KamLAND

Neutrino Telescopes 2015

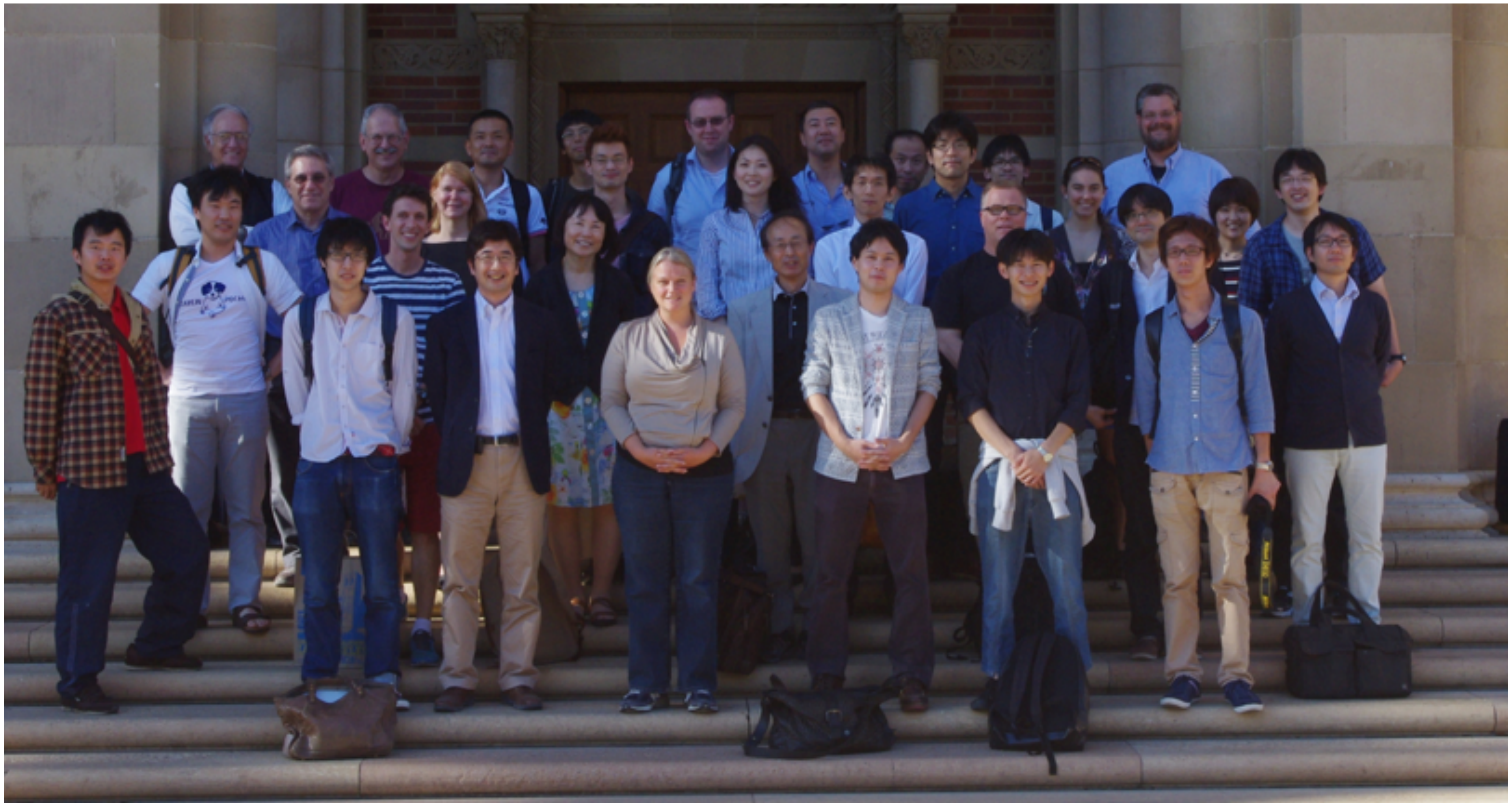
XVI International Workshop on Neutrino Telescopes

Mar. 5, 2015

Itaru Shimizu (Tohoku Univ.)

KamLAND Collaboration

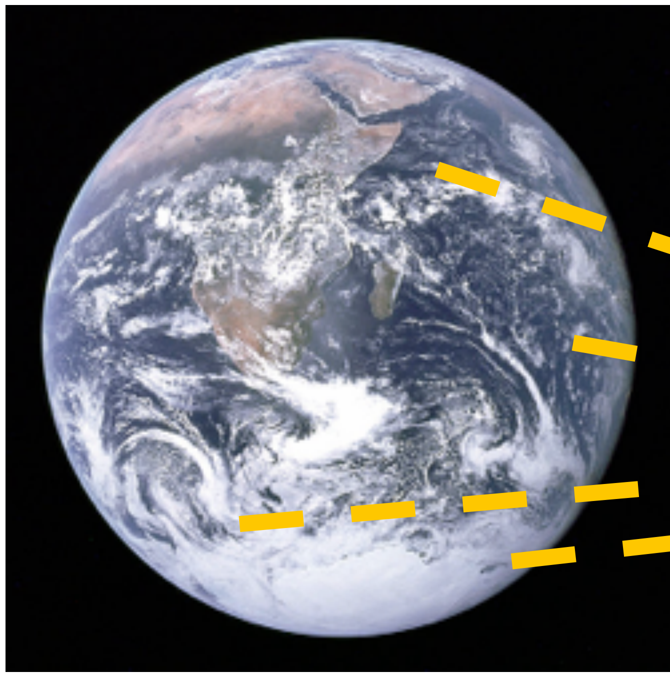
Collaboration meeting at UCLA (2014)



1 Research Center for Neutrino Science, Tohoku University
2 Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo
3 Graduate School of Science, Osaka University
4 Department of Physics and Astronomy, University of Alabama
5 Physics Department, University of California, Berkeley, and Lawrence Berkeley National Laboratory
6 Department of Physics, Colorado State University, Fort Collins
7 Department of Physics and Astronomy, University of Hawaii at Manoa
8 Department of Physics and Astronomy, University of Tennessee
9 Triangle Universities Nuclear Laboratory and Physics Departments at Duke University and the University of North Carolina
10 Department of Physics, University of Wisconsin
11 Nikhef, Science Park 105, 1098 XG Amsterdam

KamLAND Experiment

Earth



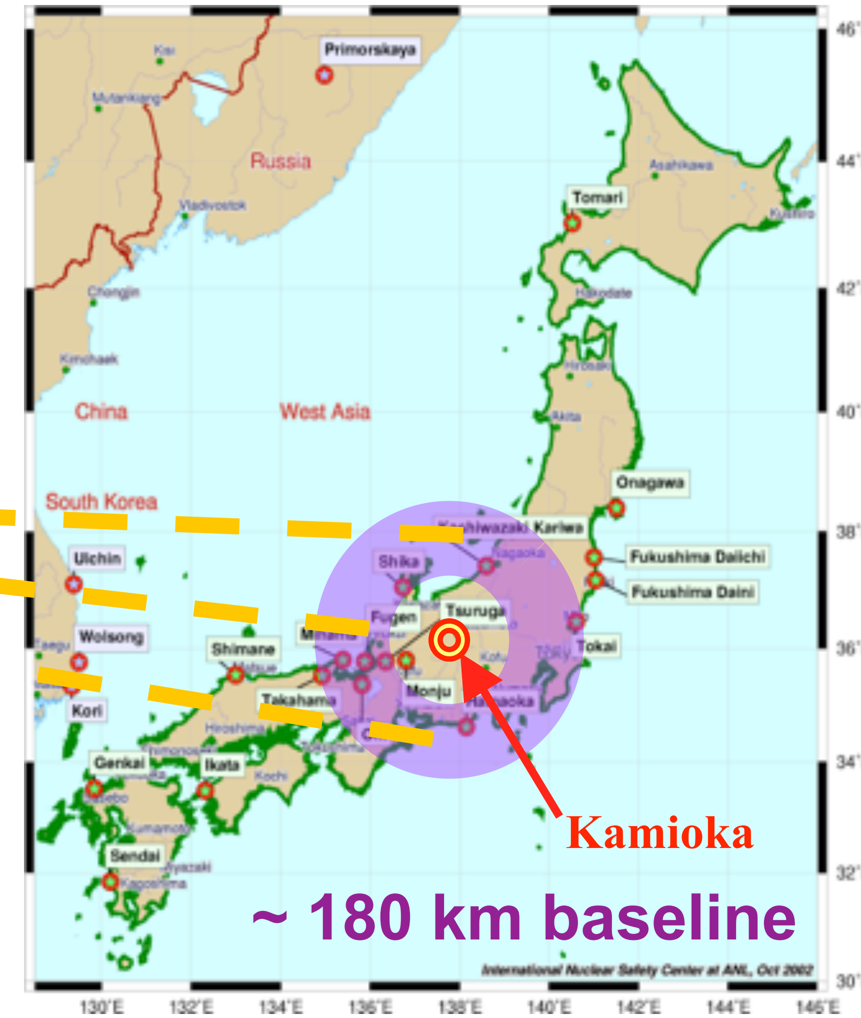
$\bar{\nu}_e$

Anti-Neutrino Detector

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

$\bar{\nu}_e$

Reactor



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

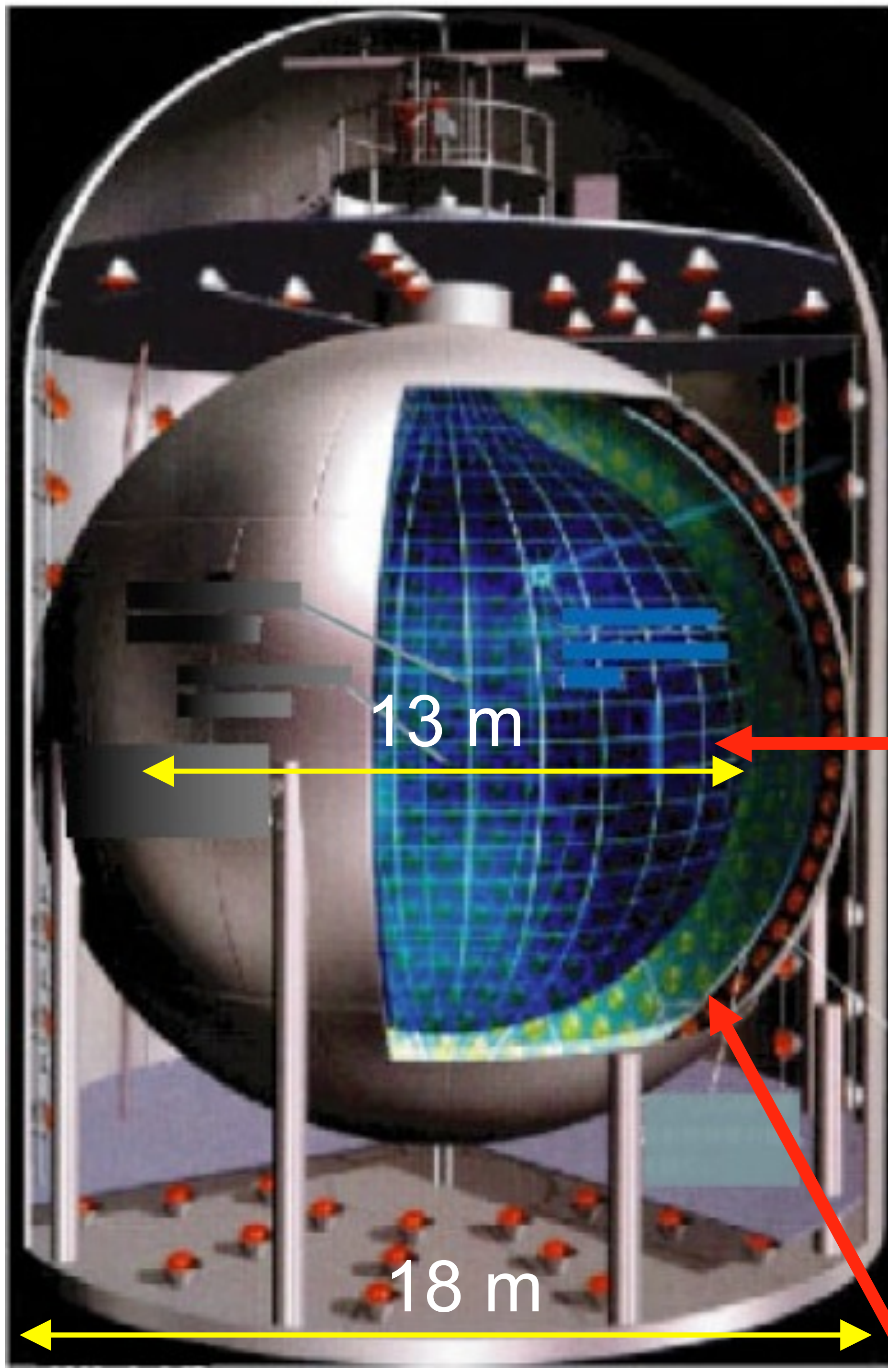
$$\Delta m^2 = (1/1.27) \cdot (E[\mathrm{MeV}]/L[m]) \cdot (\pi/2)$$
$$\sim 3 \times 10^{-5} \mathrm{eV}^2$$

reactor neutrino : sensitive to LMA solution

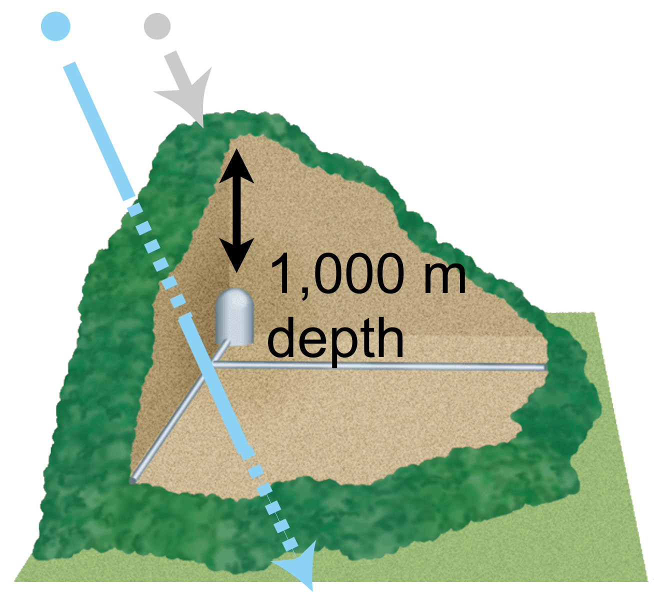
geo neutrino : U and Th decays inside the Earth

KamLAND

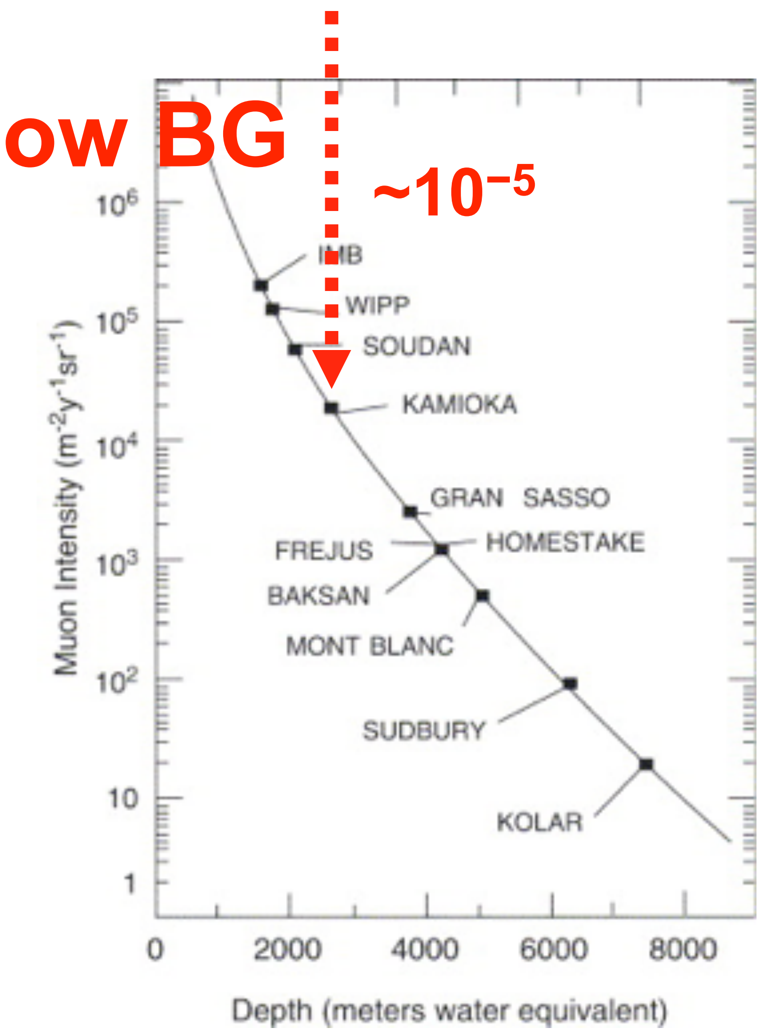
operated since 2002



neutrino , cosmic-ray



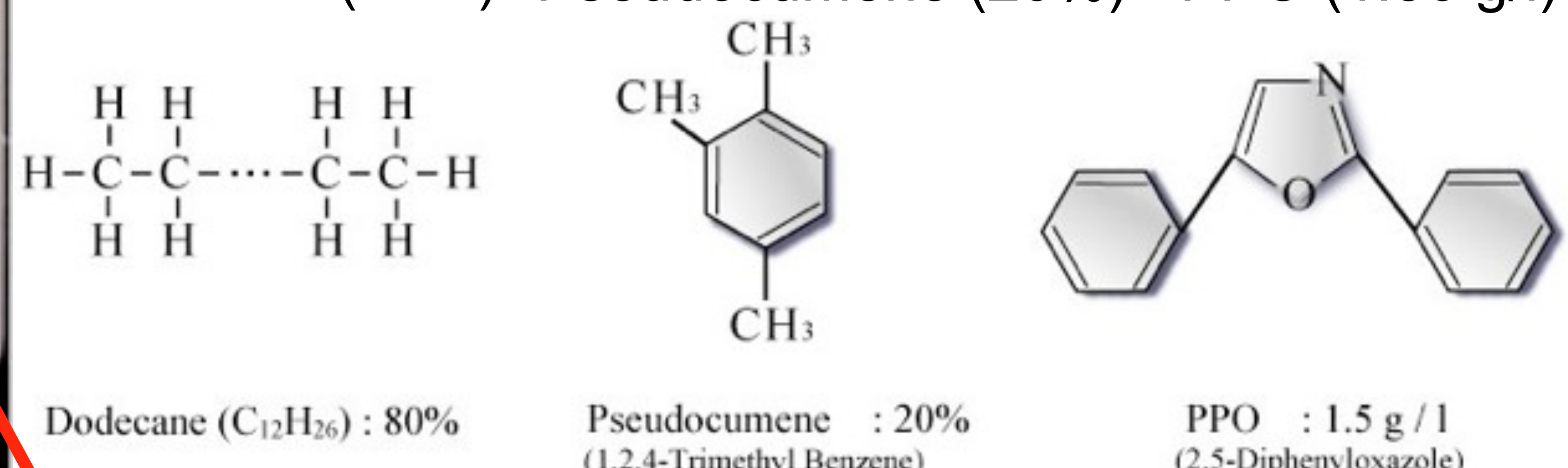
low BG



large volume

1,000 ton Liquid Scintillator

Dodecane (80%) Pseudocumene (20%) PPO (1.36 g/l)



