Majorana vs. Dirac Neutrino and Absolute Neutrino Mass Measurements

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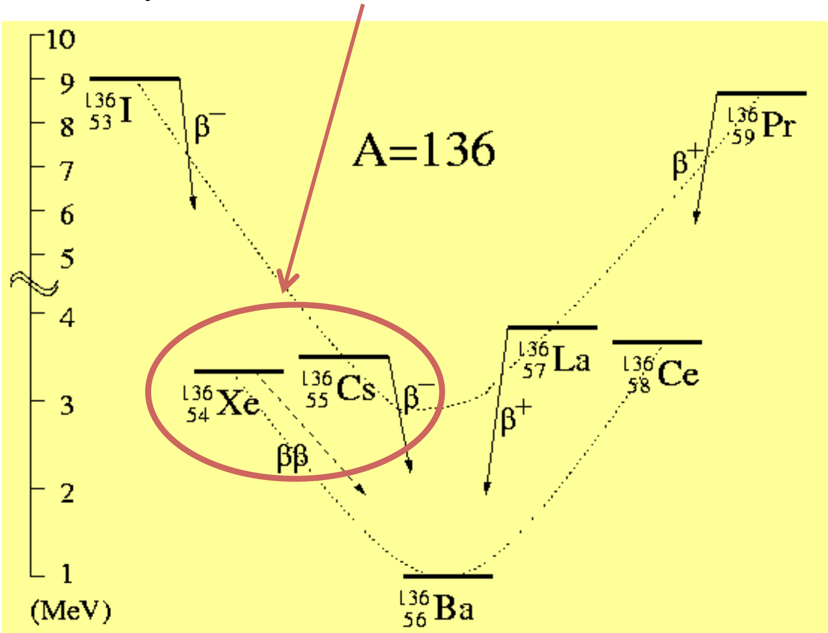
Lecture Outlines

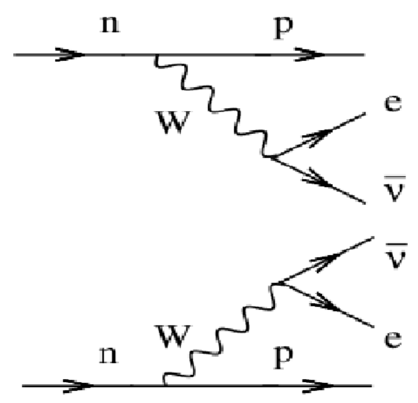
- Lecture 1: Overview
- Lecture 2: Experimental details of weak decay kinematics measurements
- Lecture 3: Experimental details of double beta decay measurements
  - Brief review of double beta decay
  - Experimental sensitivity
  - Background reduction techniques
  - Review of experimental techniques.
  - Recent results from Gerda, Kamland-Zen and EXO

Double Beta Decay

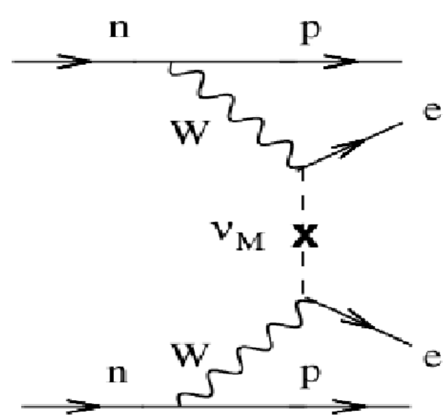
Observable if single beta decay is forbidden



Two neutrino double beta decay



Neutrinoless double beta decay



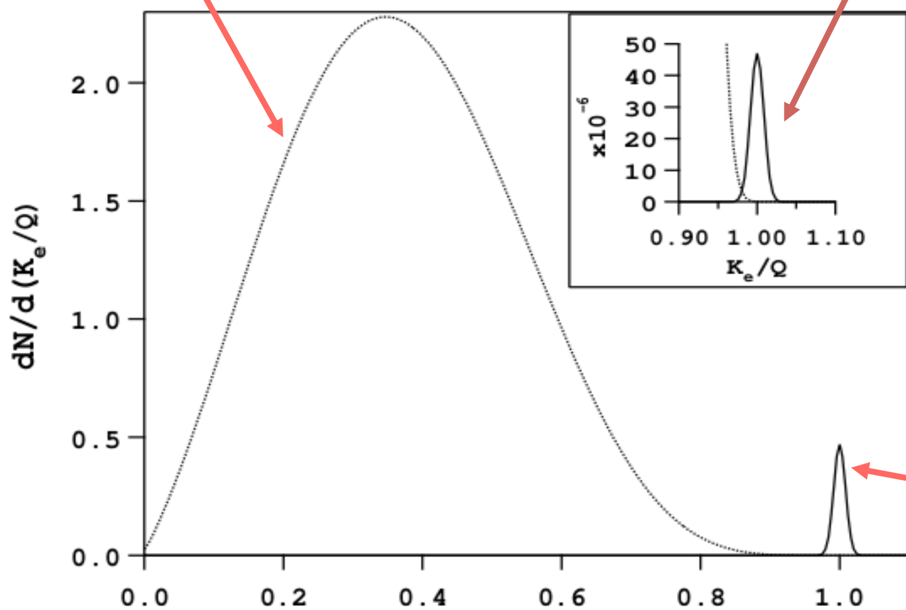
Observation of 0νββ:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

Double Beta Decay Energy Spectrum

2νββ spectrum (normalized to 1)

0νββ peak (2% FWHM) (normalized to 10^{-6})



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

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

0νββ peak (2% FWHM) (normalized to 10^{-2})

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

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 Sensitivity

The sensitivity of $T_{1/2}^{0\nu}$ is determined by the number of 0νββ events ($N_{0\nu}$) and the number of background (N_{bg}) events in the region of interest (ROI).

$$N_{0\nu} \propto \varepsilon \frac{a}{A} \frac{MT}{T_{1/2}^{0\nu}} \qquad N_{bg} \propto MTB\Gamma$$

ε is efficiency
a is isotope abundance
A is atomic mass
M is source mass
T is live time
B is background index
Γ is resolution

For background free experiments,

$$N_{0\nu} > 1 \rightarrow S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A} MT$$

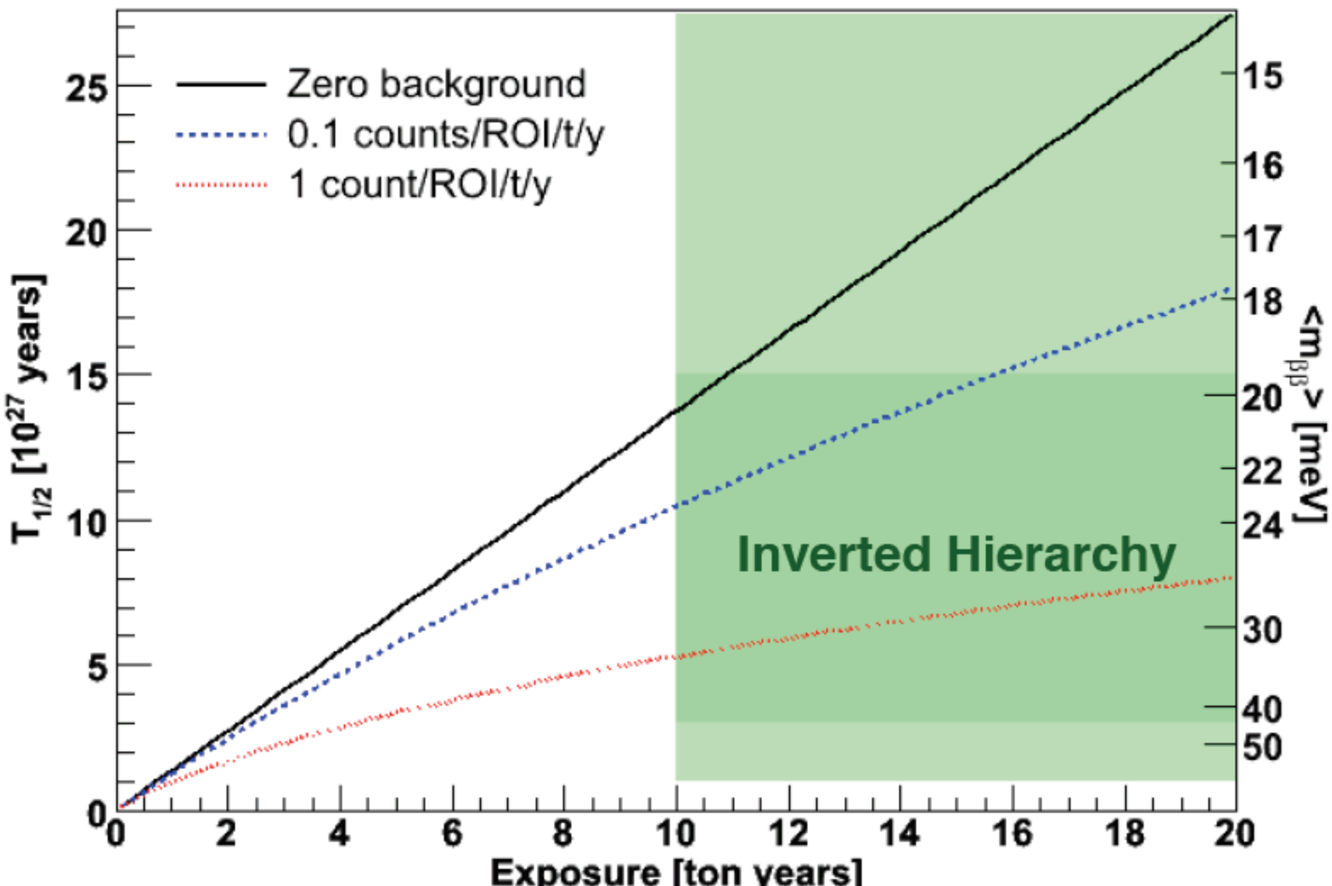
For experiments with background,

$$N_{0\nu} > \sqrt{N_{bg}} \rightarrow S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A} \sqrt{\frac{MT}{B\Gamma}}$$

Note: for small number of N_{bg} (< ~ 6) , full statistical treatment is more complicated and will often require Monte Carlo simulations.

Experimental Sensitivity (Ge)

Example: 1 ton Ge experiment



Wilkerson, APS, April Meeting, 2007

We are not near zero background limit yet!

Experimental Design Considerations

$$S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A}\left[\frac{MT}{B\Gamma}\right]^{1/2} \qquad S_{m_{\nu_{ee}}}^{0\nu} \propto \frac{1}{\sqrt{G^{0\nu}}\left|M^{0\nu}\right|}\left[\frac{A}{\varepsilon}\right]^{1/2}\left[\frac{B\Gamma}{MT}\right]^{1/4}$$

ε is efficiency, *a* is isotope abundance, *A* is atomic mass, *M* is source mass, *T* is live time
B is background index, Γ is resolution, $G^{0\nu}$ is phase space, $M^{0\nu}$ is matrix element

To maximize sensitivity:

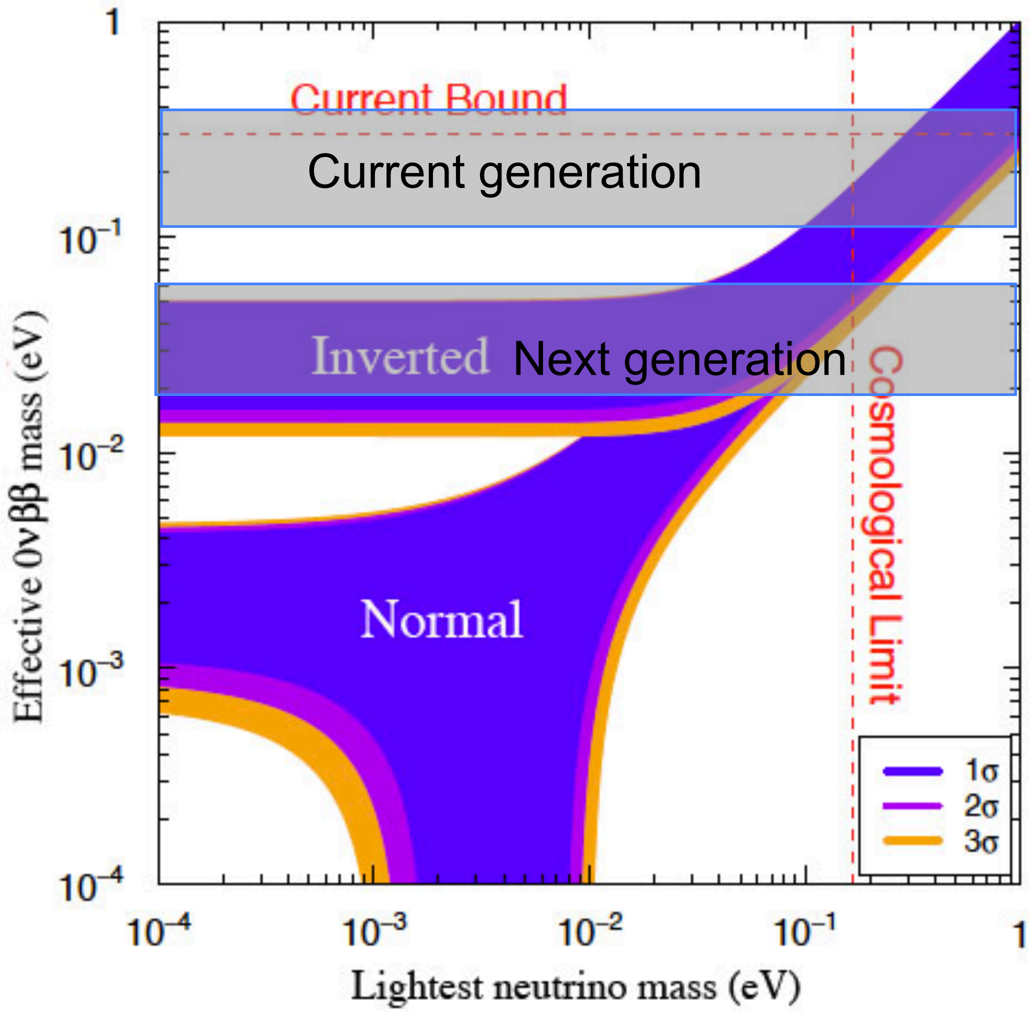
- Large isotope mass (10 – 100 kg now → 1-10 ton)
- High detection efficiency (~ 100 %)
  - source = detector?
- Good energy resolution
  - reduce flat background and resolve nearby background peaks
  - reduce 2νββ background
- Low background (10 – 100 cnts/yr/ton → 0.1 – 1 cnts/yr/ton)
  - underground detector to shield cosmic rays
  - clean material, passive and active shielding
  - discriminate against background events

Experimental Sensitivity to Neutrino Mass

Isotope Mass

10-100 kg

1-10 ton



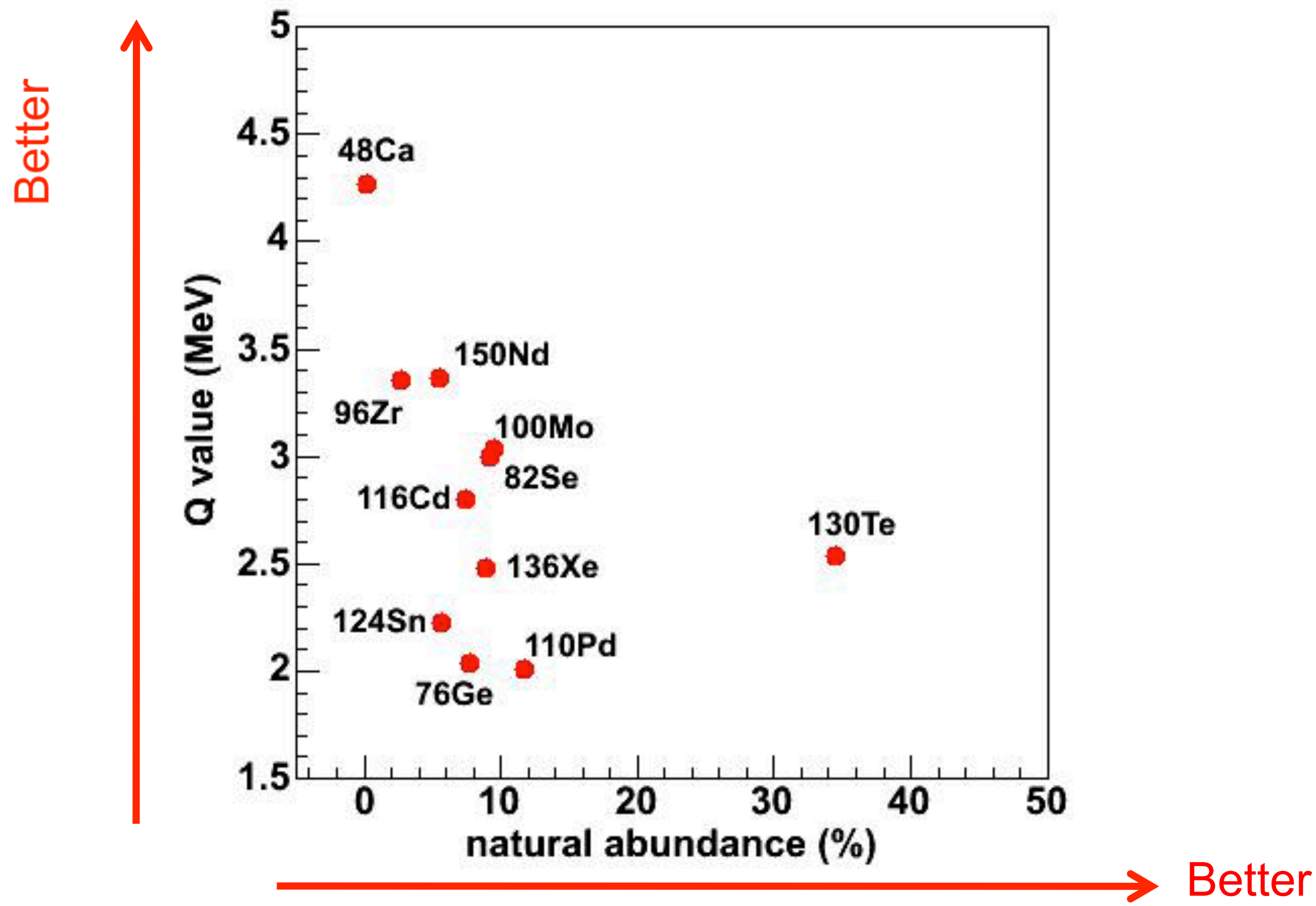
Background

10-100cts/yr/ton

0.1-1cts/yr/ton

arXiv:1203.5250v1

Choice of Isotope



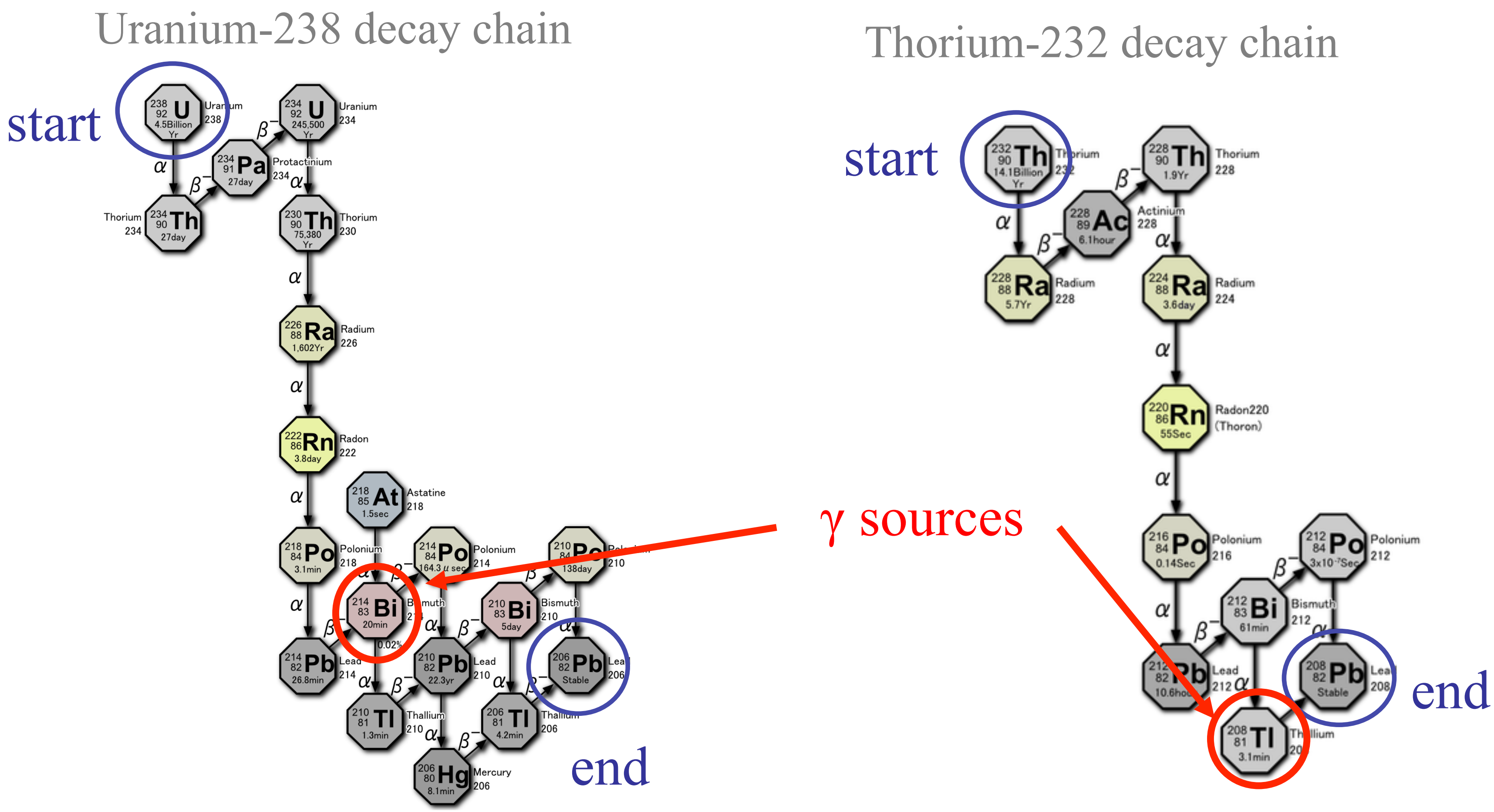
- High natural abundance means lower cost of enrichment
- Large Q value means lower background from natural radioactivity
- No golden element, detector technology and background reduction techniques are crucial considerations in isotope selection.

