

Double Beta Decay

PhyStat-v Workshop on Statistical Issues in
Experimental Neutrino Physics

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Majorana Neutrino Mass

Neutrino oscillation $\longrightarrow$ finite small masses and mixing

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

Possible mass terms

neutrino has no electric charge

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

$$\begin{array}{c} \longrightarrow \longrightarrow \\ \nu_R \quad \nu_L \end{array}$$

$$\Delta L = 0$$

$$\begin{array}{c} \longrightarrow \longleftarrow \\ \nu_L \quad \bar{\nu}_L \end{array}$$

$$\Delta L = 2$$

$$\begin{array}{c} \longrightarrow \longleftarrow \\ \nu_R \quad \bar{\nu}_R \end{array}$$

$$\Delta L = 2$$

lepton number violation

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

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

Neutrinoless Double-Beta Decay

Nucleus $\beta\beta$ -decay emitting two electrons

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

lepton number violation

$$\Delta L = 2$$

$0\nu\beta\beta$

neutrinoless double
beta-decay

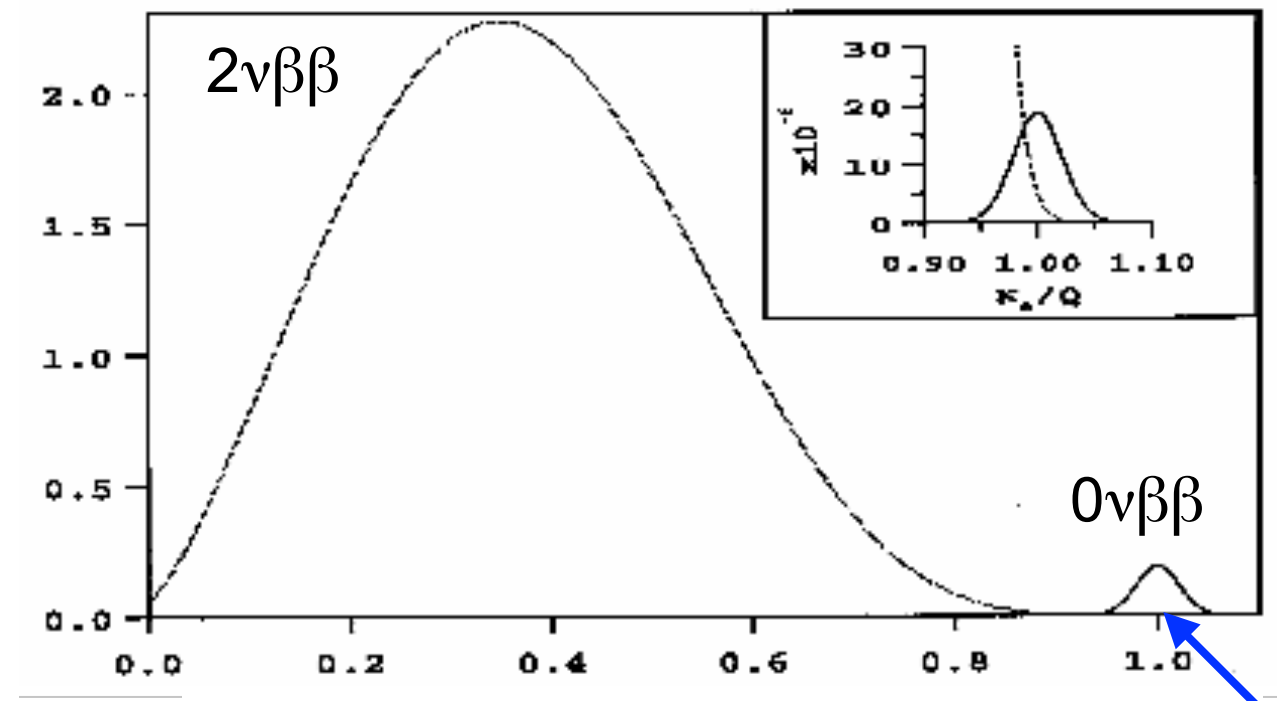
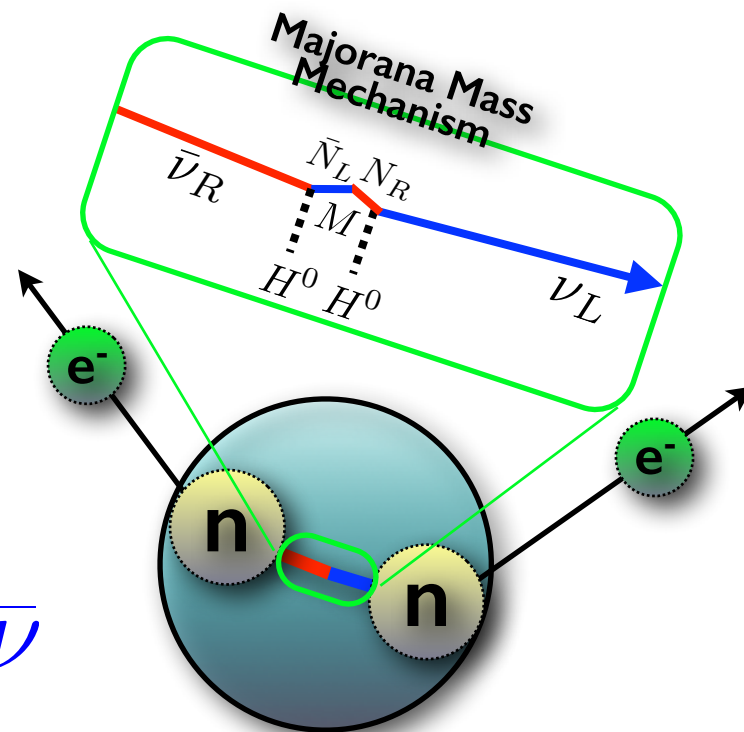
$$\nu = \bar{\nu}$$

Require the neutrino **Majorana nature**

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

↑
effective neutrino mass

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



sum energy for two electrons / Q **peak at Q-value**

decay rate

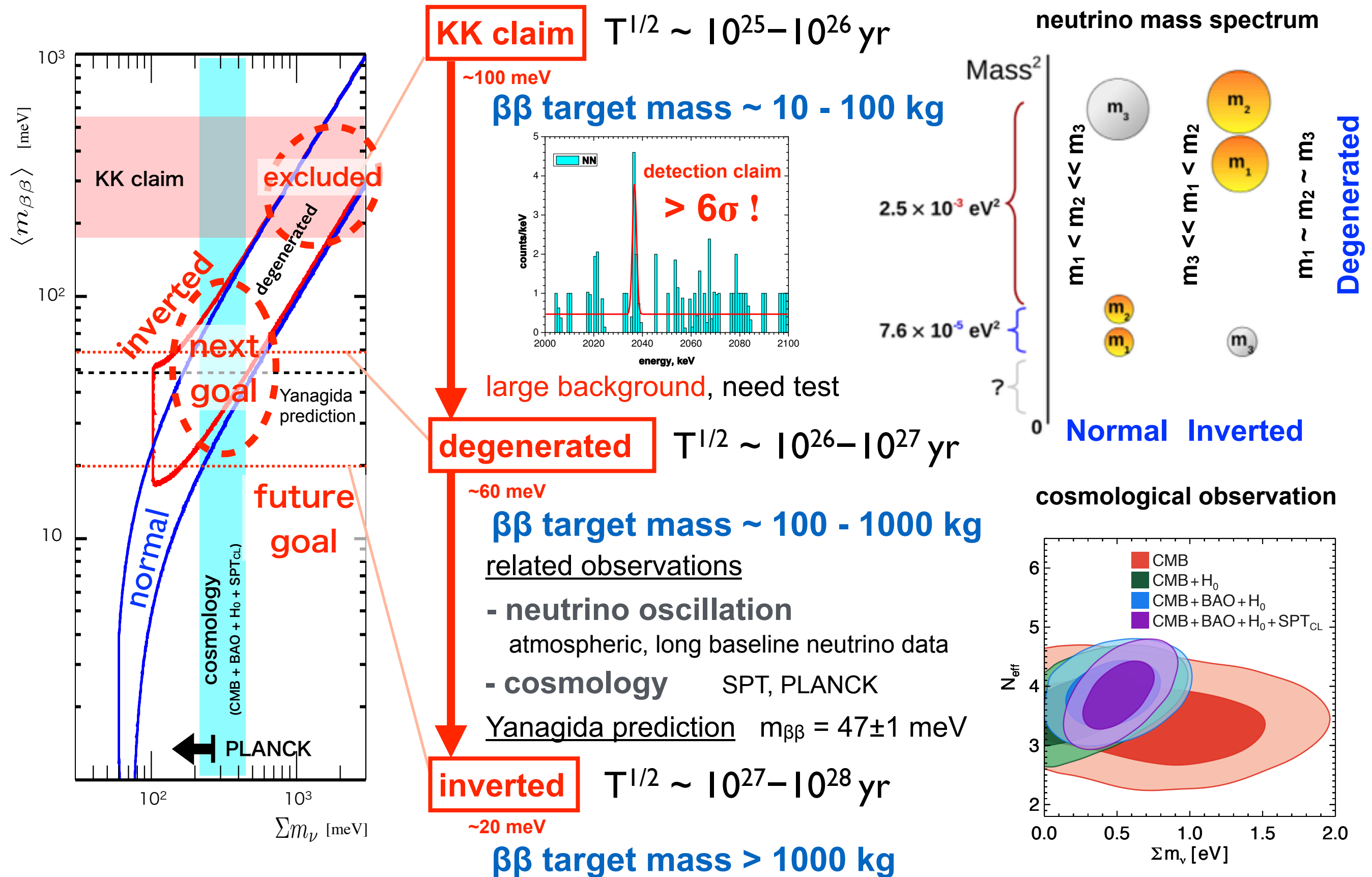
$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

nuclear matrix element
(nuclear physics)

phase space factor

effective neutrino mass
(particle physics)

Milestone of $0\nu\beta\beta$ search



Background Reduction Techniques

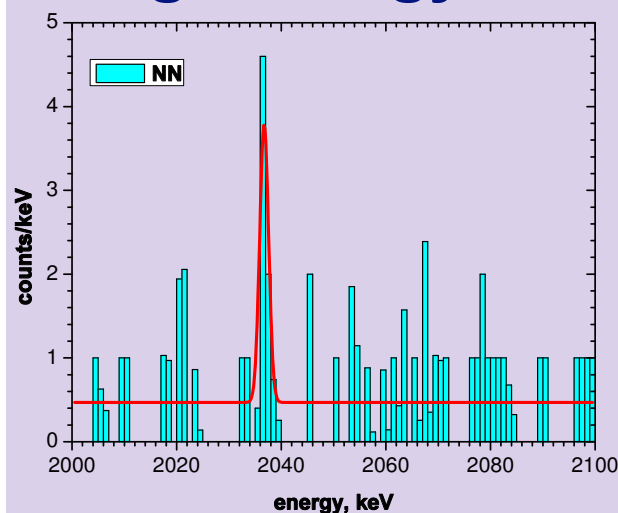
Low radioactive source/shield

High-purity source/shield to reduce radioactivity (crystal/liquid/gas purification)

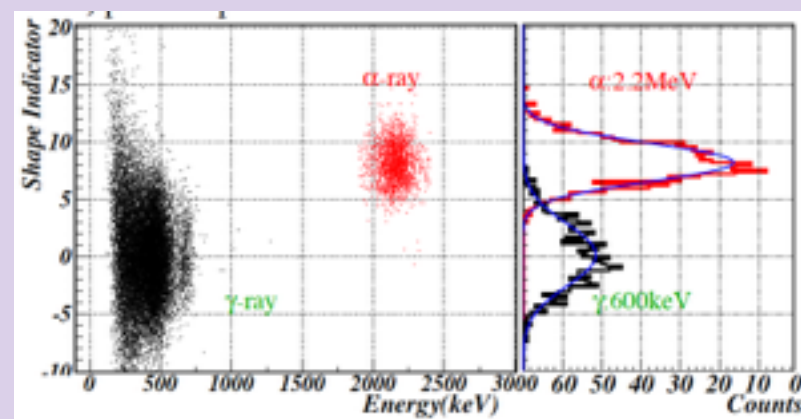
Detector at deep underground to avoid cosmogenic isotope production at underground

Experimental techniques

High energy resolution

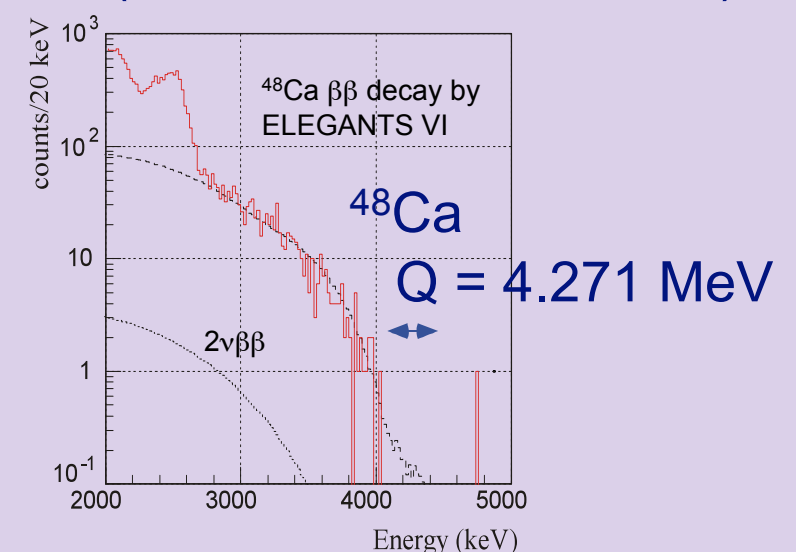


Particle identification (pulse shape discrimination)

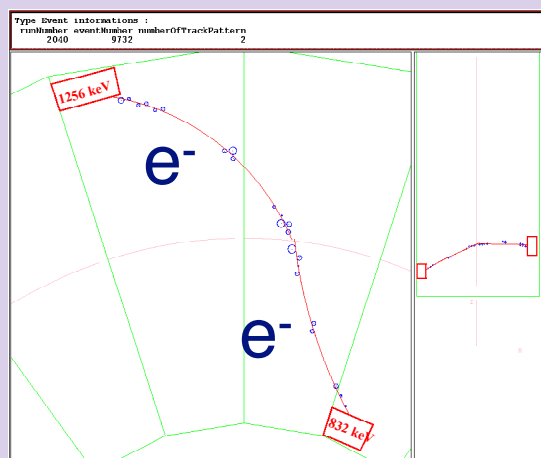


High Q-value

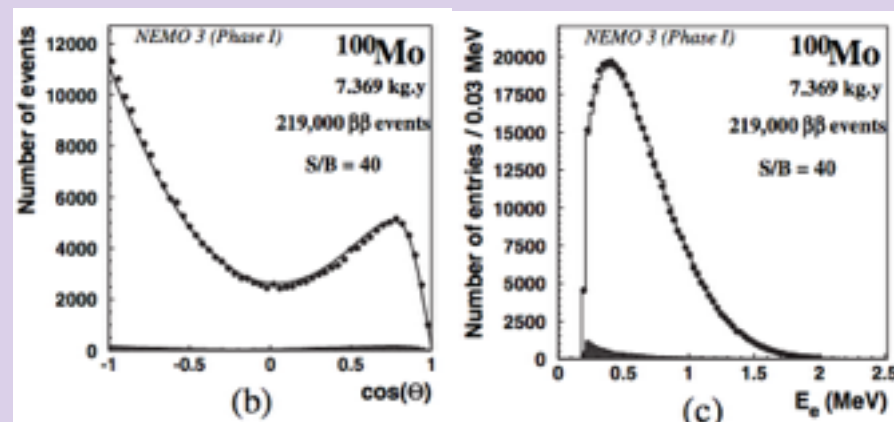
(^{48}Ca , ^{82}Se , ^{100}Mo , ^{150}Nd)



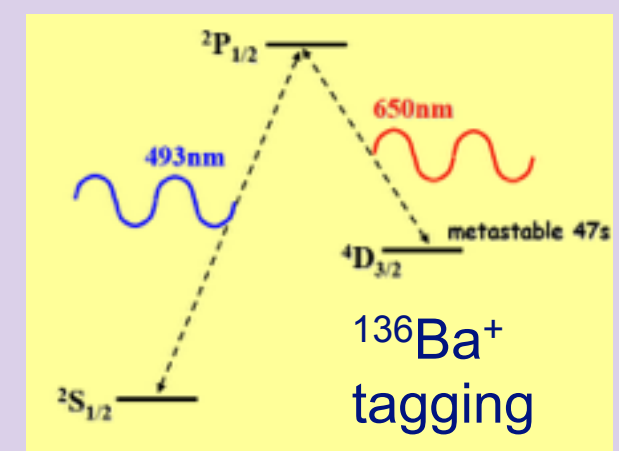
Tracking



angular correlation of two e^-
single e^- energy spectrum

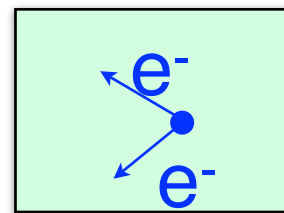


Daughter tagging

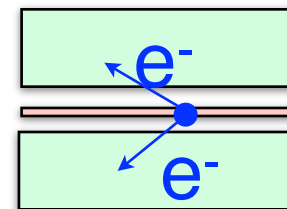


Overview of Experiments

Calorimeter
(source = target)

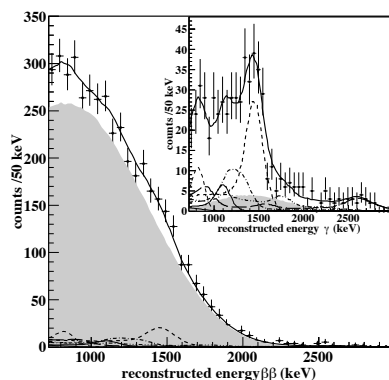


External source
(source ≠ target)



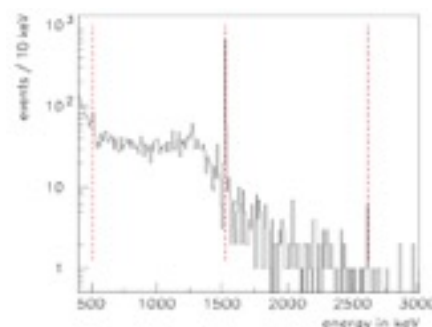
$\Delta E/E$
(FWHM)

Low resolution



1%

High resolution



Running experiments

Future experiments for IH test

KamLAND-Zen ^{136}Xe



SNO+ ^{150}Nd



CANDLES ^{48}Ca

Lucifer ^{82}Se

AMORE ^{100}Mo



CUORE(-0) ^{130}Te



Majorana ^{76}Ge



GERDA ^{76}Ge



EXO-200 ^{136}Xe

NEXT ^{136}Xe



COBRA ^{116}Cd

DCBA ^{150}Nd

MOON $^{100}\text{Mo}/^{82}\text{Se}/^{150}\text{Nd}$



SuperNEMO $^{82}\text{Se}/^{150}\text{Nd}$

Tracking

Advantage:
background identification
angular correlation

Disadvantage:
difficult to get high target-mass,
efficiency, and energy resolution

GERDA

@ Gran Sasso

Ge diodes in water tank in Phase I

BEGe in LAr in Phase II

Phase I: **Nov. 2011 - May 2013**

Phase II: **Dec. 2015 -**

GERDA Phase I

Coaxial

^{76}Ge (86% enriched)

