Experimental review on neutrinoless double beta decay

GGI Neutrino and Invisibles meeting
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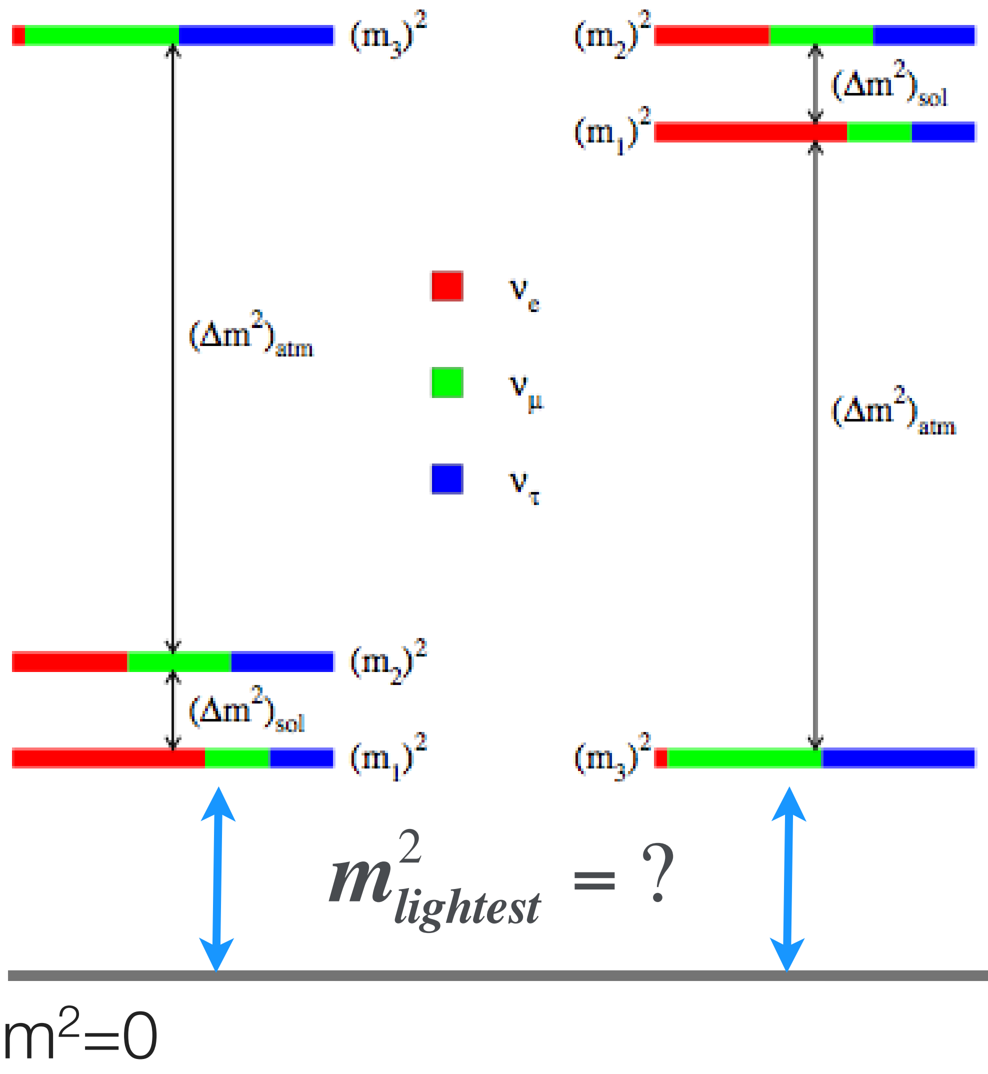
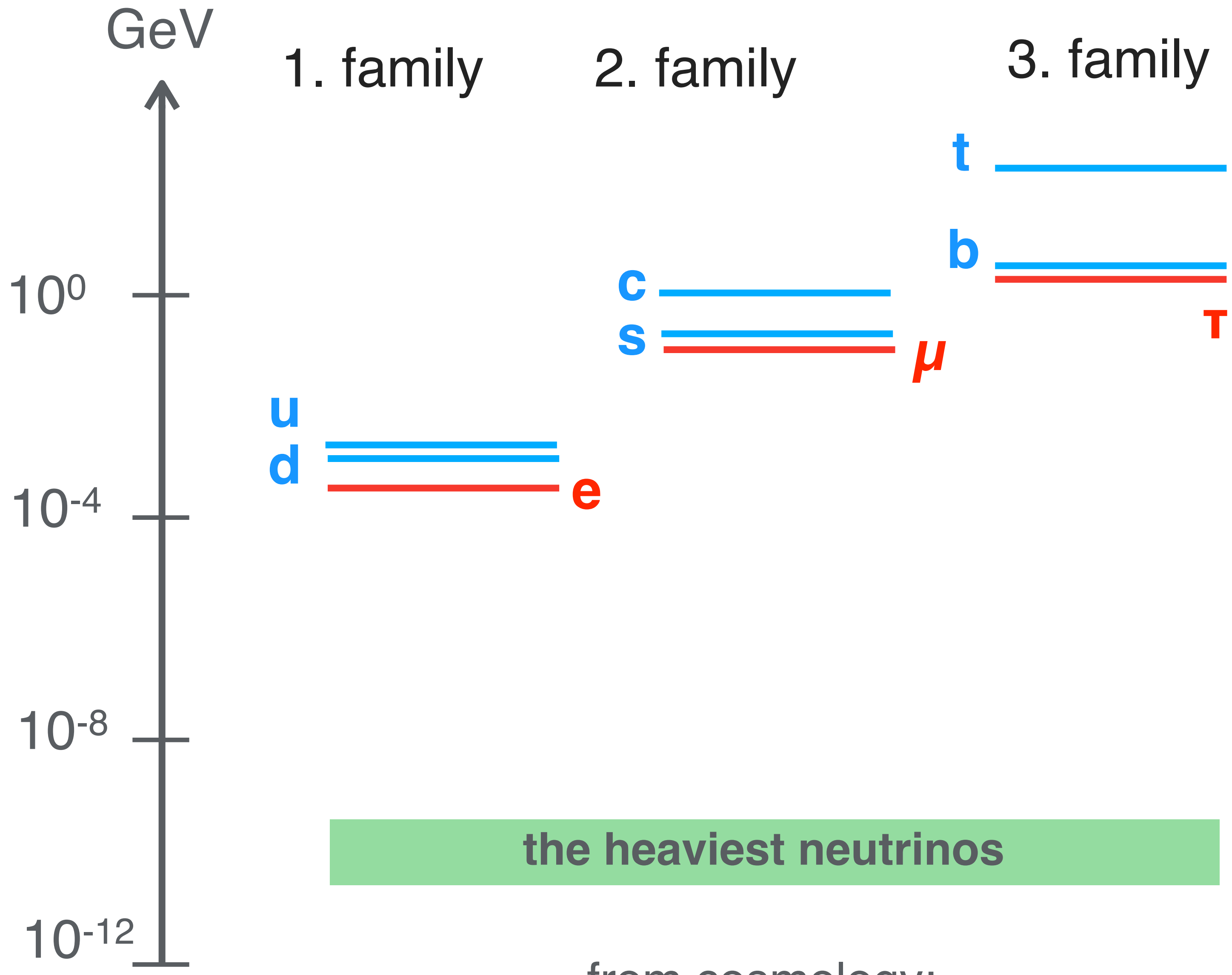
invisibles
neutrinos, dark matter & dark energy physics

Neutrinos and masses of elementary particles

- Neutrinos: much lighter than other known particles
  - ➡ Why is their mass so small?
  - ➡ What is their absolute mass scale?





from cosmology:

$$\Sigma_i m_i = 440 - 760\,\mathrm{meV}$$

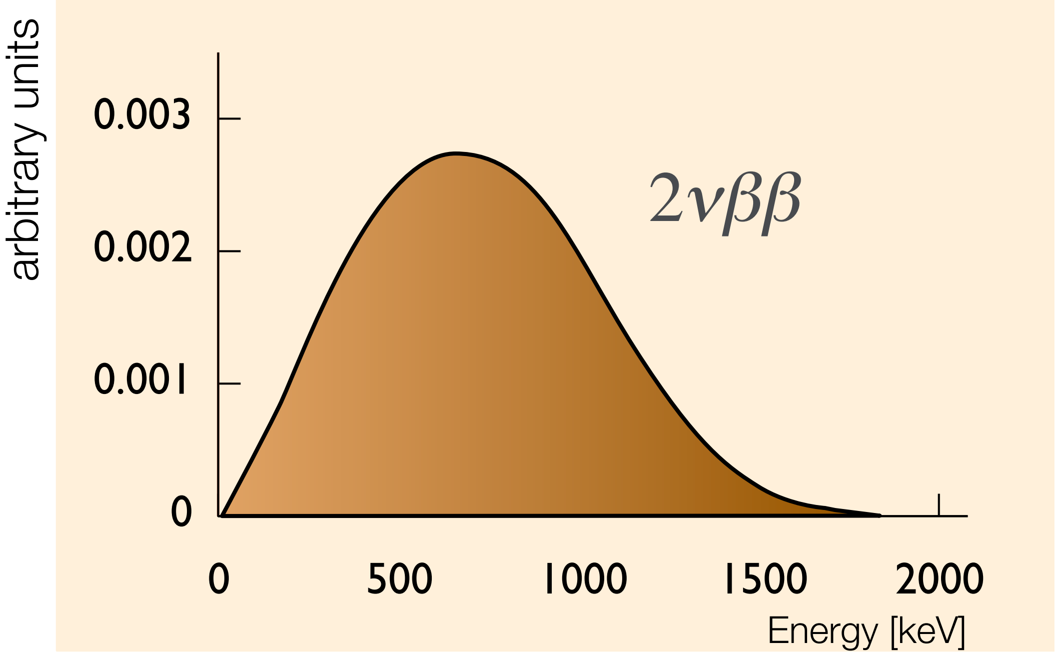
Double beta decay

- The decay with emission of 2 neutrinos was observed in more than 10 different nuclei: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

- The observed energy spectrum of the two electrons is continuous, up to the Q-value

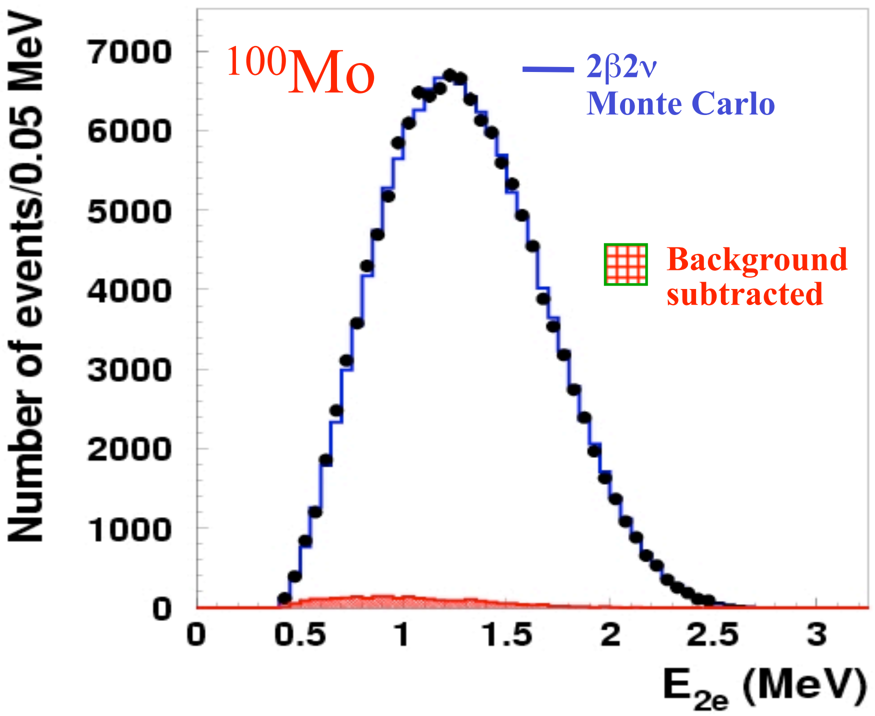
$$\Gamma^{2\nu} = \frac{1}{T^{2\nu}_{1/2}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

$$G^{2\nu} \propto (G_F \cos\theta_C)^4 Q^7 \left(1 + \frac{Q}{2} + \frac{Q^2}{9} + \frac{Q^3}{90} + \frac{Q^4}{1980}\right)$$



$$Q = E_{e1} + E_{e2} + E_{\nu 1} + E_{\nu 2} - 2m_e$$

NEMO Experiment in Modane/Frejus



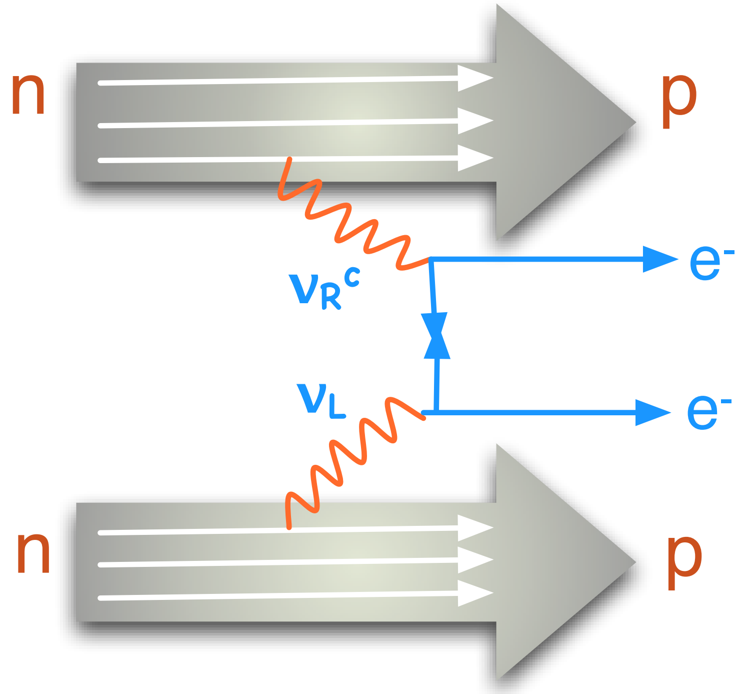
^{100}Mo: $T_{1/2}=7.15\times10^{18}$ a

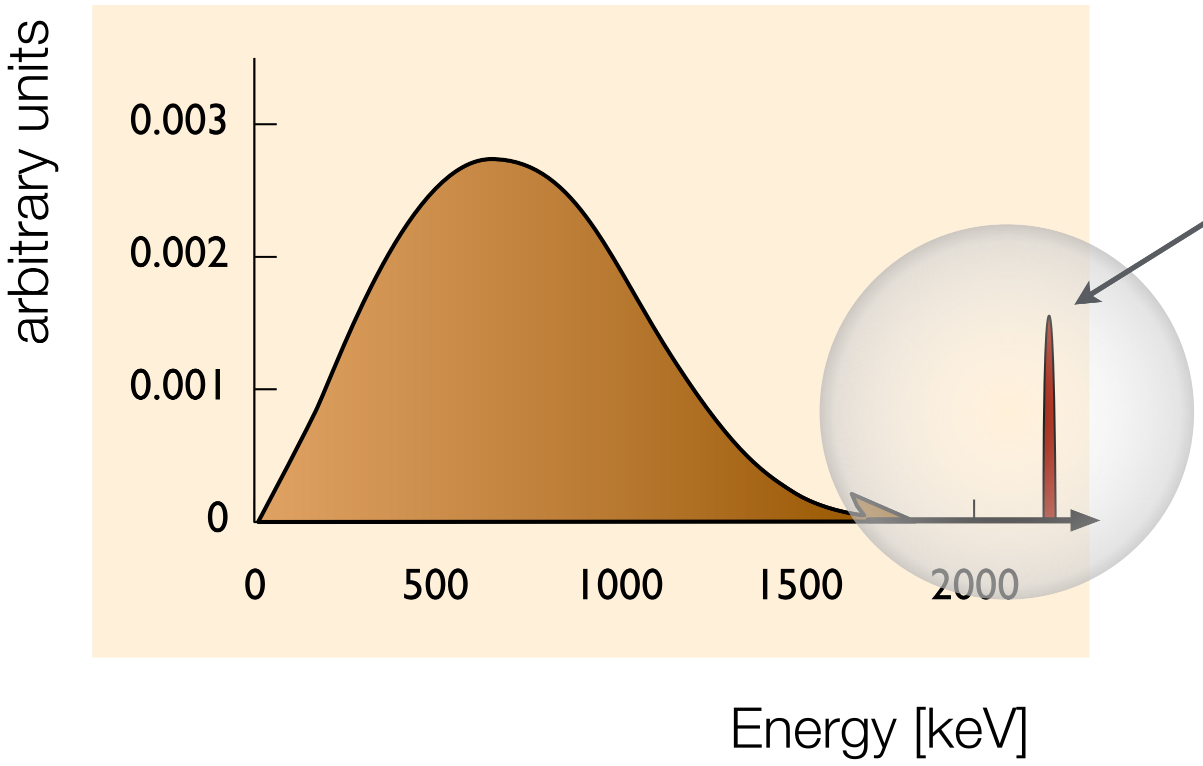
Neutrinoless double beta decay

- More interesting: the decay mode without emission of neutrinos (“forbidden” in the SM, since ΔL =2)

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

$$G^{0\nu} \propto (G_F \cos\theta_C)^4 \cdot \left[\frac{Q^5}{30} - \frac{2Q^2}{3} + Q - \frac{2}{5}\right] \propto (G_F \cos\theta_C)^4 \cdot Q^5$$



