Recent Results from KamLAND and KamLAND-Zen

T. O'Donnell, UC Berkeley & Lawrence Berkeley Lab

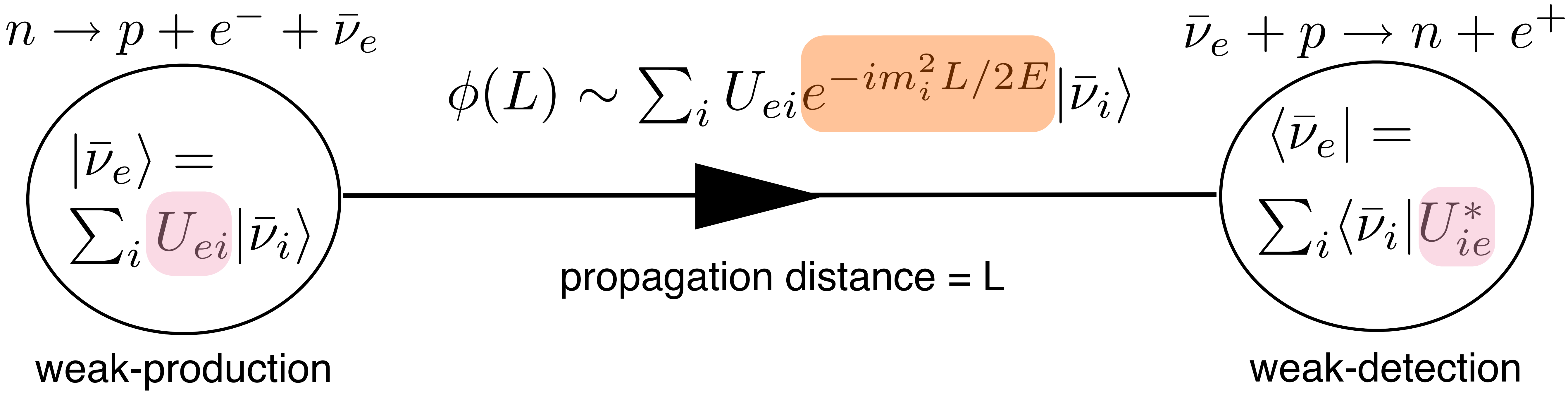
Outline

- Overview of neutrino oscillation and double beta decay
- Description of the KamLAND/KamLAND-Zen experiments
- Results from the KamLAND antineutrino analysis
- Results from the 1^{st} phase of KamLAND-Zen

Brief history of KamLAND

2013	Reactor On-Off antineutrino data
2013	1st phase of KamLAND-Zen completed
2012	Lower limit on $0\nu\beta\beta$ half-life of ^{136}Xe
2012	Observation of $2\nu\beta\beta$ decay of ^{136}Xe
2011	KamLAND-Zen begins
2011	Improved geo-neutrino measurements
2011	3-flavor oscillation studies at KamLAND
2010	Measurement of ^{8}B solar neutrino flux at KamLAND
2008	Precision measurement of neutrino oscillation
2005	Evidence for geo-neutrinos at KamLAND
2005	Evidence of spectral distortion
2003	Discovery of reactor neutrino disappearance
2002	KamAND begins

Neutrino Oscillation



- Weak eigenstates are not the same as the mass eigenstates
- Probability to detect the same weak eigenstate is a non-trivial function of time or L

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

How do we learn about U ?

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

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

- (blue) KamLAND and solar experiments, e.g SNO, Borexino
- (green) Atmospheric neutrino, long baseline accelerator e.g SuperK, MINOS
- (orange) Short baseline reactor, accelerator e.g Daya Bay, T2K
- (red) Future long baseline accelerator experiment ??

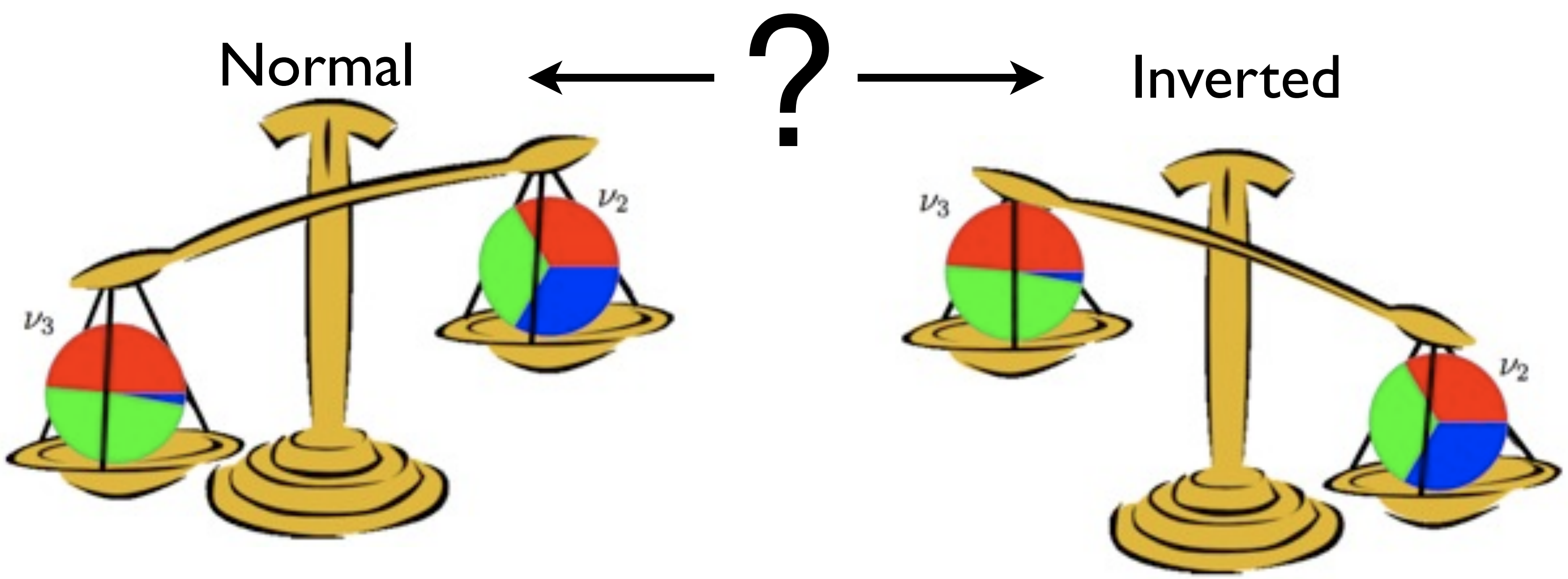
What do we know about neutrino mass ?

- 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

Some open questions ?

- What is the mass hierarchy ?



- We know $|\Delta m^2_{23}|$ from atmospheric and accelerator neutrino experiments . . . but not the sign

- What about the absolute neutrino mass ?

Double Beta Decay

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

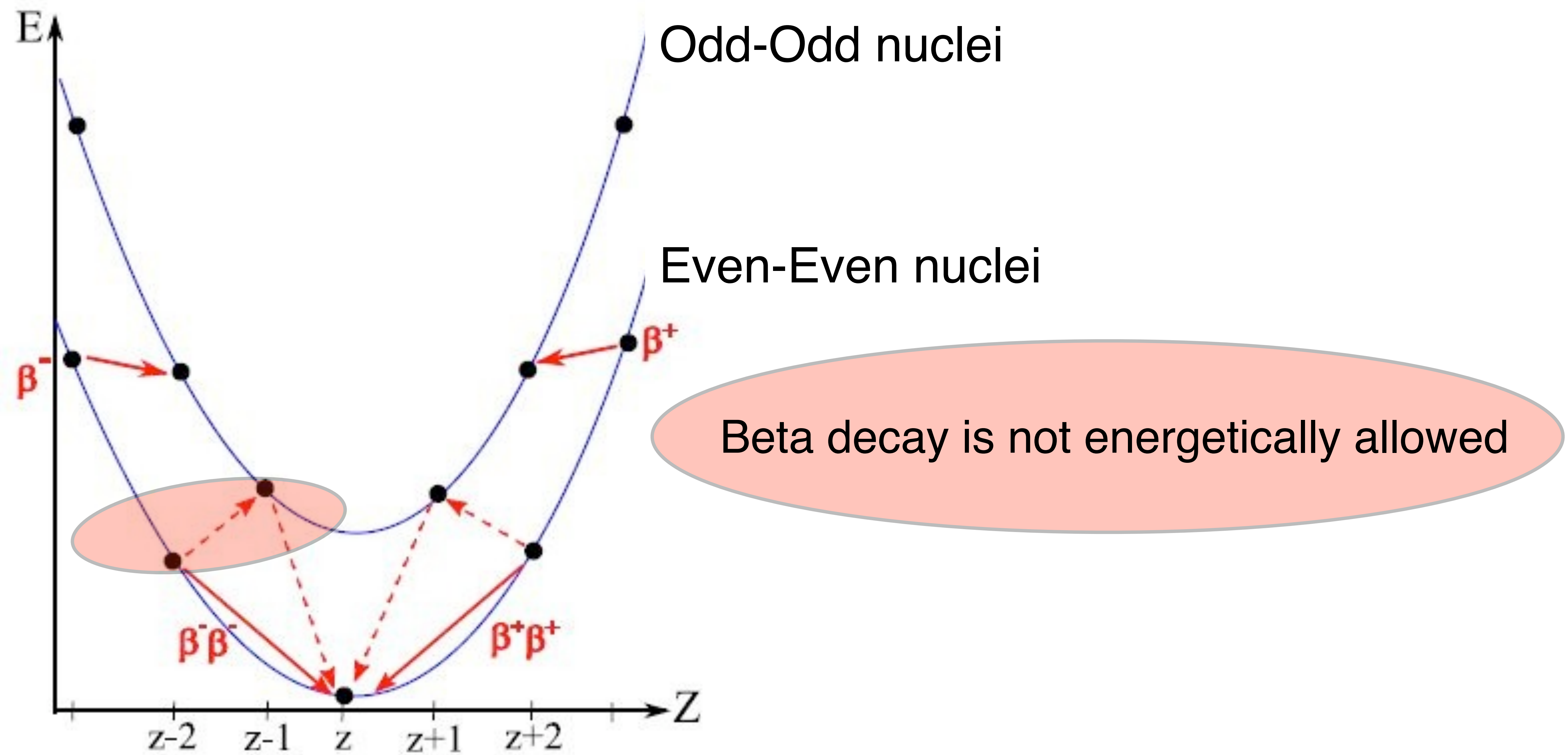
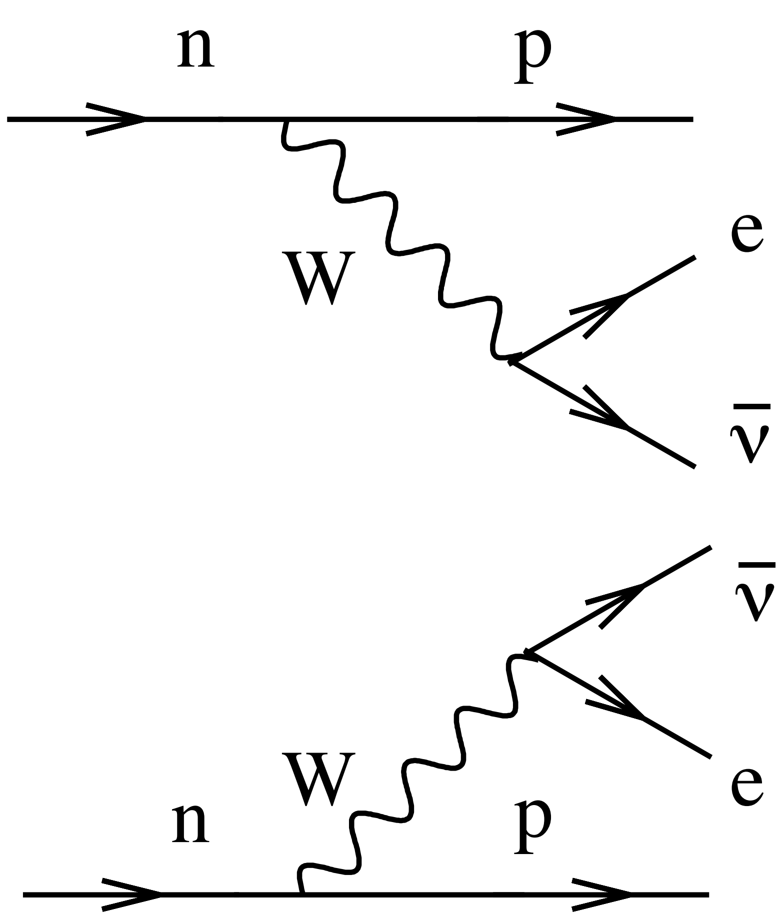


Figure adapted from: http://www.cobra-experiment.org/double_beta_decay/

Double Beta Decay



Phase space factor

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

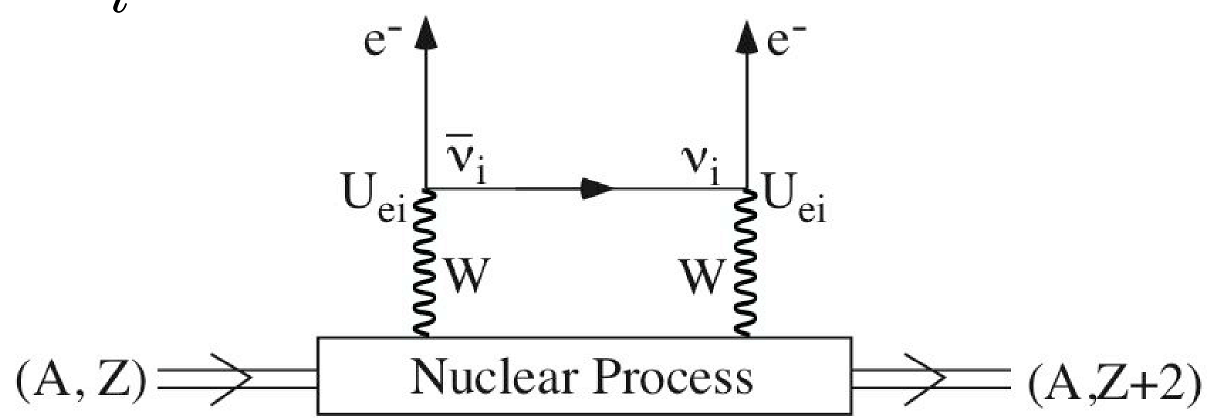
Decay half-life

Nuclear matrix element

- Simultaneous decay of 2 neutrons in a nucleus
- Second-order weak process, allowed in SM
- Observable only if ‘ordinary’ beta decay is inhibited
- Directly observed in 12 nuclei, half lives ~10^{19}-10^{21} years ! depending on the nuclear system

Neutrinoless Double Beta Decay

- Hypothetical ββ decay mode allowed if neutrinos are Majorana particles, i.e $\bar{\nu}_i \equiv \nu_i$



Phase space factor

Nuclear matrix element

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

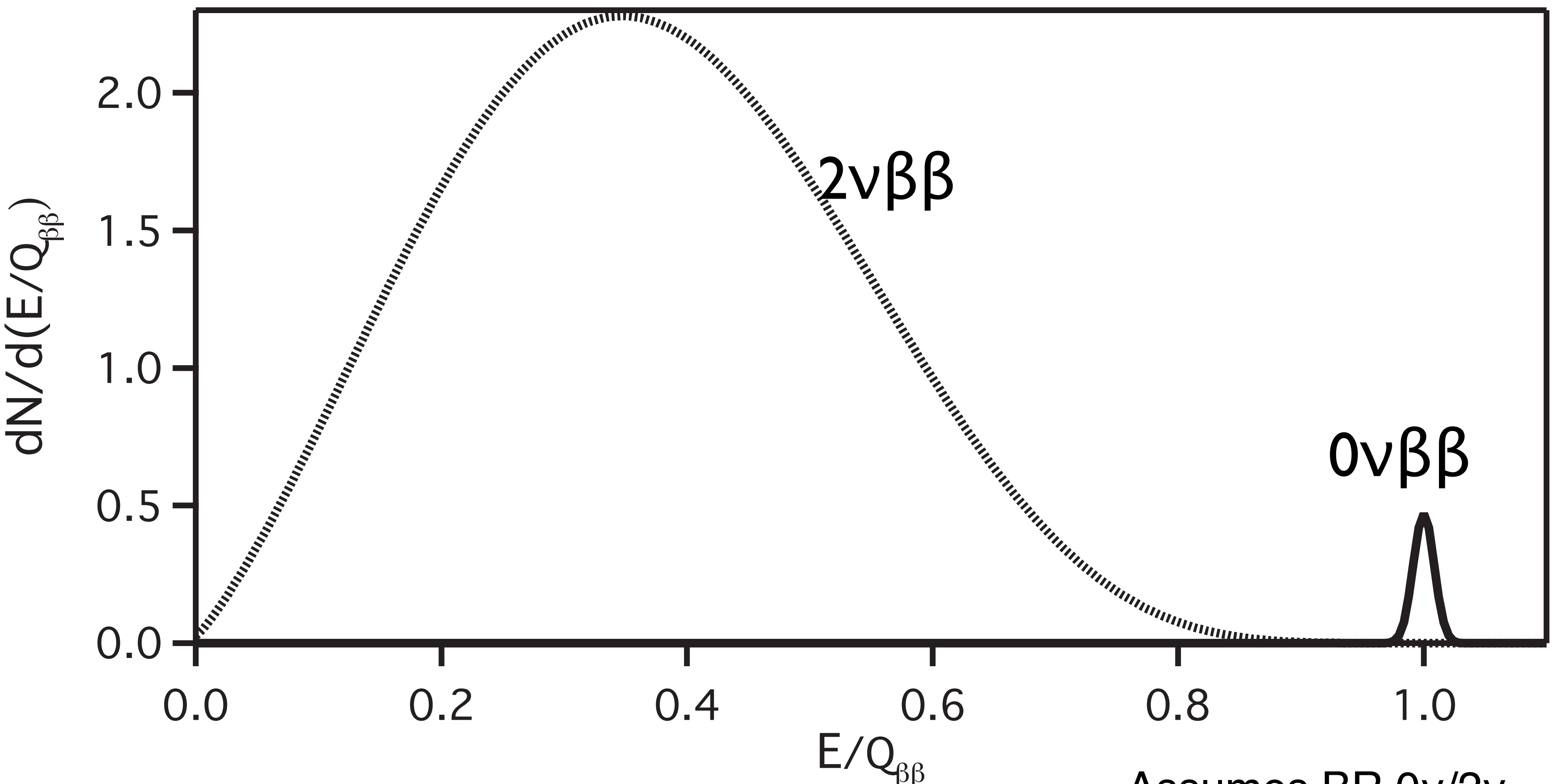
Decay half-life

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

- $M^{0\nu}$ is not known; estimates vary by factor of ~2 depending on method
- For $m_{\beta\beta}$ = 50 meV estimated half lives 10^{25} - 10^{27} years ! depending on the nuclear system

Double Beta Decay - Signature

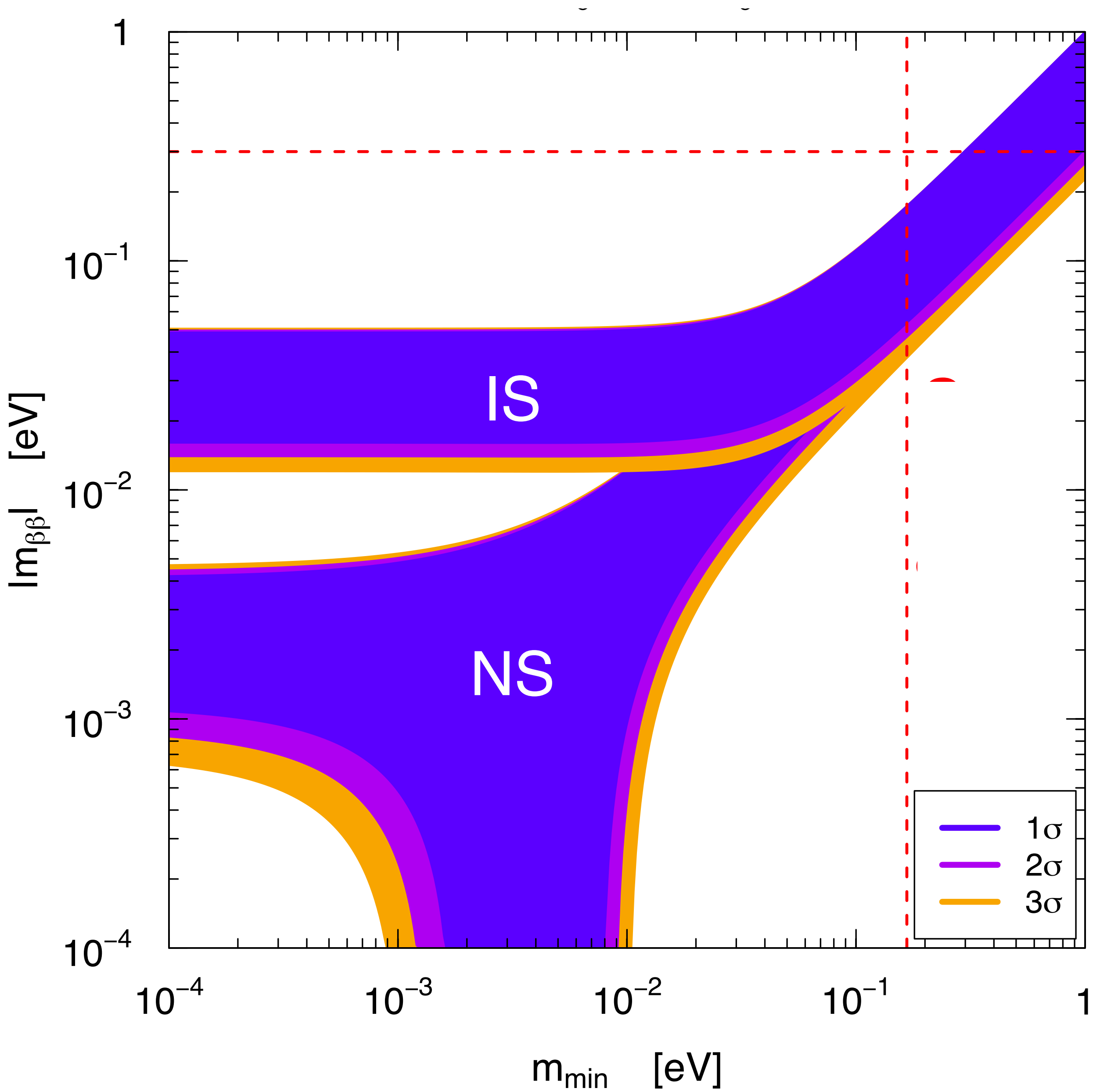
summed energy spectrum of final state electrons



