Status of Neutrinoless Double Beta Decay Searches

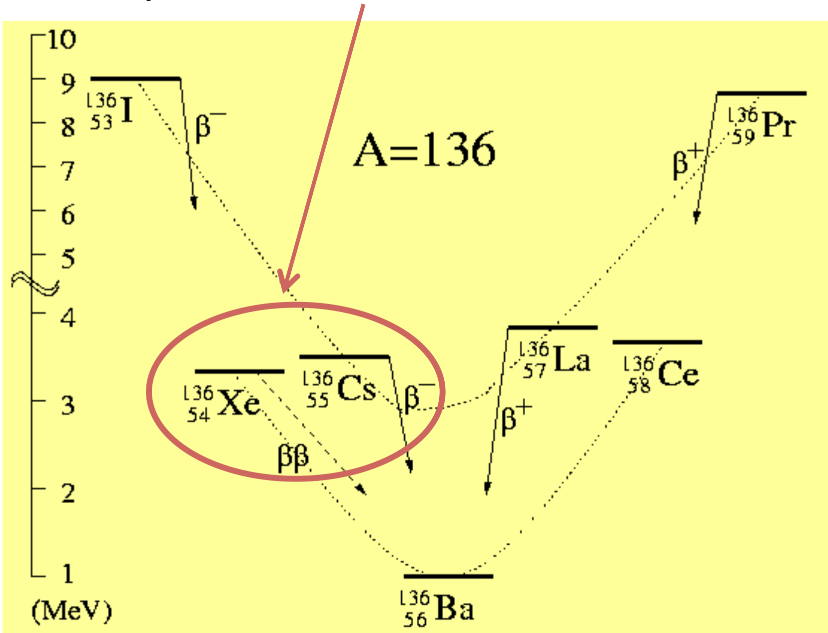
Liang Yang

University of Illinois at Urbana-Champaign

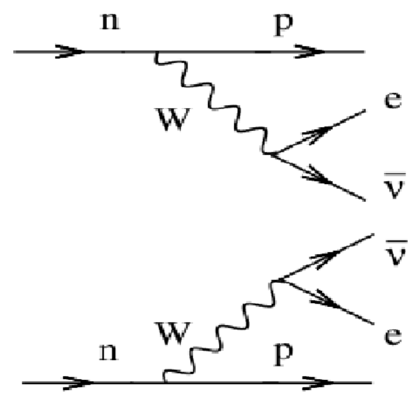
August. 22, 2013
NuFact 2013
Beijing, China

Double Beta Decay

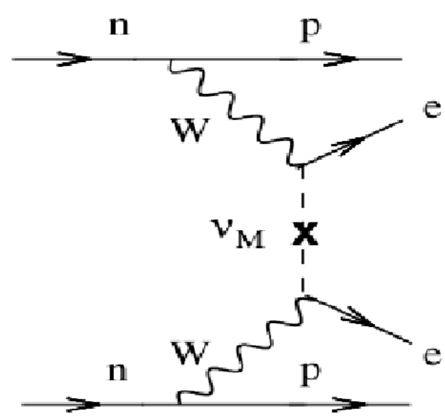
Observable if single beta decay is forbidden



Two neutrino double beta decay



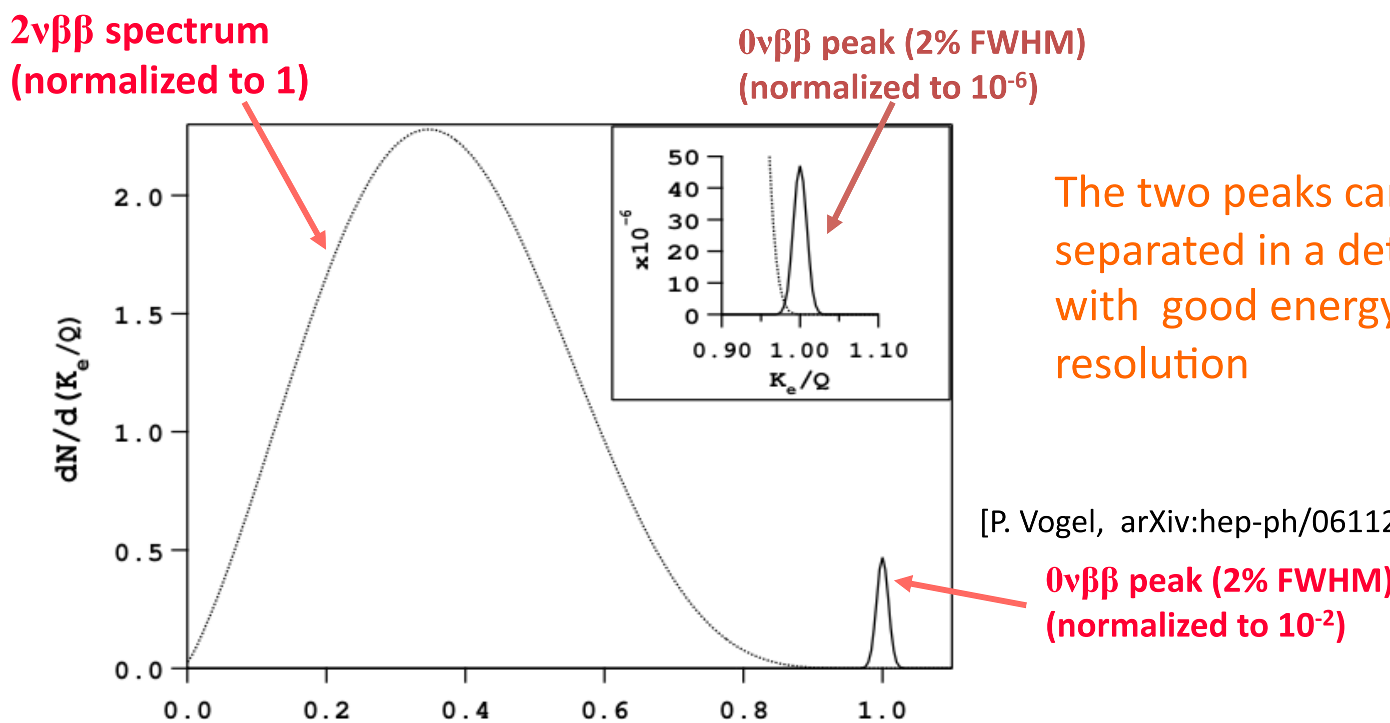
Neutrinoless double beta decay



Observation of $0\nu\beta\beta$:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

Double Beta Decay Energy Spectrum



Summed electron energy in units of the kinematic endpoint (Q)

The two peaks can be separated in a detector with good energy resolution

[P. Vogel, arXiv:hep-ph/0611243]

If 0νββ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \; G_{0\nu\beta\beta}(E_0, Z) \; \left| M_{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_{0\nu\beta\beta}$ Nuclear matrix element

$G_{0\nu\beta\beta}$ Phase space factor

$T_{1/2}^{0\nu\beta\beta}$ Measured half-life

$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_i \; \varepsilon_i \right|$$

effective Majorana ν mass
($\varepsilon_i = \pm 1$ if CP is conserved)

Experimental Limits

Isotope	0νββ half life	Experiment	<m> eV
^{48}Ca	> 1.4×10^{22} (90%CL)	ELEGANT-VI	< 7 - 44
^{76}Ge	> 1.9×10^{25} (90%CL)	Heidelberg-Moscow	< 0.35
^{76}Ge	2230^{+440}_{-310} (90%CL)	Subset of HM coll.	0.32 +/- 0.03
^{76}Ge	> 2.1×10^{25} (90%CL)	*GERDA*†	< 0.2 – 0.4
^{82}Se	> 2.1×10^{23} (90%CL)	NEMO-3	<1.2 – 3.2
^{100}Mo	> 5.8×10^{23} (90%CL)	NEMO-3	< 0.6 – 2.7
^{116}Cd	> 1.7×10^{23} (90%CL)	Solotvino	< 1.7
^{130}Te	> 2.8×10^{24} (90%CL)	Cuoricino	< 0.41 – 0.98
^{136}Xe	> 1.9×10^{25} (90%CL)	*KamLAND-Zen*††	< 0.12 – 0.25
^{136}Xe	> 1.6×10^{25} (90%CL)	*EXO-200*†††	< 0.14 – 0.38
^{150}Nd	> 1.8×10^{22} (90%CL)	NEMO-3	

[F. Avignone, S. Elliot, J. Engel, arXiv:0708: 1033v2 (2007)]
† [GERDA Collaboration, arXiv:1307.4720 (2013)]
†† [KamLAND-Zen Collaboration, Phys. Rev. Lett. 110, 062502(2013)]
††† [EXO Collaboration, Phys. Rev. Lett.109, 0322505 (2012)]