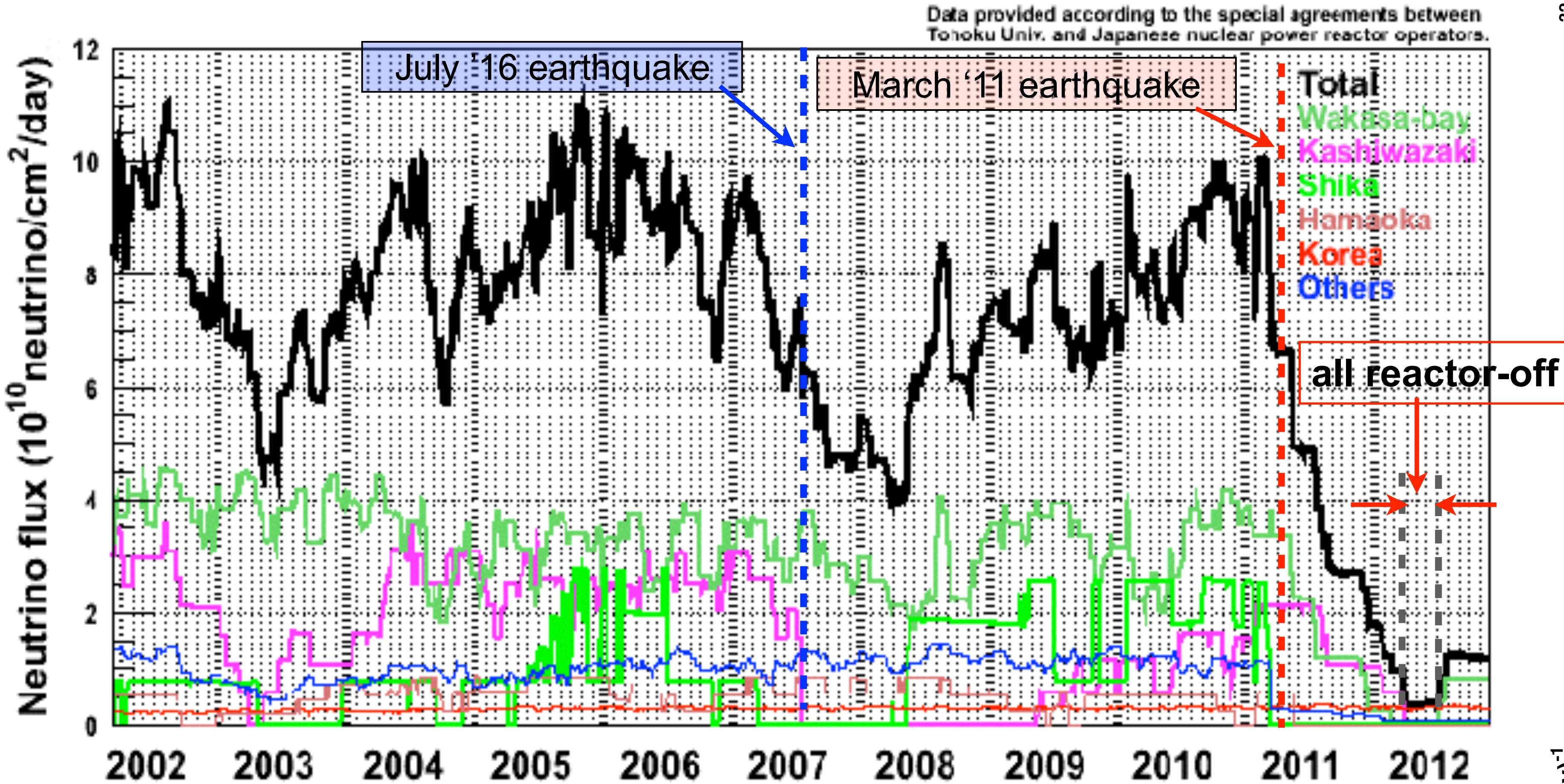
~500 p.e./MeV

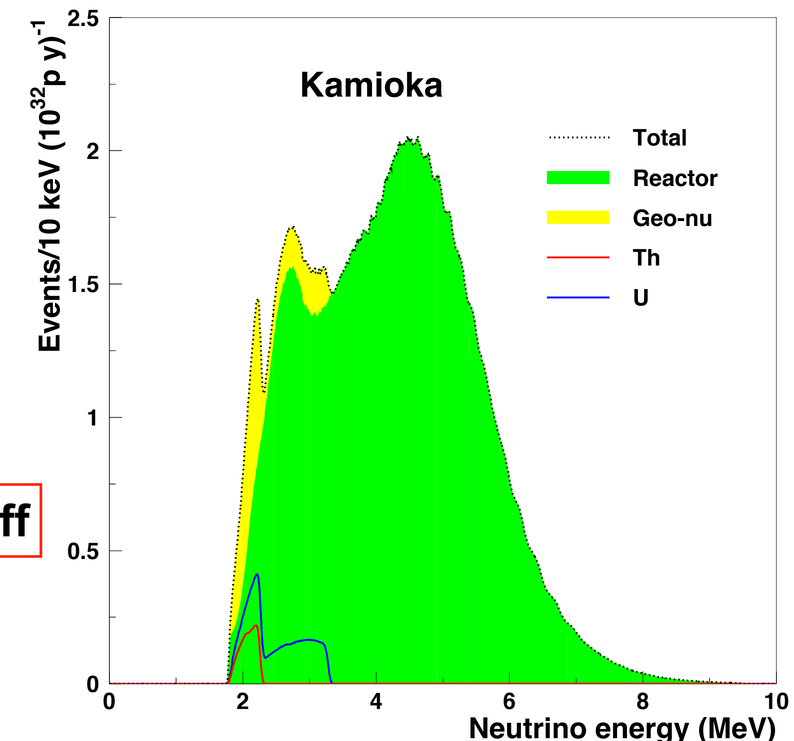
high light yield

1,325 17 inch + 554 20 inch PMTs

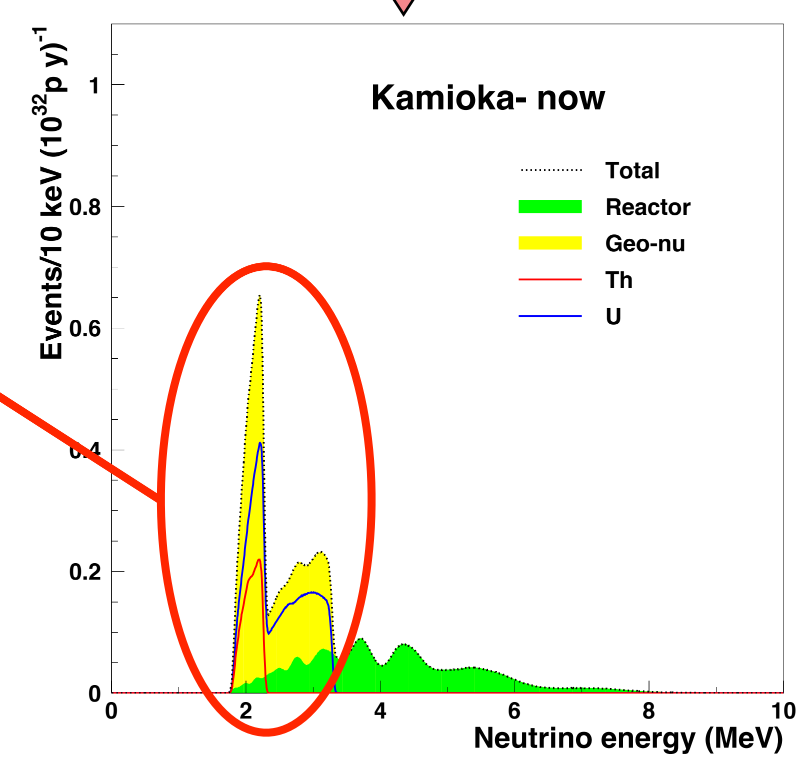
Anti-Neutrino Flux in Kamioka

time variation of reactor anti-neutrino flux





decrease of reactor neutrino



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

good data for geo neutrino observation

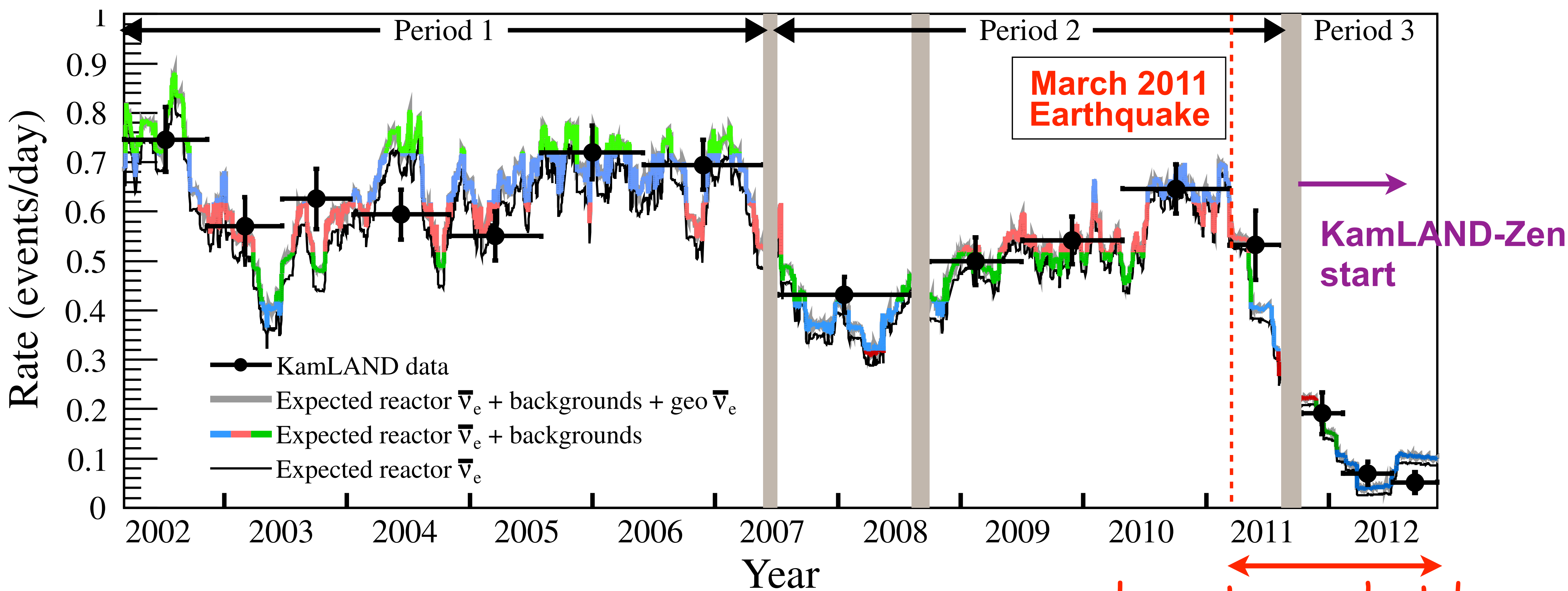
"Reactor on-off" study for neutrino oscillation and geo neutrino analysis