Total mass 17.66 kg

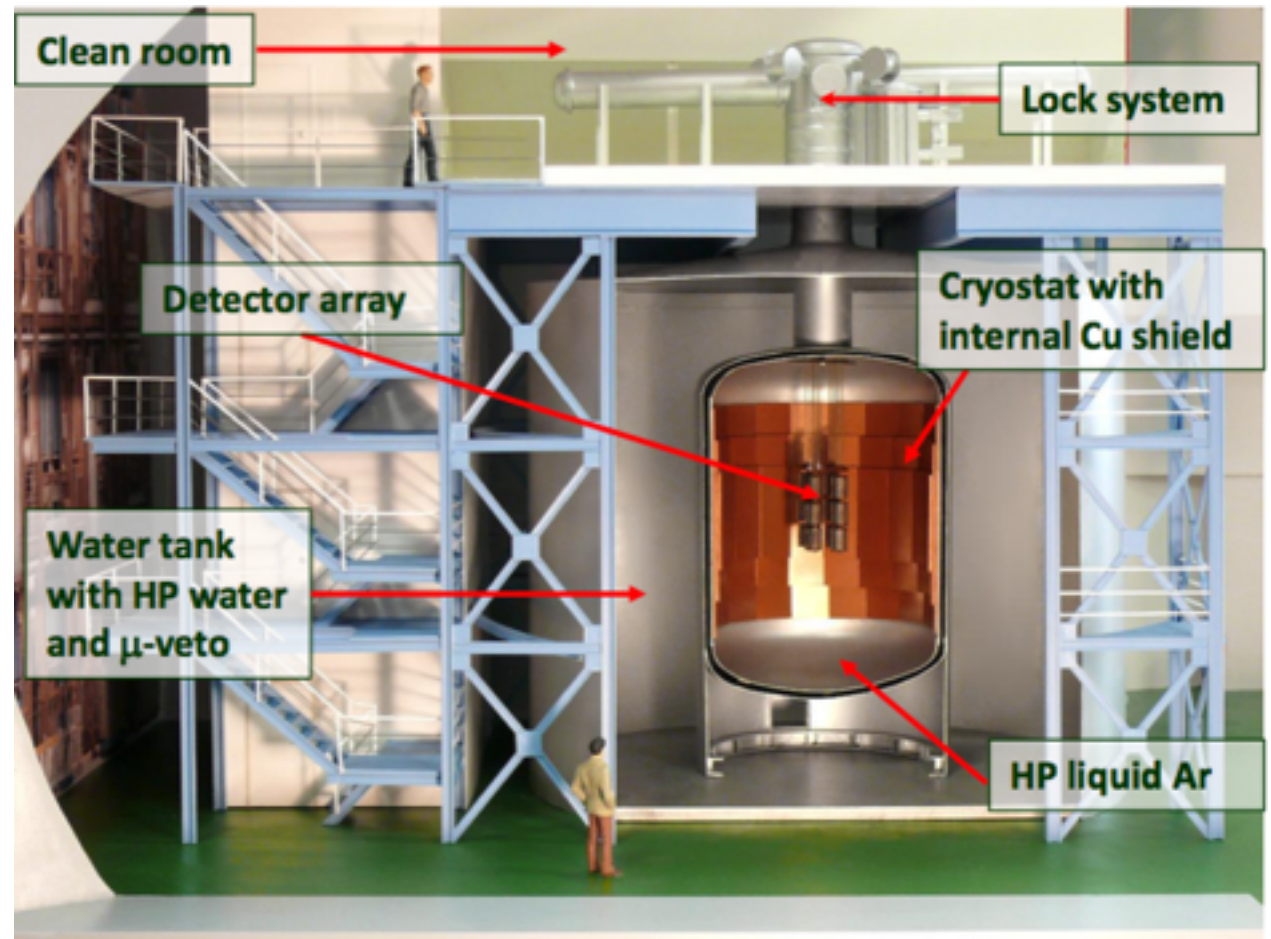
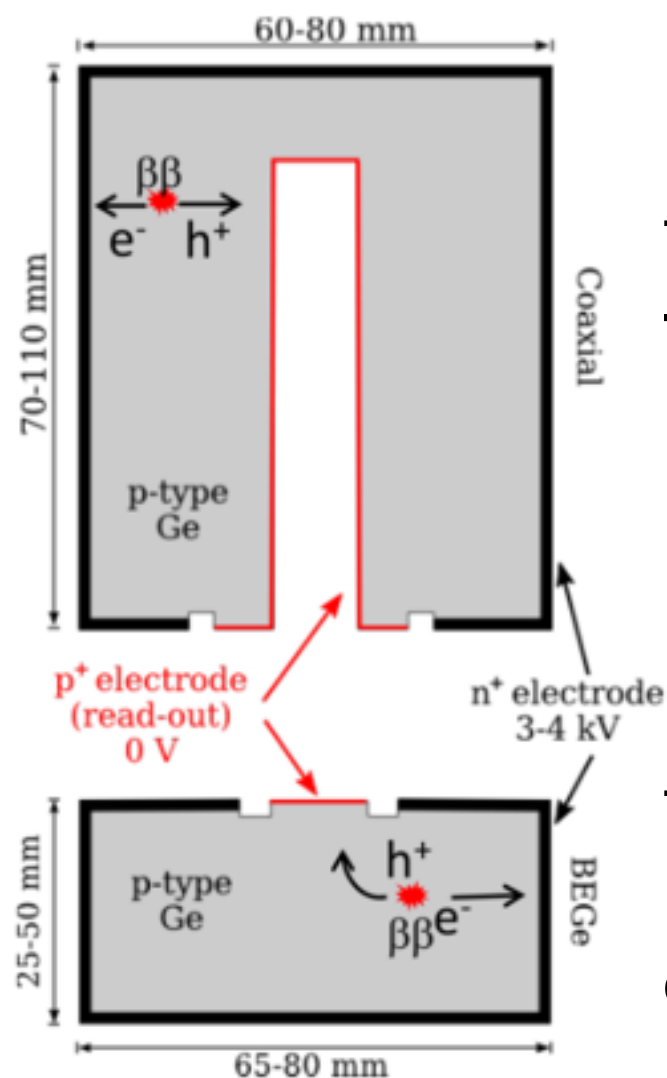
FWHM 4.8 keV @ $Q_{\beta\beta}$

BEGe

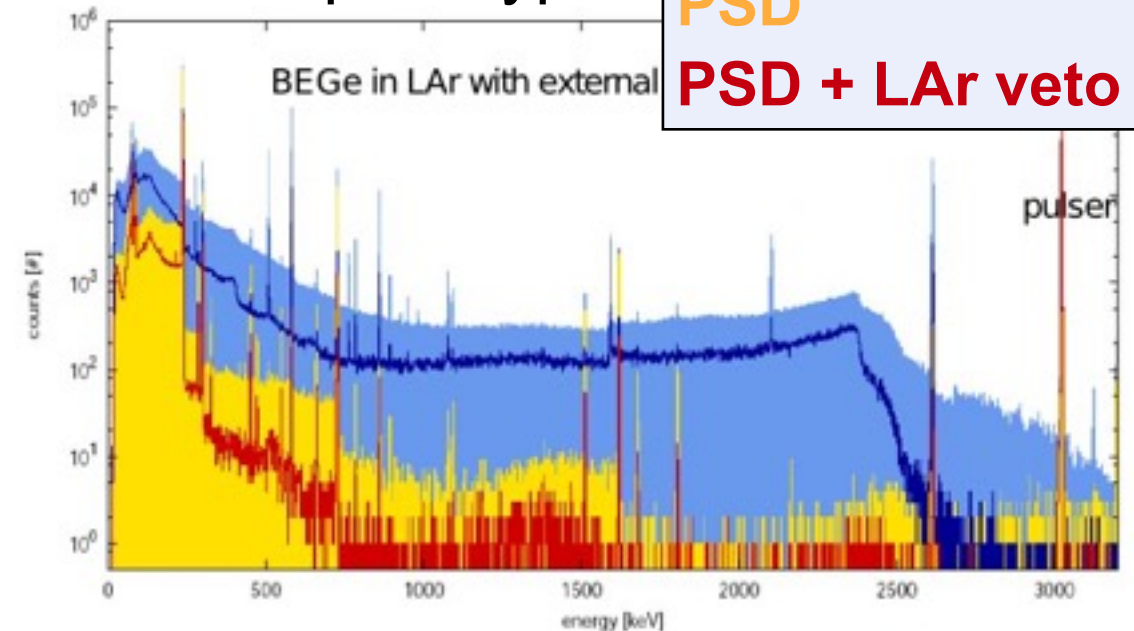
^{76}Ge (86% enriched)

Better pulse shape discrimination

FWHM 3.2 keV @ $Q_{\beta\beta}$

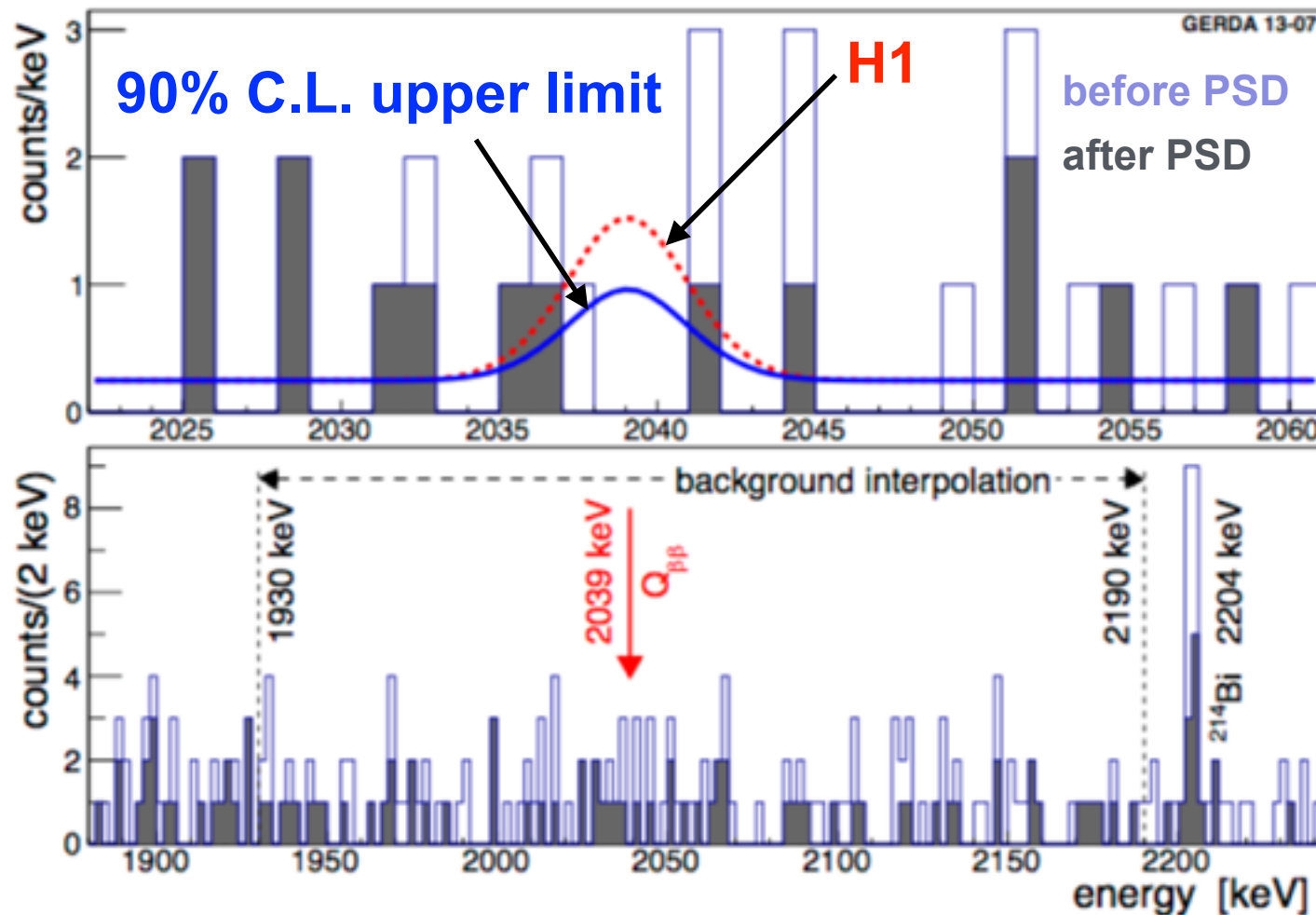


BEGe prototype



GERDA Phase I

gold-coax: 17.9 kg-yr, silver-coax: 1.3 kg-yr, BEGe: 2.4 kg-yr



PRL 111, 122503 (2013)

KK claim test

PLB 586, 198 (2004)

H0: background only

H1: KK claim signal + background

events in $\pm 2\sigma_E$

Expected signal (w/ PSD) 5.9 ± 1.4

Expected background (w/ PSD) 2.0 ± 0.3

Observed (w/ PSD) 3

Bayes factor:

$$P(H1) / P(H0) = 0.024$$

P-value:

$$P(N^{0\nu} = 0 | H1) = 0.01$$

from profile likelihood fit

Frequentist limit

- Profile likelihood fit (constraint to $1/T^{0\nu}_{1/2} \geq 0$)
- Best-Fit : $N^{0\nu} = 0$
- Median sensitivity (90% C.L.): $> 2.4 \times 10^{25}$ yr

$$T^{0\nu}_{1/2} > 2.1 \times 10^{25} \text{ yr (90\% C.L.)}$$

Bayesian limit

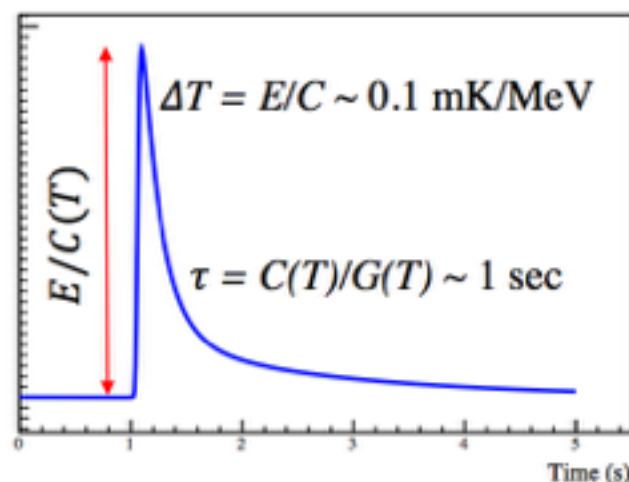
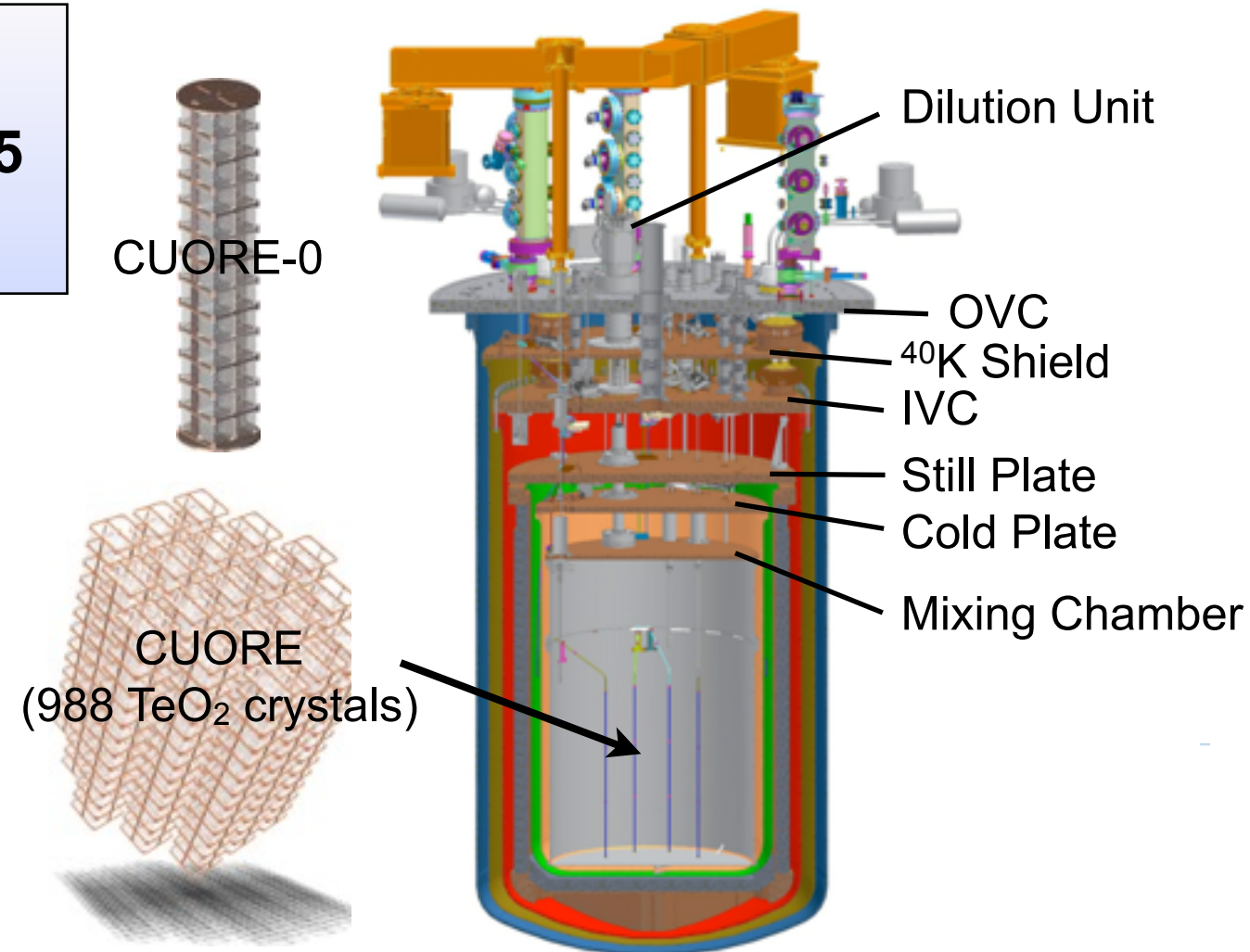
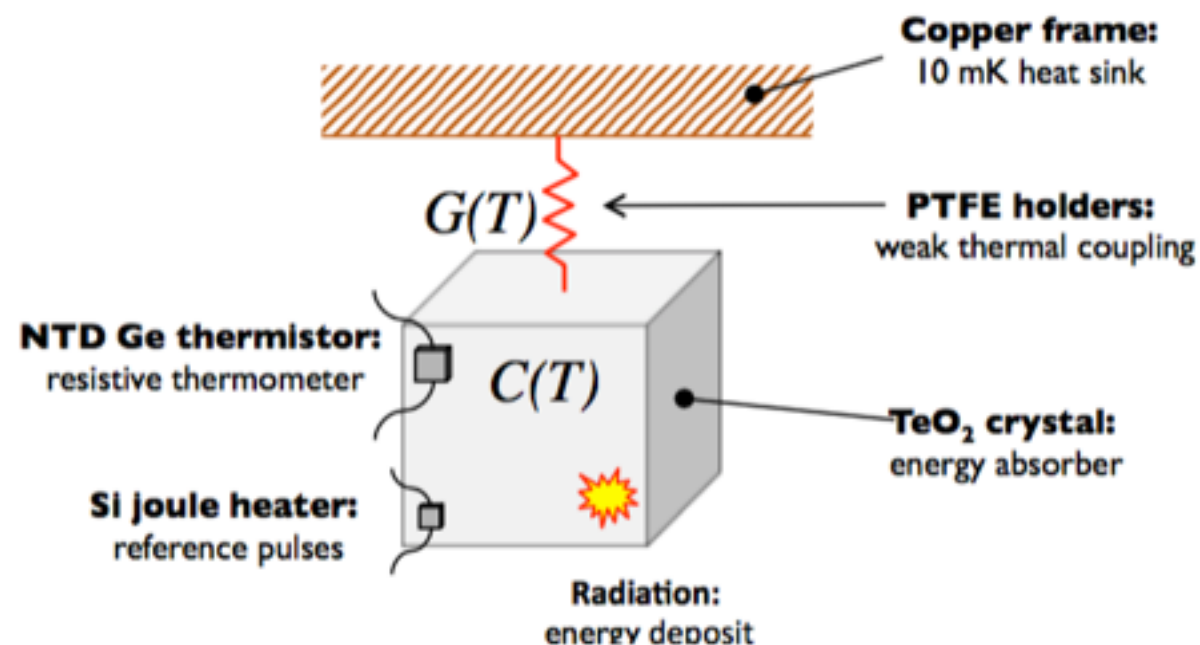
- Flat prior distribution for $1/T^{0\nu}_{1/2}$
- Best-Fit : $N^{0\nu} = 0$
- Median sensitivity (90% C.L.): $> 2.0 \times 10^{25}$ yr