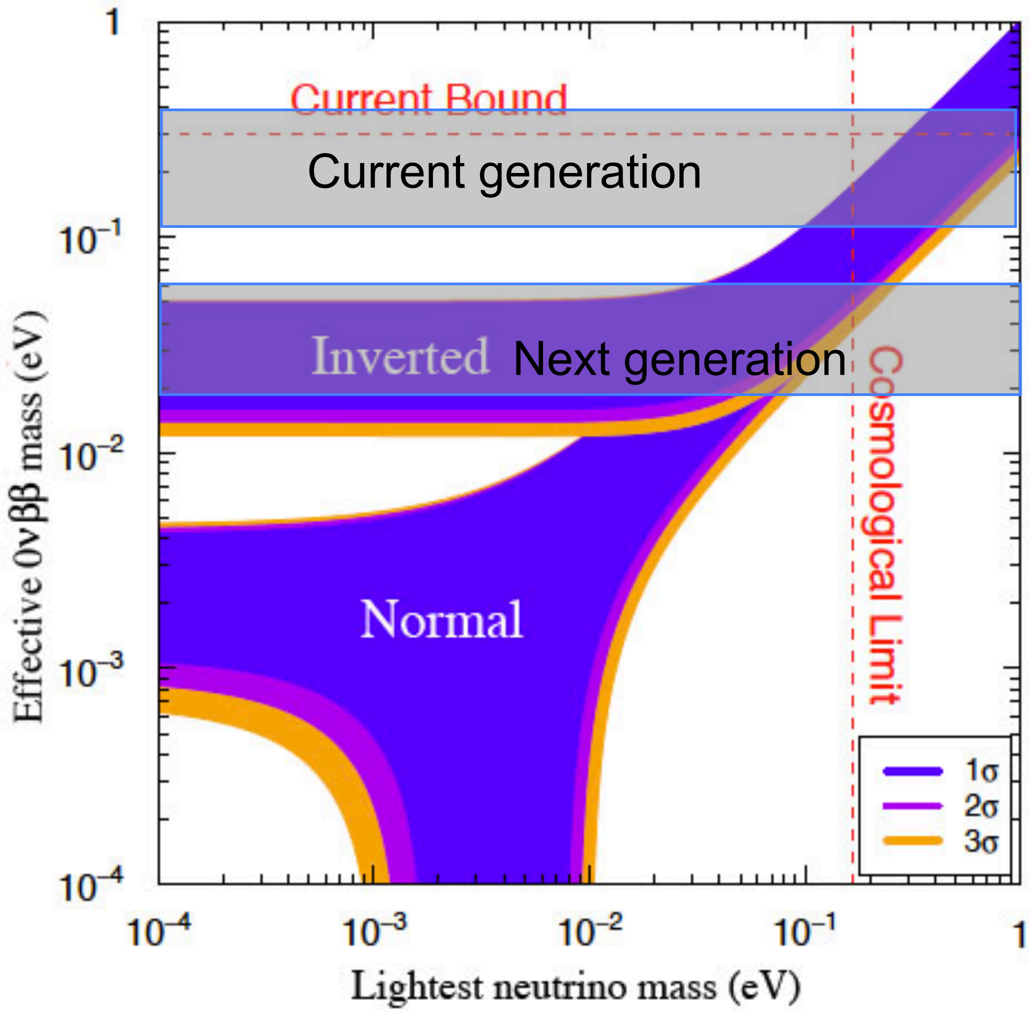
} New results within the last year!

Experimental Sensitivity to Neutrino Mass

Isotope Mass

10-100 kg

1-10 ton



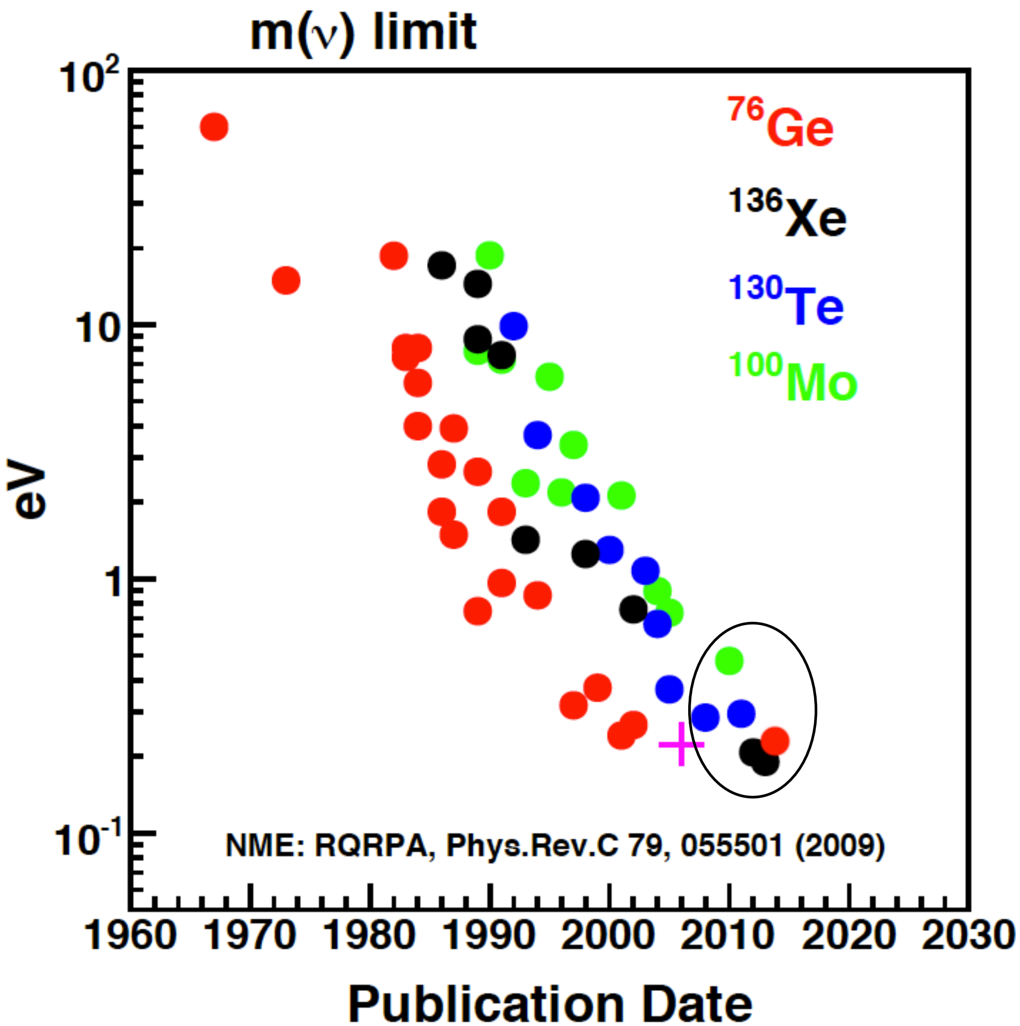
Background

10-100cts/yr/ton

0.1-1cts/yr/ton

arXiv:1203.5250v1

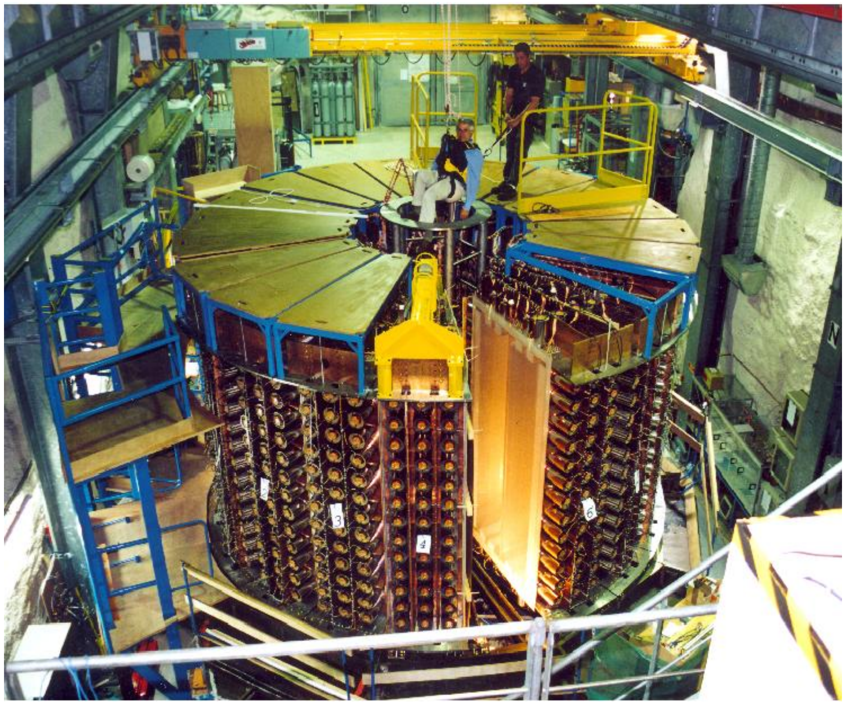
$0\nu\beta\beta$ Historical Progress



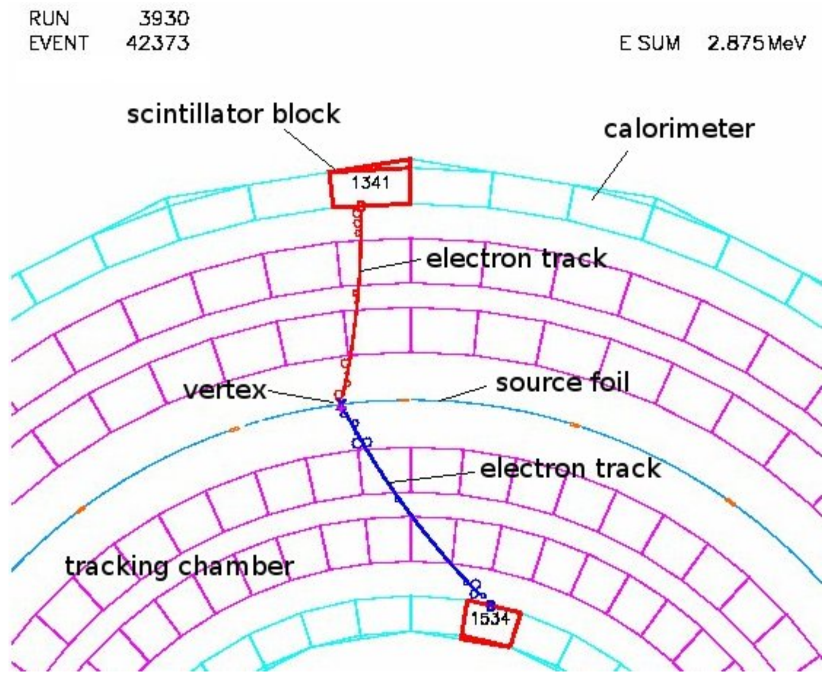
Adapted from C. Hall - Lepton Photon, June 2013

Tracking Detector: NEMO-3

(Neutrino Ettore Majorana Observatory)



