Recent results from KamLAND-Zen

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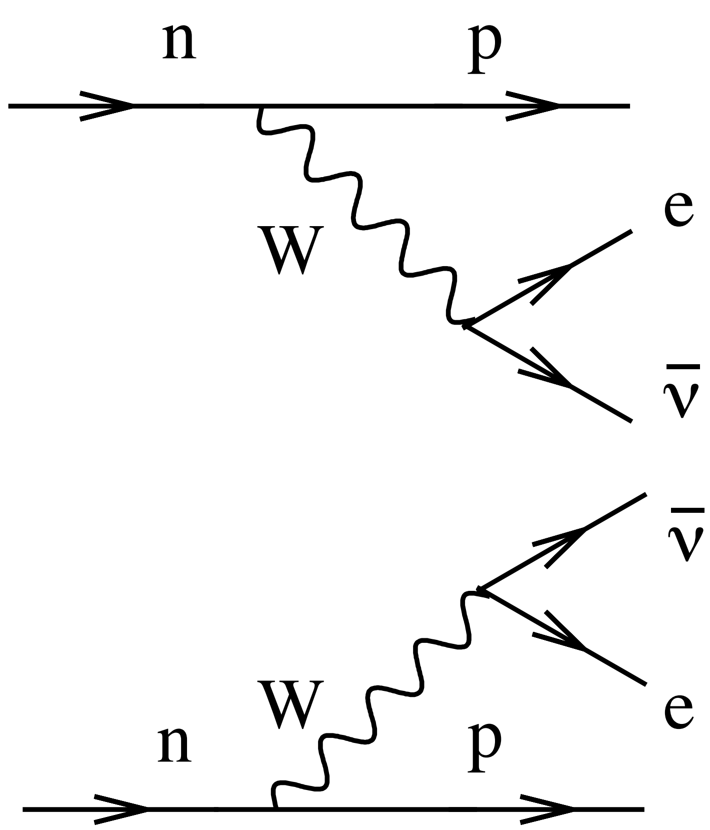
Outline

- What's so interesting about double beta decay ?
- Overview/sample of experimental approaches
- KamLAND-Zen -A new application of KamLAND
- Detector performance and data analysis
- Results from 1st phase & comparison with KKDC claim

Double Beta Decay (ββ)



Phase space factor

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

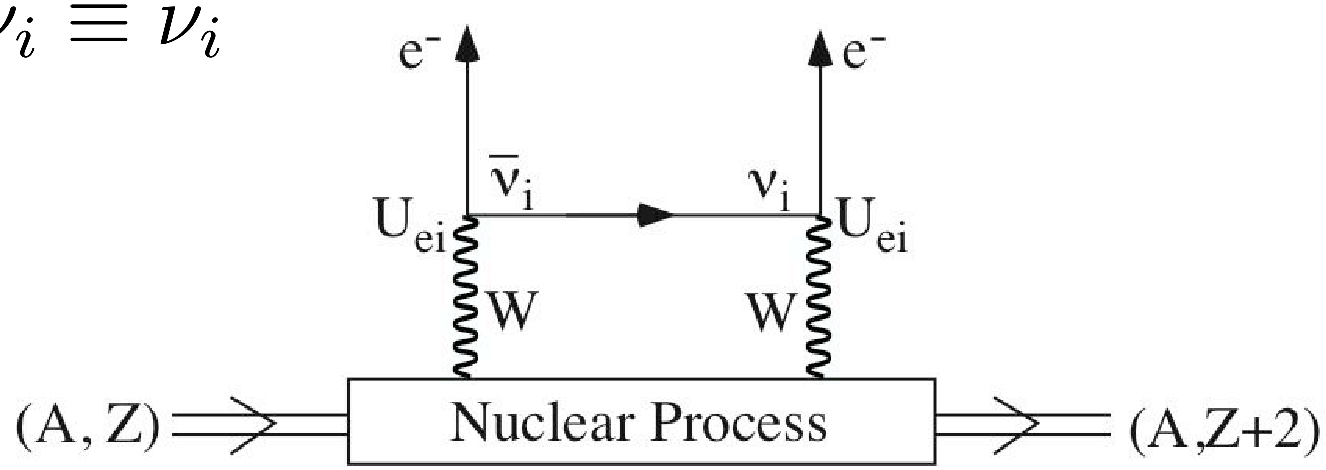
Decay half-life

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 (0νββ)

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



Phase space factor

Nuclear matrix element

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

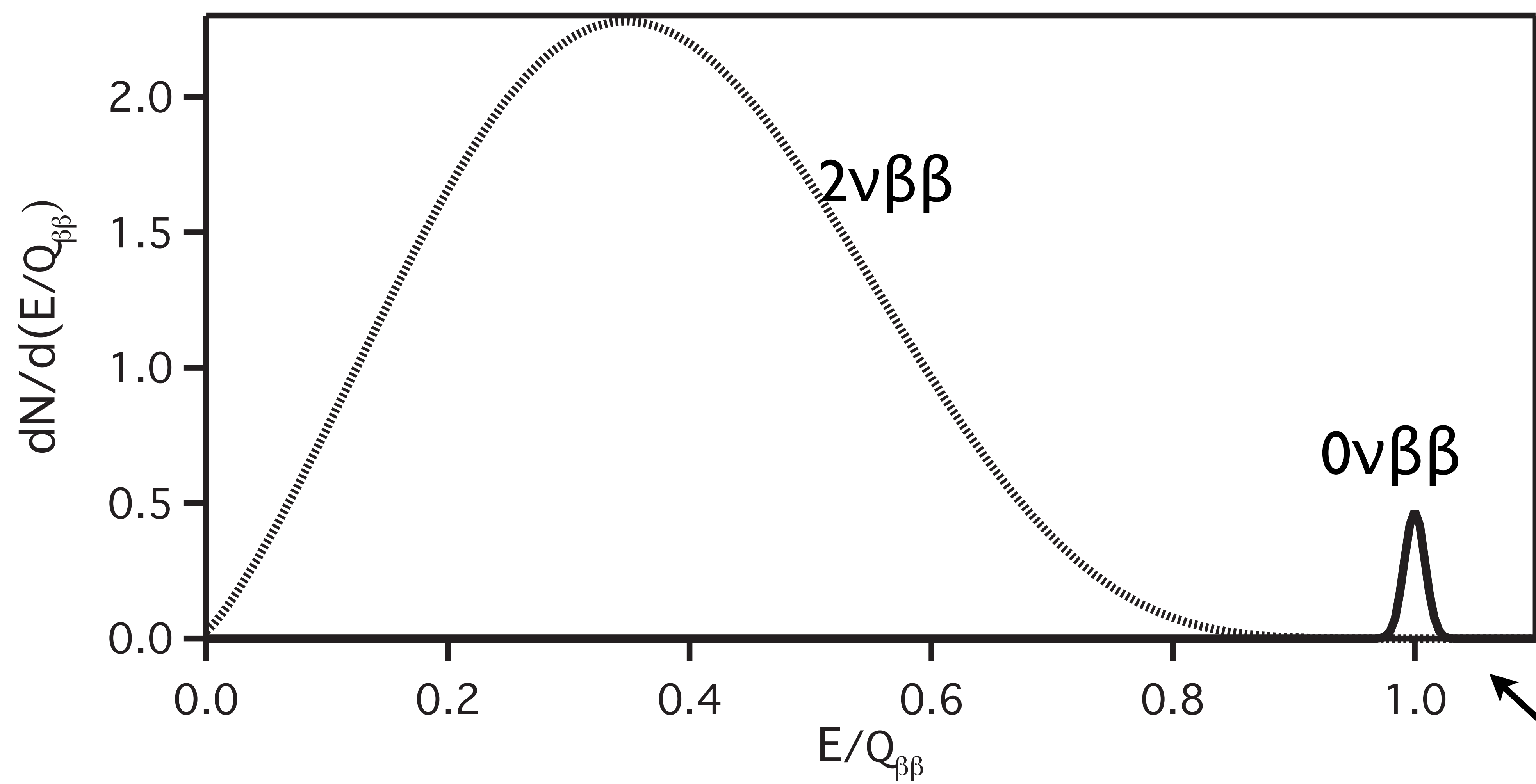
Decay half-life

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, must be estimated theoretically, 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

ββ and 0νββ Experiments

Summed energy spectrum of final state electrons



Assumes a branching ratio 0ν/2ν = 1%, detector energy resolution of 2%

"Region of interest"

- For 0νββ expect a peak at the decay Q-value in the summed energy spectrum of final state electrons

- Rule of thumb for 0νββ half-life sensitivity

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

a	isotopic abundance
ϵ	detection efficiency
M	total detector mass
b	background index (e.g cnts/keV · kg · yr)
δE	energy resolution
t	exposure time

- Want to maximize sensitivity for a given t

Some ongoing or planned 0νββ searches

- There are many searches ongoing and planned (sorry if I left out **your** experiment)

Candidate Isotope	Experiment
^{48}Ca	Candles
^{76}Ge	**Gerda**, Majorana
^{82}Se	SuperNemo,Lucifer
^{130}Te	**CUORE**
^{136}Xe	**EXO**, NEXT, **KamLAND-Zen**
^{150}Nd	SNO+