Experimental Limits

Isotope	$0\nu\beta\beta$ 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	

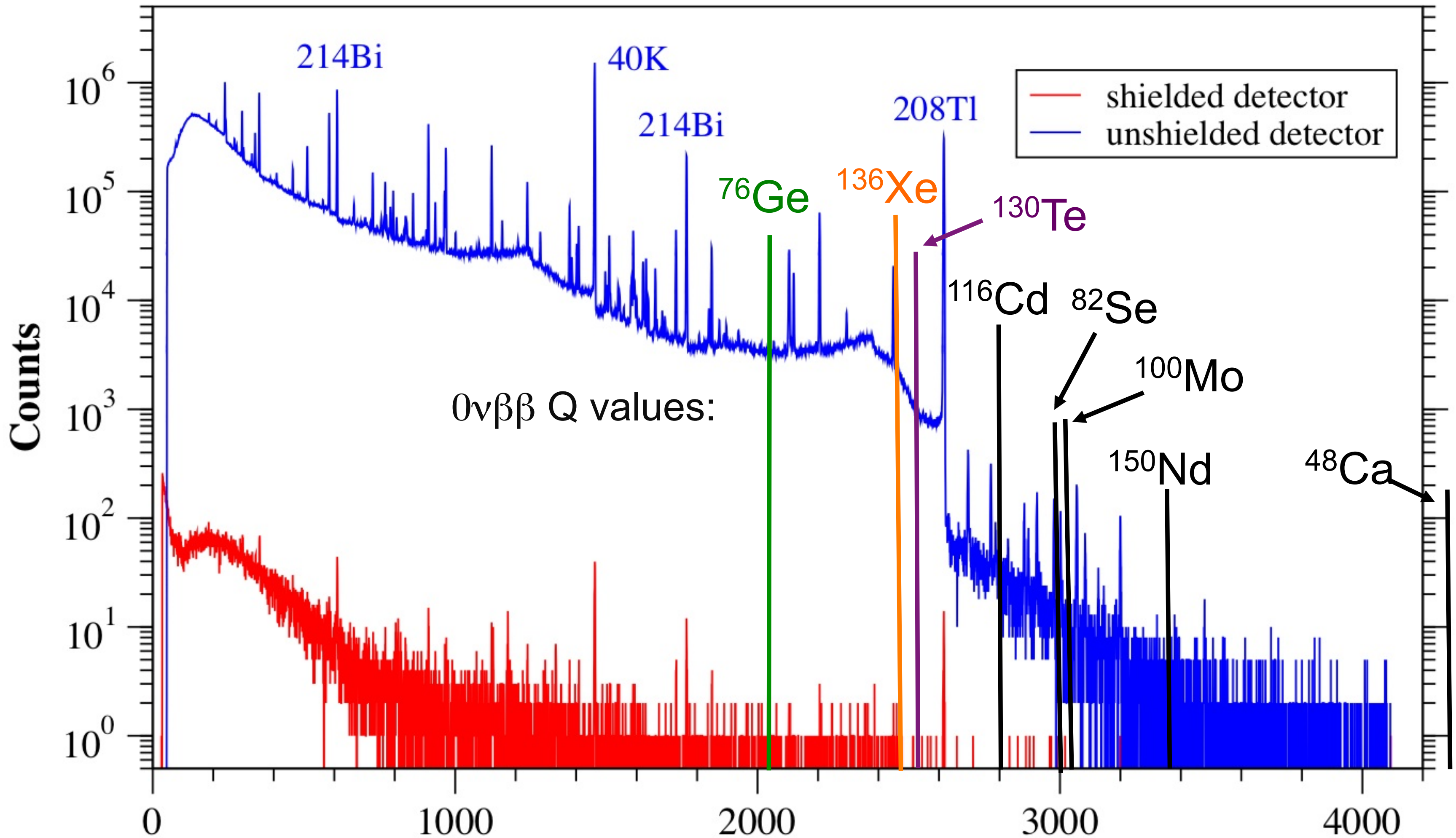
[F. Avignone, S. Elliot, J. Engel, arXiv:0708: 1033v2 (2007)]
† [GERDA Collaboration, arXiv:1307.4720 (2013)]
†† [KamLAND-Zen Collaboration, Phys. Rev. Lett. 110, 062502(2013)]
††† [EXO Collaboration, Phys. Rev. Lett.109, 0322505 (2012)]

Background from Natural Radioactivity



- Natural radioactivities on earth come from U, Th, ^{40}K (long decay lifetime ~ 10^9 yr), or cosmogenic activation, or human related activities.
- U and Th decay via a series α and β decays.
- Most troublesome background comes from high energy (~2MeV) γ rays.

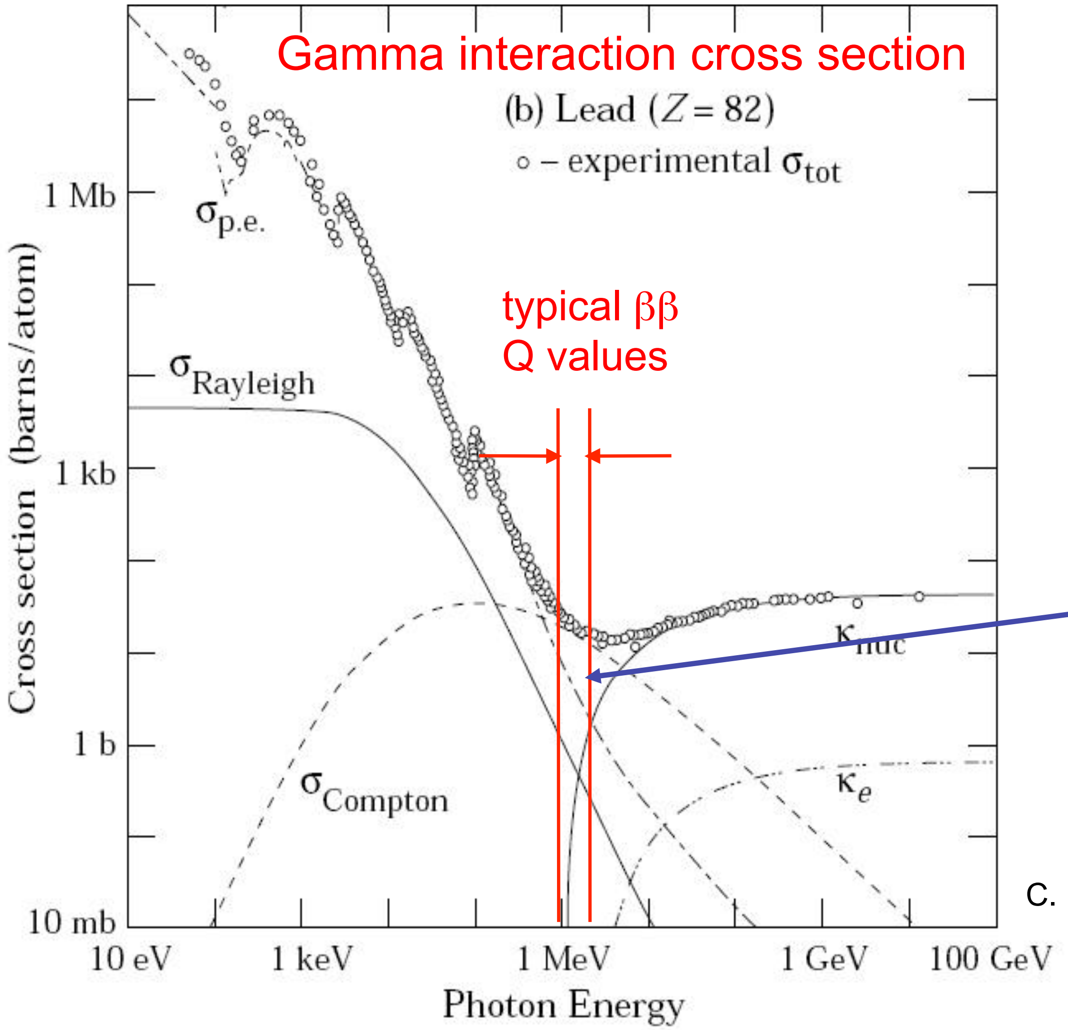
Energy Spectrum of Natural Radioactivity



Although ^{40}K decay energy is below most 0νββ Q values, gammas from U and Th are big background concerns.

Source: http://npgroup.pd.infn.it/luna/images/background.jpg
C. Hall, SnowMass premeting, 2013

Shielding Difficulties

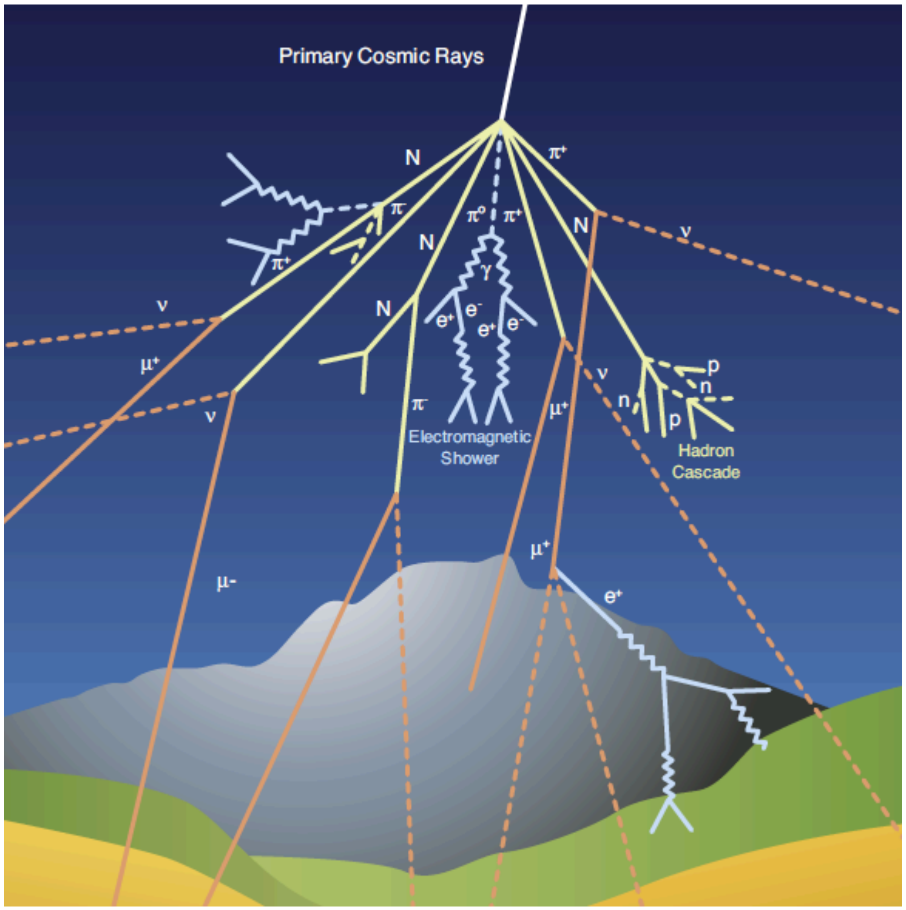


Gammas travel about 2 cm before scattering in lead

C. Hall, SnowMass premeting, 2013

- 1-3 MeV gamma rays are difficult to shield, so passive shielding or self shielding not very effective.
- It is critical to remove background form detector construction materials

Cosmic Ray Background



Source: CERN

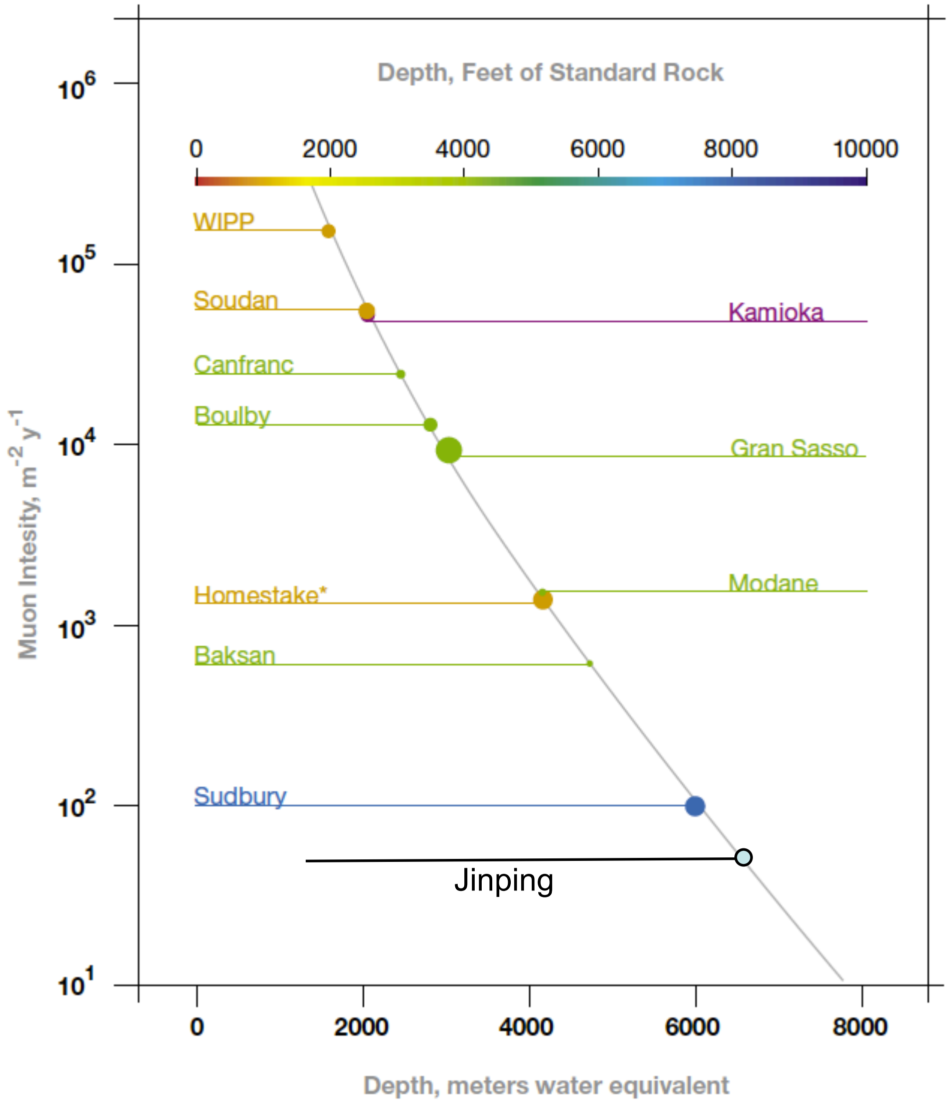
- Cosmic rays striking the upper atmosphere will create a shower of subatomic particles, including energetic muons,

- Cosmic muons can create radioactive isotopes via spallation, neutron activation and other nuclear processes.

- When muon goes through a detector, it can produce radioactive isotopes directly inside the detector.

- Muon can also produce secondary particles in material outside the detector such as fast neutrons, which later interact with the detector material.

Going Underground....



- By going to deeper underground lab, one can effectively shield against cosmic muons.

- At 6600 m.w.e., Jinping lab in Sichuan, China is the deepest underground lab, with a muon flux of ~50/m^2/yr, 9 order of magnitude reduction compared to sea level

- The muon angular and energy distribution depends on the depth, so Monte Carlo simulation is needed to understand the full background from the cosmic ray.

Underground Facilities

GERDA Experiment at Gran-Sasso

- The radioactivity in the underground cavern wall need to be shielded with ultra-clean water or lead.
- Radon purge system, additional neutron shielding, muon veto may also be required for the experiment.
- To minimize cosmogenic activation, detector material may need to produced or machined underground.

Facility	Depth [m.w.e.]	μ Flux [events / (m^2 ·year)]	Rock	^{238}U [Bq/kg]	^{232}Th [Bq/kg]	^{40}K [Bq/kg]
Jinping (PandaX)	6,600	66	marble	1.8 ± 0.2	< 0.27	< 1.1
Homestake	4,500	950	rhyolite	100	45	900
Grand Sasso – Hall B	3,500	8,030	dolomite	5.2	0.25	4.9

Underground lab rock radio-activity comparison

Experimental Methods*

Tracking Detectors:

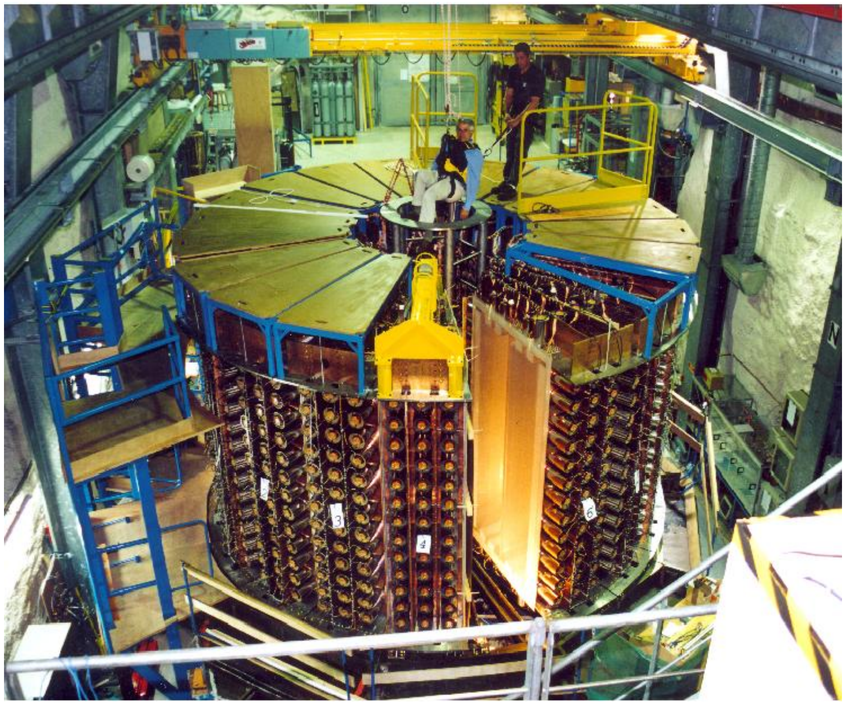
- Use tracking information of two decay electrons to reject background.
- Often in Source ≠ Detector configuration.
- The same detector can be used to study multiple isotopes (NEMO).
- Not easy to scale to large isotope mass.

