Recent Results from the KamLAND-Zen $0\nu2\beta$ Experiment

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NIKHEF

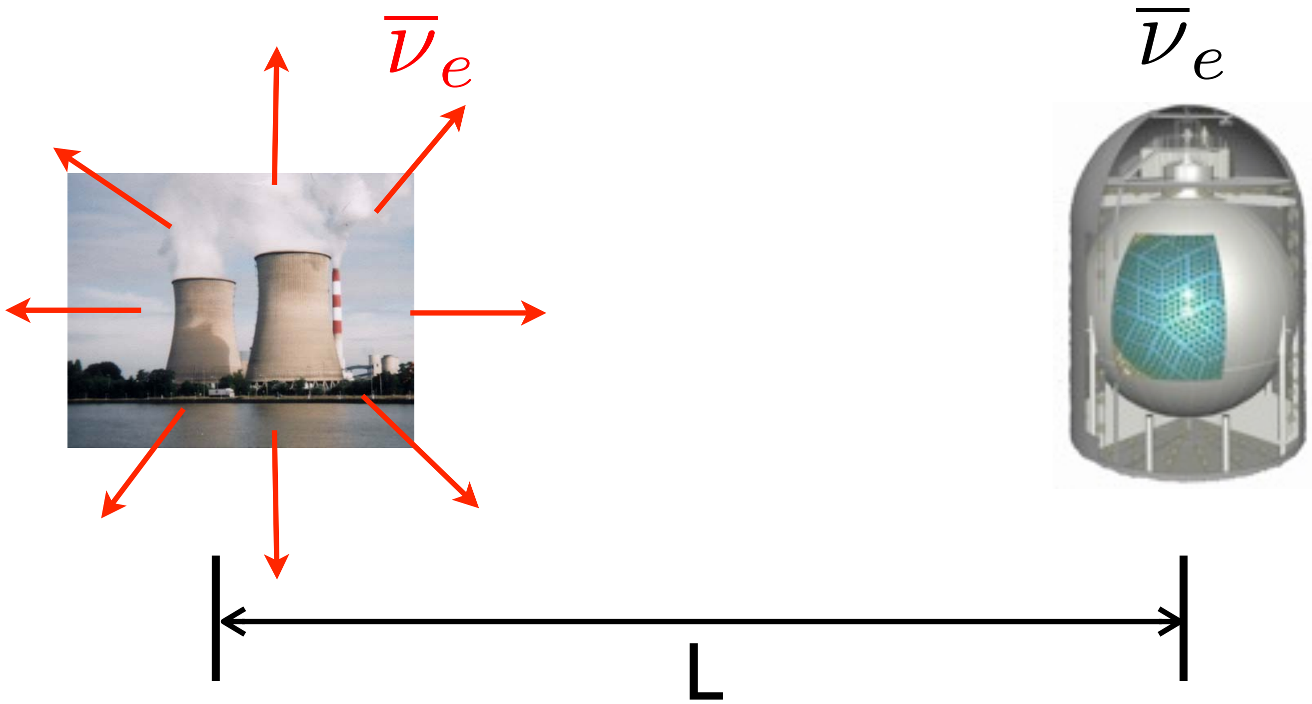
Outline

- Past KamLAND oscillation results
- Mass scales and neutrinoless double-beta decay
- How KamLAND became KamLAND-Zen
- Recent KamLAND-Zen results on double-beta decay

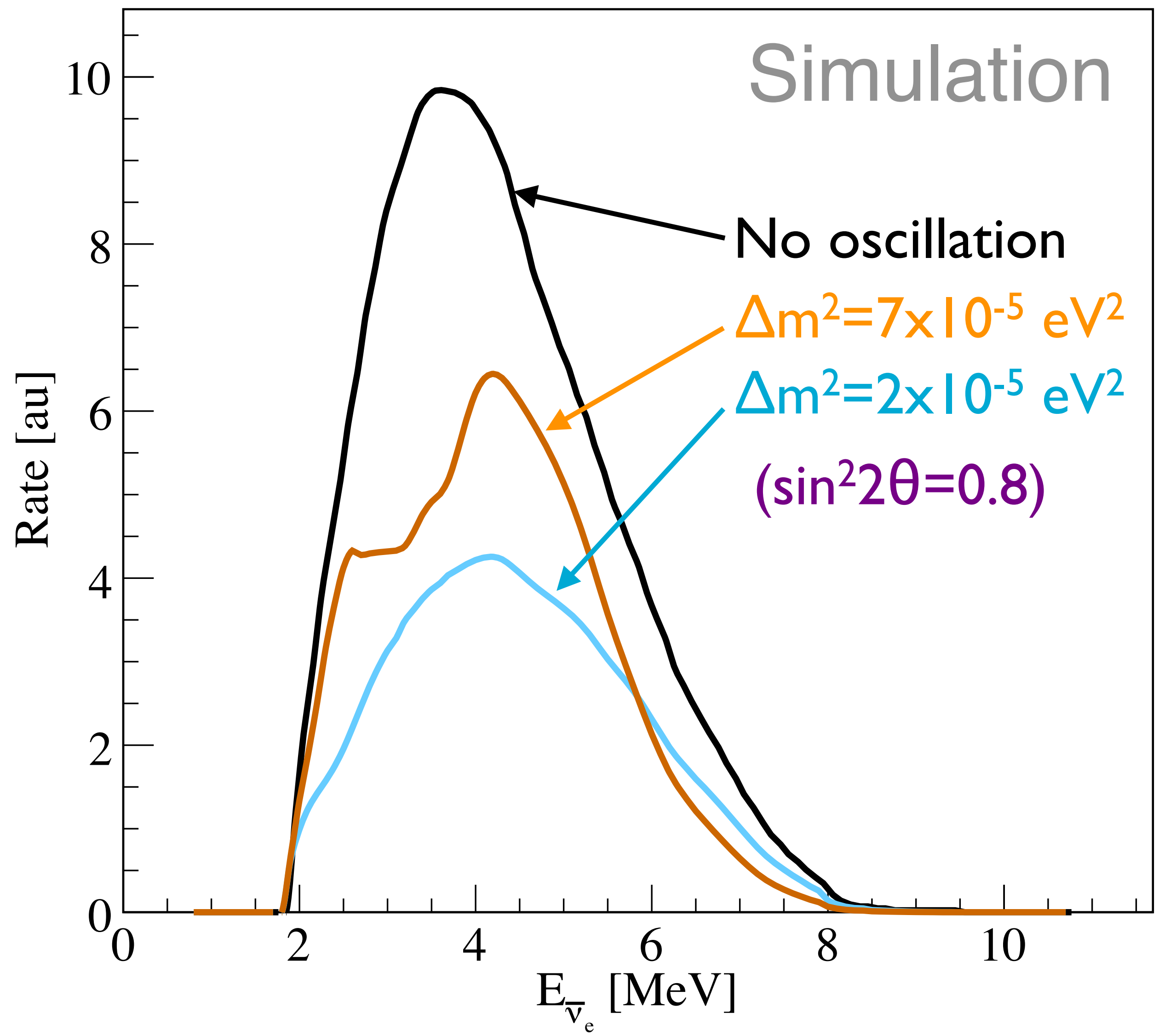
Reactors for Oscillation Studies

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}|\nu_i\rangle; \qquad \alpha = e, \mu, \tau$$

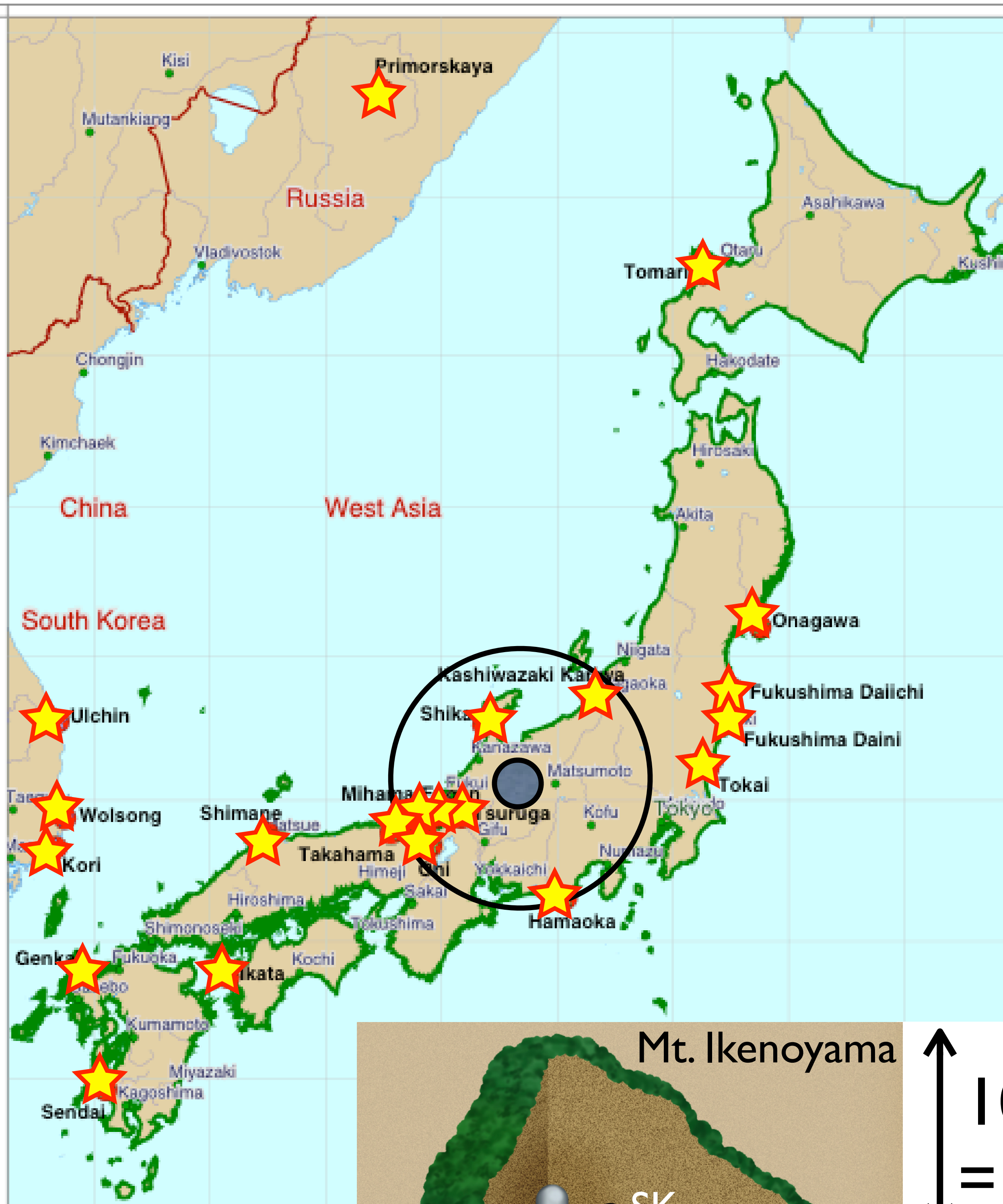
→ oscillations



$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2 L}{E}$$

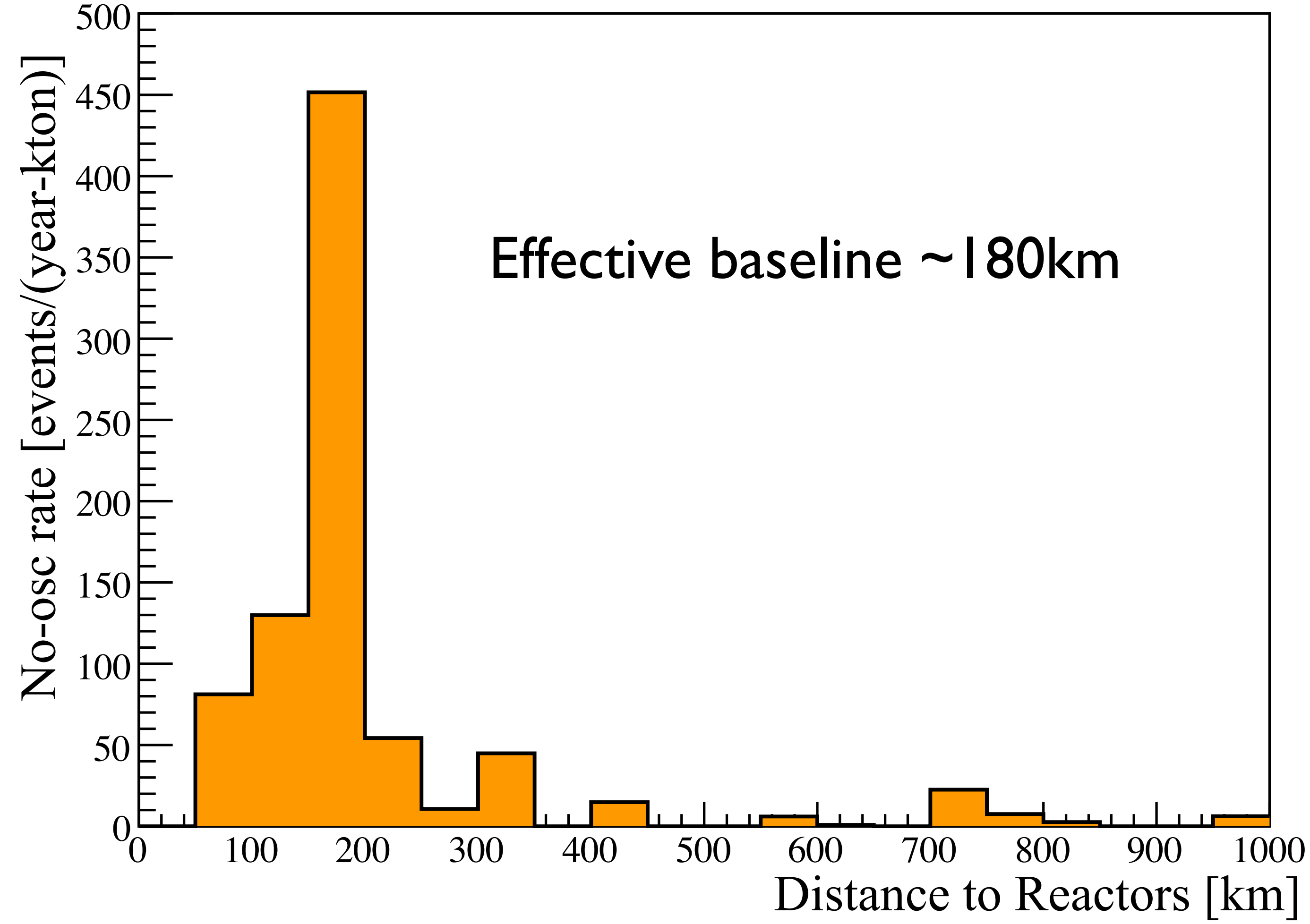


$\overline{\nu}_e$ from 54 Reactor Cores in Japan



1000m rock
= 2700 mwe

70 GW (7% of world total) is generated at 130-220 km distance from Kamioka



Reactor neutrino flux: ~6×10^{6} $cm^{-2}s^{-1}$

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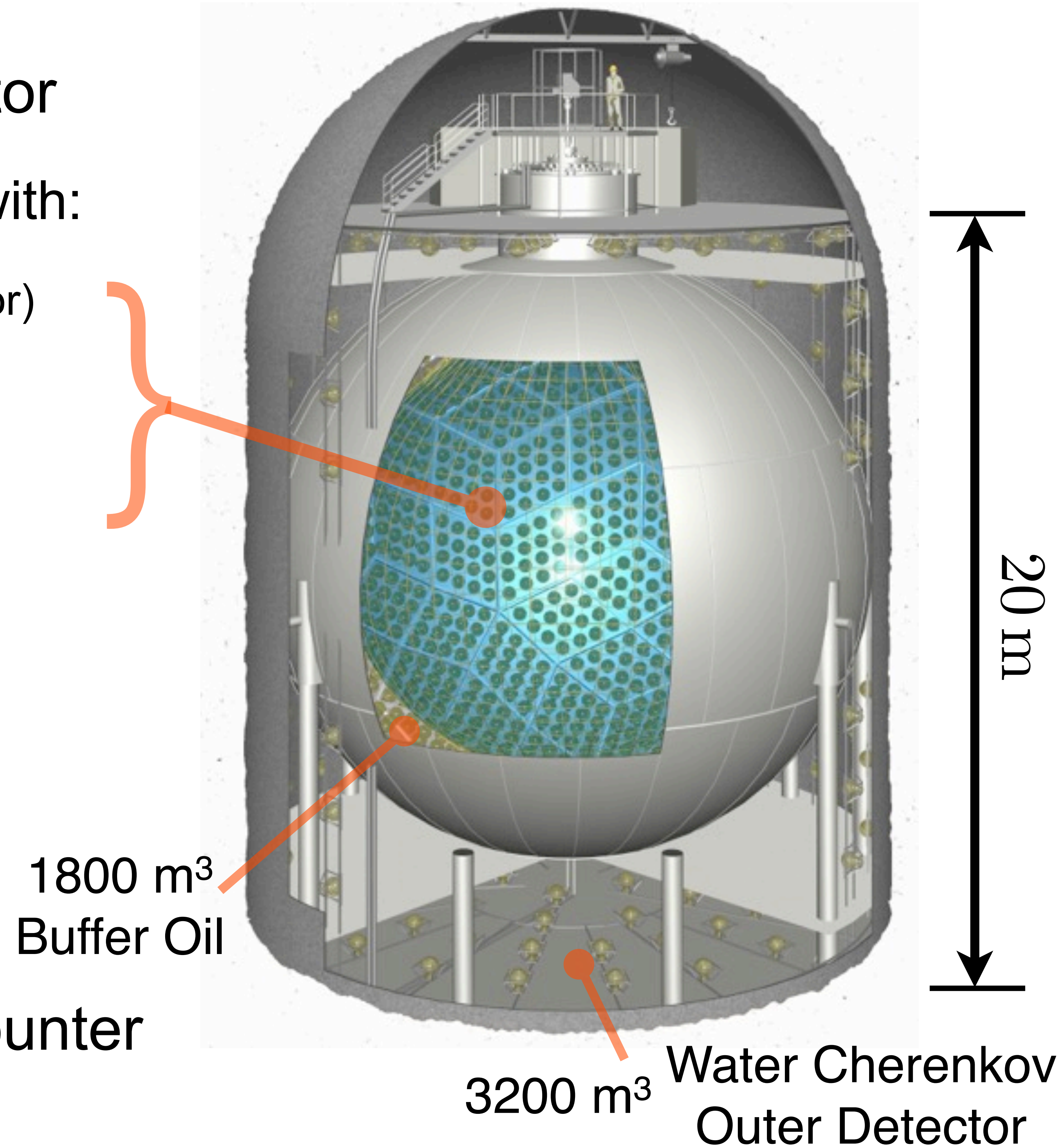
KamLAND detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scintillator)
    - 80% Dodecane (oil)
    - PPO
- 34% PMT coverage
  - ~1300 17" fast PMTs
  - ~550 20" large PMTs
- Multi-hit electronics
- Water Cherenkov veto counter



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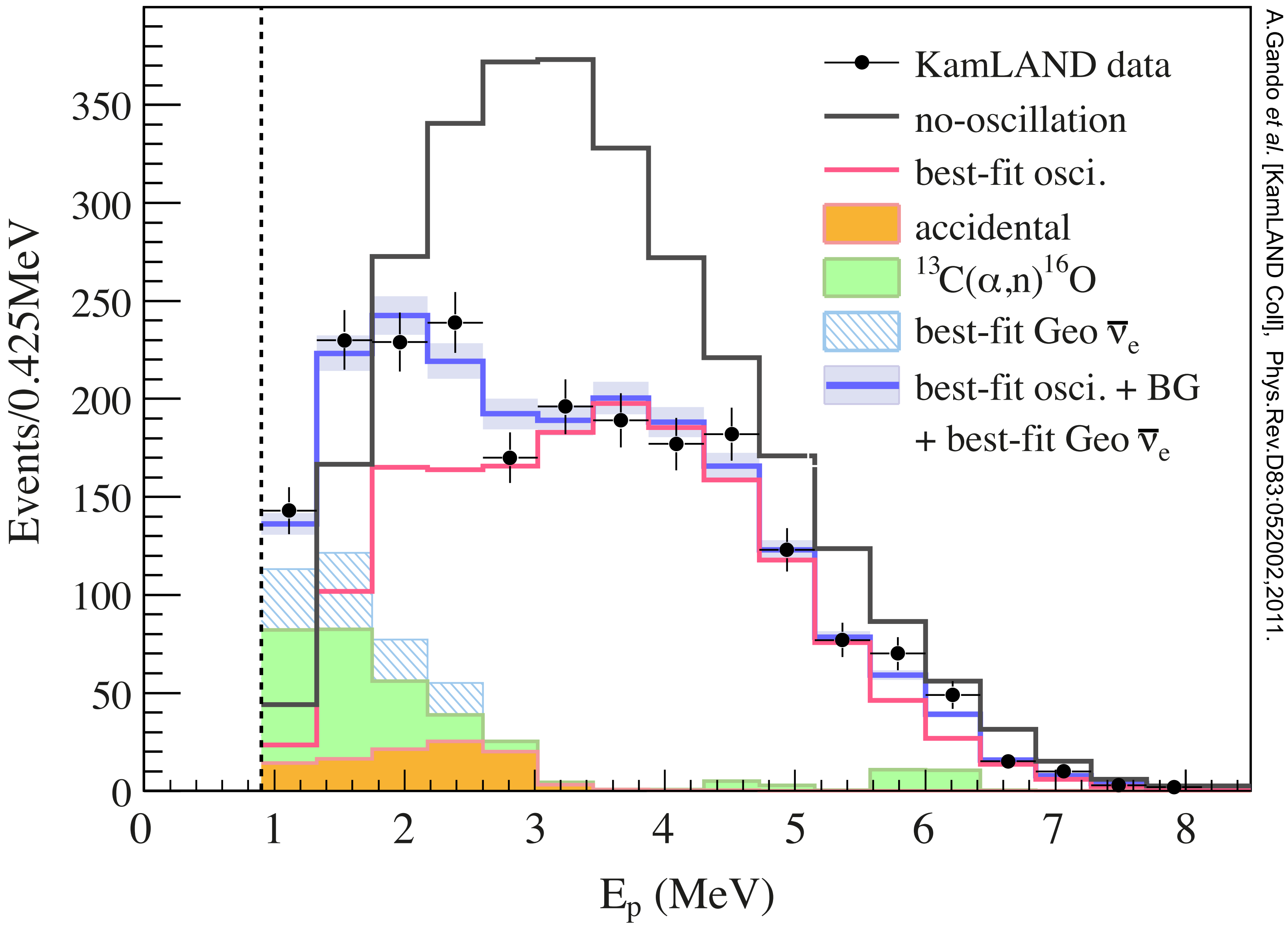
Energy Spectrum

From Mar 9, 2002 to November 4, 2009
2135 live days, 4126 ton-year exposure



Number of events:

no-osc expected	2879 ± 118
background	326 ± 26
observed	2106

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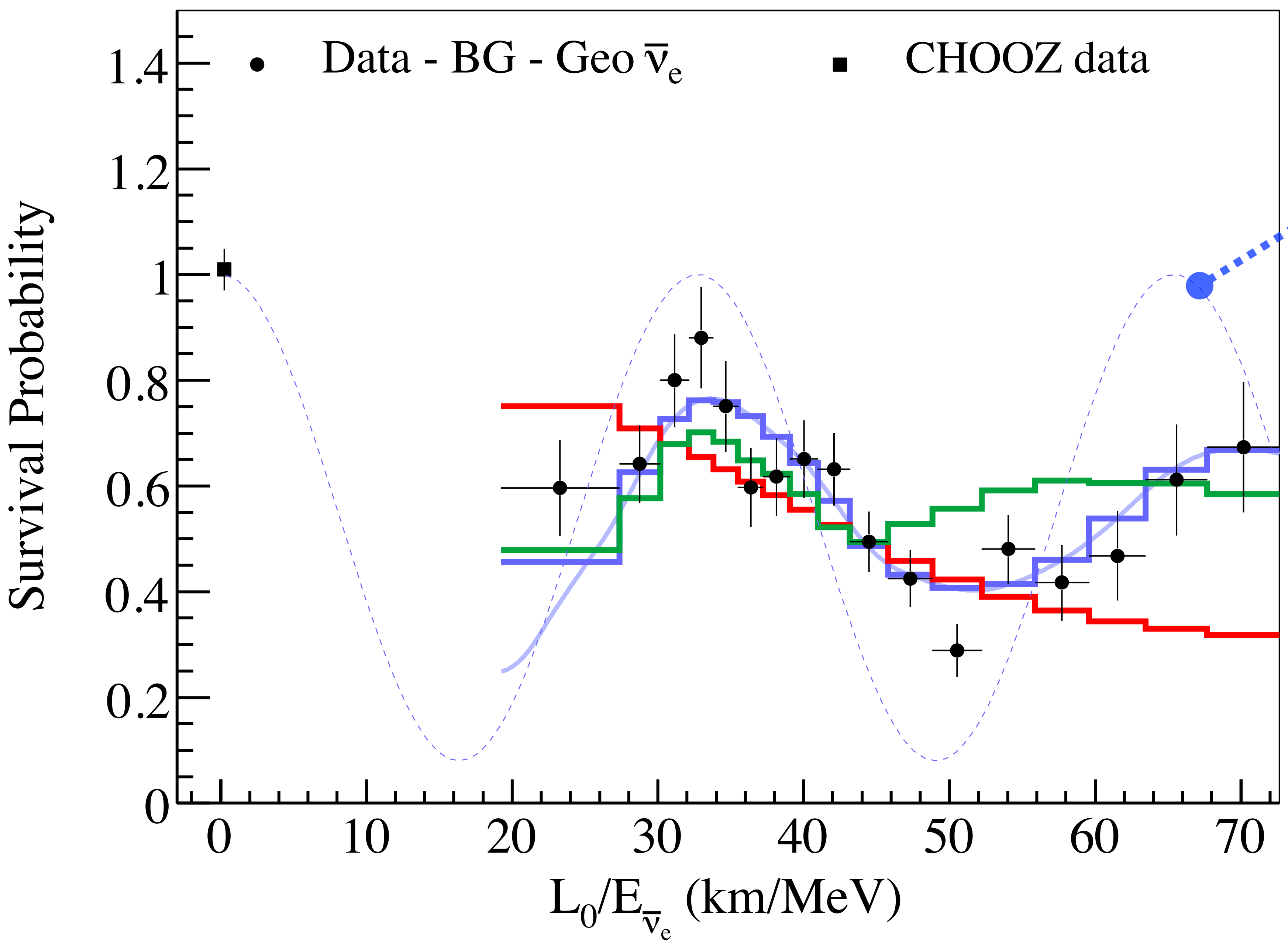
Illustration of Neutrino Oscillation



Oscillation pattern for a mono-energetic $\overline{\nu}_e$ at one baseline

LMA-1 (best fit)