Speakers present from these experiments

^{48}Ca - Candles III

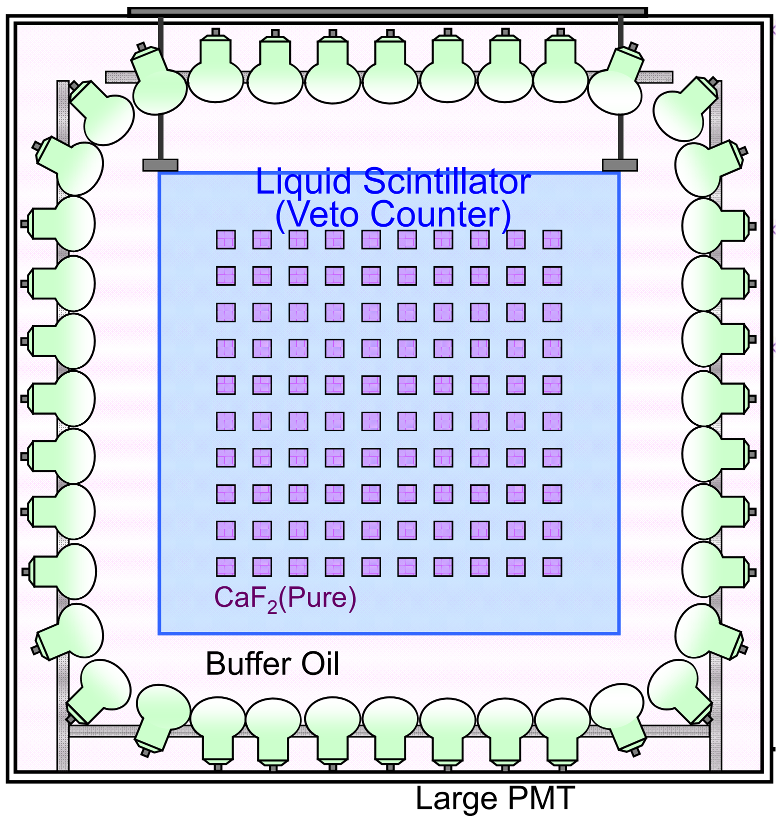


Figure taken from S. Umehara PANIC 2011

Some design parameters

a	0.187%
ϵ	$> 50\%$
M	$\sim 305\,\mathrm{kg}$
$b\,[\frac{\mathrm{cnts}}{\mathrm{keV\cdot kg\cdot yr}}]$	$\sim 1 \times 10^{-4}$
δE	$\sim 4\%$ at Q-value

- 96 $^{nat}CaF_2$ scintillator crystals (300 kg) immersed in liquid scintillator shield
- $Q_{\beta\beta}$ = 4.273 MeV -- above most natural radioactivity
- Currently running in Kamioka Mine
- Target sensitivity: $\langle m_{\beta\beta}\rangle$ ~ 500 meV
- Very competitive w.r.t most parameters
- Pursuing enrichment for future phase **(difficult for ^{48}C)**
- Existing limit from Candles predecessor Elegant VI (~0.03 kgxyr) :

$$T^{0\nu}_{1/2} > 5.8 \times 10^{22}\,\mathrm{yr} \quad (90\%\ \mathrm{C.L})$$

^{76}Ge - Gerda, Majorana

- Historically ^{76}Ge is very interesting
- Controversial claim for observation of $0\nu\beta\beta$ decay of ^{76}Ge from part of the Heidelberg-Moscow collaboration

$$T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}\ \mathrm{yr}$$ KKDC Claim (71.5 kg x yr)

- Gerda and Majorana search for $0\nu\beta\beta$ of ^{76}Ge
- Both taking phased approach with initial goal to test KKDC claim
- Stay tuned for Gerda talk this afternoon !

^{130}Te - CUORE

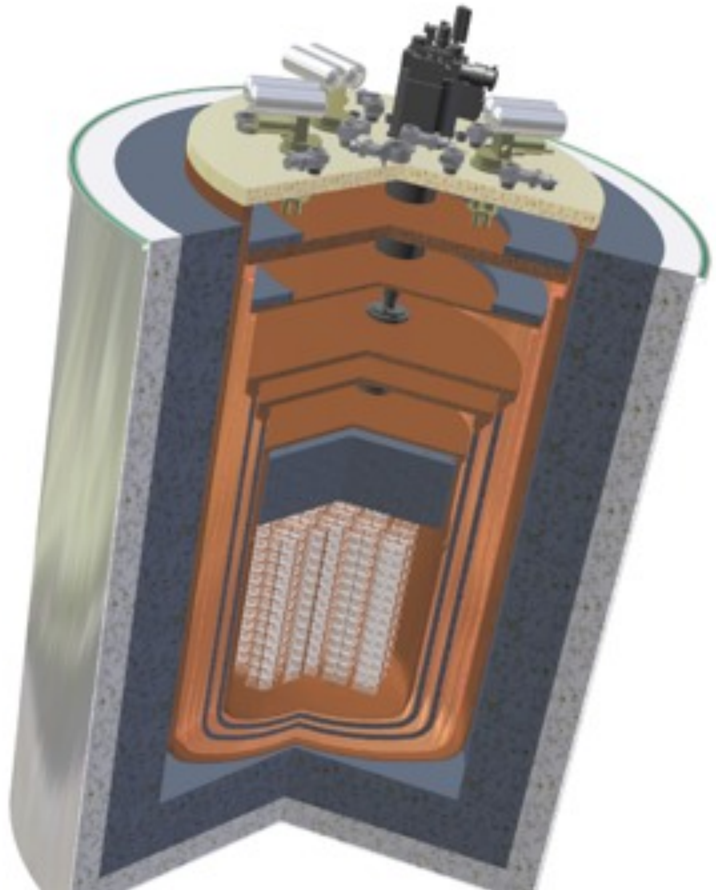


Figure courtesy of CUORE collaboration

Some design parameters

a	34%
ϵ	87%
M	$\sim 750\,\text{kg}$
$b\,[\frac{\text{cnts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}]$	$\sim 1 \times 10^{-2}$
δE (FWHM)	~ 5 keV at Q

- 988 $^{nat}TeO_2$ bolometers cooled 10mK in cryostat
- Q-value = 2.530 MeV, but excellent energy resolution
- Under construction at Gran Sasso Lab, data-taking expected early 2015
- Target sensitivity: $T_{1/2}^{0\nu} \sim 1\text{x}10^{26}$ yr
- Will hear more details from CUORE this afternoon
- Current limit from Cuoricino (19.75 kgxyr):

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

^{136}Xe - EXO, **NEXT**, KamLAND-Zen

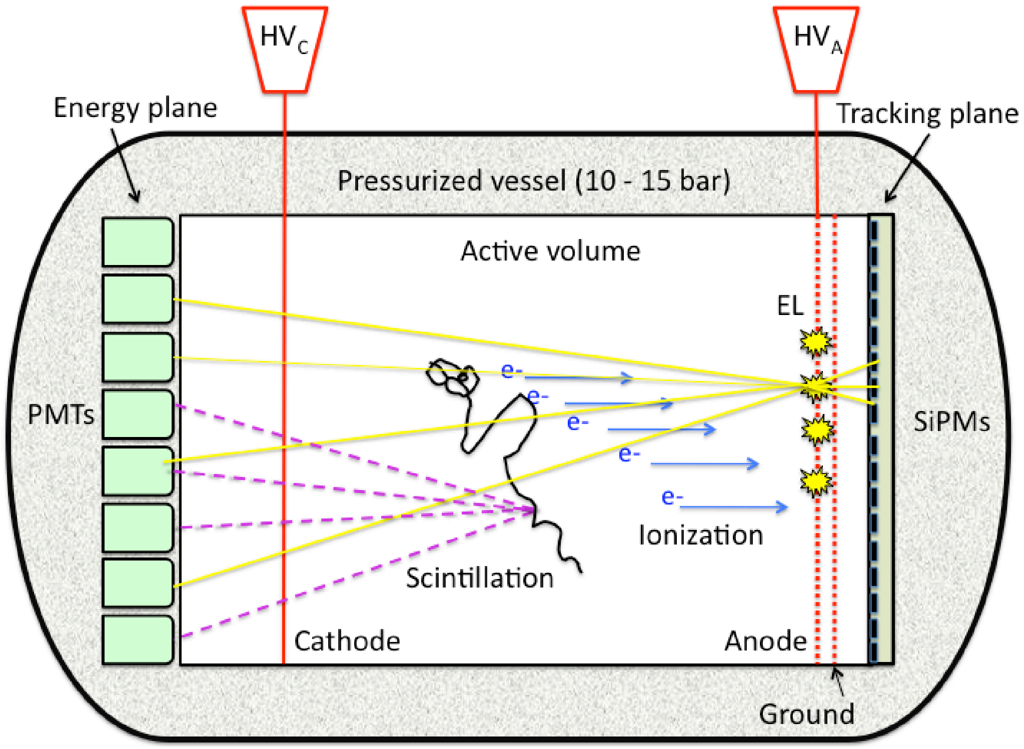


Figure from NEXT-100 TDR (2012 JINST 7 T06001)

Some design parameters

ϵ	$\sim 25\%$
$M(^{136}\mathrm{Xe})$	$100\,\mathrm{kg}$
$b\,[\frac{\mathrm{cnts}}{\mathrm{keV\cdot kg\cdot yr}}]$	$\sim 8\times 10^{-4}$
δE (FWHM)	1% at Q

- High pressure Xe-gas electro-luminescent time projection chamber
- Electroluminescent stage significantly improved E-resolution
- Approved to run at CanFranc lab, starting 2015
- Q-value = 2.457 MeV
- Event topology from TPC tracking significantly reduces background
- Target sensitivity: $T_{1/2}^{0\nu} = 6\mathrm{x}10^{25}$ yr (90% CL)
- Current limits : see EXO and KamLAND-Zen later

