# ПОИСК ДВОЙНОГО БЕТА РАСПАДА В ЭКСПЕРИМЕНТЕ EXO-200

А.А. Буренков (ИТЭФ)

ИЯИ, Троицк

26 Ноября 2012

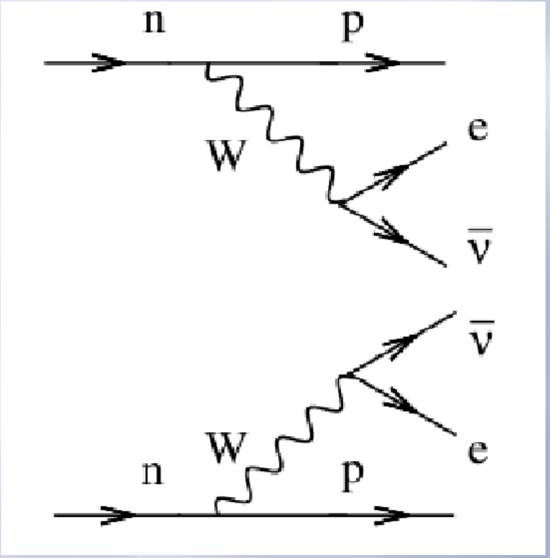
# Outline

- Double beta decay (briefly)
- EXO-200 (R&D and current status)
- First physics result from EXO-200, observation of the $^{136}Xe$ $2\nu\beta\beta$.

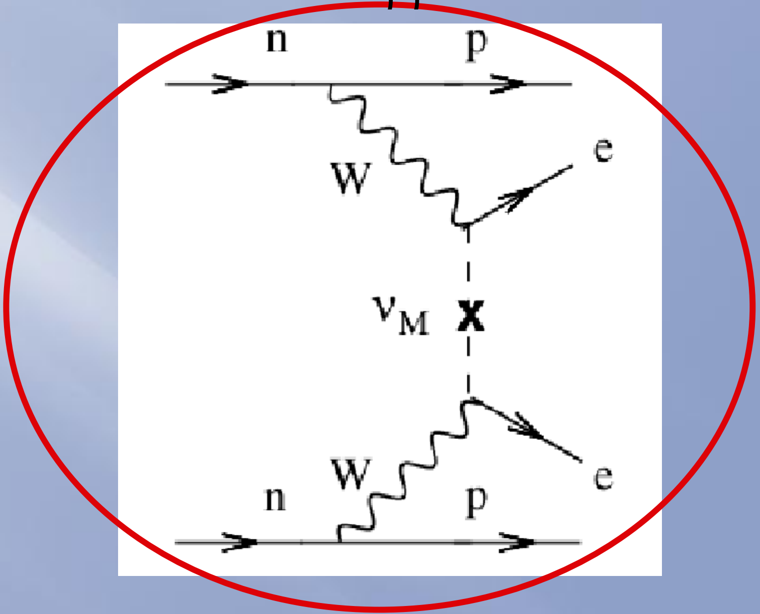
M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512

# Double beta decay

2νββ




0νββ

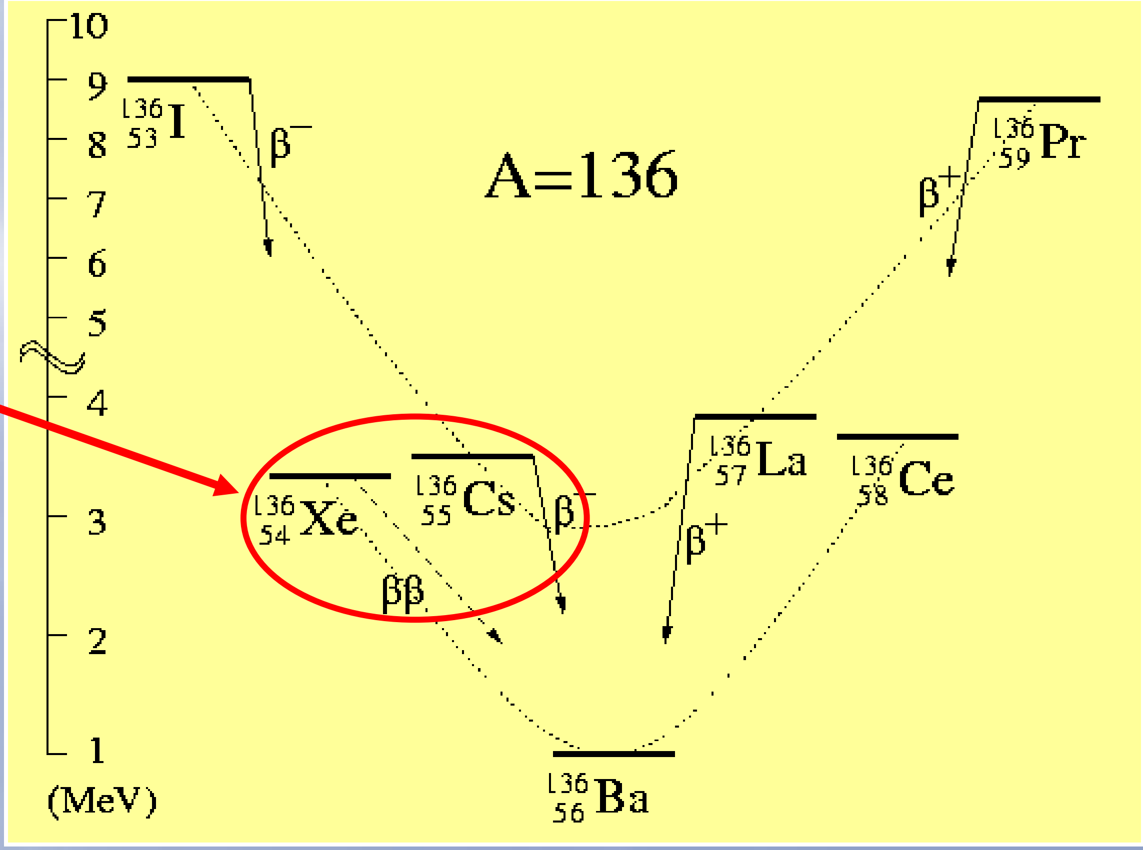



**This process can only occur for a Majorana neutrino!**

$$m_\nu \neq 0, \bar{\nu} = \nu$$

# Double beta decay

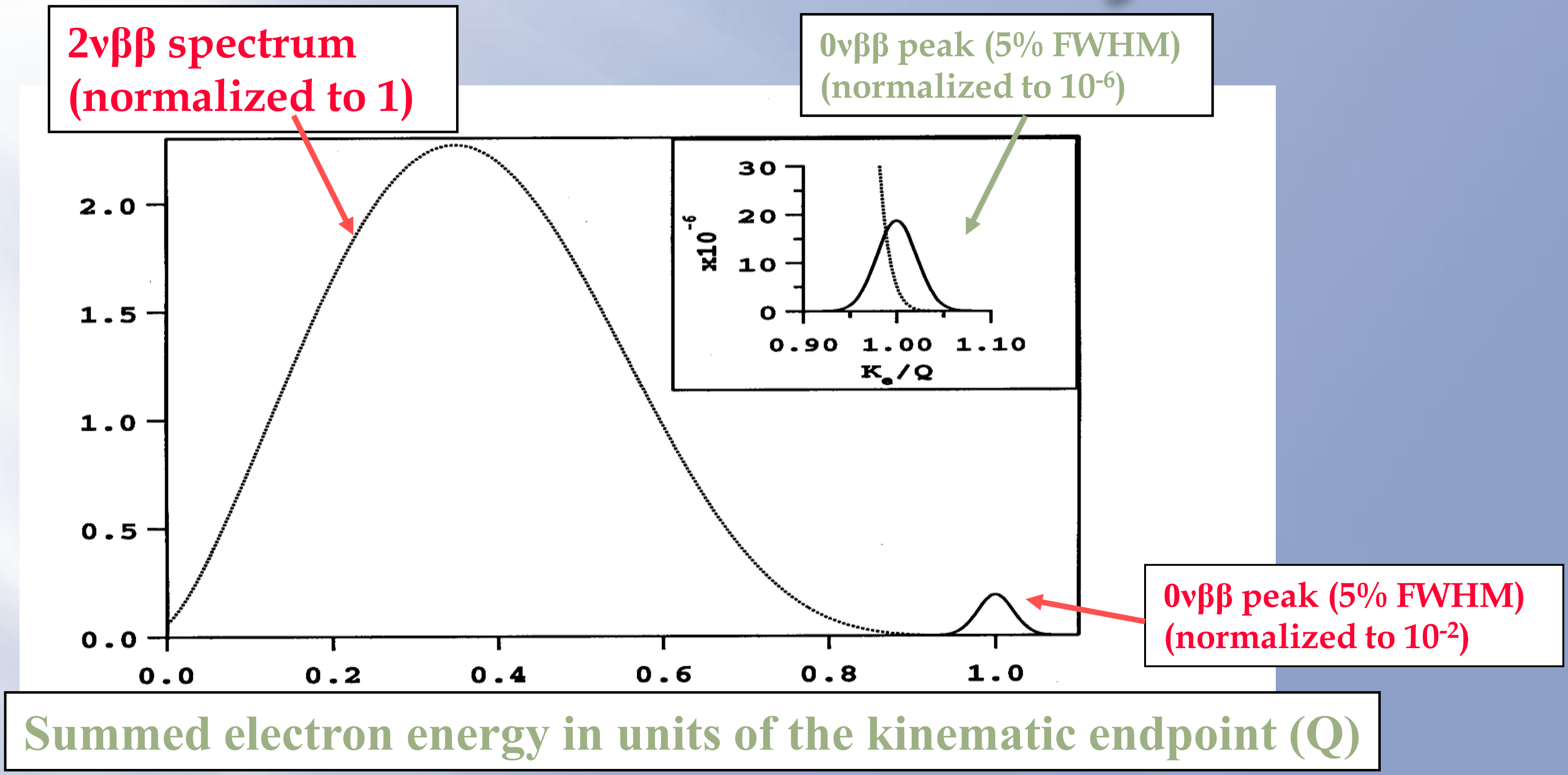
*a second-order process only detectable*
*if first order beta decay is energetically forbidden*




Atomic number (Z)

Some candidate nuclei: $^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{130}$Te, $^{136}$Xe

# Double beta decay




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

# Double beta decay

Table of 2ν halflives and matrix elements with references

| | $T_{1/2}$ (y) | $M^{2\nu}$ ($MeV^{-1}$) | |
|---|---|---|---|
| $^{48}Ca$ | $(4.3^{+2.4}_{-1.1} \pm 1.4)$E19 | 0.05±0.02 | Balysh, PRL**77**,5186(1996) |
| $^{76}Ge$ | $(1.74 \pm 0.01^{+0.18}_{-016})$E21 | 0.13±0.01 | Doerr,NIMA**513**,596(2003) |
| $^{82}Se$ | (9.6 ± 0.3 ± 1.0)E19 | 0.10±0.01 | Arnold,PRL**95**,182302(2005) |
| $^{96}Zr$ | (2.35 ± 0.14 ± 0.16)E19 | 0.12±0.01 | Argyriades,NPA**847**,168(2010) |
| $^{100}Mo$ | (7.11 ±0.02 ± 0.54)E18 | 0.23±0.01 | Arnold,PRL**95**,182302(2005) |
| $^{116}Cd$ | $(2.9^{+0.4}_{-0.3})$E19 | 0.13±0.01 | Danevich,PRC**68**,035501(2003) |
| $^{128}Te^{*}$ | (1.9 ± 0.1 ± 0.3)E24 | 0.05±0.005 | Lin,NPA**481**,477(1988) |
| $^{130}Te$ | (7.0 ± 0.9 ±1.1)E20 | 0.033±0.003 | Arnold,PRL**107**,062504(2011) |
| $^{136}Xe$ | (2.1 ± 0.04 ± 0.21)E21 | 0.019±0.001 | Ackerman,arxiv:1108.4193(2011) |
| $^{150}Nd$ | $(9.11^{+0.25}_{-0.22} \pm 0.63)$E18 | 0.06±0.003 | Argyriades,PRC**80**,032501R(2009) |
| $^{238}U^{**}$ | (2.2 ± 0.6)E21 | 0.05±0.01 | Turkevich,PRL**67**,3211(1991) |

*from geochemical ratio $^{128}Te/^{130}Te$; **radiochemical result

# The EXO collaboration

University of Alabama, Tuscaloosa AL, USA
D. Auty, M. Hughes, R. MacLellan, A. Piepke, K. Pushkin, M. Volk

University of Bern, Switzerland
M. Auger, S. Delaquis, D. Franco, G. Giroux, R. Gornea, T. Tolba, J-L. Vuilleumier, M. Weber

California Institute of Technology, Pasadena CA, USA - P. Vogel

Carleton University, Ottawa ON, Canada
A. Coppens, M. Dunford, K. Graham, C. Hägemann, C. Hargrove, F. Leonard, C. Oullet, E. Rollin, D. Sinclair, V. Strickland