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

- Peak at the decay Q-value of the transition

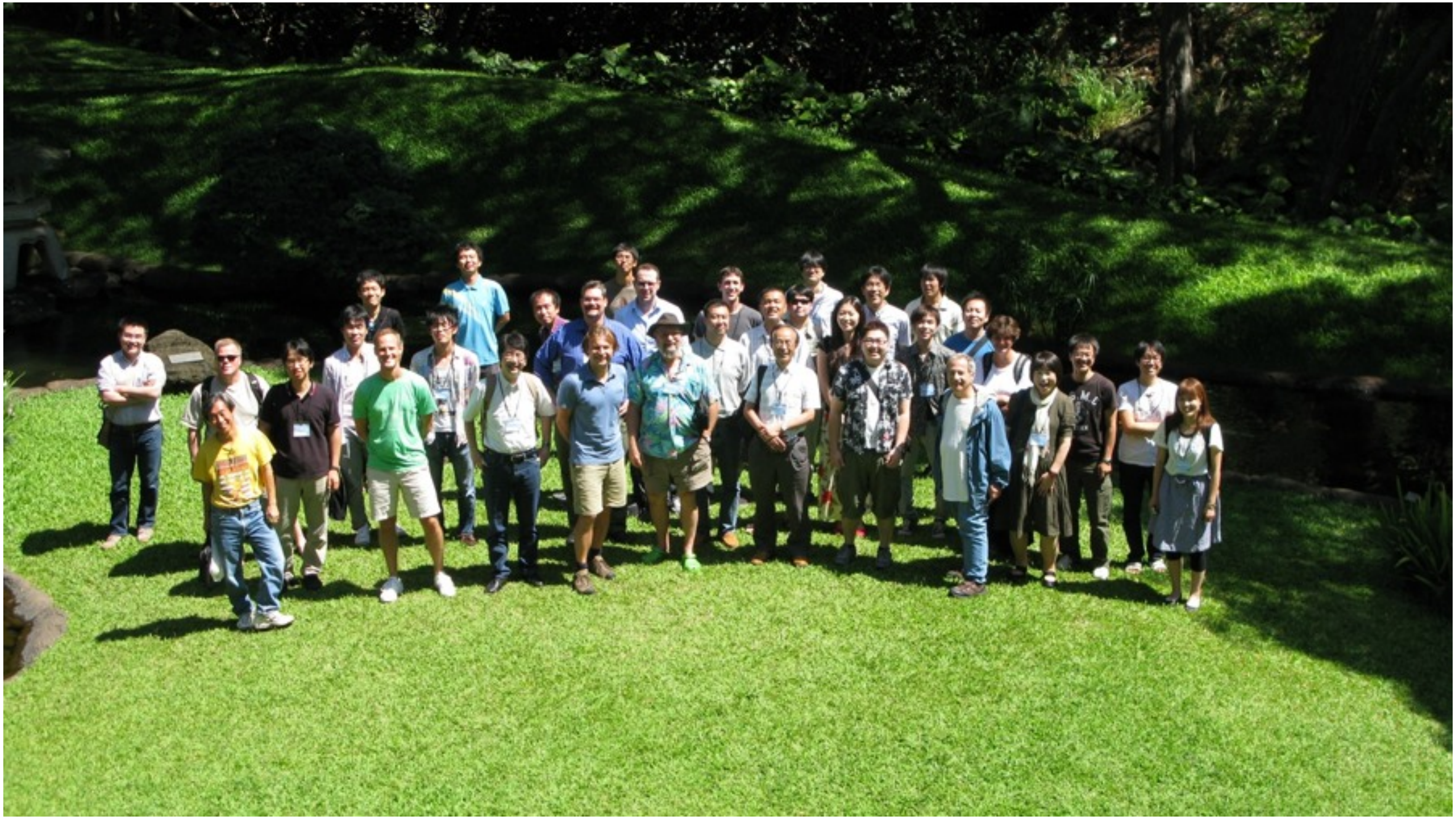
What might we learn ?



From arXiv:1203.5250v3

- If observed: learn neutrinos are Majorana fermions, maybe the hierarchy, constrains absolute mass scale
- If not observed: stringent limits help make the most of future neutrino data

KamLAND/KamLAND-Zen Collaborations



KamLAND-Zen collaboration is a subset of KamLAND

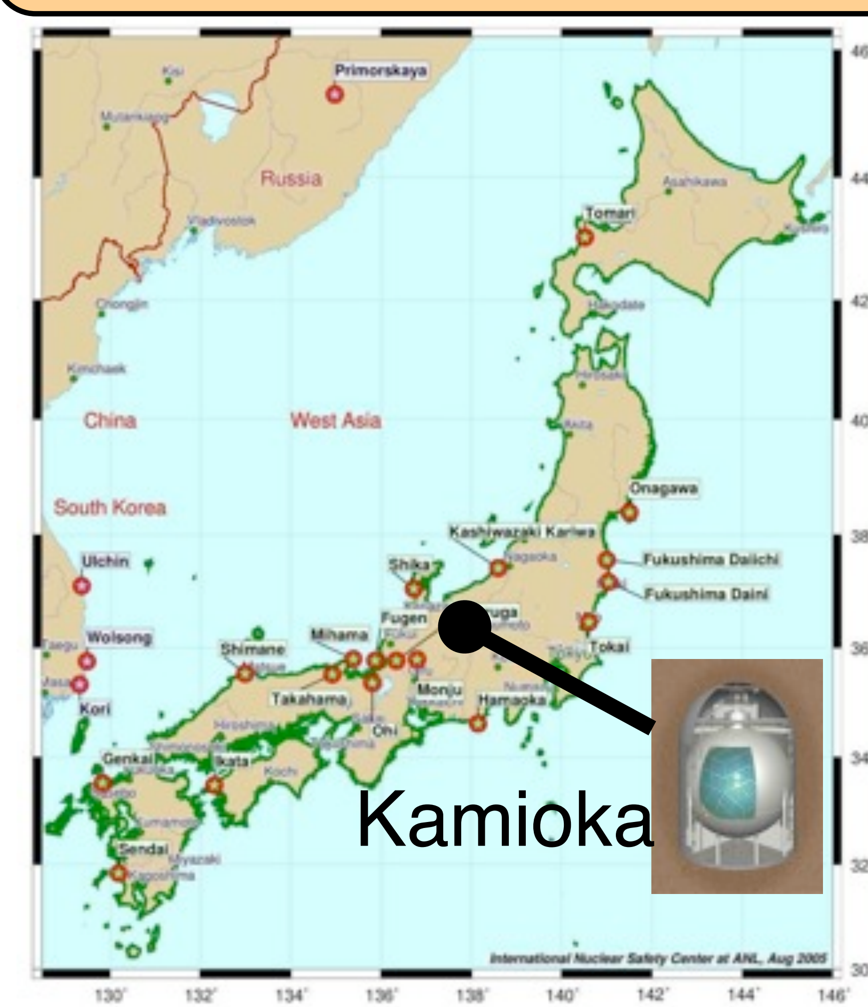
Kamioka Observatory

- Located under Mt. Ikenoyama, ~2700 m.w.e. overburden
- ‘Easy’ access
- Surrounded by Japanese commercial nuclear reactors:
  - (Typical) flux-weighted average baseline ~ 180km
  - This was key to KamLAND’s success

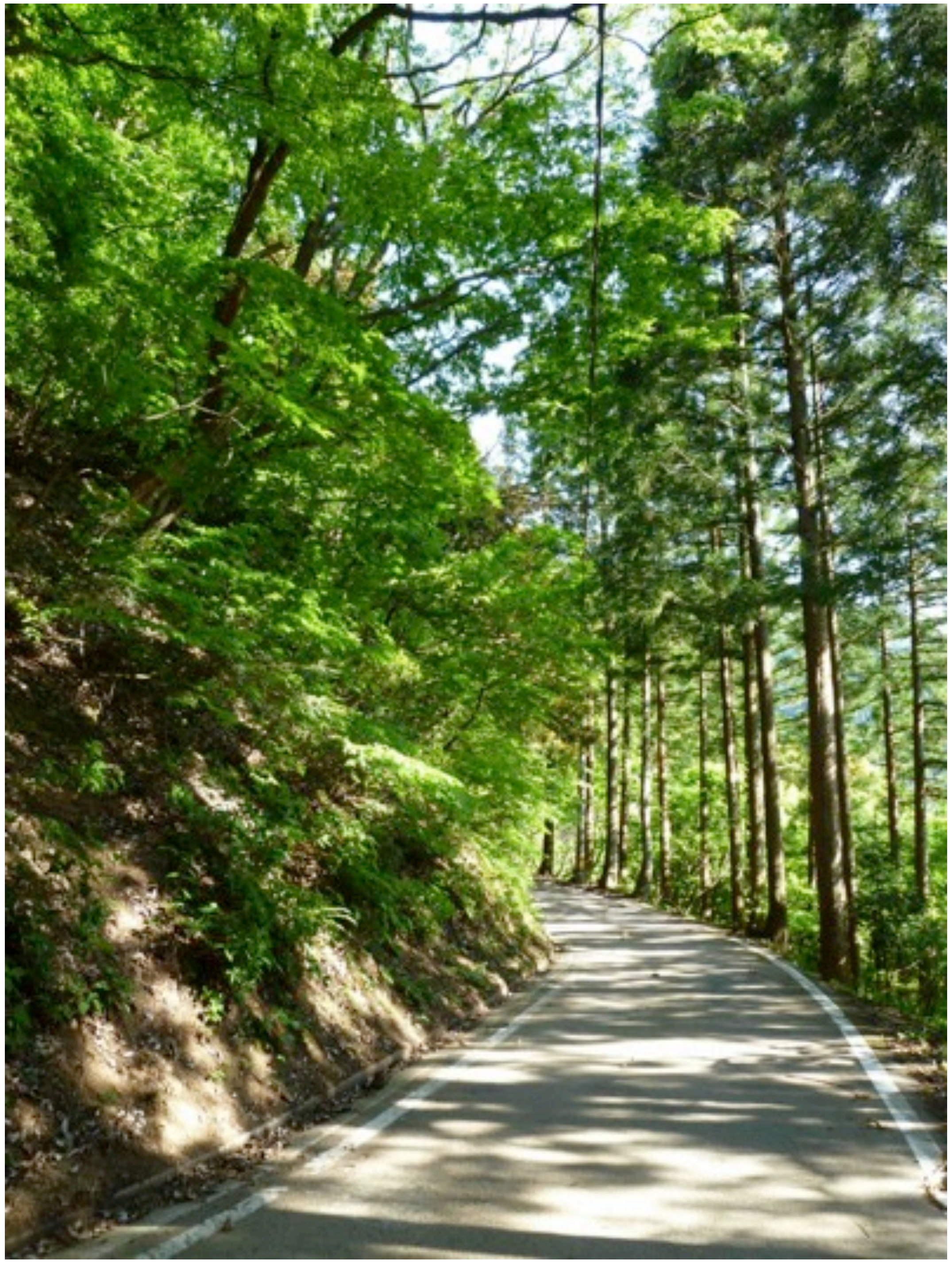
$$\Delta m^2 \sim \frac{E}{L}$$

$$\sim \frac{3\,MeV}{2\times 10^5\,m} \sim 10^{-5} eV^2$$

Reactors in and near Japan



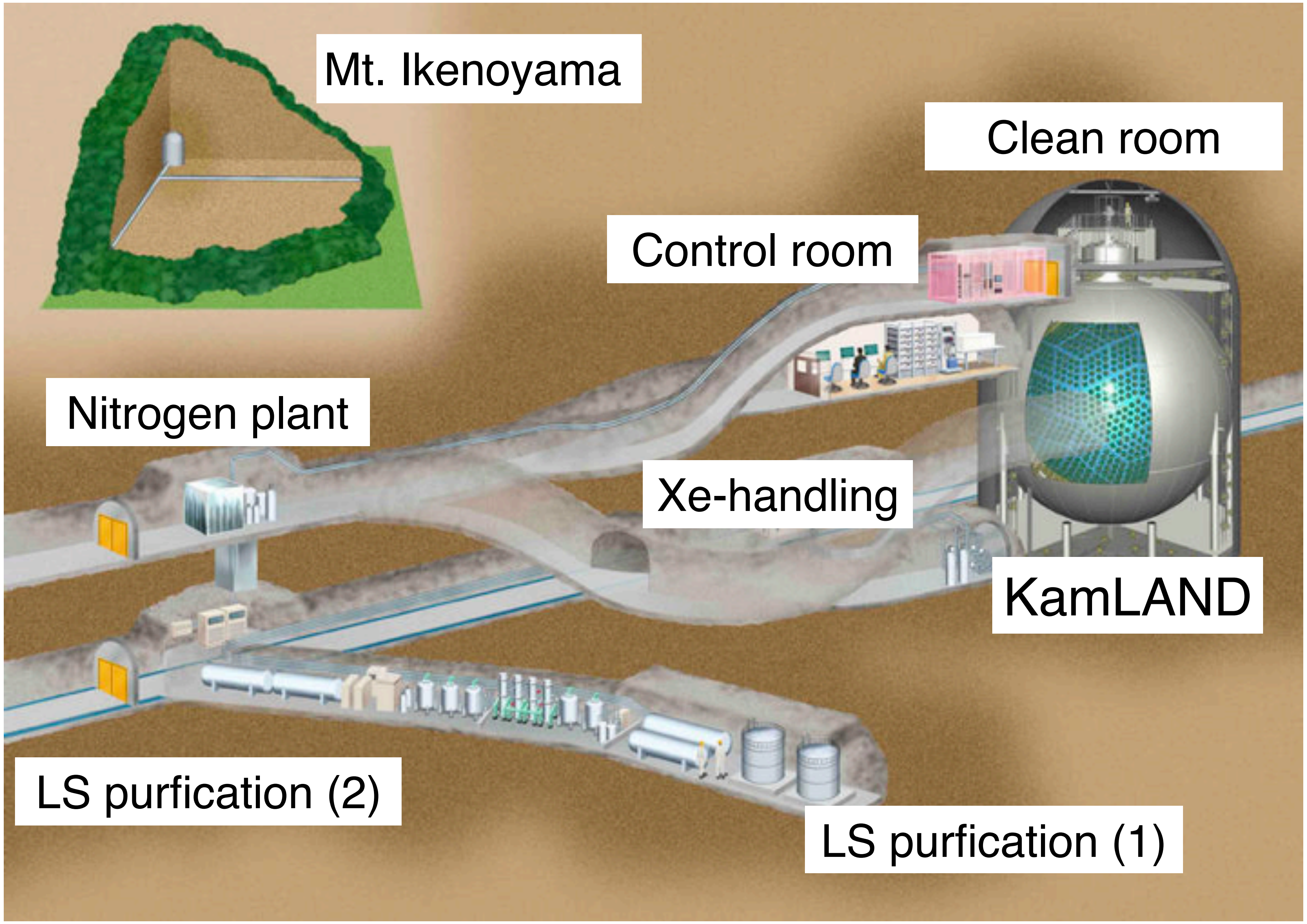
. . . beautiful countryside ....



. . . historic villages ...

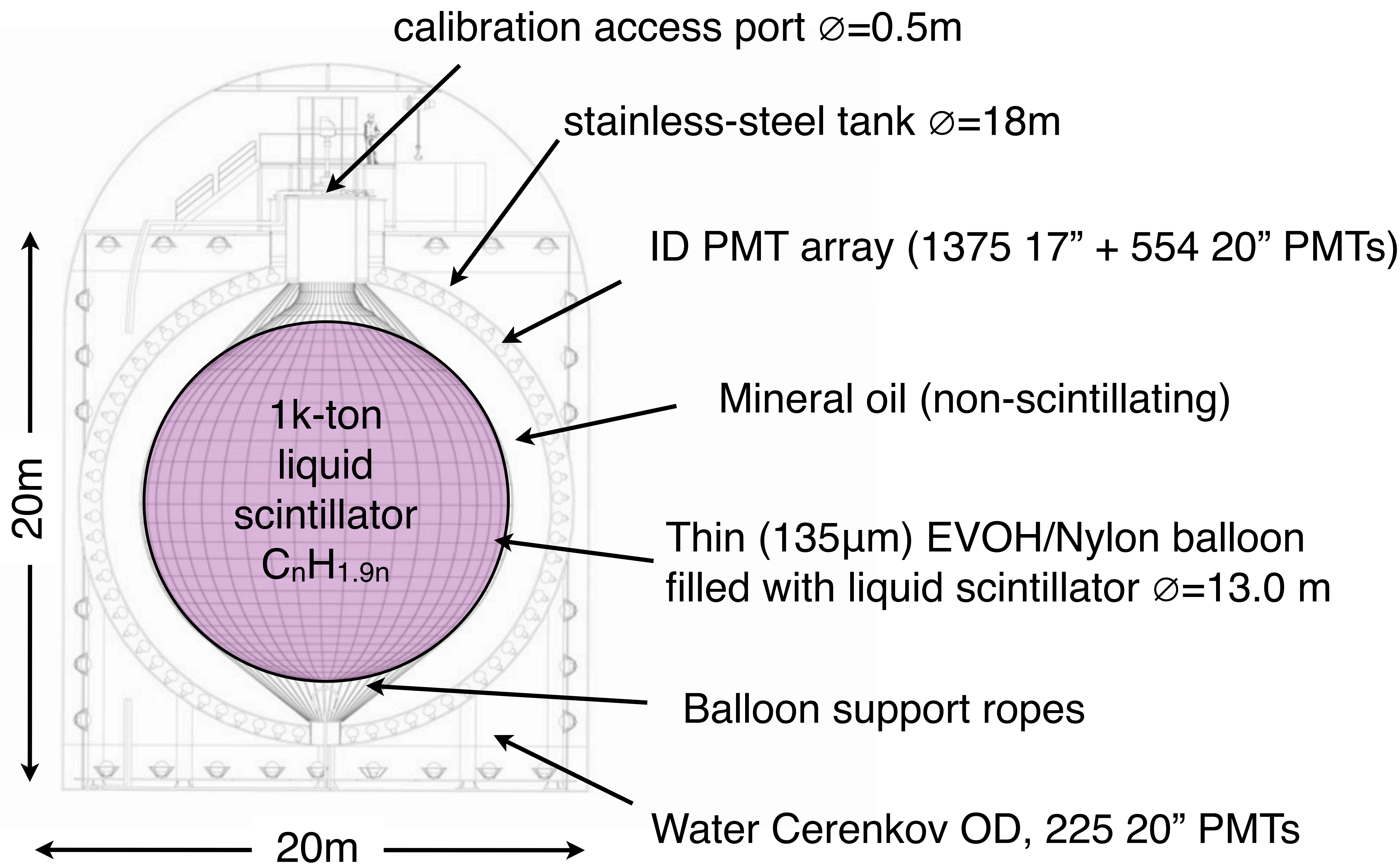
KamLAND Facility

- Under ground:



- Above ground: operations center, computing farm

KamLAND Detector



KamLAND-Zen Addition

- Idea to mount a volume of Xe-loaded LS in the center of KamLAND, really started to take shape in 2009