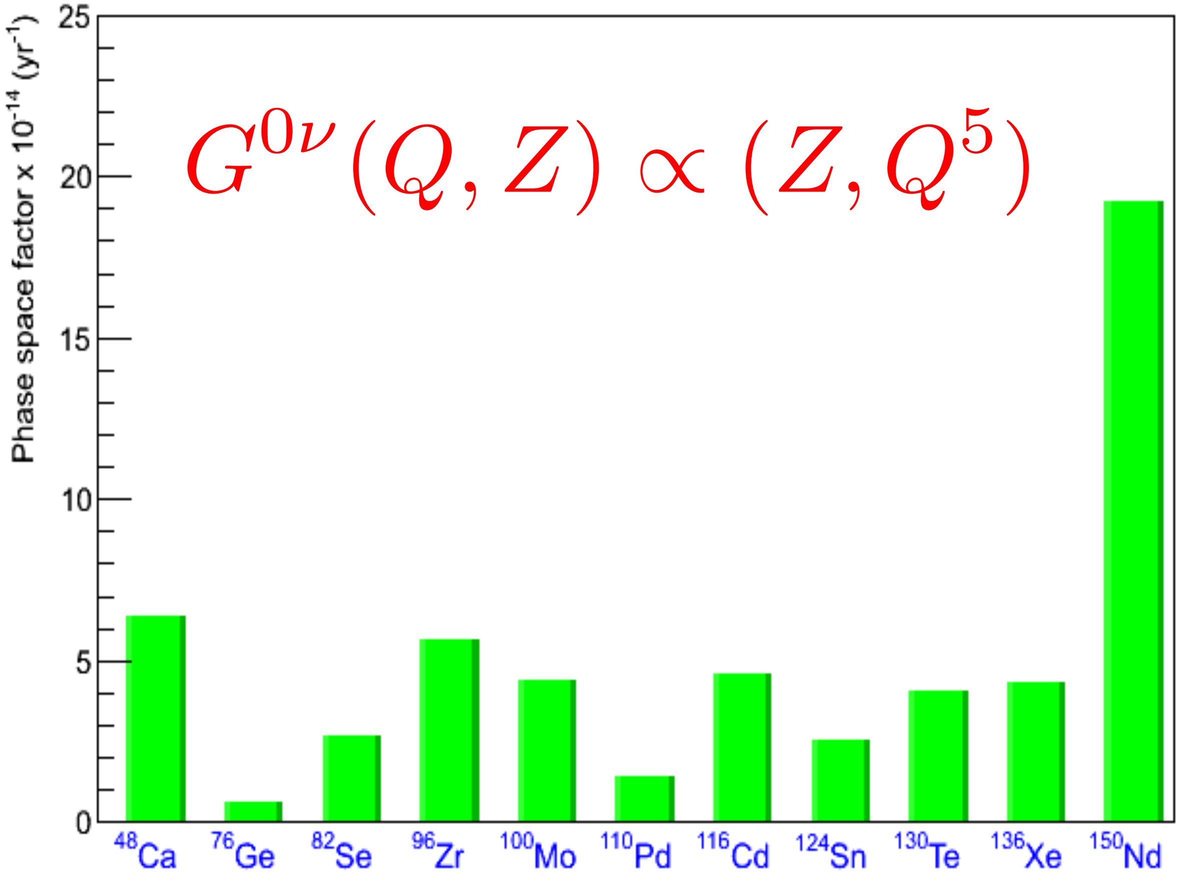


expected:
“peak” at the Q-value of the decay

$$Q = E_{e1} + E_{e2} - 2m_e$$

Phase space

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = \boxed{G^{0\nu}(Q,Z)} |M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$



$$G^{0\nu}(Q,Z) \propto (Z, Q^5)$$

F. Piquemal, Neutrino2012, Kyoto

Transition	G [10^{-14} yr^{-1}]	Q [keV]
^{48}Ca → ^{48}Ti	6.35	4373.7
^{76}Ge → ^{76}Se	0.63	2039.1
^{82}Se → ^{82}Kr	2.70	2995.5
^{100}Mo → ^{100}Ru	4.36	3035
^{116}Cd → ^{116}Sn	4.62	2809
^{130}Te → ^{130}Xe	4.09	2530.3
^{136}Xe → ^{136}Ba	4.31	2461.9
^{150}Nd → ^{150}Sm	19.2	3367.3

Matrix elements

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\boxed{|M^{0\nu}|^2}\frac{|m_{\beta\beta}|^2}{m_e^2}$$

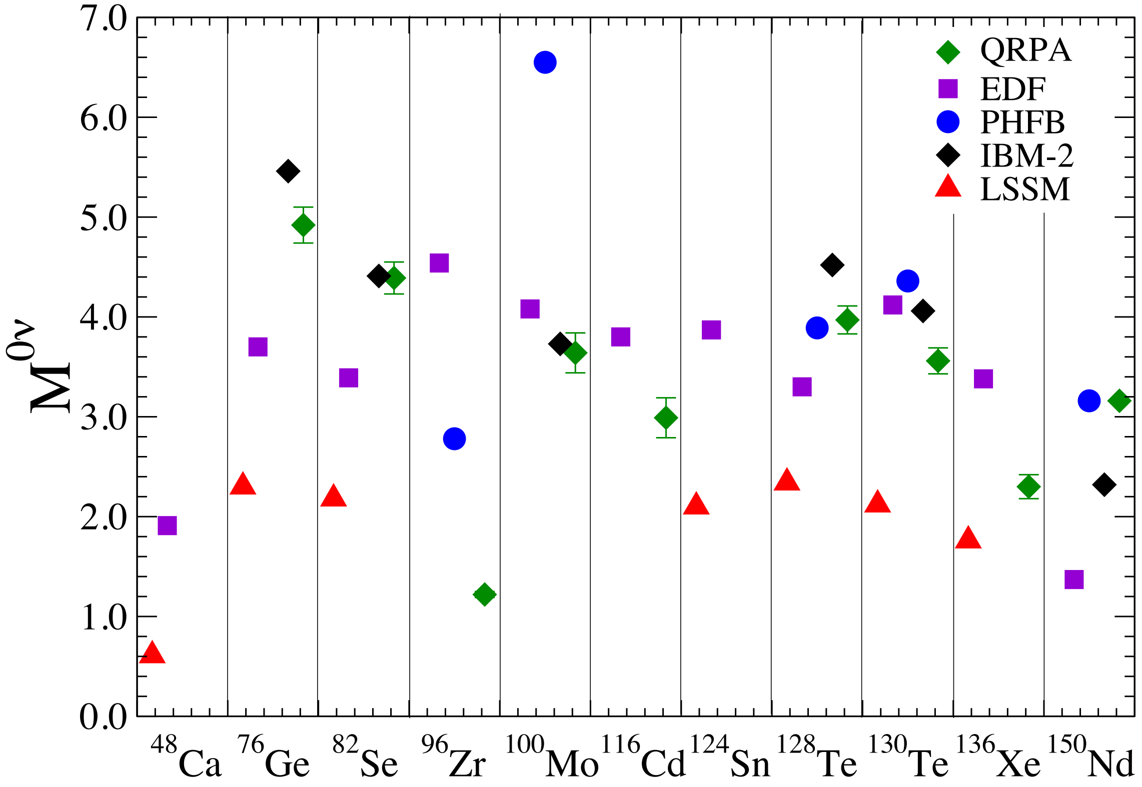


Fig. 3. Values of the NME calculated with the methods in Tab. 2 [74].

Bilenky, Giunti: arXiv:1203.5250v2

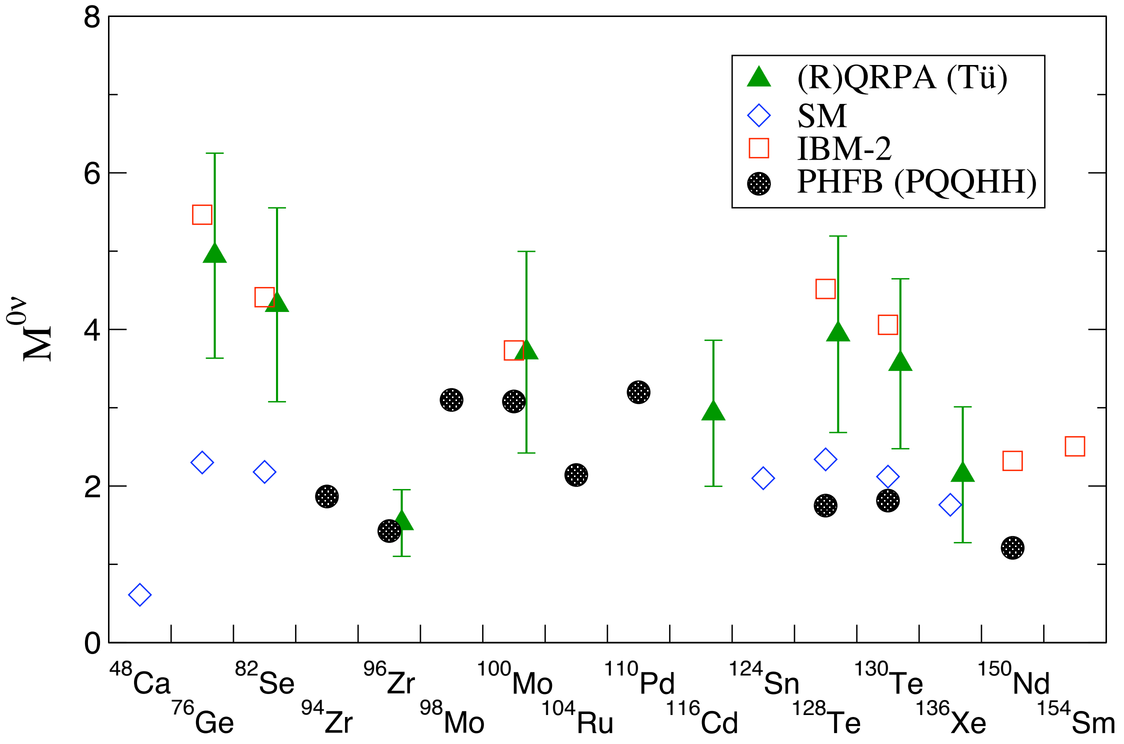


FIG. 7: (Color online) Neutrinoless double beta decay transition matrix elements for the different approaches: QRPA [5, 6], the SM [8–10], the projected HFB method [14] and the IBM [15]. The error bars for the QRPA are calculated as the highest and the lowest values for three different single nucleon basis sets, two different axial charges $g_A = 1.25$ and the quenched value $g_A = 1.00$ and two different treatments of short range correlations (Jastrow-like [25] and the Unitary Correlator Operator Method (UCOM) [26]). The radius parameter is as in this whole work $r_0 = 1.2$ fm.

arXiv:1001.3519

Matrix elements: vary by a factor of 2- 3 for a given A

Effective Majorana neutrino mass

- $|m_{\beta\beta}|$ is a mixture of m_1, m_2, m_3, proportional to the U_{ei}^2, where U_{ei} are complex entries

$$|m_{\beta\beta}| = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i(\alpha_1-\alpha_2)} + m_3|U_{e3}|^2 e^{i(-\alpha_1-2\delta)}|$$

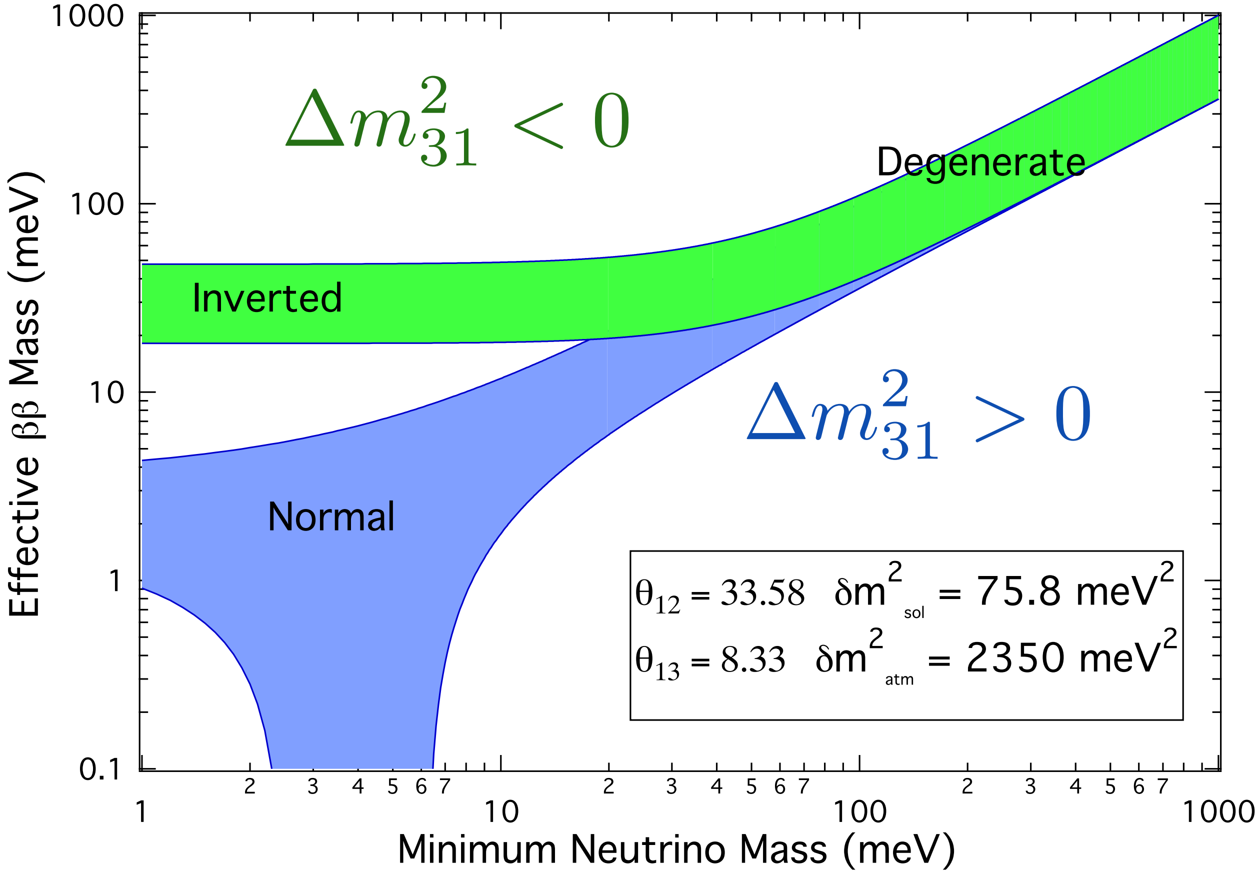
- where U = neutrino mixing matrix, $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, α_1, α_2 = Majorana phases

current sensitivities

$T_{1/2} \sim 10^{27}$ yr

$T_{1/2} \sim 10^{29}$ yr

S. Elliott, http://arxiv.org/pdf/1203.1070v1.pdf



Remark: here the exchange of a light neutrinos is considered; many other contributions are possible (Majoron, heavy Majorana neutrino exchange, right-handed currents, SUSY, etc)

For a recent review, see: http://xxx.lanl.gov/pdf/ 1205.0649.pdf

Experimental sensitivity

- Experiments observe:

$$N_{\beta\beta}^{0\nu} = \frac{a \cdot M \cdot N_A}{A} \frac{\ln 2}{T_{1/2}^{0\nu}} \cdot \epsilon \cdot t$$

- with a non-zero number of background events:

$$N_{bg} = M \cdot t \cdot B \cdot \Delta E$$

- The experimental sensitivity is thus:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{N_A \ln 2}{\sqrt{2} n_\sigma} \frac{a \cdot \epsilon}{A} \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

a = enrichment

ε = detector efficiency

M = total mass

t = measuring time

ΔE = energy resolution

B = background index

n_{sigma}= confidence level in units of sigma

Experimental requirements

- Experiments thus measure the half life of the decay, $T_{1/2}$

$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T^{0\nu}_{1/2}}}$$

Minimal requirements:

large detector masses
enriched materials
ultra-low background noise
excellent energy resolution

Additional tools to distinguish signal from background:

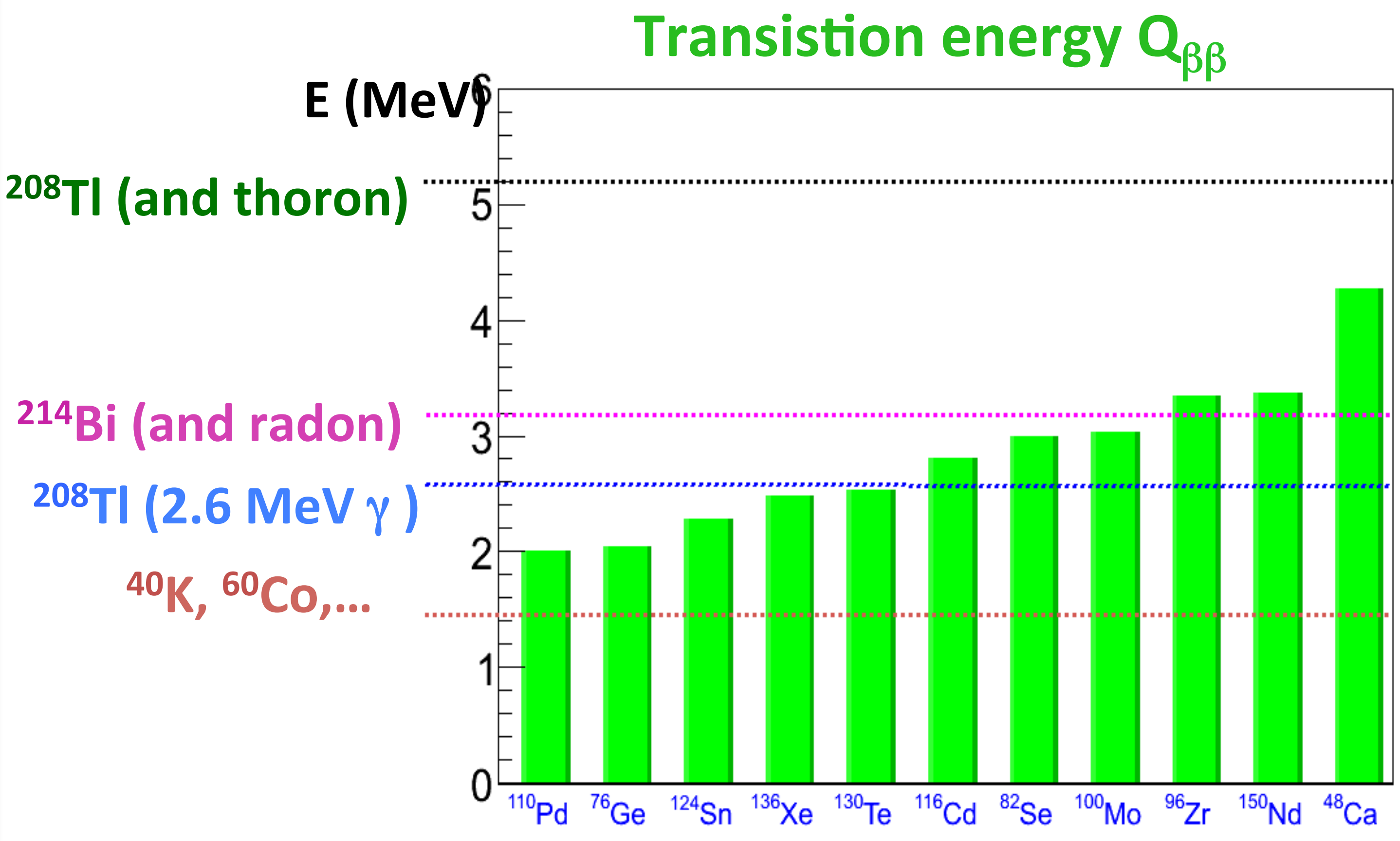
angular distribution
decay to excited states (gamma-rays)
identification of daugther nucleus

Backgrounds for double beta experiments

- primordial radionuclides (^{238}U, ^{232}Th, ^{40}K) in the detector materials, in the shielding and the concrete/rock (alpha, beta, gamma and neutrons)
- cosmic activation of detector materials (^{60}Co, ^{54}Mn, ^{65}Zn,...)
- cosmic rays - muons - and secondary particles
- radon in air, radon emanation of materials,....
- anthropogens (^{85}Kr, ^{137}Cs, ^{207}Bi,...)