Calorimeter Detectors:

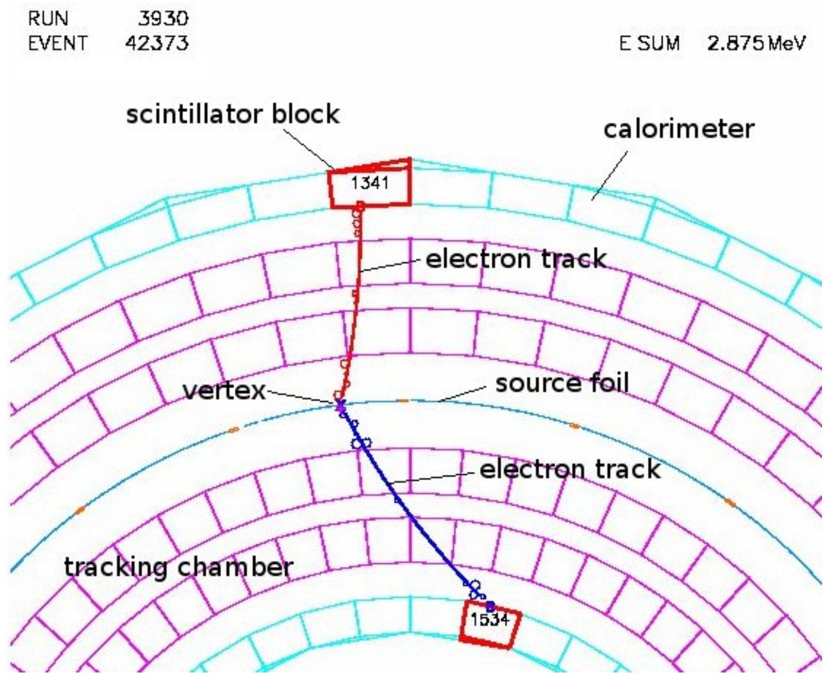
- Concentrate on measuring the sum electron energy accurately.
- Often in Source = Detector configuration
- Diverse detector techniques based on properties of the isotope under study
  - Bolometric detector (Te) (CUORE)
  - Semiconductor crystalline detector (Ge) (GERDA, MAJORANA)
  - Gas and liquid TPC (Xe) (EXO, NEXT)
  - Scintillation detector (Xe, Te, Nd …) (Kamland-Zen, SNO+)
- Cannot measure angular correlation, single electron energy, etc

* Some experiments use both tracking and calorimetric techniques, such as NEXT.

Tracking Detector: NEMO-3



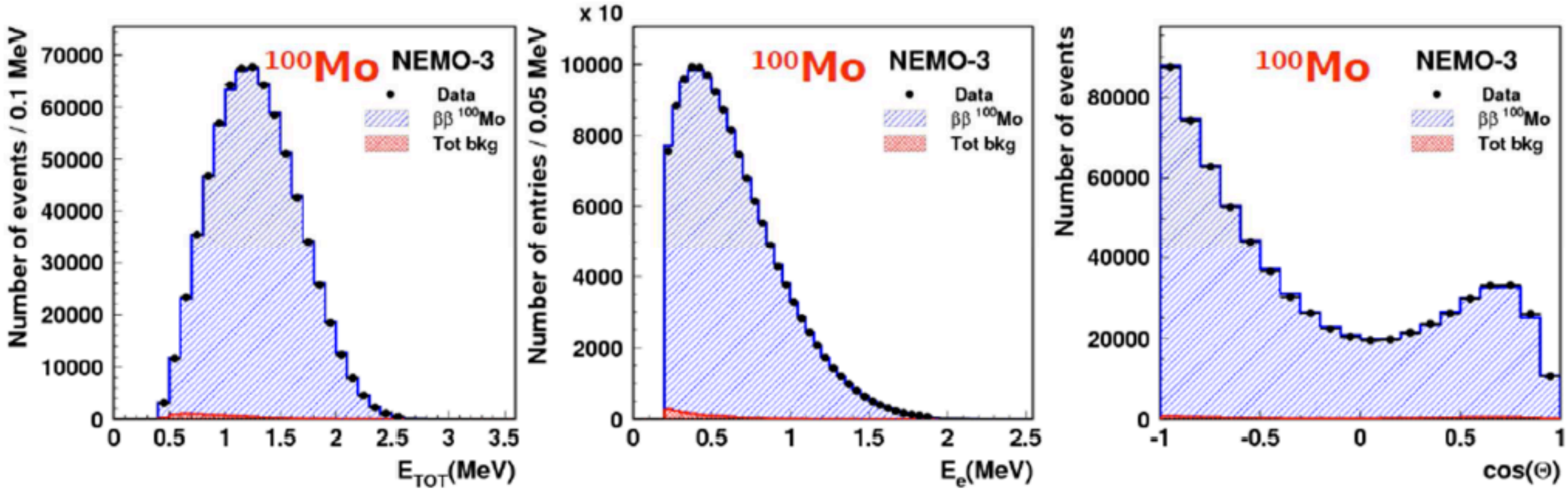
NEMO-3 detector



An ^{100}Mo $2\nu\beta\beta$ 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: 2νββ Results



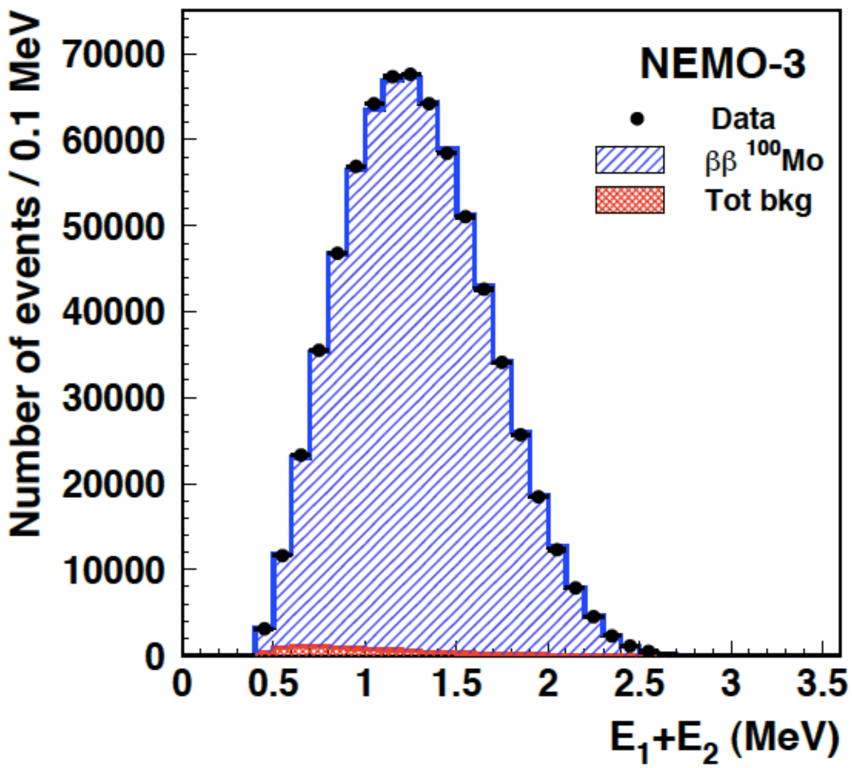
Electron sum energy | Single electron energy | Angular distribution

^{100}Mo $T_{1/2}^{2\nu\beta\beta}$:[7.16 ± 0.01 (stat) ± 0.54 (sys)] 10^{18} y

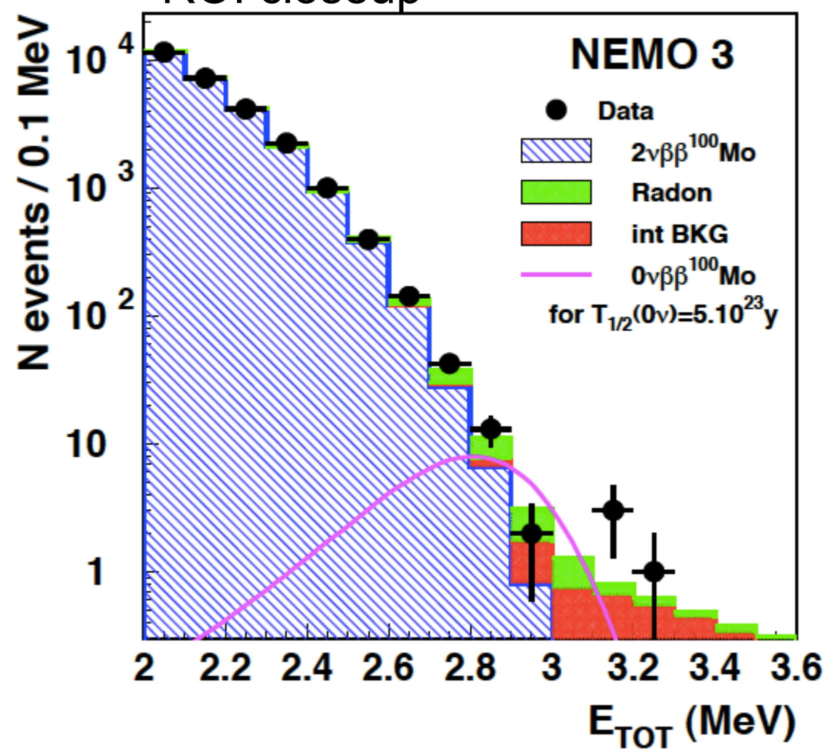
- Measured 2νββ half life for ^{100}Mo, ^{82}Se, ^{116}Cd, ^{130}Te, ^{150}Nd, ^{96}Zr and ^{48}Ca.
- Ratio of Signal/Background > 70, most halflife measurements are systematic limited
- Beautiful spectra of single electron energy and angular distribution between two decay electrons demonstrate the power of the tracking method.

NEMO-3: 0νββ Result (^{100}Mo)

Full spectrum



ROI closeup



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

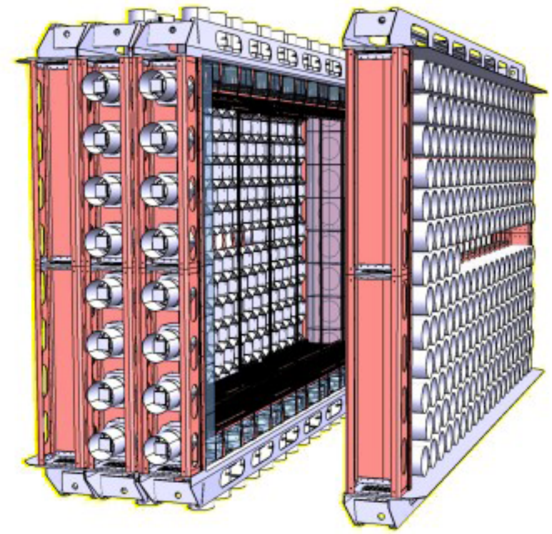
Exposure: 31.2 kg yrs

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

$m_{\beta\beta} < 0.45 – 0.93$ meV

Phys. Atom. Nucl. (2011) 74 312.

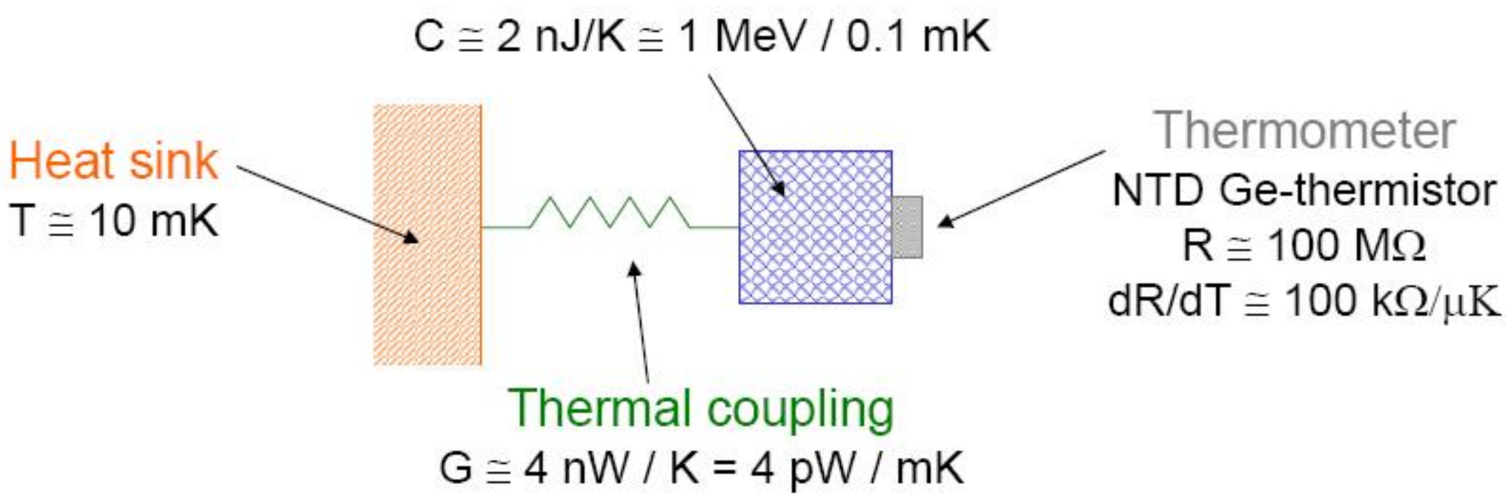
NEMO-3 → SuperNEMO

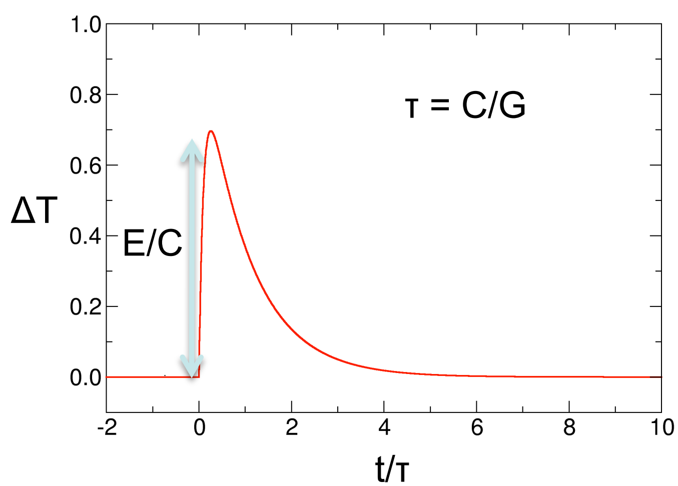


NEMO-3	Super-NEMO
1 cylindrical module	> 20 planar modules
7 kg ^{100}Mo	100-200 kg ^{82}Se (or ^{150}Nd, or ^{48}Ca)
8% FWHM @ 3MeV	4% FWHM @ 3MeV
	Factor of 10 reduction in background
$m_{\beta\beta} < 0.3 - 1$eV	$m_{\beta\beta} < 40 - 100$ meV

7 kg ^{82}Se demonstrator module under operation soon!

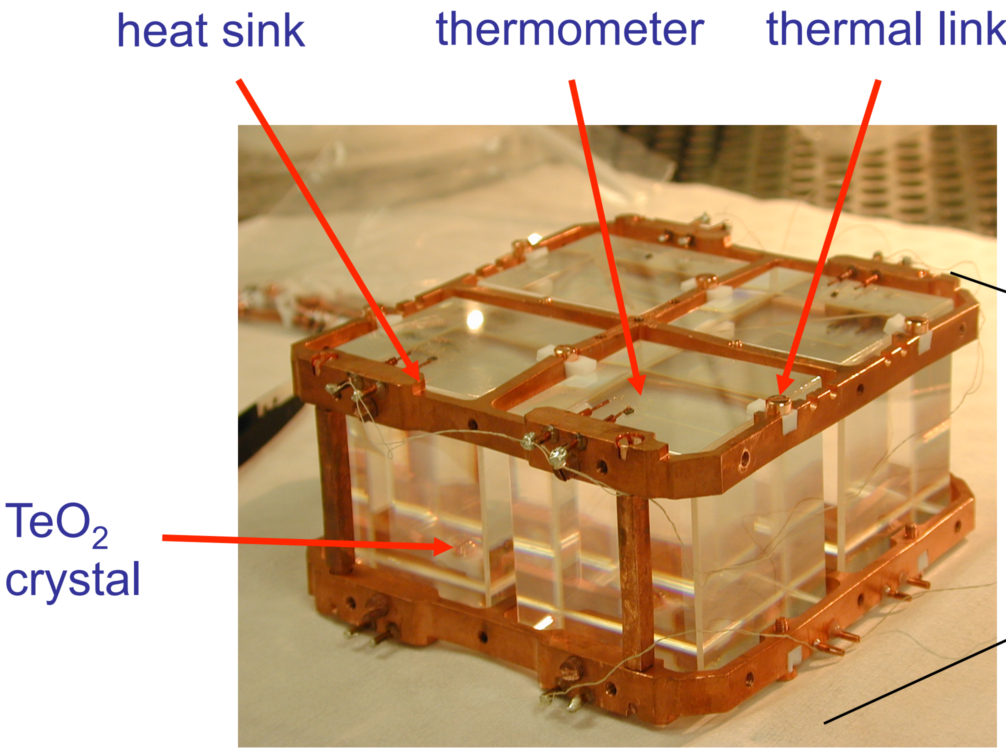
Cryogenic Bolometer: ^{130}Te

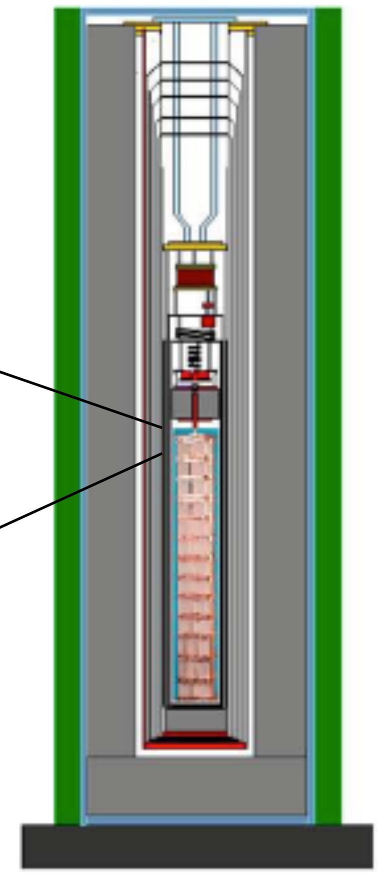




- Measure total energy deposited in the crystal.
- Techniques applicable to many isotopes. Te has the highest natural abundance.
- High energy resolution, 7-9 keV @ 2530keV.
- No information about the particle ID, external γ and surface degraded *α* are major background concerns.

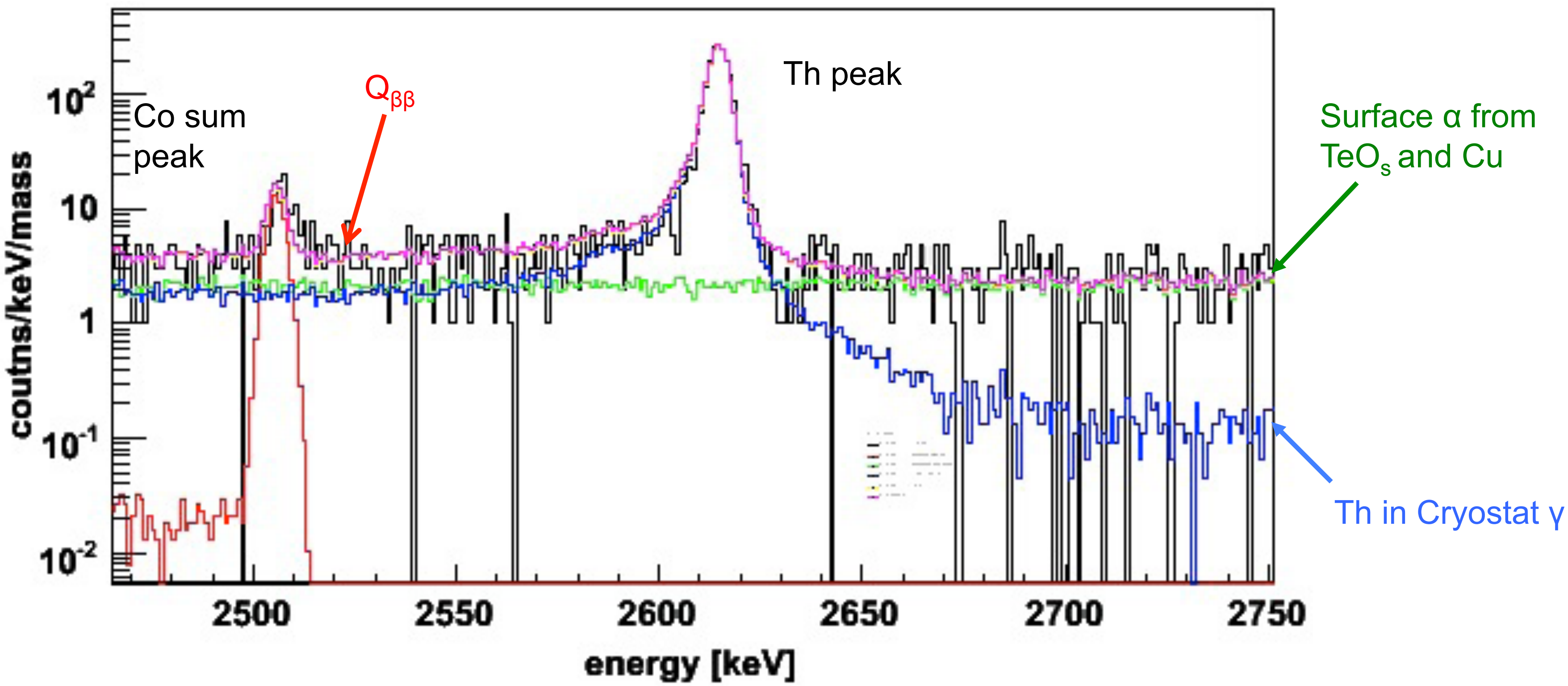
CUORICINO: Experimental Setup





- 44 5x5x5 cm^3 and 18 3x3x6 cm^2 TeO_2 crystals
- 40.7 kg Te and 11.6 kg of ^{130}Te
- Operation temperature: 8mK