Colorado State University, Fort Collins CO, USA
S. Alton, C. Benitez-Medina, C. Chambers, Adam Craycraft, S. Cook, W. Fairbank, Jr., K. Hall, N. Kaufold, T. Walton

University of Illinois, Urbana-Champaign IL, USA - D. Beck, J. Walton, L. Yang

Indiana University, Bloomington IN, USA - T. Johnson, L.J. Kaufman

University of California, Irvine, Irvine CA, USA - M. Moe

ITEP Moscow, Russia - D. Akimov, I. Alexandrov, V. Belov, A. Burenkov, M. Danilov, A. Dolgolenko, A. Karelin, A. Kovalenko, A. Kuchenkov, V. Stekhanov, O. Zeldovich

Laurentian University, Sudbury ON, Canada
E. Beauchamp, D. Chauhan, B. Cleveland, J. Farine, B. Mong, U. Wichoski

University of Maryland, College Park MD, USA
C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

University of Massachusetts, Amherst MA, USA
T. Daniels, S. Johnston, K. Kumar, A. Pocar, J.D. Wright

University of Seoul, South Korea - D. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA
M. Breidenbach, R. Conley, R. Herbst, S. Herrin, J. Hodgson, A. Johnson, D. Mackay, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen, J. Wodin

Stanford University, Stanford CA, USA
P.S. Barbeau, T. Brunner, J. Davis, R. DeVoe, M.J. Dolinski, G. Gratta, M. Montero-Díez, A.R. Müller, R. Neilson, I. Ostrovskiy, K. O'Sullivan, A. Rivas, A. Sabourov, D. Tosi, K. Twelker

Technical University of Munich, Garching, Germany
W. Feldmeier, P. Fierlinger, M. Marino

# Enriched Xenon Observatory (EXO)

- **EXO is a multi-phase program to search for the neutrinoless double beta decay of $^{136}Xe$.**

EXO-200 (first phase):

- A 200 kg liquid xenon detector currently operating underground
- Probe Majorana neutrino mass at 100-200 meV range
- Demonstrate technical feasibility of ton scale experiment

Full EXO (second phase):

- A proposed 1- 10 ton liquid or gas xenon detector
- Probe Majorana neutrino mass at 5 – 30 meV range
- R&D work for novel techniques for background suppression and energy resolution in progress

# Xenon is an Excellent Candidate for $2\nu\beta\beta$ Search

- Xenon isotopic enrichment is easier. Xe is already a gas & $Xe^{136}$ is the heaviest isotope.

- Xenon is "reusable". Can be repurified & recycled into new detector (no crystal growth).

- Monolithic detector. LXe is self shielding, surface contamination minimized.

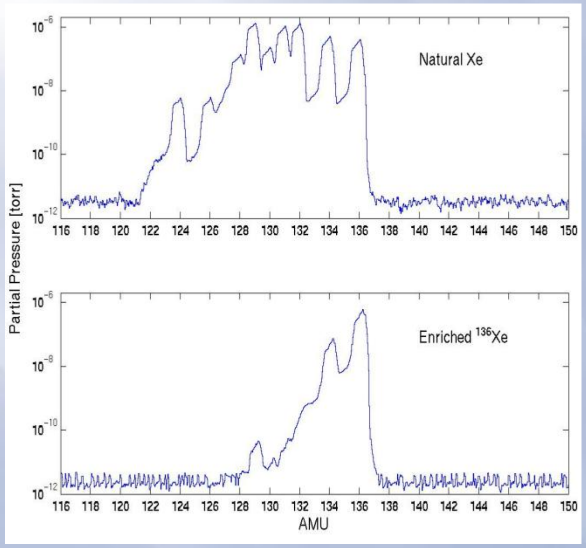
- Minimal cosmogenic activation. No long lived radioactive isotopes of Xe.

- Energy resolution in LXe can be improved. Scintillation light/ionization correlation.

- … ***admits a novel coincidence technique.*** Background reduction by Ba daughter tagging.

# EXO-200

Centrifuge facility in Russia

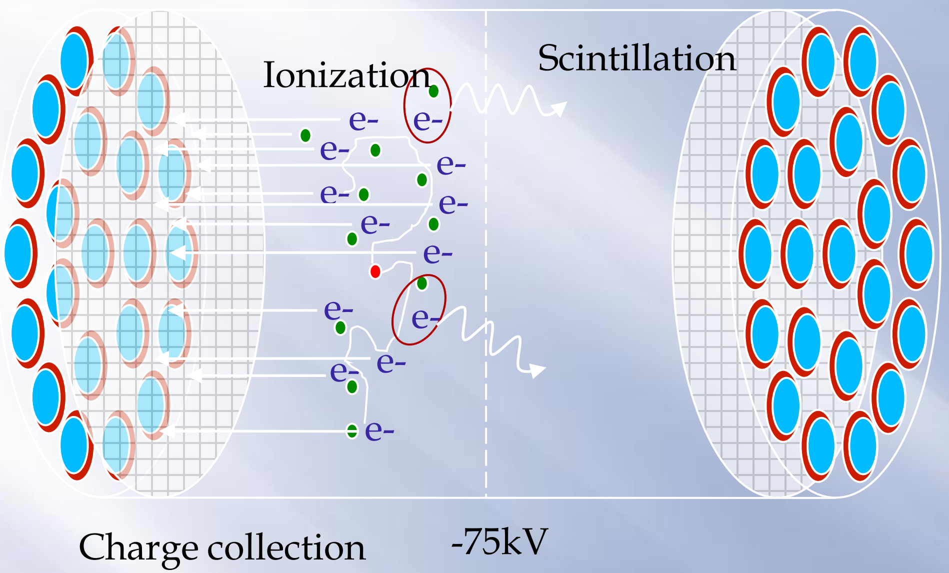



RGA mass scan of xenon samples

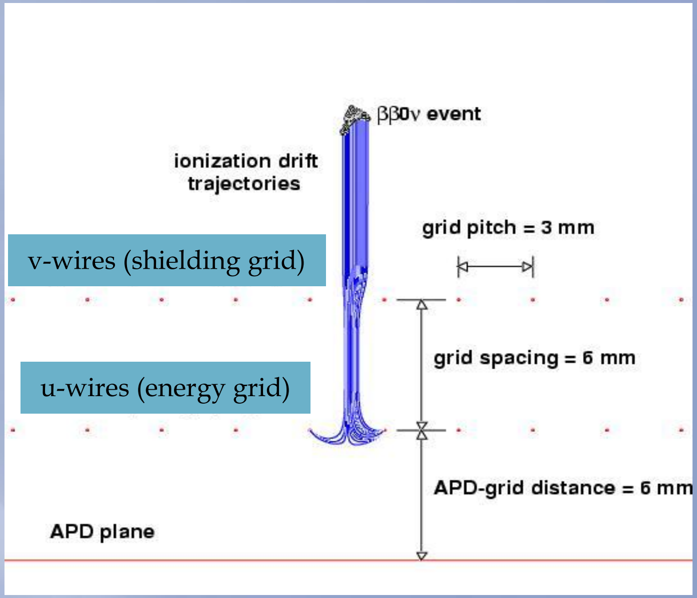
Enriched xenon storage bottles for EXO

EXO collaboration currently have 200 kg of xenon enriched to 80% = 160 kg of $^{136}$Xe

# EXO-200 Time Projection Chamber (TPC) Basics




TPC Schematics



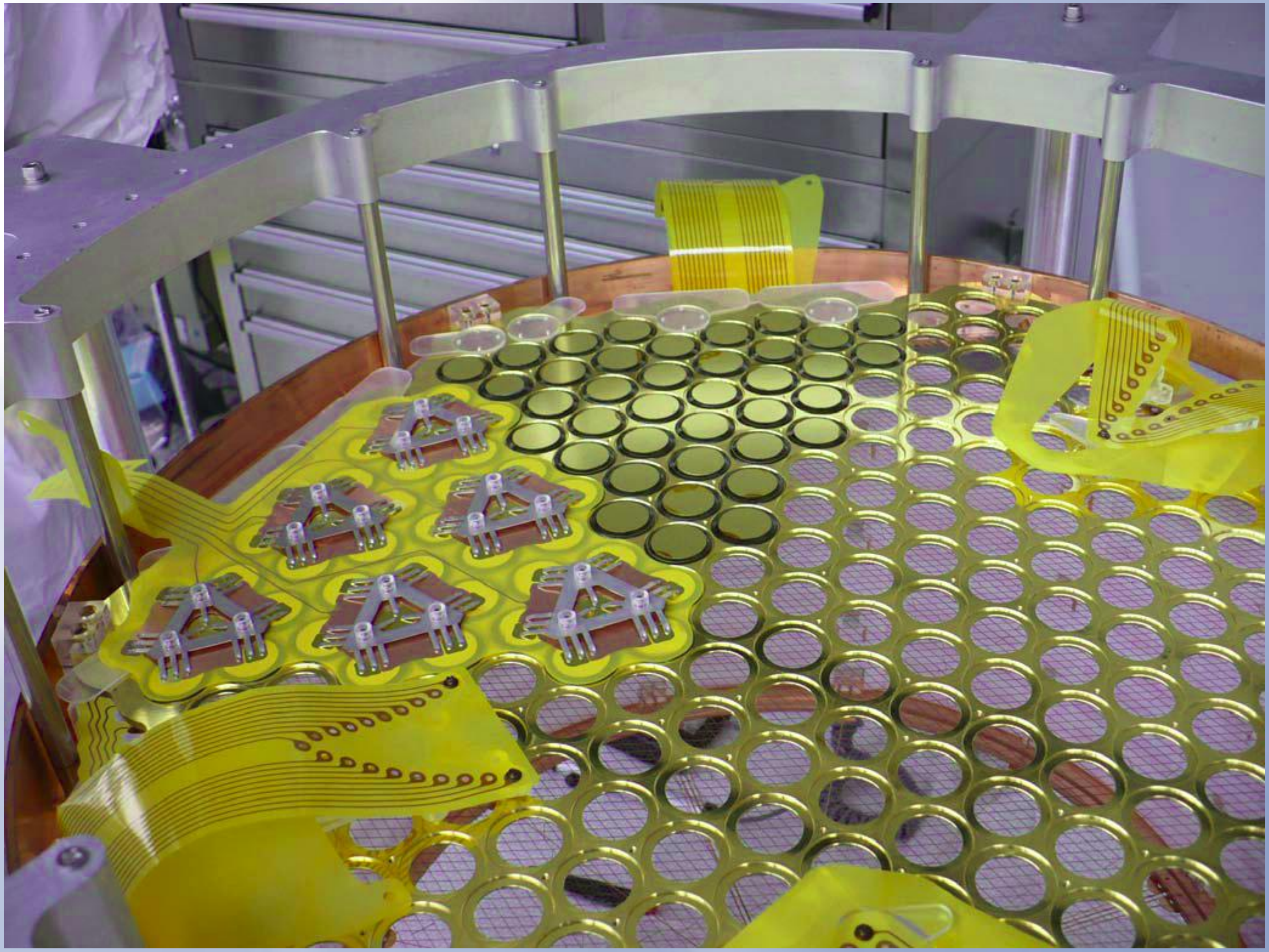

Simulation of Charge Drift

- 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.