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

CUORE

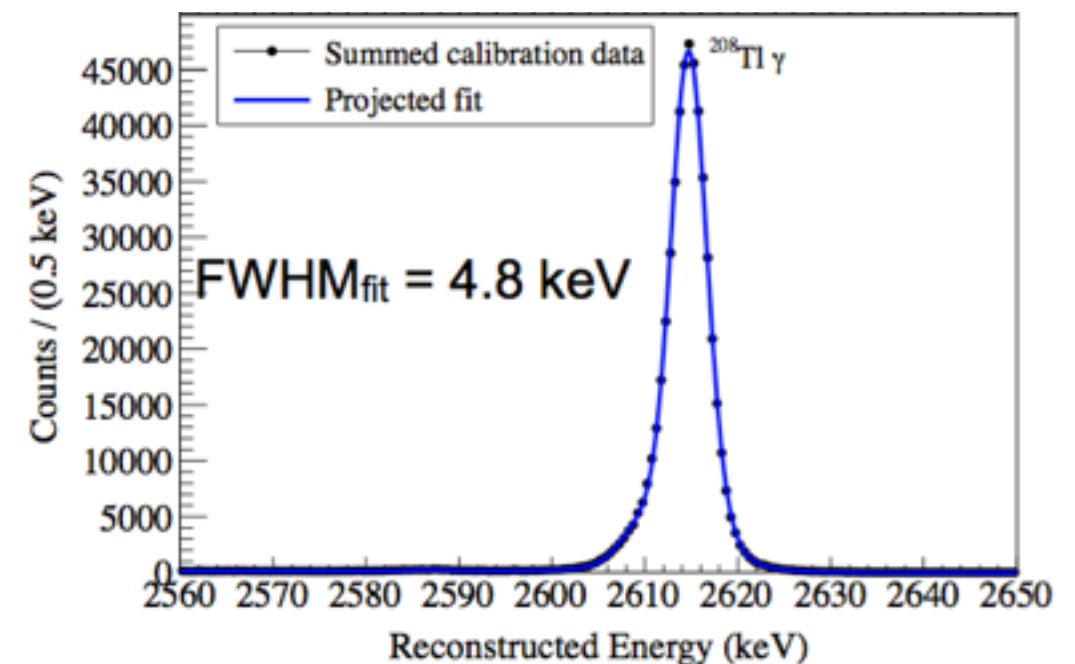
@ Gran Sasso

TeO₂ bolometers in dilution refrigerator
 Phase I (CUORE-0): **Aug. 2013 - Mar. 2015**
 Phase II (CUORE): **early 2016 -**



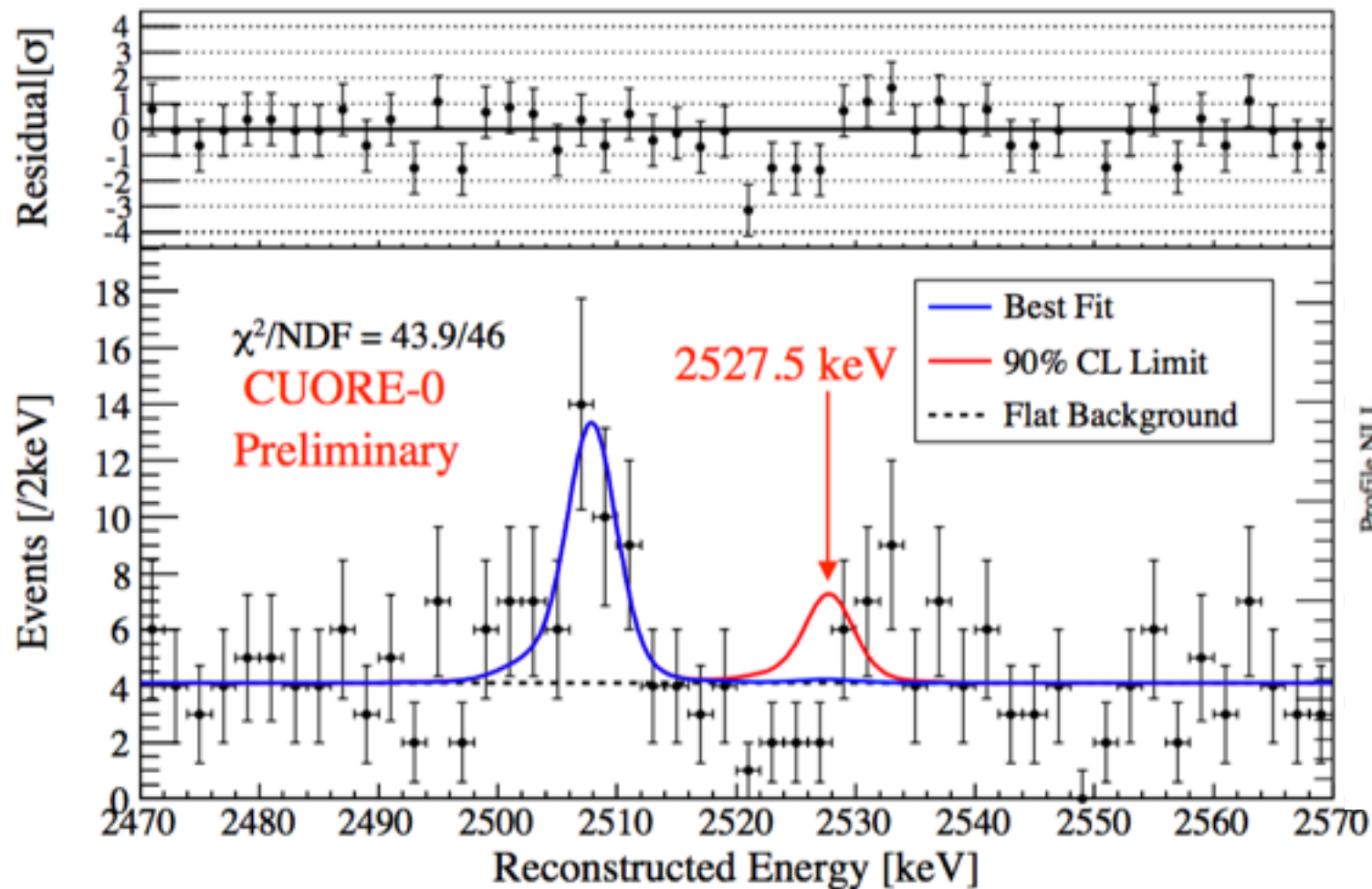
CUORE-0

52 TeO₂ 5×5×5 cm³ crystals
39 kg TeO₂ (10.9 kg ¹³⁰Te)
Operating temp. ~ 10 mK
FWHM 5.1 keV @ Q_{ββ}



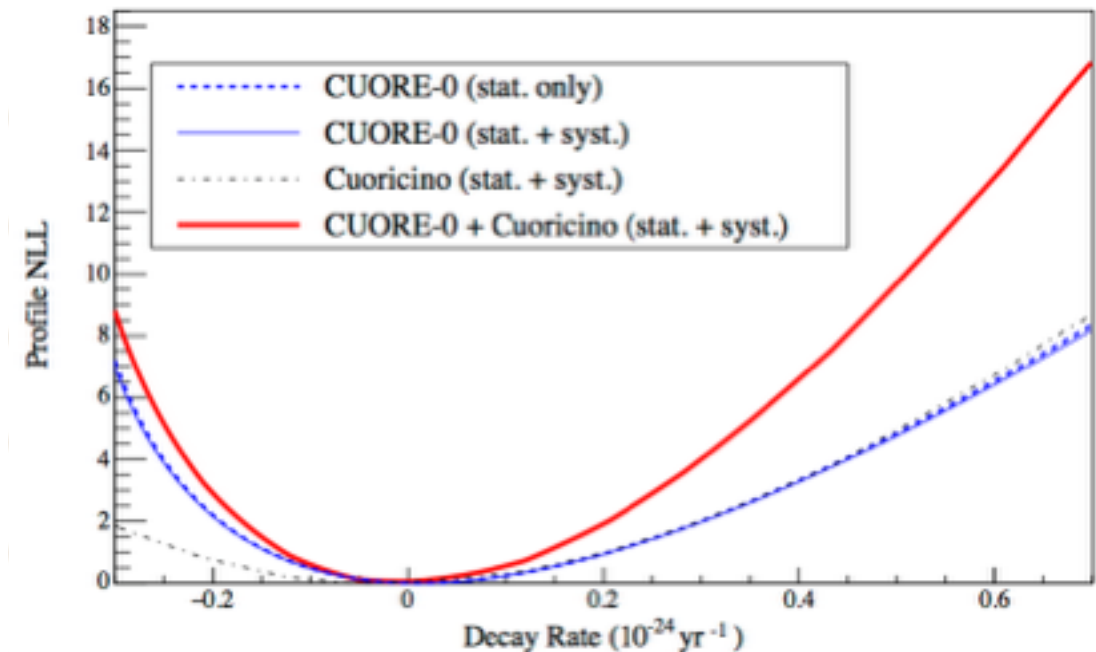
CUORE-0

9.8 kg-yr exposure of ^{130}Te



PRL 115, 102502 (2015)

CUORE-0 + Cuoricino



Best-fit decay rate: $\Gamma^{0\nu\beta\beta} (^{130}\text{Te}) = 0.007 \pm 0.123 \text{ (stat.)} \pm 0.012 \text{ (syst.)} \times 10^{-24} \text{ yr}^{-1}$

Frequentist limit

$$T^{0\nu}_{1/2} > 2.8 \times 10^{24} \text{ yr (90\% C.L.)}$$

CUORE-0 + Cuoricino

$$T^{0\nu}_{1/2} > 4.1 \times 10^{24} \text{ yr (90\% C.L.)}$$

Bayesian limit

$$T^{0\nu}_{1/2} > 2.7 \times 10^{24} \text{ yr (90\% C.L.)}$$

CUORE-0 + Cuoricino

$$T^{0\nu}_{1/2} > 4.0 \times 10^{24} \text{ yr (90\% C.L.)}$$

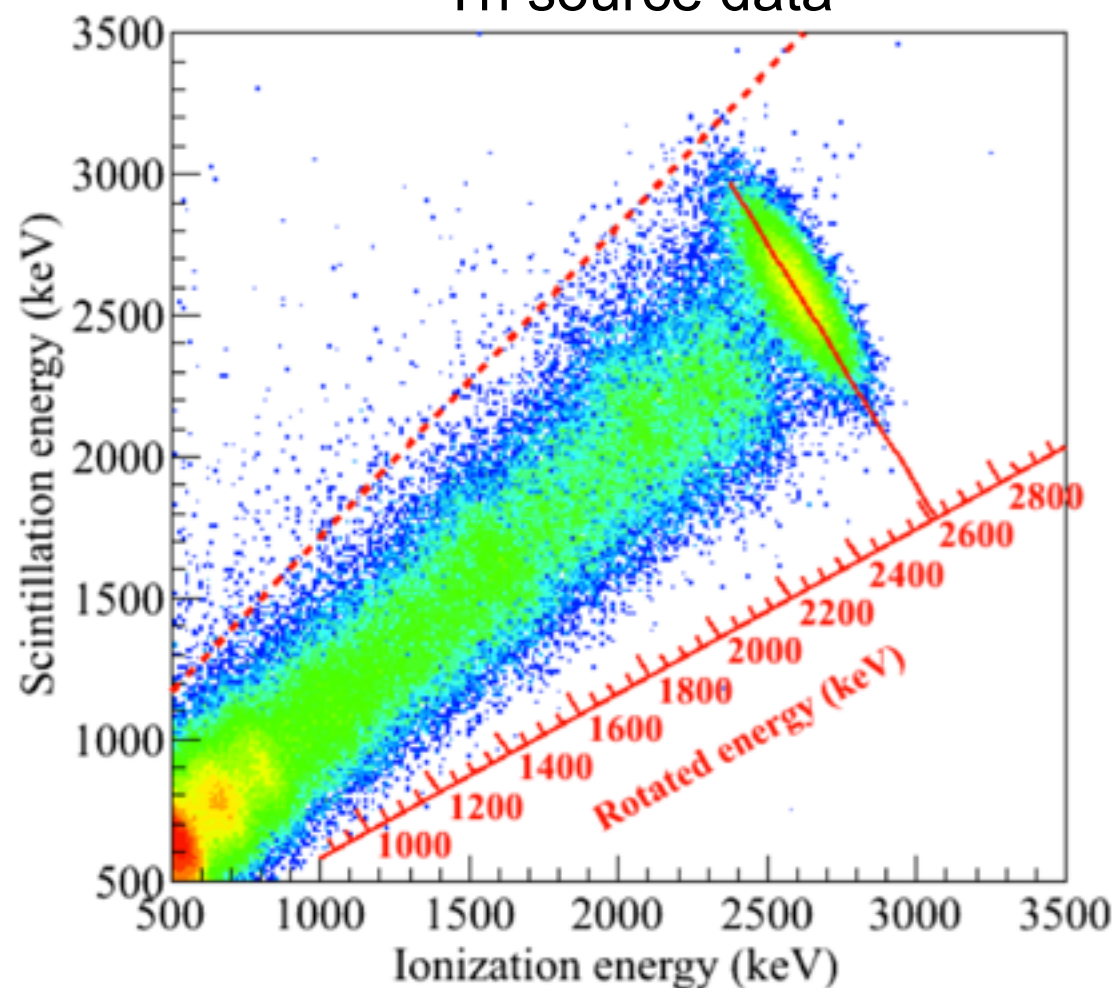
EXO-200

@ WIPP

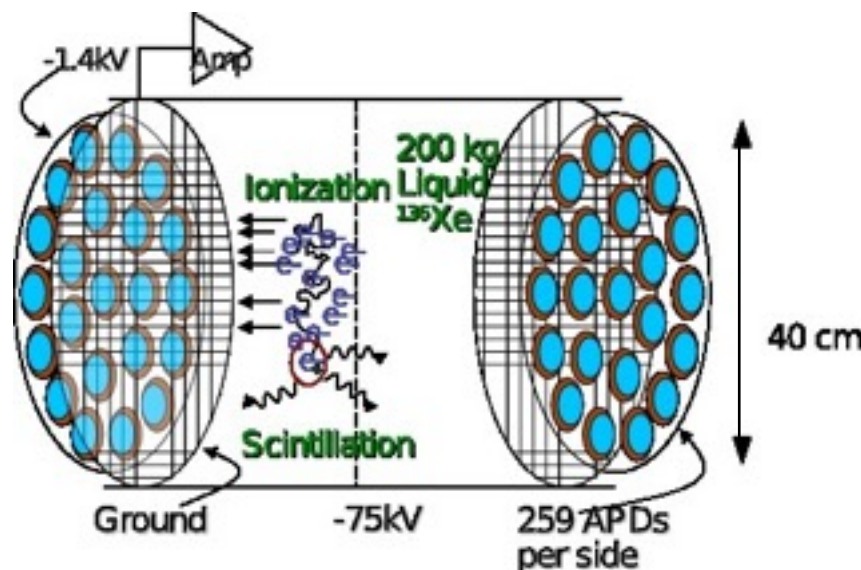
LXe TPC in copper cryostat
Phase-I: **May 2011 - Feb. 2014**
Phase-II: **Jan. 2016 -**

combination of charge and light

^{228}Th source data



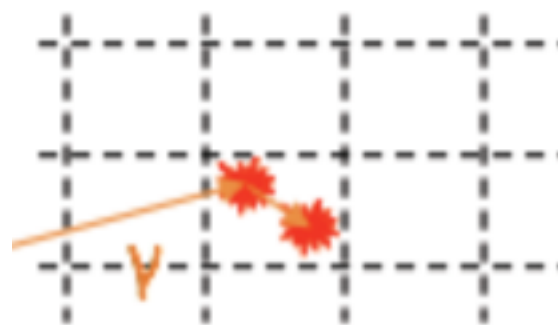
$\sigma_E = 1.4\% @ 2.6 \text{ MeV}$



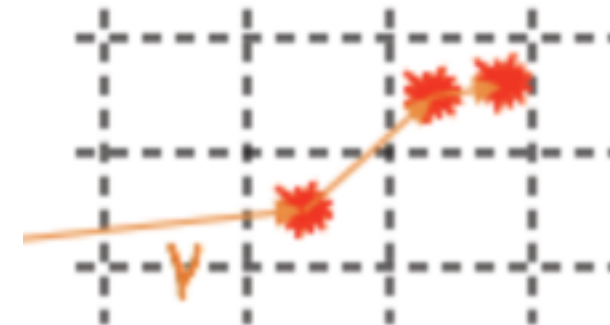
Background reduction by multiplicity

single-site (SS) events

multi-site (MS) events



charge cluster = 1



charge cluster > 1

$0\nu\beta\beta \sim 90\% \text{ SS}$

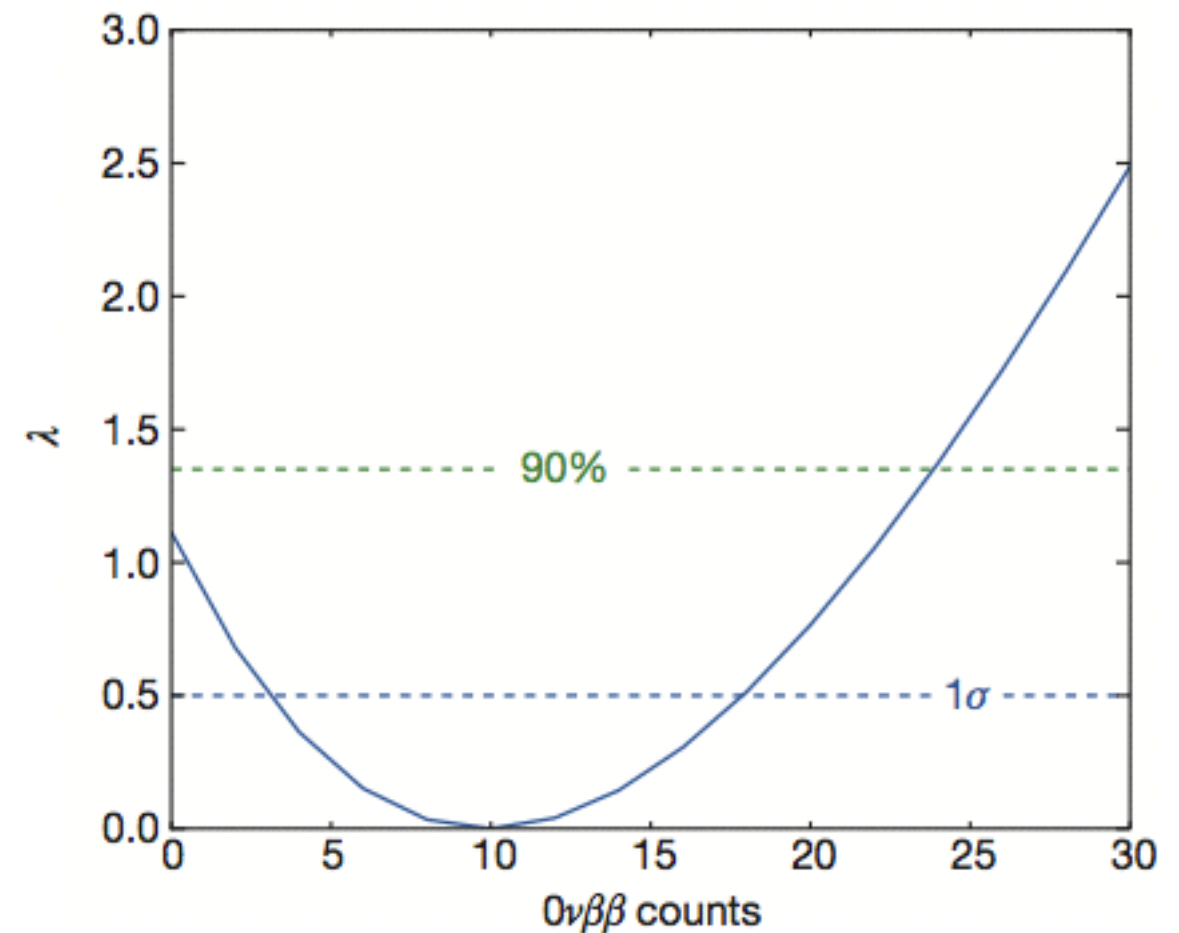
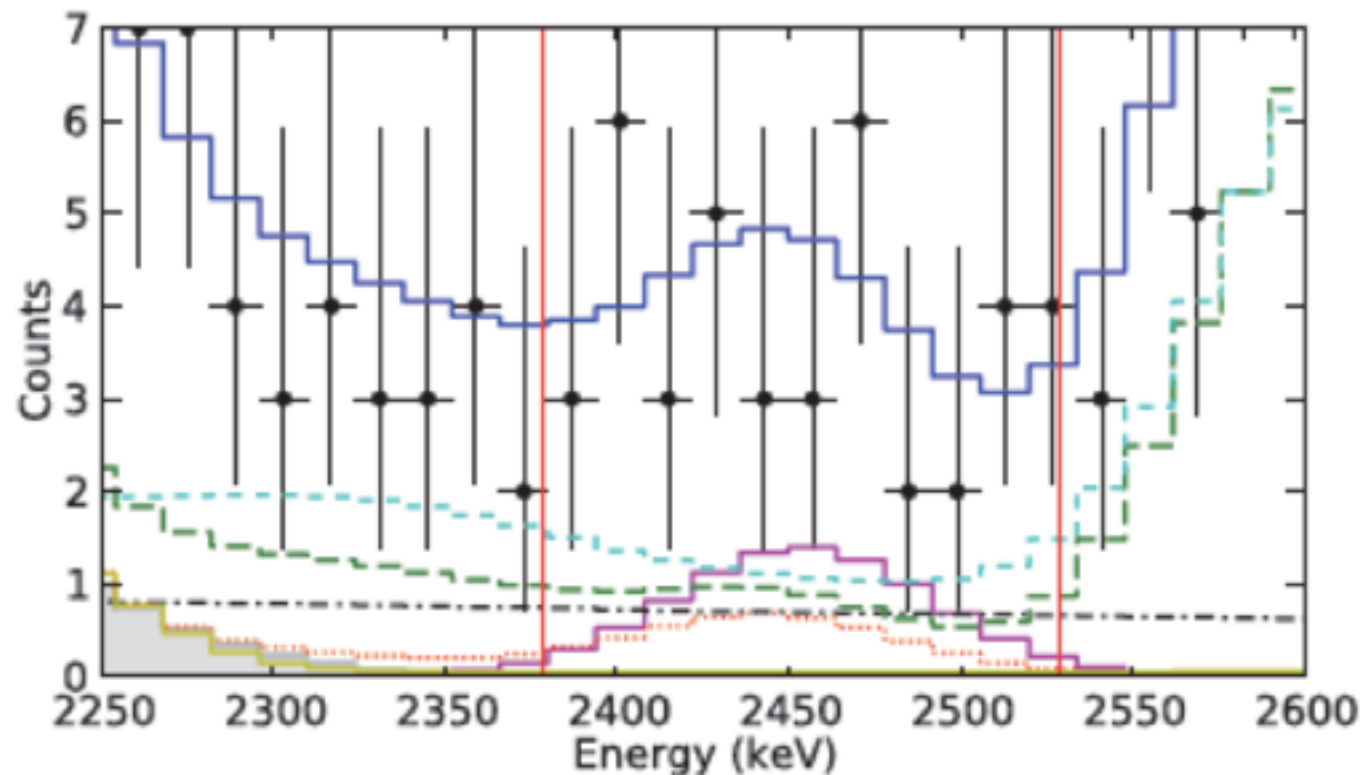
γ -ray backgrounds $\sim 30\% \text{ SS}$

