Results from the 1^{st} phase of KamLAND-Zen

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Outline

- Discovery of neutrino mass
- Double beta decay
- KamLAND, a host for KamLAND-Zen
- KamLAND-Zen setup and installation
- Detector performance and data analysis
- Results and implications from 1st phase
- Future plans for KamLAND-Zen

Discovery of neutrino mass

Solar neutrino problem

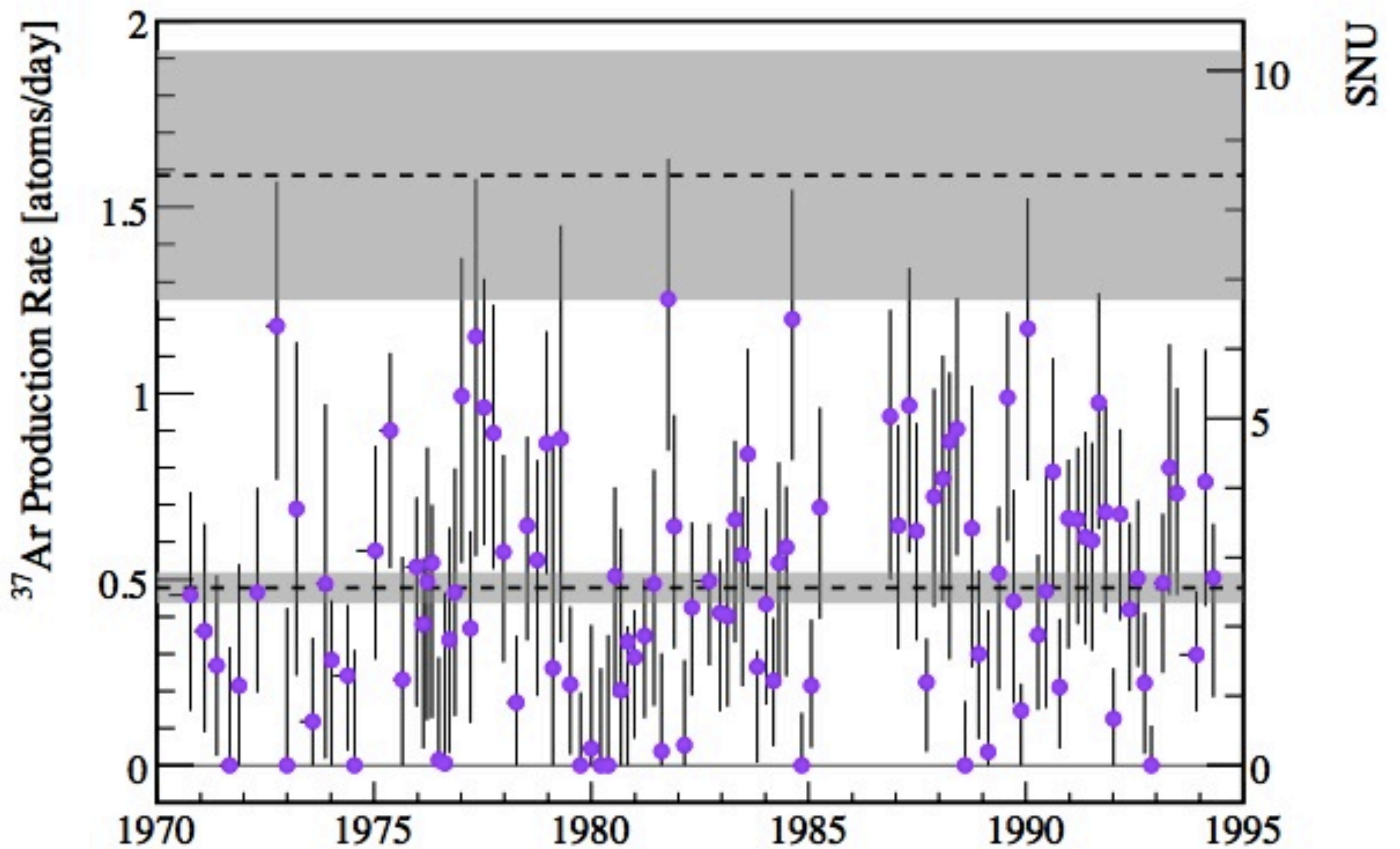
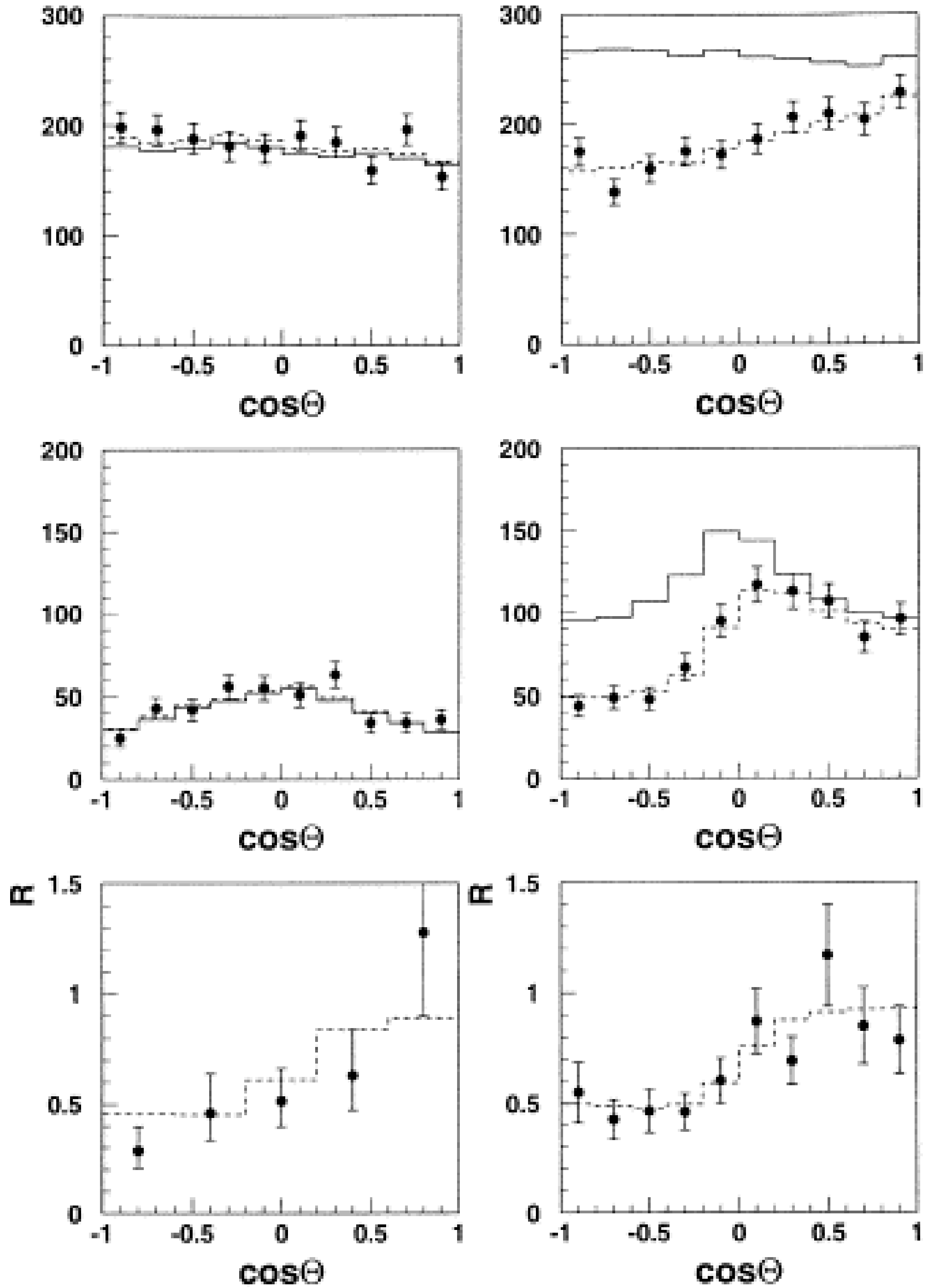


Figure courtesy of L. Winslow, PhD Thesis, UC Berkeley 2008

Davis experiment @ Homestake

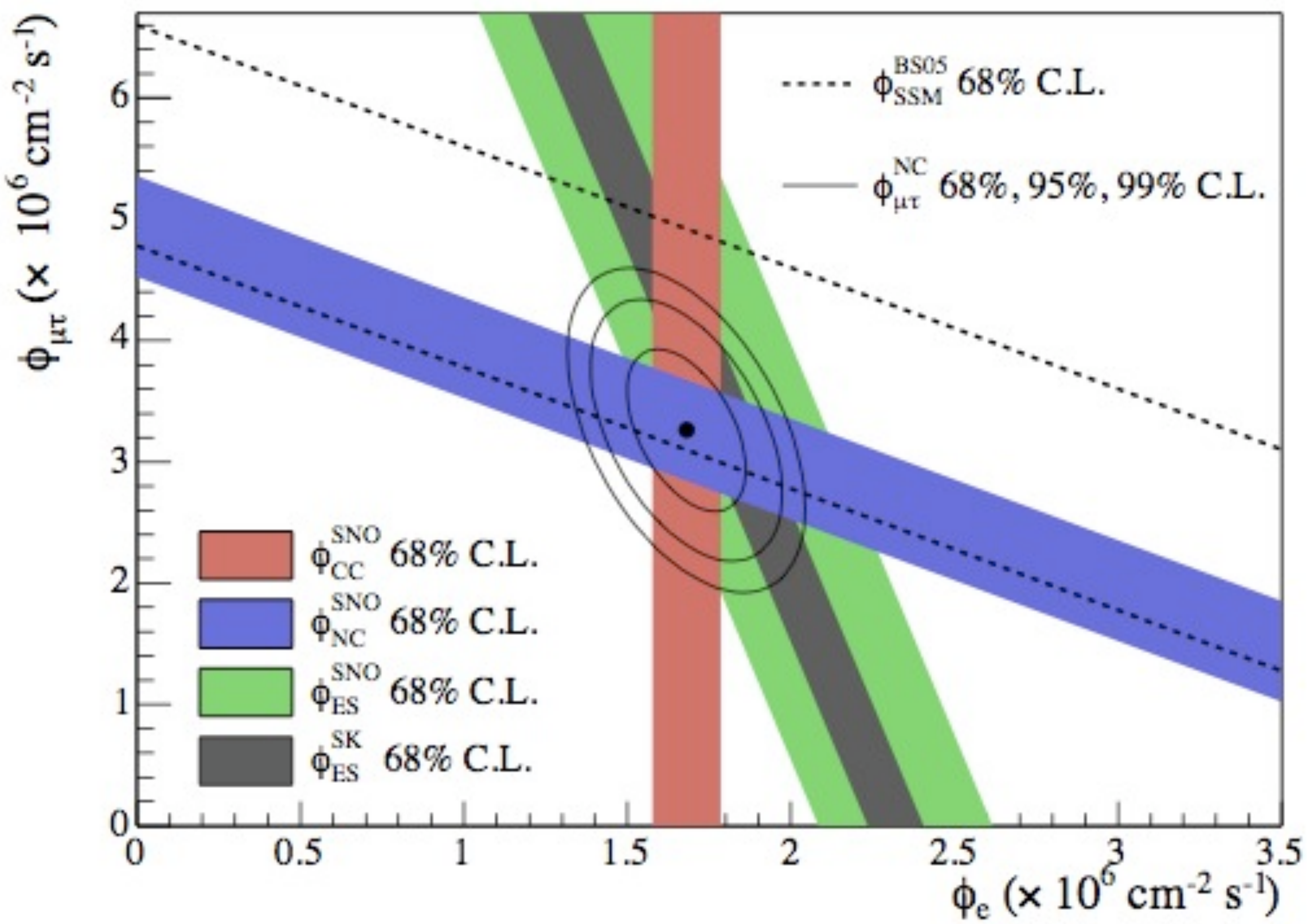
Discovery of neutrino mass

Atmospheric neutrino anomaly at Kamiokande



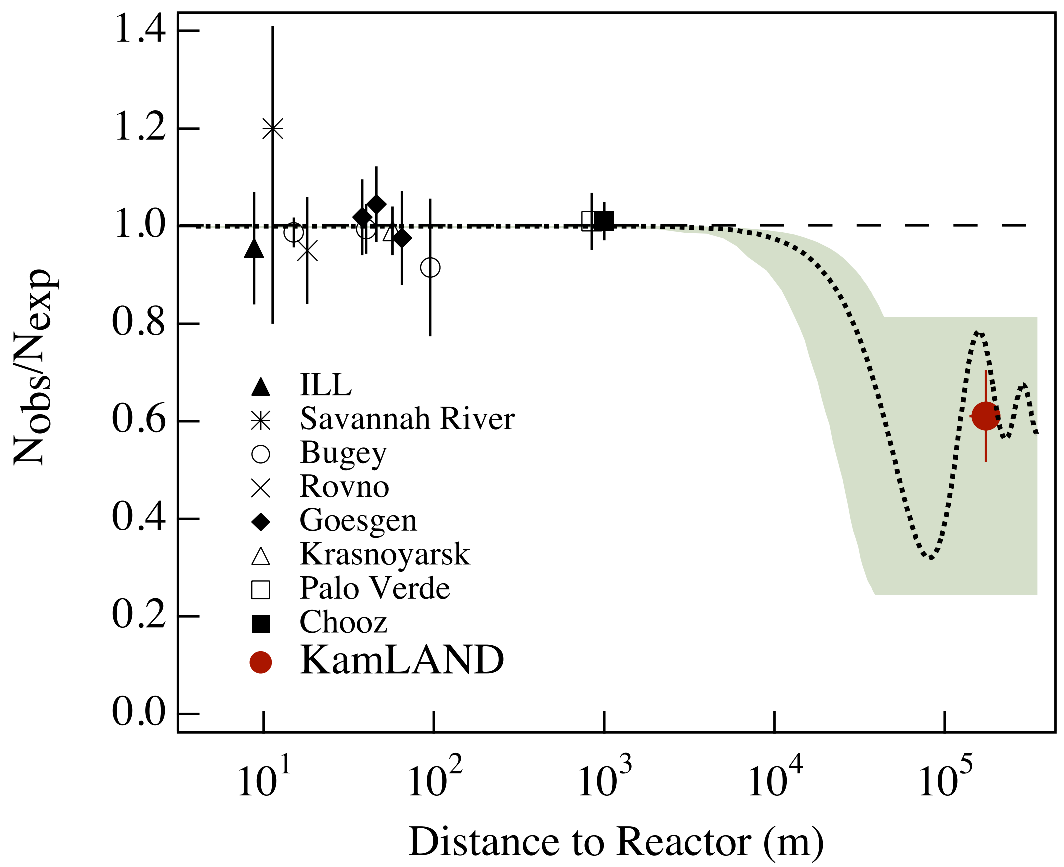
Discovery of neutrino mass

Discovery of flavor change at SNO

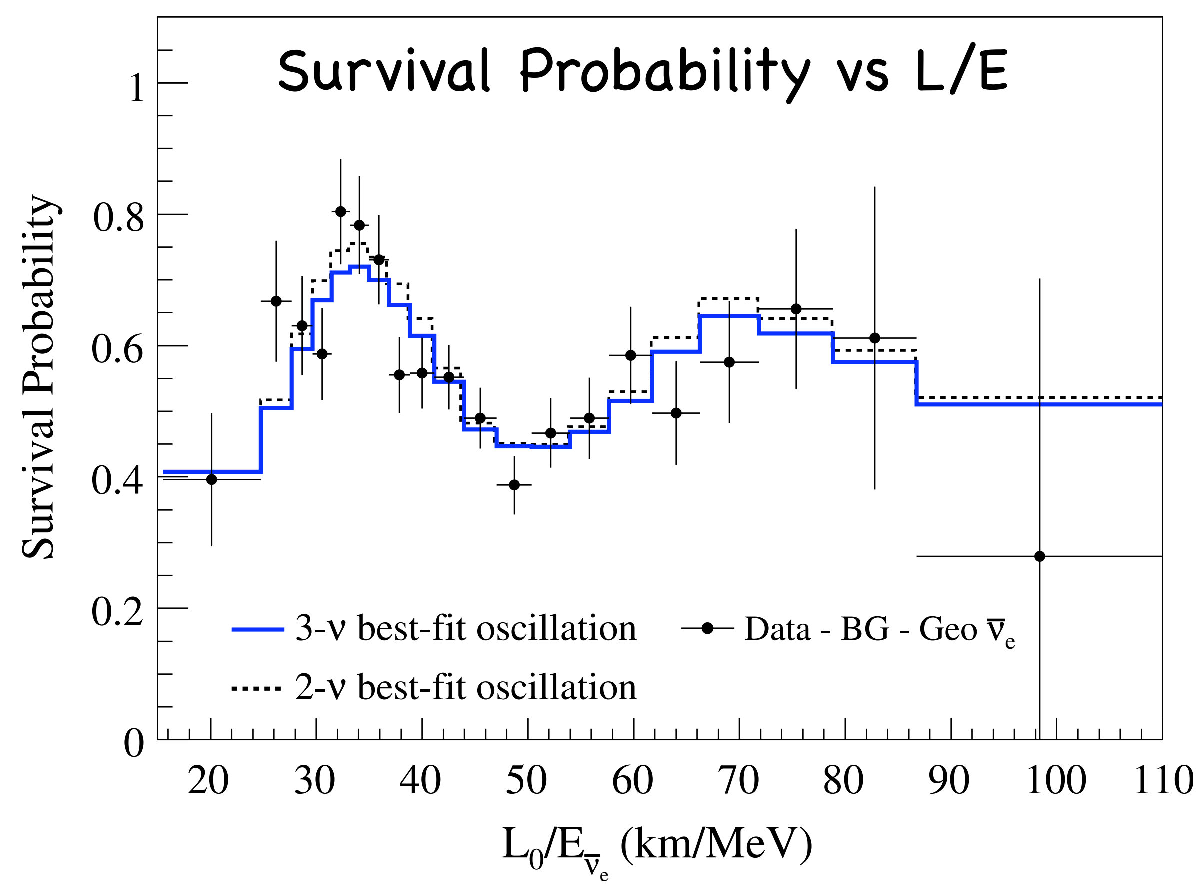


Discovery of neutrino mass

Reactor neutrino disappearance at KamLAND

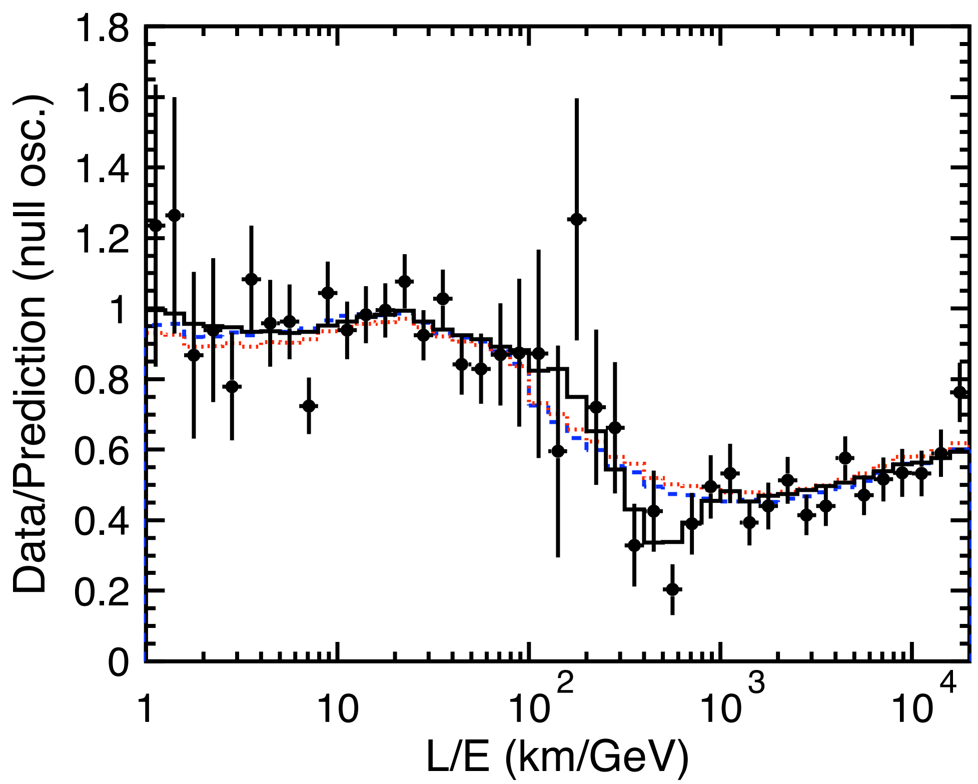


Oscillation pattern confirmed at KamLAND

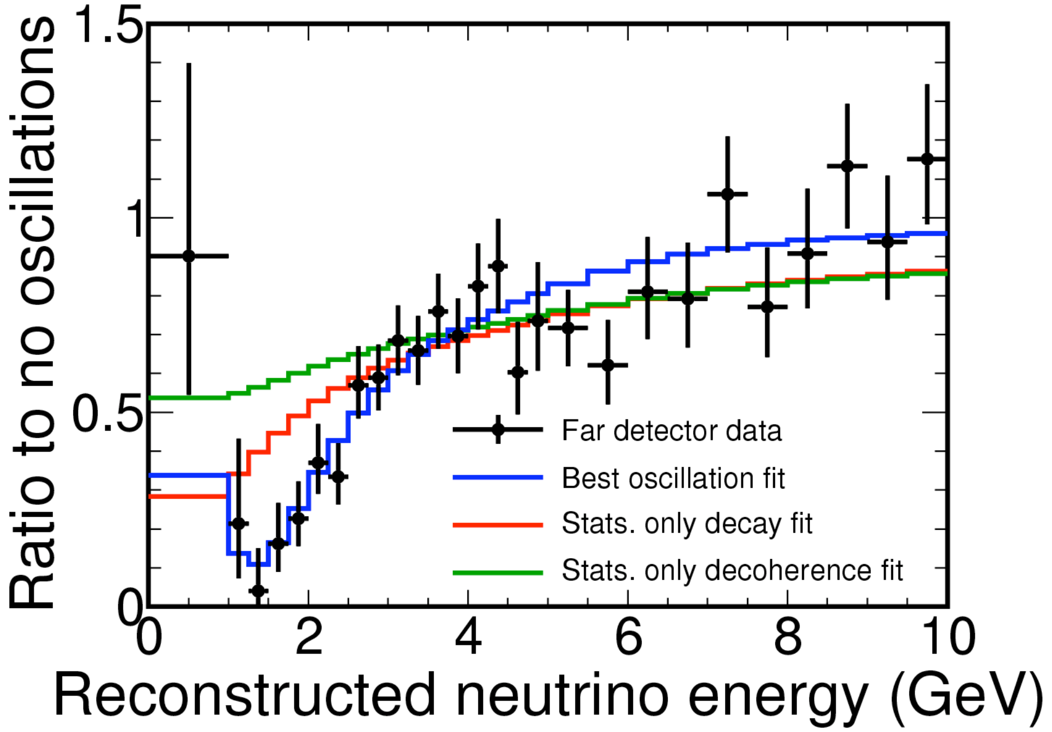


Discovery of neutrino mass

Oscillation pattern observed at SuperK



Oscillation pattern observed at MINOS



Discovery of neutrino mass

- This data is understood in the context of neutrino oscillation

$$P(\bar{\nu}_e \to \bar{\nu}_e, L) = \left| \sum_i U^*_{ie}\, e^{-im_i^2 L/2E}\, U_{ei} \right|^2$$