# Ultra-low activity Cu vessel

- Very light (~1.5mm thin, ~15kg) to minimize materials
- Different parts e-beam welded together
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done by in the CR-shielded HEPL building)

# LAPD

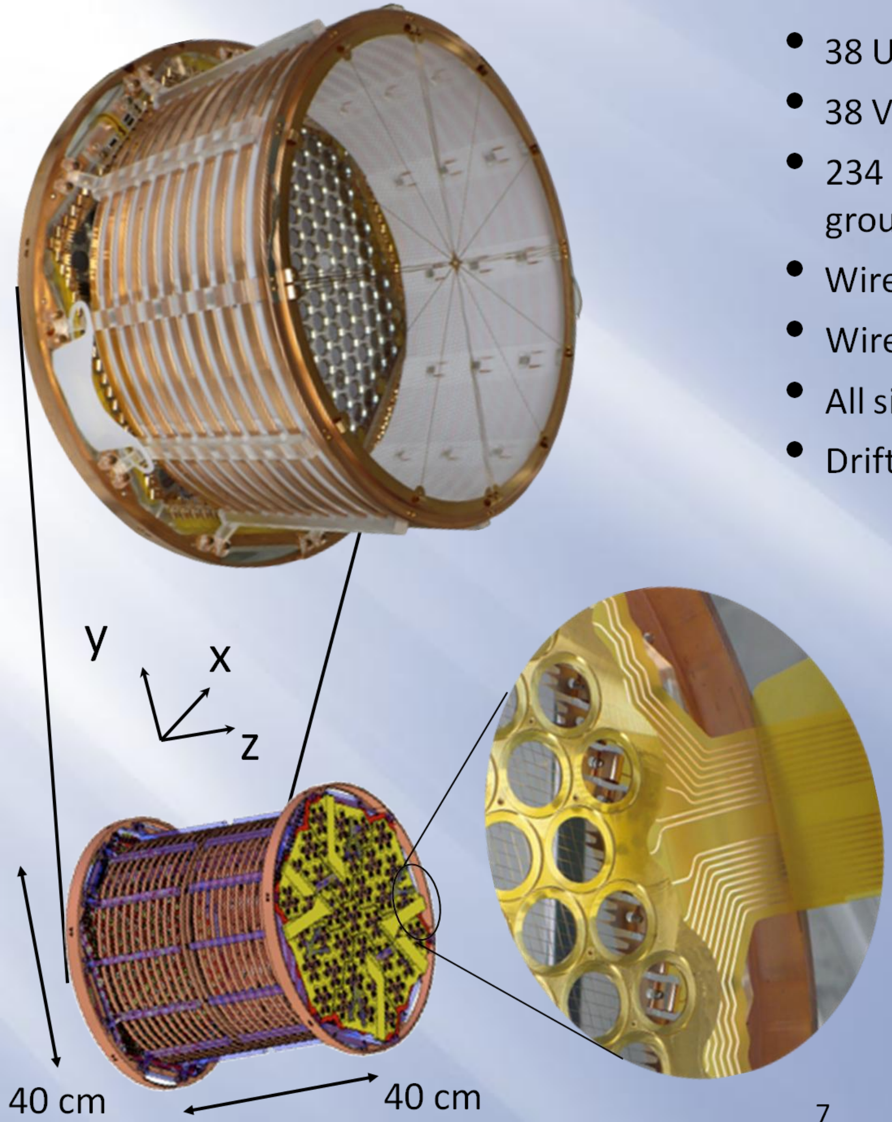


APDs are ideal for our application:
-very clean & light-weight,
-very sensitive to VUV

QE > 1 at 175nm

R. Neilson, et al.
NIM A 608 (2009) 6875

# The EXO-200 TPC

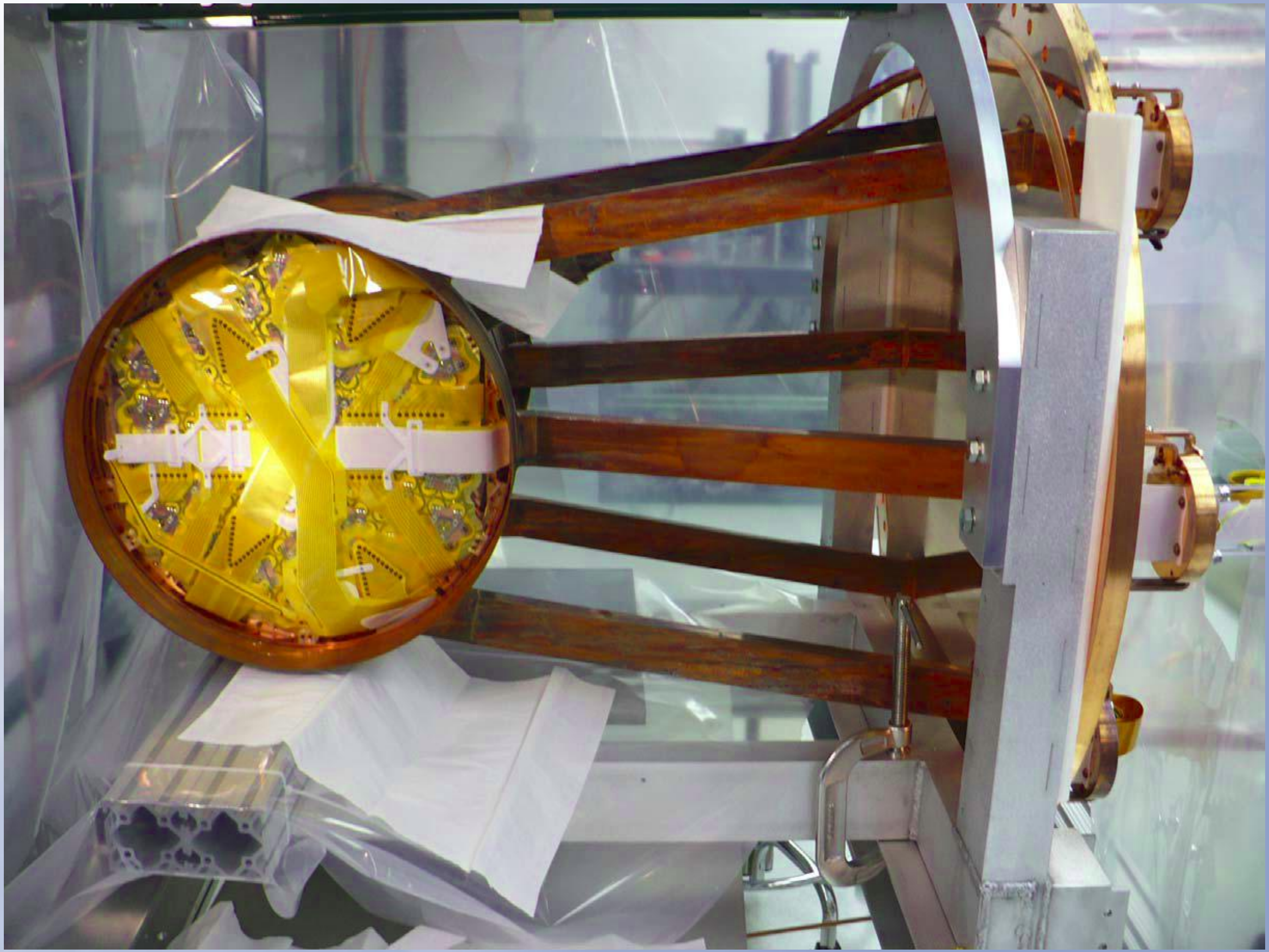


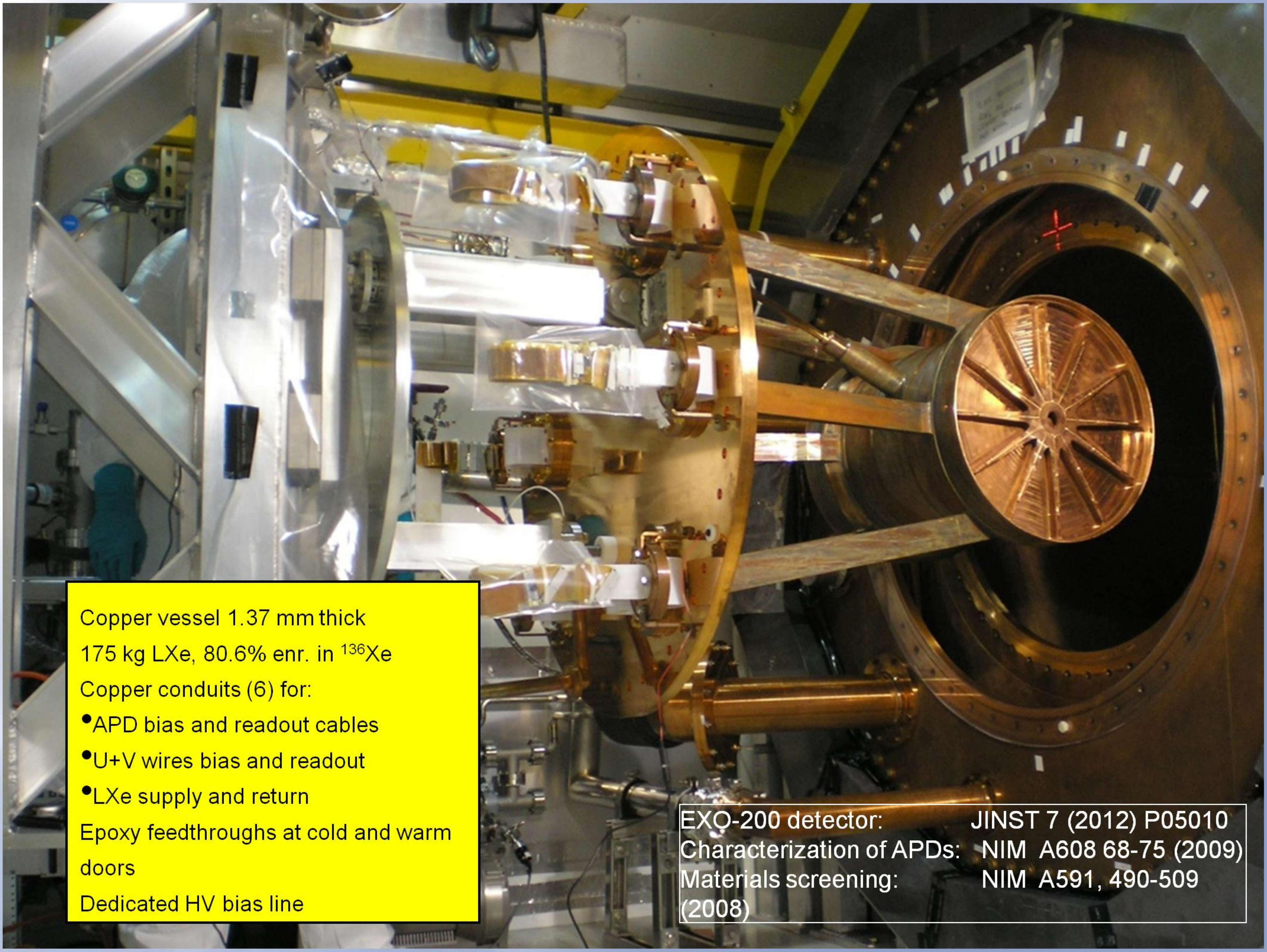

Two almost identical halves reading ionization and 178 nm scintillation, each with:

- 38 U triplet wire channels (charge)
- 38 V triplet wire channels, crossed at 60° (induction)
- 234 large area avalanche photodiodes (APDs, light in groups of 7)
- Wire pitch 3 mm (9 mm per channel)
- Wire planes 6 mm apart and 6 mm from APD plane
- All signals digitized at 1 MS/s, ±1024S around trigger
- Drift field 376 V/cm

- Field shaping rings: copper
- Supports: acrylic
- Light reflectors/diffusers: Teflon
- APD support plane: copper; Au (Al) coated for contact (light reflection)
- Central cathode, U+V wires: photo-etched phosphor bronze
- Flex cables for bias/readout: copper on kapton, no glue
- Comprehensive material screening program
- Goal: 40 cnts/2y in 0νββ ±2σ ROI, 140 kg LXe

# EXO-200 TPC Assembled





Copper vessel 1.37 mm thick

175 kg LXe, 80.6% enr. in $^{136}Xe$

Copper conduits (6) for:

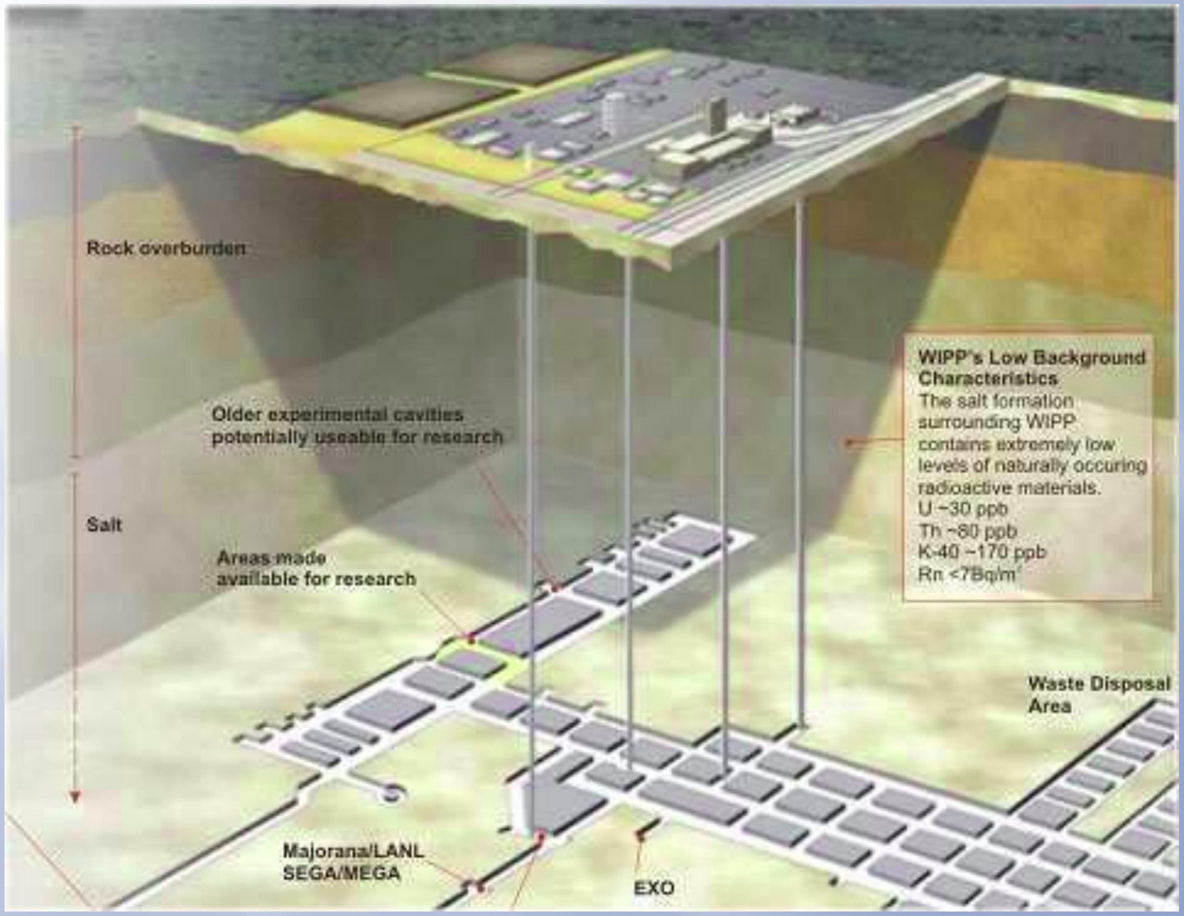
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return