EXO-200 Phase-I

123.7 kg-yr

nature 510, 229-234 (2014)

Fit to single site spectrum near $0\nu\beta\beta$ ROI:



1 $.2\sigma$ event excess
(no detection claim)

EXO-200 limit at 90% C.L.

$$T^{0\nu}_{1/2} > 1.1 \times 10^{25} \text{ yr}$$

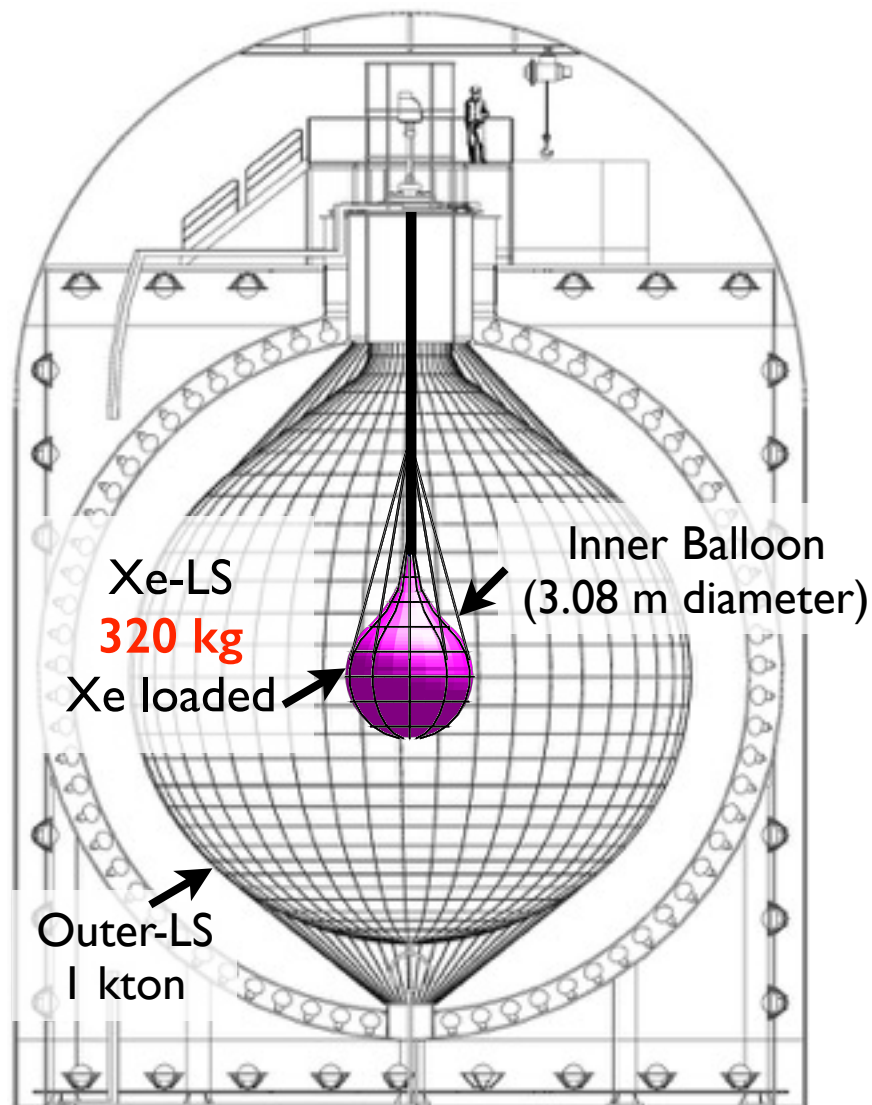


$$\langle m_{\beta\beta} \rangle < 190\text{-}450 \text{ meV}$$

KamLAND-Zen

Kamioka Liquid Scintillator Anti-Neutrino Detector
Zero Neutrino Double Beta

KamLAND-Zen Phase-I



Xenon loaded LS (Xe-LS)

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

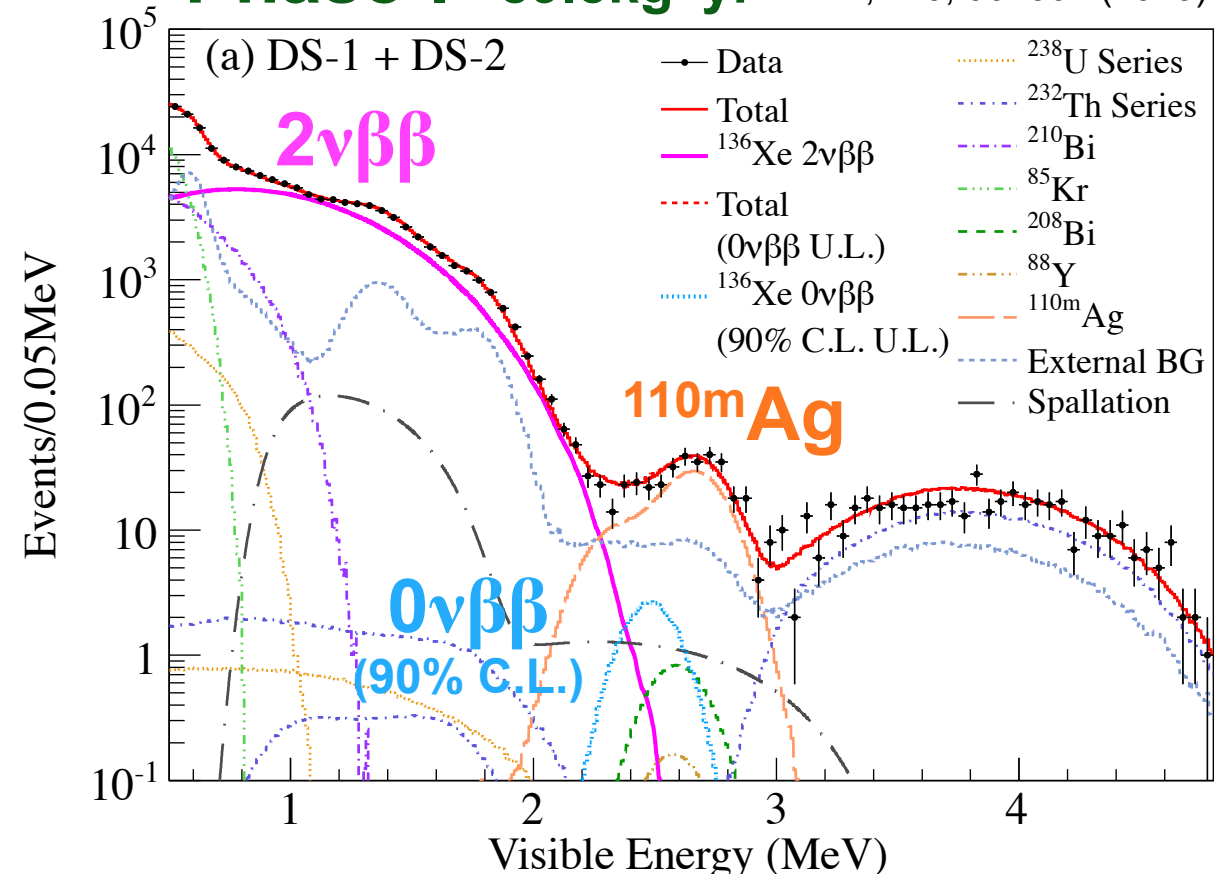
$$\sigma_E(2.5\text{MeV}) = 4\%$$

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)

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

Phase-I 89.5kg·yr PRL, 110, 062502 (2013)



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

Nylon Film with Low Radioactivities



Specially made **25 μm nylon film**
for low radioactivities in U/Th/K

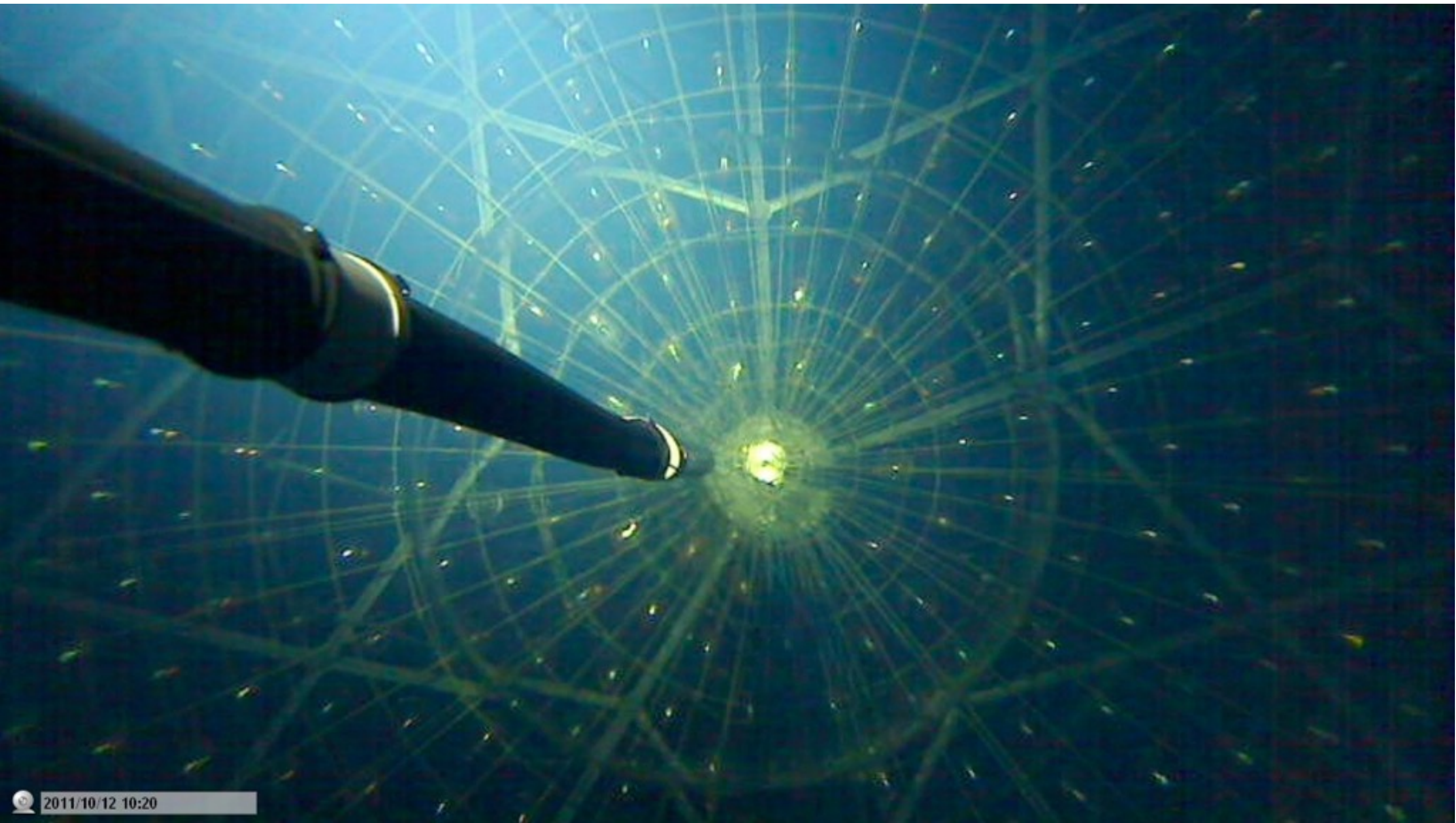
effect of ultrasonic cleaning

U : 150 $\rightarrow$ $2 \times 10^{-12} \text{g/g}$

Th : 59 $\rightarrow$ $3 \times 10^{-12} \text{g/g}$

^{40}K : 140 $\rightarrow$ $2 \times 10^{-12} \text{g/g}$





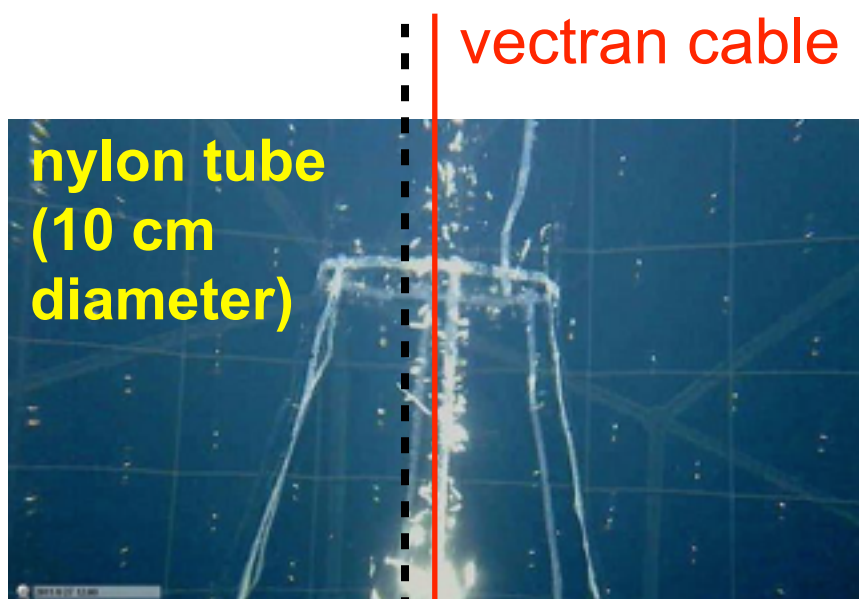
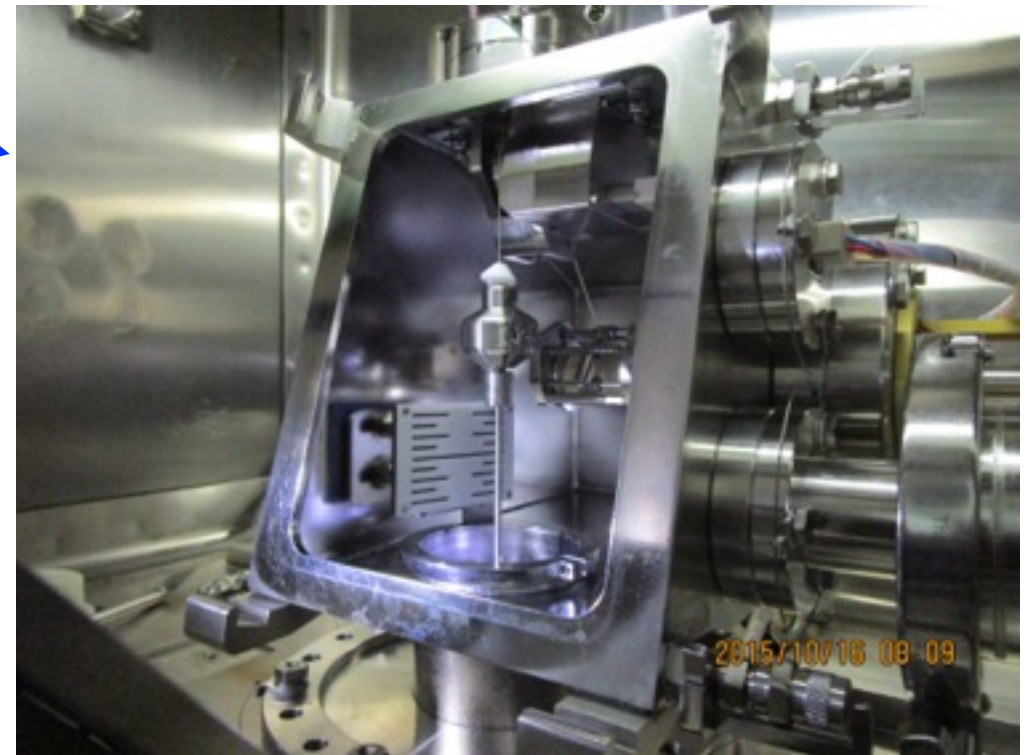
Data-taking restarted in September 2011

Source Calibration in KamLAND-Zen

Ultra-clean source calibration system to avoid the contamination of radioactive impurities

Deploy the source carefully by hand crank to control the cable tension

MiniCal system
(compact and ultra-clean)



deployment

vectran cable

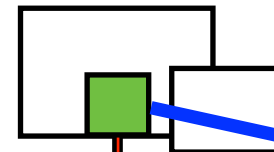
composite source

^{60}Co (1.173 + 1.333 MeV)

^{68}Ge (0.511 $\times$ 2 MeV)

^{137}Cs (0.662 MeV)

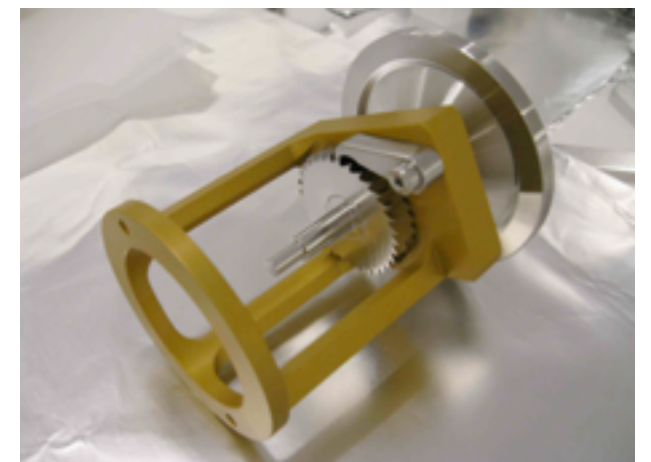
glove box



camera

narrow nylon tube

hand crank
(manual operation)