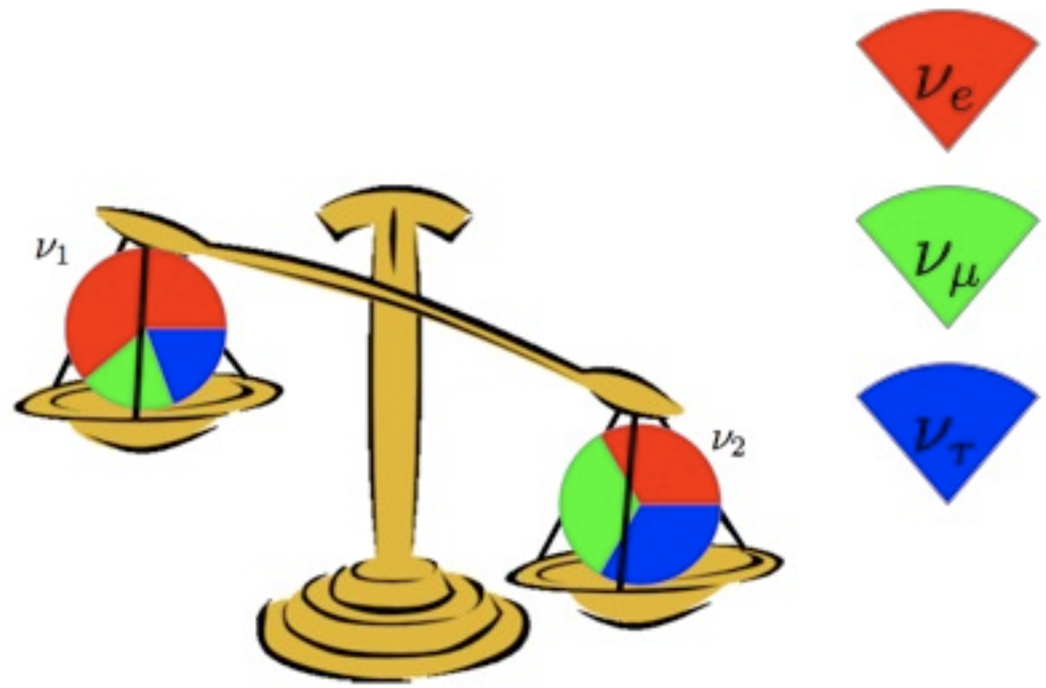
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$.

- KamLAND and solar experiments, e.g SNO
- Atmospheric neutrino, long baseline accelerator e.g SuperK, MINOS
- Short baseline reactor, accelerator e.g Daya Bay, T2K
- Future long baseline accelerator experiment ??

Discovery of neutrino mass

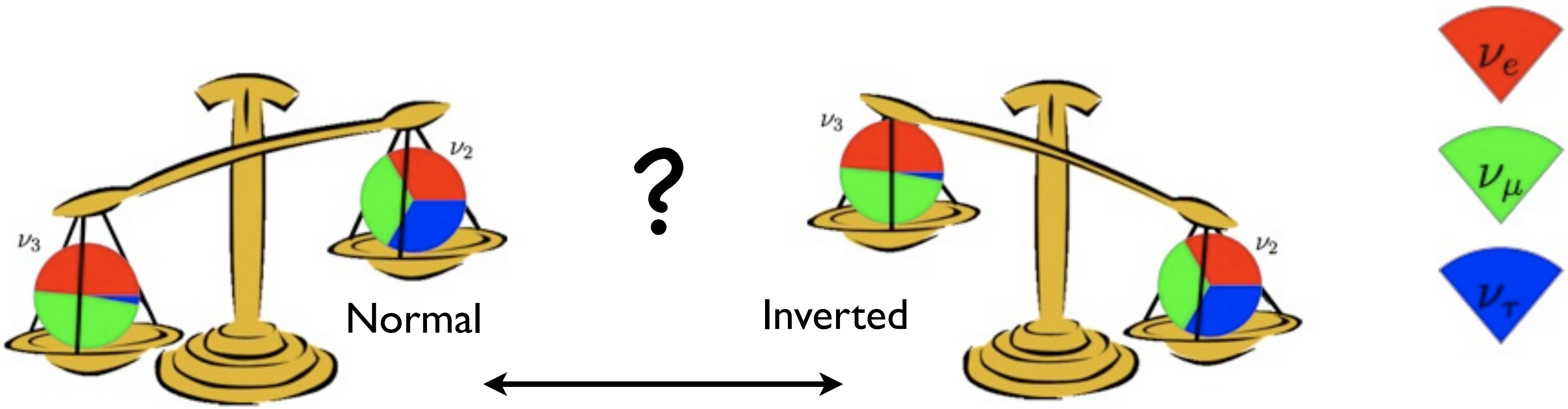
- Non-zero neutrino mass splittings: $\Delta m^2_{ij}=m^2_i-m^2_j$!



We know Δm^2_{21} very well from KamLAND and solar-neutrino experiments (solar-matter effects give the sign)

Open questions

What is the mass hierarchy ?



We know $|\Delta m^2_{23}|$ from atmospheric and accelerator neutrino experiments

We don't know the sign of Δm^2_{23} ! Maybe future long baseline accelerator ?

Open questions

Absolute neutrino ?

We don't know the absolute mass

Neutrino-less double beta decay might answer absolute mass **and** hierarchy question

Double Beta Decay

Mass parabola for isobaric nuclei with even mass number (A)

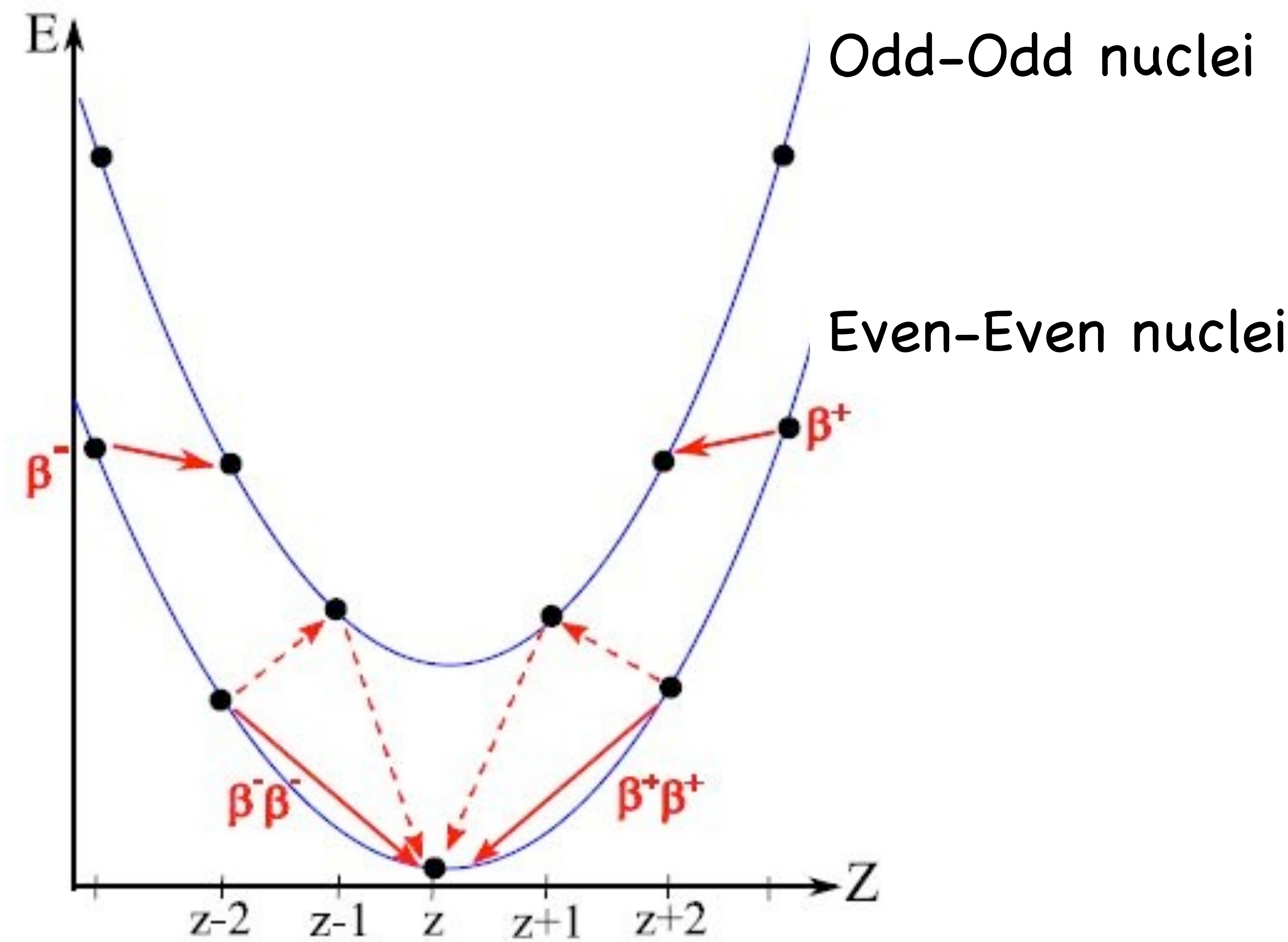
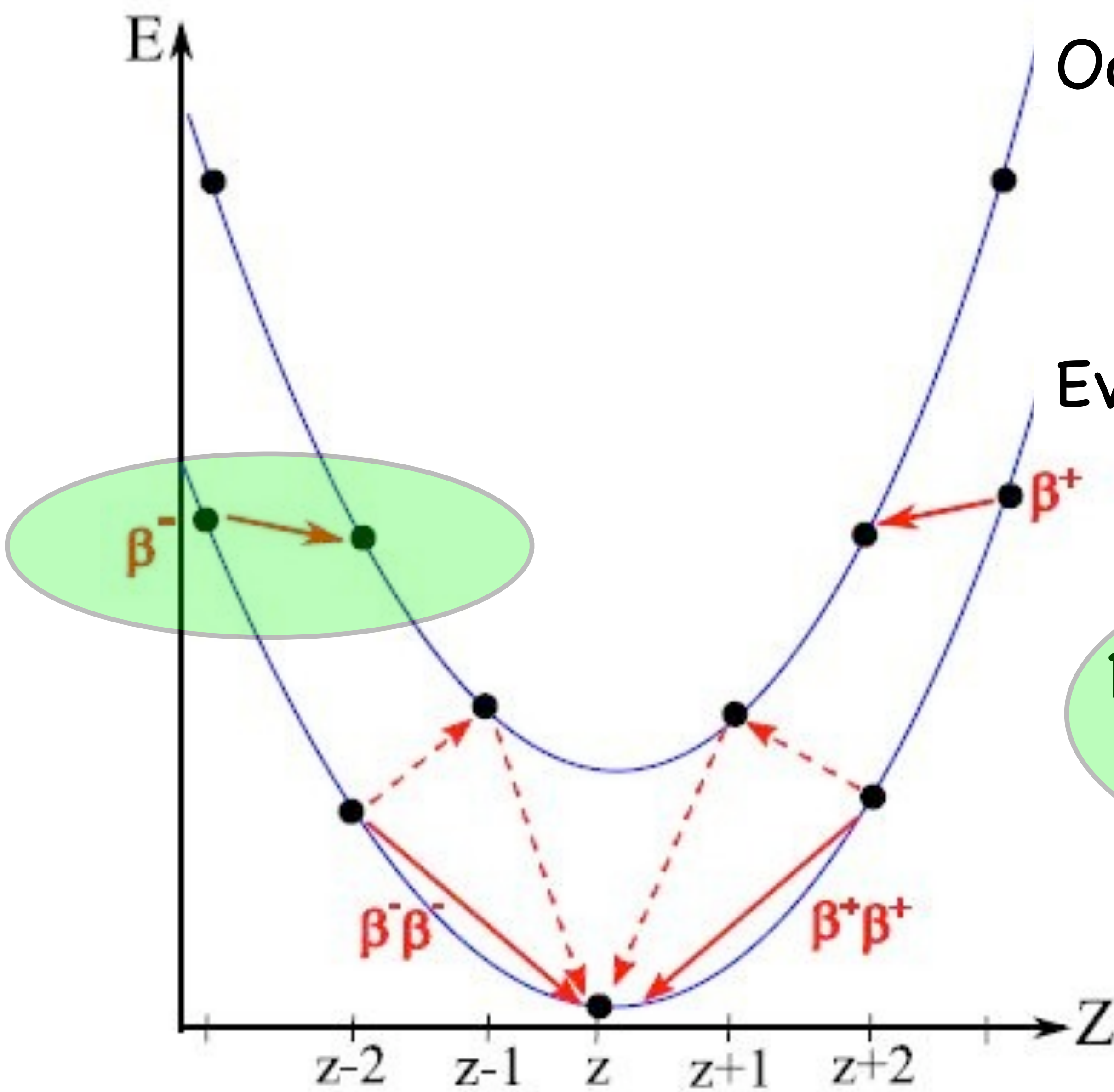


Figure adapted from: http://www.cobra-experiment.org/double_beta_decay/

Double Beta Decay

Mass parabola for isobaric nuclei with even mass number (A)



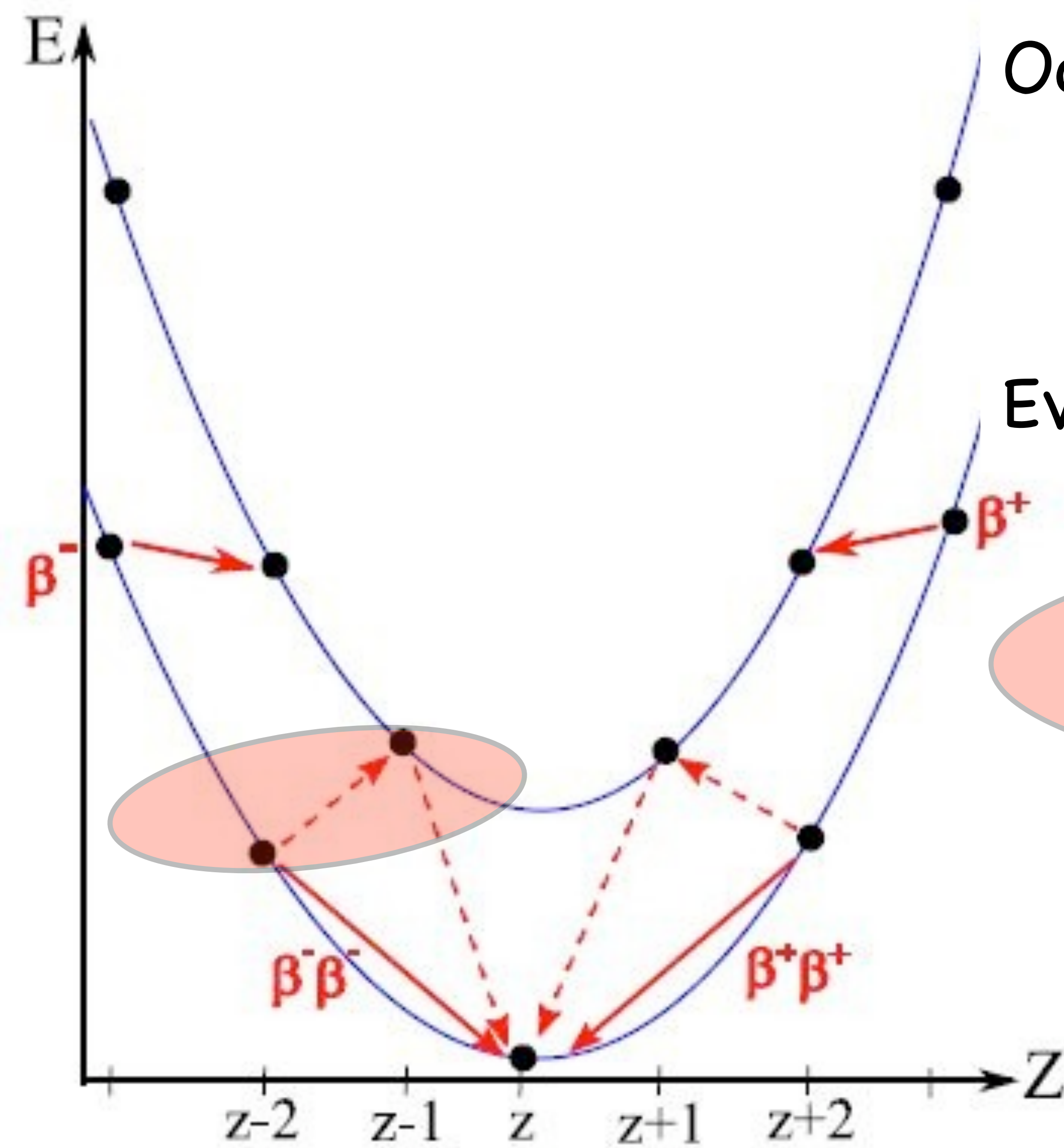
Beta decay is energetically allowed

$$(Z, A) \longrightarrow (Z+1, A) + e^{-} + \bar{\nu}_e$$

Figure adapted from: http://www.cobra-experiment.org/double_beta_decay/

Double Beta Decay

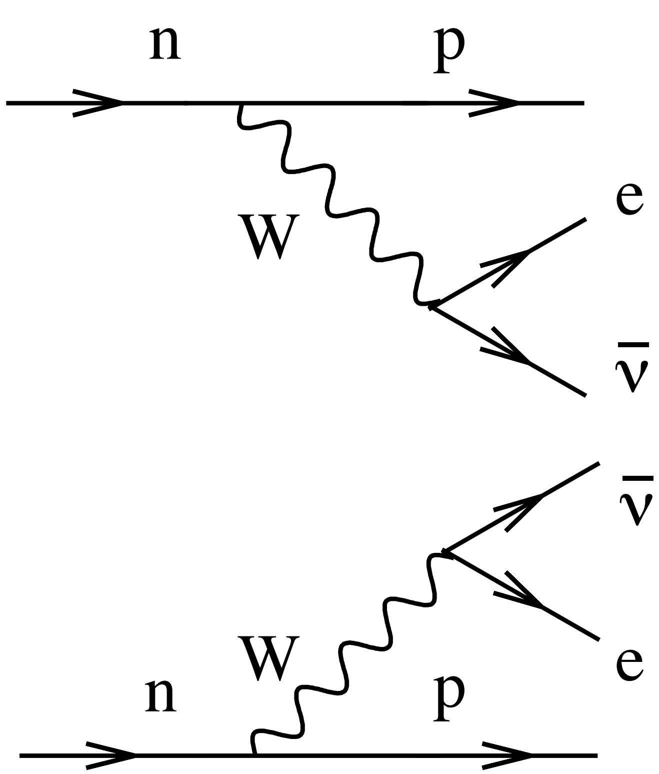
Mass parabola for isobaric nuclei with even mass number (A)



Beta decay is not energetically allowed

Figure adapted from: http://www.cobra-experiment.org/double_beta_decay/

Double Beta Decay



- Second-order weak process ... extremely rare but allowed in SM
- First studied theoretically by M. Goeppart-Mayer in 1935
- Allowed in 35 naturally occurring isotopes
- Observed in 12, first direct observation in 1987 !

