The Enriched Xenon Observatory (EXO)

Russell Neilson
Stanford University
TIPP 2011

Outline

- Introduction to double beta decay and EXO

- 200kg detector (EXO-200)
    - LXeTPC
    - Xenon gas recirculation

- Dec 2010/Jan 2011 engineering run

- Current status

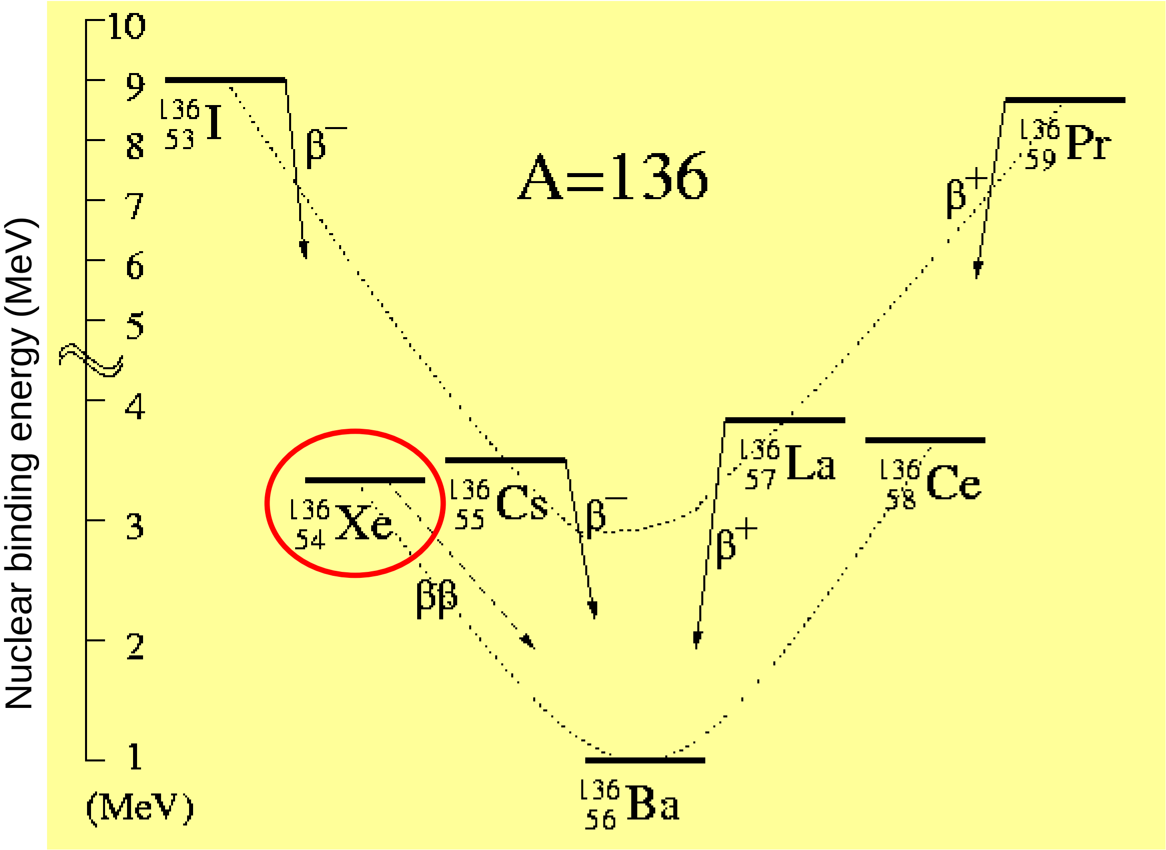
Double beta decay

Extremely rare nuclear decay where two neutrons decay into two protons simultaneously.

$(A,Z) \rightarrow (A,Z+2) + 2e^{-} \, (+2\overline{\nu}_e)$

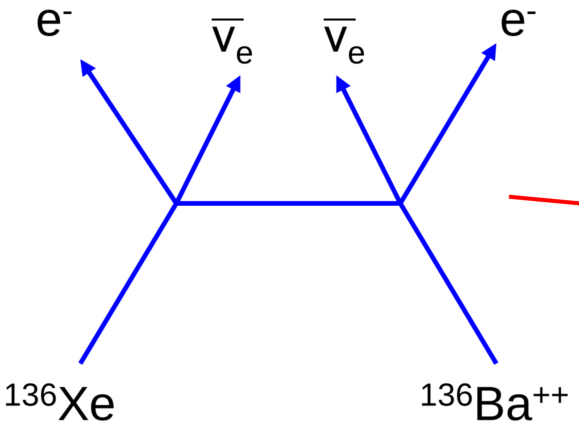
Only observable when single beta decay is energetically forbidden.

Double Beta Decay has been observed for a handful isotopes, although not for ^{136}Xe.

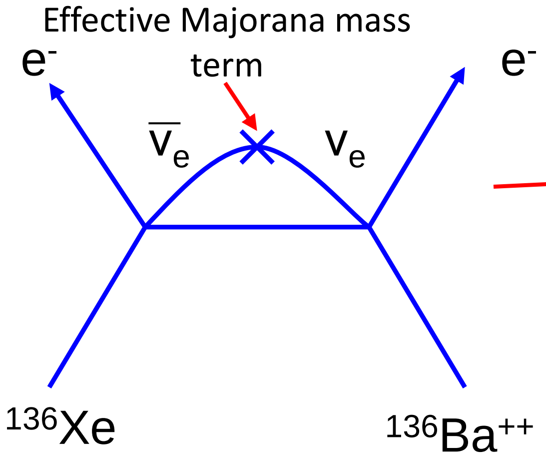


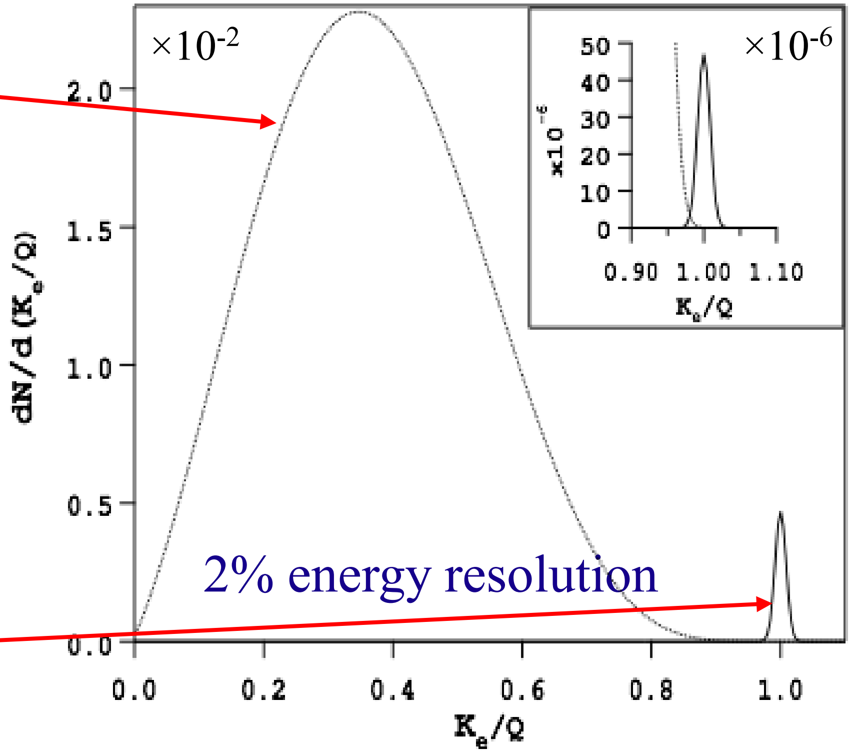
Two types of double beta decay

Two neutrino double beta decay



Neutrinoless double beta decay





2% energy resolution

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

Why use xenon?

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

Xenon is “reusable”. Can be repurified & recycled into new detector.

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

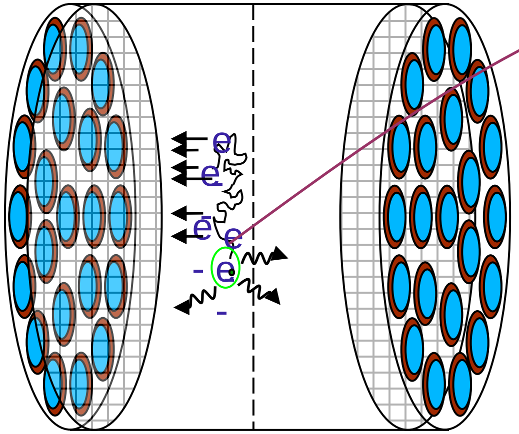
Minimal cosmogenic activation. No long lived radioactive isotopes of xenon.

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

… admits a novel coincidence technique. Background reduction by barium daughter tagging.