^{82}Se – SuperNemo

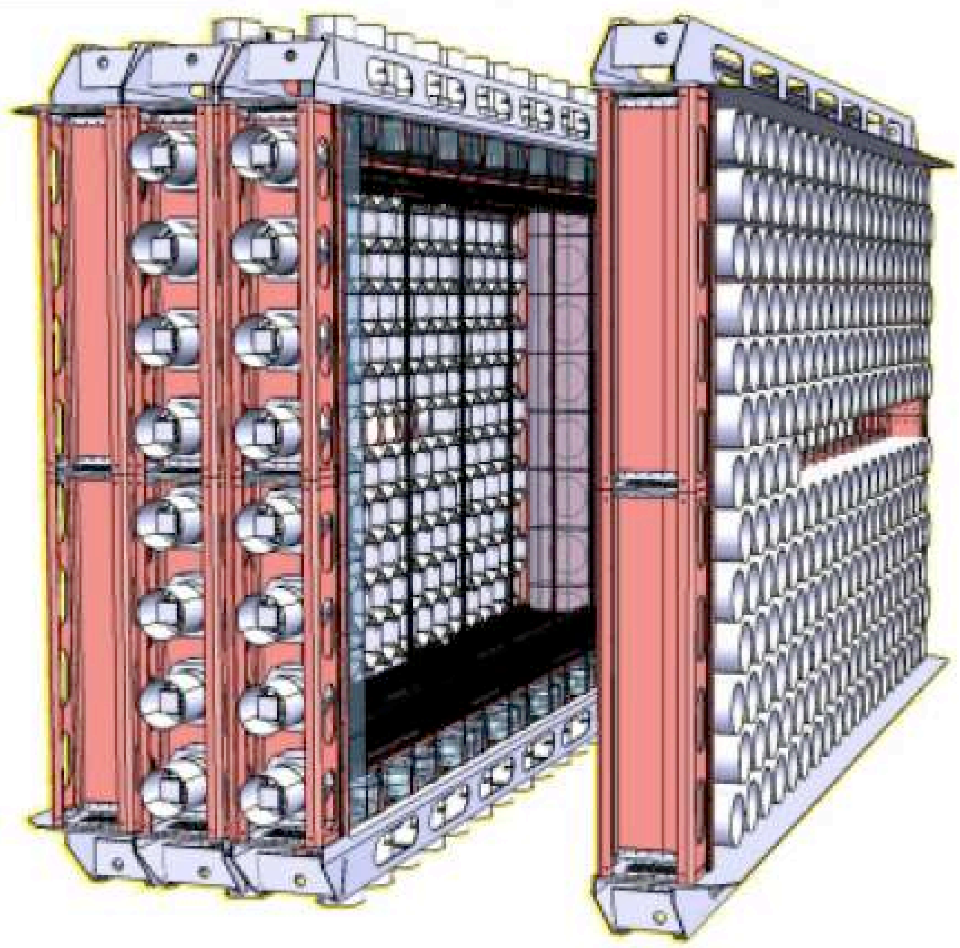


Figure from J.Phys. Conf. Ser 375 042012

Some design parameters

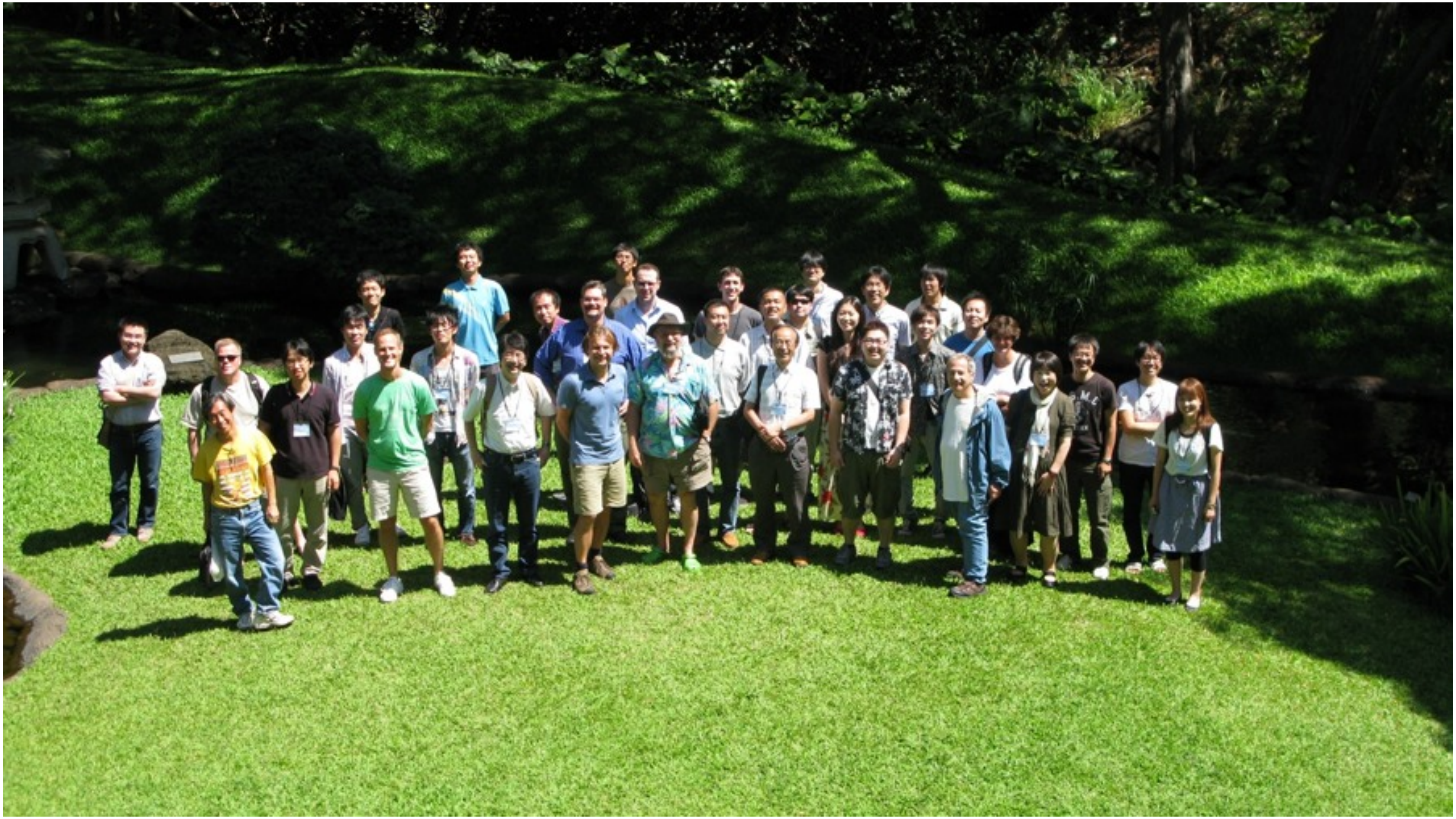
ϵ	$>30\%$
$M(^{82}\mathrm{Se})$	$100 - 200\,\mathrm{kg}$
$b\,[\frac{\mathrm{cnts}}{\mathrm{keV\cdot kg\cdot yr}}]$	$\mathcal{O}\,10^{-4}$
δE (FWHM)	4% at 3 MeV

- Place large-area thin-foils (20) of source isotope near tracking detector and calorimeter
- Initially will focus on ^{82}Se, (Q=2.995 MeV)
- Can swap-out foils for other isotopes
- Will run in Modane lab, starting ~ 2014
- Reconstruction of decay kinematics important to study $0\nu\beta\beta$ mechanism
- Target sensitivity: $T_{1/2}^{0\nu}$ = 1~2 x10^{26} yr (90% CL)
- Current limits NEMO-3:

^{100}Mo	$T^{0\nu}_{1/2}$ (90 %C.L) $> 1.0 \times 10^{24}$ yr	42 kg·yr
^{82}Se	$T^{0\nu}_{1/2}$ (90 %C.L) $> 3.2 \times 10^{23}$ yr	5.68 kg·yr