-fit oscillation

LMA-2

unting for energy

trum and

LMA-0

tor distribution

$$P_{ee} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E}\right)$$

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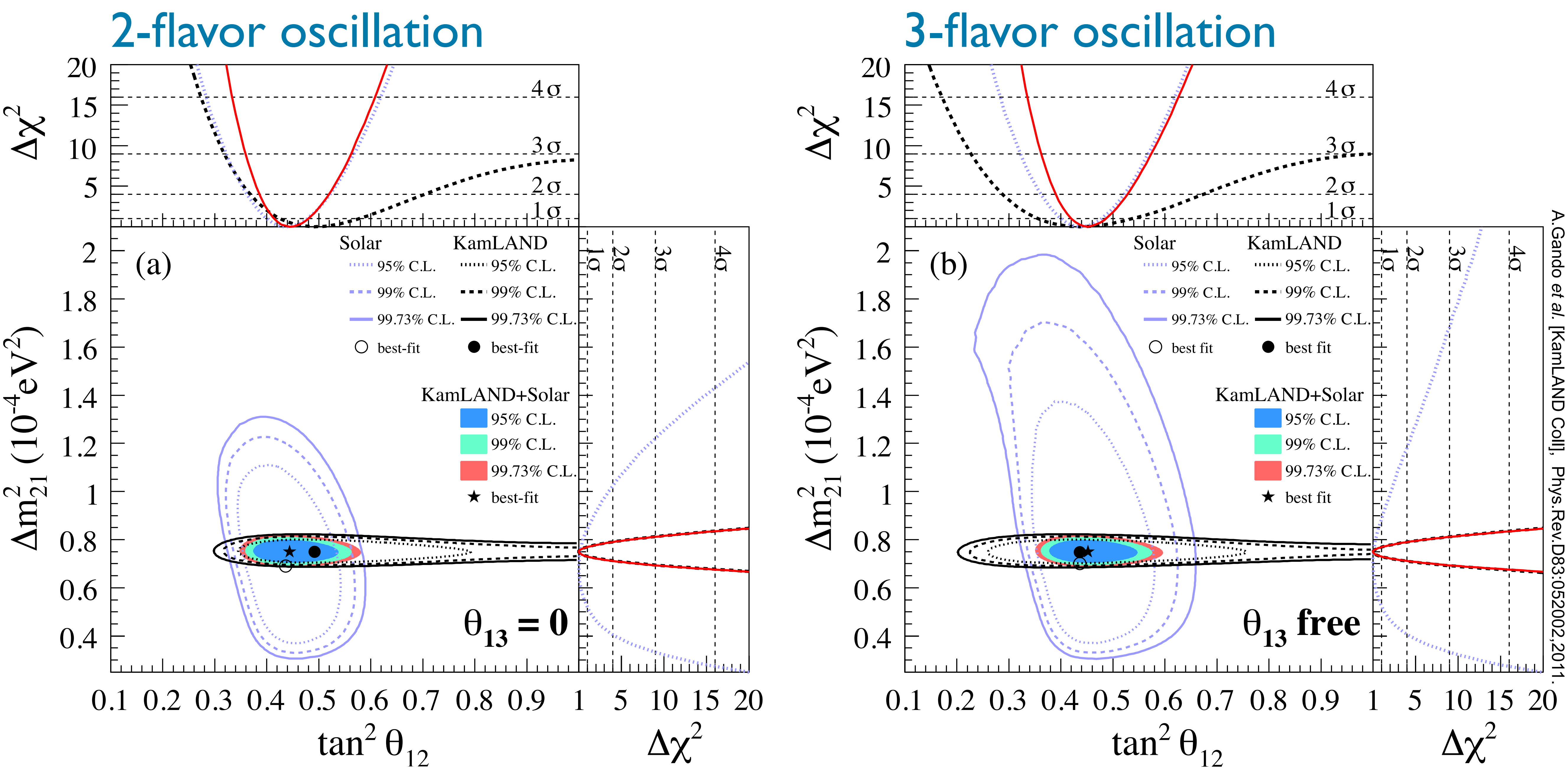
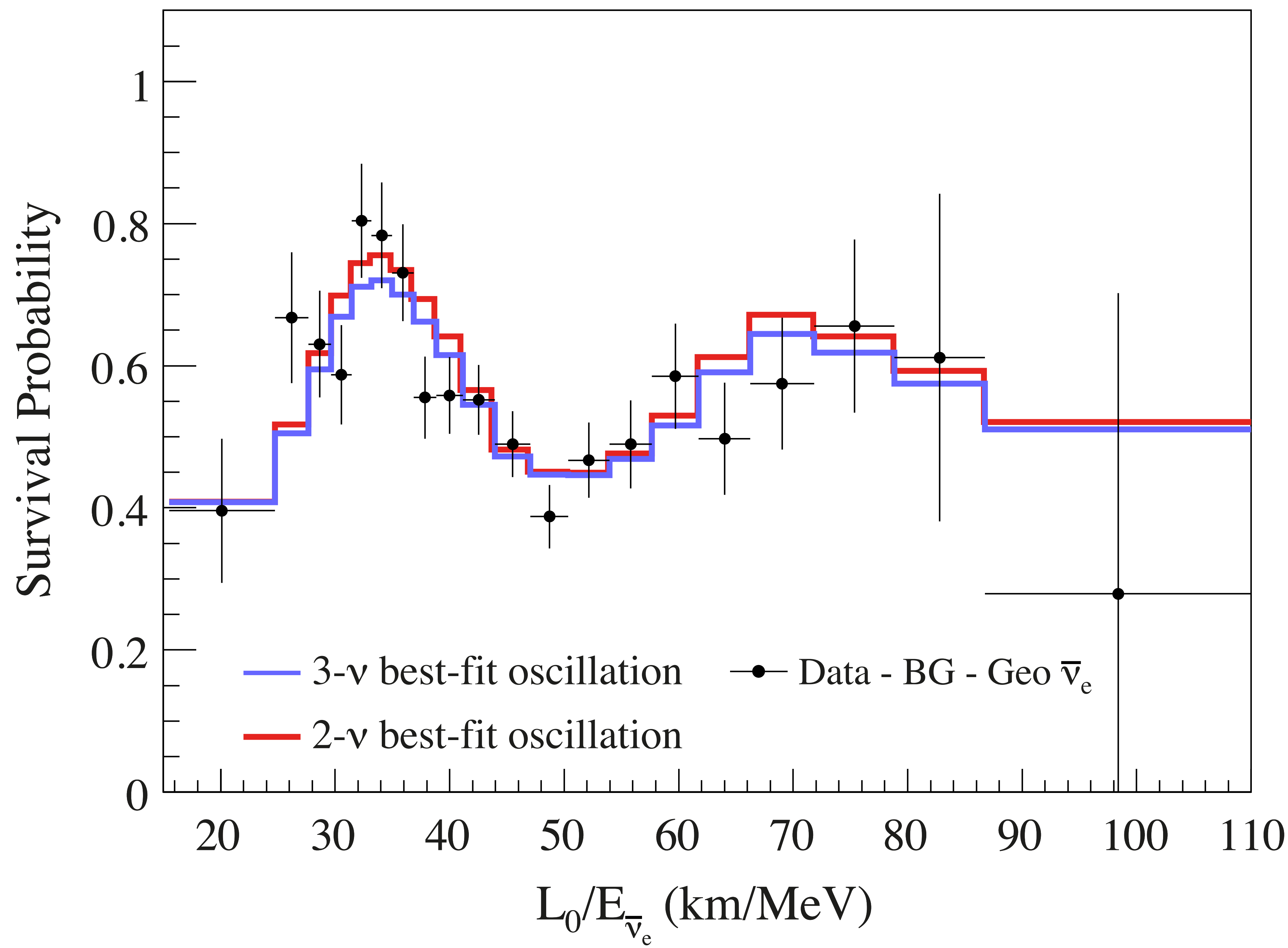
3-flavor Oscillation



$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.444^{+0.036}_{-0.030}$$

$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$$
$$\sin^2\theta_{13} = 0.020^{+0.016}_{-0.016}$$

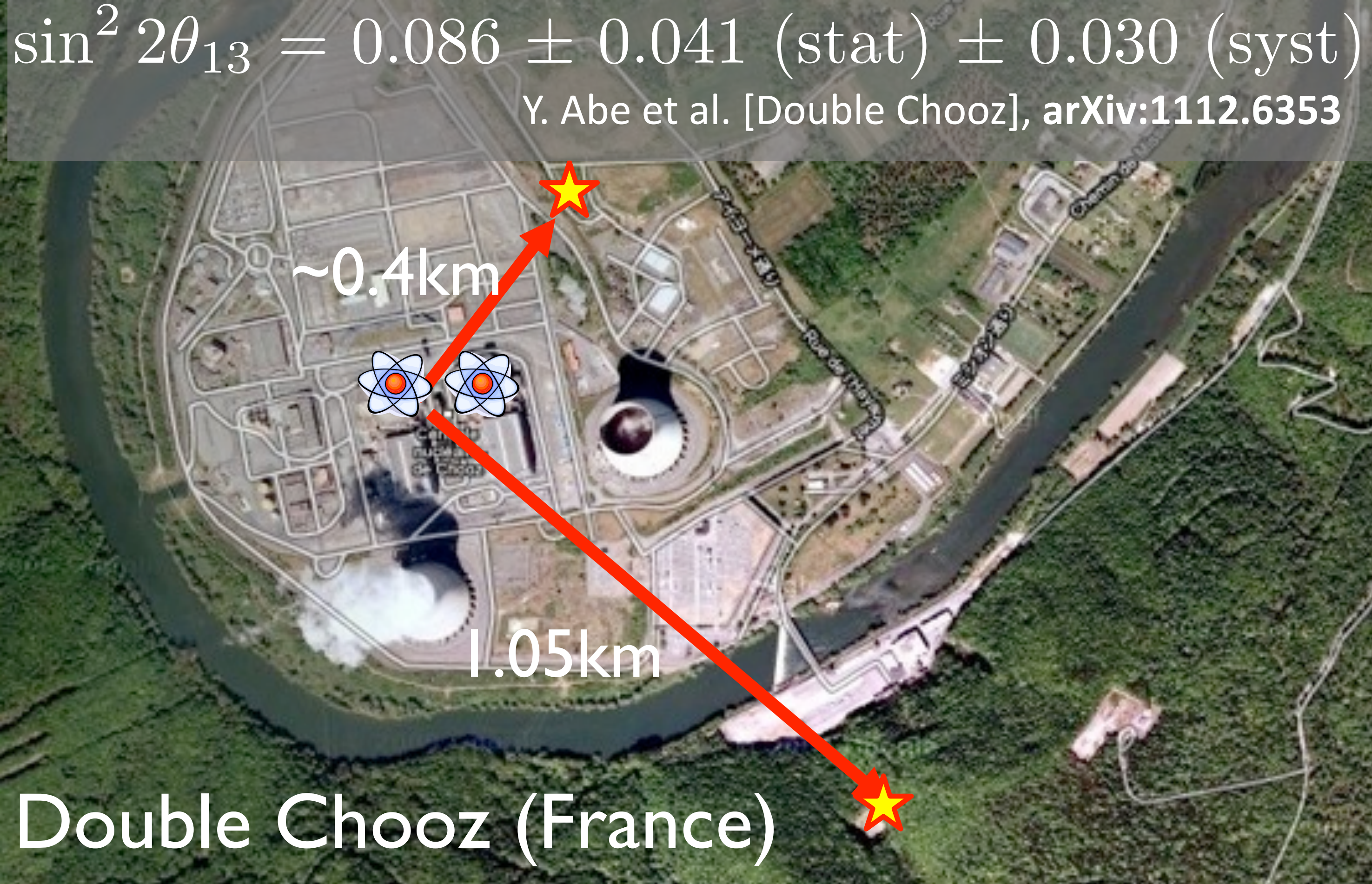
Effect of 3-nu Oscillation



$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

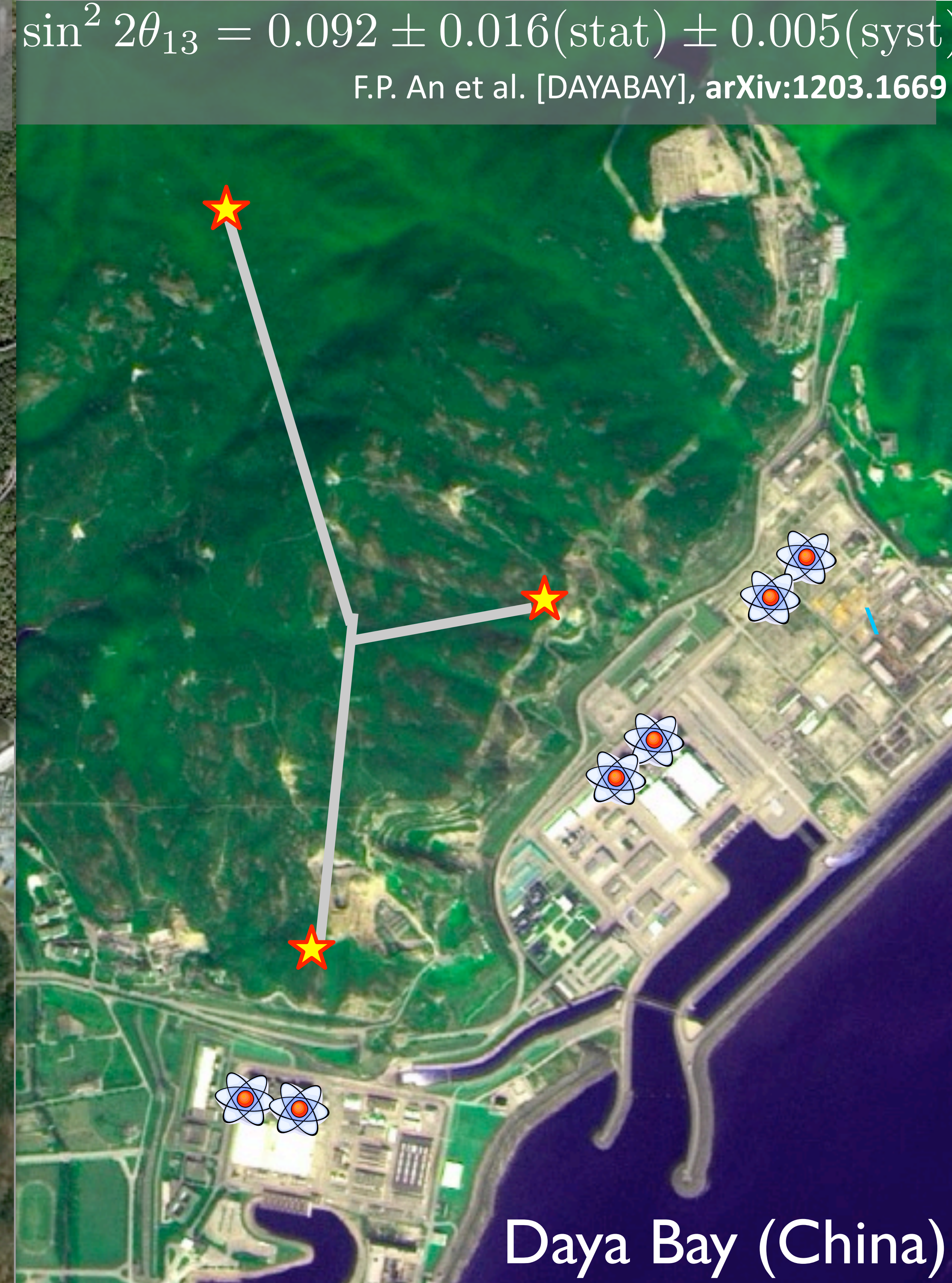
$\sin^2 2\theta_{13} = 0.086 \pm 0.041 \text{ (stat)} \pm 0.030 \text{ (syst)}$

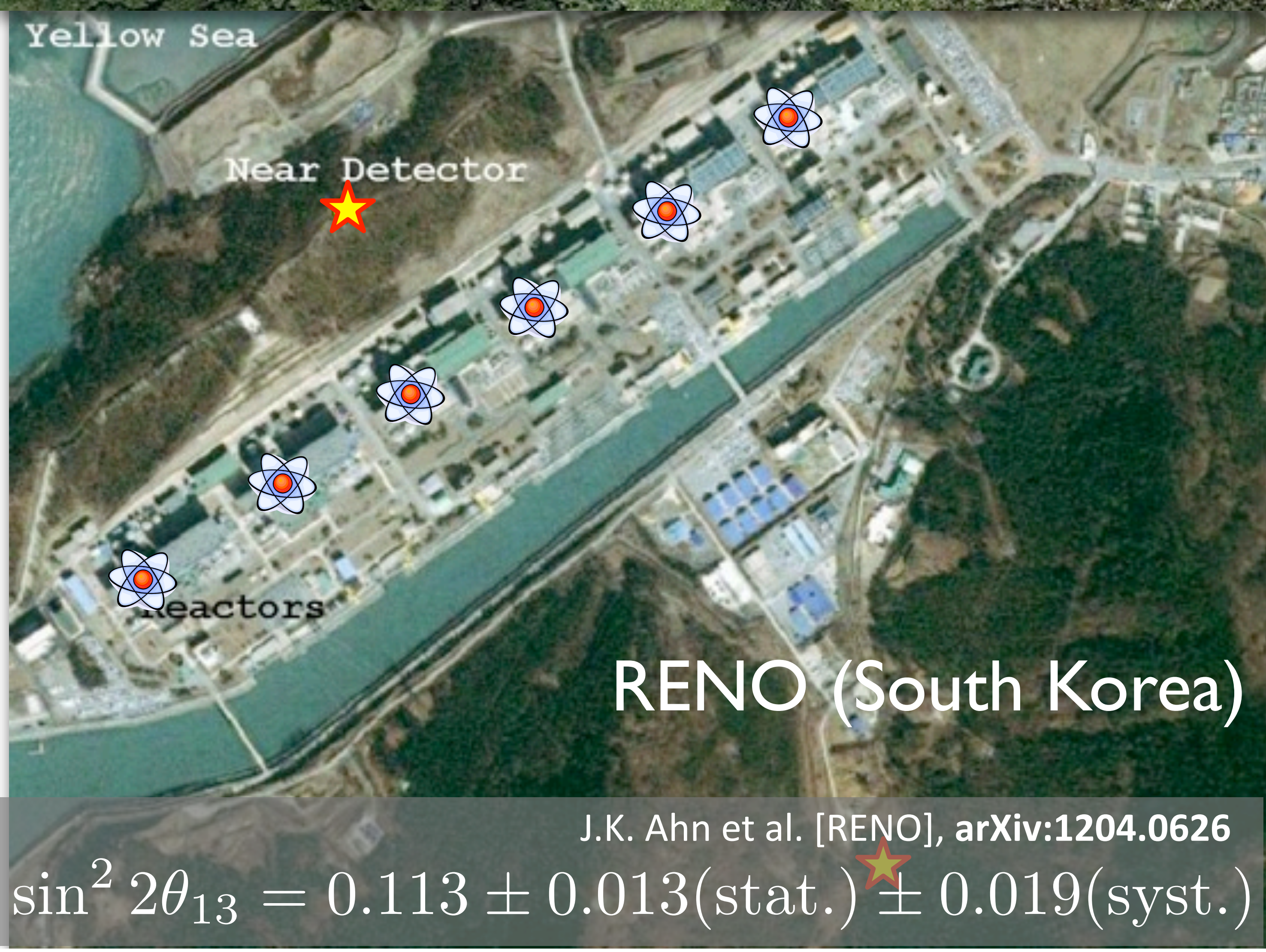
Y. Abe et al. [Double Chooz], **arXiv:1112.6353**



$\sin^2 2\theta_{13} = 0.092 \pm 0.016\text{(stat)} \pm 0.005\text{(syst)}$

F.P. An et al. [DAYABAY], **arXiv:1203.1669**





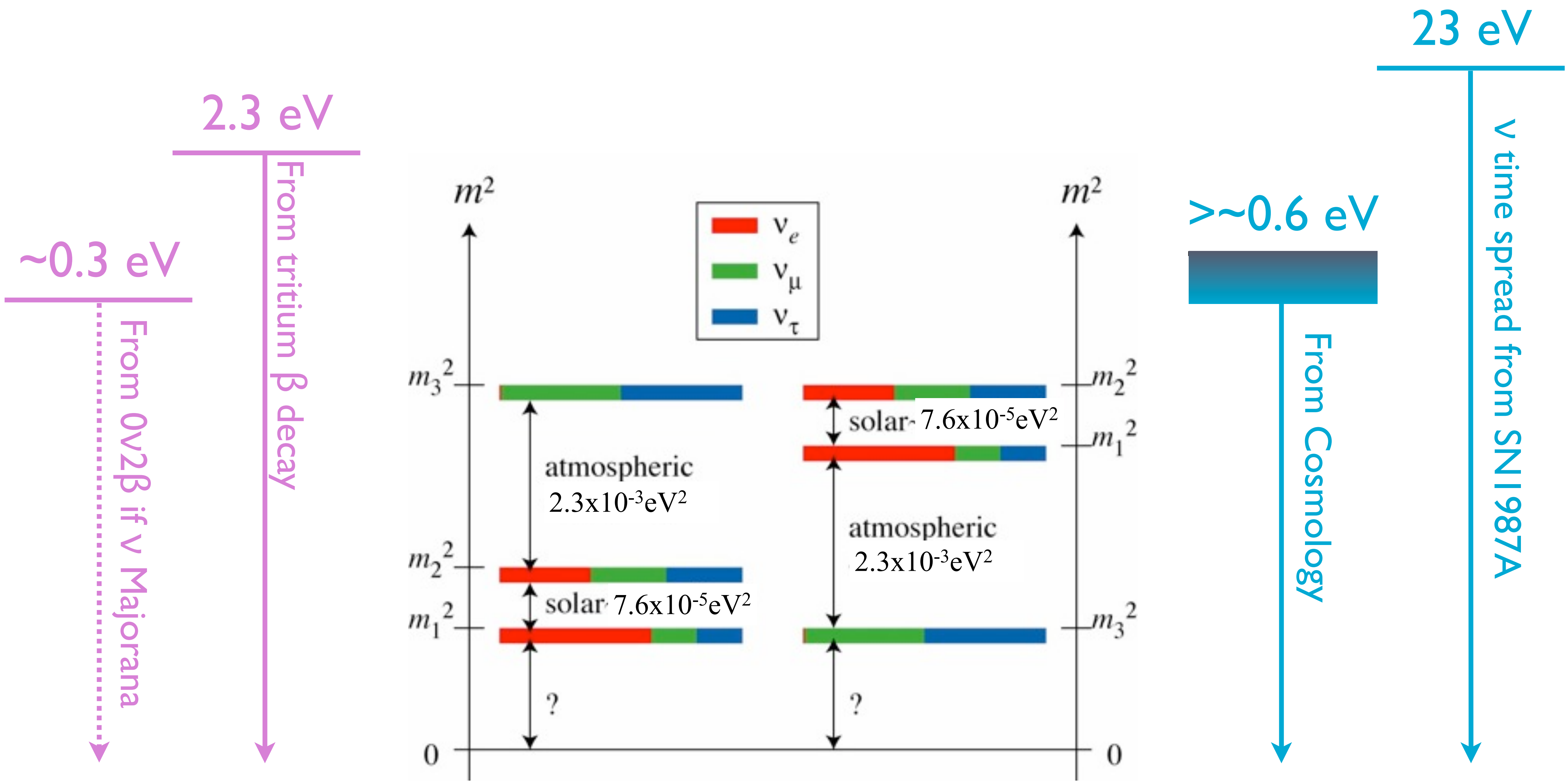
J.K. Ahn et al. [RENO], **arXiv:1204.0626**

$\sin^2 2\theta_{13} = 0.113 \pm 0.013\text{(stat.)} \pm 0.019\text{(syst.)}$

OK, so neutrinos oscillate…

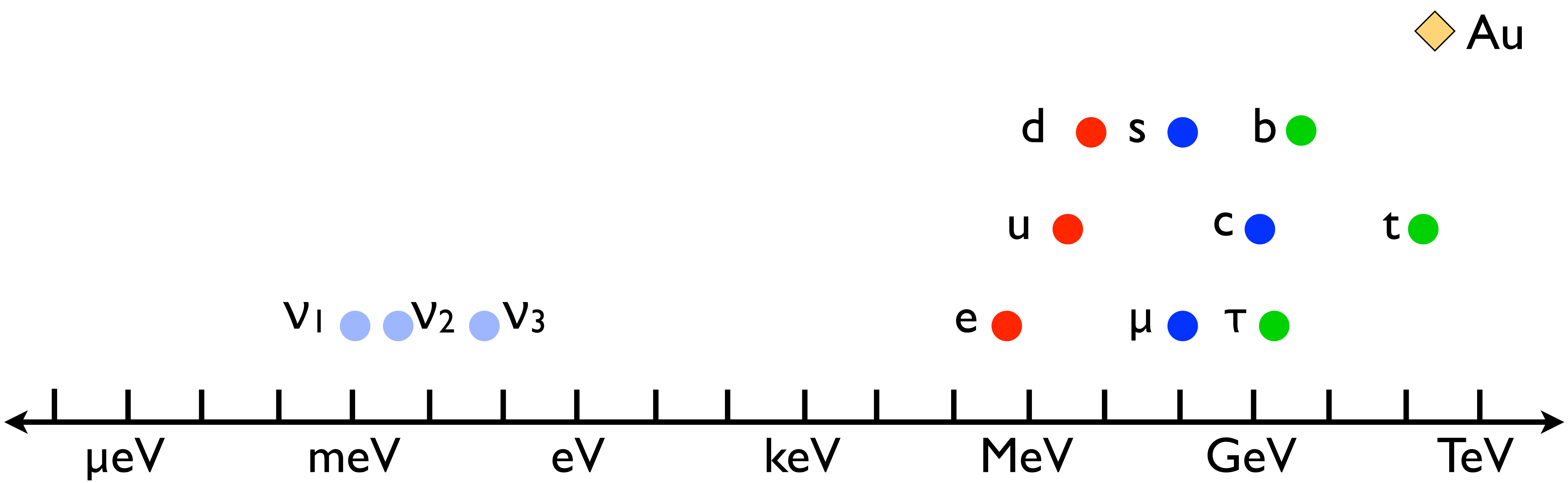
Discovery of the neutrino mass scale

… But what is the absolute neutrino mass scale?



$\rightarrow \Sigma m_i > 55$meV

Masses of Fermions



Why are neutrinos 5-6 orders less massive than other fermions?

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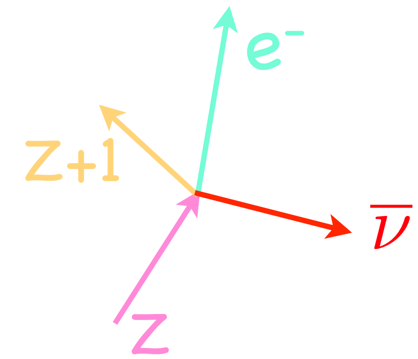
How to measure Neutrino Mass?

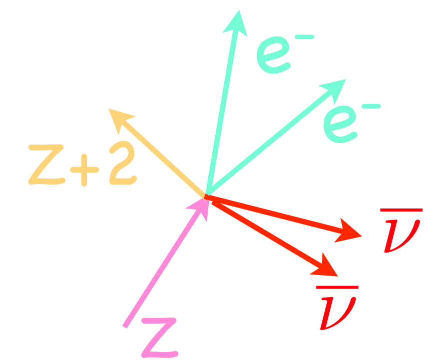
- Astrophysics
  - Supernovas - waiting for one closeby! From 1987A < ~23eV
- Cosmology
  - WMAP: $\sum m_i < 0.6$eV
- Oscillations
  - Only square of mass difference - no absolute scale
- Decays
  - μ, τ decays: relatively poor sensitivity
  - β decay
  - $\beta\beta$ decay

Beta decay

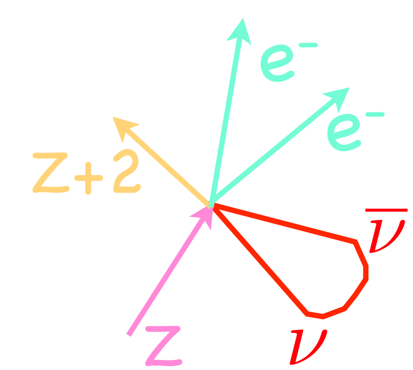
- Normal beta decay
  $^{A}_{Z}X \rightarrow ^{A}_{Z+1}X + e^{-} + \overline{\nu}_e$
  $n \rightarrow p + e^{-} + \overline{\nu}_e$



- Two neutrino double beta decay (2ν2β)
  A conventional 2nd-order nuclear physics process
  $^{A}_{Z}X \rightarrow ^{A}_{Z+2}X + e^{-} + \overline{\nu}_e + e^{-} + \overline{\nu}_e$
  $^{76}Ge \rightarrow ^{76}Se + e^{-} + \overline{\nu}_e + e^{-} + \overline{\nu}_e$



- Neutrinoless double beta decay (0ν2β)
  A hypothetical new process
  $^{A}_{Z}X \rightarrow ^{A}_{Z+2}X + e^{-}e^{-}$
  $^{76}Ge \rightarrow ^{76}Se + e^{-} + e^{-}$



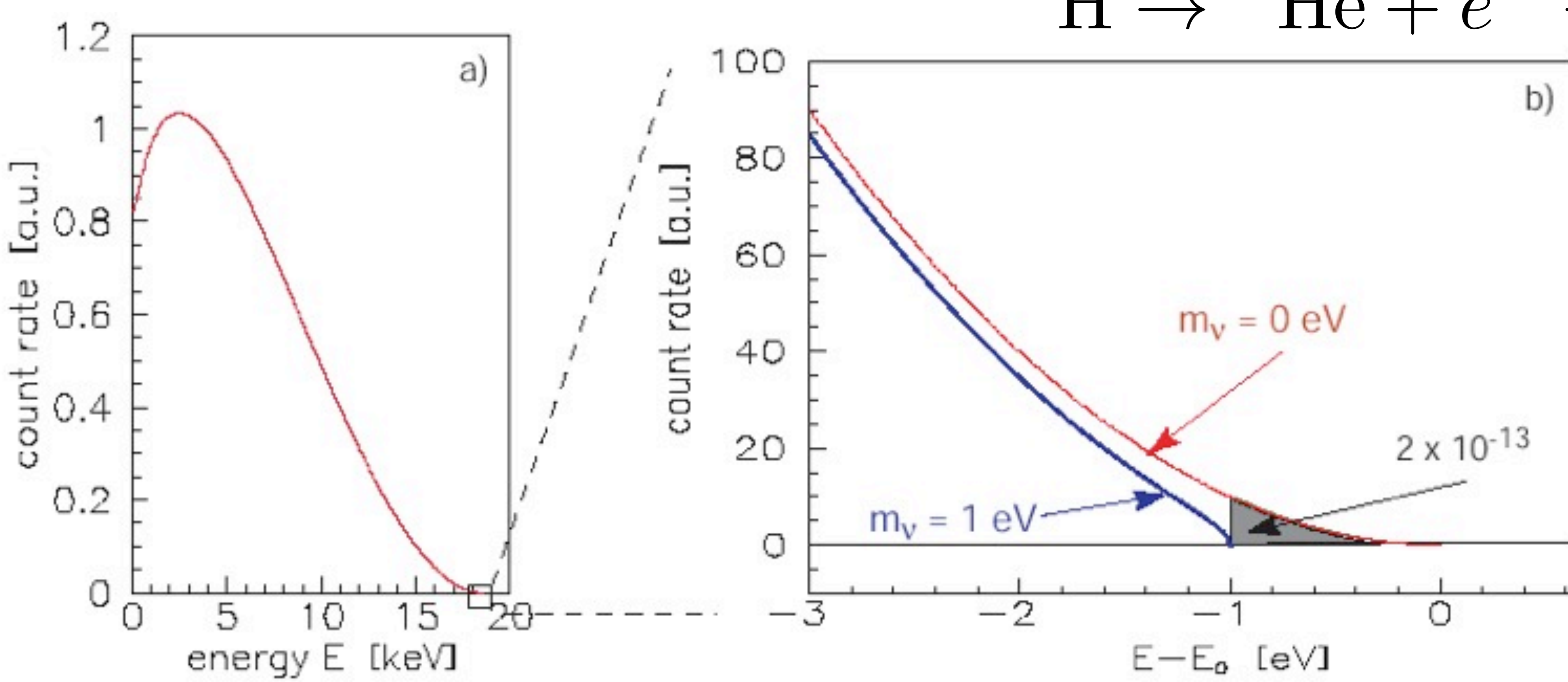
Absolute mass from β decay

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

[incoherent sum]

- The shape of the β decay energy spectrum near the endpoint depends on <mβ>
  - Based on kinematics and energy conservation
  - No model dependence

$$^3\mathrm{H} \rightarrow \, ^3\mathrm{He} + e^- + \overline{\nu}_e$$



[KATRIN LOI]