The EXO concept

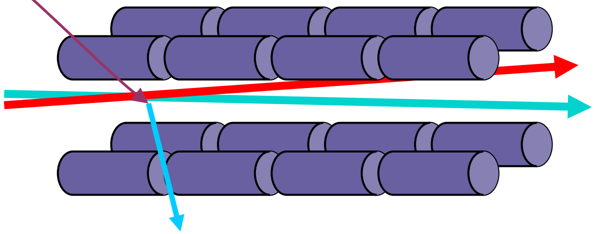
Measure energy and position of decay event in a Time Projection Chamber (TPC)

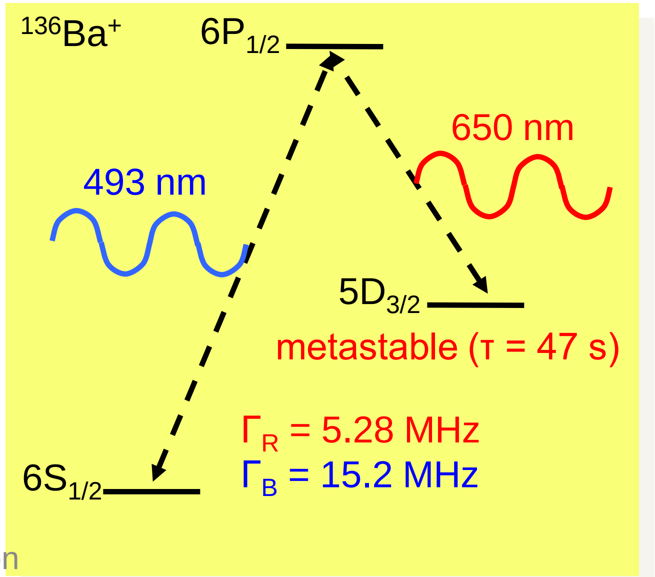


Transfer Ba⁺ to an RF trap with a probe

Identify the barium ions with laser spectroscopy

Detect flourescence light with a CCD

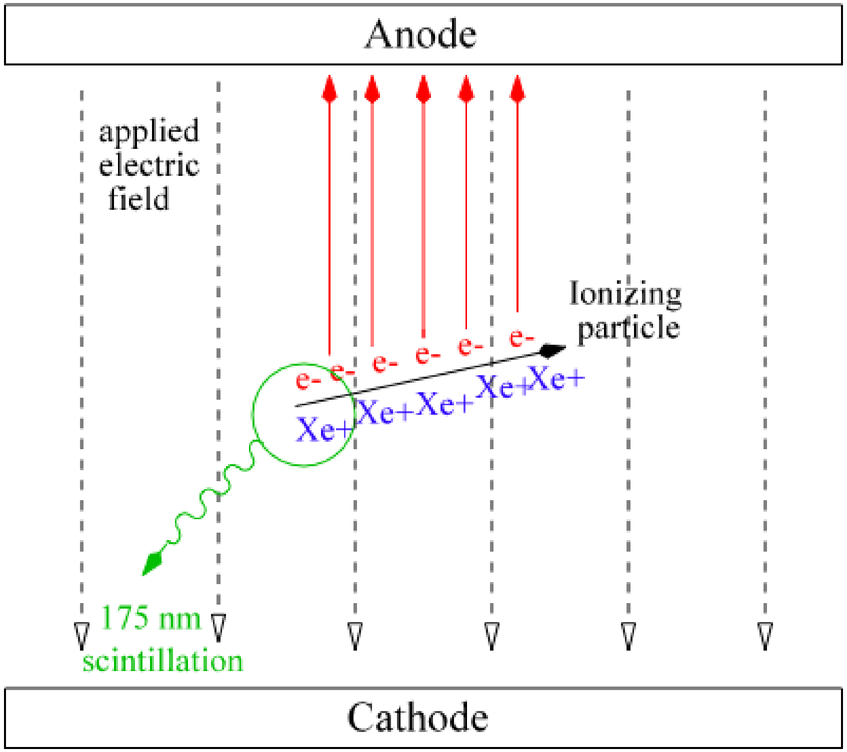




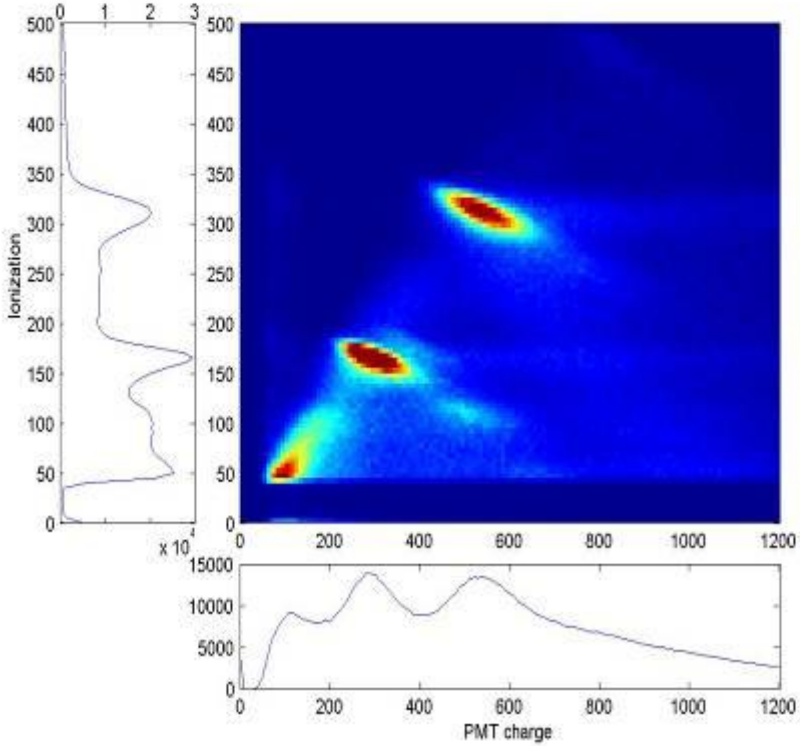
Liquid xenon energy resolution

Microscopic anti-correlation between ionization and scintillation.

Reading out both gives improved energy resolution.



1 kV/cm drift field, ^{207}Bi EC source



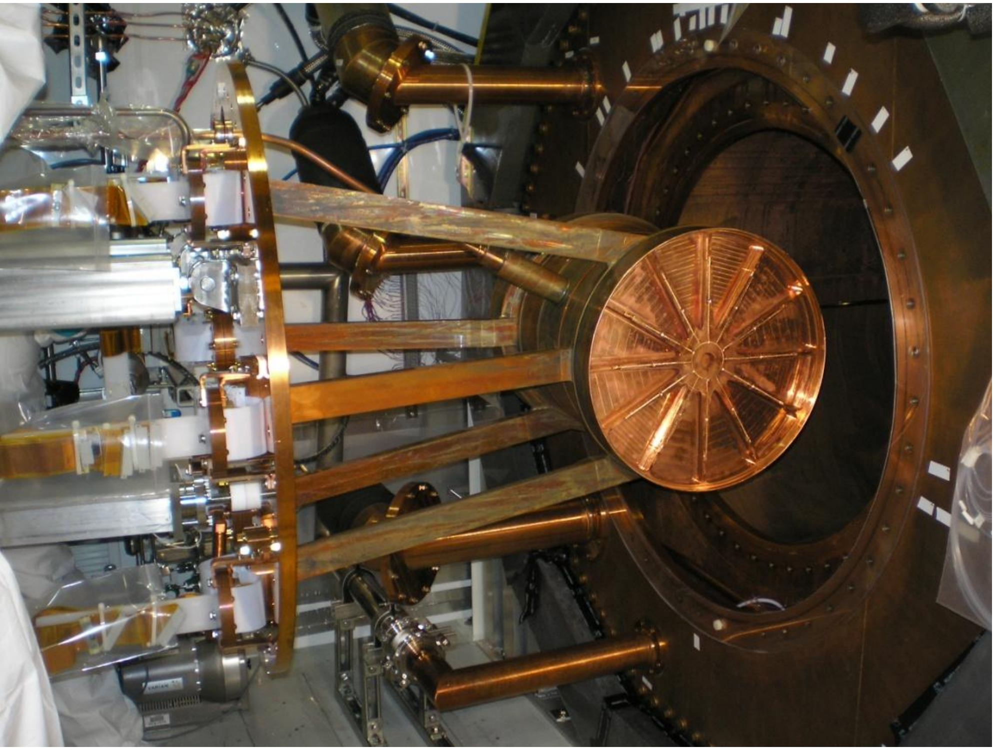
E. Conti et al., PRB: **68**(2003)054201

