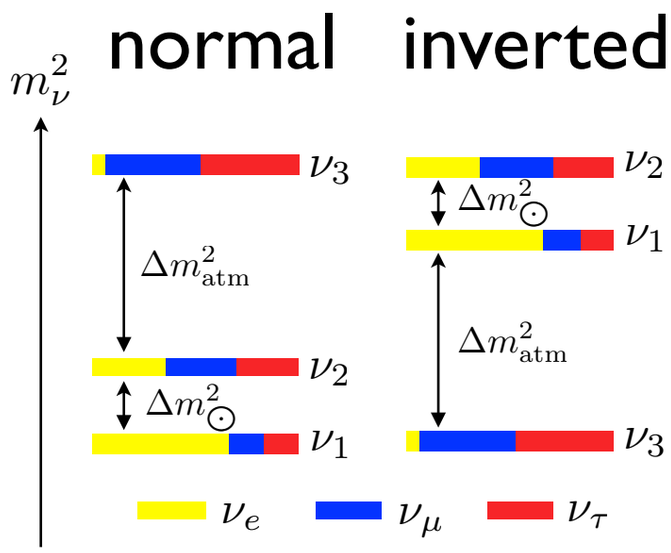
Decay rate → proportional to (neutrino mass)^2

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

phase space factor

nuclear matrix element
(nuclear physics)

effective neutrino mass
(particle physics)

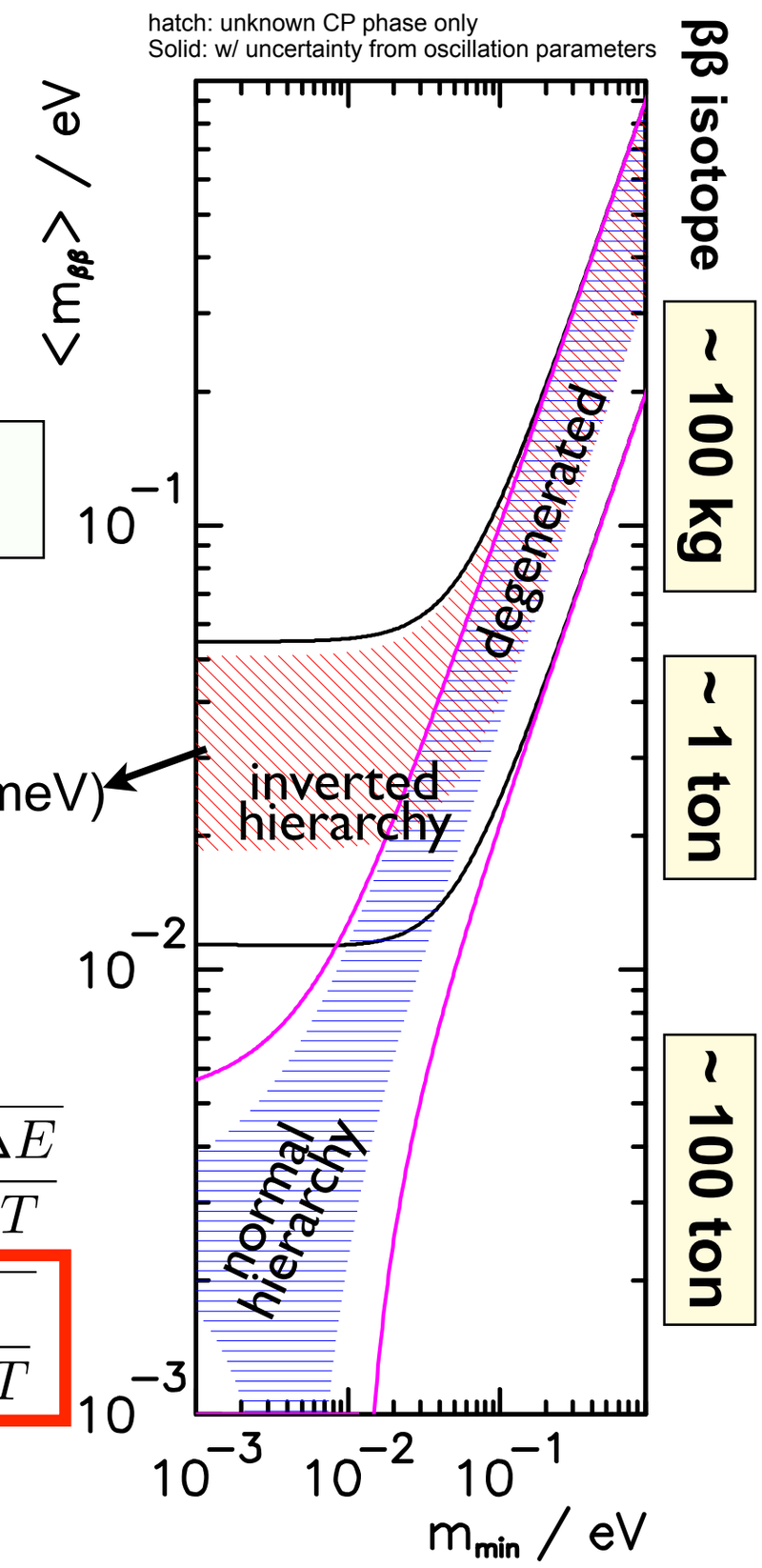


$$\langle m_{\beta\beta}\rangle \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

inverted hierarchy search (17-50 meV)

↓

ββ isotope ~ 1 ton



Experimental sensitivity (90% C.L.)

w/ BG

$B \neq 0$ $\quad T_{1/2} > \frac{\ln 2}{1.64}\frac{N_A \cdot a \cdot \epsilon}{A}\sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$ $\quad \langle m_{\beta\beta}\rangle < \sim \sqrt[4]{\frac{B \cdot \Delta E}{M \cdot T}}$

w/o BG

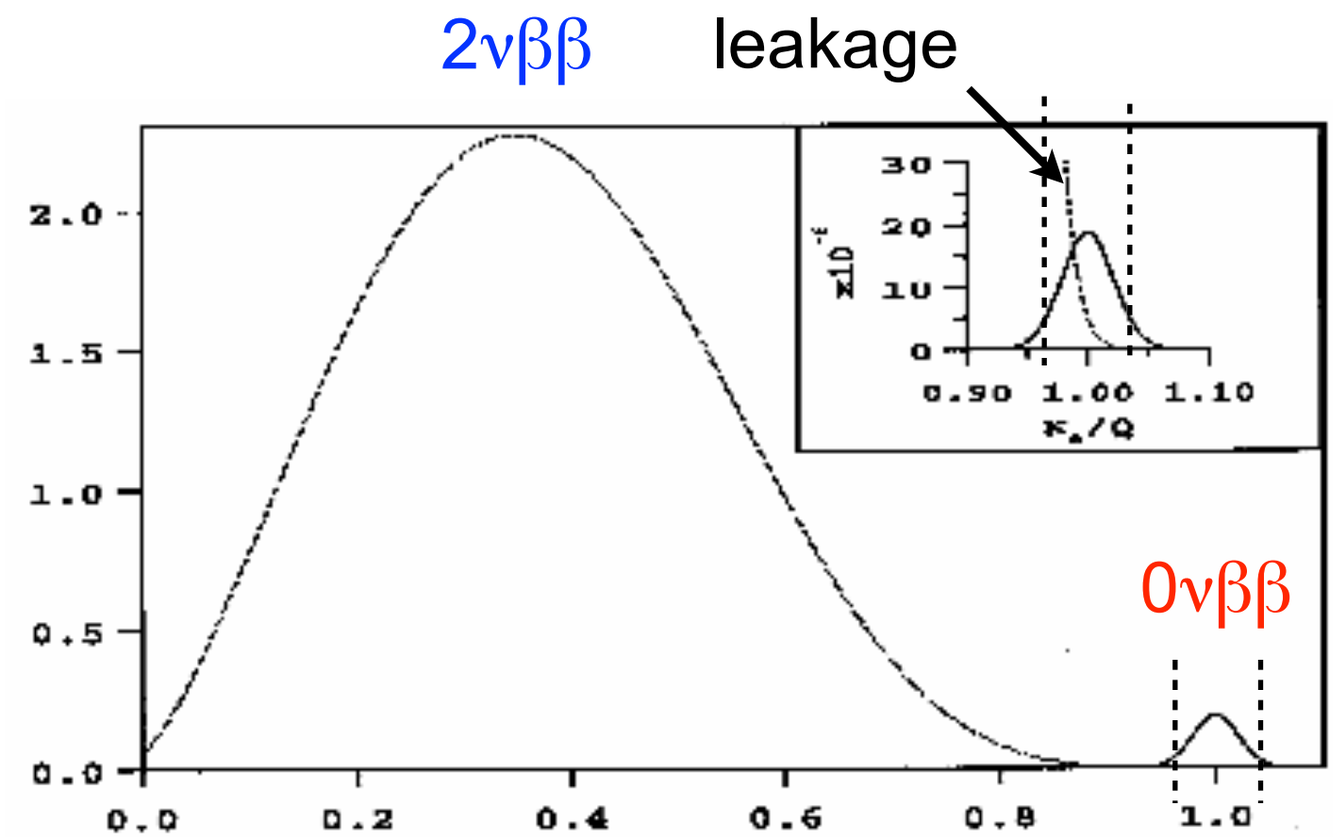
$B = 0$ $\quad T_{1/2} > \frac{\ln 2}{2.3}\frac{N_A \cdot a \cdot \epsilon}{A} M \cdot T$ $\quad \langle m_{\beta\beta}\rangle < \sim \sqrt{\frac{1}{M \cdot T}}$

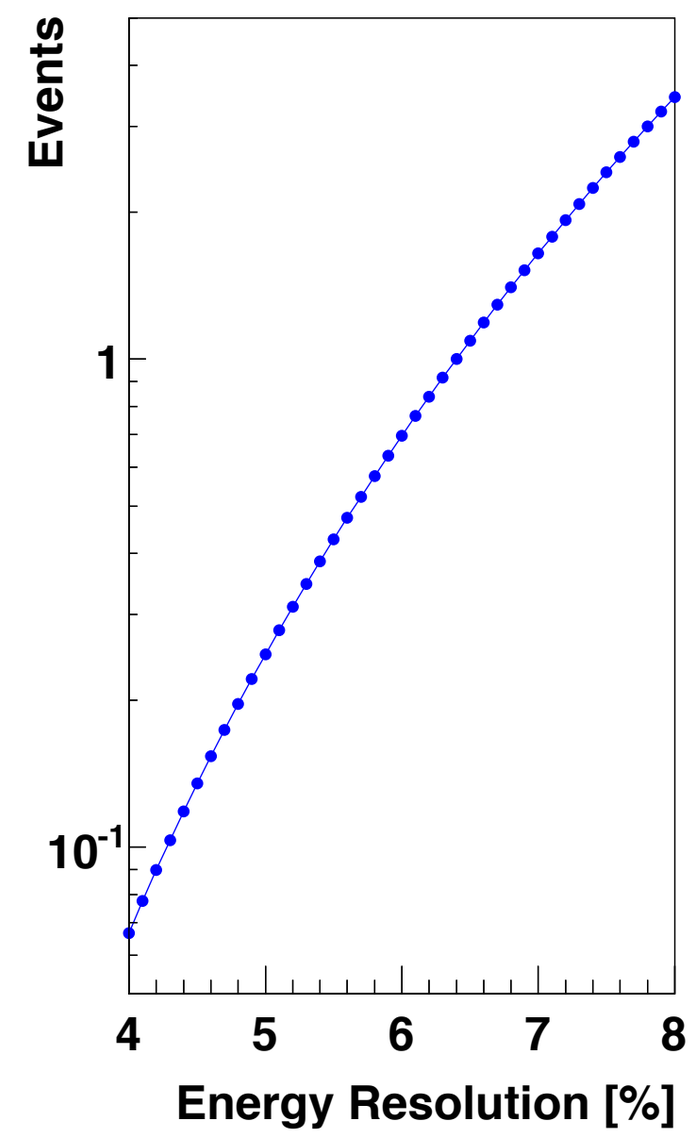
N_A = Avogadro constant
a = fraction of ββ isotope
ϵ = detection efficiency
A = mass number
M = detector mass (kg)
T = livetime (yr)
B = background (counts/keV/kg/yr)
ΔE = energy resolution (keV)

Two Neutrino Double-Beta Decay

Nucleus ββ-decay emitting two electrons and two neutrinos

$$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\overline{\nu}_e$$





2νββ is an intrinsic BG, but it can be mitigated if

- $T^{0\nu}_{1/2}$ / $T^{2\nu}_{1/2}$ is small
- Detector has a high energy resolution (ΔE) → **5.8th power!!**

Double-Beta Decay Nuclei

Nucleus	T (yr)	T (yr)	Nat. abundance (%)	Q-value (keV)	
48		(4.2	0.19	4271	max. Q, fast 2ν
76	0.86 × 10	(1.5 ± 0.1) × 10	7.8	2039	semiconductor
82	2.44 × 10	(0.92 ± 0.07) × 10	9.2	2995	
96	0.98 × 10	(2.0 ± 0.3) × 10	2.8	3351	
100	2.37 × 10	(7.1 ± 0.4) × 10	9.6	3034	fast 2ν
116	2.86 × 10	(3.0 ± 0.2) × 10	7.5	2805	
128	4.53 × 10	(2.5 ± 0.3) × 10	31.7	867	
130	2.16 × 10	(0.9 ± 0.1) × 10	34.5	2529	large nat. abundance
136	4.55 × 10	(2.11 ± 0.21) × 10	8.9	2476	slow 2ν, rare gas
150	2.23 × 10	(7.8 ± 0.6) × 10	5.6	3367	fast 0ν, 2ν

0νββ search by past experiments

^{76}Ge **Heidelberg-Moscow**

Klapdor et al. Mod.Phys.Lett.A21(2006)1547

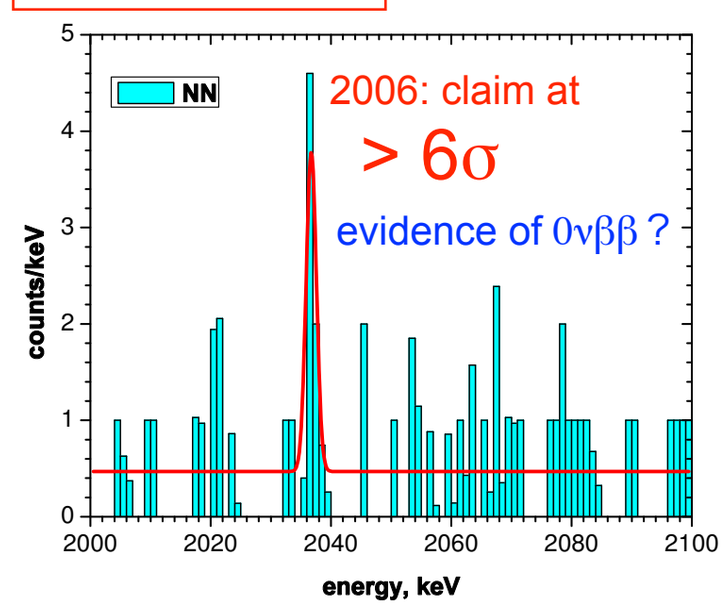
part of the collaboration (2006) claim at > 6σ

$T^{0\nu}_{1/2} \sim 2.3 \times 10^{25}$ yr still controversial ...

^{130}Te	Cuoricino	^{100}Mo, ^{82}Se	NEMO-3
^{48}Ca	ELEGANT VI	^{136}Xe	DAMA

present experiments aim to test KKDC claim

KKDC claim



KamLAND-Zen

KamLAND-Zen Collaboration

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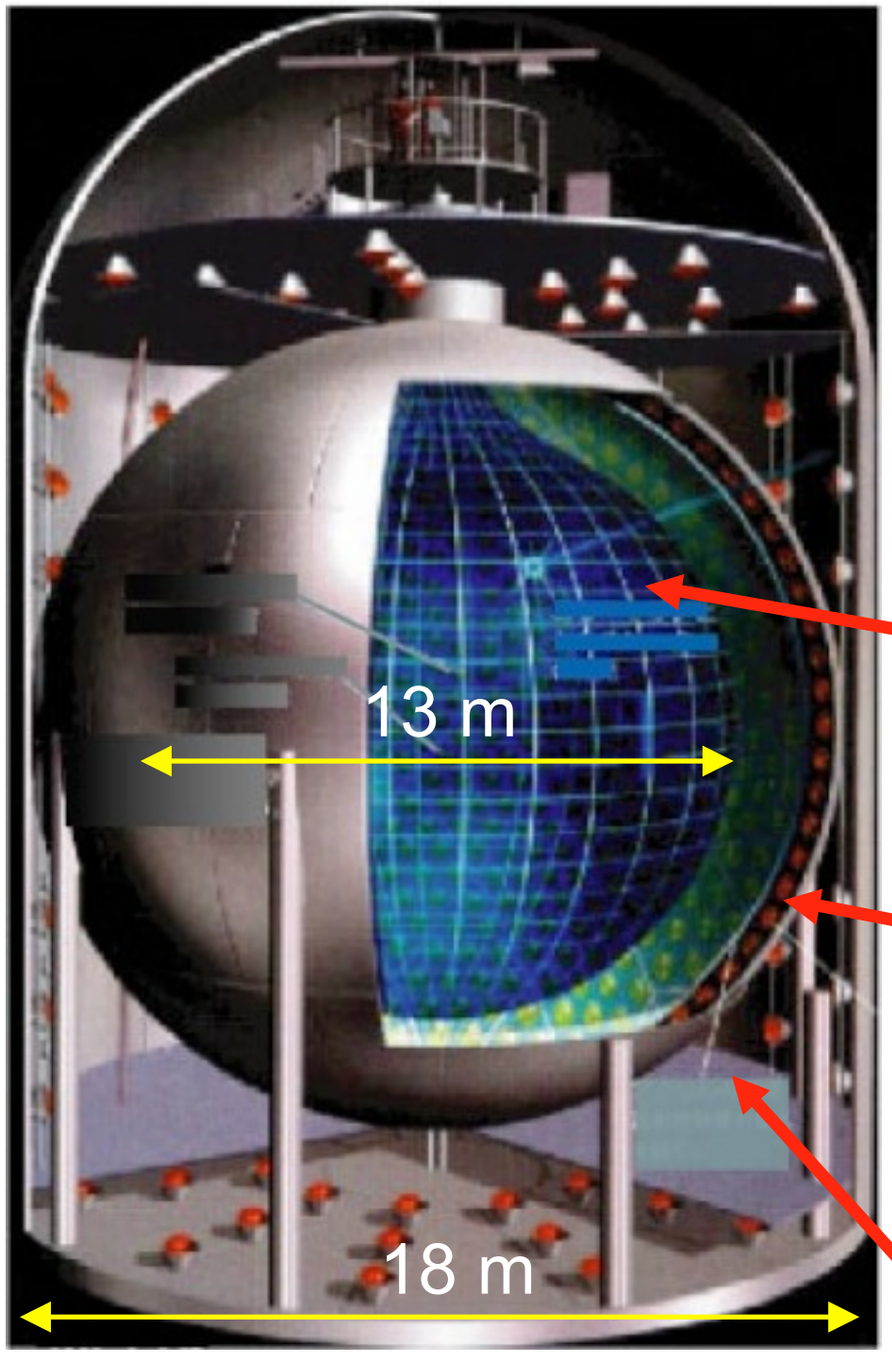
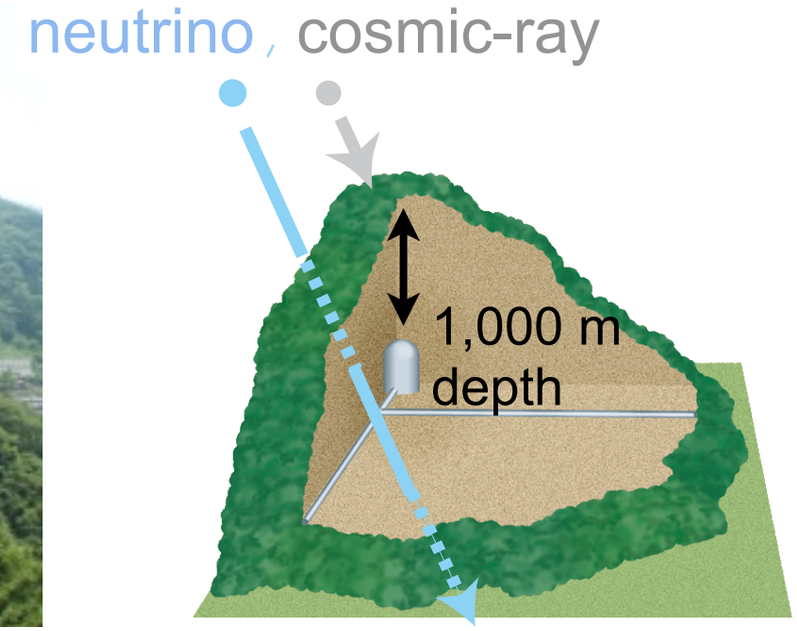
Photo in the KamLAND collaboration meeting (Mar. 2014)

KamLAND

Kamioka Liquid Scintillator Anti-Neutrino Detector

operated since 2002





1,000 ton Liquid Scintillator

Dodecane (80%) Pseudocumene (20%) PPO (1.5 g/l)

1,325 17 inch + 554 20 inch PMTs

commissioned in February, 2003

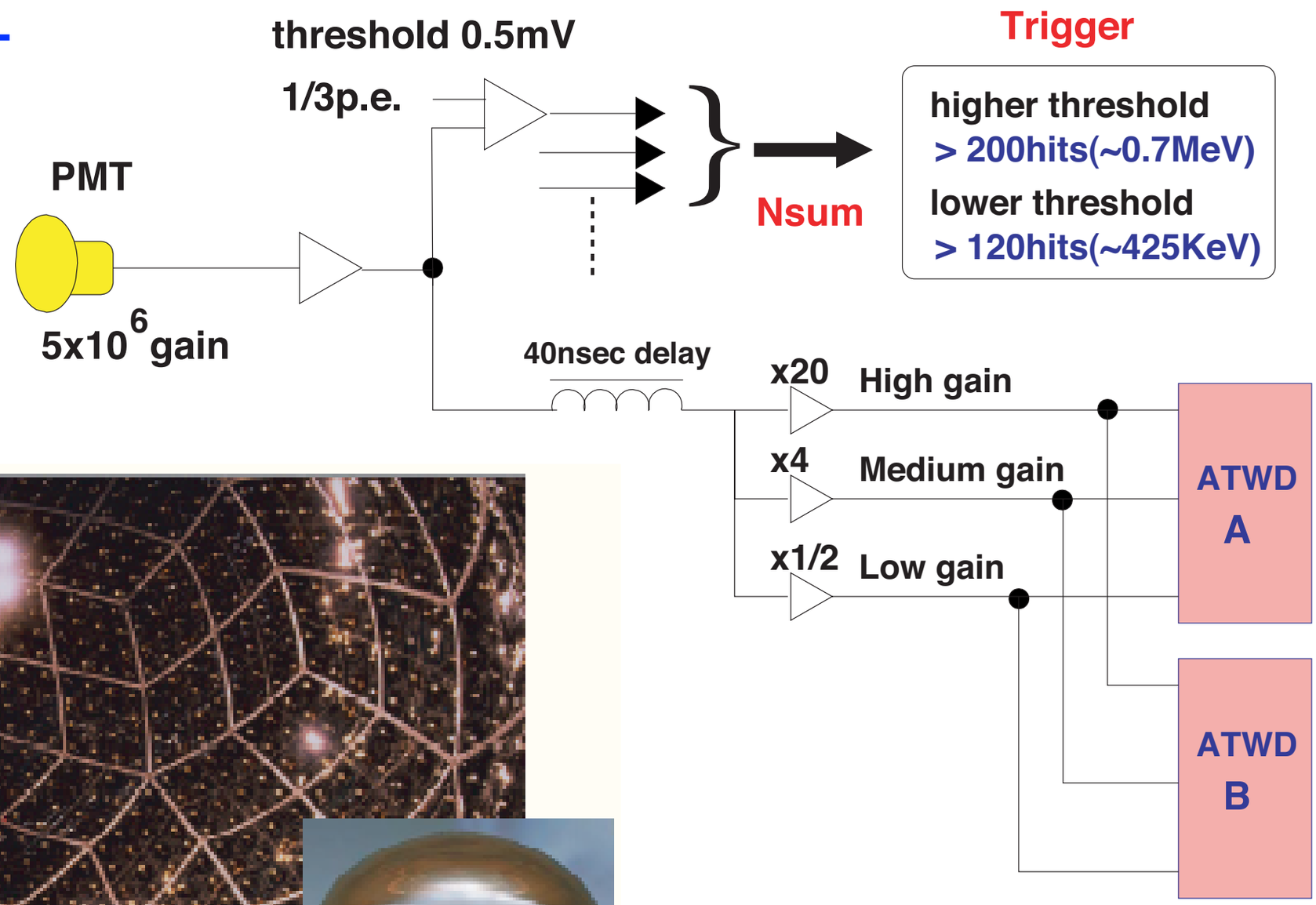
photocathode coverage : 22% → 34%

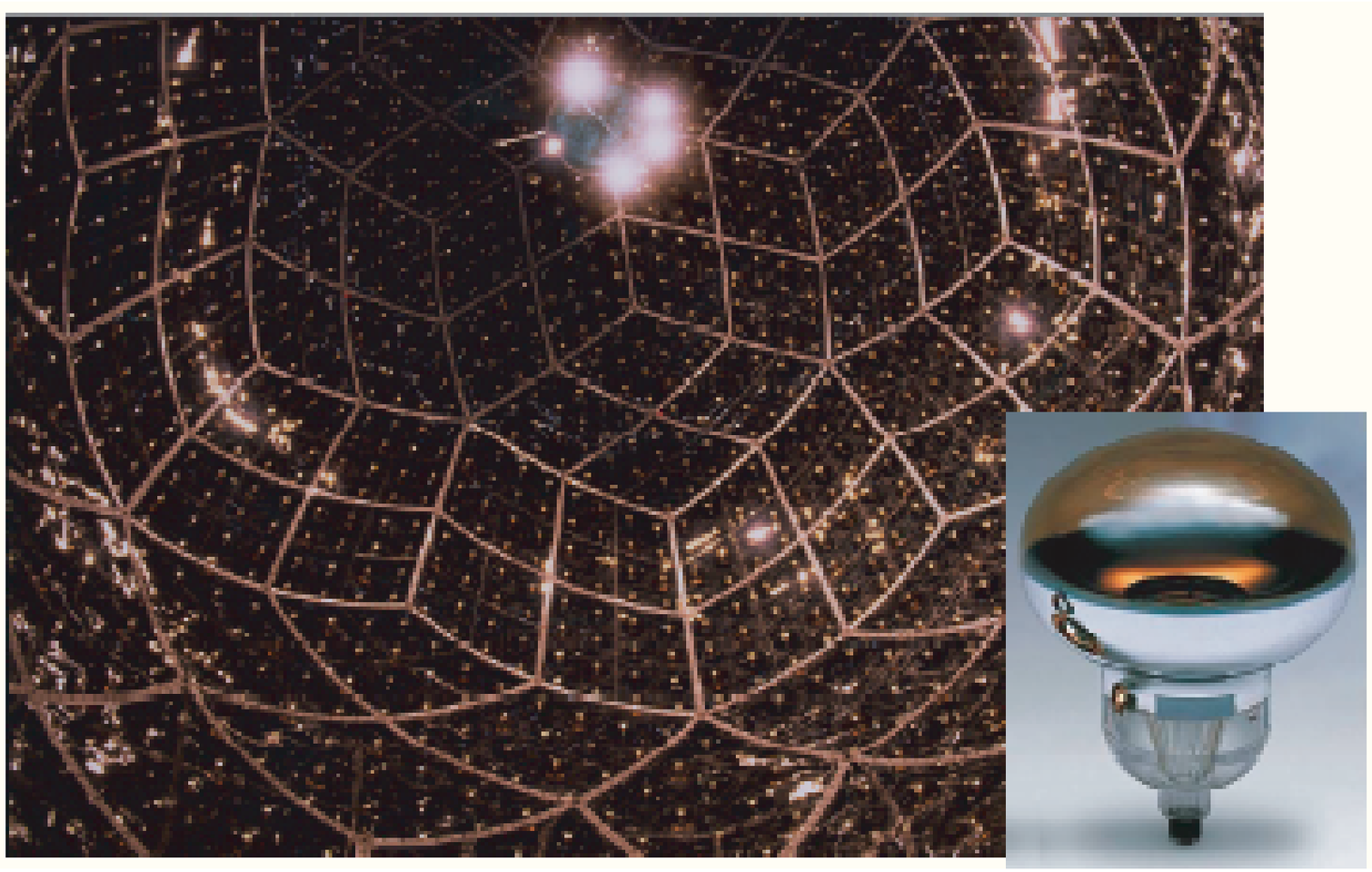
Water Cherenkov Outer Detector

Scintillation Signal Record

Large Area PMT

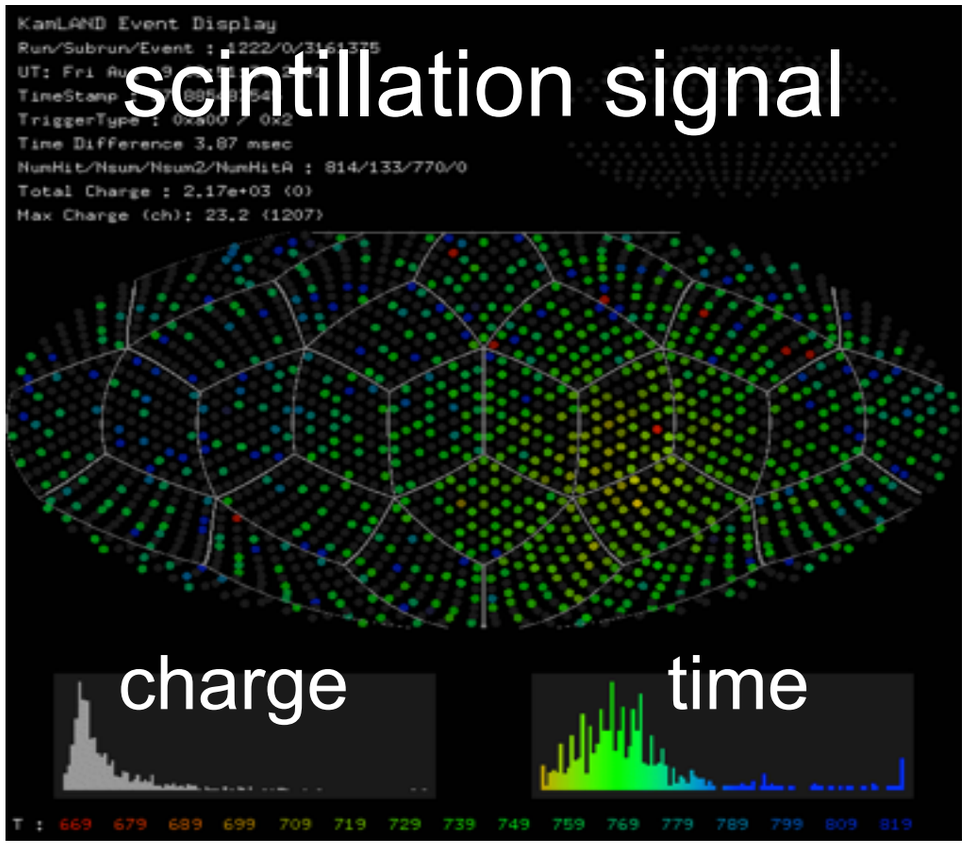
17-inch 1325
20-inch 554





cover signals from wide dynamic range
0.1 ~ 1000 p.e.

Event Reconstruction



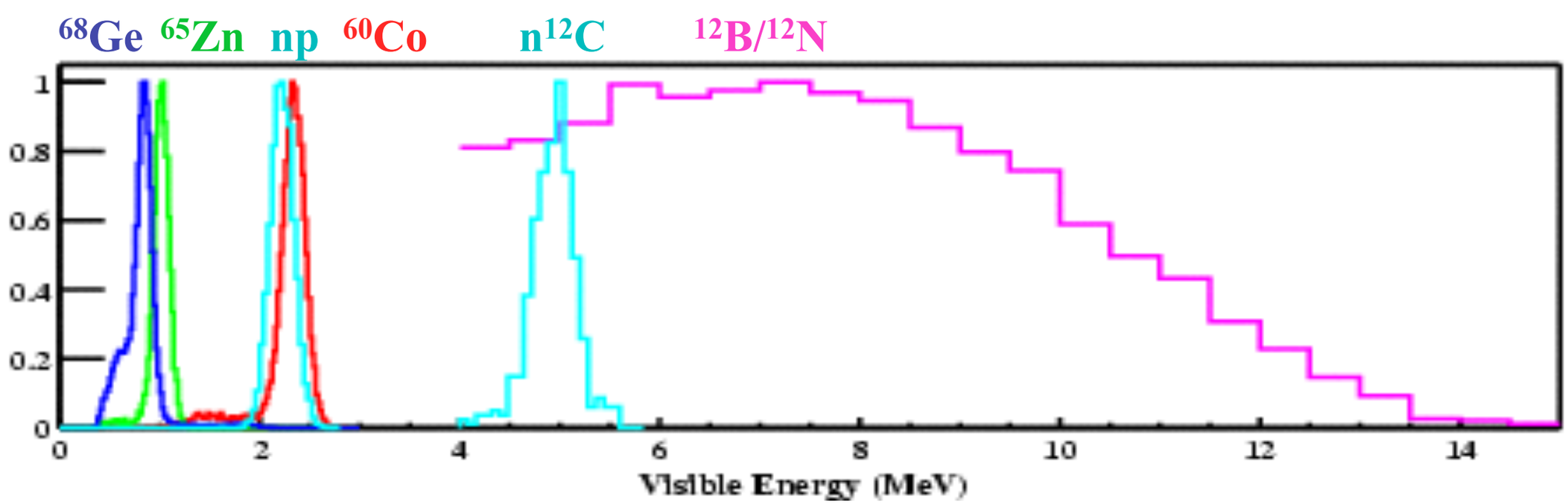
- Position resolution

$$\sigma_x = \frac{12\,cm}{\sqrt{E(MeV)}}$$

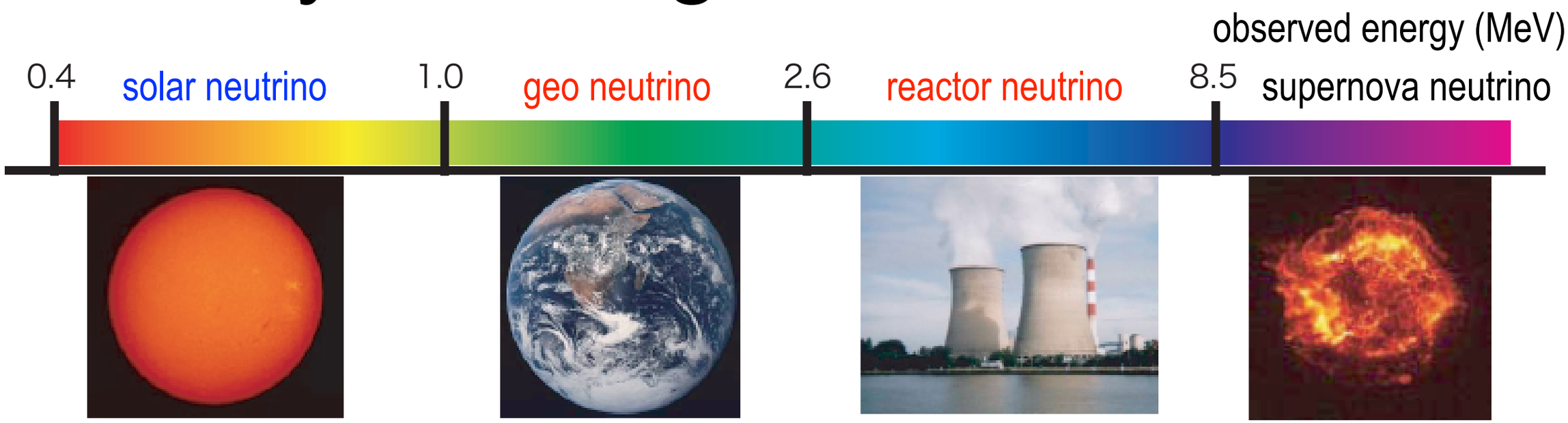
- Energy resolution

$$\frac{\sigma_E}{E} = \frac{6.5\%}{\sqrt{E(MeV)}}$$

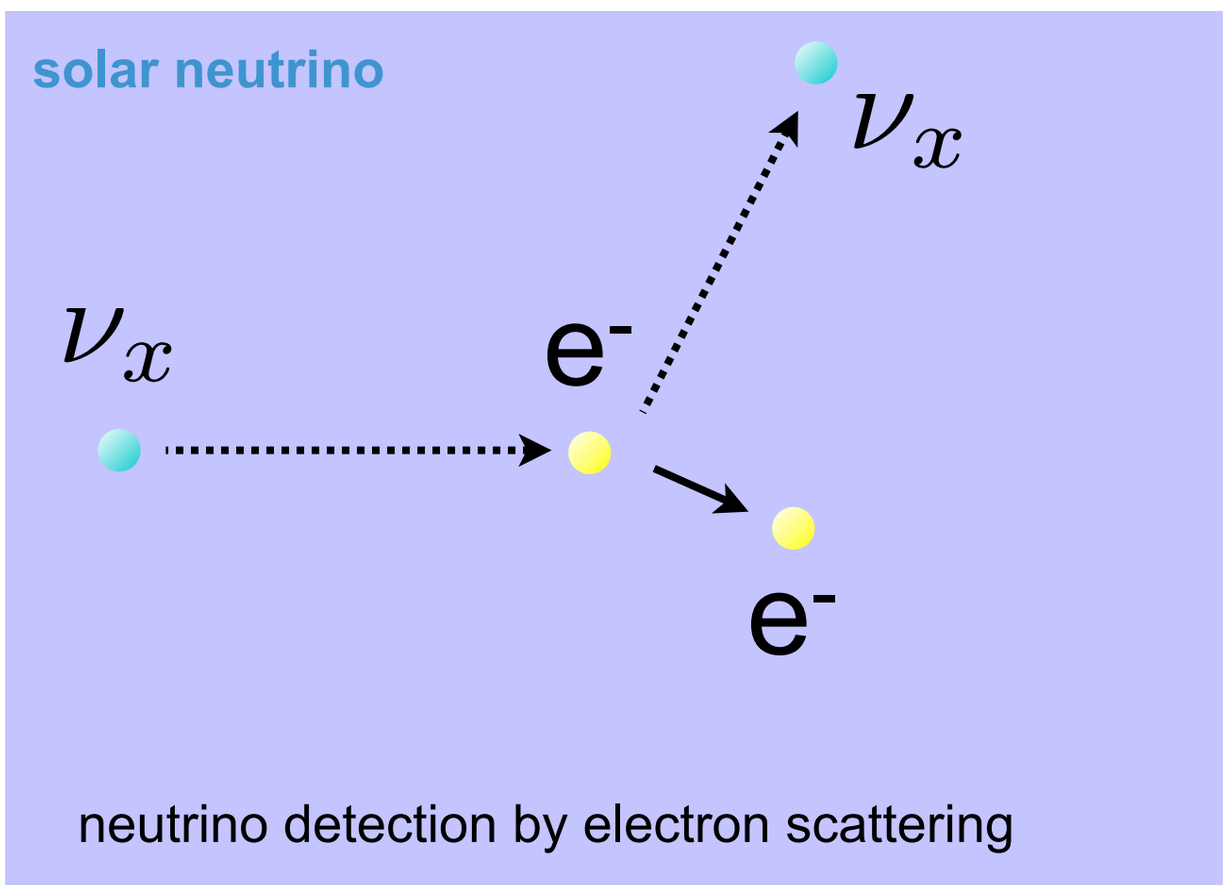
non-linear scintillation response is corrected by calibration sources