2vββ-events: irreducible background

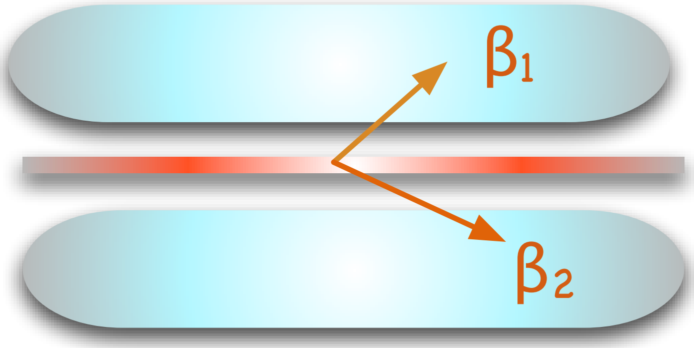
an excellent energy resolution of the detector is crucial



F. Piquemal, Neutrino2012, Kyoto

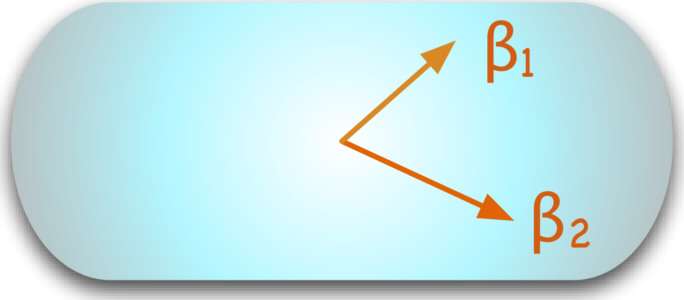
Experiments: Main Approaches

Source ≠ Detector

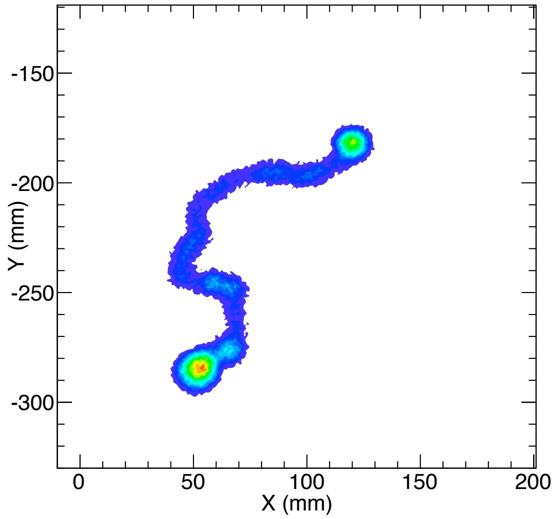


Source as thin foil
Electrons detected with: scintillator, TPC, drift chamber, semiconductor detectors
Event topology
Low energy resolution and detection efficiency

Source = Detector (calorimeters)



The sum of the energy of the two electrons is measured
Signature: peak at the Q-value of the decay
Scintillators, semiconductors, bolometers
High resolution + detection efficiency
No event topology (unless pixellized)



Source = Detector = Tracker

Source is - for example - the (high-pressure) gas of a TPC
Charge and light detected with electron multipliers and/or photosensors
Good energy and position resolution, high efficiency
Event topology very helpful in reducing the background and *in identifying the potential signal*

Existing experimental limits on $T_{1/2}$ and the effective Majorana neutrino mass

Current best sensitivities are around a few 100 meV

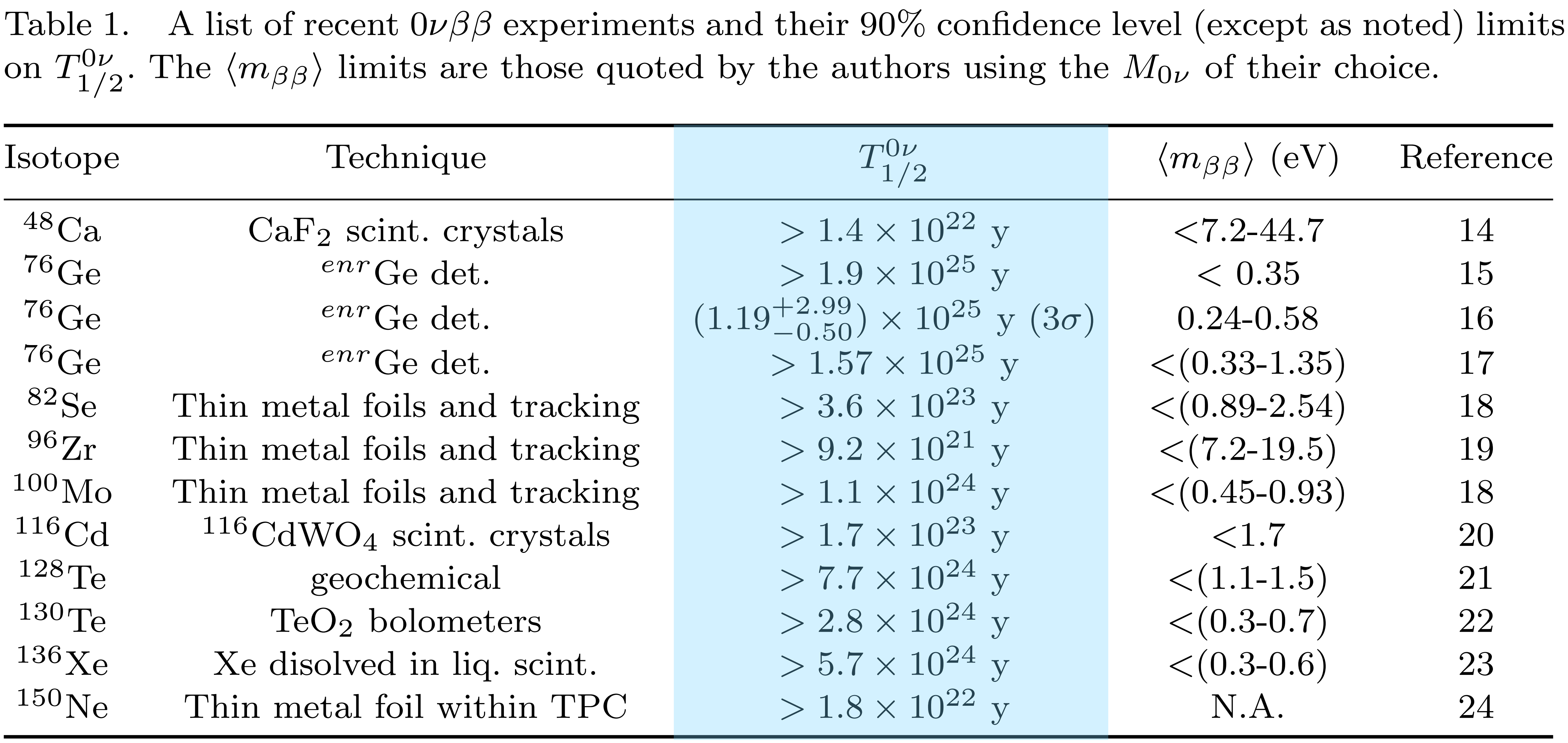
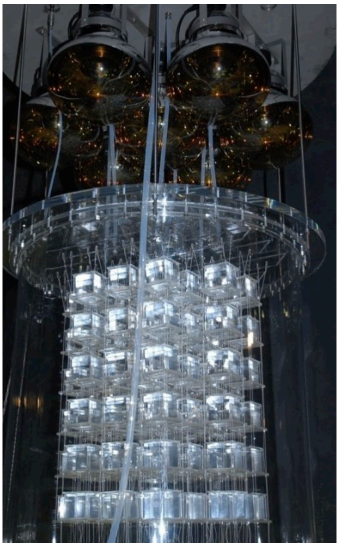
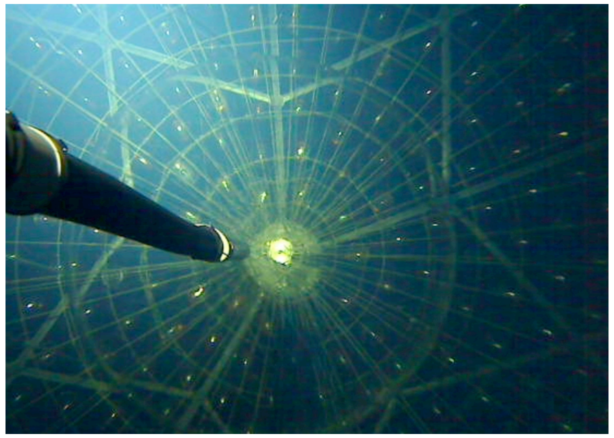


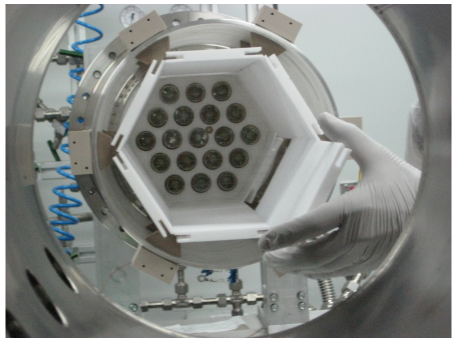
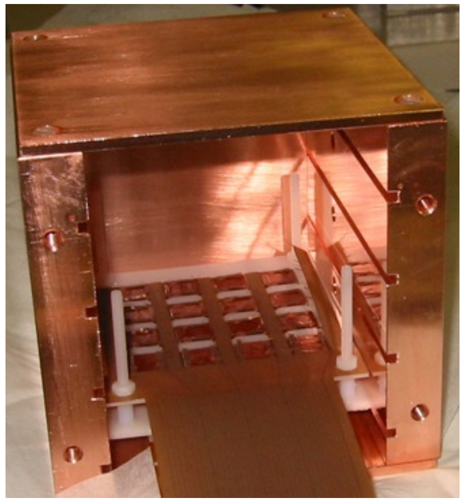
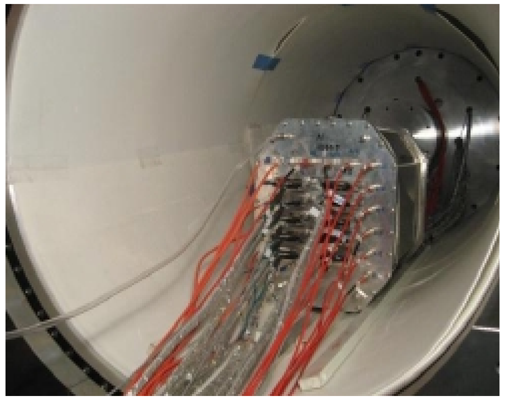
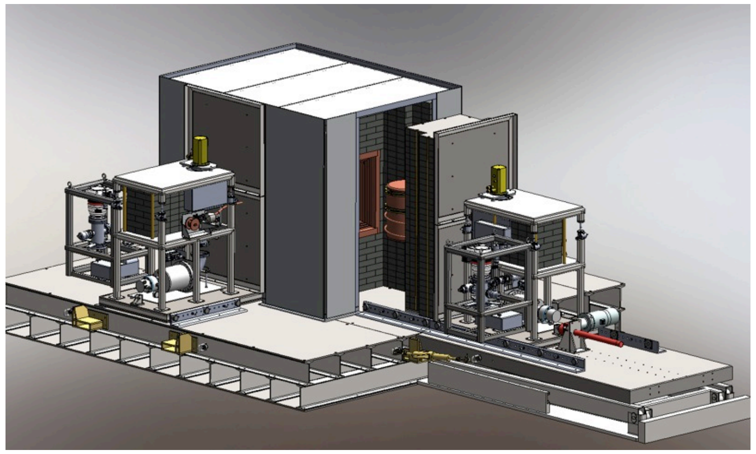
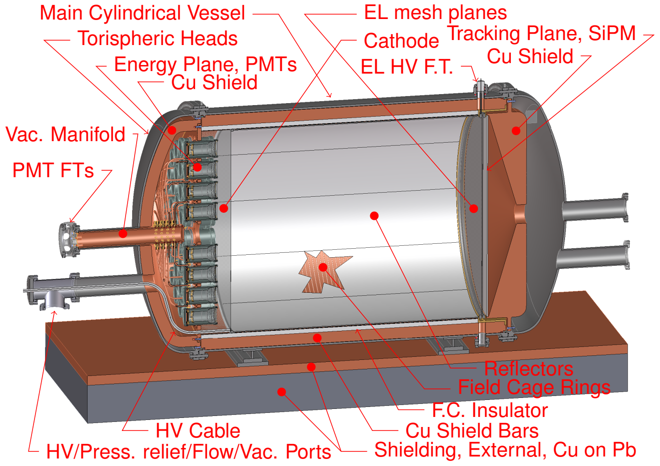
Table 1. A list of recent $0\nu\beta\beta$ experiments and their 90% confidence level (except as noted) limits on $T^{0\nu}_{1/2}$. The $\langle m_{\beta\beta}\rangle$ limits are those quoted by the authors using the $M_{0\nu}$ of their choice.

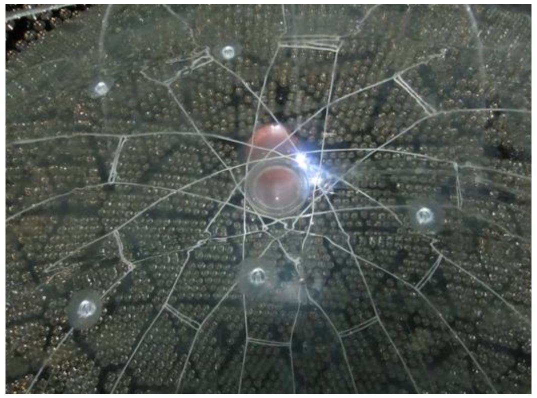
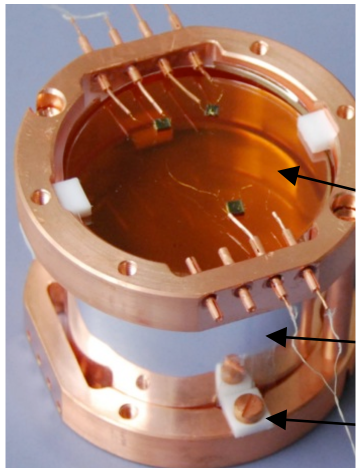
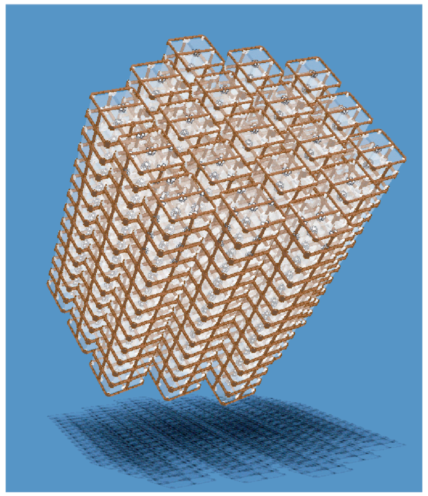
Isotope	Technique	$T^{0\nu}_{1/2}$	$\langle m_{\beta\beta}\rangle$ (eV)	Reference
^{48}Ca	CaF$_2$ scint. crystals	$> 1.4 \times 10^{22}$ y	<7.2-44.7	14
^{76}Ge	^{enr}Ge det.	$> 1.9 \times 10^{25}$ y	< 0.35	15
^{76}Ge	^{enr}Ge det.	$(1.19^{+2.99}_{-0.50}) \times 10^{25}$ y (3σ)	0.24-0.58	16
^{76}Ge	^{enr}Ge det.	$> 1.57 \times 10^{25}$ y	<(0.33-1.35)	17
^{82}Se	Thin metal foils and tracking	$> 3.6 \times 10^{23}$ y	<(0.89-2.54)	18
^{96}Zr	Thin metal foils and tracking	$> 9.2 \times 10^{21}$ y	<(7.2-19.5)	19
^{100}Mo	Thin metal foils and tracking	$> 1.1 \times 10^{24}$ y	<(0.45-0.93)	18
^{116}Cd	^{116}CdWO$_4$ scint. crystals	$> 1.7 \times 10^{23}$ y	<1.7	20
^{128}Te	geochemical	$> 7.7 \times 10^{24}$ y	<(1.1-1.5)	21
^{130}Te	TeO$_2$ bolometers	$> 2.8 \times 10^{24}$ y	<(0.3-0.7)	22
^{136}Xe	Xe disolved in liq. scint.	$> 5.7 \times 10^{24}$ y	<(0.3-0.6)	23
^{150}Ne	Thin metal foil within TPC	$> 1.8 \times 10^{22}$ y	N.A.	24