$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}|M^{2\nu}|^2$$

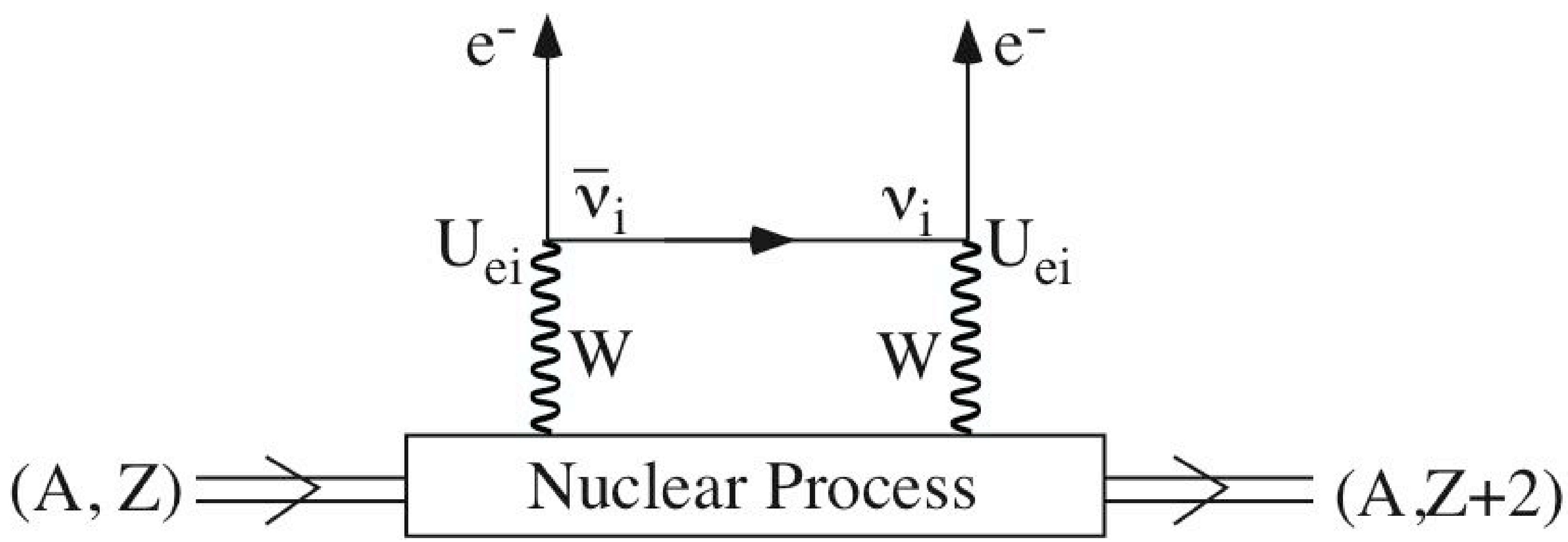
Decay half-life

Phase space factor

Nuclear matrix element

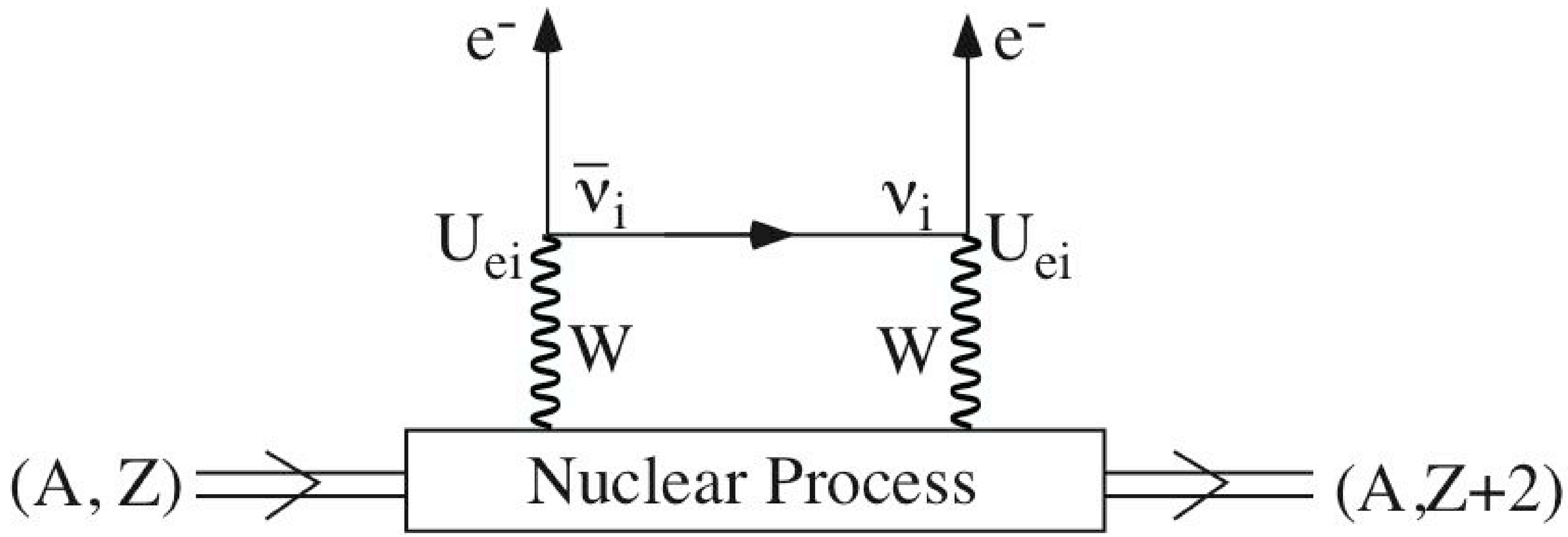
Neutrino-less Double Beta Decay

- Hypothetical mode of double beta decay allowed if neutrinos are Majorana particles



Neutrino-less Double Beta Decay

- Hypothetical mode of double beta decay allowed if neutrinos are Majorana particles



$$n \longrightarrow p + e^- + \bar{\nu}_e \qquad \nu_e + n \longrightarrow p + e^-$$

$$n \longrightarrow p + e^- + \nu_{eR} \qquad \nu_{eL} + n \longrightarrow p + e^-$$

- For Majorana neutrinos $\bar{\nu}_i \equiv \nu_i$
- Right handed and left handed helicity components couple via Majorana mass term

Neutrino-less Double Beta Decay

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

Neutrino-less Double Beta Decay

Decay half-life

Phase space factor

Nuclear matrix element

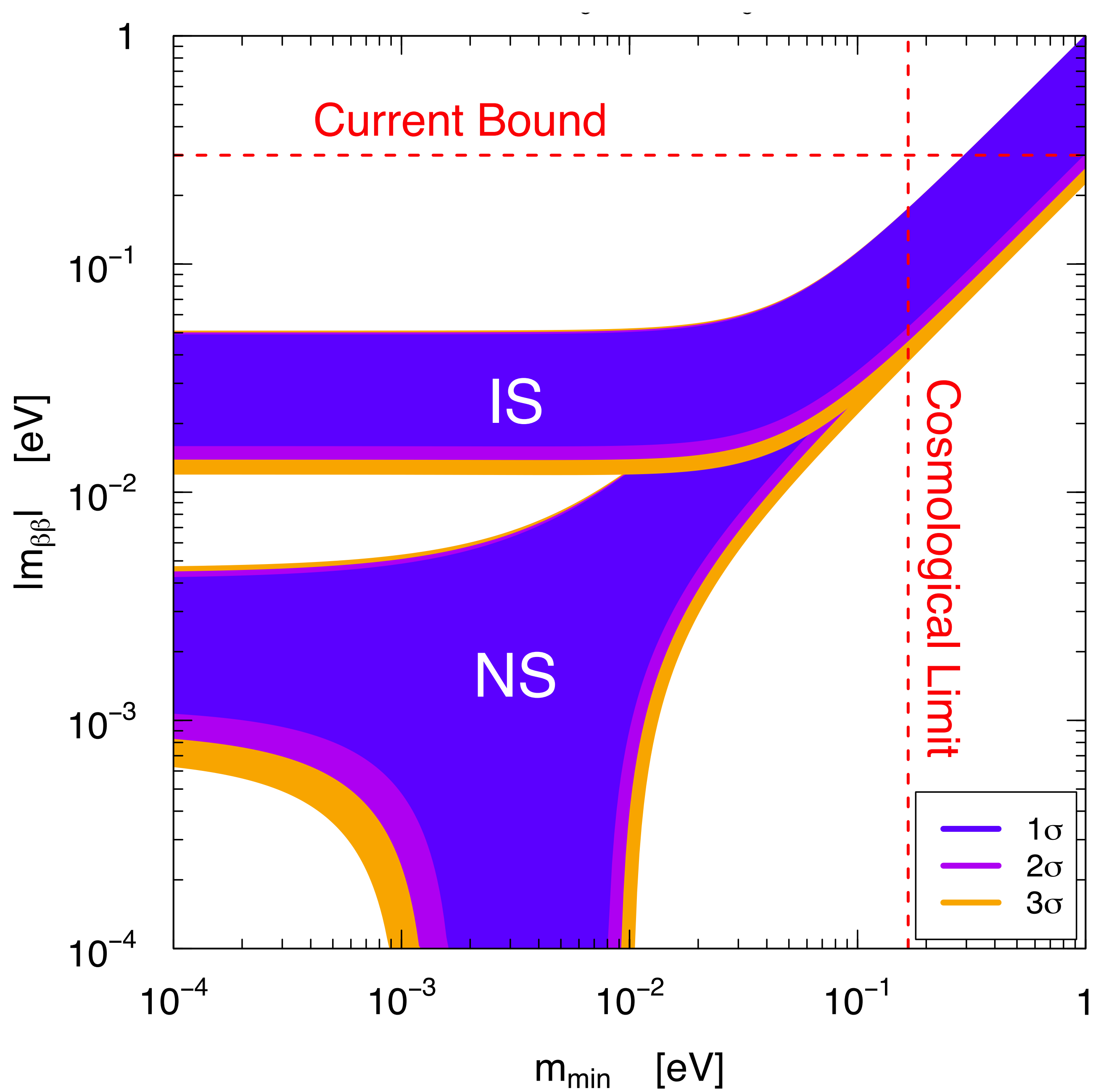
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

Effective Majorana neutrino mass

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

- Limits on or measurements of the half life can be connected to absolute neutrino mass scale
- Observation of 0vBB would:
  - Discovery of lepton number violation !
  - Show neutrino is a Majorana fermion, casting new light on matter/antimatter relationship, baryon asymmetry

Neutrino-less Double Beta Decay



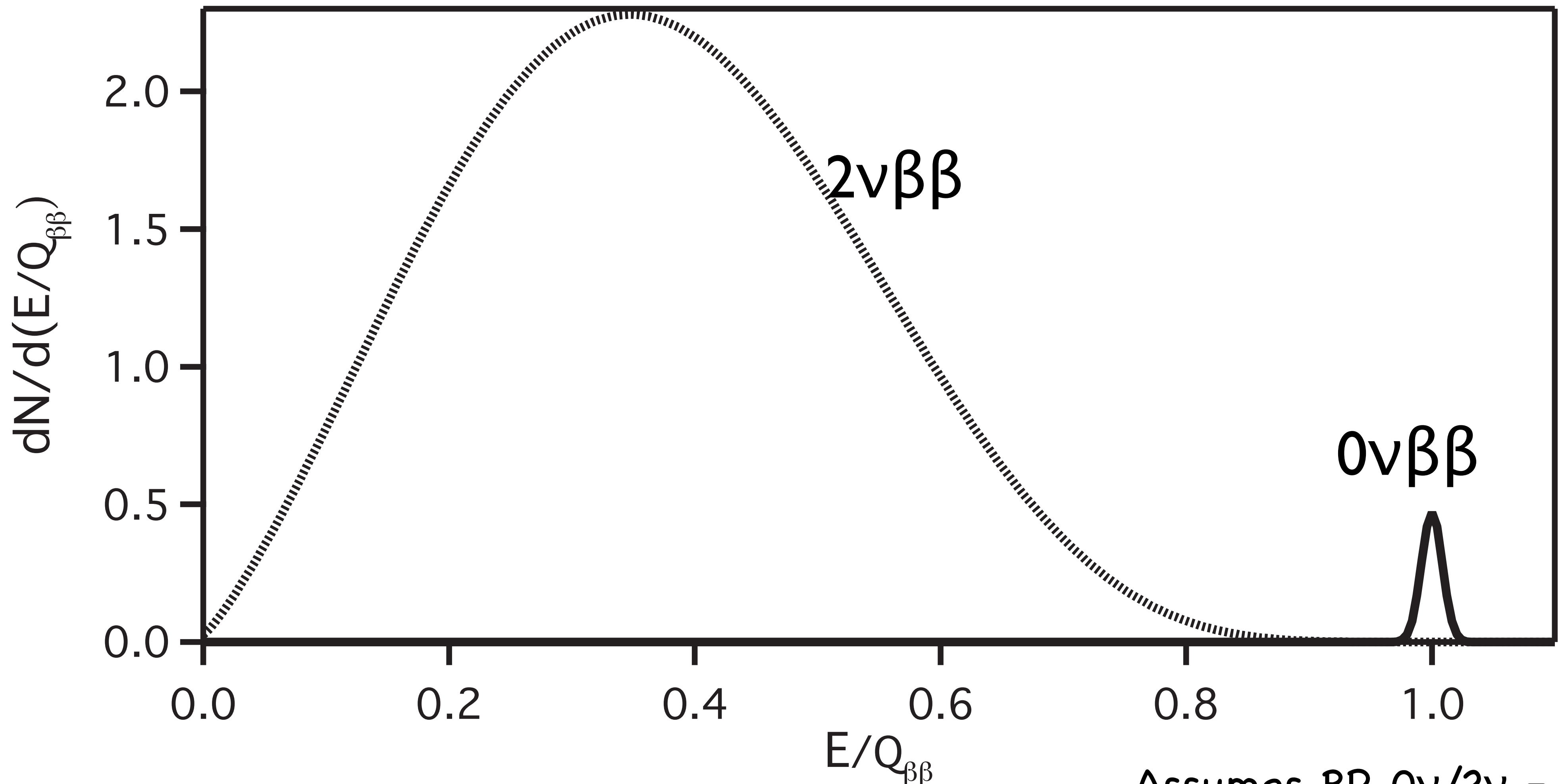
From arXiv:1203.5250v3

Potential to learn a lot from stringent limits on $T_{1/2}^{0\nu}$

- If hierarchy can be determined in other experiments (LBNE) can possibly rule out Majorana neutrinos

Neutrino-less Double Beta Decay

summed energy spectrum of final state electrons



Assumes BR 0ν/2ν = 1% and detector energy resolution is 2%

- Basic observable is a peak at the decay Q-value in the summed energy spectrum of the two final state electrons

Neutrino-less Double Beta Decay

- Rule of thumb for half-life sensitivity for a given background level

half-life sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

a	isotopic abundance of source
ε	detection efficiency
M	Total detector mass
b	background rate per unit mass per unit energy
t	exposure time
δE	energy resolution (spectral width)

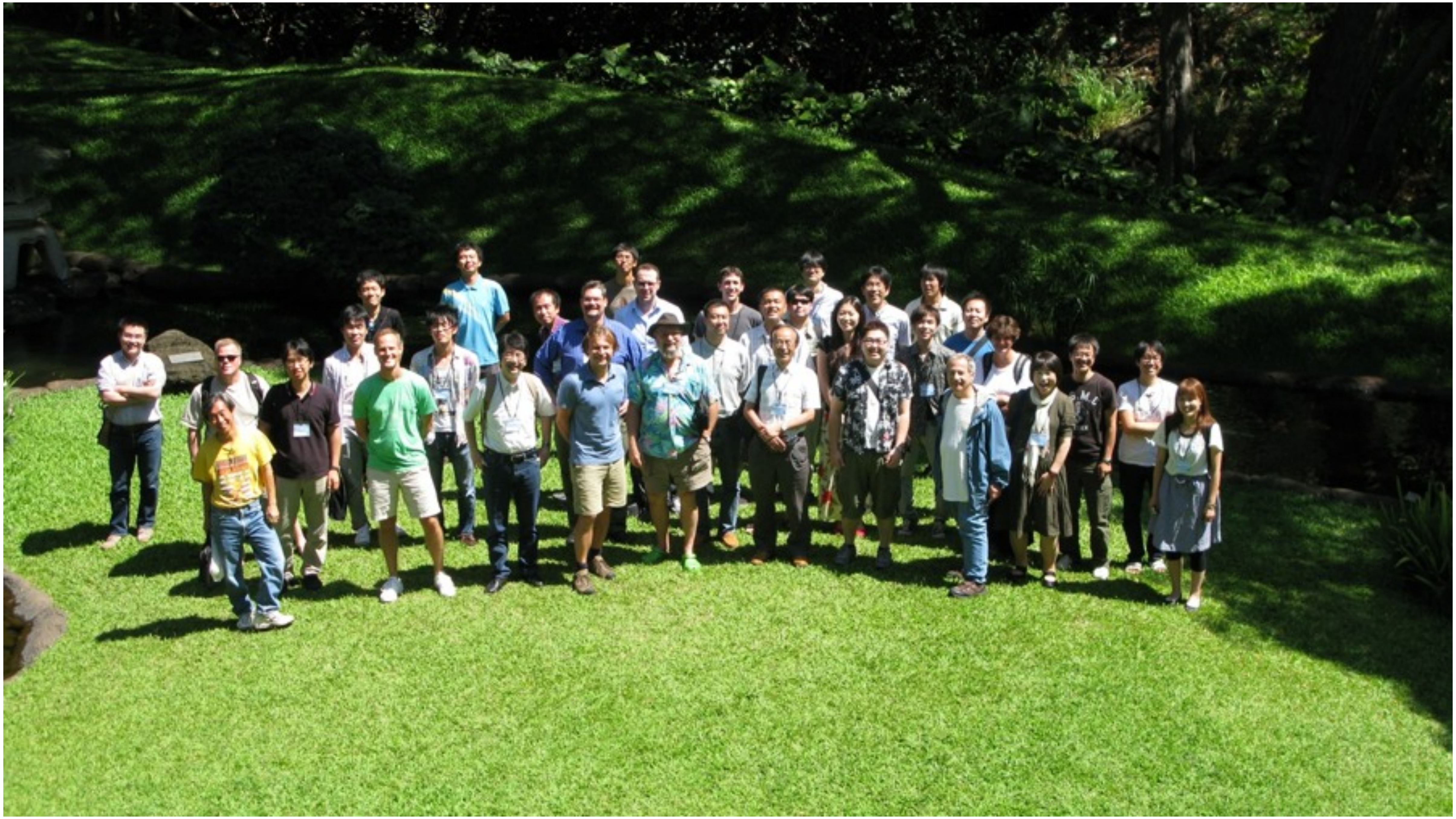
- Generally want to maximize sensitivity for a given t