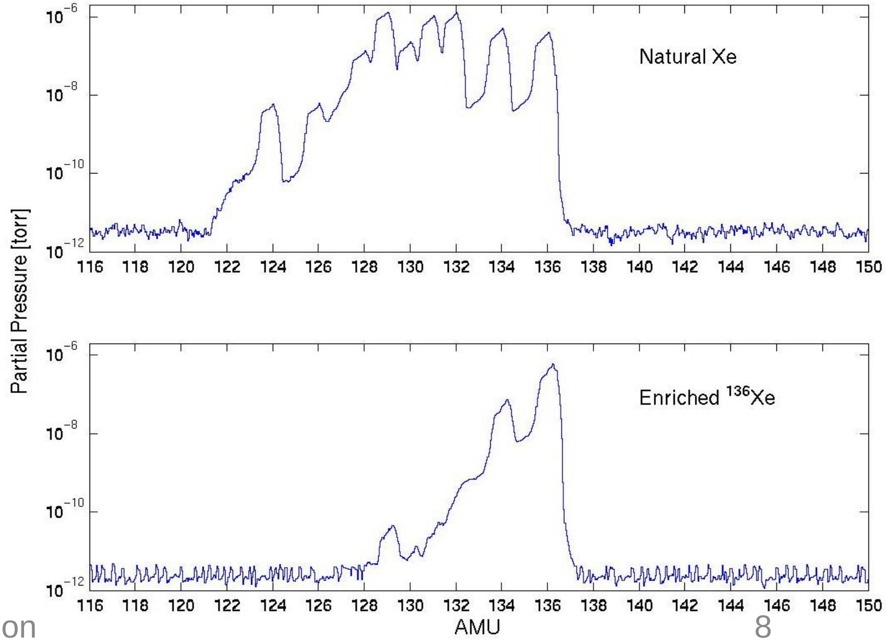
Ionization only:
σ(E)/E = 3.8% at 570keV gives 1.8% at $Q_{\beta\beta}$

Ionization and Scintillation:
σ(E)/E = 3.0% at 570keV gives 1.4% at $Q_{\beta\beta}$

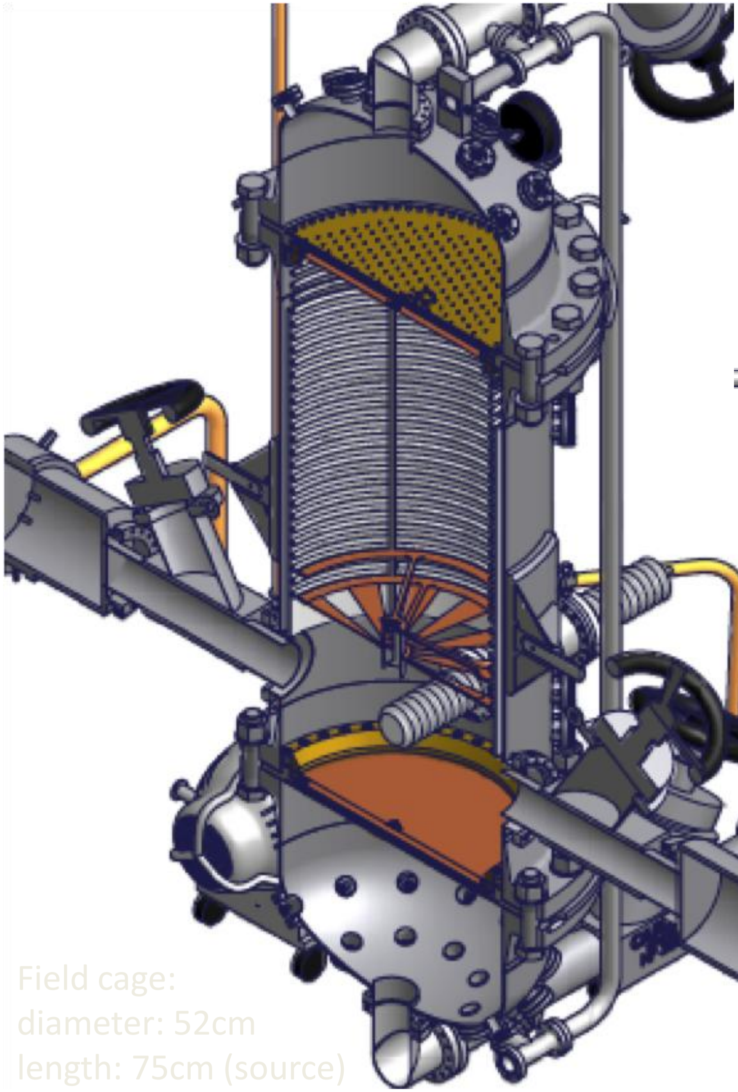
EXO-200

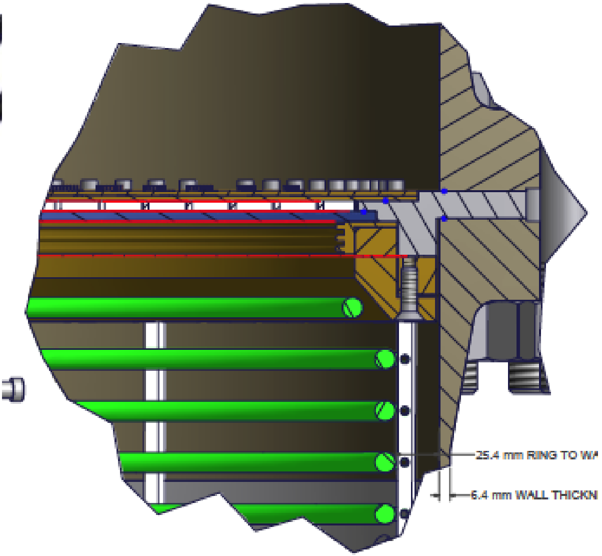
A 200kg enriched liquid xenon low-background TPC with simultaneous ionization and scintillation read-out.