NEMO-3 detector

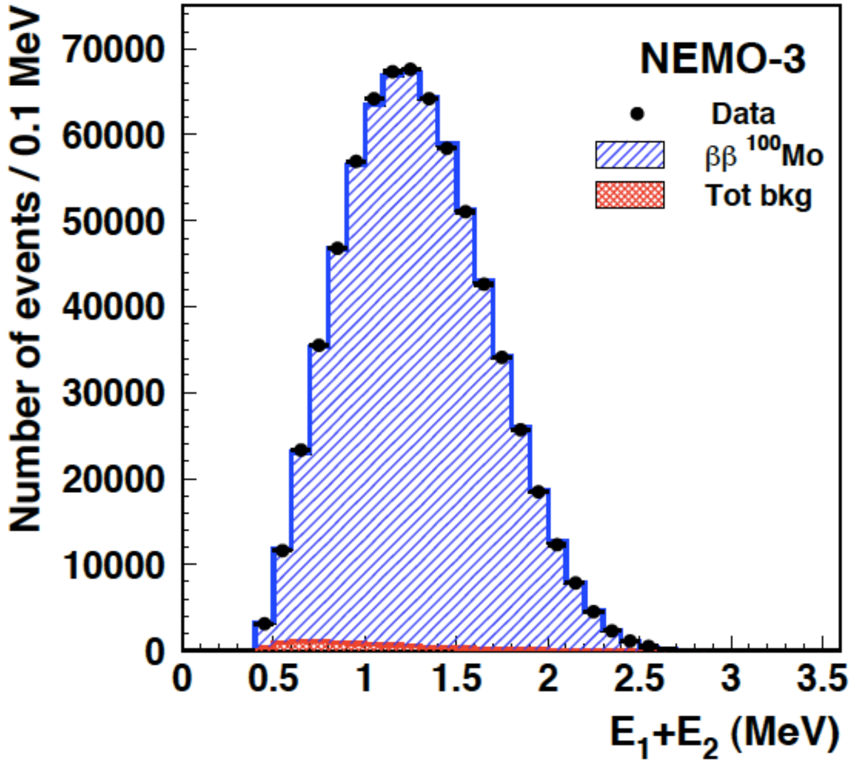


An ^{100}Mo 2νββ event

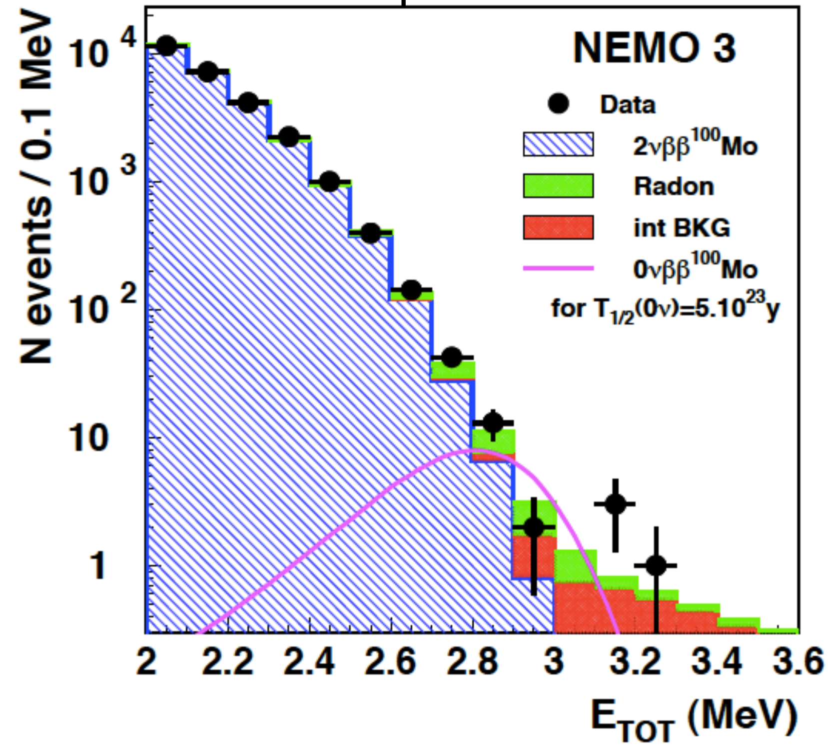
- Double beta decay isotope are in the form of thin foils ~ 60mg/cm^2.
- Decay electrons are tracked with Geiger mode drift tubes in modest magnetic field.
- The energy of the electrons are measured by plastic scintillators coupled to PMTs.

NEMO-3: 0νββ Result (^{100}Mo)

Full spectrum



ROI closeup



ROI [2.8 – 3.2] MeV 18 observed events, 16.4 ± 1.3 expected

Exposure: 31.2 kg yrs

$T_{1/2}(\beta\beta0\nu) > 1.1 \times 10^{24}$ yrs (90%C.L.)

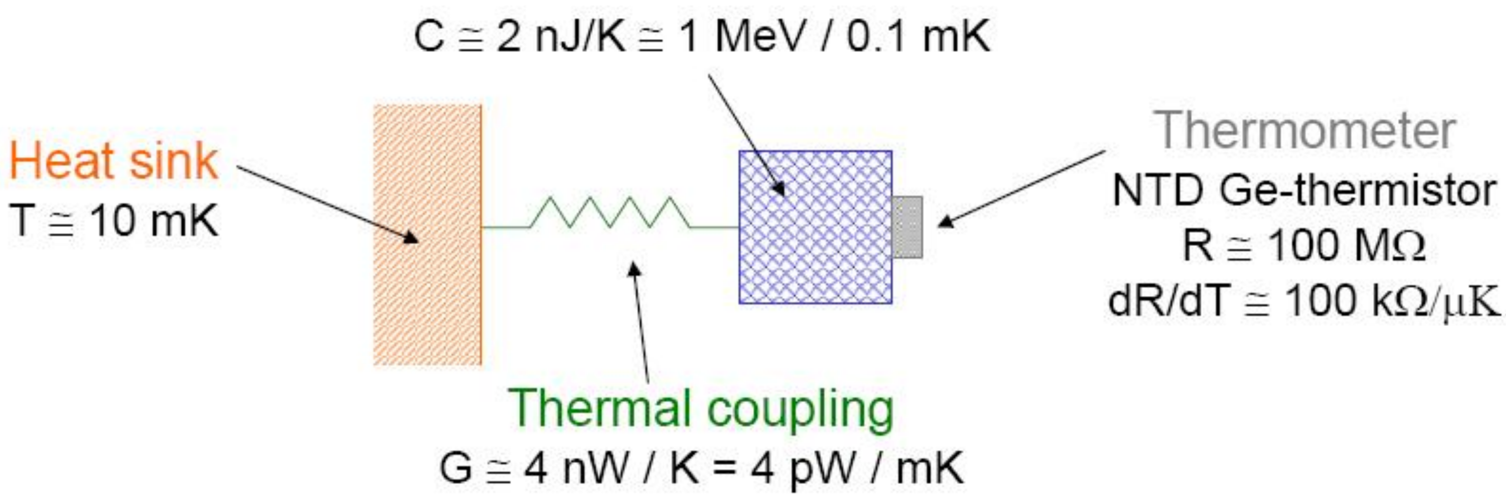
$m_{\beta\beta} < 0.45 – 0.93$ eV

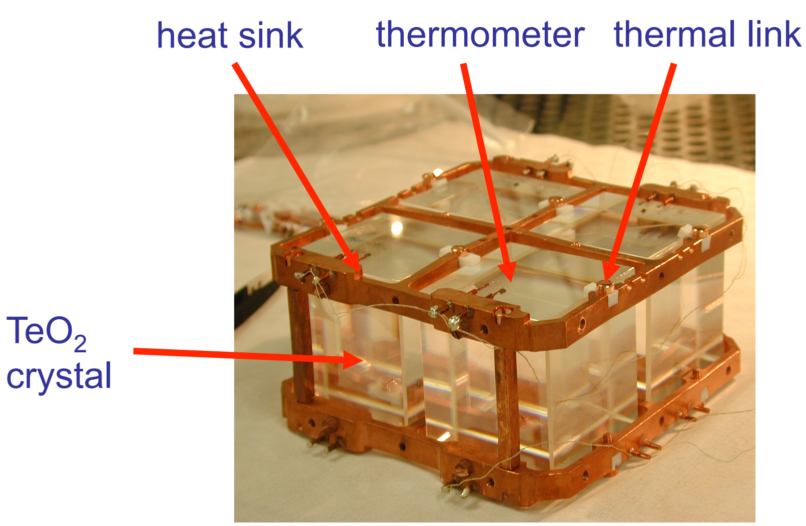
SuperNEMO: 100-200 kg ^{82}Se

$m_{\beta\beta} < 40 - 100$ meV

A.S. Barabash, et. al., Phys. Atom. Nucl. 74 (2011) 312.