Epoxy feedthroughs at cold and warm doors

Dedicated HV bias line

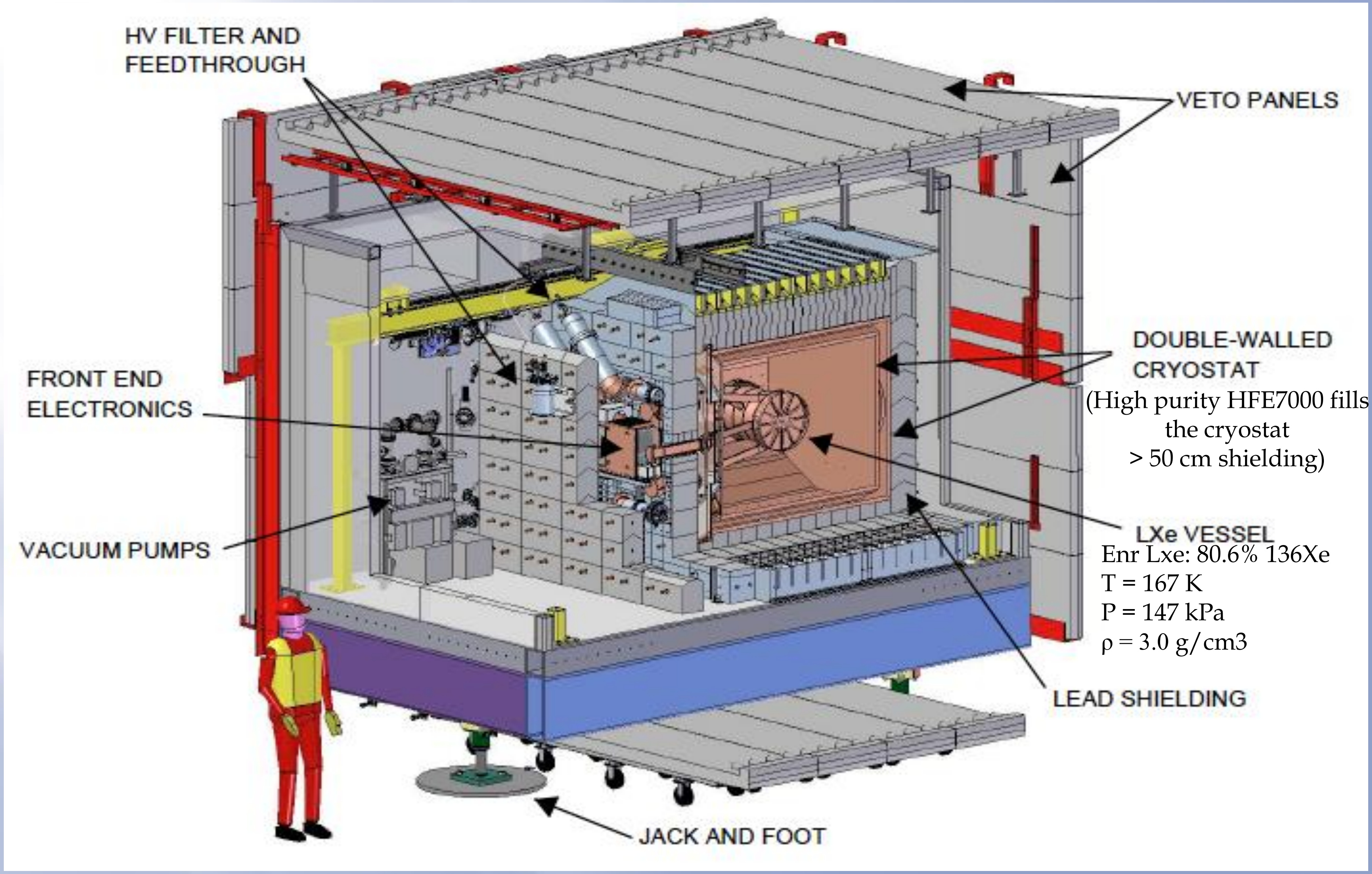
EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
Materials screening: NIM A591, 490-509 (2008)

# Underground location: Waste Isolation Pilot Plant (WIPP) Carlsbad, NM




- ~1600 meter water equivalent flat overburden
- Relatively low levels of U and Th (<100 ppb in EXO-200 drift)
- Low levels of Rn (~20 Bq/m3)
- Rather convenient access with large conveyance

# EXO-200 detector




Muon veto

50 mm thick plastic scintillator panels surrounding TPC on four sides.

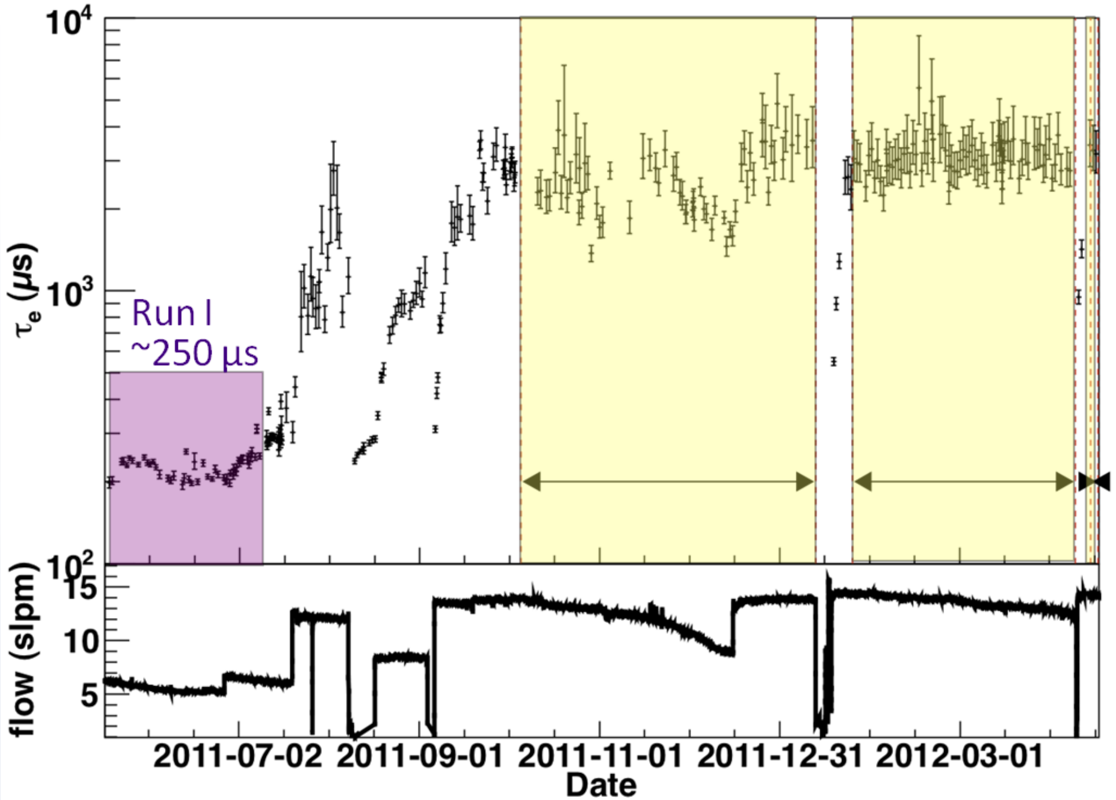
95.5 ± 0.6 % efficiency

Veto cuts (8.6% combined dead time)

- 25 ms after muon veto hit
- 60 s after muon track in TPC
- 1 s after every TPC event

# Data taking phases and xenon

| | Run I | 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 |




Sep 2011 – Hardware upgrades
- APD gain increase by factor 2
- improved U-wire shaping
- added outer lead shield

**Purity**

Xenon gas is forced through heated Zr getter by custom ultraclean pump.

Electron lifetime $\tau_e$ is determined by measuring the attenuation of the ionization signal as a function of drift time for the full-absorption peak of gamma ray sources

For this analysis, the recirculation rate was increased to 14 slpm, leading to long electron lifetimes in the TPC

At $\tau_e$ = 3 ms:
- max. drift time ~110 μs
- loss of charge is 3.6% at full drift length

Ultraclean pump:
Rev Sci Instrum. 82(10):105114
Xenon purity with mas spectroscopy:
NIM A675 (2012) 40-46
Gas purity monitors:
NIM A659 (2011) 215-228

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Gas purity monitors:
NIM A659 (2011) 215-228

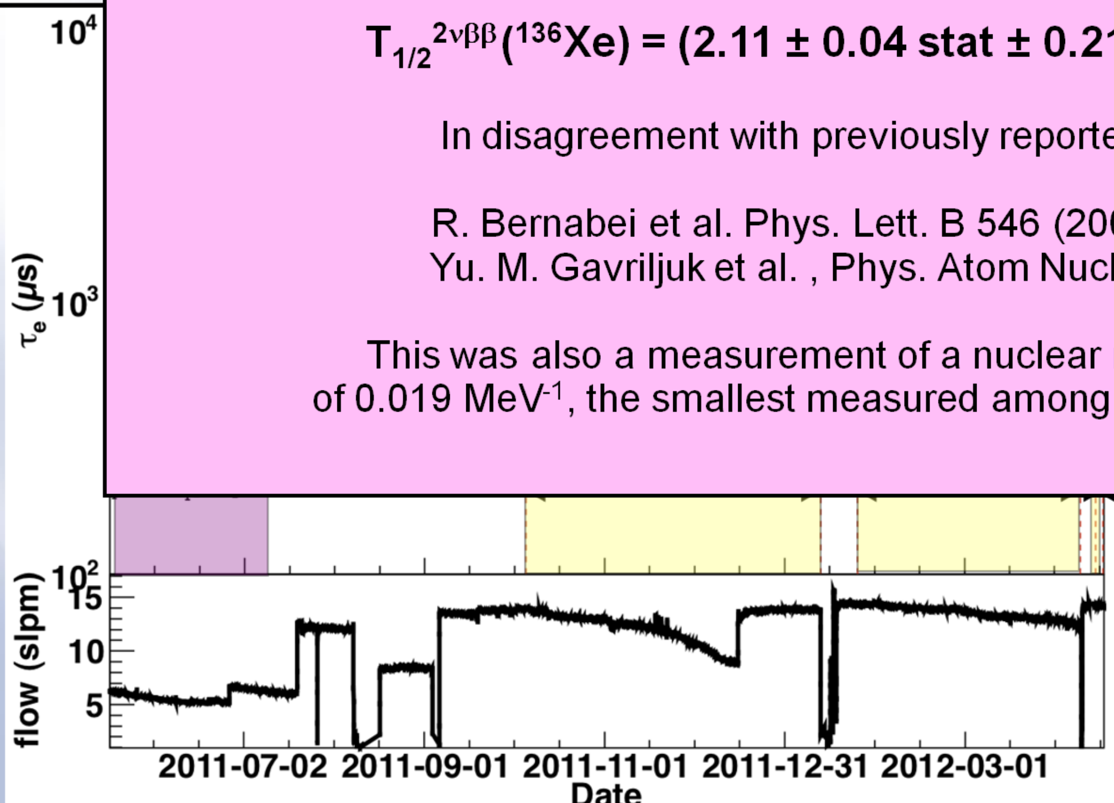
Run I Results:

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

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



# Event reconstruction

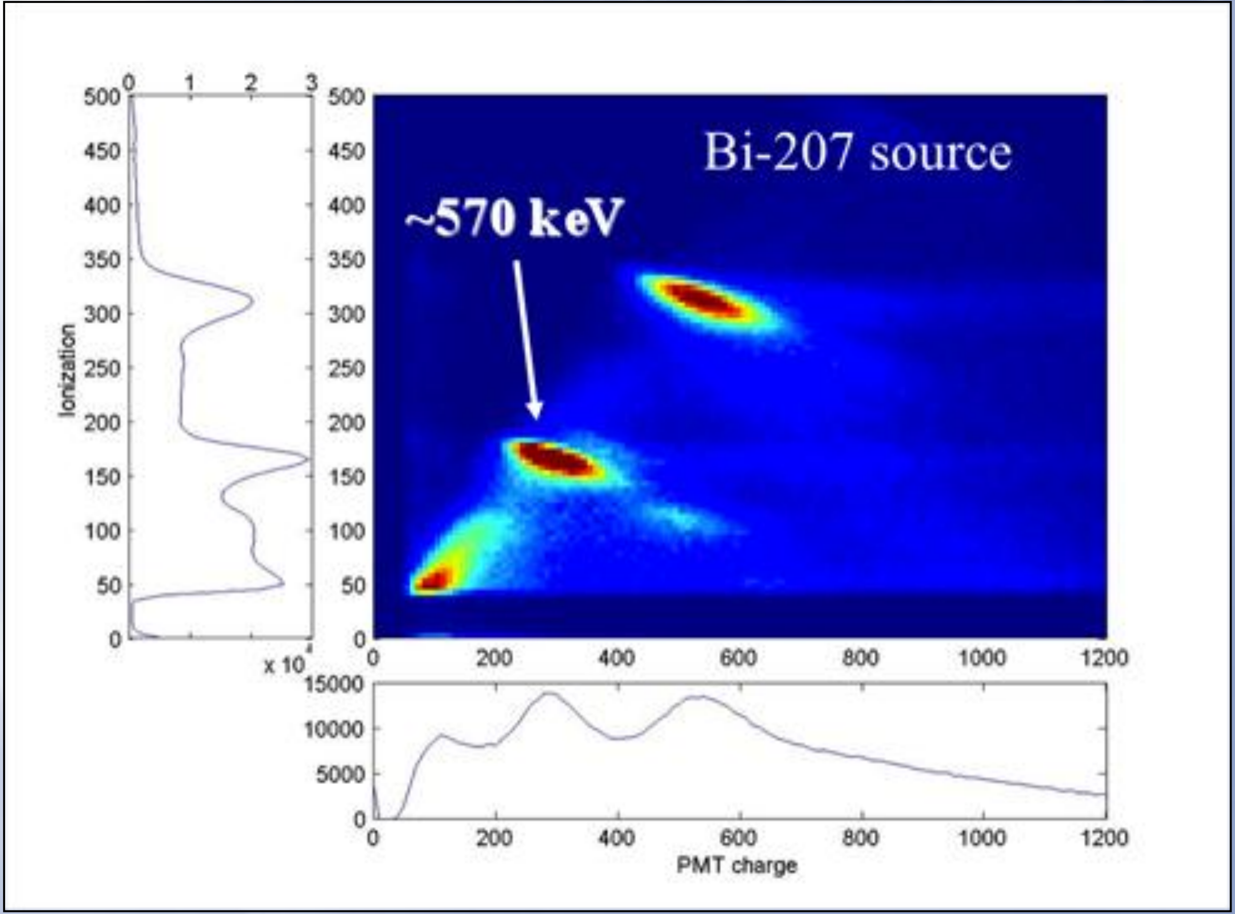
- Signal finding – matched filters applied on U,V and APDs waveforms
- Signal parameter estimation (t, E) for charge and light
- Cluster finding – assignment to Single Site (SS) or Multiple Site (MS): resolution 18mm in X and Y and 6 mm in Z

Amplitudes corrected by channel for gain variation
Signal fitting functions use individual parameters for each channel
Optimized light correction using charge position
Charge corrected for inefficiency on small drift
Require events to be fully reconstructed in 3D

Reconstruction efficiency for 0νββ is 71% – estimated by MC and verified by comparing the 2νββ MC efficiency with low background data, over a broad range in energy

SS and MS spectra are fitted simultaneously with MC-generated probability density functions

# Anti-correlation between ionization and scintillation

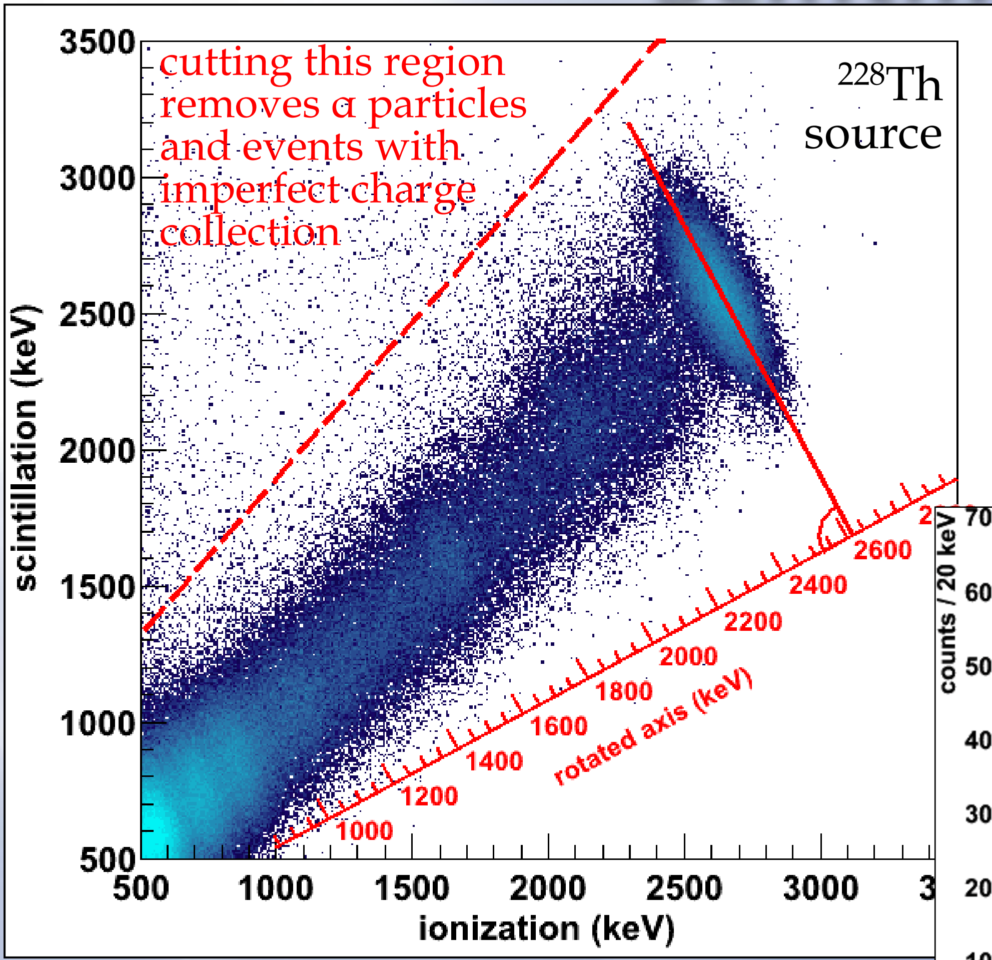



Ionization alone: 3.8% @ 570 keV or 1.8 % @ Q(ββ)

Ionization & Scintillation: 3.0% @ 570 keV or 1.4 % @ Q(ββ)

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

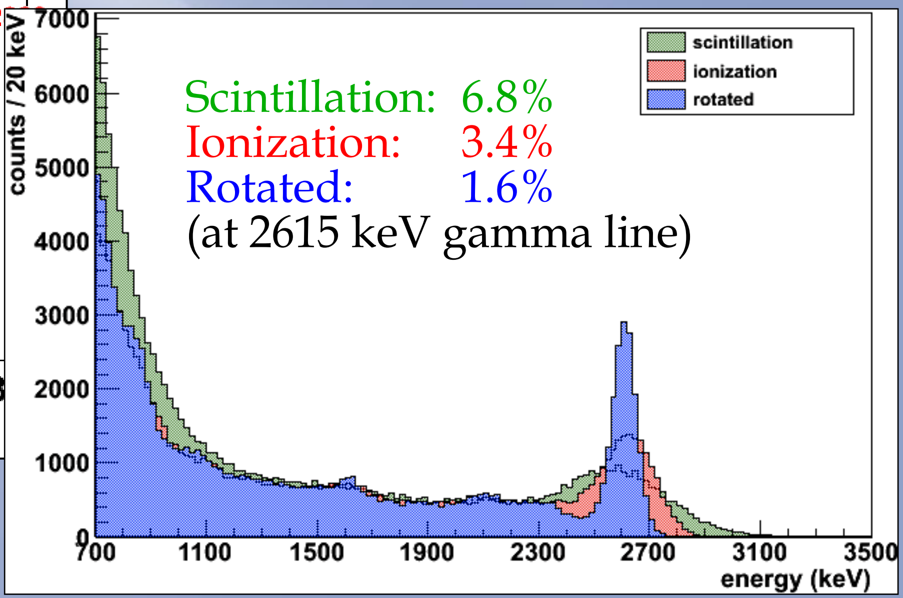
# Combining Ionization and Scintillation




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

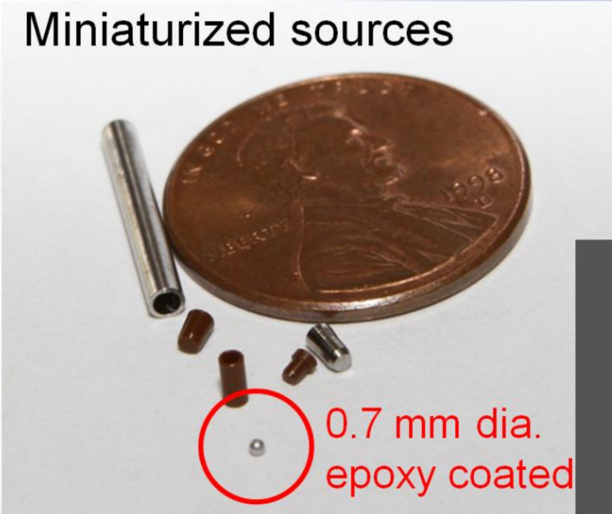
*E. Conti et al. Phys. Rev. B 68 (2003) 054201*

Use projection onto a rotated axis to determine event energy

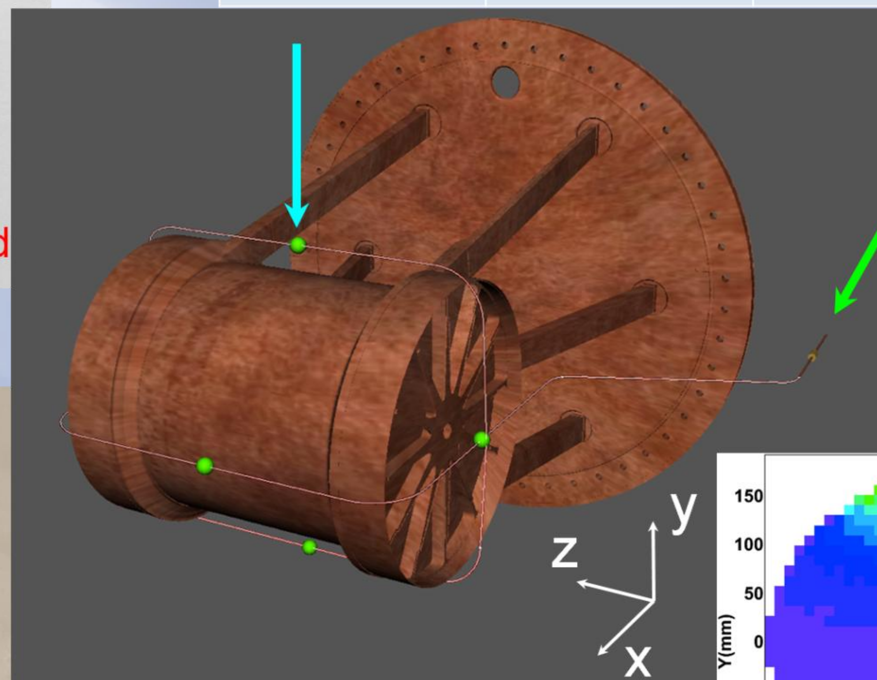


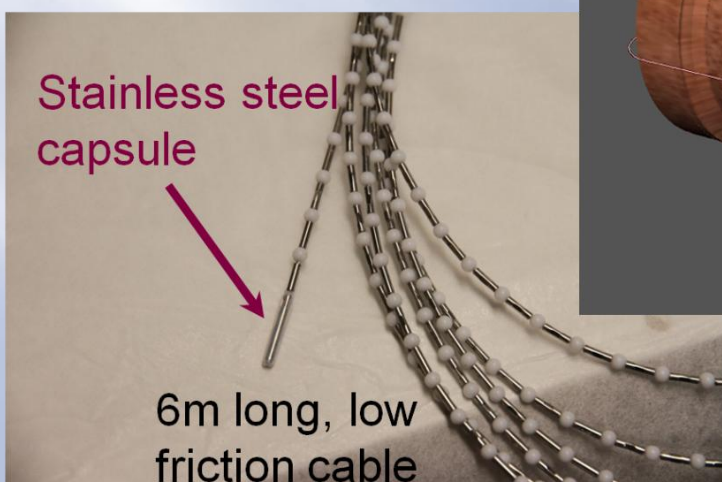

Rotation angle chosen to optimize energy resolution at 2615 keV

# Calibrations



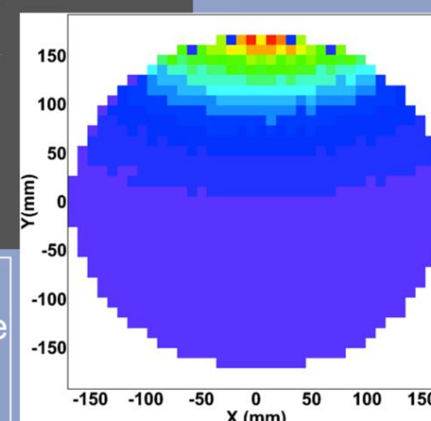

| Source | Weak (kBq) | Strong (kBq) |
|---|---|---|
| 60-Co | 3.0 | 15.0 |
| 137-Cs | 0.5 | 7.2 |
| 228-Th | 1.5 | 38.0 |