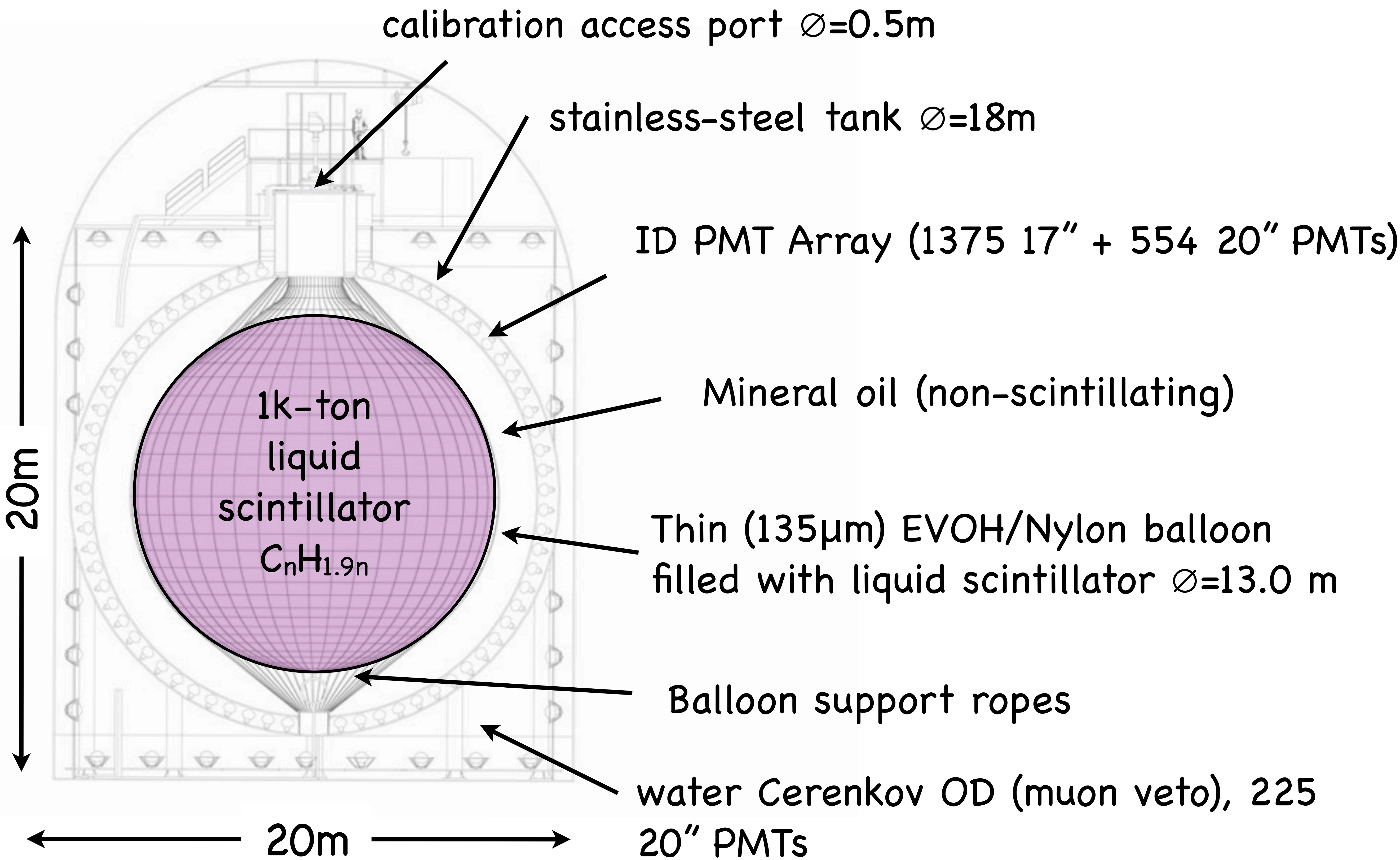
KamLAND-Zen

KamLAND/KamLAND-Zen Collaboration

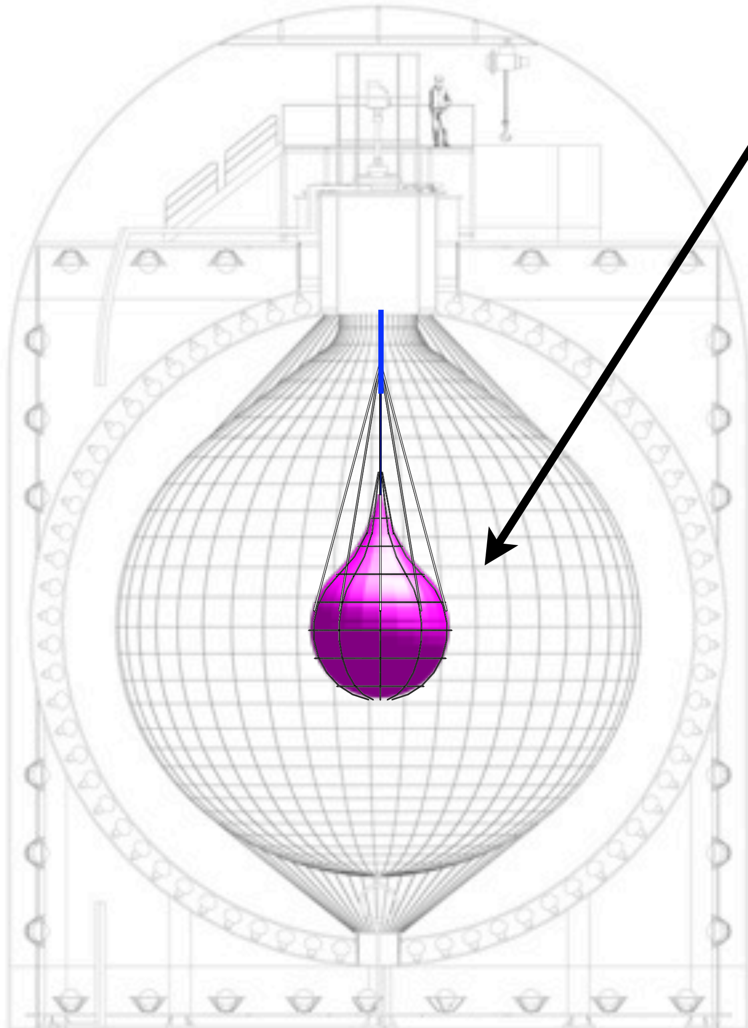


KamLAND-Zen collaboration is a subset of KamLAND

KamLAND -- host for KamLAND-Zen



KamLAND-Zen



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

^{238}U	$2x10^{-12}g/g$
^{232}Th	$5x10^{-12}g/g$
^{40}K	$6x10^{-12}g/g$
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% of KamLAND volume, reactor, geoneutrino, supernova watch etc continue in remaining KamLAND LS

KamLAND-Zen

- 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

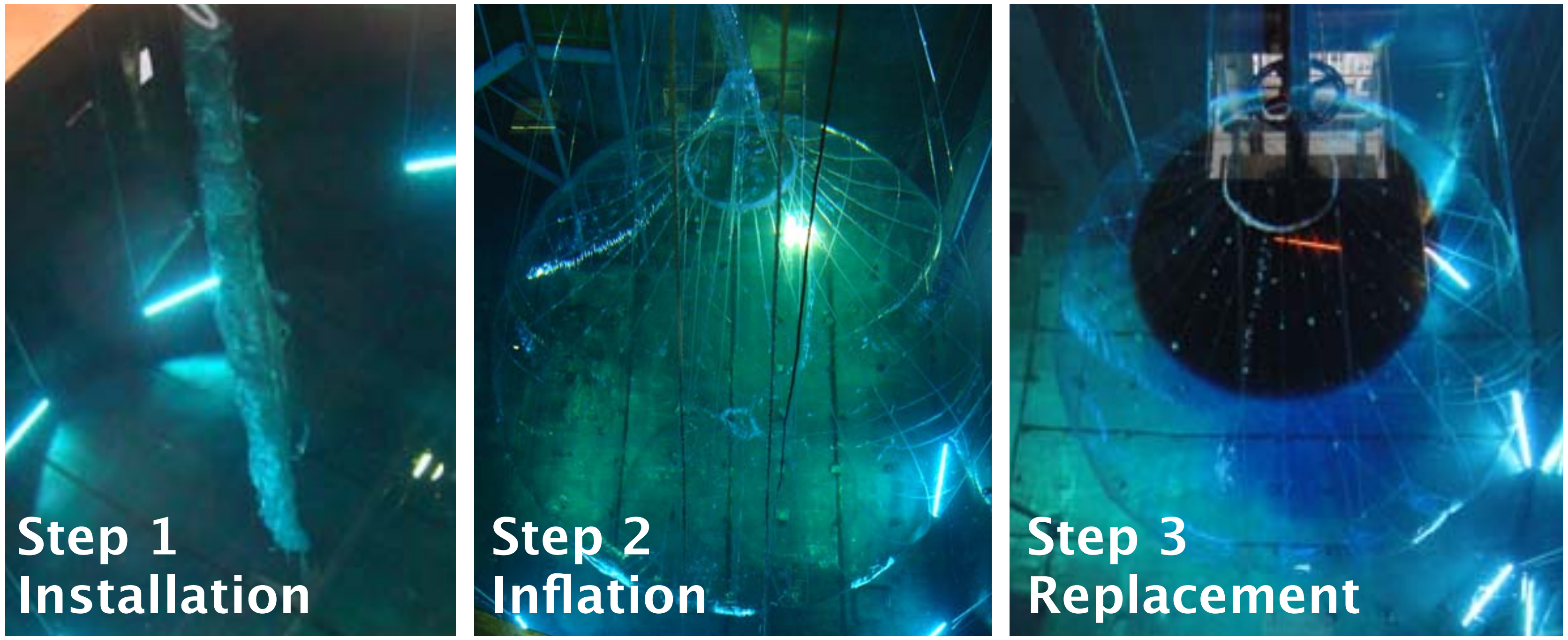


Figure courtesy of A. Gando 'First Results of Neutrinoless double beta decay Search with KamLAND-Zen', PhD Thesis, Tohoku University 2012