COURICINO: 0νββ Result



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

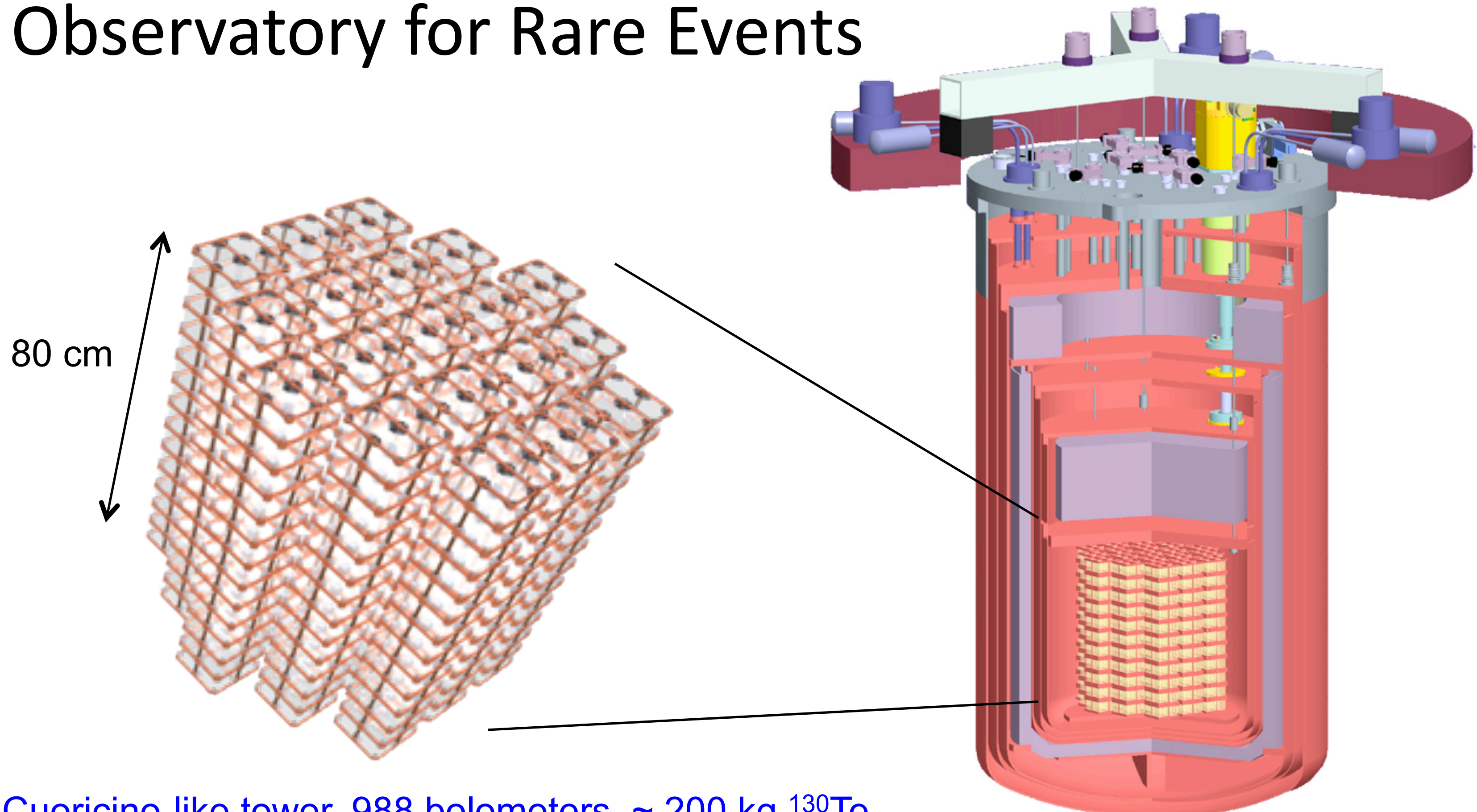
Total exposure: 19.75 kg yr ^{130}Te

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

$m_{\beta\beta} < 0.41 - 0.98$ eV

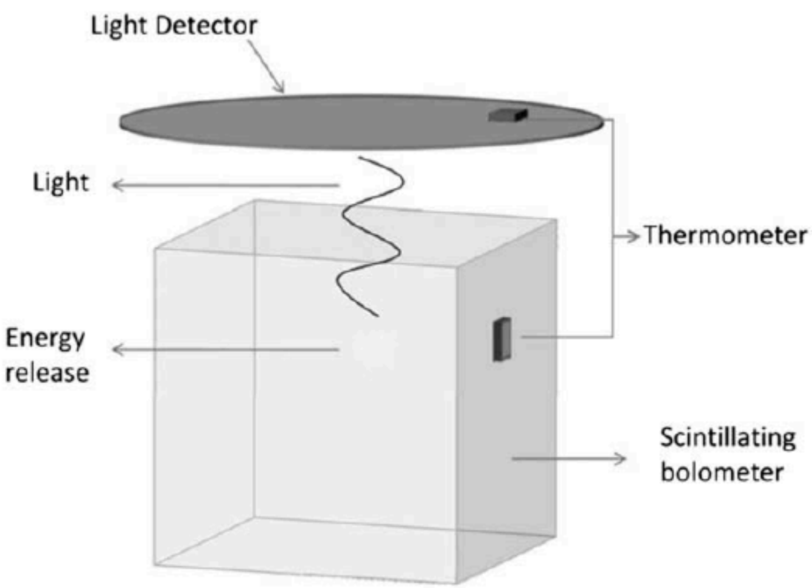
E. Andreotti et. al. Astropart. Phys. 34, 822 (2011)

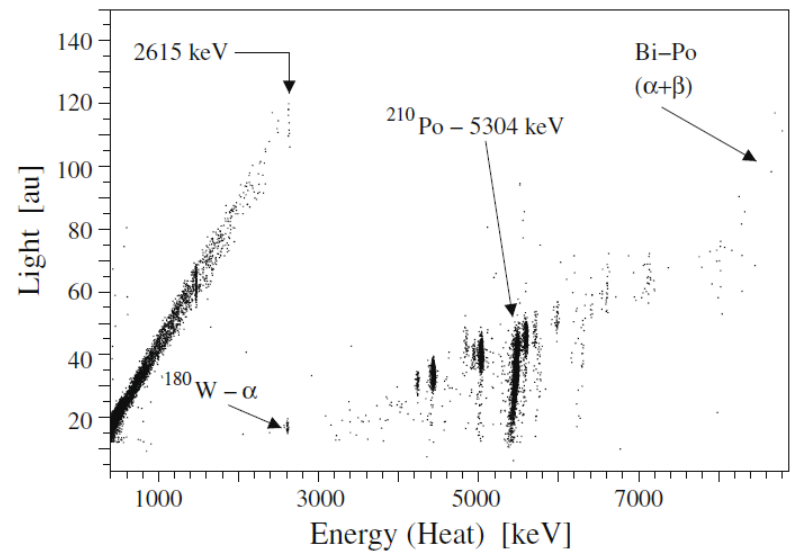
CUORE: Cryogenic Underground Observatory for Rare Events



- 19 Cuoricino-like tower, 988 bolometers, ~ 200 kg ^{130}Te
- Background goal 0.01 cnt/(keV kg yr), a factor 10-20 reduction
- Energy resolution 4.6 keV
- 5 year sensitivity, $T_{1/2}^{0\nu\beta\beta} > 1.6 \times 10^{26}$ yrs, $m_{\beta\beta} < 41 - 95$ meV

Scintillating Bolometer



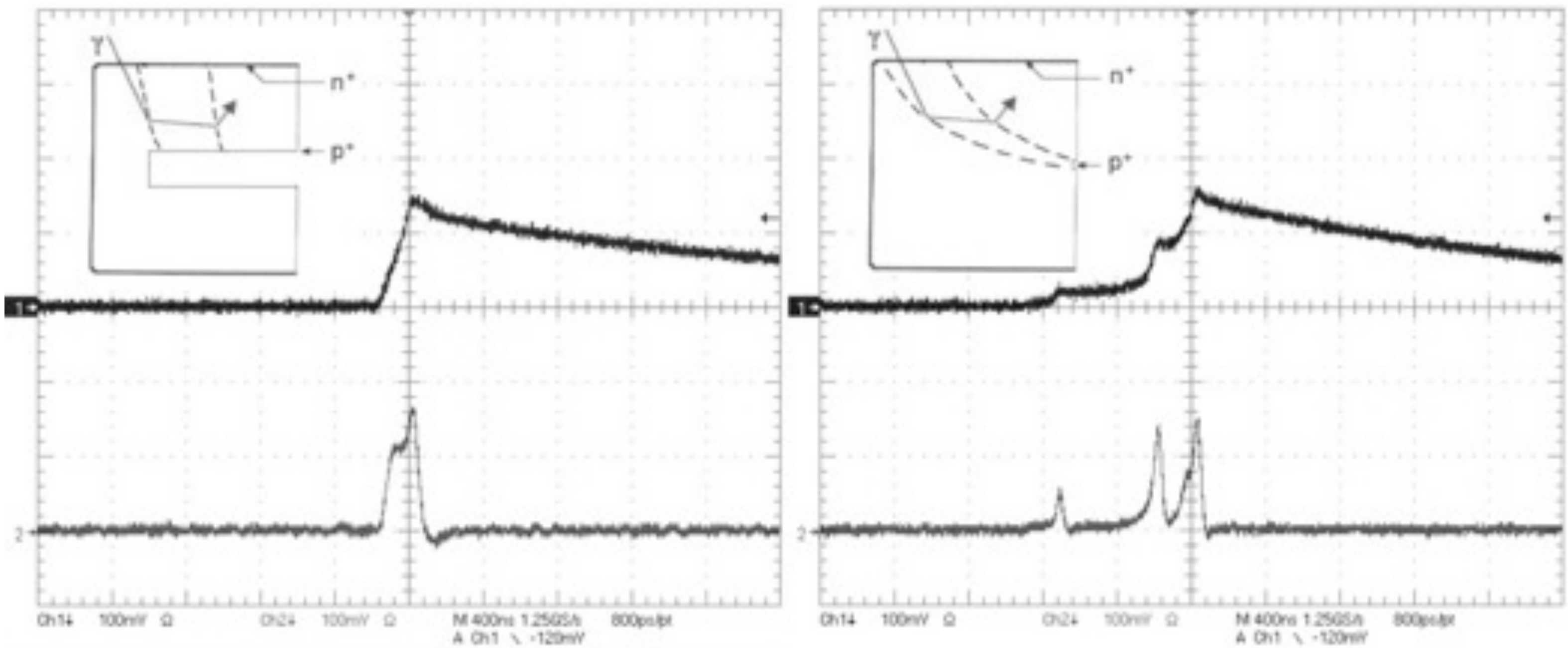


Test data with $CdWO_4$

C.Arnaboldi et. al., arXiv: 1005.1239

- Combined light/heat information from a scintillation bolometer is very effective at rejecting surface α events.
- R&D efforts underway for $CdWO_4$, ZnSe, $ZnMoO_4$ and $CaMoO_4$

Semiconductor Detector: ^{76}Ge



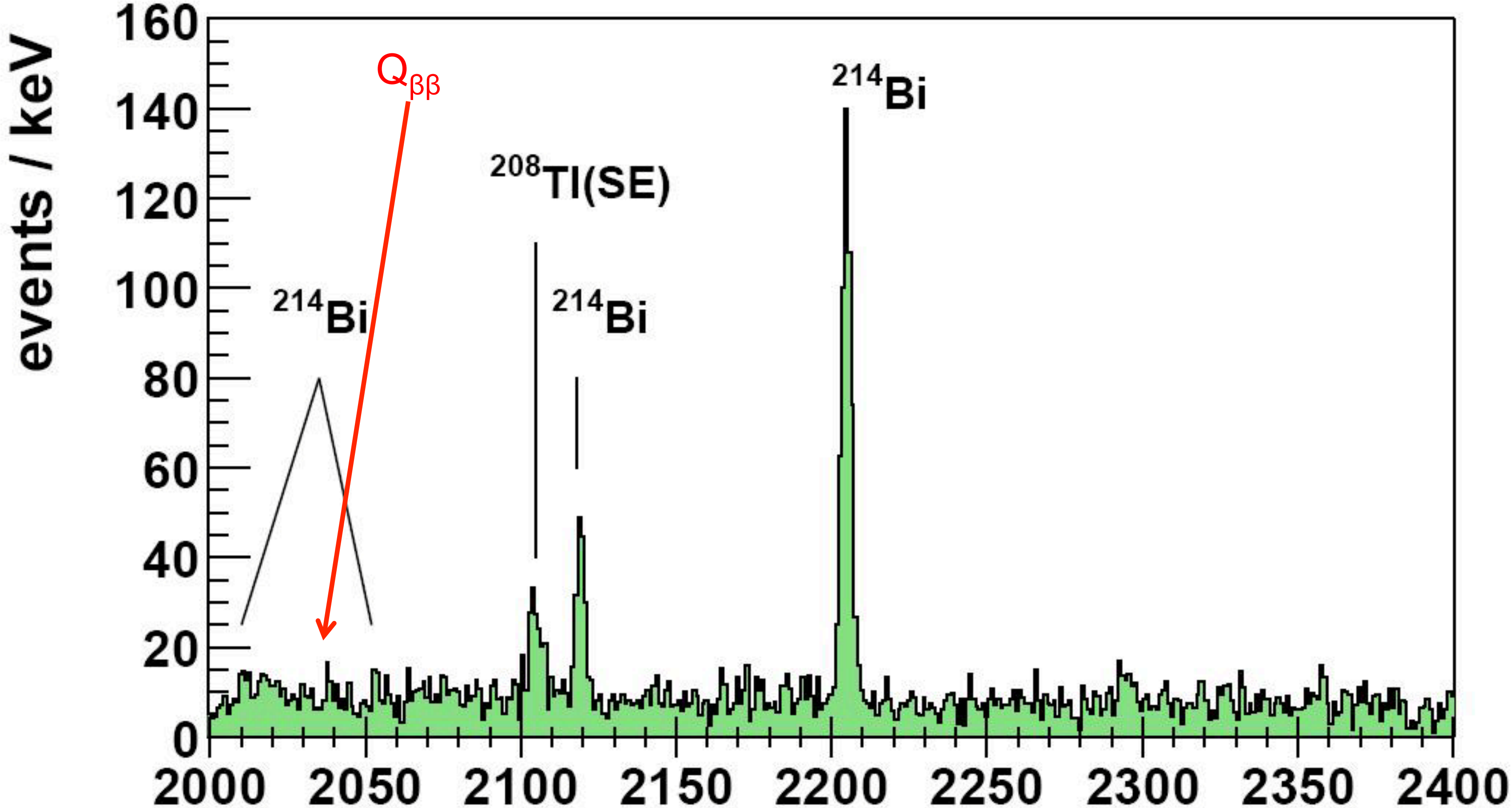
P-type semi-coaxial Detector P-type point contact Detector*

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.

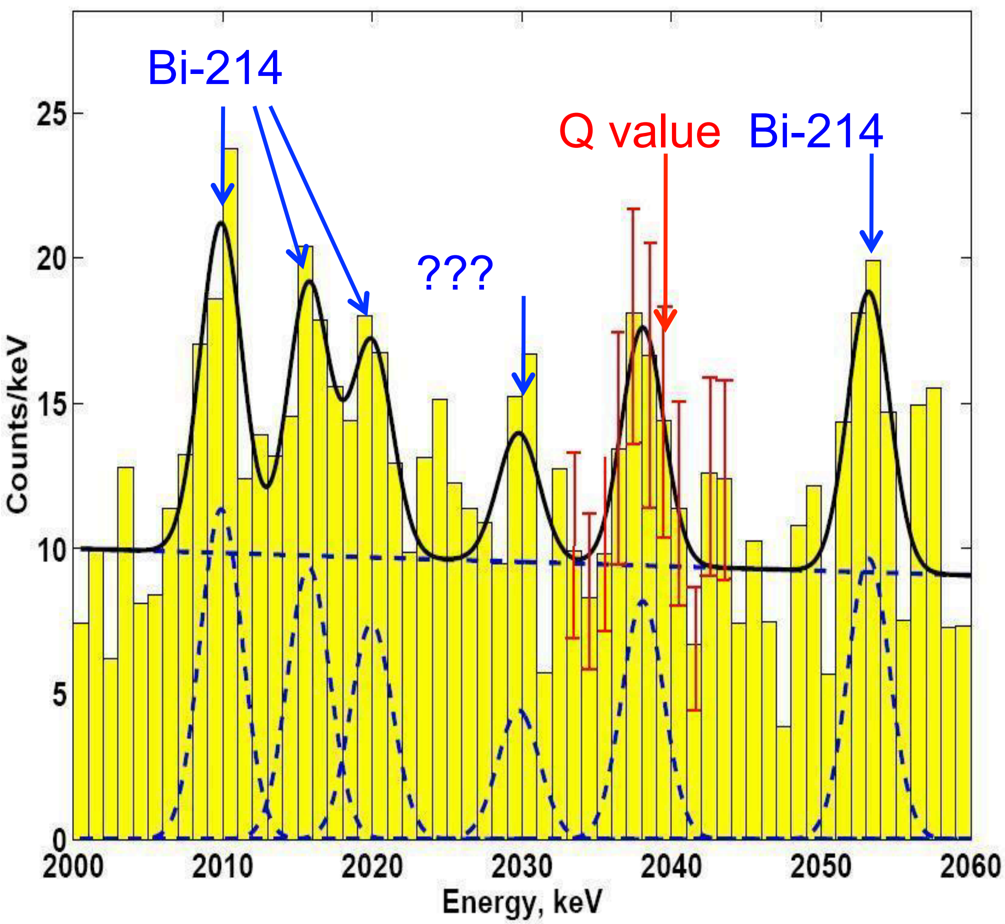
$0\nu\beta\beta$ Discovery Claim



Publication by part of the Heidelberg-Moscow Collaboration, often referred to as the Klapdor's (or KKDC) claim.

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

0νββ Discovery Claim – 2004



Spectrum near ROI

Fit model: 6 Gaussian + linear background

Four lines at 2010, 2016, 2022 and 2053 are consistent with γ from ^{214}Bi

^{214}Bi intensity from fit is 2 – 2.5 σ larger than MC prediction.

An unknown line at 2030, electron conversion of ^{214}Bi 2118 keV line?

Total exposure: 71.7 kg•yr ^{76}Ge

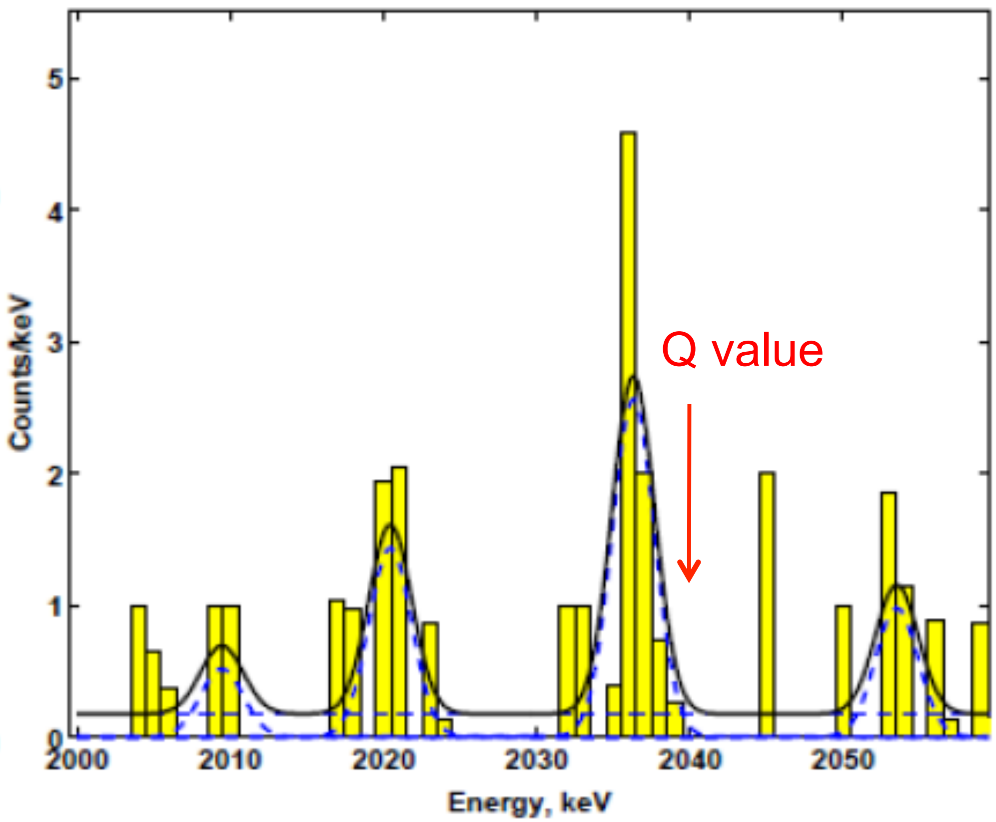
Fit intensity @ $Q_{\beta\beta}$= 28.75 ± 6.86

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

$0\nu\beta\beta$ Discovery Claim (PSA) – 2006



Spectrum near ROI,
after pulse shape analysis

A special pulse shape analysis (PSA) is applied to the data which selects only ββ like events.