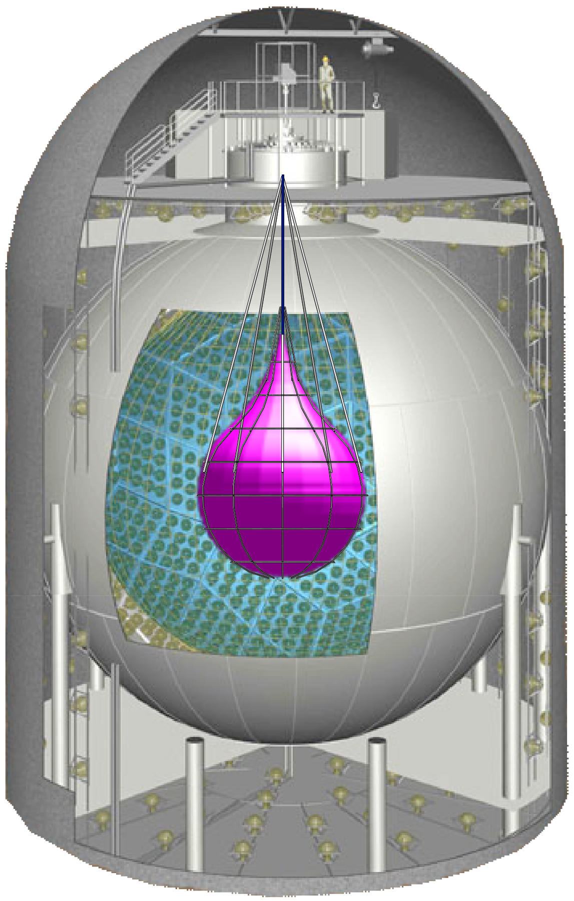
- Several advantages:

    - KamLAND-LS provides ultra-pure active shield

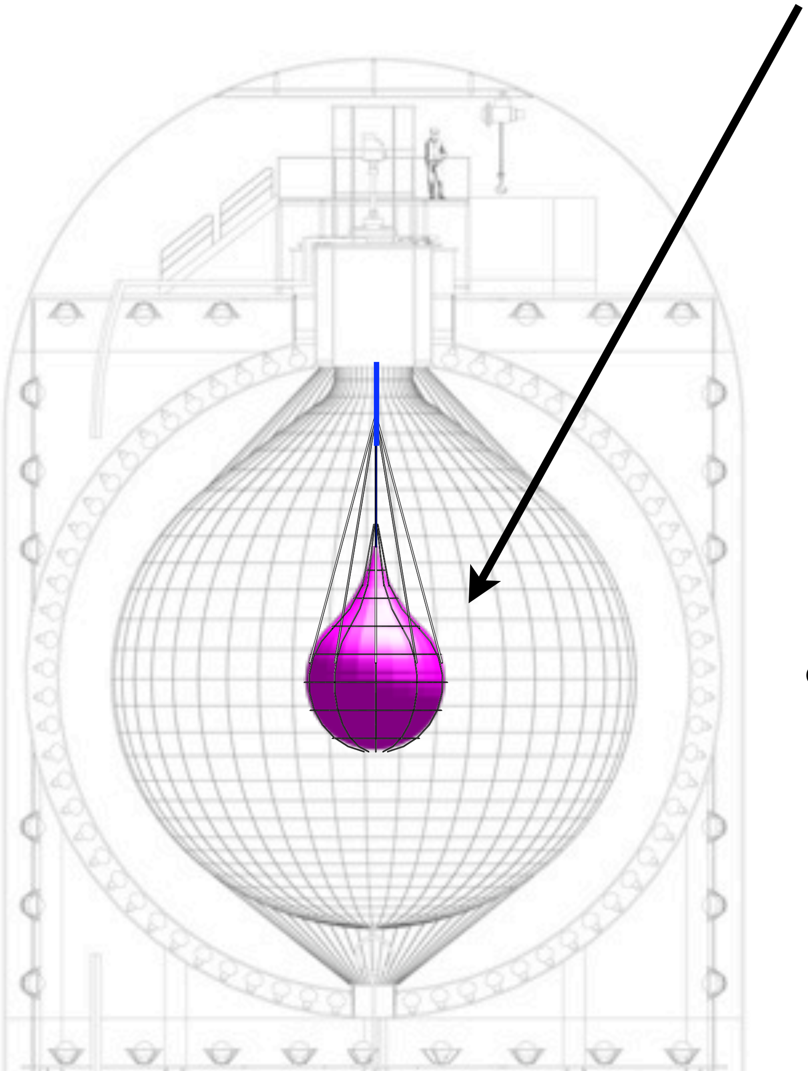
    - Mature detector, expertise and analysis tools

    - Potential to achieve large 0vBB target mass quickly

    - Possible to continue antineutrino program at KamLAND



KamLAND-Zen Experiment



- Mini-balloon ∅=3.08 m installed into center of KamLAND LS, 25μm thick nylon film

^{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

- Filled with 13 tons of Xe-loaded LS (300kg of ^{136}Xe) :

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±0.05% ^{136}Xe 8.89±0.01% ^{134}Xe	2.5% by weight

- KL-Zen is only ~1.4% of KamLAND volume: reactor, geoneutrino, supernova watch . . . continue in remaining KamLAND LS

KamLAND-Zen Experiment

- Inner-balloon fabricated in class 1 cleanroom near Sendai Spring 2011
- Great Eastern Japan Earthquake occurred (3/11/11)

Test balloon at Kamioka

Practice installation at swimming pool

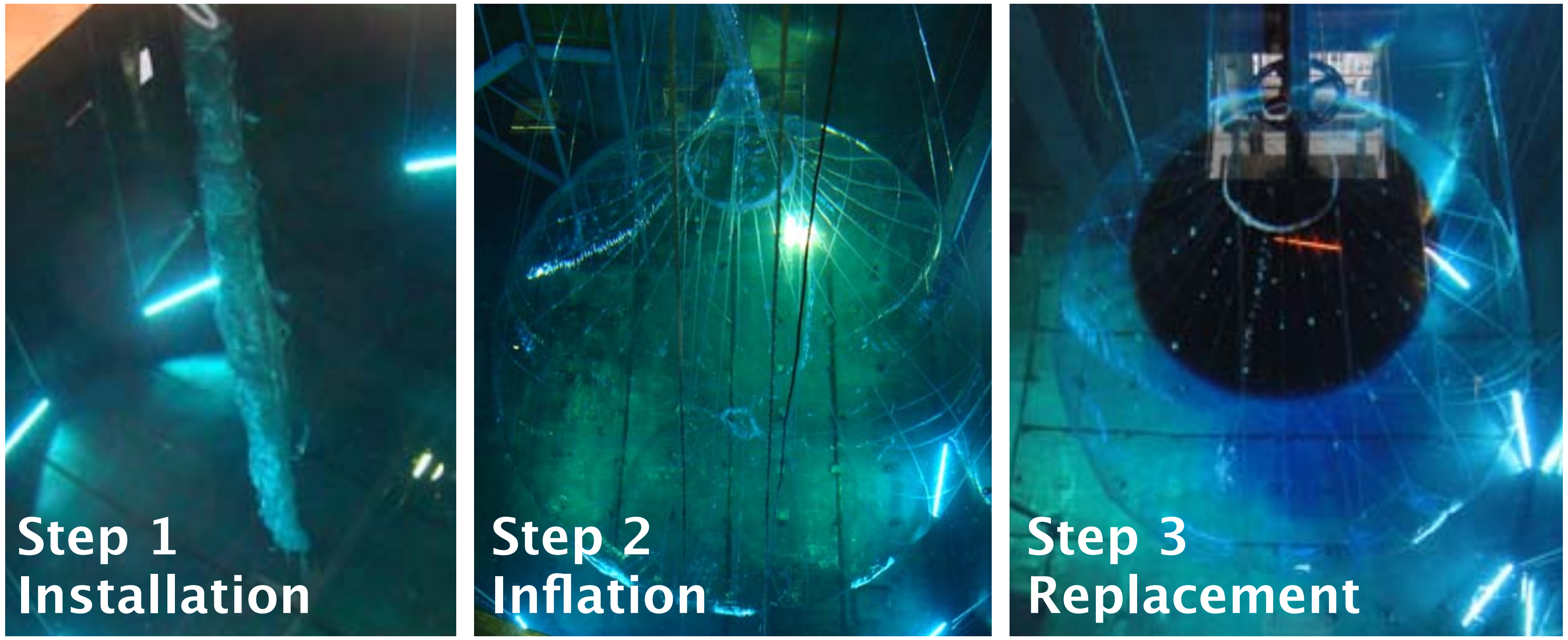


Figure courtesy of A. Gando 'First Results of Neutrinoless double beta decay Search with KamLAND-Zen', PhD Thesis, Tohoku University 2012

- Mini balloon was installed and filled in August 2011 - KamLAND-Zen began !

KamLAND/KamLAND-Zen Data taking

- 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

Detector Response

- 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

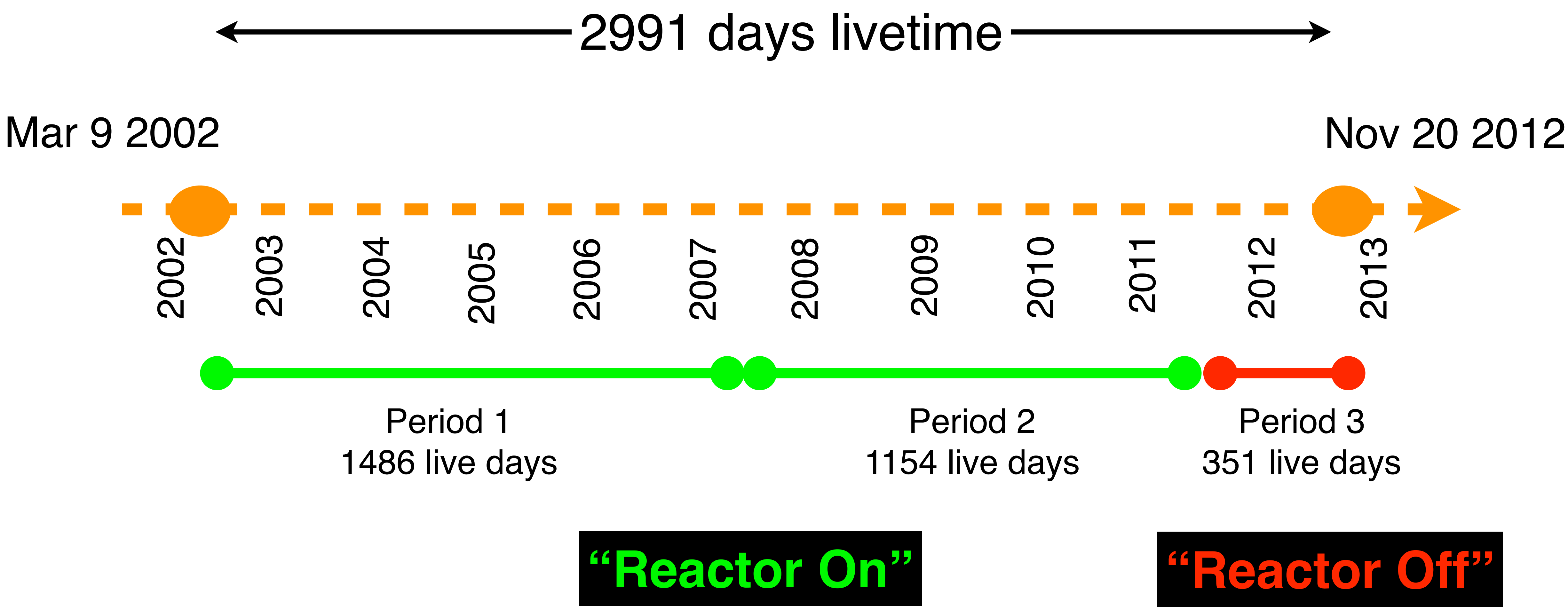
Scintillator nonlinearity from quenching

Fraction of visible energy (photo electrons) from Cherenkov effects

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

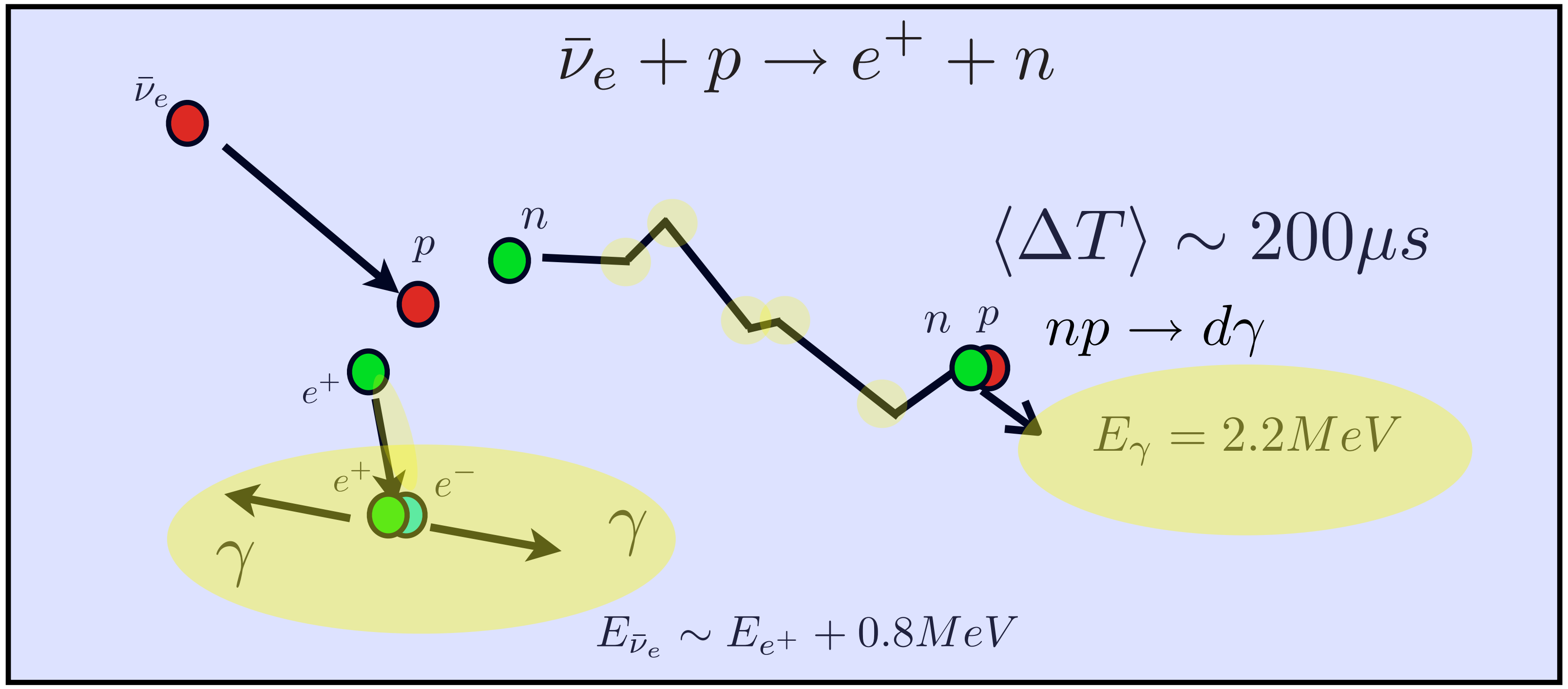
Reactor On/Off Antineutrino Dataset

- Fukushima nuclear accident triggered a regulatory shutdown of entire Japanese nuclear industry for safety review
- Dataset includes full 10 year history of KamLAND, with this new low-flux period



Antineutrino Measurement

- Antineutrinos detected via inverse beta decay reaction



- Basic antineutrino selection cuts:

Cut Name	Selection
Prompt energy	$0.9 < E_p(\mathrm{MeV}) < 8.5$
Delayed energy	$1.8 < E_d(\mathrm{MeV}) < 2.6$ $4.4 < E_d(\mathrm{MeV}) < 5.6$
Prompt-Delayed spatial separation	$\lvert\vec{R}_p - \vec{R}_d\rvert(\mathrm{m}) < 2.0$
Prompt-Delayed time separation	$0.5 < (t_d - t_p)(\mu\, s) < 1000.0$

What do we measure ?

$$\mathcal{S}_{KL}(E,t) =$$

$$\left\{ \sum_i \frac{\mathcal{F}_i(t)}{4\pi L_i^2} \sum_j f_{i,j}(t) \hat{S}_j(E) \times P(\bar{\nu}_e \to \bar{\nu}_e, L_i, E) + B(E,t) \right\} \otimes D(E,t)$$

What do we measure ?

$$\mathcal{S}_{KL}(E,t) =$$

$$\left\{ \sum_i \frac{\mathcal{F}_i(t)}{4\pi L_i^2} \sum_j f_{i,j}(t)\hat{S}_j(E) \times P(\bar{\nu}_e \rightarrow \bar{\nu}_e, L_i, E) + B(E,t) \right\} \otimes D(E,t)$$

- Depends on reactors
- Physics of interest
- Backgrounds
- Convolve with detection effects
  - ➡ cross section
  - ➡ detector response

Reactor contribution

$$\mathcal{S}_{KL}(E,t) =$$

$$\left\{ \sum_i \frac{\mathcal{F}_i(t)}{4\pi L_i^2} \sum_j f_{i,j}(t)\hat{S}_j(E) \times P(\bar{\nu}_e \rightarrow \bar{\nu}_e, L_i, E) + B(E,t) \right\} \otimes D(E,t)$$

	Parameter	Determination
L_i	base line of reactor i	-
$\mathcal{F}_i$	number of fissions in reactor i	thermal power output
$f_{i,j}$	fission fraction due to fuel isotope j	fuel composition, reactor burnup
$\hat{S}_j$	$\bar{\nu}_e$ spectrum per fission of isotope j	. . . long story . . .