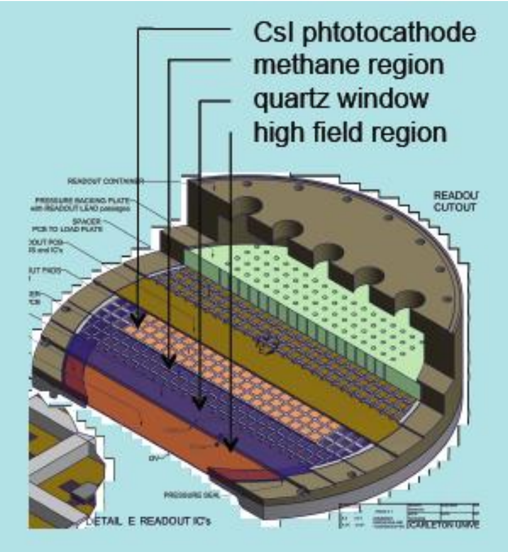


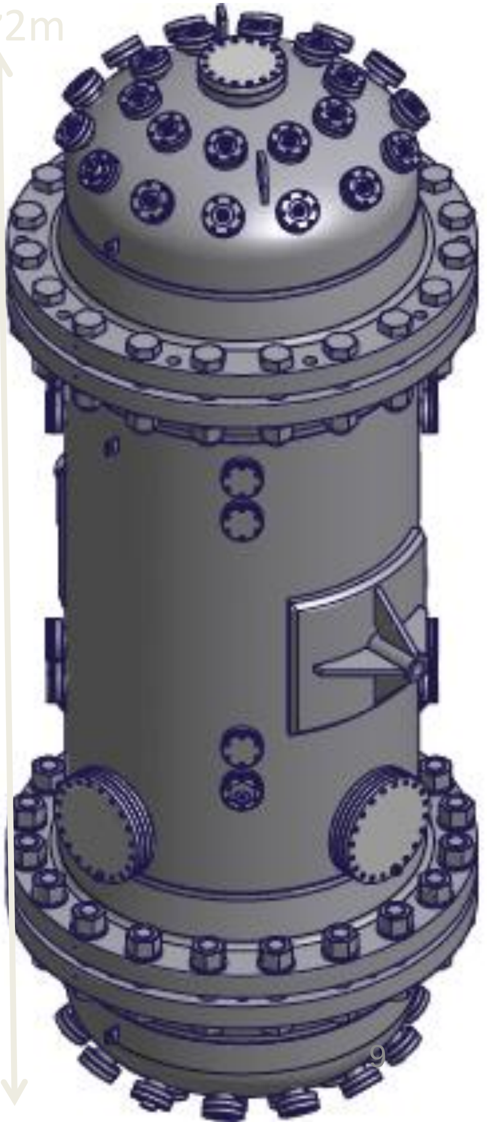


Gas xenon prototype under construction



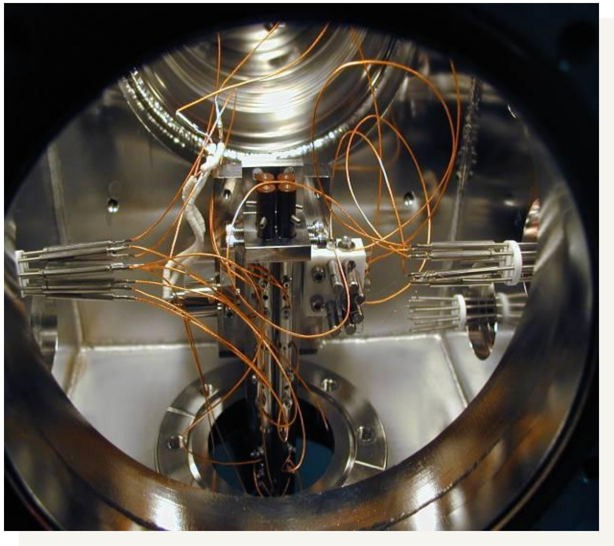


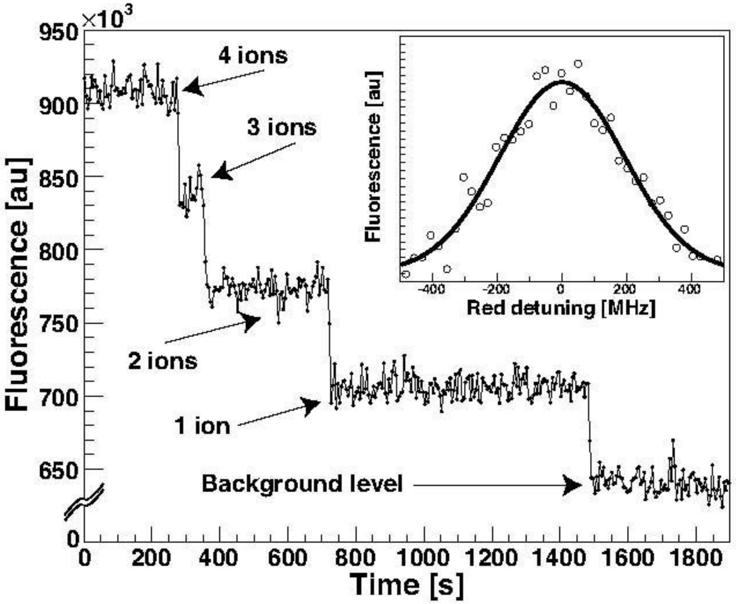




Ba$^+$ tagging R&D program

- Observed fluorescence of a single Ba$^+$ in a buffer gas filled ion trap (~ 10^{-3} torr He, some Xe)



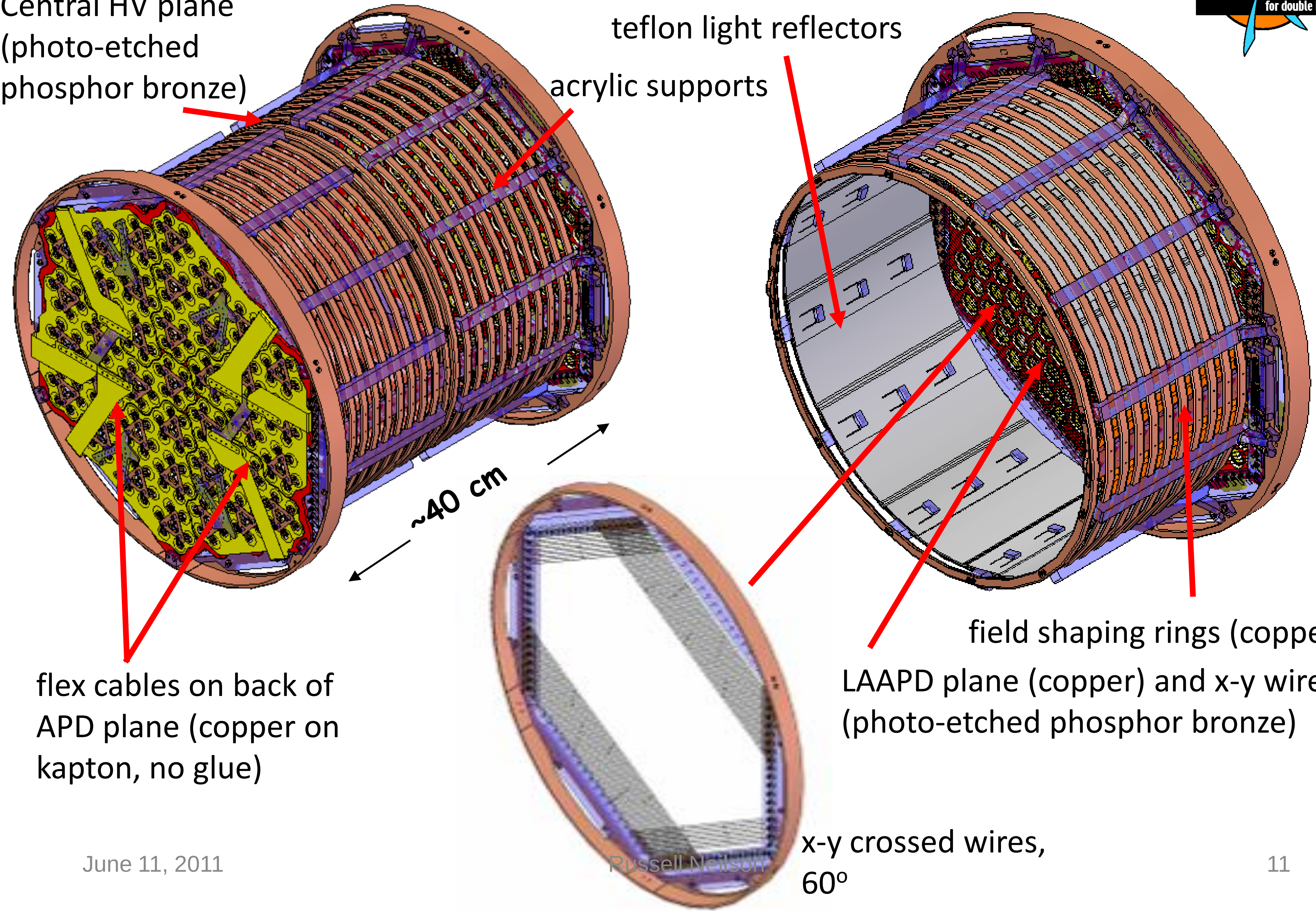


M.Green et al., Phys Rev A 76 (2007) 023404
B.Flatt et al., NIM A 578 (2007) 409

See next talk by Karl Twelker: *Single ion detection for an ultra-sensitive neutrino-less double beta decay search with the Enriched Xenon Observatory.*

EXO-200 TPC

Enriched Xenon Observatory
EXO
for double beta decay



Central HV plane (photo-etched phosphor bronze)

teflon light reflectors

acrylic supports

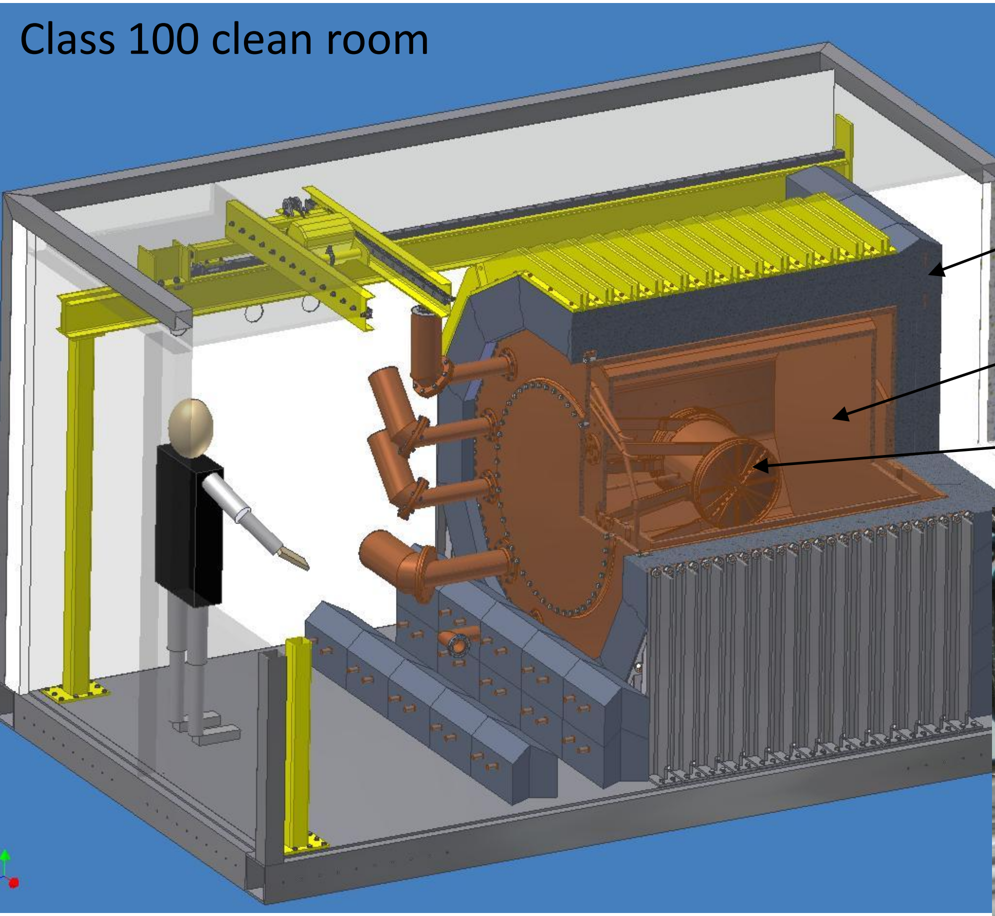
flex cables on back of APD plane (copper on kapton, no glue)

field shaping rings (copper)