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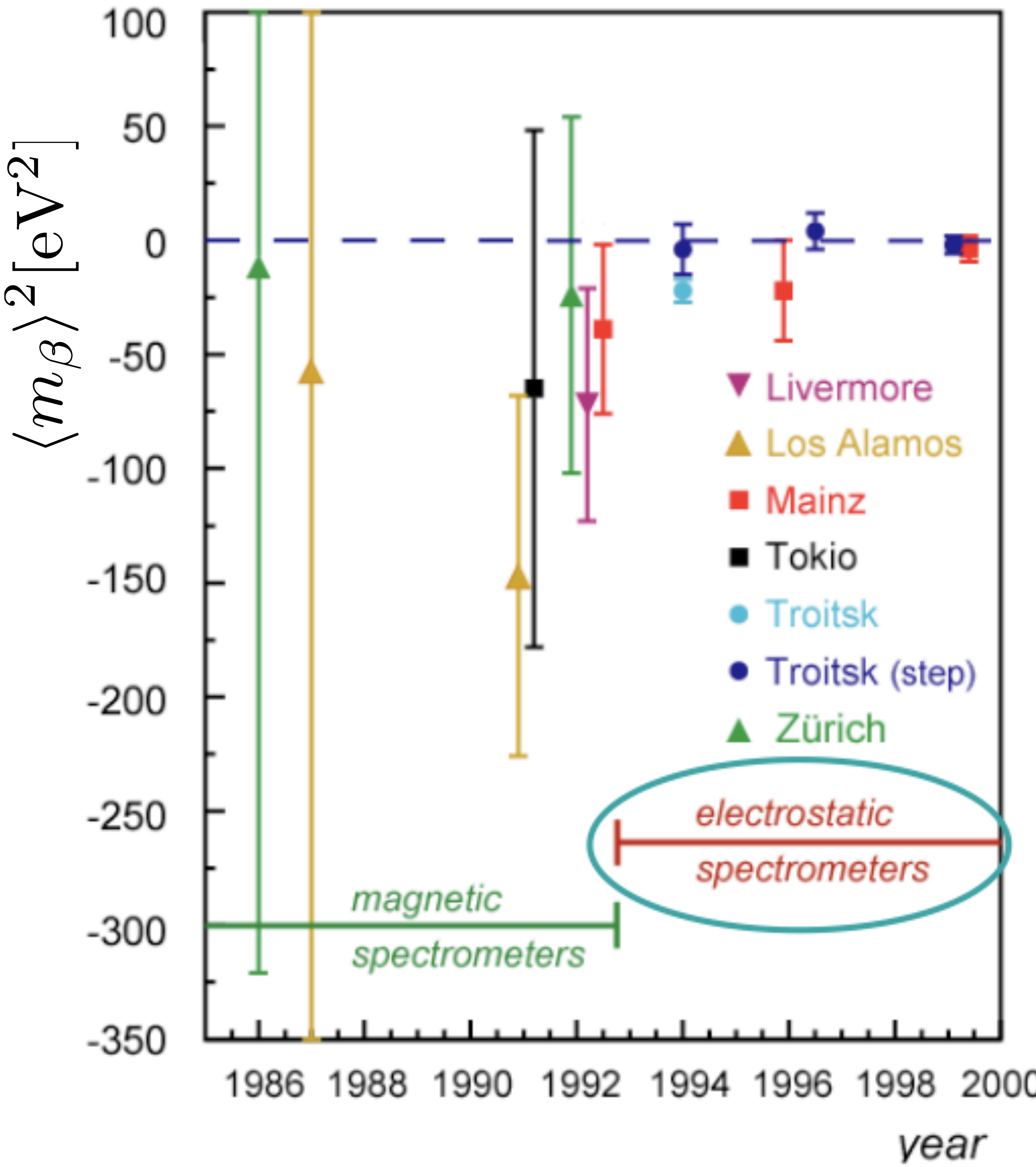
Current best limits on <mβ>

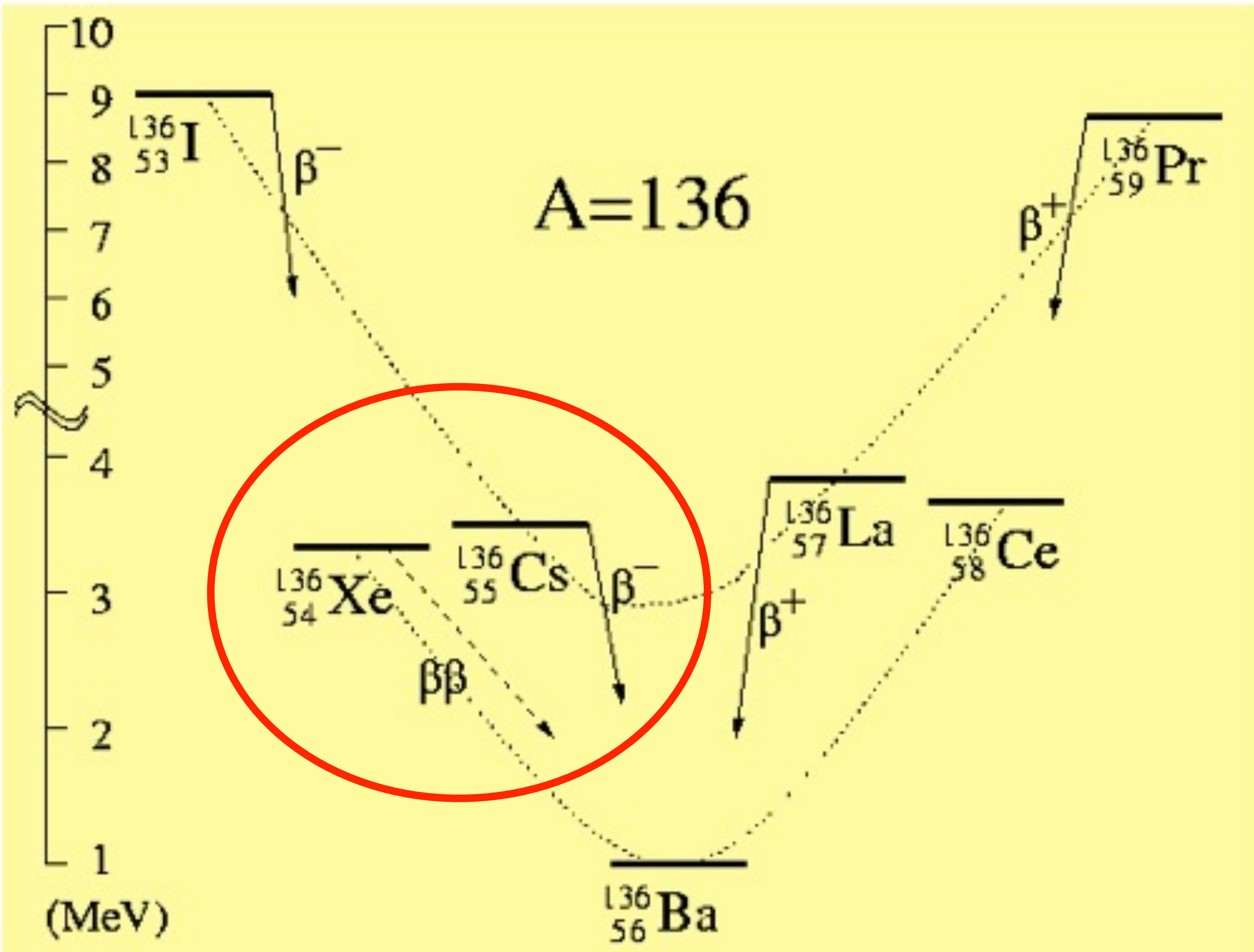


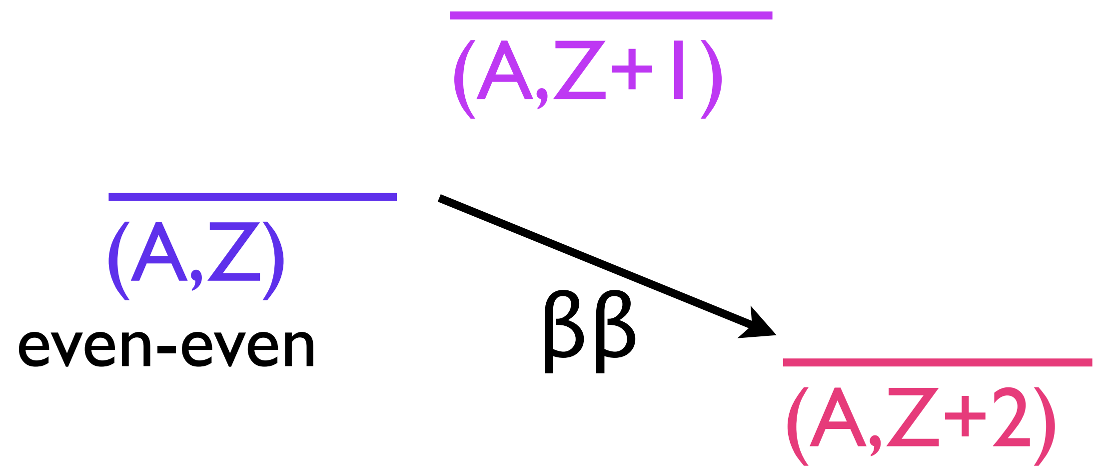
$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2} < 2.3\,\mathrm{eV}$$

While these table-top experiments made impressive gains, they have run out of steam

Next: KATRIN experiment

Double beta decay Isotopes



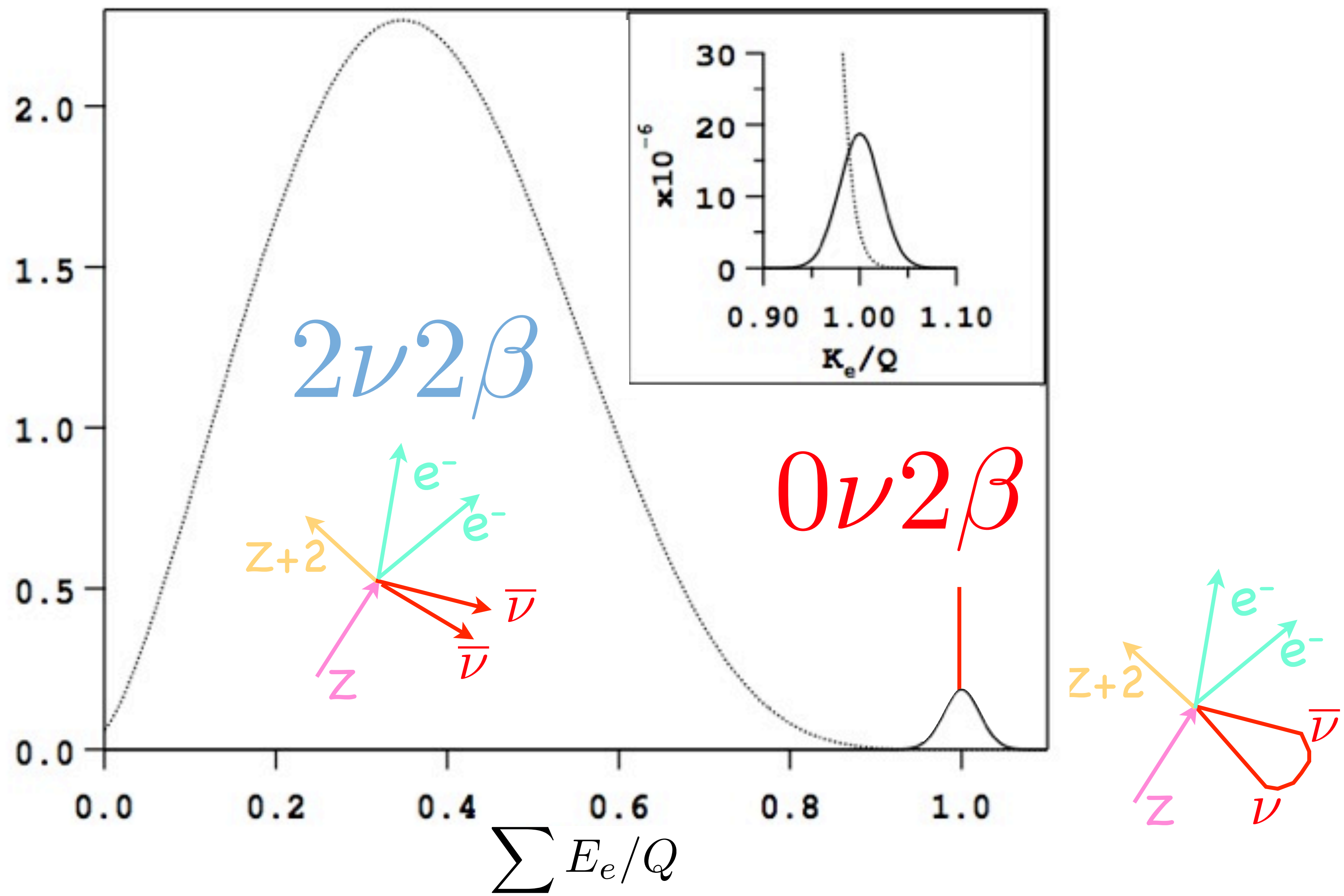


A second-order process only detectable if first-order beta decay is energetically forbidden

Experiments only measure the energy of the two electrons

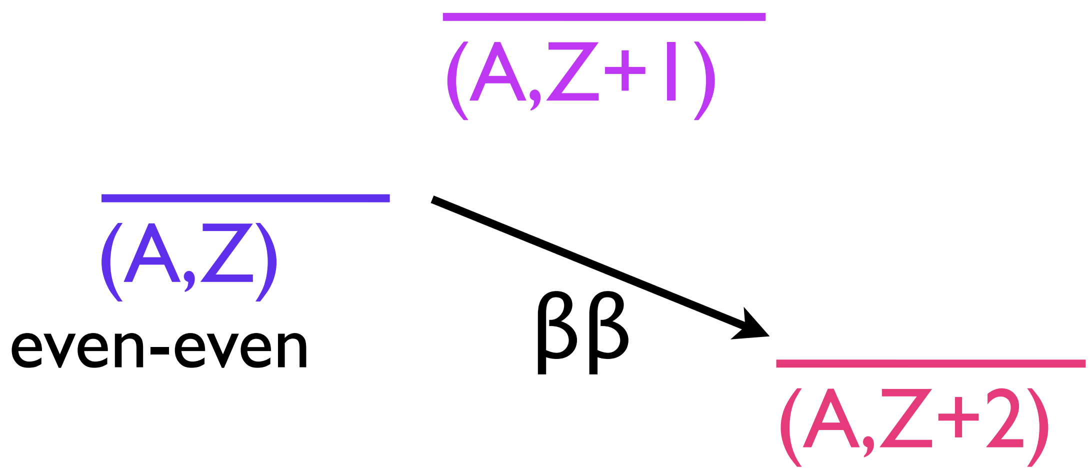
With energy resolution

Without energy resolution



Candidate 0ν2β Nuclei

Candidates are even-even nuclei



[Candidates with Q>2 MeV]

Candidate	Q[MeV]	%Abund
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.530	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

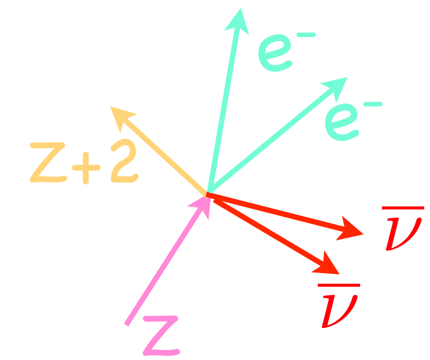
Natural abundance of 0ν2β candidates is low
→ enrichment necessary

2ν2β has been measured

$$(T^{2\nu}_{1/2})^{-1} = G_{2\nu}(Q,Z)|M_{2\nu}|^2$$

Phase Space factor

Nuclear Matrix Element



- Conserves lepton number
- Does not discriminate between Dirac and Majorana neutrinos
- Not sensitive to neutrino mass scale
- Nevertheless: slow process!

Isotope	$T_{1/2}^{2\nu}$ [yr]
^{48}Ca	4.2±1.0 x 10^{19}
^{76}Ge	1.5±0.1 x 10^{21}
^{82}Se	0.92±0.07 x 10^{20}
^{96}Zr	2.0±0.3 x 10^{19}
^{100}Mo	7.1±0.4 x 10^{18}
^{116}Cd	3.0±0.2 x 10^{19}
^{128}Te	2.5±0.3 x 10^{24}
^{130}Te	0.9±0.1 x 10^{21}
^{150}Nd	7.8±0.8 x 10^{18}
^{238}U	2.0±0.6 x 10^{21}

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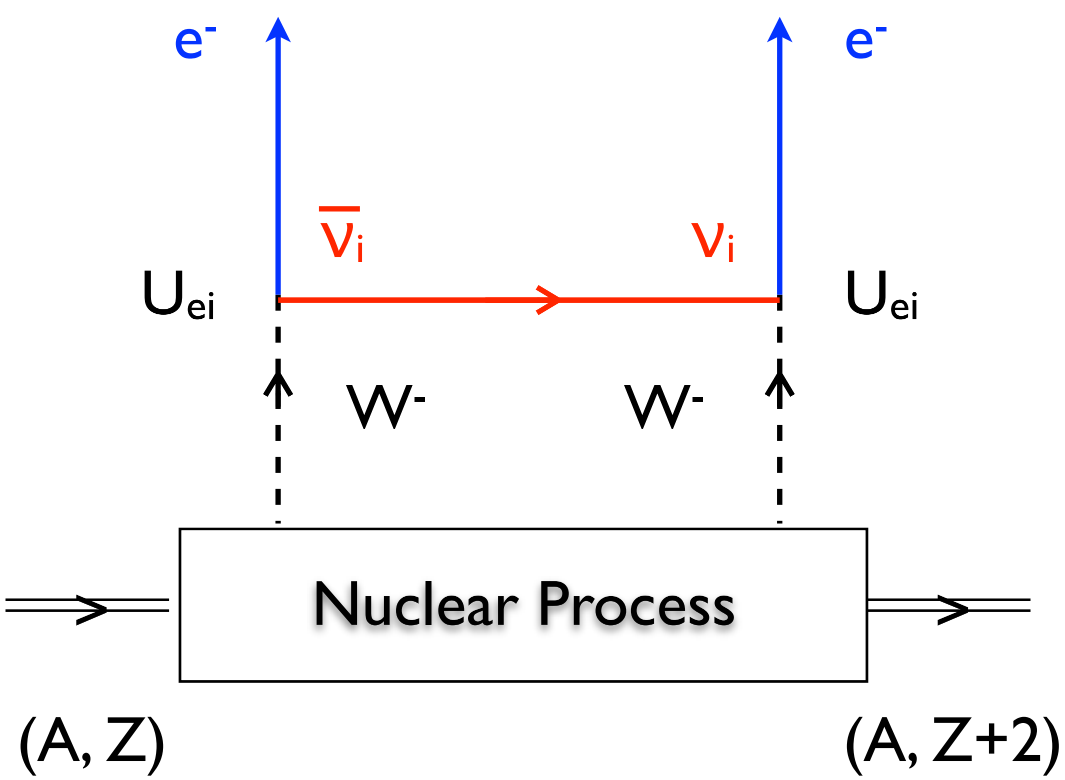
Lepton Number Violation

Neutrinoless double beta decay:



$$\begin{aligned} M_\nu &\neq 0 \\ \nu &= \overline{\nu} \\ |\Delta L| &= 2 \end{aligned}$$

Helicity has to flip

Total Lepton Number Violation

See Saw Mechanism

In terms of chiral nu-fields can write mass term in Lagrangian:

$$\mathcal{L}_m = -m_D\overline{\nu^0_R}\nu^0_L - \frac{1}{2}M_R\overline{(\nu^0_R)^c}\nu^0_R + \text{h.c.}$$

$$= -\frac{1}{2}\left[\overline{(\nu^0_L)^c}, \overline{\nu^0_R}\right]\begin{bmatrix} 0 & m_D \\ m_D & M_R \end{bmatrix}\begin{bmatrix} \nu^0_L \\ (\nu^0_R)^c \end{bmatrix} + \text{h.c.}$$

Neutrino Mass Matrix

Nothing in SM prevents M_R to be very large and m_D of the same order as other SM particles!

Diagonalizing Mass Matrix and rewriting fields in terms of **Majorana nus**:

$$\mathcal{L}_m = -\frac{1}{2}\frac{m_D^2}{M_R}\overline{\nu}\nu - \frac{1}{2}M_R\overline{N}N$$

Mass of ν

Mass of very heavy N

Half of the neutrinos are "invisible" very heavy (~10^{15}GeV) N's!

What mass does 0ν2β measure?

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\boxed{\langle m_{\beta\beta}\rangle^2}$$

Phase Space factor: Calculable

Nuclear Matrix Element: Hard to calculate

Interesting physics

Effective Majorana mass:

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

[coherent sum]

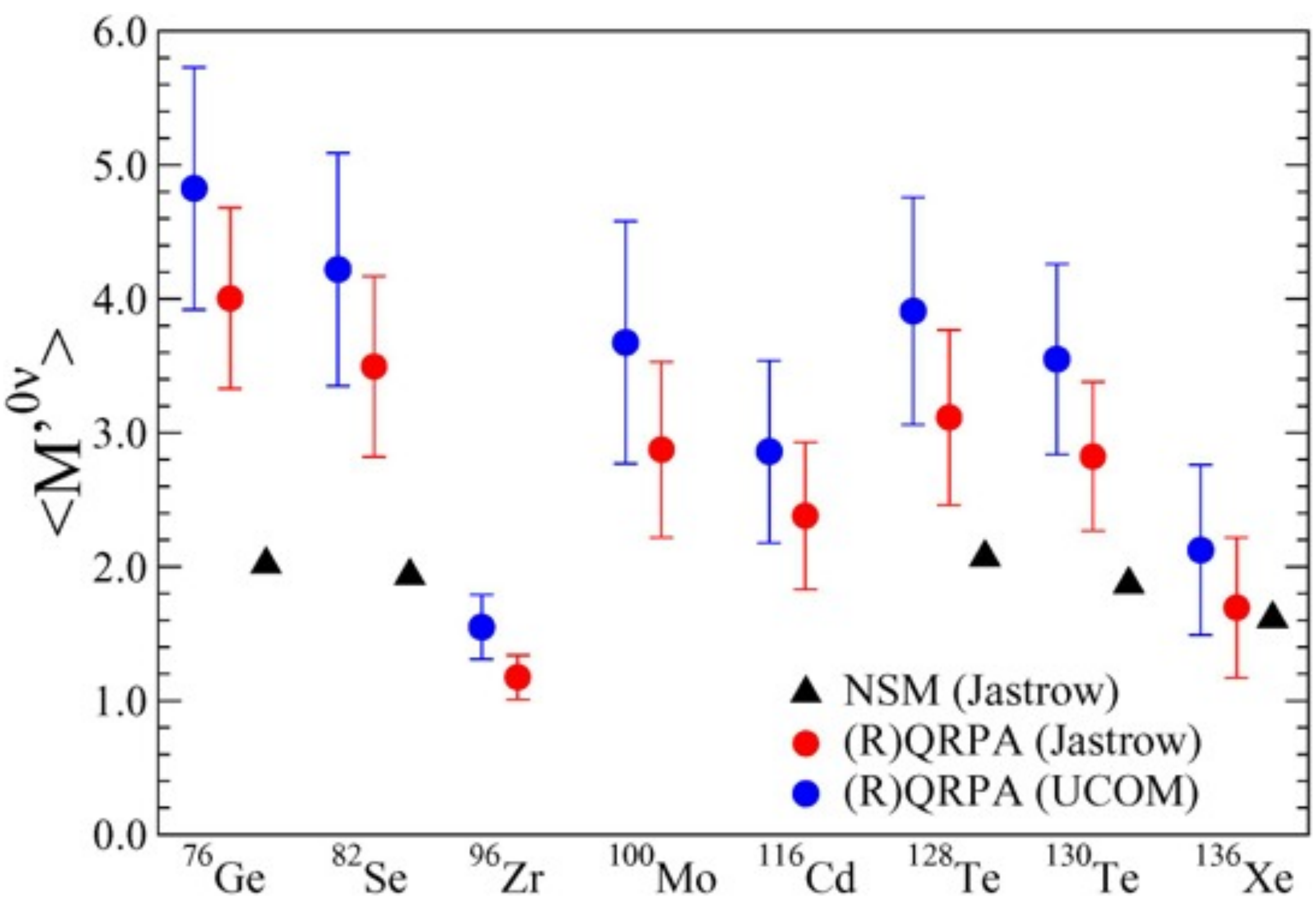
Where U_{ei} elements from the Lepton Mixing Matrix

$$U = \begin{matrix} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \begin{matrix} \nu_1 & \nu_2 & \nu_3 \\ \left[\begin{matrix} c_{12}c_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} \end{matrix}\right. & \begin{matrix} s_{12}c_{13} \\ c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} \\ -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} \end{matrix} & \left.\begin{matrix} s_{13}e^{-i\delta} \\ s_{23}c_{13} \\ c_{23}c_{13} \end{matrix}\right] \end{matrix}$$

$$\times \operatorname{diag}\left(e^{i\alpha_1/2},\ e^{i\alpha_2/2},\ 1\right) .$$

Nuclear Matrix Elements

- Complicated theoretical calculations
  - Quasiparticle Random Phase Approximation (QRPA)
  - Shell Model



F.Simkovic et al., Phys.Rev.C77:045503,2008.

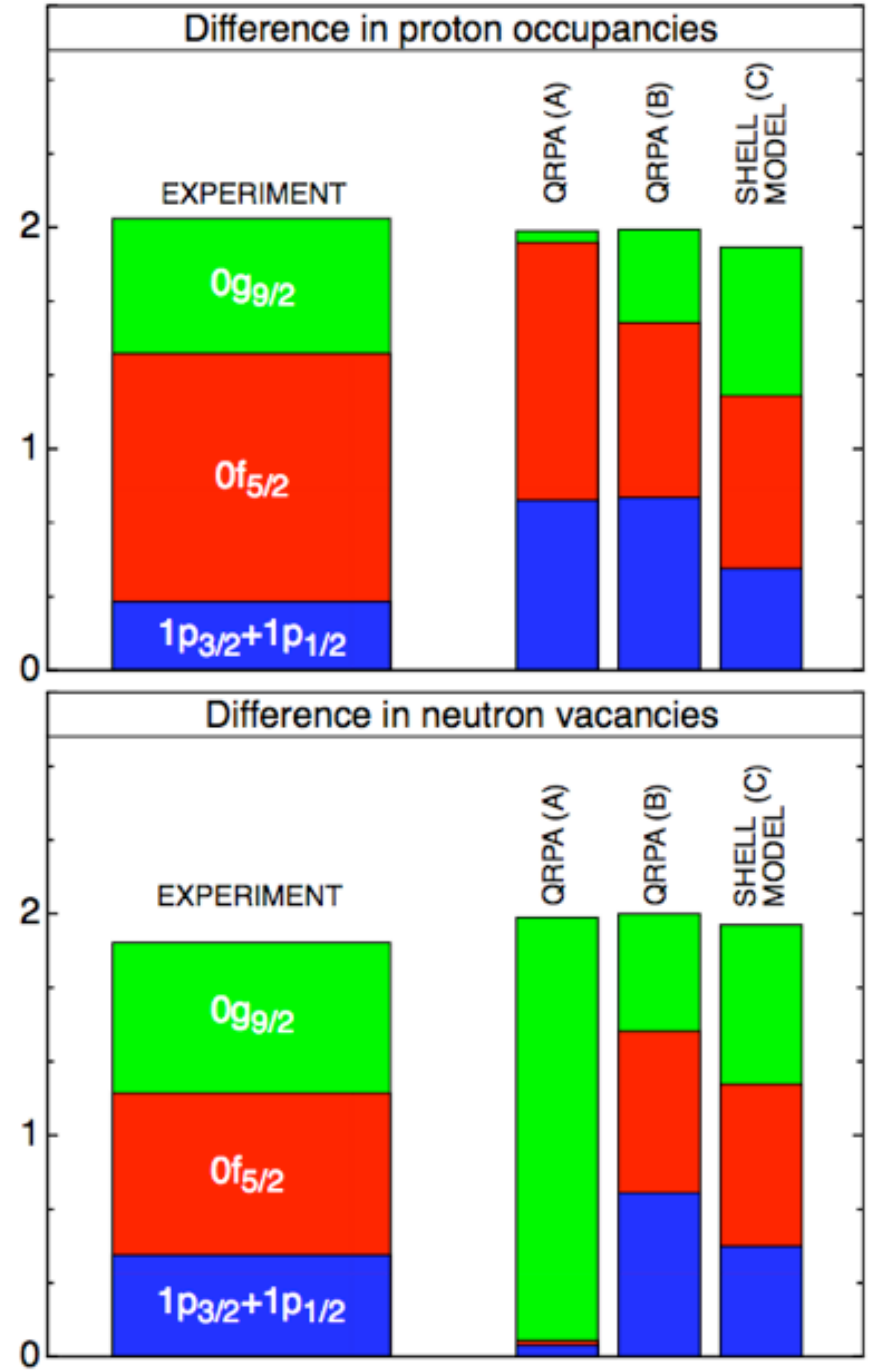
Shell Model calculations ~1.5-2x smaller than QRPA

Chief reason for large uncertainties in $\langle m_{\beta\beta} \rangle$!!

Improving Nuclear Matrix Elements

- NME calculations are notoriously difficult
- Attempts to include experimental data on occupation of valence orbits
- Recent results from nucleon transfer reactions on ^{76}Ge & ^{76}Se
  - 25% correction on NME in QRPA
- Similar experiments done for ^{130}Te and in progress for ^{136}Xe

Difference ^{76}Ge → ^{76}Se



B.P.Kay et al., Phys. Rev. C79, 021301(2009).