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

Event reconstruction

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

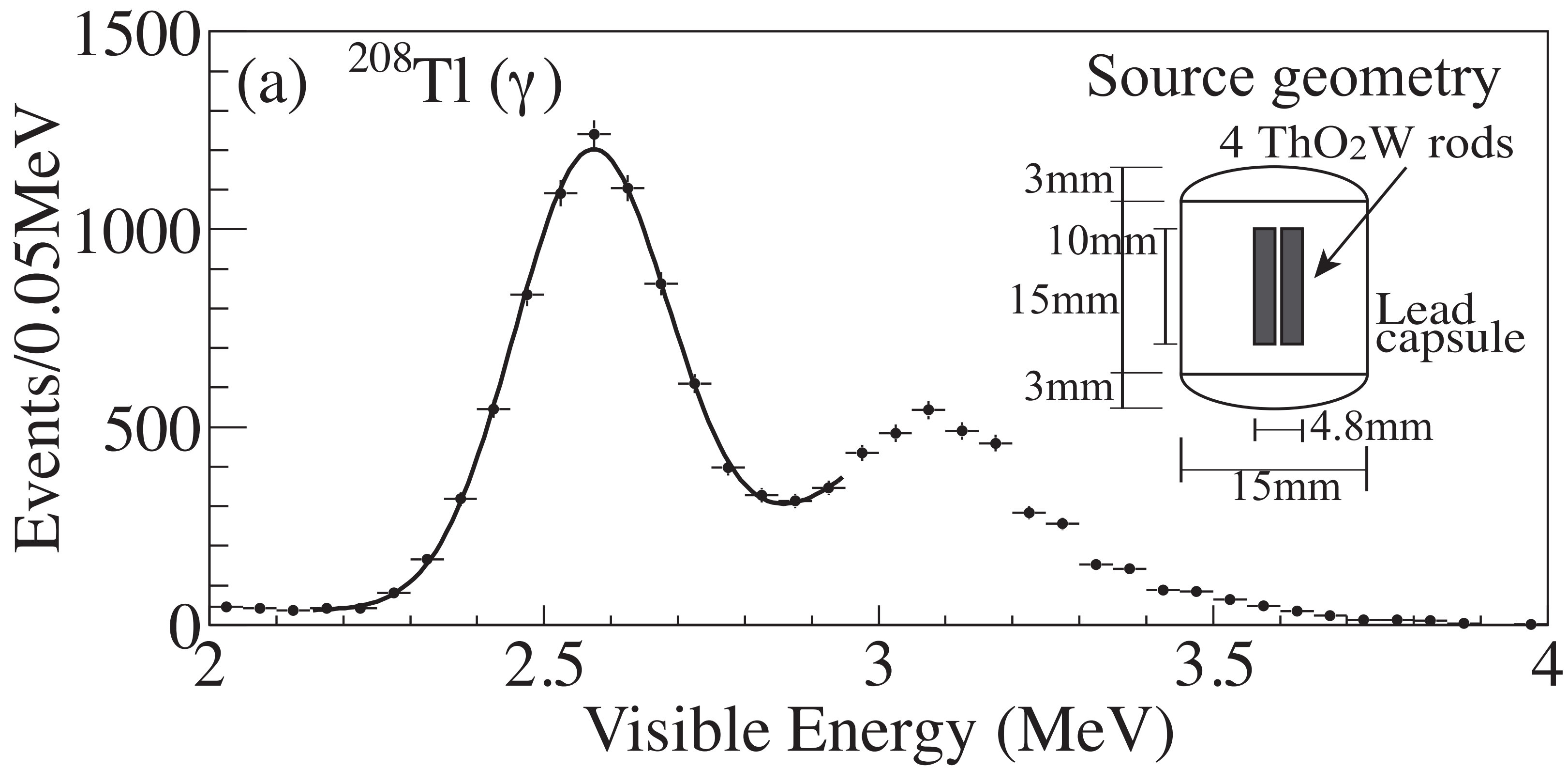
- Ultimately analysis is done in terms of visible energy

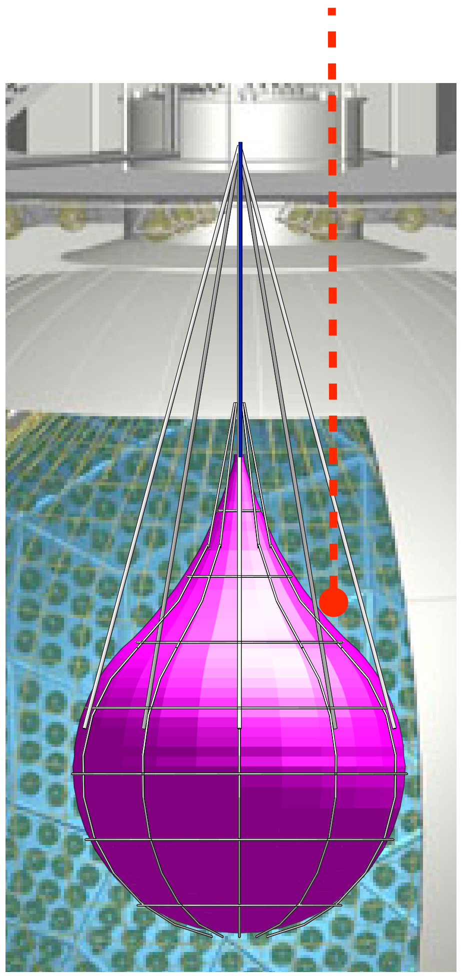
- Real energy of particles must be converted to visible or reconstructed energy

- 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 Calibration - I

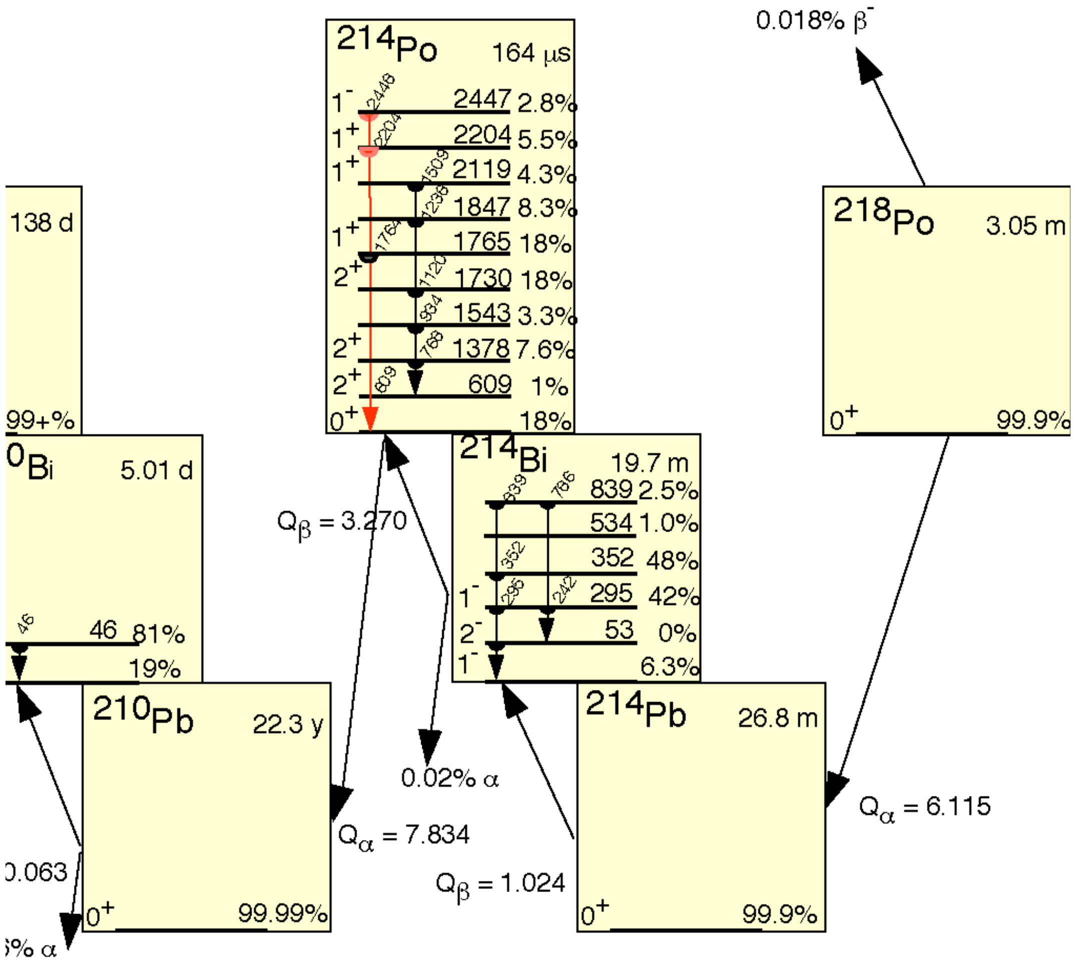
- ThO_2W source (208Tl) source deployed close to outer edge of inner-balloon