Neutrino-less Double Beta Decay

Ongoing/planned searches

Candidate Isotope	Experiment
48Ca	Candles
76Ge	Gerda/Majorana
82Se	SuperNemo
100Mo	Moon
116Cd	Cobra
130Te	CUORE-0/CUORE/Cobra
136Xe	EXO, NEXT, KamLAND-Zen
150Nd	SNO+

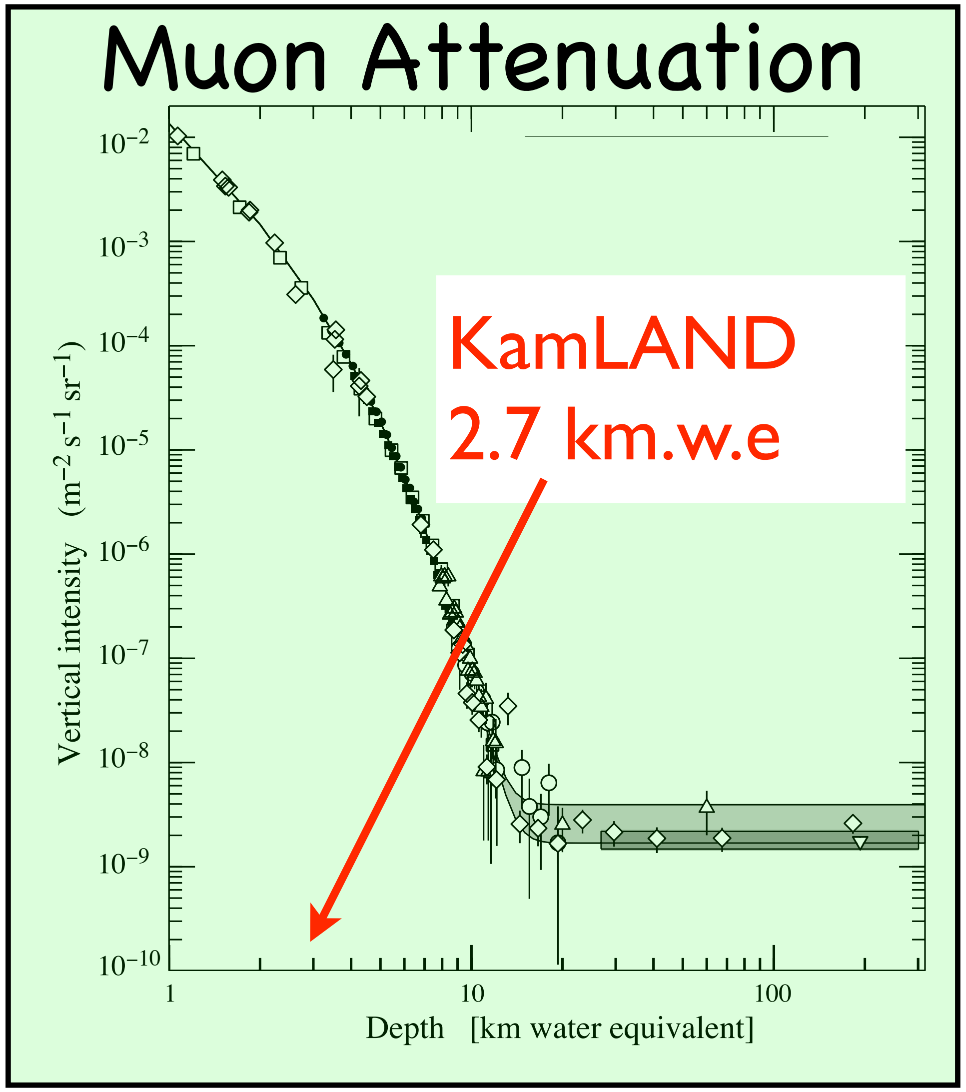
KamLAND/KamLAND-Zen collaboration



KamLAND-Zen collaboration is a subset of KamLAND

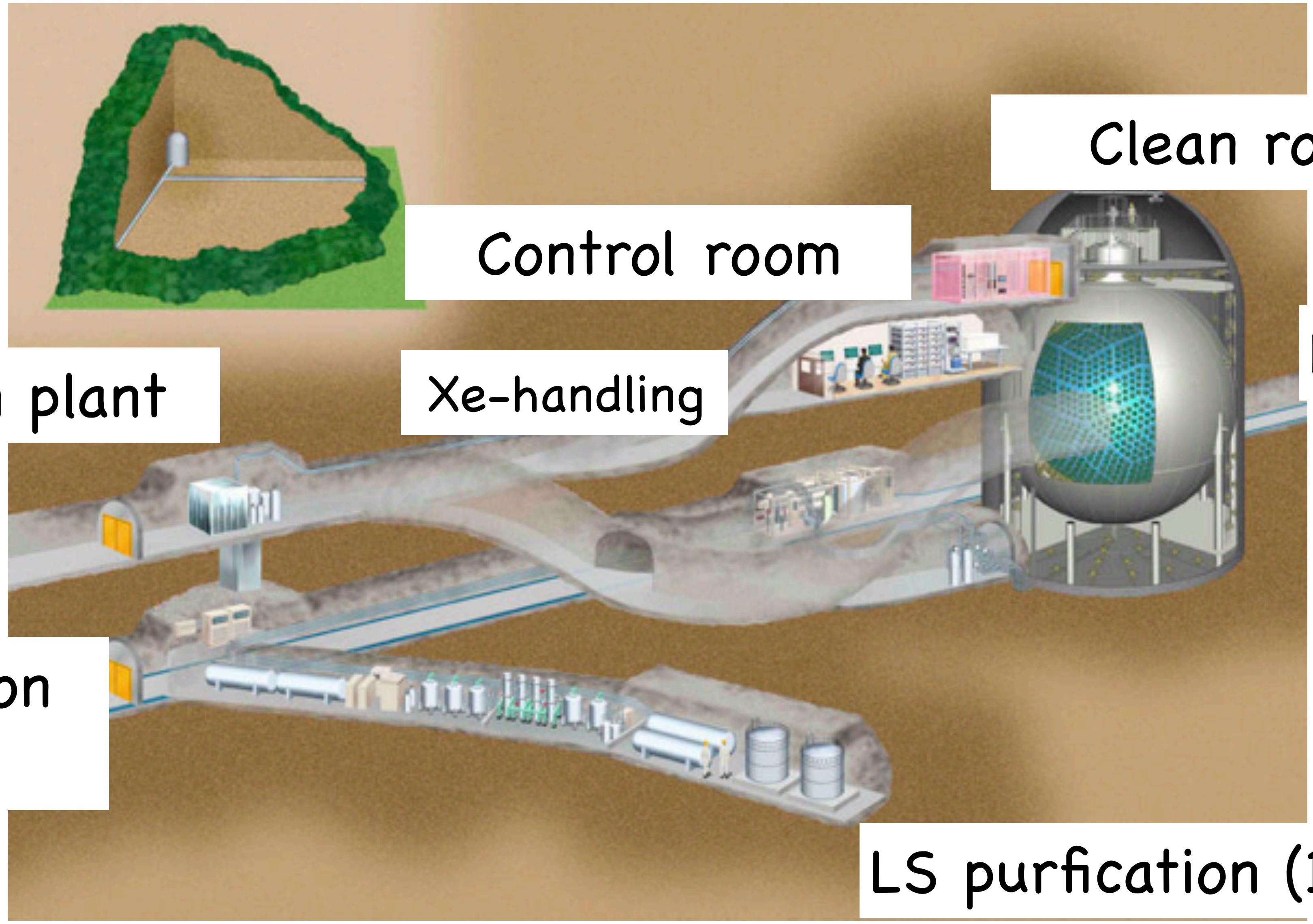
KamLAND -- host for KamLAND-Zen

- Located in the Kamioka Mine, Japan

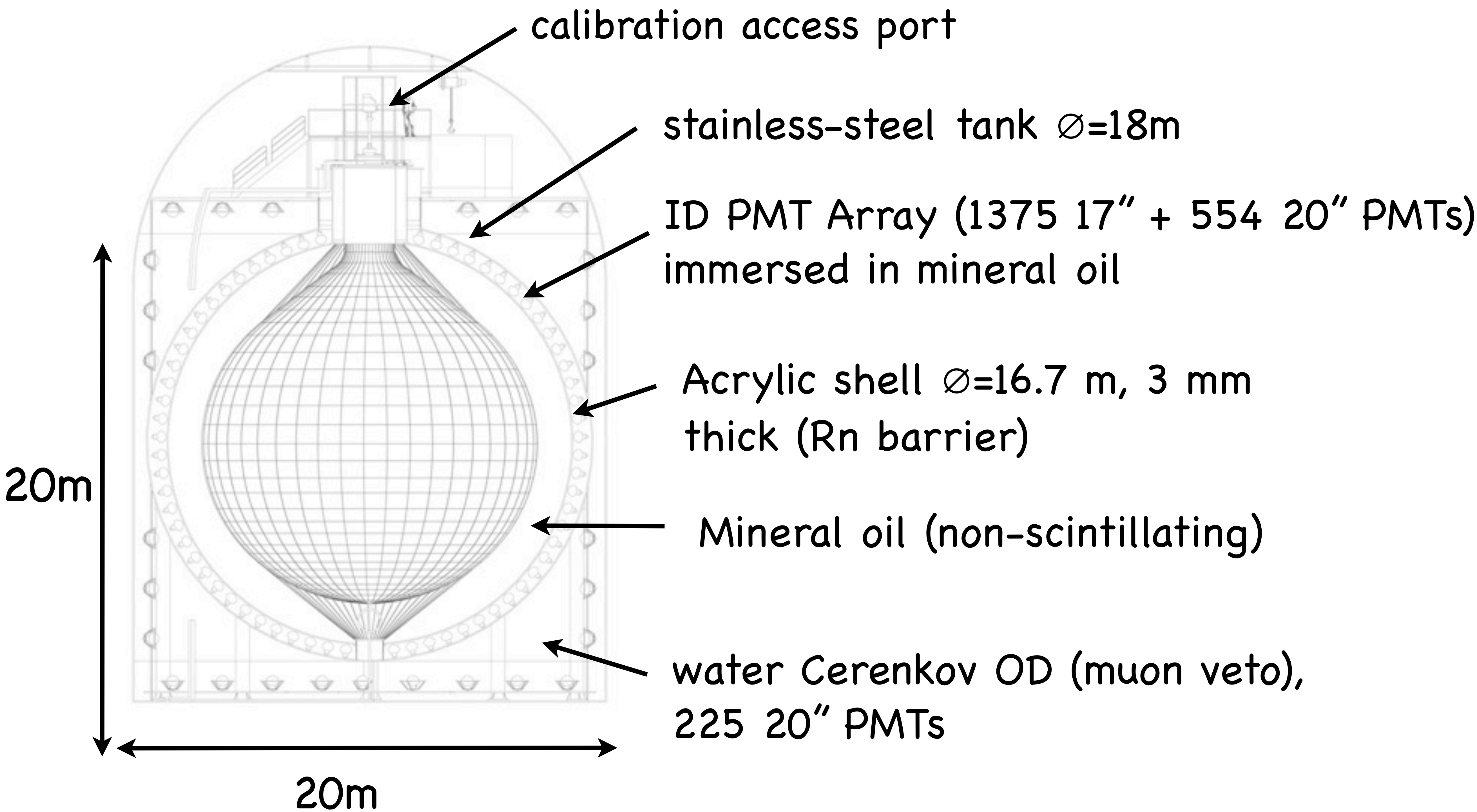


- Designed to study anti-neutrinos from Japanese nuclear reactors

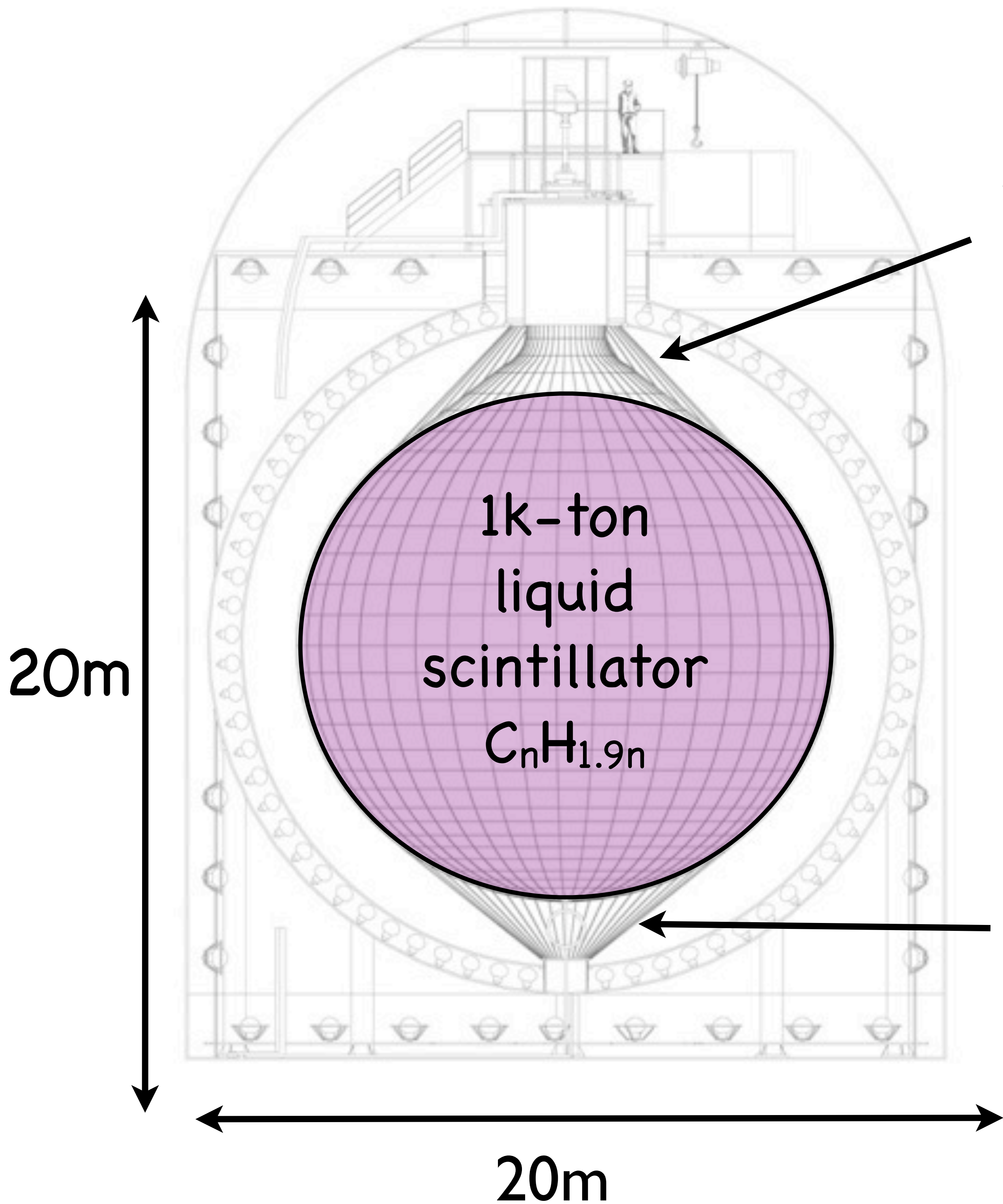
KamLAND Detector -- host for KamLAND-Zen



KamLAND -- host for KamLAND-Zen



KamLAND -- host for KamLAND-Zen



Component	Chemical formula	Fraction
Dodecane	$C_{12}H_{26}$	80.2%(by volume)
Pseudocumene	C_9H_{12}	19.8%(by volume)
PPO	$C_{15}H_{11}NO$	1.35 g/l

KamLAND -- host for KamLAND-Zen

- Scintillation light observed by array of ~1800 PMTs
- PMT waveforms digitized and saved for offline analysis if programmable trigger conditions are met (~300GB/day)
- PMT charge and hit time extracted from waveforms
- Events tagged as muons/point-like
- Muon track, event position and energy reconstruction based on PMT charge and hit-time distributions

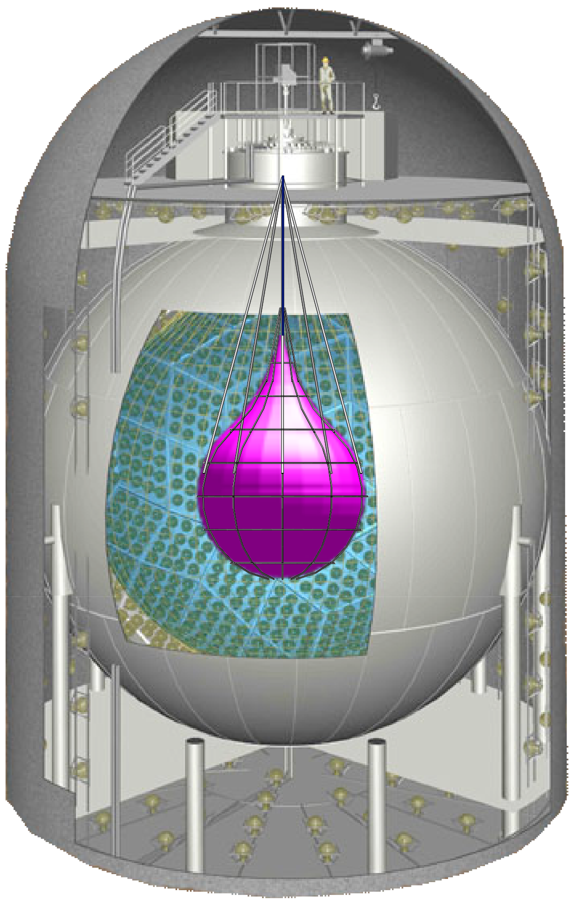
KamLAND -- host for KamLAND-Zen

- Very productive experiment in operation since 2002
  - Reactor antineutrino oscillation results, best measurement of 'solar' mass splitting
  - Geo-neutrino detection
  - Limits on high-energy extra terrestrial antineutrinos
  - Study of cosmogenic spallation products

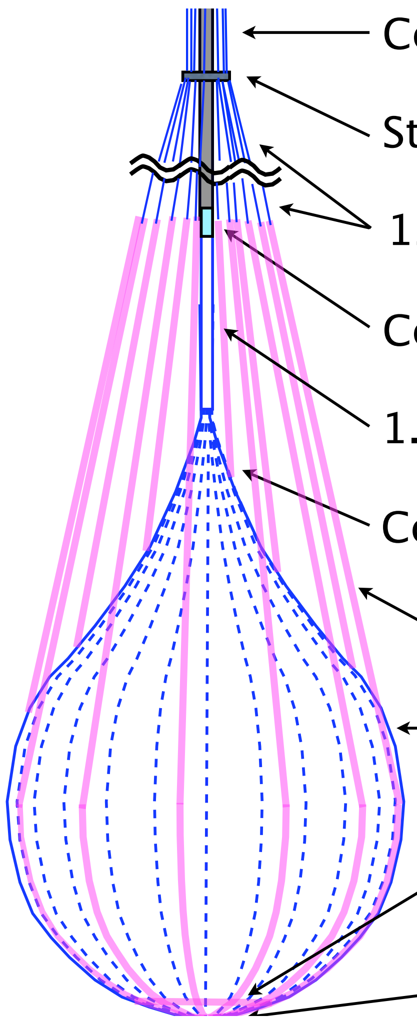
- LS purification between 2007-2009
  - Improved geo-neutrino results
  - High energy solar neutrinos
  - Low energy solar neutrinos ... coming soon

KamLAND Zen

- Idea to mount a volume of Xe-loaded LS in the center of KamLAND
- Several advantages
  - KamLAND-LS provides massive ultra-pure active shield
  - Mature detector, expertise and analysis tools
  - Potential to achieve large 0vBB target mass quickly
  - Possible to continue ongoing antineutrino program at KamLAND
- Japanese side of collaboration (Tohoku University) received a major equipment grant in 2009 and KamLAND-Zen was born



KamLAND-Zen - Inner Balloon (IB)