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Claimed observation of 0ν2β in Ge

5 detectors (10.96 kg) enriched to 86%

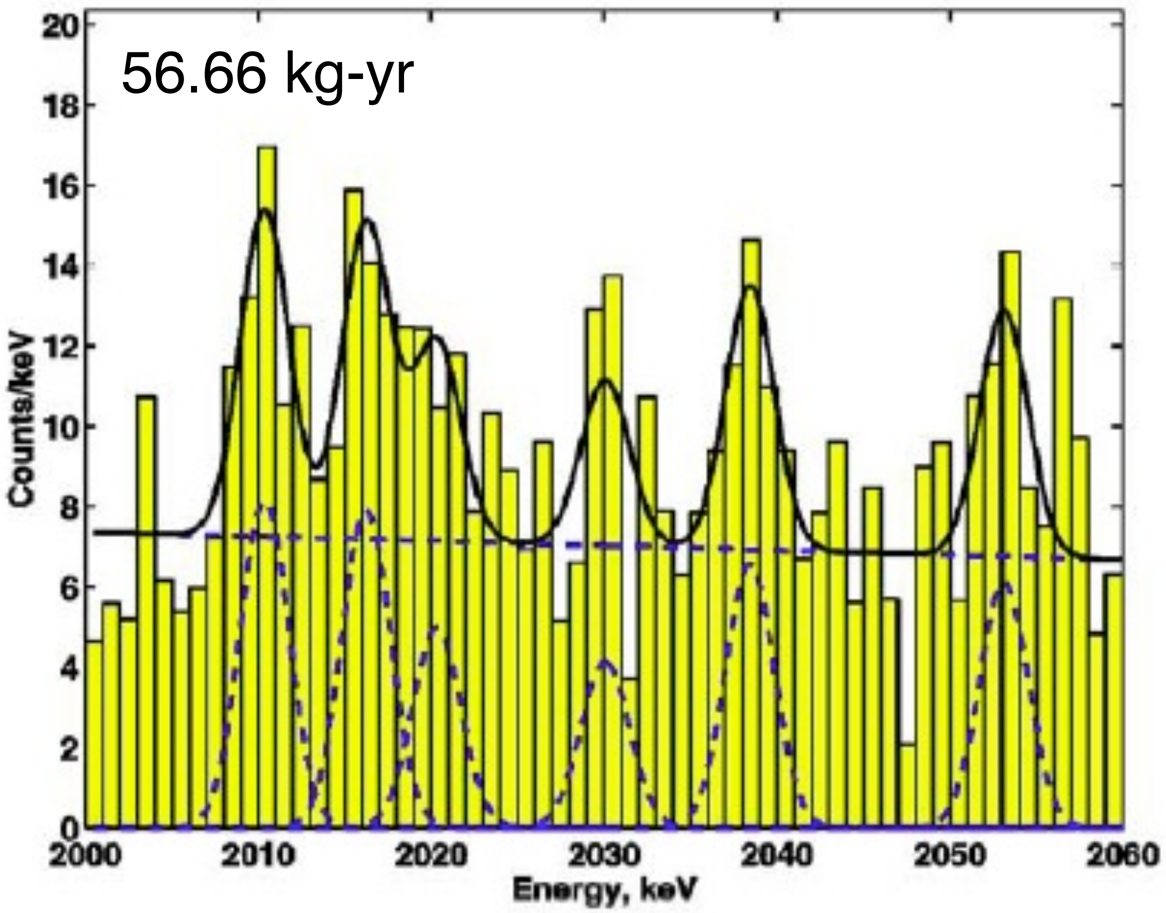
$T_{1/2}$ = 1.6 x 10^{25} *years* (4σ C.L.)

Majorana ν Mass (dep. on nuclear matrix element)

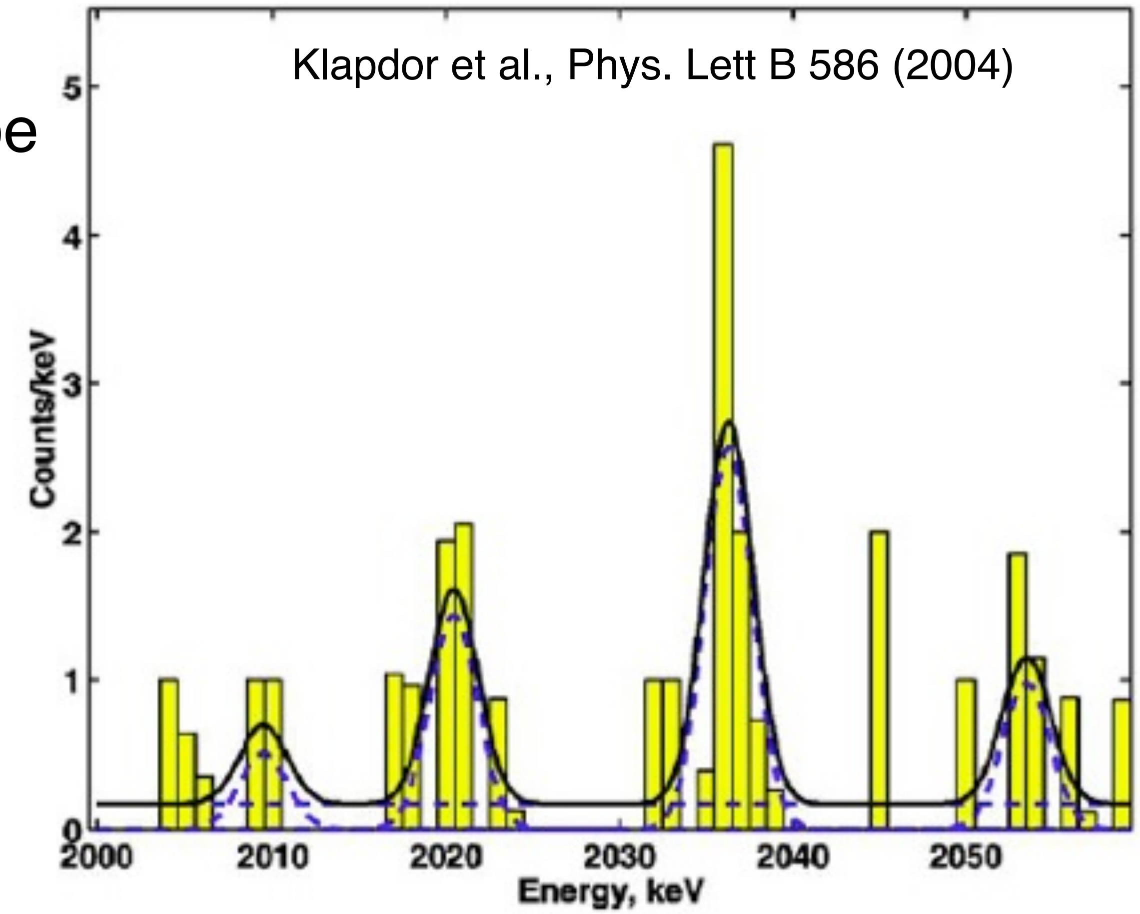
$<m_{\beta\beta}>$ = 0.2-0.6 eV

$<m_{\beta\beta}>_{best}$ = 0.45 *eV*

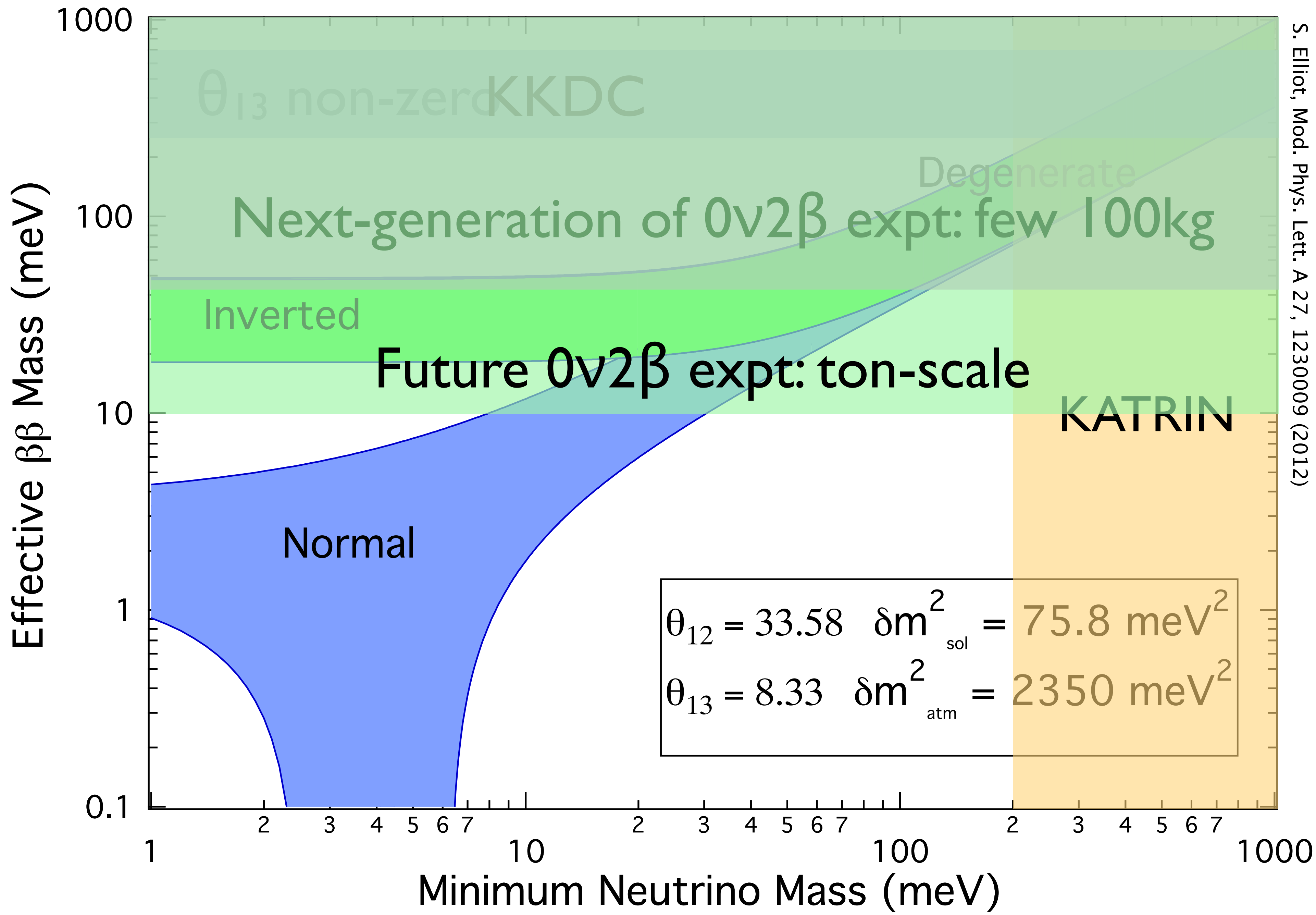
Analysis controversial, however this has become a benchmark experiment



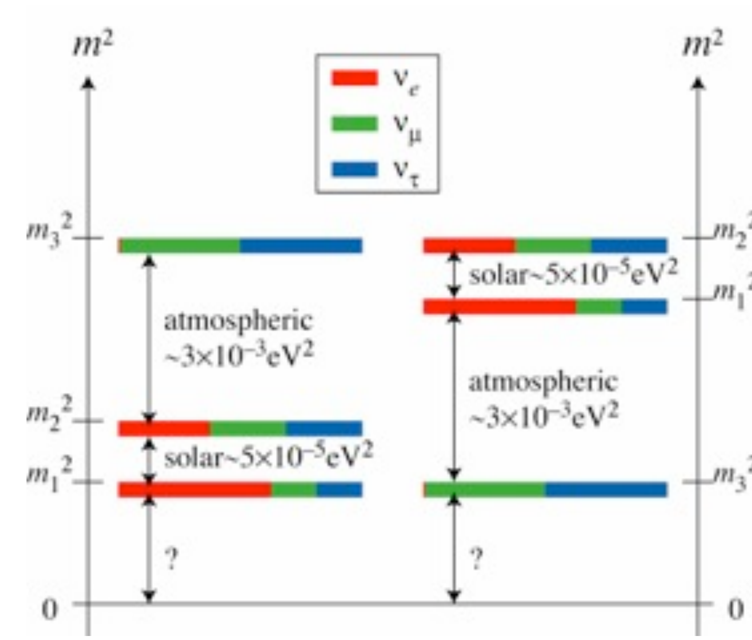
Pulse-shape selection



Effective Majorana Mass



S. Elliot, Mod. Phys. Lett. A 27, 1230009 (2012)



Normal Inverted

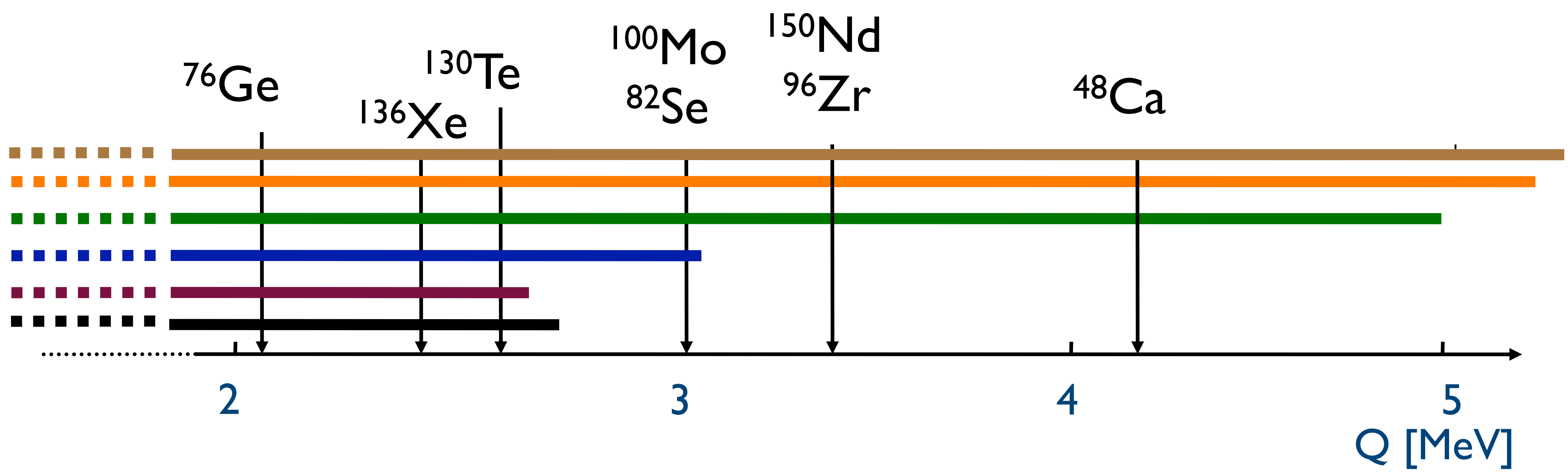
What does observation of 0ν2β imply?

- Observation of 0ν2β would:
  - Establish that the neutrino is a massive Majorana particle
  - Demonstrate lepton number violation
  - Measure the effective Majorana mass
- Necessary ingredient for See-Saw mechanism

Q and Background

Natural radioactivity (^{40}K, ^{60}Co, ^{234m}Pa, external ^{214}Bi and ^{208}Tl…)
^{214}Bi and Radon
^{208}Tl (2.6 MeV γ line) and Thorium
γ from (n,γ) reactions
Surface or bulk contamination in α emitters

Cosmogenic production



Experimental sensitivity

More conventional to express it in $T_{1/2}$:

$$T_{1/2}^{0\nu} \propto \epsilon \frac{a}{A} \sqrt{\frac{Mt}{b \Delta E}}$$

Detector Efficiency

Isotopic Fraction

Detector Mass

Running Time

Atomic Mass

Background Rate

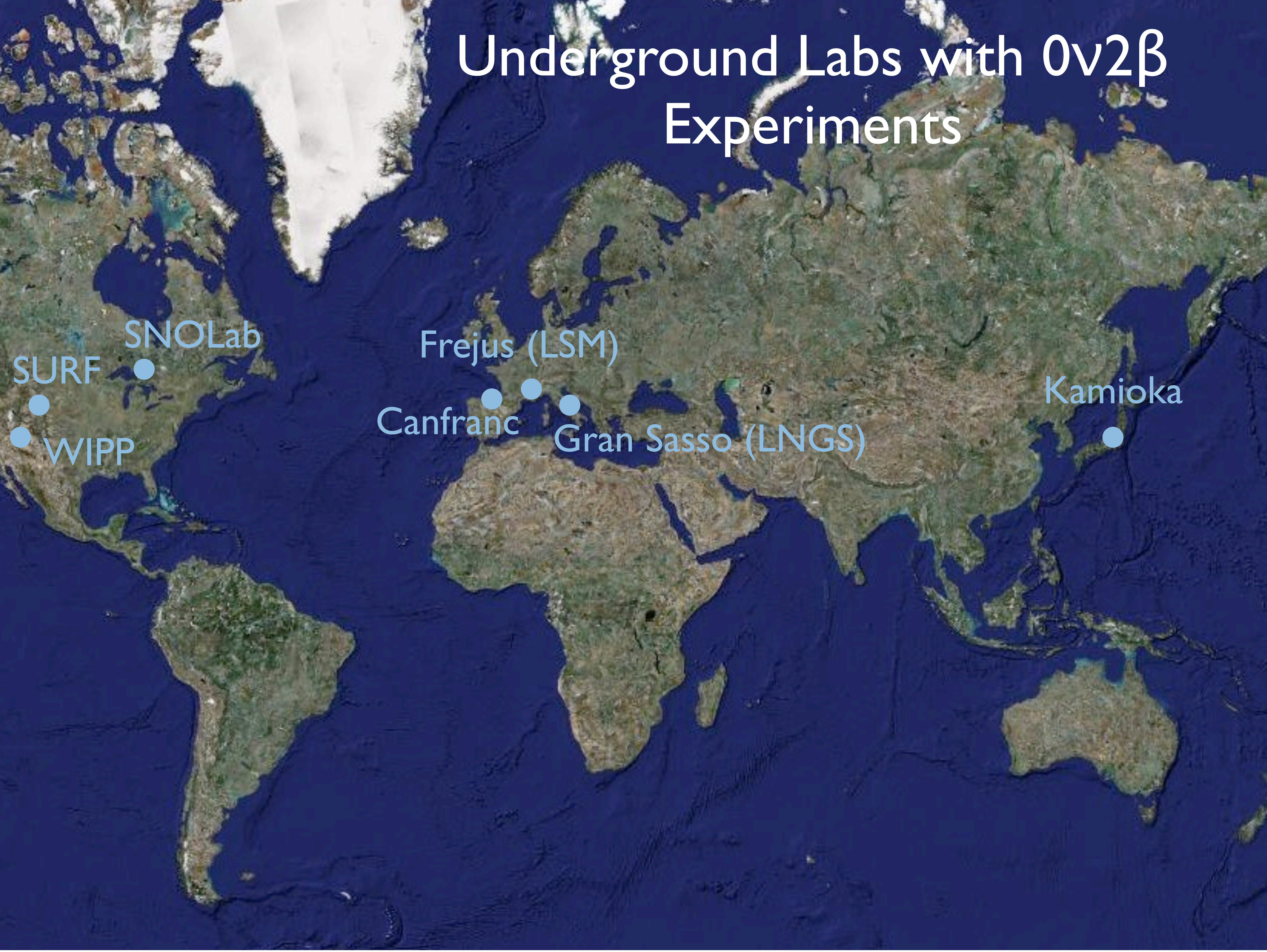
Detector Resolution

Reminder: $\langle m_{\beta\beta} \rangle = M_{0\nu} [G_{0\nu} T_{1/2}^{0\nu}]^{-1/2}$

Incomplete overview of experiments

Isotope	Experiment	Technique	Mass	Enriched	$Q_{\beta\beta}$ [MeV]	Start/Stage
^{130}Te	Cuoricino	TeO_2 bolometers	40.7kg	No	2.6	Done
^{82}Se, ^{100}Mo	NEMO-3	tracko-calo	0.9kg/6.9kg	Yes	3.37	Done
^{76}Ge	GERDA	Ge diodes in LN_2	34.3kg	86%	2.04	2009
^{136}Xe	EXO-200	LXe [tracking]	150kg	80%	2.47	2010
^{136}Xe	KamLAND	Isotope in LS	400kg	90%	2.47	2012
^{130}Te	CUORE	TeO_2 bolometers	204kg	No	2.53	2014
^{150}Nd	SNO+	Isotope in LS	56kg	No/50%	3.37	2014
^{76}Ge	Majorana	Ge diodes	30-60kg	86%	2.04	2015
^{82}Se, ^{150}Nd	SuperNEMO	tracko-calo	100kg	Yes	3.37	2014
^{100}Mo	MOON	tracking	1t	No	3.03	Prototype
^{116}Cd	COBRA	CdZnTe semicond	?	No	2.80	Prototype
^{48}Ca	CANDLES	CaF_2 cryst in LS	few t	No	4.27	Prototype

Underground Labs with 0ν2β Experiments



KamLAND-Zen Collaboration

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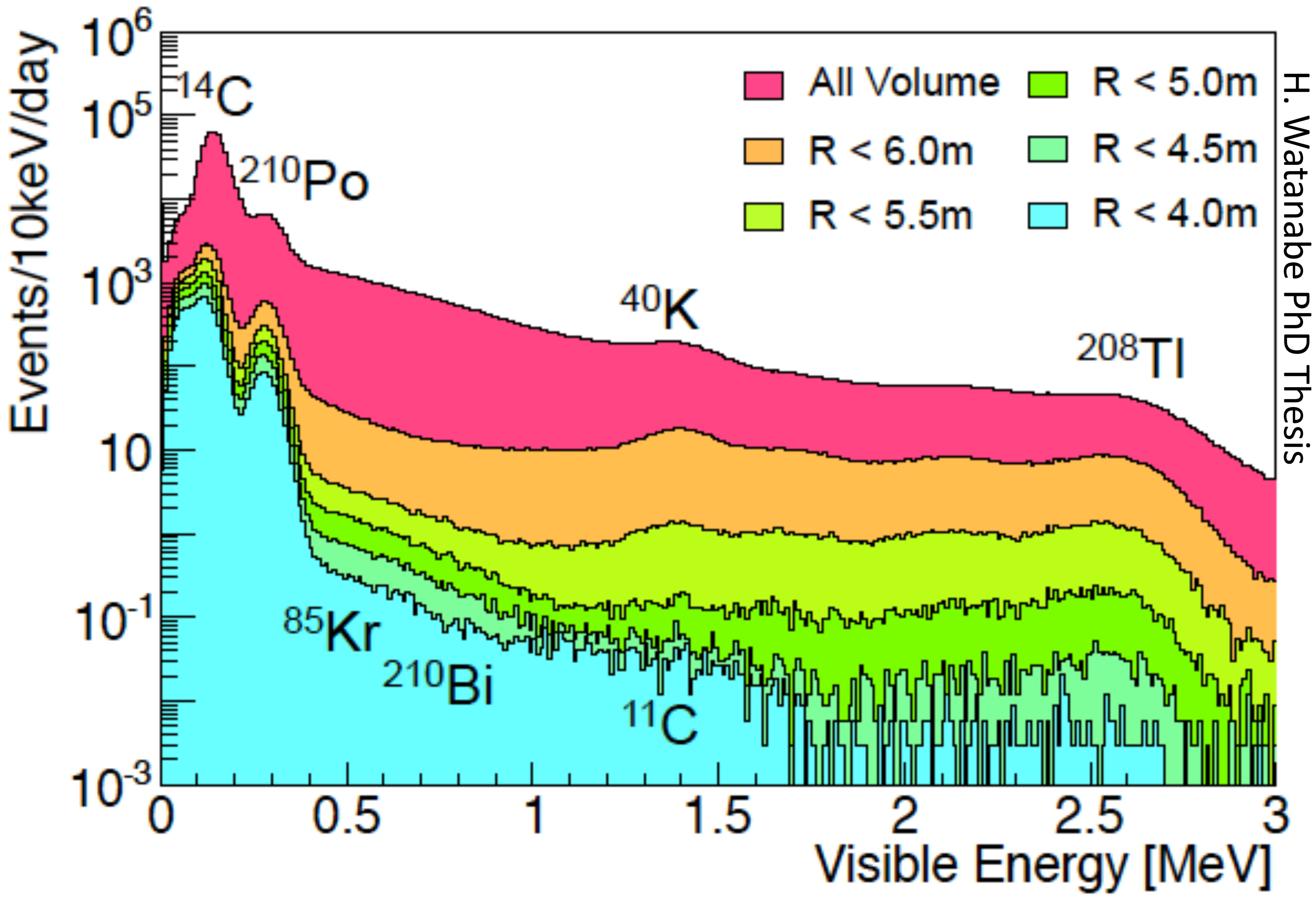
[7] *Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA and Physics Departments at Duke University, North Carolina Central University, and the University of North Carolina at Chapel Hill*
[8] *Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, Washington 98195, USA*
[9] *Nikhef and the University of Amsterdam, Science Park, Amsterdam, the Netherlands*

KamLAND Scintillator



Natural BGs:

^{238}U: $<10^{-17}$ g/g

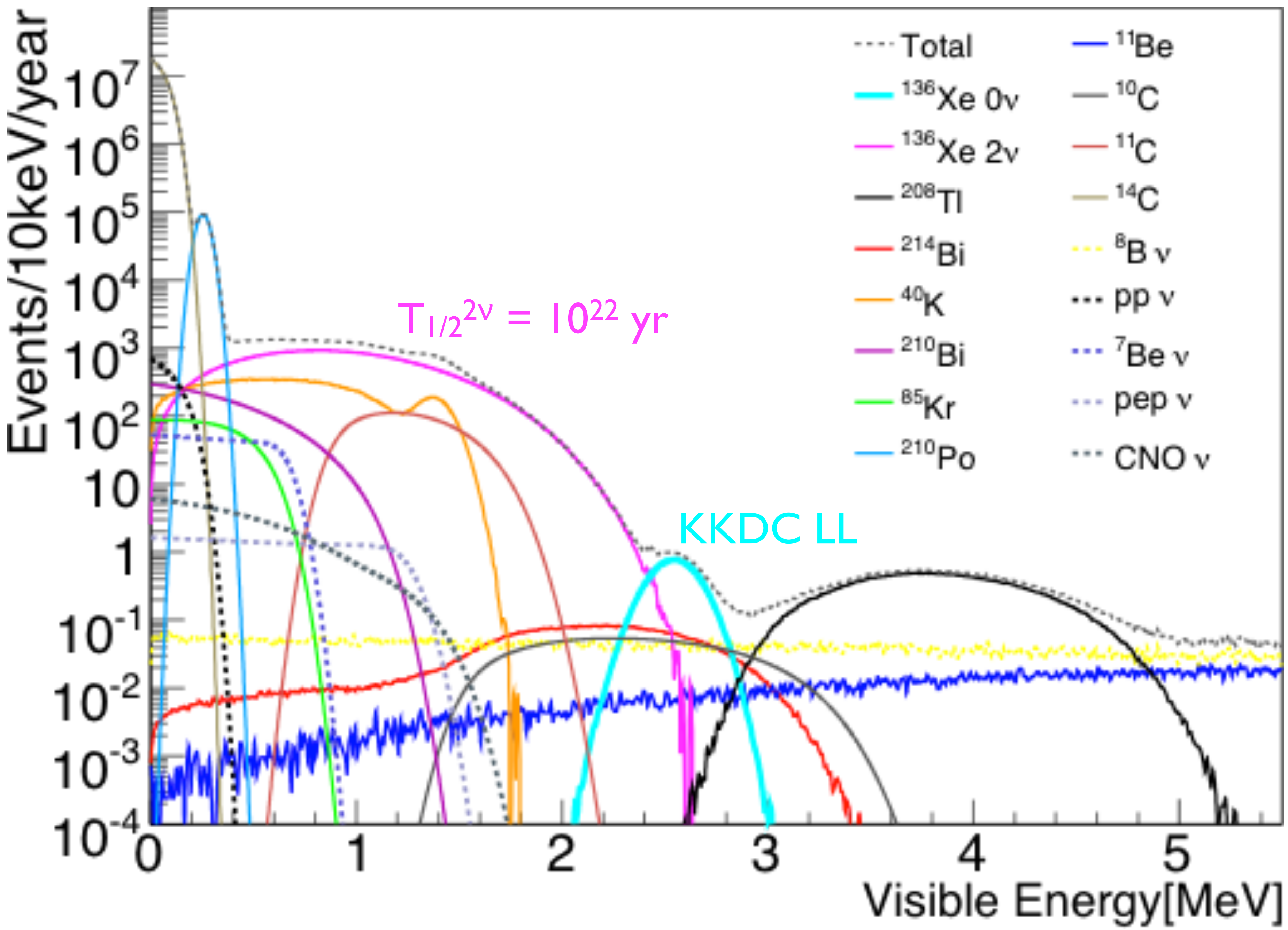
^{232}Th: $<10^{-16}$ g/g

^{40}K: $\lesssim 10^{-16}$ g/g

One of the cleanest environments in the world!