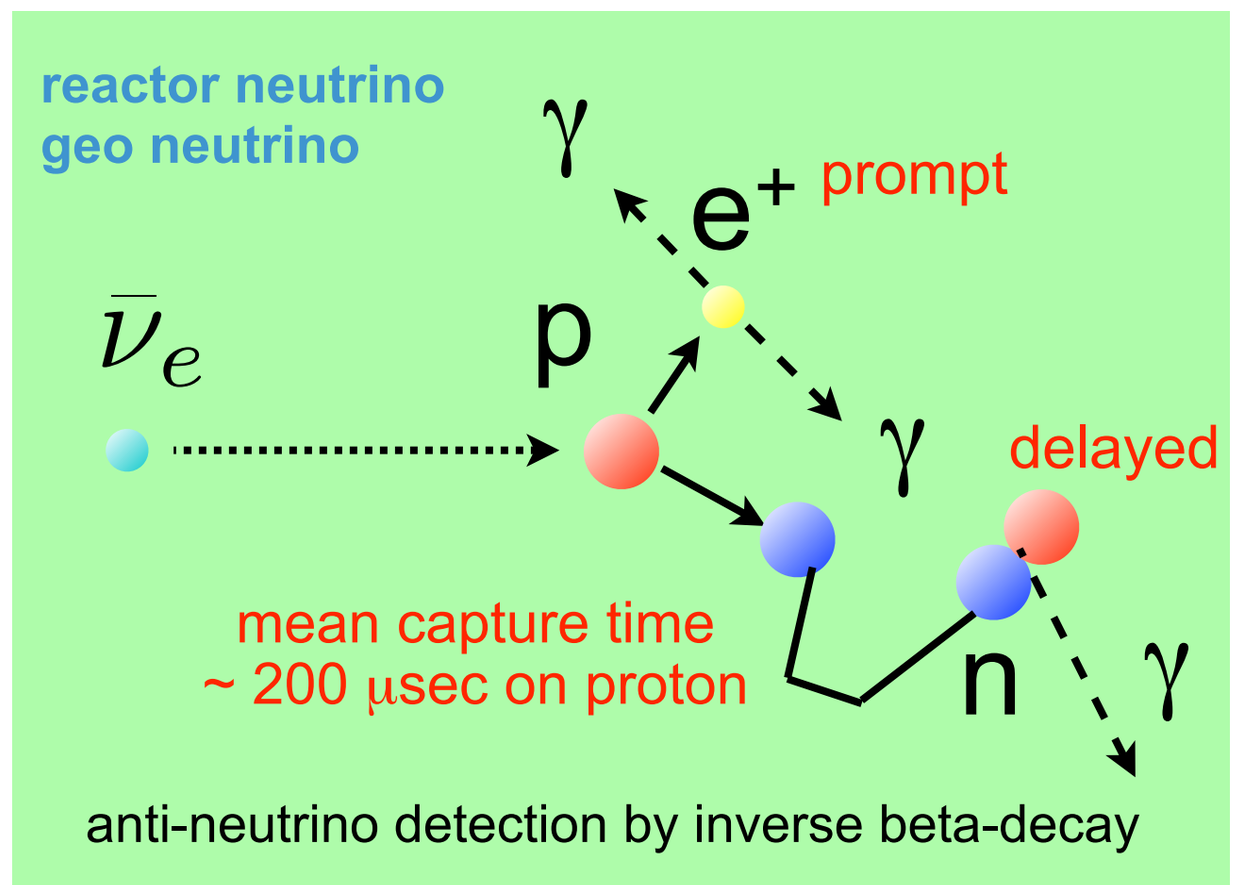
Physics Target in KamLAND



Neutrino

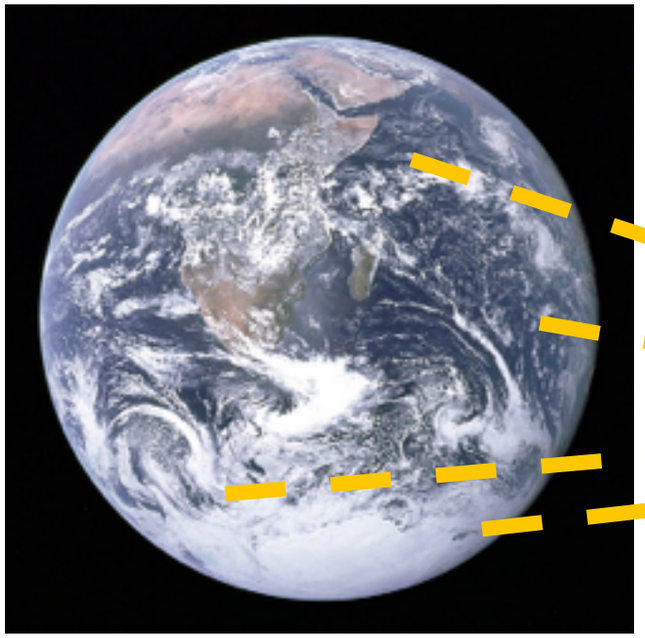


Anti-Neutrino



Anti-Neutrino in KamLAND

Earth

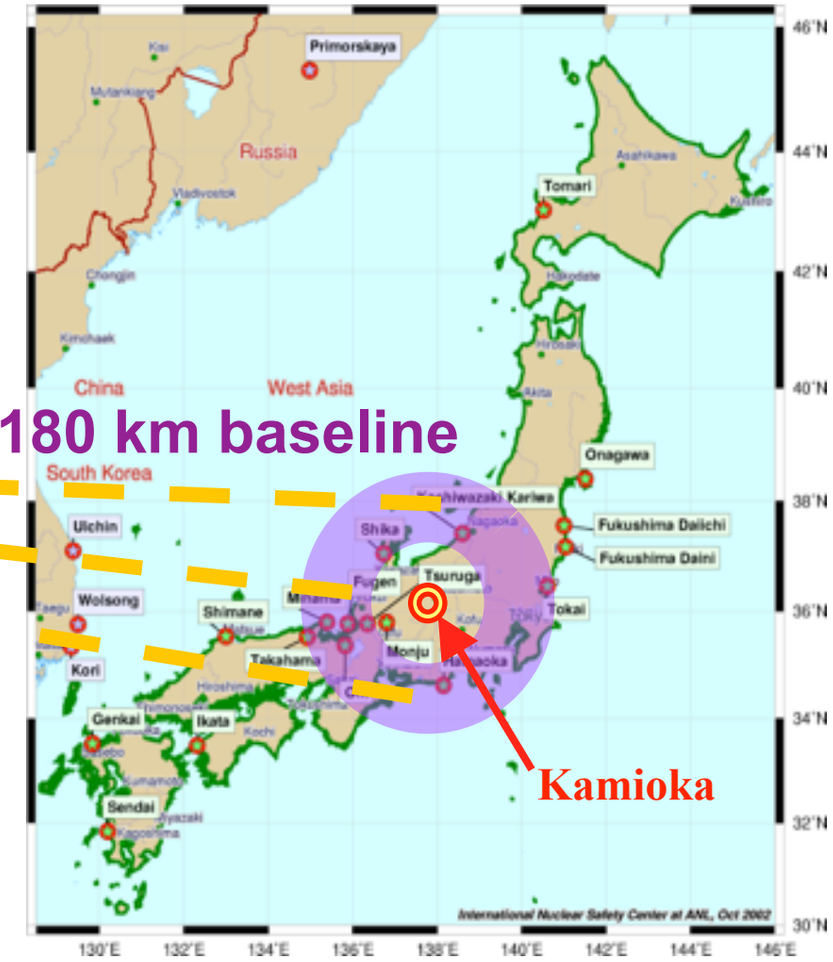


$\bar{\nu}_e$

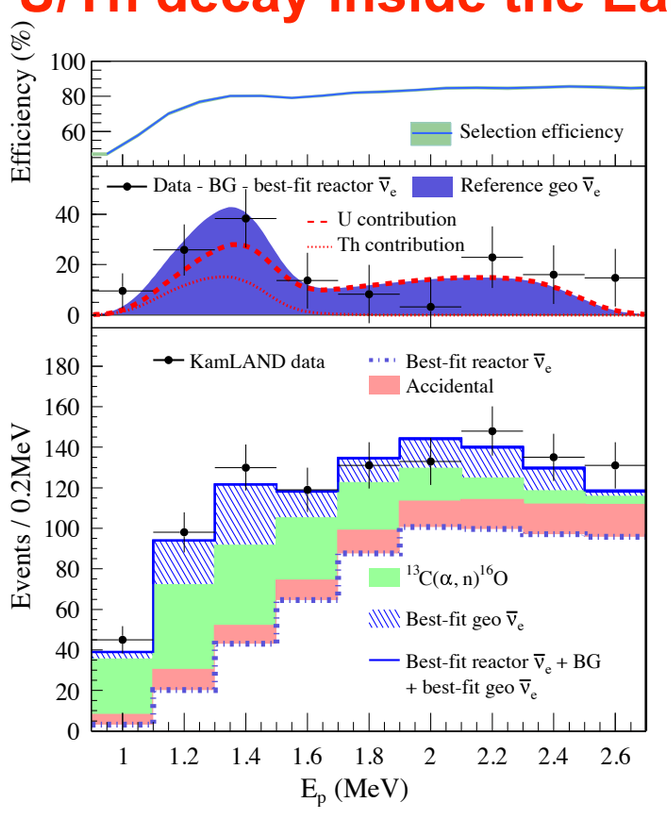
34% photo-coverage with
1325 17" and 554 20" PMTs

$\bar{\nu}_e$

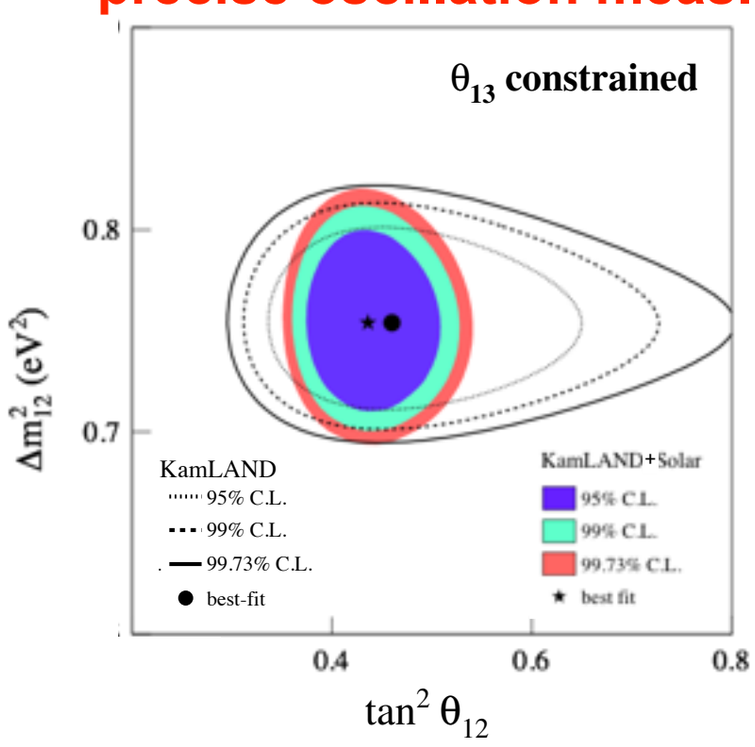
Reactor



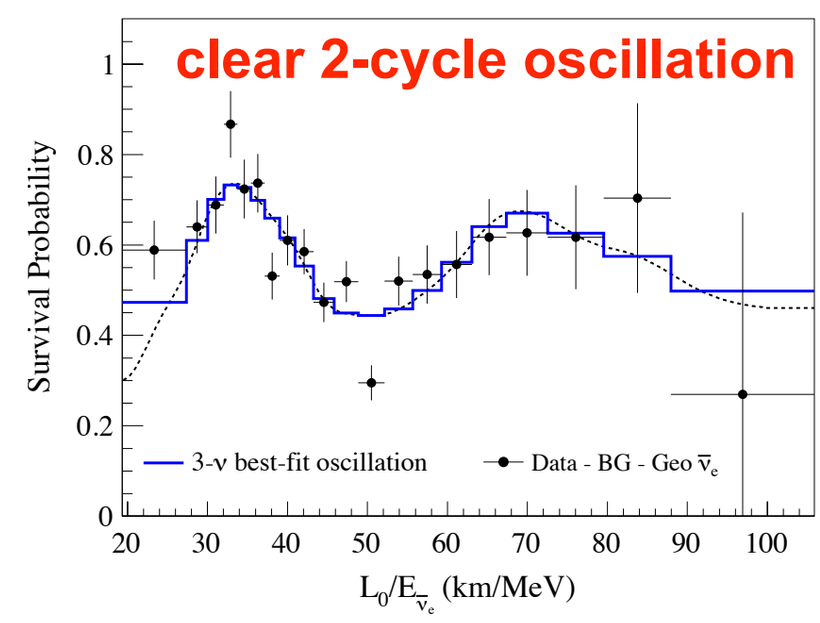
U/Th decay inside the Earth



precise oscillation meas.

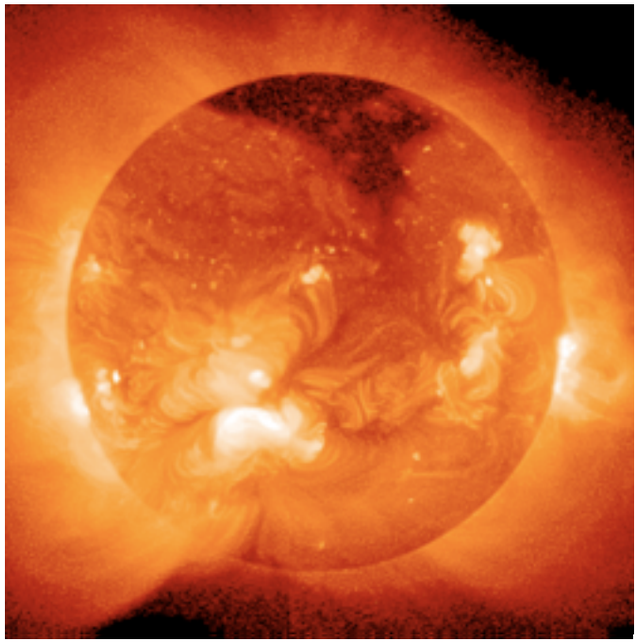


clear 2-cycle oscillation



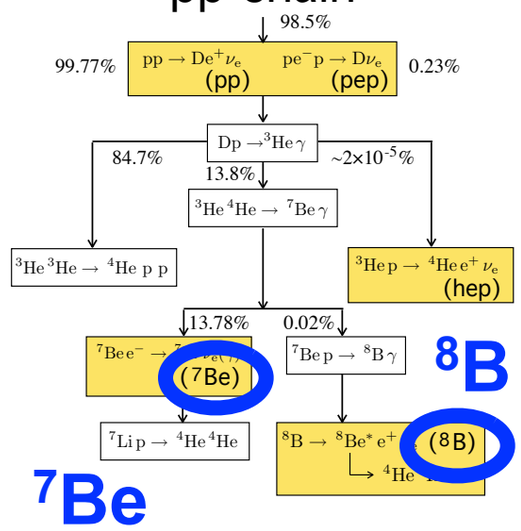
Neutrino in KamLAND

Sun



nuclear fusion in the Sun

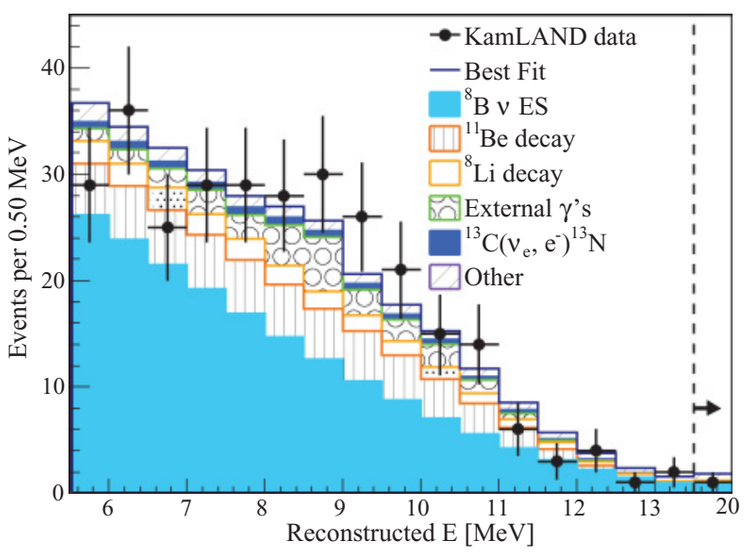
pp chain



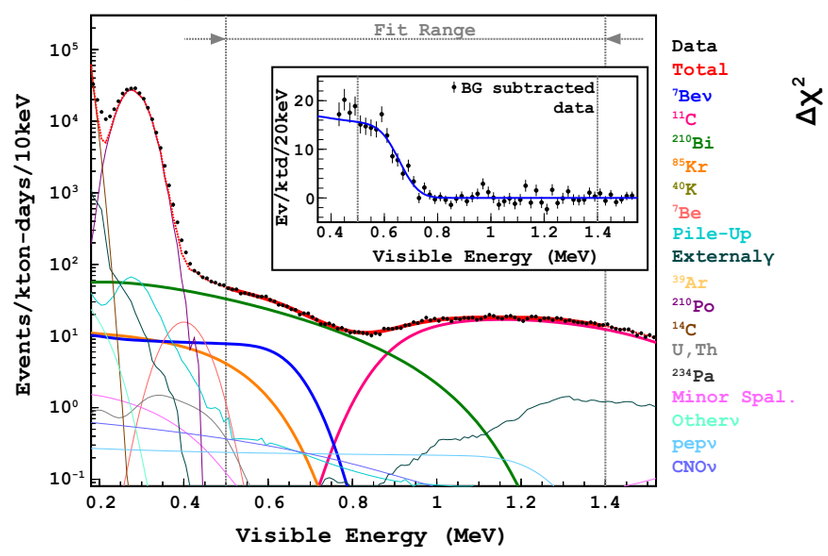
A.M. Serenelli et al., Astro. Phys. J.743, 24 (2011)

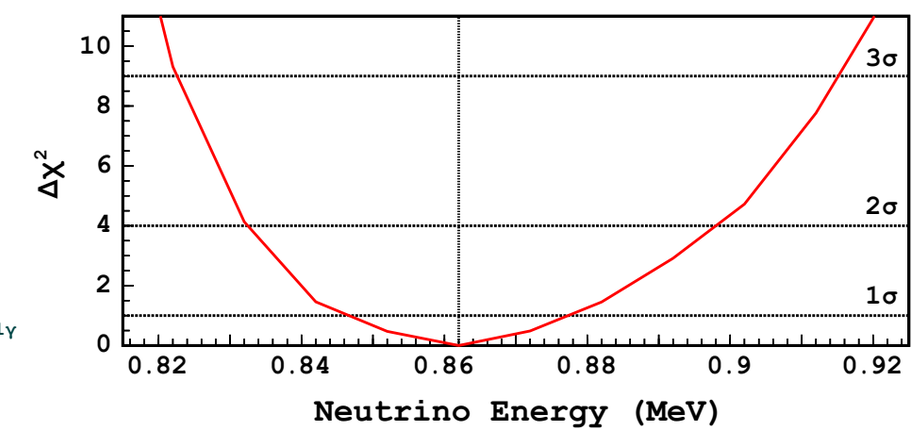
ν flux	GS98	AGSS09
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$
pep	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$
^{7}Be	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$ -9%
^{8}B	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$
^{13}N	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$
^{15}O	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$
^{17}F	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$
χ^2/P^{agr}	3.5/90%	3.4/90%

^{8}B PRC84, 035804(2011)



^{7}Be arXiv:1405,6190





862 keV ^{7}Be solar ν flux

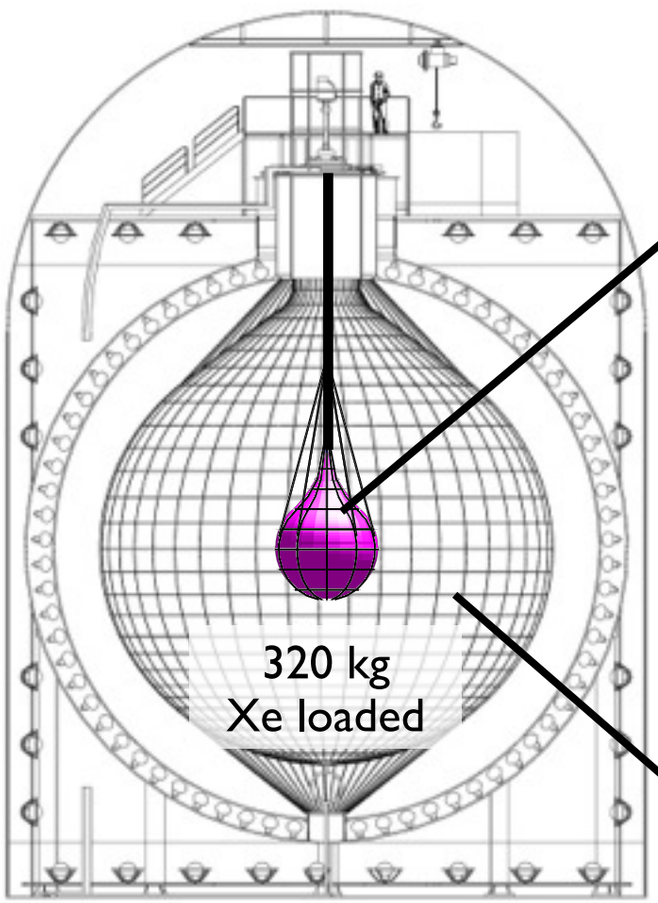
$3.26 \pm 0.50 \times 10^{9}/cm^{2}/s$

$5.82 \pm 0.98 \times 10^{9}/cm^{2}/s$ (no ν osci.)

KamLAND-Zen Experiment

Zero Neutrino Double Beta

KamLAND-Zen



Xenon loaded LS

decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
Xenon	2.44 wt%

neutrino-less double-beta decay search with ^{136}Xe LS

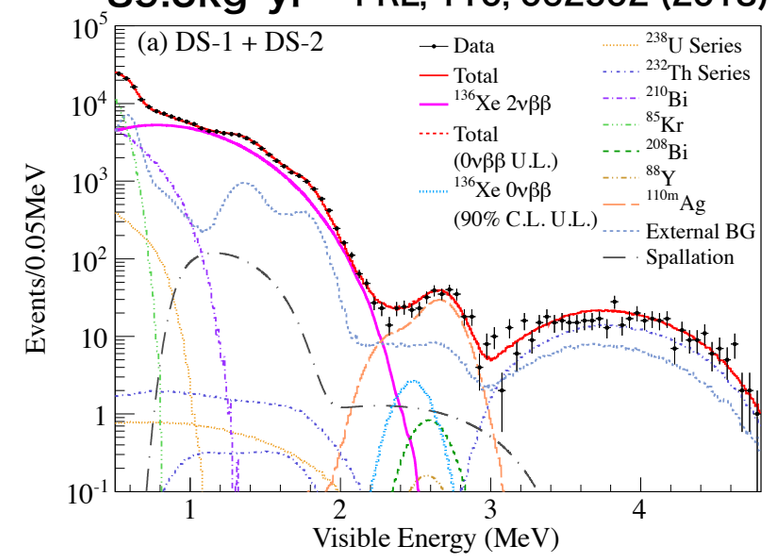
reactor & geo neutrino measurements continue

KamLAND LS

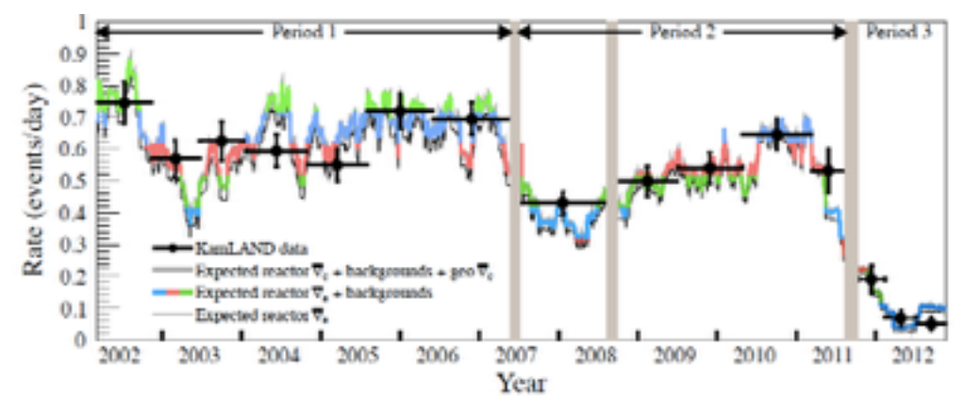
dodecane	80%
pseudo-cumene	20%
PPO	1.36 g/liter

double-beta decay search with **low background**

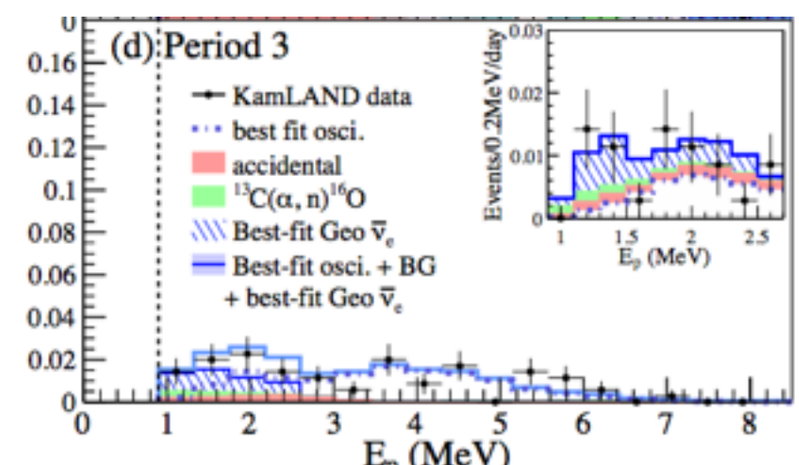
89.5kg•yr PRL, 110, 062502 (2013)



anti-neutrino flux variation arXiv:1303.4667



geo neutrino data during reactor shutdown



Why Xe?

- Isotopic enrichment (centrifugal) established
- Gas purification is possible
- Soluble to LS more than 3 wt%, easily extracted
- Slow 2νββ requires modest energy resolution

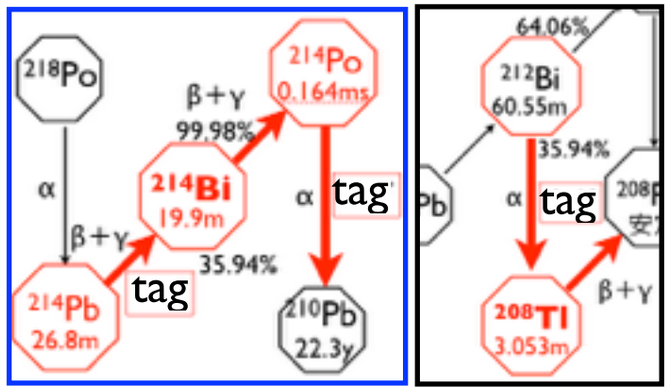
Test Balloon Installation

<u>3.4 m ϕ Mini-balloon</u>

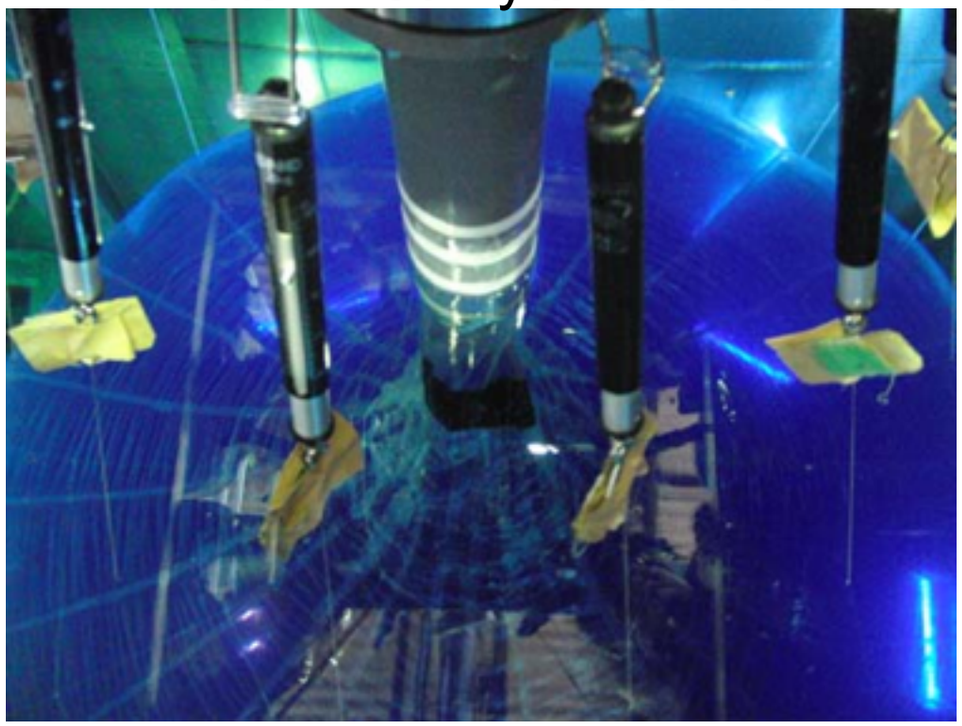
target { low radioactivity (~ 10^{-12} g/g U ,Th)
thin (25μm)

↓

^{214}Bi, ^{208}Tl reduction by alpha tagging



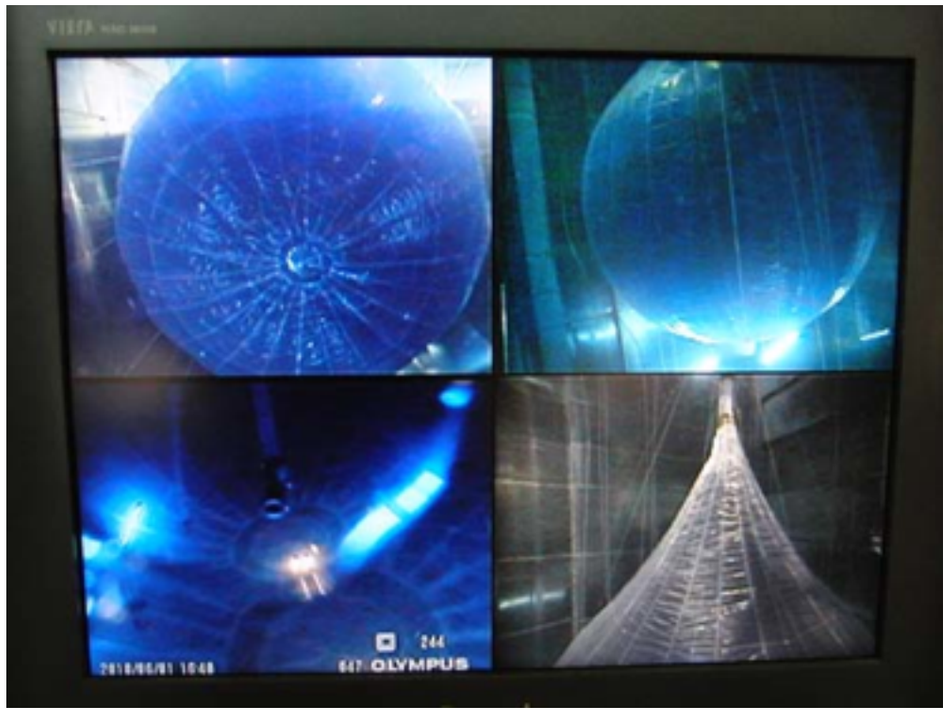
Water filled nylon balloon



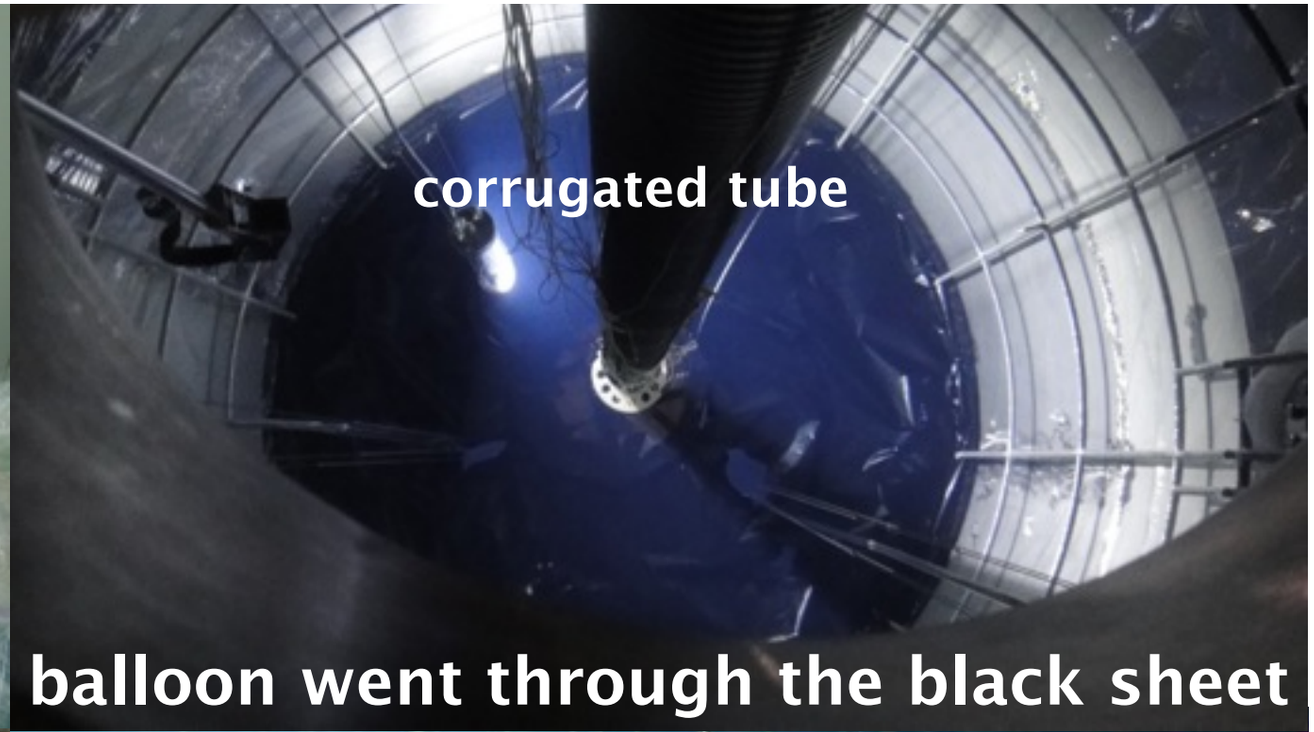
Air filled nylon balloon

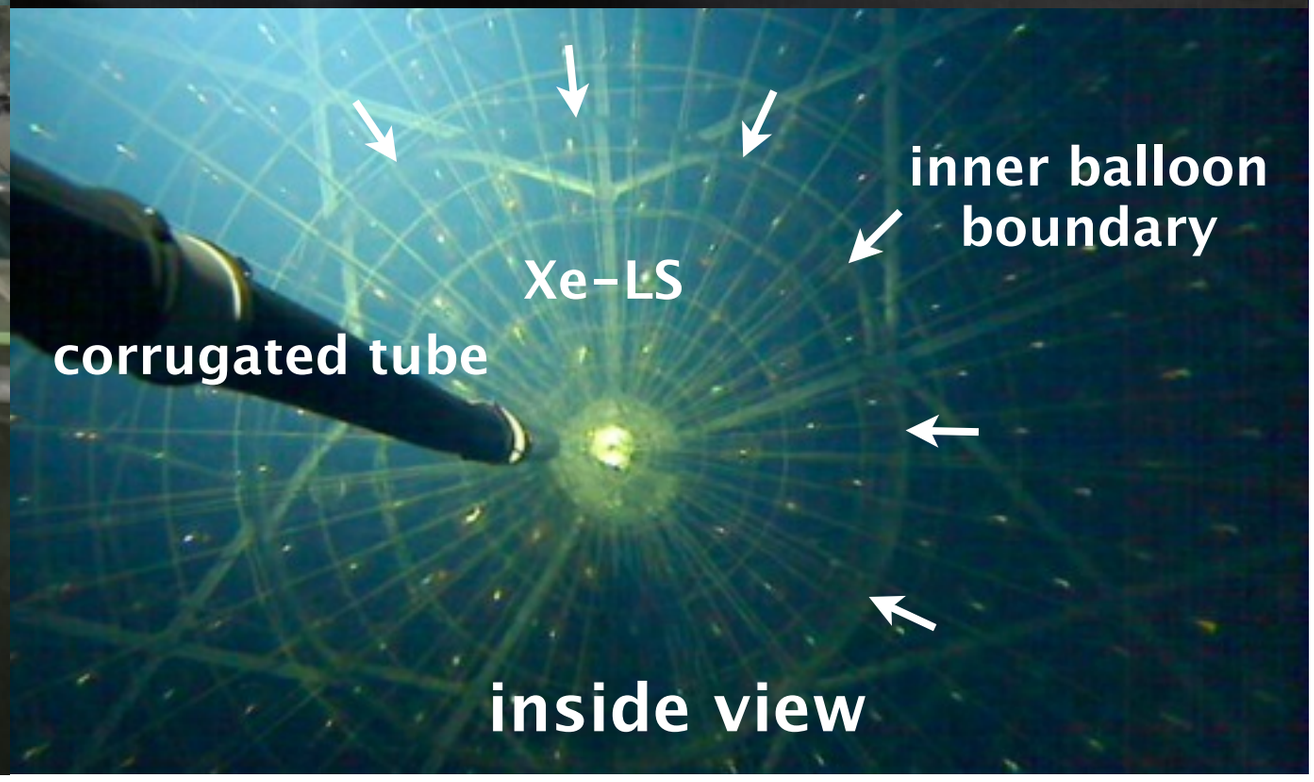
Installation in water

Monitor camera



Construction in 2011

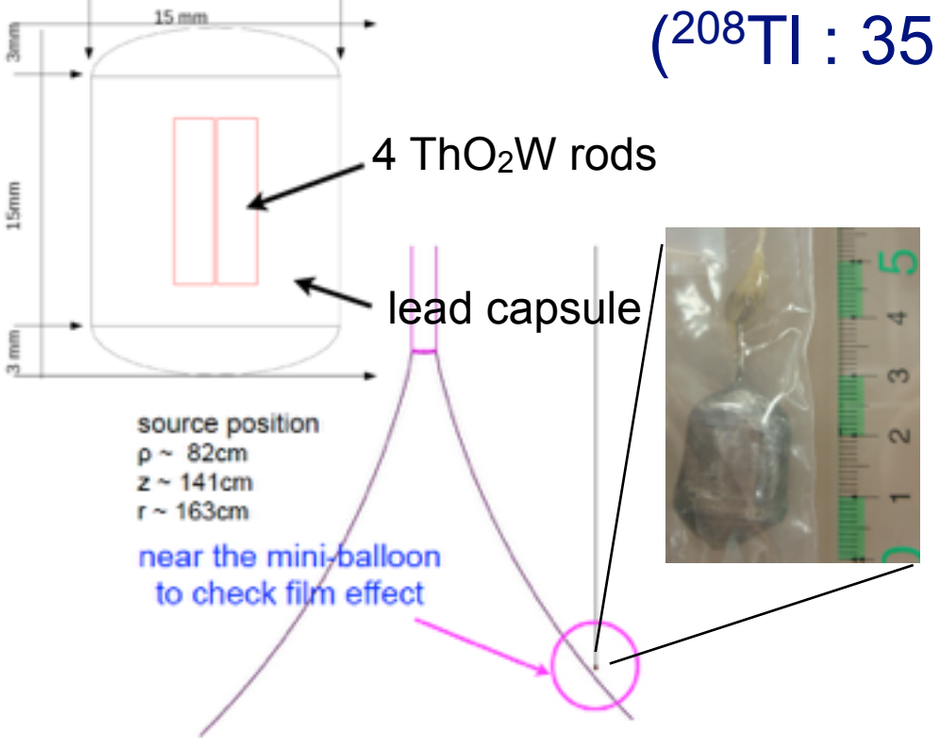




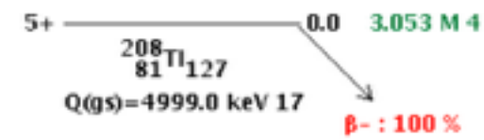
Energy Calibration

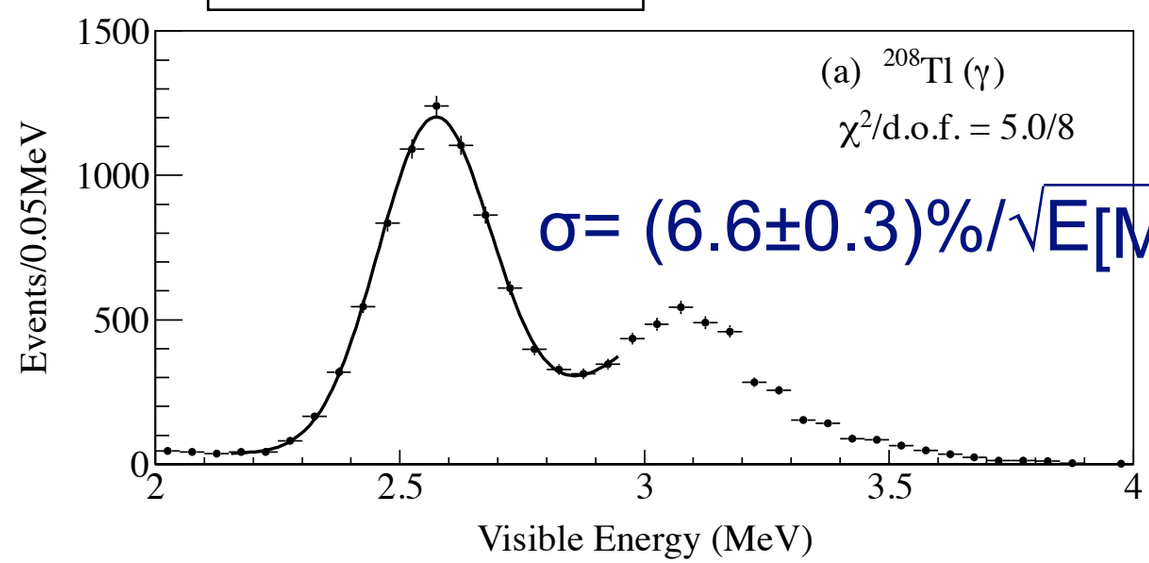
ThO_2W electrode w/ ^{232}Th 2~4 wt%

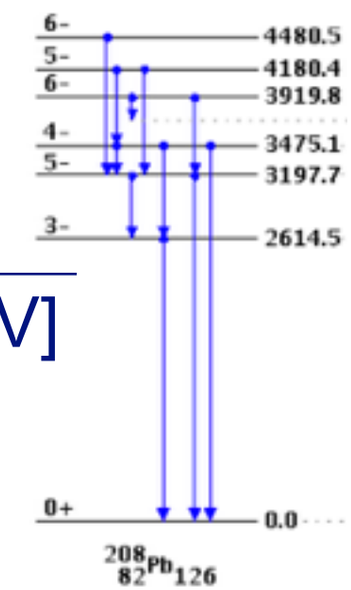
(^{208}Tl : 35.9%)