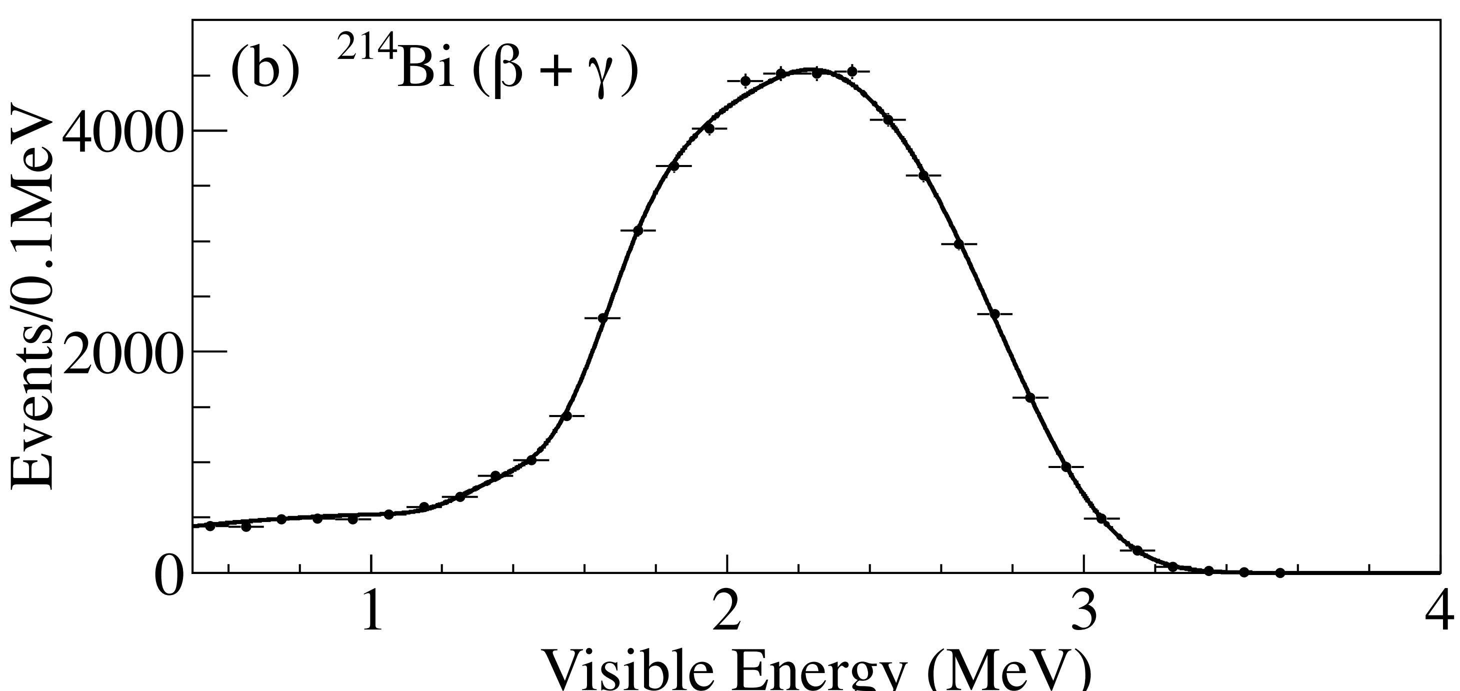


Energy resolution Xe-LS $\sigma_E/E = (6.6+/0.3)\ \%/\surd E$

Energy Calibration - II



- ^{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



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

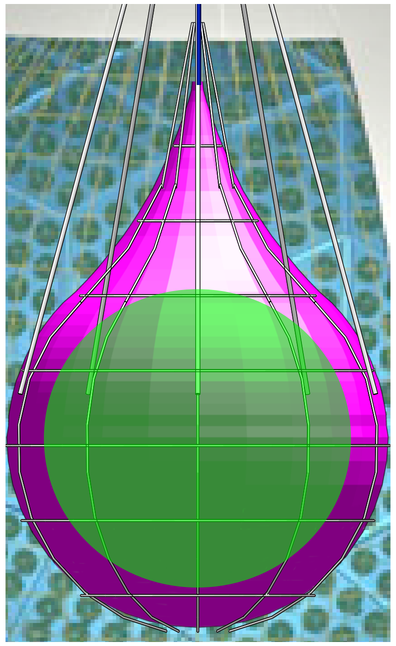
TABLE I: Two data sets used in this ^{136}Xe $0\nu\beta\beta$ decay analysis.

	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

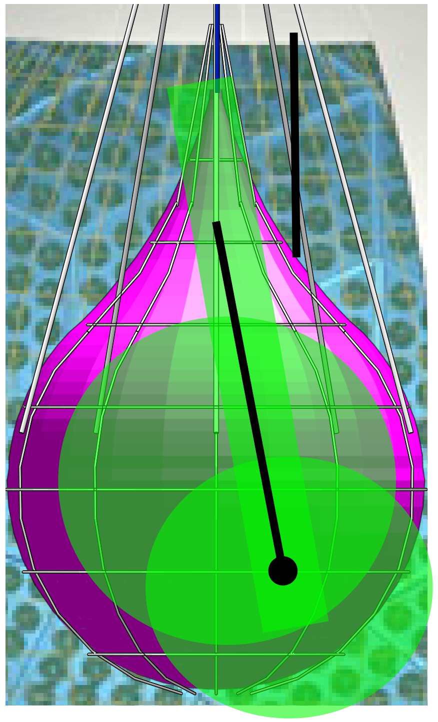
PRL **110** 062502 (2013)

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

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

after fiducial volume cut BB Selection efficiency: 99.8 +/- 0.2 %

Dead time from cuts: <0.2 %

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

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 x10^{-16}g/g
^{232}Th	1.8+/- 0.1 x10^{-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

Constrained in model

Signal	$2\nu\beta\beta$	
	$0\nu\beta\beta$	
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

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

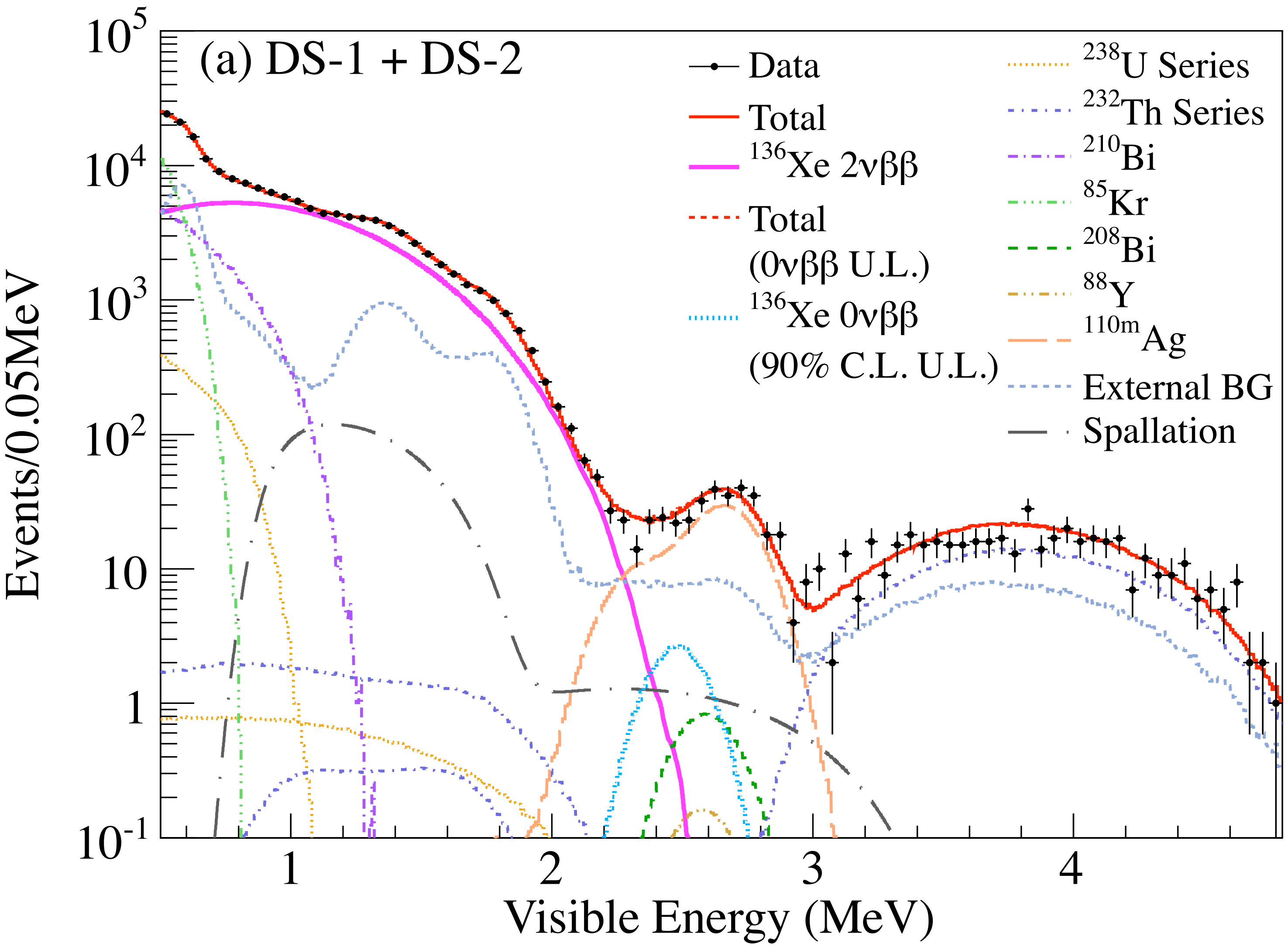
Signal	$2\nu\beta\beta$
	$0\nu\beta\beta$
Backgrounds	40K
	^{222}Rn-^{210}Pb
	^{228}Th-^{208}Pb
	^{232}Th-^{228}Th (^{228}Ac)
	^{238}U-^{222}Rn (^{234}Pa)
	^{85}Kr
	^{210}Bi
	^{134}Cs,^{137}Cs
	^{129m}Te,^{95}Nb,^{90}Y,^{89}Sr
	^{110m}Ag,^{60}Co,^{88}Y,^{208}Bi
	^{10}C
	^{11}C
Detector response (Energy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