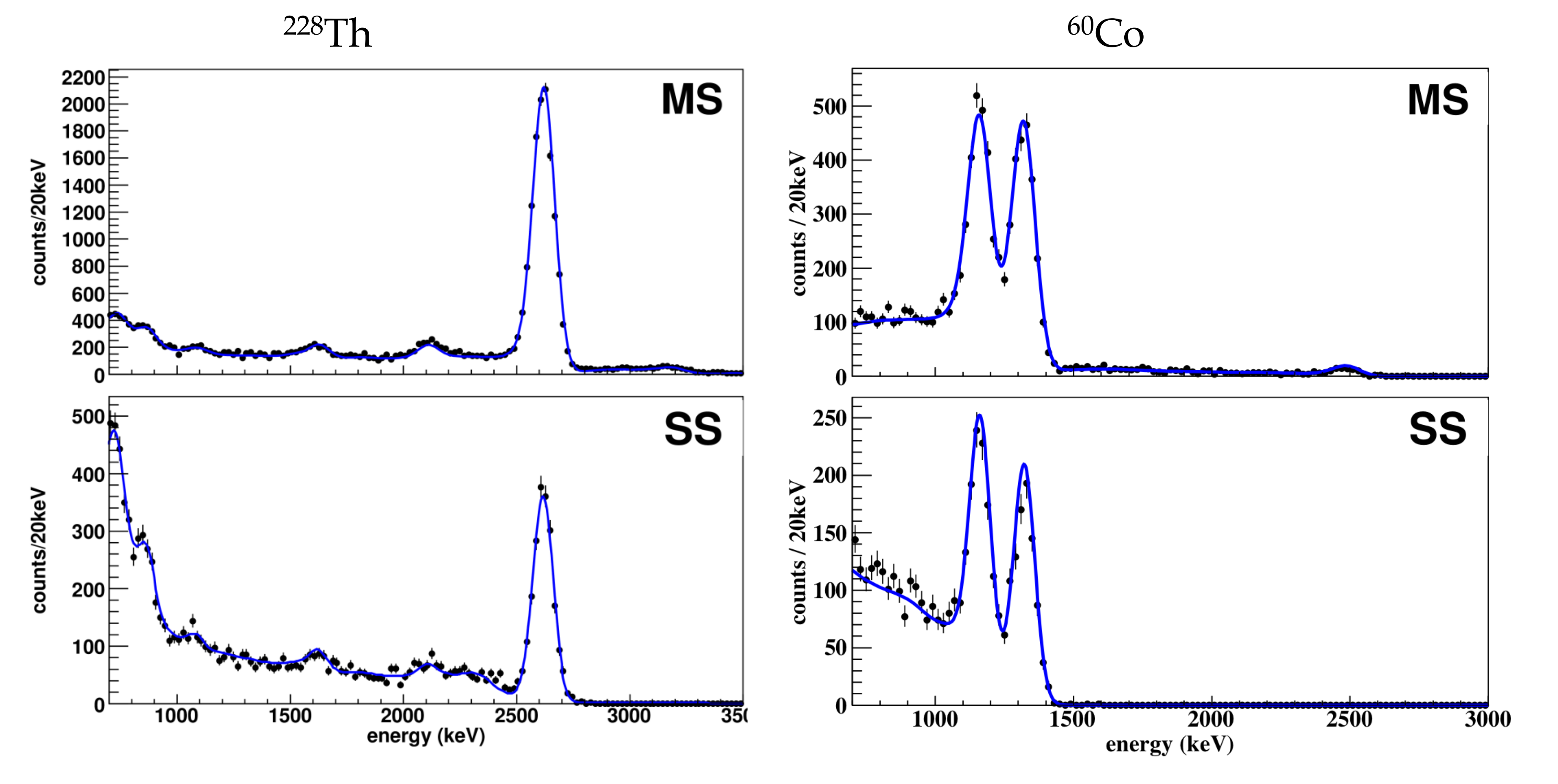




Provide 4 full energy deposition peaks in the energy range 662 keV – 2615 keV

weak $^{228}$Th

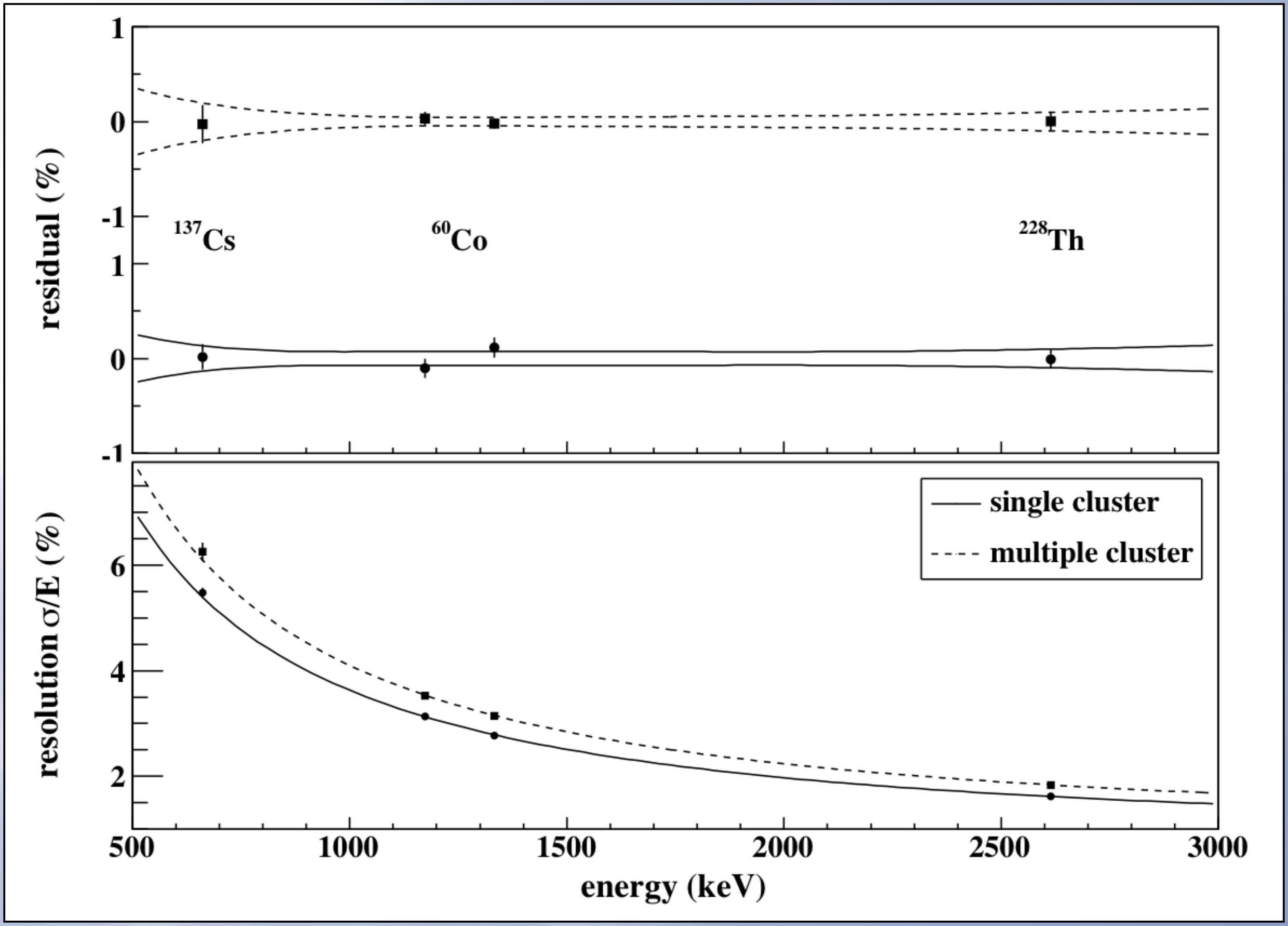


# $^{228}$Th and $^{60}$Co Source Shape




- Multi site (MS) and single site (SS) data (black points) are compared to model (blue curve)
- Single site fraction agrees to within 8.5%
- Can measure source activities to within 9.4%

# Energy Calibration




Using quadratic model for energy calibration, single- and multi-site residual are < 0.1%

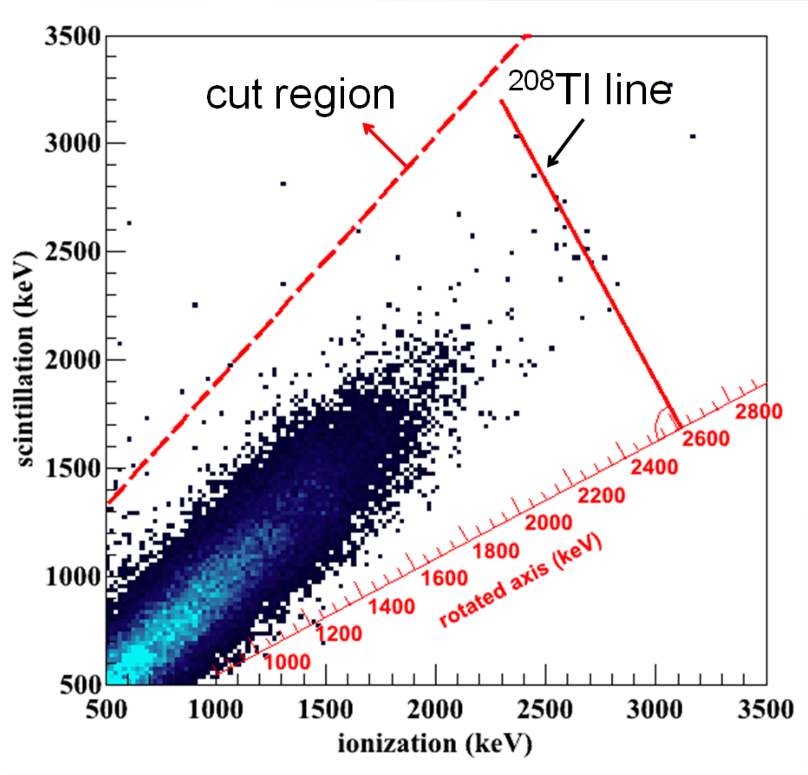
Energy resolution model:

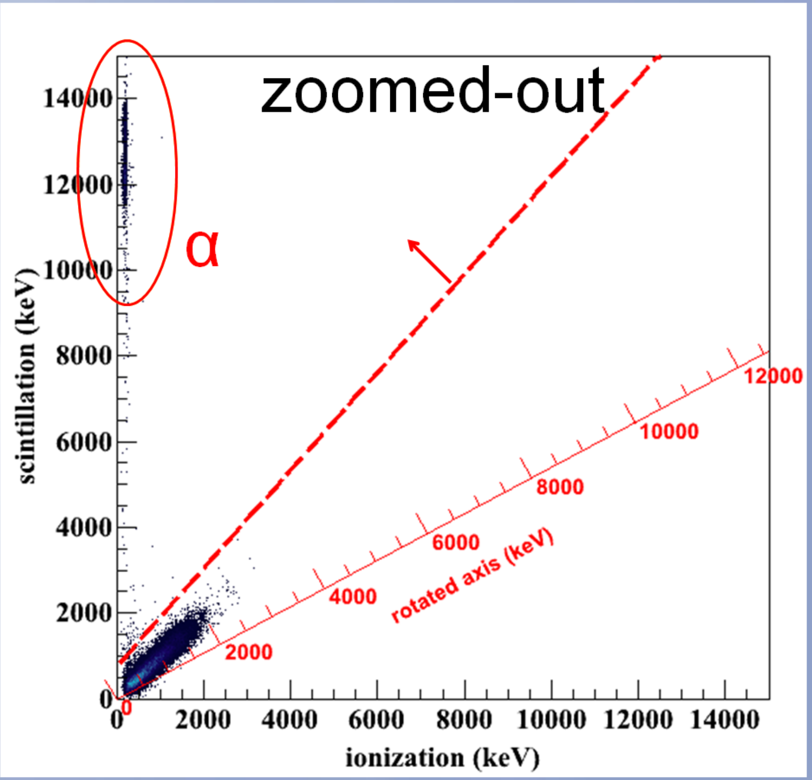
$$\sigma^2_{Tot} = p_0^2 E + p_1^2 + p_2^2 E^2$$