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

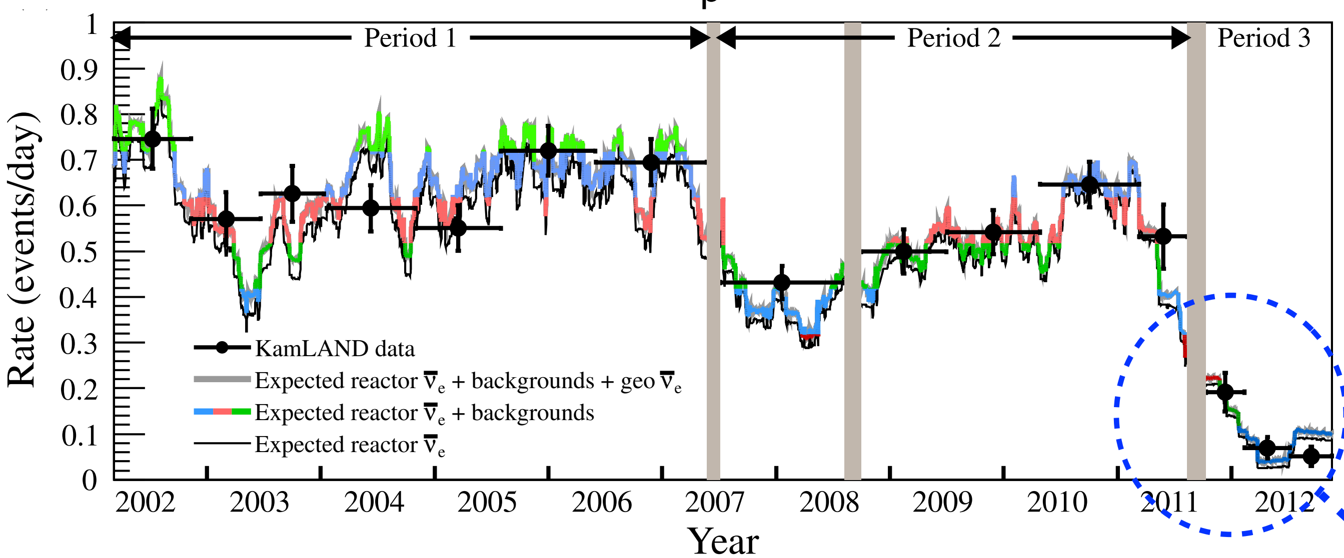


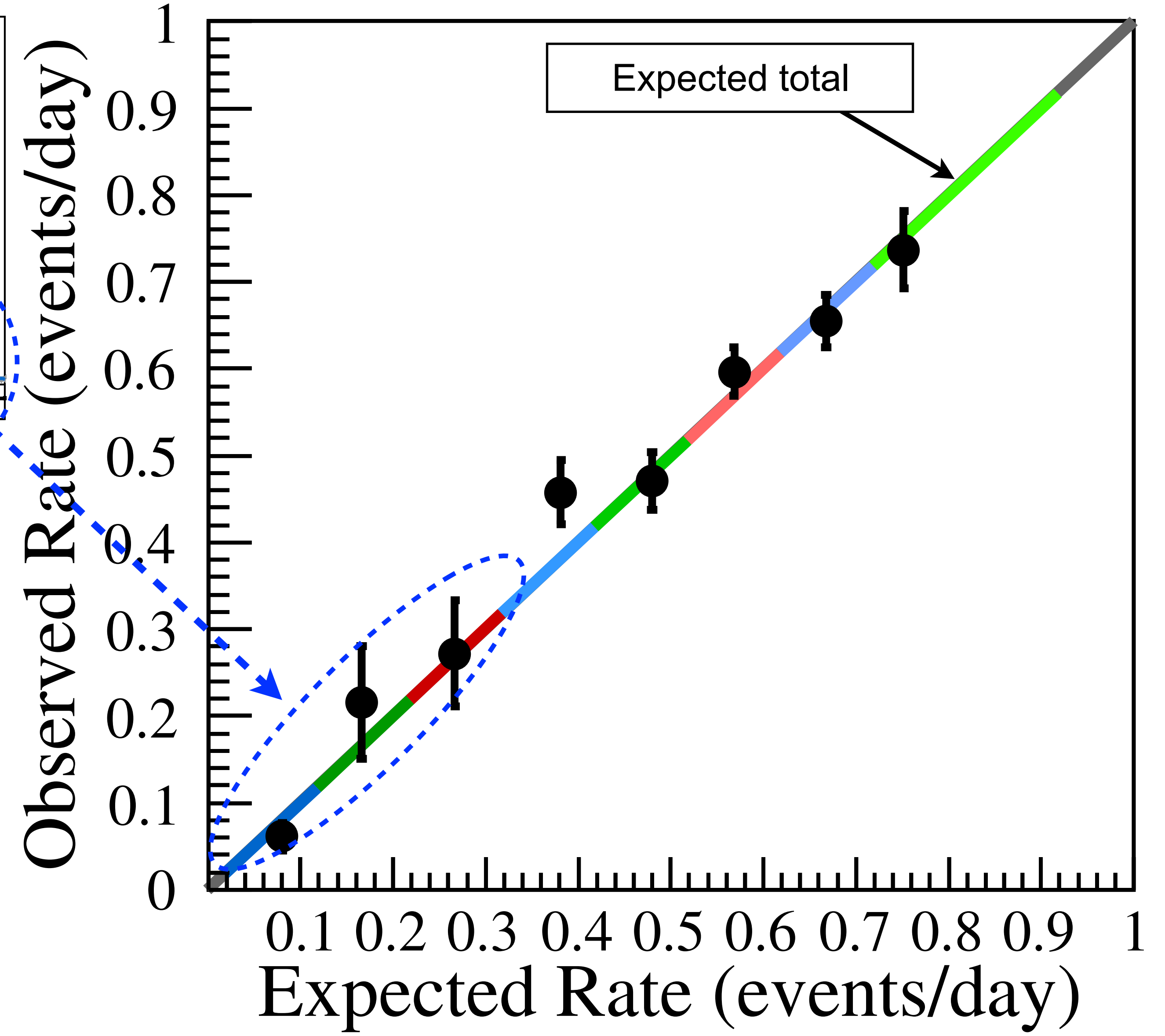
long-term shutdown
of Japanese reactor

Data have good agreement with expected rate

Correlation Plot

2.6 < E_p < 8.5 MeV





provide good data to confirm our background

↓

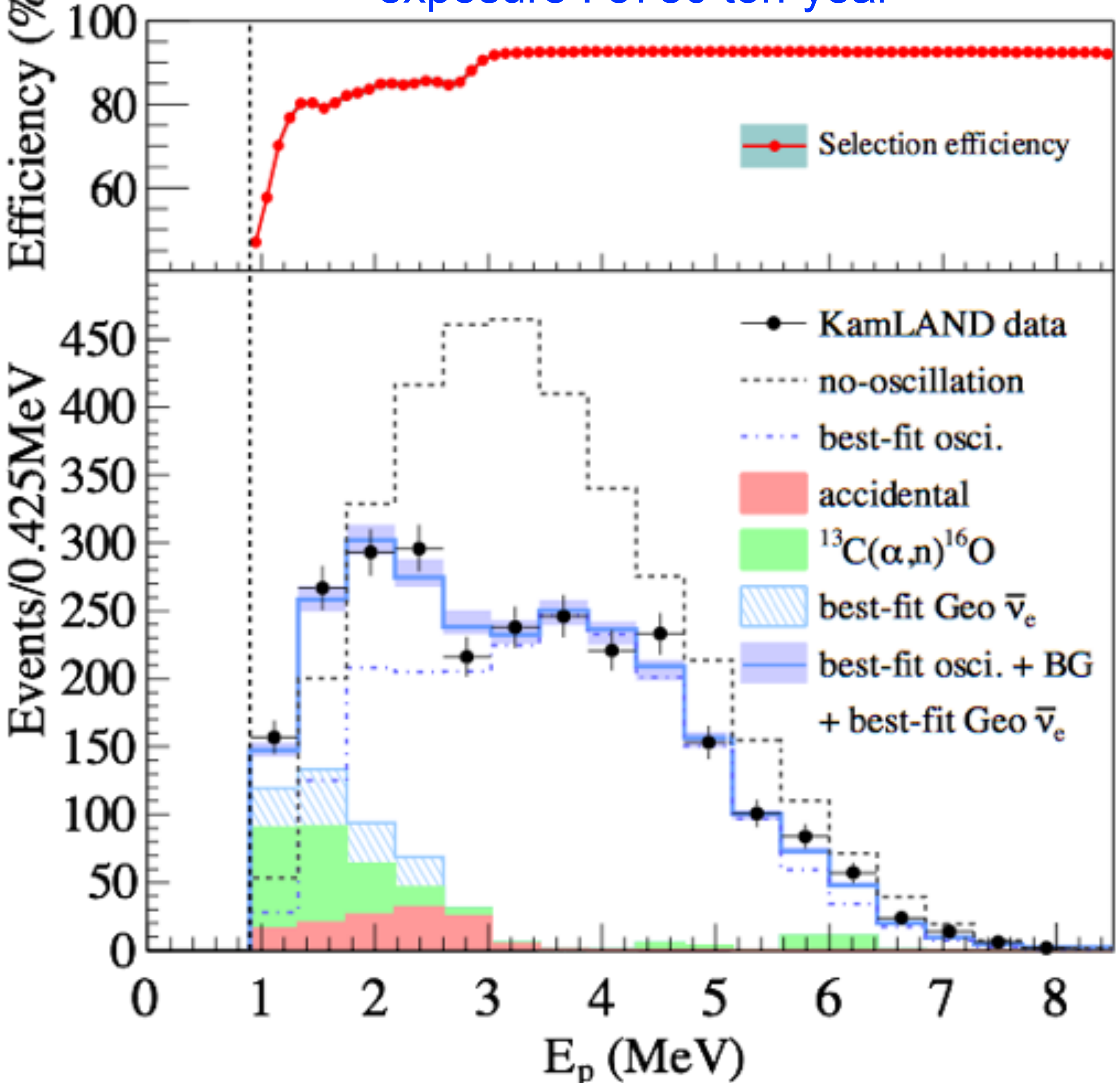
"Rate + Shape + Time" analysis

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

time dependent

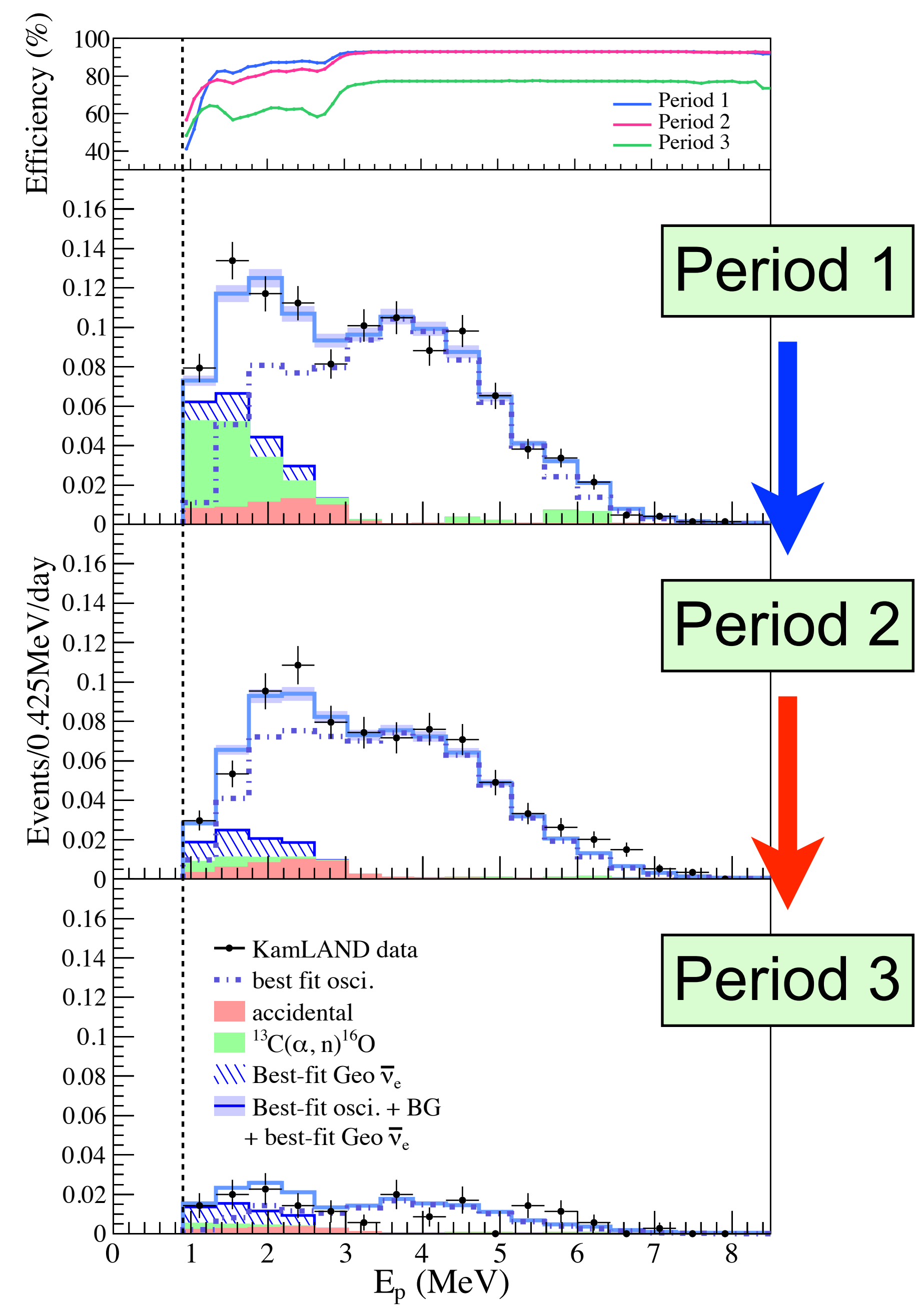
Observed Energy Spectrum

exposure : 5780 ton-year



purification (α,n) ↓

earthquake reactor ↓



significant reduction

KamLAND only

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

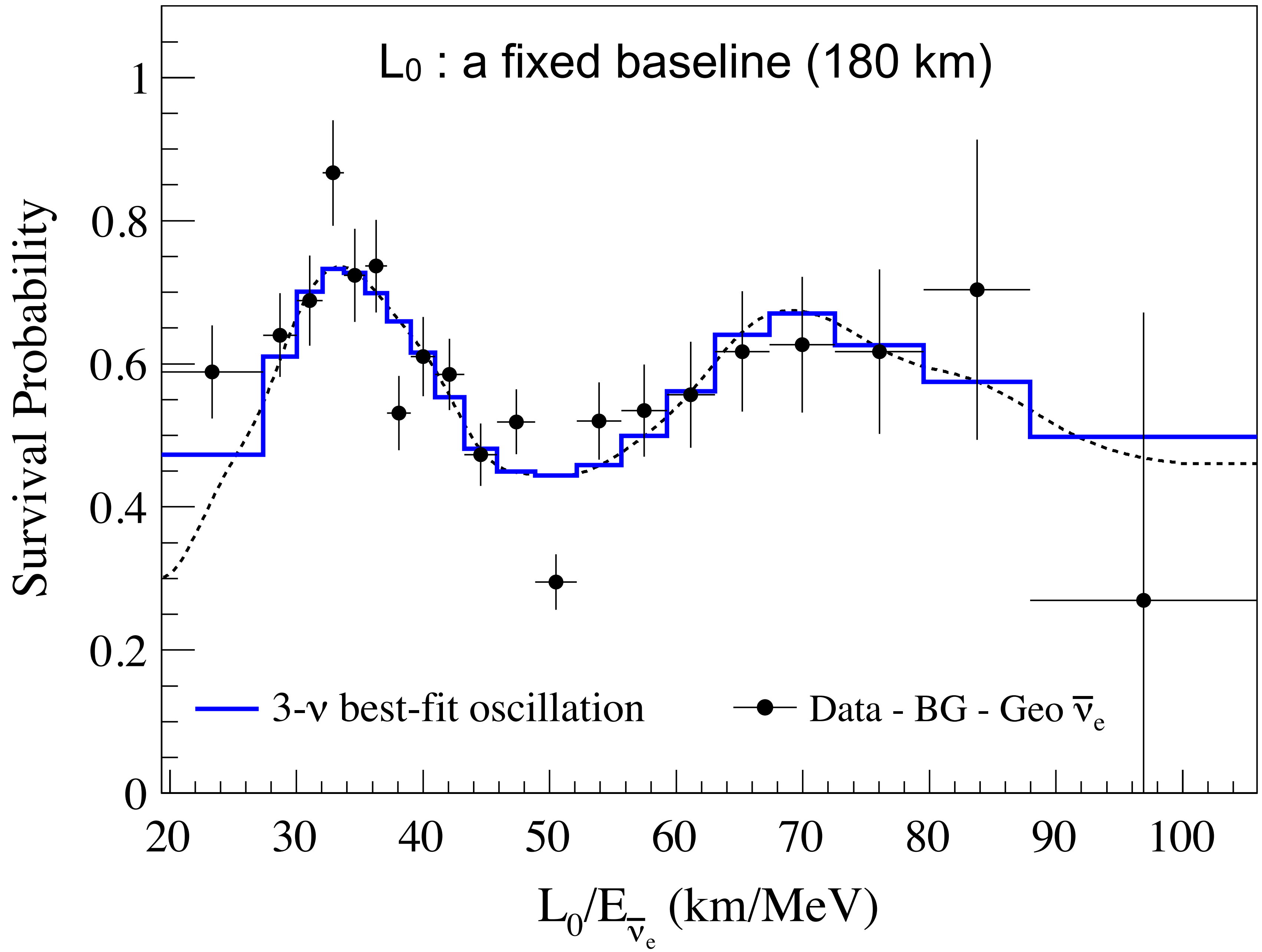
$$\tan^2\theta_{12} = 0.481^{+0.092}_{-0.080}$$

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

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

L/E plot

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



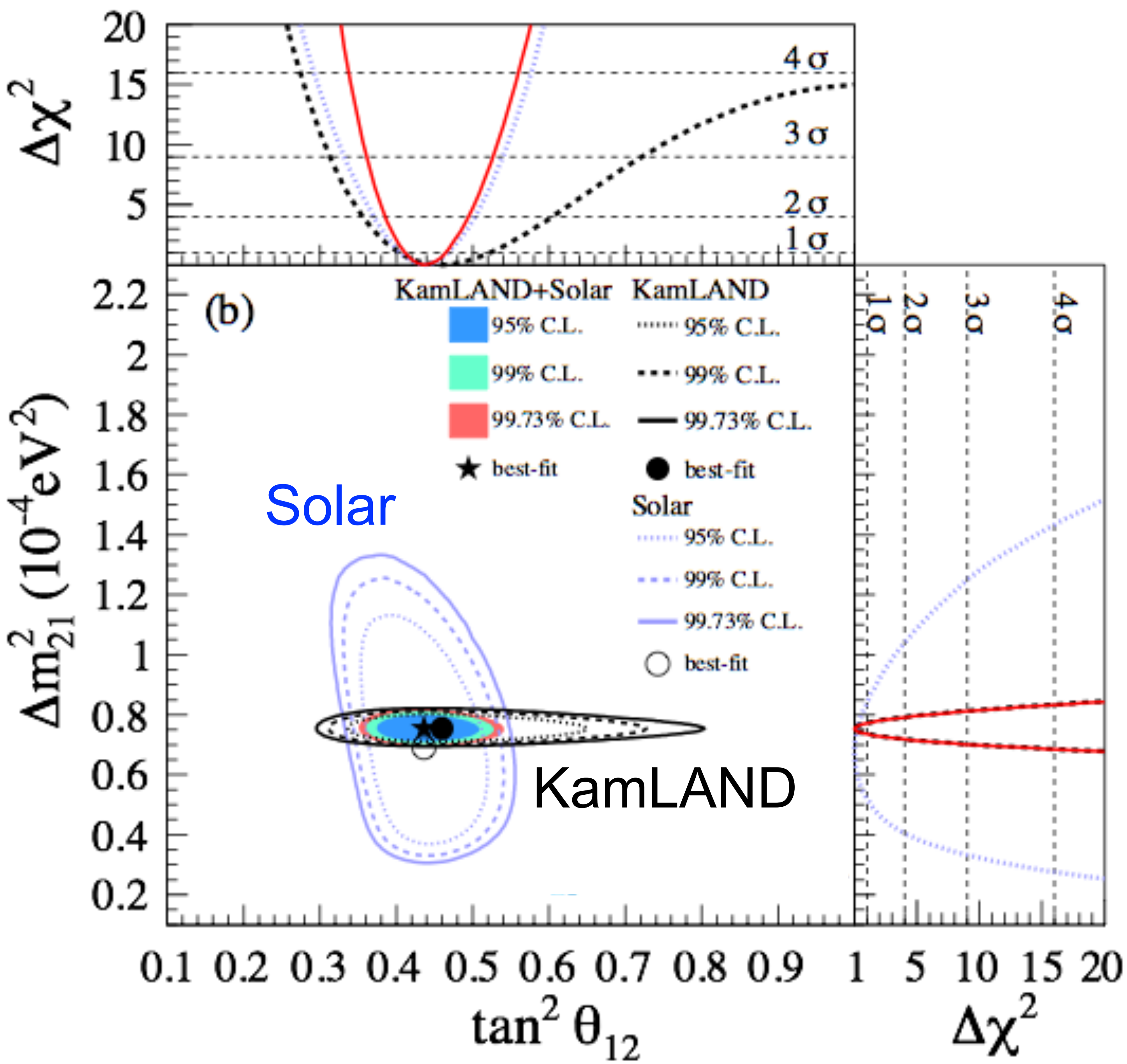
KamLAND data covers almost 2 cycle of oscillation

→ **strong evidence of neutrino oscillation**

3-Flavor Oscillation Parameters

θ_{12}: Solar constraint is dominant

Δm^2: KamLAND constraint is dominant



survival probability

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

electron density

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

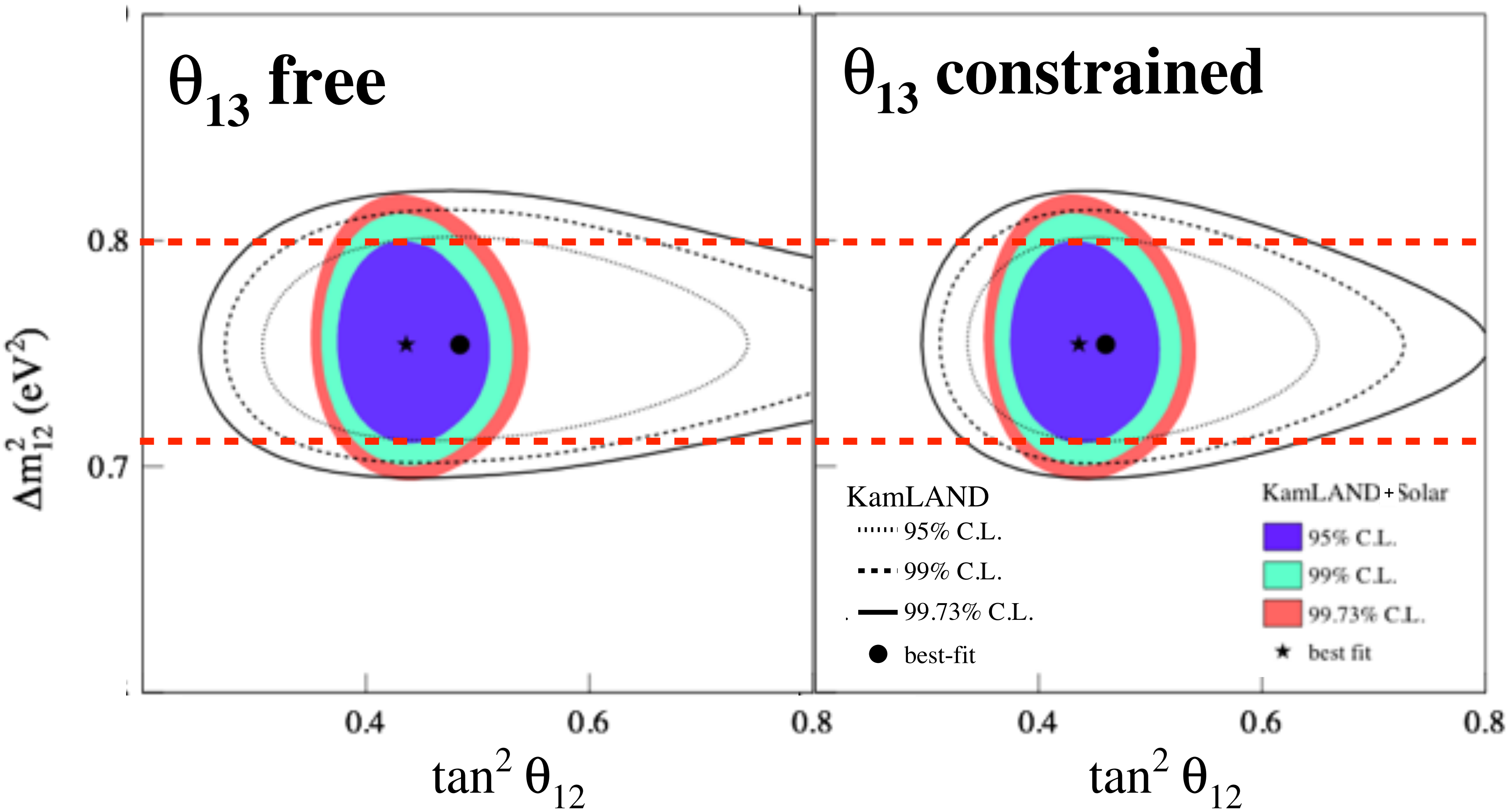
atmospheric oscillation length is completely averaged out ~~Δm^2_{31}~~

solar + KamLAND + θ_{13} experiments

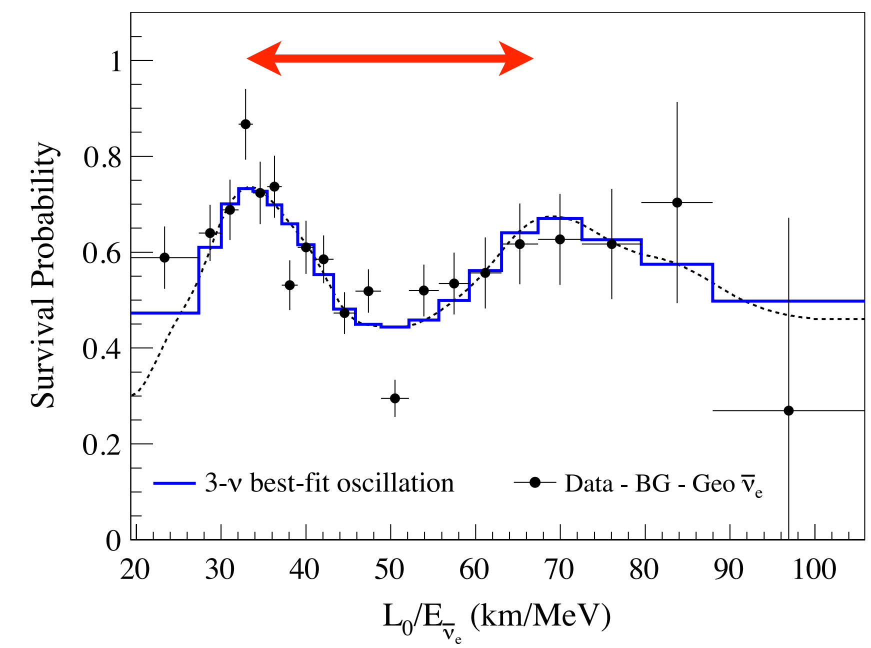
$$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$$
$$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$$