Source deployment in Xe-LS in October 2015

Event Reconstruction

Vertex reconstruction $\rightarrow \mathbf{x}, \mathbf{y}, \mathbf{z}, t$

$$L = \prod_i^{N_{hits}} \varphi_{inv}(\Delta t_i) \quad \Delta t_i = t_i - t - TOF_i$$

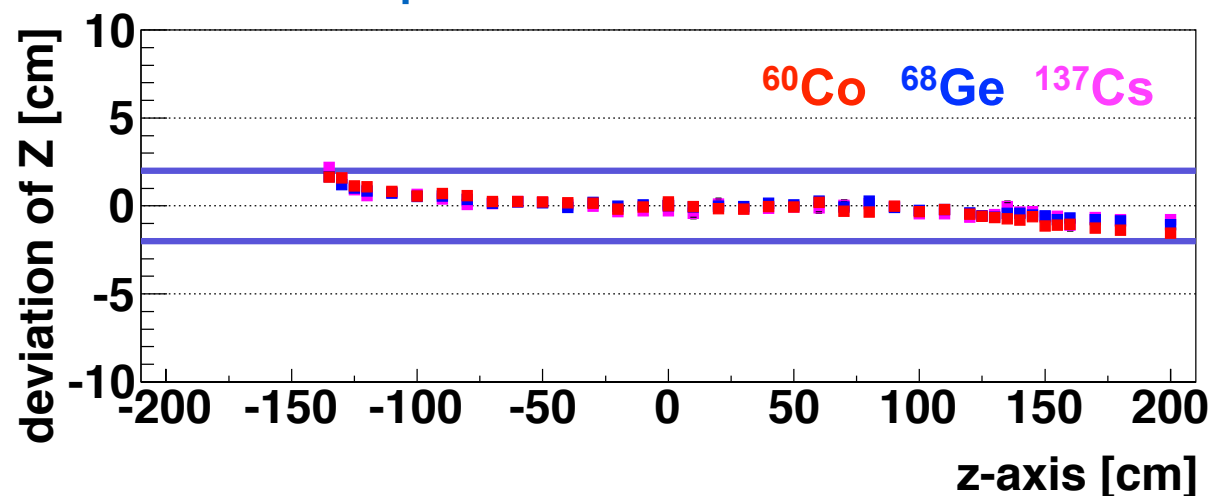
vertex reconstruction from PMT hit-time information considering charge dependence

Energy reconstruction $\rightarrow E_{vis}$

$$L = \prod_i^{no-hit} \kappa_{i,0}(\vec{R}_{PMT_i}, \vec{R}_{source}, E_{vis}) \prod_i^{hit} \left[\sum_j \kappa_{i,j}(\vec{R}_{PMT_i}, \vec{R}_{source}, E_{vis}) f_{i,j}(q_i) \right] \varphi_{inv}(\Delta t_i | \mu_i)$$

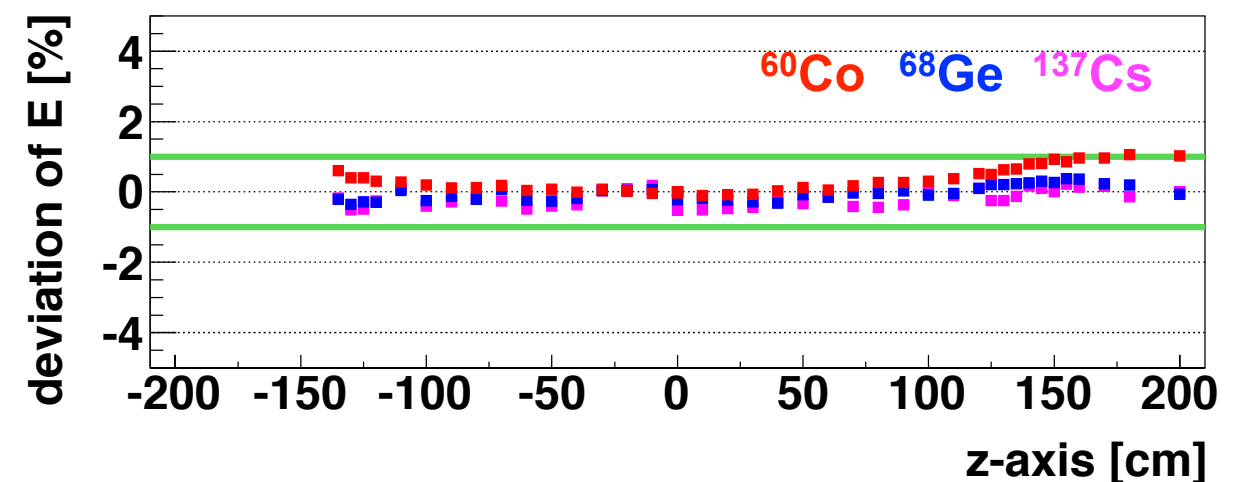
energy reconstruction from PMT hit/no-hit + charge + time information

z-dependence of vertex



position dependent bias < 2.0 cm
(< 1.0 cm for $|z| < 1.0$ m)

z-dependence of energy



position dependent bias < 1.0%

Background in KamLAND-Zen

Large

^{110m}Ag (Xe-LS: largest BG source)

- Xe: distillation / adsorption
- LS: replacement by new purified LS

reduction goal : 1/100

^{214}Bi (mini-balloon: U daughter)

- optimization of fiducial volume
- production of new mini-balloon

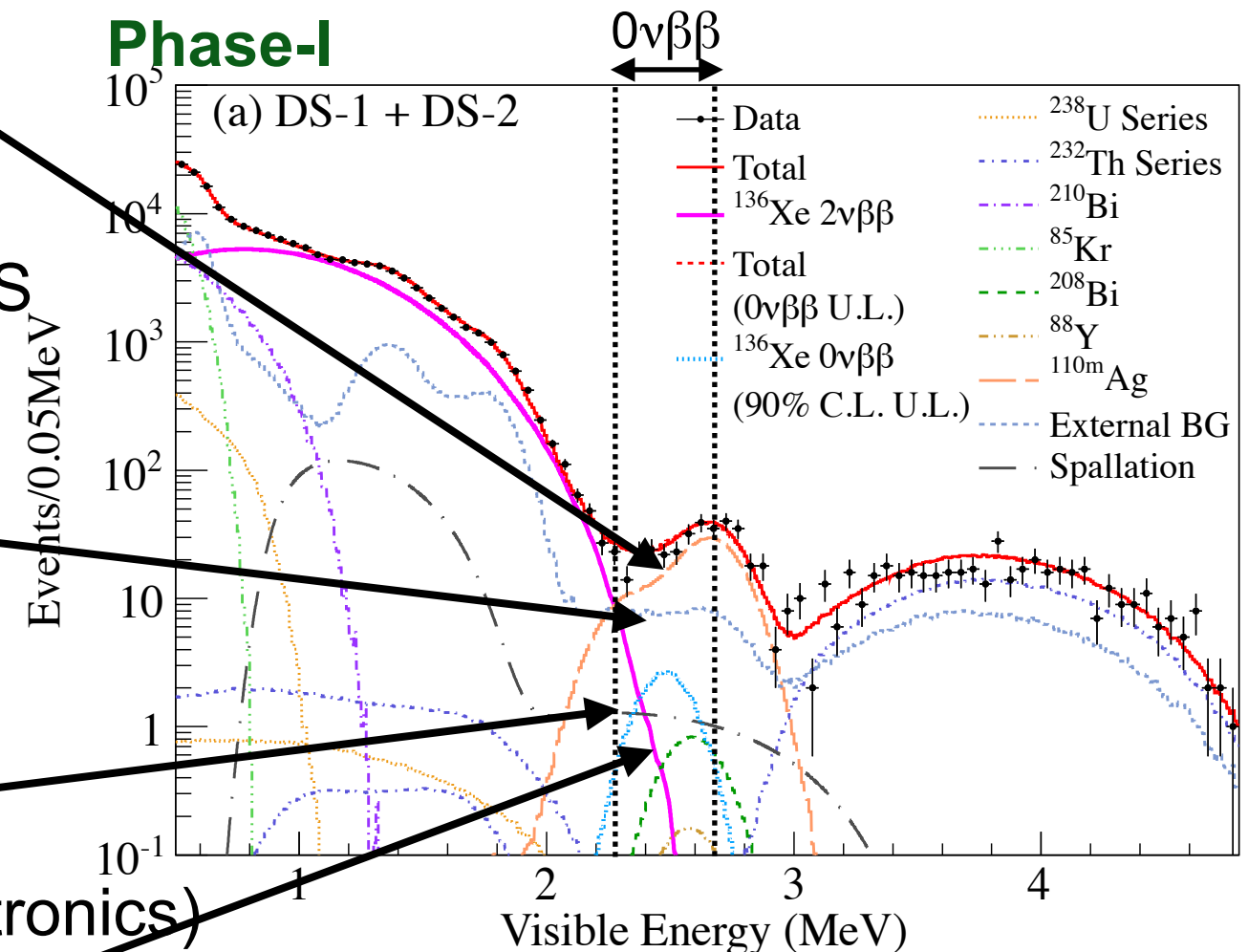
^{10}C (XeLS: muon spallation)

- μ -n- ^{10}C coincidence tag (new electronics)

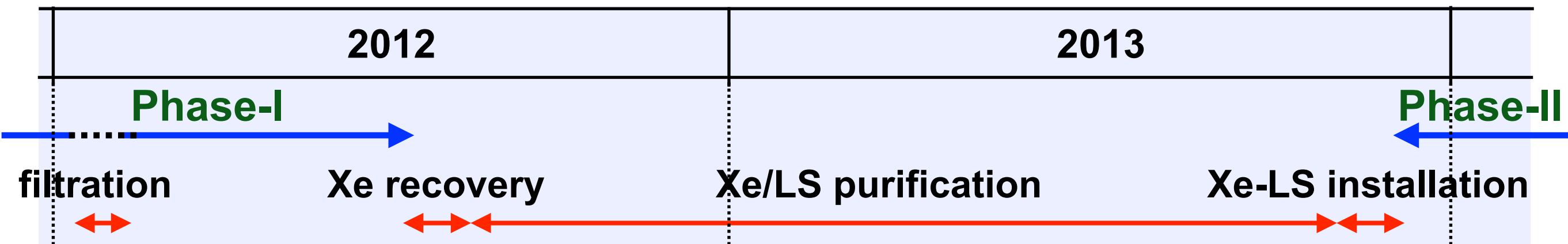
$2\nu\beta\beta$ (XeLS: energy resolution)

Small

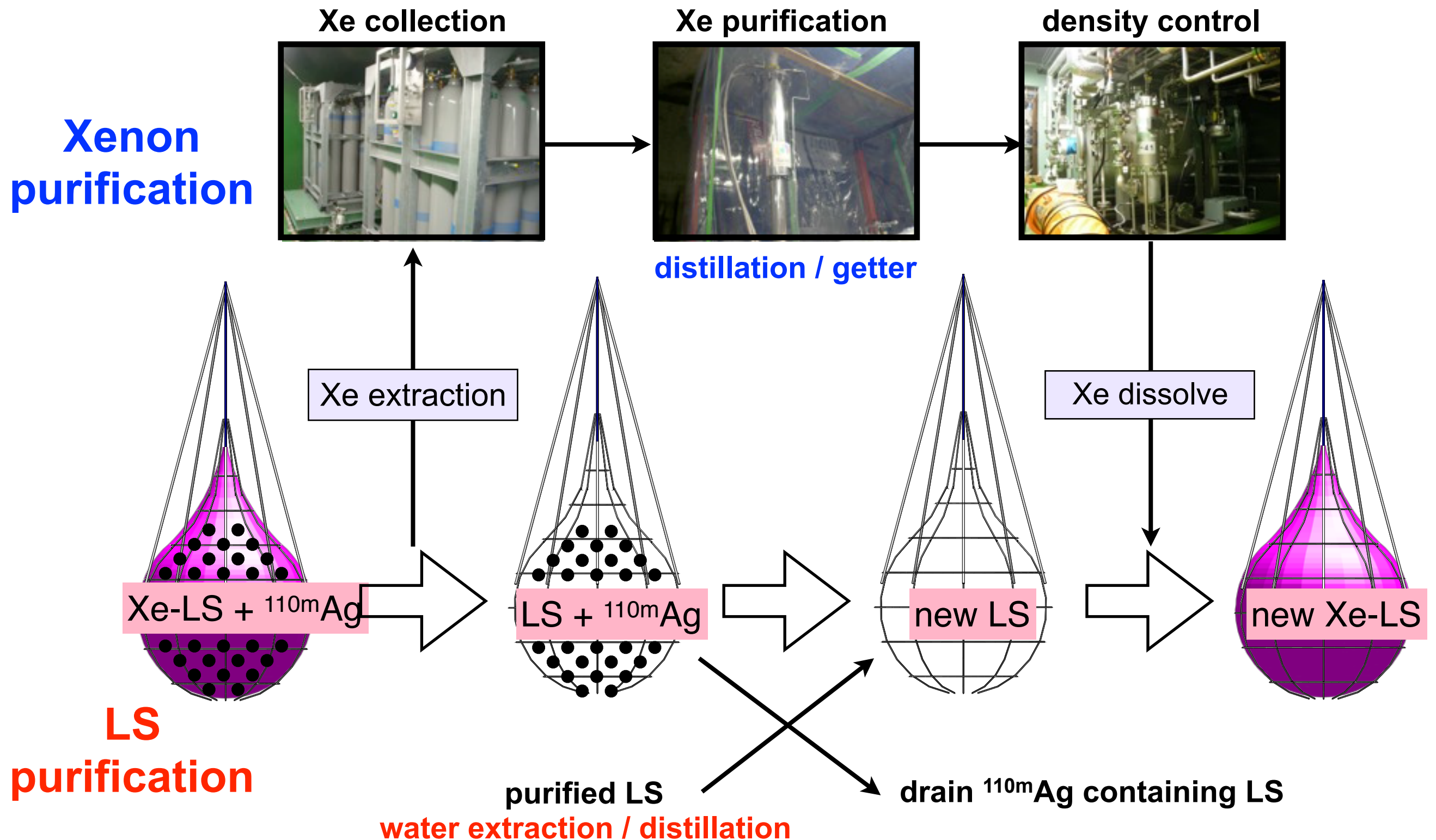
- brighter LS, light collecting mirror, high Q.E. PMT (future: KamLAND2-Zen)



Xe-LS purification (~1.5 yr)



Purification Strategy

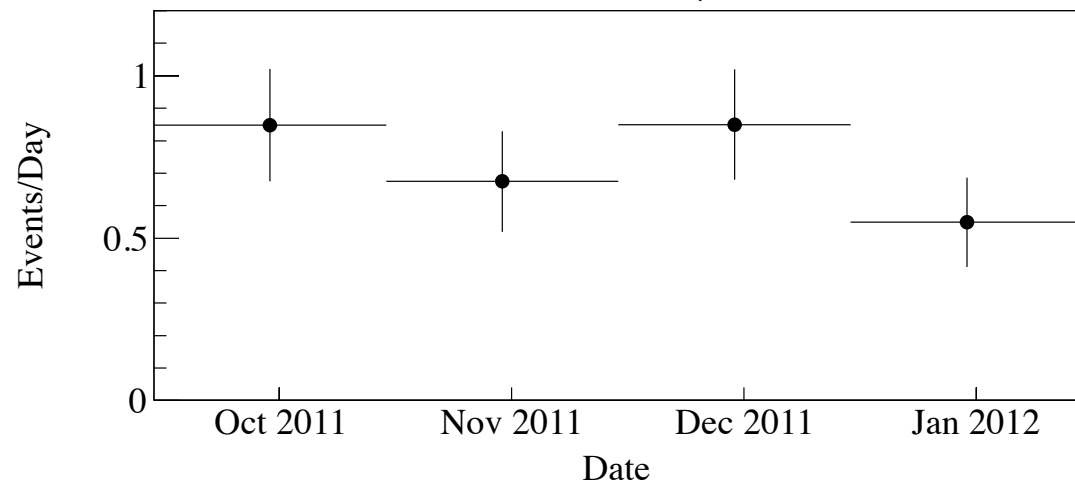


Xenon and LS purification to reduce radioactive impurities

^{110m}Ag Background Reduction

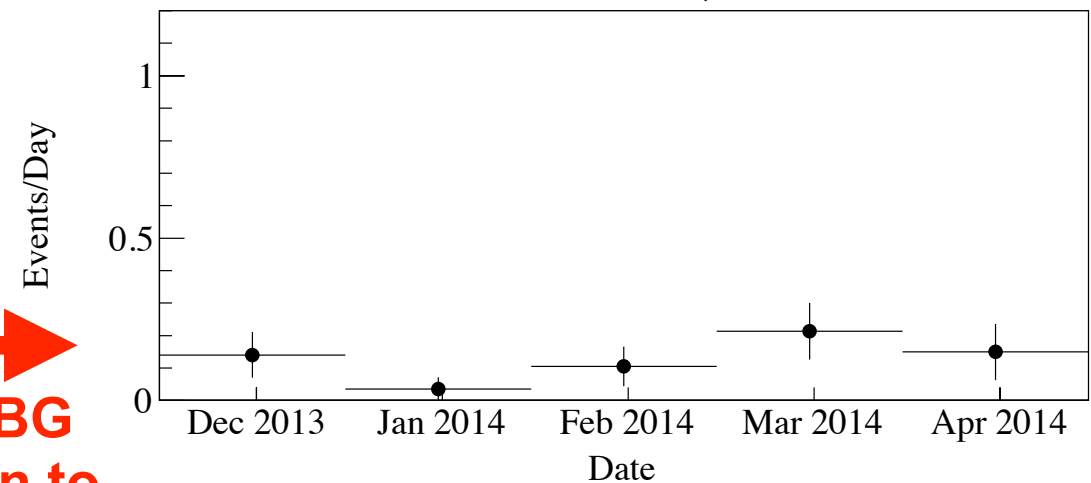
Phase-I (first 112.3 days)