Background in ROI dropped from 0.17 cnts/(keV kg yr) to 0.015 cnts/(keV kg yr)

PSA efficiency not quoted in the paper, but a value of 100% is used.

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

Authors claim significance of 6.5 σ.

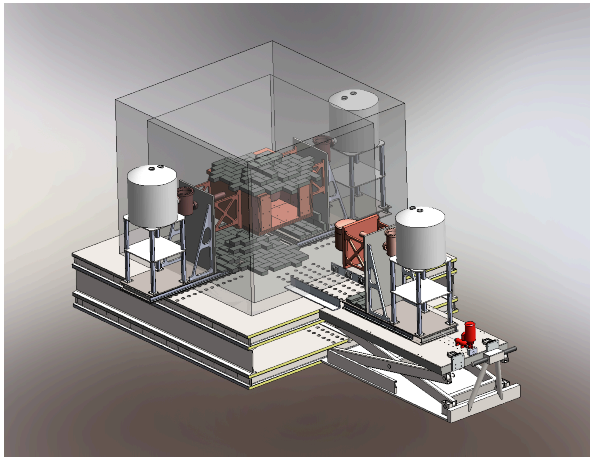
$T_{1/2}^{0\nu} = 2.23_{-0.31}^{+0.44} \times 10^{25}$ yr.

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

Mod. Ge Exps: MAJORANA and GERDA

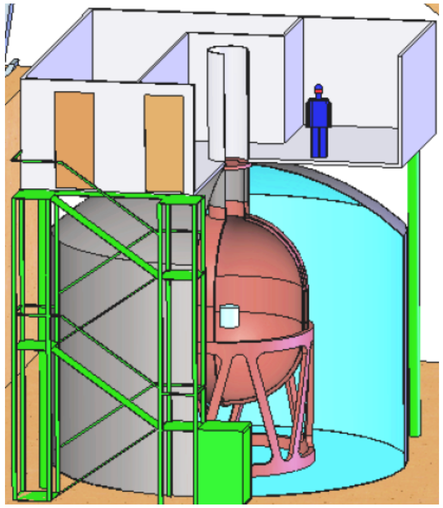
- ^{76}Ge experiments can check the Klapdor claim in a model independent way.
- More than ten times lower background.
- Superior detector technology, enriched BEGe, (MAJORANA and GERDA Phase II)

MAJORANA



- Use electroformed high purity Co as shielding, Cu/Pd passive outer shielding
- 4π plastic scintillator veto.
- DEMONSTRATOR: 30 kg ^{enr}Ge, 10 kg ^{nat}Ge

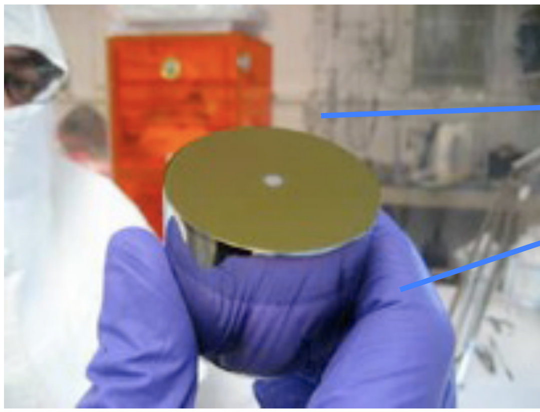
GERDA

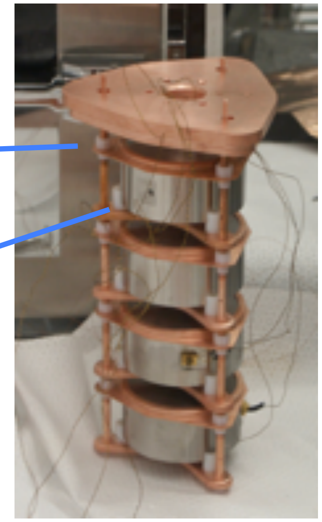


- Operate 'bare' Ge crystal in liquid Ar
- Liquid Ar can be used as active veto
- Water Cherenkov μ veto
- Phase I: ~ 18 kg, Phase II: + 20kg

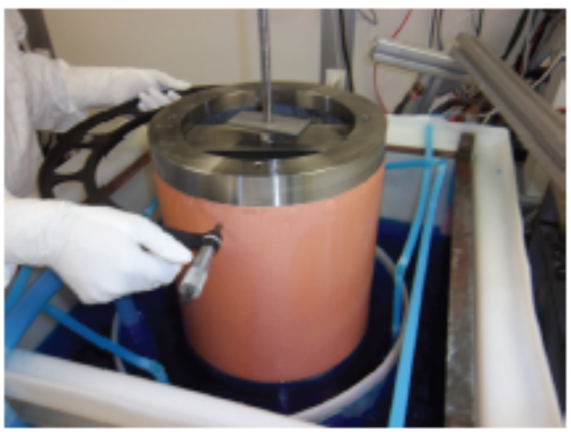
Very different background reduction strategy. Intention to merge for tonne scale experiment with the best techniques.

MAJORANA DEMONSTRTOR





Enriched P-type point contact detector assembly



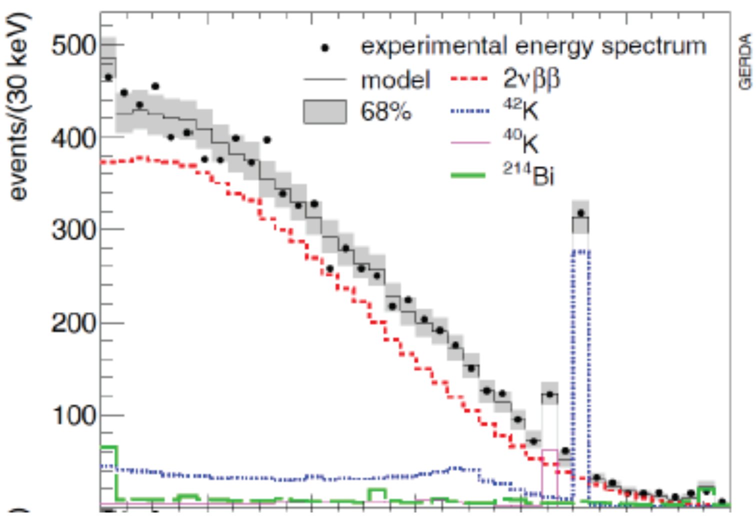
Electroformed copper

- Full detector commissioning in 2014
- Physics data taking in 2015
- Physics opportunity for low-mass dark matter search.

GERDA Status

Construction, 08-10

Deployment of three strings of detector. Phase I physics data take start in Nov. 2011

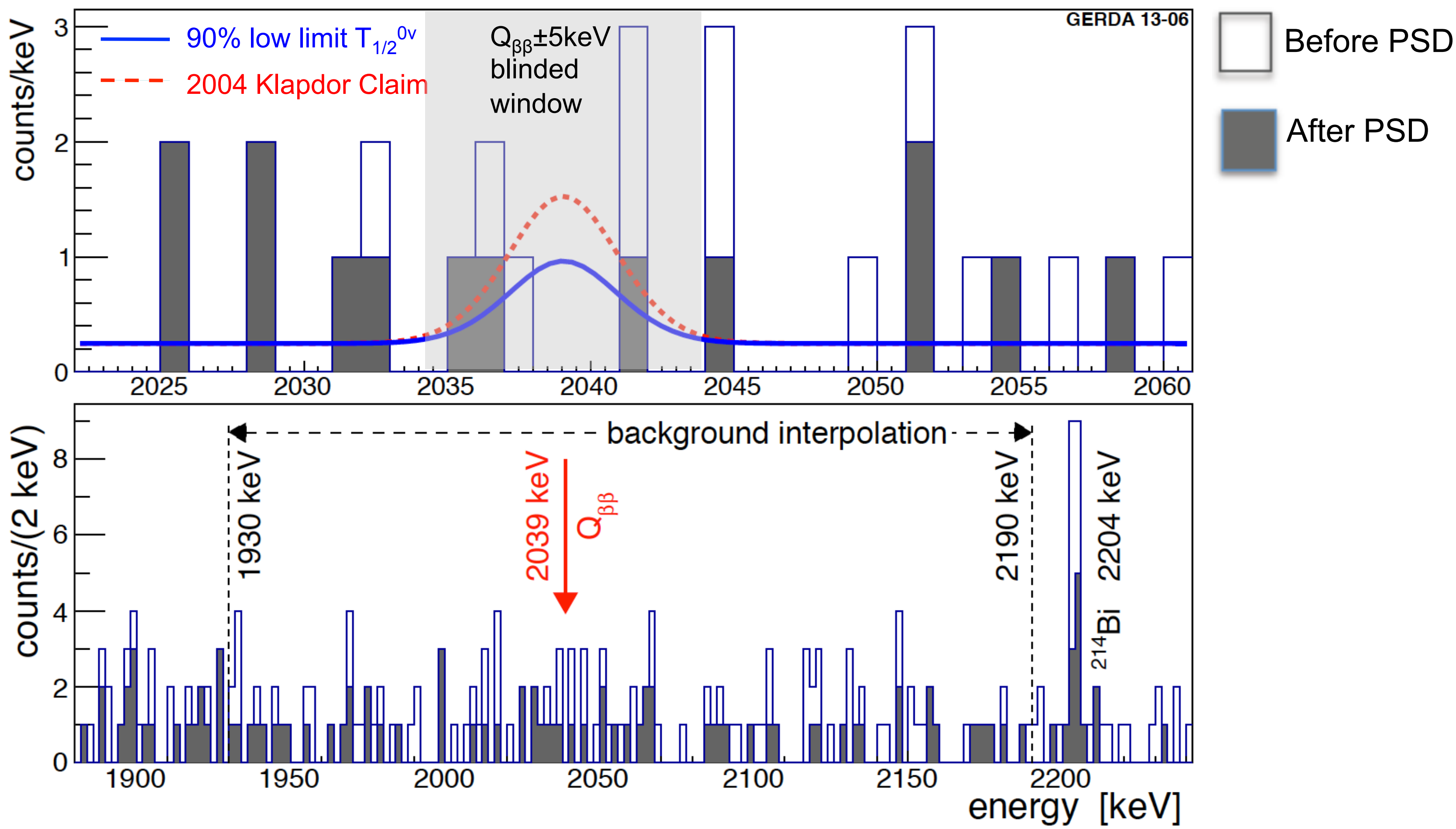


Measurement of ^{76}Ge 2νββ with 5.04 kg yr exposure

- Data taken with 8 enriched diodes from HdM and IGEX, plus one natural
- June 2012, deployed 5 Phase II BEGe detectors
- 0νββ data set unblinded in June, 2013
- Phase I results presented in July, 2013

GERDA Phase I Result

[GERDA Collaboration], arXiv, 1307.4720 (2013)



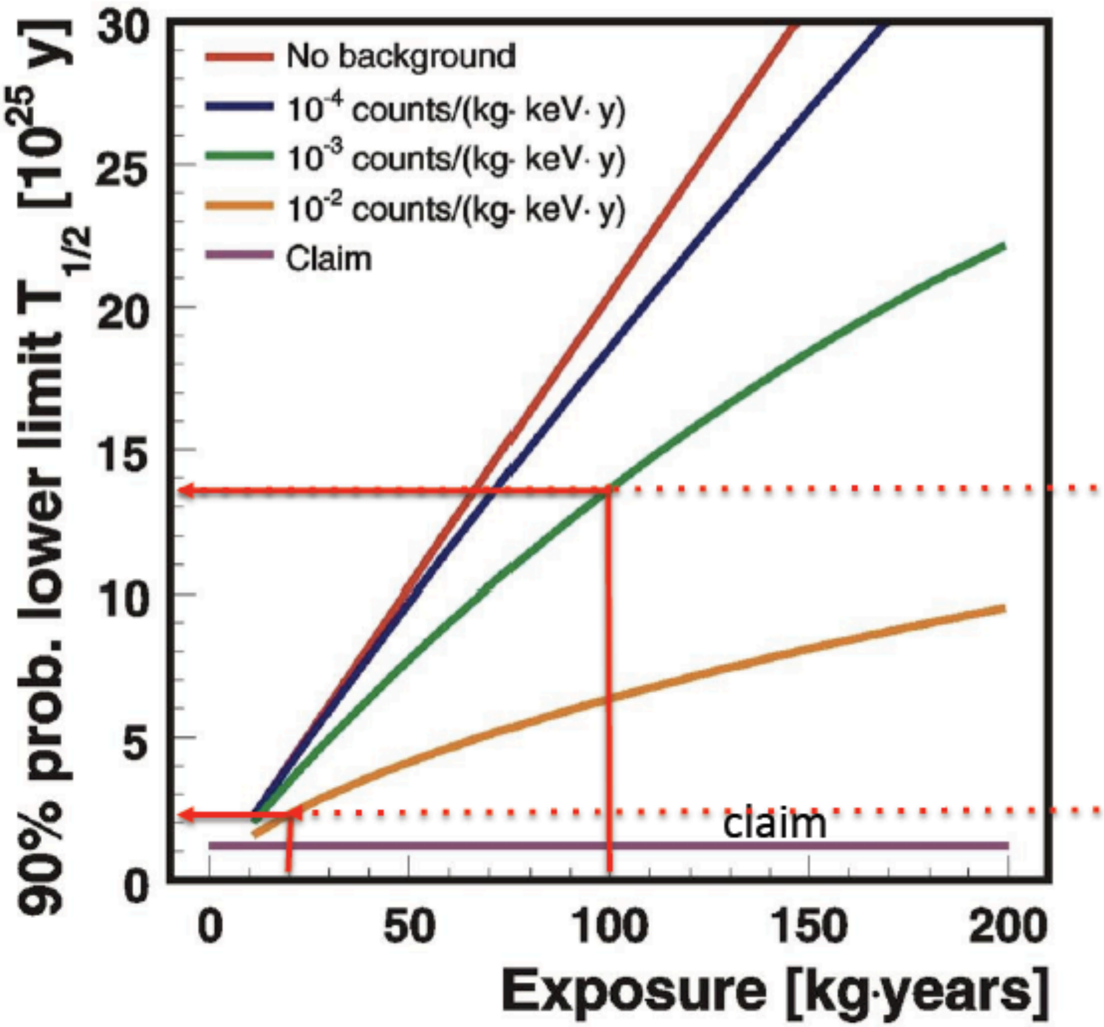
Total exposure: 21.6 kg yr

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

$T_{1/2}^{0\nu} > 2.1\times10^{25}$ yr (90% C.L.)

2004 claim strongly disfavored!

GERDA Sensitivity

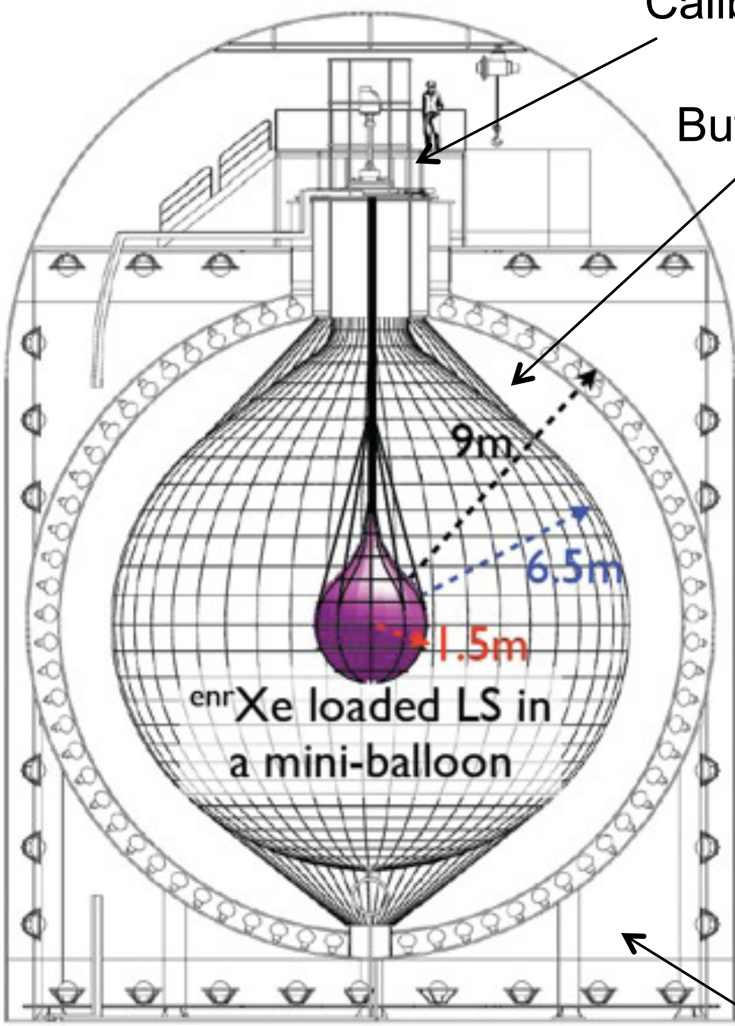


Phase II:
Add new enr. BEGe detectors (20 kg)
BI ≈ 0.001 cts / (keV kg yr)
Sensitivity after 100 kg yr

Phase I:
Use refurbished HdM & IGEX (18 kg)
BI ≈ 0.01 cts / (keV kg yr)
Sensitivity after 20 kg yr

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

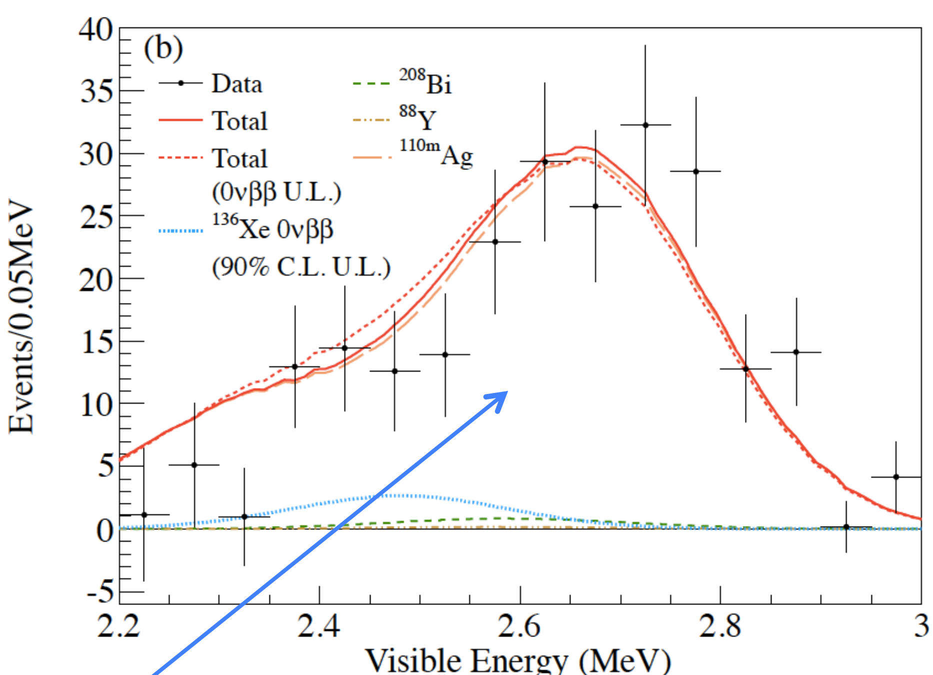
Scintillation Detector: Kamland-Zen



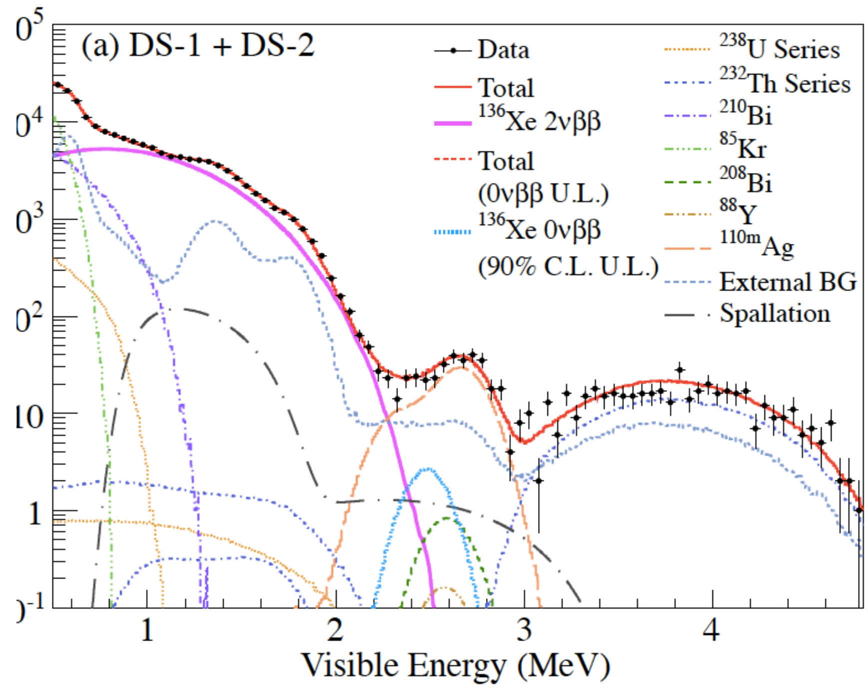
- Experience with large liquid scintillator detectors show that LS can be made extremely pure.
- Radioactivity from PMTs and vessel can be shielded by LS and confining double beta decay isotopes inside a central volume.
- Pro: can be scale to large mass fairly easily. Most detector background well understood. 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