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

Geo Neutrino

Bulk Silicate Earth (BSE) model

Radioactive decay in the Earth (Uranium, Thorium)

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

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

U : 8 TW

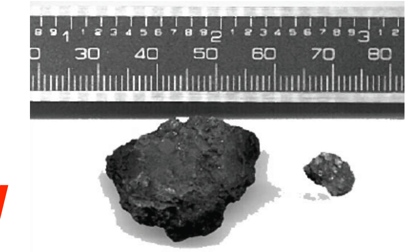
Th : 8 TW

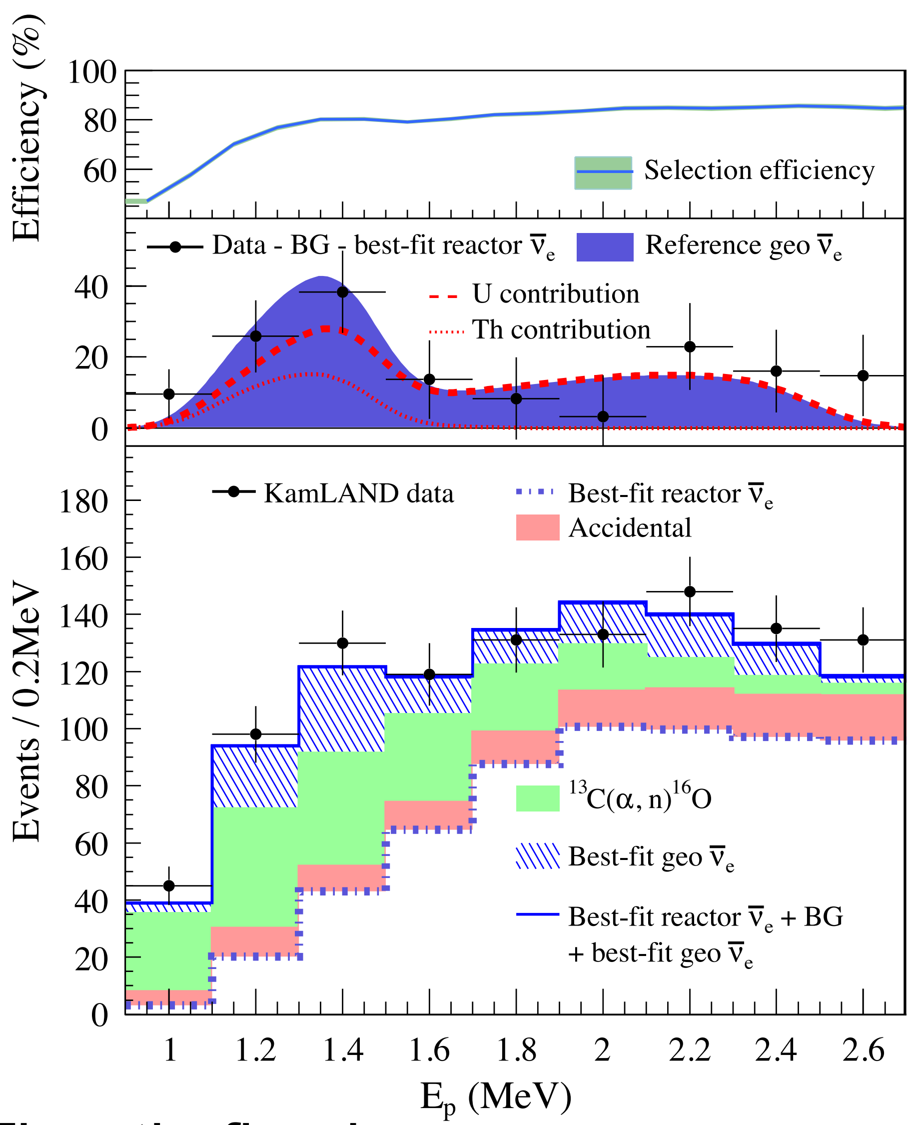
K : 4 TW

Total ~ **20 TW**

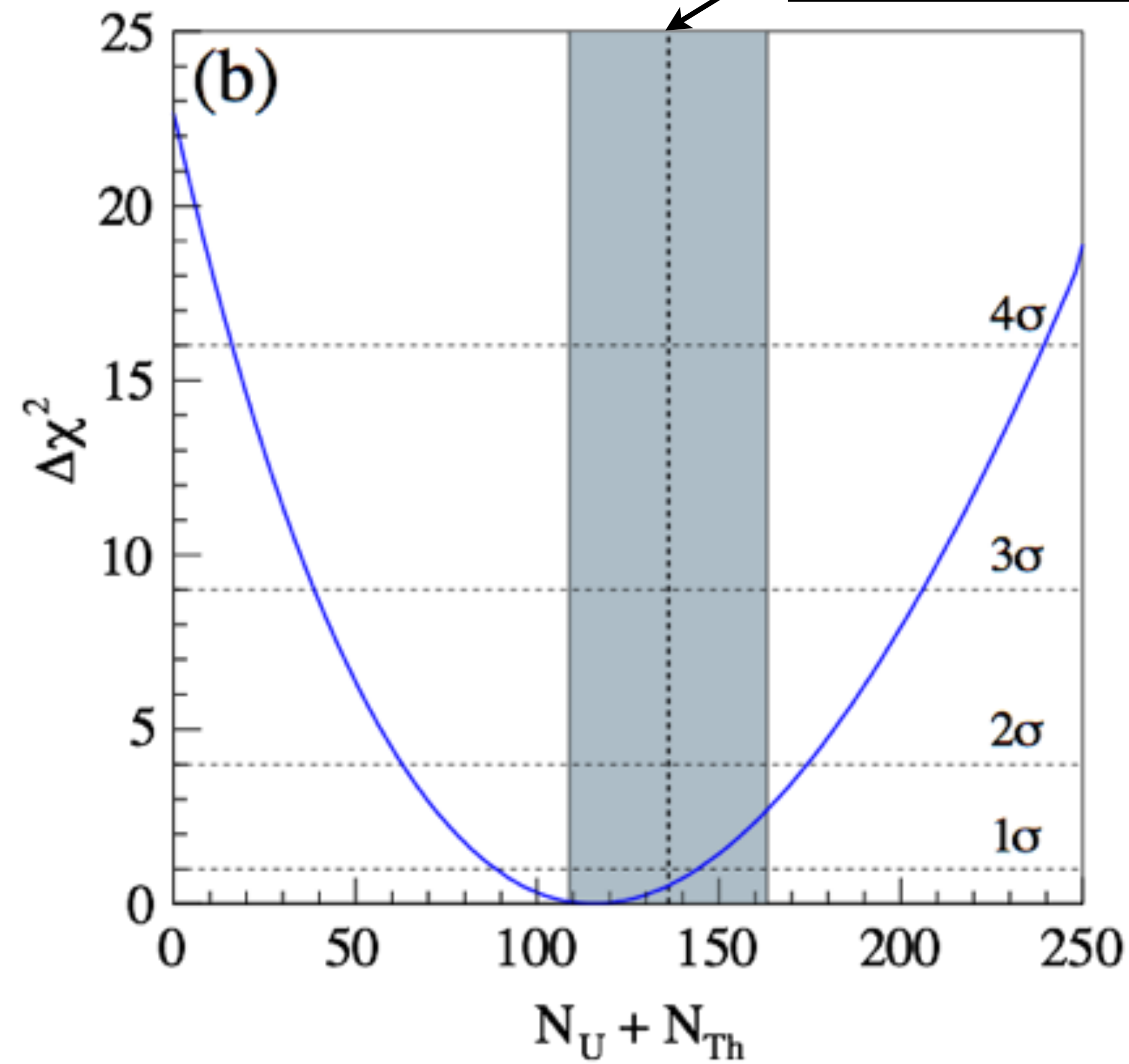
Geochemical model

chondrite meteorite





earth model prediction
EPSL 258, 147 (2007)



U/Th ratio fixed

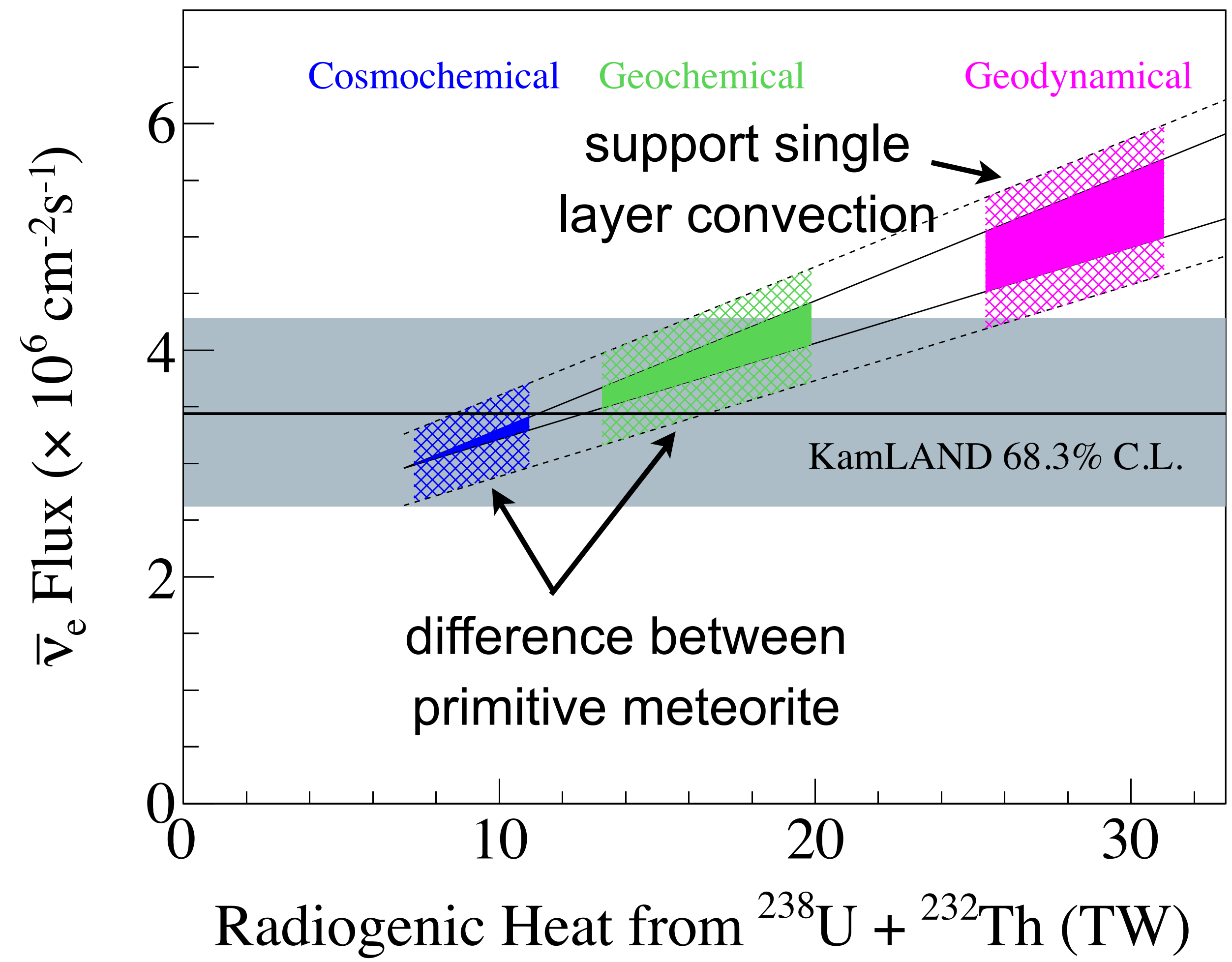
$N_{geo} = 116^{+28}_{-27}$ events $\quad F_{geo} = 3.4^{+0.8}_{-0.8} \times 10^6\ /\mathrm{cm}^2/\mathrm{sec}\ \ (30.7^{+7.5}_{-7.3}\ \mathrm{TNU})$

Earth Model Comparison

Three classes BSE compositional estimates

O. Šramek et al. Earth. Plan. Sci. Letters 361 (2013) 356–366

Model	Cosmochem.	Geochem.	Geodyn.
A	12 ± 2	20 ± 4	35 ± 4
A	43 ± 4	80 ± 13	140 ± 14
A	146 ± 29	280 ± 60	350 ± 35
Th/U	3.5	4	4
K/U	12000	14000	10000
Tot. Power (TW)	11 ± 2	20 ± 4	33 ± 3
Mantle power (TW)	3.3 ± 2.0	12 ± 4	25 ± 3
Mantle Urey ratio	0.08 ± 0.05	0.3 ± 0.1	0.7 ± 0.1



KamLAND result

radiogenic	**$14.2^{+7.9}_{-5.1}$ TW**
heat flow from Earth's surface	47±2 TW

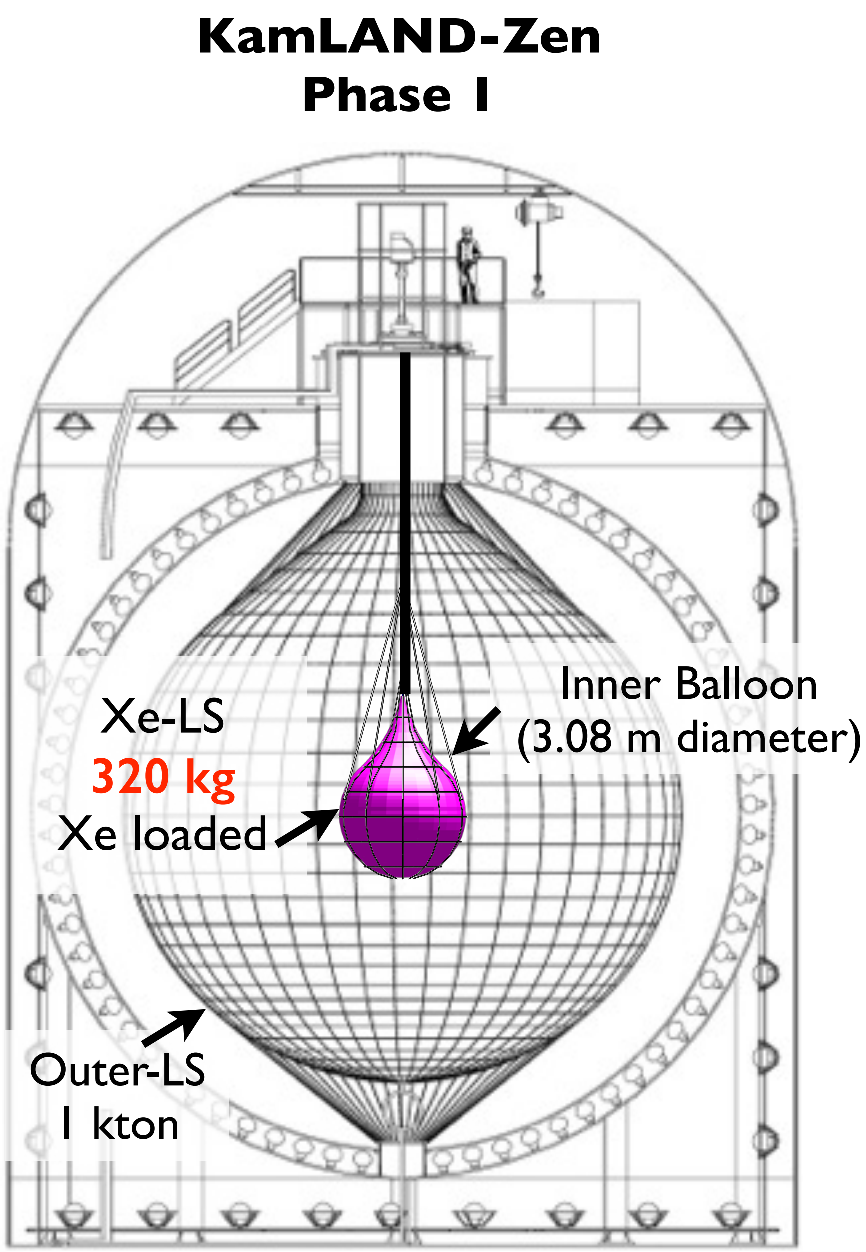
Geodynamical prediction with homogeneous hypothesis is disfavored at 89% C.L.