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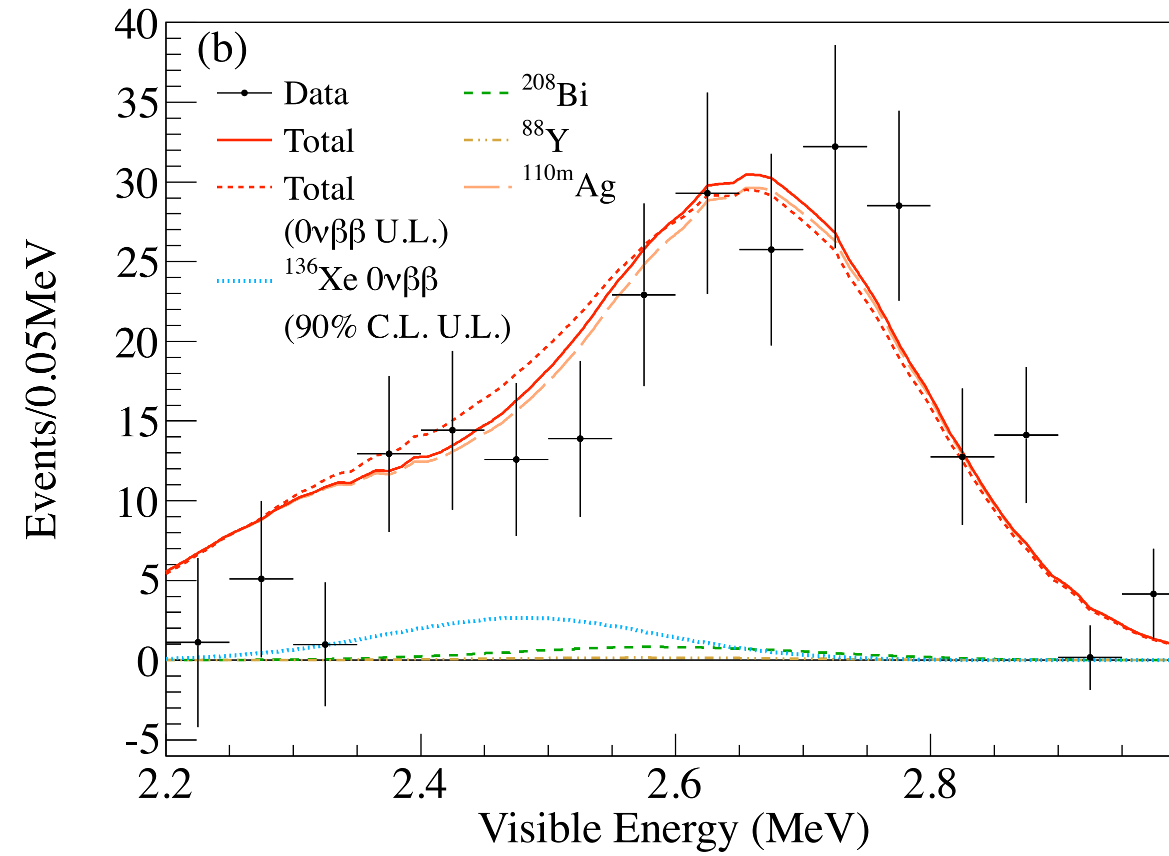
Close up of 0vBB region
(Data - known bkg)



Double beta decay results

- Two neutrino mode:

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

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

- 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 1.0×10^{25}yr.
- 12% chance to get limit greater than one reported

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 0νββ of 136Xe

- We will hear more details from EXO this afternoon

- EXO results:

$T^{2\nu}_{1/2}$ = 2.23 +/- 0.017 (stat) +/- 0.22 (syst) x 10^{21} yr PRL **107** 212501 (201

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

Combination of KL-Zen and EXO

- Combined analysis of KLZ and EXO 0vBB data:

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

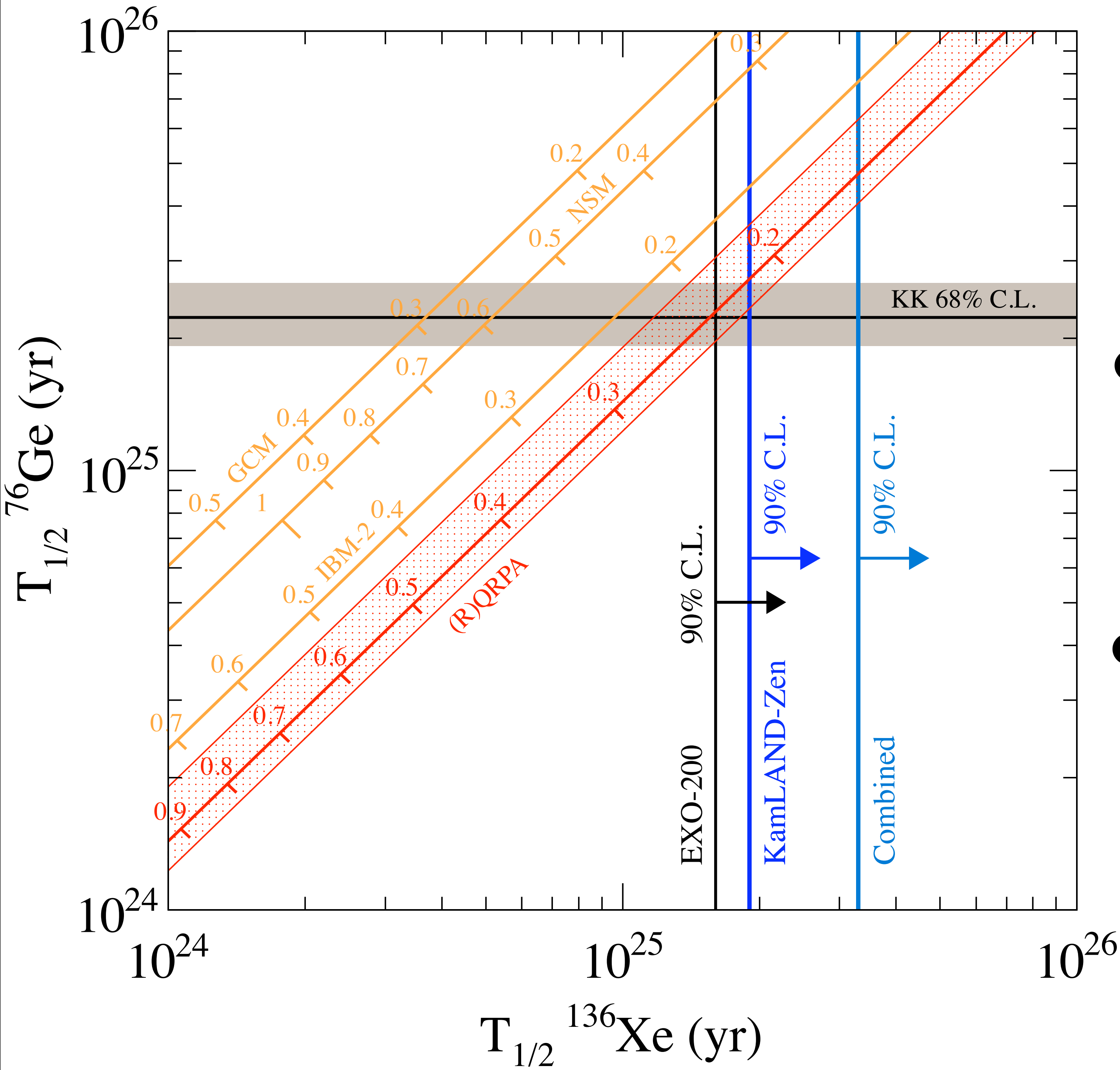
- Expected sensitivity of combined experiment: 1.6 x 10^{25}yr.

- 7% chance to get limit greater than one reported

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

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

Comparison with KKDC Claim



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- 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

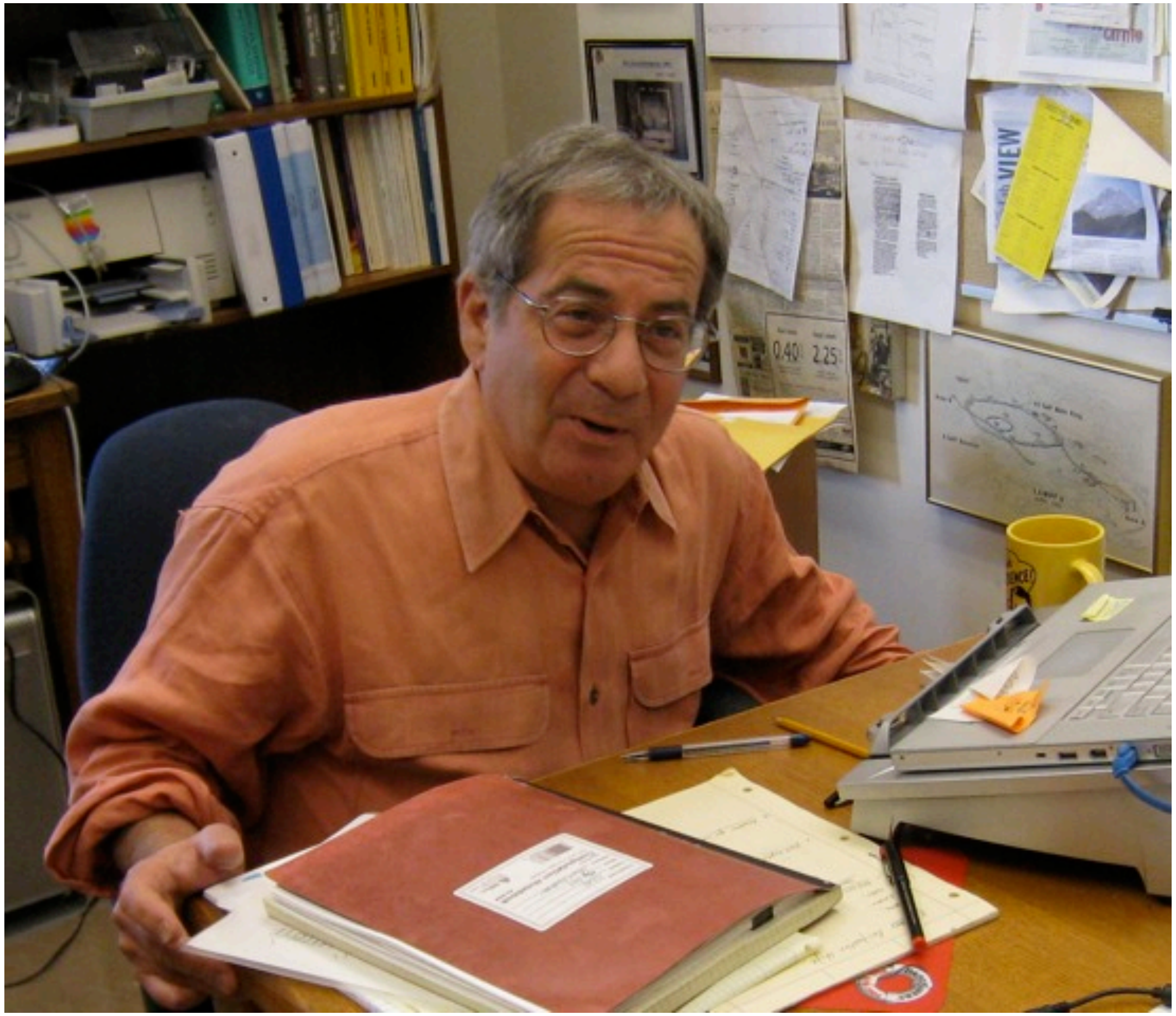
- KamLAND-Zen was a very effective modification of the KamLAND detector