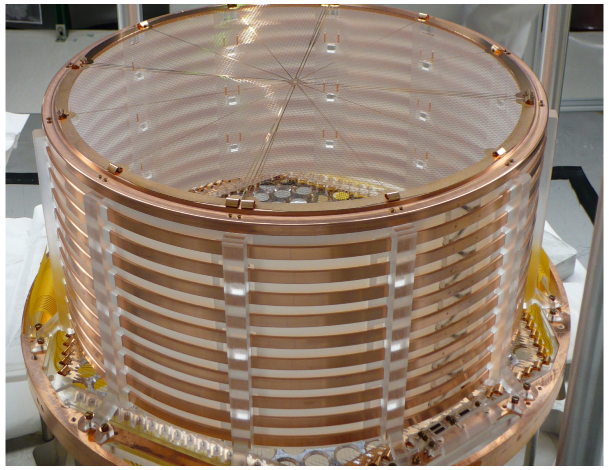
S. Elliott, http://arxiv.org/pdf/1203.1070v1.pdf

Current, near-future, future experiments

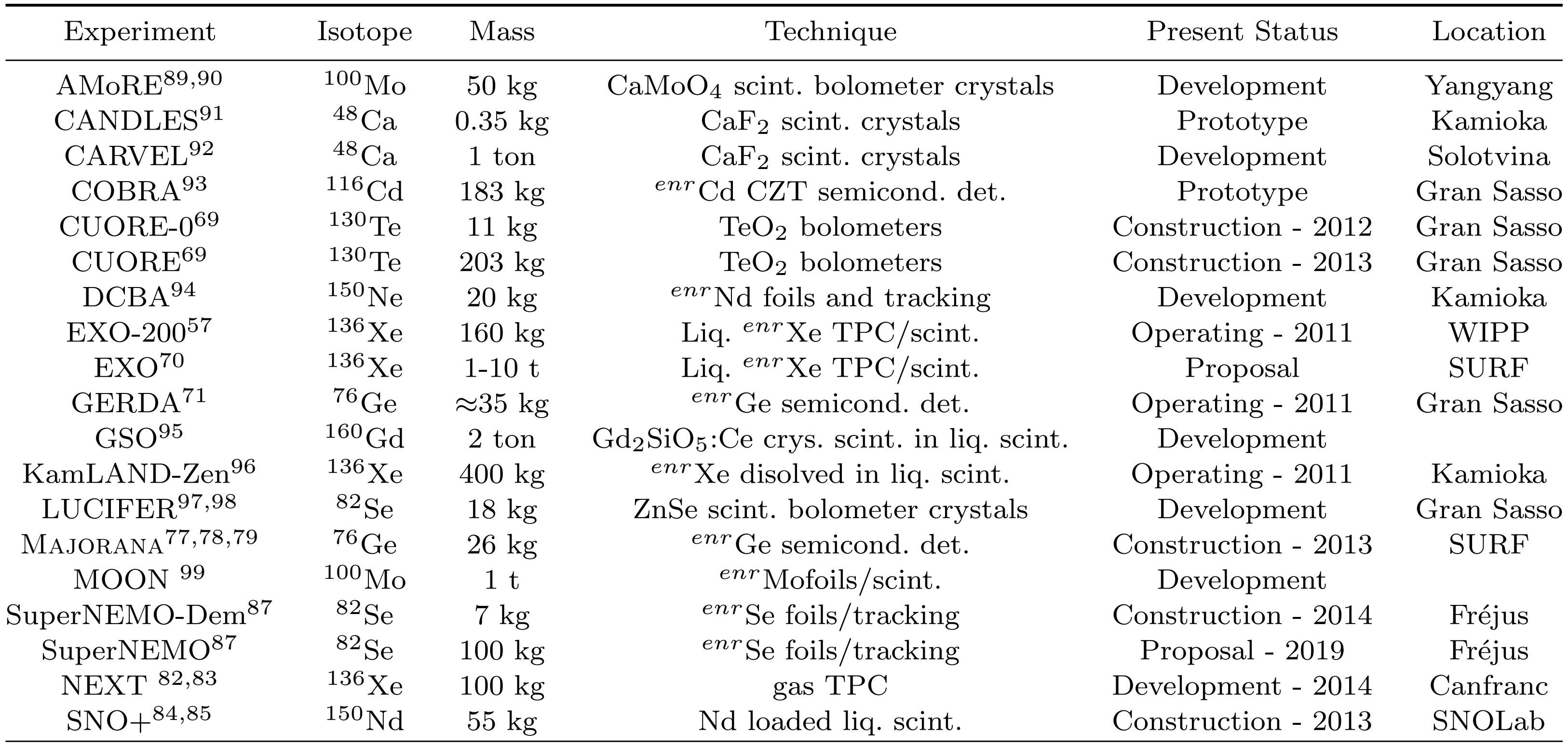






Current, near-future, future experiments

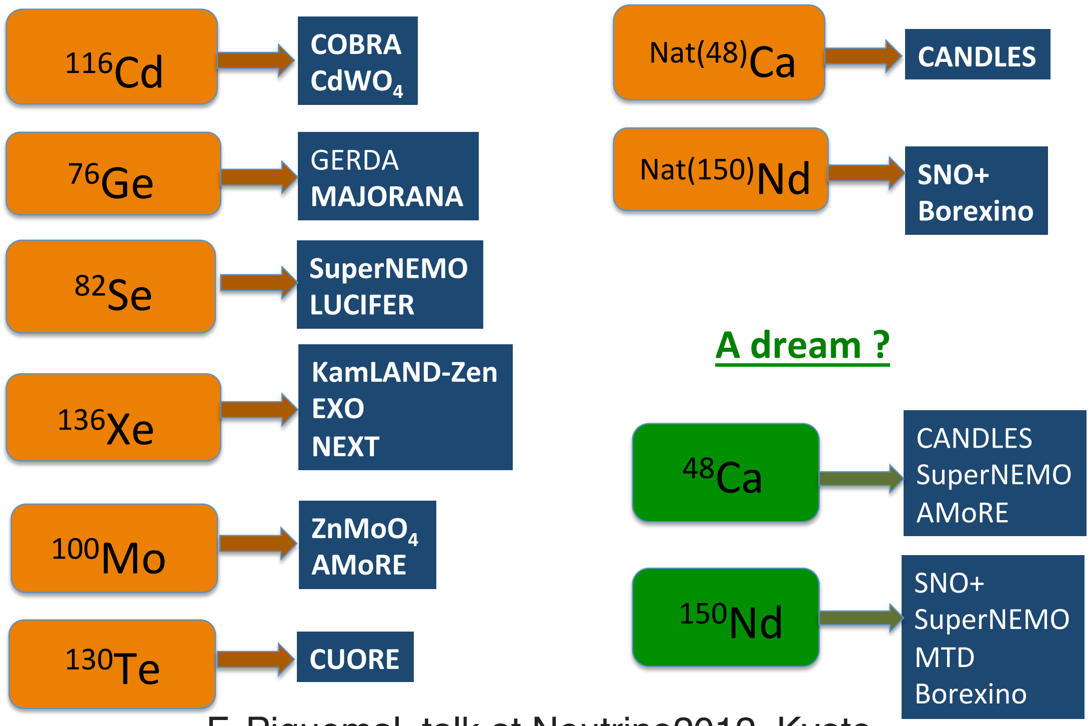
Existing and proposed experiments

Table 2. A summary list of the $0\nu\beta\beta$ proposals and experiments.



Experiment	Isotope	Mass	Technique	Present Status	Location
AMoRE[89,90]	^{100}Mo	50 kg	CaMoO$_4$ scint. bolometer crystals	Development	Yangyang
CANDLES[91]	^{48}Ca	0.35 kg	CaF$_2$ scint. crystals	Prototype	Kamioka
CARVEL[92]	^{48}Ca	1 ton	CaF$_2$ scint. crystals	Development	Solotvina
COBRA[93]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[69]	^{130}Te	11 kg	TeO$_2$ bolometers	Construction - 2012	Gran Sasso
CUORE[69]	^{130}Te	203 kg	TeO$_2$ bolometers	Construction - 2013	Gran Sasso
DCBA[94]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development	Kamioka
EXO-200[57]	^{136}Xe	160 kg	Liq. ^{enr}Xe TPC/scint.	Operating - 2011	WIPP
EXO[70]	^{136}Xe	1-10 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SURF
GERDA[71]	^{76}Ge	$\approx$35 kg	^{enr}Ge semicond. det.	Operating - 2011	Gran Sasso
GSO[95]	^{160}Gd	2 ton	Gd$_2$SiO$_5$:Ce crys. scint. in liq. scint.	Development	
KamLAND-Zen[96]	^{136}Xe	400 kg	^{enr}Xe disolved in liq. scint.	Operating - 2011	Kamioka
LUCIFER[97,98]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Development	Gran Sasso
MAJORANA[77,78,79]	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Construction - 2013	SURF
MOON [99]	^{100}Mo	1 t	^{enr}Mofoils/scint.	Development	
SuperNEMO-Dem[87]	^{82}Se	7 kg	^{enr}Se foils/tracking	Construction - 2014	Fréjus
SuperNEMO[87]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal - 2019	Fréjus
NEXT [82,83]	^{136}Xe	100 kg	gas TPC	Development - 2014	Canfranc
SNO+[84,85]	^{150}Nd	55 kg	Nd loaded liq. scint.	Construction - 2013	SNOLab

Steve Elliott: http://arxiv.org/pdf/1203.1070v1.pdf



^{116}Cd → COBRA CdWO$_4$

^{76}Ge → GERDA MAJORANA

^{82}Se → SuperNEMO LUCIFER

^{136}Xe → KamLAND-Zen EXO NEXT

^{100}Mo → ZnMoO$_4$ AMoRE

^{130}Te → CUORE

Nat(48)Ca → CANDLES

Nat(150)Nd → SNO+ Borexino

A dream ?

^{48}Ca → CANDLES SuperNEMO AMoRE

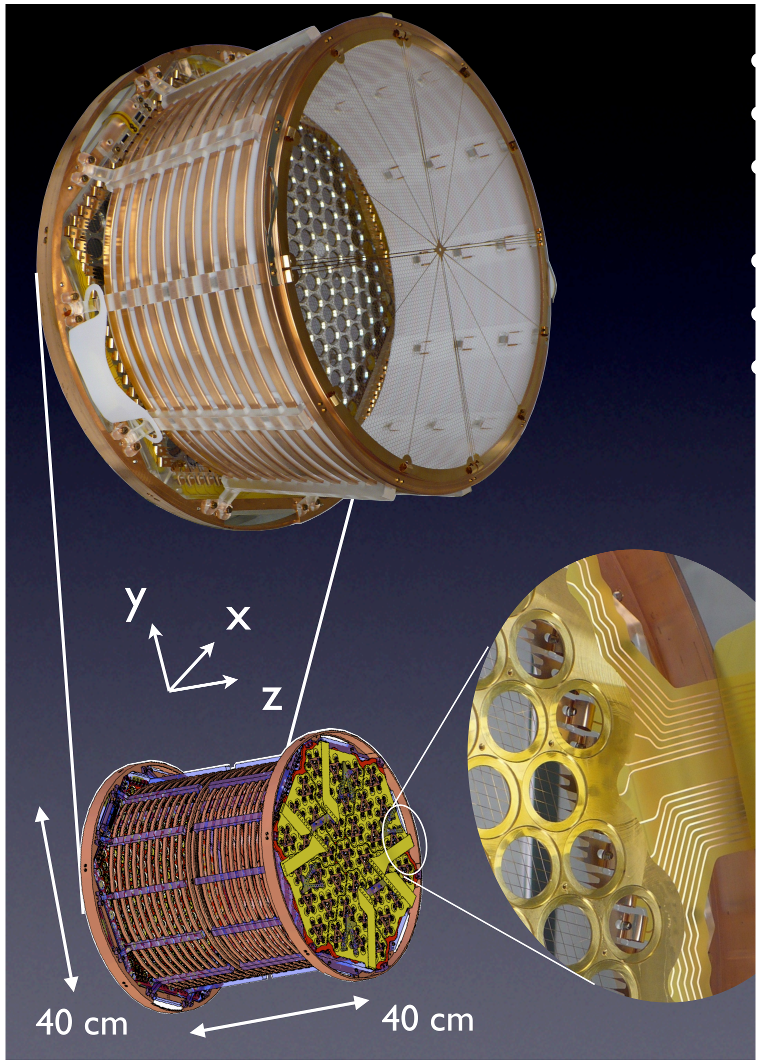
^{150}Nd → SNO+ SuperNEMO MTD Borexino

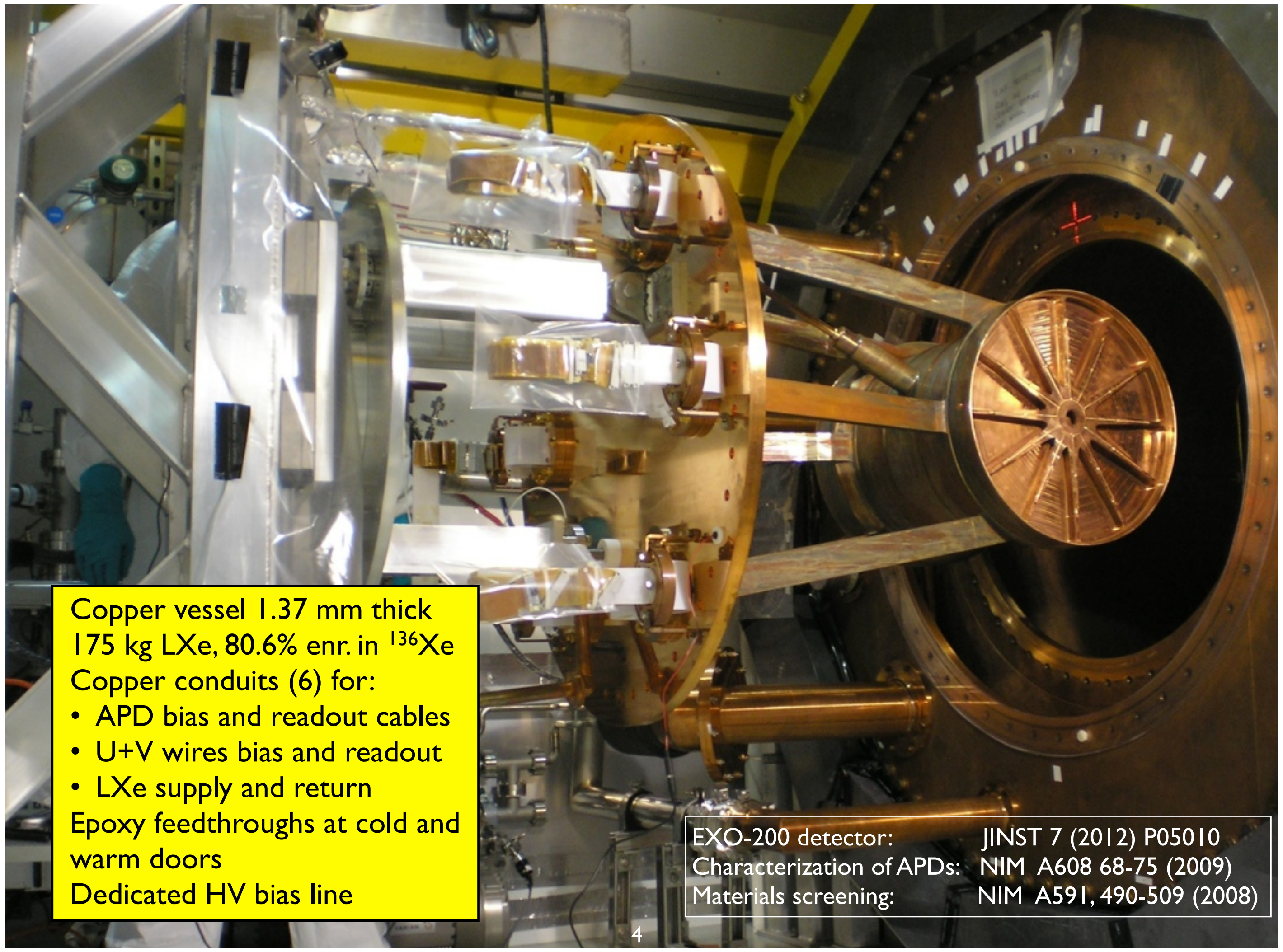
F. Piquemal, talk at Neutrino2012, Kyoto

Recent results

EXO-200

- Liquid xenon TPC: 175 kg LXe, 80.6% enriched in 136Xe
- Charge and light readout (triplet wire channels and large area avalanche photodiodes)
- Drift field: 376 V/cm





Copper vessel 1.37 mm thick
175 kg LXe, 80.6% enr. in ^{136}Xe
Copper conduits (6) for:
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return

Epoxy feedthroughs at cold and warm doors
Dedicated HV bias line

EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

EXO-200

- So far, 2 data taking phases
- First measurement of ^{136}Xe 2-neutrino half life; limit on the 0-neutrino mode

	Run 1	Run 2 (this analysis)
Period	May 21, 11 – Jul 9, 11	Sep 22, 11 – Apr 15,12
Live Time	752.7 hr	2,896.6 hr
Exposure (^{136}Xe)	4.4 kg-yr	26.3 kg-yr
Publ.	PRL 107 (2011) 212501	arXiv:1205:5608