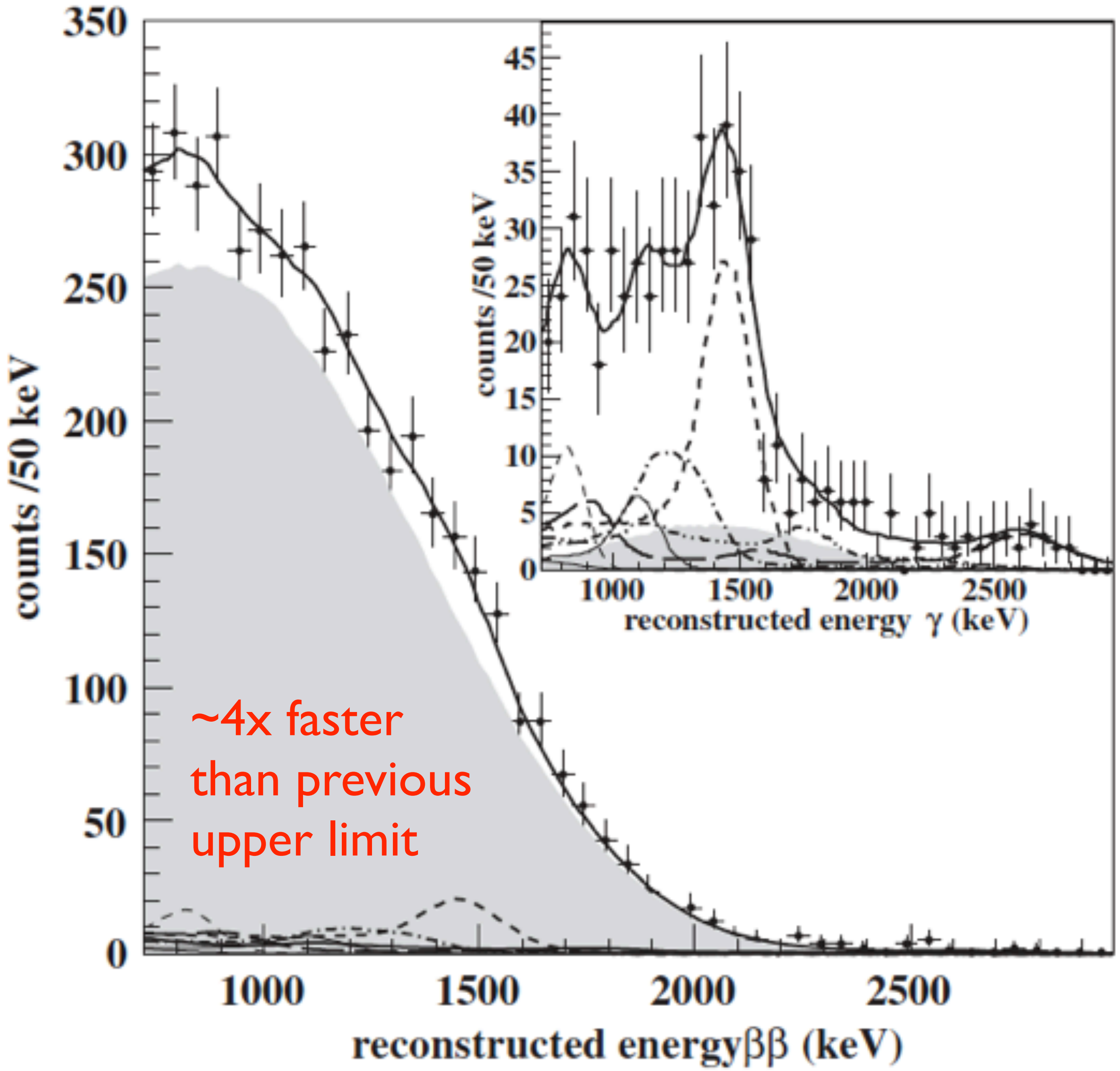
Simulated ^{136}Xe 0νββ signal in KL

As of 2010…



EXO-200 ^{136}Xe 2νββ

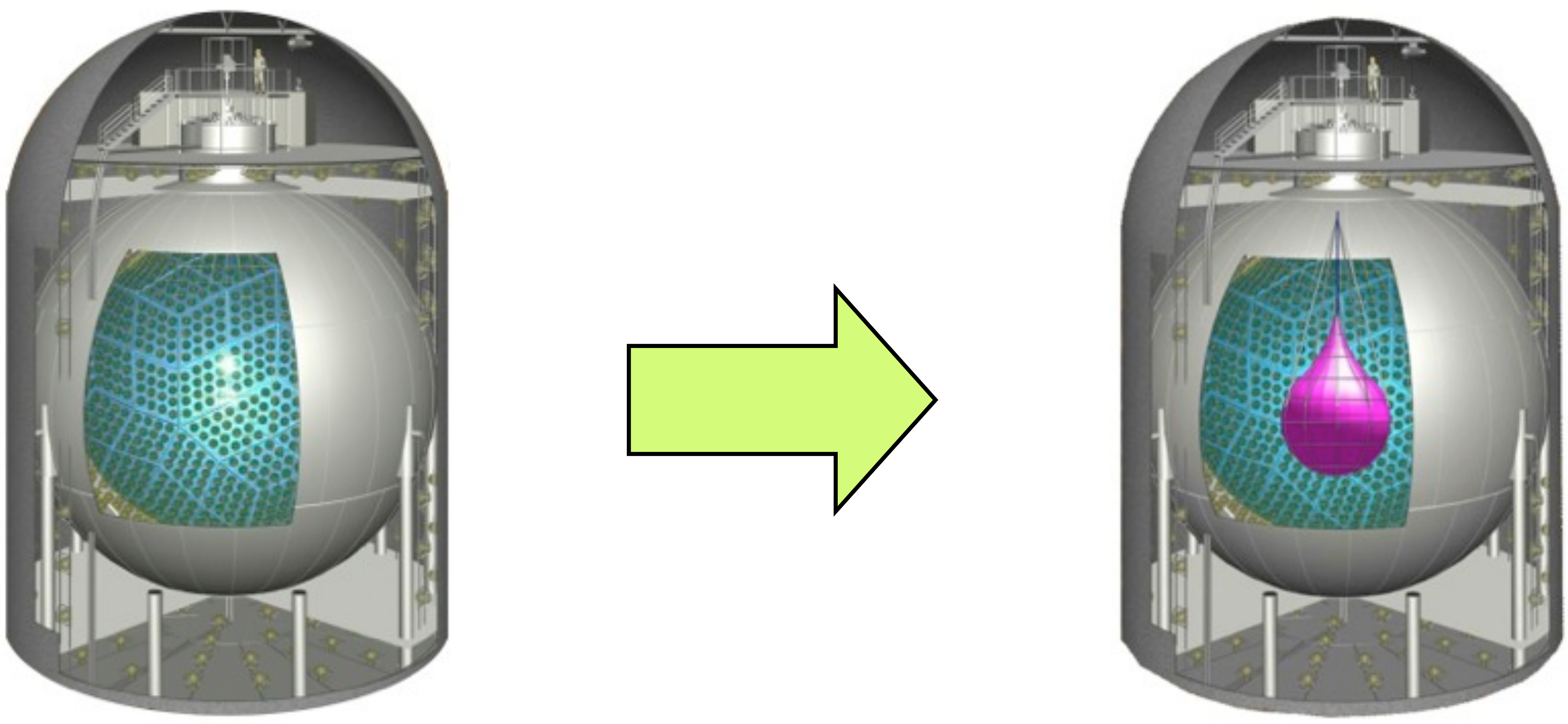
EXO-200 August 2011 Data release



N. Ackerman et al. [EXO Collaboration], Phys. Rev. Lett. 107, 212501 (2011)

$T_{1/2}^{2\nu}$ = [2.11 ± 0.04 (stat) ± 0.21 (syst)] x 10^{21} yr

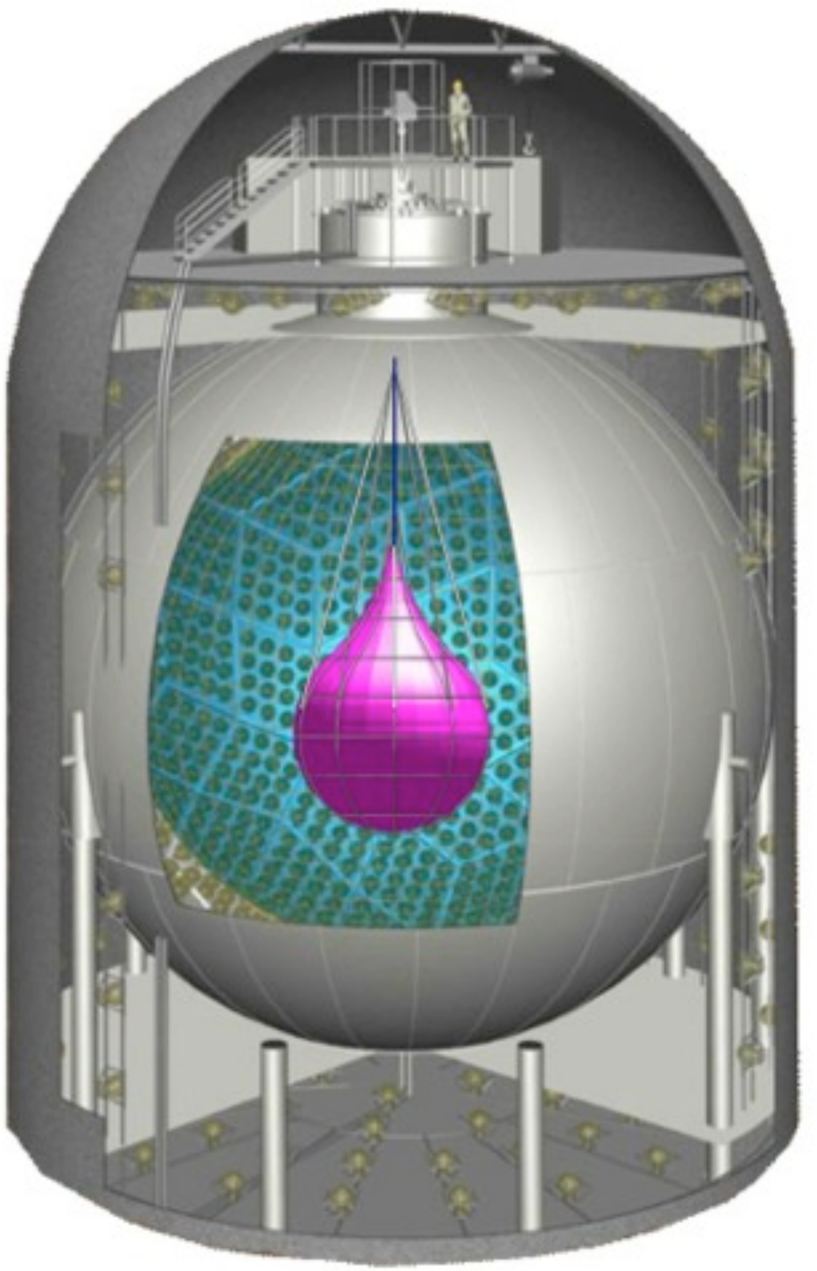
Towards the KamLAND-Zen detector



KamLAND KamLAND-Zen

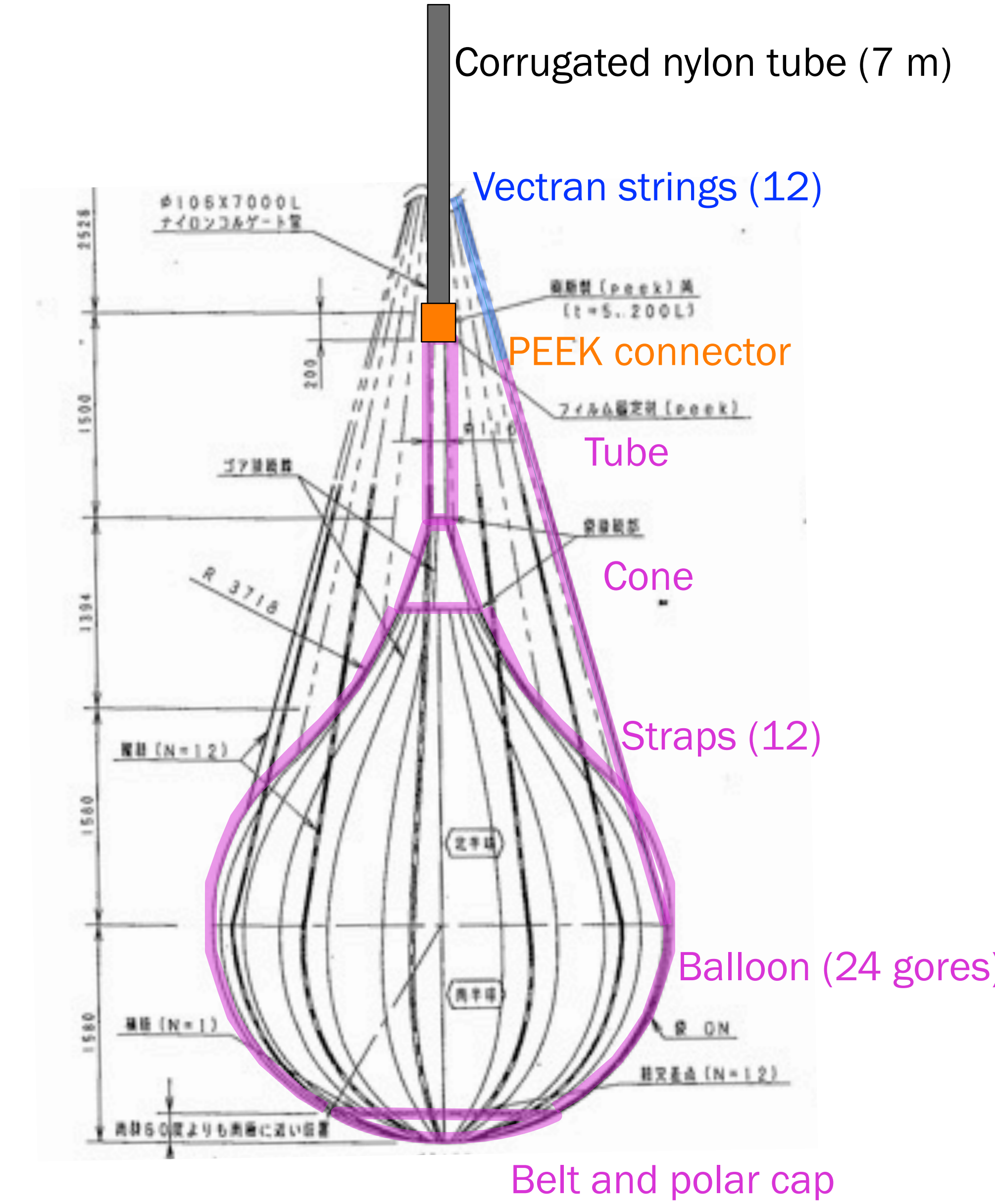
KamLAND-Zen advantages & disadvantages

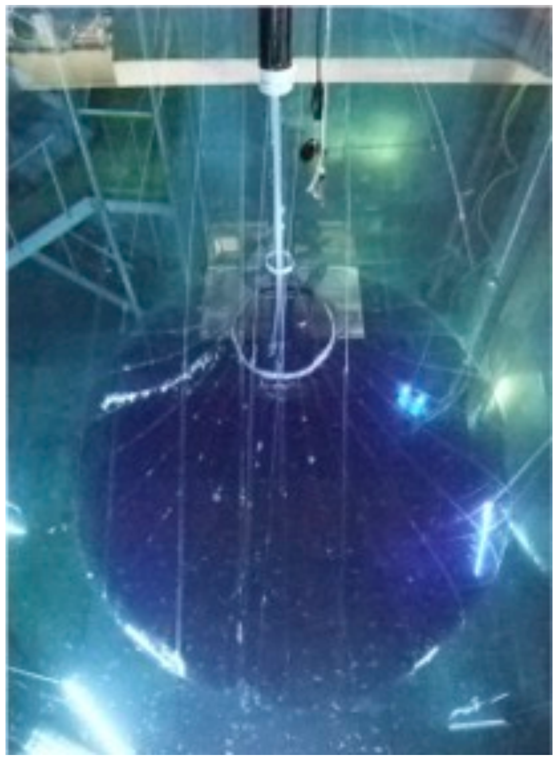
- +Well-understood detector
- +Highly pure, self-shielding environment
- +Large ββ source mass, scalable
- -Relatively poor energy resolution
- -No particle identification



Miniballoon

- Requirements
  - Chemical compatibility with LS
  - Mechanically strong, low radioactivity
  - Barrier against Xe
  - Transmission of scintillation light

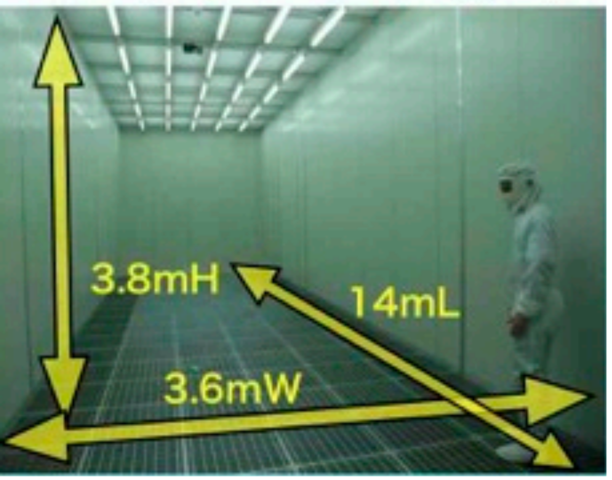


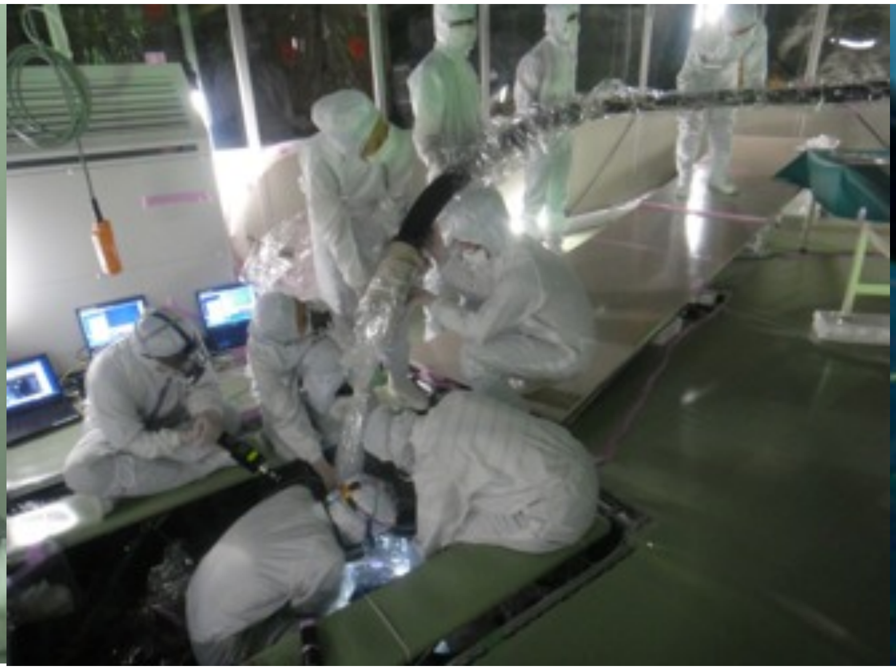


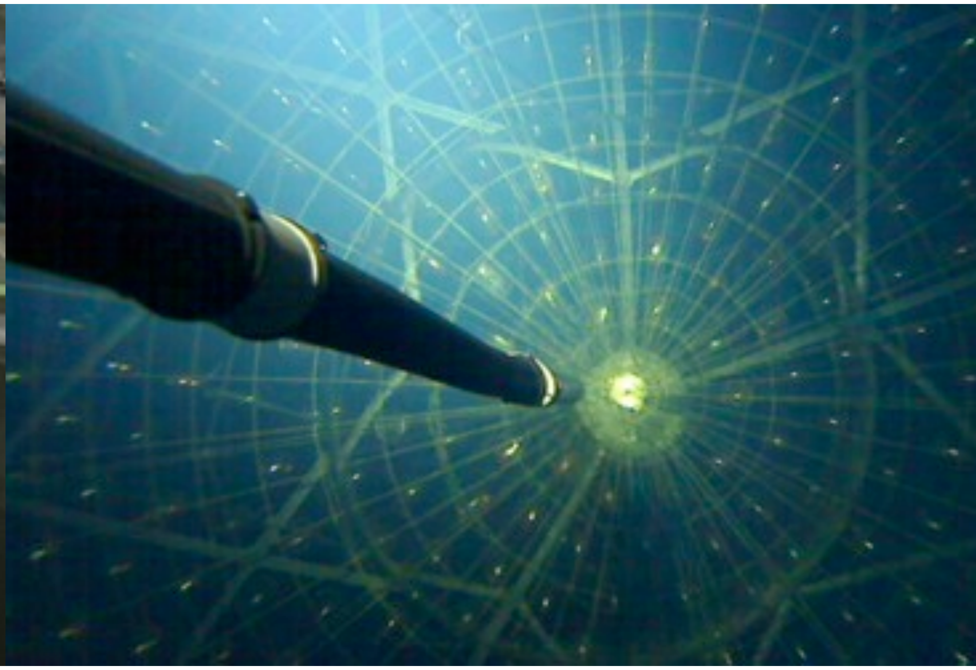
- Material: 25 μm thick ultra-pure nylon
  - U/Th/K ≲ 10^{-12} g/g
- 1/4 & full scale tests in air and water

Mini-Balloon Construction

May-Aug 2011

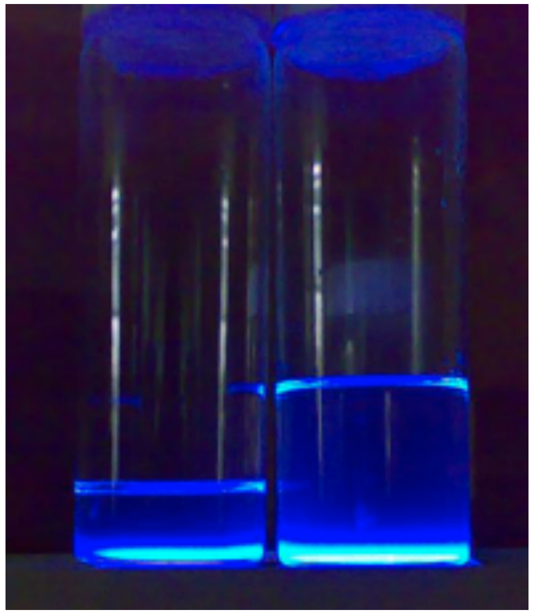


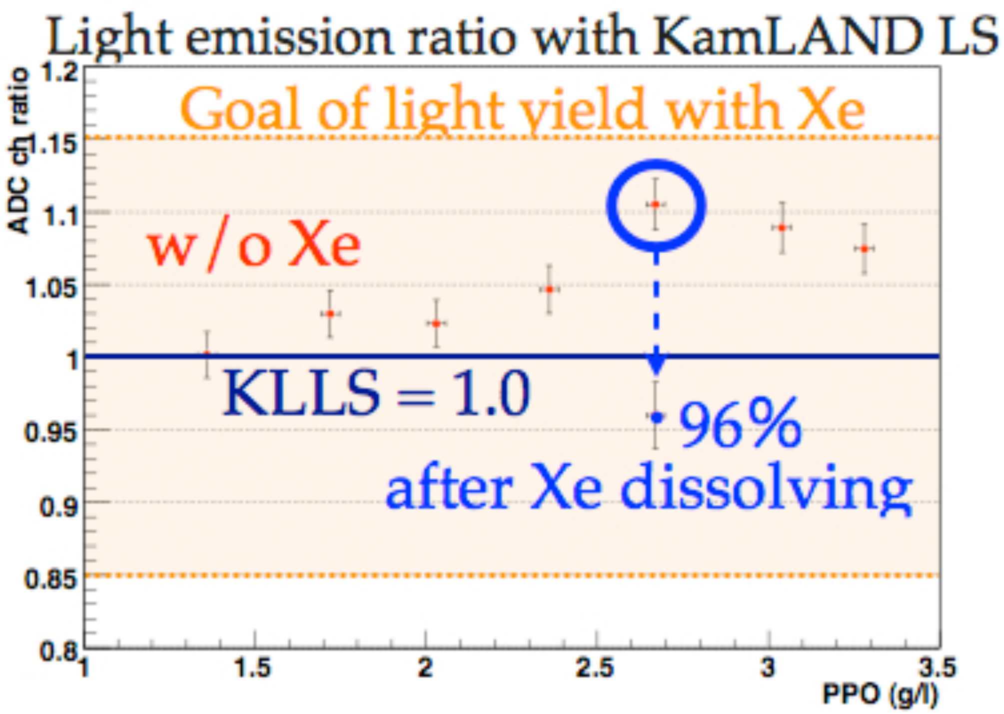


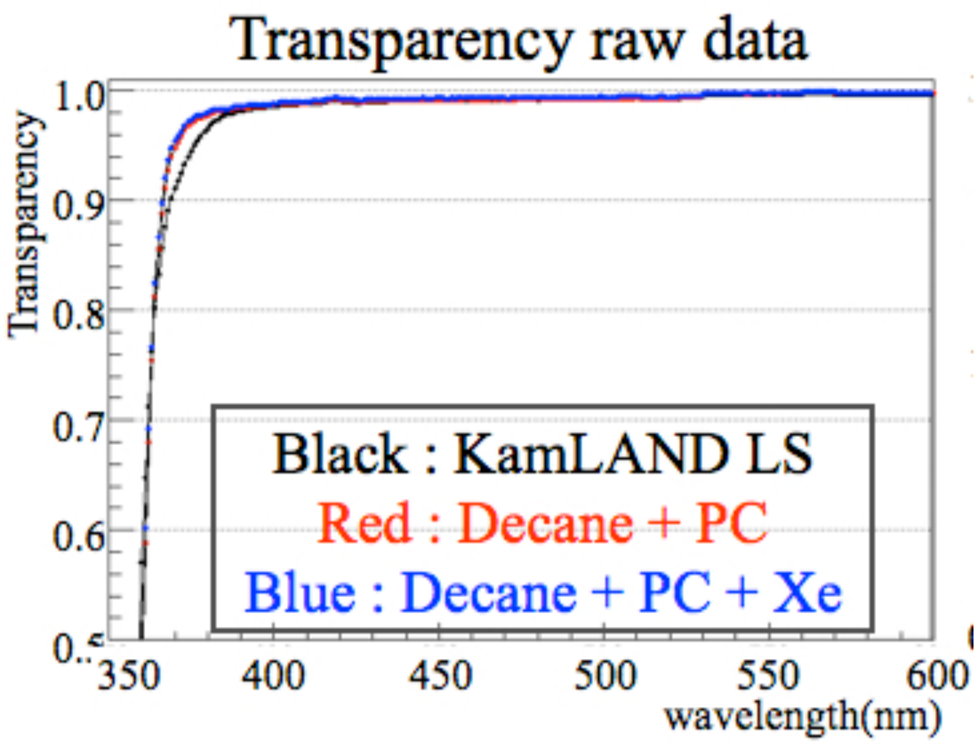


Xe-LS R&D

- Maximize Xe mass in LS, but maintain light yield and transparency
- Must also match density of KamLAND LS for balloon integrity
- Trade PPO ☐ Xe: optimal point at 2.7 g/L PPO = 2.5% ^{enr}Xe (by weight)