- >99.9% of fissions come from ^{235}U(56%), ^{238}U (8%),^{239}Pu (30%), & ^{241}Pu (6%)
- We use shape of "improved S_j" but normalize to cross-section per fission of each reactor is adjusted to reproduce the Bugey4 measurement (1.4 % uncertainty)

Backgrounds

$$\mathcal{S}_{KL}(E,t) =$$

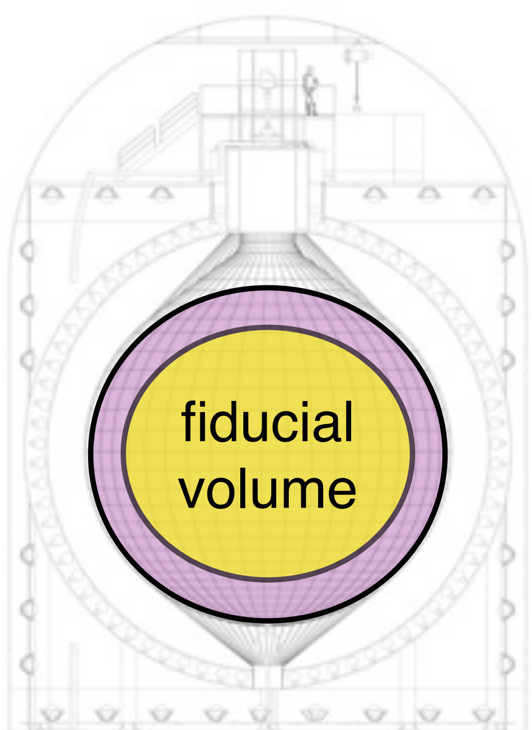
$$\left\{ \sum_i \frac{\mathcal{F}_i(t)}{4\pi L_i^2} \sum_j f_{i,j}(t)\hat{S}_j(E) \times P(\bar{\nu}_e \rightarrow \bar{\nu}_e, L_i, E) + B(E,t) \right\} \otimes D(E,t)$$

- Accidental coincidences
- alpha-n processes: $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$
- Geo-neutrinos
- Others:
  - Spallation products (^{9}Li/^{8}He)
  - Atmospheric neutrinos and fast neutrons

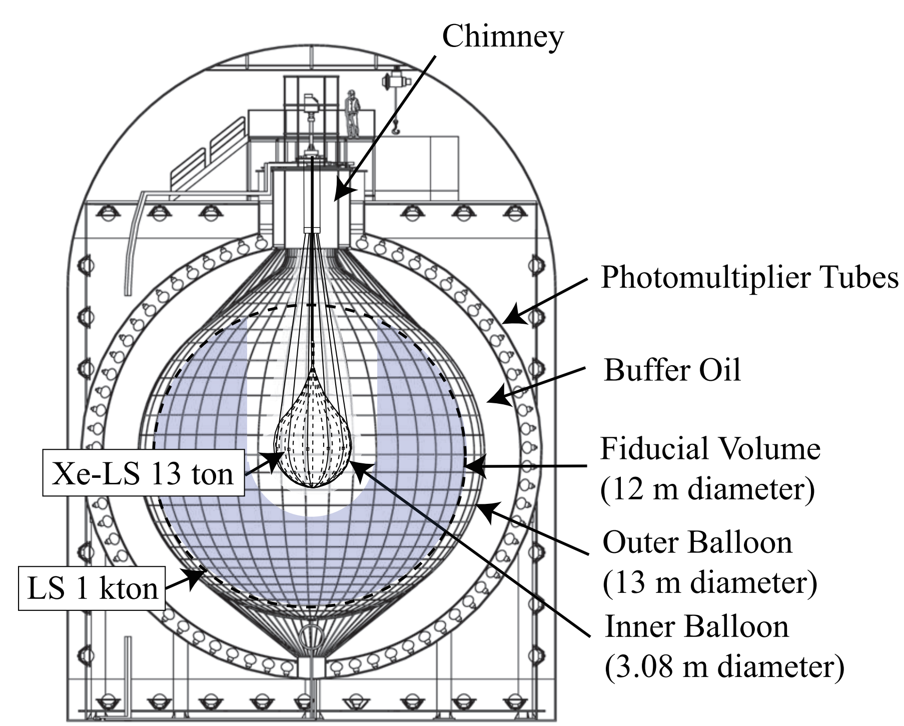
Backgrounds: Accidentals

- Mostly caused by low energy radioactivity on big balloon (prompt) and ^{208}Tl-γ (delayed)
- Controls:
  - Fiducial volume cut (R_p <6m,R_d<6m)
  - liquid scintillator purification 2007~2009
  - Joint PDF $P(E_d,R_p,R_d,dR_{p\text{-}d},dT_{p\text{-}d})$ is different for accidental and signal-like pairs, use this to construct likelihood selection (a.k.a L_{Cut})

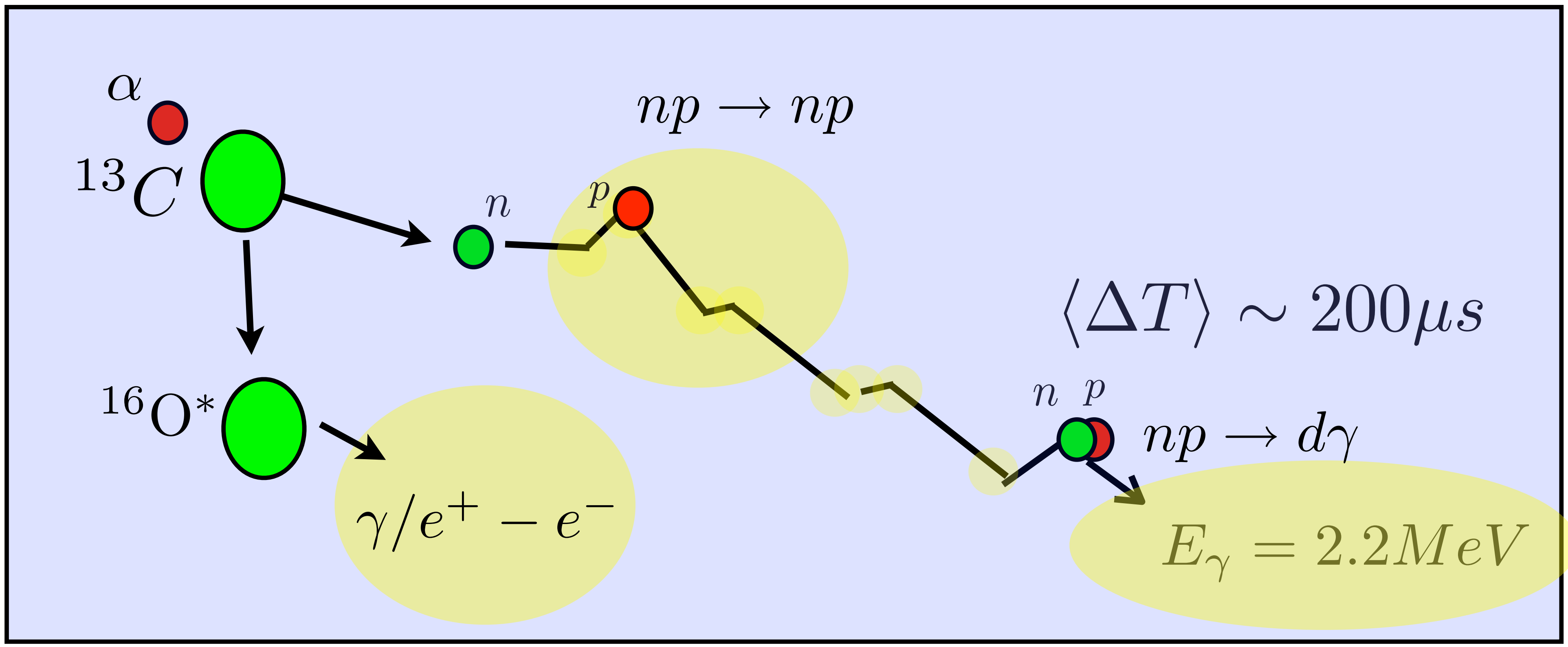
Period 1+2: Simple spherical cut



Period 3: Also veto volume around Zen balloon



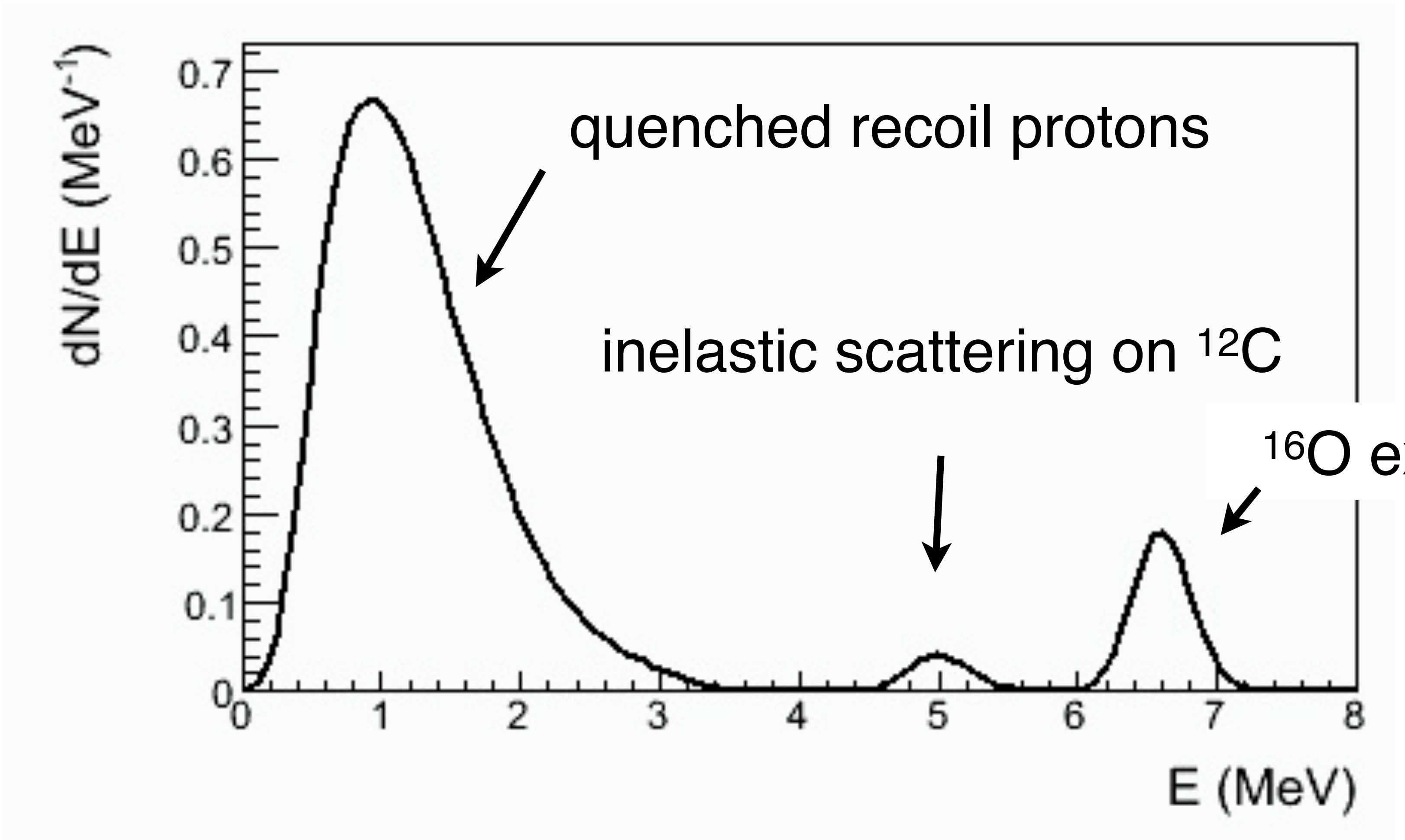
Backgrounds: alpha-n



- Dominant α-source: ^{210}Po (daughter of ^{222}Rn)
- Mimics inverse β decay:

Backgrounds: alpha-n

Simulated prompt α-n spectrum

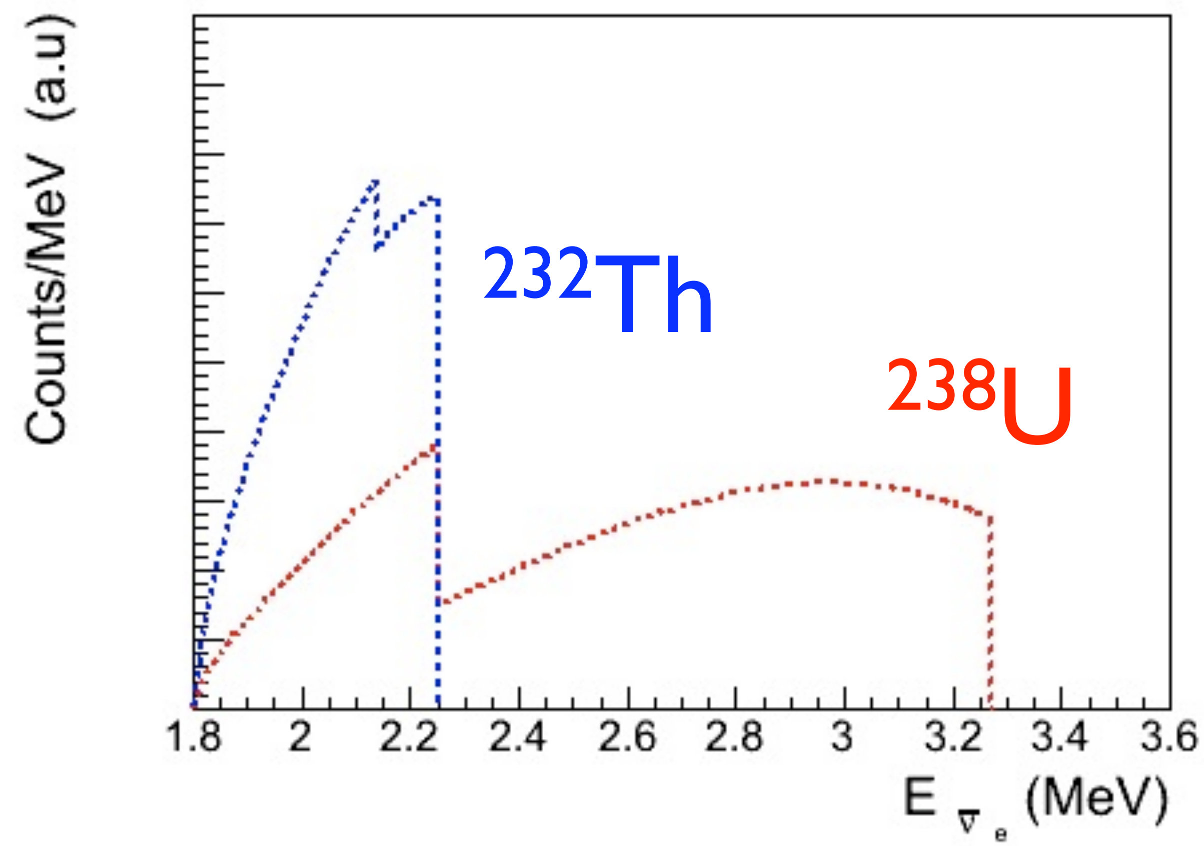


- simulation tested with ^{210}Po-^{13}C calibration source
- ^{210}Pb rate reduced 20-fold by liquid scintillator purification in 2007~2009

Backgrounds: Geo-neutrinos

- anti-neutrinos expected from decays of ^{232}Th, ^{238}U in the earth

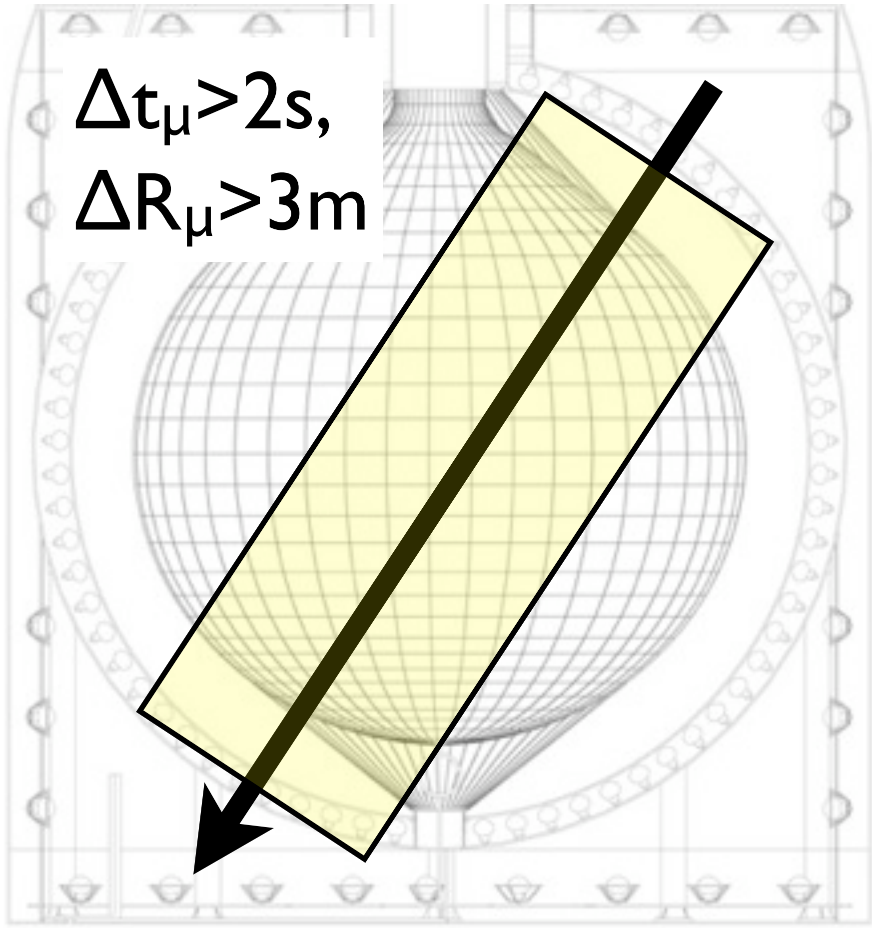
Expected inverse β decay spectrum



- expected geo-neutrino rate is very model dependent, only spectrum shape is used in the analysis

- geo-neutrinos are an interesting ‘signal’ in their own right . . . more later

Backgrounds: Spallation



- ^{9}Li/^{8}He produced by cosmic rays
  - Delayed neutron beta emitter (τ ~200 ms)
  - Veto pairs within 2s of muon and 3m cylinder of well tracked muons

- Fast neutrons produced by untagged muons in the OD, contribution estimated by GEANT4 simulation

- Atmospheric neutrino contribution estimated with NUANCE simulation

Background Summary

TABLE I: Estimated backgrounds for $\overline{\nu}_e$ in the energy range between 0.9 MeV and 8.5 MeV after event selection cuts.

	Background	Period 1 (1486 days)	Period 2 (1154 days)	Period 3 (351 days)	All Periods (2991 days)
1	Accidental	76.1 ± 0.1	44.7 ± 0.1	4.7 ± 0.1	125.5 ± 0.1
2	^{9}Li/^{8}He	17.9 ± 1.4	11.2 ± 1.1	2.5 ± 0.5	31.6 ± 1.9
3	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}_{\mathrm{g.s.}}$, elastic scattering	160.4 ± 16.4	16.5 ± 3.8	2.3 ± 1.0	179.0 ± 21.1
	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}_{\mathrm{g.s.}}$, $^{12}\mathrm{C}(n, n')^{12}\mathrm{C}^{*}$ (4.4 MeV γ)	6.9 ± 0.7	0.7 ± 0.2	0.10 ± 0.04	7.7 ± 0.9
4	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}^{*}$, 1st e.s. (6.05 MeV $e^{+}e^{-}$)	14.6 ± 2.9	1.7 ± 0.5	0.21 ± 0.09	16.5 ± 3.5
	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}^{*}$, 2nd e.s. (6.13 MeV γ)	3.4 ± 0.7	0.4 ± 0.1	0.05 ± 0.02	3.9 ± 0.8
5	Fast neutron and atmospheric neutrino	< 7.7	< 5.9	< 1.7	< 15.3
Total		279.2 ± 22.1	75.2 ± 7.6	9.9 ± 2.1	364.1 ± 30.5

- Geo-neutrino constrained by spectrum

Candidates expected from reactors (no oscillation)	3564 +/- 145
Candidates expected from background (ex. geo-nu)	364.1 +/- 30.5
Candidates observed	2611

Antineutrino Analysis

- Oscillation framework

$$P_{ee}^{3\nu} = \cos^4\theta_{13}\widetilde{P}_{ee}^{2\nu} + \sin^4\theta_{13} \ .$$

$$\widetilde{P}_{ee}^{2\nu} = 1 - \sin^2 2\theta_{12M}\sin^2\left(\frac{\Delta m_{21M}^2 L}{4E_\nu}\right),$$

$$\sin^2 2\theta_{12M} = \frac{\sin^2 2\theta_{12}}{(\cos 2\theta_{12} - A/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}} \ ,$$

$$\Delta m_{21M}^2 = \Delta m_{21}^2\sqrt{(\cos 2\theta_{12} - A/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}} \ .$$

- Likelihood for unbinned maximum likelihood analysis

$$\begin{aligned}\chi^2 \ = \ & \chi_{\mathrm{rate}}^2(\theta_{12}, \theta_{13}, \Delta m_{21}^2, N_{\mathrm{BG}1\to5}, N_{\mathrm{U,Th}}^{\mathrm{geo}}, \alpha_{1\to4}) \\ & -2\ln L_{\mathrm{shape}}(\theta_{12}, \theta_{13}, \Delta m_{21}^2, N_{\mathrm{BG}1\to5}, N_{\mathrm{U,Th}}^{\mathrm{geo}}, \alpha_{1\to4}) \\ & +\chi_{\mathrm{BG}}^2(N_{\mathrm{BG}1\to5}) + \chi_{\mathrm{syst}}^2(\alpha_{1\to4}) \\ & +\chi_{\mathrm{osci}}^2(\theta_{12}, \theta_{13}, \Delta m_{21}^2) \ .\end{aligned}$$