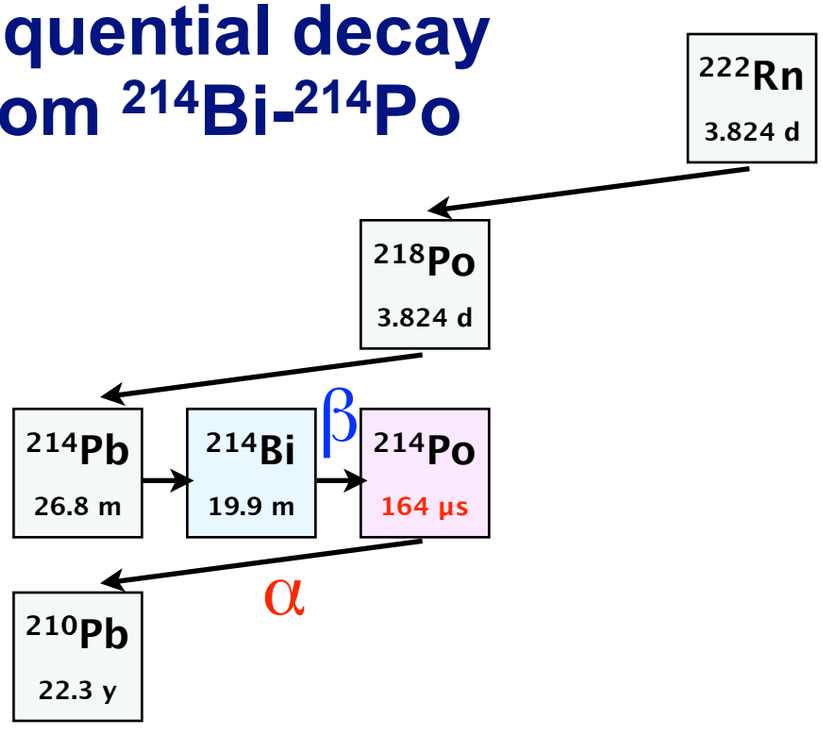
^{208}Tl decay
(2.6 MeV γ)



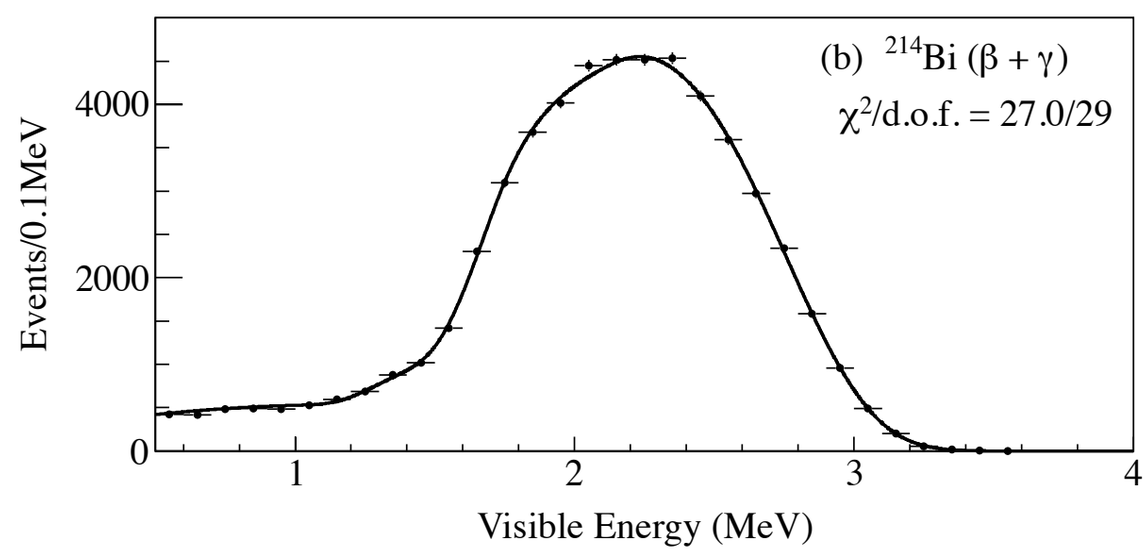


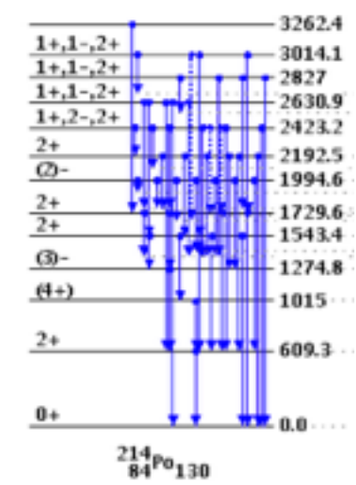


Sequential decay from ^{214}Bi-^{214}Po



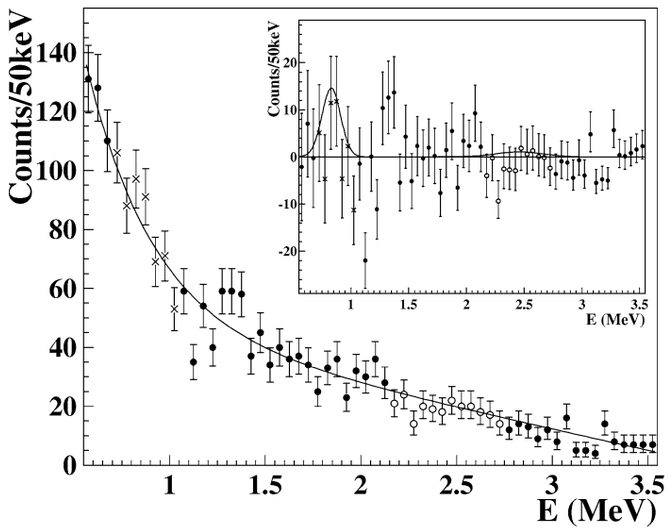
^{214}Bi decay
(β + γ)





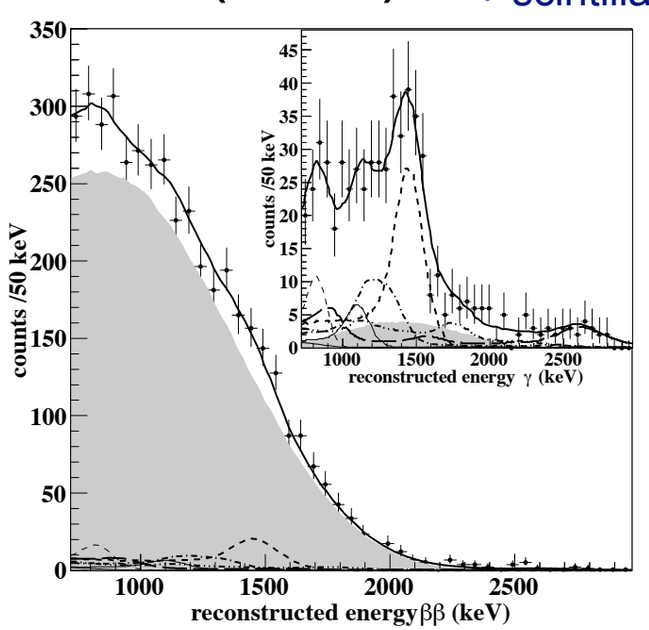
^{136}Xe 2νββ Decay Half-life

DAMA (2002) Liquid Xe scintillator



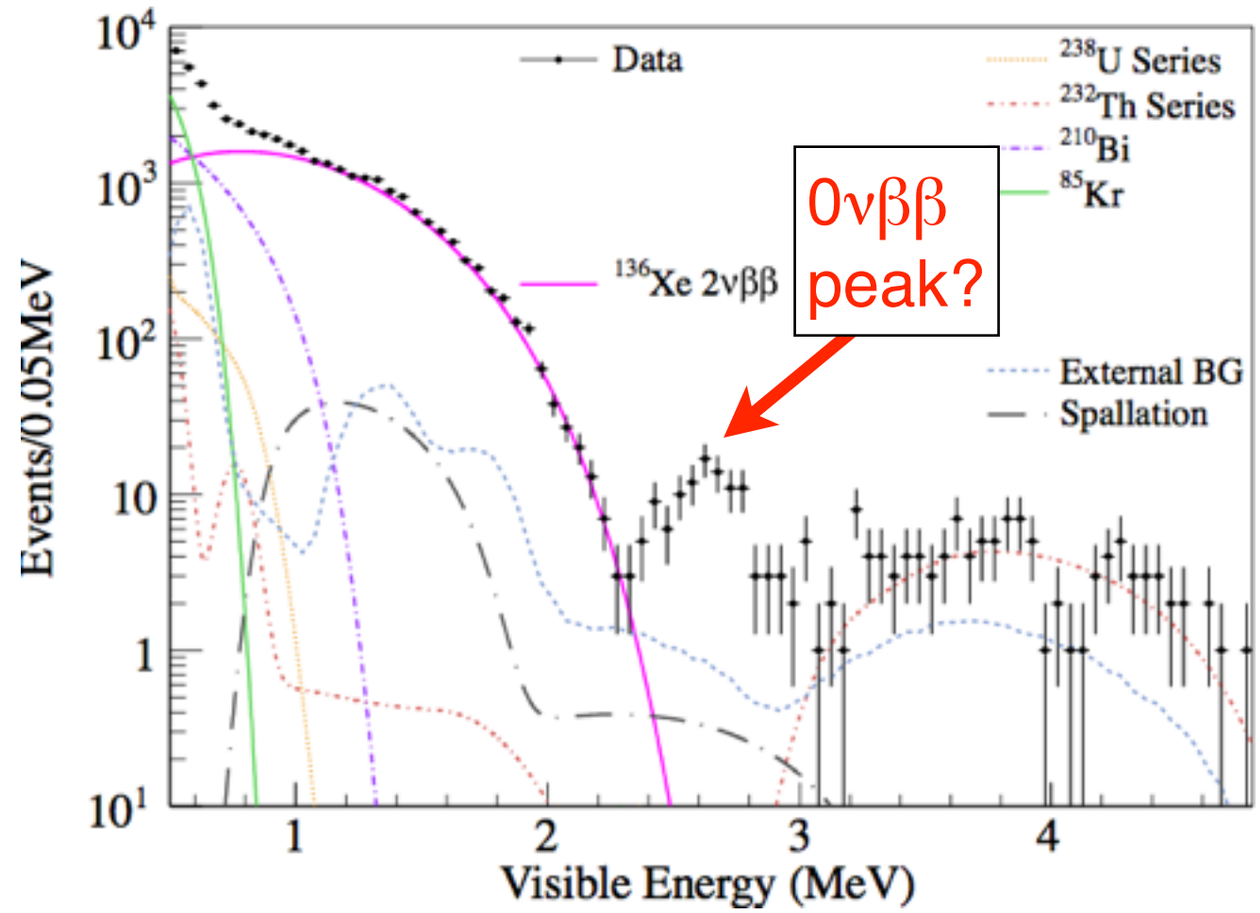
$T^{2\nu}_{1/2} > 1.0 \times 10^{22}$ yr at 90% C.L.

EXO-200 (2011) Liquid Xe TPC + scintillator



$T^{2\nu}_{1/2} = 2.11 \pm 0.04(\text{stat}) \pm 0.21(\text{syst}) \times 10^{21}$ yr

KamLAND-Zen (2012) Xe loaded liquid scintillator



Data-set : 2011 10/12~2012 1/2 total livetime 77.6 days

$T^{2\nu}_{1/2} = 2.38 \pm 0.02(\text{stat}) \pm 0.14(\text{syst}) \times 10^{21}$ yr

- measured with highest statistics so far
- consistent with EXO-200 result

All Decay Search from ENSDF

thousands of millions of
all nuclei and decay path in the ENSDF data-base have been surveyed

ENSDF (Evaluated Nuclear Structure Data File) http://ie.lbl.gov/databases/ensdfserve.html

Published material: Nuclear Wallet Cards, Nuclear Data Sheets, Table of Isotopes

Service site: NuDat (IAEA,BNL), Isotope Explorer (LBNL, Lund)

basic data file related to nuclear structure and decays

↓

calculate visible energy spectrum of backgrounds
(including LS quenching effect and energy resolution)

eg. decay path of $^{110m}Ag \rightarrow {}^{110}Cd$ constructed from ENSDF

decay

```
===DECAY===
File   :all_ensdf2.txt
Levels :110Cd   *ADOPTED LEVELS, GAMMAS                    00NDS    200003
Parent :110AG  P 117.59    5.6:          249.76 D  4          2892.2    16
Product:110Cd   *110AG B- DECAY (249.76 D)                 00NDS    200003
Normal :      N 0.957     3          0.9856  6 1.01
Level Gamma Transi. Energy(keV) Halflife(s)   beta-(%)   beta+      EC     alpha
---                            (keV, upper:endpoint, lower: average)
nlevel=23

nlevel=23
 1              0.00  1.00000E+30   0.0000    0.0000    0.0000    0.0000
                              0.00          0.00      0.00
                              0.00          0.00      0.00
   ngamma=0  (original: 0)
 2            657.76  5.39000E-12   0.0000    0.0000    0.0000    0.0000
                              0.00          0.00      0.00
                              0.00          0.00      0.00
   ngamma=1  (original: 1)
   1   2 ->   1    657.76          100.0000
 3           1475.79  6.80000E-13   0.0000    0.0000    0.0000    0.0000
                              0.00          0.00      0.00
                              0.00          0.00      0.00
   ngamma=2  (original: 2)
```

Name of a Decay

Branching ratio for states of daughter nuclei

γ-cascade

```
===CASCADE===
3
  620.3553   0.0000E+00
  884.6781   7.3000E-13
  657.7600   5.3900E-12
 11.752492
path: 7->4->2->1
3
  687.0091   0.0000E+00
  818.0244   6.8000E-13
  657.7600   5.3900E-12
 18.087727
path: 7->3->2->1
2
  687.0091   0.0000E+00
 1475.7792   6.8000E-13
 10.276061
path: 7->3->1
2
 1505.0280   0.0000E+00
  657.7600   5.3900E-12
 59.883721
path: 7->2->1
-1
```

Energy of each gamma ray

Lifetime for each state

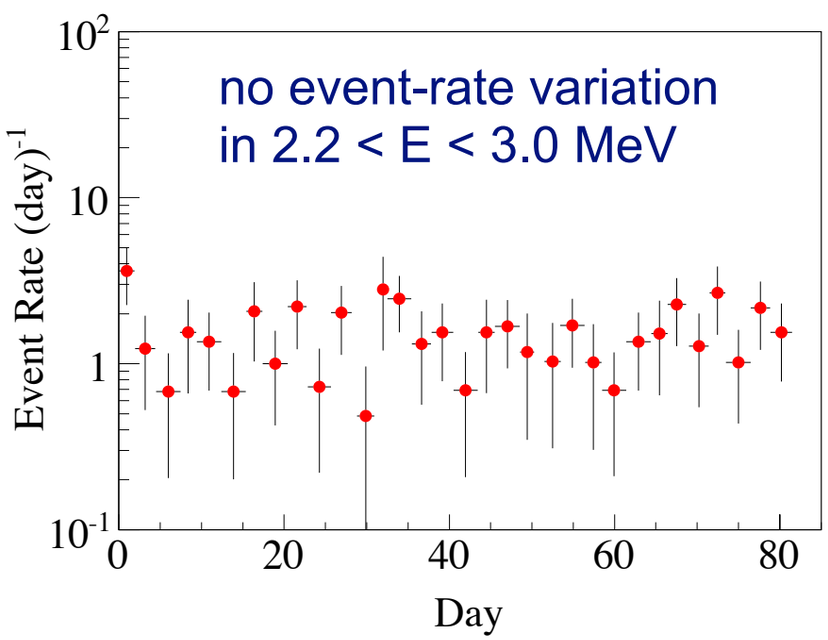
Cascade path

Identified Background Candidates

background candidates with peak around $0\nu\beta\beta$ ($2.4 < E < 2.8$ MeV)

β^- decay + IT decay

A	element	Z	parent state	sum of half life(s)
60	Co	27		1.66E+08
68	Co	27		0.331
83	Se	34		16.6
82	Br	35		1.27E+05
106	Rh	45	meta	1.56E+08
110	Ag	47	meta	2.16E+07
116	In	49	meta	1.48E+04



lifetimes longer than 30 days

β^+ decay, EC + IT decay

A		Z	parent state	sum of halflife (s)
52	MN	25		5.13E+05
57	NI	28		1.28E+05
82	RB	37	meta	2.21E+06
86	Y	39	meta	6.23E+04
88	Y	39		1.64E+07
93	MO	42	meta	4.94E+04
92	TC	43		4.77E+02
93	TC	43	meta	2.67E+03
100	RH	45		3.89E+05
106	Ag	47	meta	7.15E+05
108	In	49		4.11E+03
110	In	49		3.25E+04
115	Te	52	meta	4.98E+02
149	Ho	67	meta	5.60E+01
156	Ho	67	meta	4.68E+02
160	Ho	67		1.81E+04
176	Ta	73		2.91E+04
203	Bi	83		4.23E+04
208	Bi	83		1.16E+13
210	At	85		2.92E+04
212	FR	87		1.20E+03

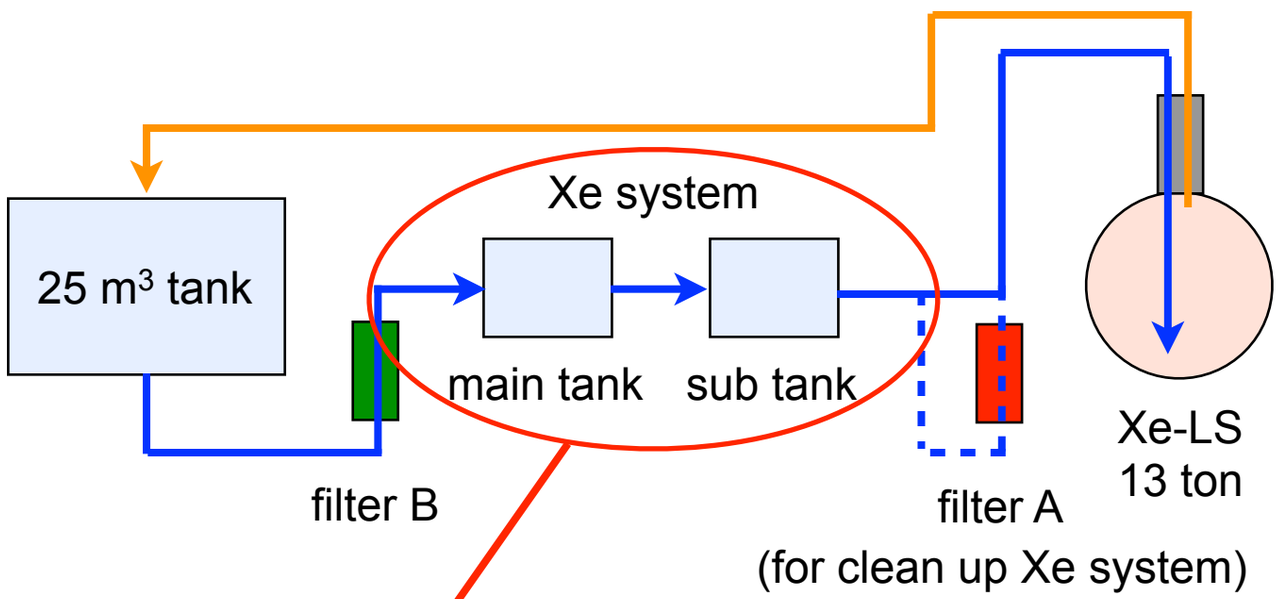
→ only 4 nuclei **^{110m}Ag (250 d), ^{208}Bi (3.68×10^5 yr), ^{88}Y (107 d), ^{60}Co (5.27 yr)**

Material Impurity Analysis

ICP-MS measurement

impurity analysis with mass spectroscopic analysis

material samples: filter A, filter B, Xe bottle, Xe-LS, Dummy-LS



measurement of ^{209}Bi, ^{107}Ag, ^{89}Y

	Bi209	Ag107	Y89
FilterA *	48ng	2300ng	
FilterB *	22ng	<50ng	870ng
Xe bottle *	40ng	<100ng	<100ng
XeLS	<10ppt		
XeLS (circuration)	<10ppt	<40ppt	<10ppt
Dummy LS		<40ppt	<2ppt
Amount in LS (13ton)	<0.1mg	<0.4mg	<0.1mg

Ag, Bi are contained in solder (Xe system)

^{208}Bi environmental activity of ^{208}Bi is ~0.18 mBq/gBi A.Shinohara et.al, Appl.Radiot.Isot.Vol.37,No10,p1025, (1986)

To explain the BG level at 2.6 MeV, ~1 ppb ^{209}Bi in Xe-LS is required,

but the obtained limit is < 10 ppt ⟶ environmental ^{208}Bi was excluded

^{110m}Ag environmental activity of ^{110m}Ag in solder is checked by Ge detector

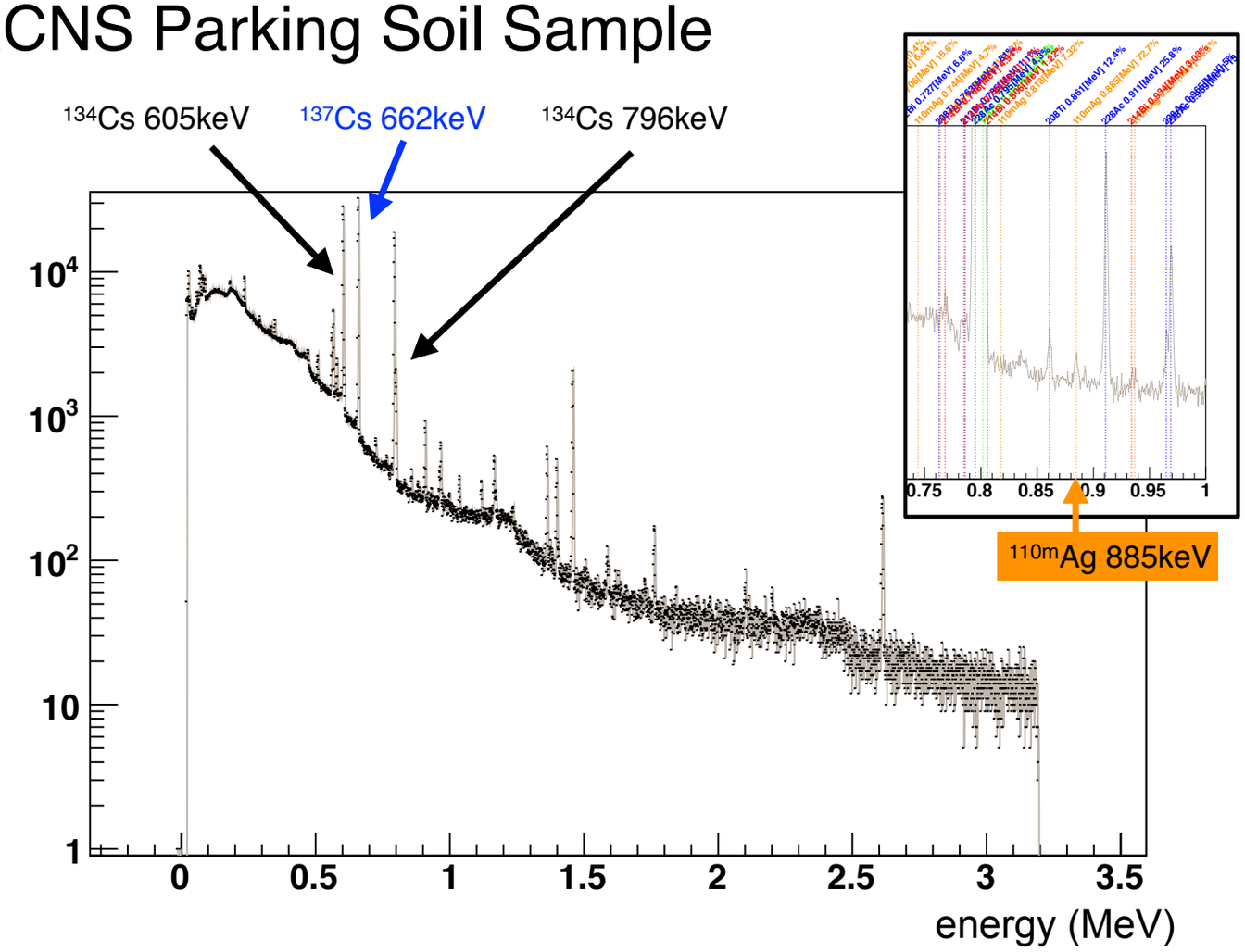
⟶ environmental ^{110m}Ag was excluded

Possible Impurity Source

Fukushima-I reactor fallout

soil sample taken near the balloon production facility
→ ^{110m}Ag (250 d) is identified by Ge detector

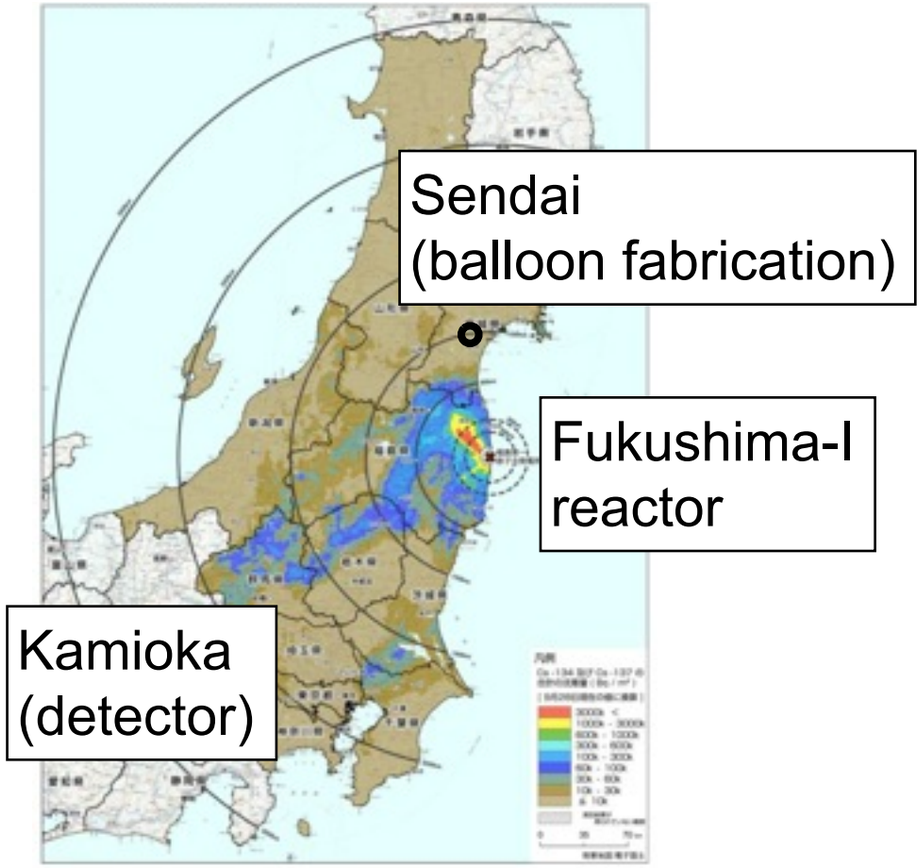
RCNS Parking Soil Sample



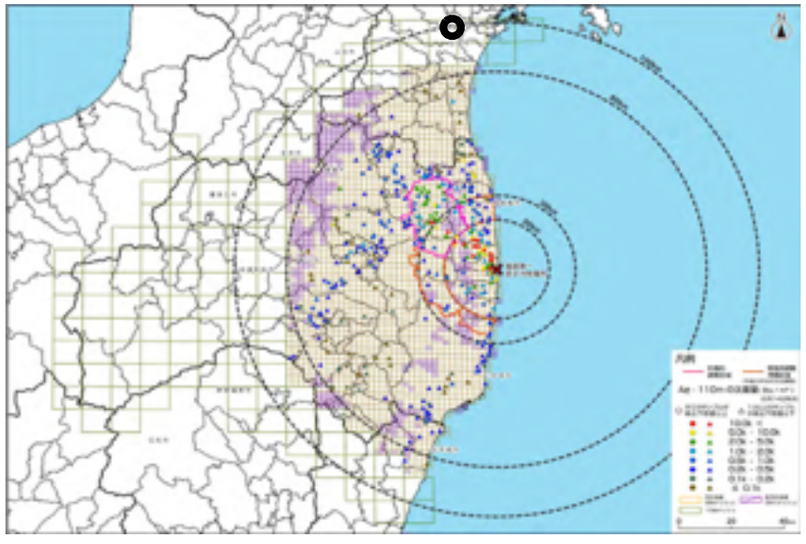
activity ratio of ^{110m}Ag/^{137}Cs ~ 0.004

^{208}Bi (3.68x10^5 yr), ^{88}Y (107 d), and ^{60}Co (5.27 yr) are not detected near Fukushima and our soil samples

^{134}Cs + ^{137}Cs fallout



^{110m}Ag fallout



Cosmogenic Spallation at Underground

cosmic-ray muon spallation in Xe-LS

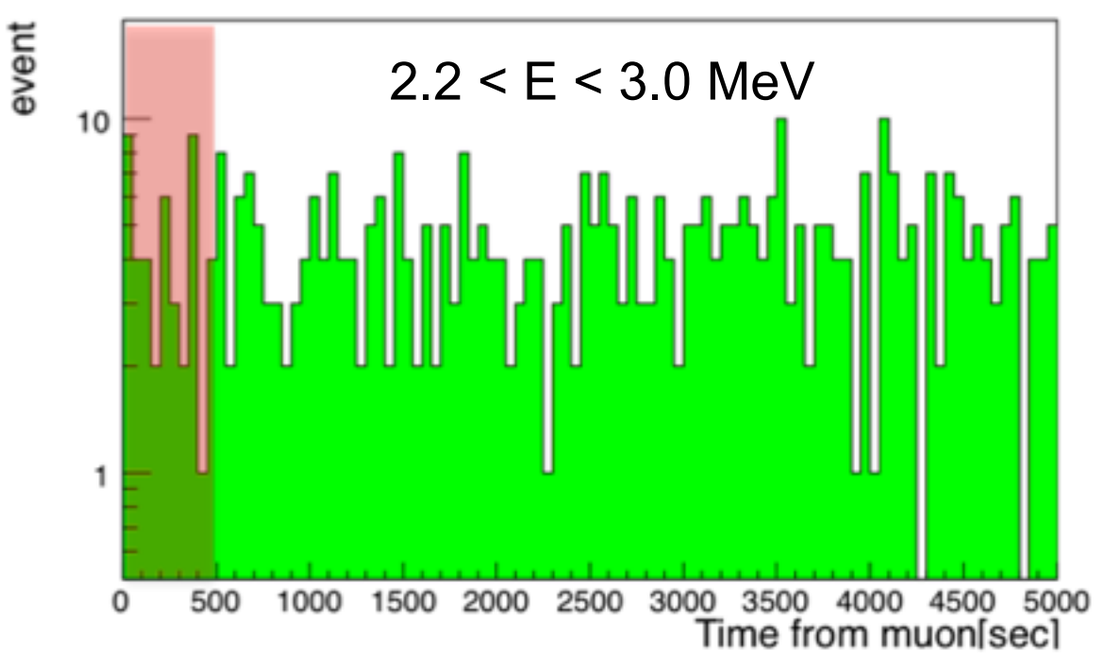
carbon (^{12}C) target	previously studied in KamLAND LS
xenon (^{136}Xe, ^{134}Xe) target	need reevaluation !!

underground products

- short-lived nuclei ($T_{1/2}$ < 100 s)
  study of time correlation with muons
  < 0.02 /ton·day (90% CL) ⟶ small