LAAPD plane (copper) and x-y wires (photo-etched phosphor bronze)

x-y crossed wires, 60°

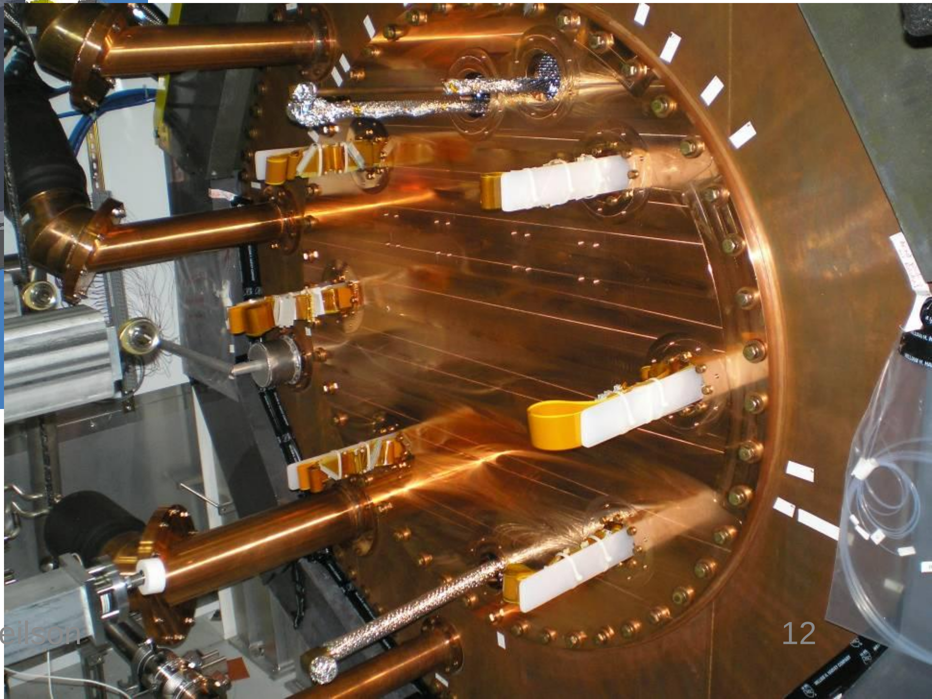
EXO-200 cryostat and lead shielding



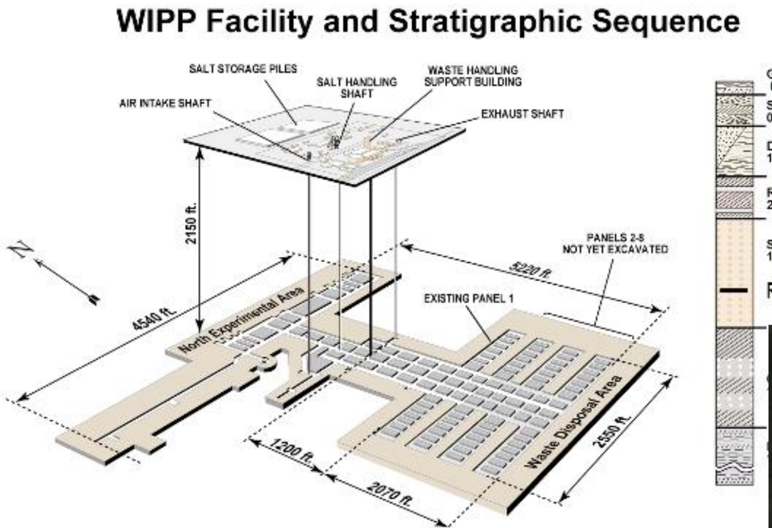
Lead shielding

Copper cryostat filled with
HFE heat transfer fluid

TPC



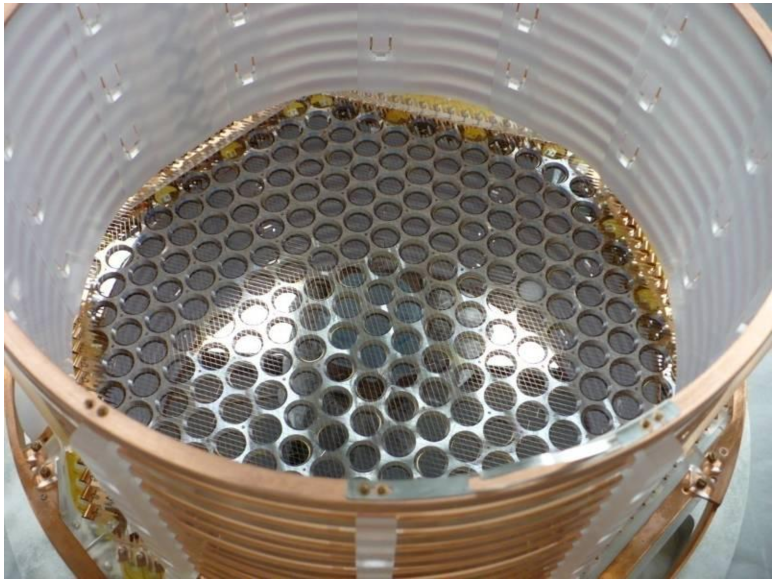
WIPP underground facility

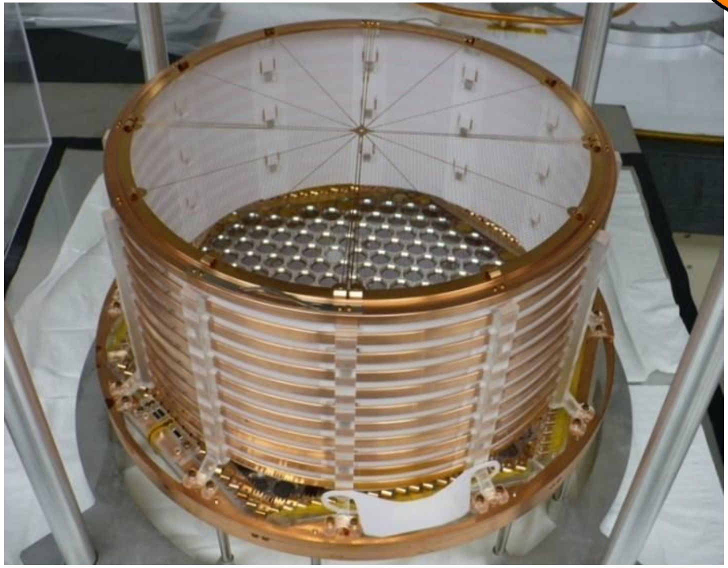


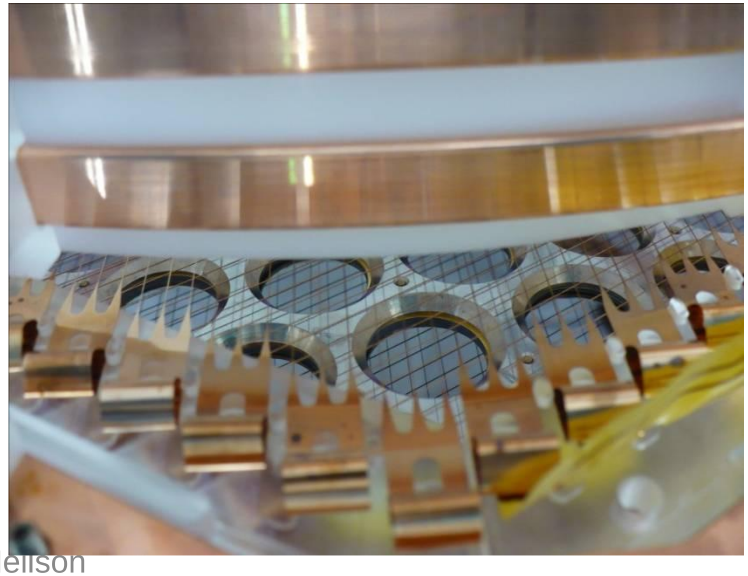
1600m water equivalent depth

EXO-200 has been assembled and commissioned at Stanford, and transported to WIPP in Carlsbad, NM.