$2.2 < E < 3.0 \text{ MeV}, R < 1 \text{ m}$

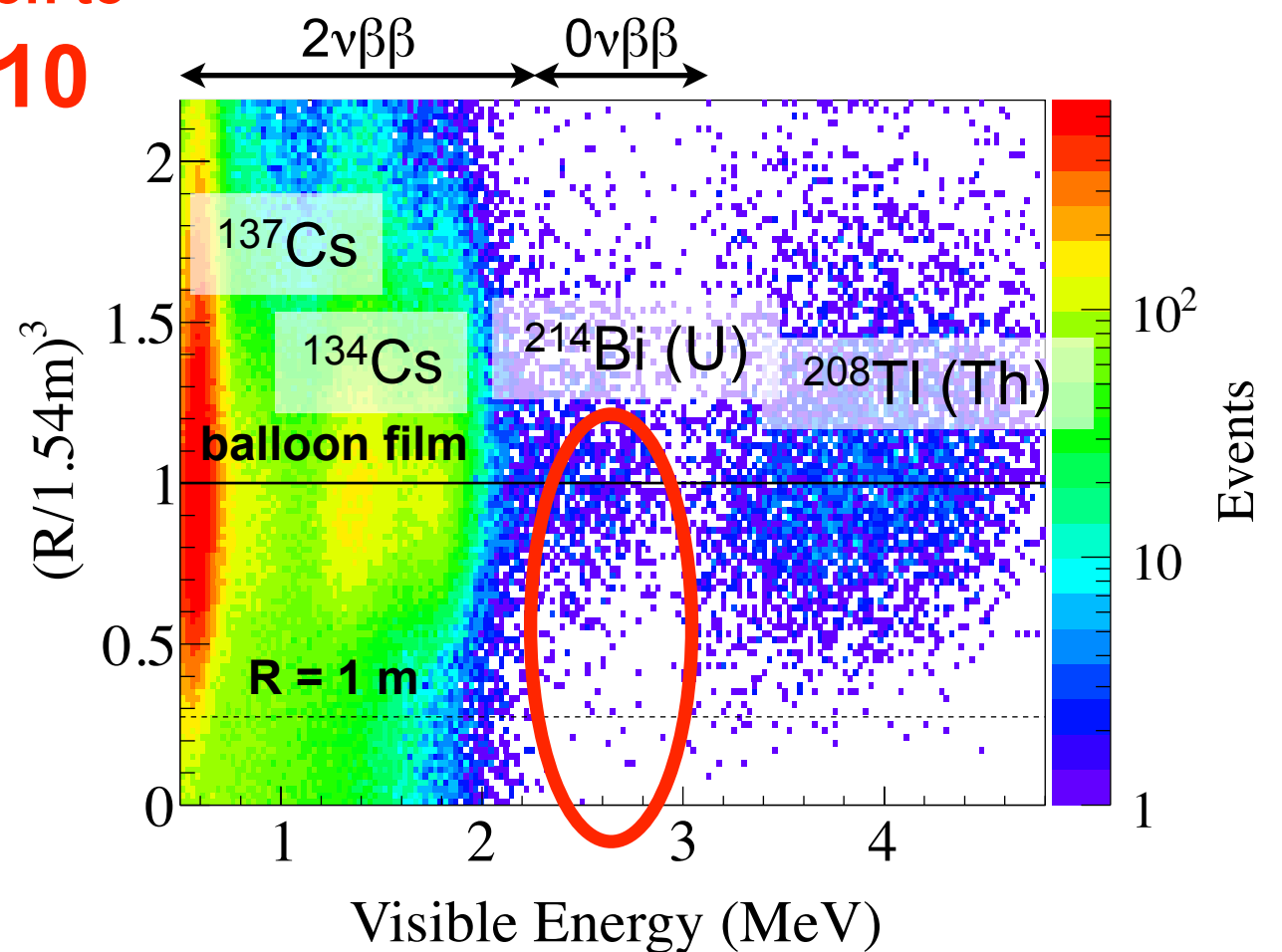
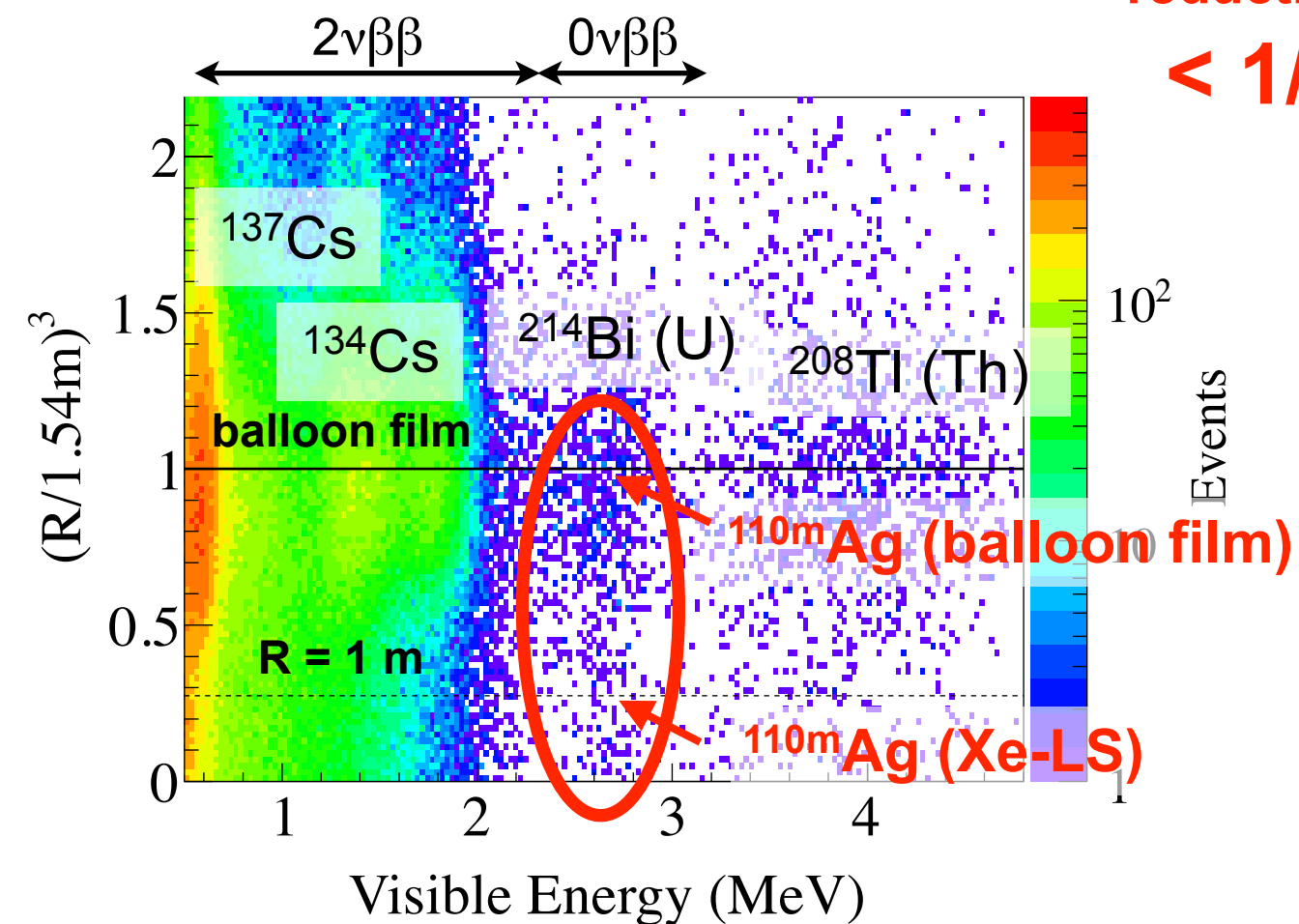


Phase-II (first 114.8 days)

$2.2 < E < 3.0 \text{ MeV}, R < 1 \text{ m}$



**^{110m}Ag BG
reduction to
< 1/10**

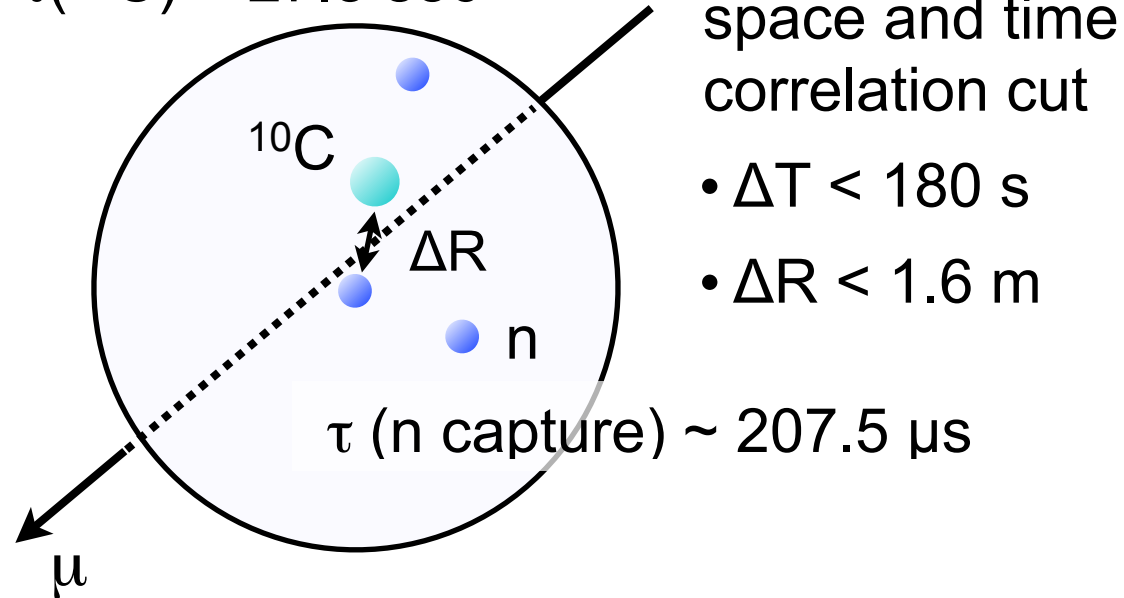


Primary BG : ^{214}Bi (U) at balloon / spallation ^{10}C / remaining ^{110m}Ag ?

Spallation Cut after Cosmic-ray Muon

^{10}C rejection by neutron tagging

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



Baseline
restorer and
signal splitter

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

Trigger module

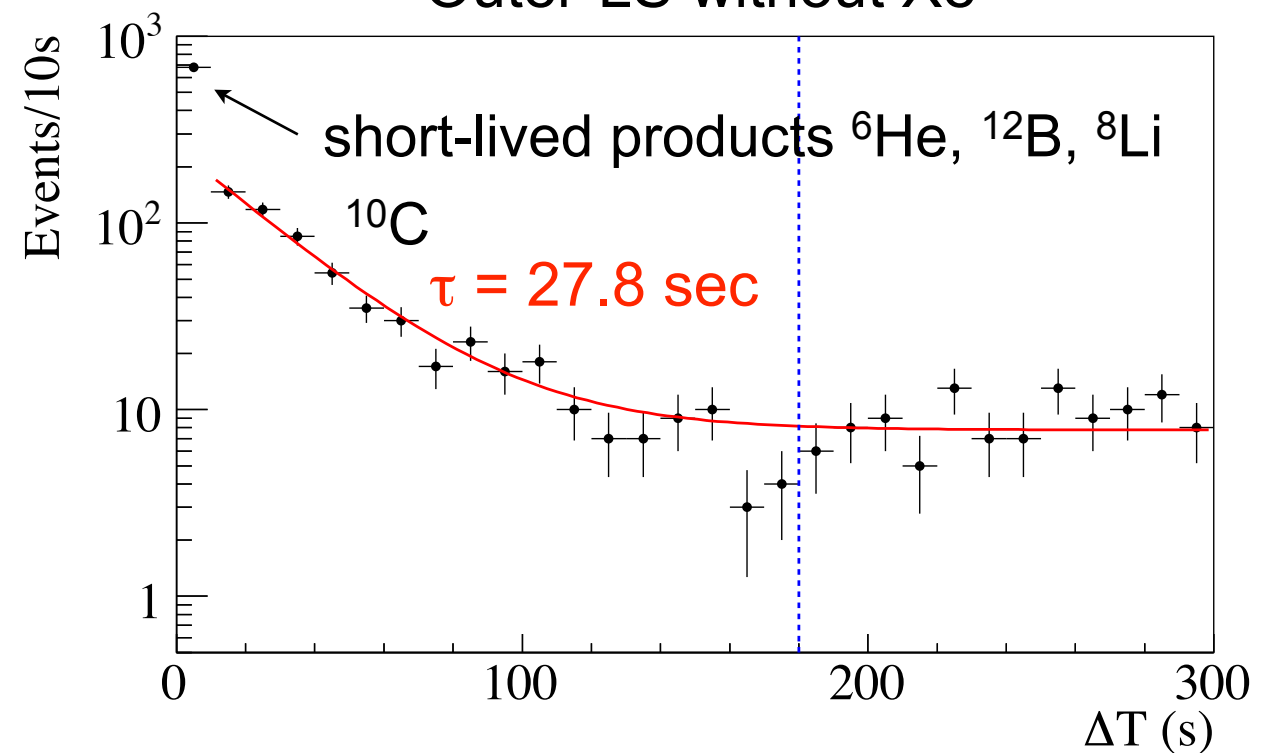
BG rejection efficiency (^{10}C) $64 \pm 4\%$

signal inefficiency 7%

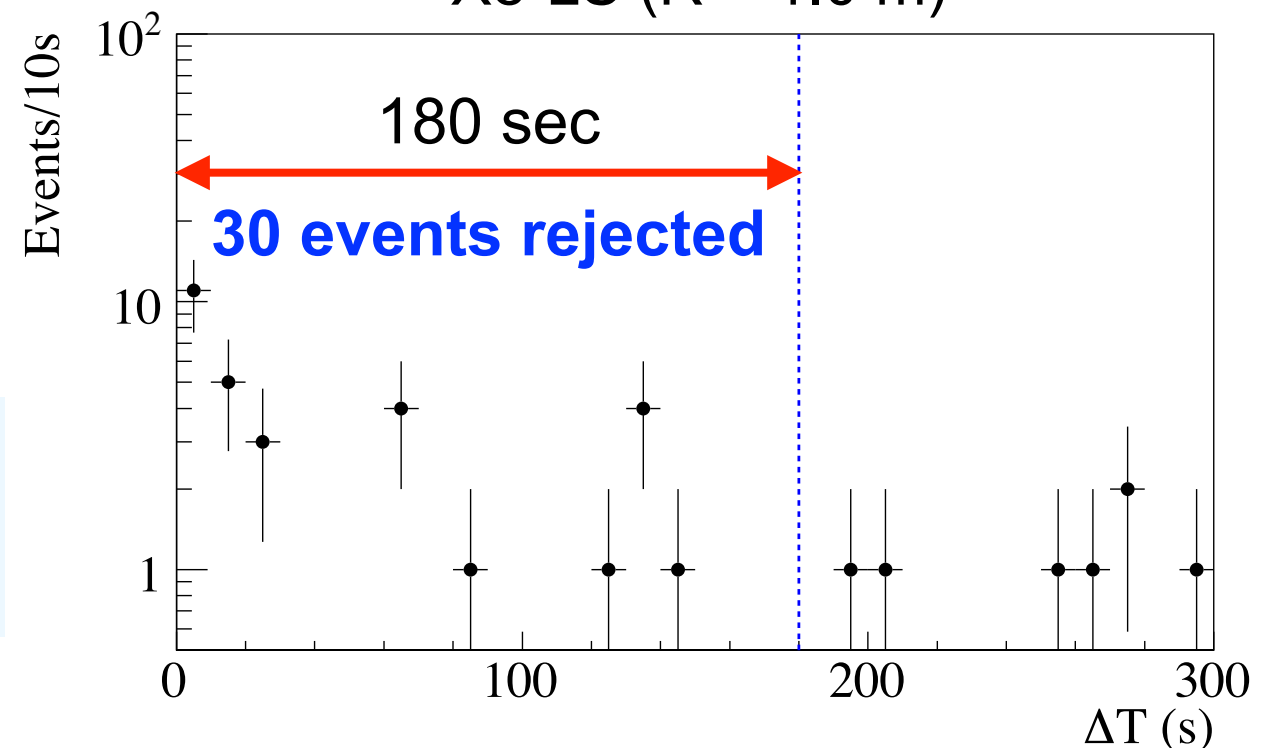
Efficient background rejection

$$2.2 < E < 3.5 \text{ MeV}$$

Outer-LS without Xe



Xe-LS ($R < 1.0 \text{ m}$)

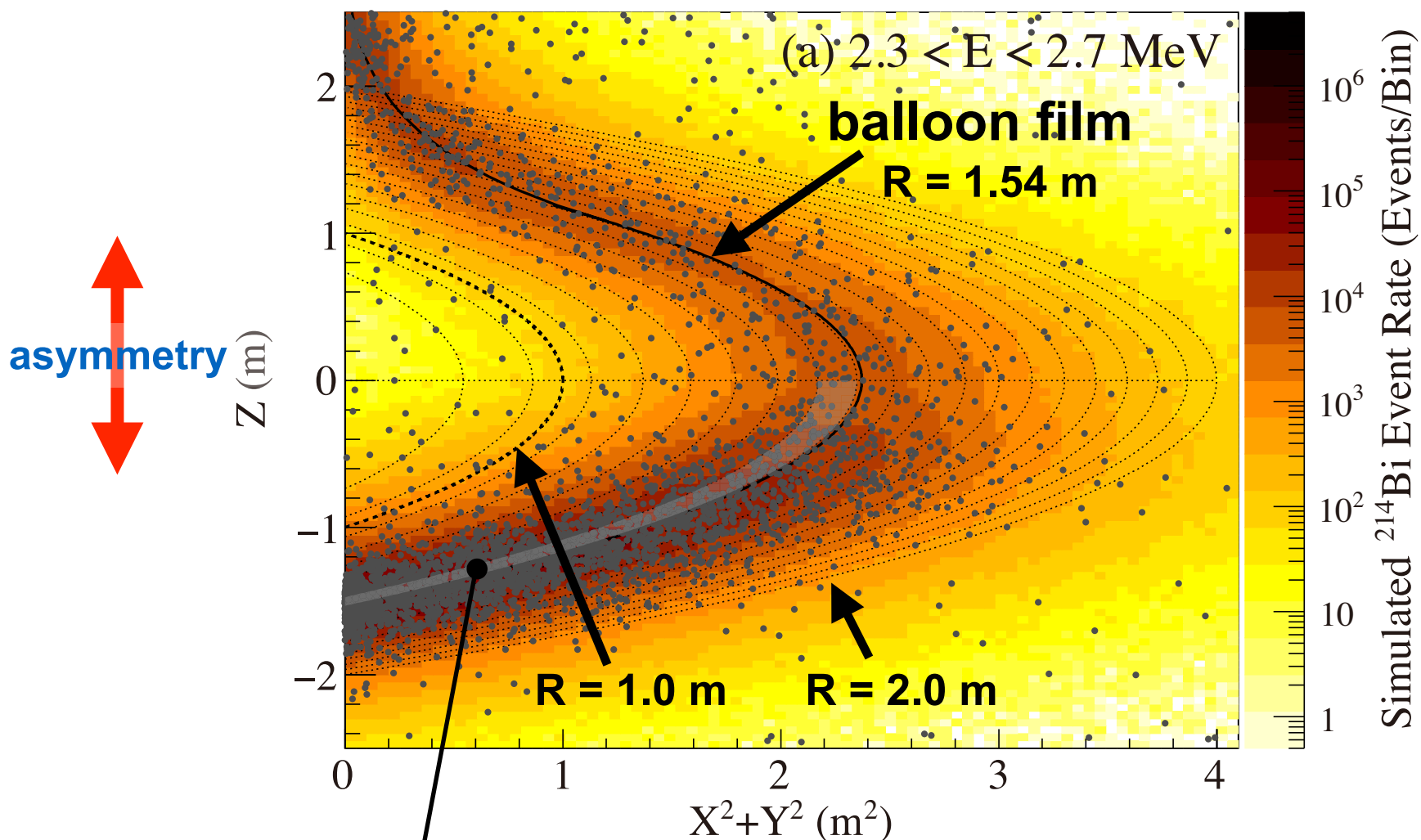


Optimization of Volume Selection

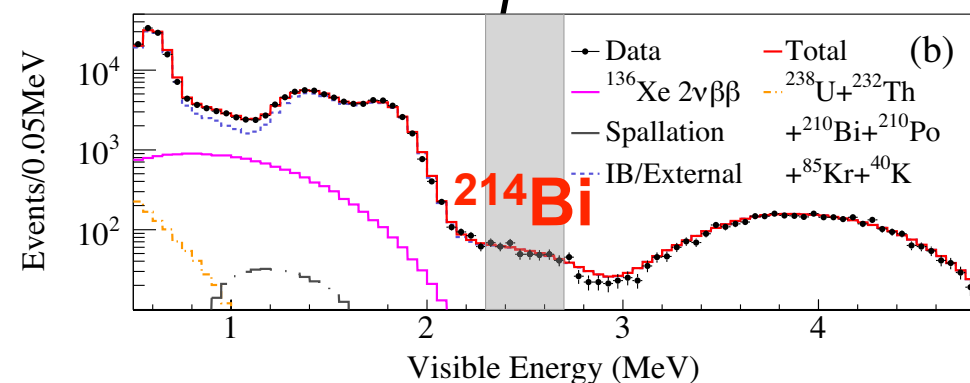
ROI : $2.3 < E < 2.7$ MeV

candidate events (black points)