All composition models are still consistent within ~2σ

Geo-ν measurement is in agreement with BSE models

KamLAND-Zen

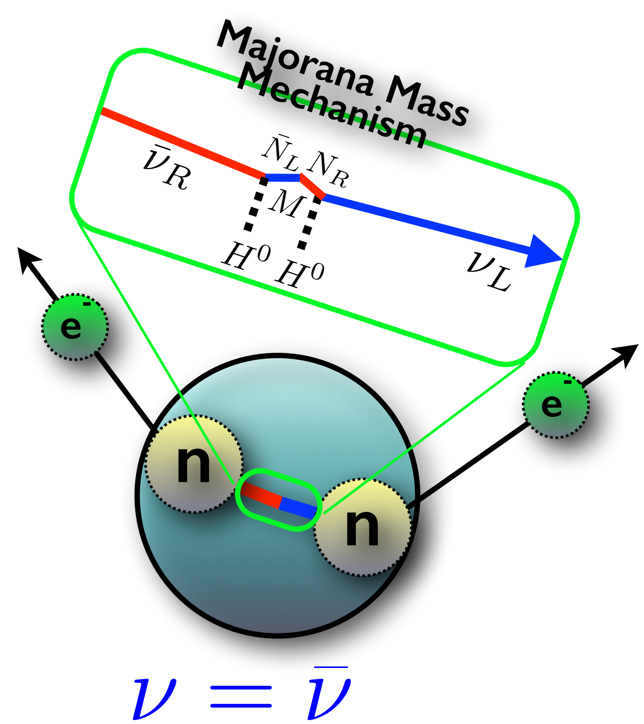
Kamioka Liquid Scintillator Anti-Neutrino Detector
Zero Neutrino Double Beta

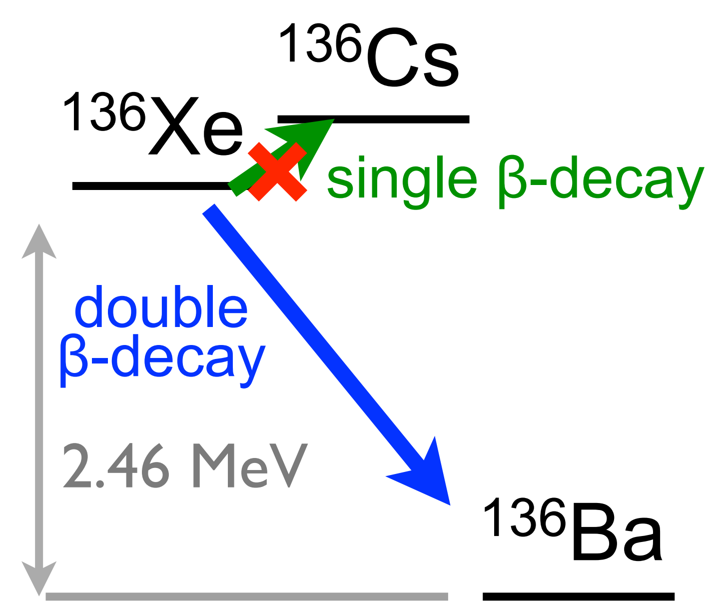


Advantage of KamLAND

- running detector : start quickly with relatively low cost
- big and pure : no BG from external gamma-rays
- purification of LS, replacement of mini-balloon are possible

→ **high scalability** (a few ton of Xe)





Xenon loaded LS (Xe-LS)

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

$\sigma_E(2.5MeV) = 4\%$

KamLAND-Zen : funded in 2009 / Fabrication in 2010-2011

Start phase 1 : 320 kg Xe start in Sep. 2011

Purification activity in Jun. 2012 (~1.5 year)

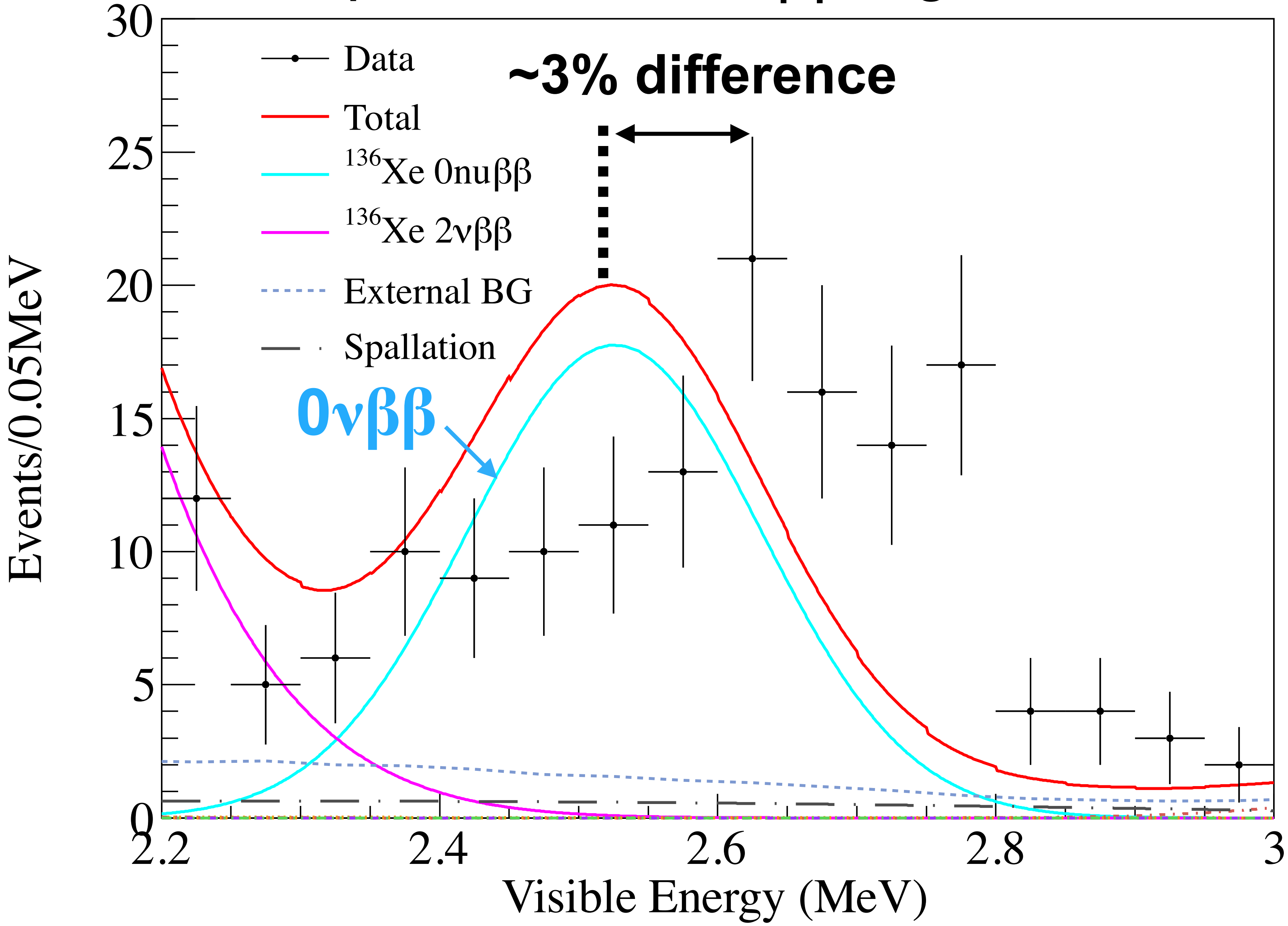
Start phase 2 : 383 kg Xe start in Dec. 2013

Construction in 2011

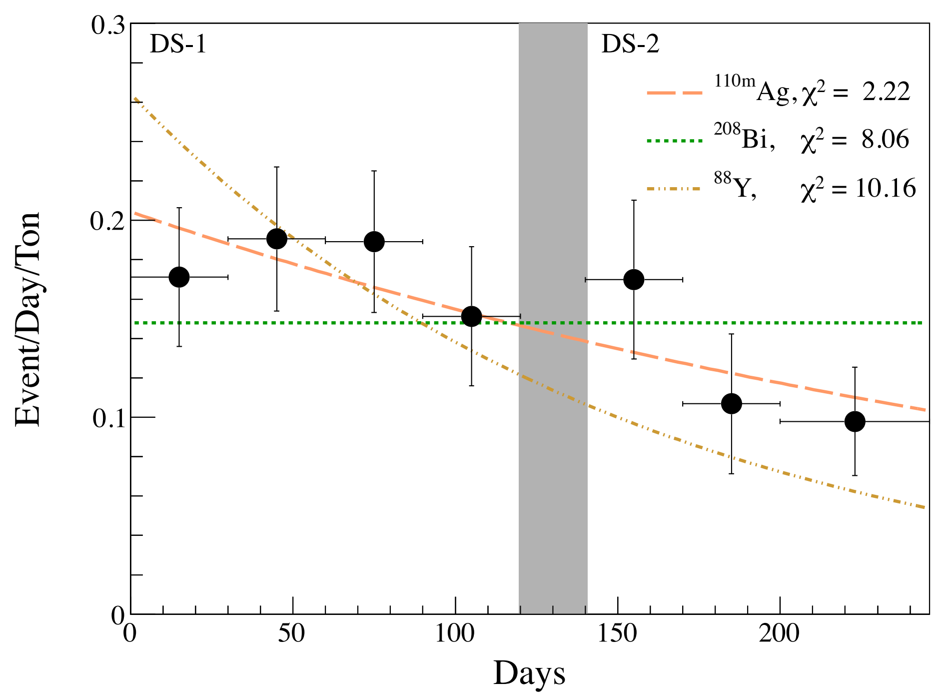
Unexpected Background for 0νββ

Phase 1 (first 112.3 days)

peak fit with 0νββ signal



event rate variation（2.2 < E < 3.0 MeV）



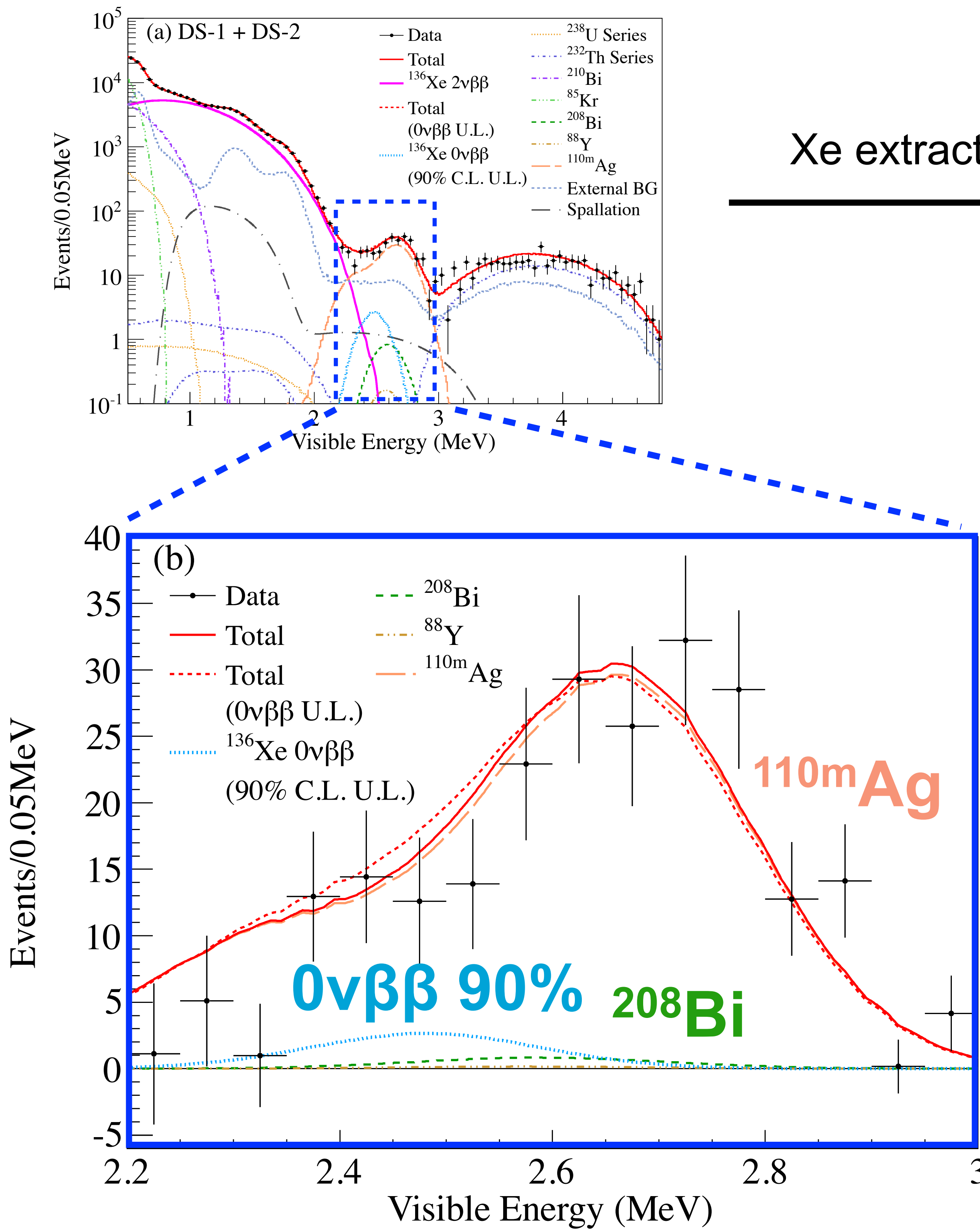
consistent with ^{110m}Ag decay (250 days)

different peak position and time variation in event rate

^{136}Xe 0νββ only is rejected at more than 8σ level

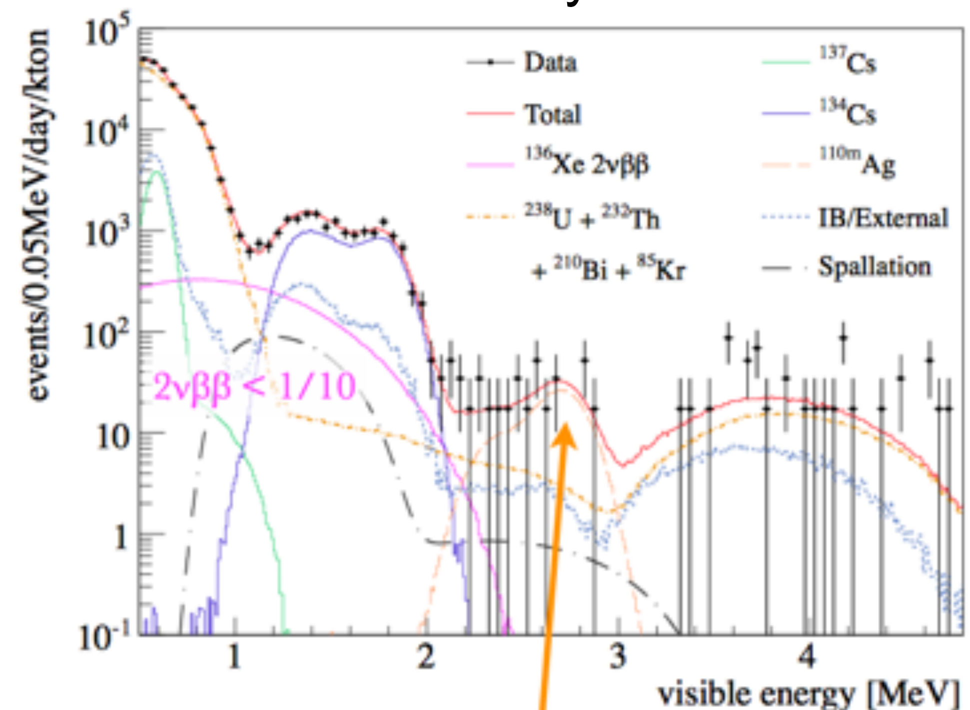
Limit on half-life of ^{136}Xe $0\nu\beta\beta$

Phase 1 (213 days)



Xe extraction →

15.5 days



remaining Ag BG around 2.6MeV

demonstration of Xe on-off measurement

89.5kg·yr

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

KamLAND-Zen Phase 1 (2012)

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

use same NME (parameter)

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

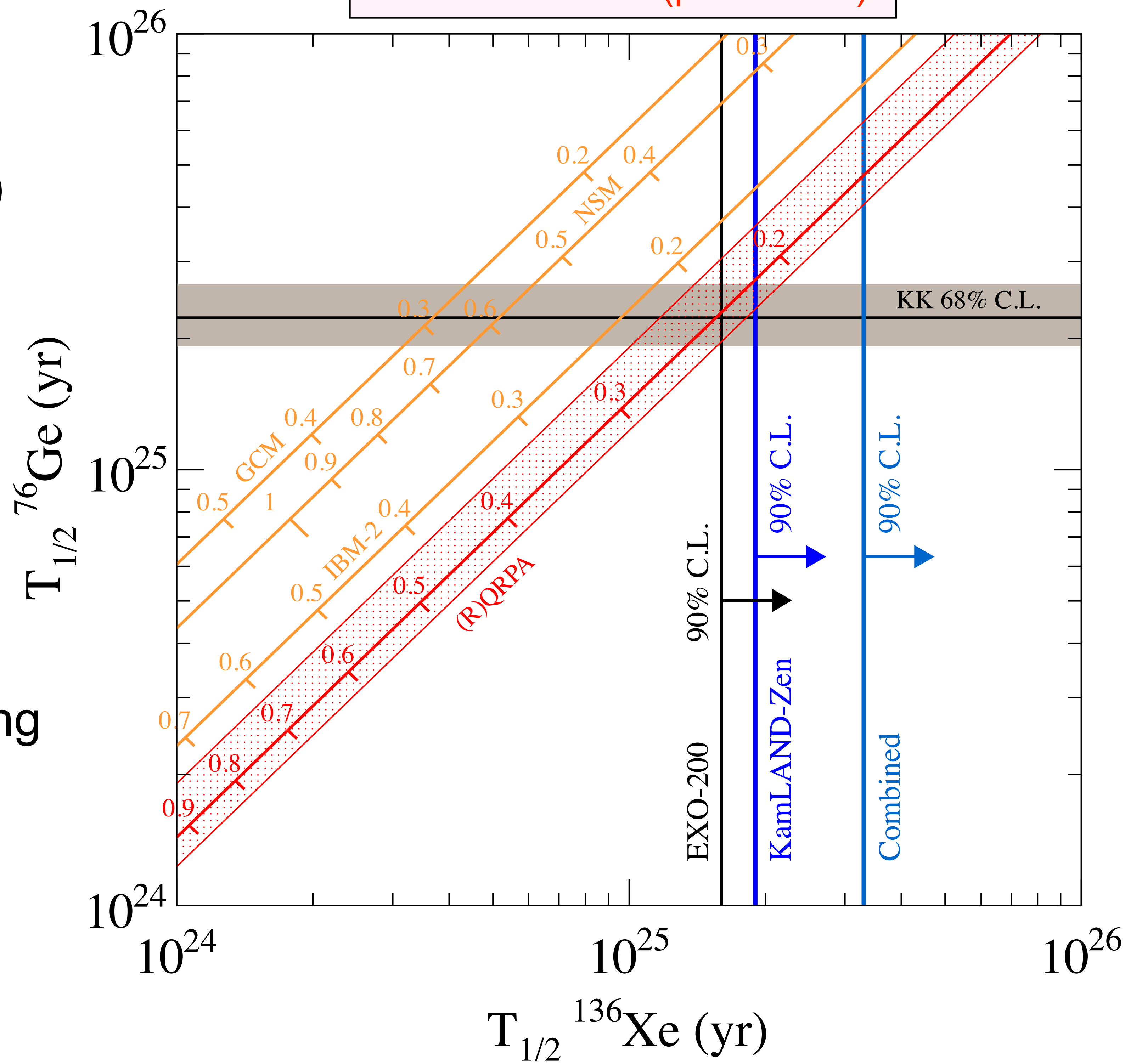
↓ + EXO-200

$T_{1/2} > 3.4\times10^{25}$ 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