- Combined EXO-KLZ half-life lower limit on $T_{1/2}^{0\nu}$ of ^{136}Xe in tension with KKDC claim for available NME calculations

- There is a rich and diverse program of double beta decay searches in progress/planned

- These experiments will have sensitivity to further test KKDC claim and probe $\langle m_{\beta\beta} \rangle$ down to 50~100 meV

Dedication

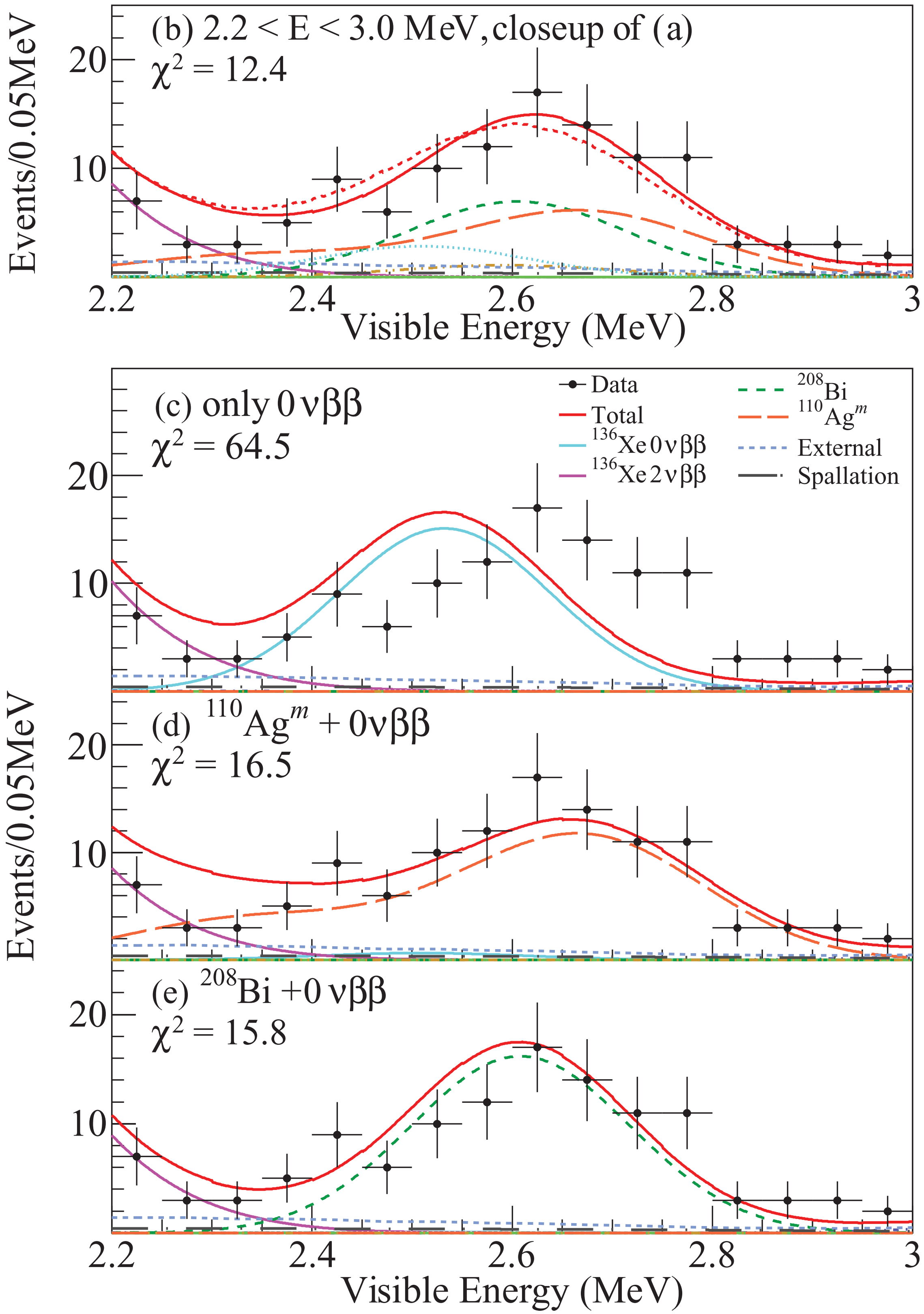


Stuart Freedman

Fondly remembered collaborator, mentor, and friend

Extra slides

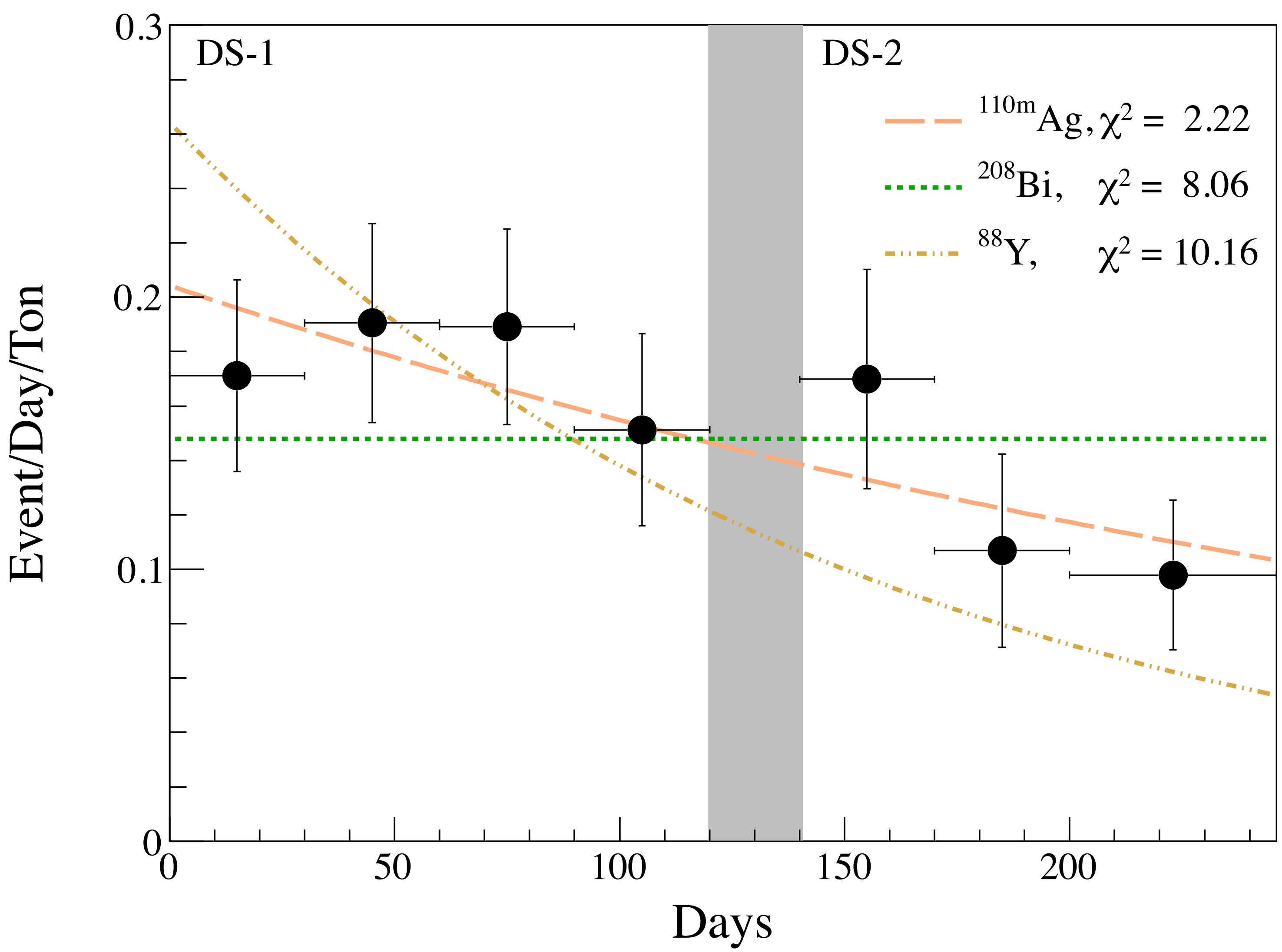
Investigating background near 2.6 MeV



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

Energy scale model

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

Energy scale model

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

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

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 $< 100\,\text{s}$	
$1.2\ \text{MeV} < E < 2.0\ \text{MeV}$	< 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