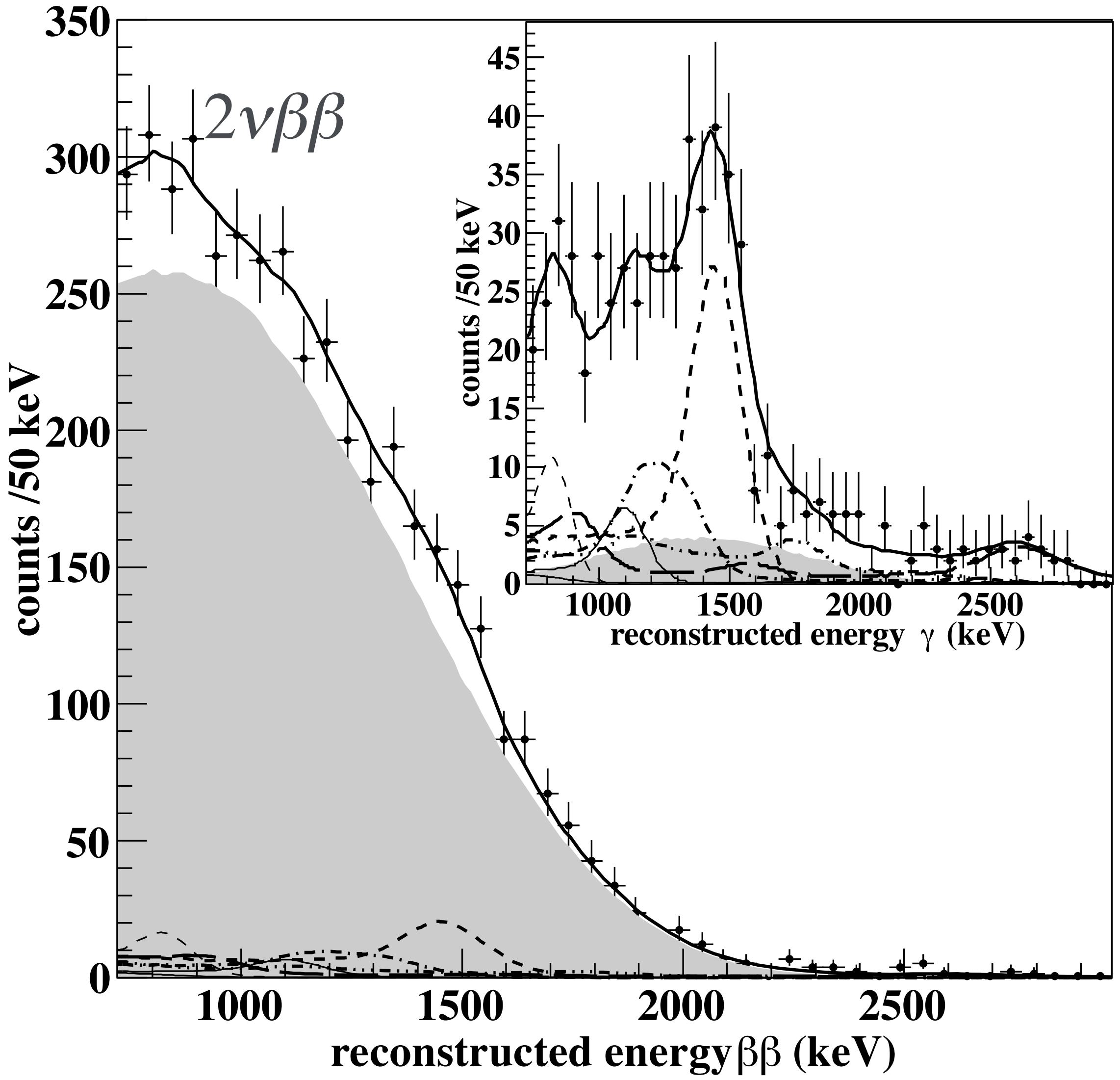
Run 1 Results:

$T_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (2.11 ± 0.04 stat ± 0.21 sys) · 10^{21} yr

In disagreement with previously reported limits by

R. Bernabei et al. Phys. Lett. B 546 (2002) 23, and
Yu. M. Gavriljuk et al. , Phys. Atom Nucl. 69 (2006)

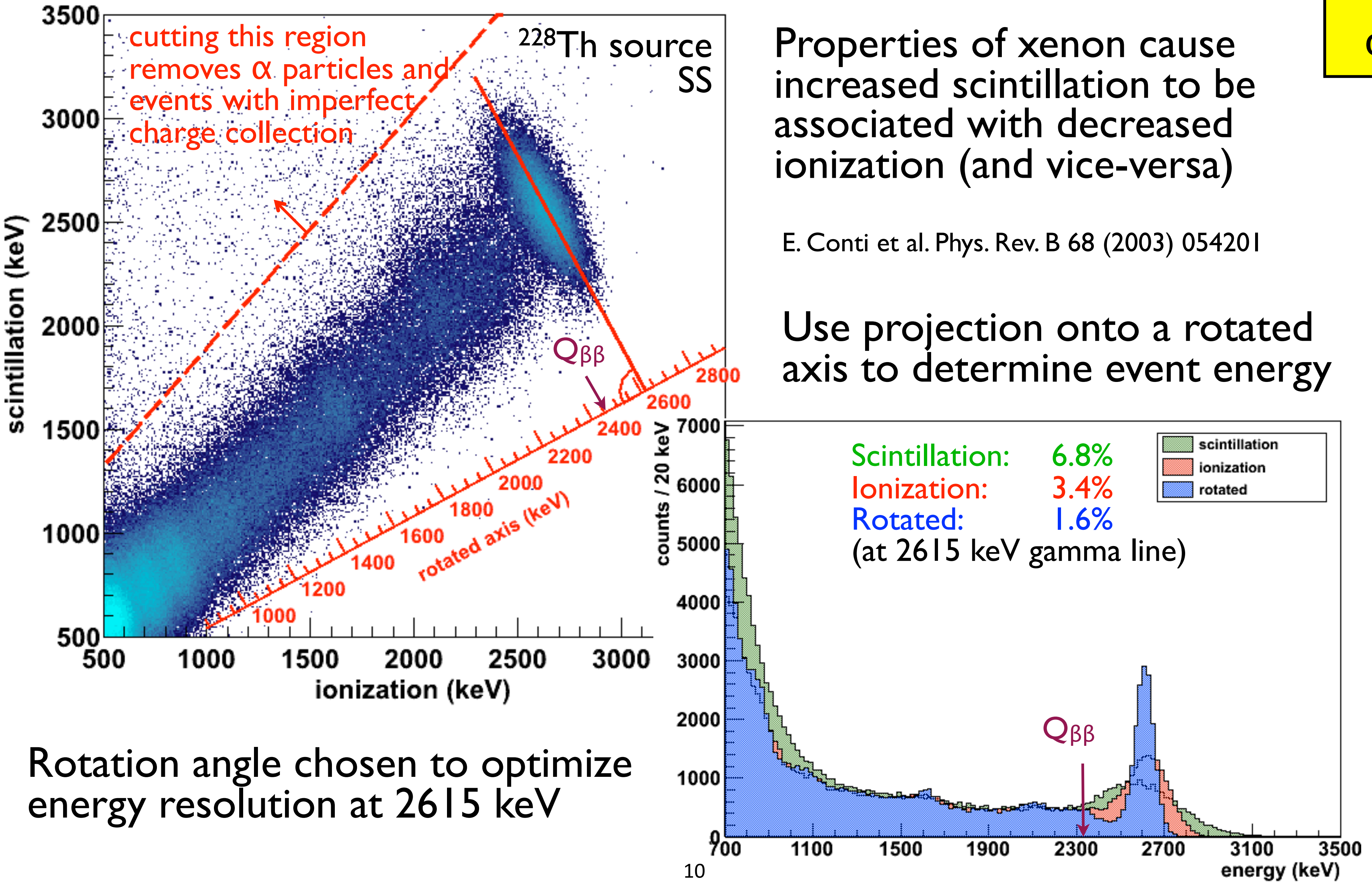
This was also a measurement of a nuclear matrix element of 0.019 MeV^{-1}, the smallest measured among the 2νββ emitters



EXO-200: resolution and calibration

- Good energy resolution by linear combination of scintillation and charge signals

At $Q_{\beta\beta}$ (2458 keV):
σ/E = 1.67 % (SS)
σ/E = 1.84 % (MS)



cutting this region removes α particles and events with imperfect charge collection

^{228}Th source SS

Scintillation: 6.8%
Ionization: 3.4%
Rotated: 1.6%
(at 2615 keV gamma line)

Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa)

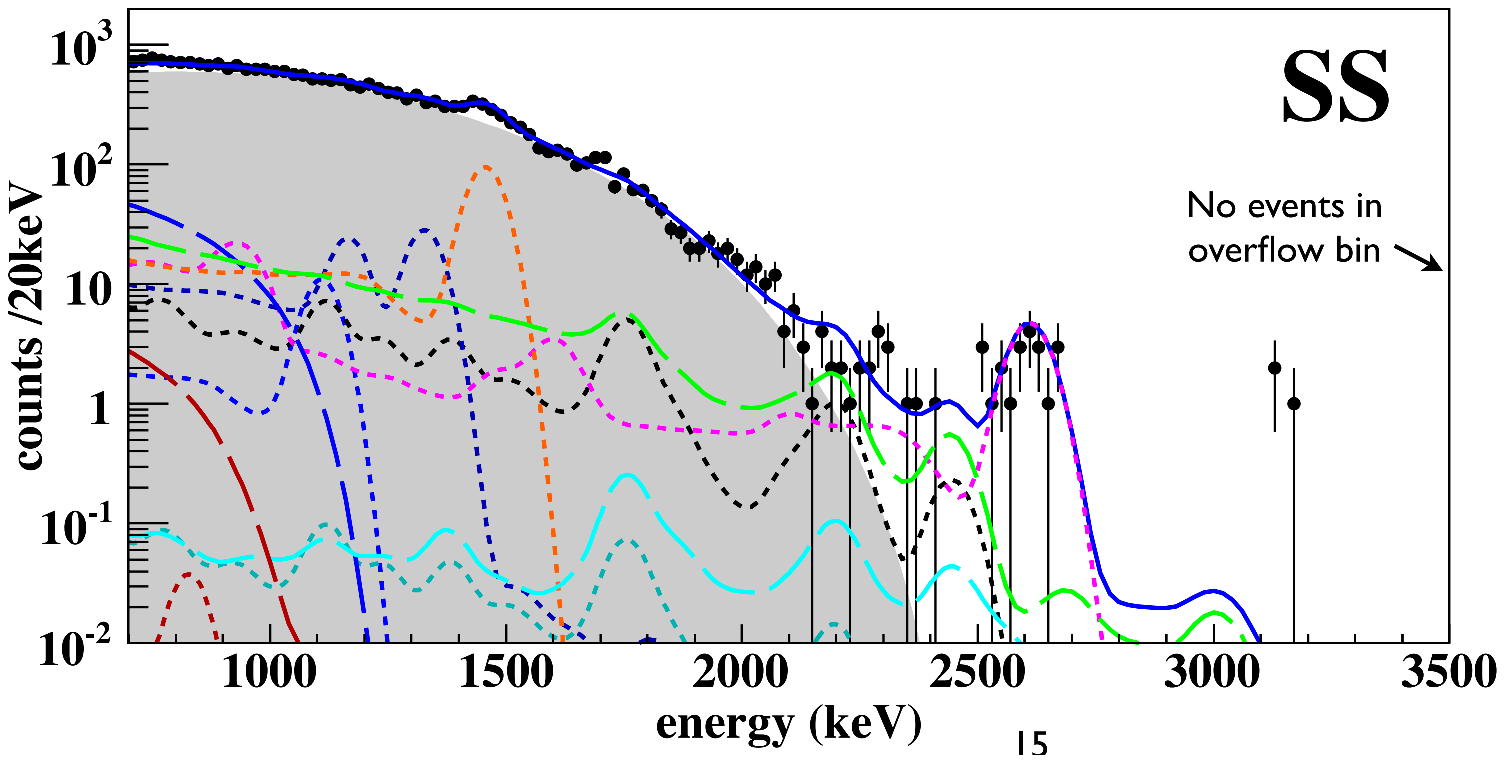
E. Conti et al. Phys. Rev. B 68 (2003) 054201

Use projection onto a rotated axis to determine event energy

Rotation angle chosen to optimize energy resolution at 2615 keV

EXO-200: low-background spectrum

- Observed 22‘000 2-neutrino events in 32.5 kg yr exposure
- Background PDFs fitted along with 2-neutrino and 0-neutrino PDFs



$T_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (2.23 ± 0.017 stat ± 0.22 sys) · 10^{21} yr

In agreement with previously reported value by

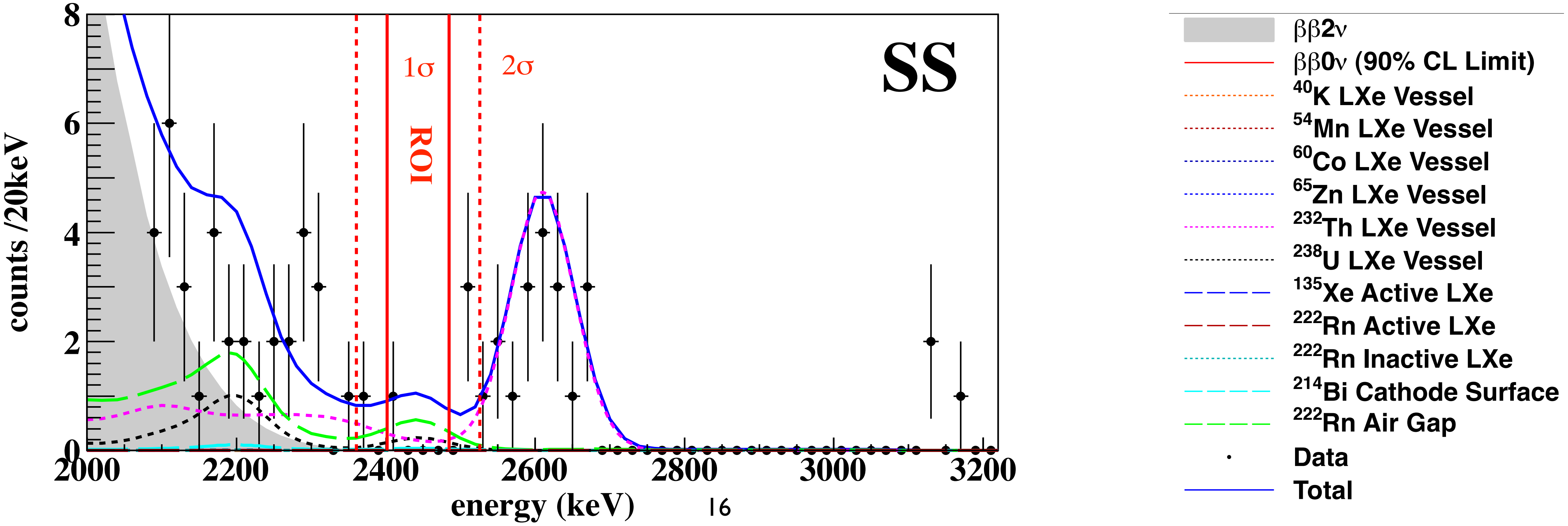
EXO-200 Phys.Rev.Lett. 107 (2011) 212501

and

KamLAND-ZEN Phys.Rev.C85:045504,2012)

EXO-200: low-background spectrum

- No 0-neutrino signal observed => lower limit on $T_{1/2}$



	Expected events from fit			
	±1 σ		±2 σ	
^{222}Rn in cryostat air-gap	1.9	±0.2	2.9	±0.3
^{238}U in LXe Vessel	0.9	±0.2	1.3	±0.3
^{232}Th in LXe Vessel	0.9	±0.1	2.9	±0.3
^{214}Bi on Cathode	0.2	±0.01	0.3	±0.02
All Others	~0.2		~0.2	
Total	4.1	±0.3	7.5	±0.5
Observed	1		5	
Background index b ($kg^{-1}yr^{-1}keV^{-1}$)	$1.5 \cdot 10^{-3}$ ± 0.1		$1.4 \cdot 10^{-3}$ ± 0.1	

From profile likelihood:

$$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}\ \text{yr}$$

$$\langle m_{\beta\beta} \rangle < 140\text{–}380\ \text{meV}$$

(90% C.L.)

arXiv:1205.5608 – Subm. to PRL

KAMLAND-Zen

Enlightenment is
found in nothing.
↓
Truth is found in
$0\nu2\beta$.