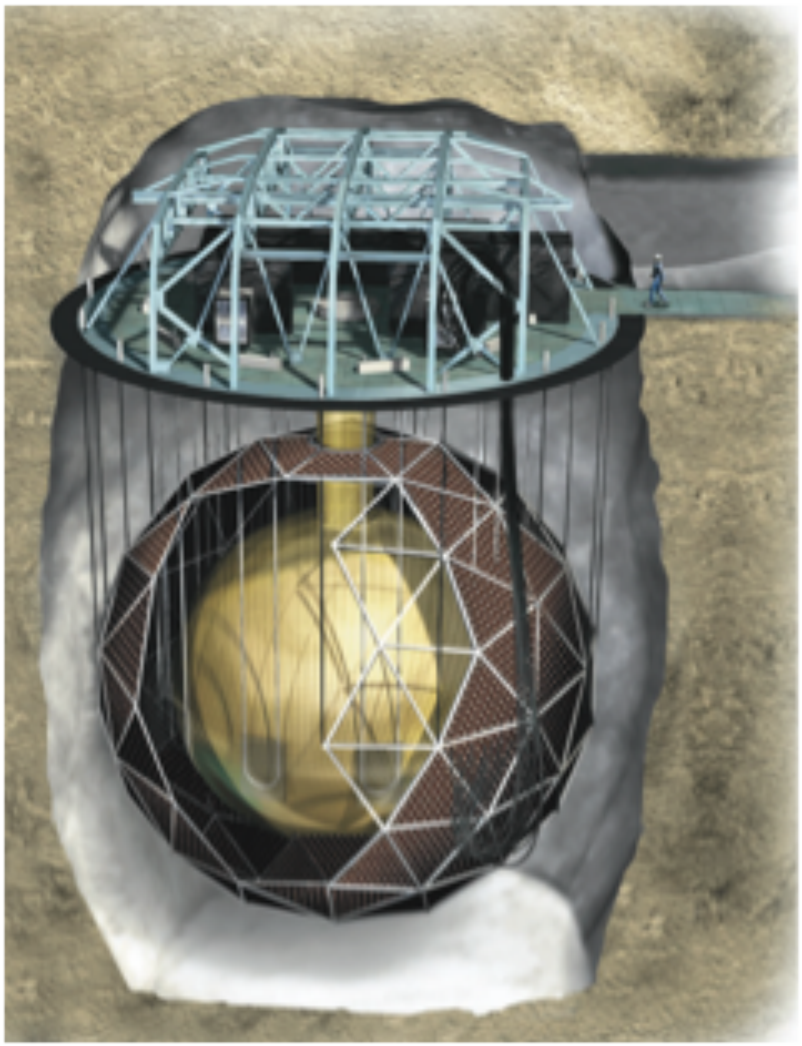


^{110m}Ag Bg from Xe cosmogenic spallation production suspected. Xe purification underway.

$T_{1/2}(\beta\beta0\nu) > 1.9 \times 10^{25}$ yr (90% C.L.)
$m_{\beta\beta} < 140 - 380$ meV
Exposure: 89.5 kg yr

Phys. Rev. Lett 110, 062502 (2013)

SNO+

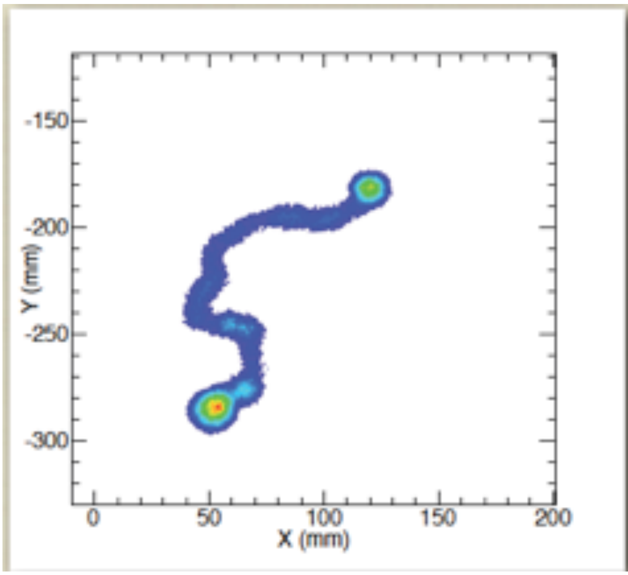


Reuse the SNO detector, replace D_2O with liquid scintillator doped with double beta decay isotope.

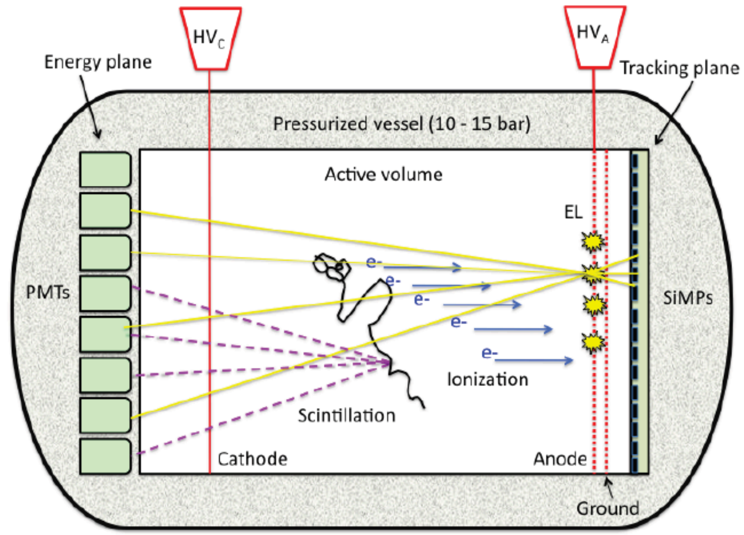
Isotope of choice has changed from Nd to Te

Scintillator data expected in 2014

Time Projection Chamber (TPC): NEXT



Simulated 0νββ track

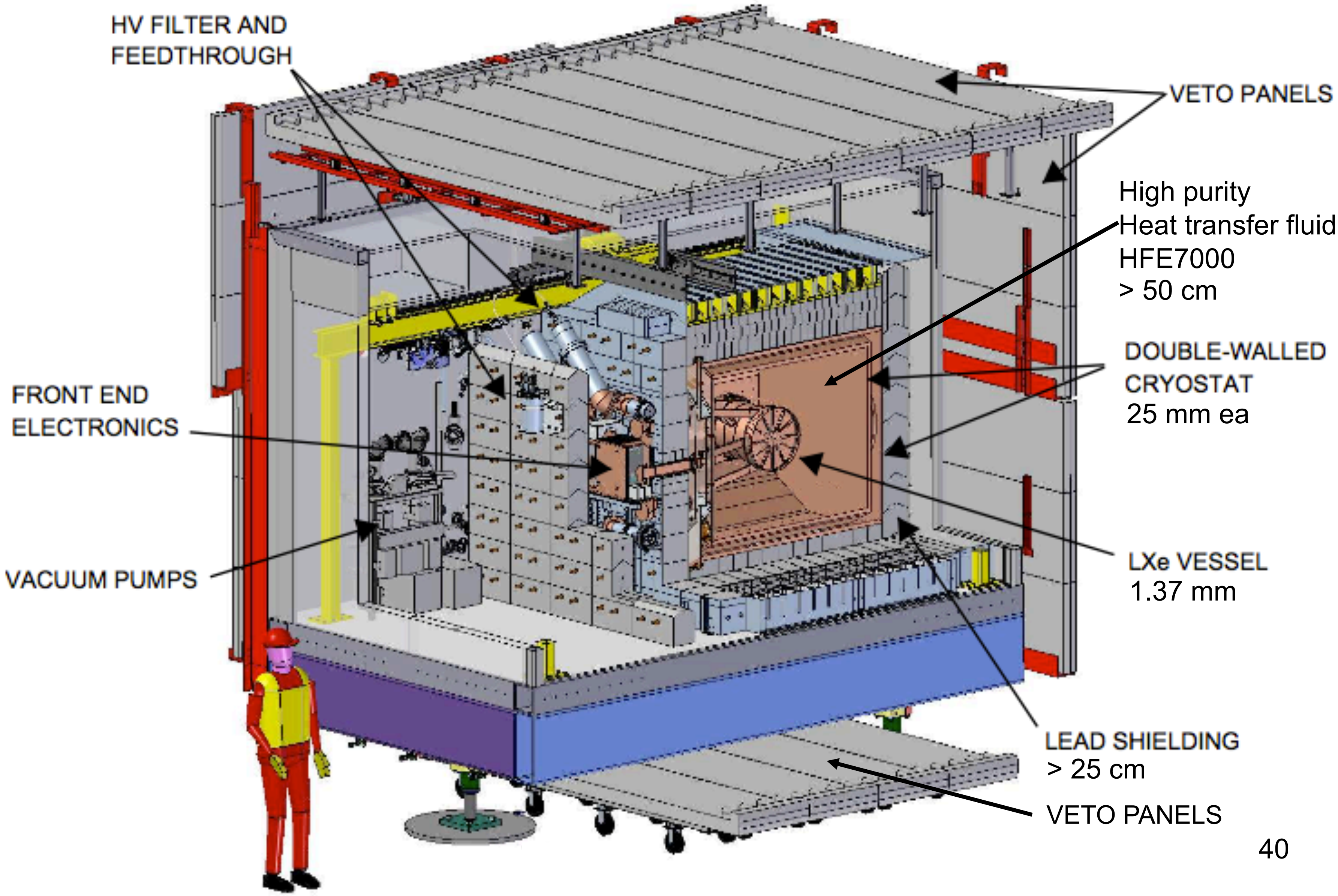


Detector design

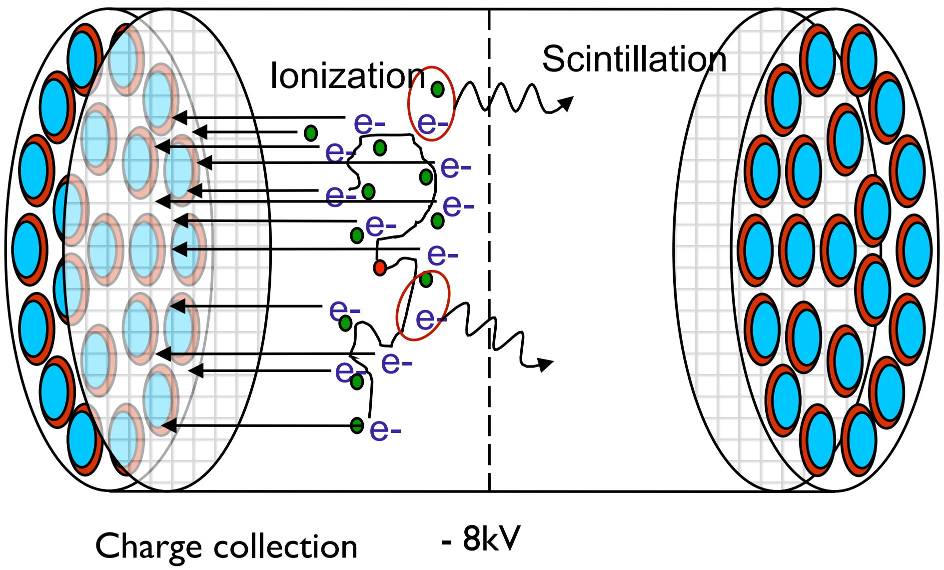
NEXT technical design report, arXiv:1202:0721

- Neutrino Experiment with a Xenon TPC (NEXT) is a high pressure (10 bar) gas ^{136}Xe experiment
- Energy resolution < 1%, background index 10^-4 counts/(keV kg y)
- High gamma background rejection (~10^6) using event topology.
- Commissioning of the NEXT-100 detector planned in 2014.

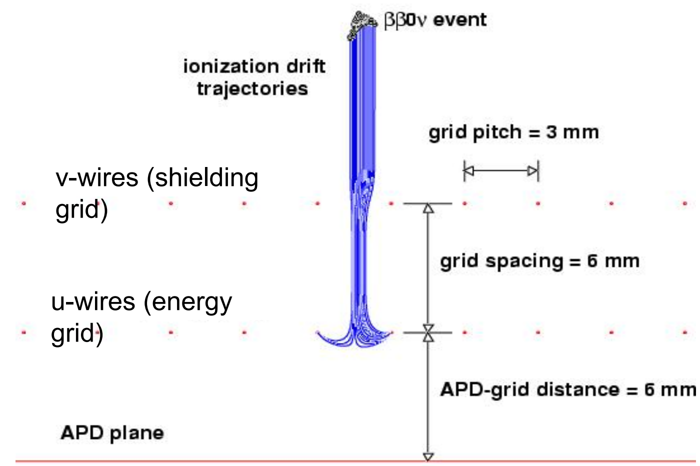
The EXO-200 Detector: Liquid Xenon TPC



EXO-200 Time Projection Chamber (TPC)



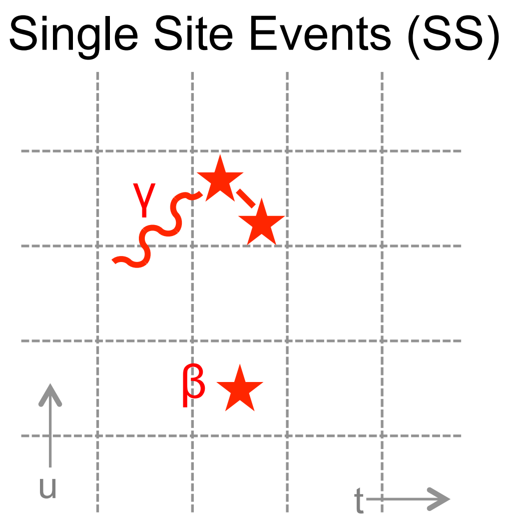
TPC Schematics

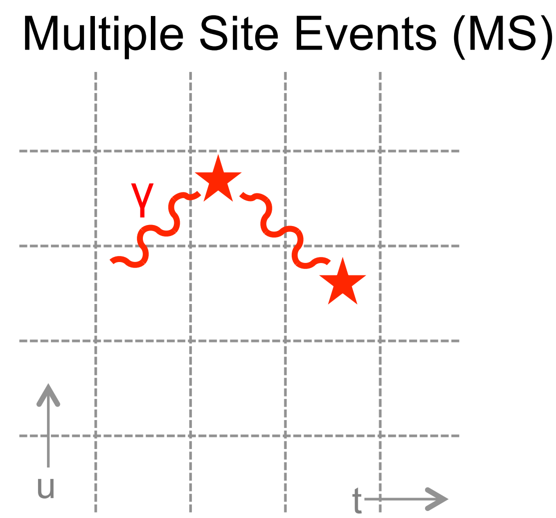


Simulation of Charge Drift

- Two TPC modules with common cathode in the middle.
- APD array observes prompt scintillation for drift time measurement.
- V-position given by induction signal on shielding grid.
- U-position and energy given by charge collection grid.

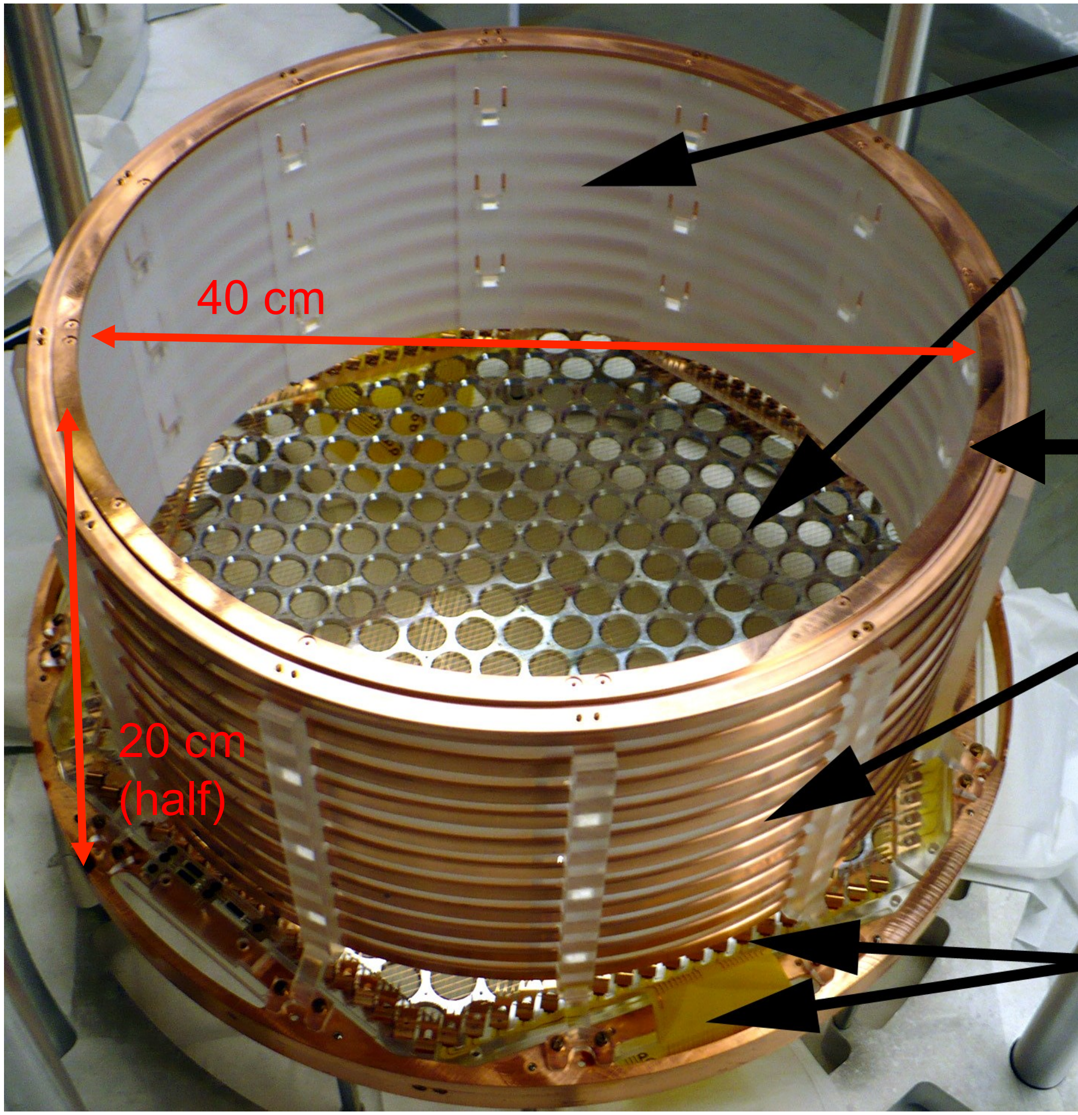
Topological Event Information





- The time projection chamber allows the rejection of some gamma backgrounds because Compton scattering results in multiple energy deposits.
- We can distinguish multiple charge deposits with resolution 18 mm in u, and 6 mm in z.
- SS/MS discrimination is powerful tool not only for background rejection, but also for signal discovery

EXO-200 TPC



Teflon Reflectors
(increase light collection)

APD plane and wire planes
(wires are photo-etched)