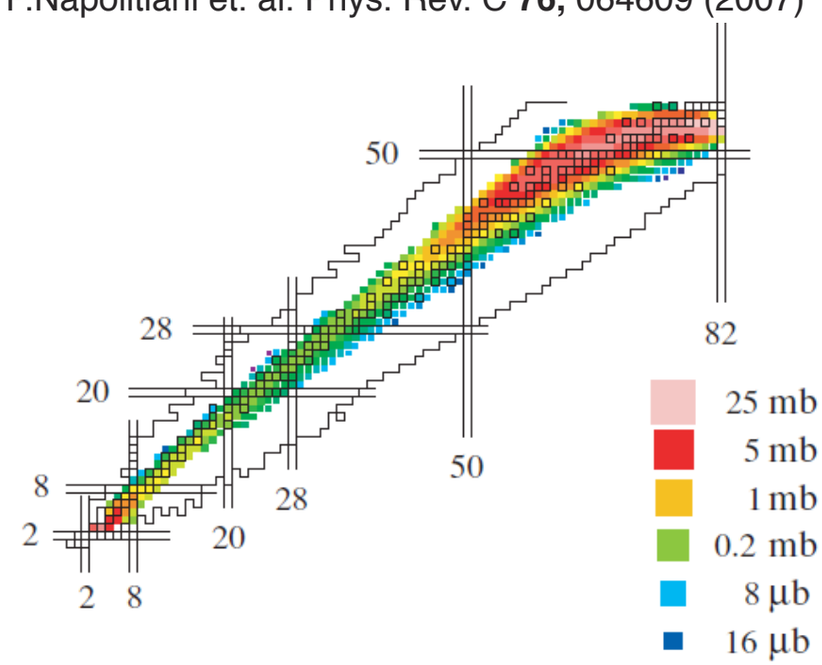
- long-lived nuclei (100 s < $T_{1/2}$ < 30 d)
  study of E spectrum
  w/ close A, Z nuclei ⟶ negligible

time correlation from muons



cross section data of proton-^{136}Xe

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



Underground spallation products are not serious backgrounds

Cosmogenic Spallation at Aboveground

cosmogenic spallation in Xe

Xe (^{136}Xe) gas enriched in Russia
→ gas bottle was transported by airplane

cosmic-ray proton/neutron is dominant source

flux is ~100 times higher than sea-level

how to estimate

^{136}Xe + p (1 GeV) cross section

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

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

surface: X = 100 days

mine: Y = **0**, 100, 300, 600 days

aboveground products

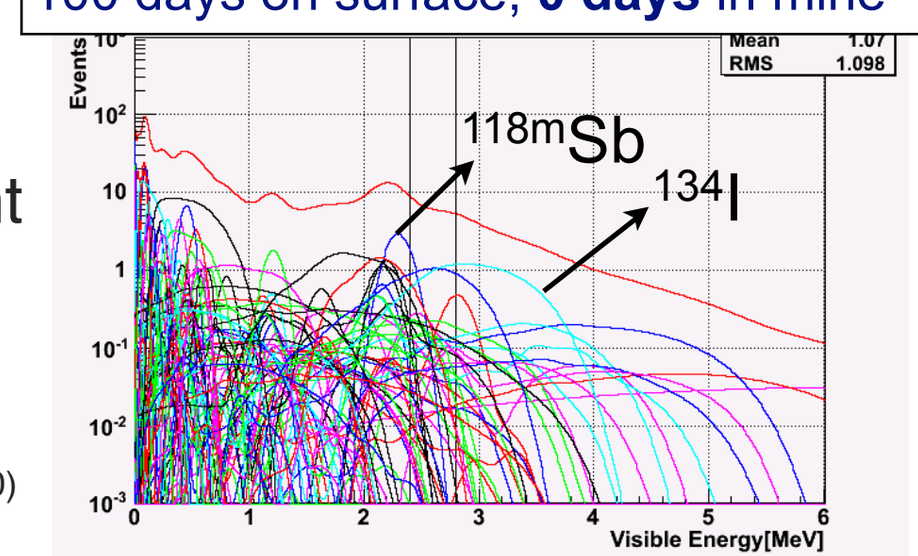
cross-section of ^{136}Xe + 1 GeV proton

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

production by surface proton/neutron is dominant

→ ^{110m}Ag and ^{88}Y are candidate BG

100 days on surface, **0 days** in mine



For reference, aboveground spallation in other experiments

enriched ^{76}Ge ^{57}Co, ^{54}Mn, ^{68}Ge, ^{65}Zn, ^{60}Co PRC 82, 054610 (2010)

enriched ^{116}Cd ^{110m}Ag, ^{106}Ru arXiv:1108.2771

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aboveground products

cross-section of ^{136}Xe + 1 GeV proton

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

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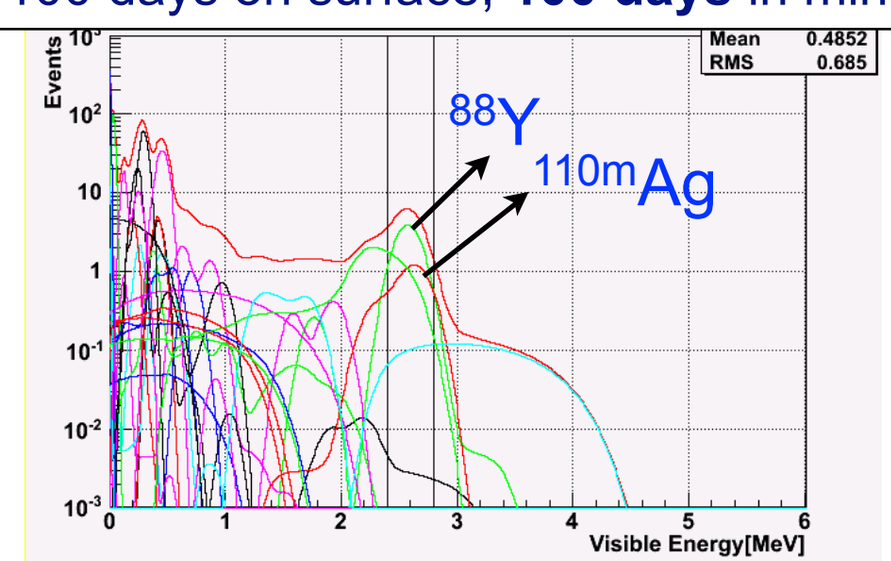
→ ^{110m}Ag and ^{88}Y are candidate BG

100 days on surface, **100 days** in mine



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X = 100 days Y = 0, 100, **300**, 600 days

aboveground products

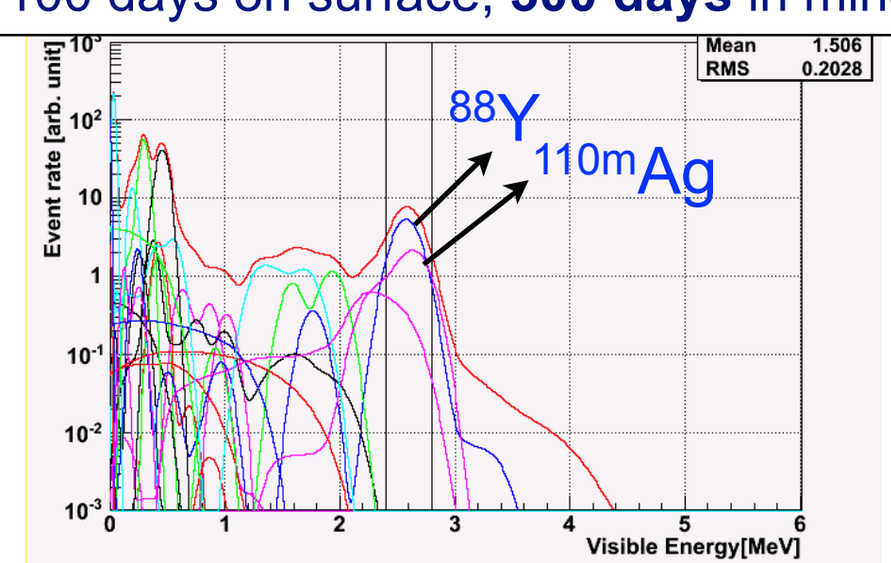
cross-section of ^{136}Xe + 1 GeV proton

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

production by surface proton/neutron is dominant

⟶ ^{110m}Ag and ^{88}Y are candidate BG

100 days on surface, **300 days** in mine



For reference, aboveground spallation in other experiments

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Cosmogenic Spallation at Aboveground

cosmogenic spallation in Xe

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⟶ gas bottle was transported by airplane

cosmic-ray proton/neutron is dominant source

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how to estimate

^{136}Xe + p (1 GeV) cross section

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

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

surface: X = 100 days

mine: Y = 0, 100, 300, **600** days

aboveground products

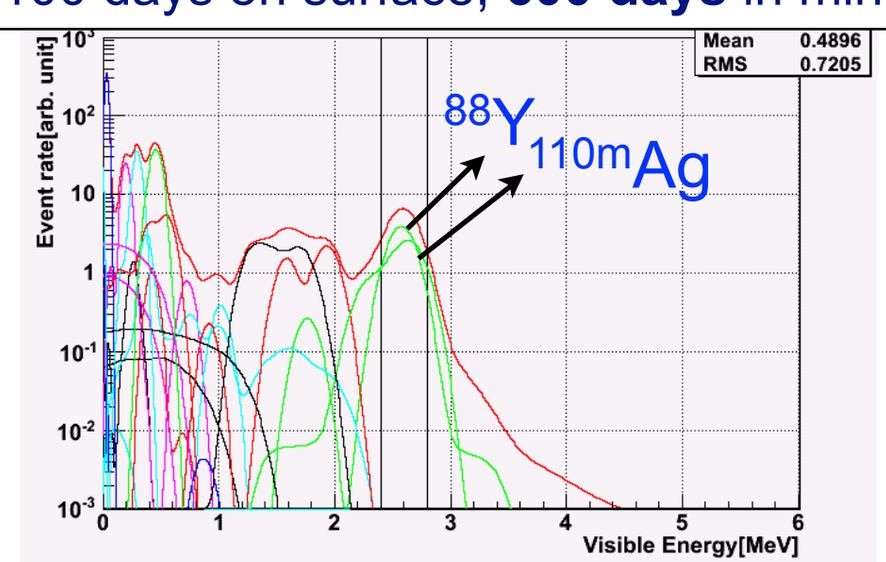
cross-section of ^{136}Xe + 1 GeV proton

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

production by surface proton/neutron is dominant

⟶ ^{110m}Ag and ^{88}Y are candidate BG

100 days on surface, **600 days** in mine



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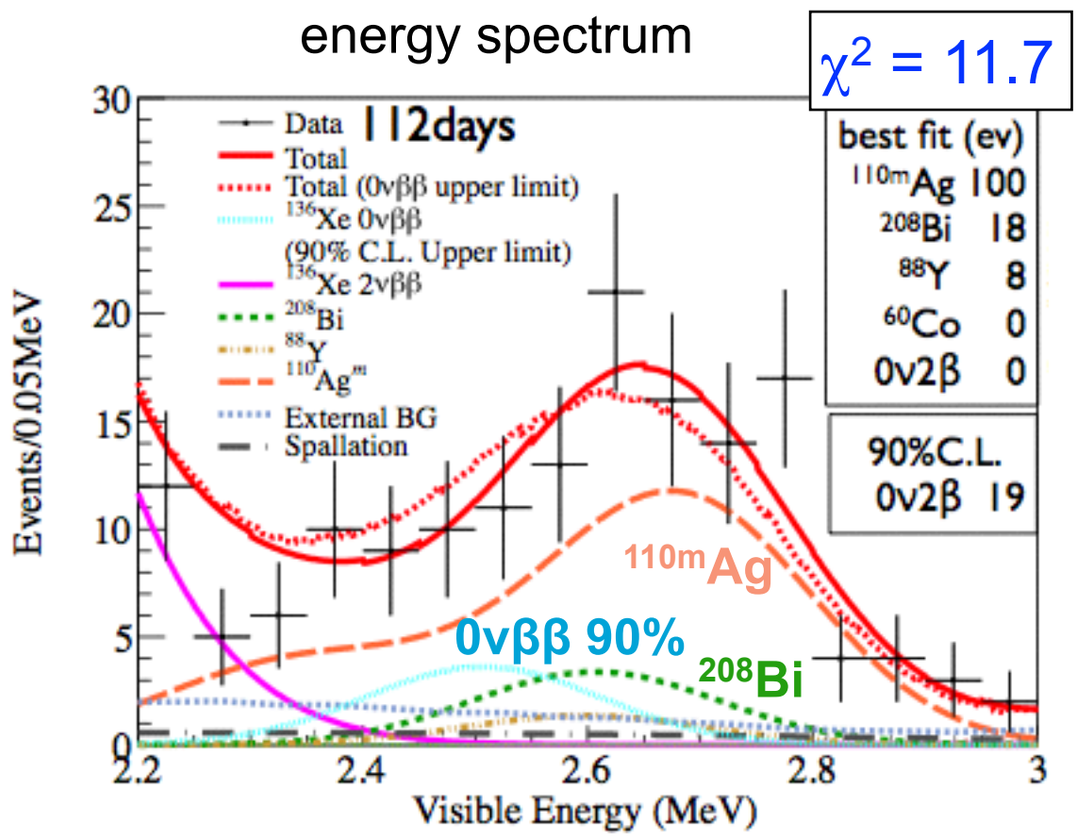
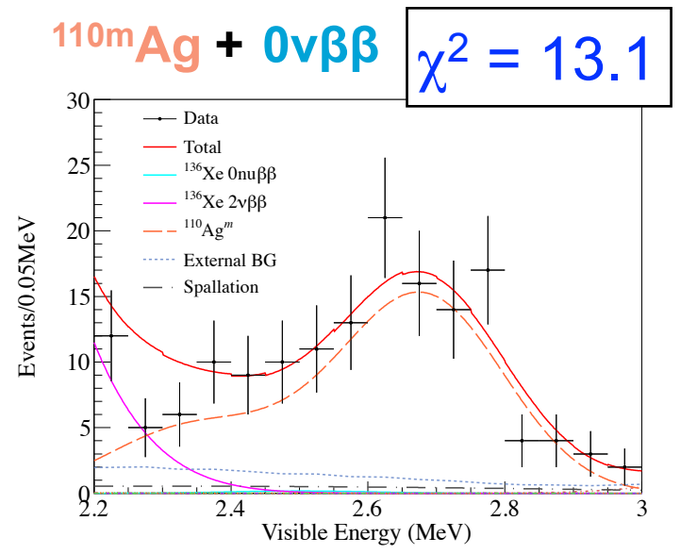
Background

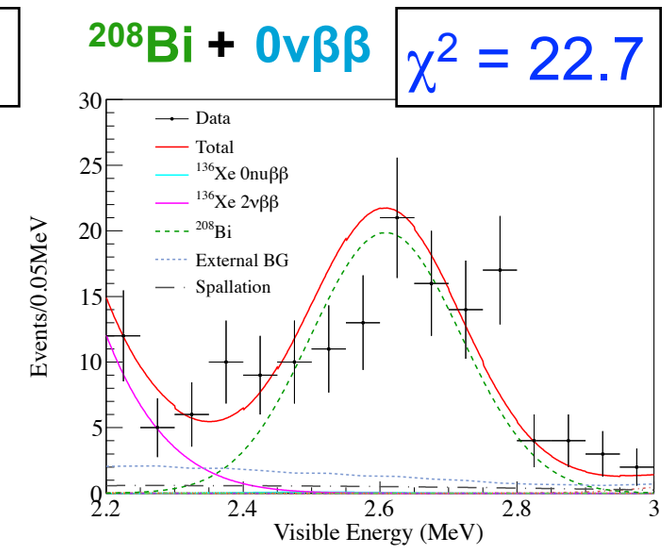
112.3 day livetime

energy spectrum

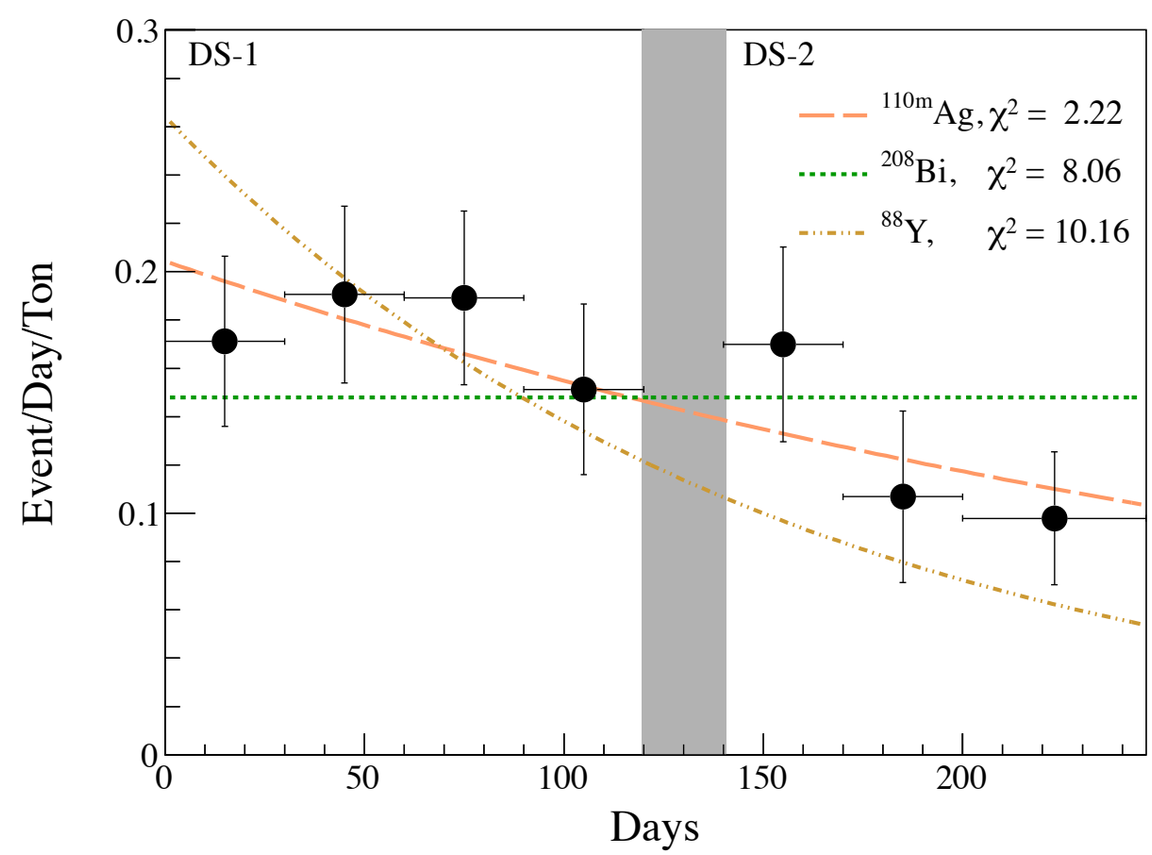


	χ^2	χ^2
simul. fit	12.4	11.6
0ν+	16.5	13.1
0ν+	15.8	22.7 △
0ν+	16.7	22.2 △
0ν+	65	82.9 ✕
0ν only	64.5	85 ✕





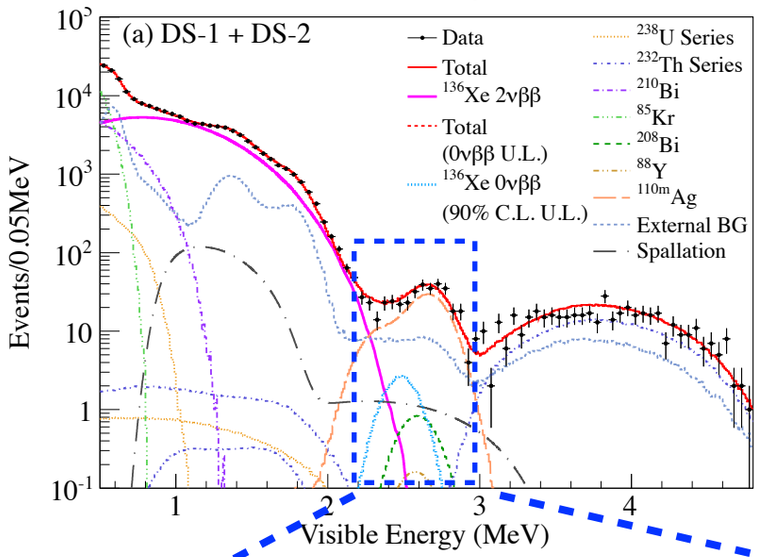
event rate variation (2.2 < E < 3.0 MeV)



consistent with ^{110m}Ag decay (250 days)

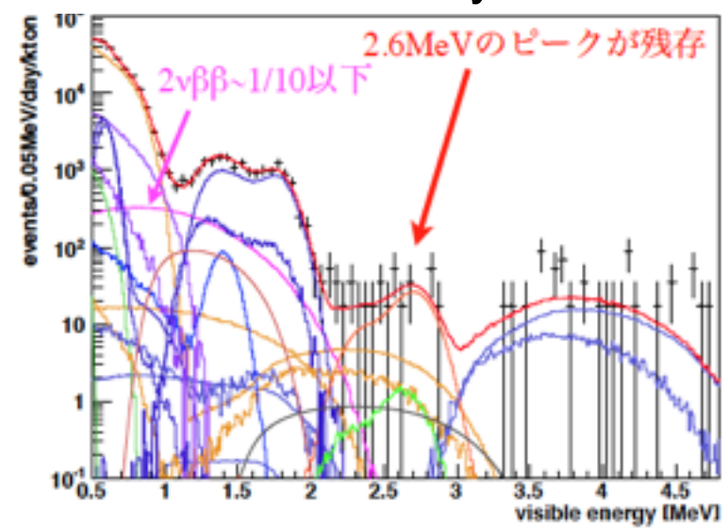
Limit on half-life of ^{136}Xe 0νββ

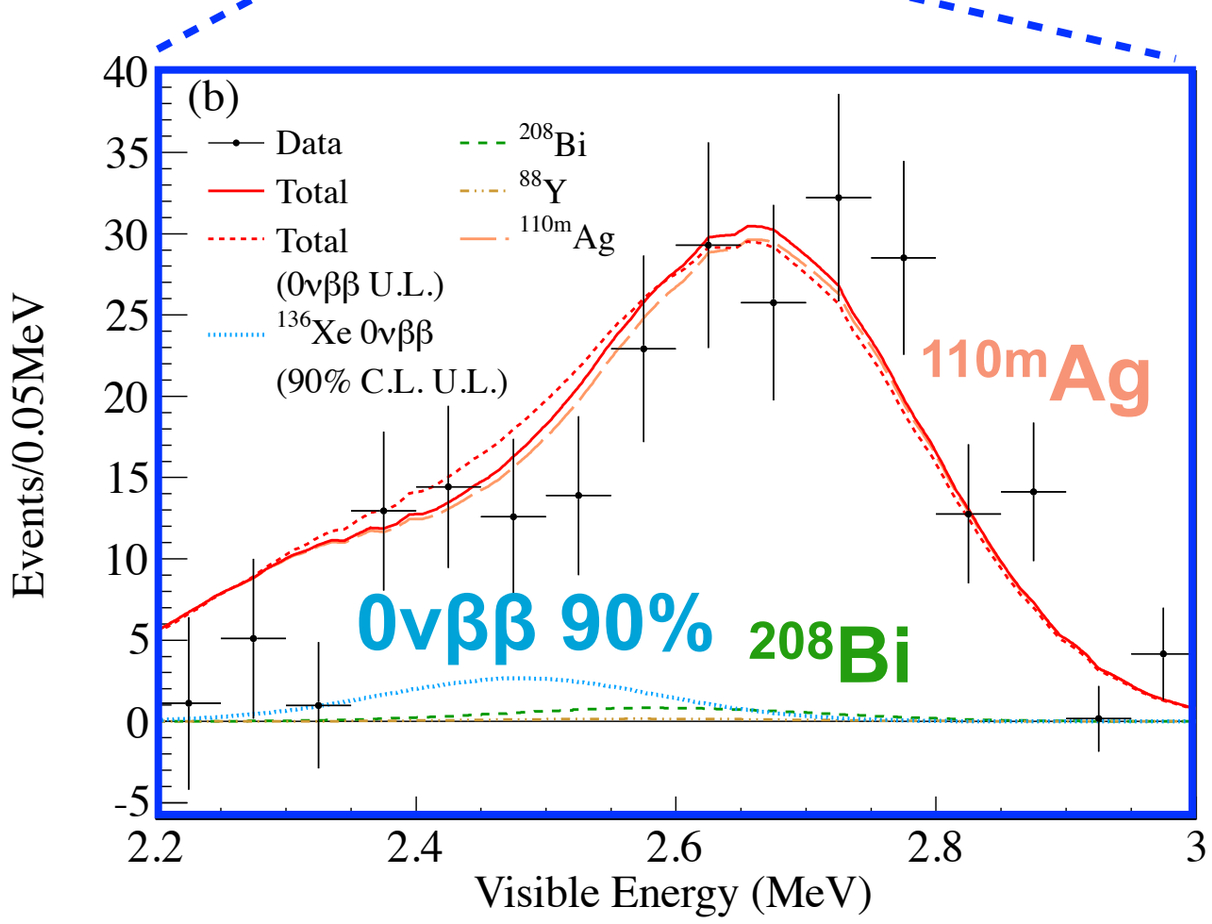
213 days



Xe extraction

15.5 days





89.5kg·yr

$T^{0\nu}_{1/2} > 1.9\times10^{25}$ yr (90% C.L.)

KamLAND-Zen Phase 1 (2012)

$T_{1/2}(^{136}Xe) \rightarrow \langle m_{\beta\beta}\rangle \rightarrow T_{1/2}(^{76}Ge)$

use same NME (parameter)

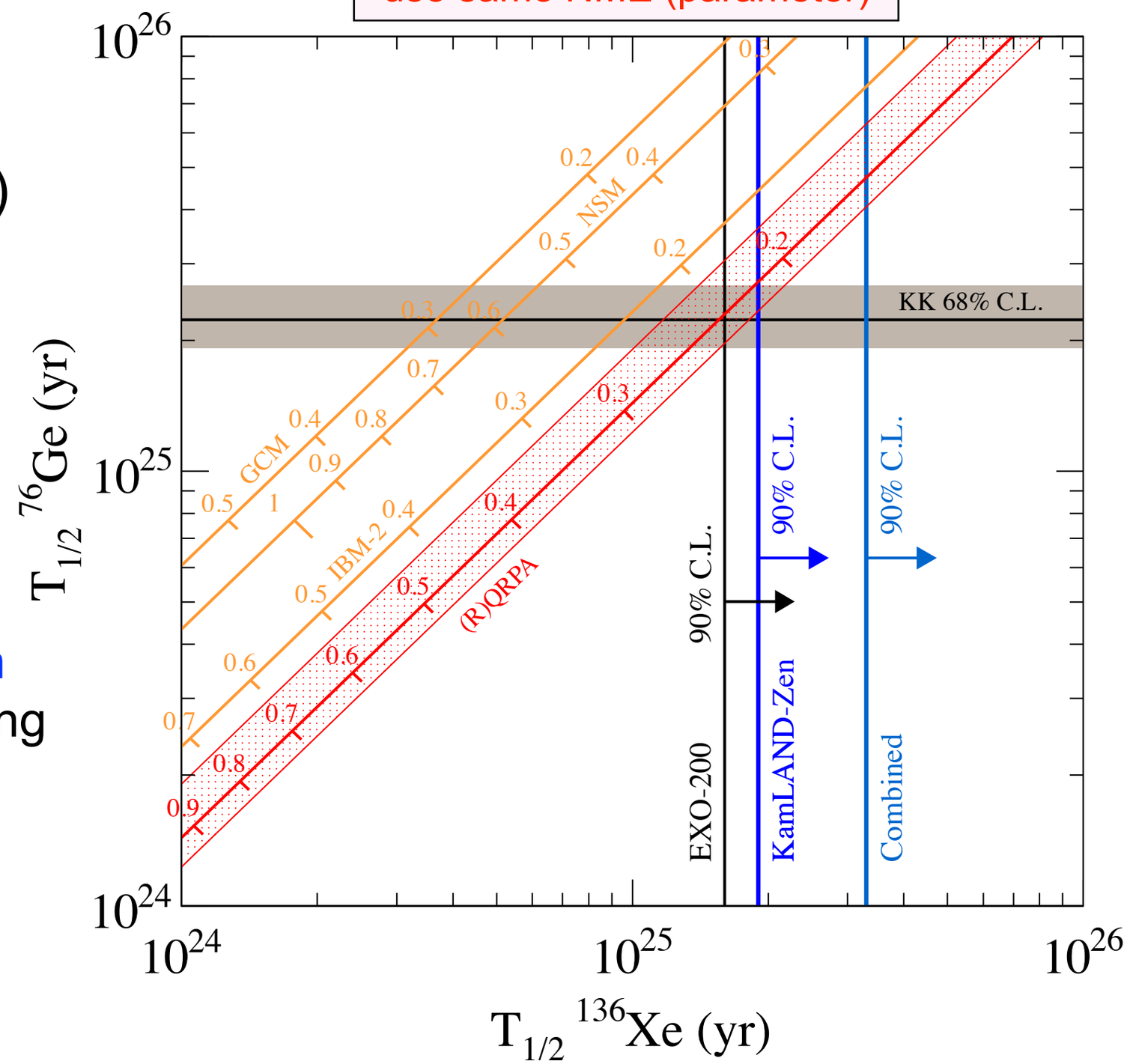
$T_{1/2} > 1.9\times10^{25}$ yr （KL-Zen）

↓ + EXO-200

$T_{1/2} > 3.4\times10^{25}$ yr (combined)

↓ uncertainty from NME

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



It is **inconsistent with KK claim** at more than 97.5% C.L. assuming light Majorana neutrino and available nuclear models

Improvement Efforts after Phase 1

1. Remove radioactive impurities by Xe-LS purification

candidates of ~2.6 MeV peak

⟶ only 4 nuclei ^{110m}Ag (250 d), ^{208}Bi (3.68x10^5 yr), ^{88}Y (107 d), ^{60}Co (5.27 yr)

lifetime longer than 30 days

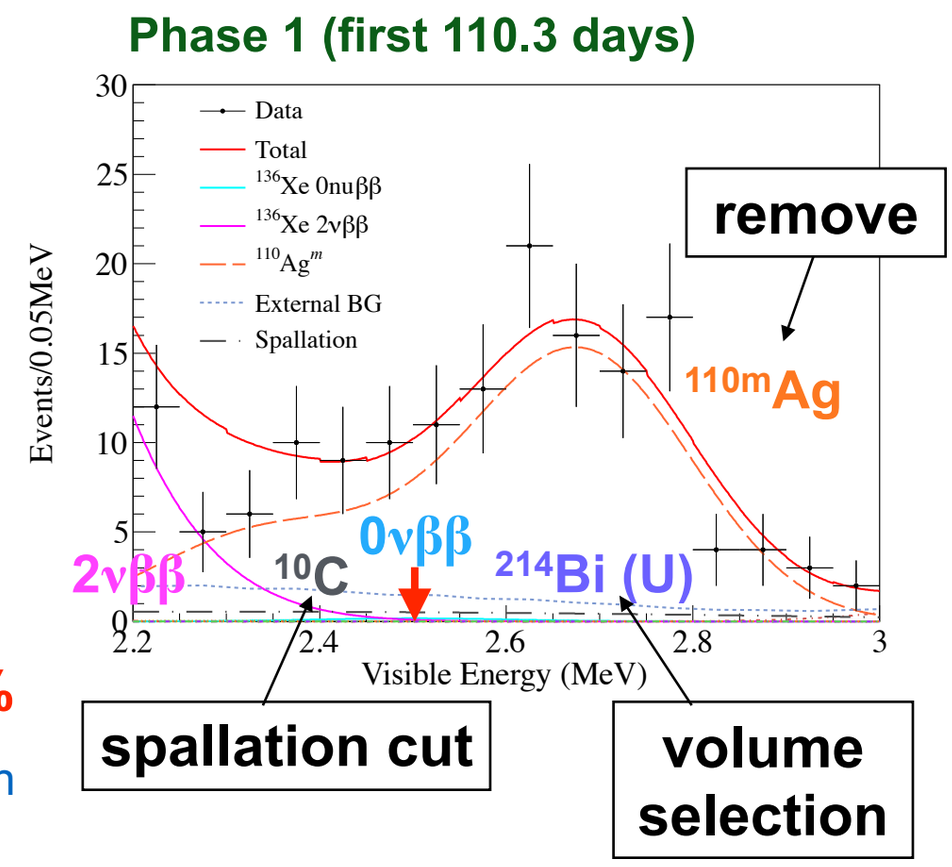
detected in Fukushima fallout

Two possible sources:

(1) contamination by Fukushima-I reactor fallout

(2) cosmogenic Xe spallation while above ground

"primary" background source (^{110m}Ag) can be removed by Xe-LS purification



2. Increase amount of Xenon

	phase 1		phase 2
Xe concentration	(2.44 ± 0.01) wt%	⟶	(2.96 ± 0.01) wt%

increase of S/N ~ 1.2 Xe-pressurized phase is a future option

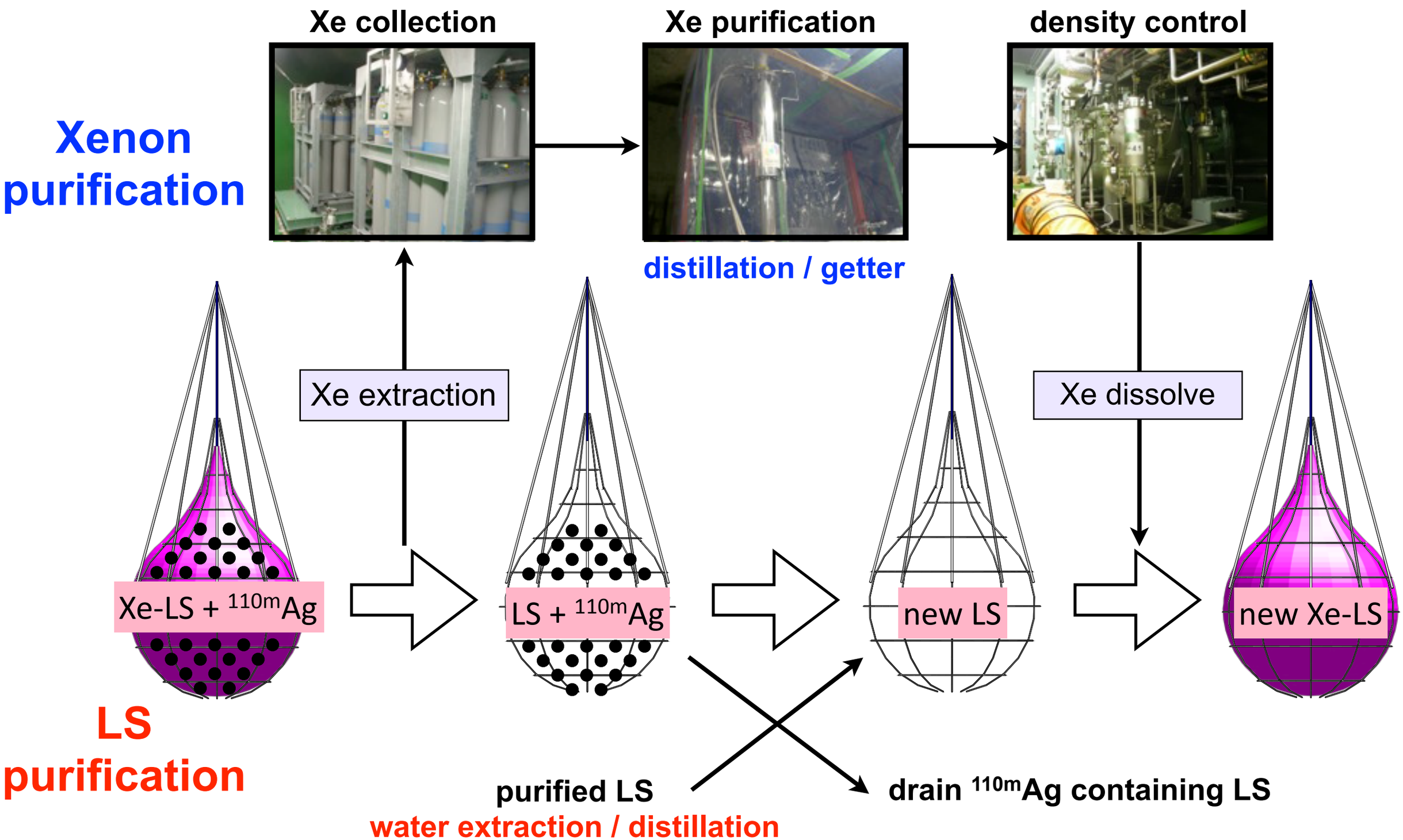
3. Spallation cut after muon

muon-neutron-^{10}C (τ = 27.8 s) triple coincidence ⟶ **^{10}C background rejection**

4. Optimization of volume selection

fiducial volume limitation by ^{214}Bi (U) on the balloon film ⟶ **multi-volume selection**

Purification Strategy



Xenon and LS purification to reduce radioactive impurities

Circulation of LS

Purification activity for 1.5 years

Jun. 2012 Xe extraction from Xe-LS

leakage trouble in diaphragm pump ⟶ increase of balloon film BG

⟶ confirm ^{110m}Ag remains in Xe-depleted LS

Jul. 2012 Xe purification by distillation and getter

Aug. 2012 Replacement by **new purified LS**

⟶ confirm ^{110m}Ag reduction to

1/3 - 1/4 **not enough …**

Nov. 2012 LS distillation in circulation mode (×**1**)

fire accident in the purified air system

Jul. 2013 LS distillation in circulation mode (×**2**)

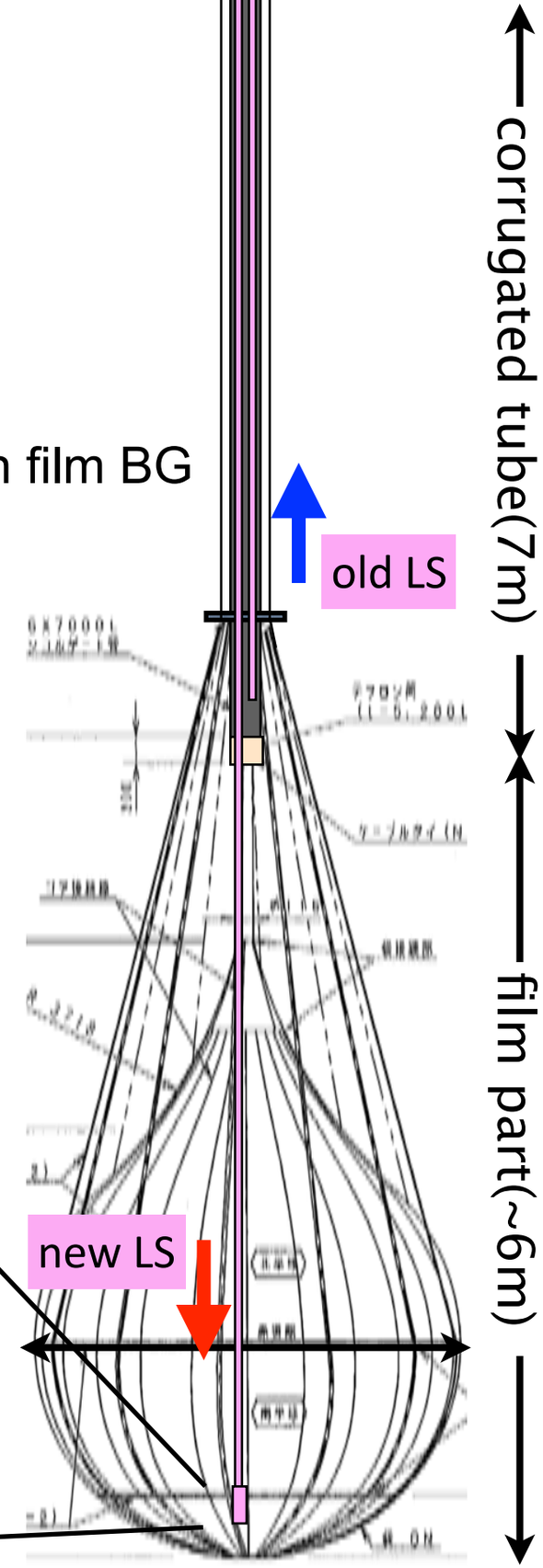
Oct. 2013 Replacement by **new purified LS**