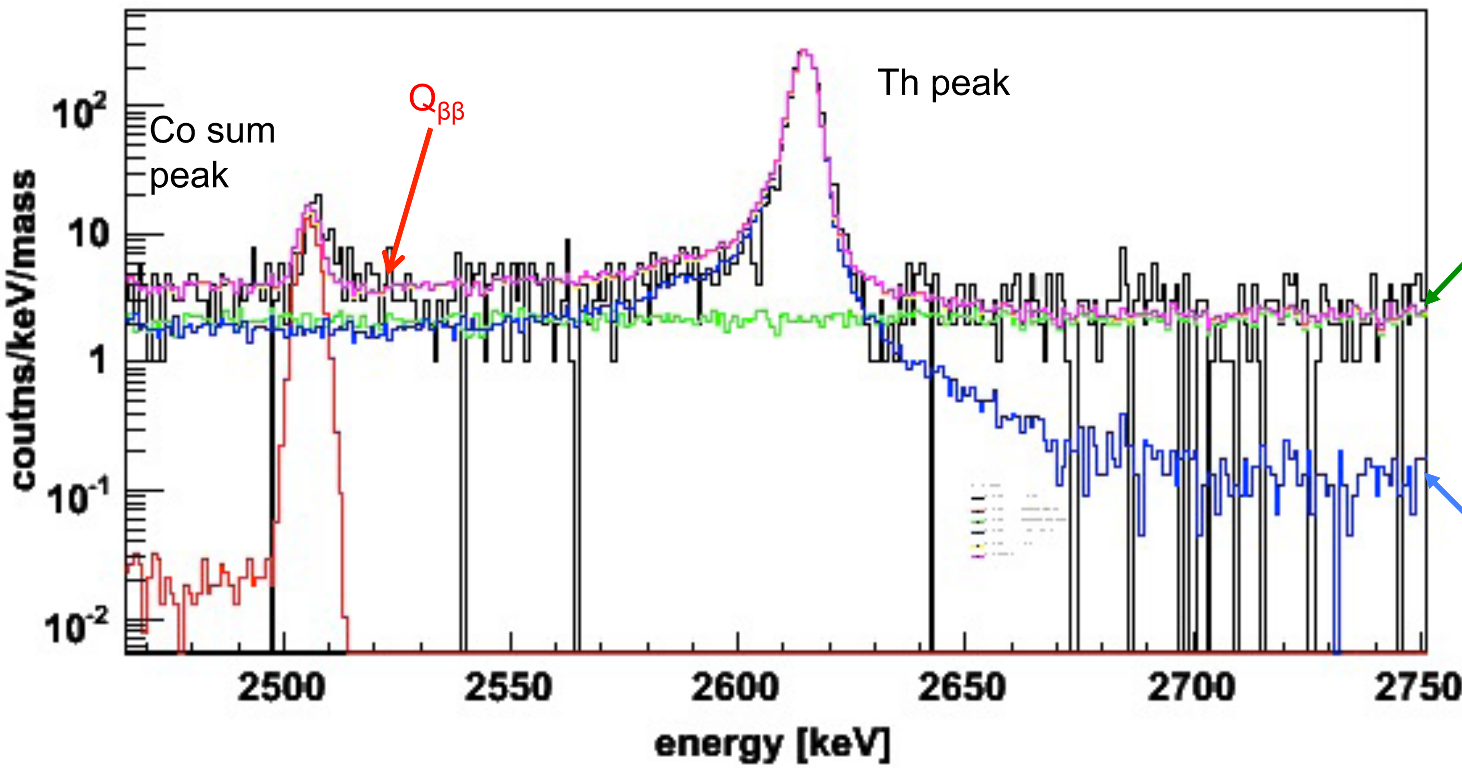
Cryogenic Bolometer: ^{130}Te





- Measure total energy deposited in the crystal.
- Techniques applicable to many isotopes. Te has the highest natural abundance.
- High energy resolution, 7-9 keV @ 2530keV.
- No information about the particle ID, external γ and surface degraded *α* are major background concerns.

COURICINO: 0νββ Result



Bg in ROI: 0.16 cnts/(kg keV yr)

Total exposure: 19.75 kg yr ^{130}Te

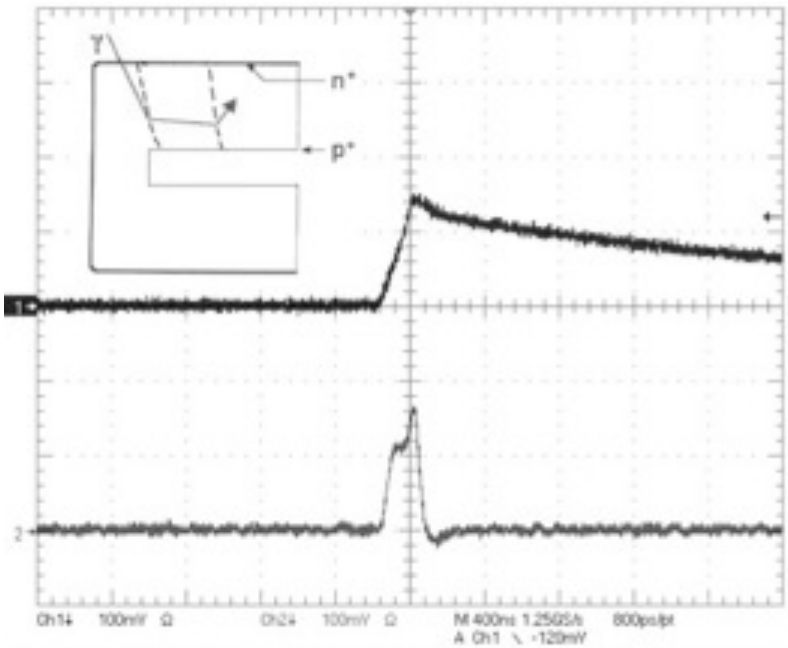
$T_{1/2}(\beta\beta0\nu) > 2.8 \times 10^{24}$ yrs (90%C.L.)

$m_{\beta\beta} < 0.41 – 0.98$ eV

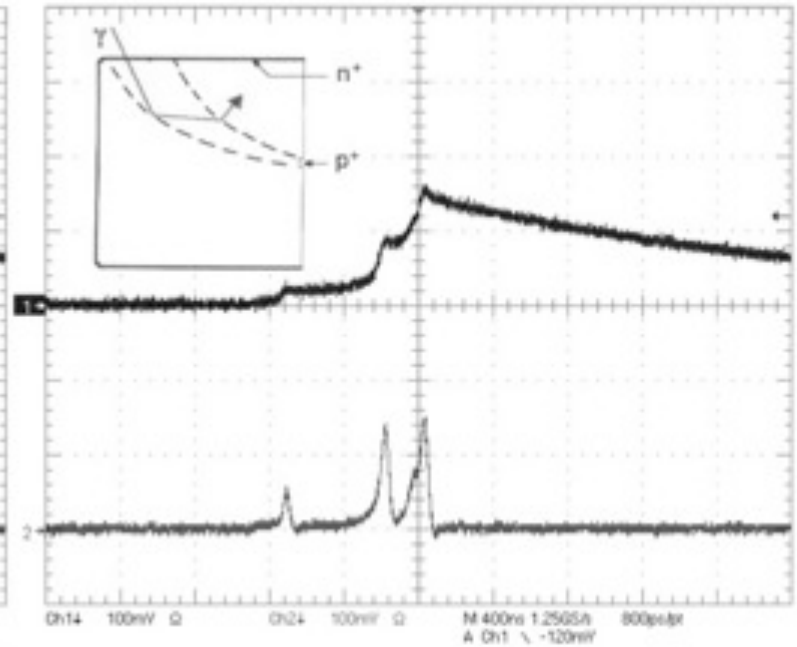
CUORE: 200 kg ^{130}Te, 5 year sensitivity, $m_{\beta\beta} < 41 – 95$ meV

E. Andreotti et. al. Astropart. Phys. 34, 822 (2011)

Semiconductor Detector: ^{76}Ge



P-type semi-coaxial Detector



P-type point contact Detector*

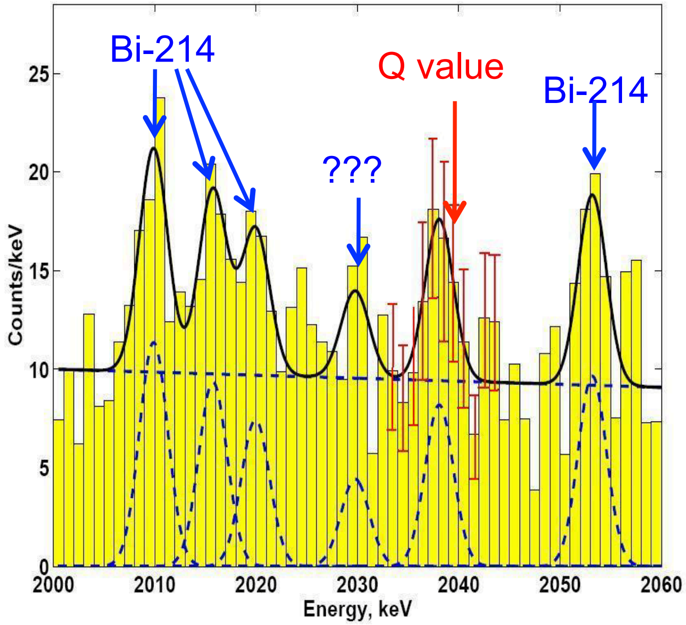
Barbeau et al., JACP 09 (2007) 009; Luke et al., IEEE trans. Nucl. Sci. 36, 926 (1989).

- Excellent energy resolution (4keV FWHM at Q value)
- Pulse shape analysis rejects multiple site events within a single crystal.
- P-type point contact crystal has superior single vs. multi-site rejection capability.
- Modest Q value (2039 keV), cosmogenic activation of Ge and Cu cryostat

*Also called Broad Energy Ge (BEGe) Detector.

$0\nu\beta\beta$ Discovery Claim

Spectrum near ROI



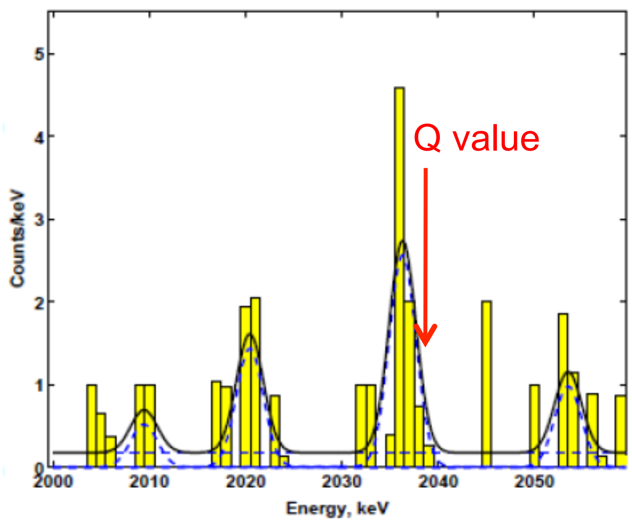
Total exposure: 71.7 kg•yr ^{76}Ge

Fit intensity @ $Q_{\beta\beta}$= 28.75 ± 6.86

Authors claim significance of 4.2 σ.