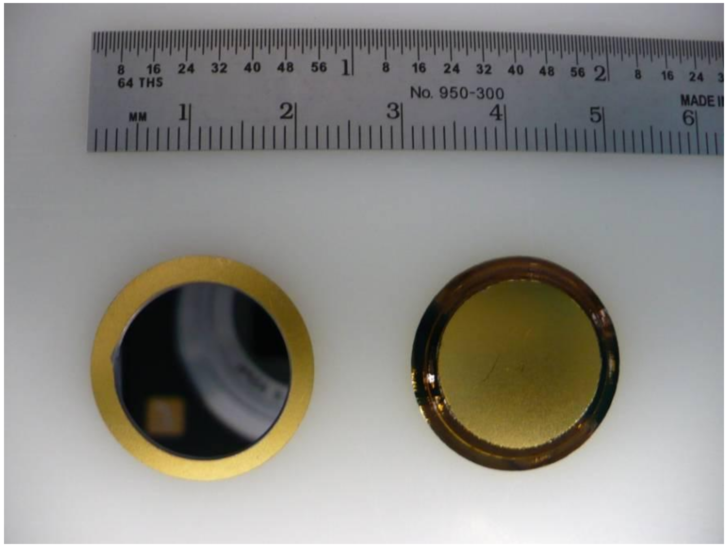
LXeTPC



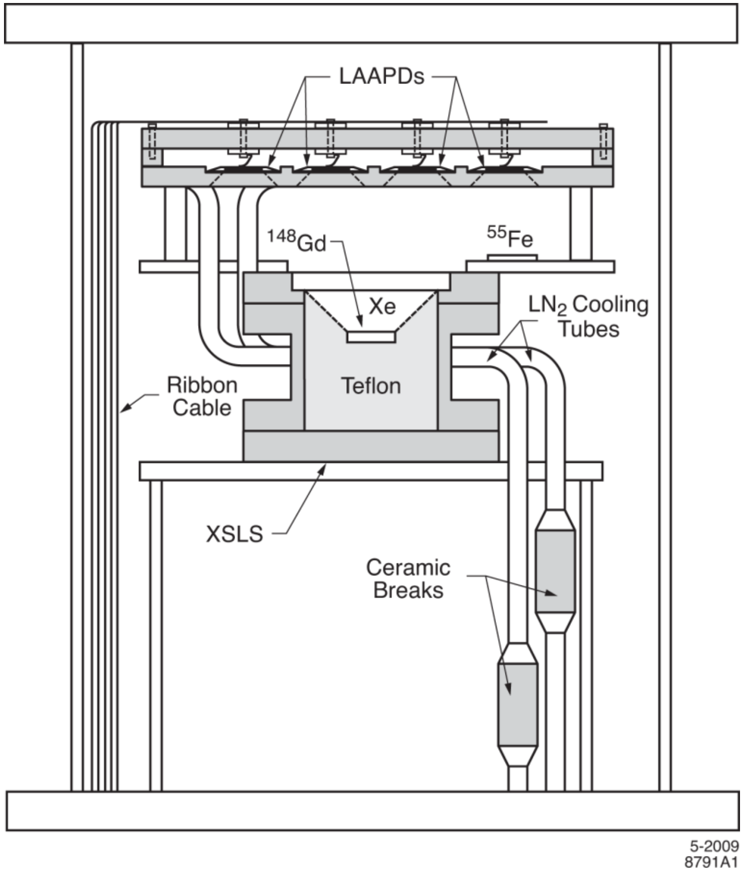




LAAPDs for scintillation light detection



- API 200mm^2 active area LAAPD.
- Low intrinsic radioactive contamination.
  - Lightweight (0.5g each)
  - Made from high purity silicon
  - Fabricated in clean room environments
  - High purity aluminum supplied to API
- High quantum efficiency for 175nm light (>50%).
- Small physical size.

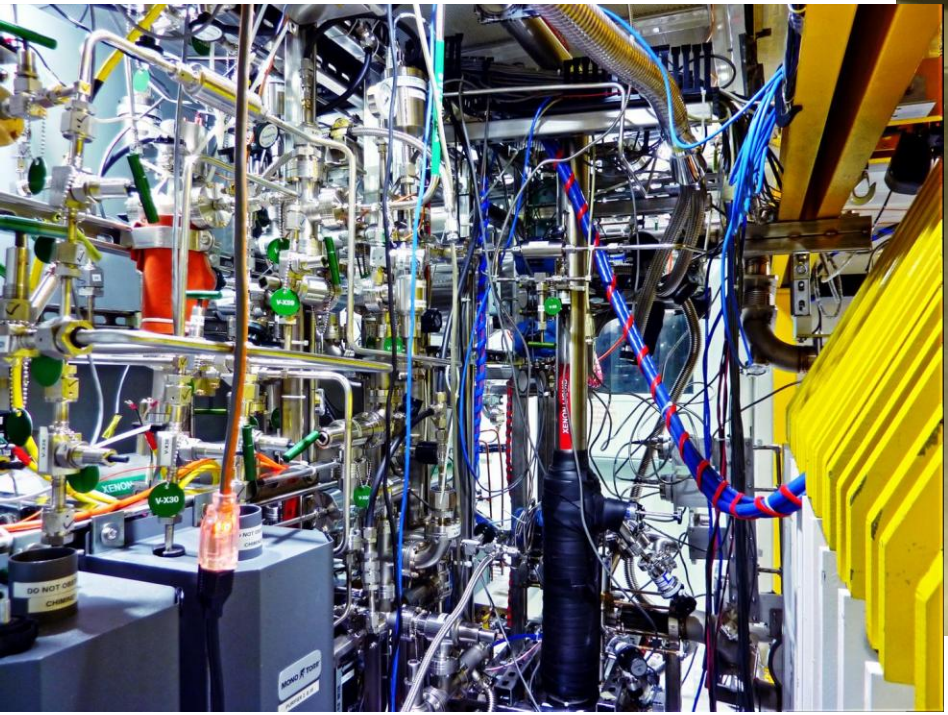


16 LAAPD characterization chamber

R. Neilson et al., NIM A 608 (2009) 68--75

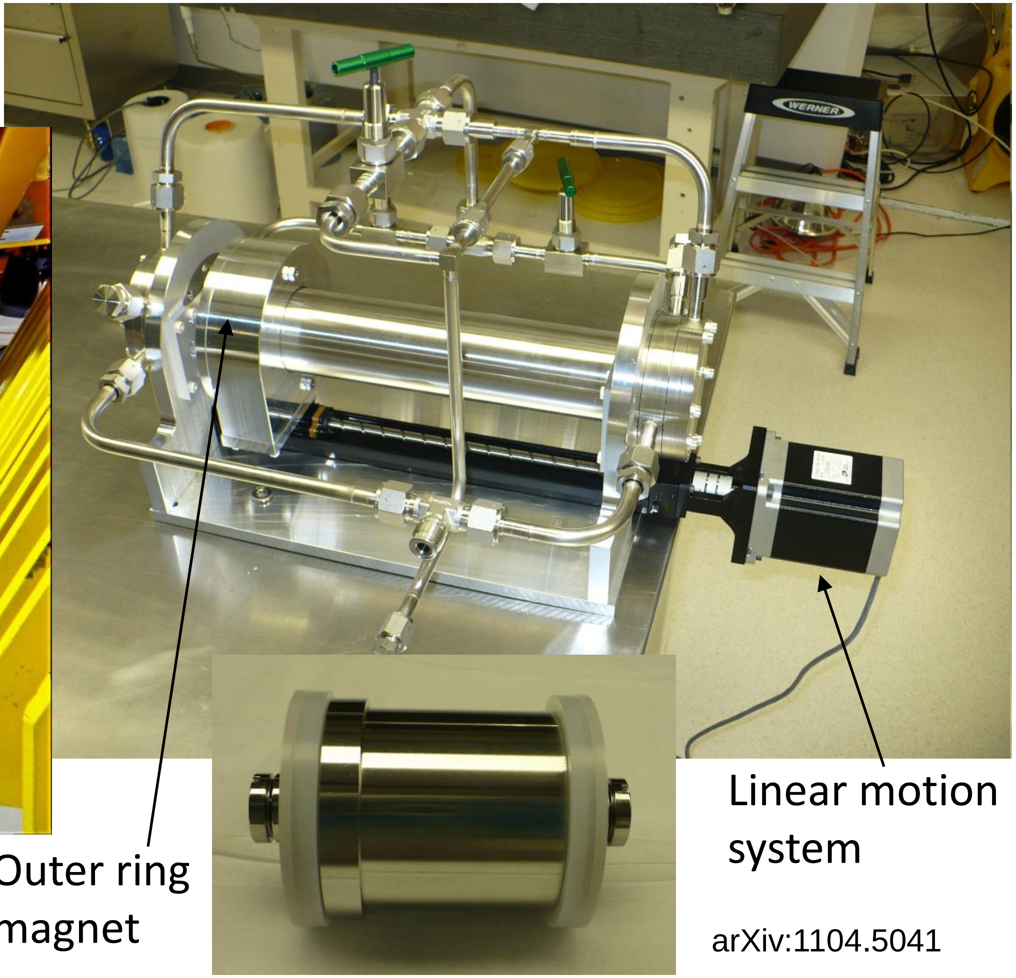
Gas phase recirculation

Xenon can be continuously re-circulated and purified up to ~20 SLPM in gas phase.