Resolution dominated by constant (noise) term $p_1$

At Qββ (2458 keV):
σ/E = 1.67 % (SS)
σ/E = 1.84 % (MS)

# Low background 2D SS spectrum

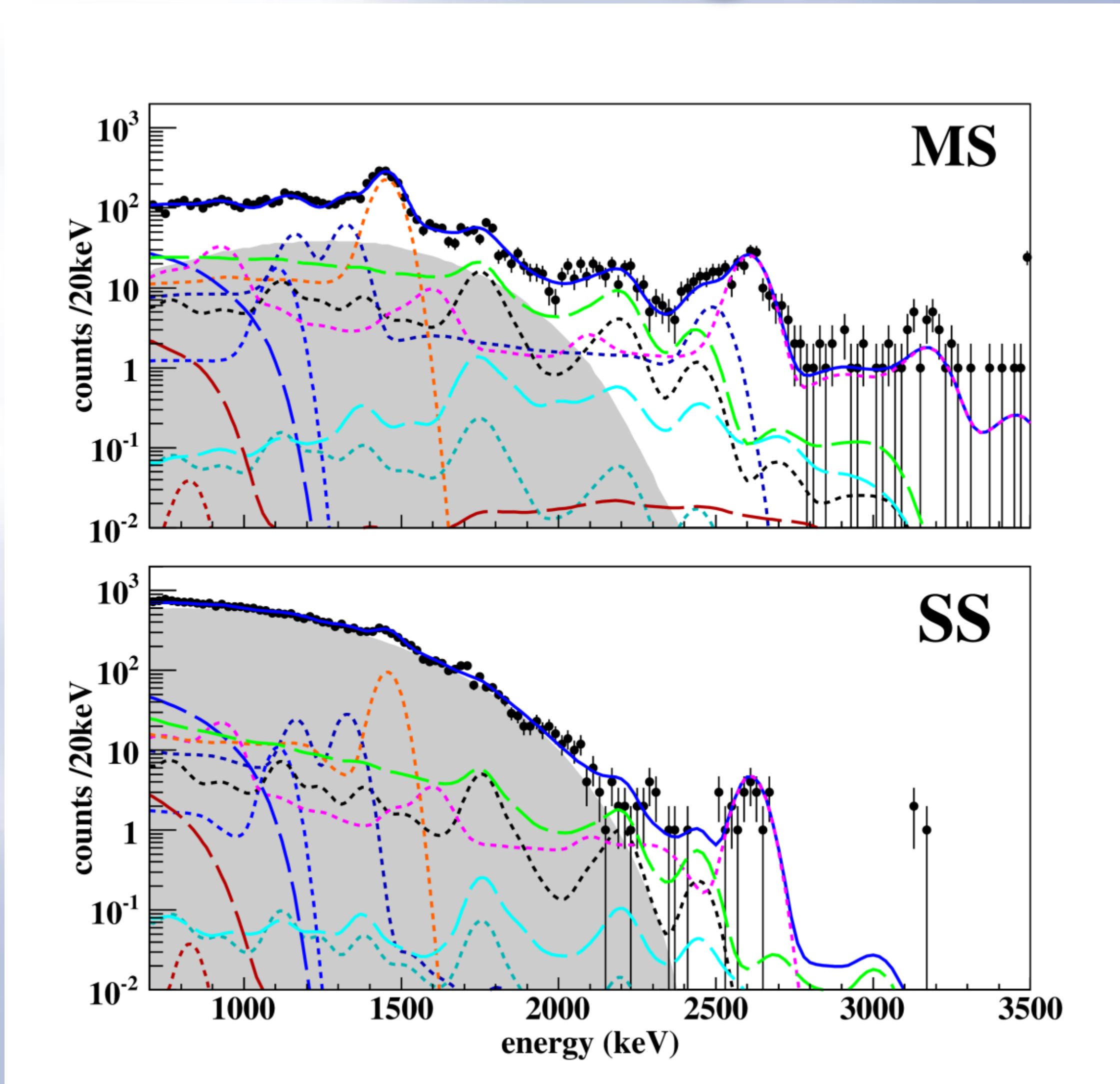


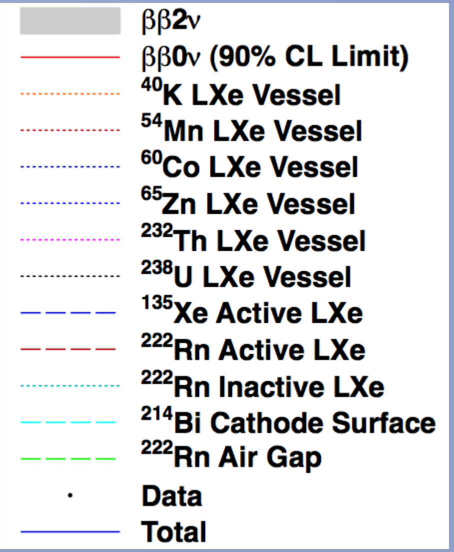

Events removed by diagonal cut:

•alpha events (they leave large ionization density, which leads to more recombination, which means more scintillation light)events near edge of detector, where not all the charge ends up on the collection wires

# Low Background Spectrum




- Trigger fully efficient above 700 keV
- Low background run livetime: **120.7 days**
- Active mass: **98.5 kg LXe (79.4 kg $^{136}$LXe)**
- Exposure: **32.5 kg·yr**
- Total dead time (vetos): 8.6%
- Various background PDFs fitted along with 2νββ and 0νββ PDFs



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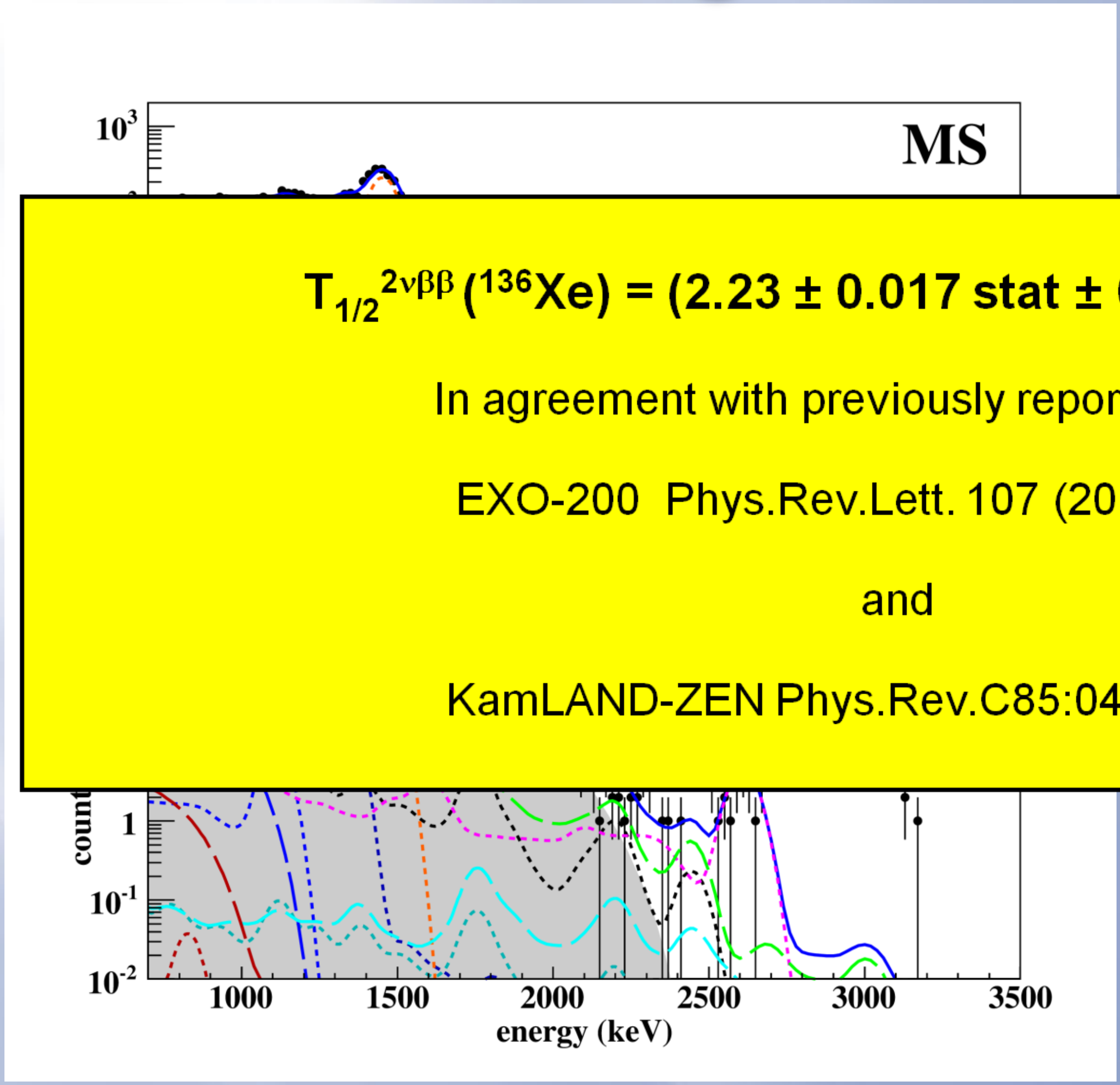


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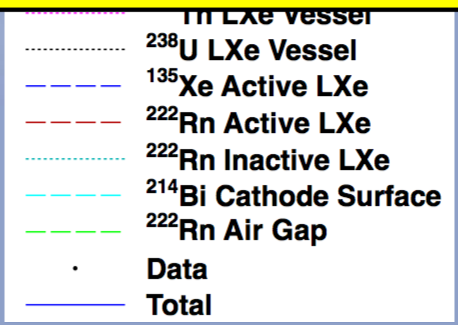



**$T_{1/2}^{2\nu\beta\beta}(^{136}Xe) = (2.23 \pm 0.017\ \text{stat} \pm 0.22\ \text{sys})\cdot 10^{21}$ yr**

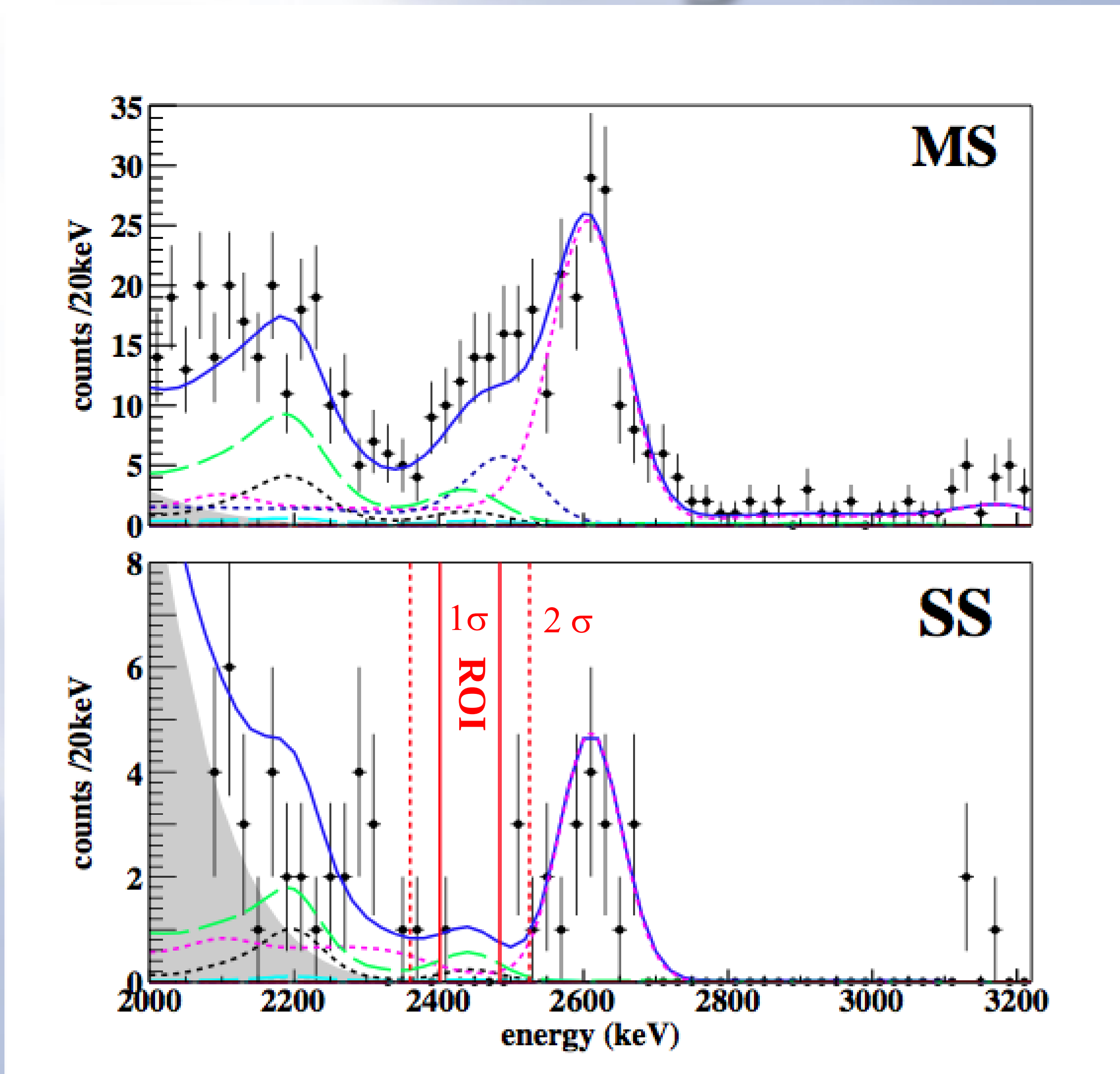
In agreement with previously reported value by