$T_{1/2}^{0\nu} = 1.19_{-0.23}^{+0.37} \times 10^{25}$ yr

HV. Klapdor-Kleingrothaus, et. al,
Nucl. Instrum, and Meth, A 522 (2004) 371-406



Spectrum near ROI, after pulse shape analysis

After pulse shape analysis (PSA), background in ROI dropped from 0.17 cnts/(keV kg yr) to 0.015 cnts/(keV kg yr)

Fit intensity @ $Q_{\beta\beta}$= 11.32 ± 1.75

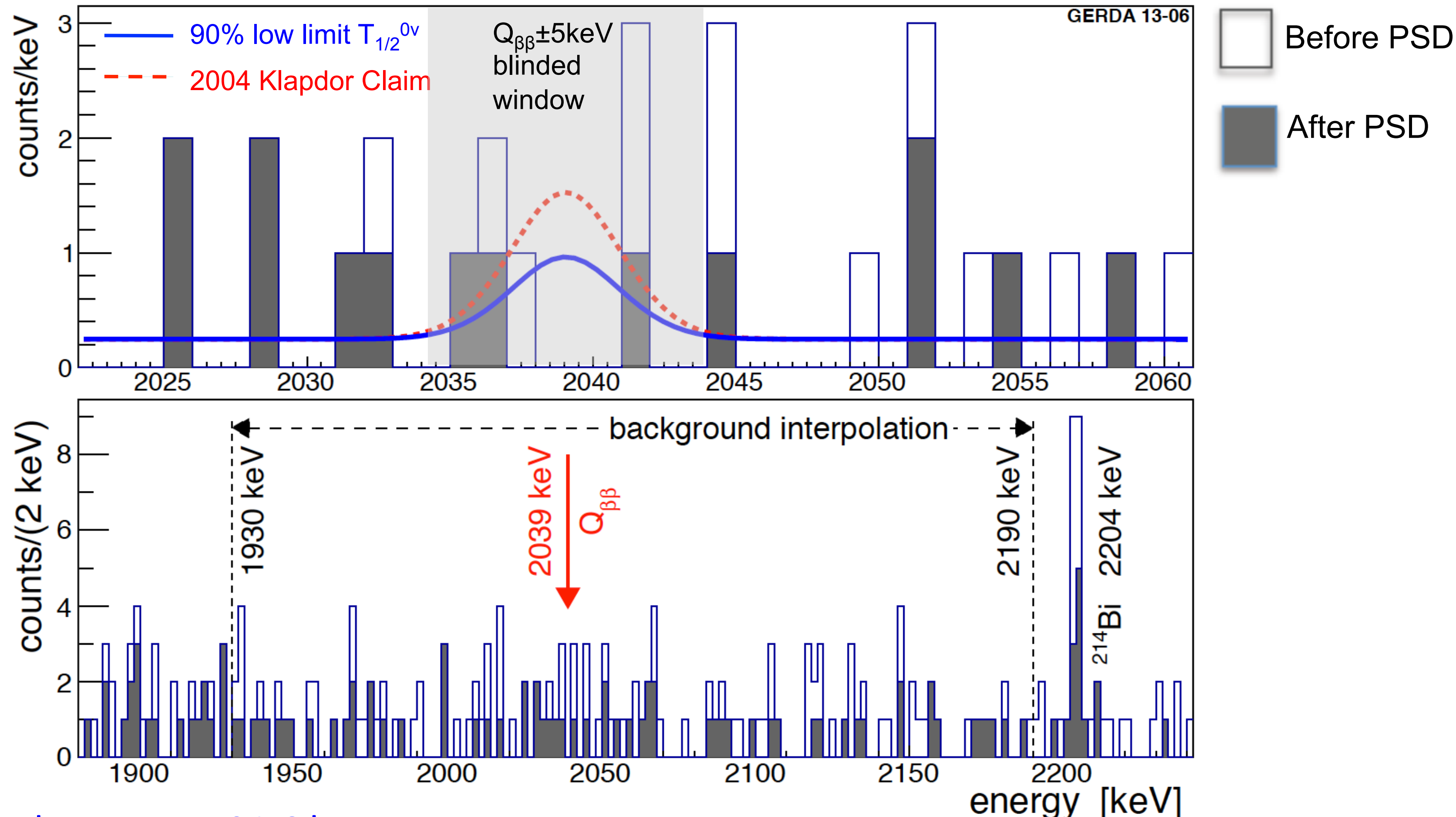
Authors claim significance of 6.5 σ.

$T_{1/2}^{0\nu} = 2.23_{-0.31}^{+0.44} \times 10^{25}$ yr.

Mod. Phys. Lett., A 21, 1547 (2006)

GERDA Phase I Result

[GERDA Collaboration], arXiv, 1307.4720 (2013)



Total exposure: 21.6 kg yr

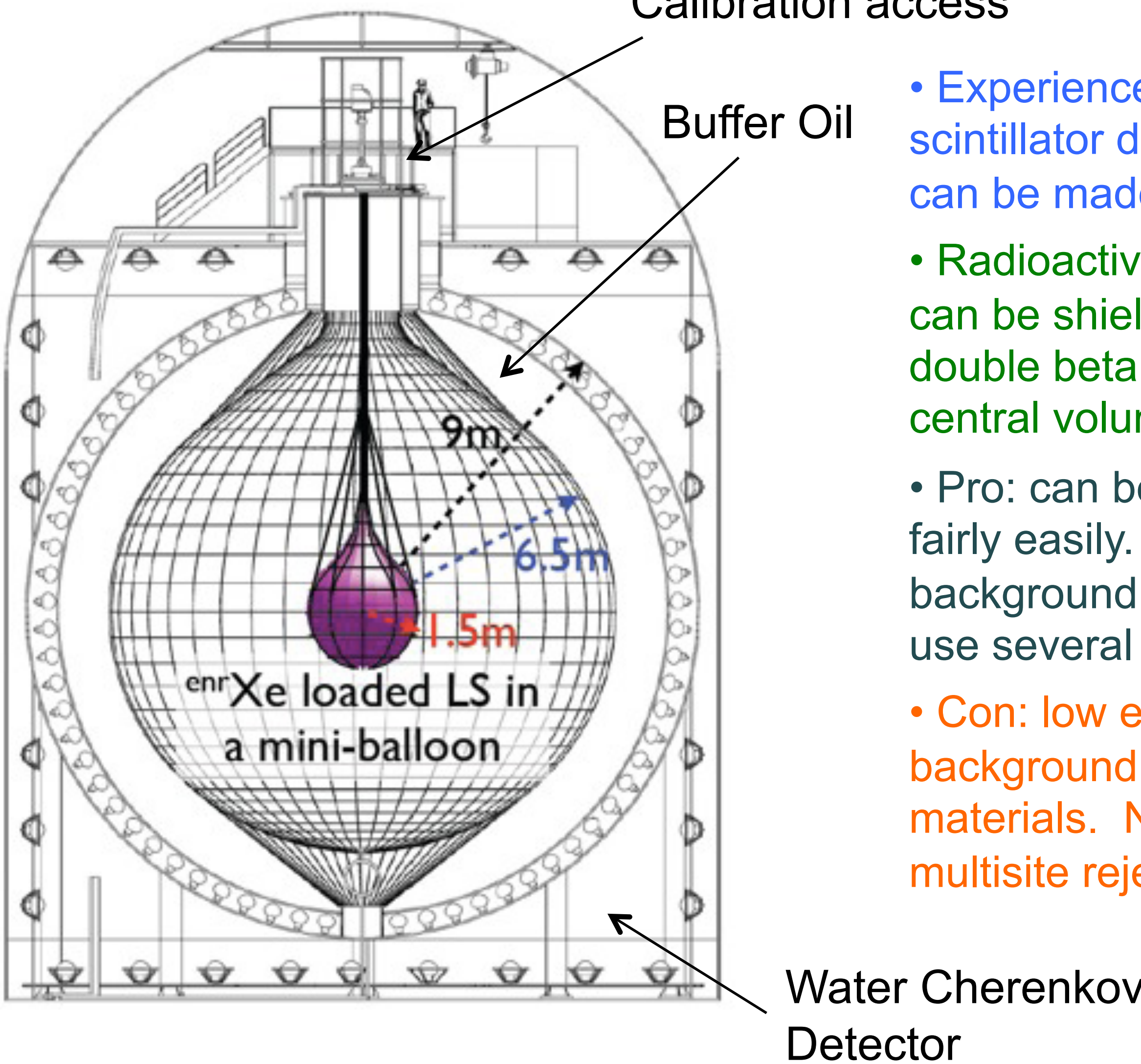
Bg index after PSD: 0.01 cnts/(keV kg yr)

$T_{1/2}^{0\nu}$ > 2.1×10^{25} yr (90% C.L.)

2004 claim strongly disfavored!