Xenon gas system

Magnetic xenon pump



Outer ring magnet

Linear motion system

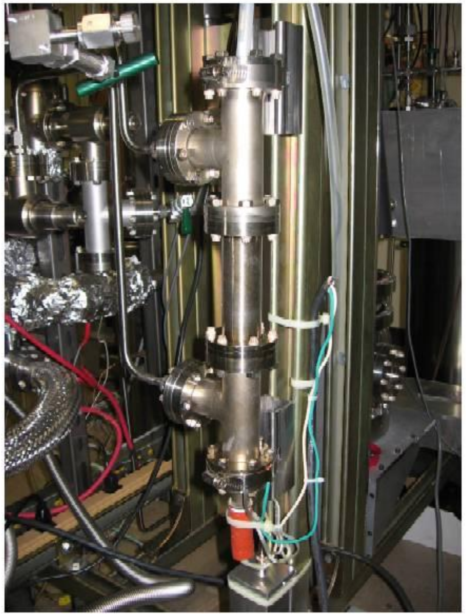
Inner magnet welded in SS can

arXiv:1104.5041

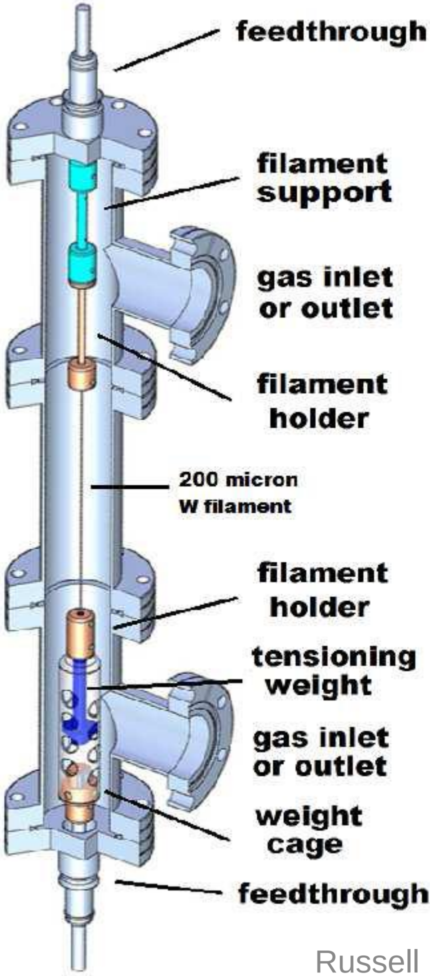
Gas purity measurement

Gas purity monitor

Electronegative impurities detected by measuring their effect on emission from a tungsten filament



arXiv:1106.1812



Xenon cold trap

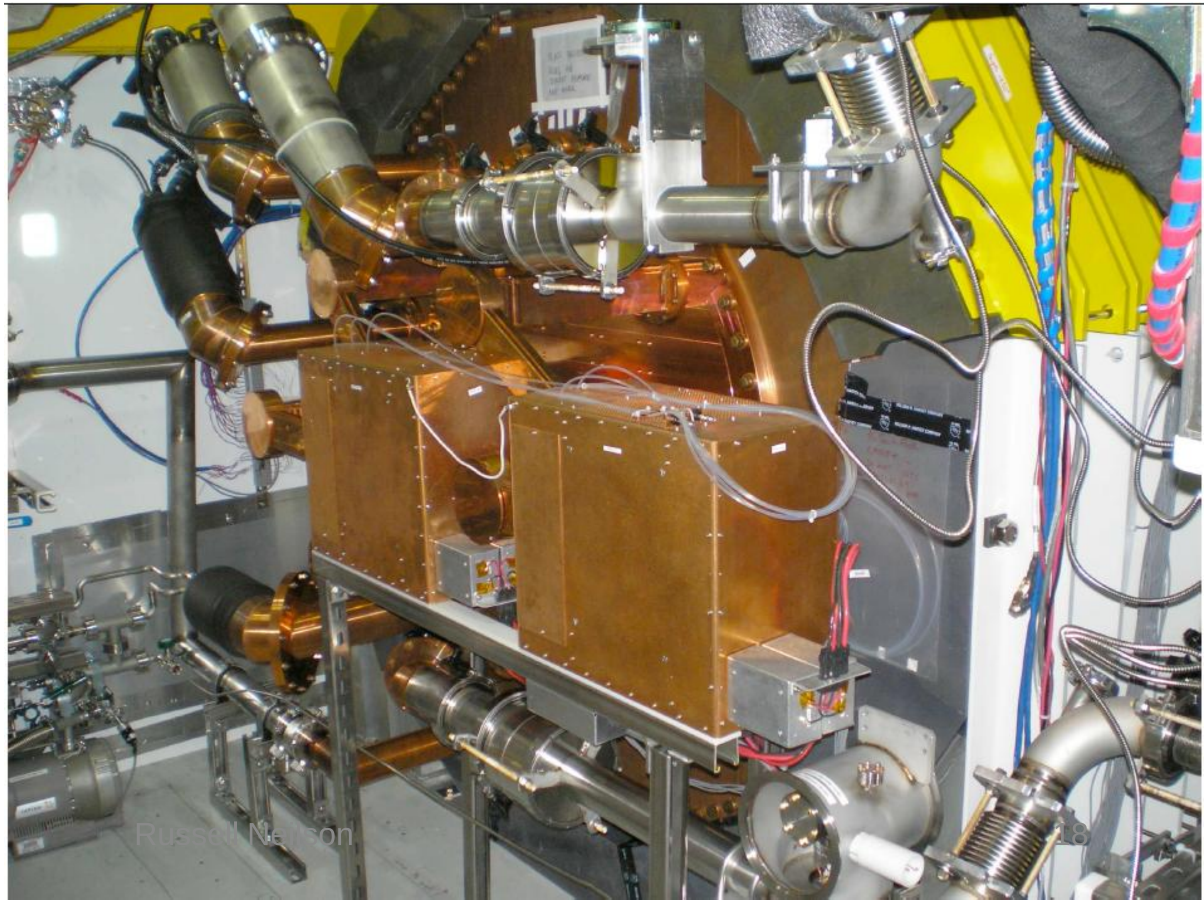
Xenon is frozen out to allow measurements of impurities below 100ppt with an RGA.