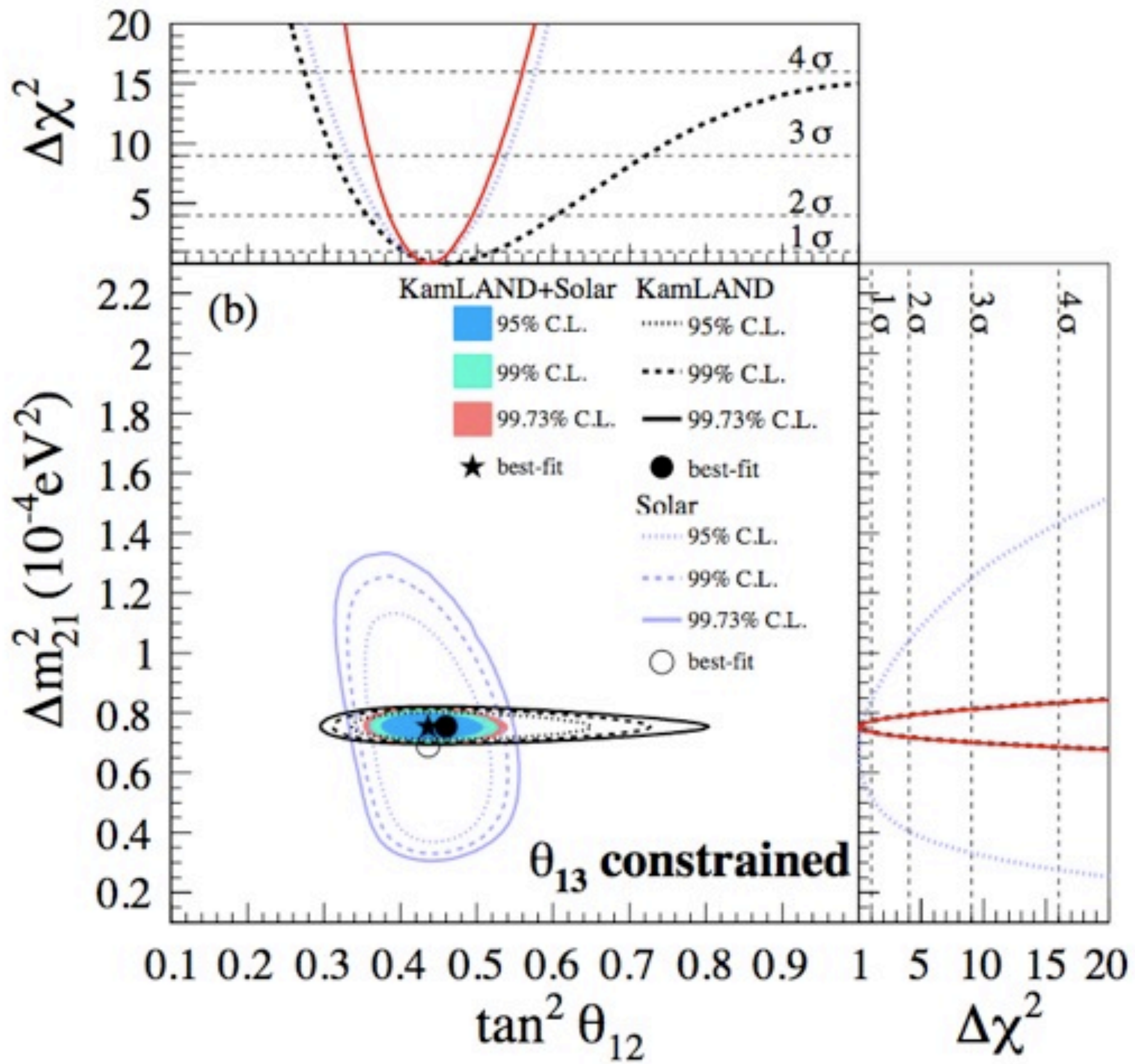
This term used to incorporate constraints from other experiments

Systematic Error Summary

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8 / 1.8	$\overline{\nu}_e$-spectra [32]	0.6 / 0.6
Rate	Fiducial volume	1.8 / 2.5	$\overline{\nu}_e$-spectra [24]	1.4 / 1.4
	Energy scale	1.1 / 1.3	Reactor power	2.1 / 2.1
	$L_{cut}(E_{\rm p})$ eff.	0.7 / 0.8	Fuel composition	1.0 / 1.0
	Cross section	0.2 / 0.2	Long-lived nuclei	0.3 / 0.4
	Total	2.3 / 3.0	Total	2.7 / 2.8

period 1 / period 2+3

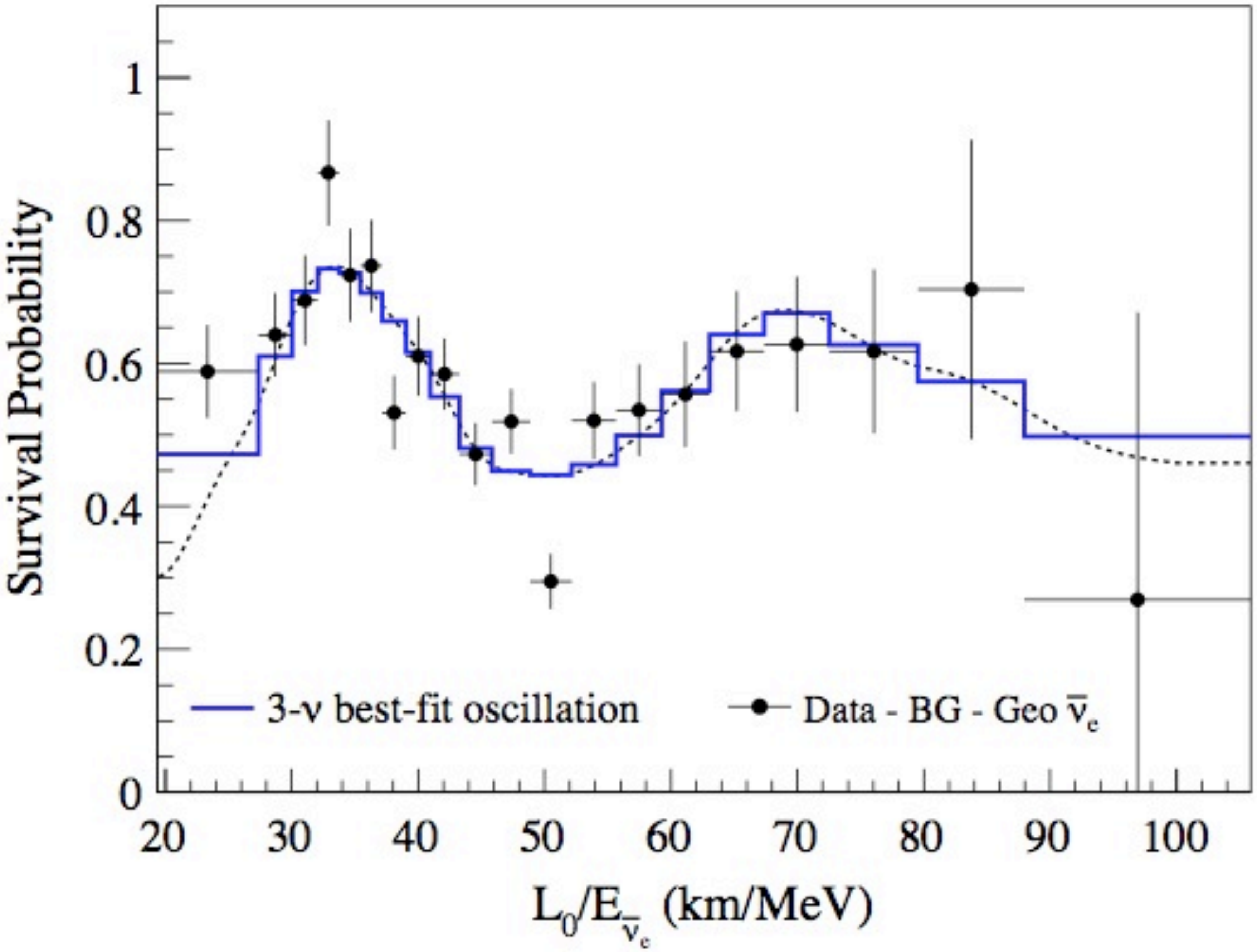
Oscillation Parameters



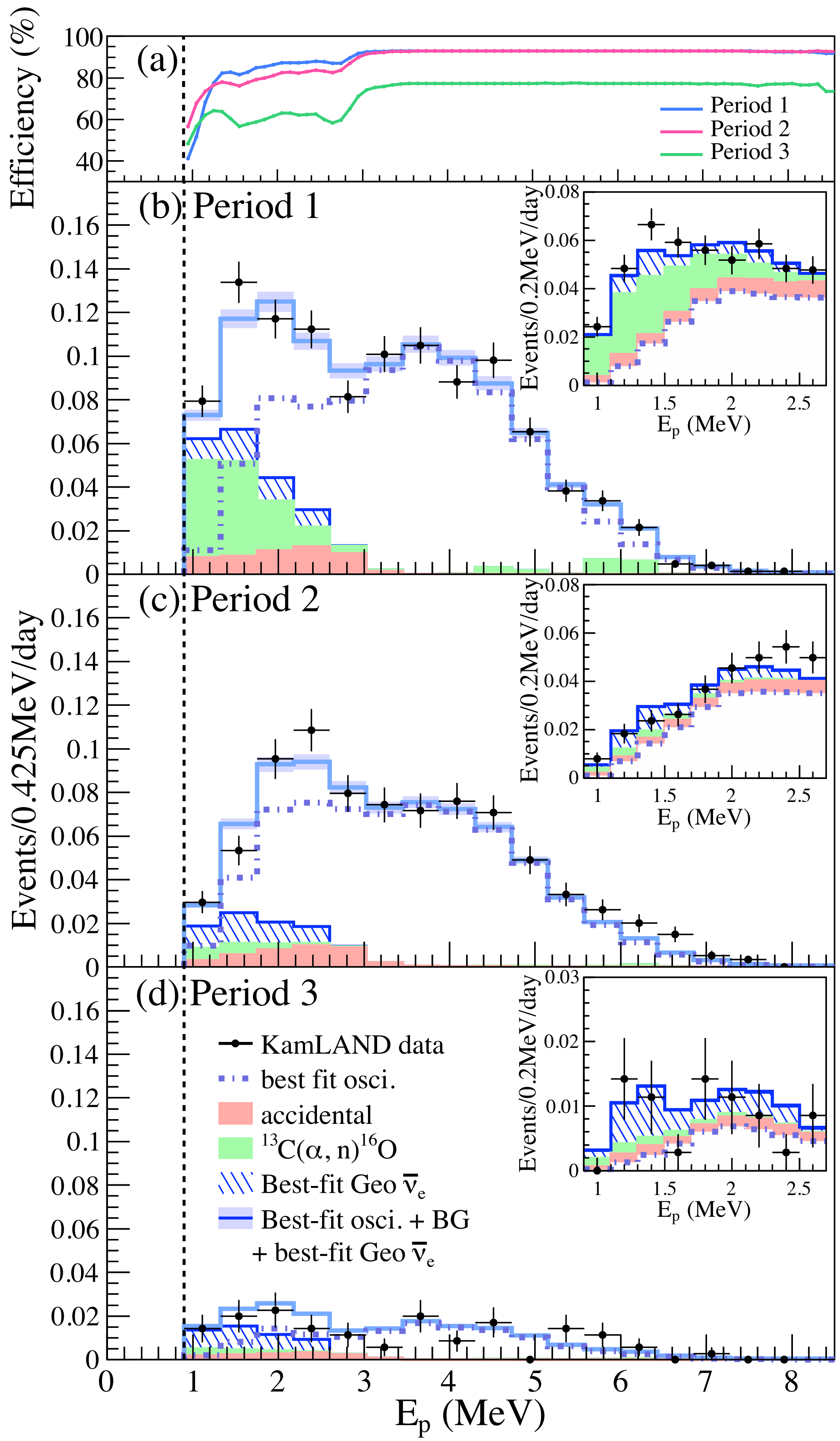
Data combination	Δm^2_{21} *	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
KamLAND	$7.54^{+0.19}_{-0.18}$	$0.481^{+0.092}_{-0.080}$	$0.010^{+0.033}_{-0.034}$
KamLAND + solar	$7.53^{+0.19}_{-0.18}$	$0.437^{+0.029}_{-0.026}$	$0.023^{+0.015}_{-0.015}$
KamLAND + solar + θ_{13}	$7.53^{+0.18}_{-0.18}$	$0.436^{+0.029}_{-0.025}$	$0.023^{+0.002}_{-0.002}$

*(x 10^{-5} eV^2)

Visualization of Survival Probability



Prompt Energy Spectrum



Period 1

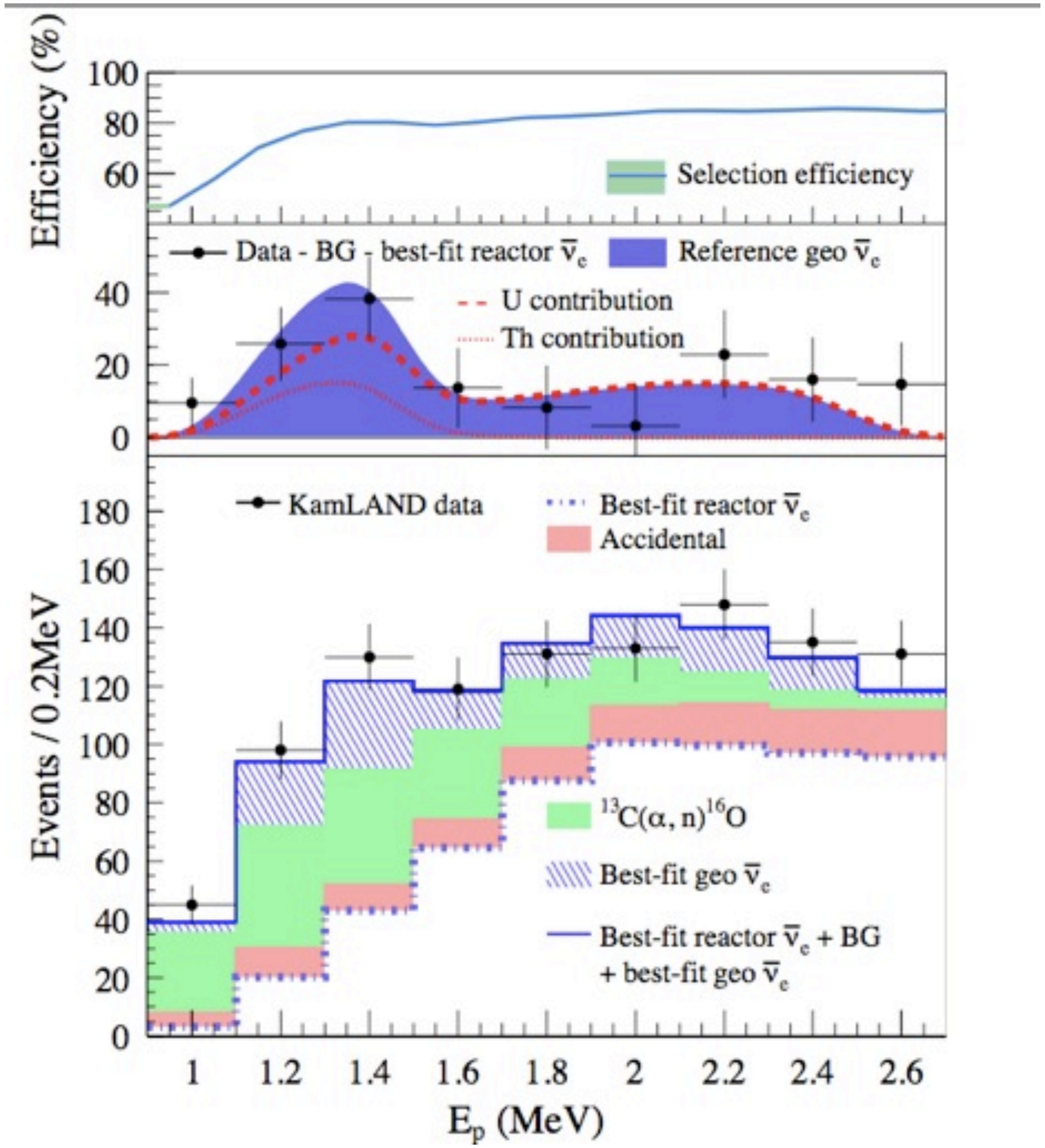
Period 2, lower bkg

Period 3, reactor “off”

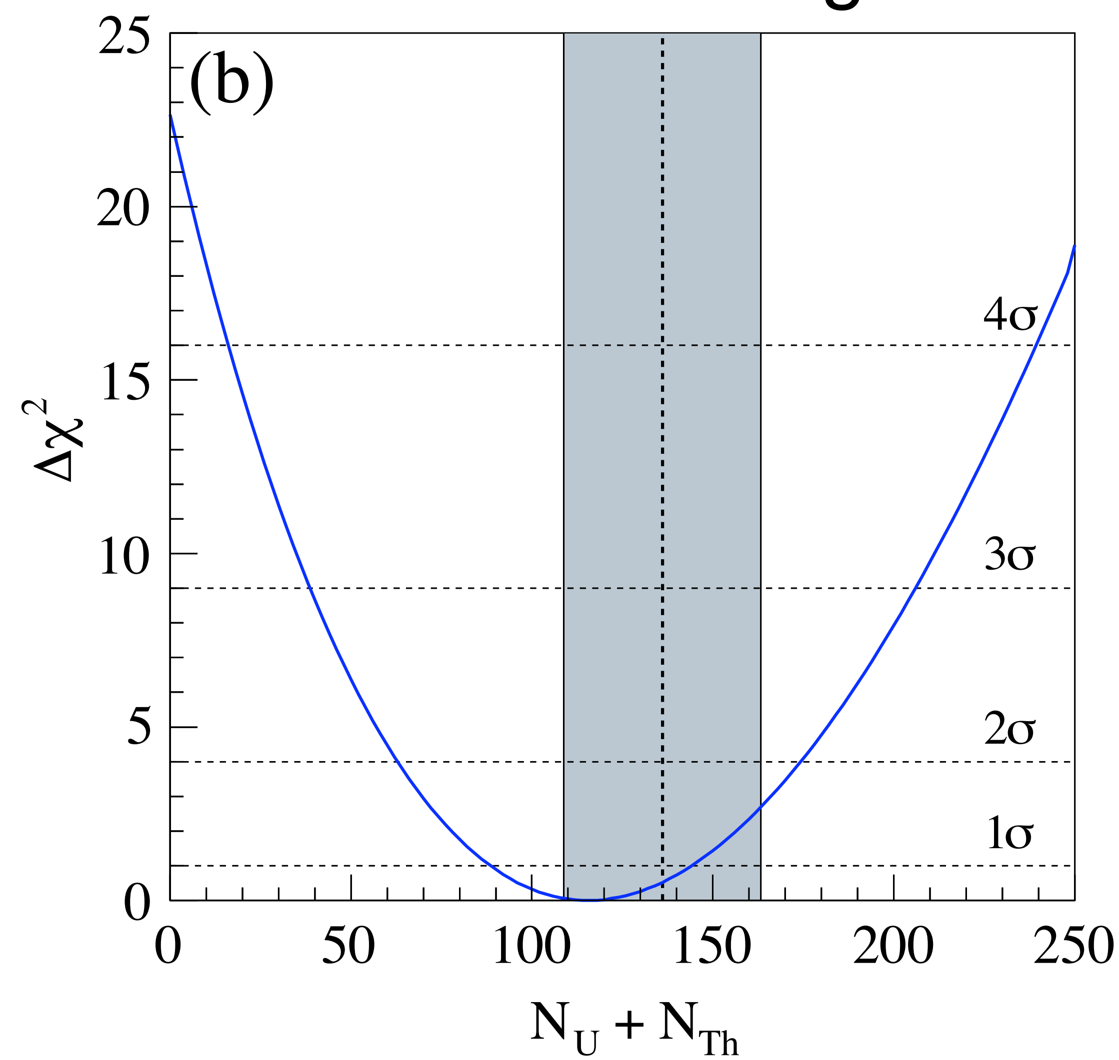
Geoneutrino measurement

- Fit yields an estimate for the geoneutrino flux

Prompt spectrum



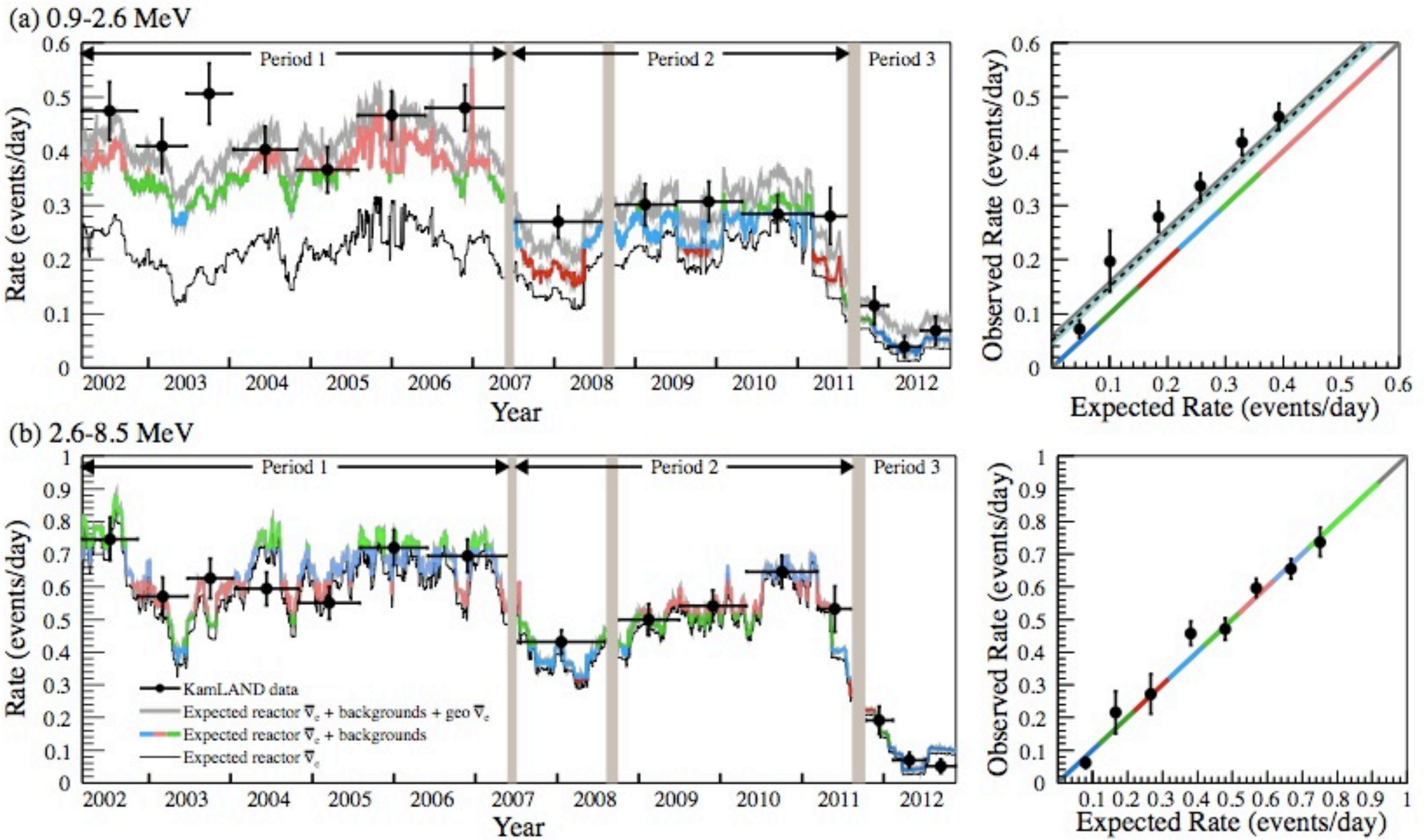
Best-fit number of geo-nu



(Th/U mass ratio fixed to 3.9)