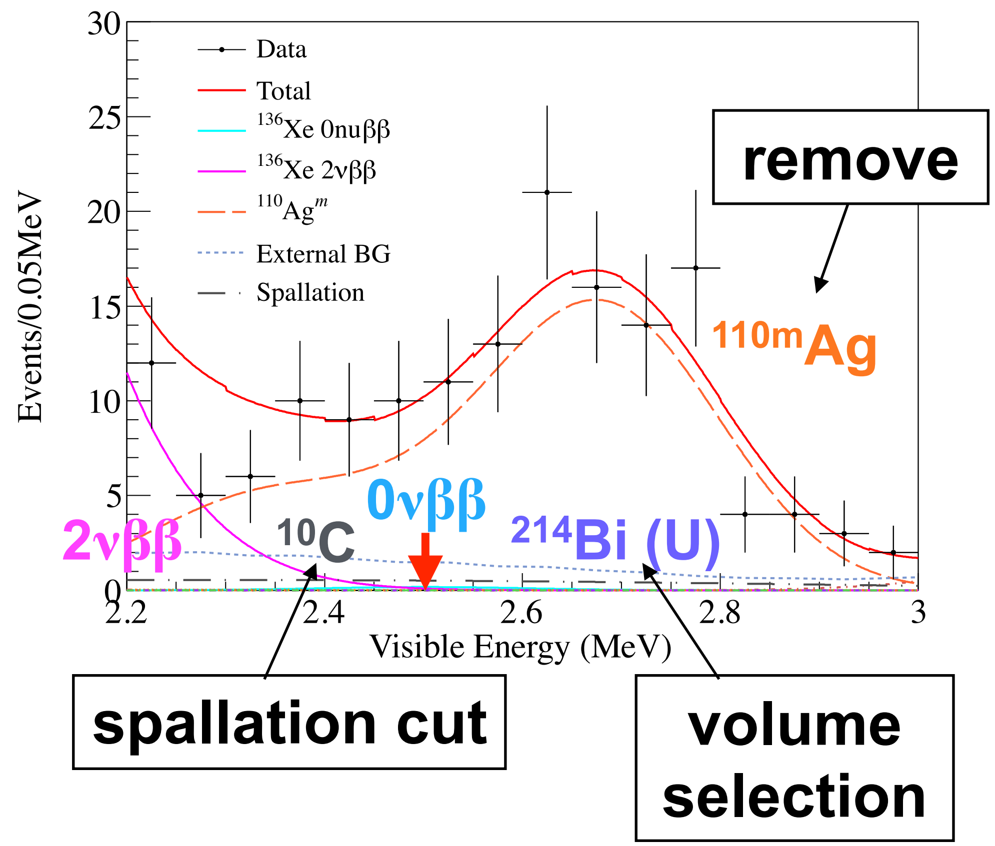
Two possible sources:

(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

Phase 1 (first 112.3 days)



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

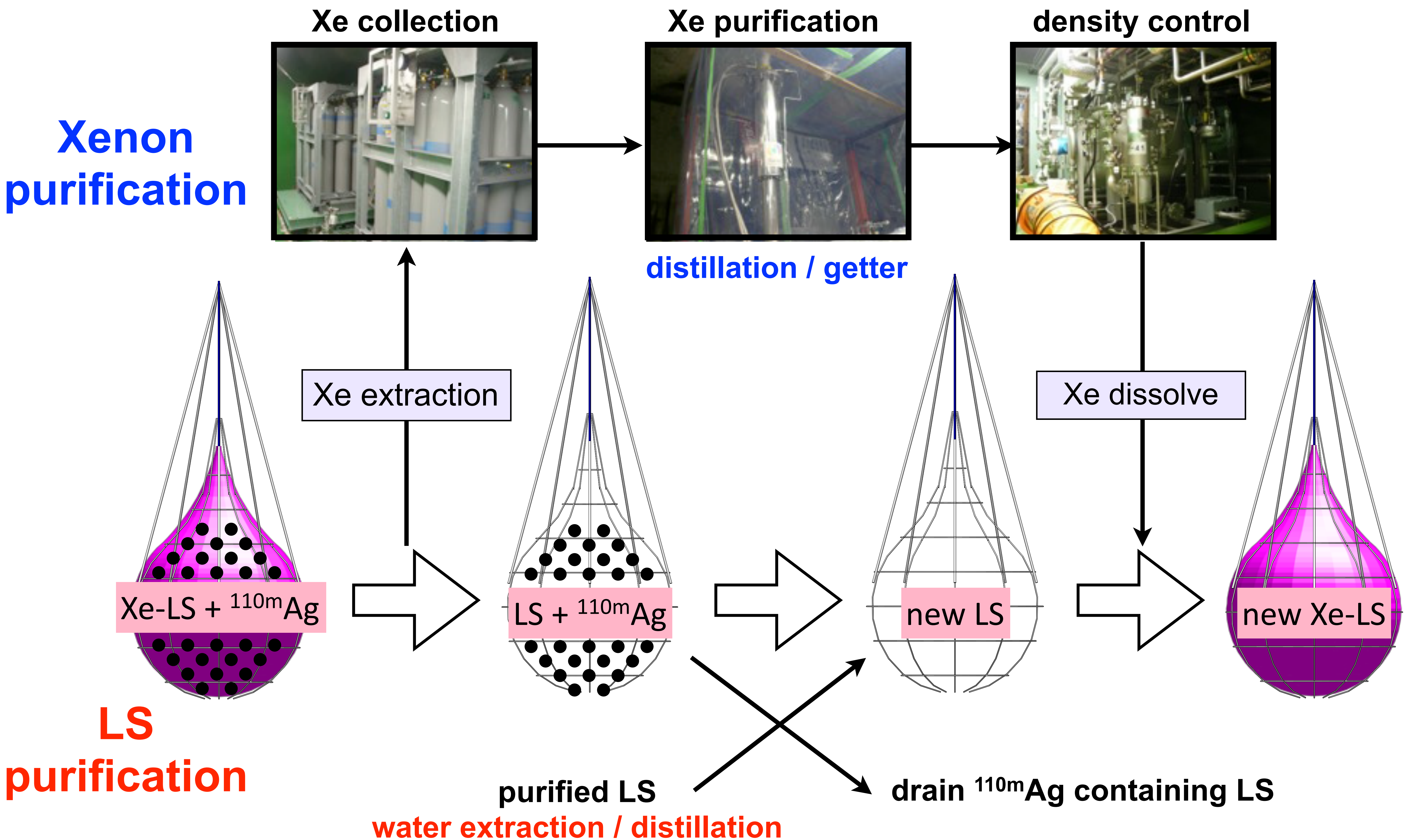
3. Spallation cut after muon

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

4. Optimization of volume selection

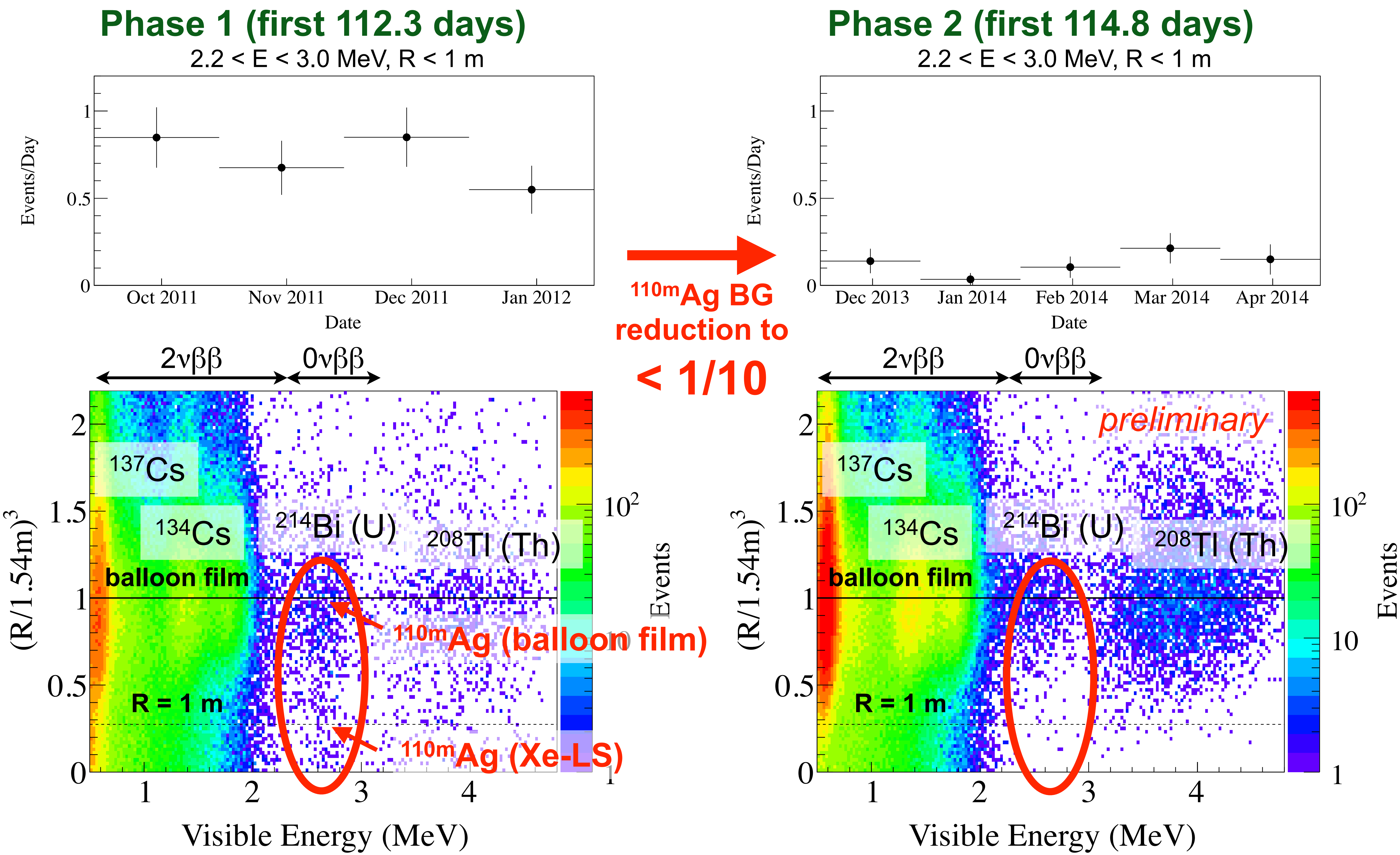
fiducial volume limitation by ^{214}Bi (U) on the balloon film → multi-volume selection

Purification Strategy



1/3 - 1/4 reduction by one replacement

^{110m}Ag Background Reduction

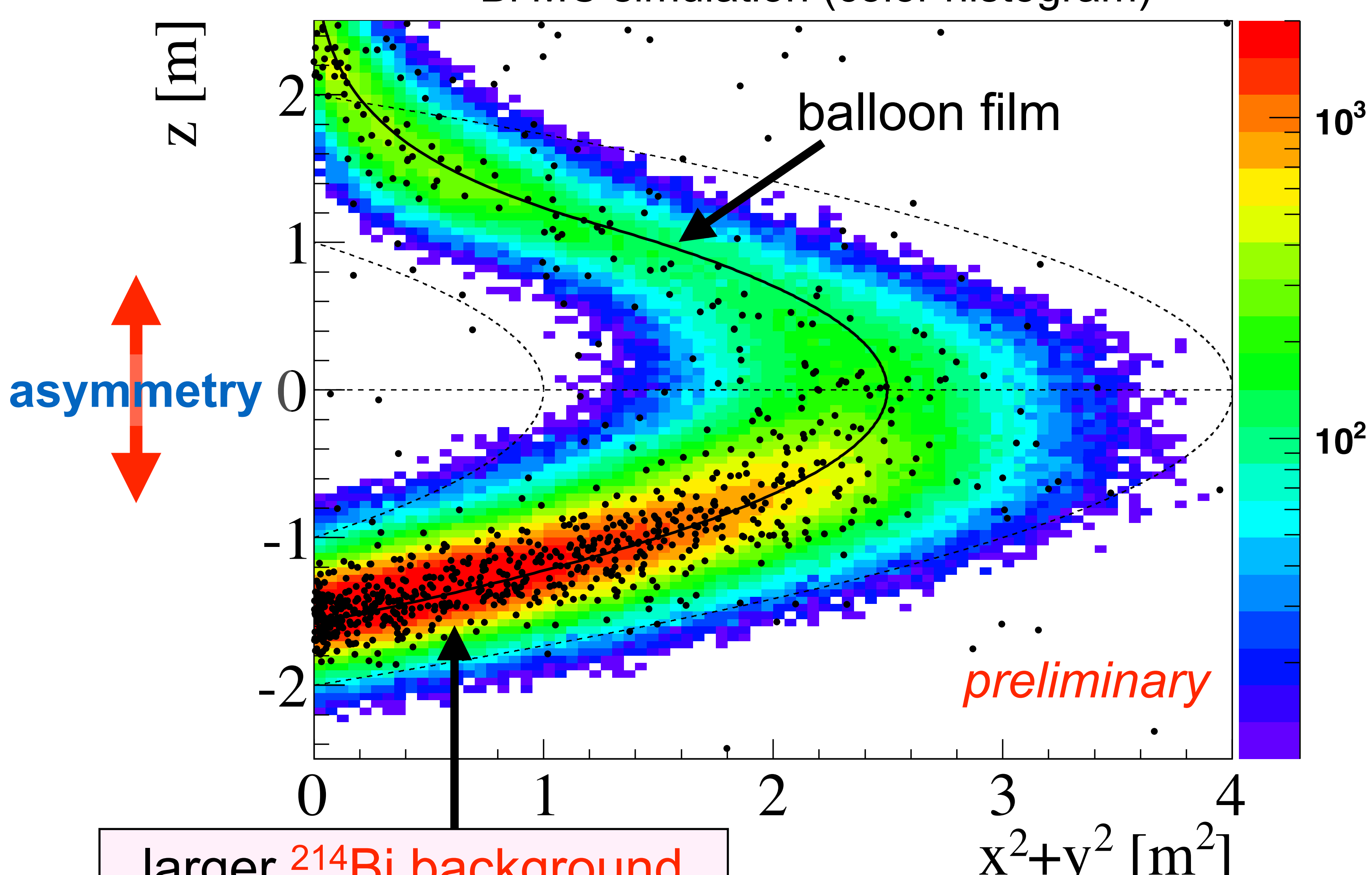


Primary BG : ^{214}Bi (U) at balloon / spallation ^{10}C / remaining ^{110m}Ag?

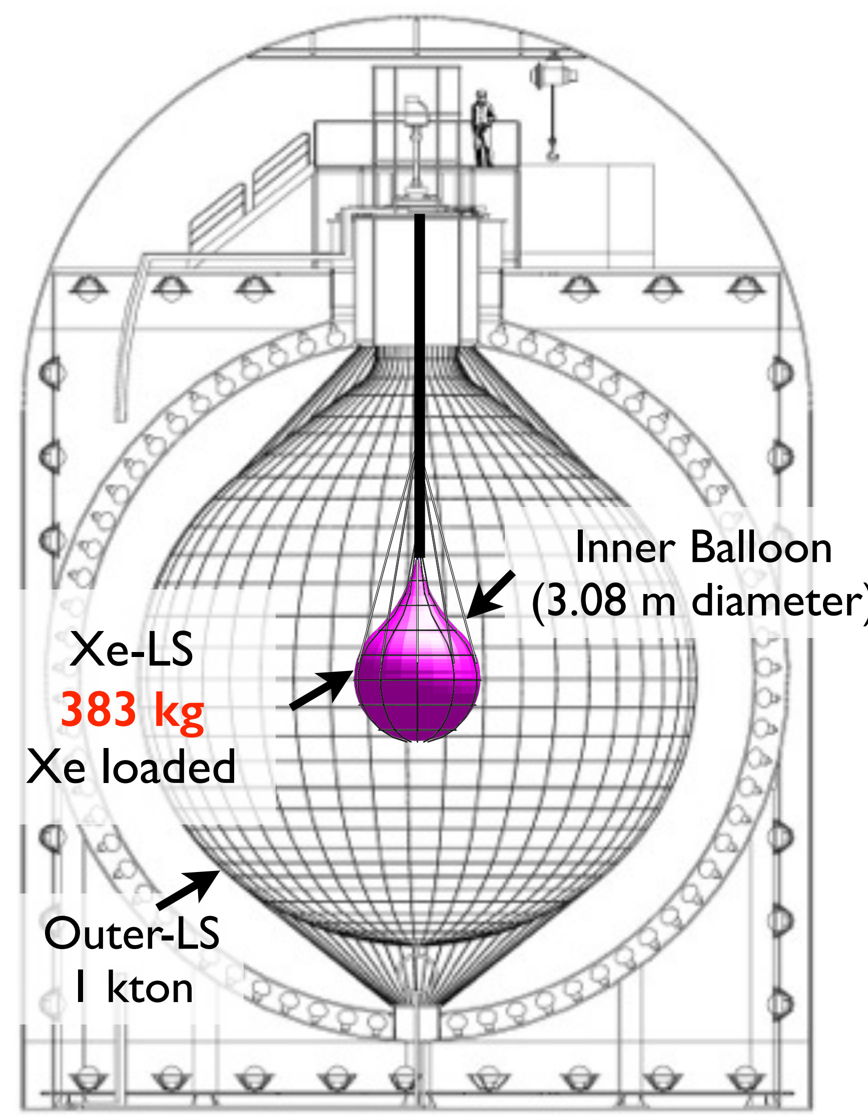
Optimization of Volume Selection

ROI : 2.3 < E < 2.7 MeV

candidate events (black points)
^{214}Bi MC simulation (color histogram)



KamLAND-Zen Phase 2



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

multi-volume selection for analysis optimization

↓

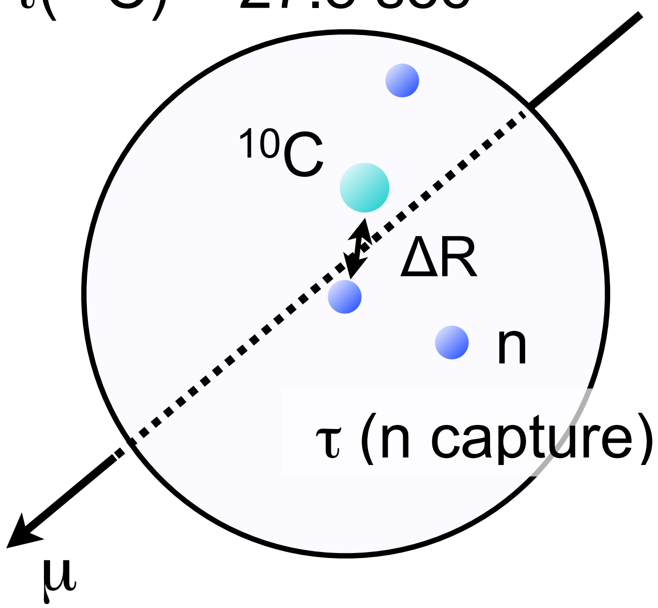
target volume for spectral fit : R < 2.0 m

40 equal volume bins
(20 bins + 20 bins in upper / lower hemisphere)

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

Baseline restorer and signal splitter | 1GHz FADC + 3 range 200 MHz FADC for each channel | Trigger module