Practice balloon mounted at Kamioka mine

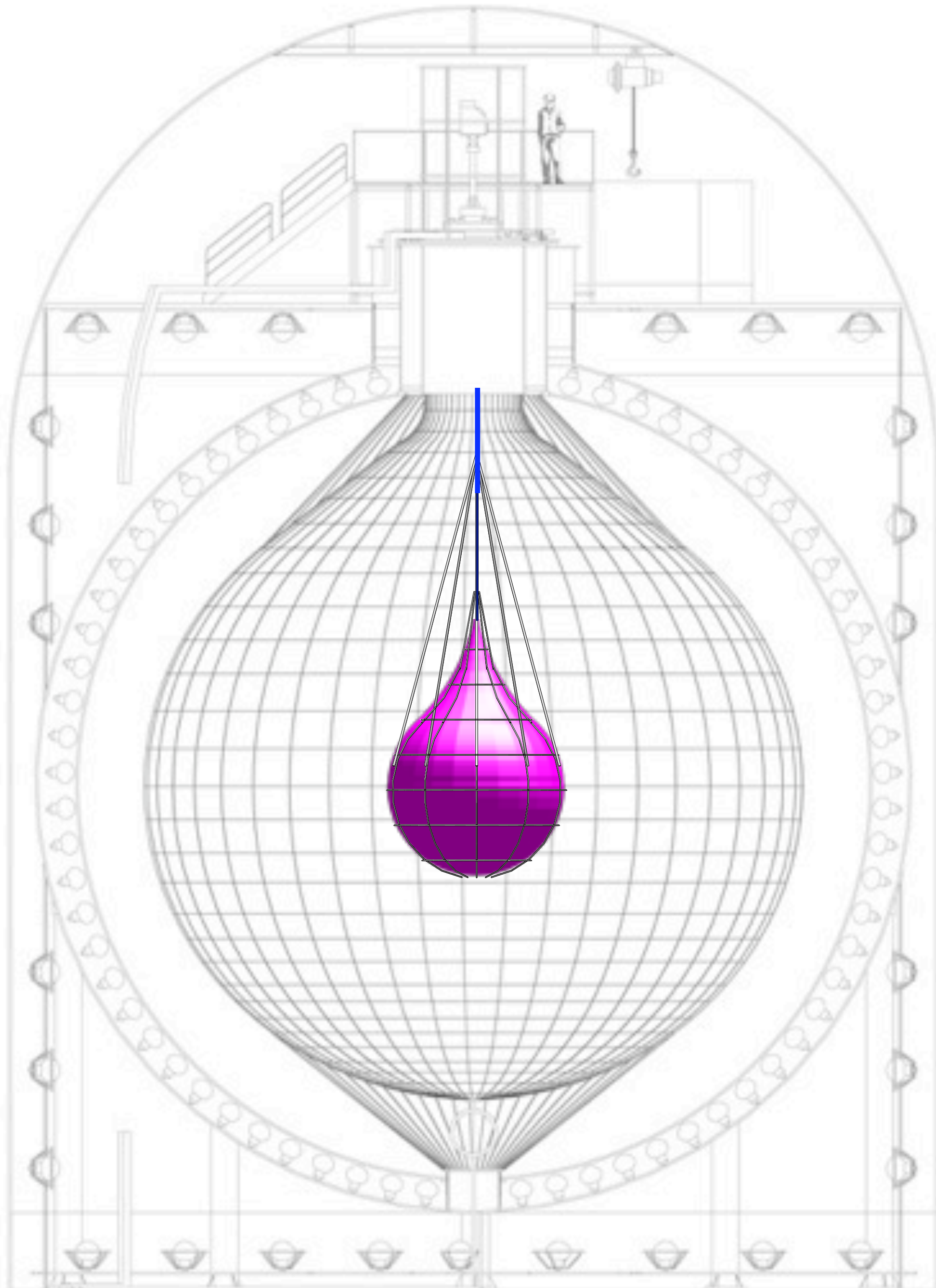
Figure courtesy of A. Gando 'First Results of Neutrinoless double beta decay Search with KamLAND-Zen', PhD Thesis, Tohoku University 2012

Container for Xe target:

- Mini balloon ∅=3.08 m
- 25μm thick nylon film specially manufactured

^{238}U	2×10^{-12}g/g
^{232}Th	5×10^{-12}g/g
^{40}K	6×10^{-12}g/g
Xe leakage	<0.26kg/yr

KamLAND-Zen



Xe-loaded LS

Component	Chemical formula	Fraction
Decane	$C_{10}H_{26}$	82%(by volume)
Pseudocumene	C_9H_{12}	18%(by volume)
PPO	$C_{15}H_{11}NO$	2.7 g/l
Dissolved Xe	$90.93\pm0.05\%$ ^{136}Xe $8.89\pm0.01\%$ ^{136}Xe	2.5% by weight

Cocktail driven by:

- Maximize loaded Xe
- Match density of Xe-LS and KamLAND-LS
- Maintain light yield of Xe-LS within 10% of KL-LS

KamLAND-Zen

Inner-balloon fabrication in class 1 clean room Spring 2011

Great Eastern Japan Earthquake occurred (3/11/11)

Figure courtesy of A. Gando 'First Results of Neutrinoless double beta decay Search with KamLAND-Zen', PhD Thesis, Tohoku University 2012

KamLAND-Zen

Inner balloon rehearsal installation

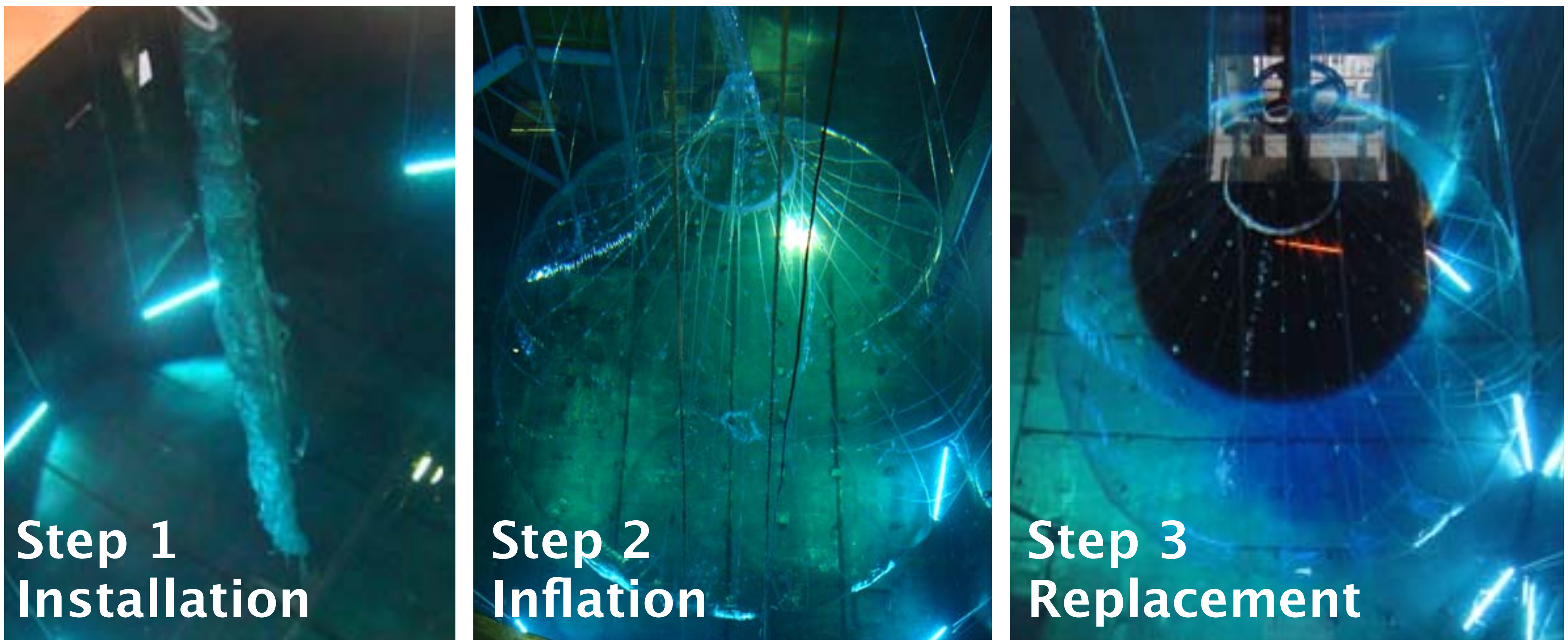
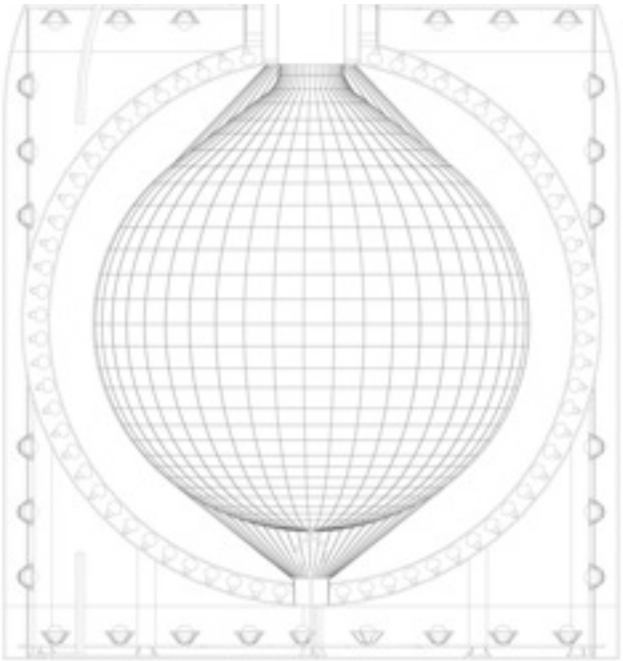


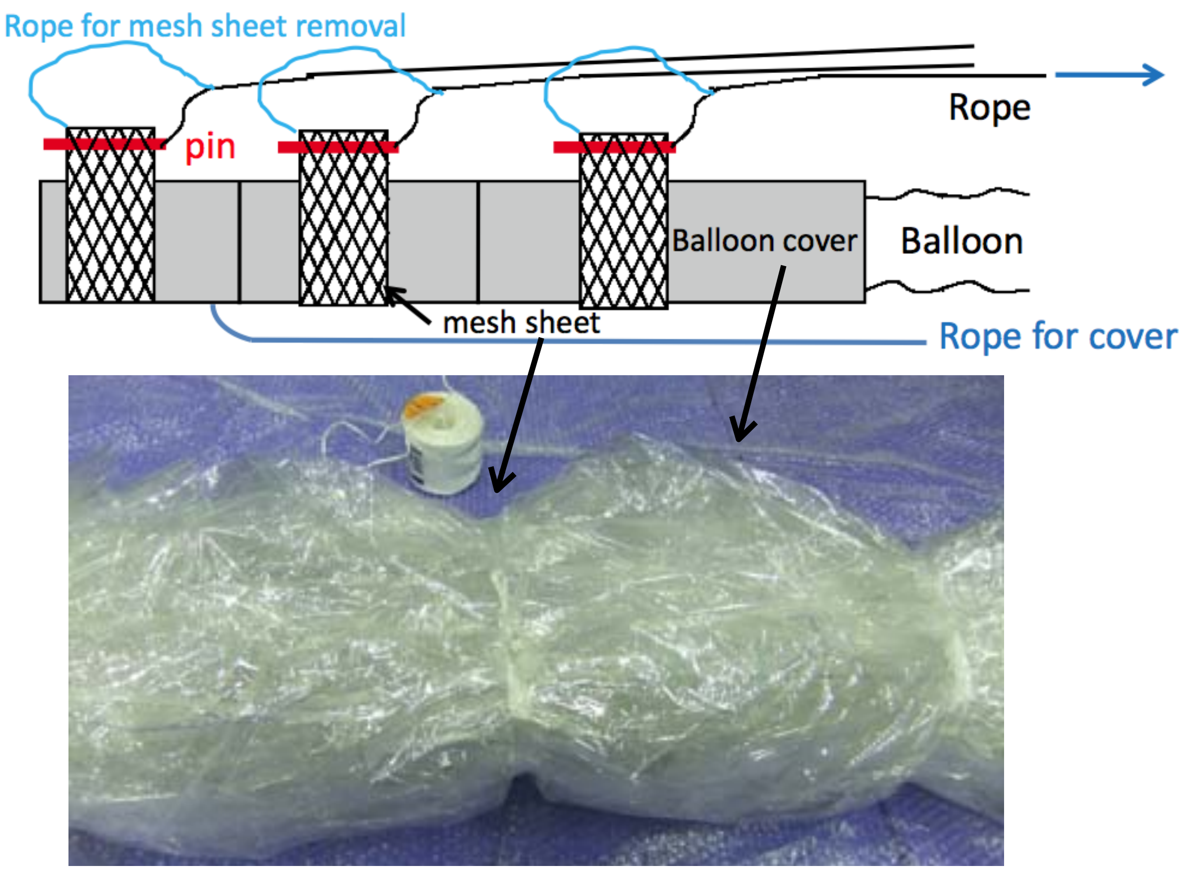
Figure courtesy of A. Gando 'First Results of Neutrinoless double beta decay Search with KamLAND-Zen', PhD Thesis, Tohoku University 2012

IB Installation in KamLAND

KamLAND calibration hardware decommissioned

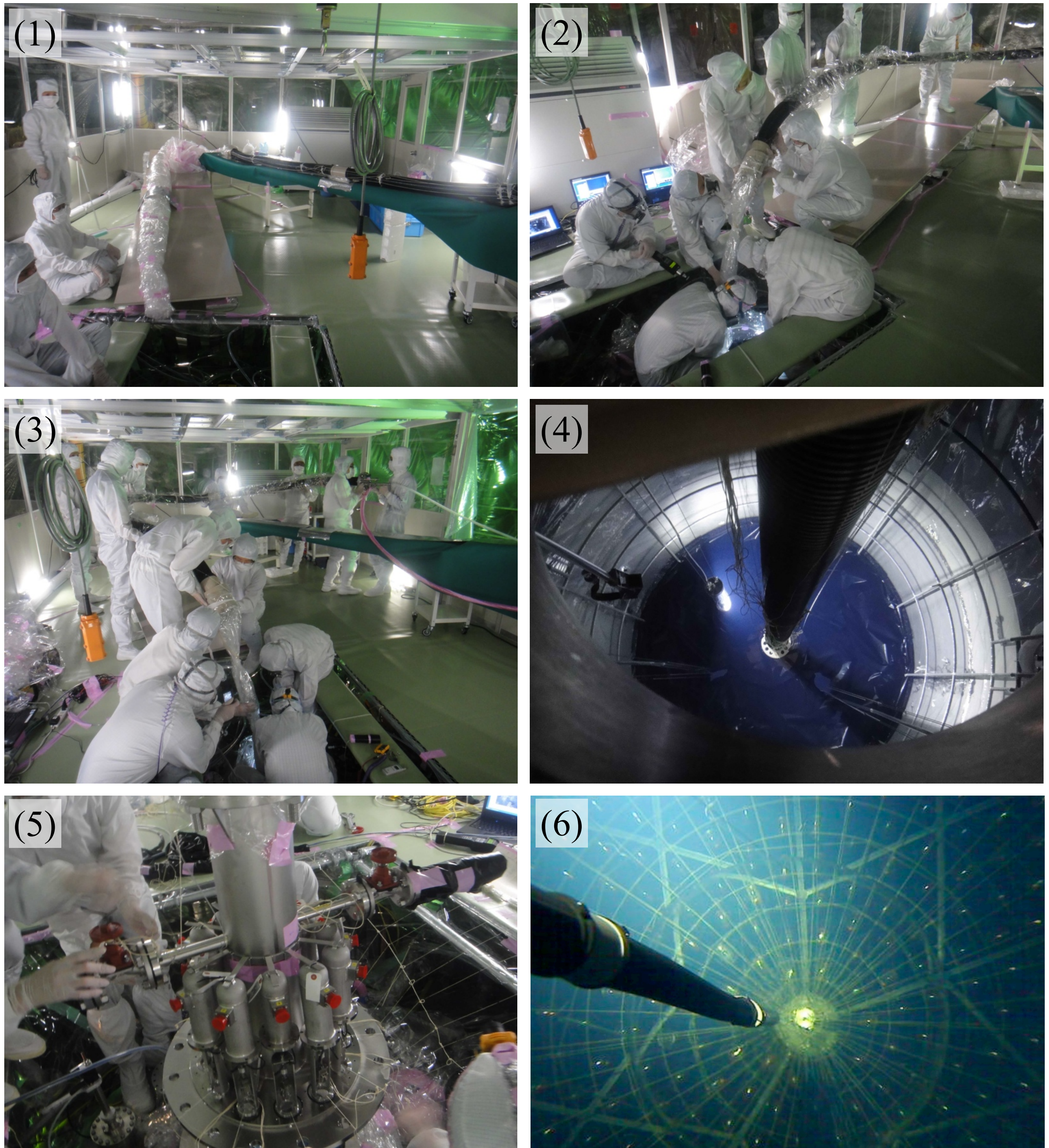


Class 100 mini clean room installed



IB rolled as 'snake', everything had to fit through 50cm diameter entrance !

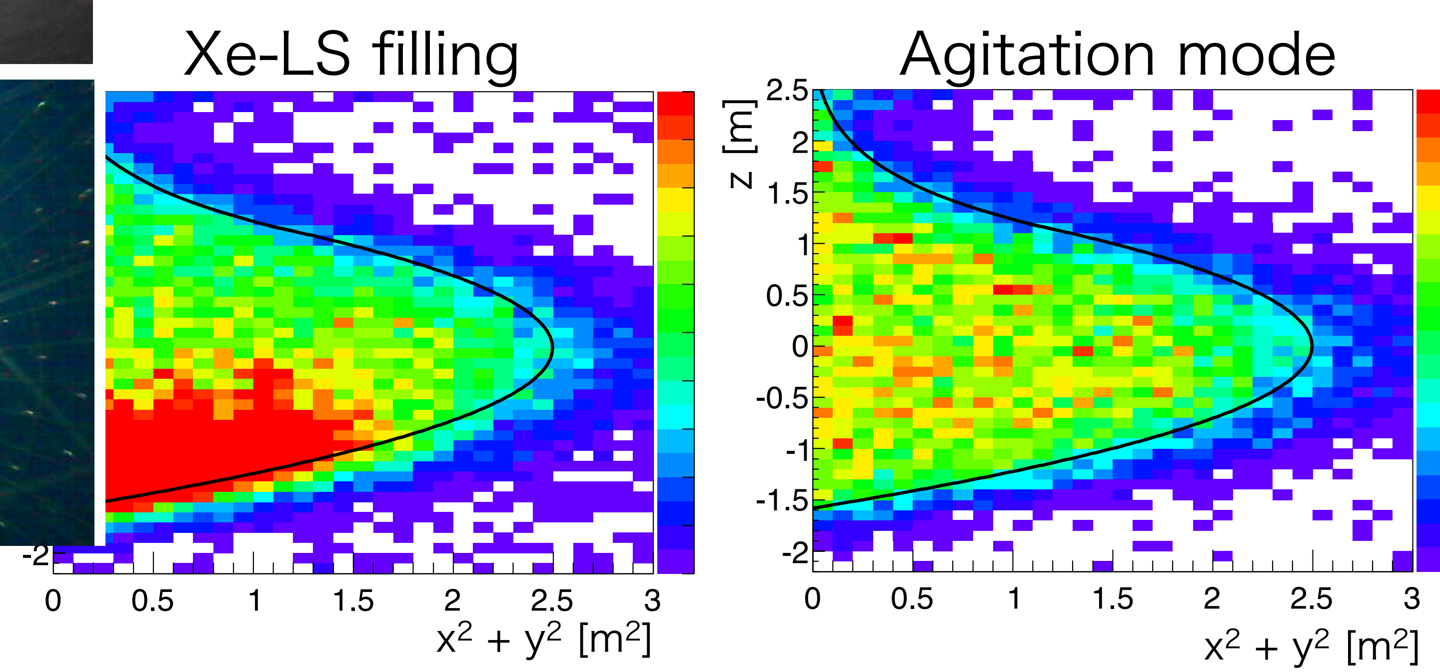
KamLAND-Zen



Filled and leak checked with 'dummy LS'

'Dummy LS' replaced with Xe-LS

Real-time monitoring during filling and commissioning of IB



Event reconstruction

- Event position (vertex) reconstructed using the PMT hit time distribution, energy reconstructed using the hit-charge distribution (visible energy E_{vis})

- Same algorithms as used from KamLAND --- 'tried and tested' over decade long operation

- Updates to reconstruction due to Xe-LS, new balloon hardware, discontinuity in light yield, estimated from Geant4 simulation, checked by calibration

Energy scale model

- Ultimately analysis is done in terms of visible energy
- Real energy of particles must be converted to visible or reconstructed energy
- Energy scale model accounts for particle- and energy dependent effects:
  - Scintillator quenching effects via first order Birk's model
  - Energy loss by Cherenkov emission
- Detector energy resolution

Energy scale model

$$\frac{\bar{E}_{vis}}{E_{\mathrm{real}}} = A \times \left(\frac{1}{1+R} \cdot \frac{1}{1+k_B(dE/dx)} + \frac{R}{1+R} \cdot \frac{dN_{\mathrm{Ch}}}{dE} \right)$$