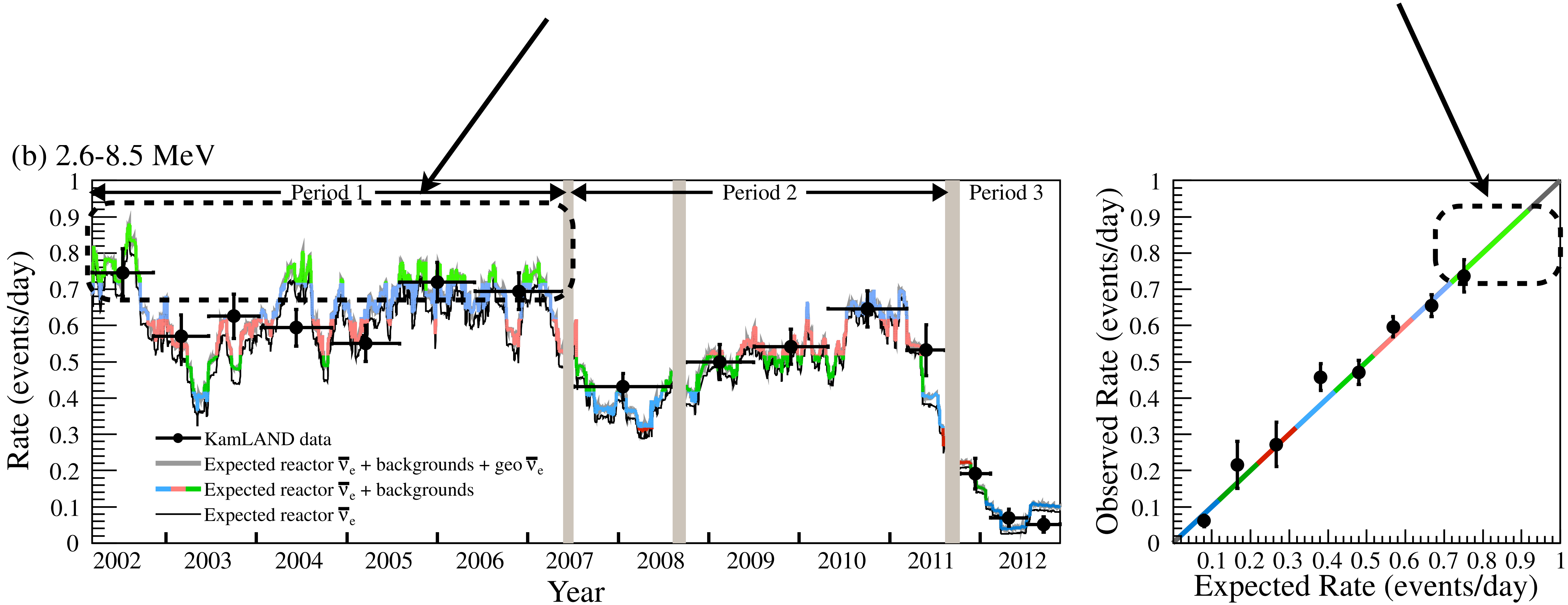
Best-fit (N_U+N_{Th}): 116 $^{+28}_{-27}$

Antineutrino flux variation at KamLAND



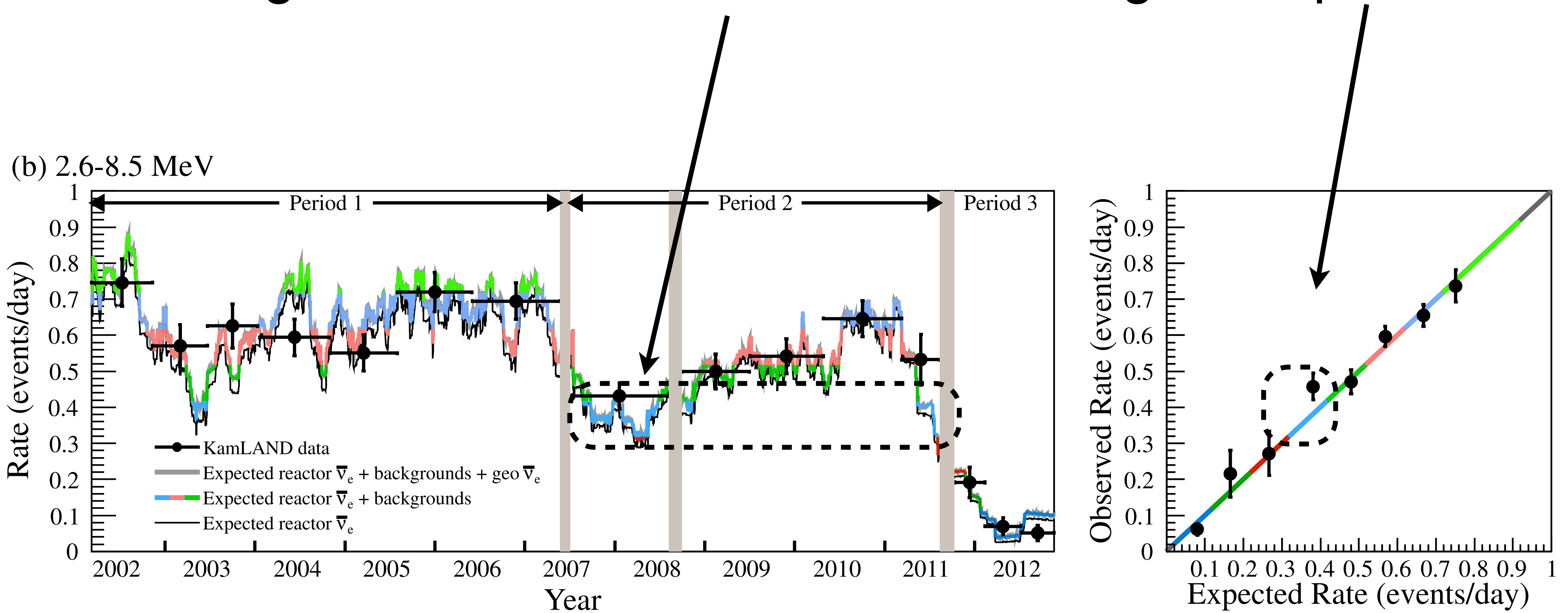
Antineutrino flux variation at KamLAND

Integrate the rate at different times to get the point



Antineutrino flux variation at KamLAND

Integrate the rate at different times to get the point



KamLAND-Zen: 1st phase 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
- Dataset summary

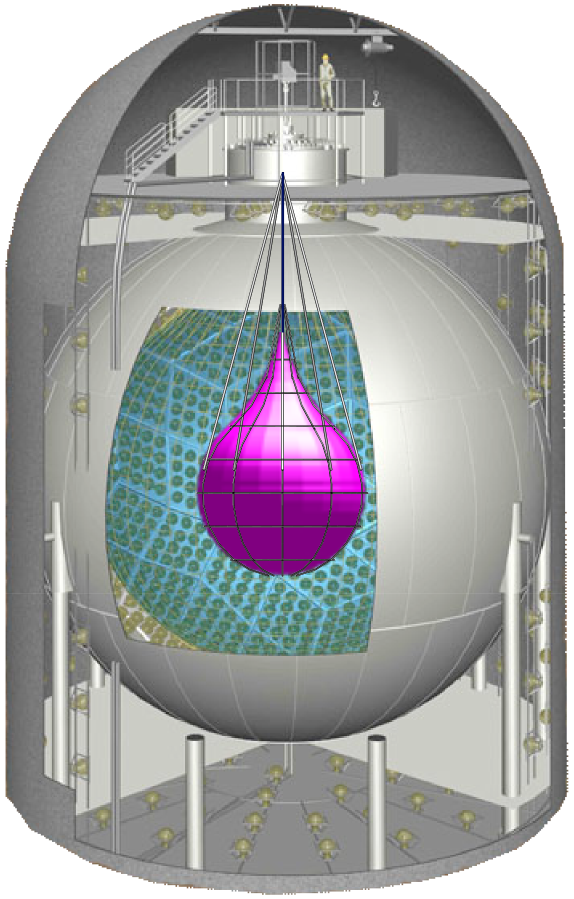
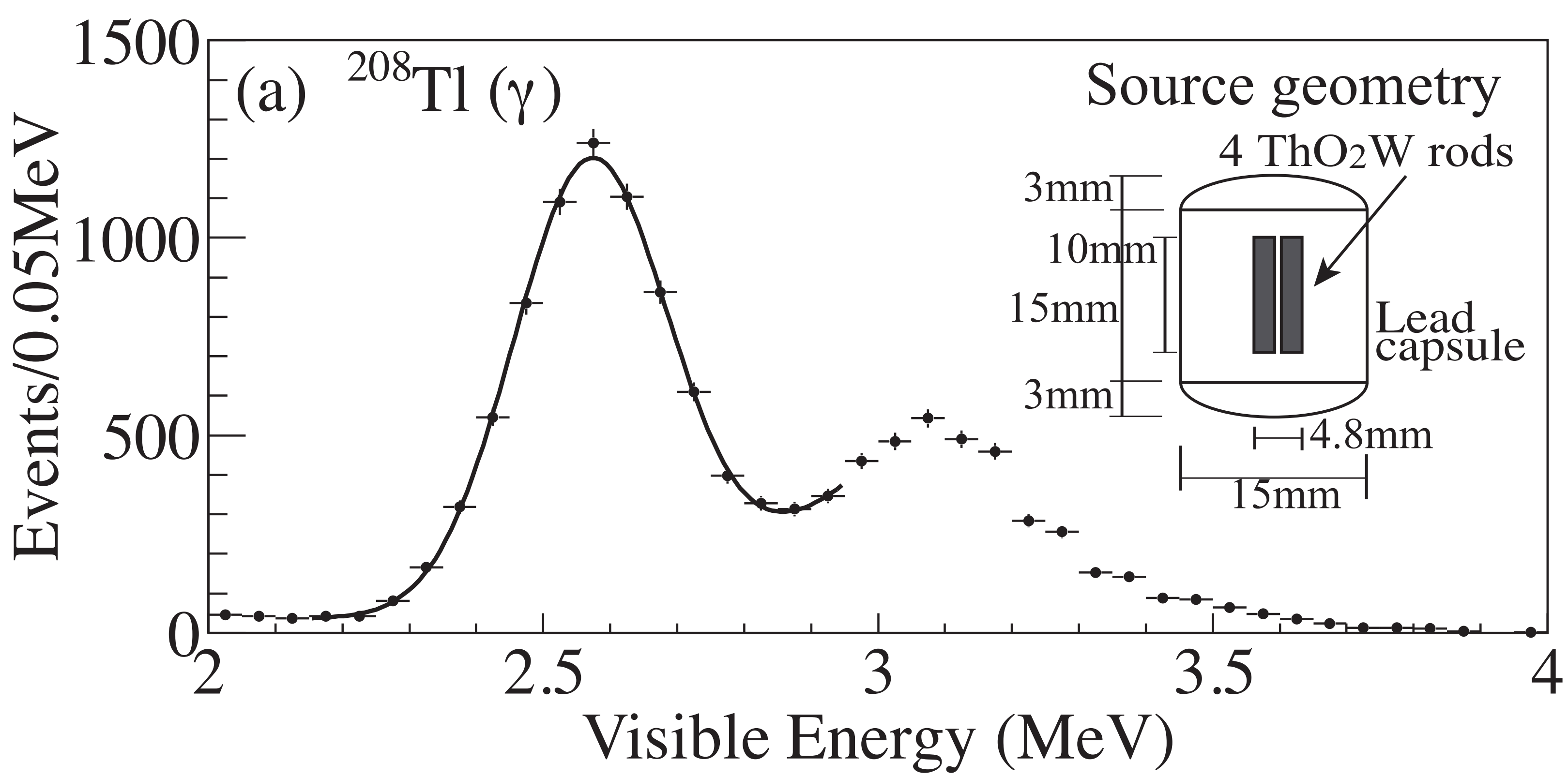


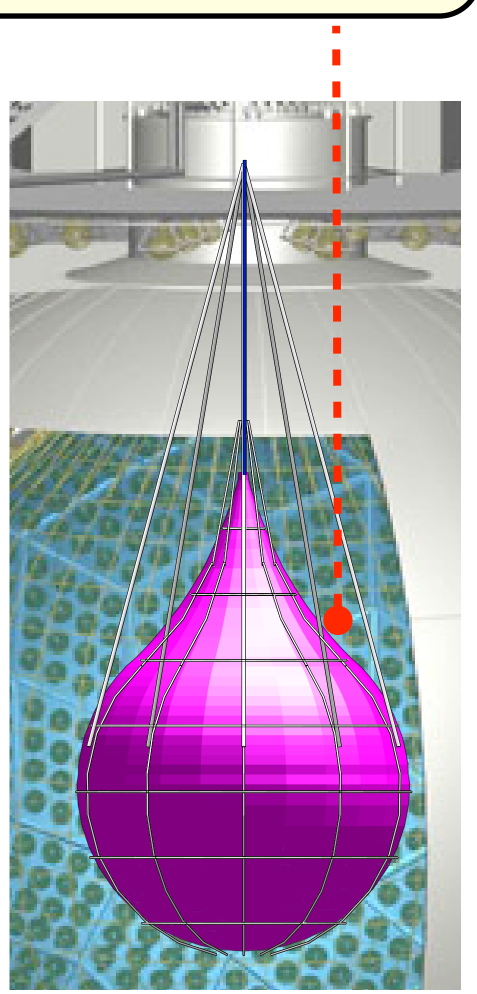
TABLE I: Two data sets used in this ^{136}Xe $0\nu\beta\beta$ decay analysis.

	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

KamLAND-Zen: Energy Calibration

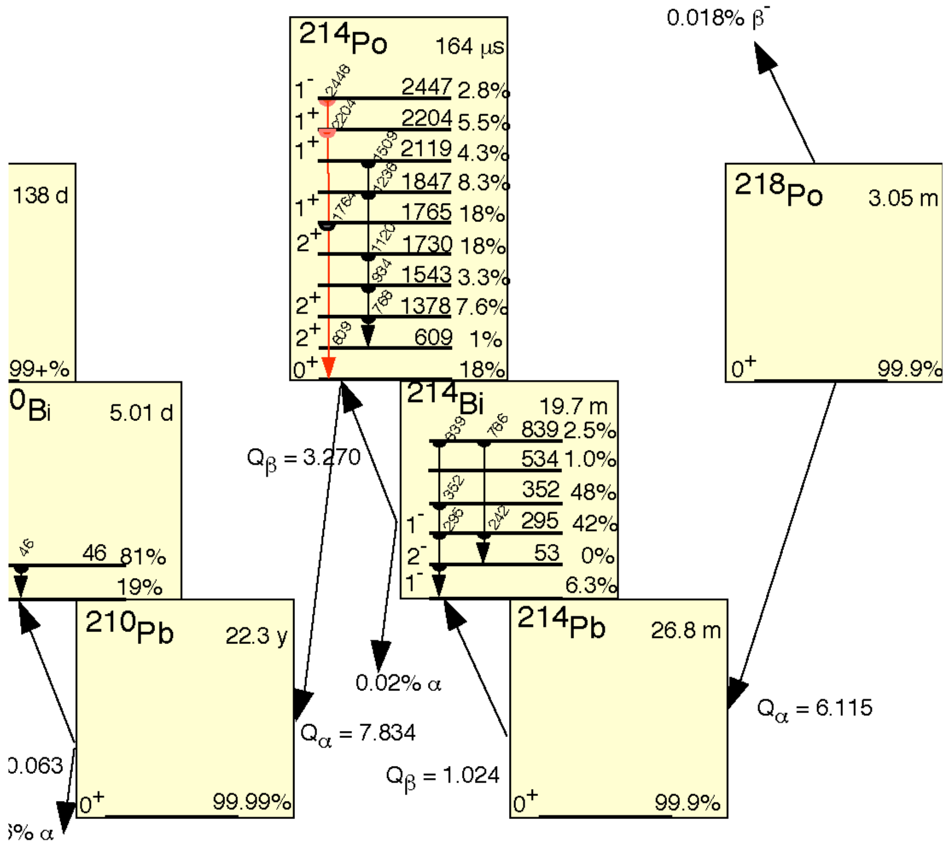
- ThO_2W source (^{208}Tl) source deployed close to outer edge of inner-balloon



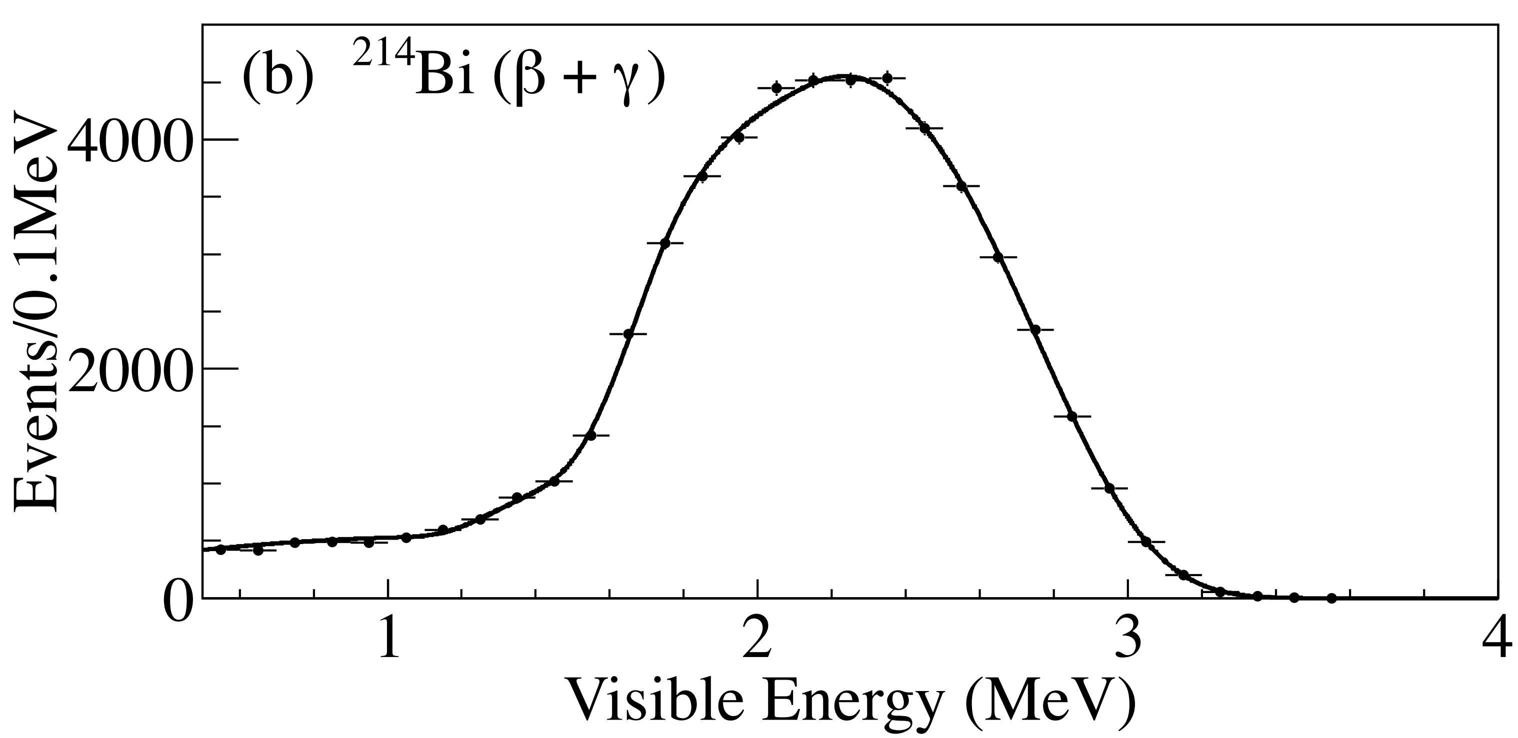


Energy resolution Xe-LS $\sigma_E/E = (6.6+/0.3)\ \%/\sqrt{E}$

KamLAND-Zen: Energy Calibration

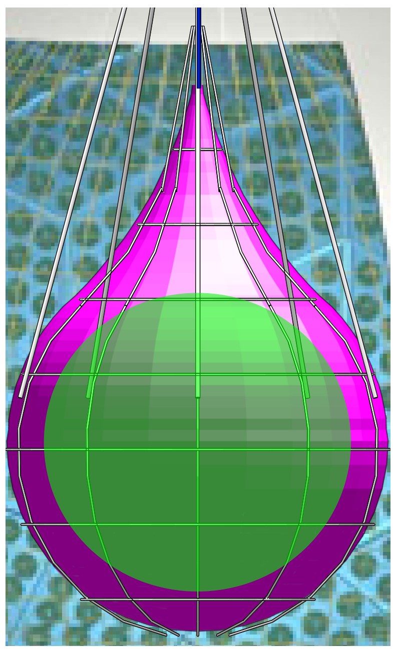


- ^{214}Bi tagged by coincidence with ^{214}Po alpha (daughter of ^{222}Rn)
- Fit to ^{214}Bi and ^{208}Tl data to determine energy scale parameters
- Stability monitored with spallation neutron capture gammas