^{214}Bi MC simulation (color histogram)



volume bin

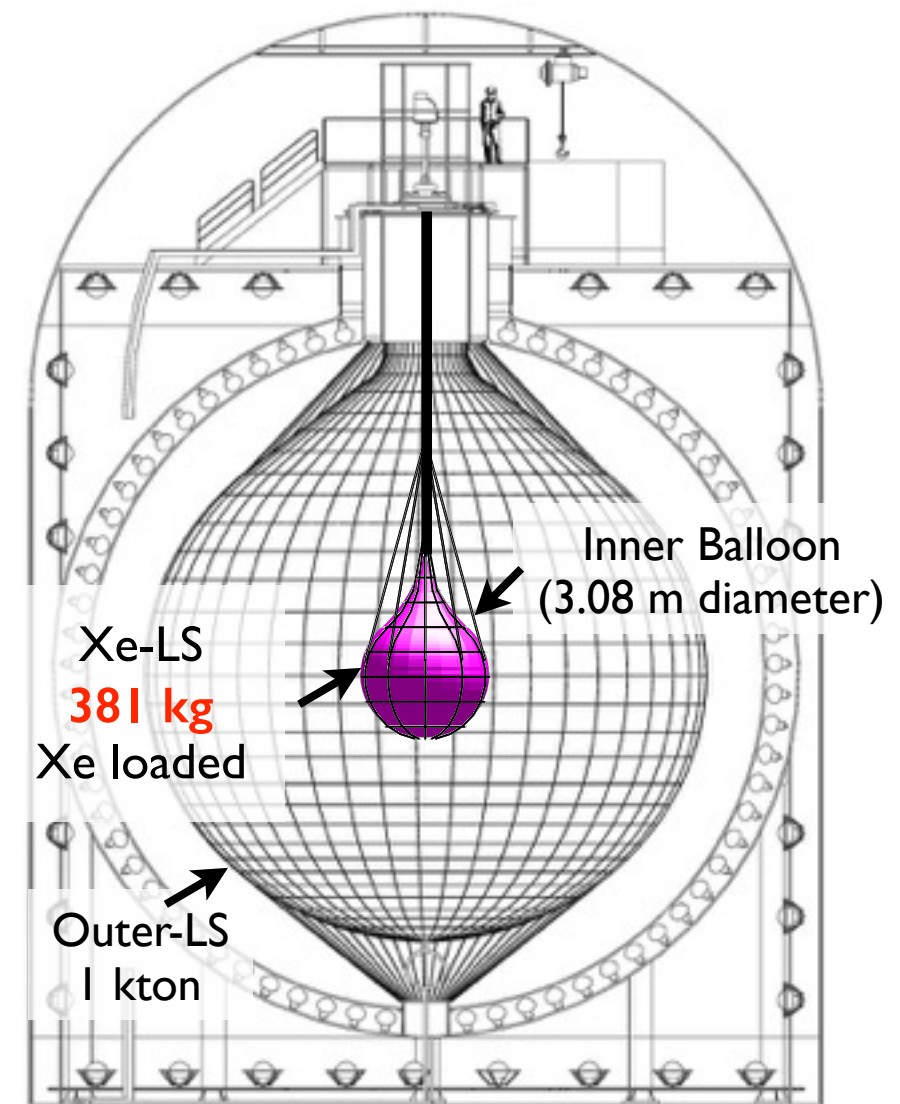


fiducial volume limitation by ^{214}Bi (^{238}U) on the balloon film

multi-volume selection for analysis optimization

40 equal volume bins in $R < 2.0$ m
(20 bins + 20 bins in upper / lower hemisphere)

**KamLAND-Zen
Phase-II**



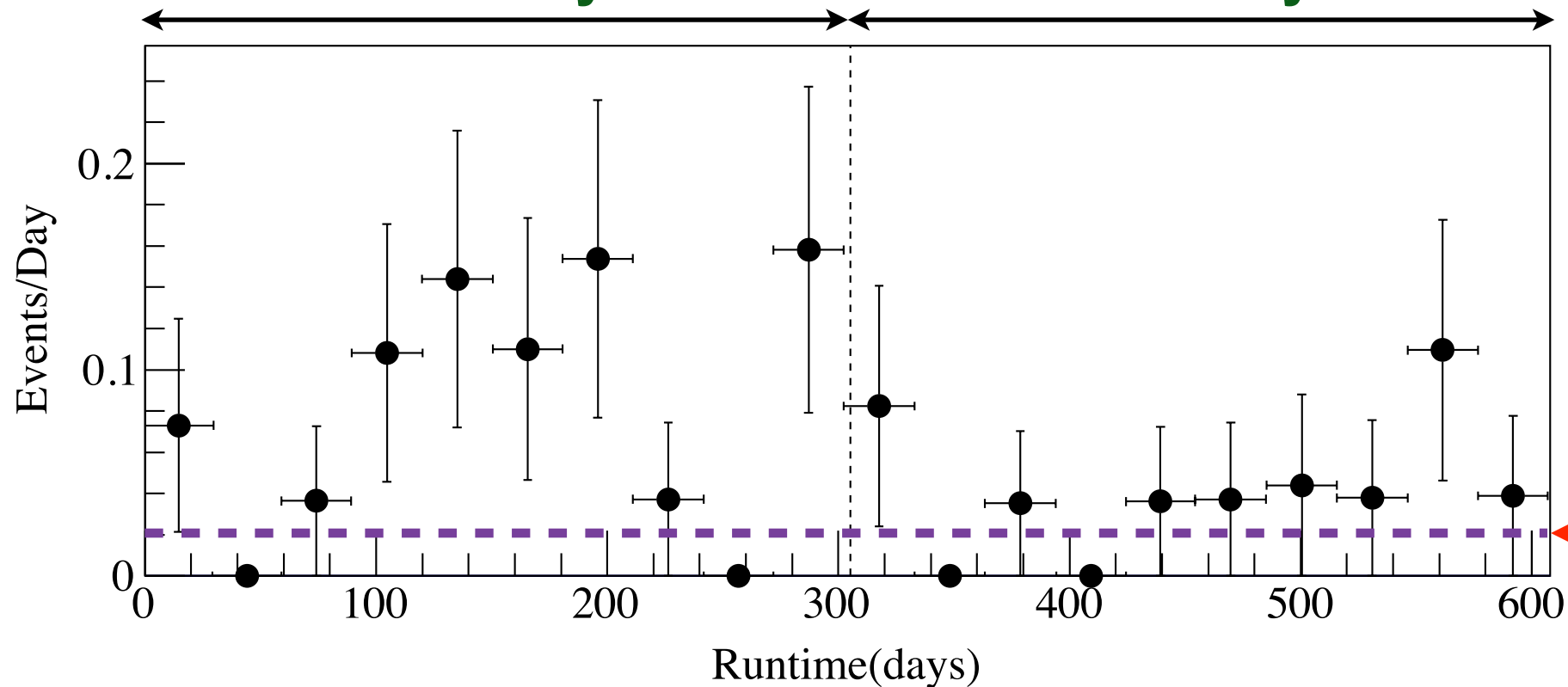
Time Variation of Event Rate

ROI : $2.3 < E < 2.7$ MeV, $R < 1.0$ m
($0\nu\beta\beta$ search sensitivity is dominated by this data)

Phase-II (534.5 days)

Period-1
270.7 days

Period-2
263.8 days



$\sim 2\sigma$ discrepancy from
simple $^{110\text{m}}\text{Ag}$ decay

known BG rate
other than $^{110\text{m}}\text{Ag}$

22 events

11 events

$^{110\text{m}}\text{Ag}$ may decrease by “dust” settling to the bottom of the balloon film (unpredictable)



Data-set division into two equal time period $\sim ^{110\text{m}}\text{Ag}$ lifetime ($\tau = 360$ days)

Definition of Chi-Square

Binned maximum likelihood method

energy-volume bin (2D)

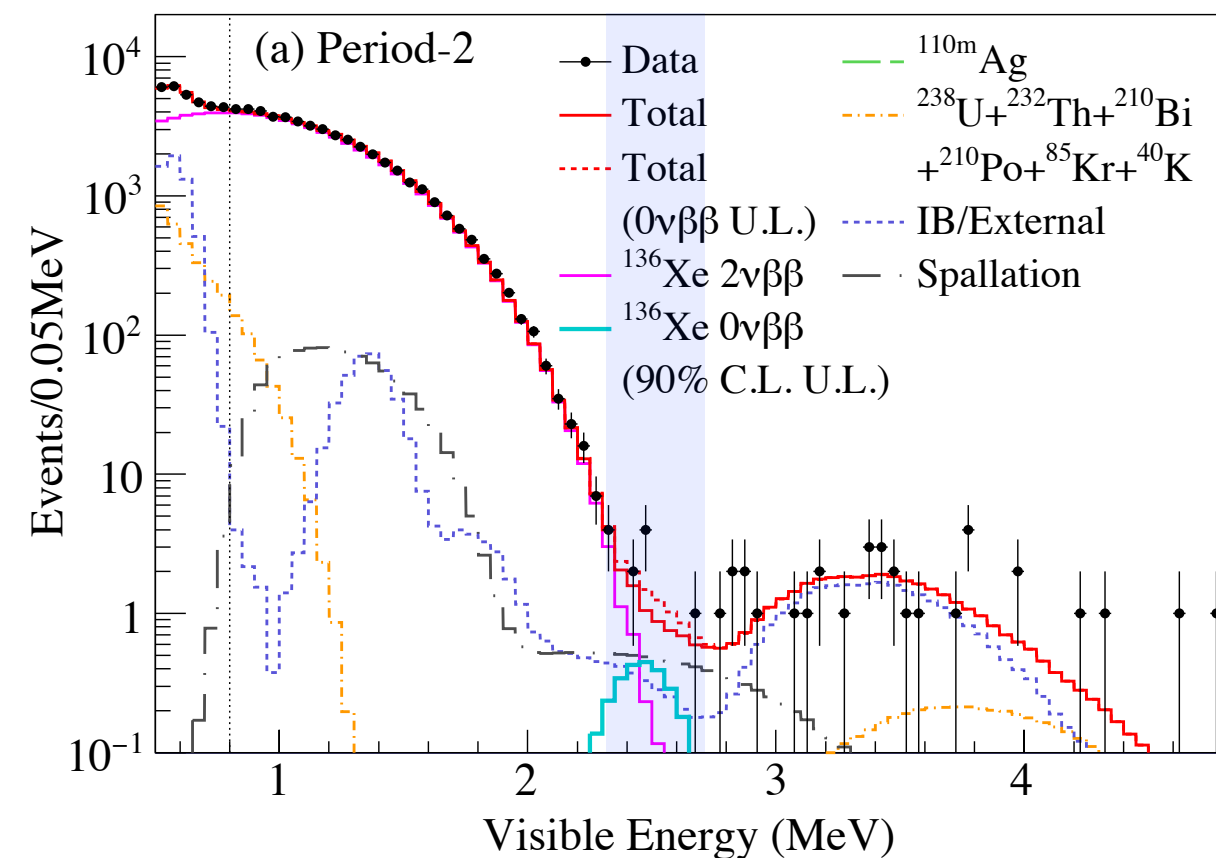
$$\chi^2 = 2 \sum_i^{energy} \sum_j^{volume} \left[\mu_{i,j}(N_{0\nu\beta\beta}, N_{BG}, \alpha) - n_{i,j} + n_{i,j} \ln \frac{n_{i,j}}{\mu_{i,j}(N_{0\nu\beta\beta}, N_{BG}, \alpha)} \right] + \chi_{BG}^2(N_{BG}) + \chi_{syst}^2(\alpha)$$

N_{BG} : background rates

α : systematic parameters

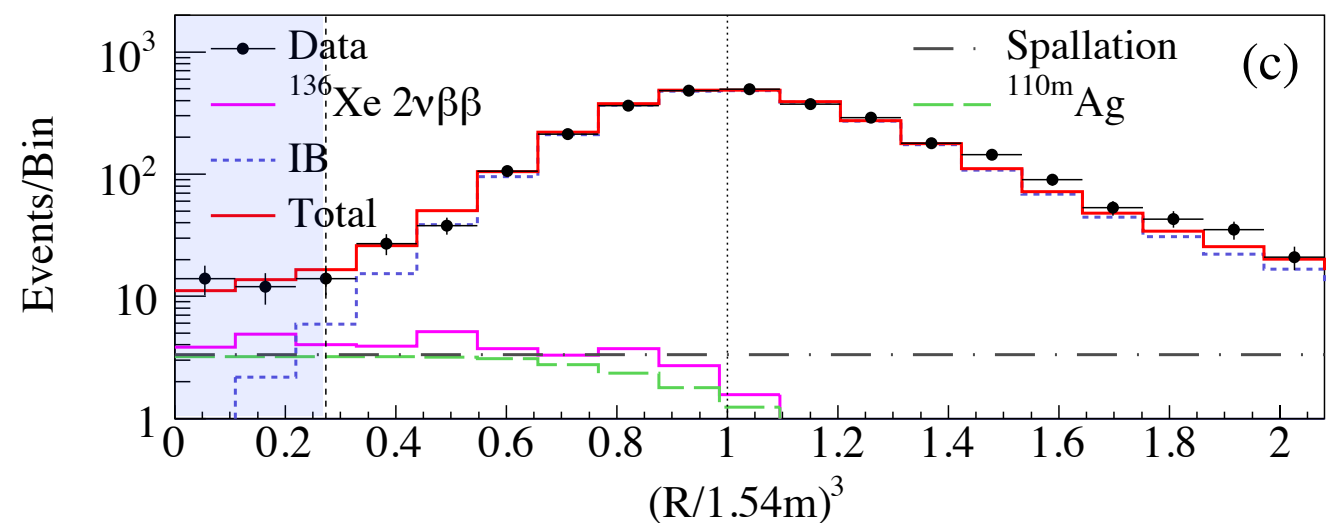
2νββ

sensitive
to 0νββ



sensitive
to 0νββ

214Bi



^{214}Bi rate is well determined by
the data in outer-volume bins

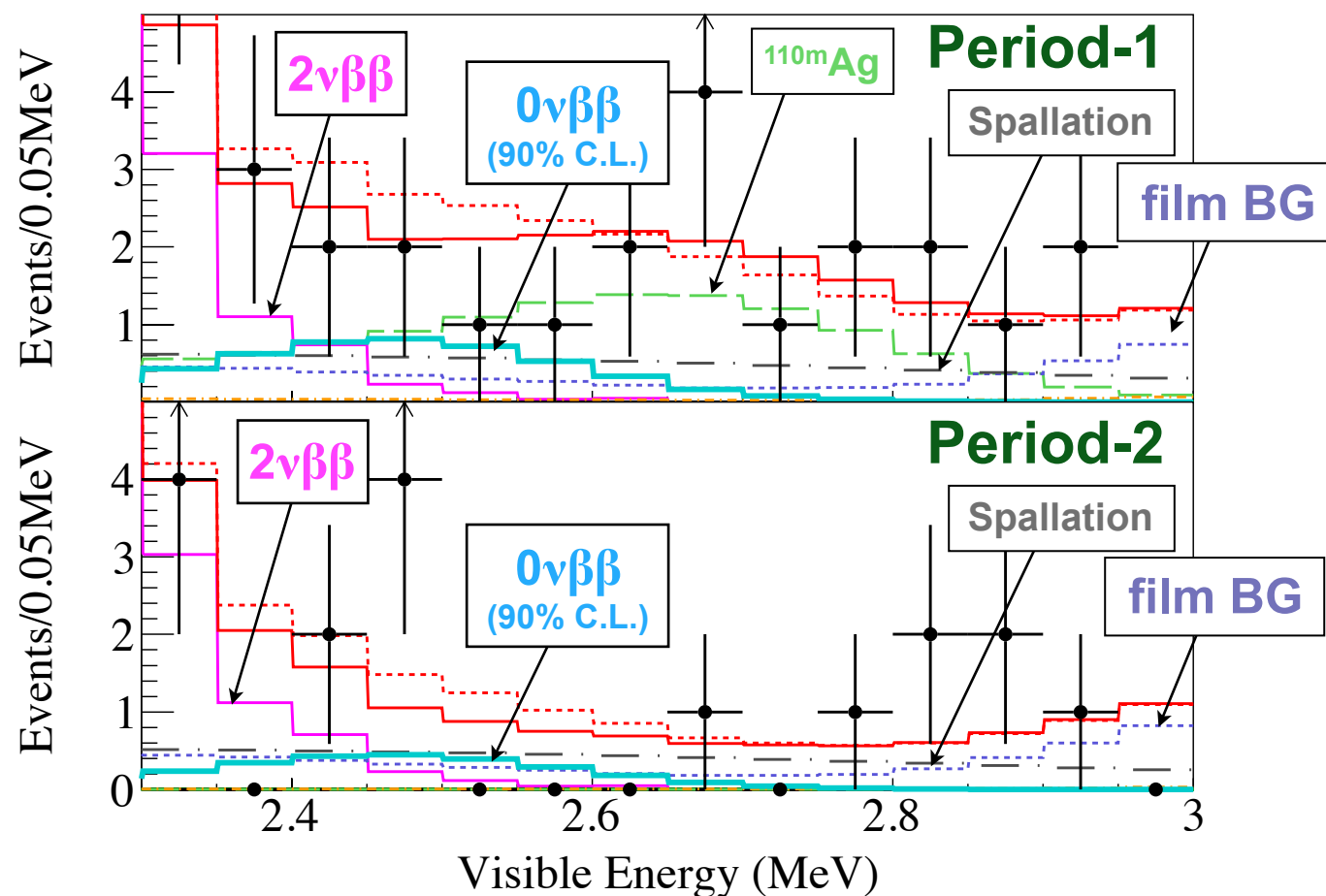
Background and 0νββ rates are evaluated simultaneously

Fit to Energy Spectra for $0\nu\beta\beta$

Estimation and Best-fit (ROI : $2.3 < E < 2.7$ MeV, $R < 1.0$ m)

		$^{136}\text{Xe } 0\nu\beta\beta$	$^{136}\text{Xe } 2\nu\beta\beta$	$^{214}\text{Bi (LS)}$	$^{110\text{m}}\text{Ag}$	$^{214}\text{Bi (film)}$	spallation	Total BG	Observed
Period-1 (270.7 days)	Estimated	-	-	0.23 ± 0.04	-	-	3.8 ± 0.9	-	22
	Best-fit	0	5.48	0.25	8.0	2.55	4.5	20.8	
Period-2 (263.8 days)	Estimated	-	-	0.03 ± 0.01	-	-	3.7 ± 0.9	-	11
	Best-fit	0	5.29	0.03	0.002	2.45	3.7	11.5	

Internal ($R < 1.0$ m)



Fit to Energy-Volume 2D spectra

Limits on $0\nu\beta\beta$ at 90% C.L.

Period-1 < 5.6 events/day/kton-LS

Period-2 < 3.2 events/day/kton-LS

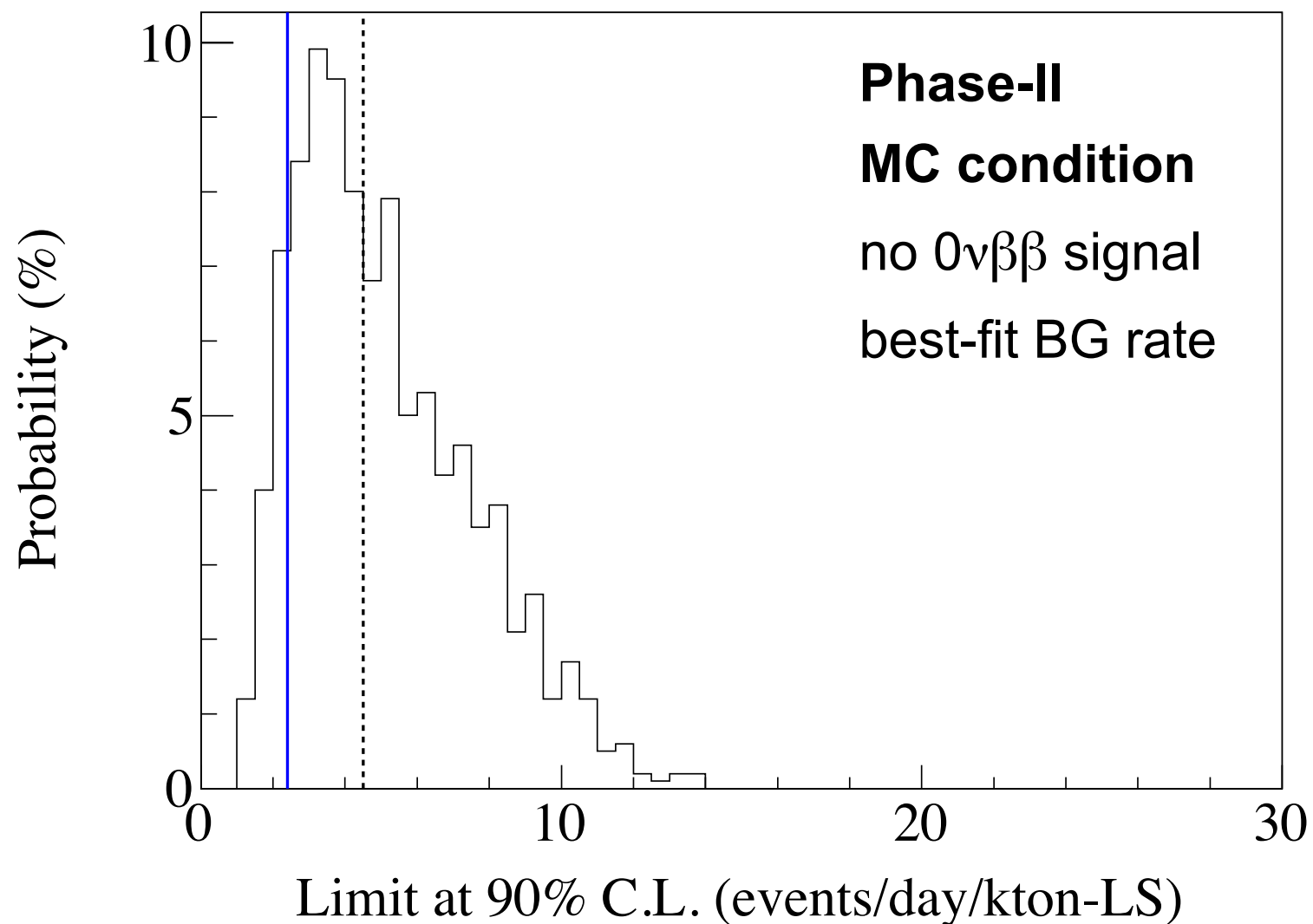
Combined < 2.4 events/day/kton-LS

↓

$$T^{0\nu}_{1/2} > 9.6 \times 10^{25} \text{ yr}$$

Limits from Toy MC

distribution of $0\nu\beta\beta$ limits from Toy MC



$$T_{1/2}^{0\nu} > 9.6 \times 10^{25} \text{ yr} \quad 11\% \text{ of the time}$$

$$T_{1/2}^{0\nu} > 4.9 \times 10^{25} \text{ yr} \quad 50\% \text{ of the time}$$

Sensitivity is checked by MC assuming best-fit BG rate

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

combined result (Phase-I + Phase-II)

Half-life limit at 90% C.L.