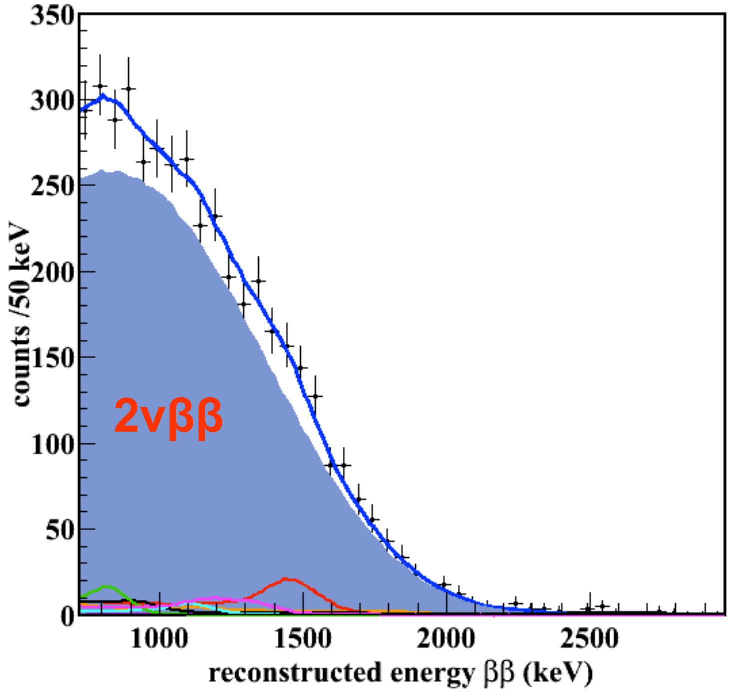
Central HV plane
(photo-etched phosphor bronze)

Acrylic supports
and field
shaping rings

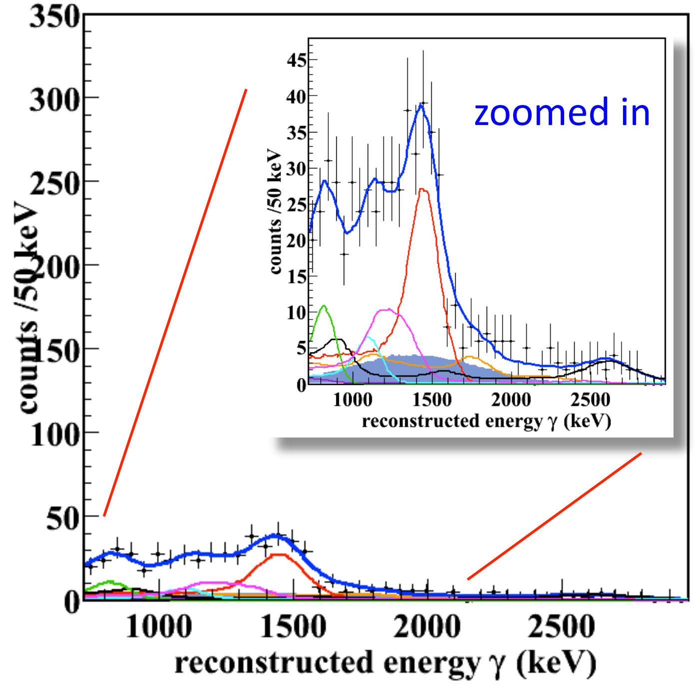
Kapton flex cables
(spring connections
eliminate solder joints
and glue)

First observation of the 2νββ decay in ^{136}Xe (2011)

single - cluster



multiple - cluster



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

[Ackerman et al Phys Rev Lett 107 (2001) 212501]

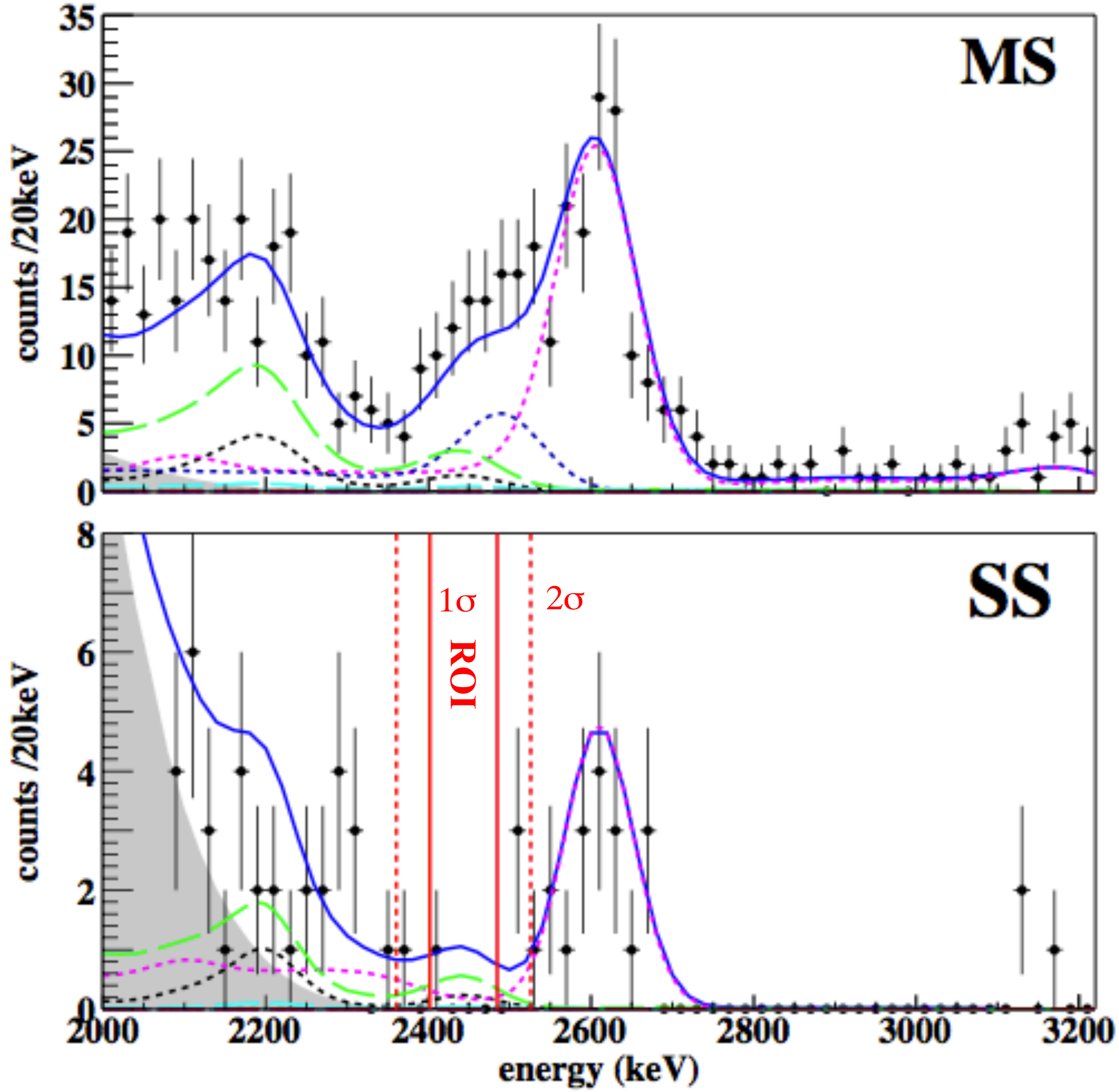
In significant disagreement with previous limits:

$T_{1/2} > 1.0 \cdot 10^{22}$ yr (90% C.L.) (R. Bernabei *et al*. Phys. Lett. B 546 (2002) 23)
$T_{1/2} > 8.5 \cdot 10^{21}$ yr (90% C.L.) (Yu. M. Gavriljuk *et al.*, Phys. Atom. Nucl. 69 (2006) 2129)

Later confirmed by KamLAND-ZEN, $T_{1/2}$=(2.38 ± 0.02stat ± 0.14sys)·10^{21} yr
[A.Gando et al. Phys Rev C 85 (2012) 045504]

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:

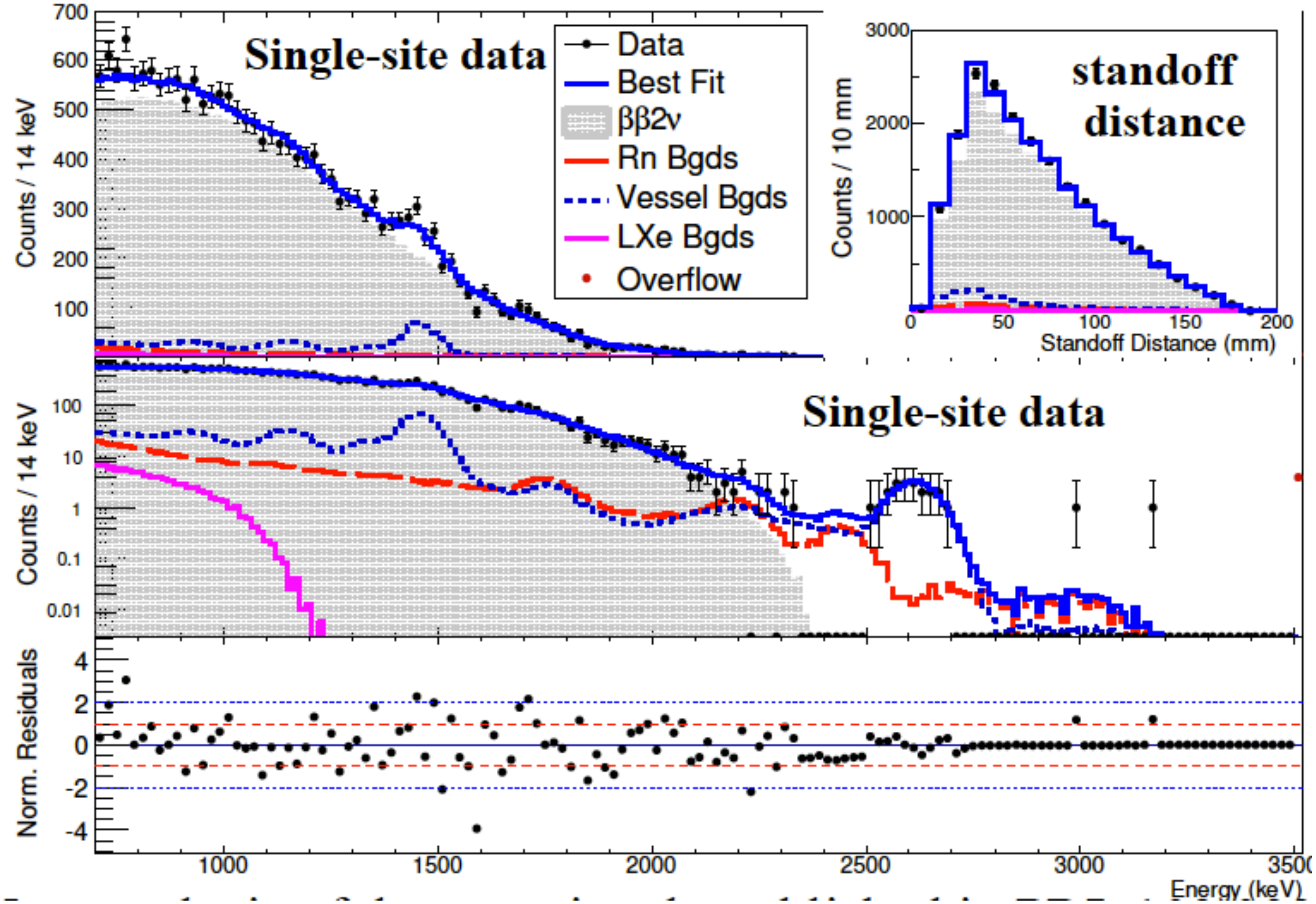
$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ **yr**

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

(90% C.L.)

PRL, 109, 032505 (2012)

New Result: 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

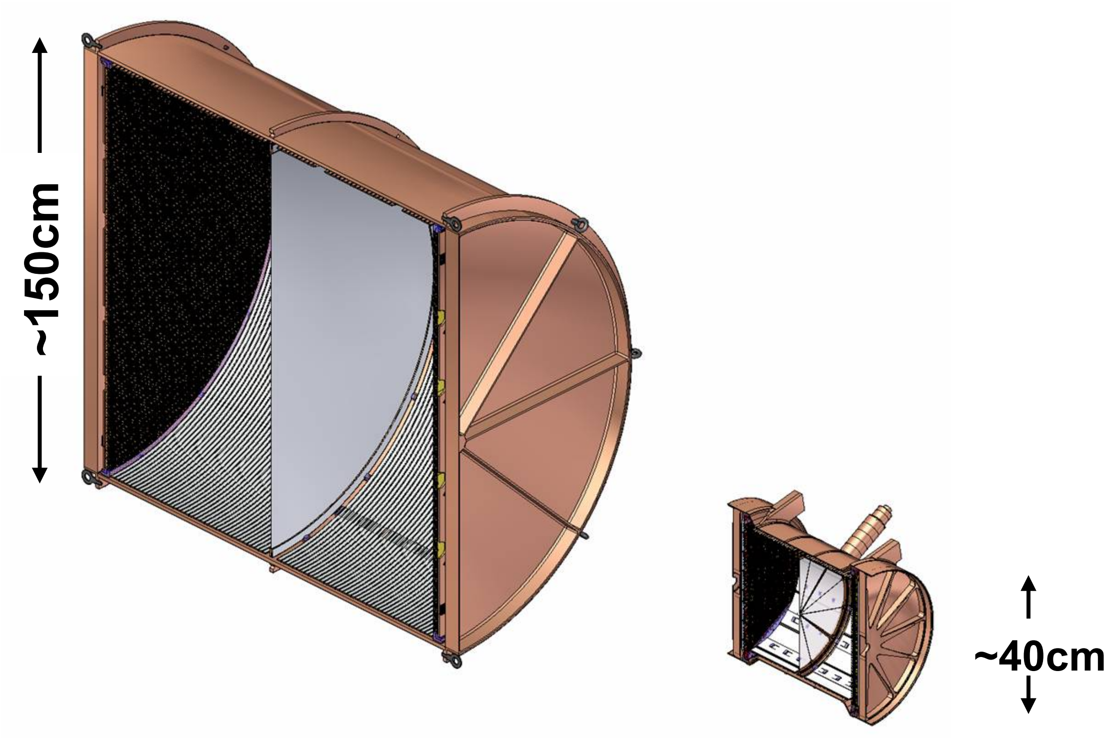
nEXO Detector

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

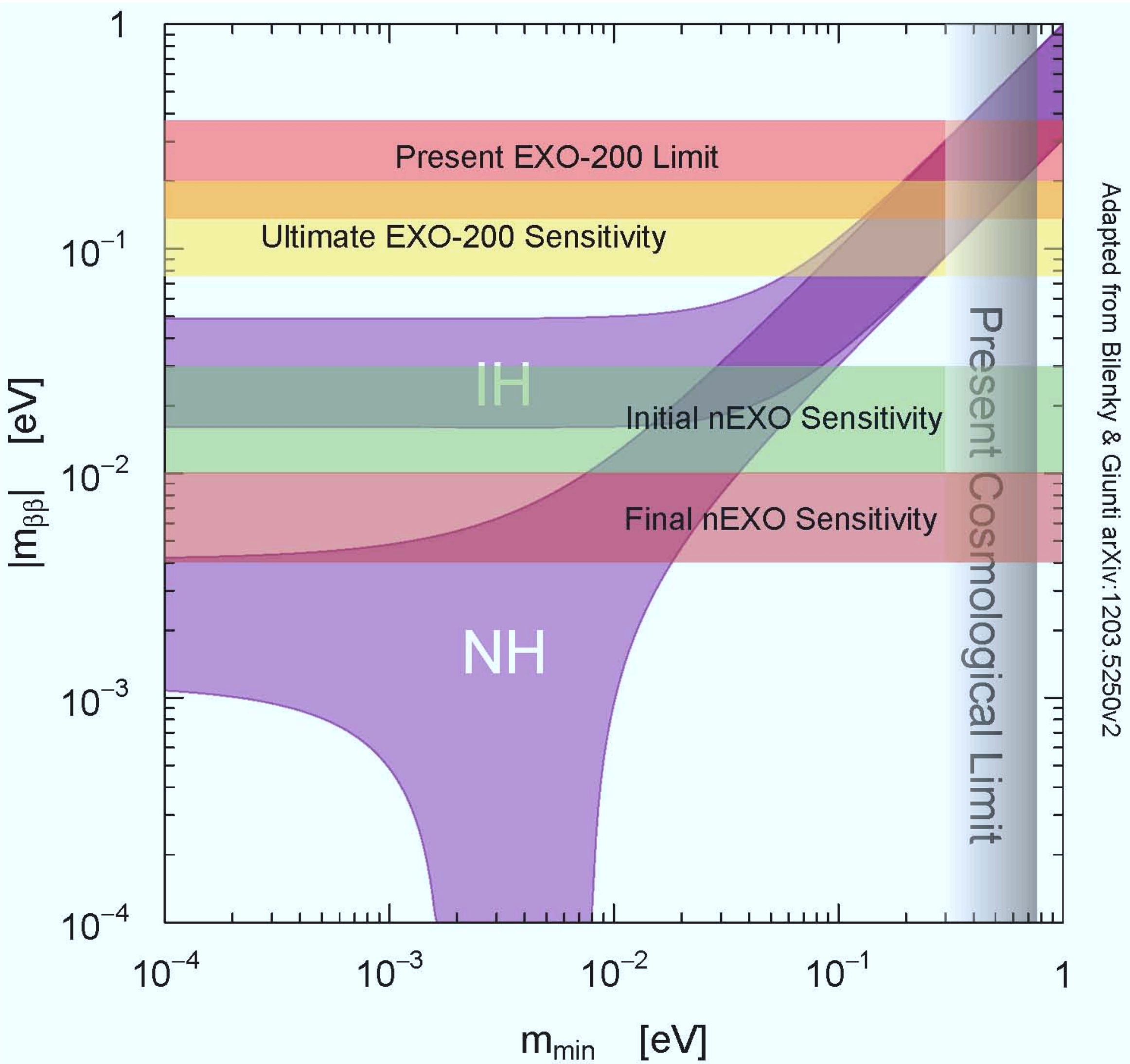
• 4 tonnes of active ^{enr}Xe (80% or higher), 1.4% (σ) energy resolution.

• 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

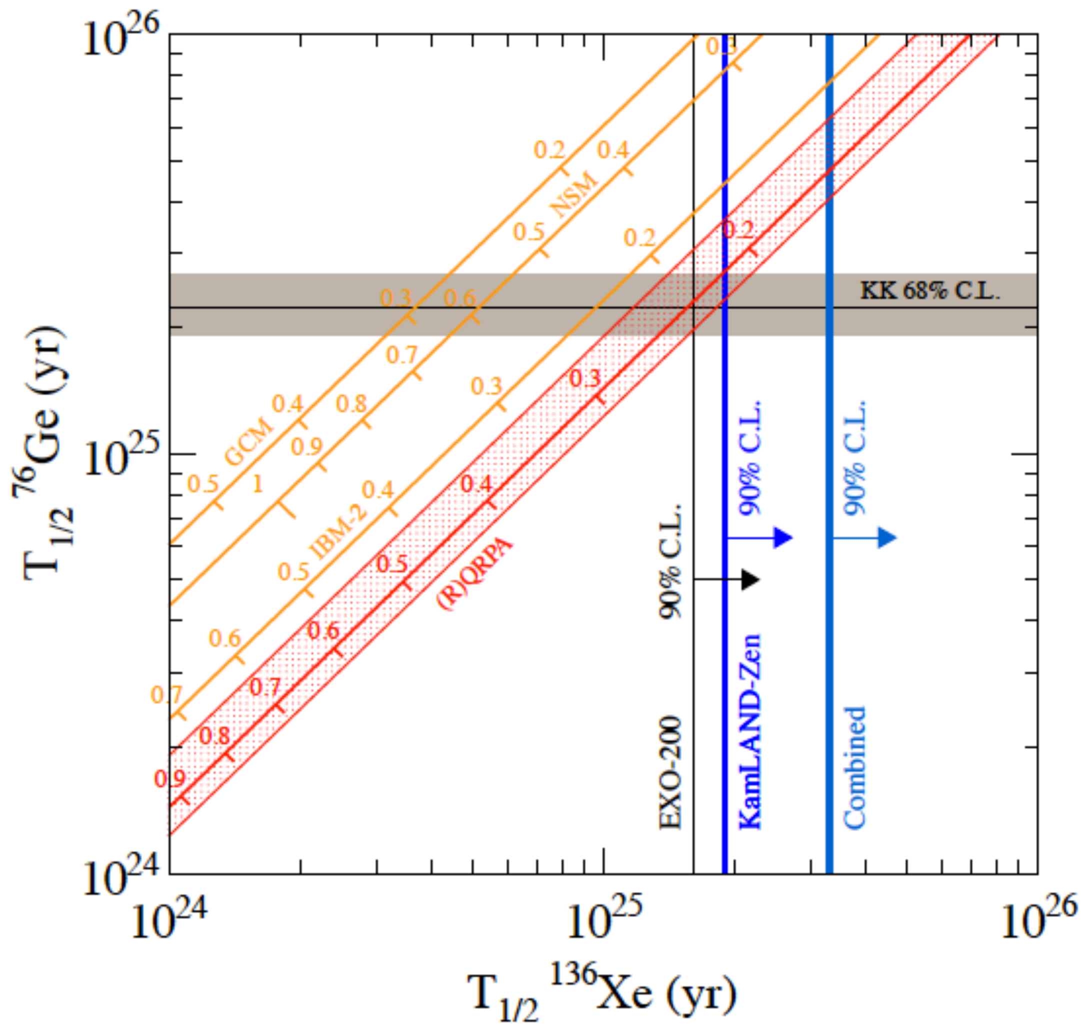
The EXO-200 "Ultimate" sensitivity: 90%CL for no signal in 4 yrs livetime with new analysis & Rn removal