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

and

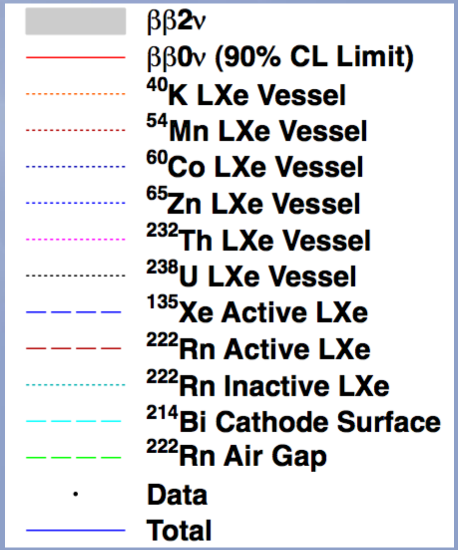
KamLAND-ZEN Phys.Rev.C85:045504,2012)

# Low Background Spectrum

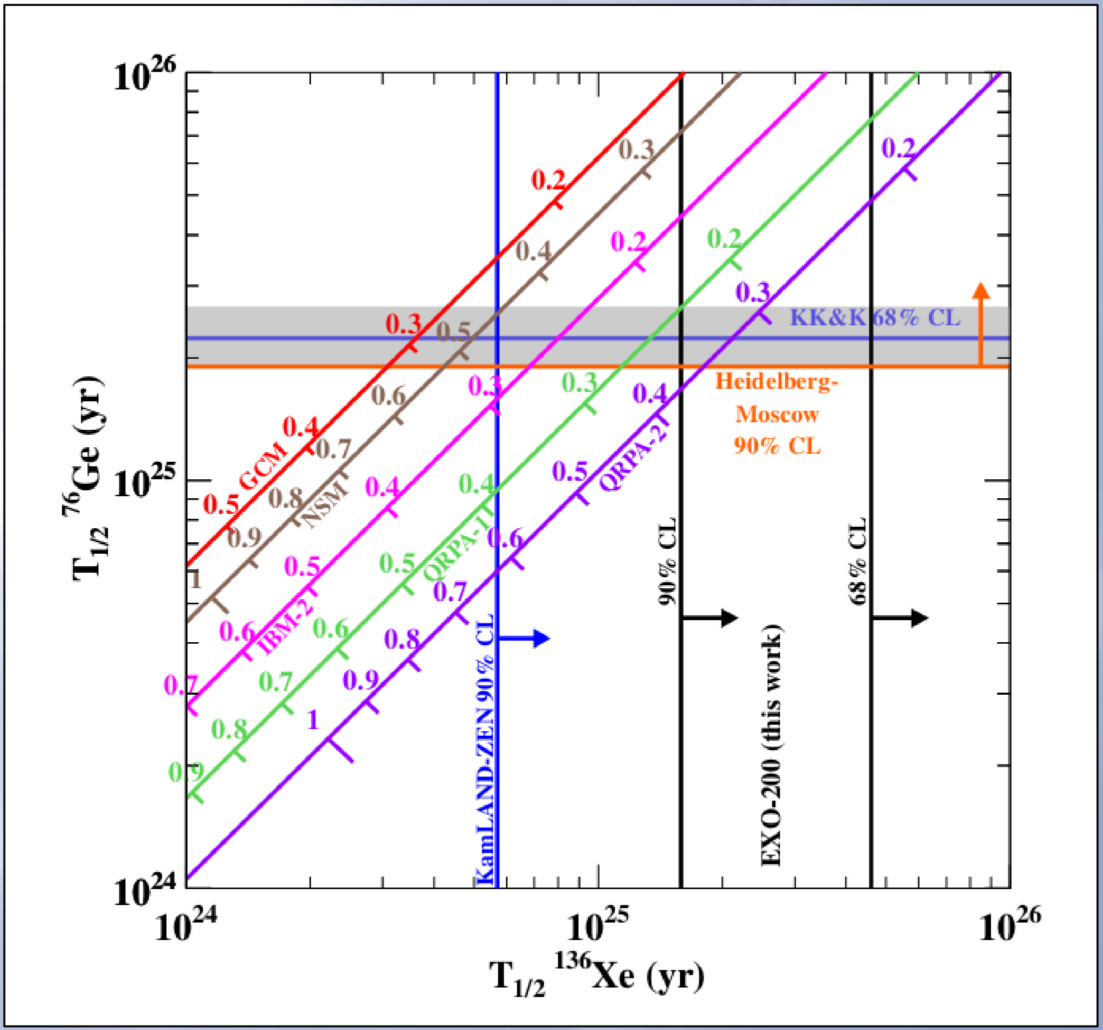



Profile likelihood fit to entire SS and MS spectra to extract limits for $T_{1/2}^{0\nu\beta\beta}$

No 0ν signal observed



# Limits on $T_{½}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta} \rangle$




90% C.L. limit compared with Recent $^{136}$Xe constraints (KamLAND-ZEN) >2.5 factor improvement.

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

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

**(90% C.L.)**

[arXiv:1205.5608]

Tension with discovery claim in Ge.


KamLAND-Zen Collaboration
Phys. Rev. C 85 (2012) 045504]
[H.V. Klapdor-Kleingrothaus et al.
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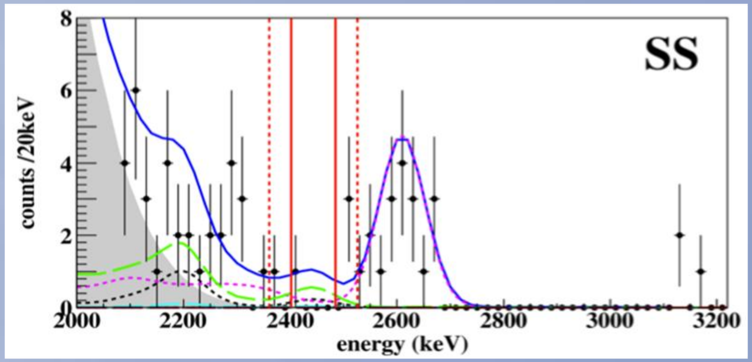
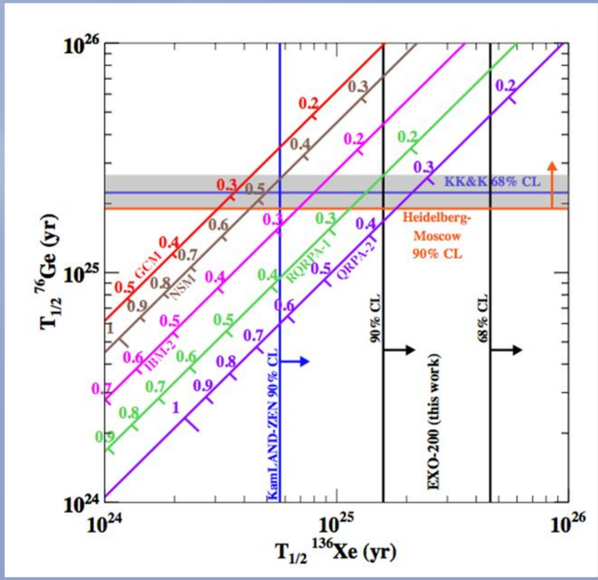
# Conclusions

- EXO-200 is taking low background data
- Detector working well, met our goals:
- Energy resolution: 1.67% at $Q_{\beta\beta}$
- Background: $1.5 \times 10^{-3}$ $kg^{-1}keV^{-1}yr^{-1}$
- 1 (5) counts in 1σ (2σ) 0νββ ROI



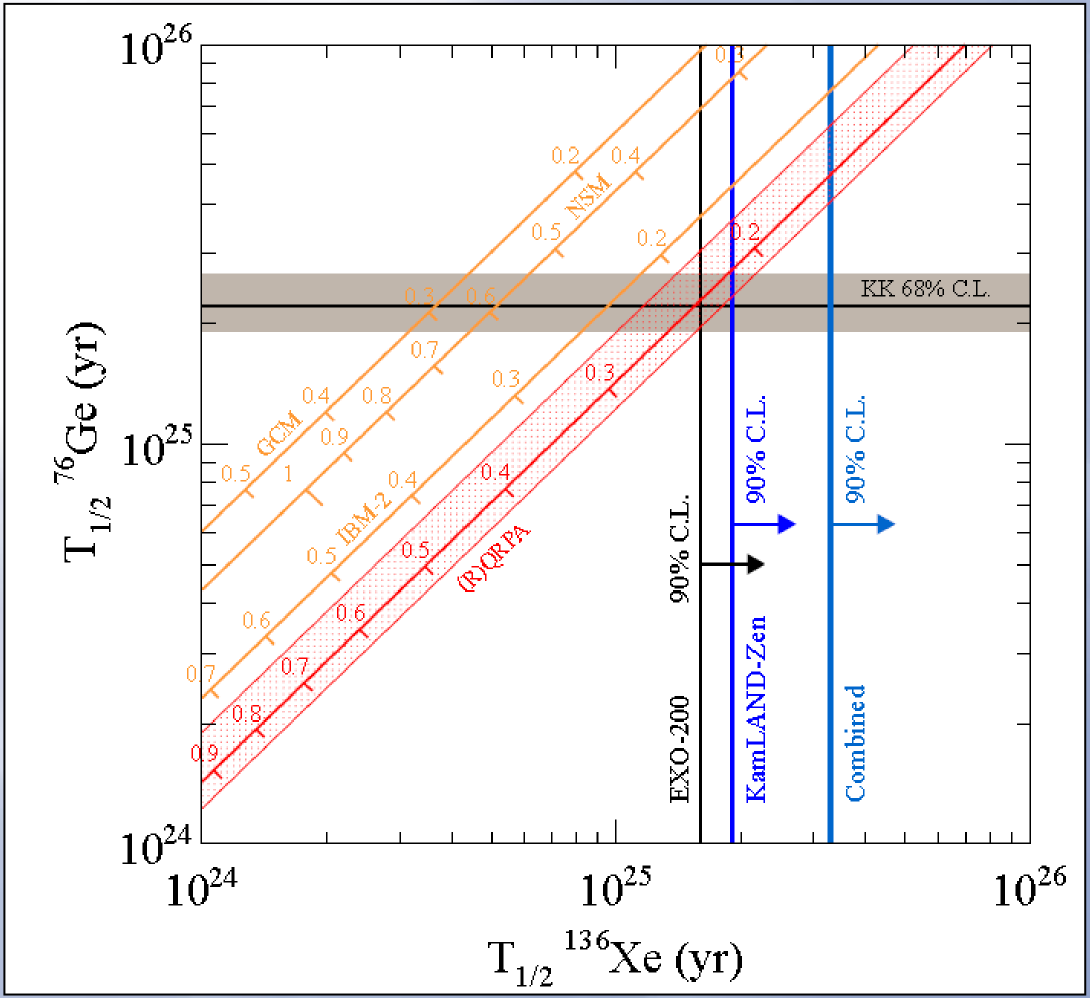

$T_{1/2}^{0\nu\beta\beta} > 1.6\cdot10^{25}$ yr
$\langle m_{\beta\beta}\rangle < 140–380$ meV
(90% C.L.)

arXiv:1205.5608 – Subm. to PRL




- Improvements on σ and b in progress
- EXO-200 approved to run for 4 more years

# Limit on Neutrinoless Decay of $^{136}Xe$ from the First Phase of KamLAND-Zen




**$T_{1/2}^{0\nu\beta\beta} > 1.9 \cdot 10^{25}$ yr combined**

**$T_{1/2}^{0\nu\beta\beta} > 3.4 \cdot 10^{25}$ yr**

**$\langle m_{\beta\beta} \rangle < 120 – 250$ mV (90% C.L.)**

[arXiv:1211.3863]

89.5 kg-yr of 136Xe