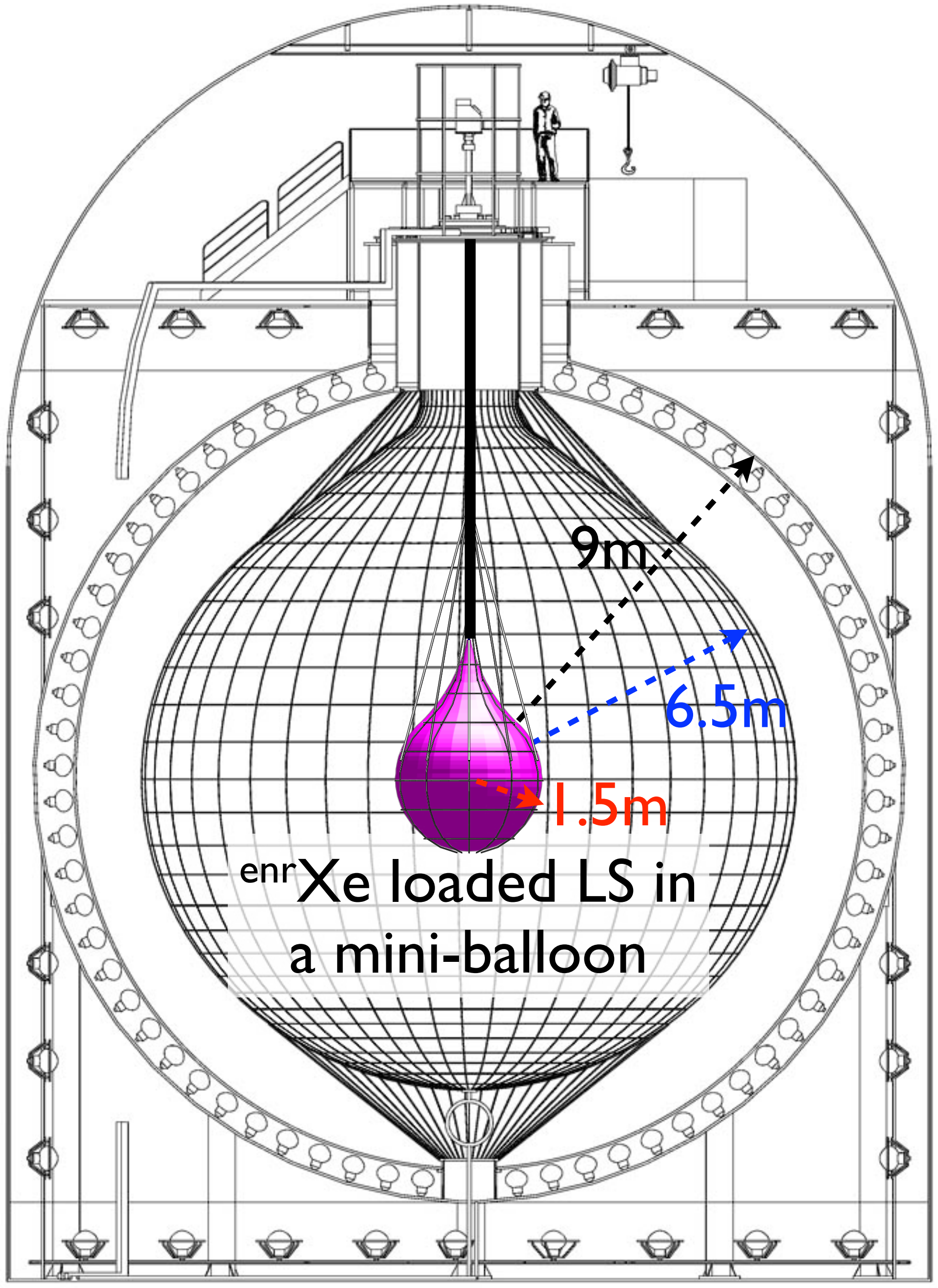
Results from KamLAND-Zen

Kunio Inoue
RCNS, Tohoku University
(KamLAND-Zen collaboration)

Neutrino2012, 6 June 2012, Kyoto

- Scintillator loaded with xenon
- 320 kg 90% enriched ^{136}Xe so far (more than 600 kg in the Kamioka mine)
- Advantages: huge and clean (U: 3.5e-18 g/g, Th: 5.2e-17 g/g) running detector
- Xe-LS can be purified, and is highly scalable
- No escape or invisible energy from gammas and beta: good background identification
- Disadvantage: relatively poor energy resolution
- no beta/gamma discrimination
- limited LS composition

Zero Neutrino
double beta decay search



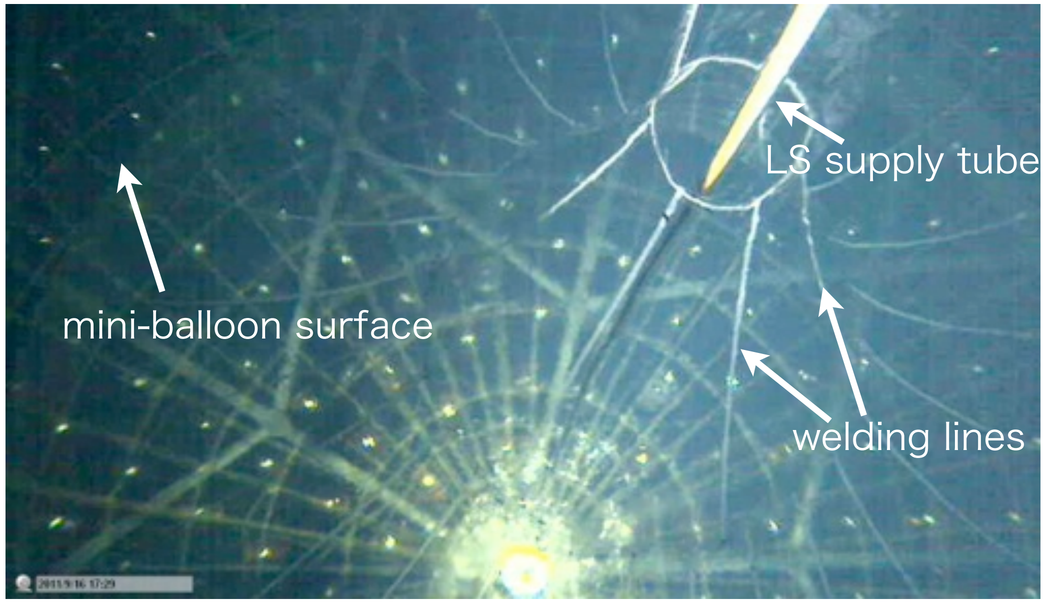
KamLAND-Zen: installation


Installation in a class 10~100 clean room built at the top of KamLAND

balloon and corrugated tube deployment

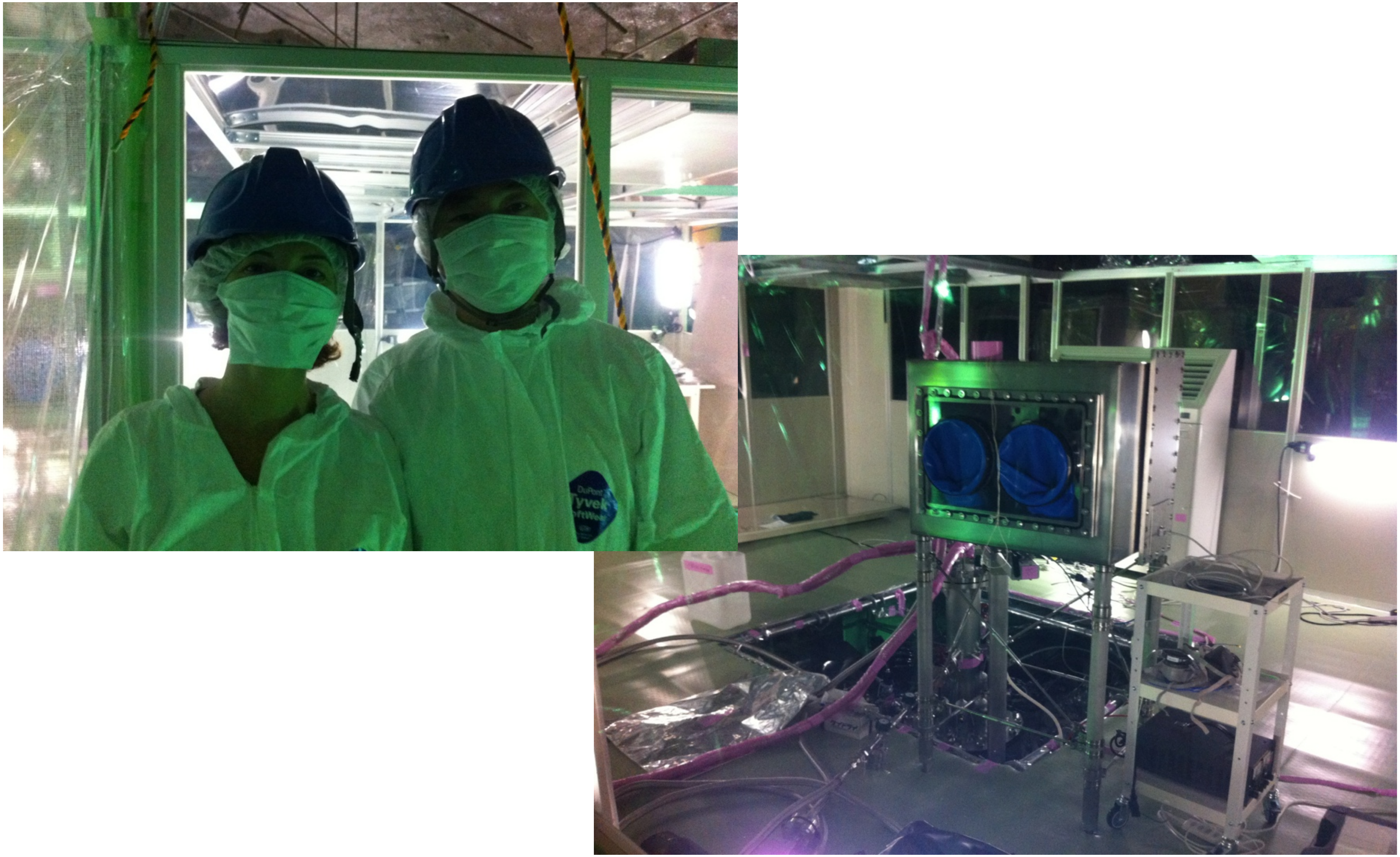

balloon went through the black sheet


installation completed



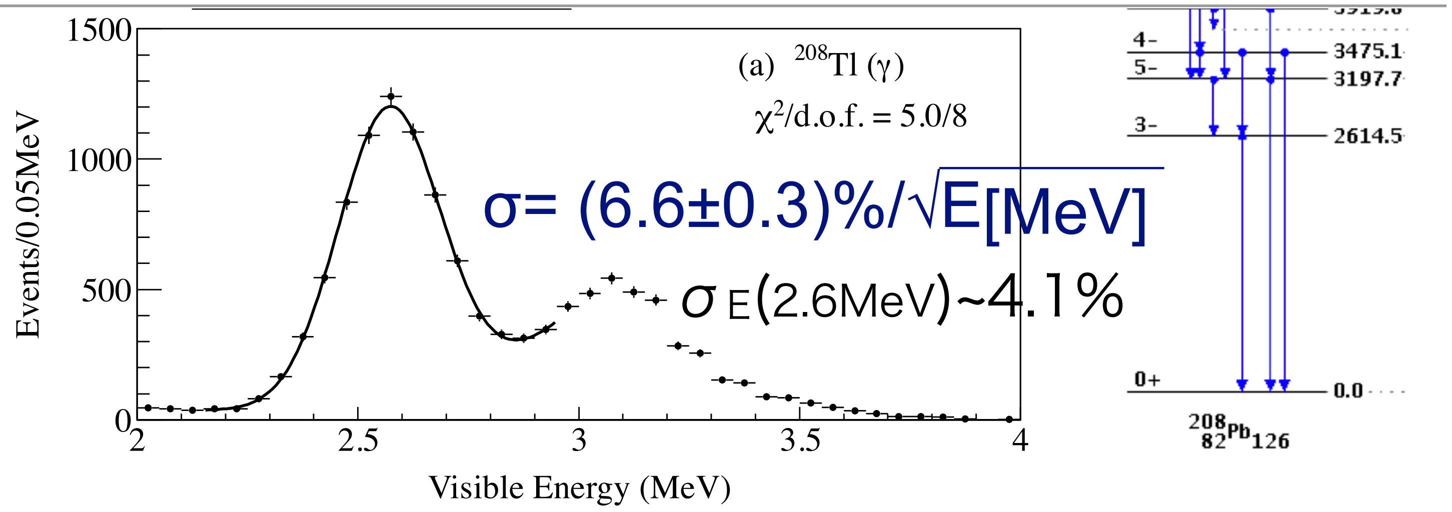
mini-balloon inflated with dummy LS and then replaced with Xe-loaded LS
density tuning finished and tubes to be extracted

KamLAND-Zen



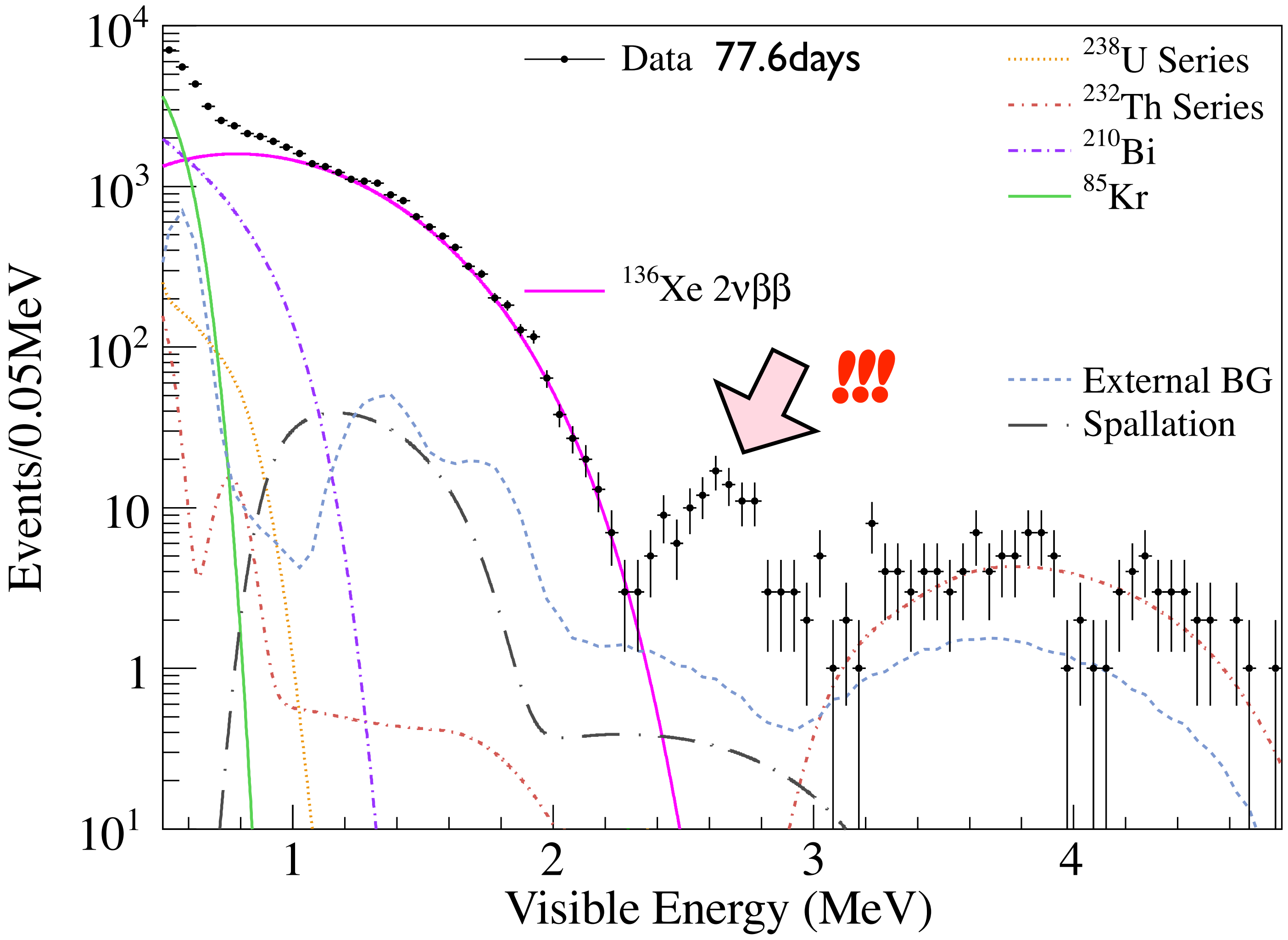
KamLAND-Zen: energy calibration and low-background spectrum

- Resolution at 2.6 MeV: sigma ~ 4.1%



$\sigma = (6.6\pm0.3)\%/\sqrt{E[\mathrm{MeV}]}$

σ_E(2.6MeV)~4.1%



KamLAND-Zen (2012) Xe loaded liquid scintillator

$T^{2\nu}_{1/2}$=2.38±0.02(stat)±0.14(syst) ×10^{21} years

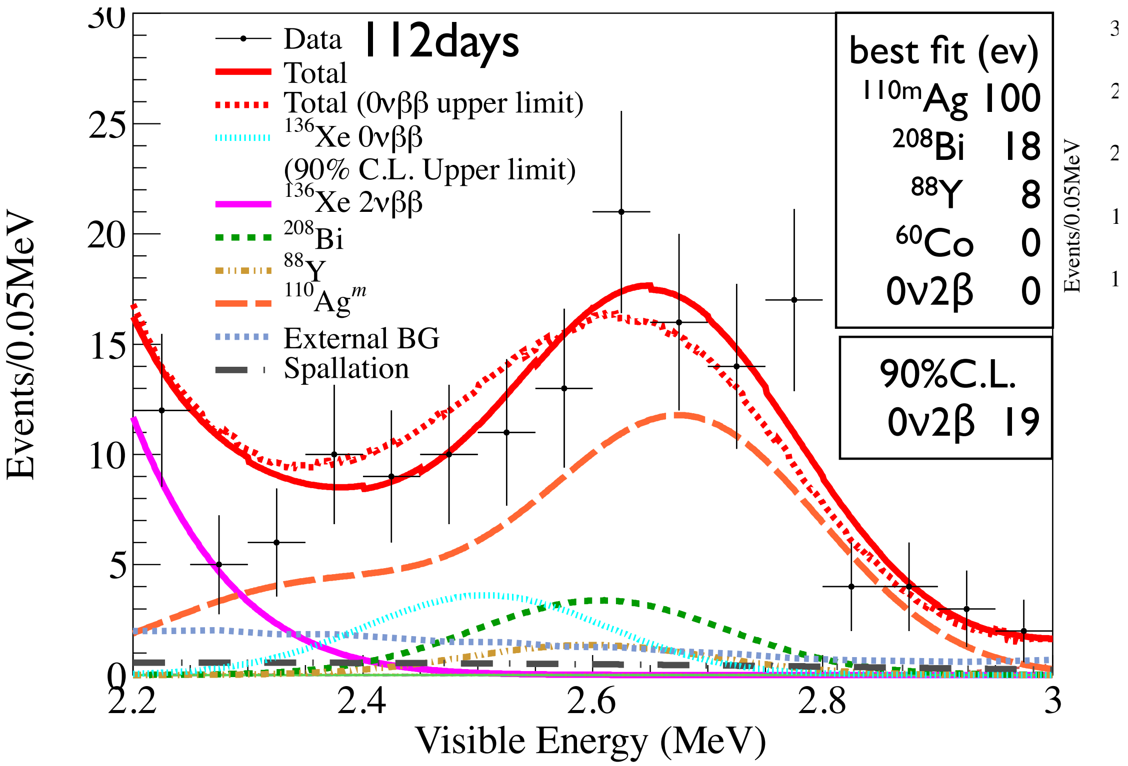
Phys.Rev.C85,045504(2012)

update $T^{2\nu}_{1/2}$=2.30±0.02(stat)±0.12(syst) ×10^{21} years

arXiv:1205.6372

KamLAND-Zen: low-background spectrum

- Peak around the Q-value; however, peak position is different



simultaneous fit and 90% CL upper limit for 0ν2β

(χ^2 at 2.2~3.0MeV)

	χ^2 112days	
simul. fit	11.6	
$0\nu+{}^{110m}$Ag	13.1	
$0\nu+{}^{208}$Bi	22.7	△
$0\nu+{}^{88}$Y	22.2	△
$0\nu+{}^{60}$Co	82.9	✕
0ν only	85.0	✕

BG is likely to be ^{110m}Ag

$T^{0\nu}_{1/2} > 5.7\times10^{24}$ years at 90% C.L. (78days)

factor 5 improvement from DAMA

$T^{0\nu}_{1/2} > 6.2\times10^{24}$ years (KL-Zen 112days)

(ref. current best is 16×10^{24} years from EXO-200)

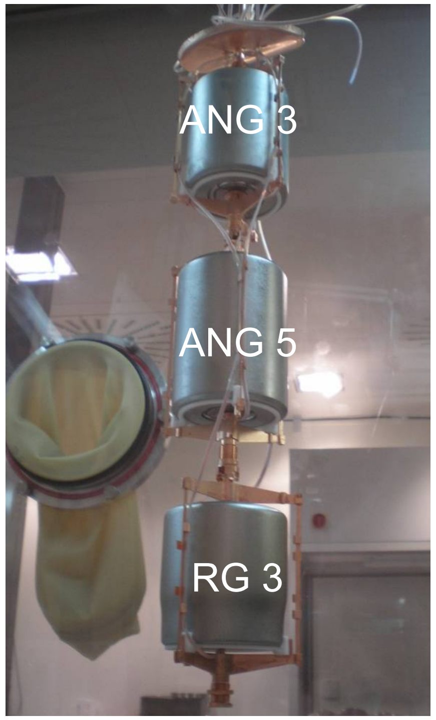
↓

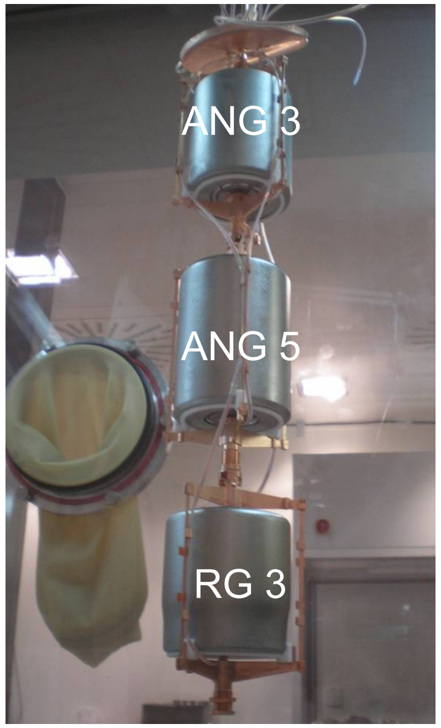
(R)QRPA (CCM SRC)
Phys.Rev.C79,055501(2009)

$\langle m_{\beta\beta}\rangle$ <0.26~0.54 eV @90% C.L.