Energy scale model

$$\frac{\bar{E}_{vis}}{E_{\mathrm{real}}} = A \times \left(\frac{1}{1+R} \cdot \frac{1}{1+k_B(dE/dx)} + \frac{R}{1+R} \cdot \frac{dN_{\mathrm{Ch}}}{dE} \right)$$

Overall linear response of detector

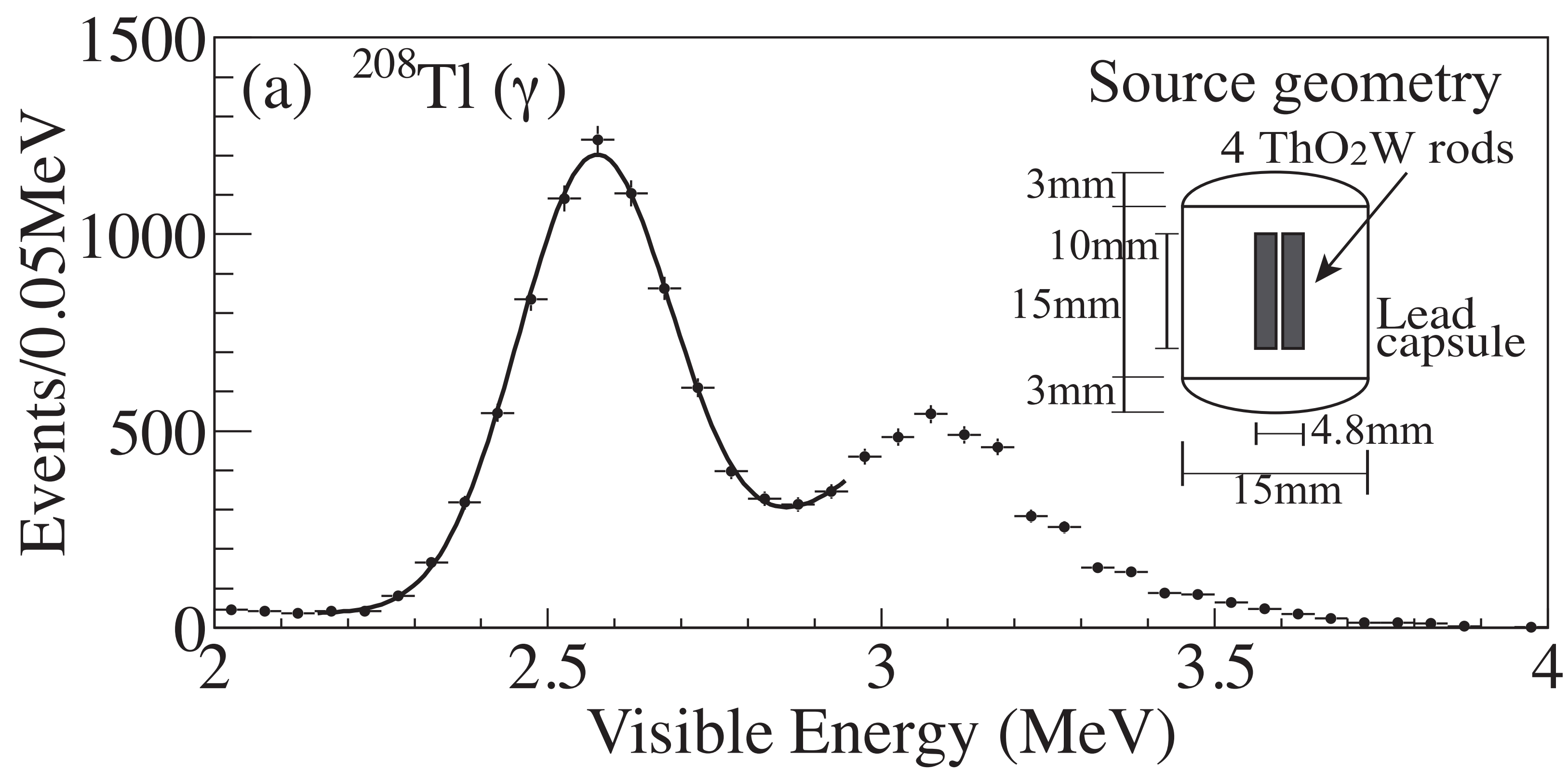
Scintillator nonlinearity from quenching

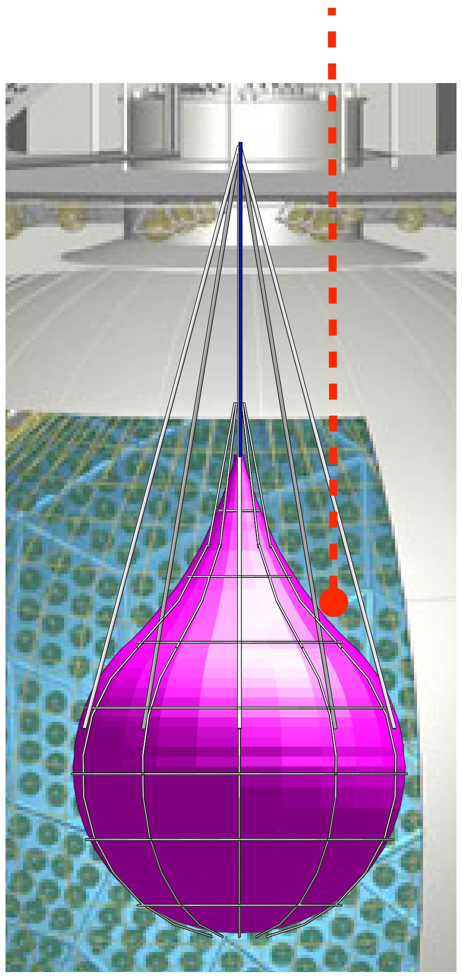
Fraction of visible energy (photo electrons) from Cherenkov effects

E_{vis} distribution obtained by smearing $\bar{E}_{vis}$ with gaussian resolution

Energy Calibration

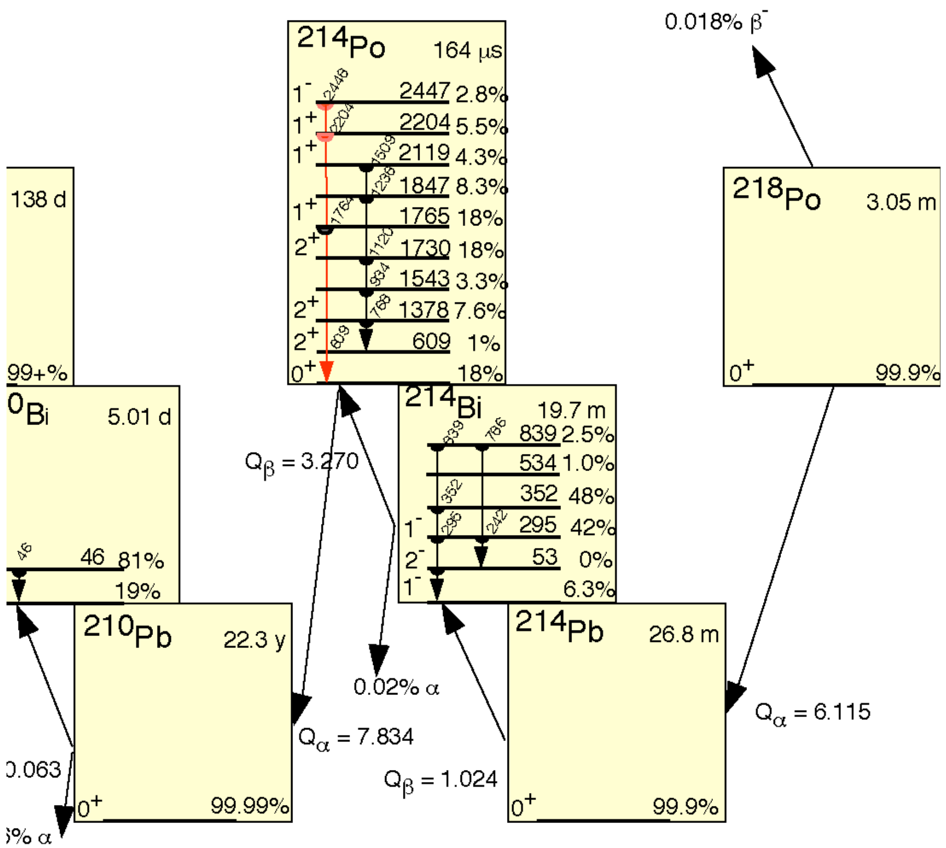
- ThO_2W source (208Tl) source deployed close to outer edge of inner-balloon



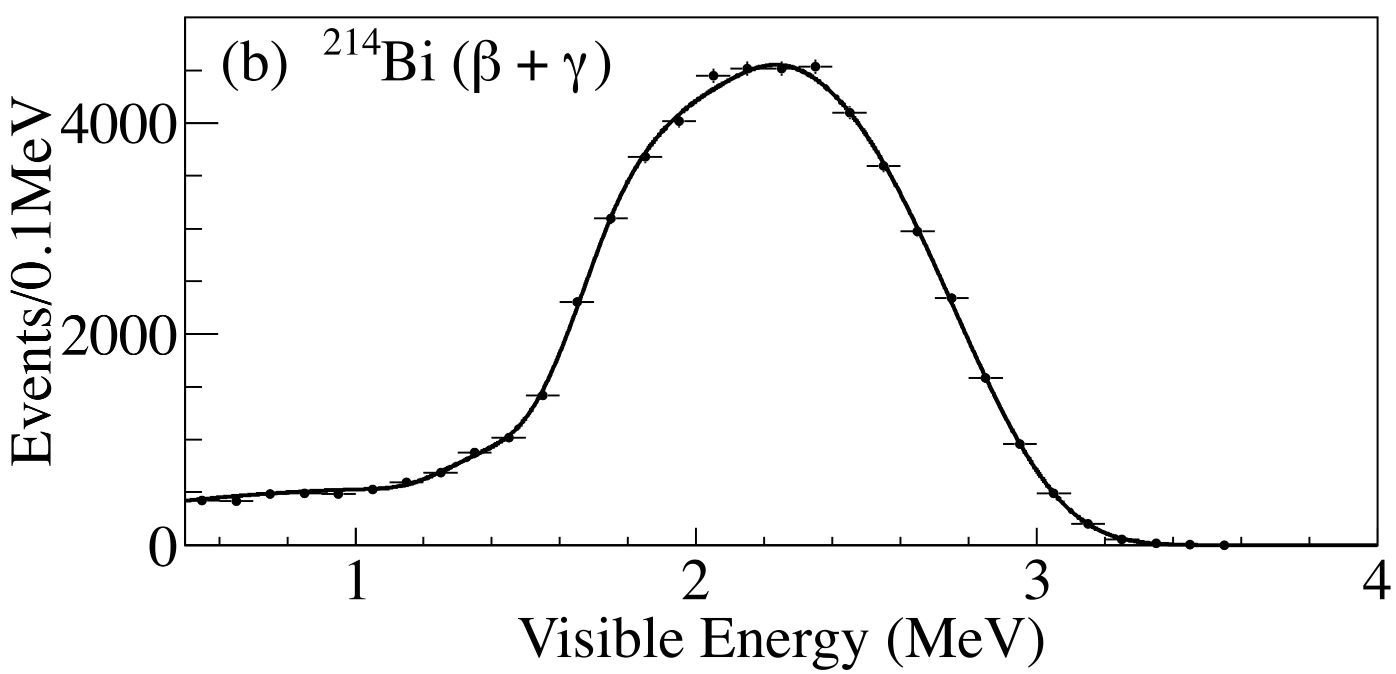


Energy resolution Xe-LS σ_E/E = (6.6+/0.3) %/√E

Energy Calibration



- ^{214}Bi tagged by coincidence with ^{214}Po alpha (^{222}Rn introduced during LS filling)
- Fit to ^{214}Bi and ^{208}Tl data to determine energy scale parameters
- Stability monitored with spallation neutron capture gammas



Data set

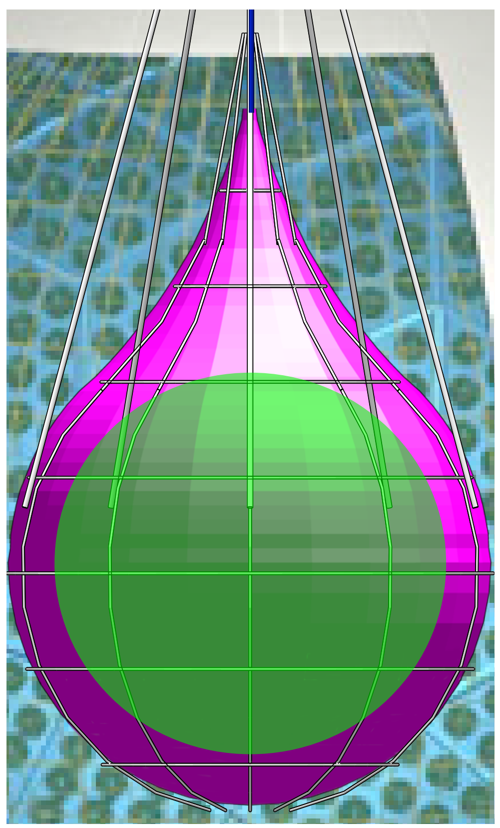
- First phase data set: Oct 12 2011 - June 14 2012
- Divided into 2 periods: DS1, DS2, filtration hardware introduced in Feb. 2012, plumbing remained inside Xe-LS afterwards

TABLE I: Two data sets used in this ^{136}Xe $0\nu\beta\beta$ decay analysis.

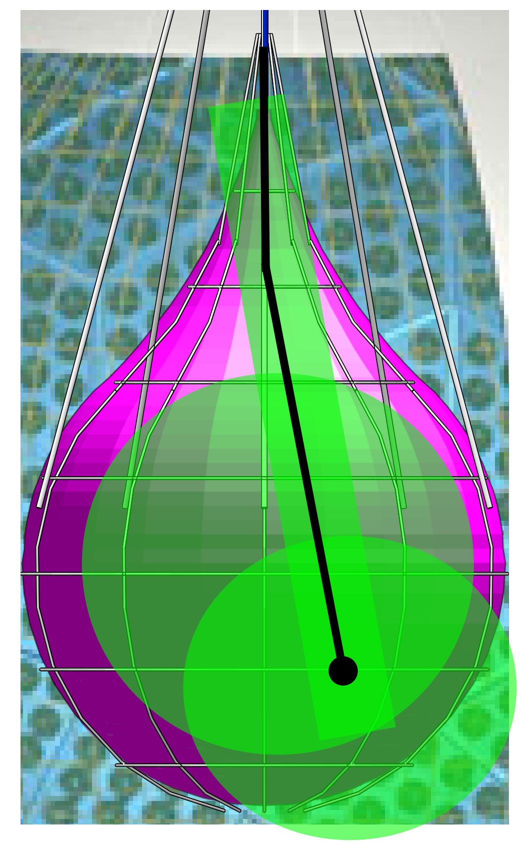
	DS-1	DS-2	Total
livetime (days)	112.3	101.1	213.4
fiducial Xe-LS mass (ton)	8.04	5.55	-
Xe concentration (wt%)	2.44	2.48	-
^{136}Xe mass (kg)	179	125	-
^{136}Xe exposure (kg-yr)	54.9	34.6	89.5

Event selection

- Fiducial volume cut to reject background from mini-balloon and filtration hardware



DS1: $R<1.35$m



DS2 (filtration plumbing):
$R<1.35$m
$dR_{tube} >0.2$m
$dR_{nozzle}>1.2$m

Event selection

- Fiducial volume cut to reject background from mini-balloon
- Coincidence cuts:
  - Veto events within 2ms after muon candidates
  - Veto event pairs (E_1,T_1), (E_2,T_2) with $(T_2-T_1< 3ms)$ and $0.35<E_2< 1.5$ MeV (^{214}Bi-Po, ^{212}Bi-Po cut)
  - Veto event pairs (E_1,T_1), (E_2,T_2) with $(T_2-T_1< 1ms)$ and $E_1 > 1.5$ MeV (antineutrino cut)
- Vertex-Time-Charge (VTQ) cut, based on PMT hit-time distribution, to remove noise events

BB Selection efficiency: 99.8 +/- 0.2 %

Dead time from cuts: <0.2 %

Backgrounds

- Residuals from inner balloon (IB) surface
- Spallation backgrounds
- Internal contamination of Xe-LS

Inner Balloon (IB) Backgrounds

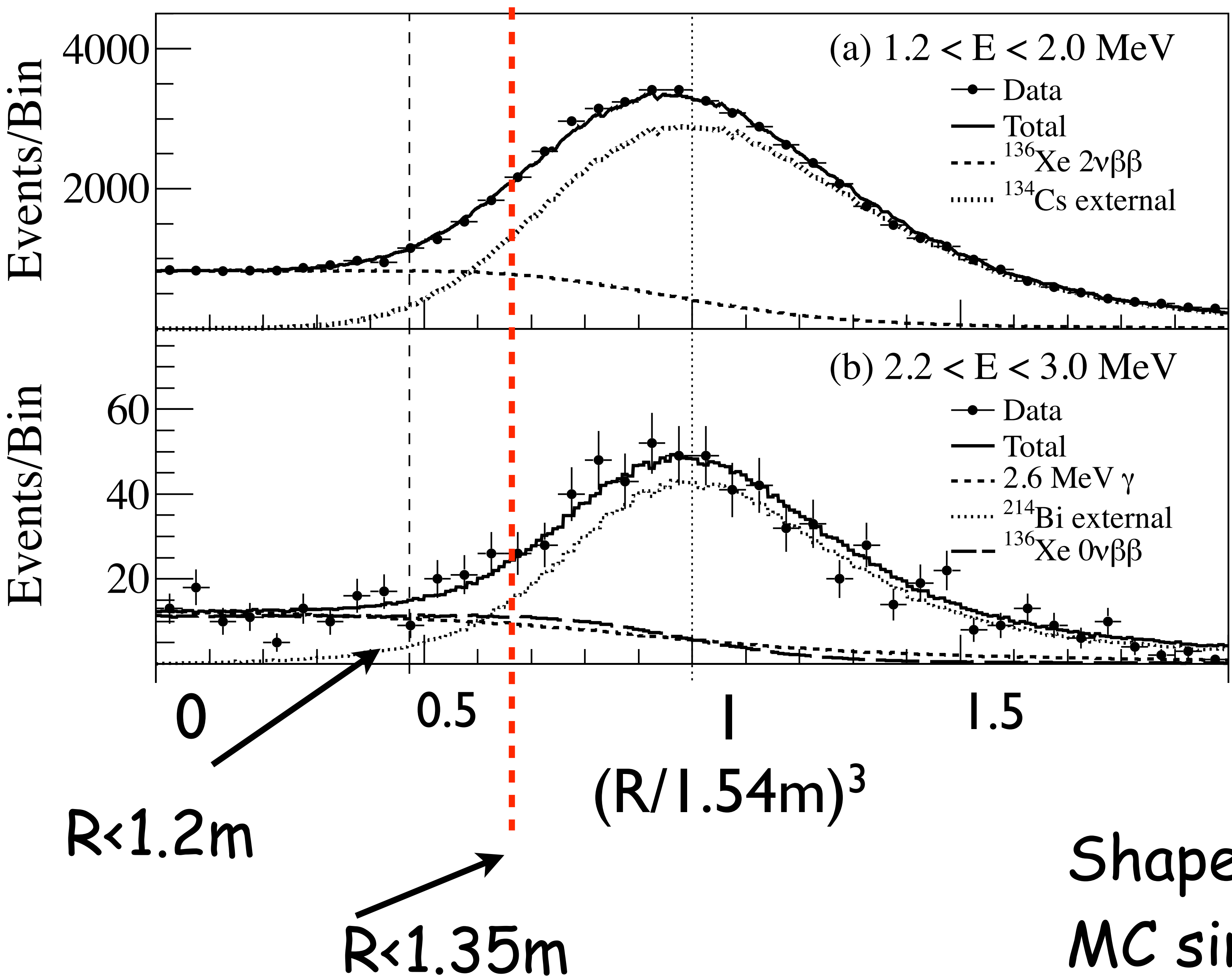
- Estimated from spectral analysis of events reconstructing near IB surface

- Between 1.2 MeV <E < 2.0 MeV IB activity dominated by ^{134}Cs, consistent with fallout from Fukushima reactor incident