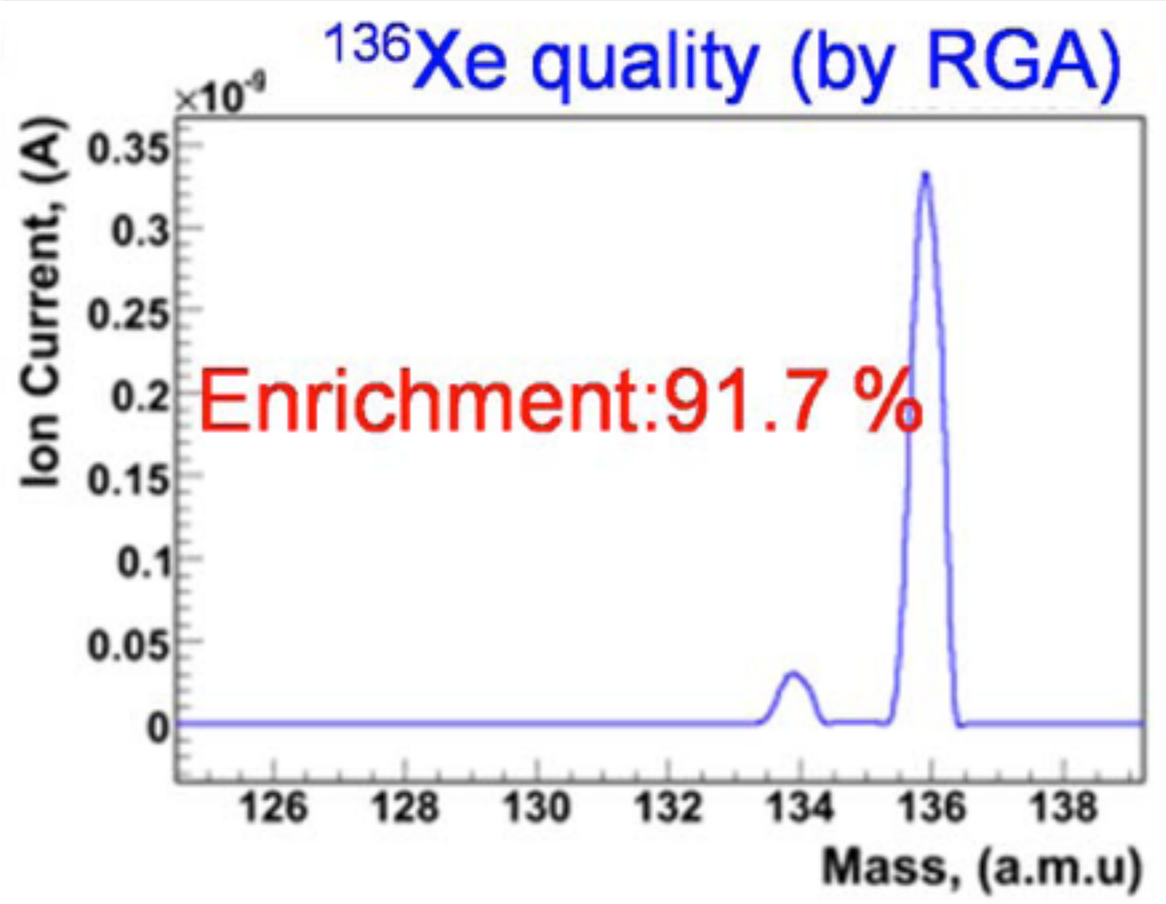




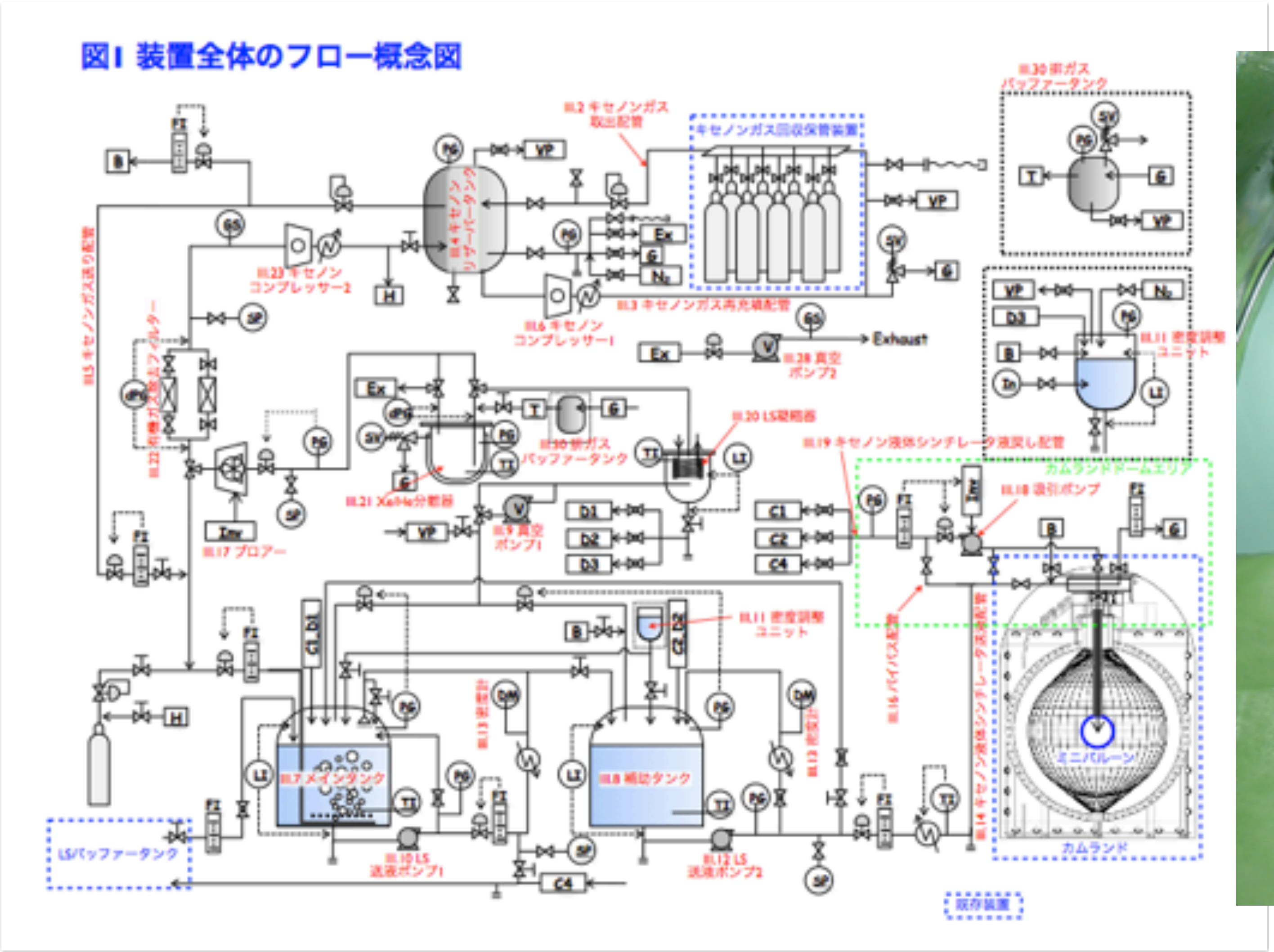


Xe Procurement

- Enrichment by gas centrifuge in Russia
- 190 kg purchased in 2009
- 215 kg purchased in 2010

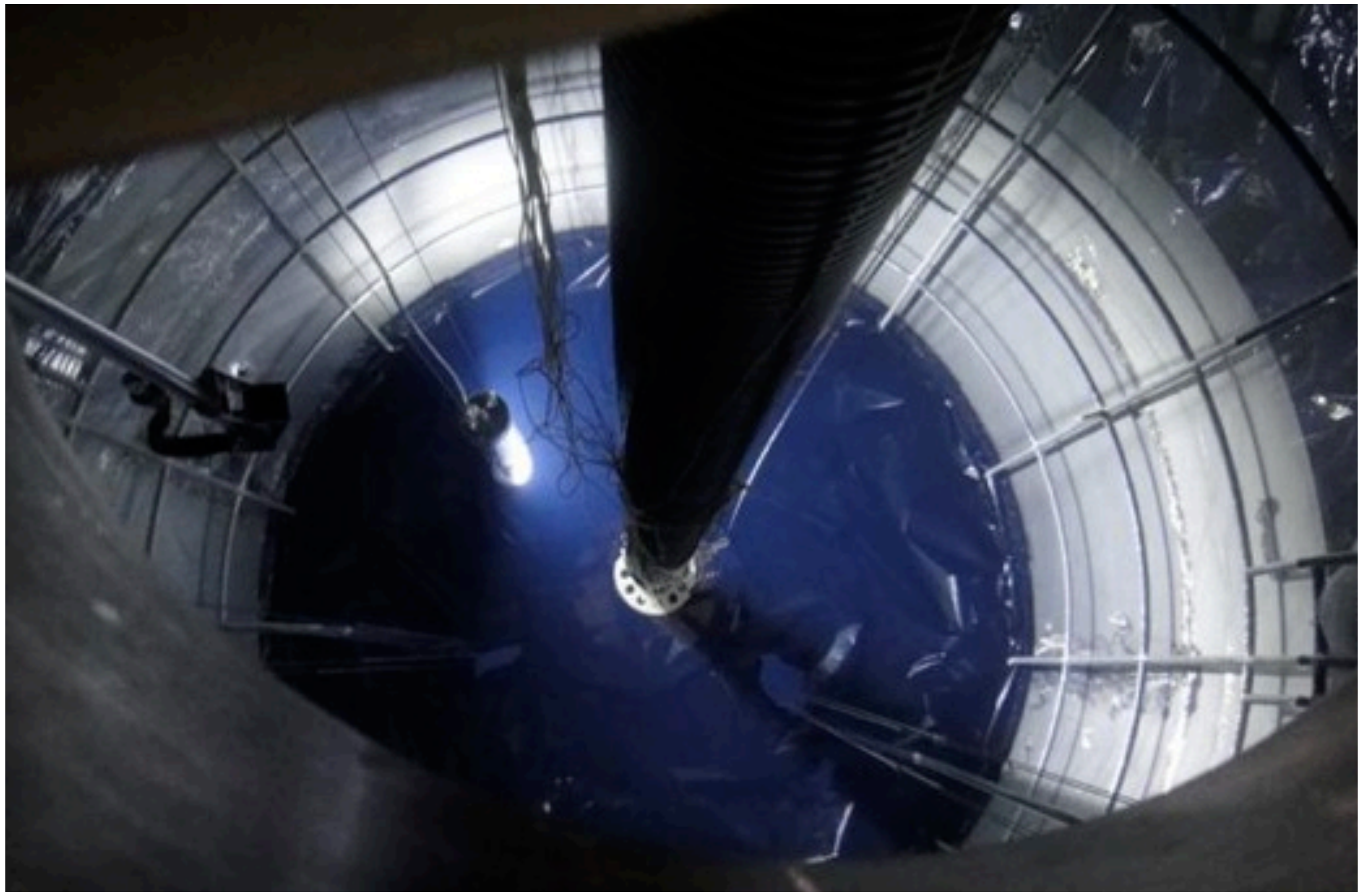


Xe-LS Handling System



Mini-balloon Installation (August 2011)

Clean room at the top of detector



Filling the Mini Balloon

Aug-Sept 2011

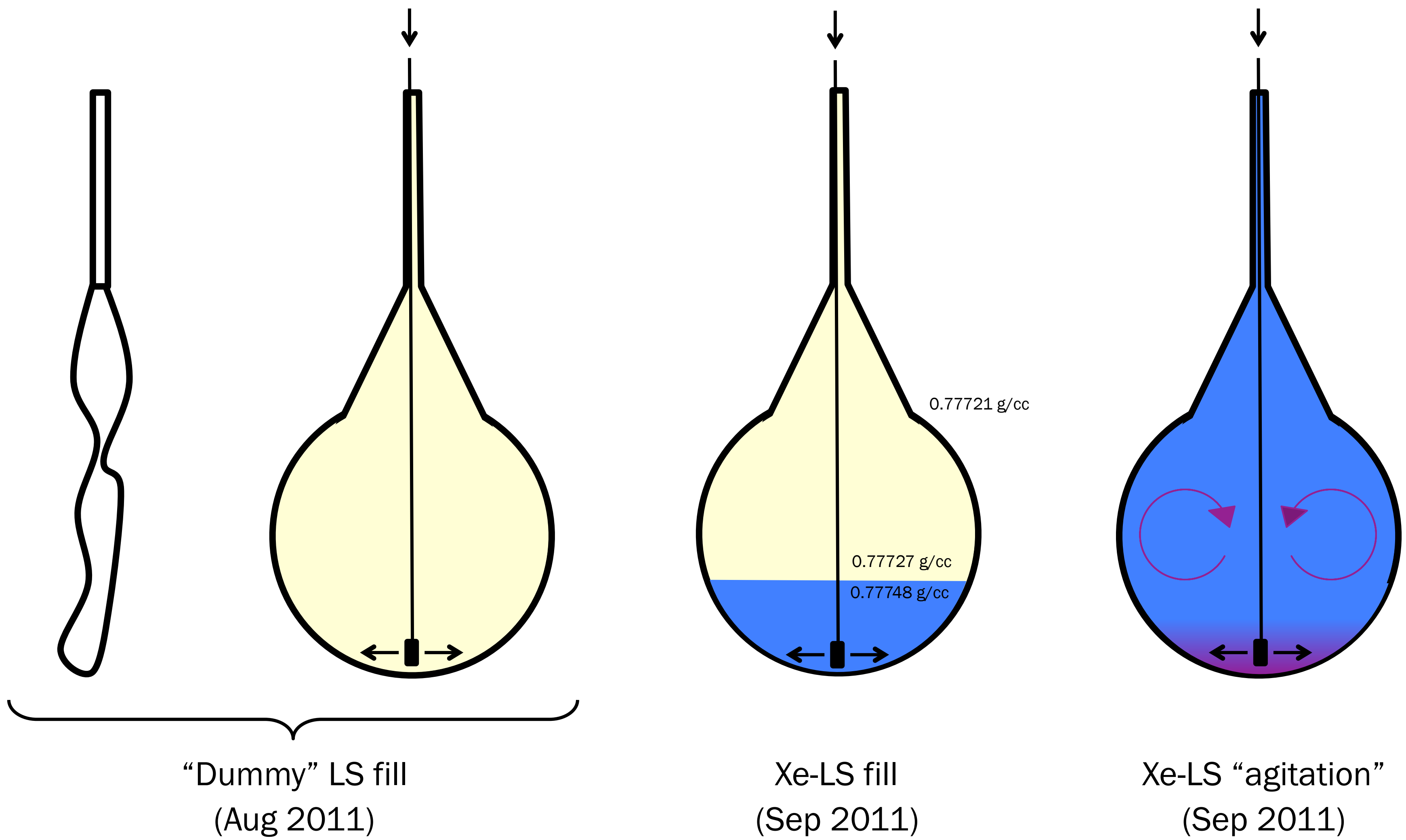
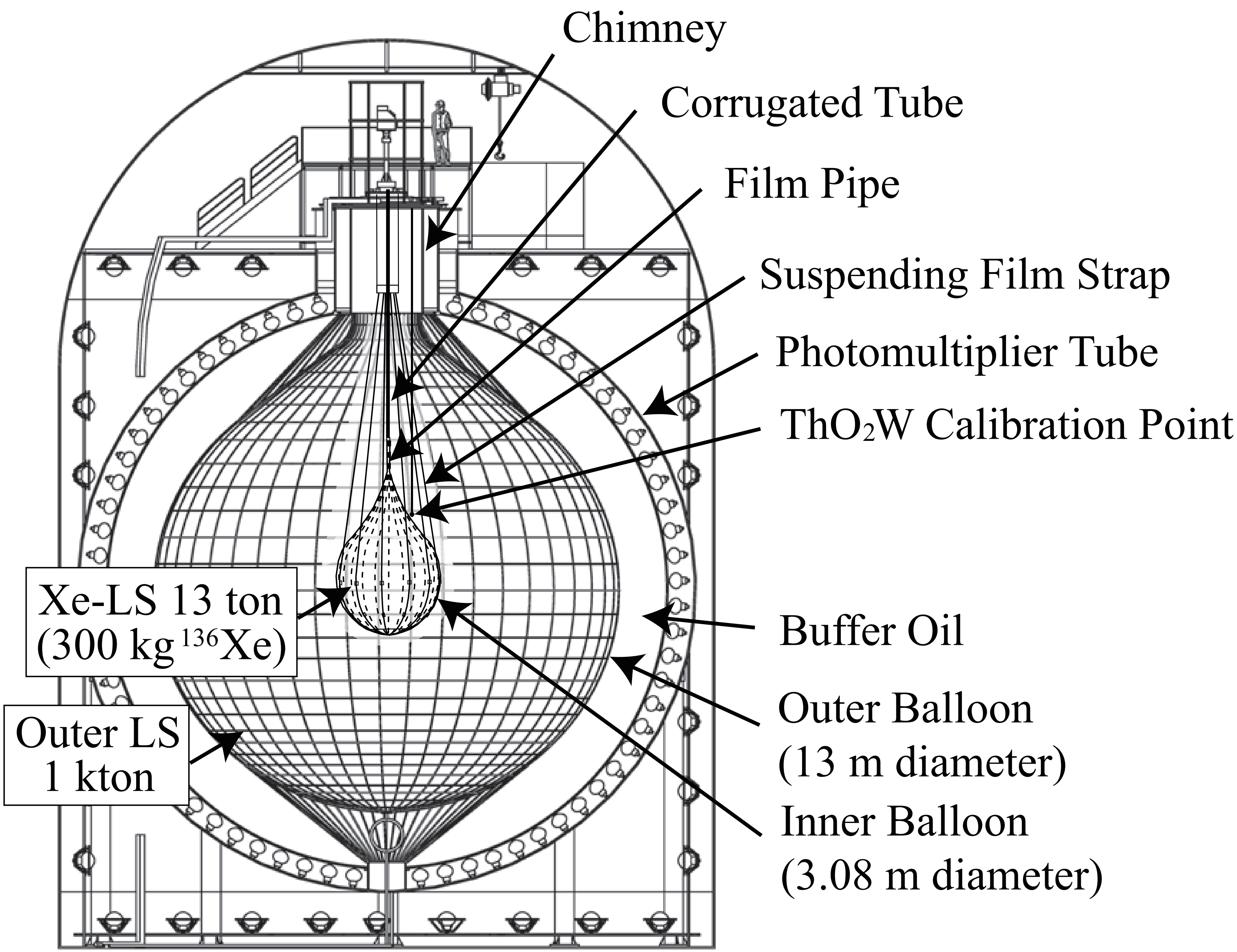
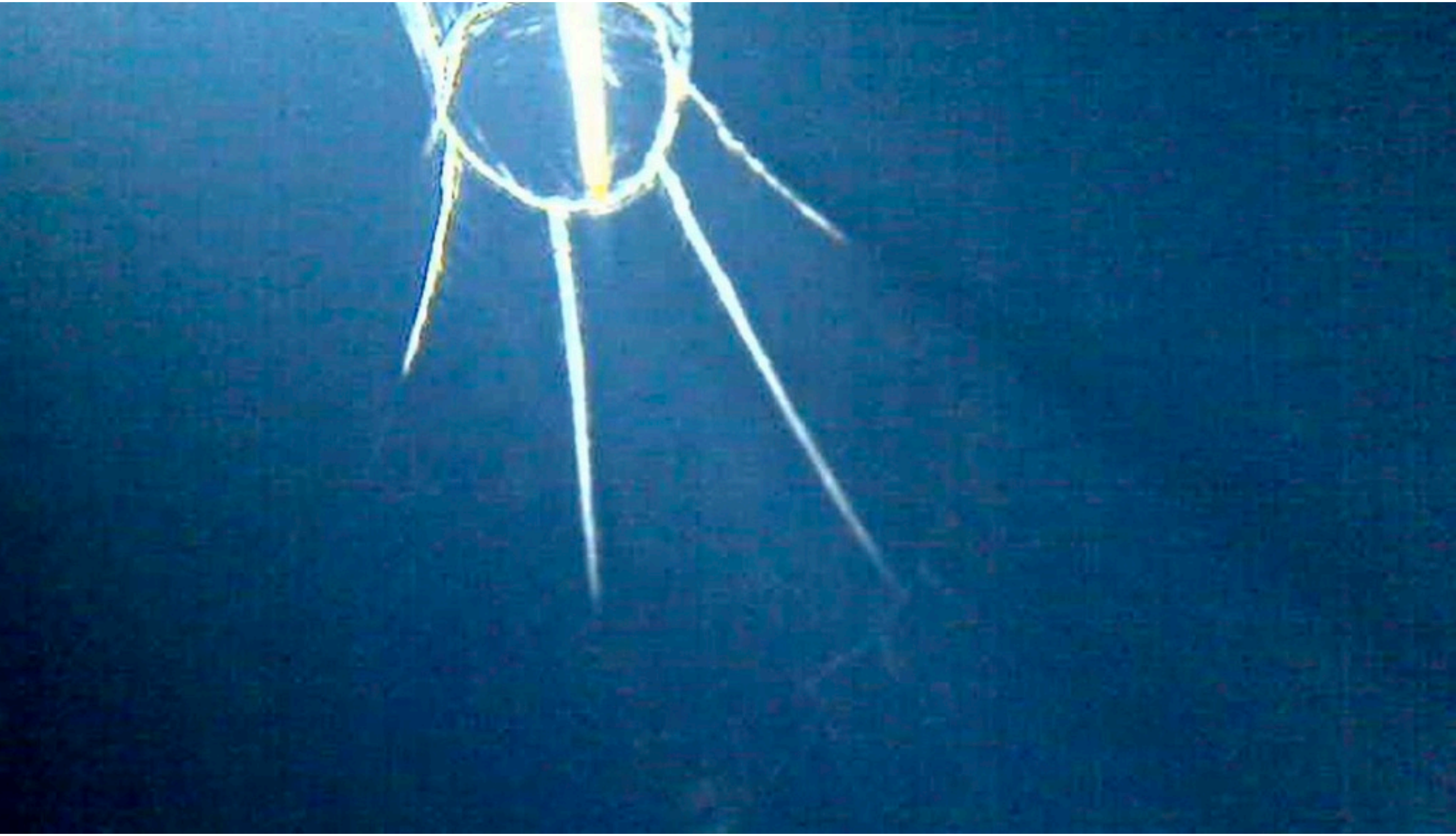


Diagram of the detector

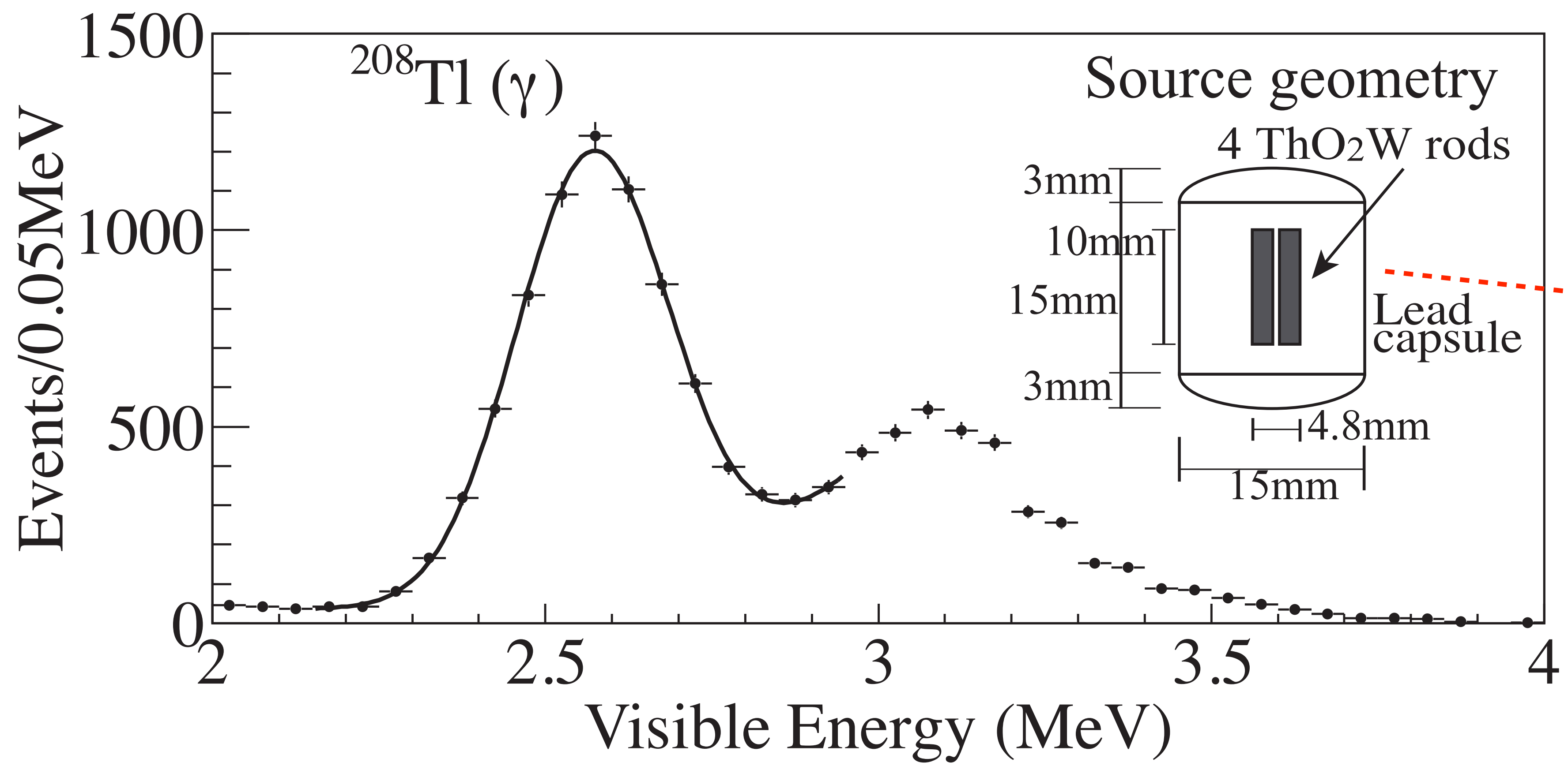


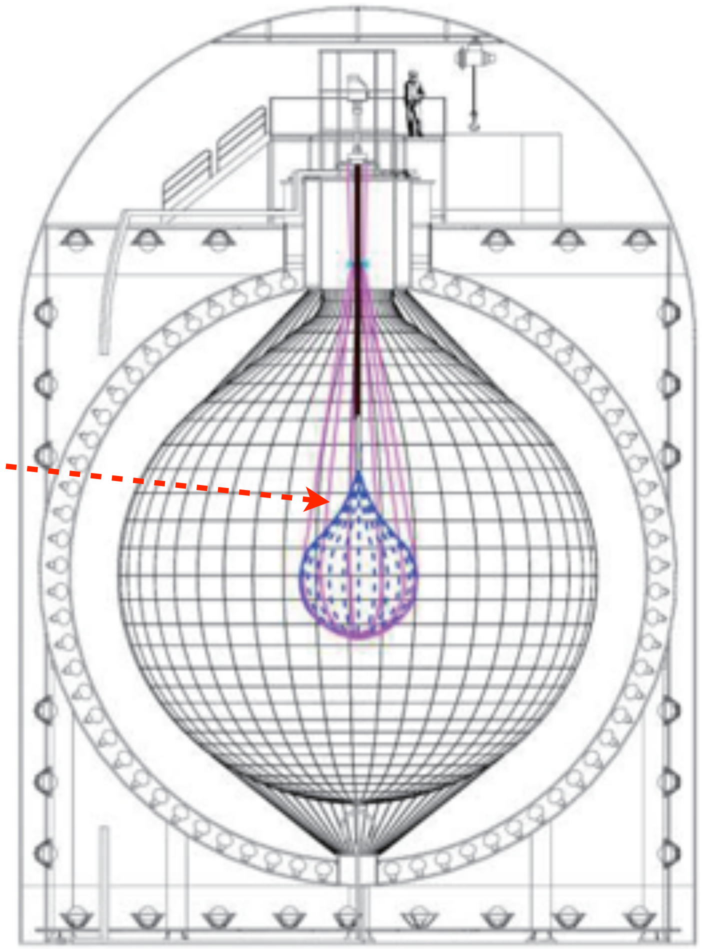


Calibration

KamLAND is well-understood. Previous reconstruction algorithms can be easily adapted

Energy calibration

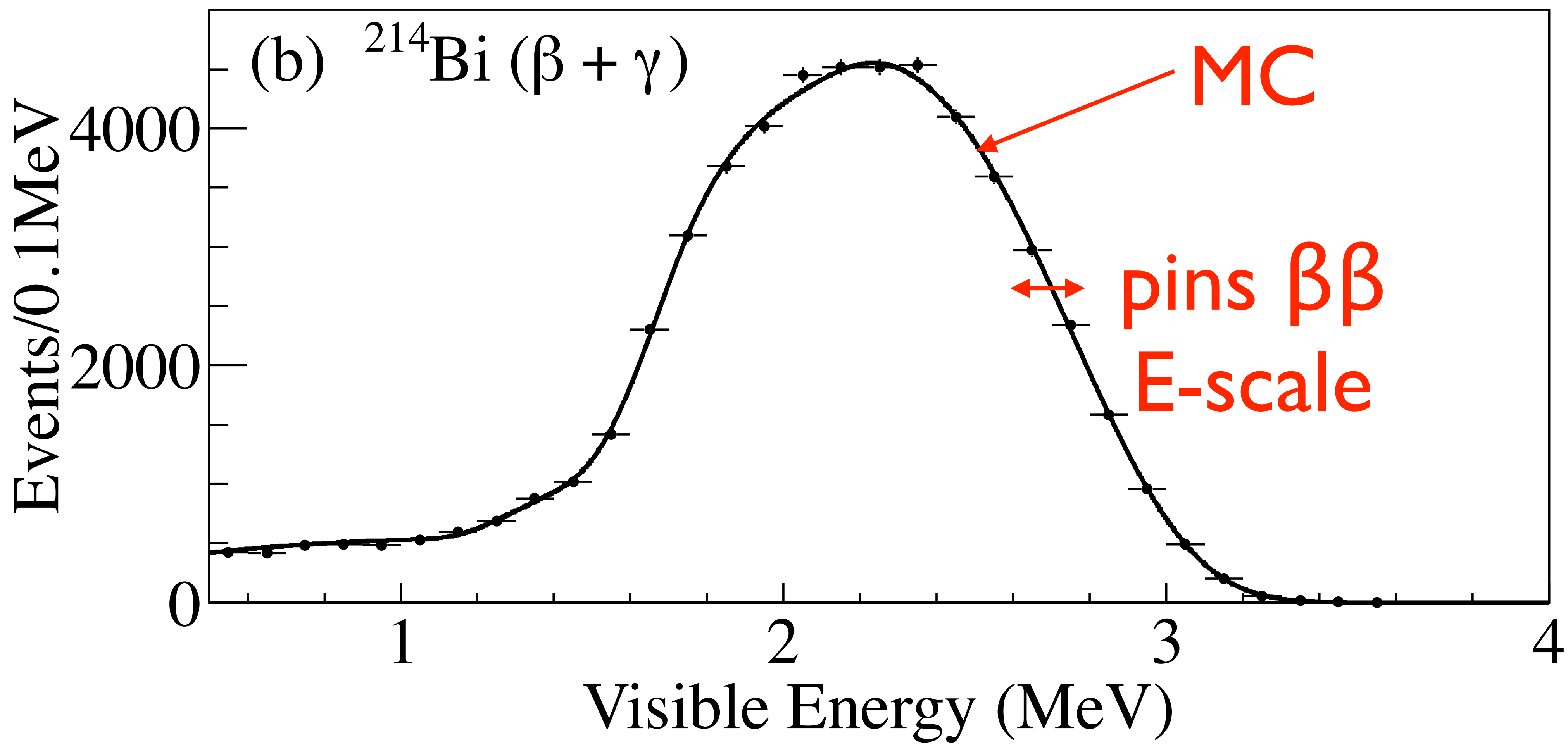




$\sigma = (6.6 \pm 0.3)\% / \sqrt{\text{MeV}}$

In-situ ^{214}Bi Fit

from ^{222}Rn (τ = 5.5 days) at start of data taking



^{214}Bi together with the ThO_2W source determine energy scale

0νββ Candidate Selection

- Fiducial volume: R < 1.2 m

Fiducial mass = 129 kg ^{136}Xe

- Vetos:
  - Muons (>10k p.e. or >5 OD hits) and 2ms following them
  - Bi-Po coincidences (Δt < 3 ms, 0.35 MeV < E_{prompt} < 1.5 MeV)
  - Anti-neutrinos (Δt < 1 ms, E_{prompt} > 1.5 MeV)