KamLAND-Zen

Phase-I $T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ yr}$

Phase-II $T_{1/2}^{0\nu} > 9.6 \times 10^{25} \text{ yr}$

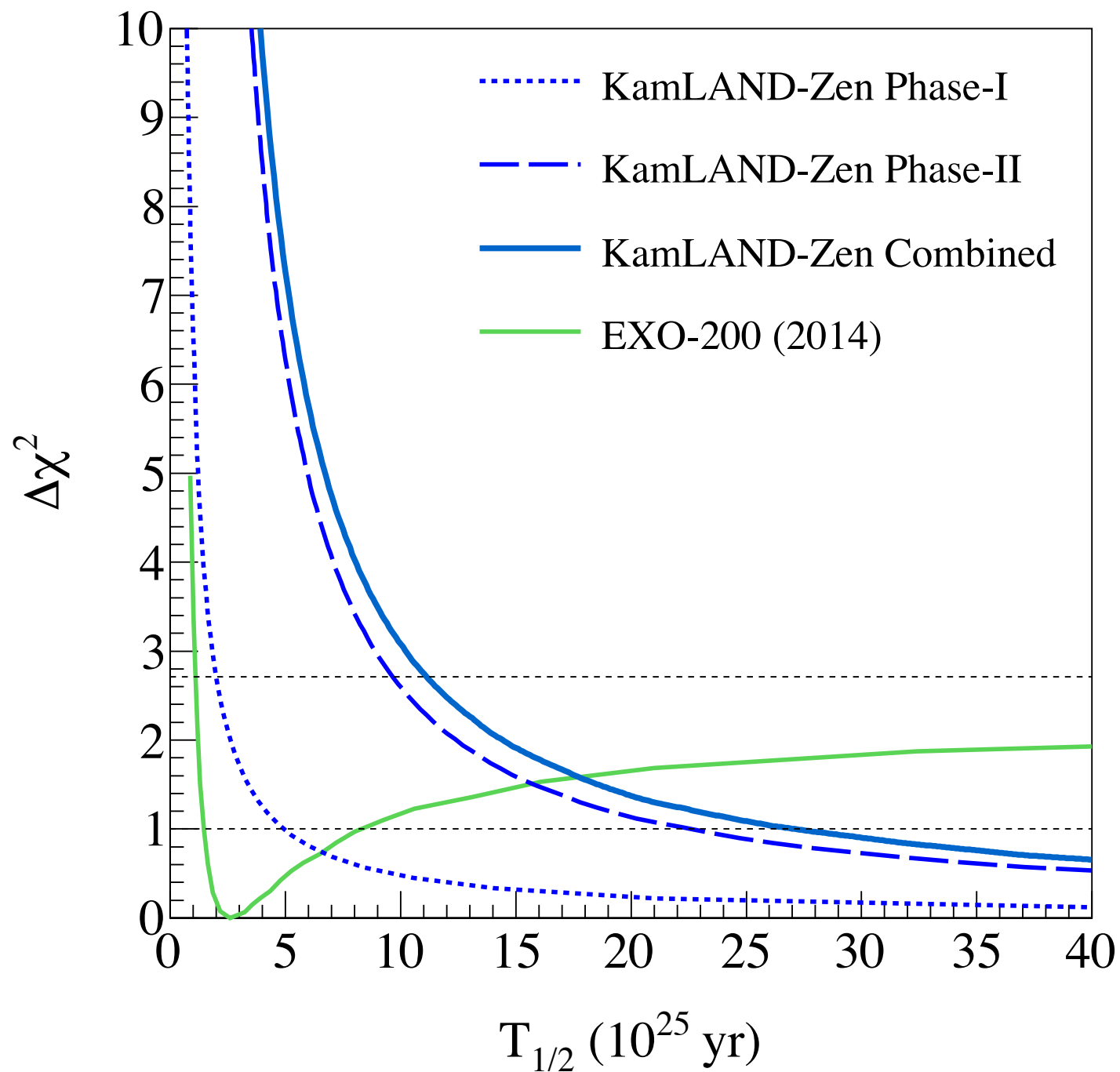
Combined $T_{1/2}^{0\nu} > 1.1 \times 10^{26} \text{ yr}$
(factor ~ 6 improvement)

$\langle m_{\beta\beta} \rangle < 60\text{-}161 \text{ meV}$

Decay rate $\rightarrow$ proportional to (neutrino mass)²

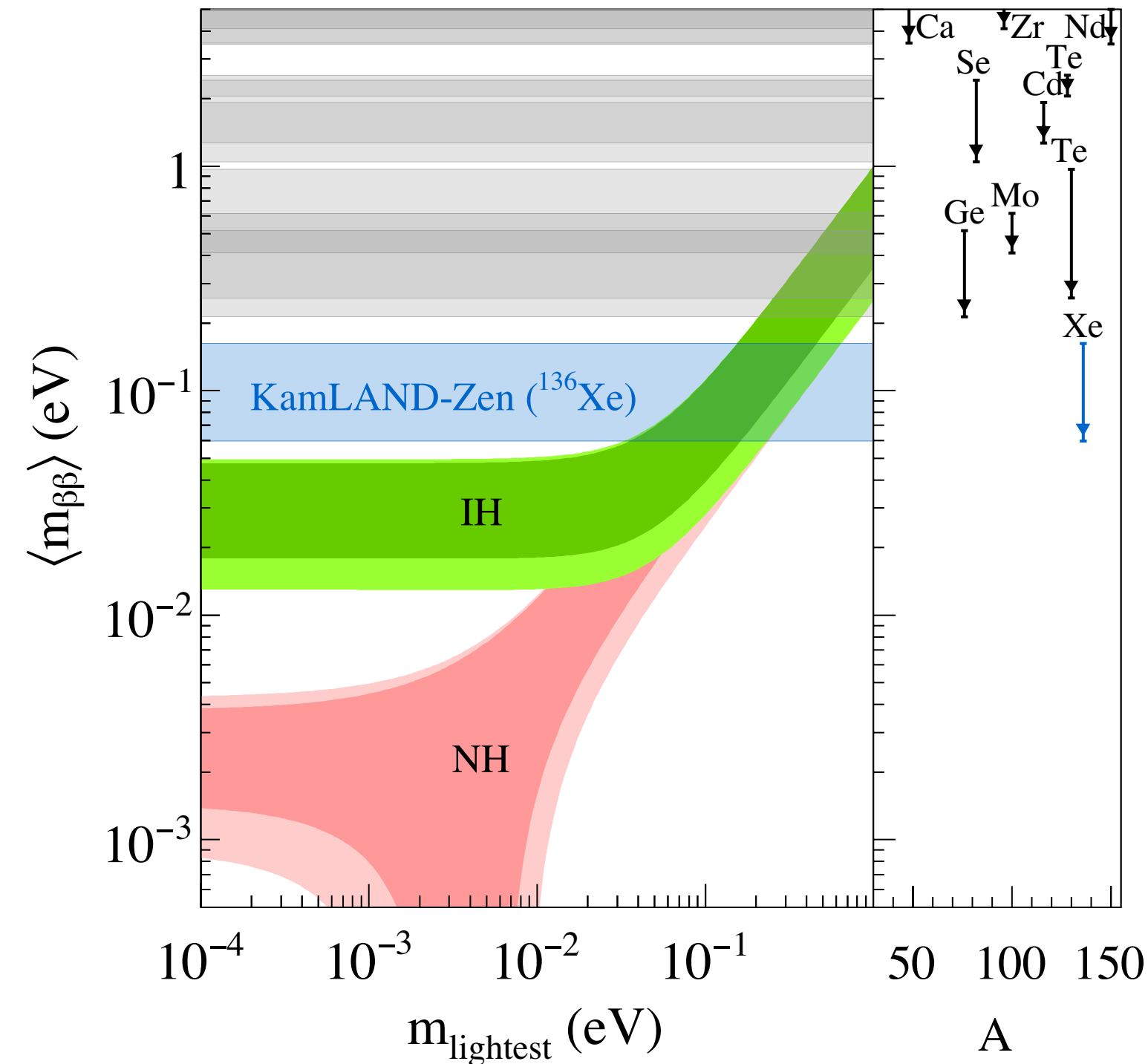
$$[T_{1/2}^{0\nu}]^{-1} = \underbrace{G^{0\nu}(Q_{\beta\beta}, Z)}_{\text{PSF}} \underbrace{|M^{0\nu}|^2}_{\text{NME}} \langle m_{\beta\beta} \rangle^2$$

Longest half-life limit ($> 10^{26} \text{ yr}$) among $\beta\beta$ isotopes



Limits on Neutrino Mass

90% C.L. upper limit



KamLAND-Zen (^{136}Xe)

$$\langle m_{\beta\beta} \rangle < 60-161 \text{ meV}$$

$$m_{\text{lightest}} < 180-470 \text{ meV}$$

including uncertainties from
CP phases and v-osci. par.

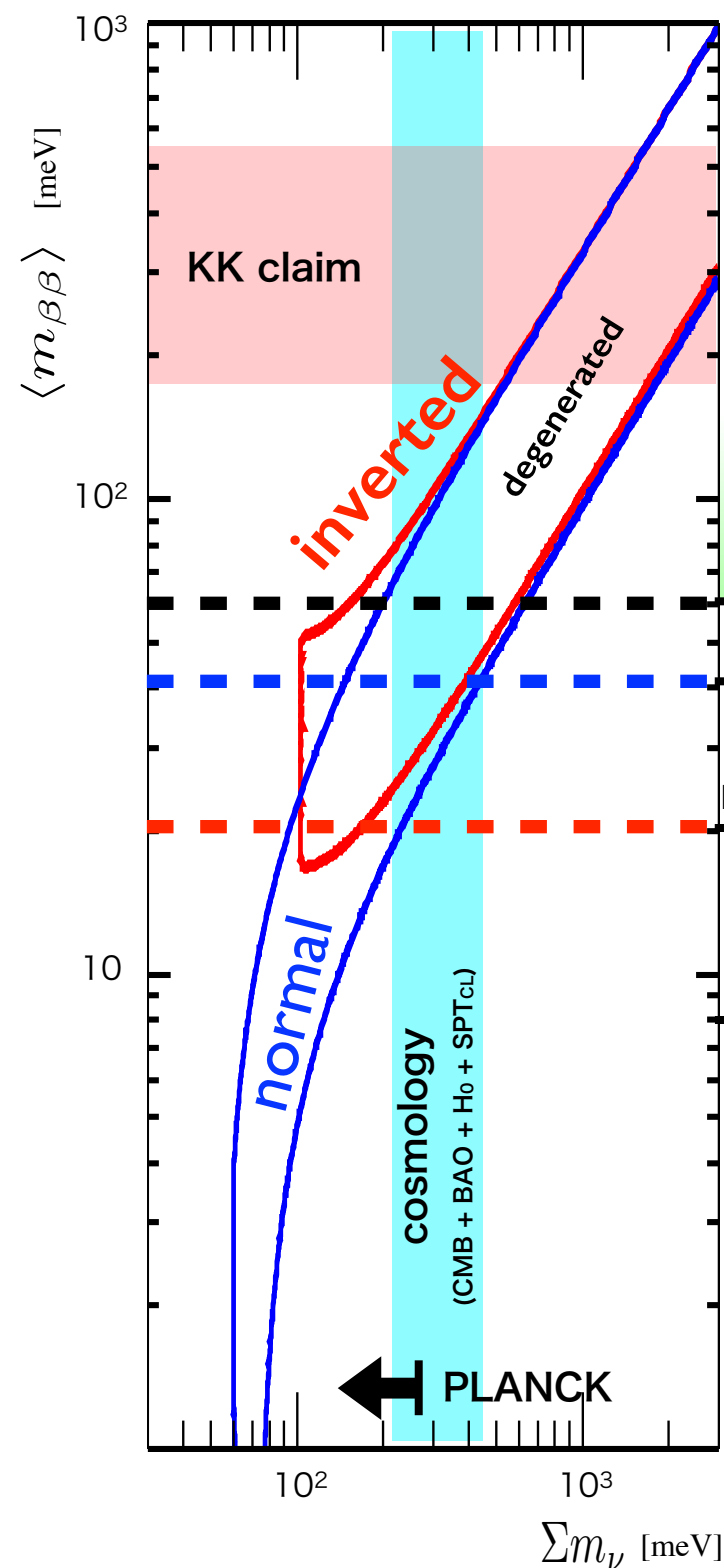
NME calculations assuming $g_A \sim 1.27$

small $\uparrow$ SkM-HFB-QRPA (PRC87, 064302 (2013))
ISM (Nucl. Phys. A 818, 139 (2009))
QRPA (PRC 87, 045501 (2013))
SRQRPA (J. High Energy Phys. 02, 025 (2013))
pnQRPA (PRC 91, 024613 (2015))
IBM-2 (PRC 91, 034304 (2015))
large $\downarrow$ EDF (PRL 105, 252503 (2010))

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

First search below 100 meV ~ near IH region

Prospects of KamLAND-Zen



$0\nu\beta\beta$ search sensitivity can be enhanced by various KamLAND-Zen upgrade plans

KamLAND-Zen 400 (Phase-I + Phase-II)

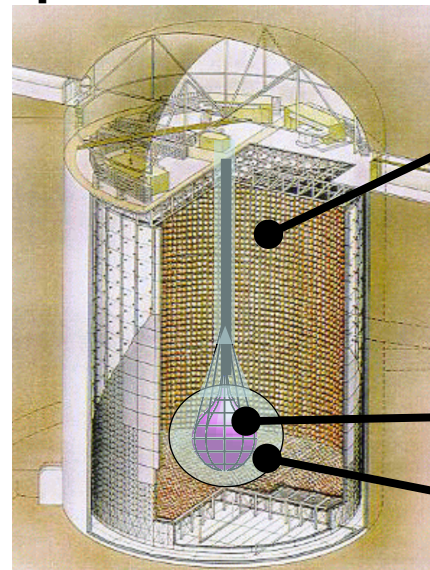
$\langle m_{\beta\beta} \rangle < 60-161 \text{ meV} \quad @ 90\% \text{ C.L.}$

uncertainty of nuclear matrix element

KamLAND-Zen 800 (750 kg Xe),
high purity mini-balloon

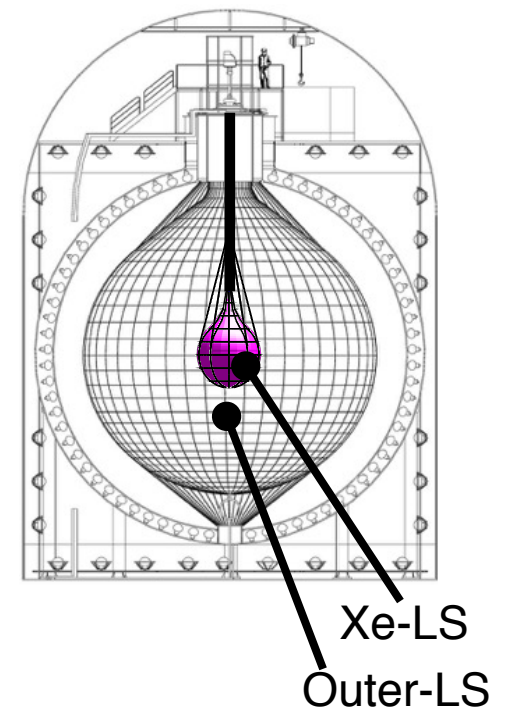
KamLAND2-Zen 1000 kg, high light yield LS
 $\sigma_E(2.5\text{MeV}) = 4\% \rightarrow 1.8\%$

Super-KamLAND-Zen

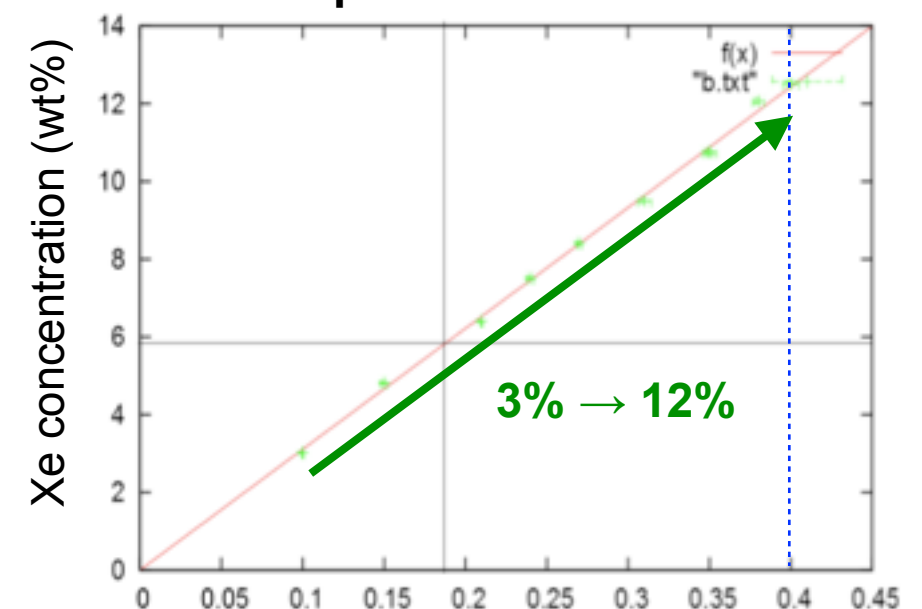


increase decay target nuclei by pressurized Xe

KamLAND-Zen



pressurized Xe



Xe partial pressure (MPa)

4 times at 30 m depth

Summary

- Neutrinoless double-beta decays provide an important probe for physics beyond the Standard Model.
- Recent status of running experiments and their data treatments were reviewed.
- New results from KamLAND-Zen were presented.

KamLAND-Zen limits on $0\nu\beta\beta$ at 90% C.L. arXiv:1605.02889

Phase 1 (213 days)

$$T^{0\nu}_{1/2} > 1.9 \times 10^{25} \text{ yr}$$

Phase 2 (535 days)

$$T^{0\nu}_{1/2} > 9.6 \times 10^{25} \text{ yr}$$

Combined

$$T^{0\nu}_{1/2} > 1.1 \times 10^{26} \text{ yr}$$



NME calculations assuming $g_A \sim 1.27$

$$\langle m_{\beta\beta} \rangle < 60\text{-}161 \text{ meV}$$

- Next generation experiments are planned aiming at a test of inverted neutrino mass hierarchy.