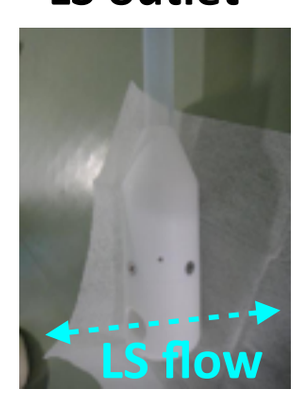
Nov. 2013 Dissolving **purified Xe** into LS

Dec. 2013 Start phase 2 data-taking

⟶ confirm ^{110m}Ag reduction to

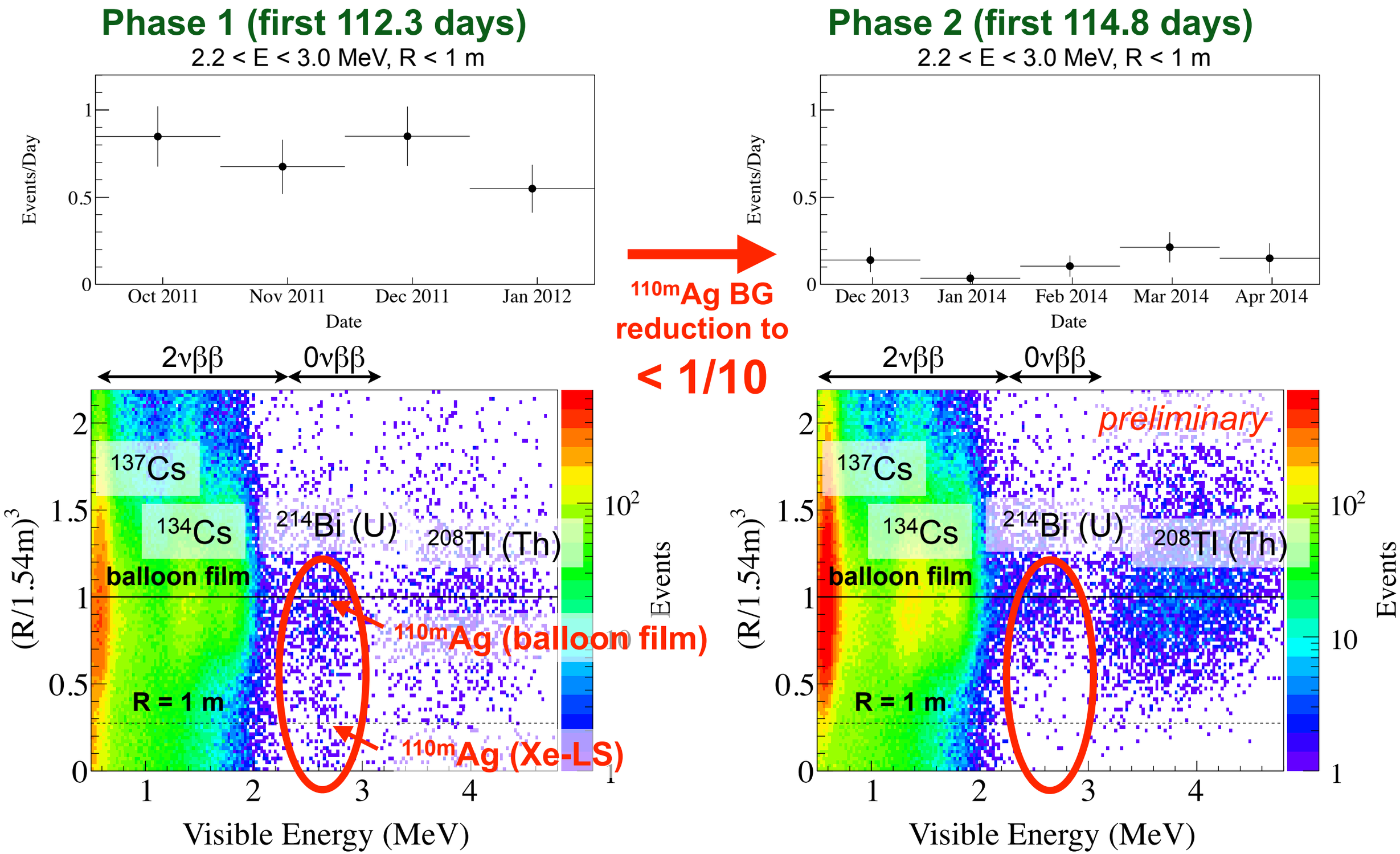
< 1/10 **including the decay**





Phase 2 (low BG) data-taking started on Dec. 11, 2013

^{110m}Ag Background Reduction



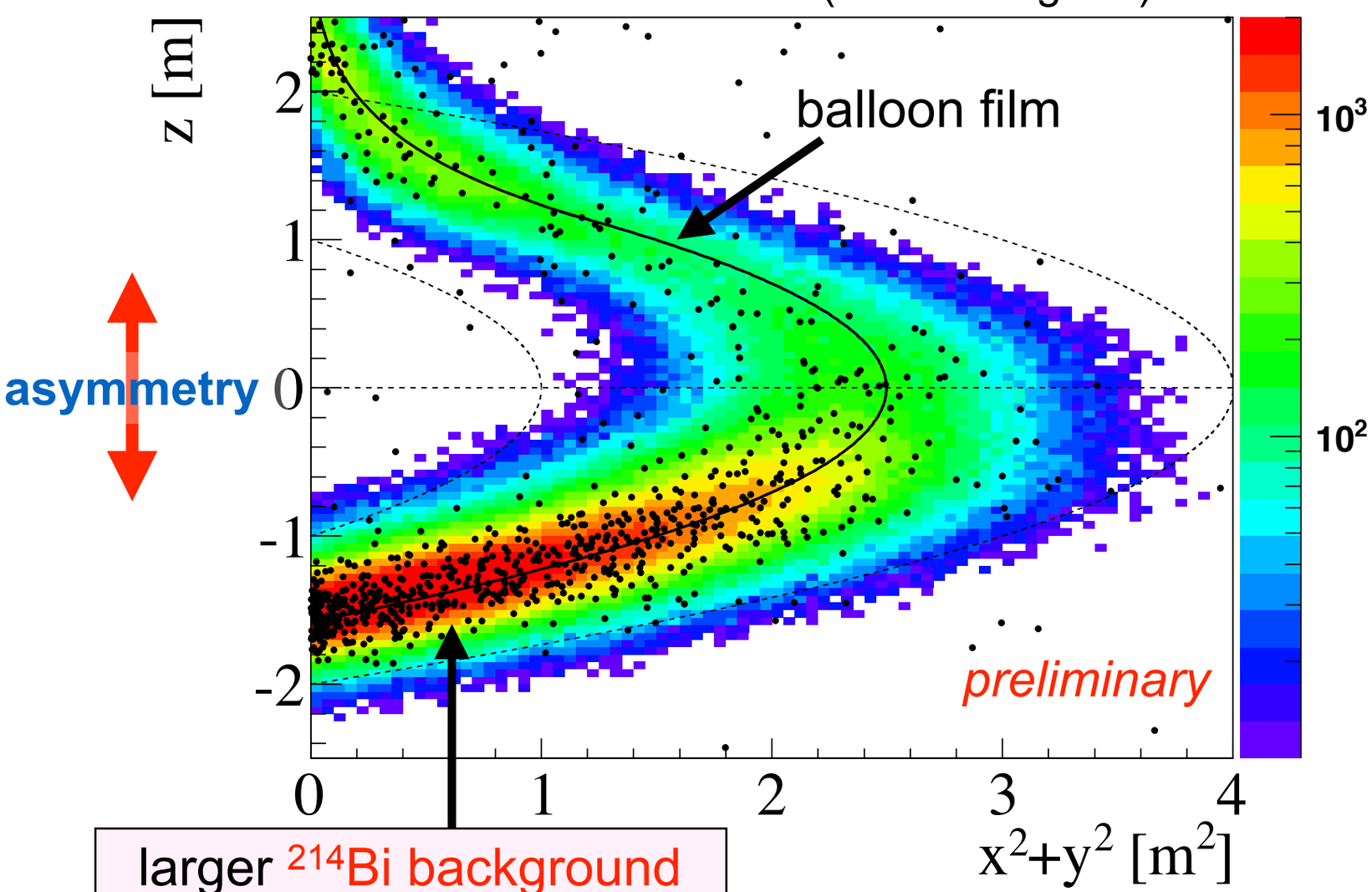
Primary BG : ^{214}Bi (U) at balloon / spallation ^{10}C / remaining ^{110m}Ag?

Optimization of Volume Selection

ROI : 2.3 < E < 2.7 MeV

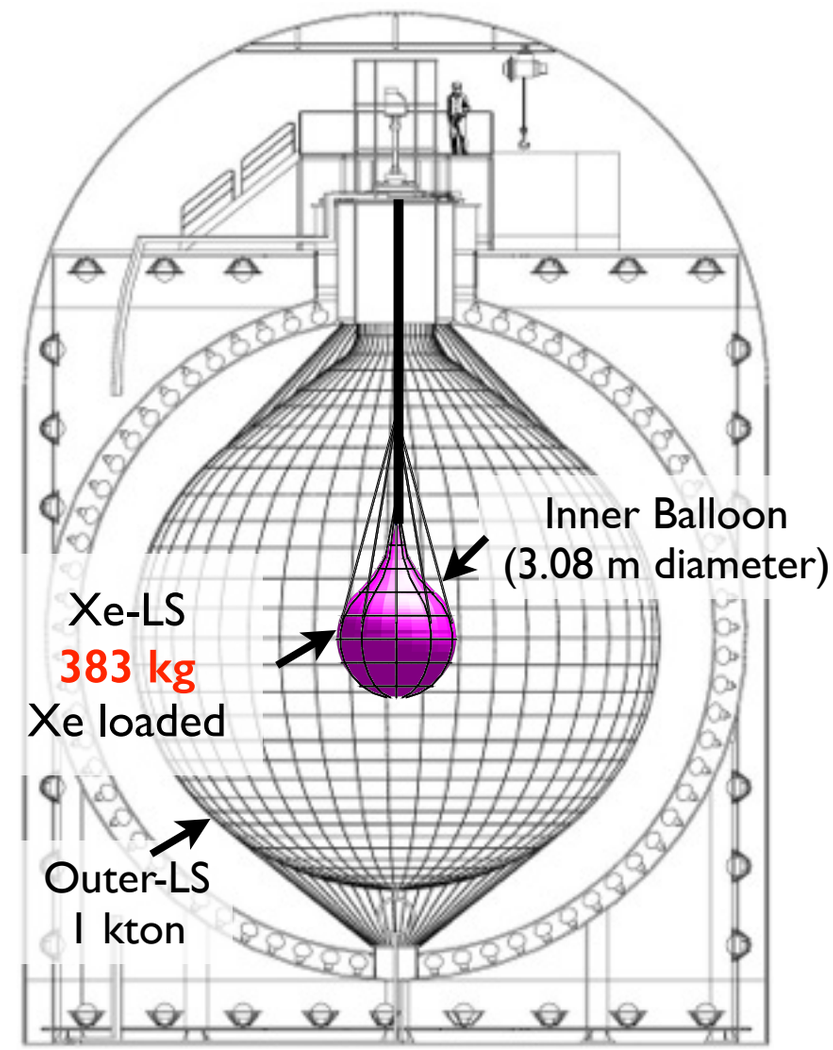
candidate events (black points)

^{214}Bi MC simulation (color histogram)



larger ^{214}Bi background at balloon bottom
(due to leakage in diaphragm pump)

KamLAND-Zen Phase 2



multi-volume selection for analysis optimization

↓

target volume for spectral fit : R < 2.0 m **40 equal volume bins**

(20 bins + 20 bins in upper / lower hemisphere)

Verification of ^{214}Bi Vertex Distribution

vertex is reconstructed from each PMT hit timing

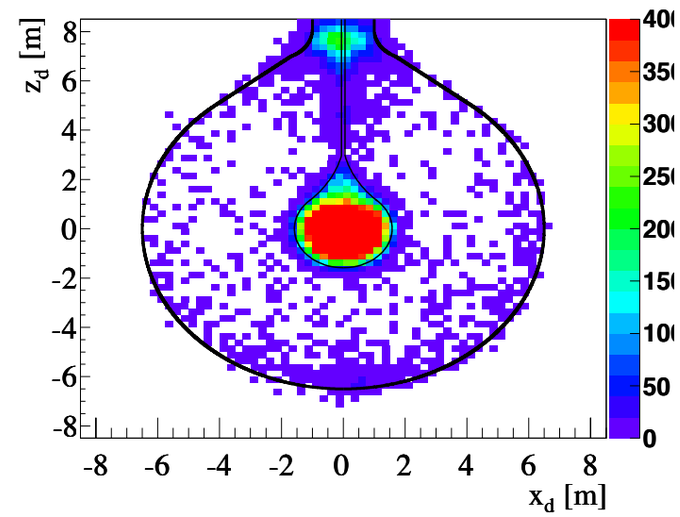
dispersion by gamma-ray diffusion and finite timing resolution

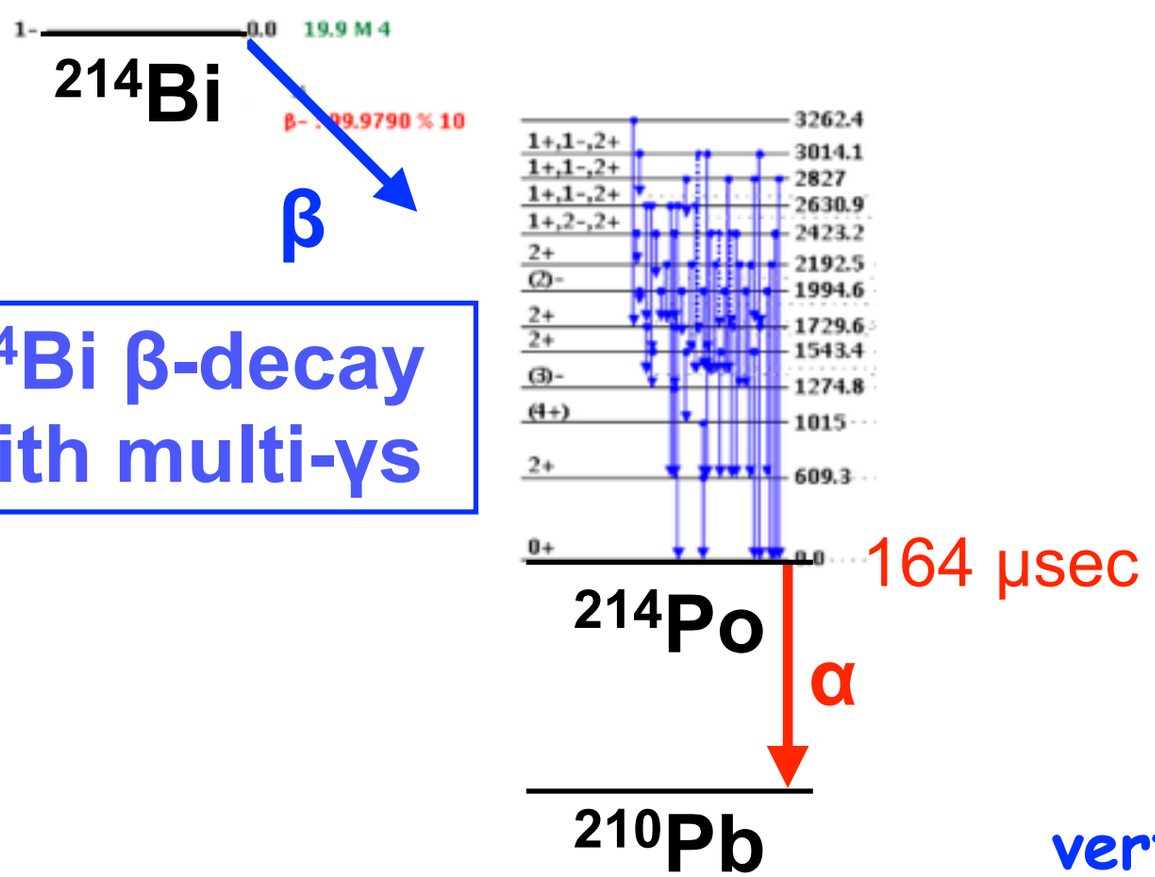
↓

evaluated by detector full MC simulation

(Geant4 detector simulation tuned for KamLAND)

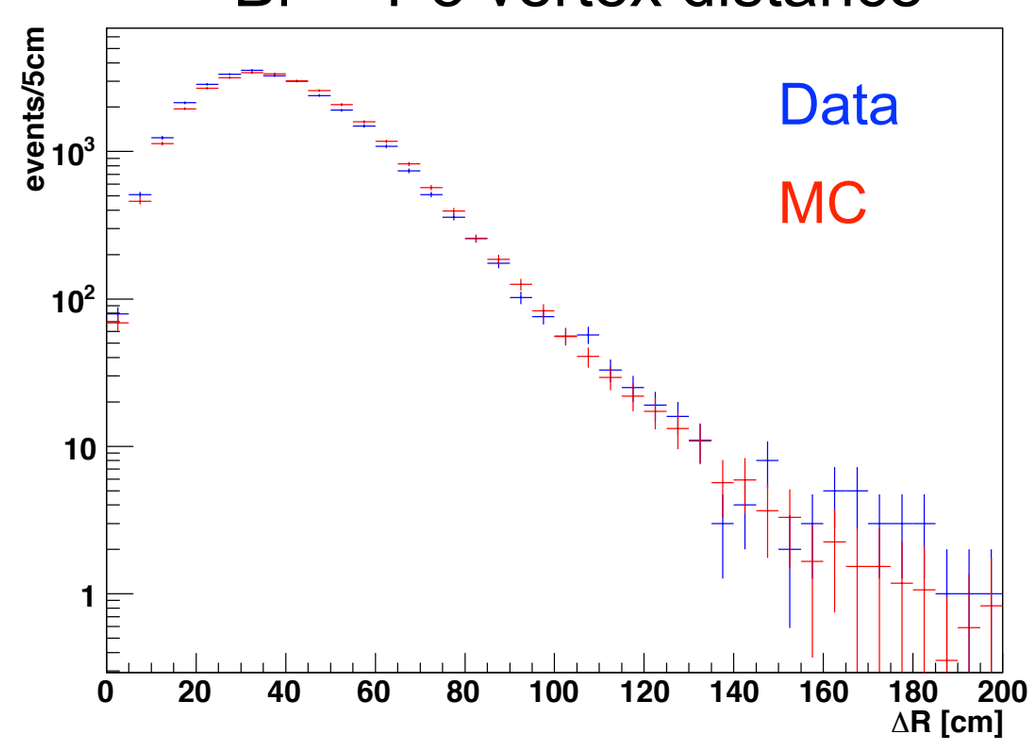
pure ^{214}Bi-^{214}Po samples from initial ^{222}Rn





^{214}Bi β-decay with multi-γs

^{214}Bi-^{214}Po vertex distance

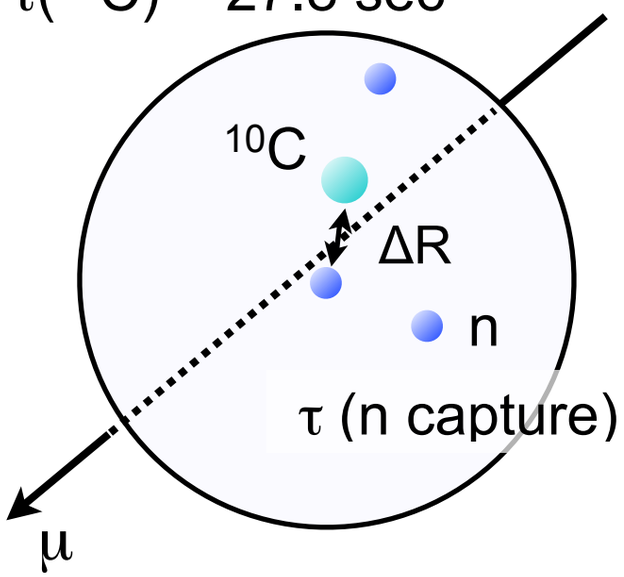


vertex distribution is well reproduced

Spallation Cut after Cosmic-ray Muon

^{10}C rejection by neutron tagging

$\tau(^{10}C)$ = 27.8 sec



space and time correlation cut

- ΔT < 180 s
- ΔR < 1.6 m

preliminary

τ (n capture) ~ 207.5 μs

Baseline restorer and signal splitter

1GHz FADC + 3 range 200 MHz FADC for each channel

Trigger module

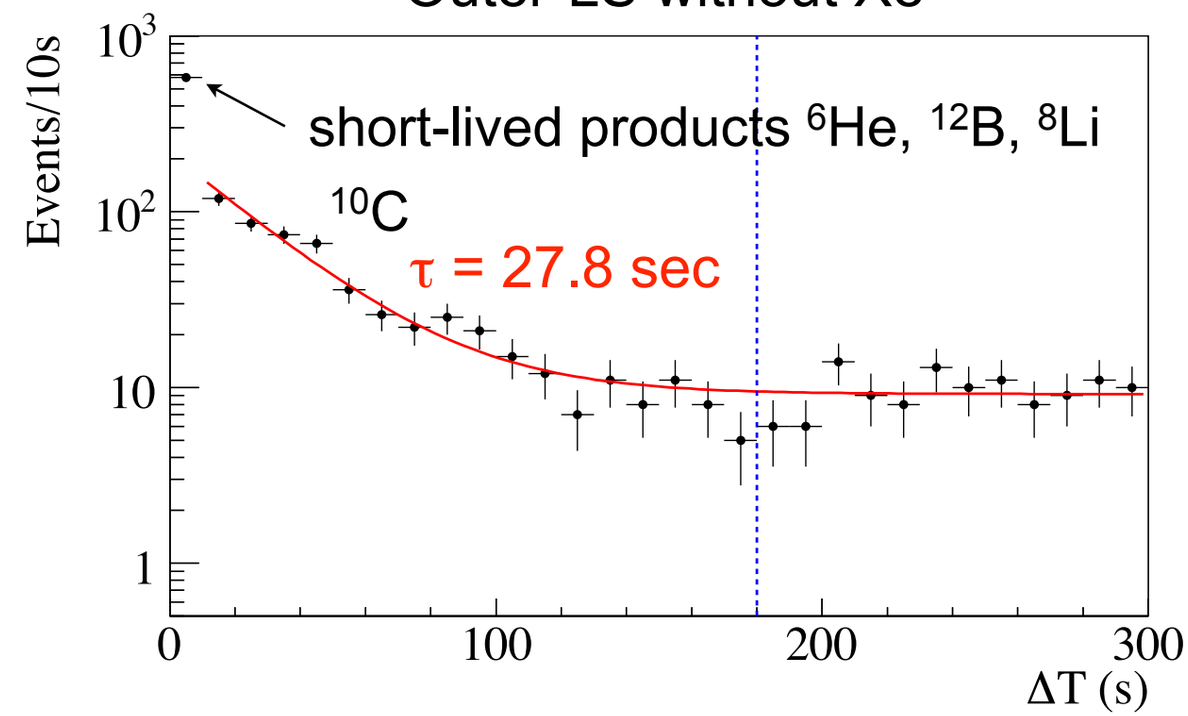
preliminary

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

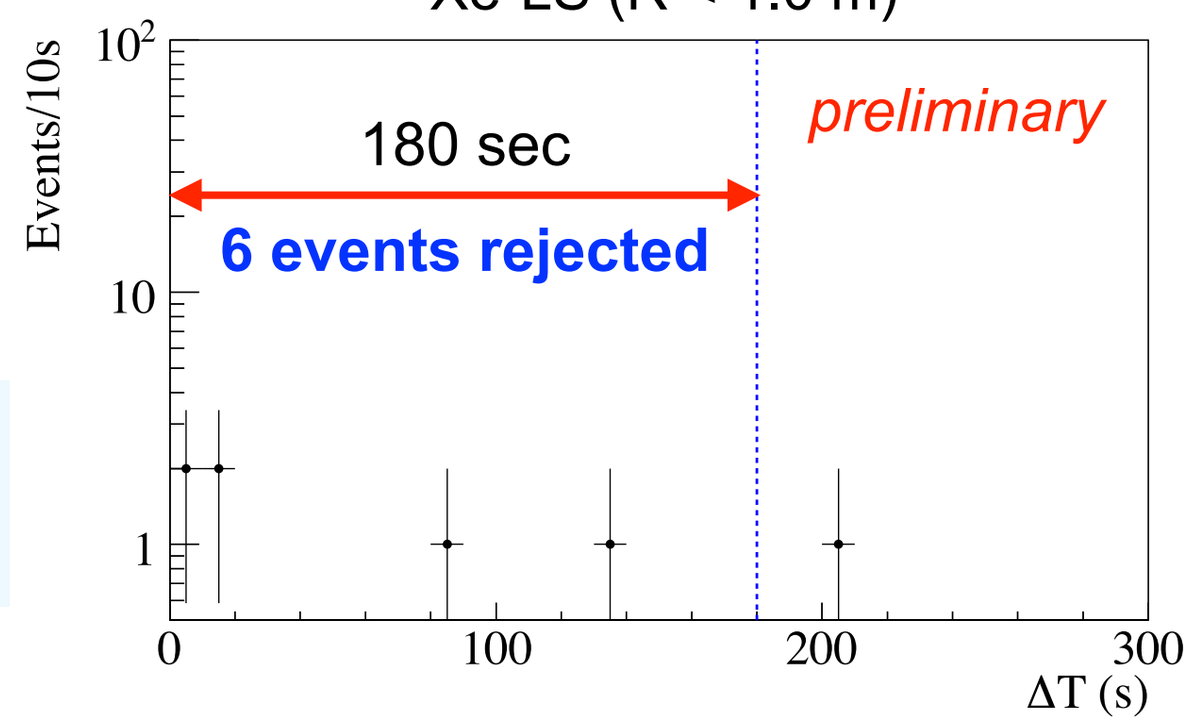
Efficient background rejection

2.2 < E < 3.5 MeV

Outer-LS without Xe



Xe-LS (R < 1.0 m)

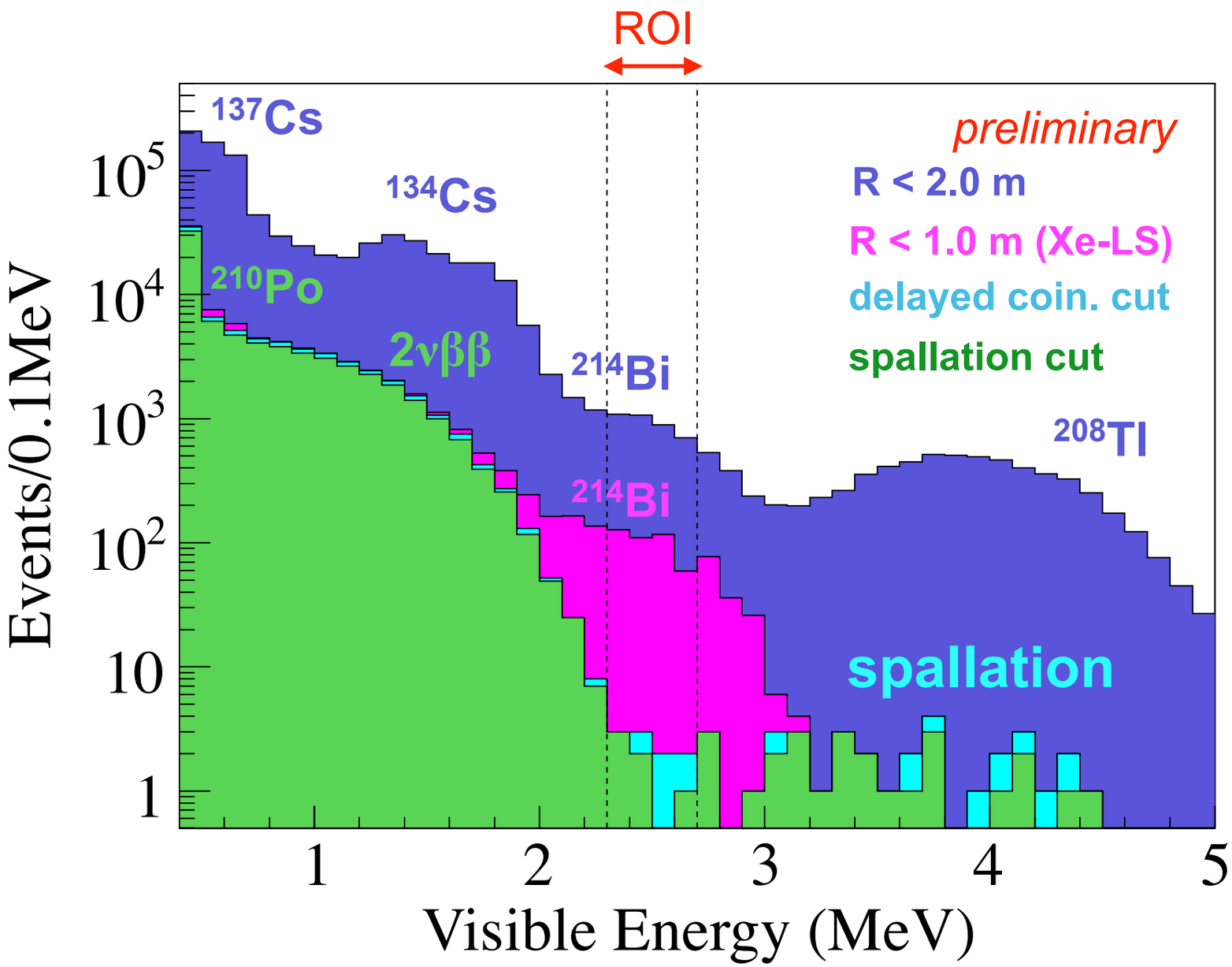


Event Reduction

Phase 2 **114.8 days**

ββ isotope ^{136}Xe **90.77% enriched** $Q_{\beta\beta}$ = 2458 keV

348 kg ^{136}Xe in all volume Dec. 11, 2013 - May 1, 2014



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

Dec. 11, 2013 - May. 1, 2014
around mini-balloon
(R < 2.0 m)
&
muon veto

3756 events

volume cut
R < 1.0 m
(V = 4.2 m^3)

413 events

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

10 events

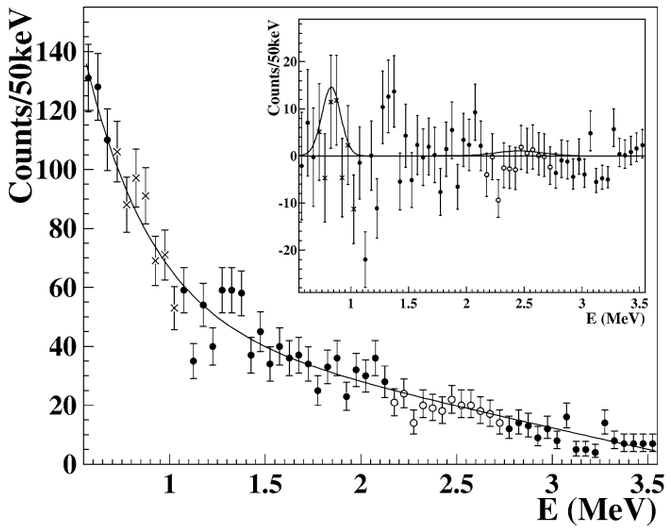
Spallation cut

6 events
(Livetime 114.8 days)

Volume selection and spallation cut distinguish backgrounds

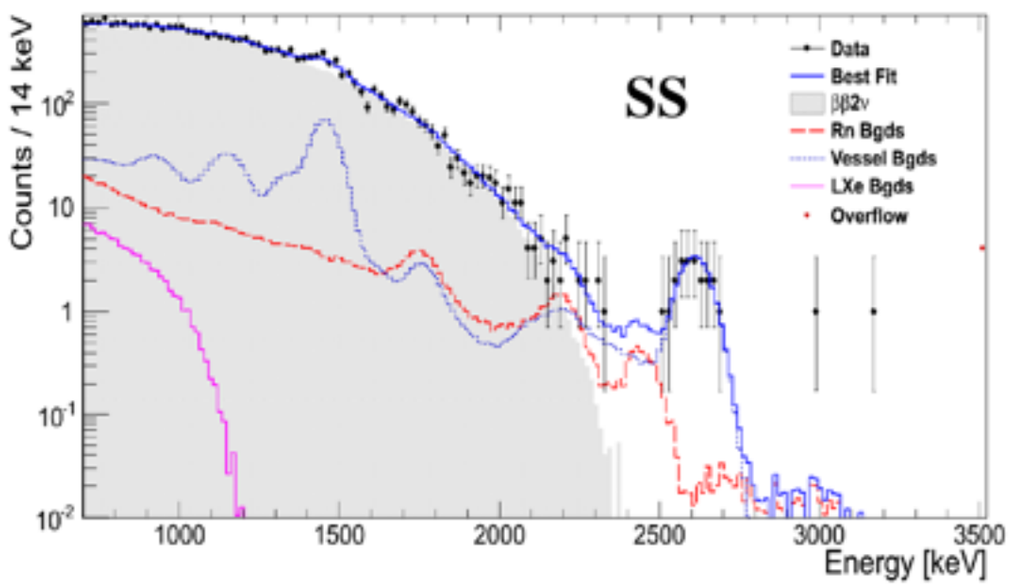
Fit to Energy Spectrum for 2νββ

DAMA (2002) Liquid Xe scintillator



$T^{2\nu}_{1/2} > 1.0 \times 10^{22}$ yr at 90% C.L.