Phase I complete, moving towards phase II, larger expo. and lower background

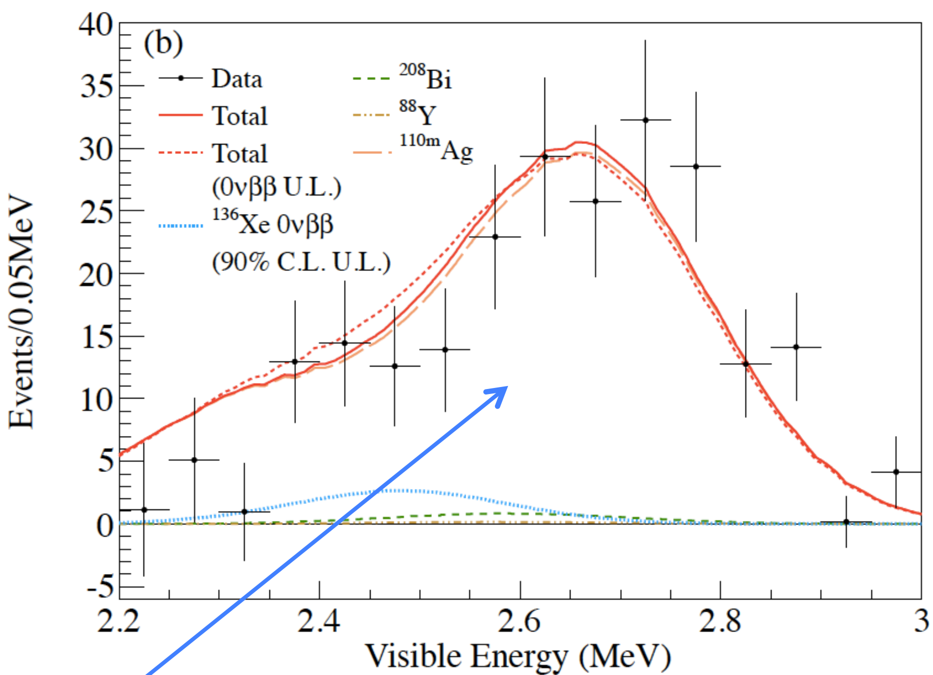
Scintillation Detector: KamLAND-Zen



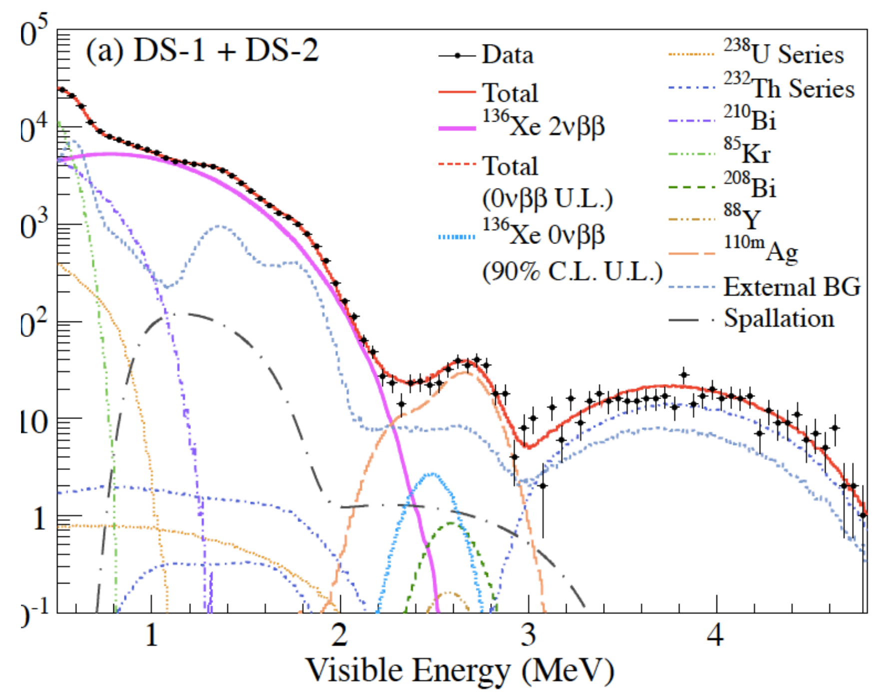
- Experience with large liquid scintillator detectors show that LS can be made extremely pure.
- Radioactivity from PMTs and vessel can be shielded by LS and confining double beta decay isotopes inside a central volume.
- Pro: can be scale to large mass fairly easily. Most detector background well understood. Can use several different isotopes.
- Con: low energy resolution, background from $2\nu\beta\beta$ and balloon materials. No single site and multisite rejection.

KamLAND-Zen: ^{136}Xe Result

ROI closeup



Full spectrum



^{110m}Ag Bg from Xe cosmogenic spallation production suspected. Xe purification underway.

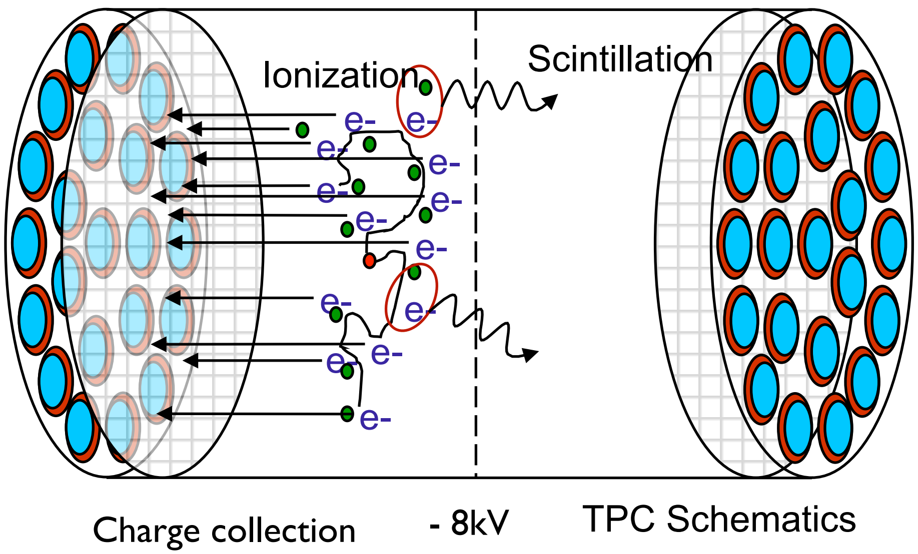
Exposure: 89.5 kg yr

$T_{1/2}(\beta\beta0\nu) > 1.9 \times 10^{25}$ yr (90% C.L.)

$m_{\beta\beta} < 140 – 380$ meV

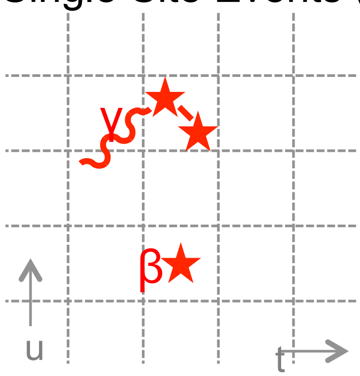
Phys. Rev. Lett 110, 062502 (2013)

Liquid Xenon TPC: EXO-200

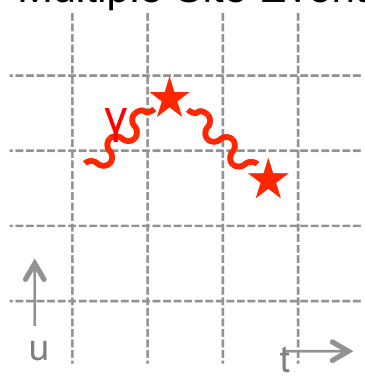


The EXO-200 time projection chamber uses both scintillation and ionization signals to fully reconstruct energy depositions inside liquid xenon

Single Site Events (SS)

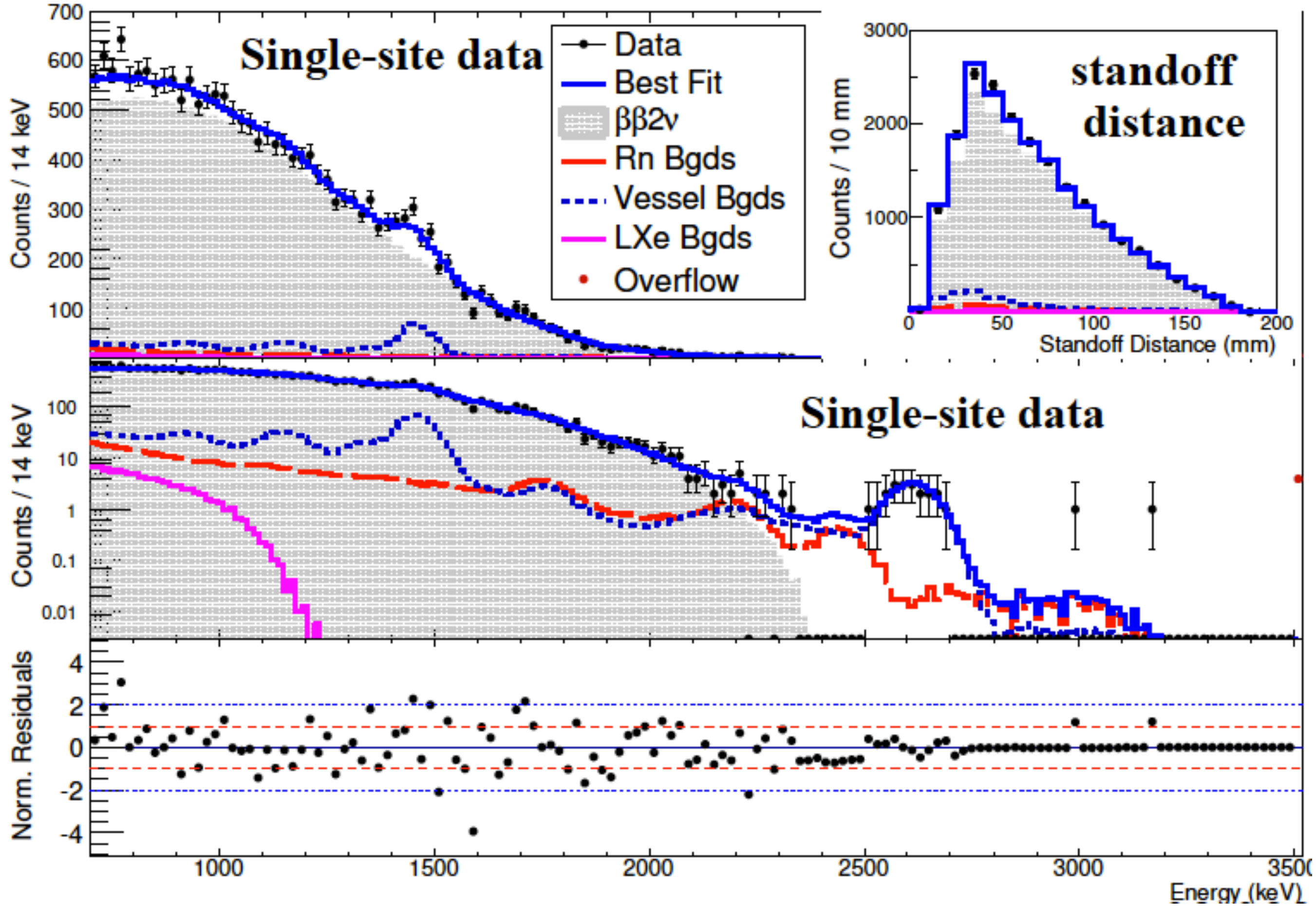


Multiple Site Events (MS)



Event topology is a powerful tool not only for gamma background rejection, but also for signal discovery.