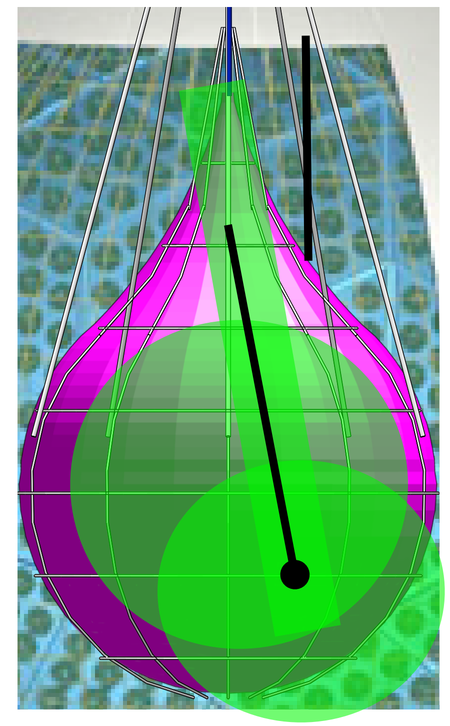


KamLAND-Zen: Event Selection

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



DS1: R<1.35m



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

- Fiducial volume cut optimized to reduce background for 0nubb analysis

KamLAND-Zen: 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)

- After fiducial volume cut bb selection efficiency: 99.8 +/- 0.2 %

- Dead time from cuts: <0.2 %

KamLAND-Zen: Remaining backgrounds

- Residual background from mini balloon
  - Events on mini balloon reconstructing inside fid. volume due to vertex resolution
  - 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
- Spallation backgrounds
  - ^{10}C and ^{11}C estimated from previous KamLAND data
  - Not much previous data on Xe spallation products. We can place limits on short lived Xe-products using post-muon data
  - Longer lived spallation products estimated to be negligible from simulation

KamLAND-Zen: 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 $\times10^{-16}$g/g
^{232}Th	1.8+/- 0.1 $\times10^{-15}$g/g

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

^{208}Bi (EC)	$\tau=5.31\times10^{5}$ 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

KamLAND-Zen: Data 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

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

KamLAND-Zen: 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

KamLAND-Zen: 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

KamLAND-Zen: 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

KamLAND-Zen: Fit Model

Signal	$2\nu\beta\beta$ $0\nu\beta\beta$	Constrained in model
Backgrounds	40K	
^{214}Bi-Po coincidences	^{222}Rn-^{210}Pb	IB contribution from balloon study
^{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
	^{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

KamLAND-Zen: 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

KamLAND-Zen: Fit Model

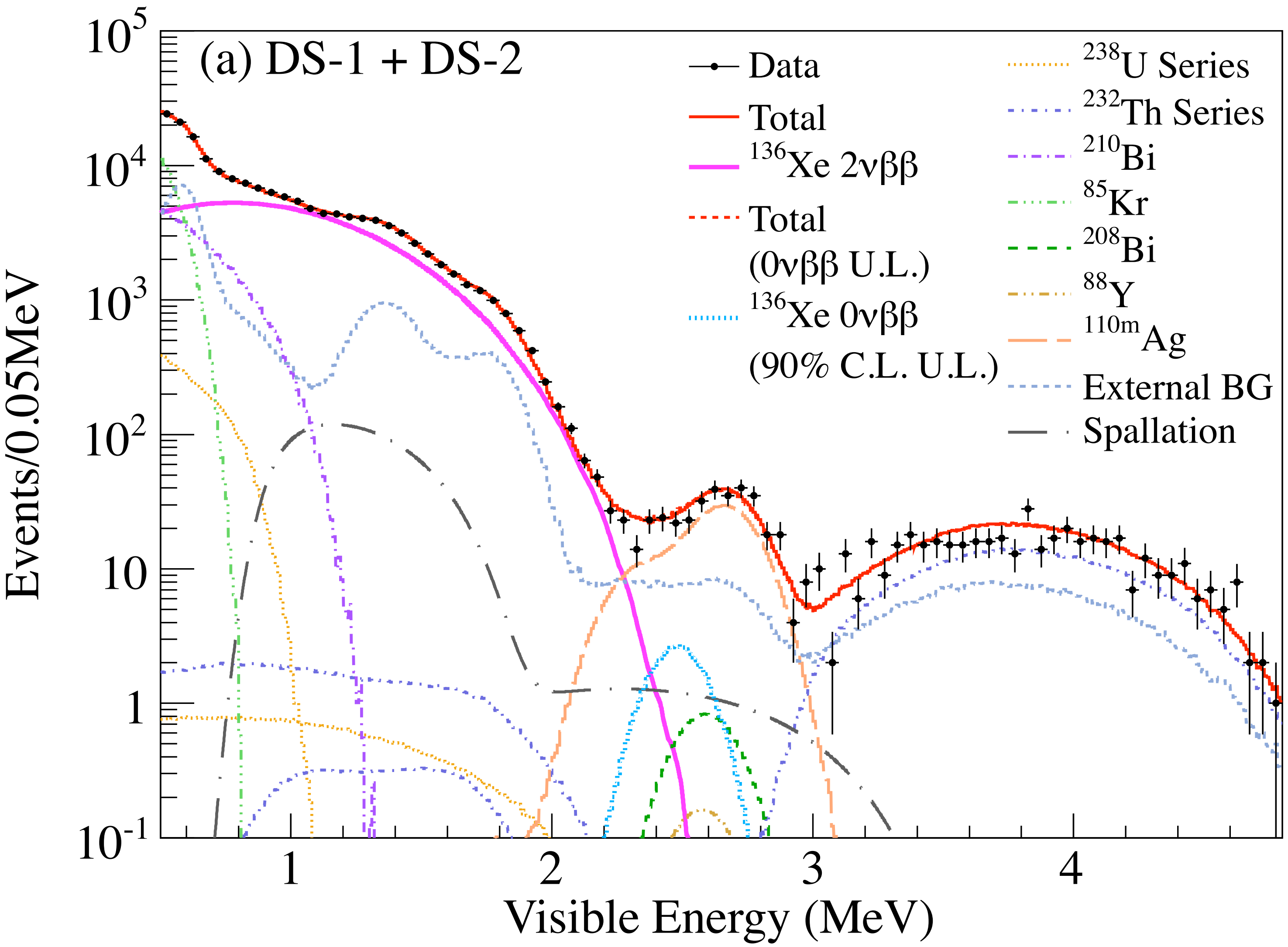
Signal	$2\nu\beta\beta$
	$0\nu\beta\beta$
Backgrounds	40K
	^{222}Rn-^{210}Pb
	^{228}Th-^{208}Pb
	^{232}Th-^{228}Th (^{228}Ac)
	^{238}U-^{222}Rn (^{234}Pa)
	^{85}Kr
	^{210}Bi
	^{134}Cs,^{137}Cs
	^{129m}Te,^{95}Nb,^{90}Y,^{89}Sr
	^{110m}Ag,^{60}Co,^{88}Y,^{208}Bi
	^{10}C
	^{11}C
Detector response (Energy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

No assumption about filtration is made in fit

Rates in DS1 and DS2 are independent in fit

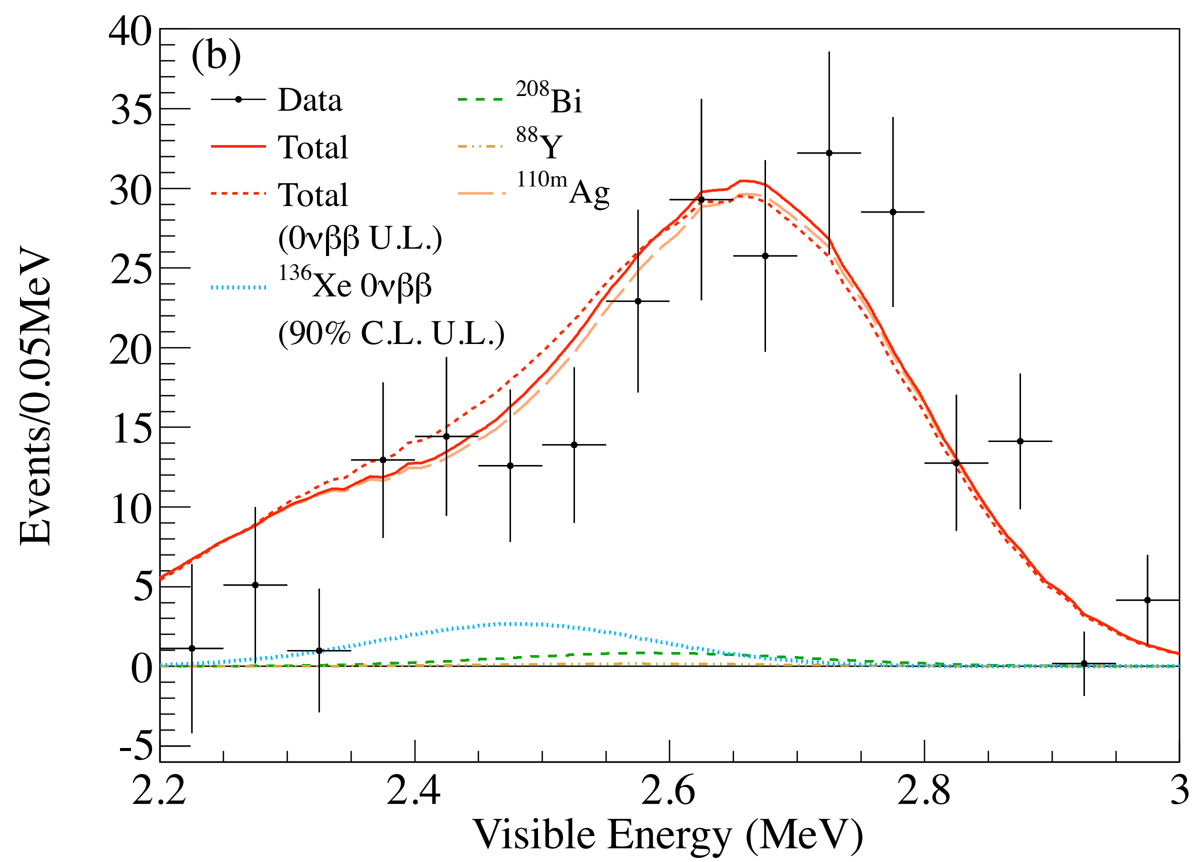
KamLAND-Zen: Fit Result

Candidate spectrum +
Best-fit decomposition for DS1 and DS2



PRL **110** 062502 (2013)

Close up of 0vBB region
(Data - known bkg)



KamLAND-Zen: 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) $\pm$ 3.4 (syst)	80.2 ± 1.8 (stat) $\pm$ 3.3 (syst)

$$T^{2\nu}_{1/2} = 2.30 \pm 0.03\,(\text{stat}) \pm 0.09\,(\text{syst}) \times 10^{21}\ \text{yr}$$

- 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 x 10^{25}yr.
- 12% chance to get limit greater than one reported

KamLAND-Zen: 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-200

- The EXO-200 experiment also searches from $0\nu\beta\beta$ of 136Xe

- EXO results:

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

PRL **107** 212501 (2012)

$T^{0\nu}_{1/2}$ >1.6 x 10^{25} yr (90% CL) PRL **109** 032505 (2012)

Recent update:

$T^{2\nu}_{1/2}$ = 2.172 +/- 0.017 (stat) +/- 0.060 (syst) x 10^{21} yr

http://arxiv.org/abs/1306.6106

Combination of KL-Zen and EXO

- Combined analysis of KLZ and EXO 0vBB data:

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

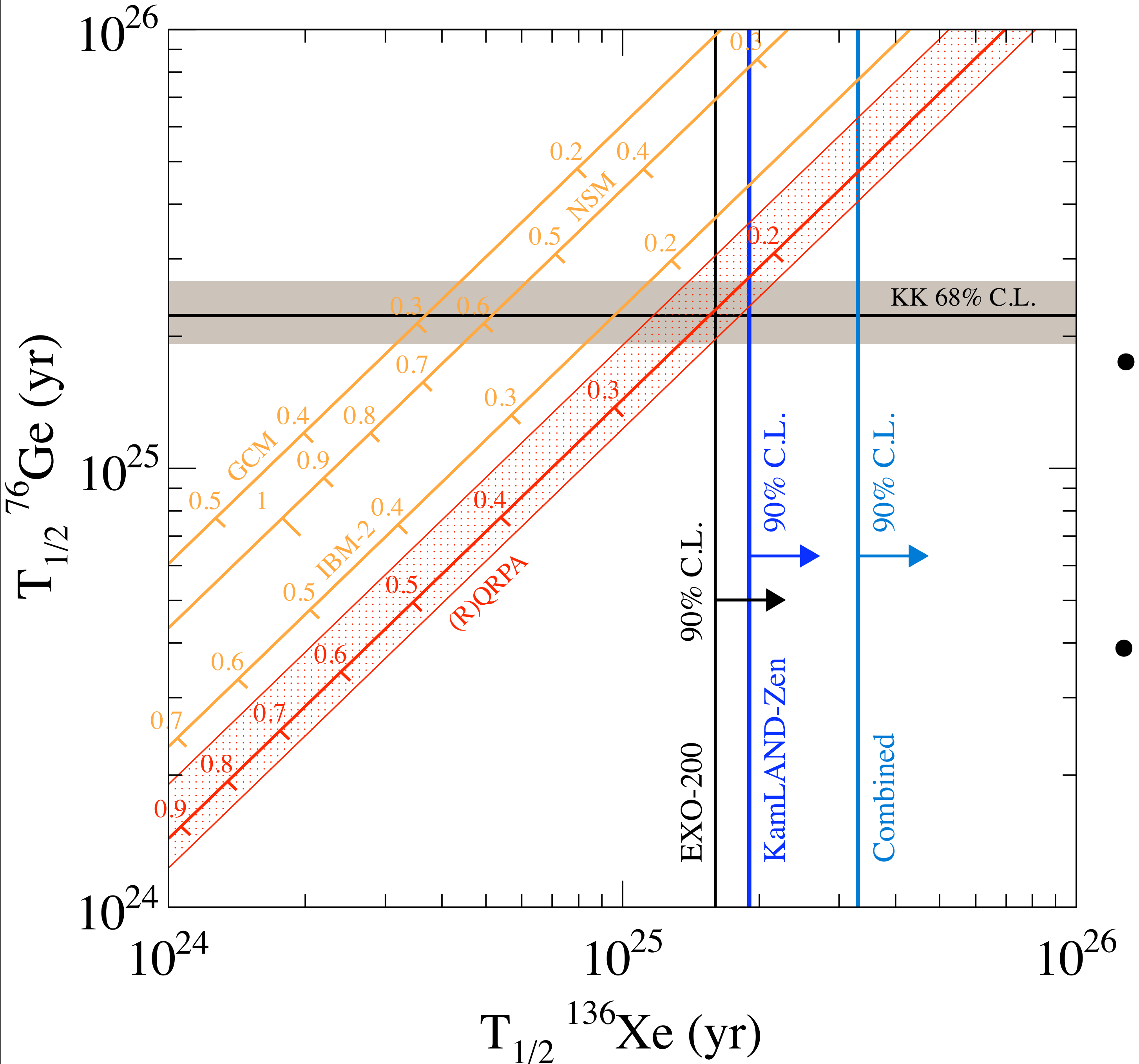
- Expected sensitivity of combined experiment: 1.6 x 10^{25}yr.

- 7% chance to get limit greater than one reported

- Using a range of available nuclear matrix elements mass limit:

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

Comparison with KKDC Claim



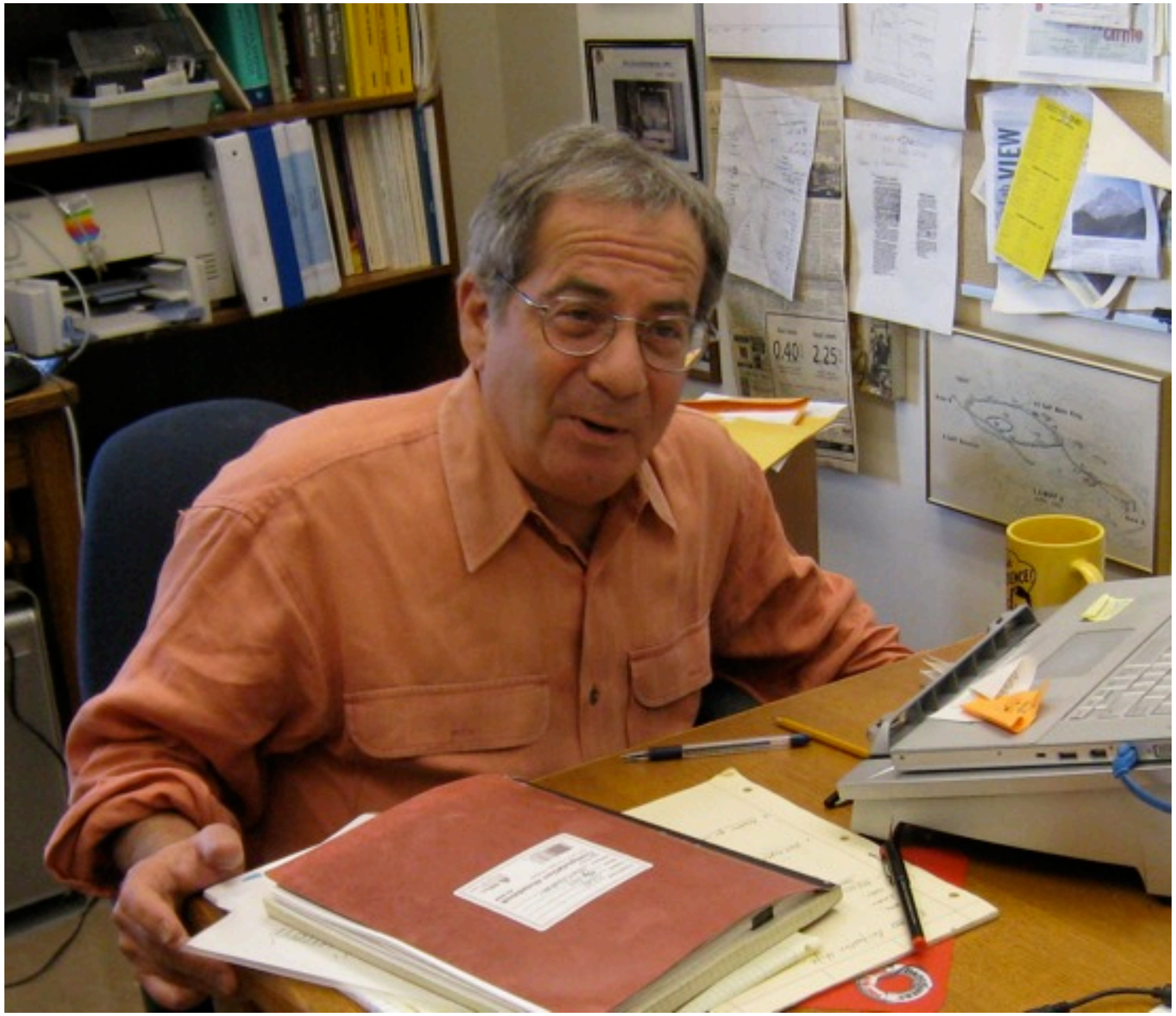
PRL **110** 062502 (2013)