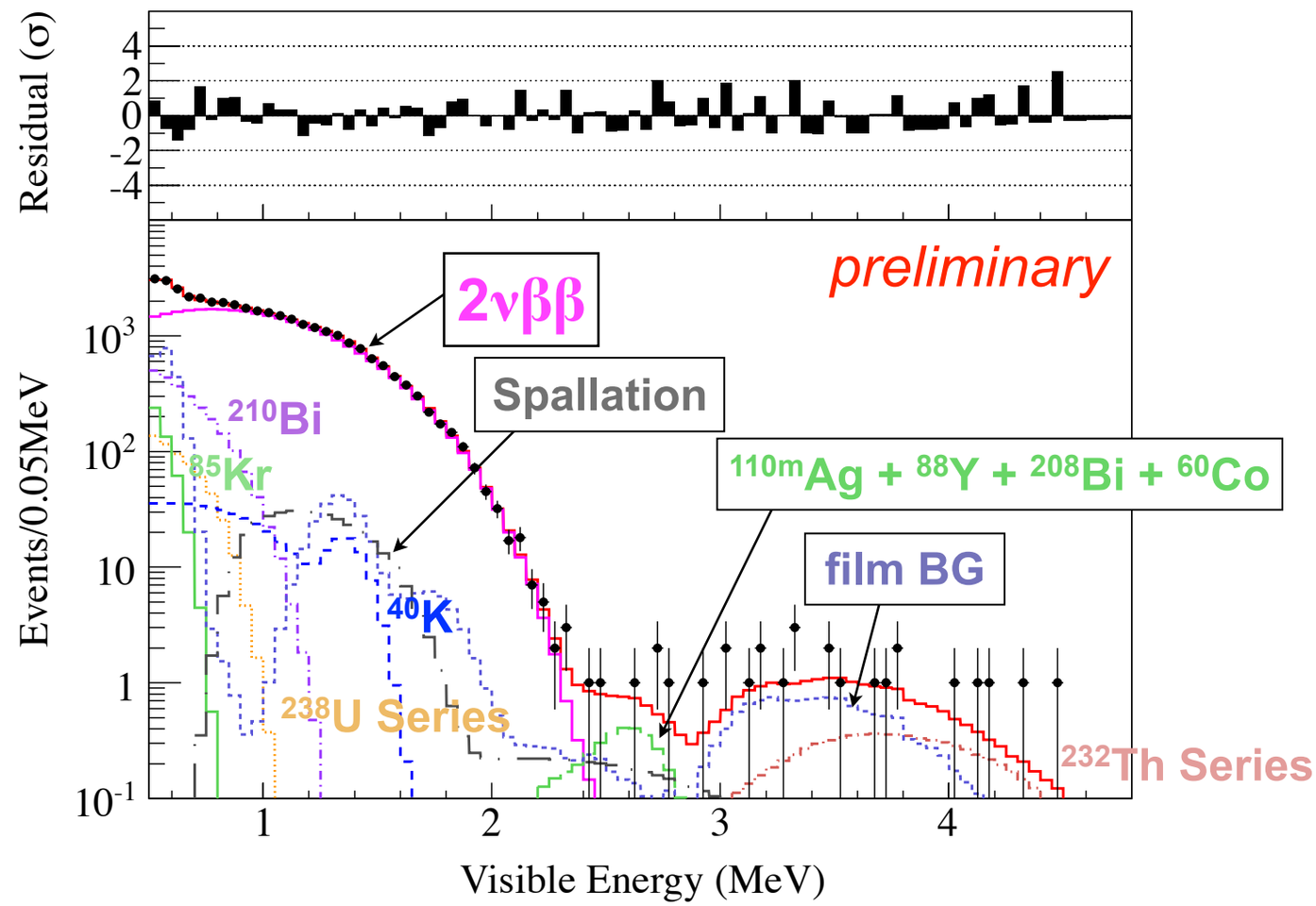
EXO-200 (2013) Liquid Xe TPC + scintillator



$T^{2\nu}_{1/2} = 2.165 \pm 0.016(\text{stat}) \pm 0.059(\text{syst}) \times 10^{21}$ yr ← consistent with EXO-200

KamLAND-Zen (2014) Xe loaded liquid scintillator

Phase 2 **Internal (R < 1.0 m)**



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

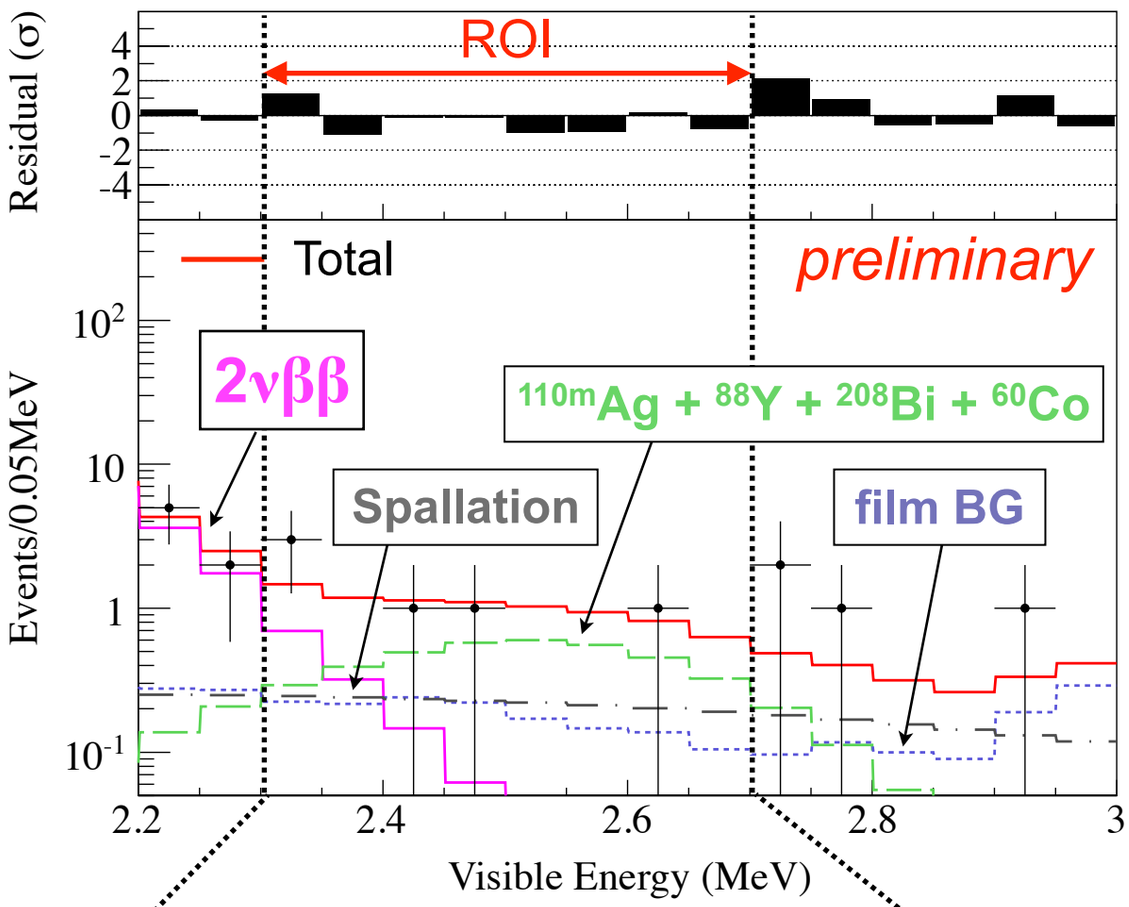
consistent with KamLAND-Zen Phase 1

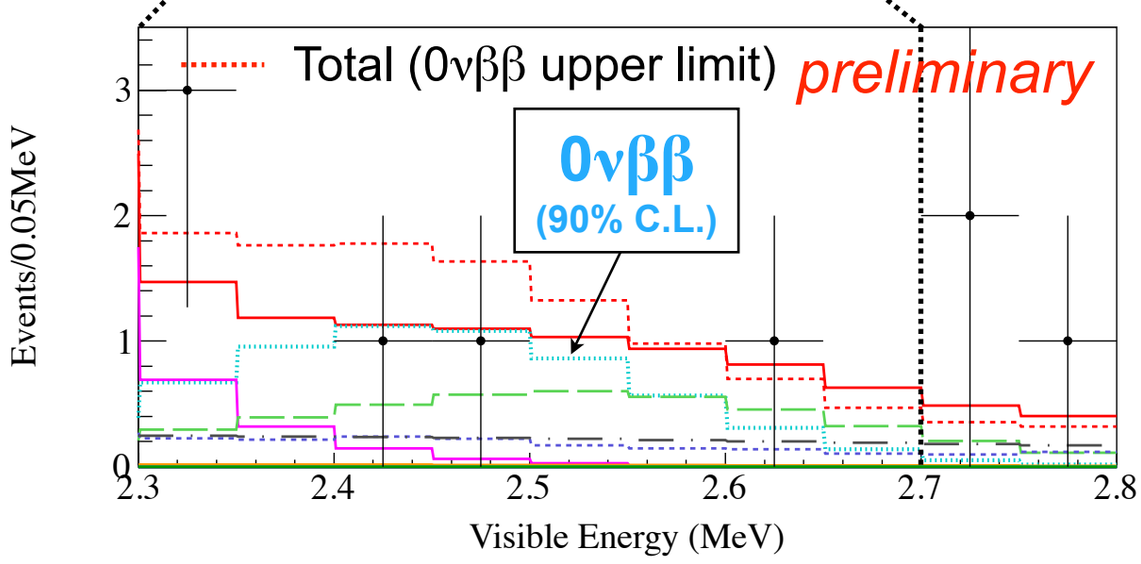
↓

$T^{2\nu}_{1/2} = 2.30 \pm 0.02(\text{stat}) \pm 0.12(\text{syst}) \times 10^{21}$ yr

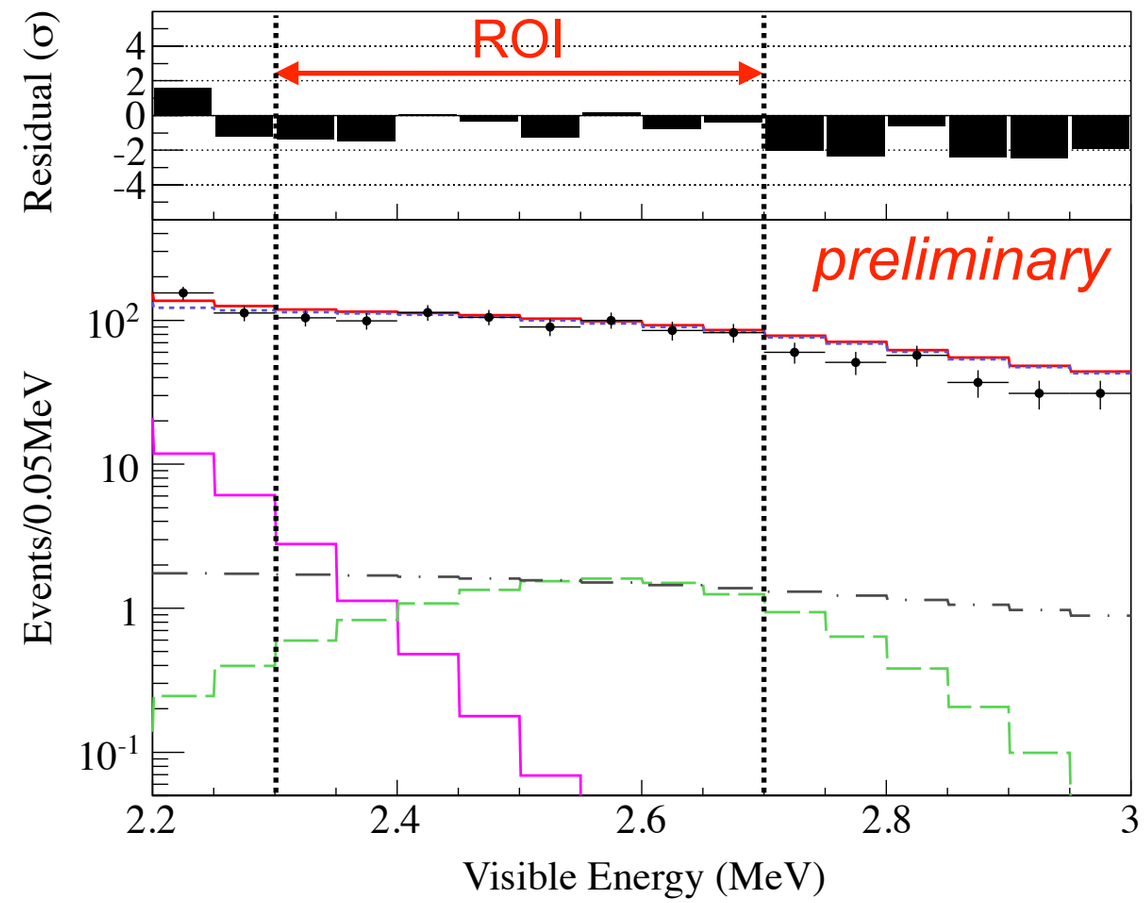
Fit to Energy Spectra for 0νββ

Internal (R < 1.0 m)





External (1.0 < R < 2.0 m)



Fit to Energy-Volume 2D spectra

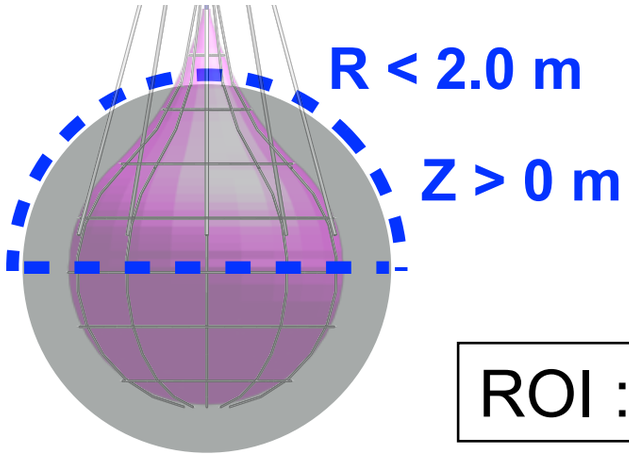
Limits on 0νββ at 90% C.L.

< 17.0 events/day/kton-LS

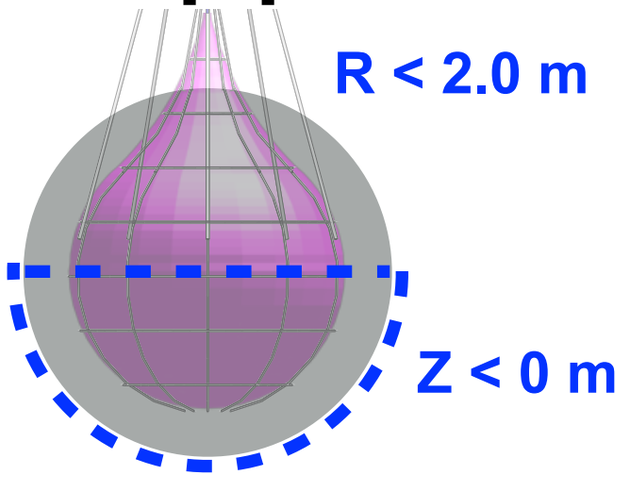
↓

$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr

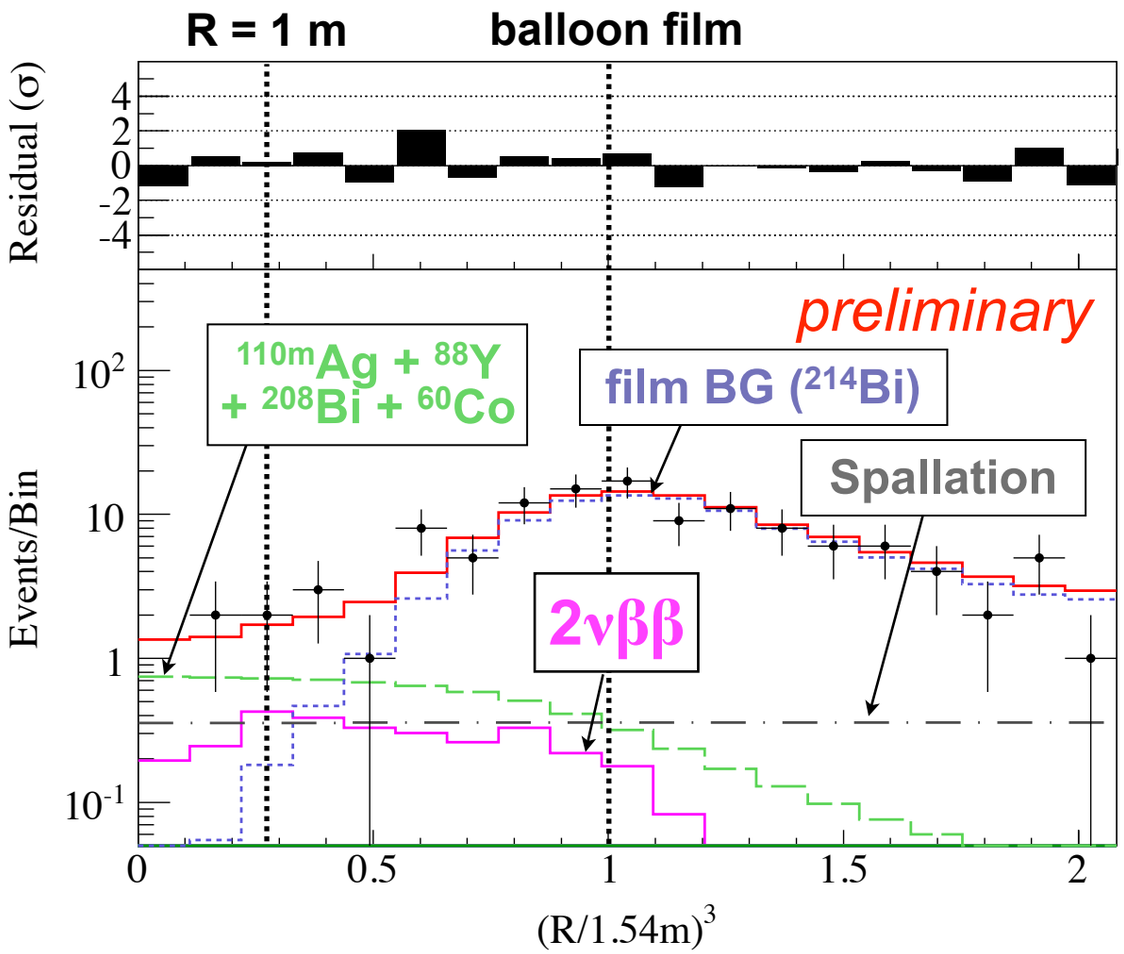
Fit to R^3 Spectra for $0\nu\beta\beta$



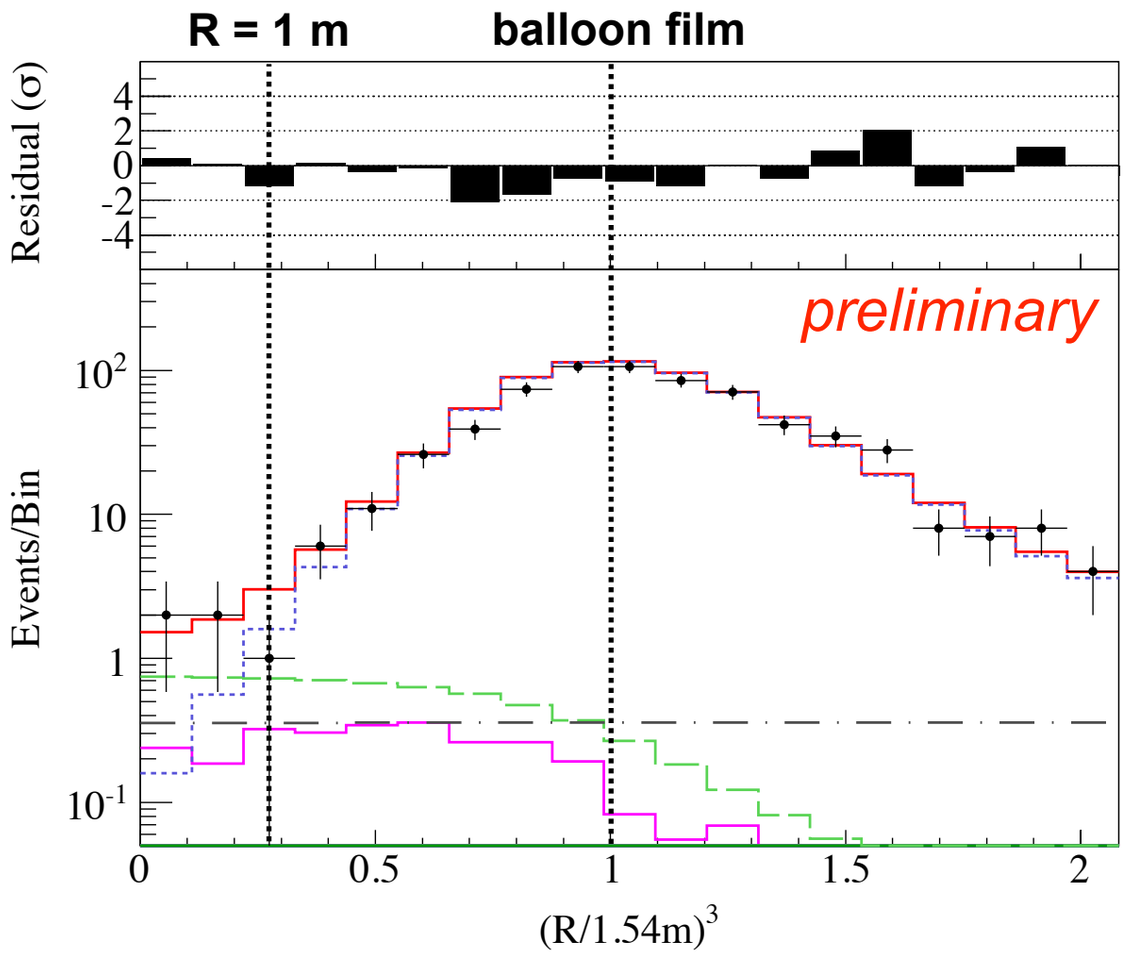
ROI : 2.3 < E < 2.7 MeV



Upper hemisphere (Z > 0 m)



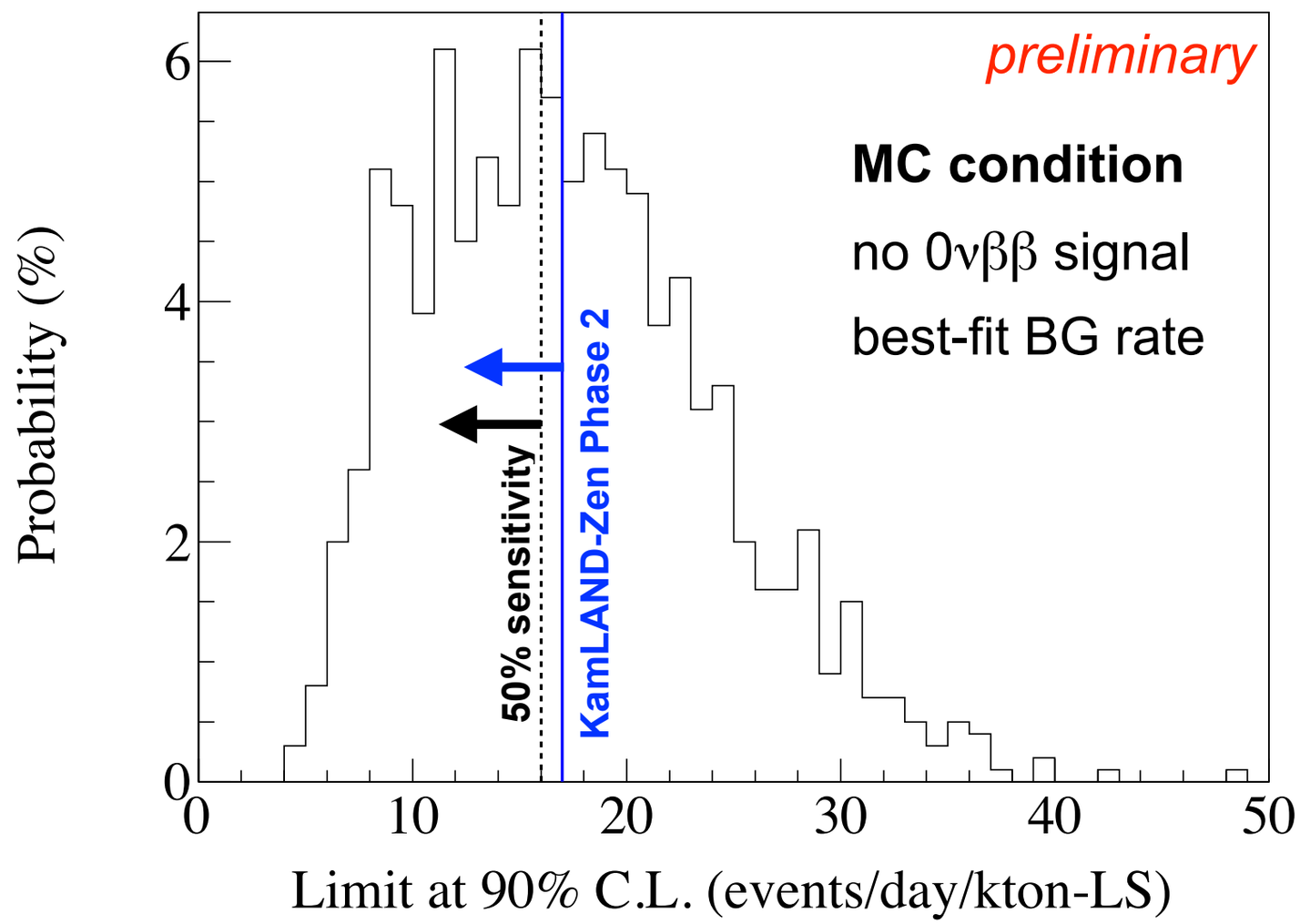
Lower hemisphere (Z < 0 m)



^{214}Bi vertex dispersion is consistent with data

Upper Limits from Toy MC

distribution of 0νββ limits from Toy MC



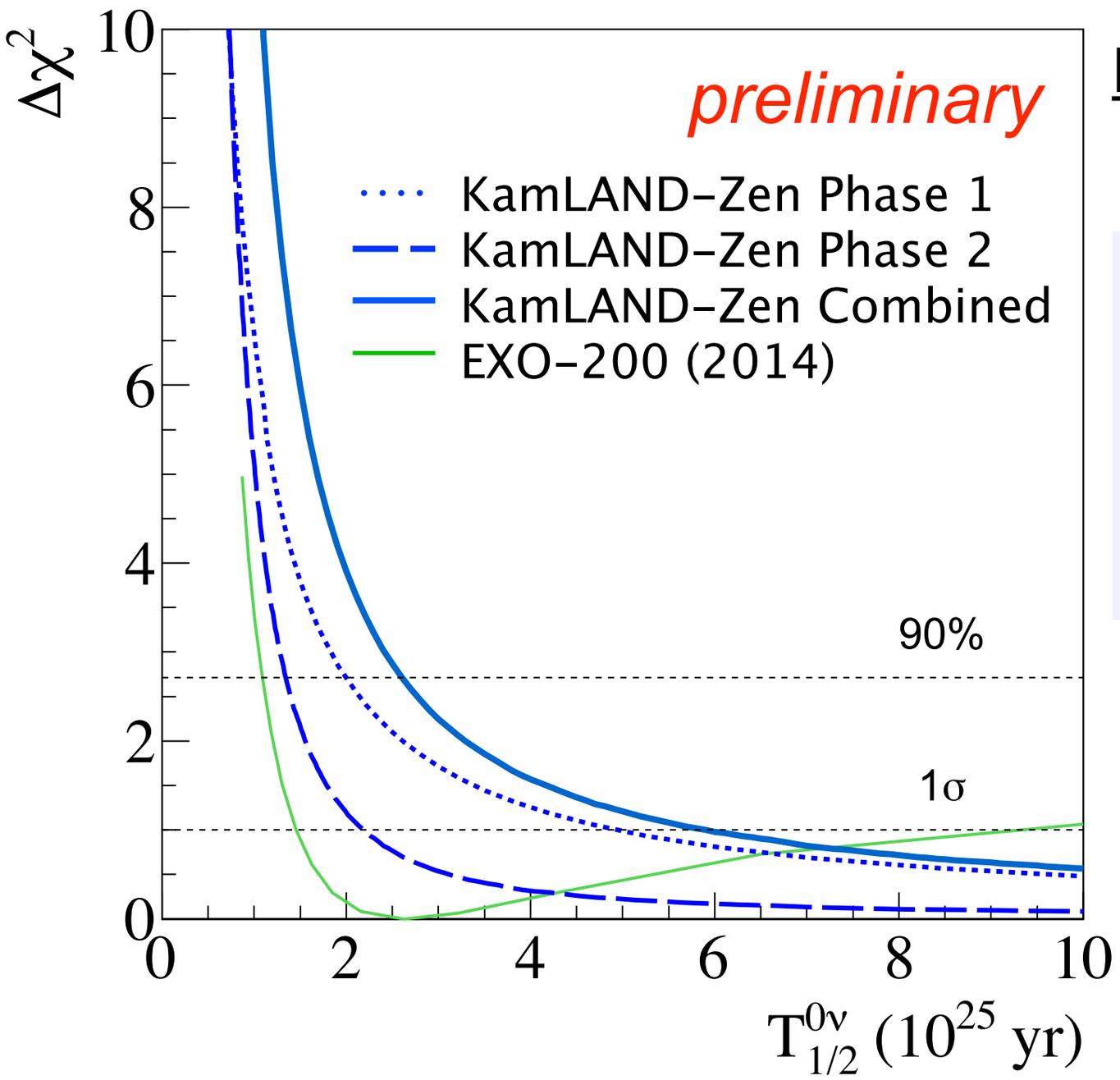
< 17 events/day/kton-LS 52% of the time

< 16 events/day/kton-LS 50% of the time

Sensitivity is checked by MC assuming best-fit BG rate

^{136}Xe 0νββ Decay Half-life

combined result (Phase 1 + 2)



Half-life limit at 90% C.L.

KamLAND-Zen

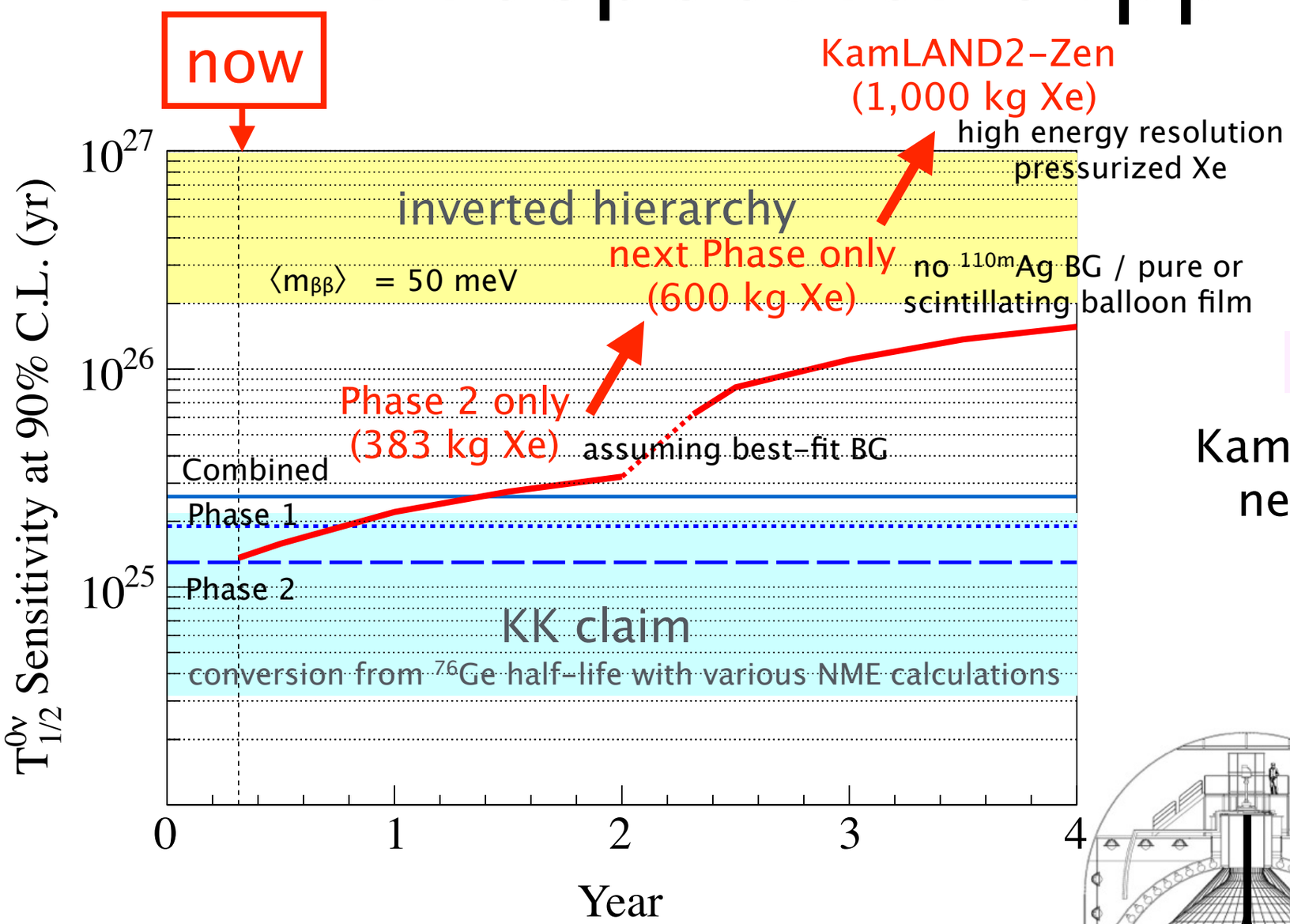
Phase 1	$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr
Phase 2	$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr
Combined	$T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr

QRPA NME model
J. Phys. G 39 124006 (2012)

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

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

Prospect for 0νββ Search

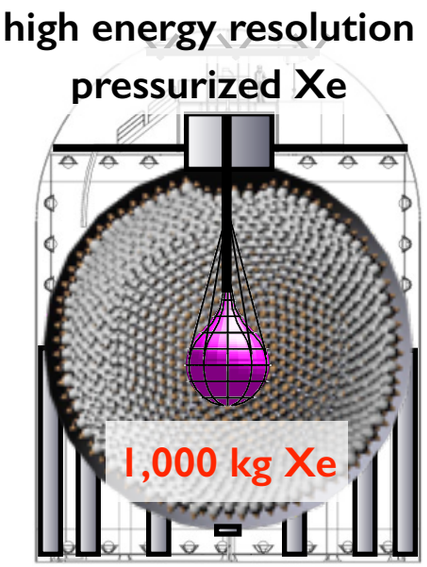


Future sensitivity
KamLAND-Zen Phase 1
KamLAND-Zen Phase 2
KamLAND-Zen Combined

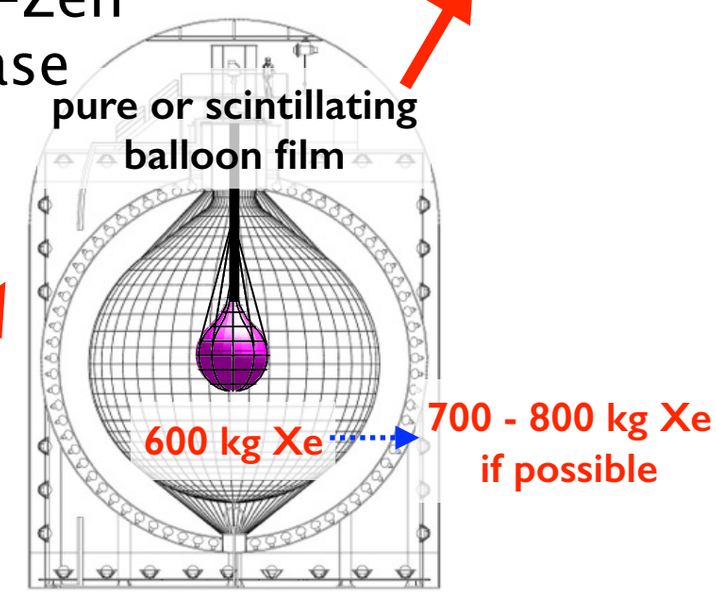
KamLAND2-Zen

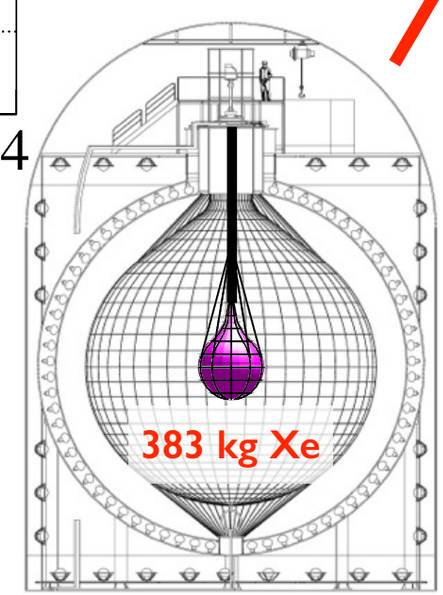
test of inverted neutrino mass hierarchy

target ⟨mββ⟩ ~ 20 meV



KamLAND-Zen next phase





KamLAND-Zen Phase 2

Detector improvements are planned in the near future

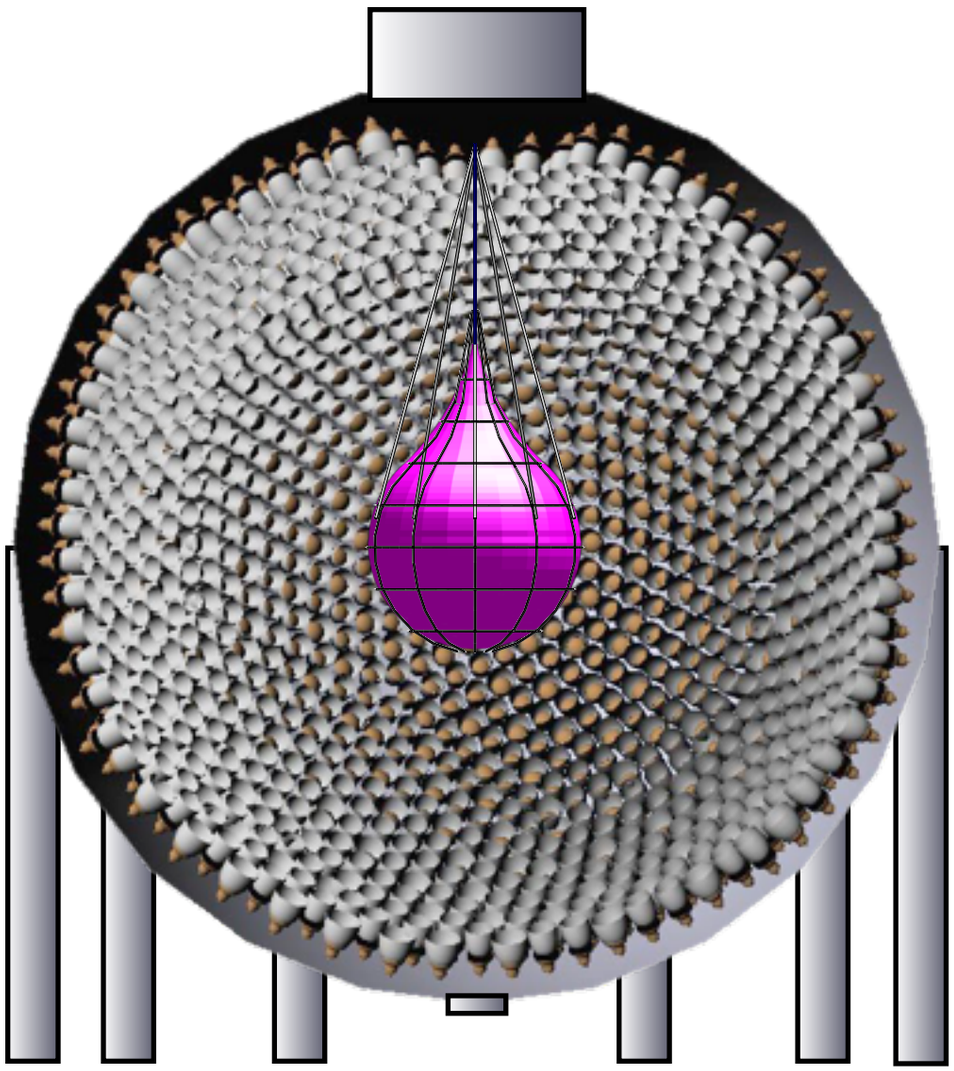
KamLAND2-Zen

General-purpose

larger crane
strengthen floor
enlarge opening

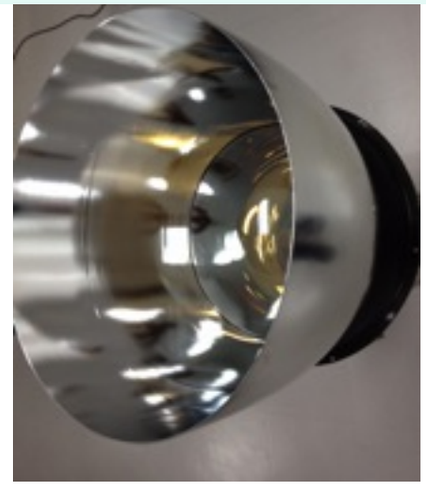
accommodate various devices
CaF_2, $CdWO_4$, NaI, …

1000 kg enriched Xe

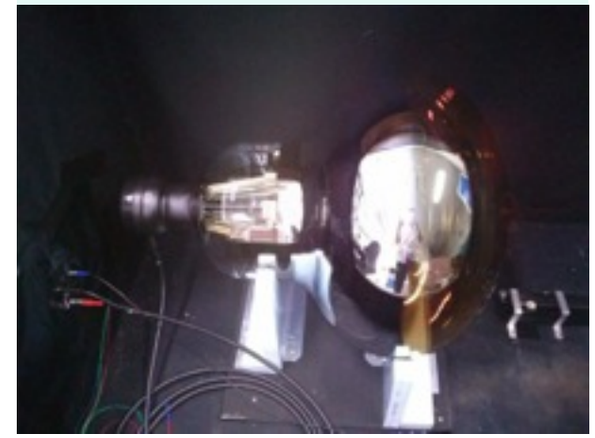


High performance

Winstone Cone



High Q.E. PMT



17”Φ→20”Φ, ε=22% → 30%

Photo-coverage > **x2**

Light Collection Eff. > **x1.8**

x1.9

New Liquid Scintillator

x1.4

KamLAND liquid scintillator	8,000 photon/MeV
typical liquid scintillator	12,000 photon/MeV

σ(2.6MeV)= 4% → < 2.5%

naive calc. < 2%

target $\langle m_{\beta\beta} \rangle$ ~ 20 meV / 5 year

Summary

- We demonstrated the Xe-LS purification by circulating the liquid scintillator.
- The overall reduction factor for the ^{110m}Ag background including the decay is more than 10.
- New results from KamLAND-Zen are presented.