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)

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



Kamland-Zen & EXO-200

Comparison with Klapdor 2006 claim

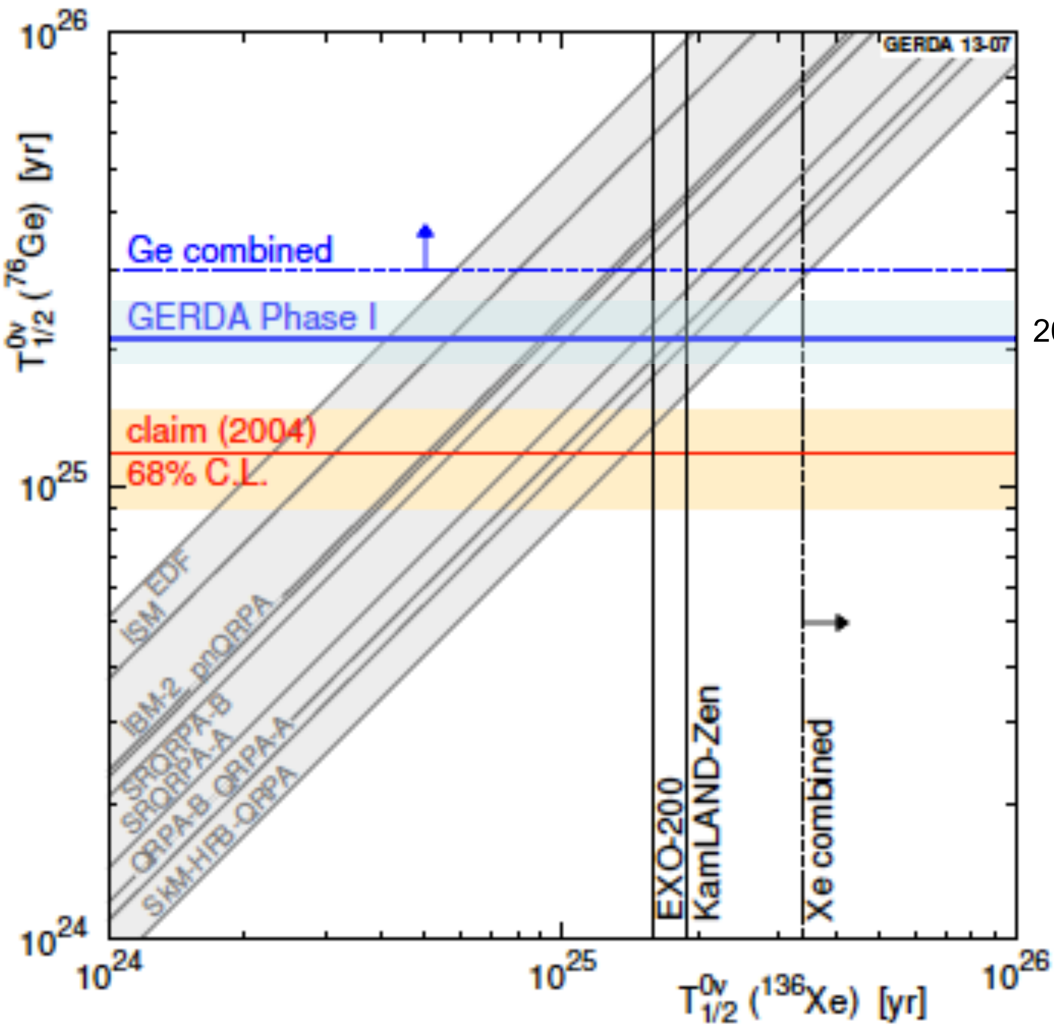
Phys.Rev.Lett.110:06250 (2013)

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

Gerda Phase I

Comparison with Klapdor 2004 claim

arXiv:1307.4720

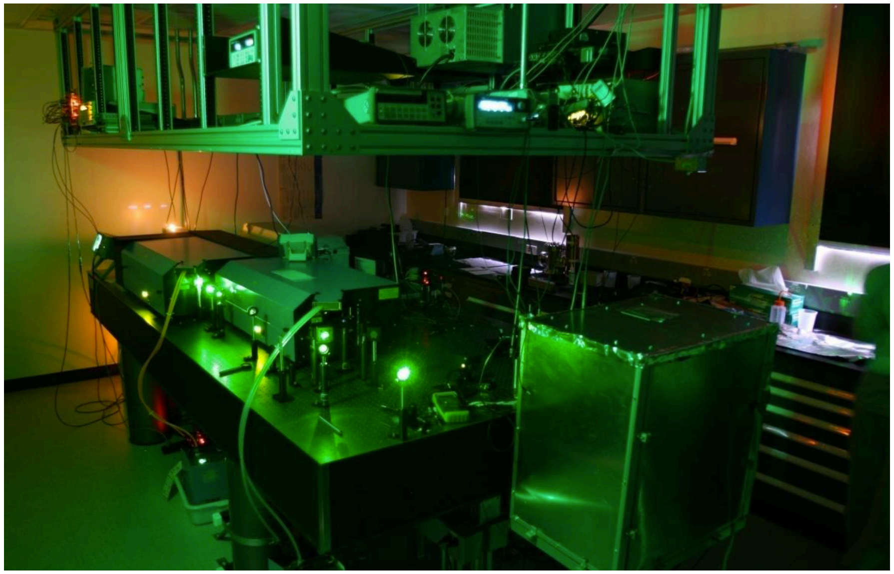


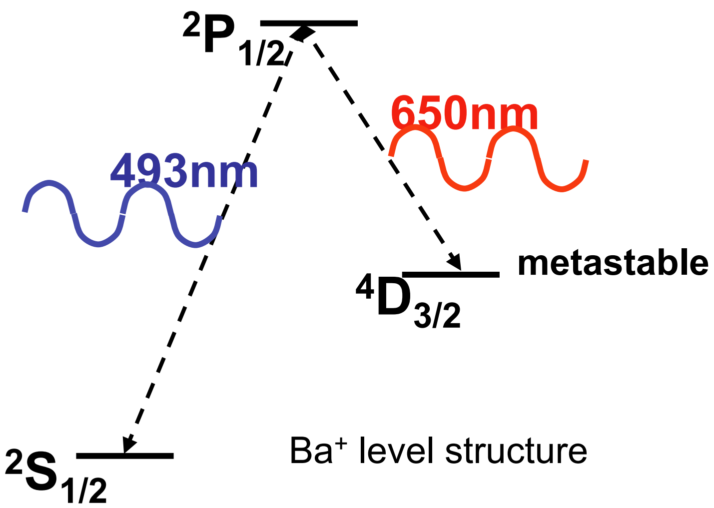
2006 claim

Kamland-Zen & EXO-200

Barium Tagging for Background Rejection

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$





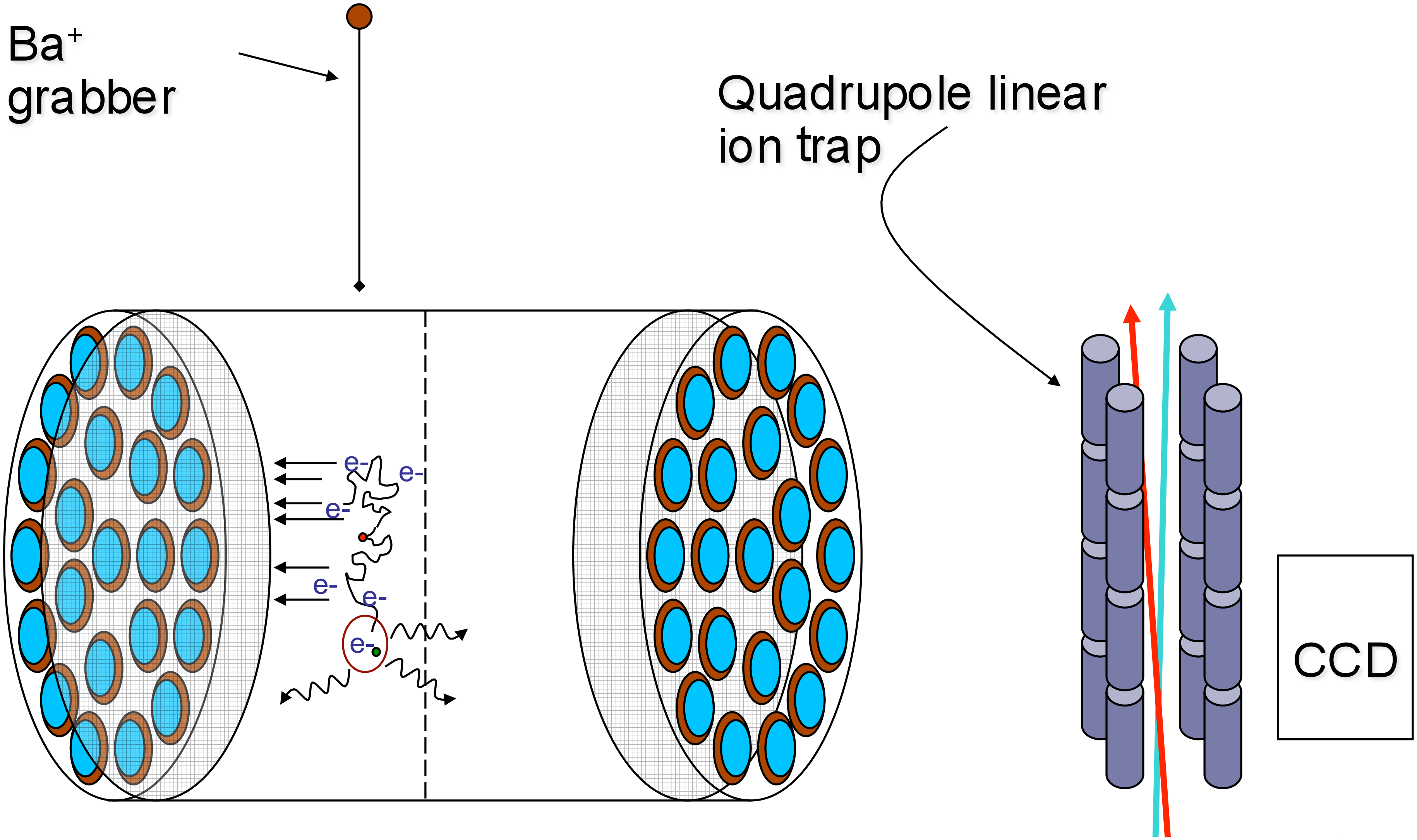
Ba^+ level structure

• In-situ identification of decay daughter nucleus Ba can be used to eliminate all radioactivity induced background.

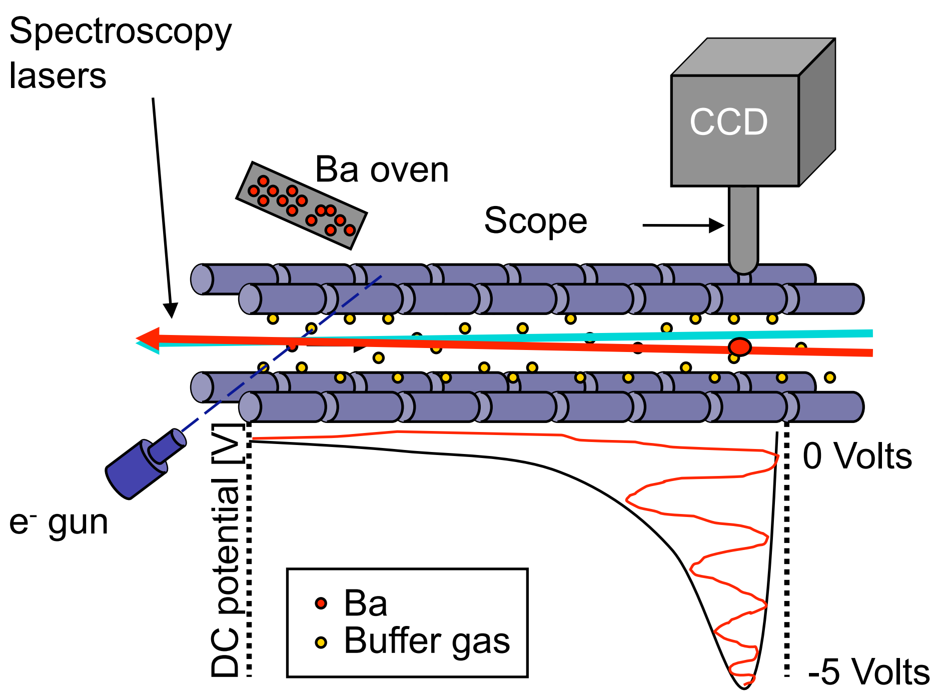
• Ba ions have nice laser spectroscopy signatures.

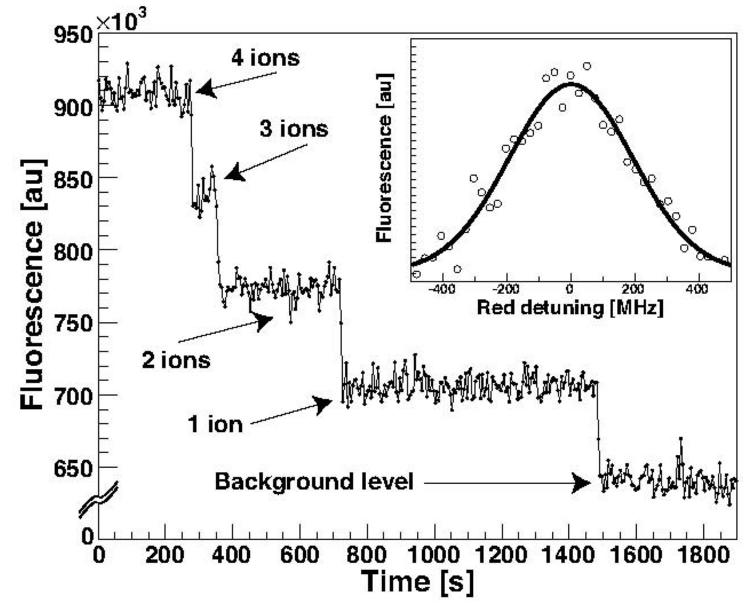
• Difficult problem to detect a single ion inside few hundred kgs of xenon.

Extracting Ba^+ and Detecting in Ion Trap



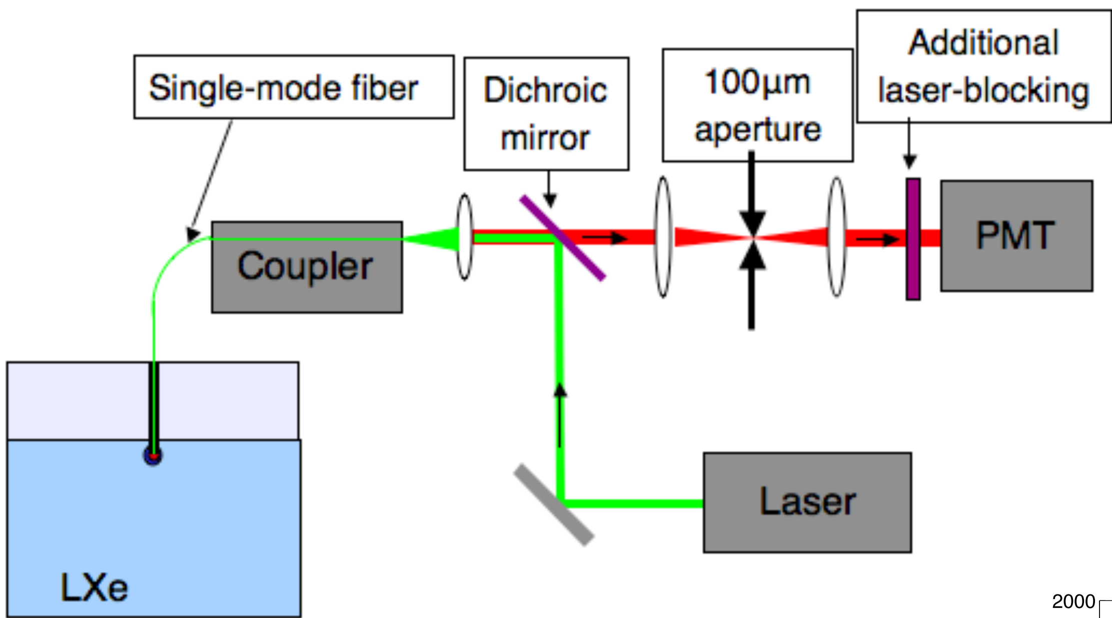
Barium Ion Trapping in Buffer Gas Environment

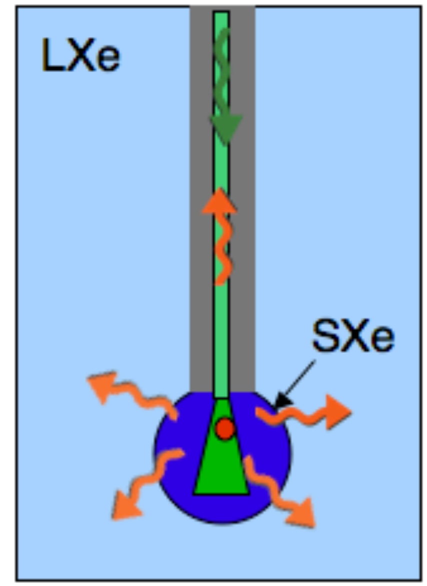


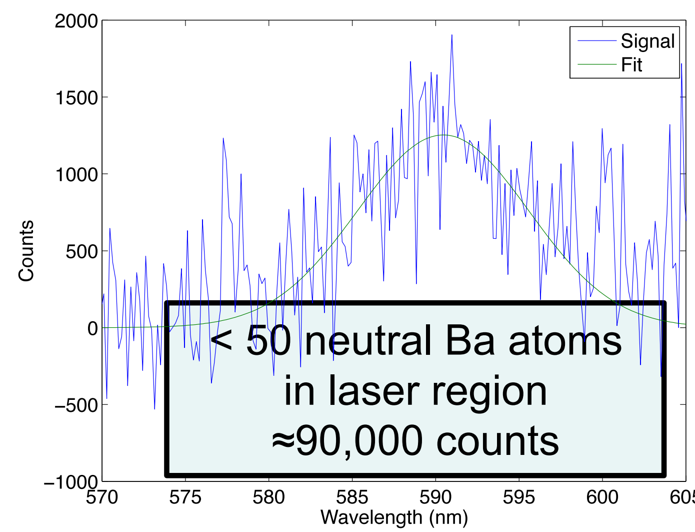


- Have developed techniques for detecting single barium ion in a buffer gas filled ion trap (~ 10^{-3} torr He, some Xe).
- ~ 9σ observation at 25s storage time.
- R&D efforts currently focus on develop a suitable probe to take barium from the liquid xenon bath and deliver it into the ion trap.

Direct Barium Tagging in Solid Xenon







Laser light delivered by fiber to single Ba atom or ion in solid xenon. Fluorescence collected back up the fiber and detected by PMT or APD.

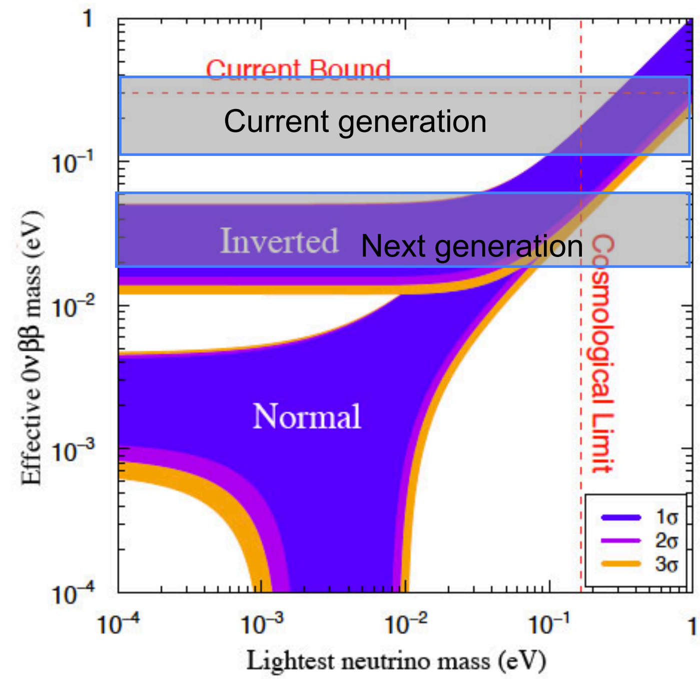
Detection limit in R&D setup : < 50 Ba atoms.
Improvement in collection efficiency and laser intensity => *single Ba detection possible.*

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 hierarchy.



arXiv:1203.5250v1

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