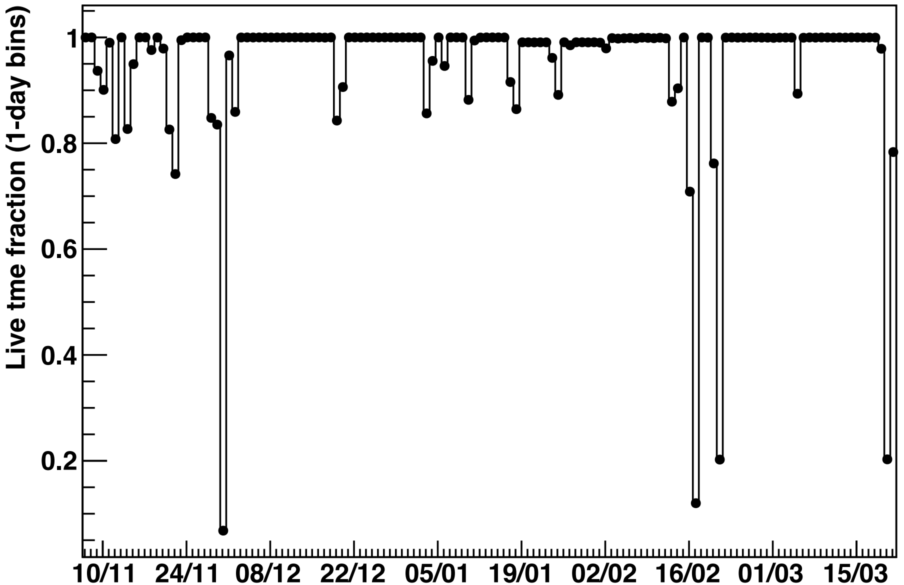
GERDA

- HPGe detectors in liquid argon (U/Th in LAr < 7×10^{-4} µBq/kg)



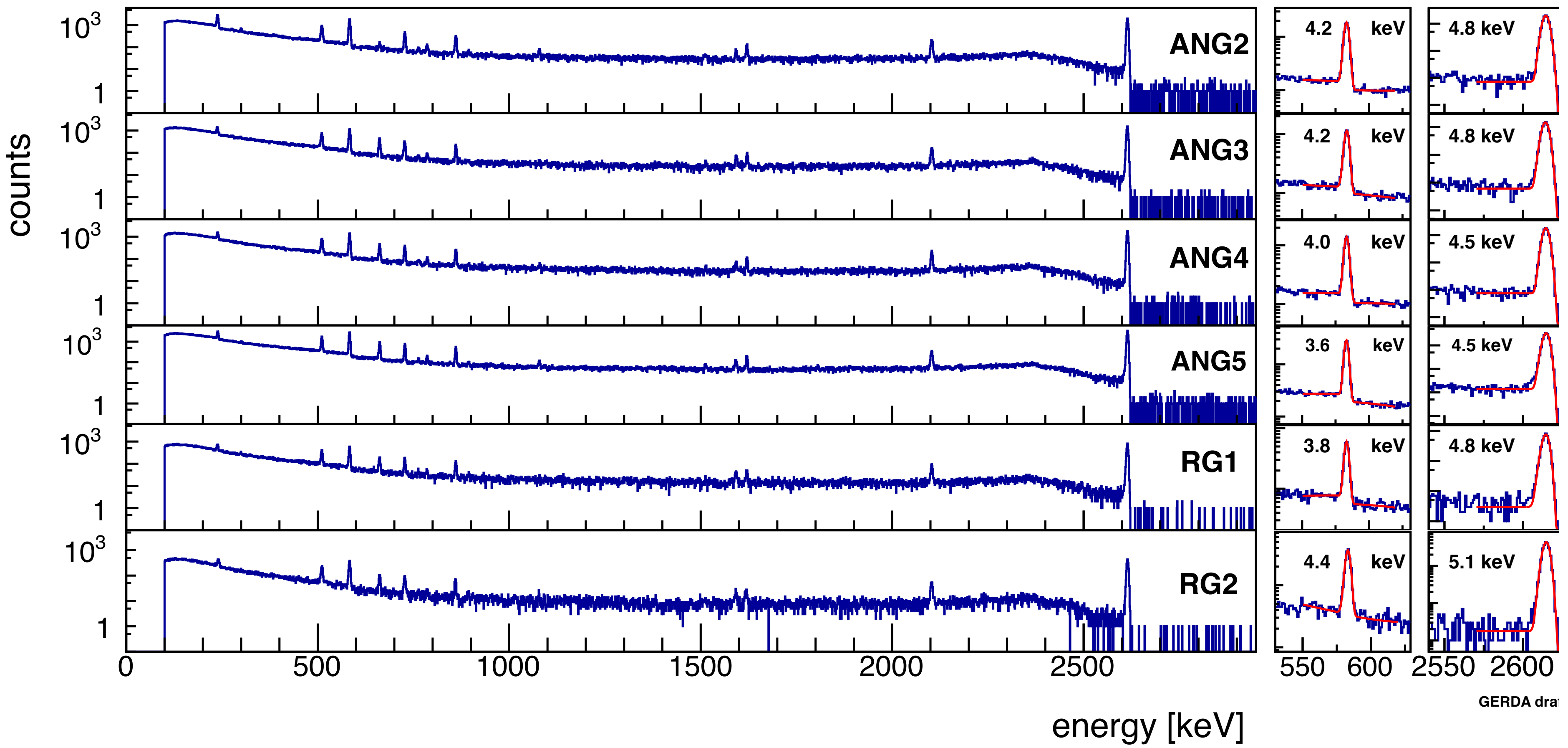


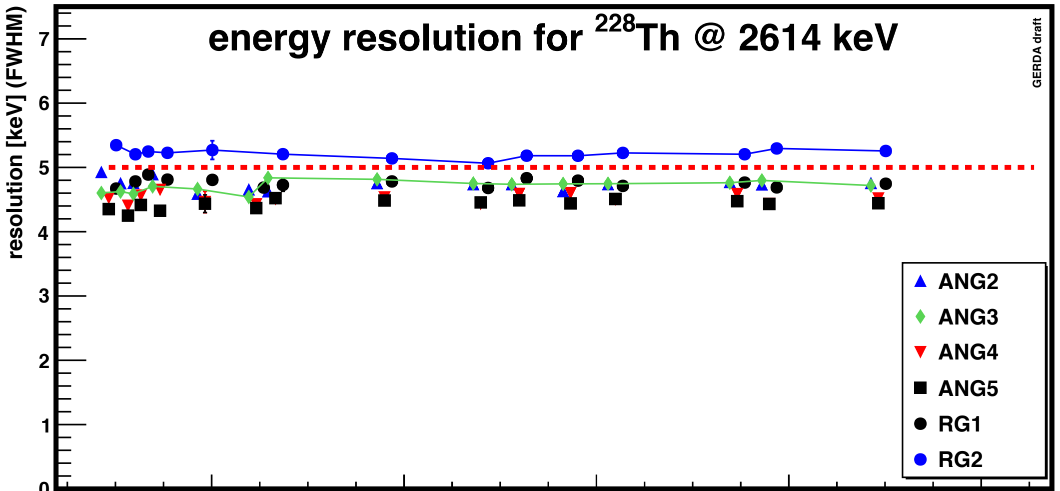
- Physics run started on November 9, 2011



GERDA Calibration

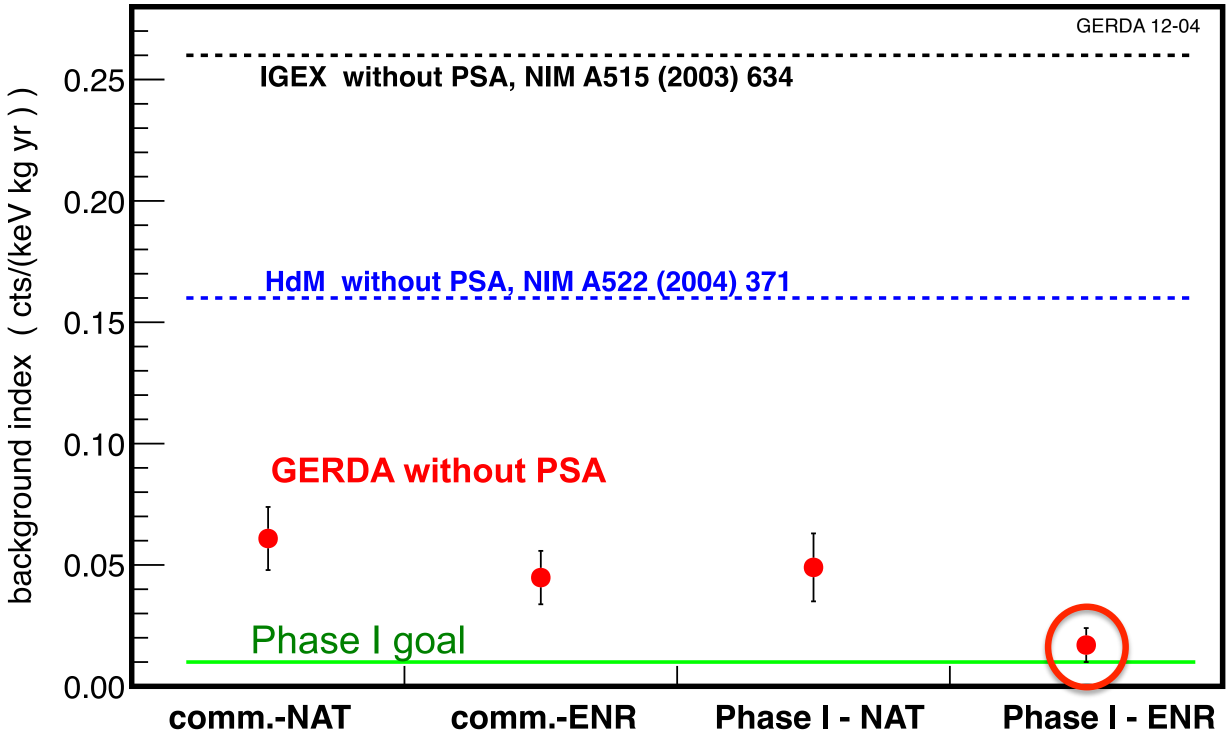
- Energy resolution: ~ 4.5 - 5 keV (FWHM) at 2.6 MeV

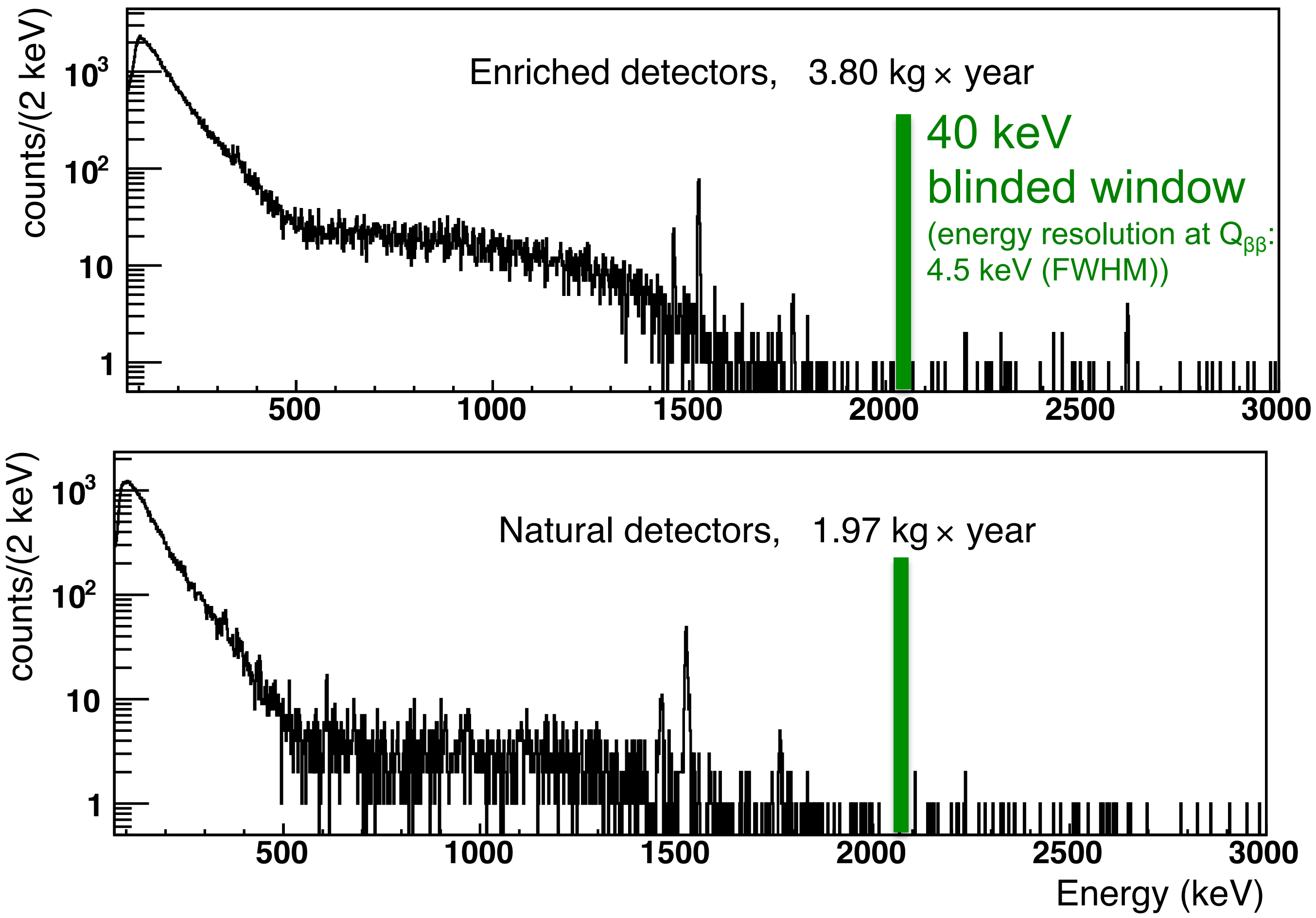




GERDA low-background spectrum

- Background goal of ~ 10^{-2} events/(kg yr keV) was reached
- Phase II (BEGe) detectors in production and testing
- LAr instrumentation (PMTs or SiPM & scintillating fibers) in development
- End of phase I and start of phase II: spring 2013