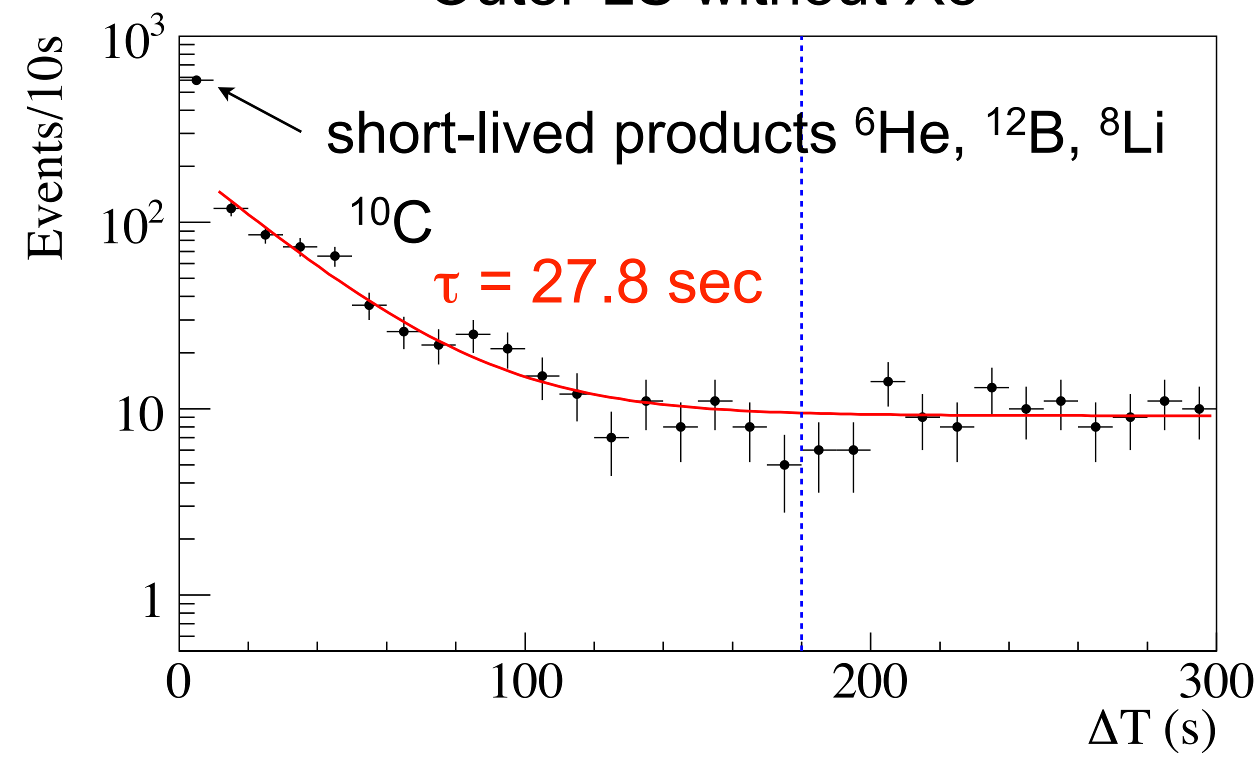
preliminary

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

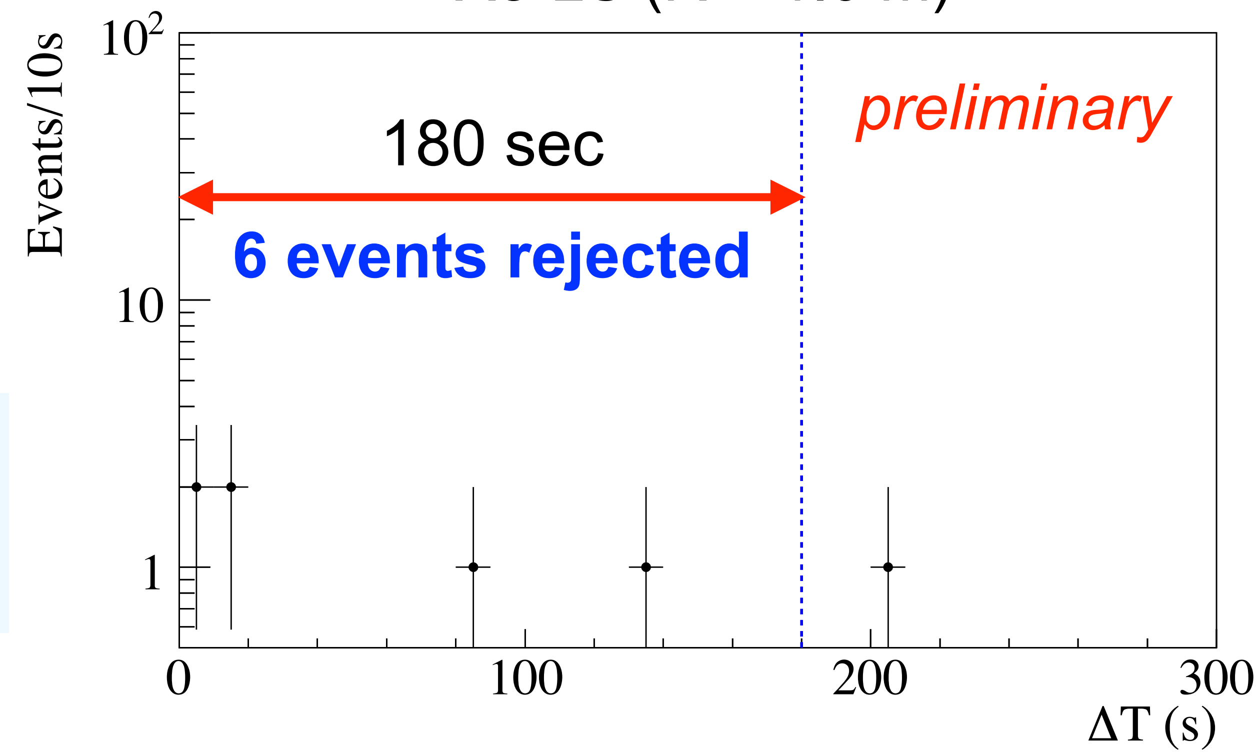
Efficient background rejection

2.2 < E < 3.5 MeV

Outer-LS without Xe

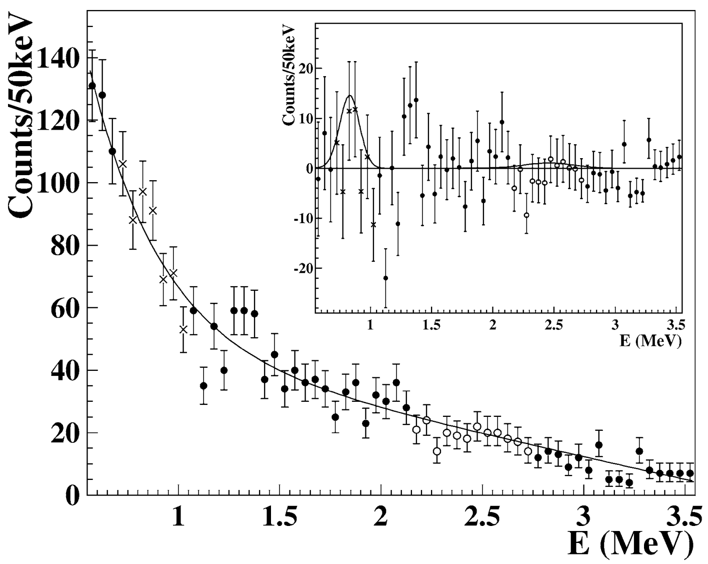


Xe-LS (R < 1.0 m)



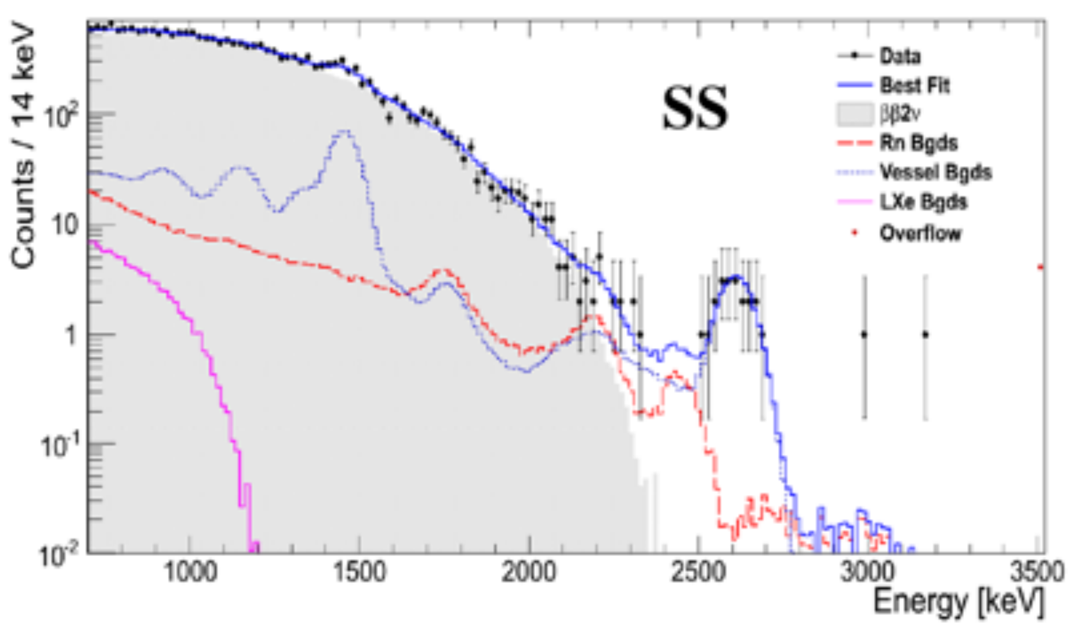
Fit to Energy Spectrum for 2νββ

DAMA (2002) Liquid Xe scintillator



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

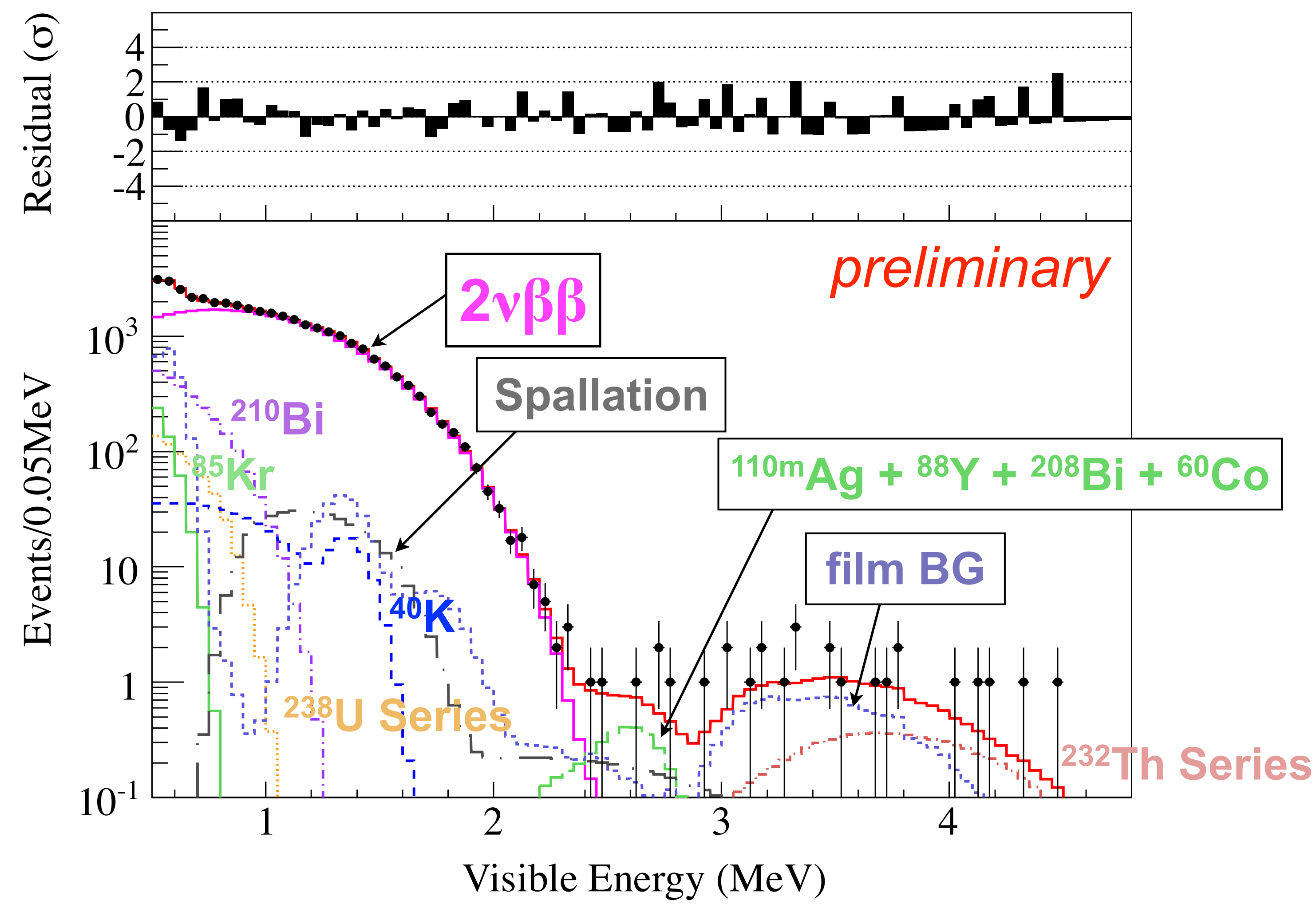
EXO-200 (2013) Liquid Xe TPC + scintillator



$T^{2\nu}_{1/2} = 2.165 \pm 0.016(\text{stat}) \pm 0.059(\text{syst}) \times 10^{21}$ 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

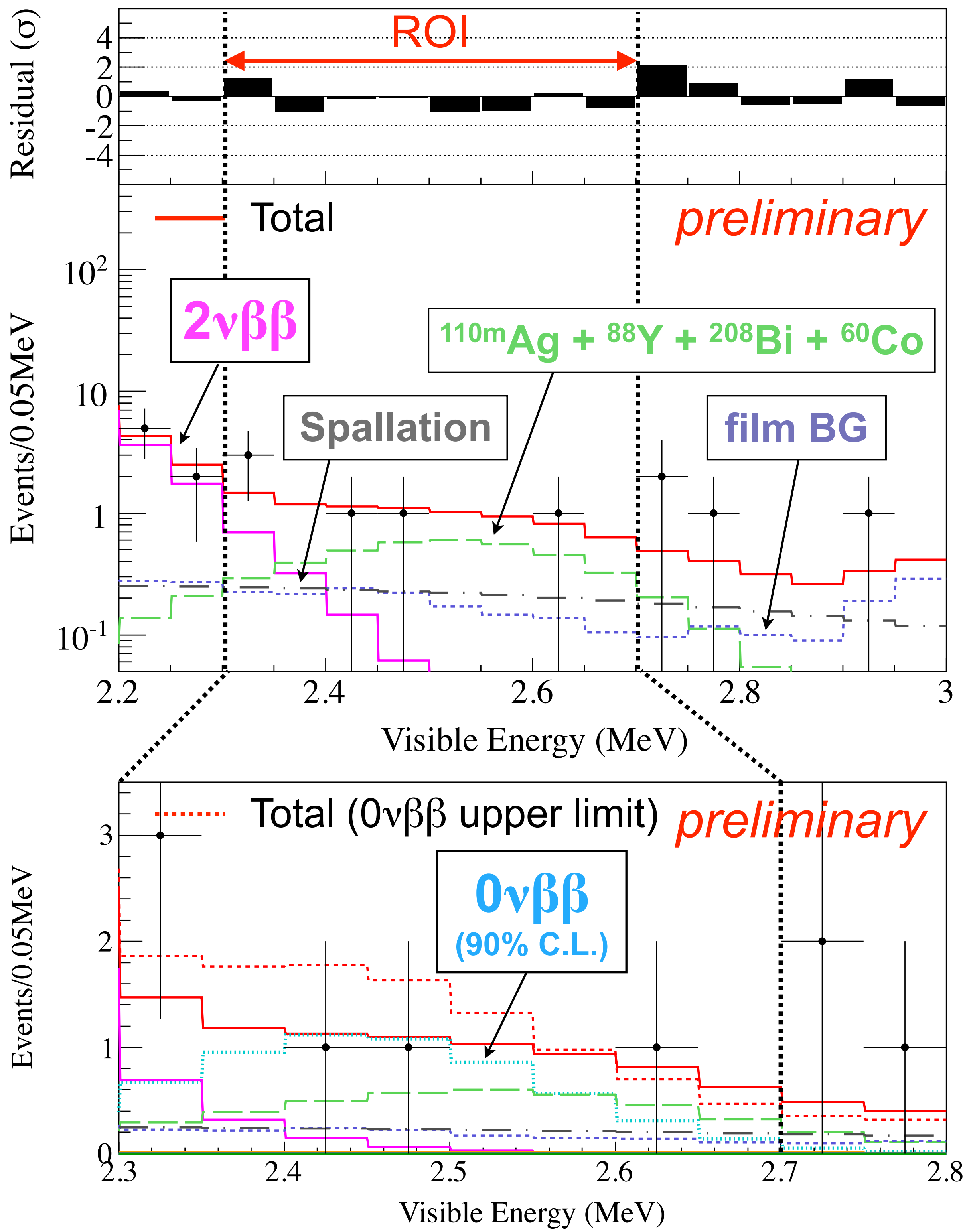
consistent with KamLAND-Zen Phase 1

↓

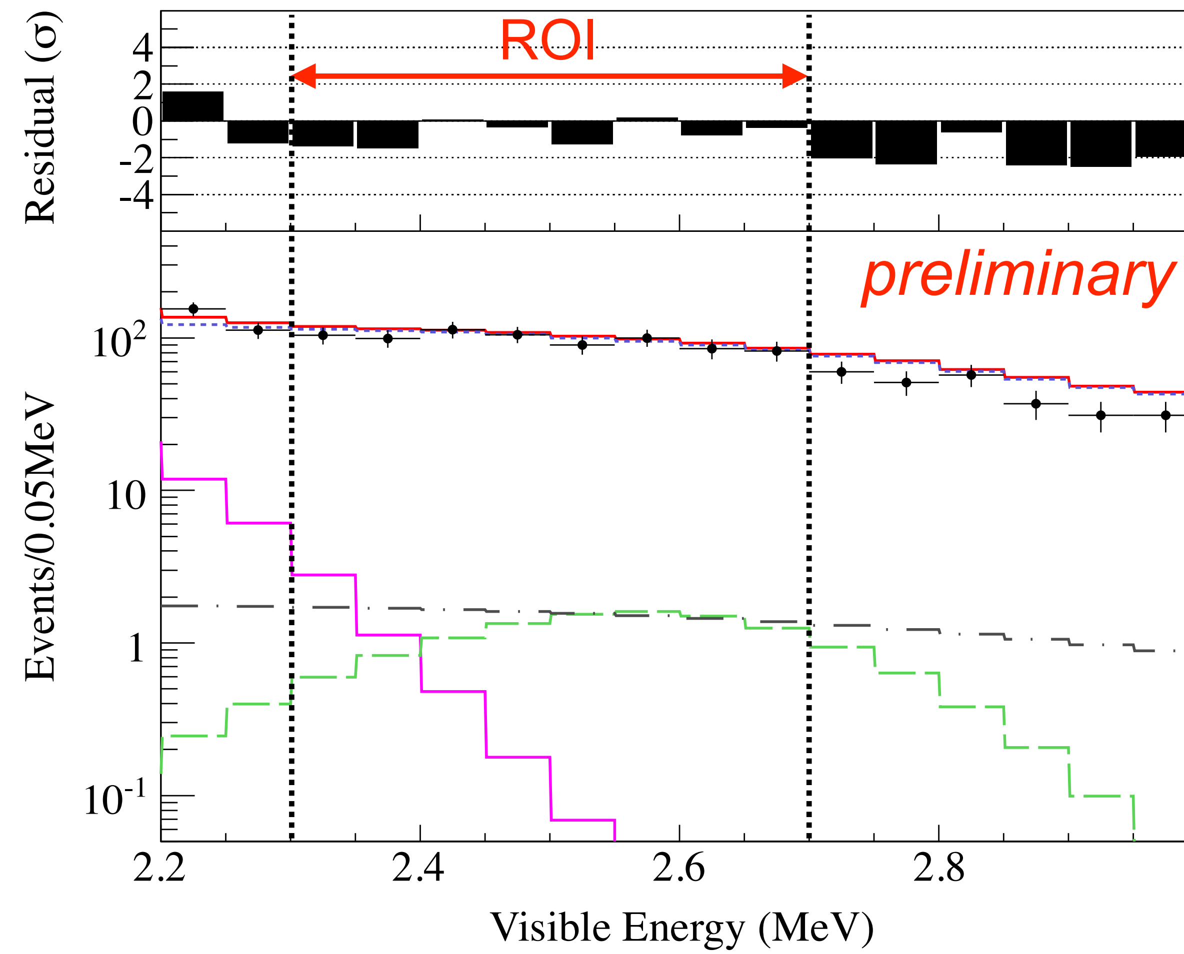
$T^{2\nu}_{1/2} = 2.30 \pm 0.02(\text{stat}) \pm 0.12(\text{syst}) \times 10^{21}$ yr

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.