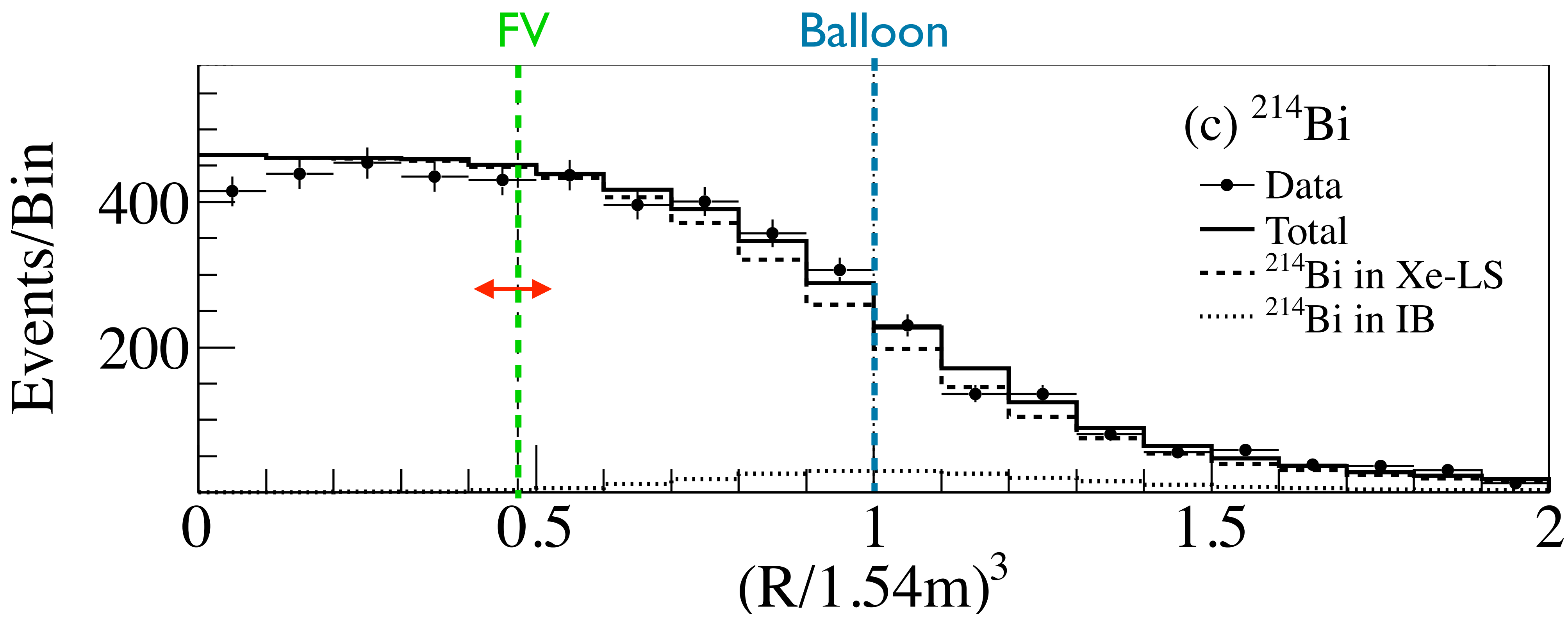
Livetime = 77.6 days

- Noise cuts (good vertex)

ε > 99.9%

Systematic Uncertainties

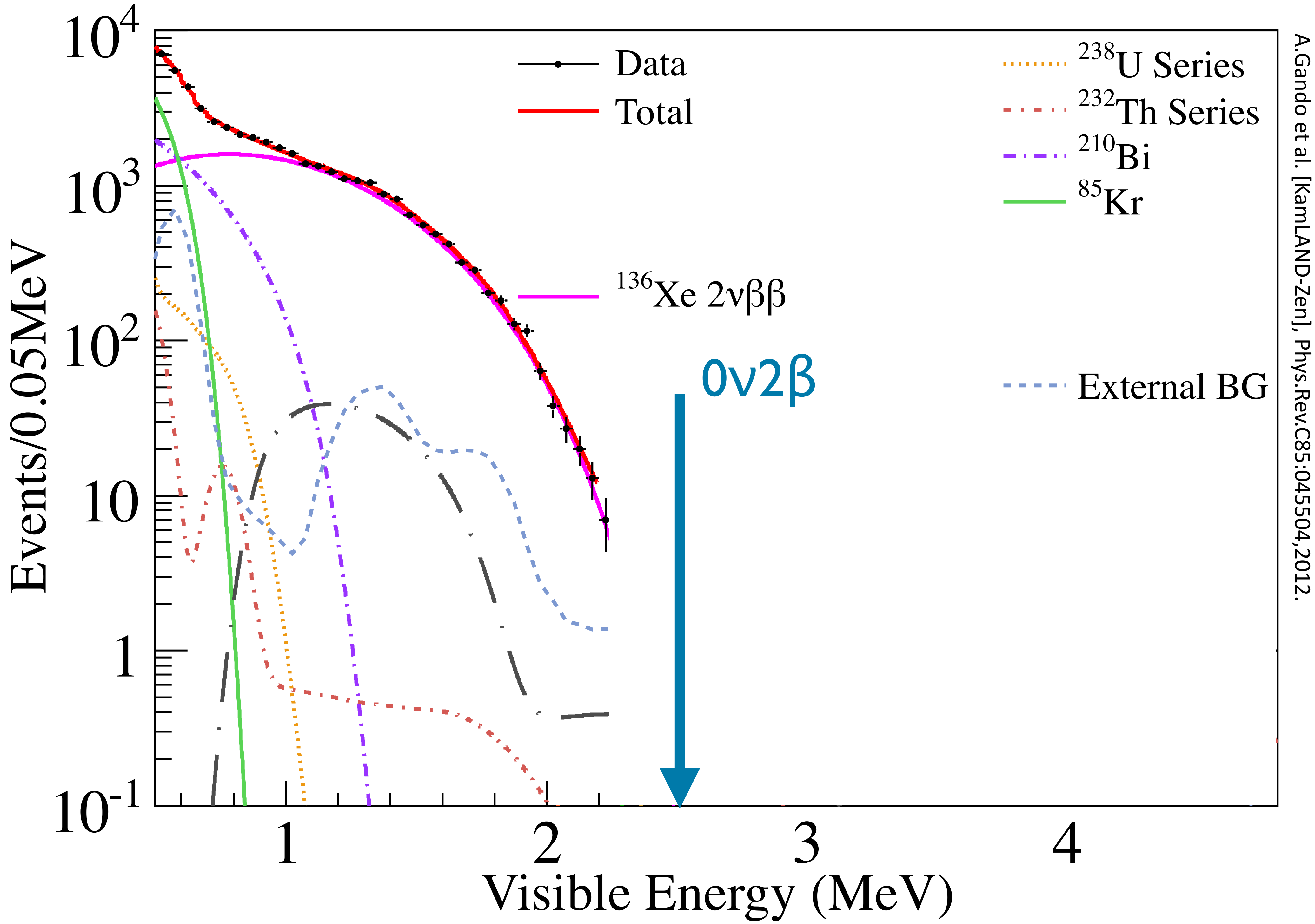
- Fiducial Volume: R^3 of ^{214}Bi in early data uniform to within 5.2%



- Xe concentration measured with gas chromatography to within 2.8%
- Enrichment, E-scale, efficiency, livetime,
  Xe-LS edge effect uncertainties all <0.3%

Combined systematic uncertainty: 5.9%

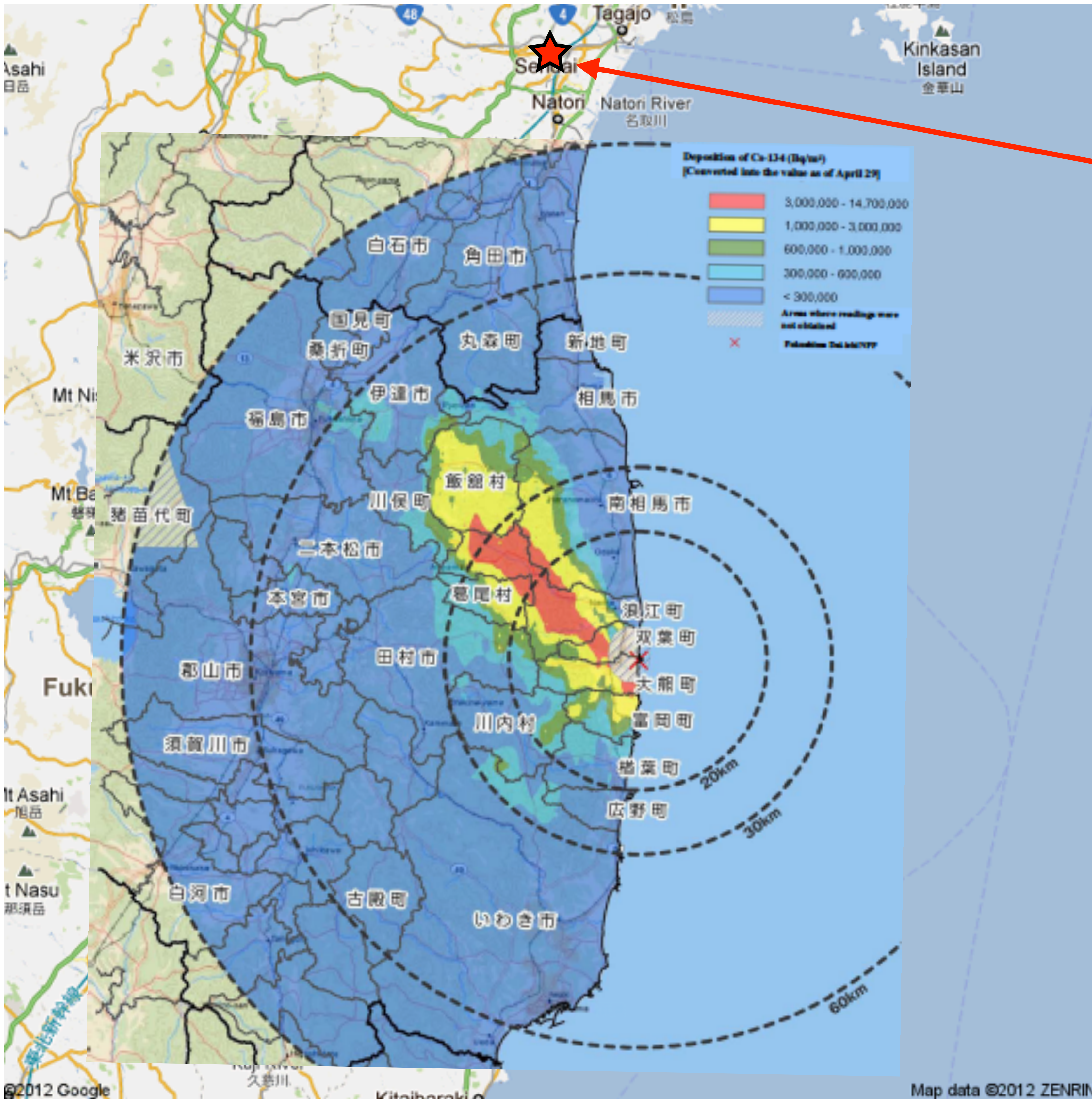
Energy Spectrum



$T_{1/2}^{2\nu}$ = [2.38 ± 0.02 (stat) ± 0.14 (syst)] x 10^{21} yr

Consistent with EXO 2.11x10^{21} yr

Fukushima Fallout



http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/05/10/1304797_0506.pdf

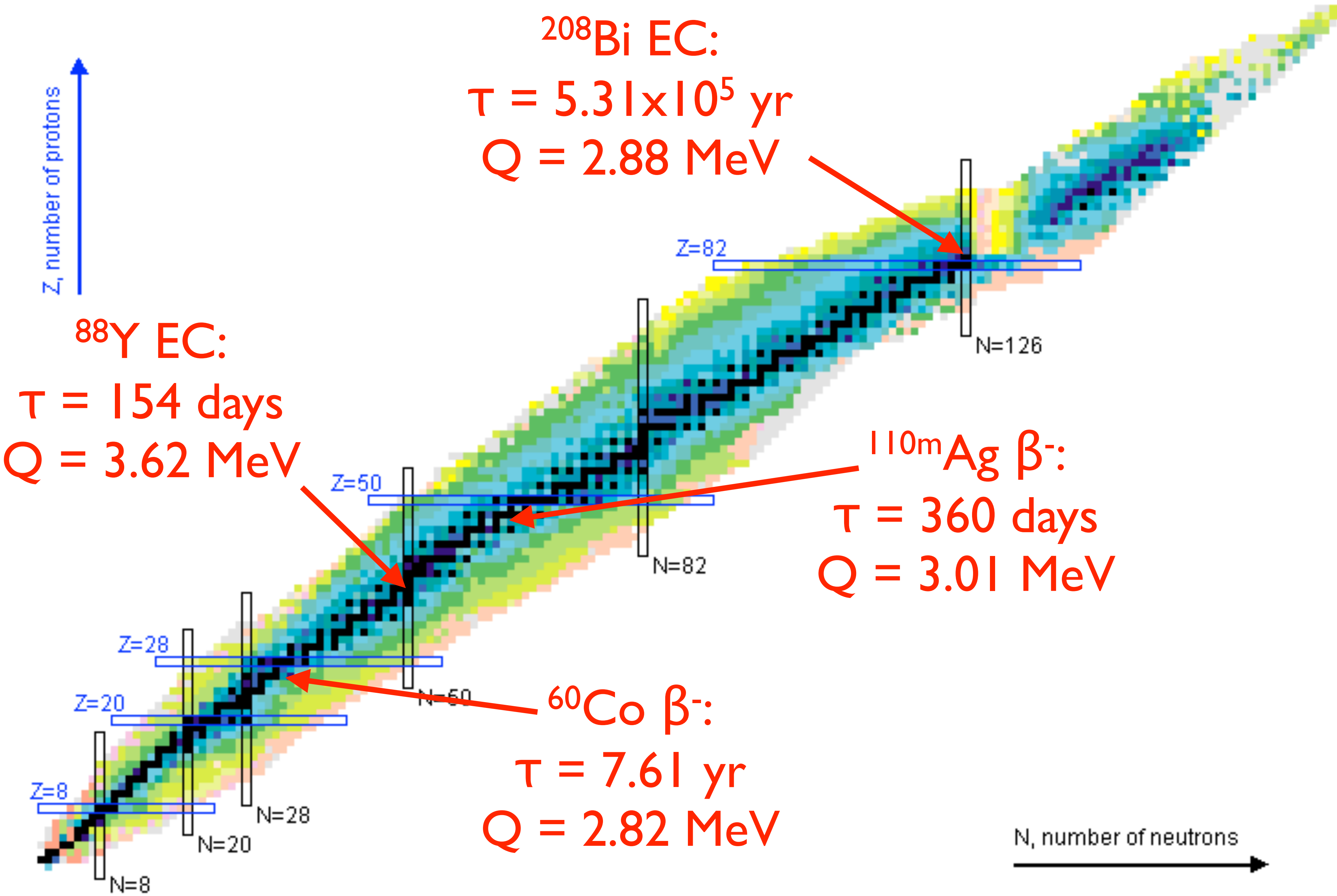
Tohoku University and balloon fabrication ~100km from Fukushima NPP

Exhaustive search for 0ν2β-like signal

- Exhaustive search for unknown contamination
  - Spallation product
  - Fukushima fallout
- Spallation
- ^{11}C: 1.11 ± 0.28 ev/(ton-day)
- ^{10}C: 0.0211 ± 0.0044 ev/(ton-day)
- Spallation neutron yield 13±6% higher (absorb in yield systematics)
- n capture on H, C; no evidence of n capture on Xe
- No evidence of muon followers with $\tau < 100$s

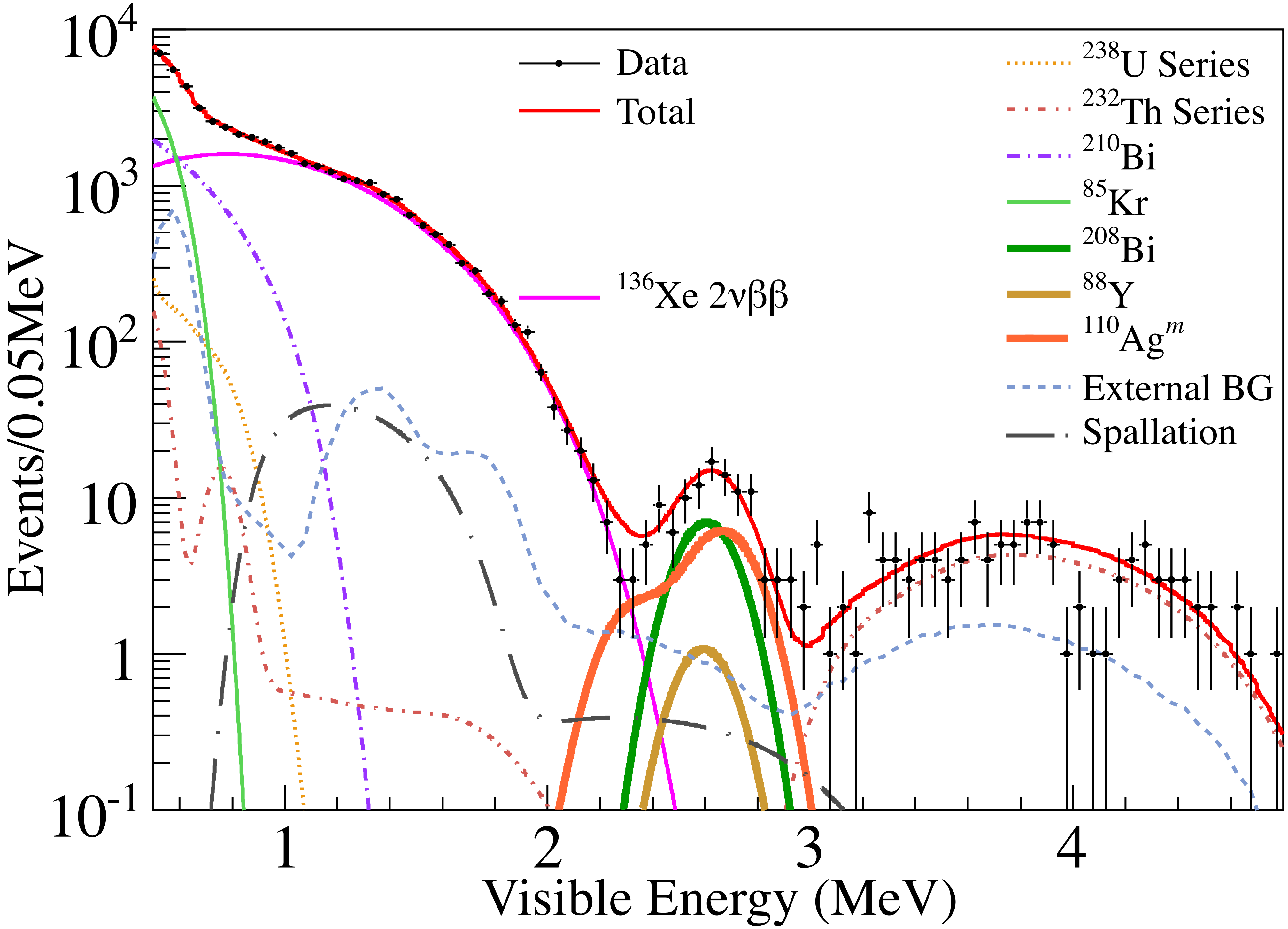
Results from the ENSDF search

- Search through *thousands* of isotopes in ENSDF and *millions* of decay paths that can give a peak between 2.4MeV and 2.8MeV
  - Account for all particle-dependent energy non-linearities
  - Require τ > 30 days, or 100s < τ < 30 days if production cross section is fairly large



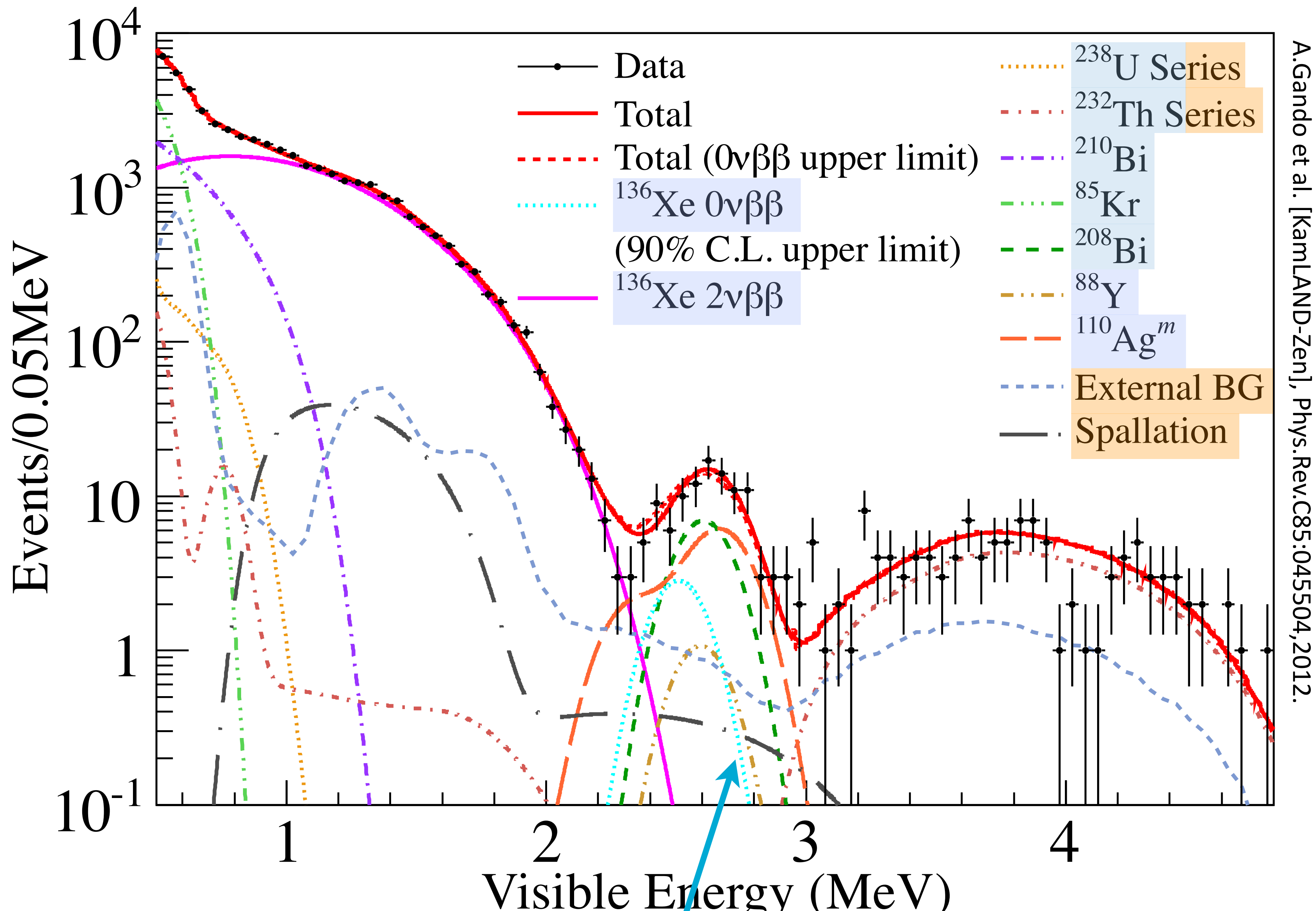
NuDat 2.6

Fit of Backgrounds to Peak



Full Fit

Some fit parameters are free, others constrained



Fitted 0ν2β Upper Limit Rate

free parameter

constrained

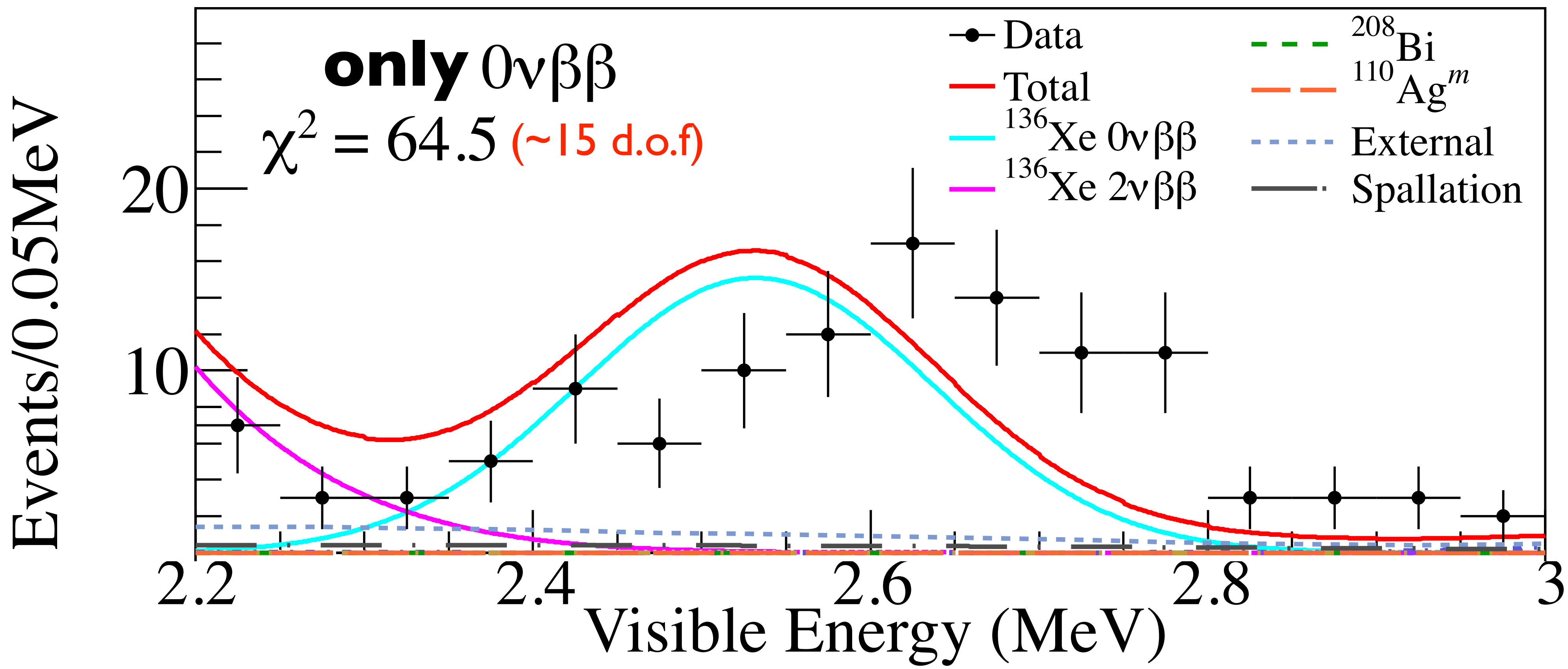
Components not shown have best fit = 0

$T_{1/2}^{0\nu} > 5.7 \times 10^{24}$ yr (90% C.L.)

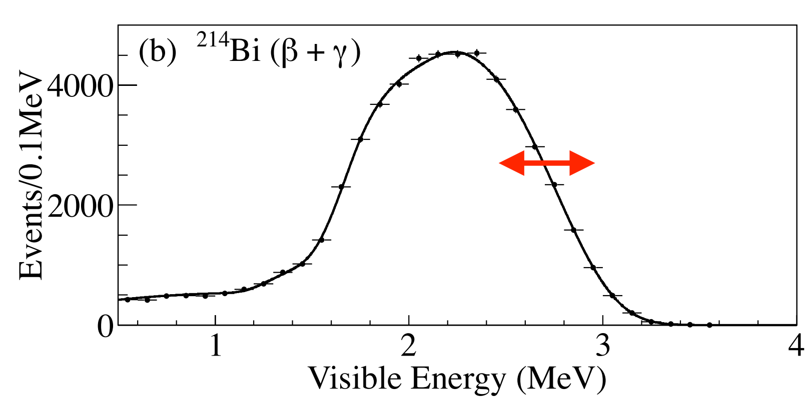
→ 5x better than previous limit

Linear Scale

Zoom-in and linear scale

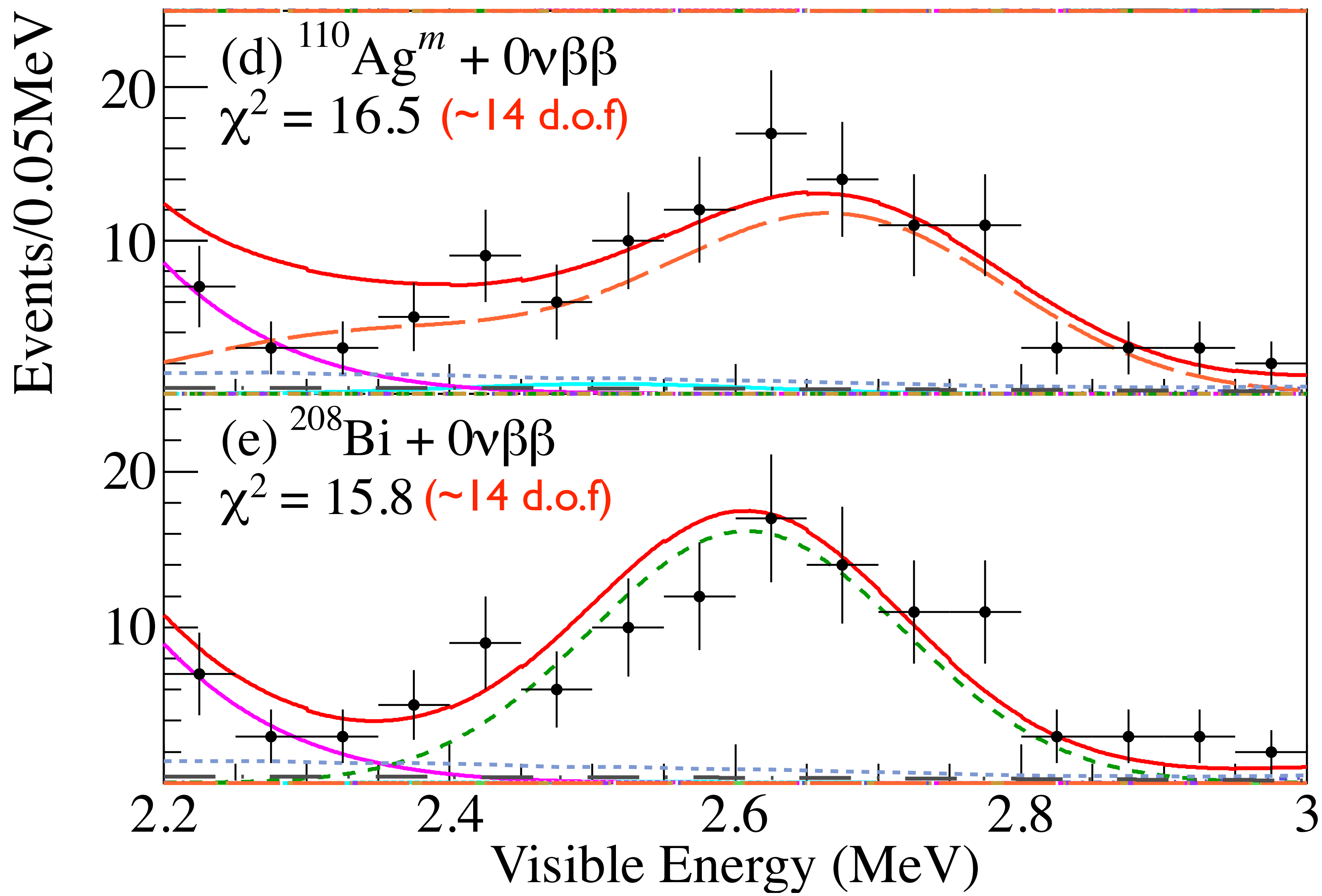


→ It's not $0\nu\beta\beta$ decay (>5σ)



Energy scale is tightly constrained

Alternative Hypotheses



→ Little further discriminating power

Is the background from Fukushima?