- Between 2.2 MeV < E < 3.0 MeV IB activity is dominated by ^{214}Bi decays

- Residual background from IB in the fiducial volume comes from simulation

Inner Balloon (IB) Backgrounds



2ν-window

0ν-window

Shape of R^3 curves come from MC simulation

Spallation Backgrounds

- Cosmogenic production of ^{10}C and ^{11}C
- ^{10}C and ^{11}C can be vetoed by muon-neutron-β triple coincidence but this is not pursued for now

Isotope	Event rate $(\text{ton day})^{-1}$
Spallation product from ^{12}C [a]	
^{10}C	$(2.11 \pm 0.44) \times 10^{-2}$
^{11}C	1.11 ± 0.28
Spallation products from xenon with lifetime < 100 s	
$1.2 \text{ MeV} < E < 2.0 \text{ MeV}$	< 0.3
$2.2 \text{ MeV} < E < 3.0 \text{ MeV}$	< 0.02

- Not much previous data on Xe spallation products. Limits above estimated from KLZ data
- Longer lived spallation products estimated to be negligible from Geant4 simulation

Internal Xe-LS Backgrounds

- Residual ^{232}Th (^{212}Bi-Po) and ^{238}U (^{214}Bi-Po) in Xe-LS assuming equilibrium:

^{238}U	1.3+/- 0.2 $\times 10^{-16}$g/g
^{232}Th	1.8+/- 0.1 $\times 10^{-15}$g/g

- Searched Table of Isotopes for long-lived isotopes leading to decays in the ROI for 0vBB search

^{208}Bi (EC)	τ=5.31x10^5 yr	Q=2.88 MeV
^{88}Y(EC)	τ=154 d	Q=3.62 MeV
^{60}Co (β^-)	τ=7.61 yr	Q=2.82 MeV
^{110m}Ag (β^-)	τ=360 d	Q=3.01 MeV

Analysis

- Binned maximum likelihood fit to the energy spectrum of candidates (energy-likelihood)
- Time-likelihood to constrain some backgrounds in 0vBB ROI by their decay lifetime
- Penalty-likelihood to account for other constraints on some fit parameters, e.g energy scale model

$$\chi^2 = \chi^2_{energy} + \chi^2_{time} + \chi^2_{penalty}$$

Fit model

Signal	$2\nu\beta\beta$
	$0\nu\beta\beta$
Backgrounds	40K
	^{222}Rn-^{210}Pb
	^{228}Th-^{208}Pb
	^{232}Th-^{228}Th (^{228}Ac)
	^{238}U-^{222}Rn (^{234}Pa)
	^{85}Kr
	^{210}Bi
	^{134}Cs,^{137}Cs
	^{129m}Te,^{95}Nb,^{90}Y,^{89}Sr
	^{110m}Ag,^{60}Co,^{88}Y,^{208}Bi
	^{10}C
	^{11}C
Detector response (Energy scale)	A, k_B, R

Fit model

Signal	$2\nu\beta\beta$
	$0\nu\beta\beta$
Backgrounds	40K
	^{222}Rn-^{210}Pb
	^{228}Th-^{208}Pb
	^{232}Th-^{228}Th (^{228}Ac)
	^{238}U-^{222}Rn (^{234}Pa)
	^{85}Kr
	^{210}Bi
	^{134}Cs, ^{137}Cs
	^{129m}Te, ^{95}Nb, ^{90}Y, ^{89}Sr
	^{110m}Ag, ^{60}Co, ^{88}Y, ^{208}Bi
	^{10}C
	^{11}C
Detector response (Energy scale)	A, k_B, R

Possible fallout products

Fit model

Signal	$2\nu\beta\beta$
	$0\nu\beta\beta$
Backgrounds	40K
	^{222}Rn-^{210}Pb
	^{228}Th-^{208}Pb
	^{232}Th-^{228}Th (^{228}Ac)
	^{238}U-^{222}Rn (^{234}Pa)
	^{85}Kr
	^{210}Bi
	^{134}Cs,^{137}Cs
	^{129m}Te,^{95}Nb,^{90}Y,^{89}Sr
	^{110m}Ag,^{60}Co,^{88}Y,^{208}Bi
	^{10}C
	^{11}C
Detector response (Energy scale)	A, k_B, R

Possible backgrounds in 0vBB ROI from ENDSF database search

Fit model

Signal	$2\nu\beta\beta$	Constrained in model
	$0\nu\beta\beta$	
Backgrounds	40K	
^{214}Bi-Po coincidences	^{222}Rn-^{210}Pb	IB contribution from balloon study and MC
^{212}Bi-Po coincidences	^{228}Th-^{208}Pb	
	^{232}Th-^{228}Th (^{228}Ac)	
	^{238}U-^{222}Rn (^{234}Pa)	
	^{85}Kr	
	^{210}Bi	
	^{134}Cs, ^{137}Cs	IB contribution from balloon study and MC
	^{129m}Te, ^{95}Nb, ^{90}Y, ^{89}Sr	
	^{110m}Ag, ^{60}Co, ^{88}Y, ^{208}Bi	
	^{10}C	Spallation studies at KamLAND
	^{11}C	
Detector response (Energy scale)	A, k_B, R	Calibration, ^{214}Bi study

Fit model

Signal	$2\nu\beta\beta$
	$0\nu\beta\beta$
Backgrounds	40K
	^{222}Rn-^{210}Pb
	^{228}Th-^{208}Pb
	^{232}Th-^{228}Th (^{228}Ac)
	^{238}U-^{222}Rn (^{234}Pa)
	^{85}Kr
	^{210}Bi
	$^{134}Cs, ^{137}Cs$
	$^{129m}Te, ^{95}Nb, ^{90}Y, ^{89}Sr$
	$^{110m}Ag, ^{60}Co, ^{88}Y, ^{208}Bi$
	^{10}C
	^{11}C
Detector response (Energy scale)	A, k_B, R

Unconstrained in model

contribution in Xe-LS unconstrained

Fit model

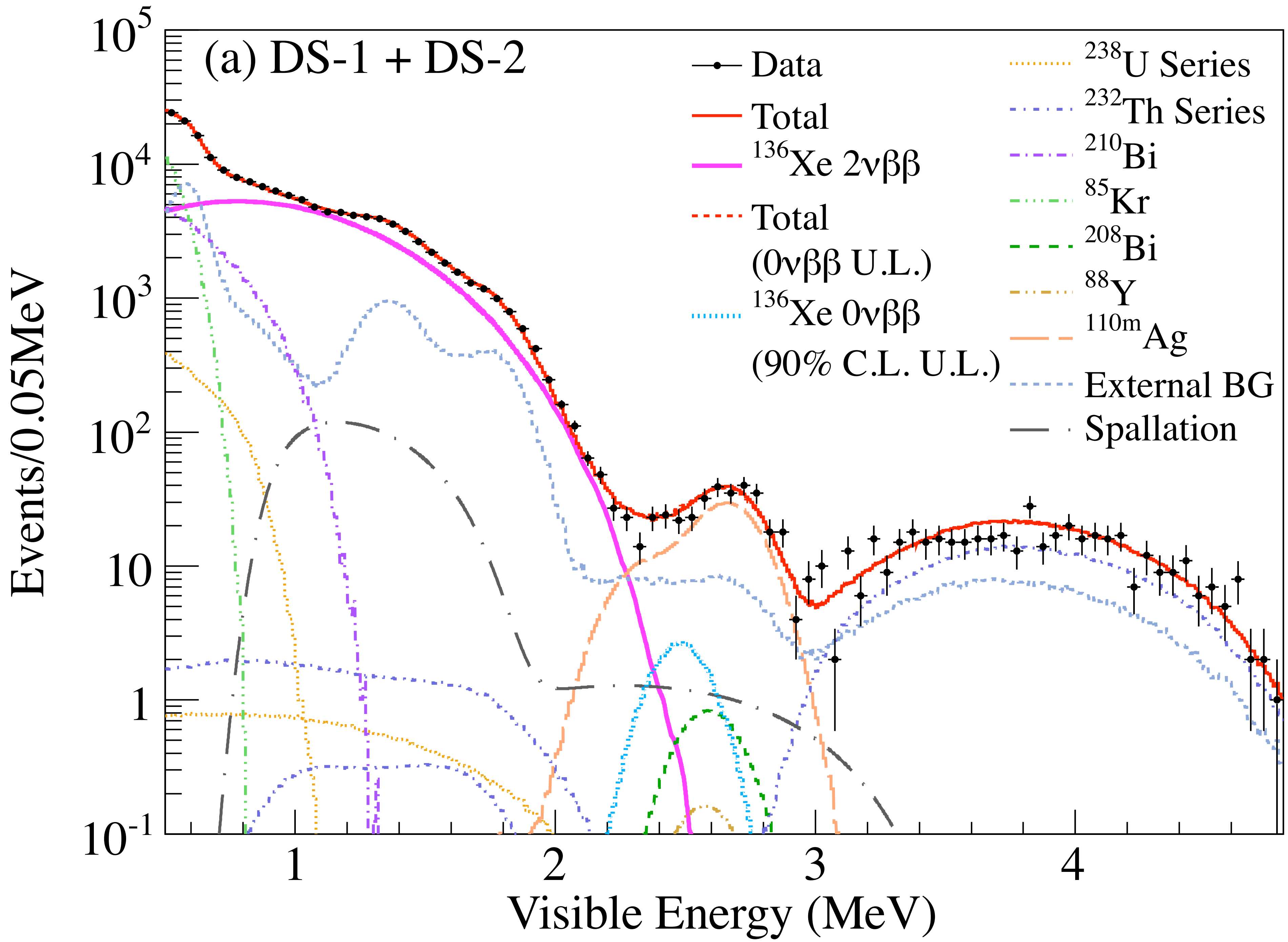
Signal	$2\nu\beta\beta$
	$0\nu\beta\beta$
Backgrounds	40K
	^{222}Rn-^{210}Pb
	^{228}Th-^{208}Pb
	^{232}Th-^{228}Th (^{228}Ac)
	^{238}U-^{222}Rn (^{234}Pa)
	^{85}Kr
	^{210}Bi
	^{134}Cs, ^{137}Cs
	^{129m}Te, ^{95}Nb, ^{90}Y, ^{89}Sr
	^{110m}Ag, ^{60}Co, ^{88}Y, ^{208}Bi
	^{10}C
	^{11}C
Detector response (Energy scale)	A, k_B, R

No assumption about filtration is made in fit

Rates in DS1 and DS2 are independent in fit

Result

Candidate spectrum + Best-fit decomposition for DS1 and DS2



Double beta decay results

Two neutrino mode

	DS-1	DS-2
$2\nu\beta\beta$ Rate $(\text{ton}\cdot\text{day})^{-1}$	82.9 ± 1.1 (stat) ± 3.4 (syst)	80.2 ± 1.8 (stat) ± 3.3 (syst)

$$T^{2\nu}_{1/2} = 2.30 \pm 0.03\,(\text{stat}) \pm 0.07\,(\text{syst}) \times 10^{21}\,\text{yr}$$

Neutrino-less mode

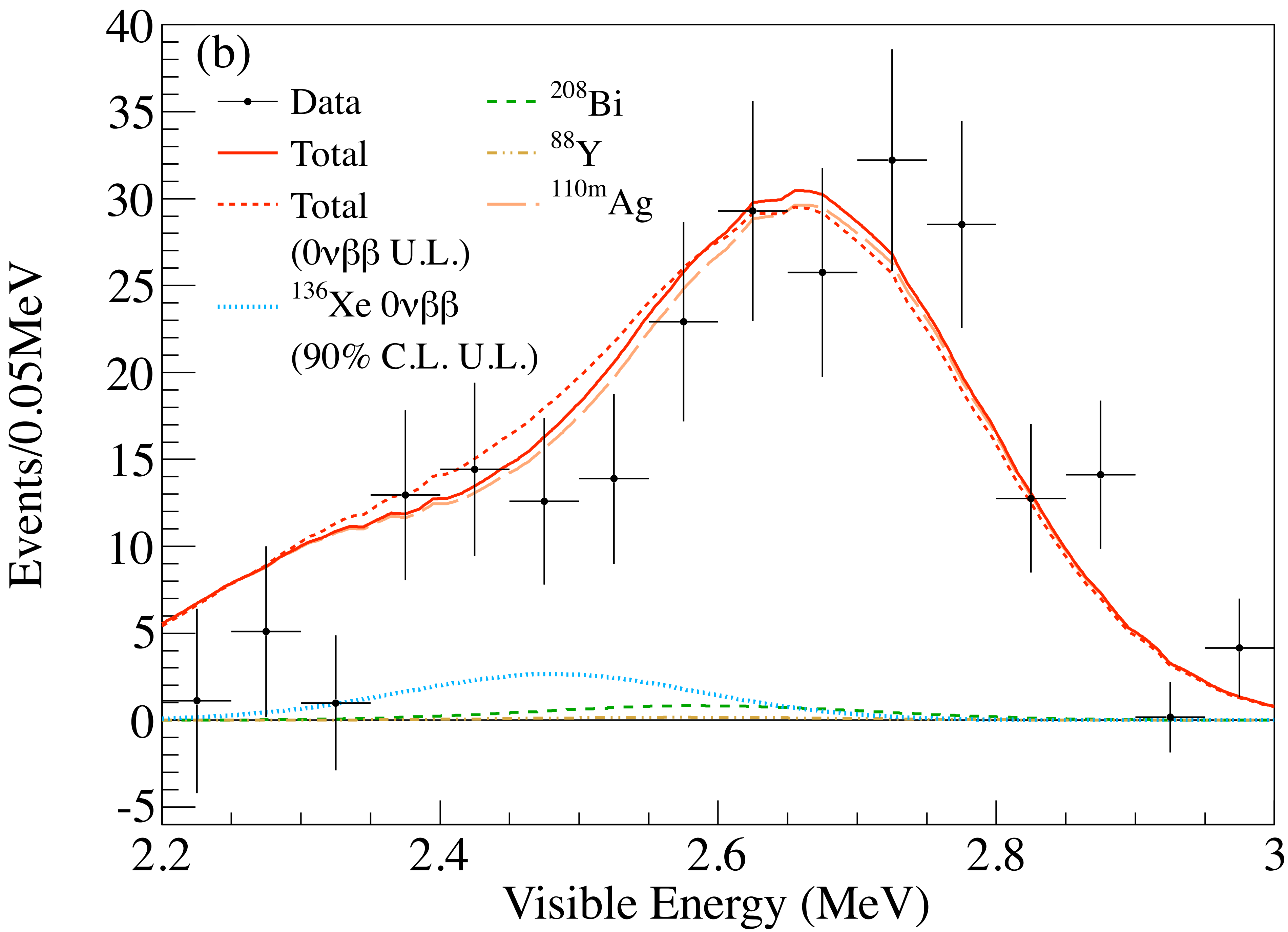
	DS-1	DS-2
N $(0\nu\beta\beta)$ (90% C.L upper limit)	<16	<8.7

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

Expected sensitivity from MC of ensemble of experiments is 1.0×10^{25}yr.

12% chance to get limit greater than one reported

Close-up of 0vBB region



Systematic Error

	DS1	DS2
Fid. vol.	3.9%	4.1%
Xe-concentration	0.34%	0.37%
Xe-enrichment	0.05%	0.05%
energy scale	0.3%	0.3%
detection efficiency	0.2%	0.2%
Total	3.9%	4.1%

- Fid. vol. systematic error estimated from difference between nominal fiducial volume and fraction of ^{214}Bi tagged events that pass fid. vol. cuts

EXO

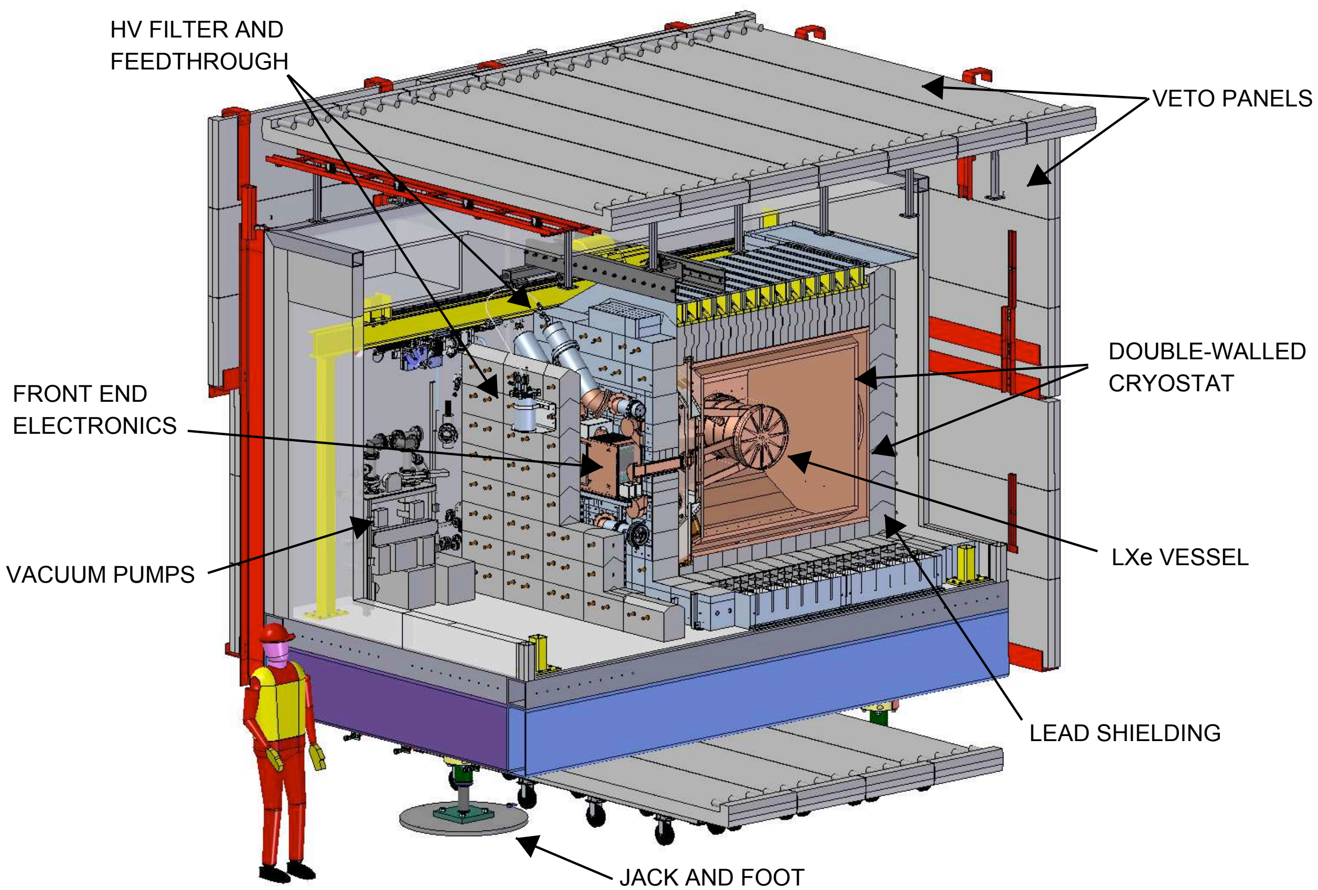


Figure 2. Cutaway view of the EXO-200 setup, with the primary subassemblies identified.