- Combined EXO-200 and KLZ result is inconsistent with KKDC claim in ^{76}Ge at 97.5% CL even for best-case NME
- NME is a major caveat in comparison of half life limits in
- If we treat spread in NME calculations as statistical error then EXO-200 and KLZ result is inconsistent with KKDC claim in ^{76}Ge at 95.6% CL

Conclusion

- KamLAND-Zen was a very effective modification of the KamLAND detector
- Capitalized on existing infrastructure, to quickly realize competitive double beta decay search
- 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 !
- KamLAND antineutrino program continues in parallel ... new low-flux data points due to protracted shutdown of Japanese reactors

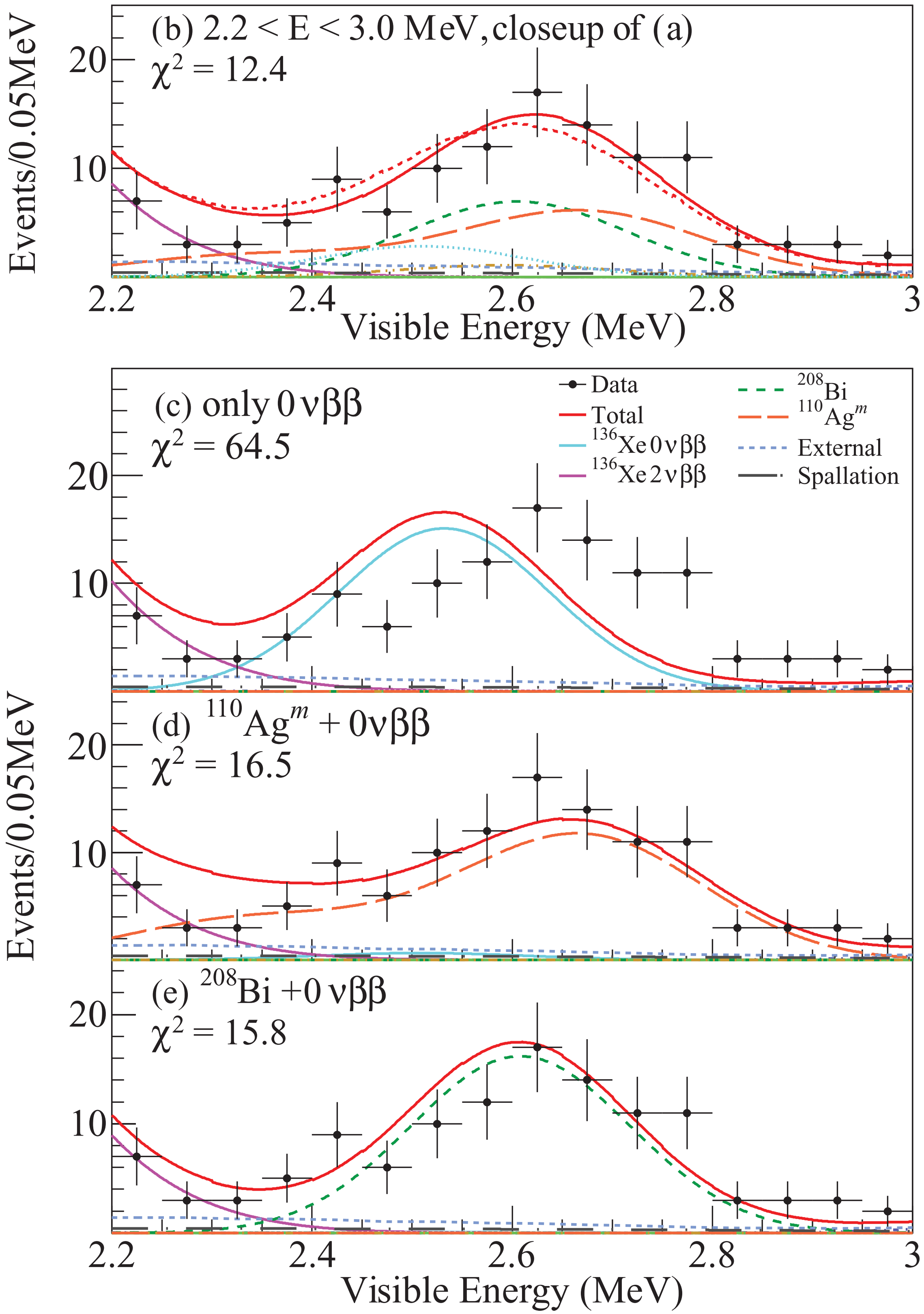
Dedication



Stuart Freedman

Fondly remembered collaborator, mentor, and friend

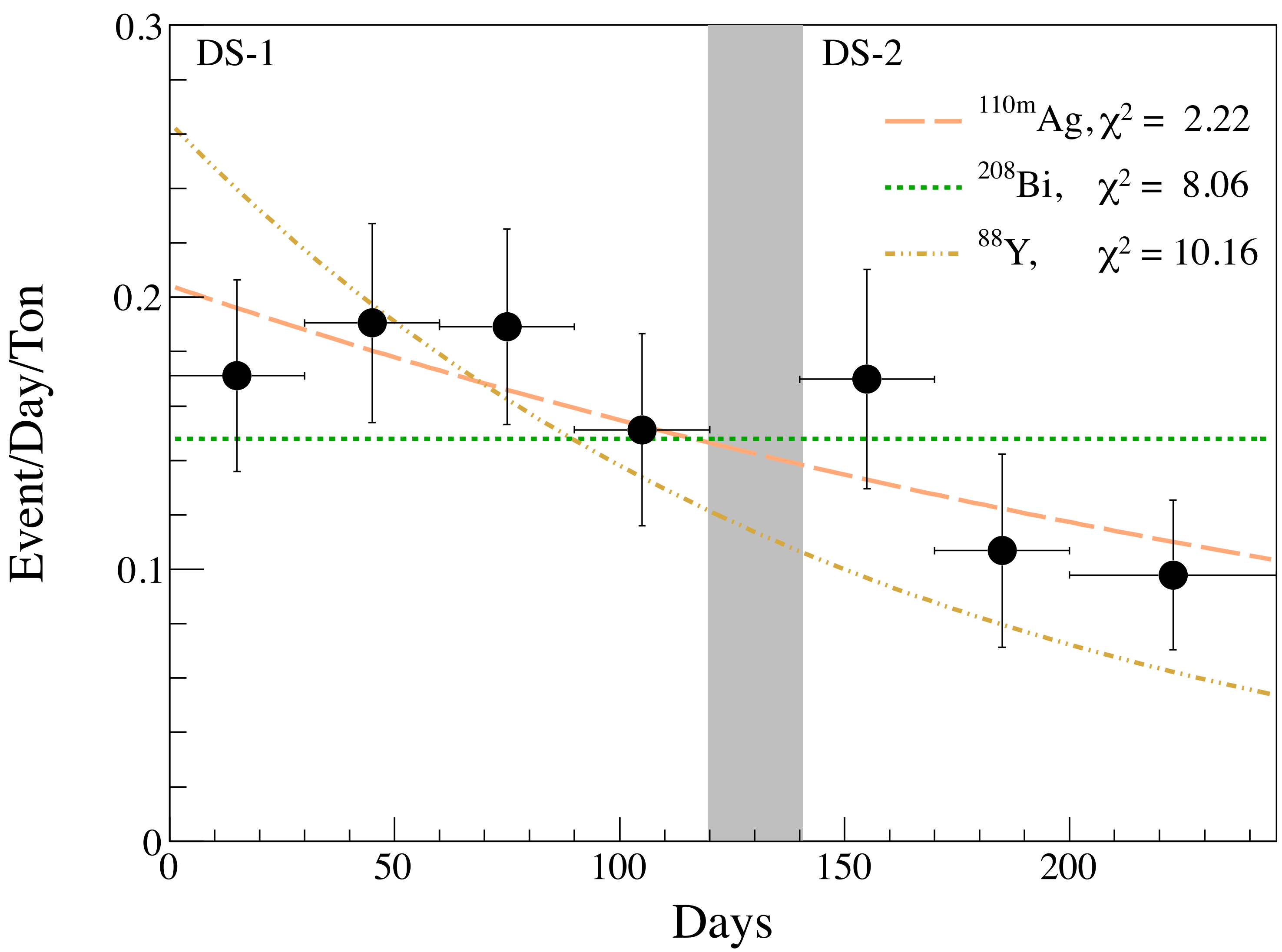
Investigating background near 2.6 MeV



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

Energy scale model

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

Spallation Backgrounds

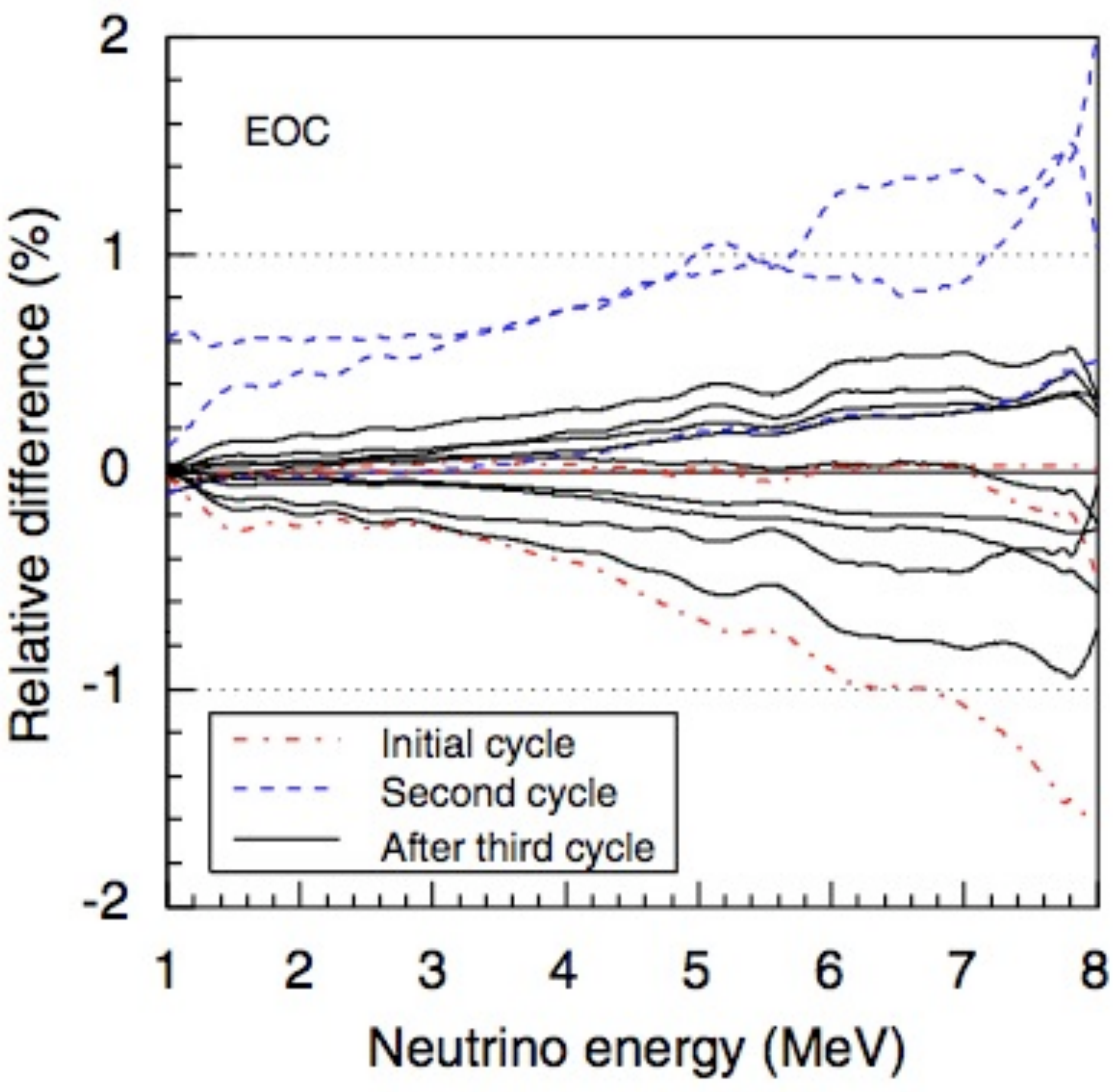
- Cosmogenic production of ^{10}C and ^{11}C
- ^{10}C and ^{11}C can be vetoed by muon-neutron-β triple coincidence but this is not pursued for now

Isotope	Event rate (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 MeV $< E <$ 2.0 MeV	< 0.3
2.2 MeV $< E <$ 3.0 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

Reactor contribution: fission fractions $f_{i,j}$

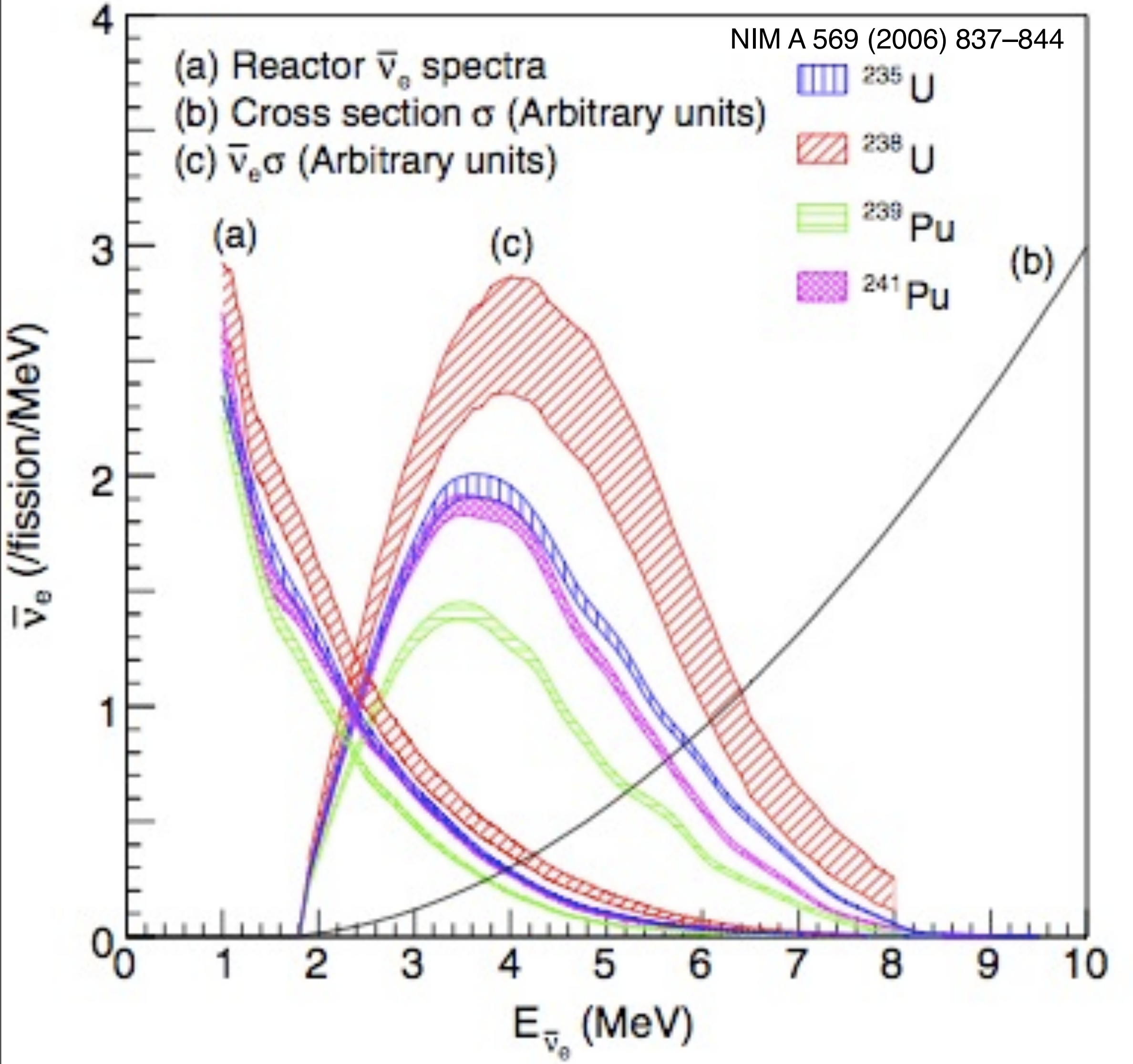
Comparison of simplified and detailed f_{ij} calculation



NIM A 569 (2006) 837–844

- 56 cores, detailed simulation impractical
- Simplified semi-empirical model parametrized by
  - thermal power output
  - fuel burnup
  - initial fuel composition
- Relative difference < 1% for most cores

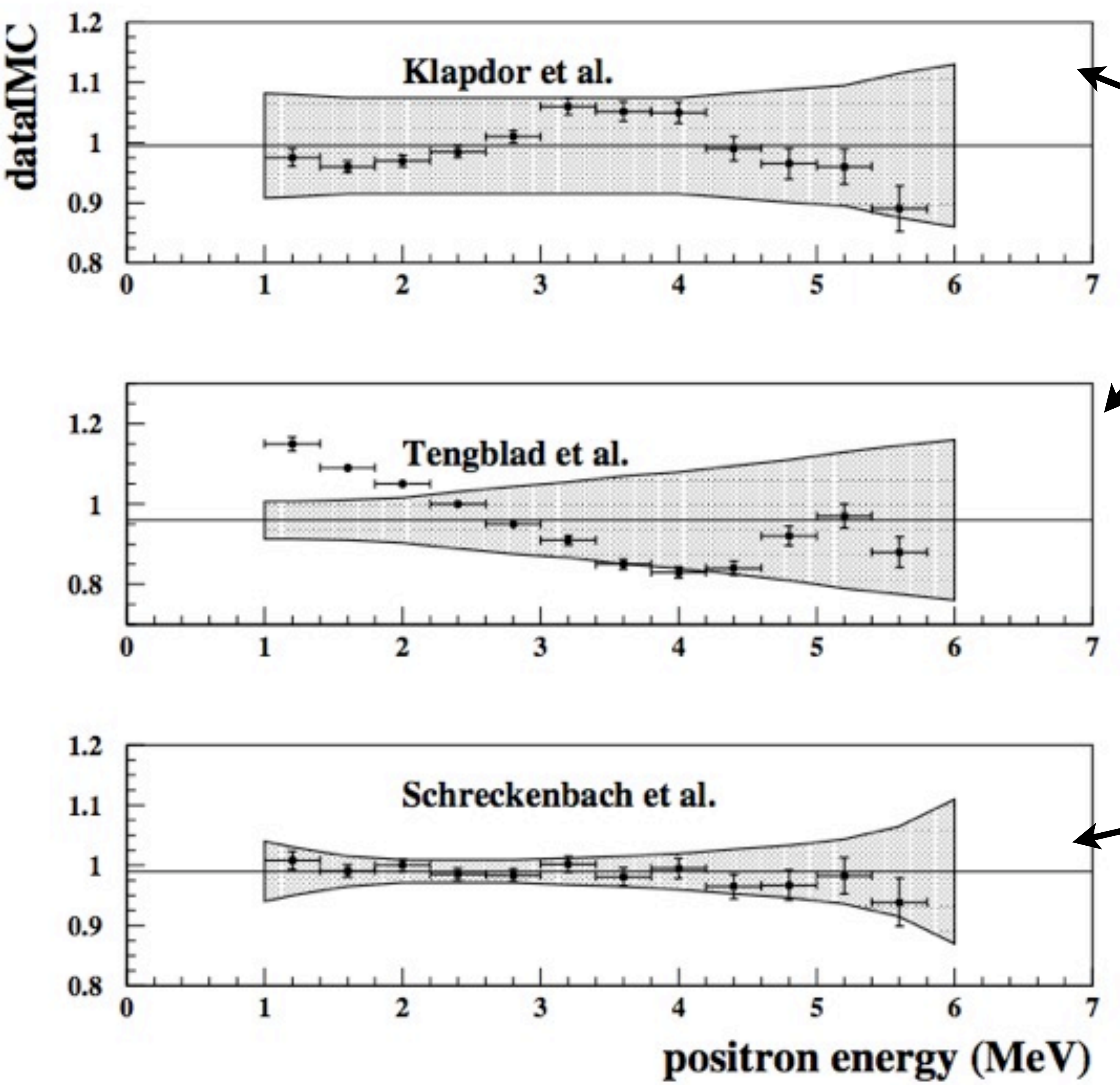
Reactor contribution: spectra per fission



- ^{235}U, ^{239}Pu, ^{241}Pu taken from Schreckenbach et al.
- ^{238}U taken from calculation by Vogel
- New method of estimating the antineutrino spectrum per fission
  - Consistent shape with older method
  - ~3% higher flux normalization
- To get around this the cross-section per fission of each reactor is adjusted to reproduce the Bugey4 measurement (1.4 % uncertainty)

Test of approaches at Bugey reactor experiment

(measured/model-predicted) e^+ spectrum



Some “Direct” approaches

Semi-empirical approach

Eur. Phys. J. C 27, 331–374 (2003)