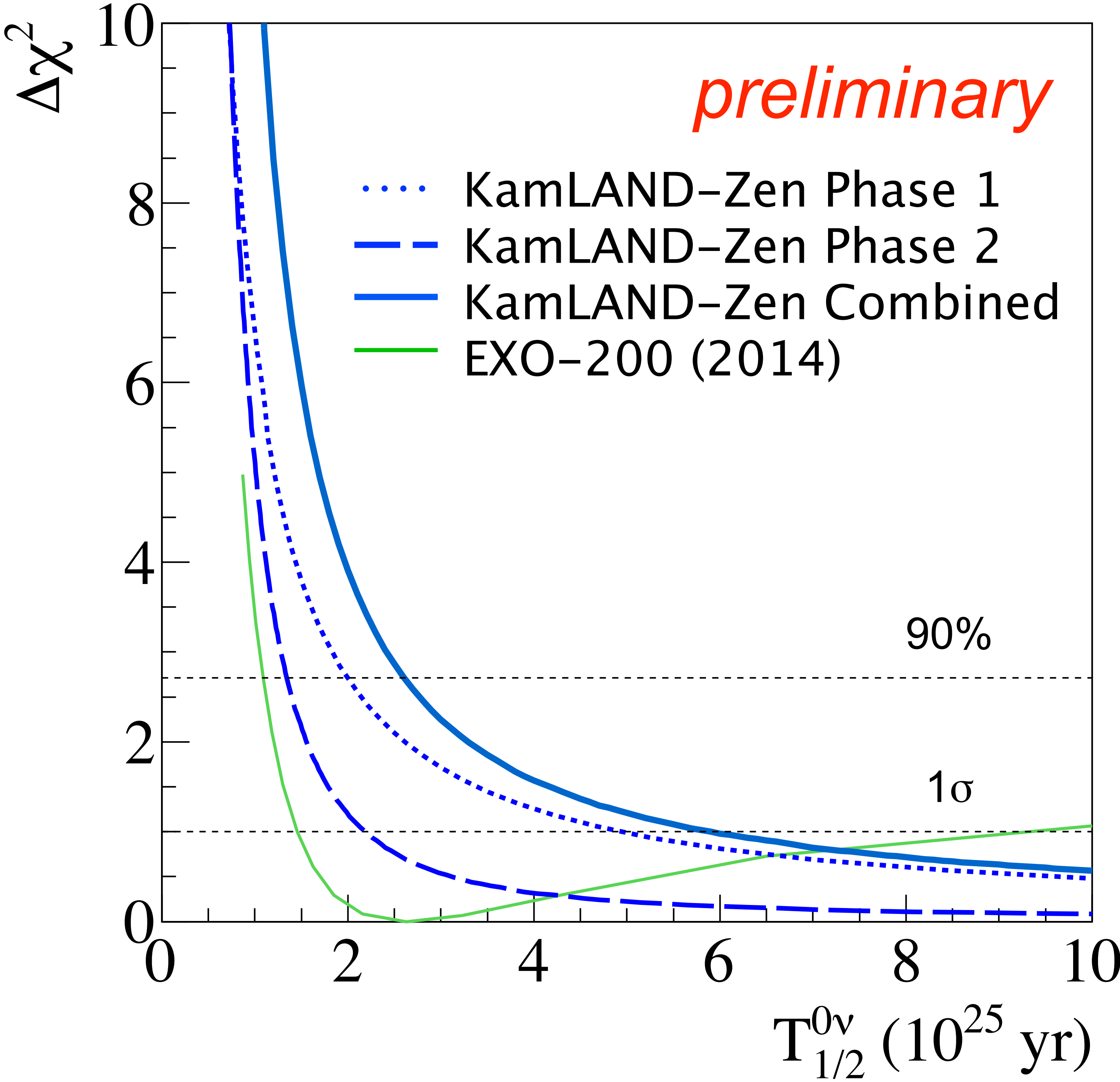
< 17.0 events/day/kton-LS

↓

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

^{136}Xe $0\nu\beta\beta$ Decay Half-life

combined result (Phase 1 + 2)



<u>Half-life limit at 90% C.L.</u>

KamLAND-Zen

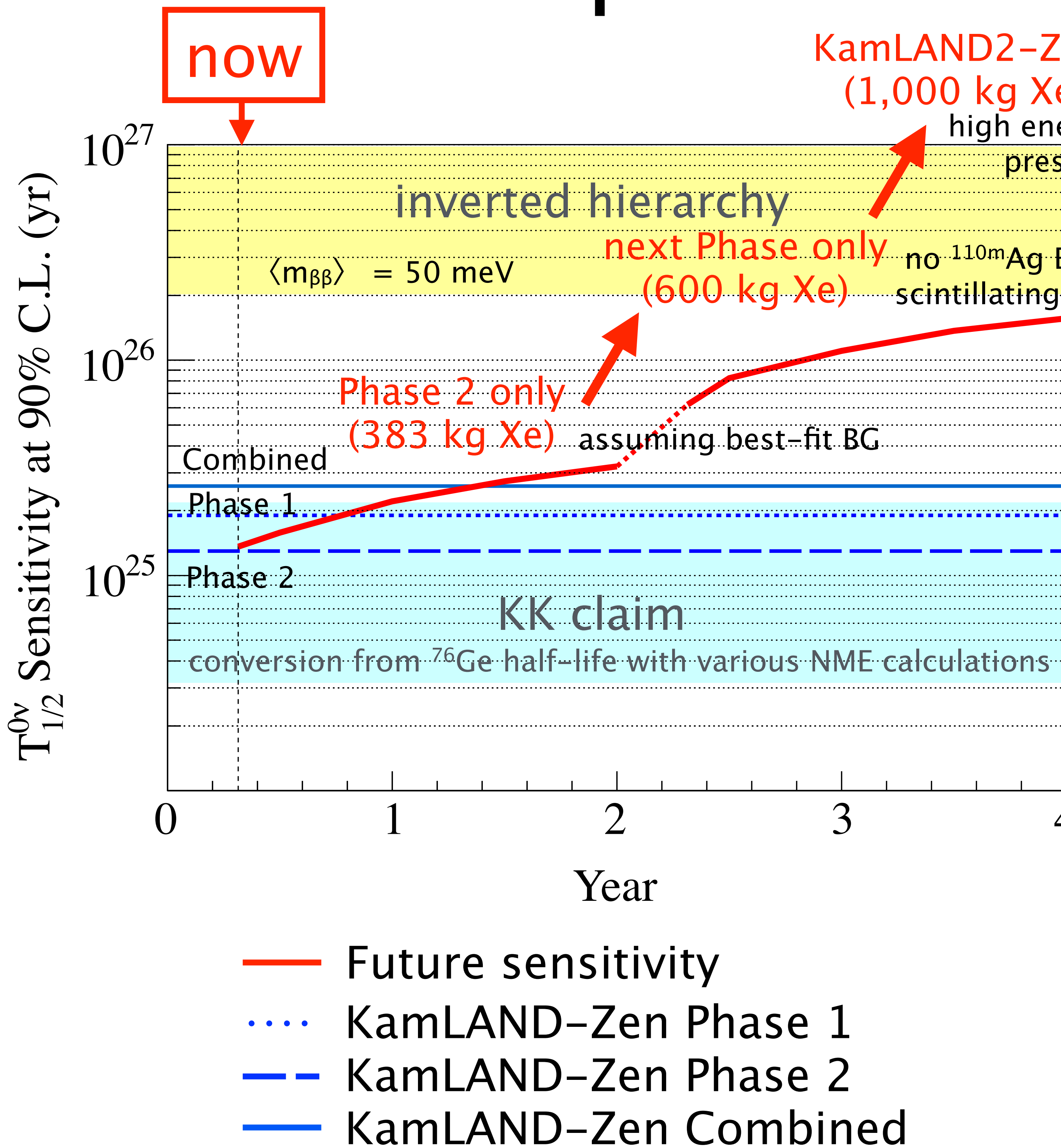
Phase 1	$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr
Phase 2	$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr
Combined	$T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr

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

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

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

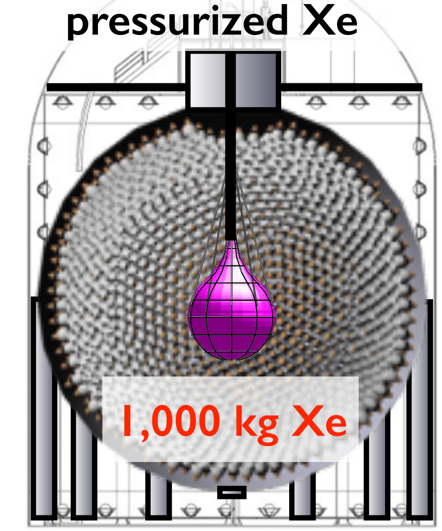
Prospect for 0νββ Search



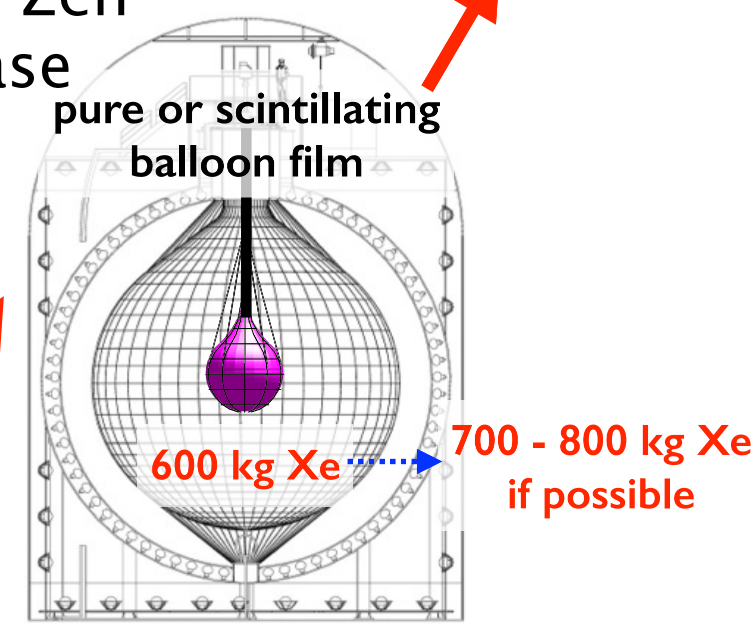
KamLAND2-Zen

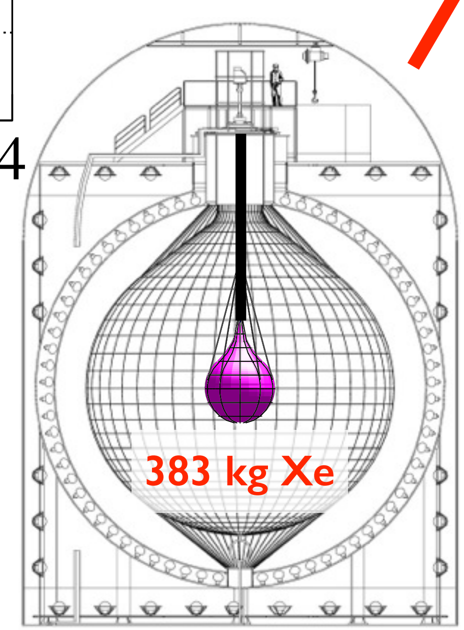
test of inverted neutrino mass hierarchy

target ⟨$m_{\beta\beta}$⟩ ~ 20 meV



KamLAND-Zen next phase





KamLAND-Zen Phase 2

Detector improvements are planned in the near future

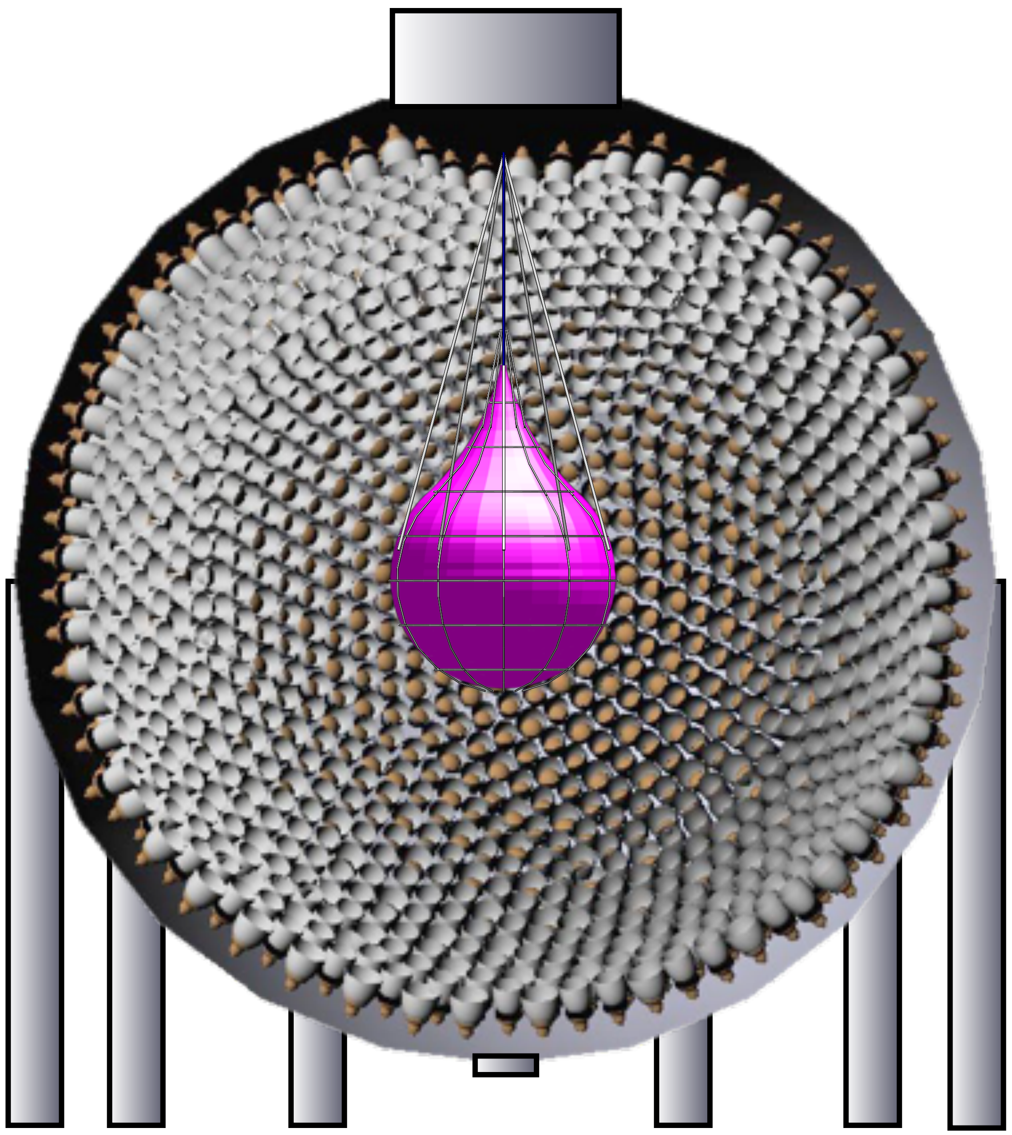
KamLAND2-Zen

General-purpose

larger crane
strengthen floor
enlarge opening

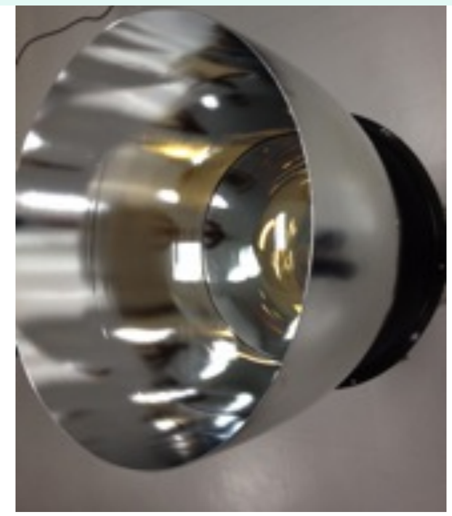
accommodate various devices
CaF_2, $CdWO_4$, NaI, …

1000 kg enriched Xe

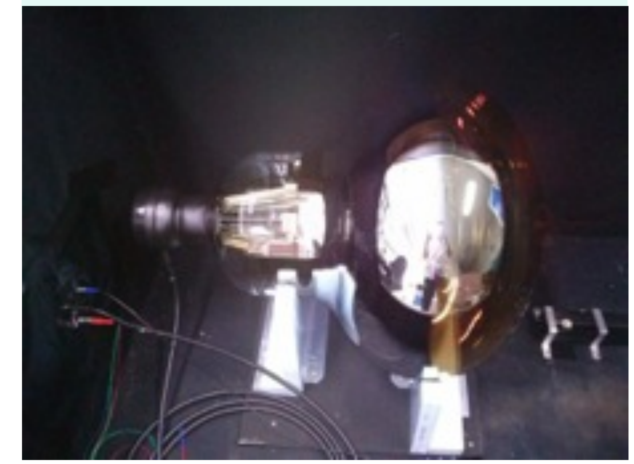


High performance

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

- Anti-neutrino results are presented.
  - Observed geo-ν flux is consistent with Earth model
  - Three flavor oscillation analysis of reactor-ν is presented

solar + KamLAND + θ_{13} experiments

$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025} \quad \Delta m^2 = 7.53^{+0.18}_{-0.18} \times 10^{-5}\ \mathrm{eV}^2$$

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

- Double beta decay searches are presented.
  - Limits on $0\nu\beta\beta$ for ^{136}Xe 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	$T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr

↓

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

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