- Filled with liquified Xe, enriched to 80.6% in ^{136}Xe remaining is ^{134}Xe
- Fiducial volume of 79.4kg
- TPC allows 3D reconstruction of events in detector
- Measure both scintillation energy and ionization energy of events
- Located at a depth of 1585 MWE at WIPP

EXO Results

Close up of 0vBB region

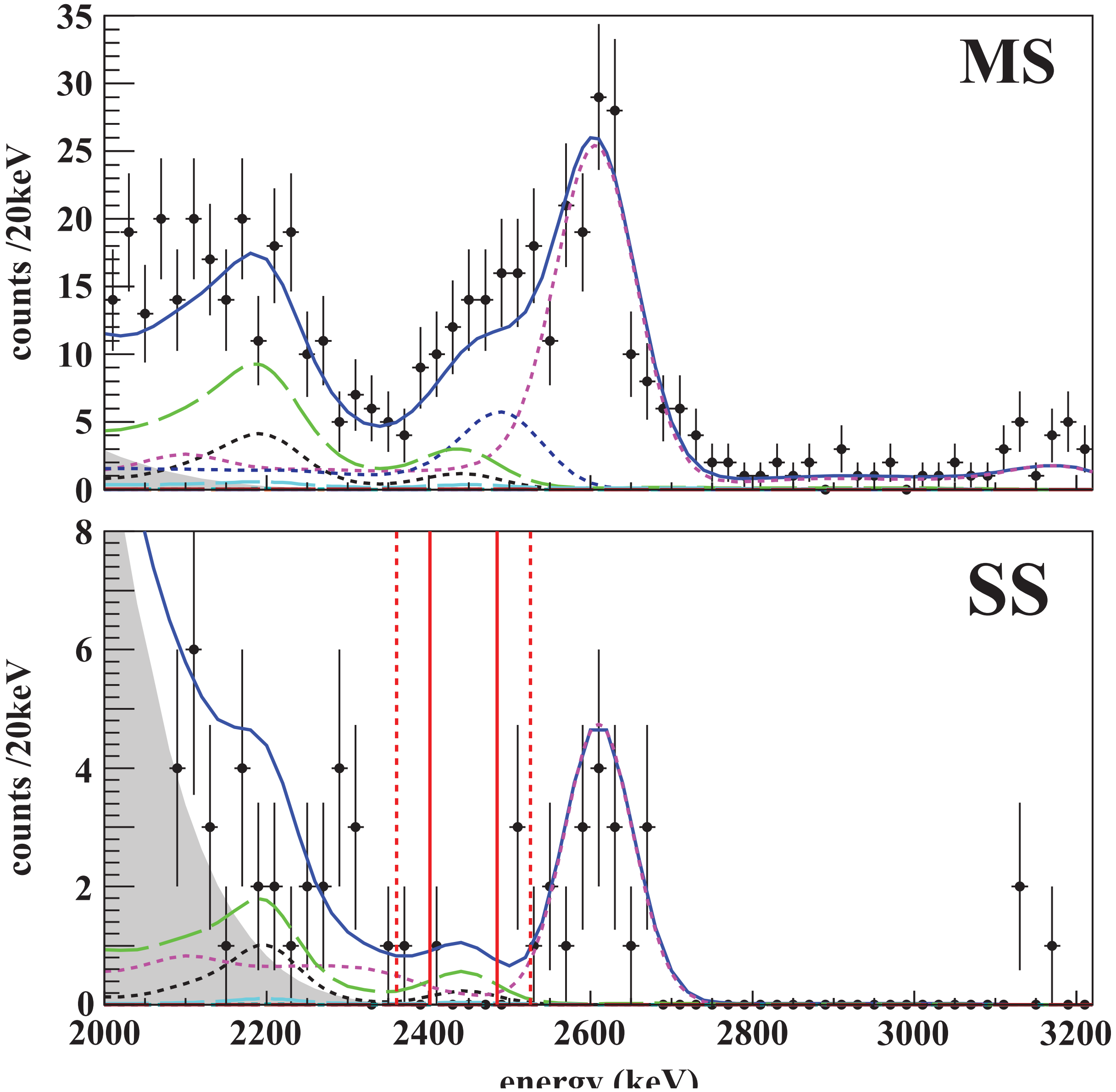


FIG. 5 (color). Energy spectra in the ^{136}Xe $Q_{\beta\beta}$ region for MS (top) and SS (bottom) events. The 1 (2)σ regions around $Q_{\beta\beta}$ are shown by solid (dashed) vertical lines. The $0\nu\beta\beta$ PDF from the fit is not visible. The fit results have the same meaning as in Fig. 4.

- Expect 4.1+/-0.3 events from background in 1σ window around Q-value
- Observed 1

$T^{2\nu}_{1/2}$ = 2.23 +/- 0.017 (stat) +/- 0.22 (syst) x 10^{21} yr

$T^{0\nu}_{1/2}$ >1.6 x 10^{25} yr (90% CL)

Combination of KL-Zen and EXO

Combined analysis of KLZ and EXO 0vBB data:

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

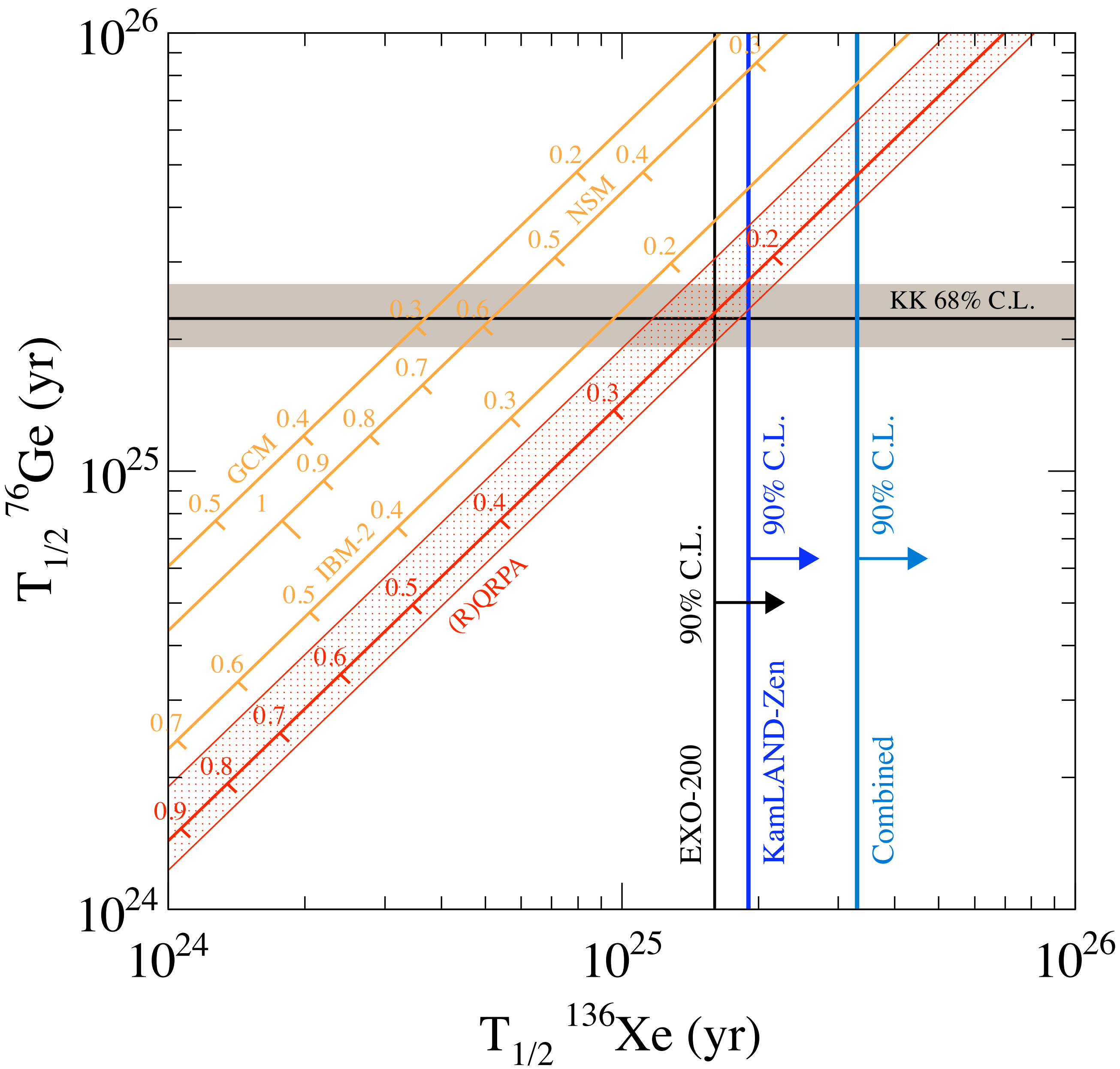
Expected sensitivity of combined experiment is 1.6 x 10^{25}yr.

7% chance to get limit greater than one reported

Using a range of available nuclear matrix elements mass limit:

$$\langle m_{\beta\beta} \rangle < (120 - 250)\ \mathrm{meV}$$

Combination of KL-Zen and EXO



Combined EXO-200 and KLZ result is inconsistent with KK claim in ^{76}Ge at 97.5% CL even for best-case NME

NME is a major caveat in interpretation of half life limit

Treating spread in NME calculations as an 'error' then EXO-200 and KLZ result is inconsistent with KK claim in ^{76}Ge at 95.6% CL

Future plans for KamLAND/KamLAND-Zen

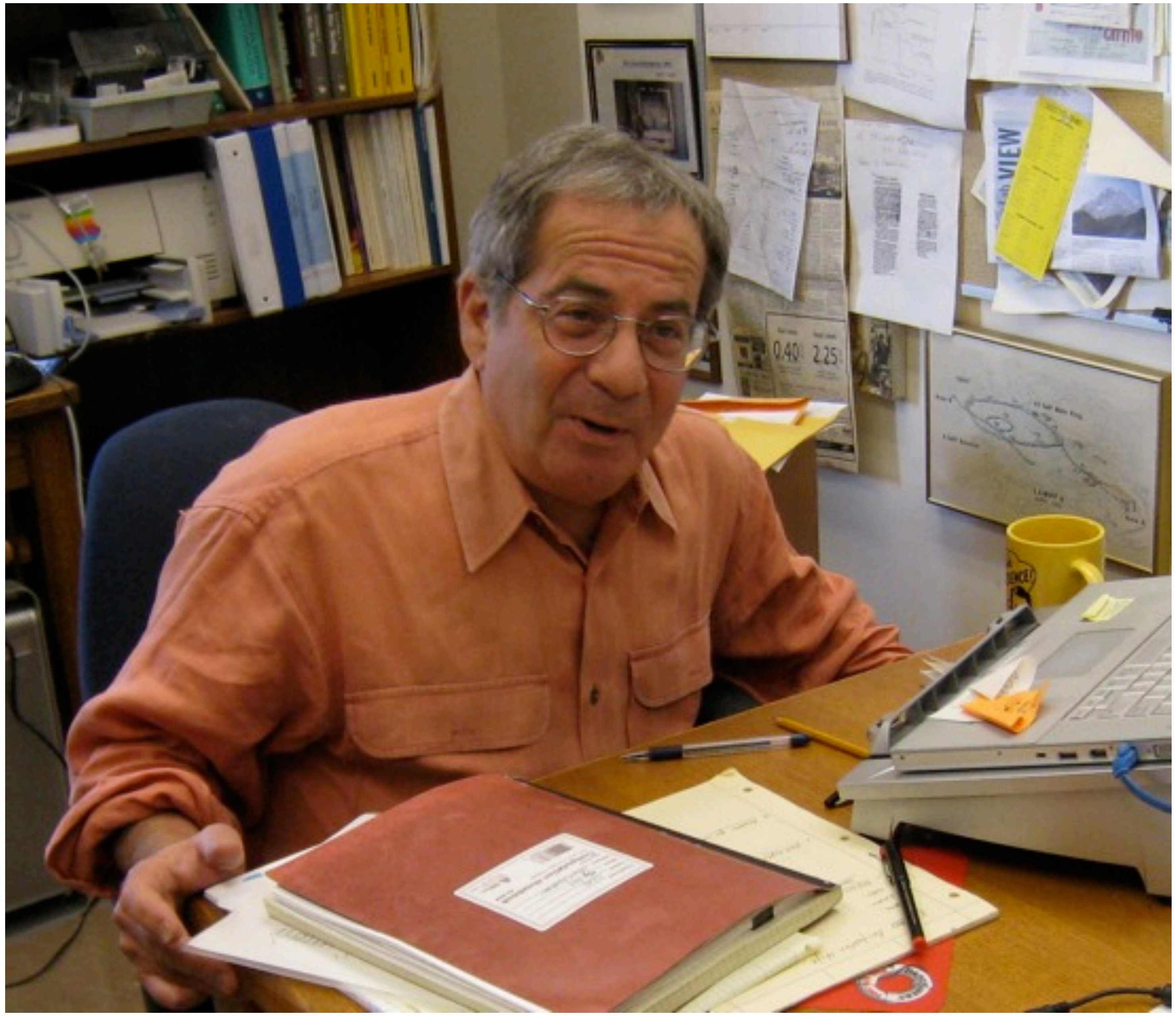
- Background in 0vBB ROI must be reduced
- Collaboration plans to distill Xe to try to remove impurities
- Investigating the option to replace IB which may have been contaminated by fallout
- Reactor and geo-neutrino studies, supernova-watch can continue in parallel with KamLAND-LS
- Longer-term: KamLAND2-Zen, ton-scale Xe-loading, retro-fit of PMT array to improve resolution

Conclusion

- KamLAND-Zen was a very effective modification of the KamLAND detector
- Capitalized on existing infrastructure, to quickly realize competitive double beta decay search
- EXO and KamLAND-Zen measured $T_{1/2}^{2\nu}$ of ^{136}Xe in close succession
- Combined half-life lower limit on $T_{1/2}^{0\nu}$ of ^{136}Xe in tension with KKDC claim for available NME calculations
- KamLAND-Zen has potential to improve significantly if ^{110m}Ag can be removed !

Please wish us
Gan-batte !

Dedication

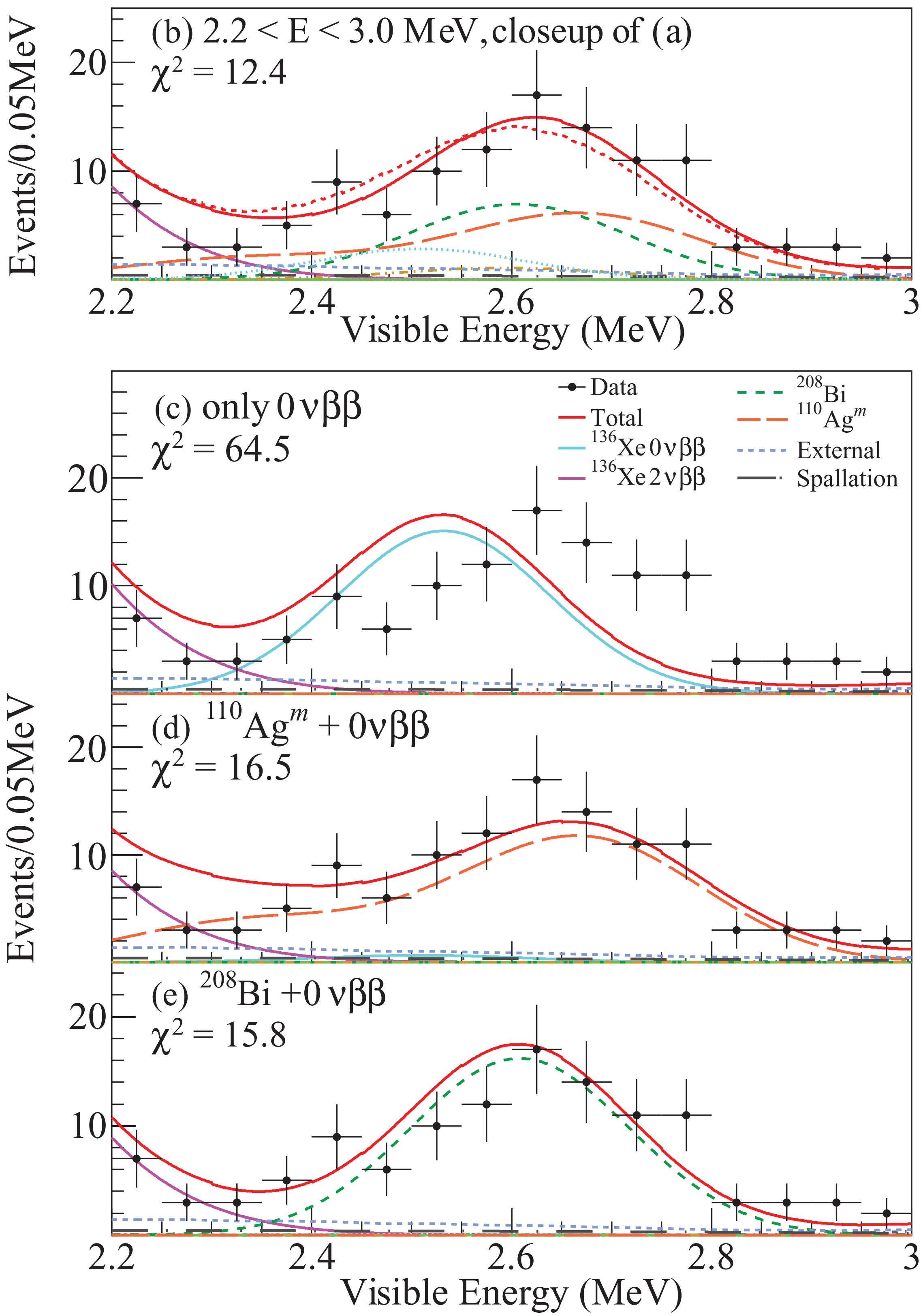


Stuart Freedman

Fondly remembered collaborator, mentor, and friend

Extra slides

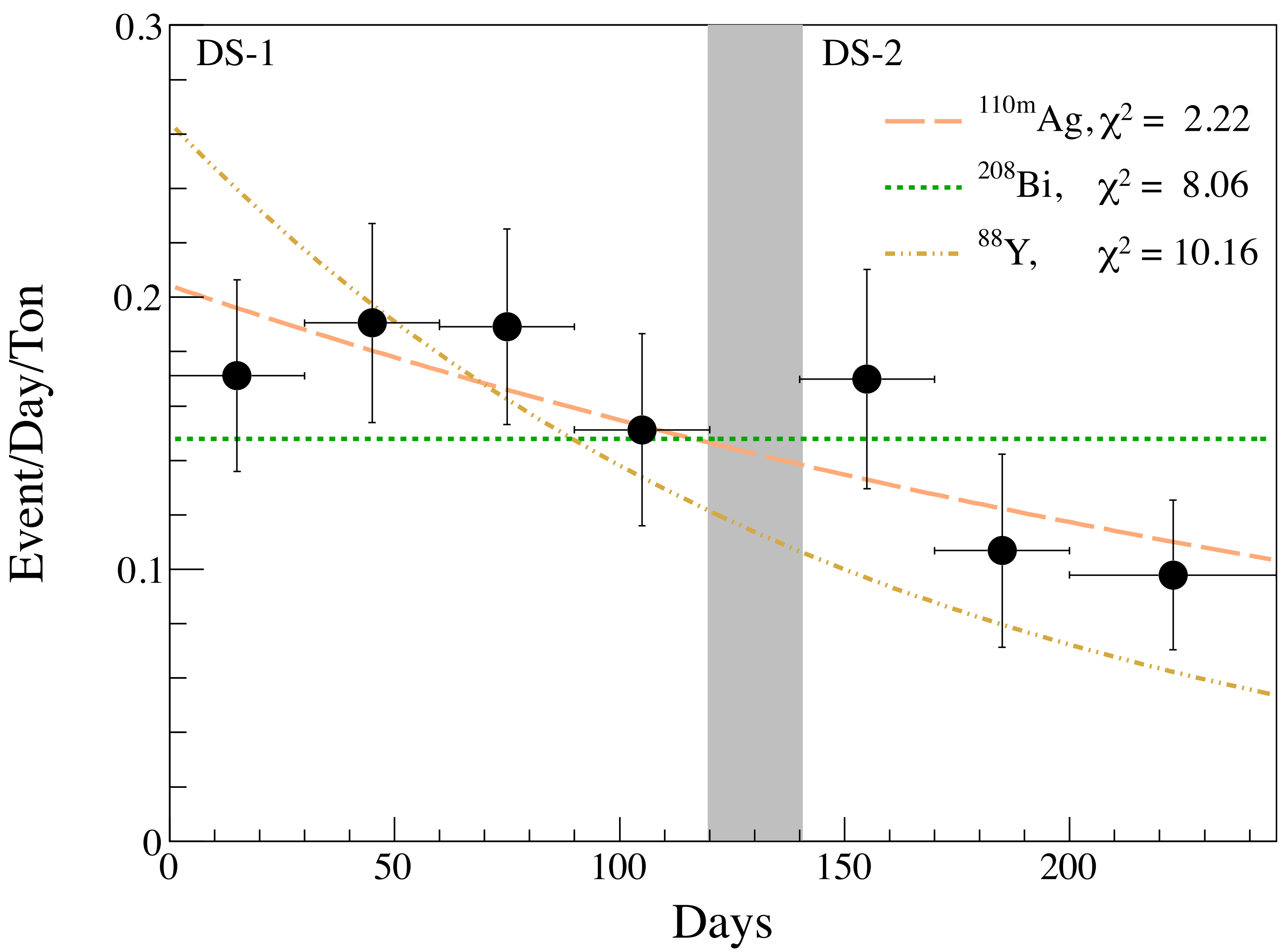
Investigating background near 2.6 MeV



From DS1 only with R<1.2 m

Investigating background near 2.6 MeV

(Events in 0vBB ROI)-(known backgrounds)



Assuming filtration has no effect ^{110m}Ag is preferred