KamLAND-Zen limits on $0\nu\beta\beta$ at 90% C.L.

preliminary

Phase 1 (213 days)	$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr
Phase 2 (115 days)	$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr
Combined	$\mathbf{T^{0\nu}_{1/2} > 2.6 \times 10^{25}}$ **yr**

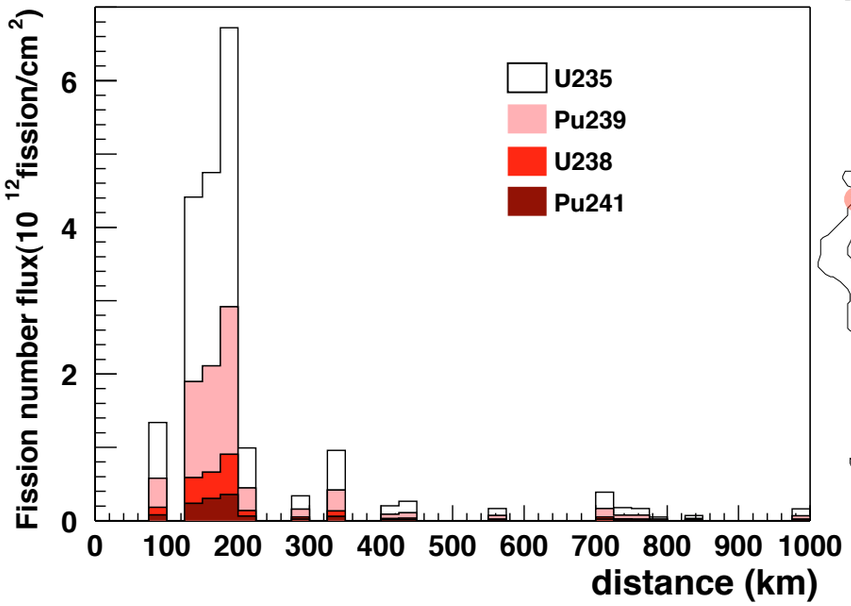
↓

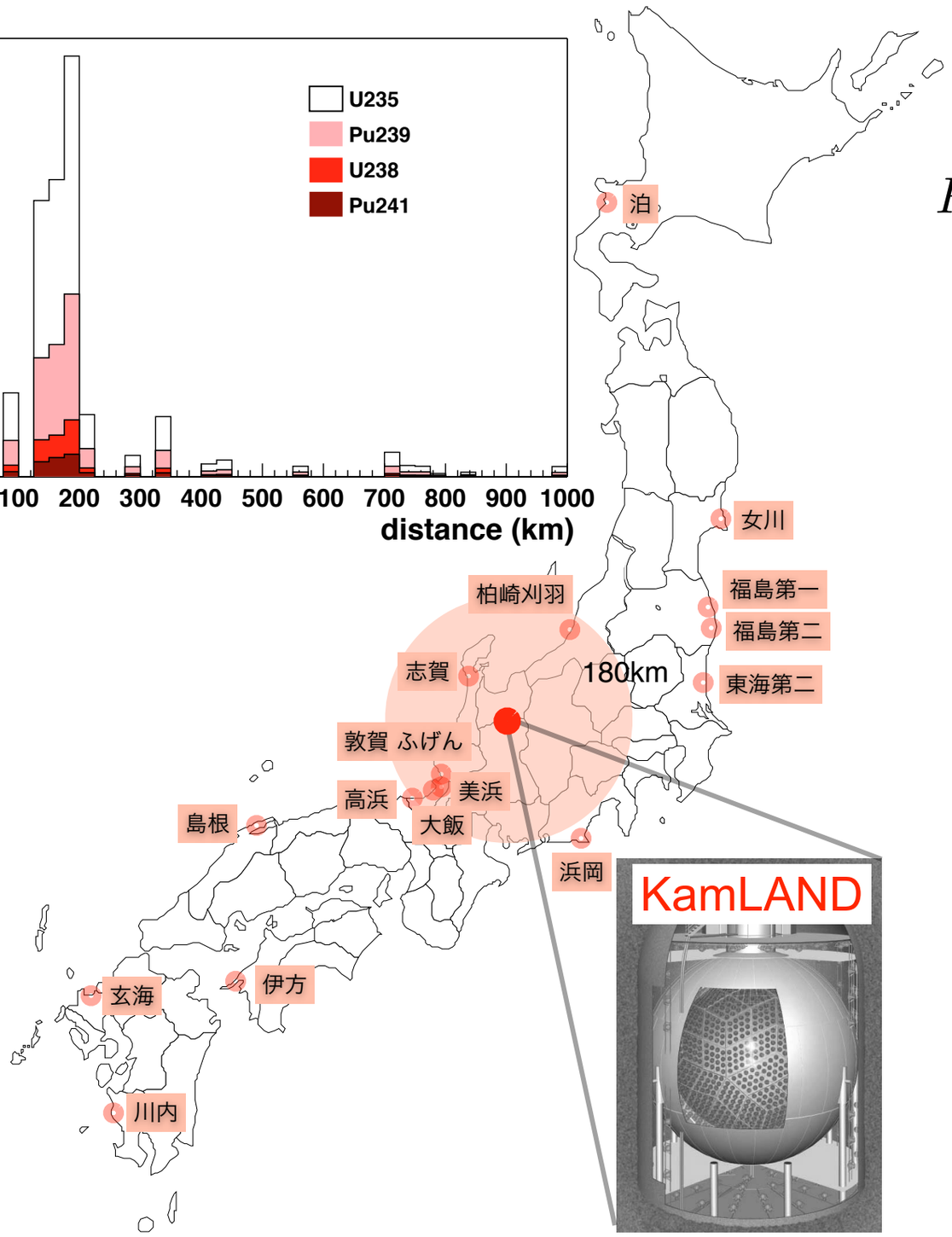
$\langle m_{\beta\beta} \rangle$ < 0.14-0.28 eV (QRPA)

- Several detector improvements are planned aiming at a test of inverted neutrino mass hierarchy.

Backup

KamLAND Experiment





2 flavor neutrino oscillation

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]l[m]}{E[\mathrm{MeV}]}\right)$$

most sensitive region

$$\Delta m^2 = (1/1.27)\cdot(E[\mathrm{MeV}]/L[m])\cdot(\pi/2)$$
$$\sim 3\times 10^{-5}\mathrm{eV}^2$$

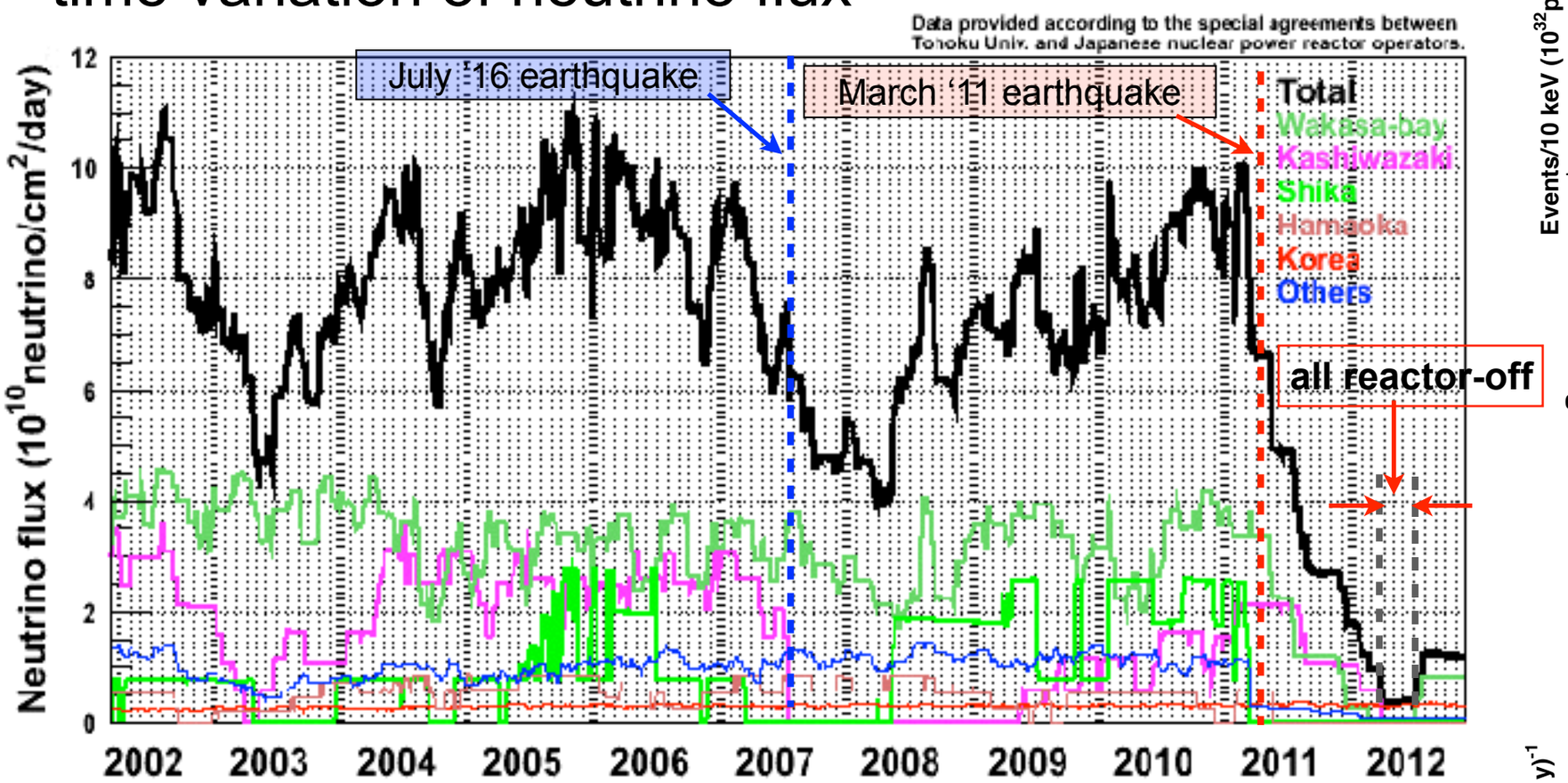
→ LMA solution

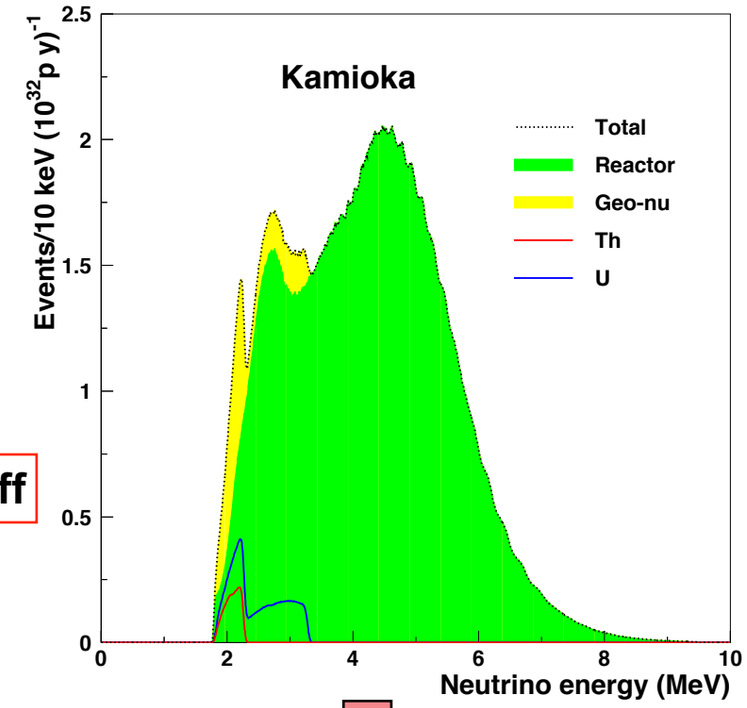
ΔL (distance spread from reactors)	
175 ± 35 km	~ 20%
ΔE (energy resolution)	
17 inch PMTs	$7.4\% / \sqrt{E(\mathrm{MeV})}$
17 inch + 20 inch	$6.5\% / \sqrt{E(\mathrm{MeV})}$

Good condition to confirm solar neutrino oscillation

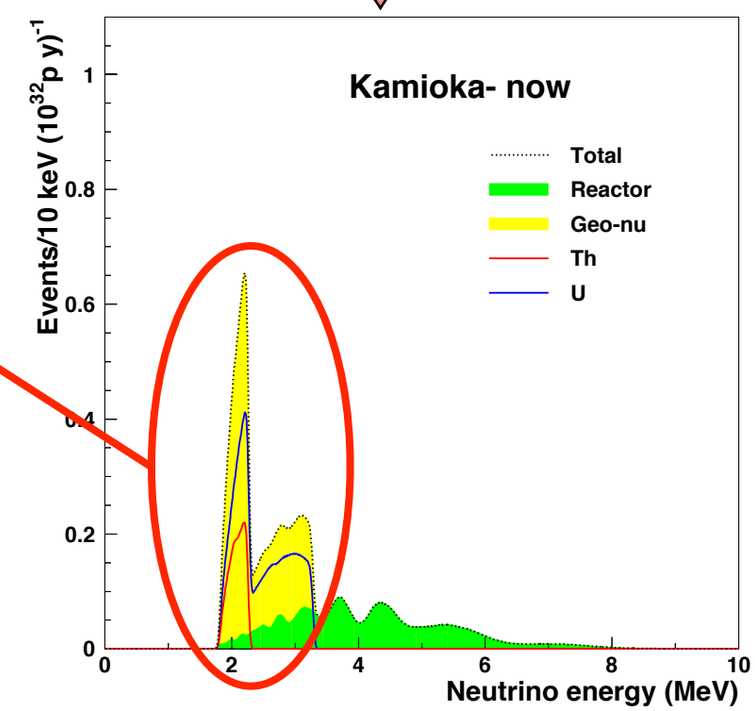
Anti-Neutrino Flux

time variation of neutrino flux





decrease of reactor neutrino

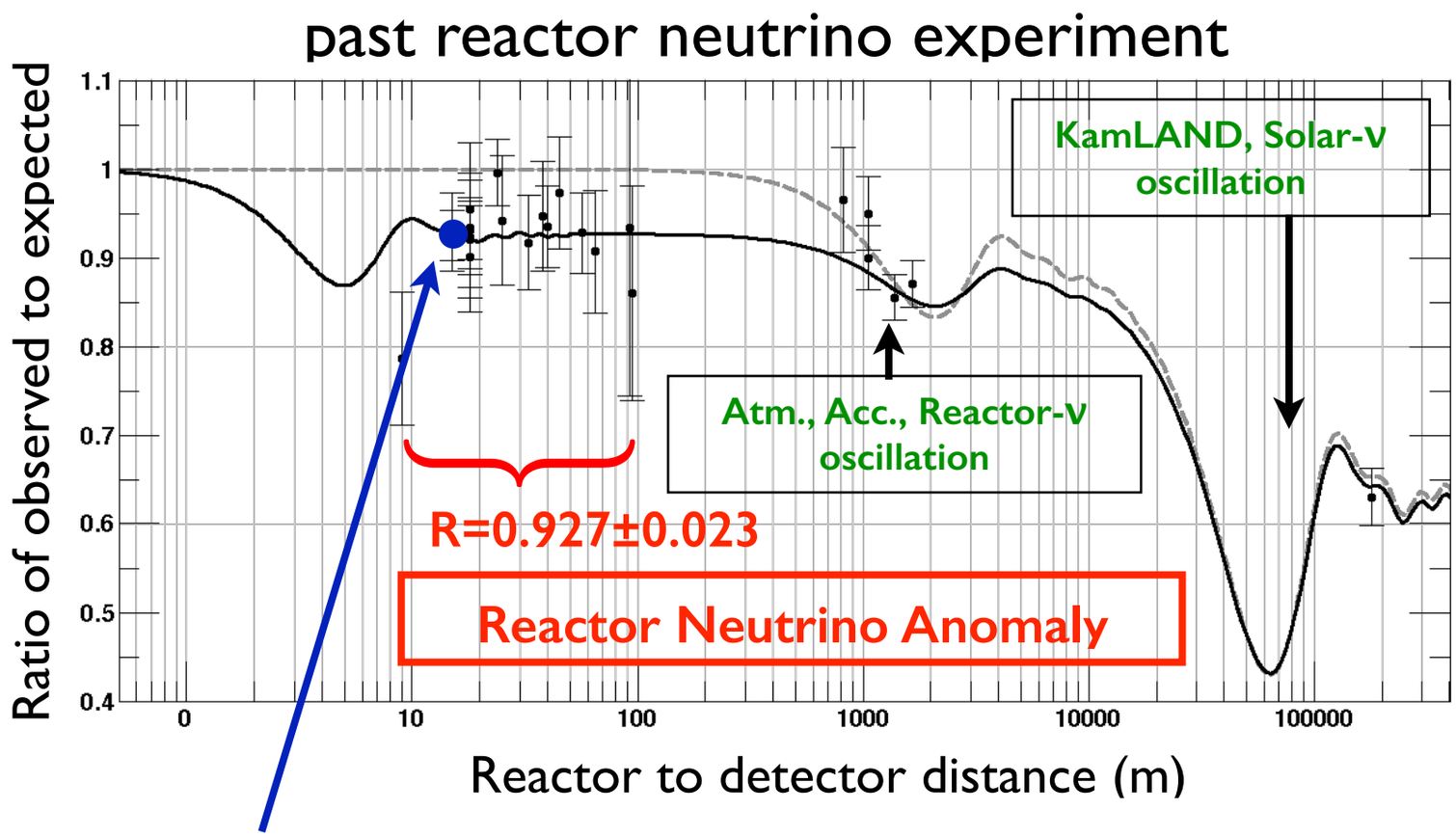


significant reduction of anti-neutrino flux from reactors after Fukushima-I accident

good data for geo neutrino observation

"Reactor on-off" study for neutrino oscillation and geo neutrino analysis

Normalization with Near Data



possibility of systematic bias or sterile-ν oscillation?

Bugey4 accuracy on the neutrino flux is **1.4%** (L = 15 m from PWR reactor)

Normalization of cross section per fission

$$\langle\sigma\rangle_{reac.} = \langle\sigma\rangle_{Bugey4} + \sum_i (\alpha_i^{reac.} - \alpha_i^{Bugey4}) \langle\sigma\rangle_i$$

(i = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu)

α_i : fractional fission rate $\langle\sigma\rangle_i = \int dE S_i(E)\sigma(E)$: effective cross section per fission

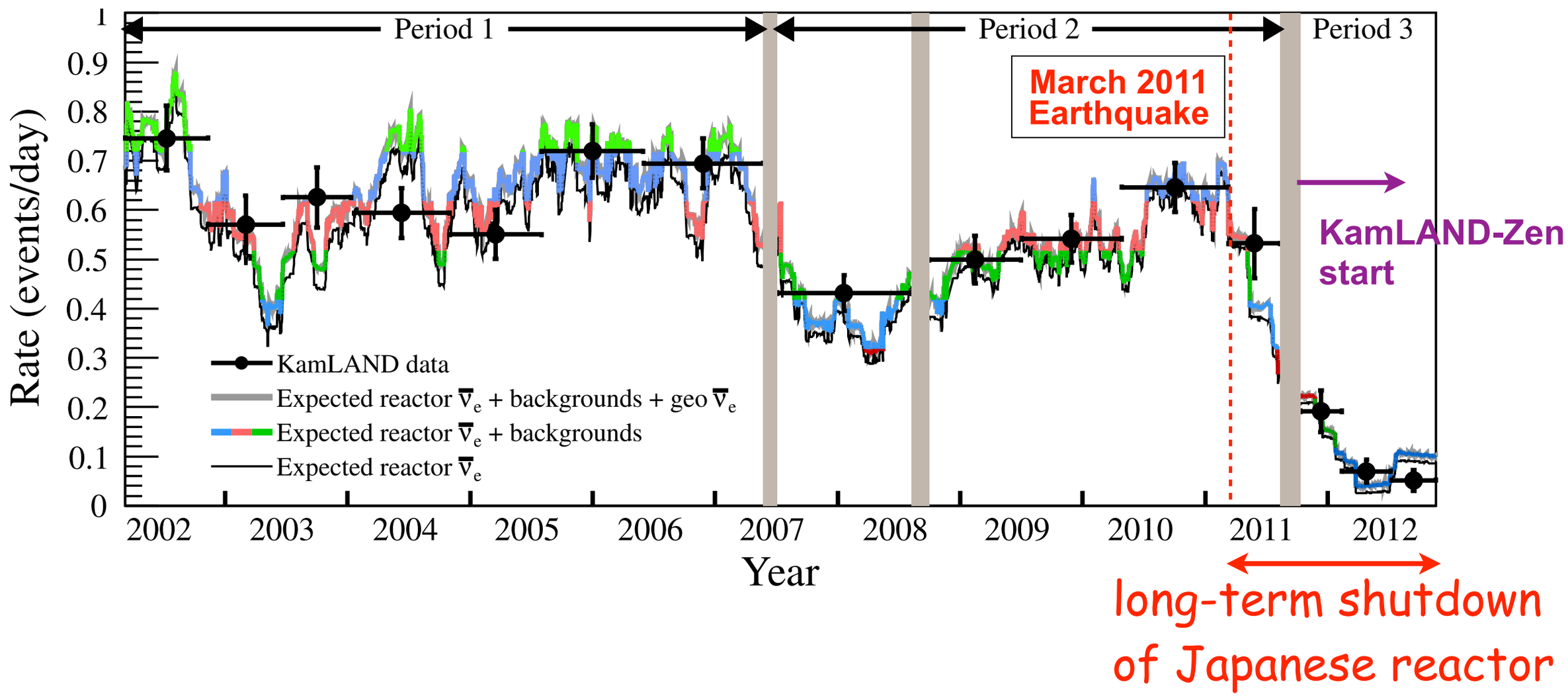
analysis is insensitive to "Reactor Neutrino Anomaly"

Time Variation of Event Rate

Total livetime
2991 days

Period 1: Mar. 2002 - May 2007
Period 2: May 2007 - Aug. 2011 (after LS purification)
Period 3: Oct. 2011 - Nov. 2012 (after KamLAND-Zen start)

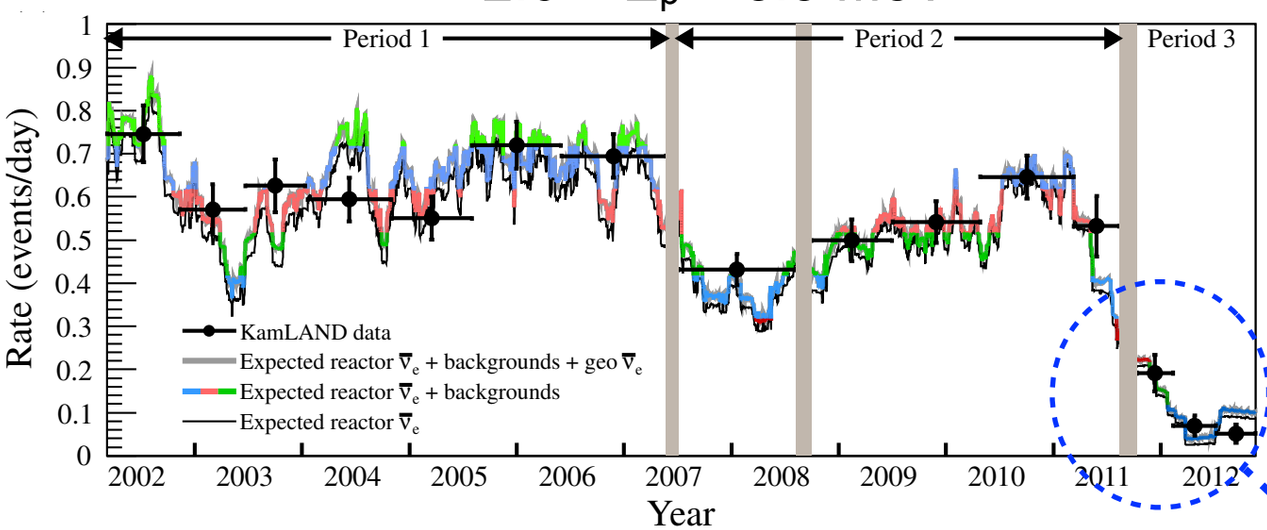
$2.6 < E_p < 8.5$ MeV

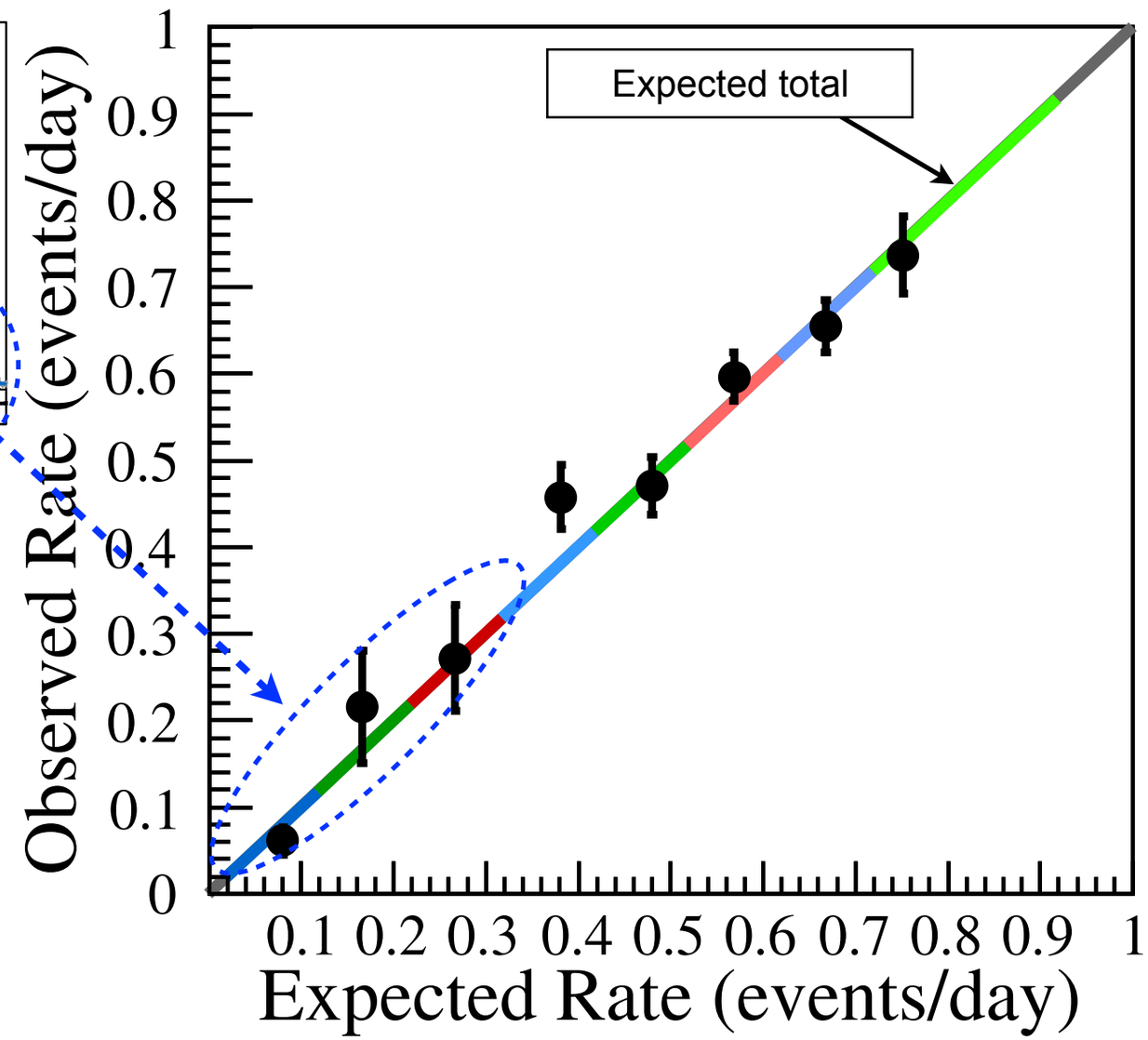


Data have good agreement with expected rate

Correlation Plot

$2.6 < E_p < 8.5$ MeV





provide good data to confirm our background

↓

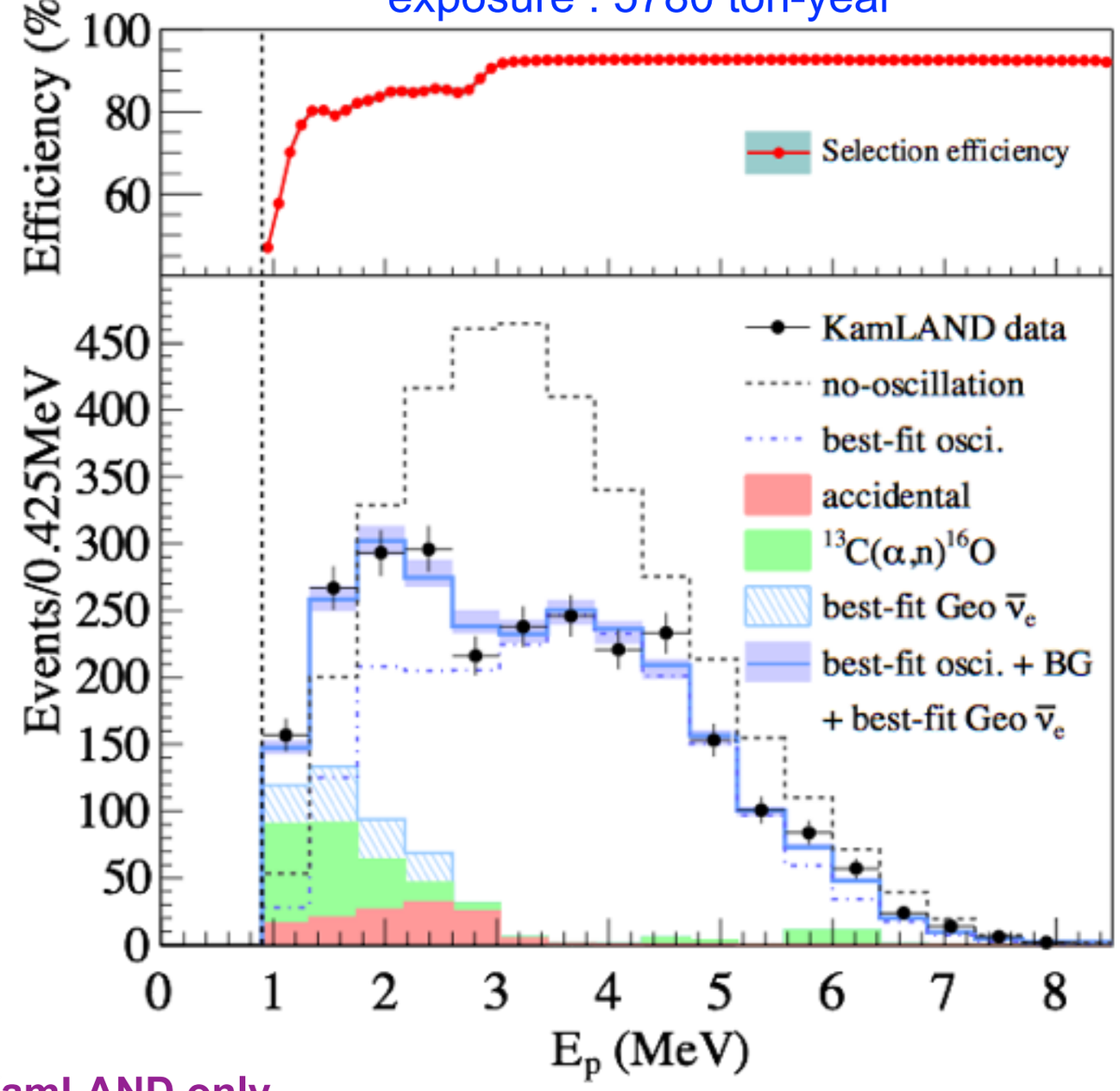
"Rate + Shape + Time" analysis

$$\chi^2 = \chi^2_{\rm rate}(\theta_{12},\theta_{13},\Delta m^2_{21},N_{\rm BG1\to5},N^{\rm geo}_{\rm U,Th},\alpha_{1\to4})$$
$$-2\ln L_{\rm shape}(\theta_{12},\theta_{13},\Delta m^2_{21},N_{\rm BG1\to5},N^{\rm geo}_{\rm U,Th},\alpha_{1\to4})$$
$$+\chi^2_{\rm BG}(N_{\rm BG1\to5})+\chi^2_{\rm syst}(\alpha_{1\to4})$$
$$+\chi^2_{\rm osci}(\theta_{12},\theta_{13},\Delta m^2_{21})\ .$$

time dependent

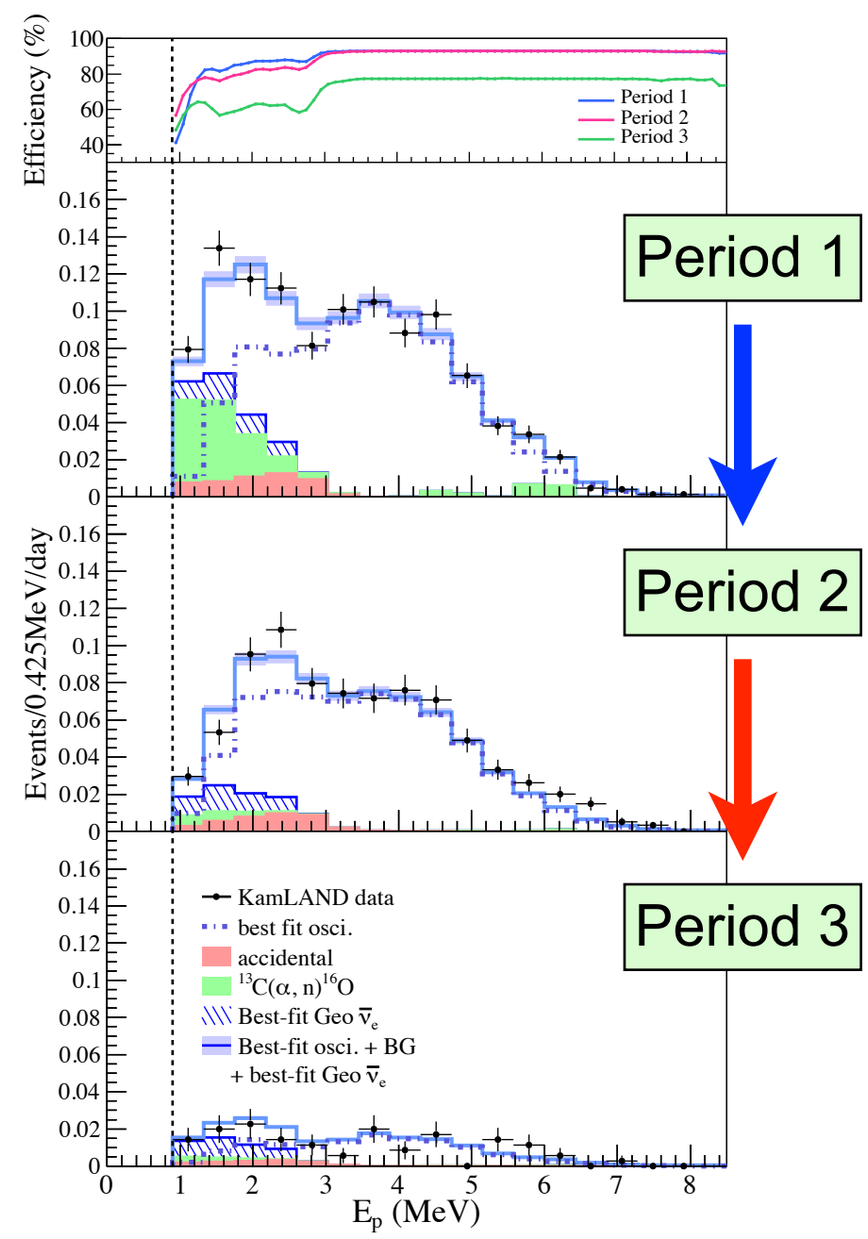
Observed Energy Spectrum

exposure : 5780 ton-year



purification **(α,n)** ↓

earthquake **reactor** ↓



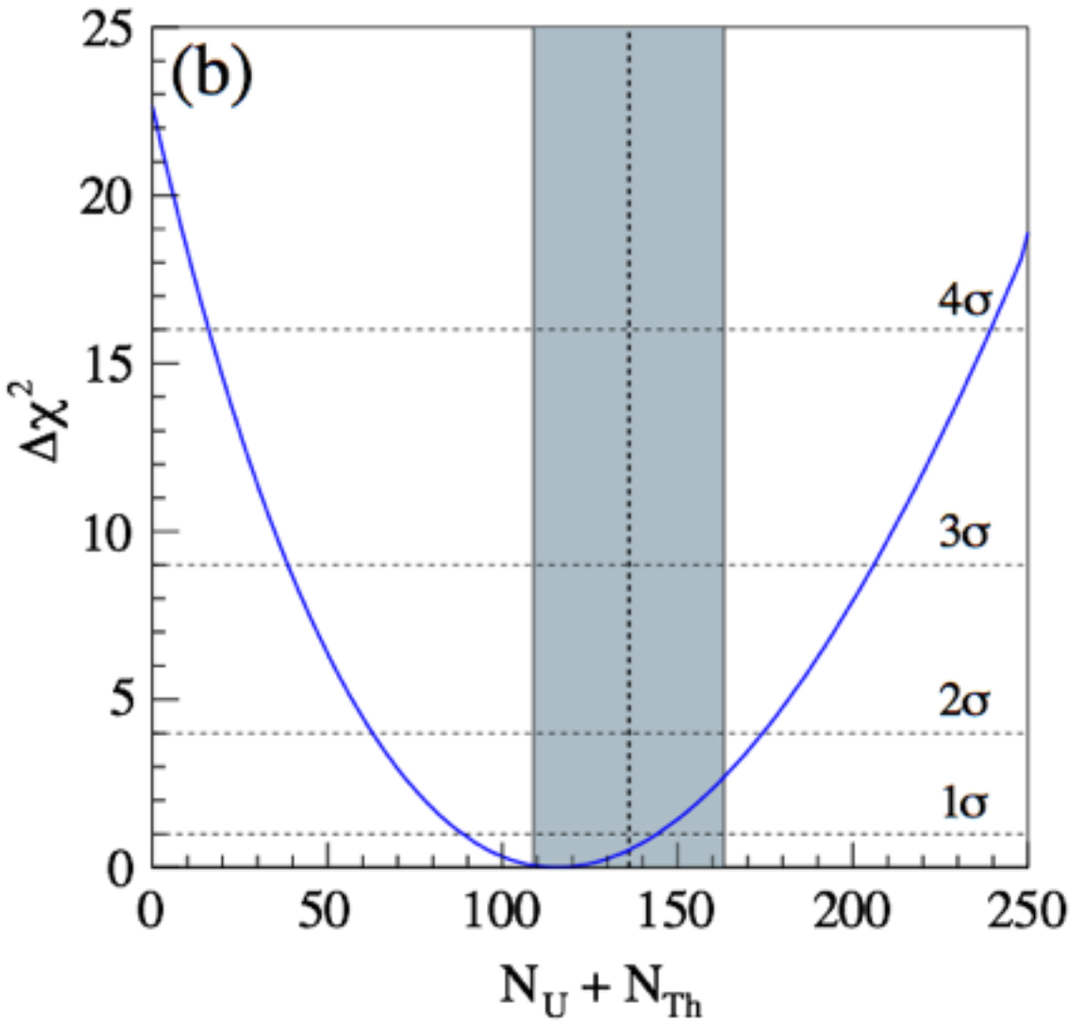
significant reduction

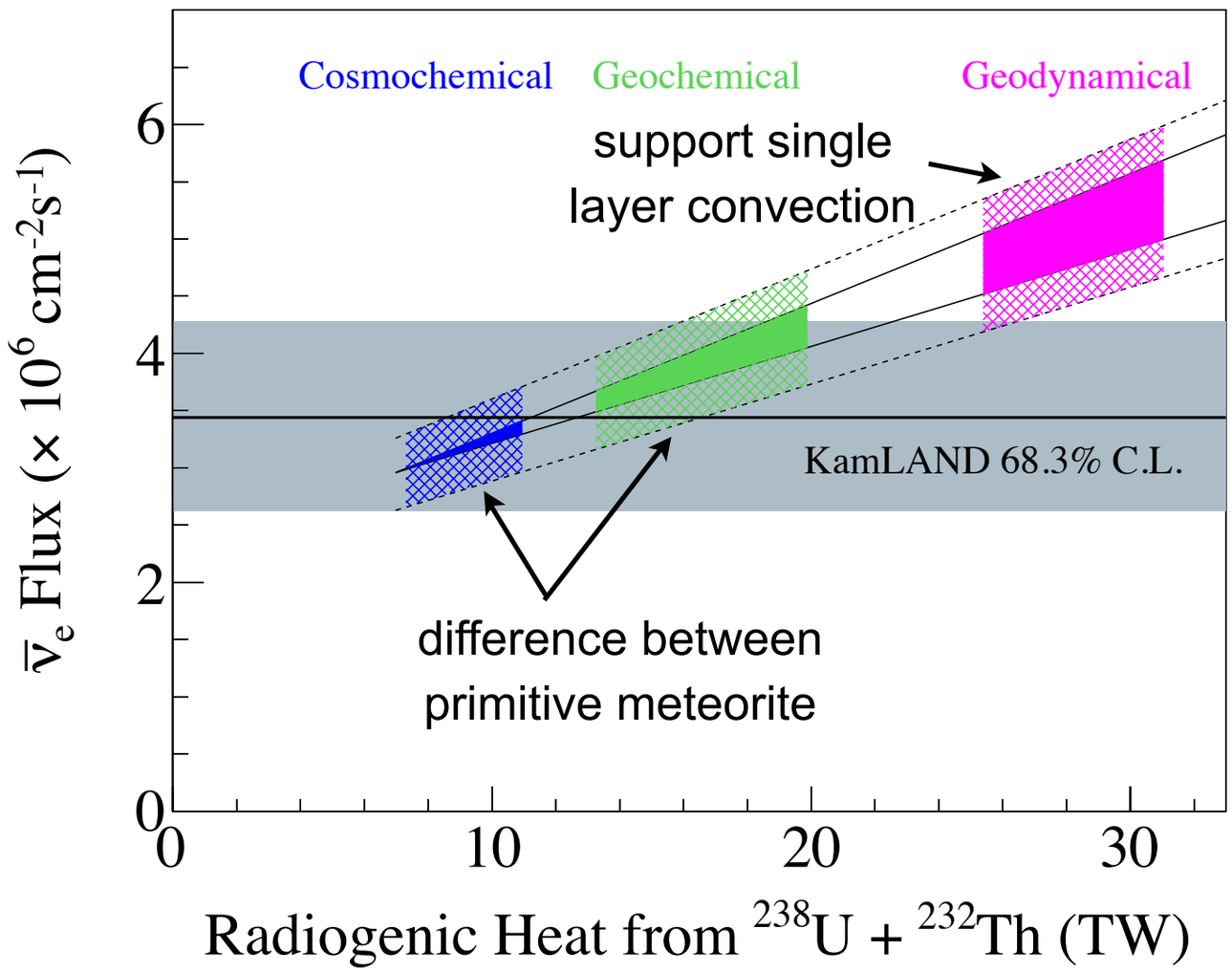
KamLAND only

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5}\mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.481^{+0.092}_{-0.080}$$
$$\sin^2\theta_{13} = 0.010^{+0.033}_{-0.034}$$