New Result: Improved 2νββ Measurement (2013)

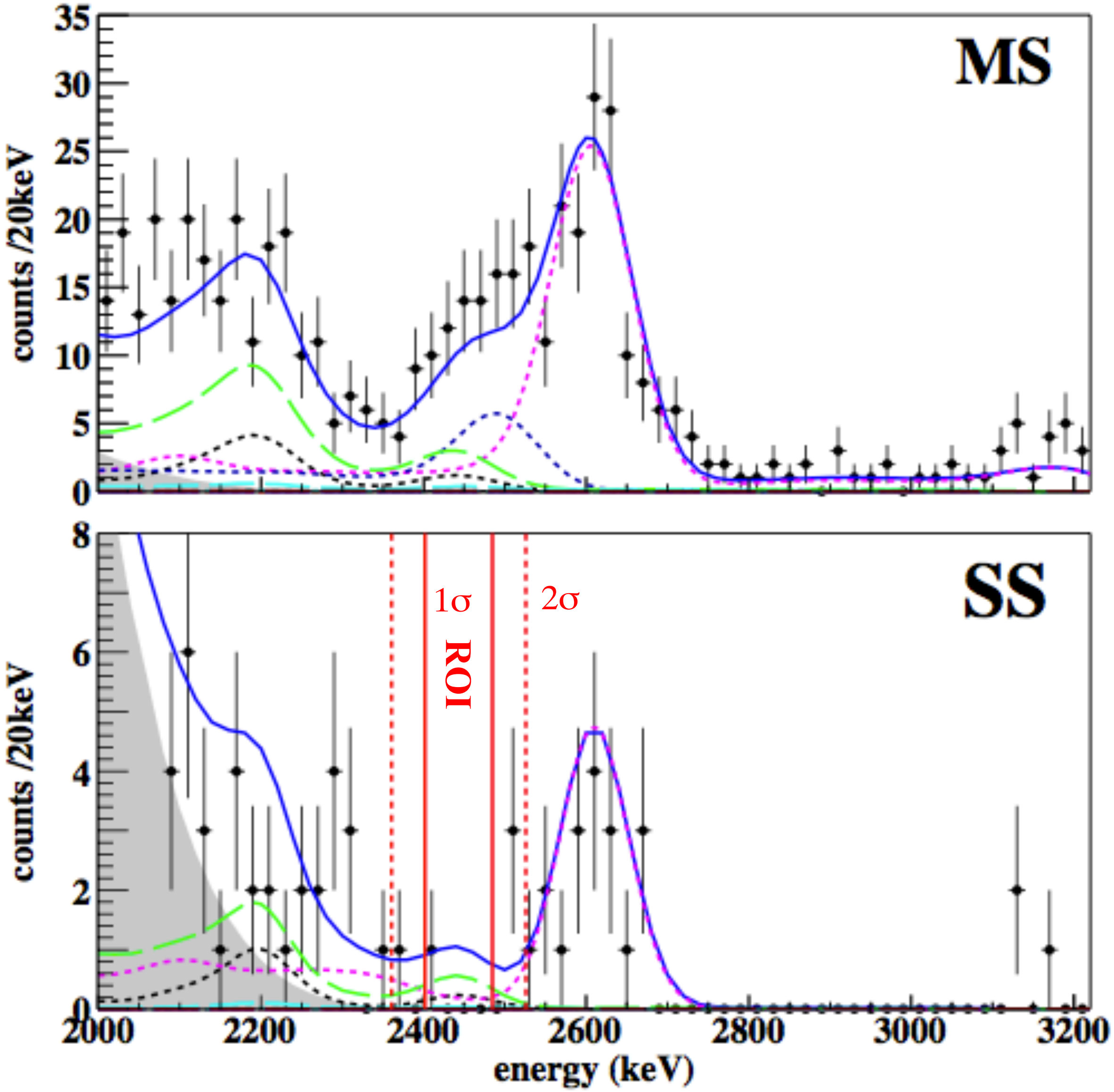


ArXiv: 1306.6106, submitted to PRC

- $T_{1/2}$ = 2.172 ± 0.017 (stat) ± 0.060 (sys) x 10^{21} yrs
- Twice as precise as any other 2νββ measurement of any isotope
- 1.77% fiducial volume uncertainty

EXO-200: 0νββ Search Result (2012)

Zoomed around 0νββ region of interest (ROI)



Exposure: 32.5 kg yr in ^{136}Xe

No 0ν signal observed

Profile likelihood fits:

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

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

(90% C.L.)

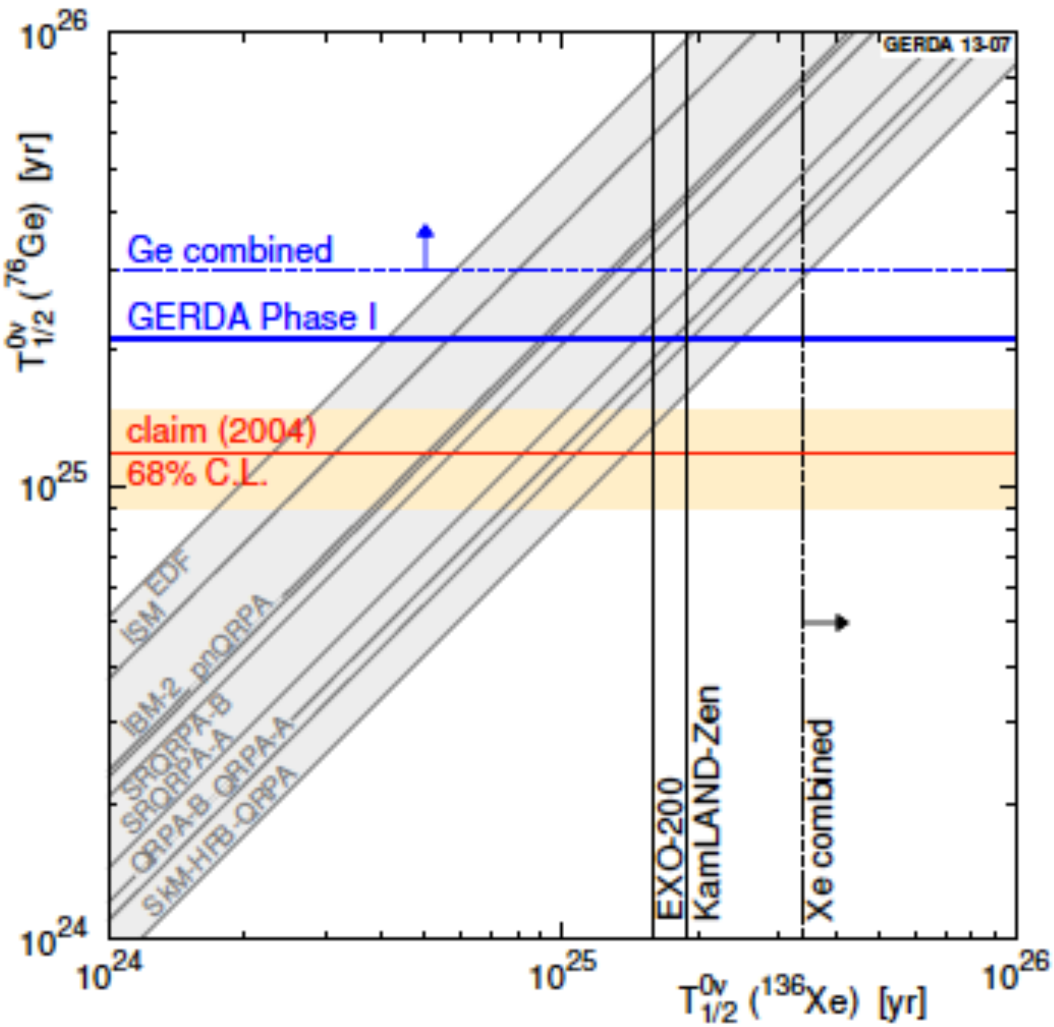
PRL, 109, 032505 (2012)

New result with 1.5 year exposure data expected soon.

Recent ^{136}Xe and ^{76}Ge Results in Tension with Claimed Discovery

GERDA Phase I

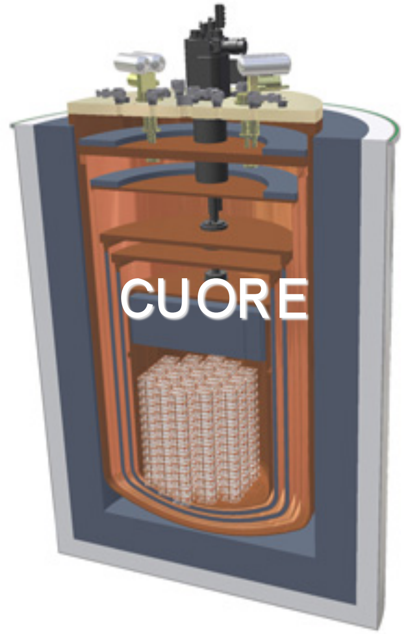
Comparison with Klapdor 2004 claim

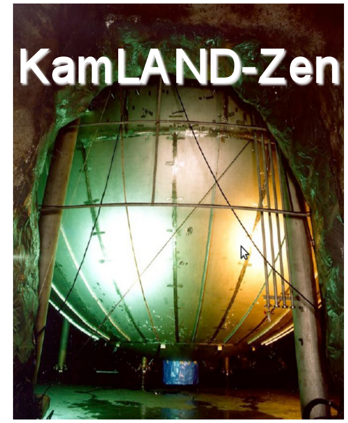


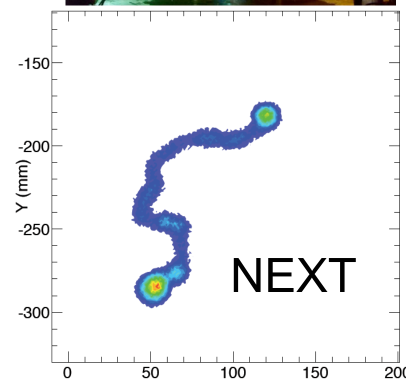
KamLAND-Zen
& EXO-200

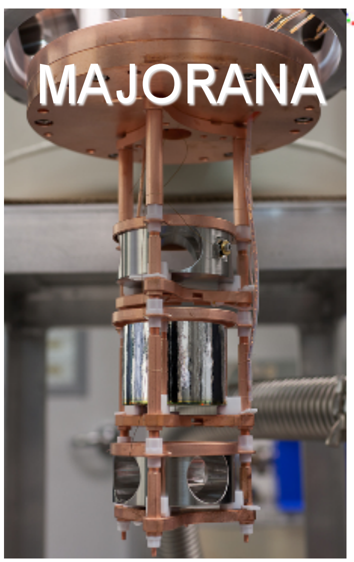
arXiv:1307.4720

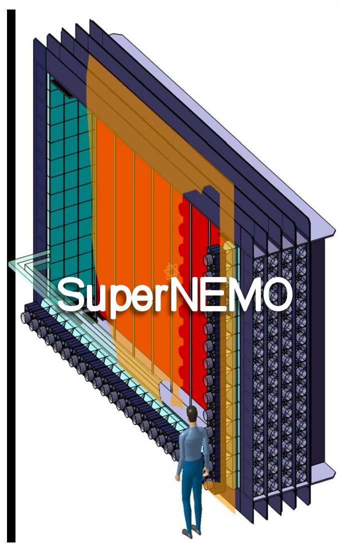
Probing the Inverted Mass Hierarchy?