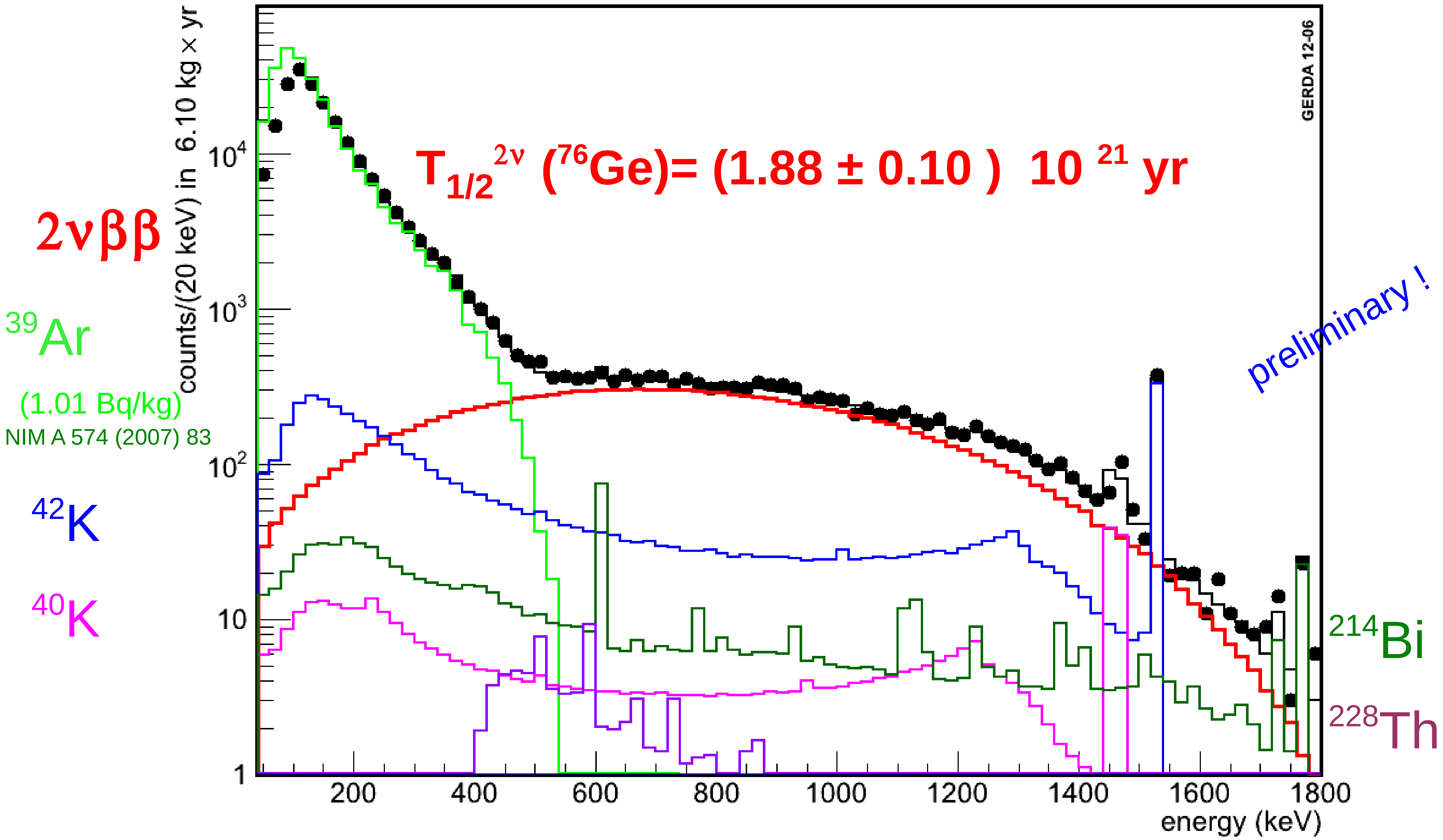




GERDA low-background spectrum

- Analysis of 2-neutrino decay mode is in progress

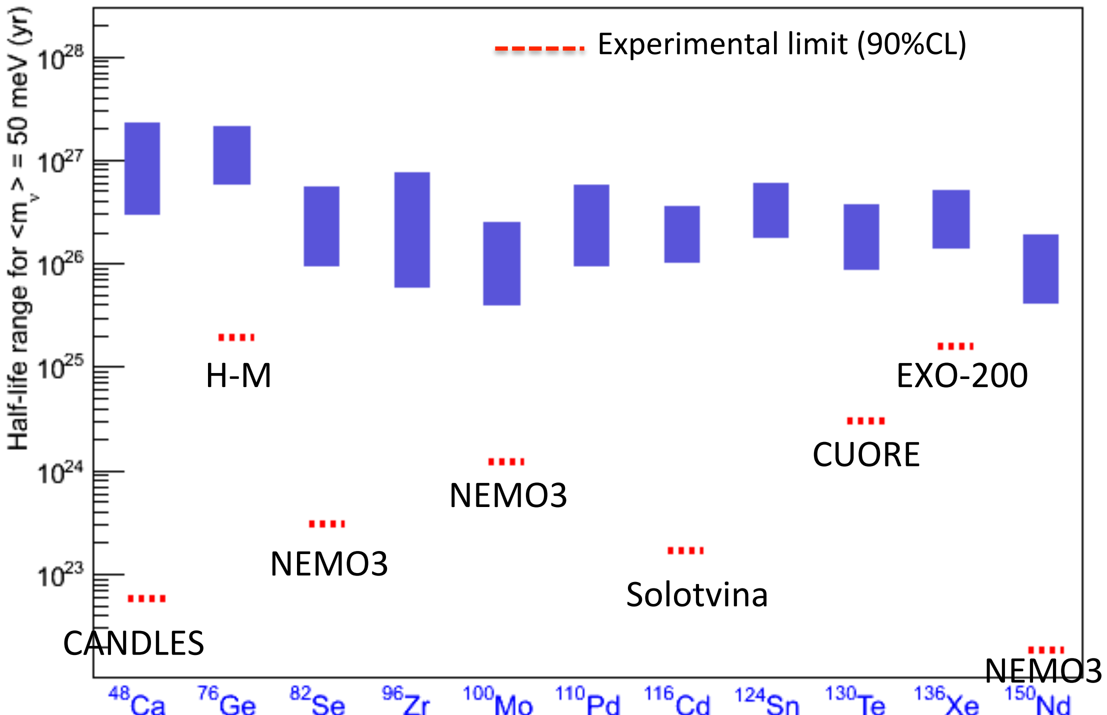
exposure : 6.1 kg yr



$T_{1/2}^{2\nu}$ (^{76}Ge)= (1.88 ± 0.10) 10^{21} yr

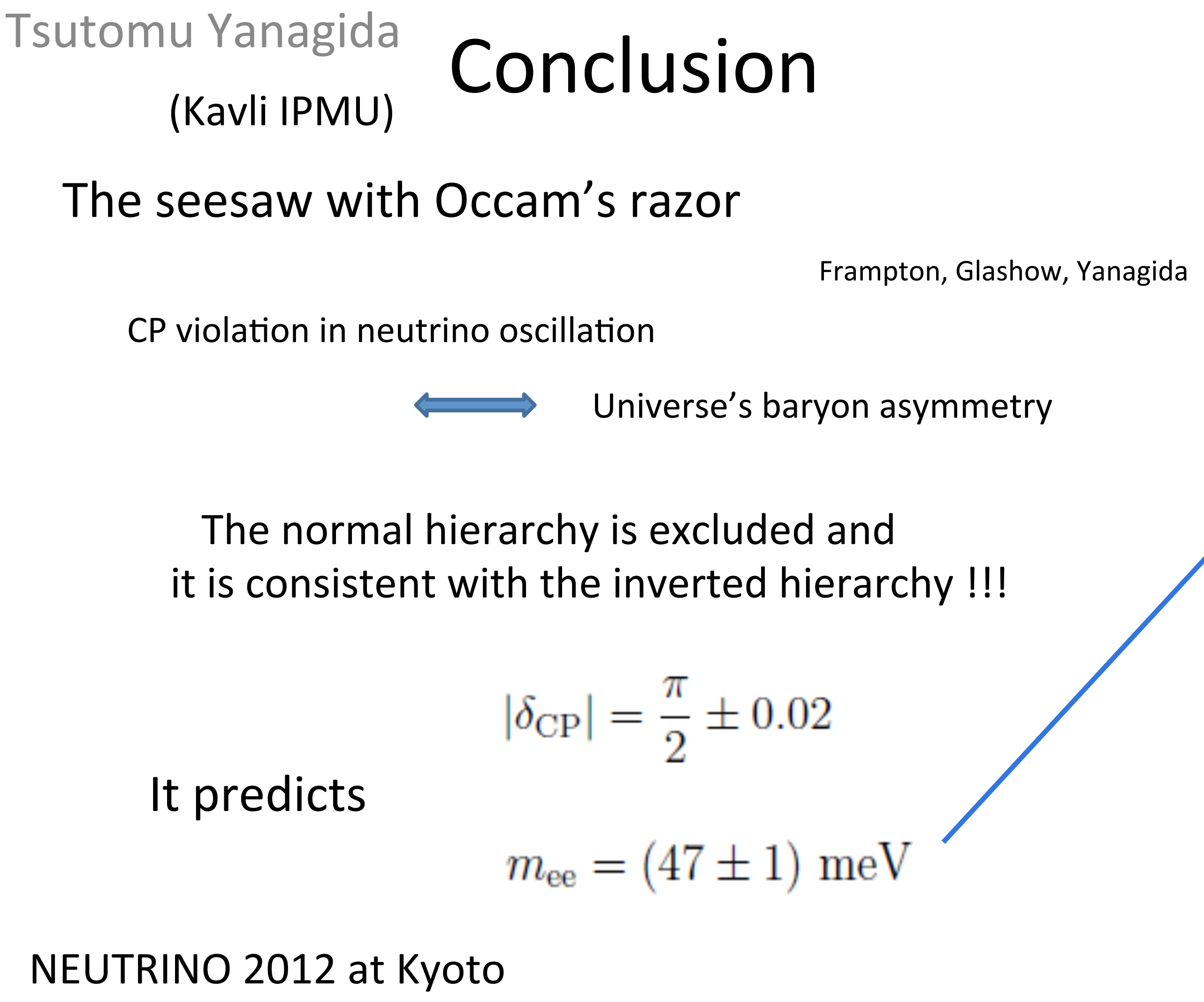
Summary

- Two-neutrino decay mode was measured for the first time in ^{136}Xe
- Xenon experiments provide competitive limits to germanium for the neutrinoless mode
- Several experiments are taking data, new results are expected soon
- Experiments under construction (or phase II of existing experiments) should achieve a sensitivity of 50 - 100 meV
- To go beyond, much lower backgrounds and larger masses are needed
- Tracking will be important to confirm a potential signal



Let us hope that...

- this prediction is true - it could be probed with future double beta experiments!



Tsutomu Yanagida

(Kavli IPMU)

Conclusion

The seesaw with Occam's razor

Frampton, Glashow, Yanagida

CP violation in neutrino oscillation

⟺ Universe's baryon asymmetry

The normal hierarchy is excluded and
it is consistent with the inverted hierarchy !!!

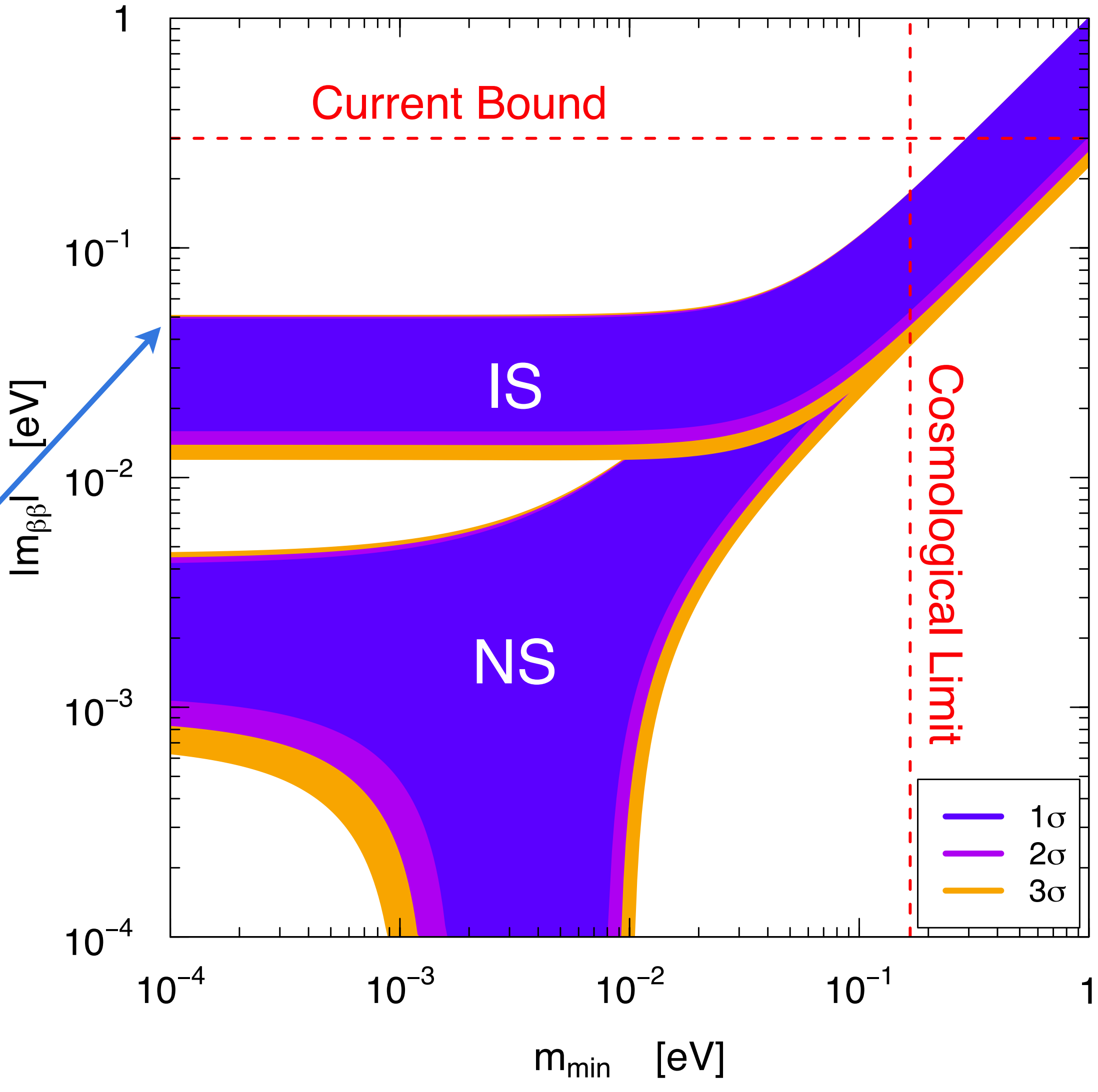
It predicts

$$|\delta_{CP}| = \frac{\pi}{2} \pm 0.02$$

$$m_{ee} = (47 \pm 1)\ \text{meV}$$

NEUTRINO 2012 at Kyoto

Bilenky, Giunti: http://xxx.lanl.gov/abs/1203.5250



End

Double beta decay

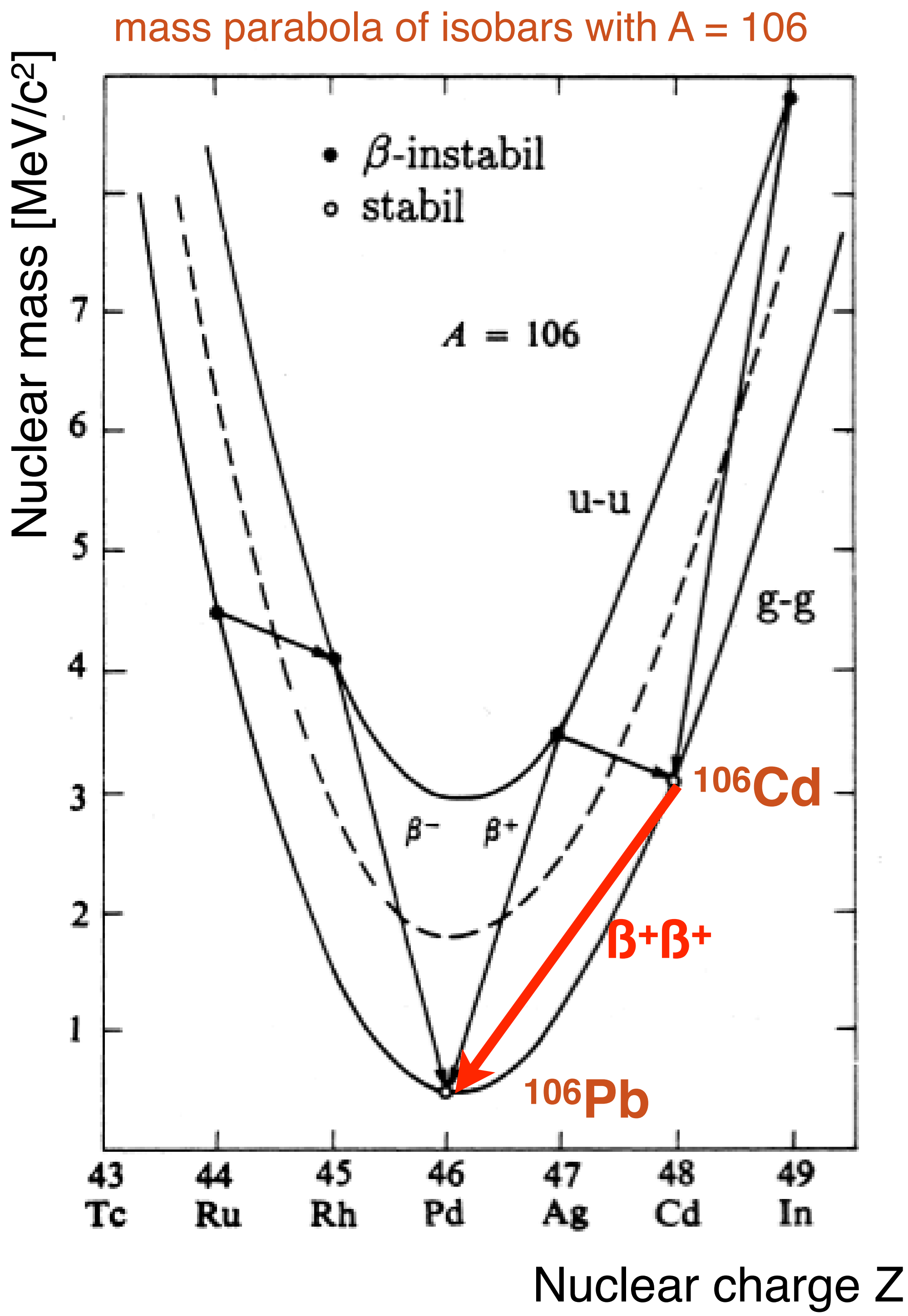
- If simple β^- or β^+-decay is forbidden on energetic grounds a nucleus can decay through a double beta mode:

$$ {}^{106}_{48}Cd \rightarrow {}^{106}_{46}Pd + 2e^{+} + 2\nu_e $$

- The probability for a decay is very small, the mean lifetime of a nucleus is much larger than the age of the universe ($\tau_U \sim 1.4\times10^{10}$ a)

$$ \tau_{2\nu} \approx 10^{20}\, a $$

- This is indeed a very rare process (as for instance proton decay, which was not yet observed)
- Nonetheless - if one uses a large amount of nuclei, the process can be observed experimentally


mass parabola of isobars with A = 106