No osci. expected	**3564 ± 145**
Background (w/o geo neutrino)	**364 ± 31**
Observed events	**2611**

Geo Neutrino





Radioactive decay in the Earth (Uranium, Thorium)

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6e^- + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}\ (100\%)$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4e^- + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}\ (100\%)$$

KamLAND result

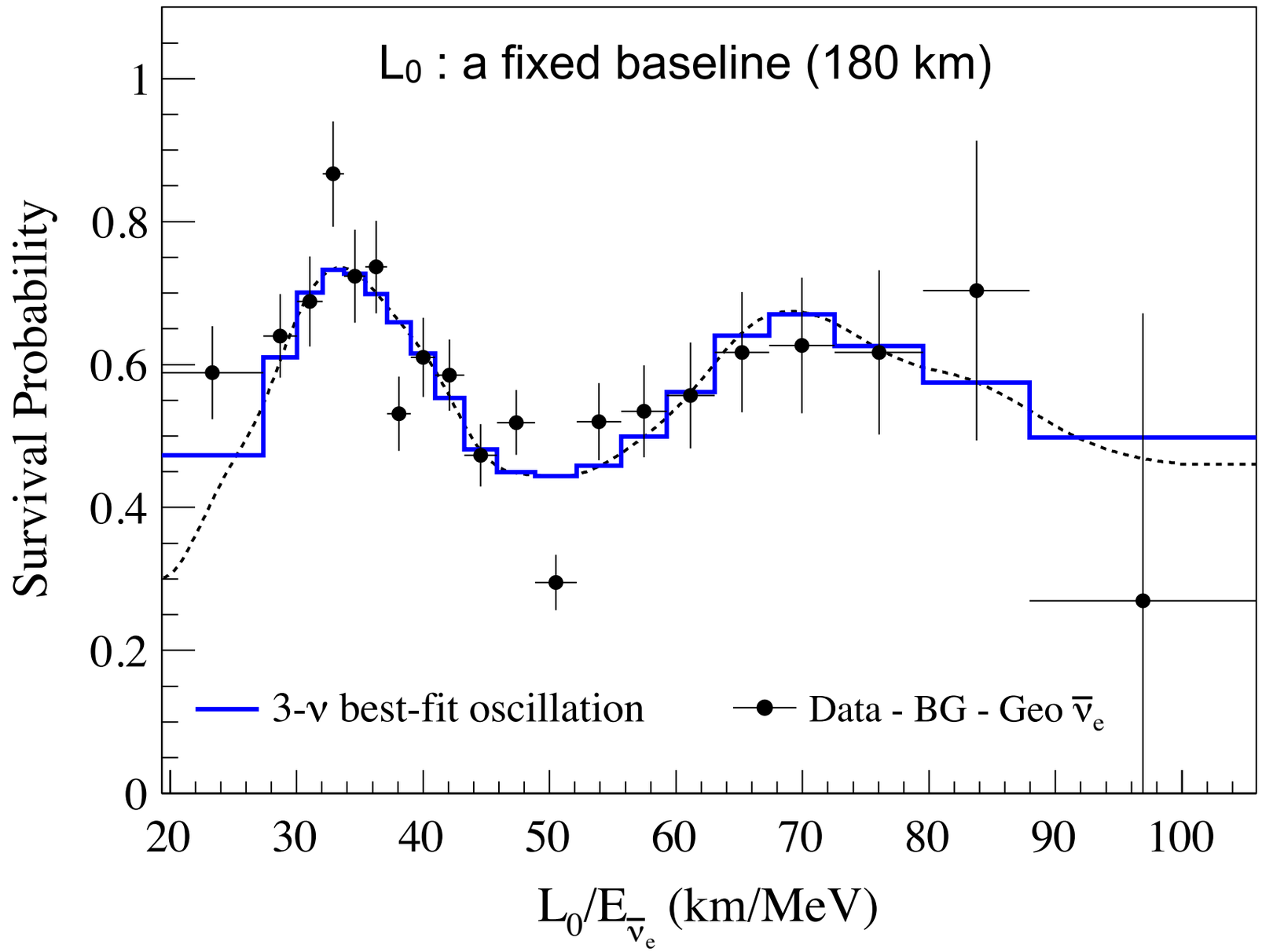
radiogenic **$14.2^{+7.9}_{-5.1}$TW**

heat low from Earth's surface 47±2 TW

Geo-ν is unconstrained for reactor oscillation analysis

L/E plot

P = (observed - B.G.) / (no osci. expected)



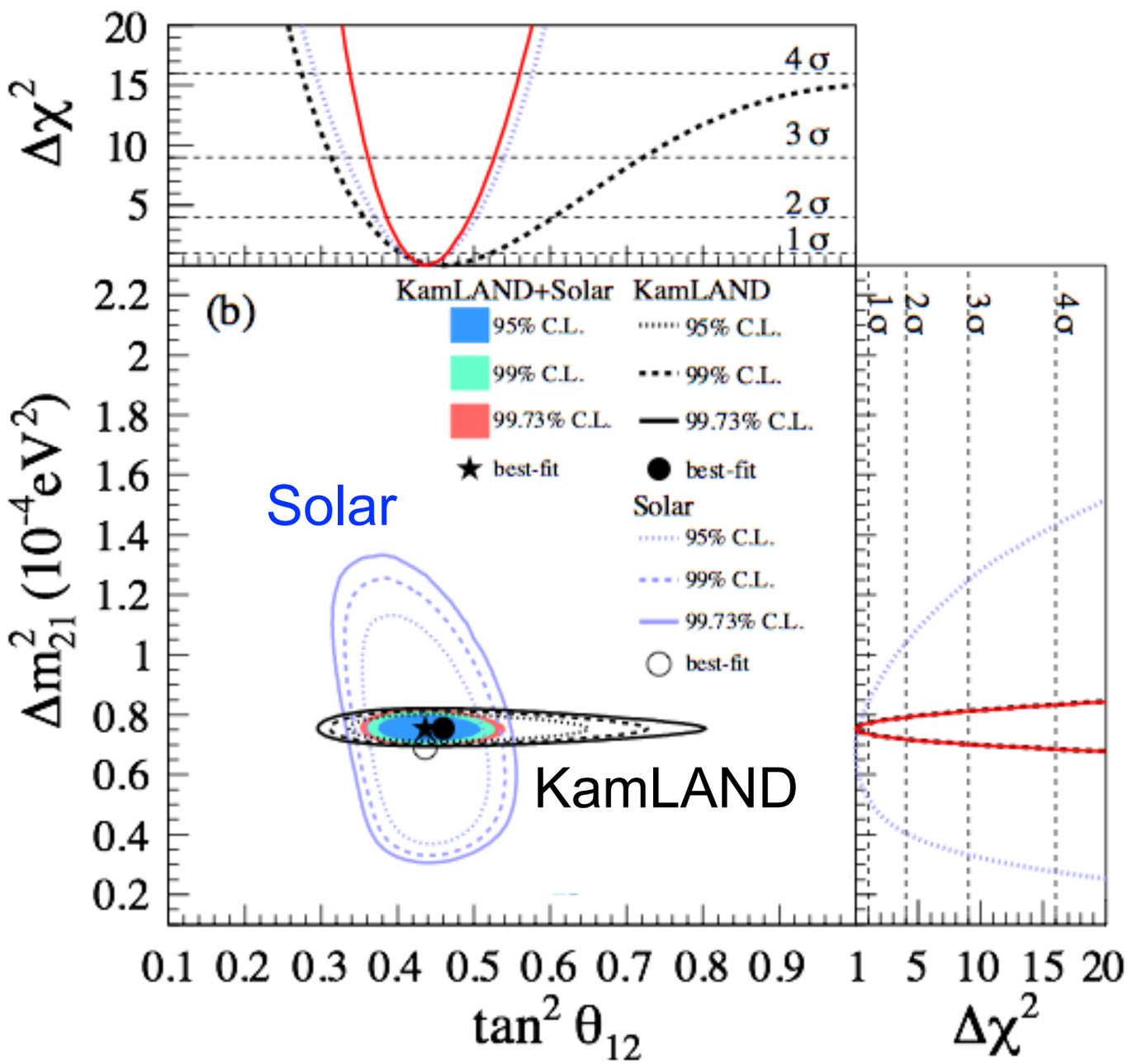
KamLAND data covers almost 2 cycle of oscillation

→ **strong evidence of neutrino oscillation**

3-Flavor Oscillation Parameters

θ_{12}: **Solar** constraint is dominant

Δm^2: **KamLAND** constraint is dominant



survival probability

$$P^{3\nu}_{ee} = \cos^4\theta_{13} P^{2\nu}_{e'e'} + \sin^4\theta_{13}$$

electron density

matter effect $N_{e'} \rightarrow N_e \cos^2\theta_{13}$

atmospheric oscillation length is completely averaged out $\cancel{\Delta m^2_{31}}$

solar + KamLAND + θ_{13} experiments

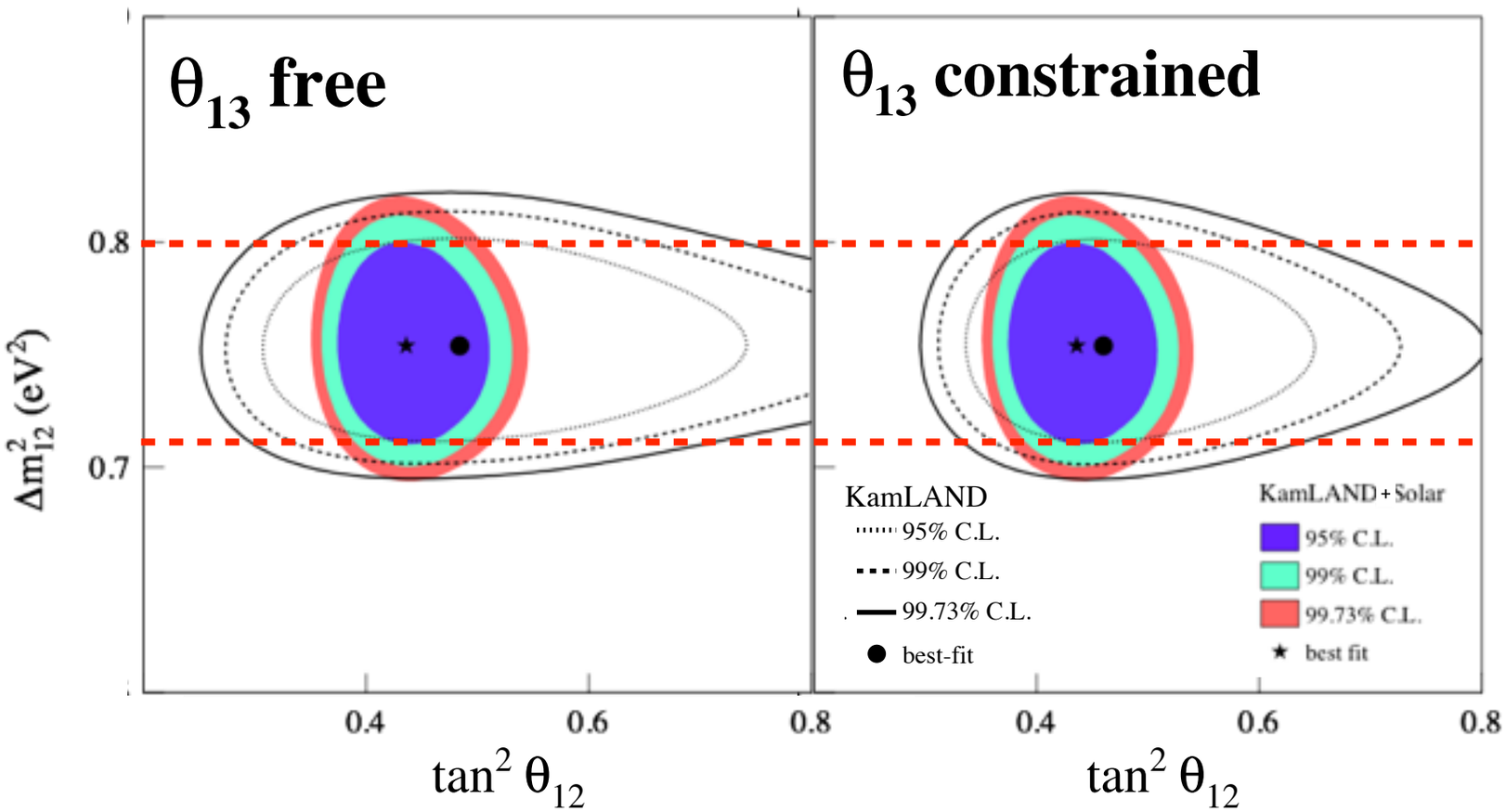
$$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$$

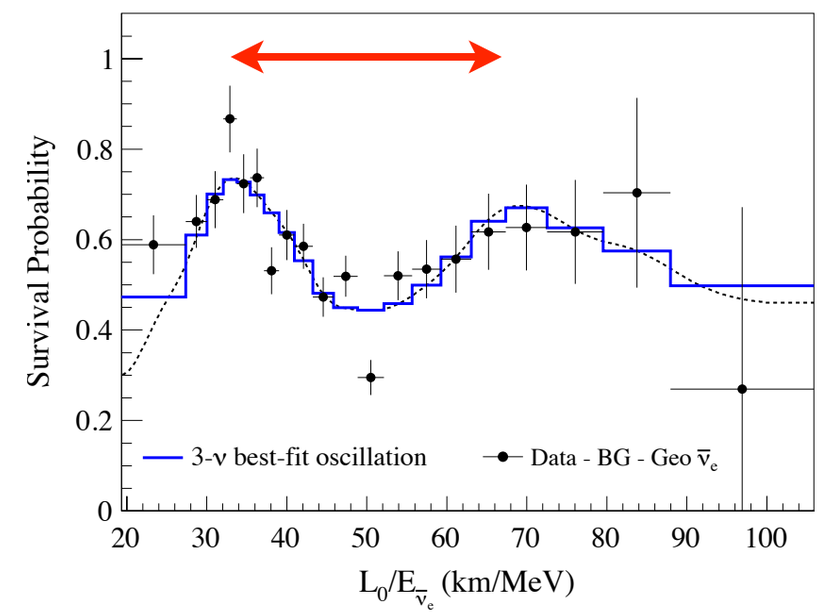
$$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$$

Precise Measurement of Δm^2

Δm^2: systematic uncertainty 1.9%
(dominated by linear energy scale uncertainty)



frequency meas.
by KamLAND



KamLAND+Solar	KamLAND+Solar+θ13
$\Delta m^2_{21} = 7.53^{+0.19}_{-0.18} \times 10^{-5}\mathrm{eV}^2$	$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\mathrm{eV}^2$
$\tan^2\theta_{12} = 0.437^{+0.029}_{-0.026}$	$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$
$\sin^2\theta_{13} = 0.023^{+0.015}_{-0.015}$	$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$

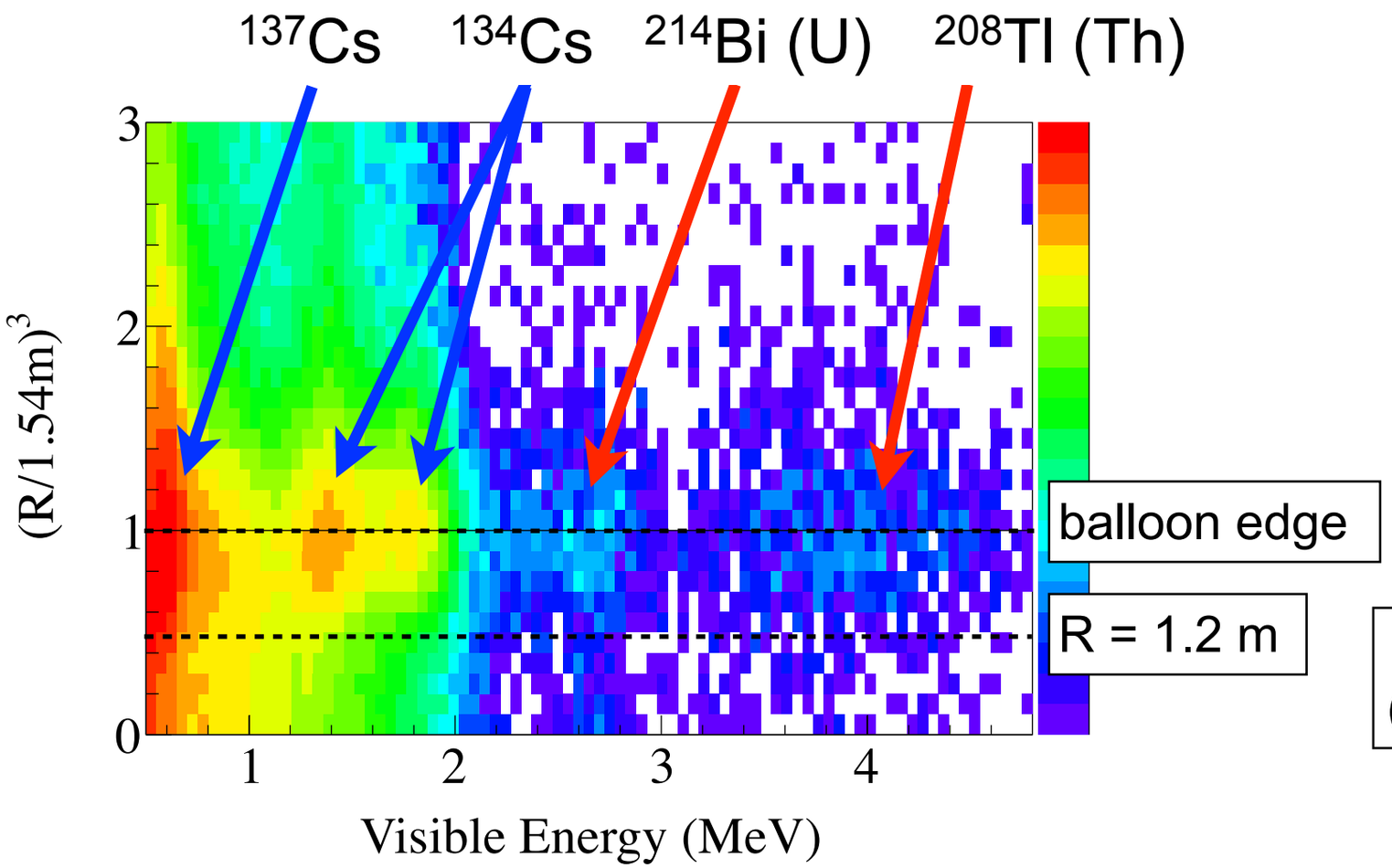
θ_{13} constraint

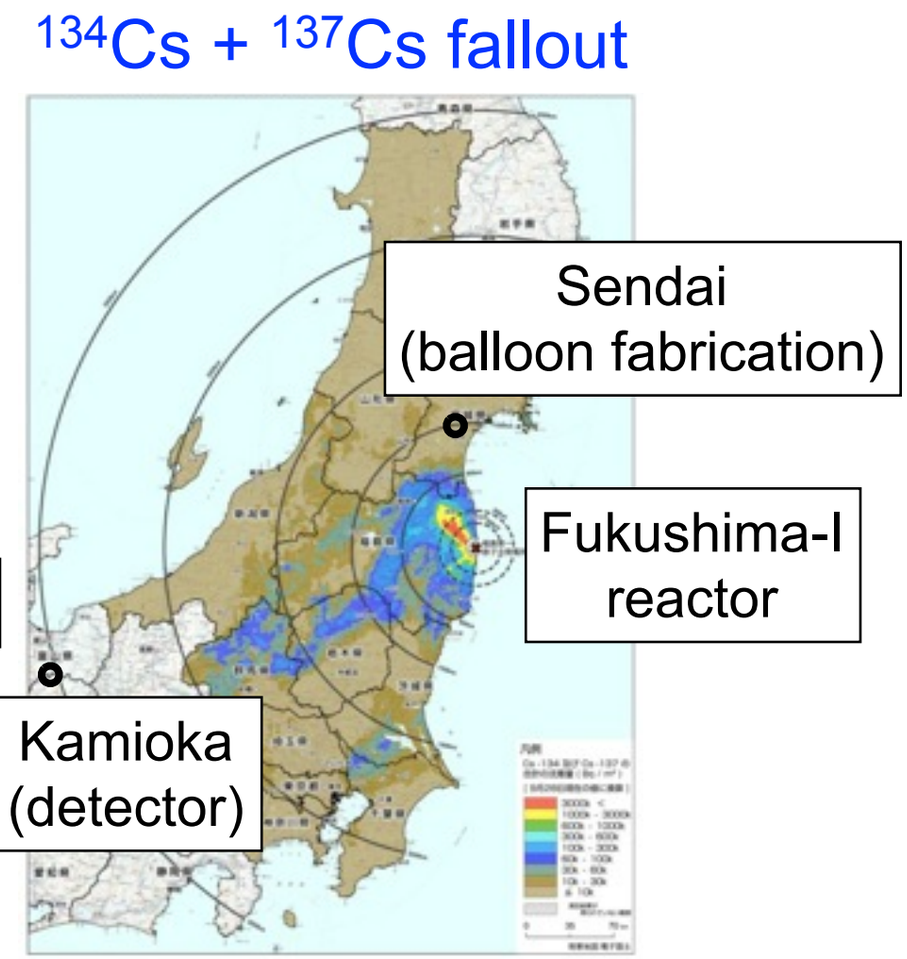
← insensitive

← no strong impact

Δm^2 is measured at 2.3% precision

Radioactive Impurities





Observed ratio of ^{134}Cs/^{137}Cs (~0.8) is consistent with Fukushima-I reactor fallout

Radioactive impurities

- Found unexpected fallout BG in 2νββ energy region, but it concentrates on the balloon possible contamination during balloon fabrication?
- U and Th impurities are higher than expected (factor ~10 in balloon)

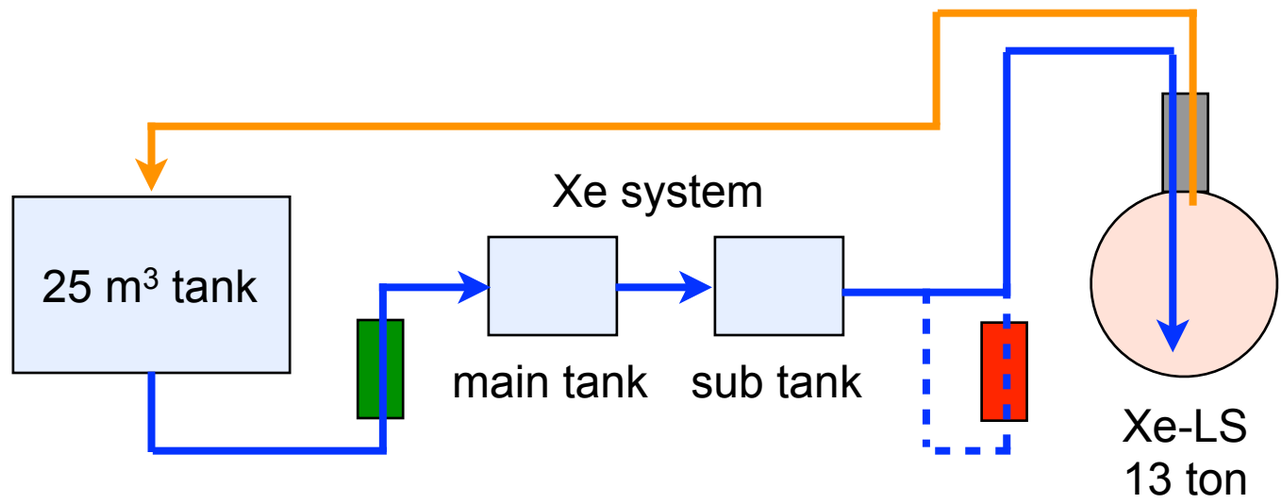
^{238}U: 3.5×10^{-16}g/g (LS), 2.2×10^{-11}g/g (balloon) → fiducial volume limitation in 0νββ analysis

^{232}Th: 2.2×10^{-15}g/g (LS), 1.4×10^{-10}g/g (balloon)

KamLAND-Zen Construction

mini balloon fabrication & installation → dummy LS filling → Xe-LS filling
(inflation) (replace)

24 gores from film



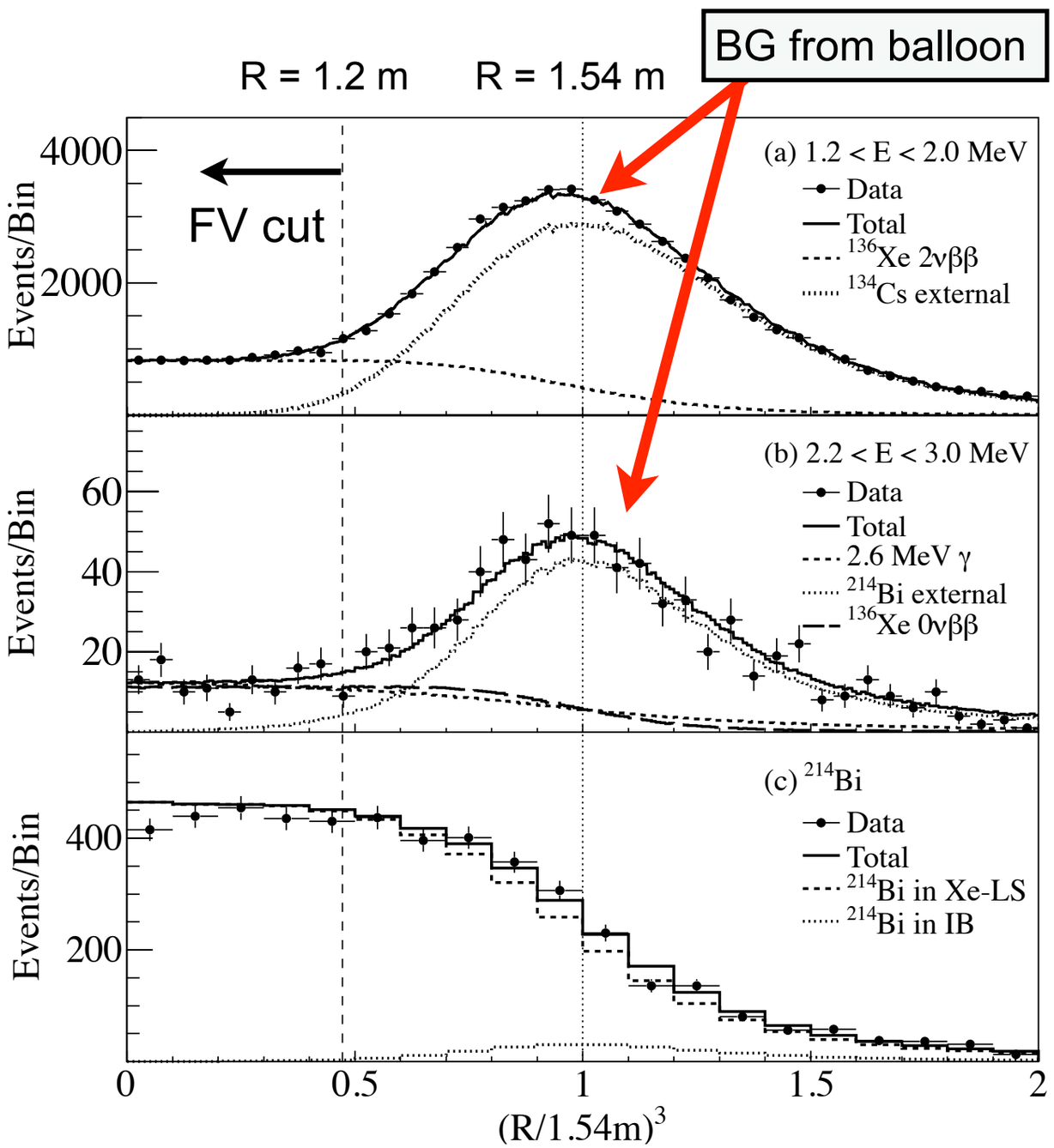
heat welding

LS storage (25 m³ x 2)

Xe loading in LS

Fiducial Volume

R^3 vertex distribution



Fiducial volume of Xe-LS

R < 1.2 m V = 7.24 m^3

Xe amount by gas chromatography

- Xe concentration = (2.52 ± 0.07) wt%

Xe amount uncertainty ⟶ 2.8%

GL Science GC-4000

- ^{136}Xe : 90.93%, ^{134}Xe : 8.89%

129 kg of ^{136}Xe in the FV

Uncertainty of the fiducial volume

^{214}Bi vertex uniformity check

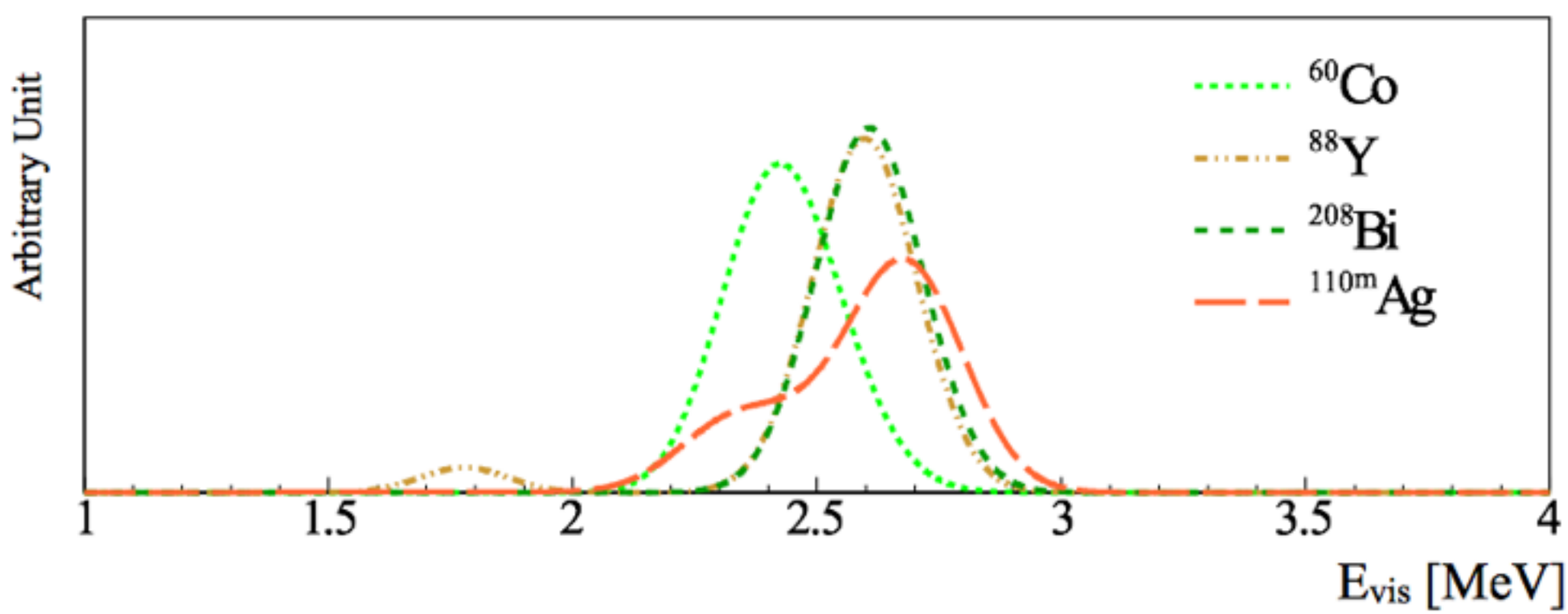
$V_{1.2m} / V_{total} = 0.438 \pm 0.005$

$N_{1.2m} / N_{total} = 0.423 \pm 0.007(stat) \pm 0.004(syst)$

FV uncertainty ⟶ 5.2%

Background Candidates

	Decay Mode	Q-Value [MeV]	Half-Life
^{110m}Ag	β^-	3.01	249.79 day
^{208}Bi	EC	2.88	3.68×10^5 year
^{88}Y	EC	3.62	106.65 day
^{60}Co	β^-	2.82	5.2714 year



Background Candidate Search

1. Radioactive impurities

long-lived nuclei ($T_{1/2}$ > 30 d)

^{238}U series, ^{232}Th series, ^{40}K, ^{85}Kr, ^{210}Bi, ^{134}Cs, ^{137}Cs, ^{90}Y, and fallout nuclei

possibility of other BG w/ peak around $0\nu\beta\beta$ (2.4 < E < 2.8 MeV)

thousands of millions of

all nuclei and decay path in the ENSDF have been surveyed

→ only 4 nuclei ^{110m}Ag (250 d), ^{208}Bi (3.68×10^5 yr), ^{88}Y (107 d), ^{60}Co (5.27 yr)

lifetime longer than 30 days

detected in Fukushima fallout

2. Cosmogenic spallation products

underground products

- short-lived nuclei ($T_{1/2}$ < 100 s)
  study of time correlation with muons
  < 0.02 /ton·day (90% CL) → small
- long-lived nuclei (100 s < $T_{1/2}$ < 30 d)
  study of E spectrum
  w/ close A, Z nuclei → negligible

aboveground products

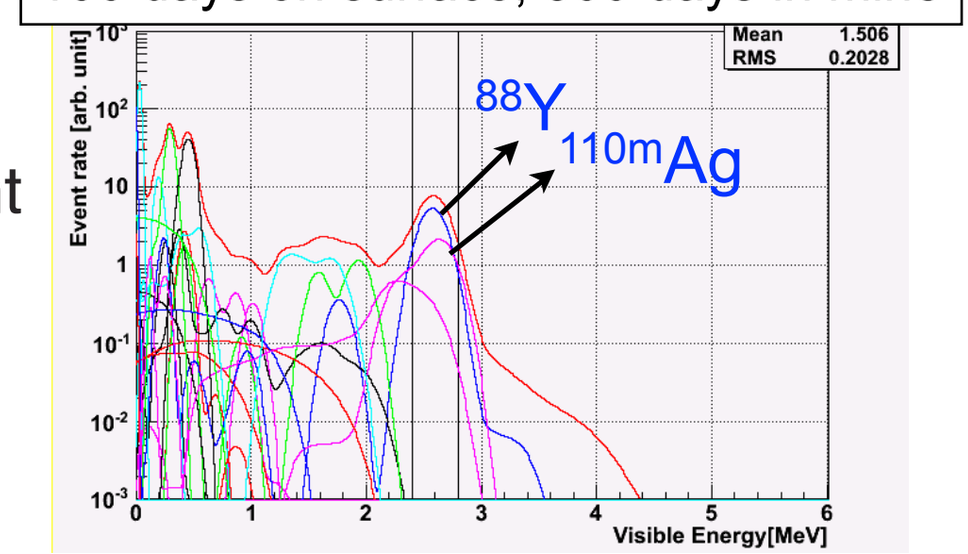
cross-section of ^{136}Xe + 1 GeV proton

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

production by surface proton/neutron is dominant

^{110m}Ag and ^{88}Y are candidate BG

100 days on surface, 300 days in mine



3. Nuclear reactions

(α, γ), $(\alpha, \alpha\gamma)$, (n, γ) → negligible

small c.s.

constrained from data