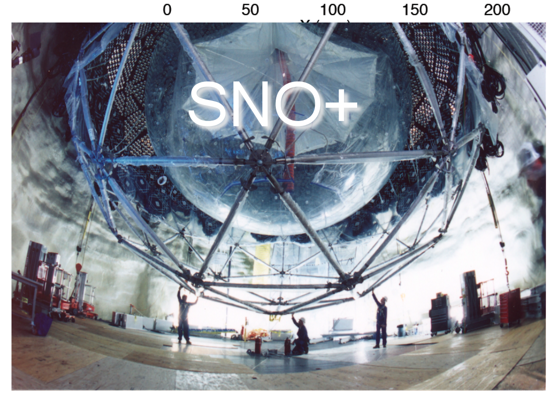












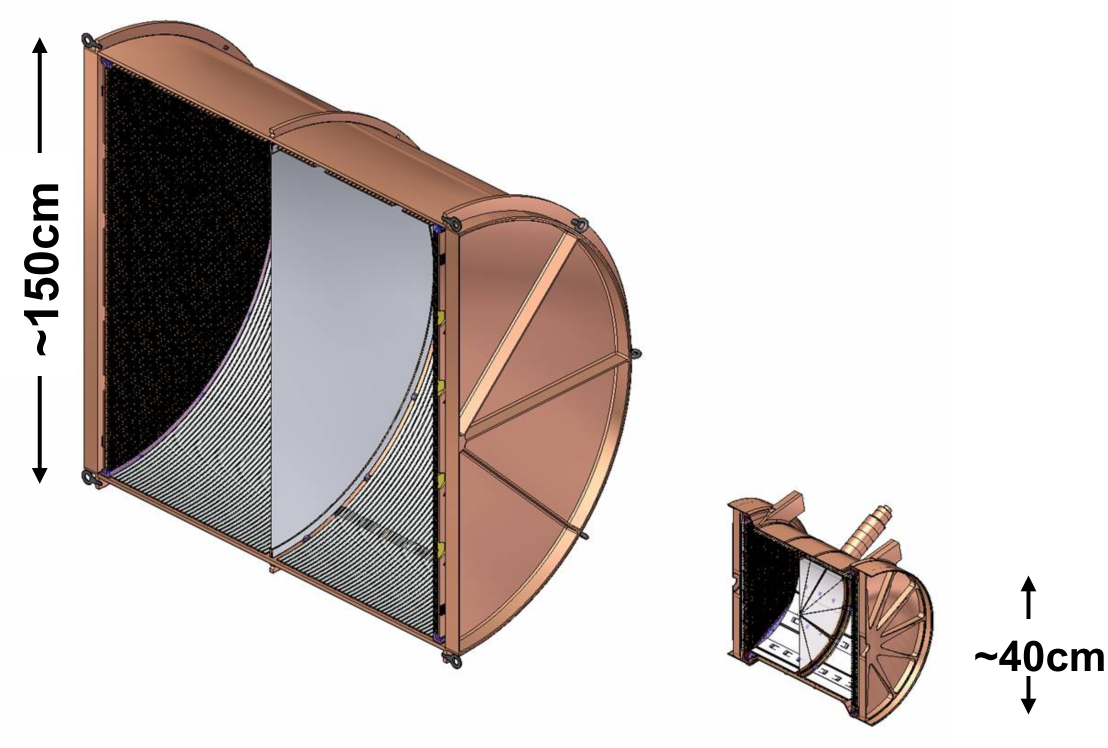
nEXO Detector

• 5 tonne LXe TPC "as similar to EXO-200 as possible", *initially* without Ba-tagging.

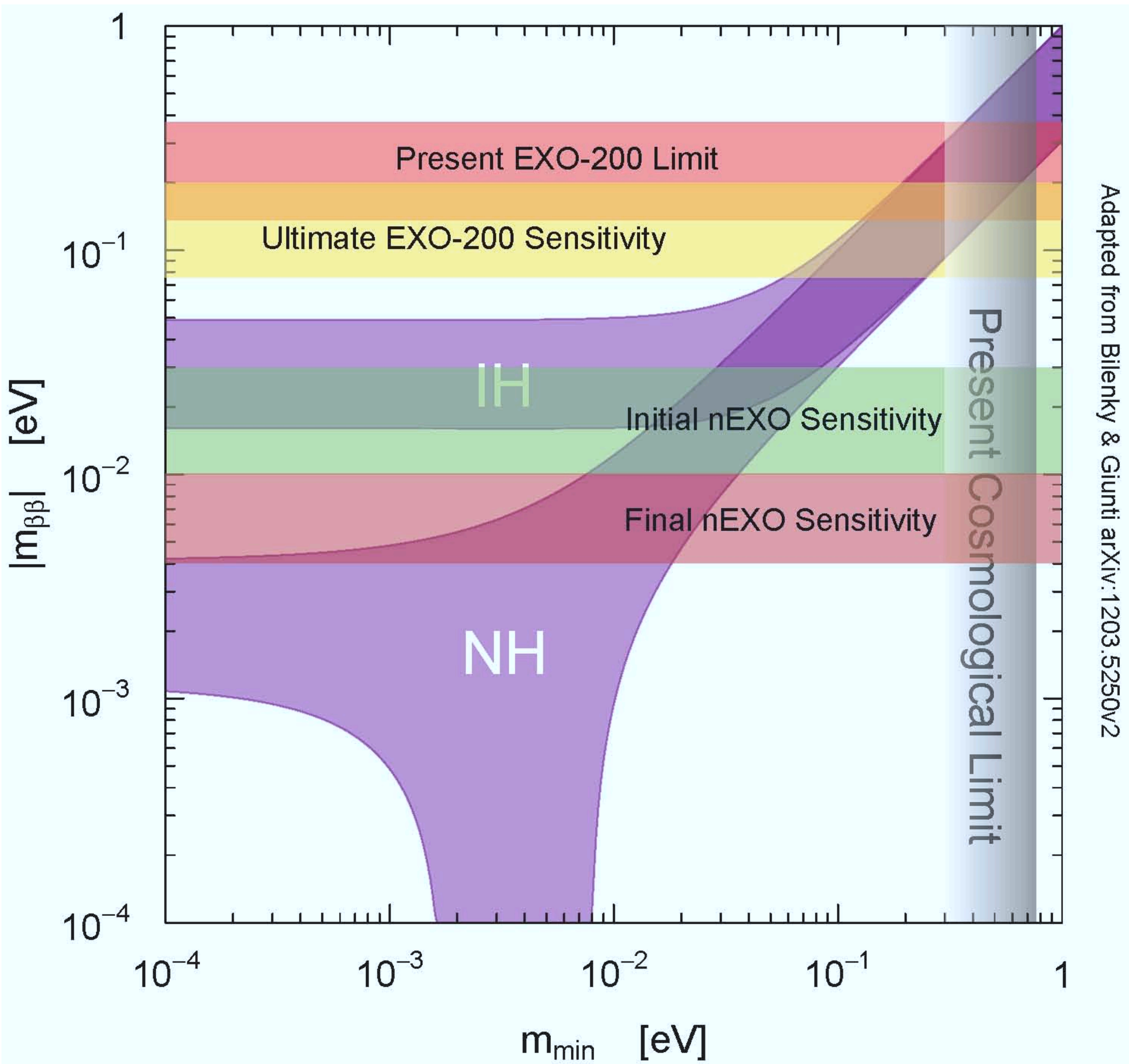
• 4 tonnes of active ${}^{enr}Xe$ (80% or higher), 1.4% (σ) energy resolution.

• Assuming Observed EXO-200 backgrounds minus the Rn in the shield. ββ-scales like the volume, the background like the surface area.

• Provide access ports for a possible later upgrade to Ba tagging



EXO-200 and nEXO projected sensitivity



Blue bands are 68%CL from oscillation experiments for “Inverted” and “Normal” Hierarchy

The EXO-200 “Ultimate” sensitivity: 90%CL for no signal in 4 yrs livetime with new analysis & Rn removal

The “Initial nEXO” band refers to a detector directly scaled from EXO-200,

The “Final nEXO” band refers to the same detector and no background other than 2v

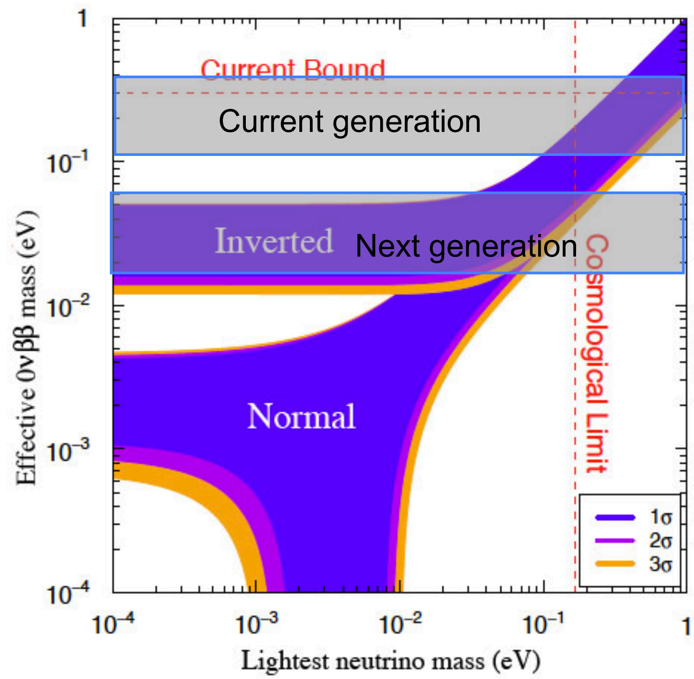
(Different barium tagging techniques under investigation)

Summary

• Neutrinoless double beta search is one of the most sensitive probes for the Majorana/Dirac nature of neutrinos.

• Recent results from EXO-200, Kamland-Zen and GERDA are in tension with the claimed discovery in ^{76}Ge.

• Next generation tonne scale experiments are posed to probe the inverted mass hierarchy region.



arXiv:1203.5250v1

New techniques and ideas are need to probe the normal hierarchy!