Isotopes found near Fukushima

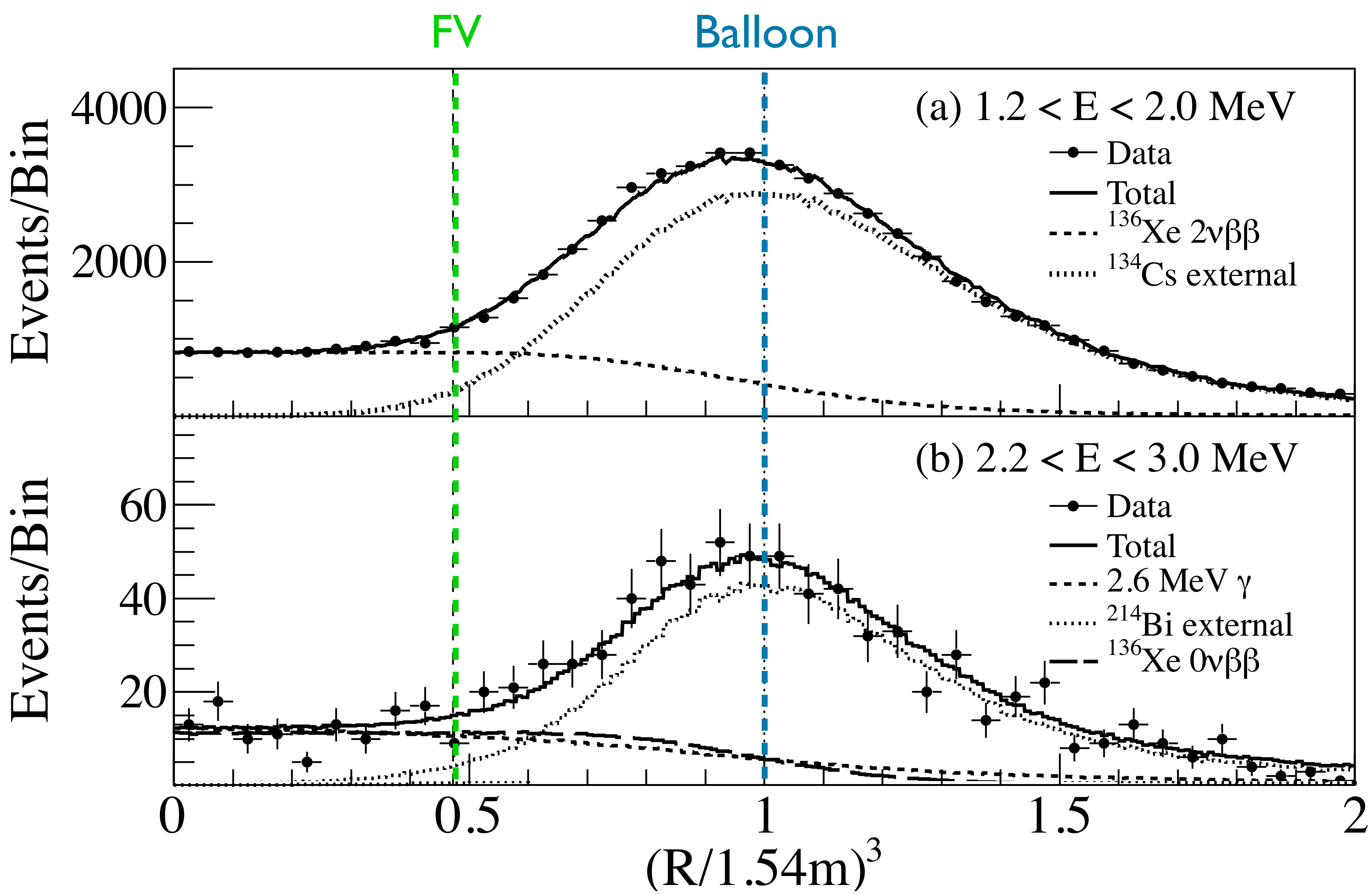
Isotopes	Found in KL-Zen?
^{134}Cs, ^{137}Cs, $^{110}Ag^m$	Yes
$^{129}Te^m$, ^{95}Nb, ^{90}Y, ^{89}Sr	Negligible

- Is the background from Fukushima?
- $^{110}Ag^m$ was found in soil samples around Sendai
- Both ^{134}Cs and ^{137}Cs reconstructed on miniballoon
  - Ratio ^{134}Cs / ^{137}Cs ~ 0.8, consistent with Fukushima fallout

→ Plausible that the background comes from Fukushima

[However, we cannot exclude cosmic activation of Xe → little known]

Balloon and Xe-LS Backgrounds



2νββ window

LS: 2νββ

Balloon: ^{134}Cs, ^{137}Cs

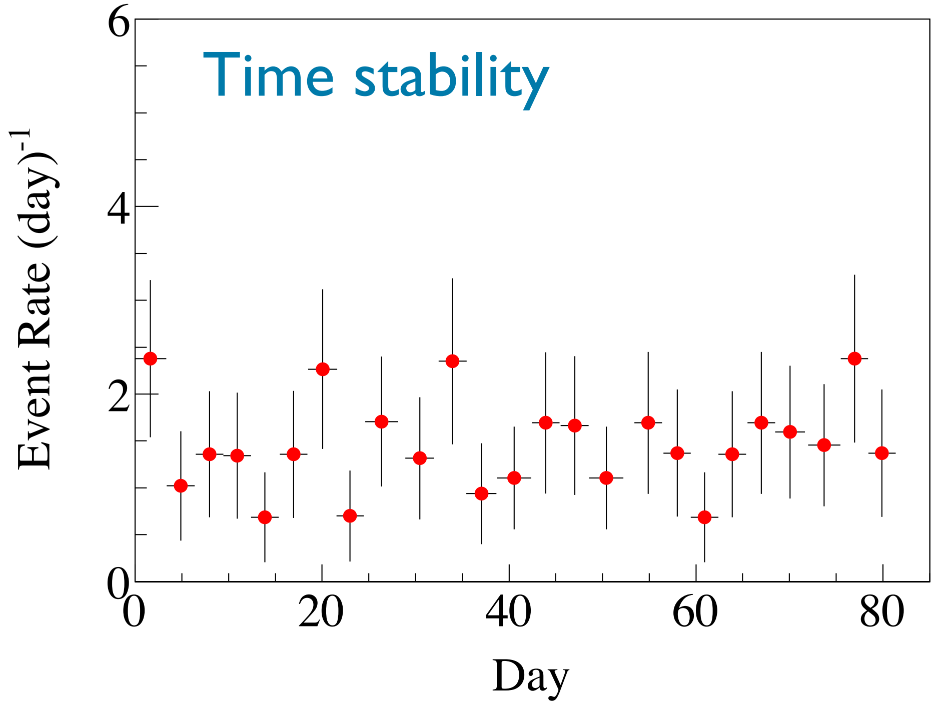
0νββ window

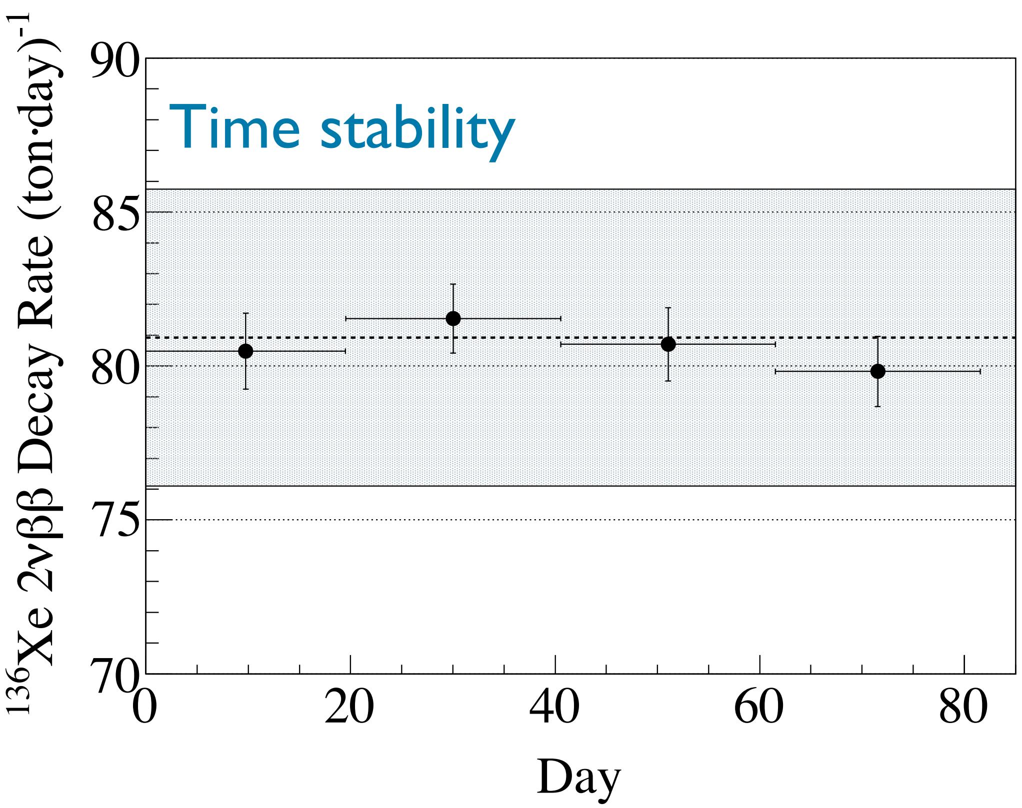
LS: "something"

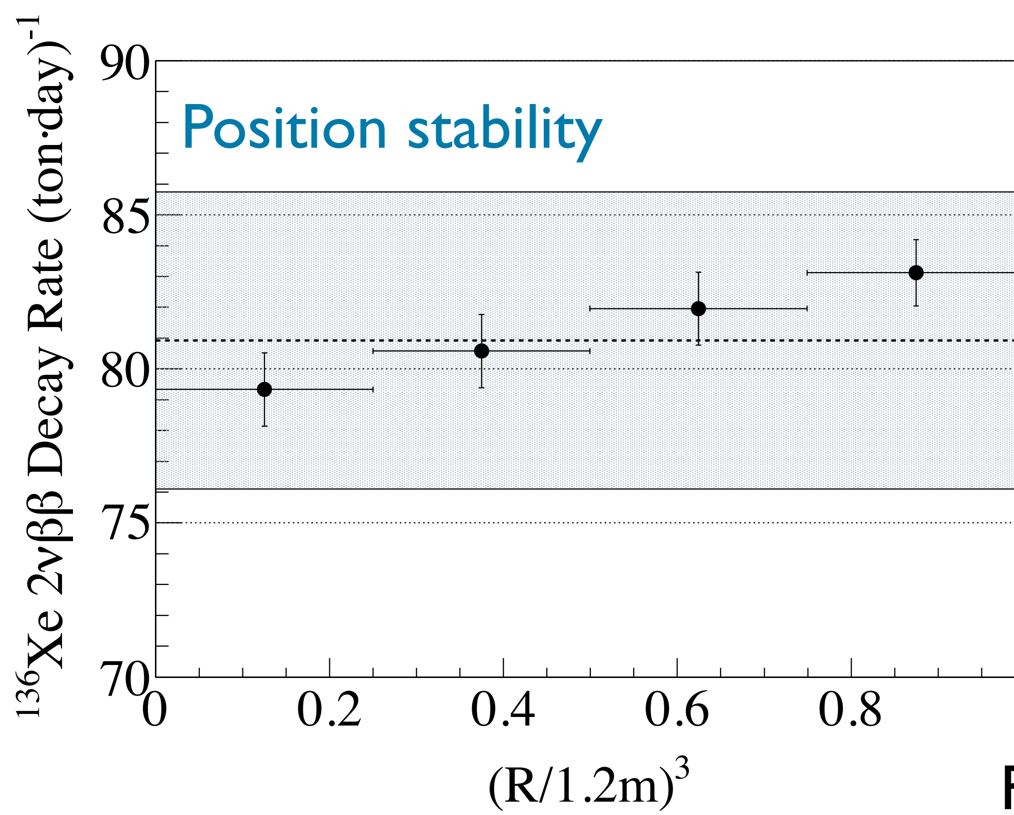
Balloon: ^{214}Bi

Stability of the events

[0νββ window]







FV boundary

Options to Explore 0νββ Peak

- ~~^{110m}Ag: τ = 360d; ^{88}Y: τ = 154 d~~
  ~~→ Wait to see if a decay time emerges~~

Not practical

- Purify the scintillator
  - ~~Filtration~~
  - Destillation

No change with 50-nm PTFE filter, 2.3 volume exchanges

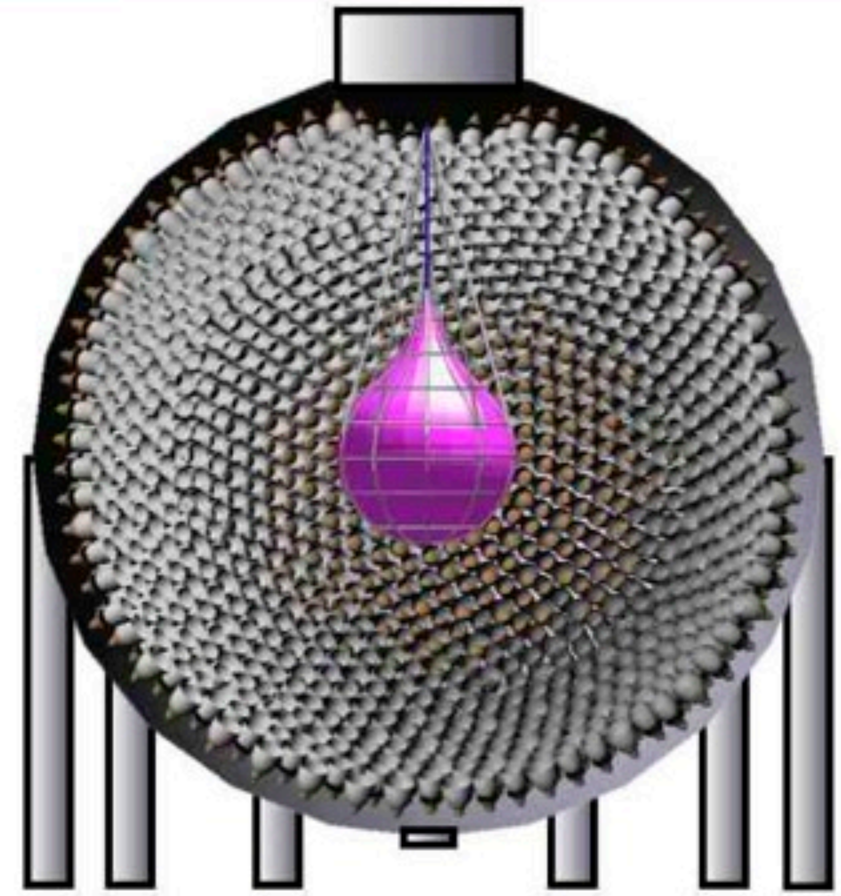
- Run without ^{136}Xe

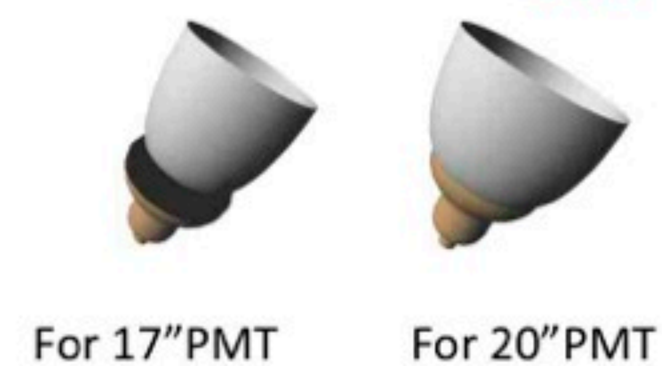
Distillation

- Remove Xe-LS and replace with fresh “dummy” LS
- Distill & purify Xe while running with “dummy” LS
- Fill miniballoon with new, cleaner Xe-LS
- Deploy calibration sources inside miniballoon

Longer Term Future: KamLAND2-Zen

- 2^{nd} Phase of KamLAND-Zen (~2016)
    - 1 ton of ^{136}Xe
    - Enhanced Xe-LS
    - Winston cone reflectors to increase PMT coverage from 24% → ~70%
- May be able to cover inverted hierarchy

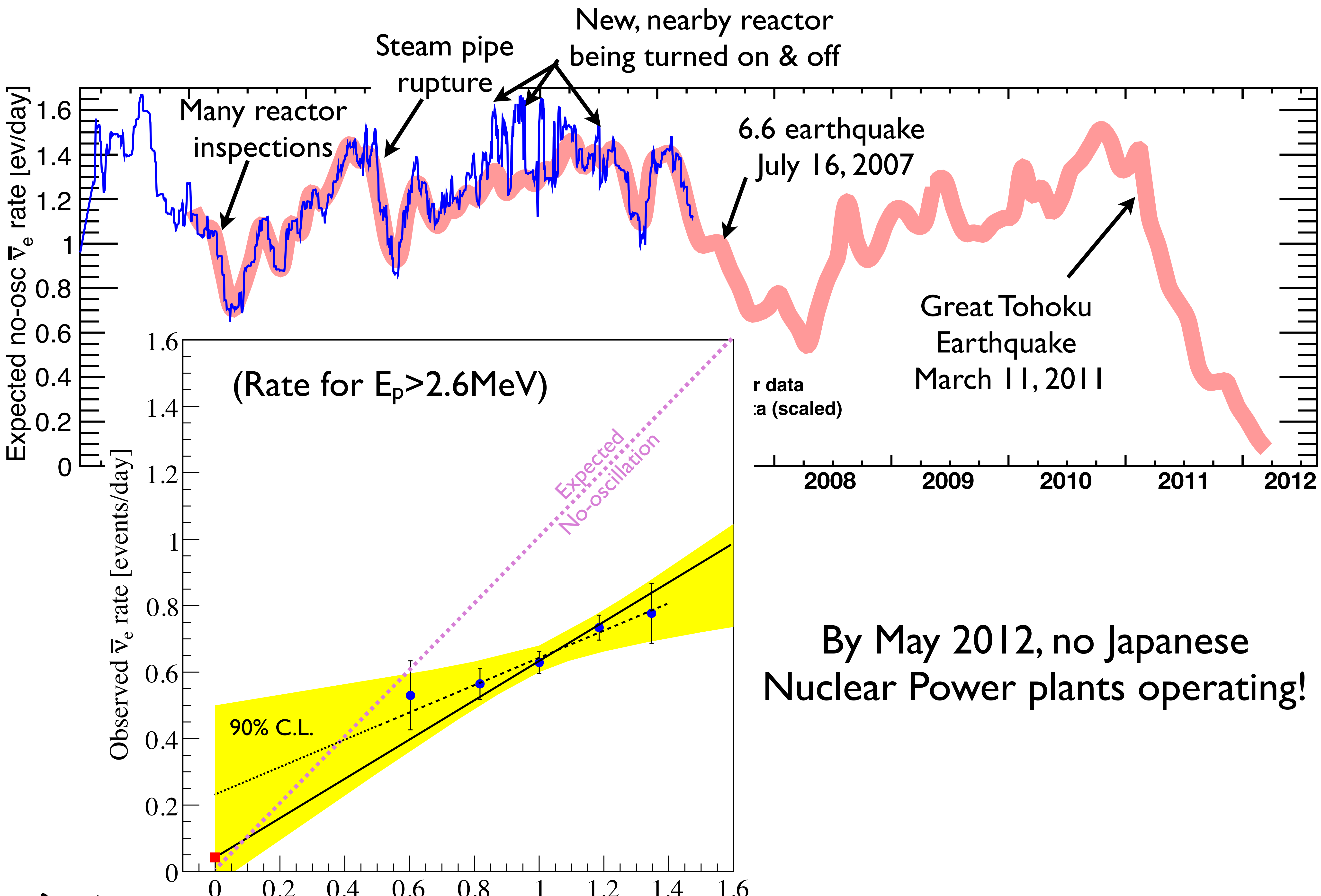




Summary

- KamLAND-Zen released first data based on 77.6days of exposure 129kg of ^{136}Xe (380kg total)
  - $2\nu2\beta$: $T_{1/2}^{2\nu}$ = [2.38 ± 0.02 (stat) ± 0.14 (syst)] x 10^{21} yr
    - Confirms EXO-200 measurement
  - $0\nu2\beta$: 5x better limit → $T_{1/2}^{0\nu} > 5.7 \times 10^{24}$ yr (90% C.L.)
- We will purify the detector to remove contaminants
- Plans to upgrade the detector for more light collection and 1 ton ^{136}Xe.
- Reactor and geo-neutrino measurements ongoing…

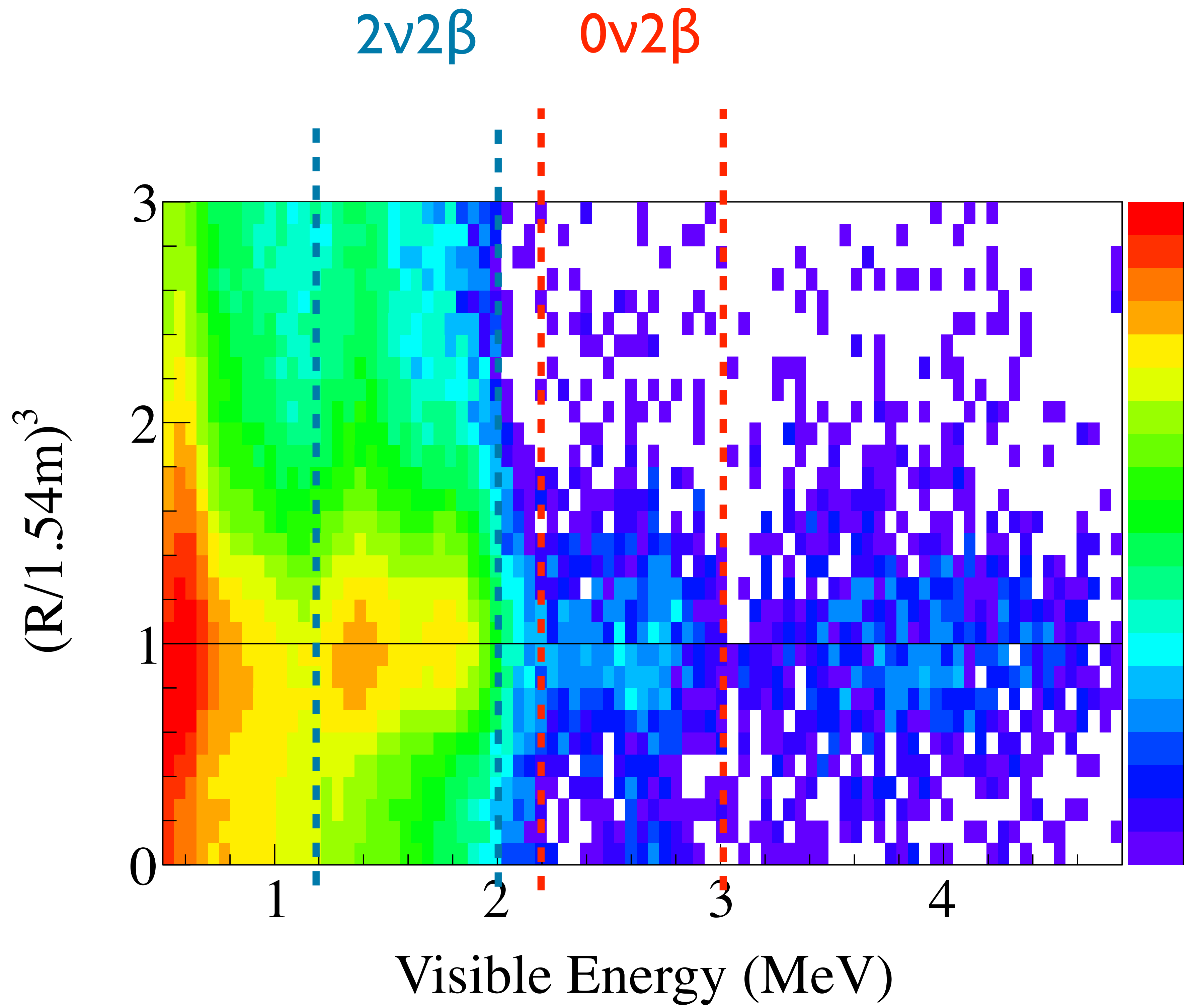
Reactor Signal Changes with Time



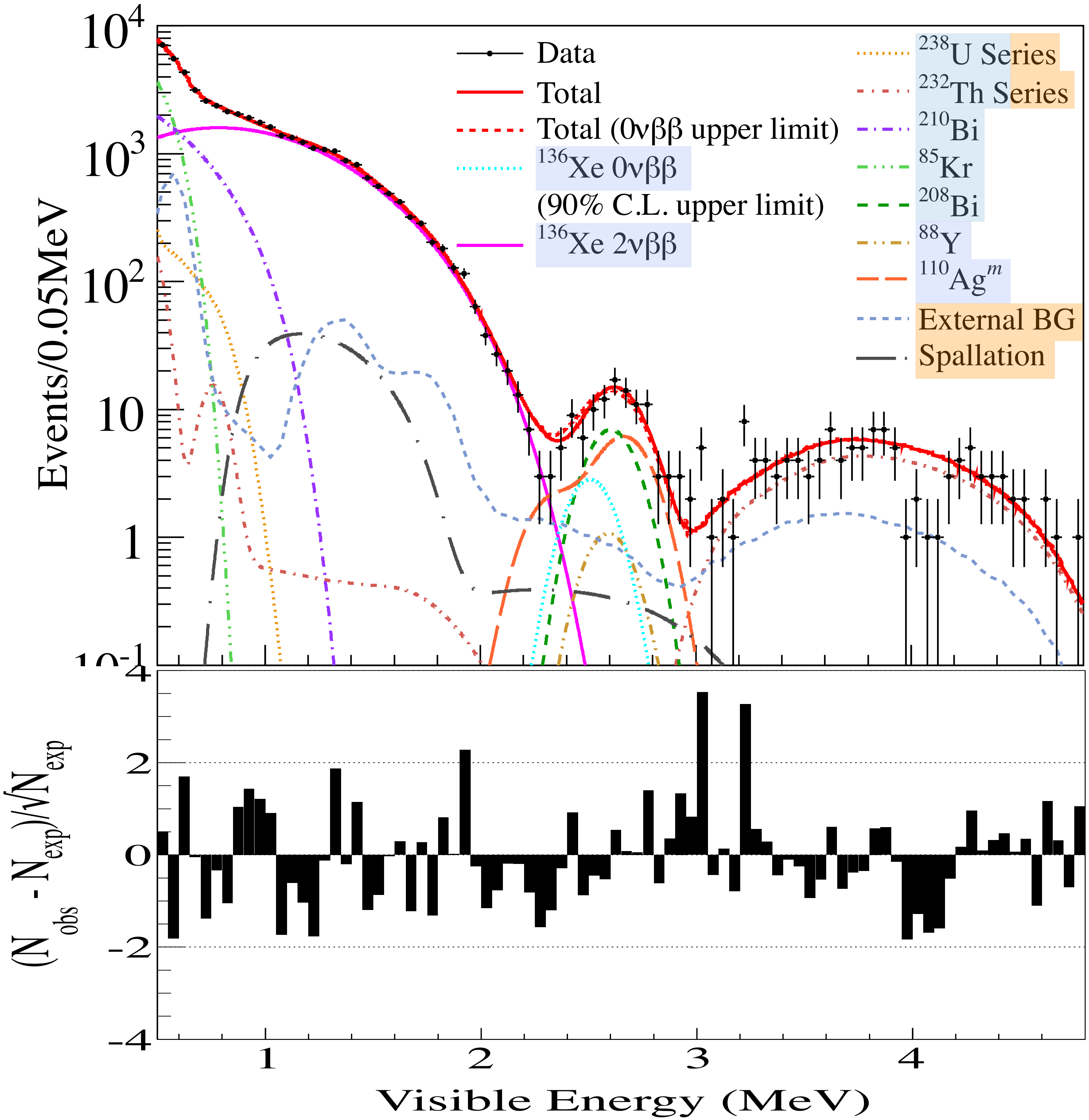
By May 2012, no Japanese Nuclear Power plants operating!

Patrick

Spectrum at different radii



Residuals



free parameter

constrained

Components not shown have best fit = 0