arXiv:1002.2742

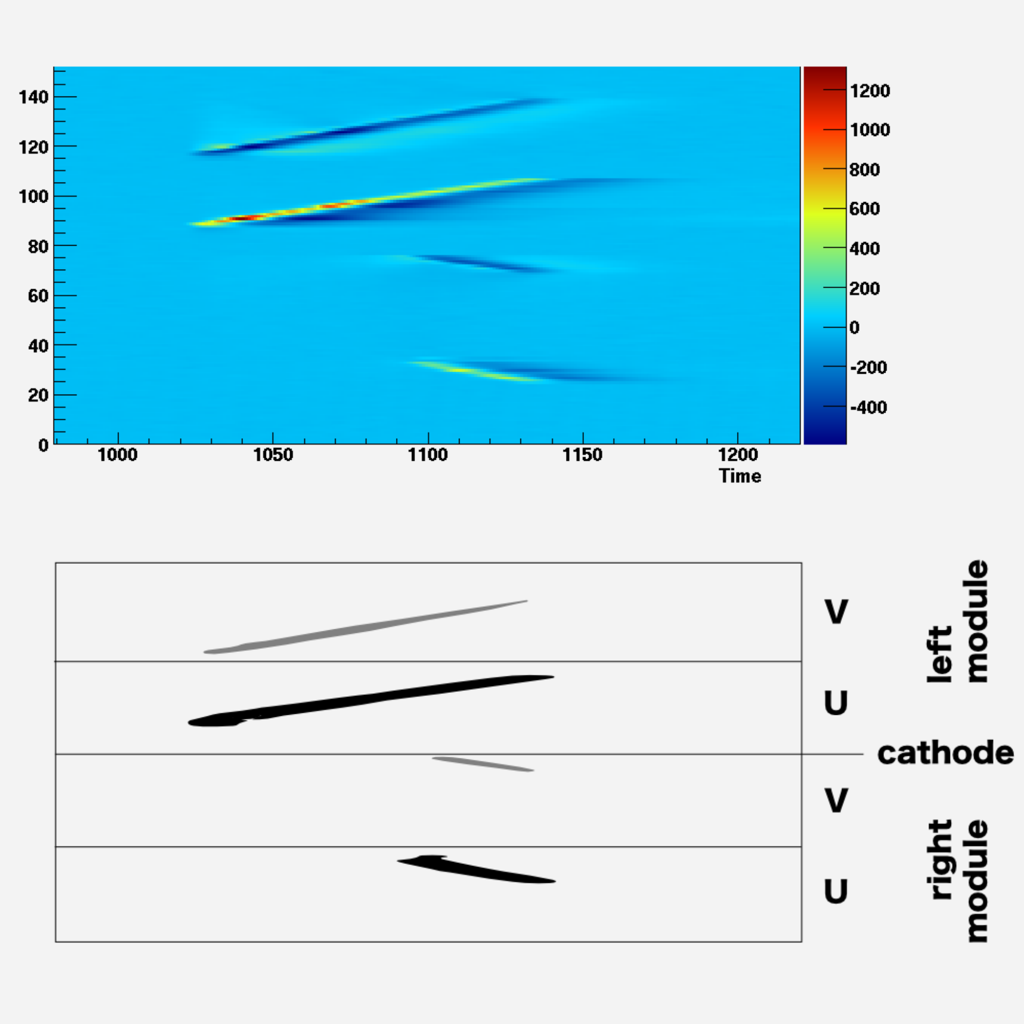
Engineering run Dec 2010/Jan 2011

- Check stability of all LXe/GXe systems
- Check Xe purity
- Check electronics
- Generally test detector performance
- Test Xe emergency recovery

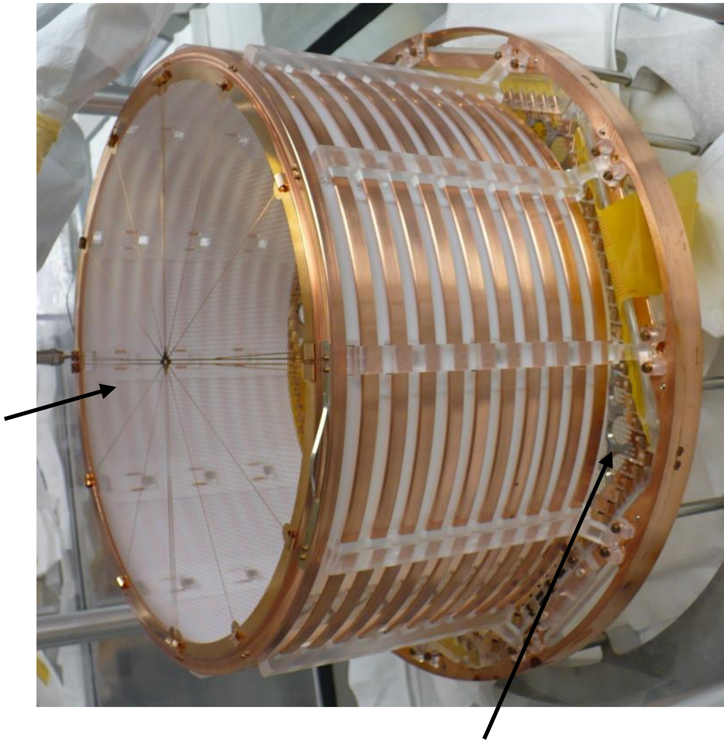
- No front shielding
- No Rn enclosure
- No Rn trap in Xe system
- No veto counter
- Natural Xe



Muon track in EXO-200



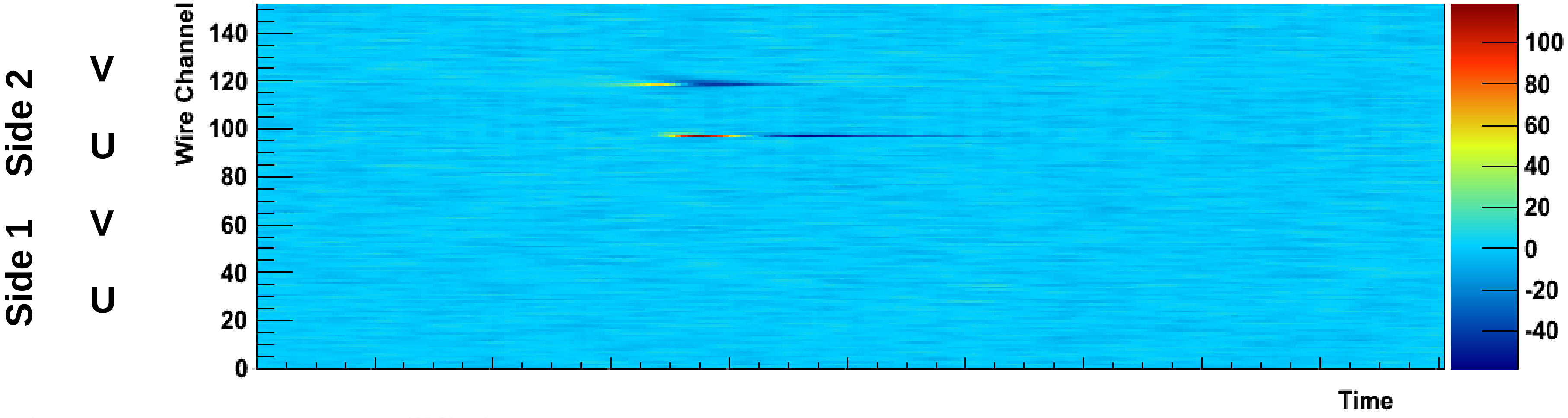
One of the two TPC modules

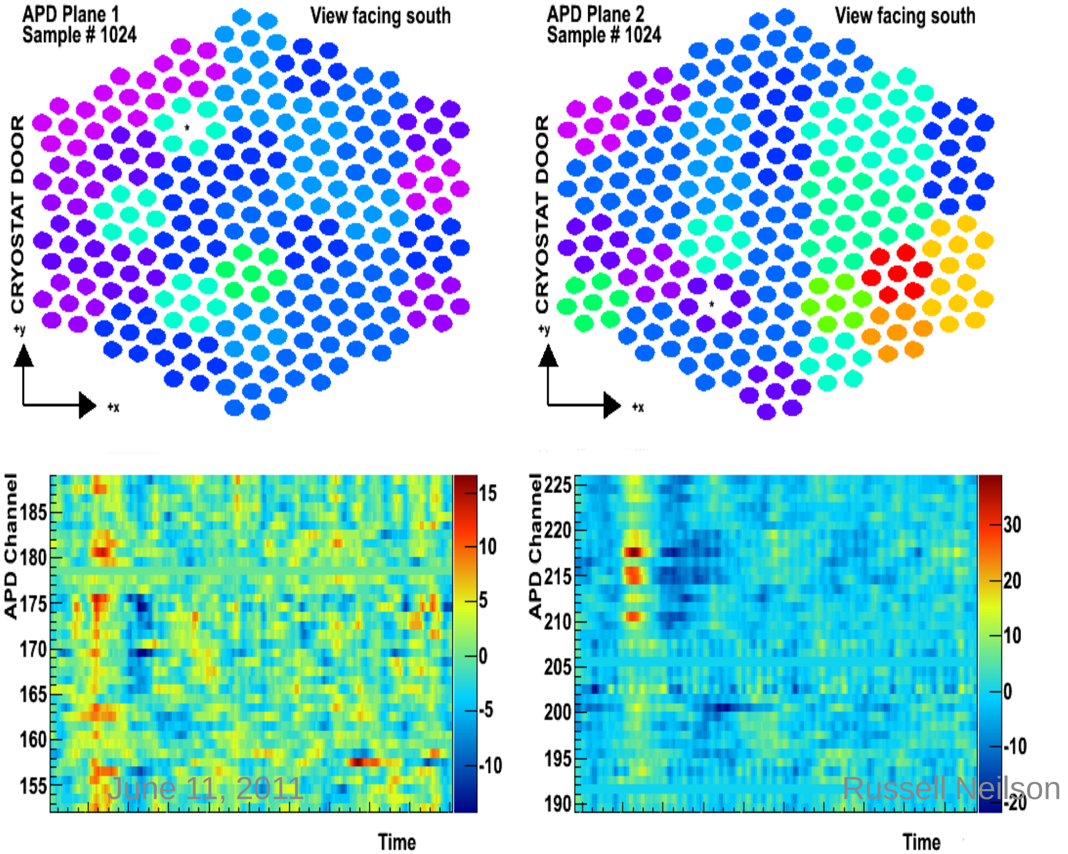


Cathode

U and V wires

Single-site energy deposition



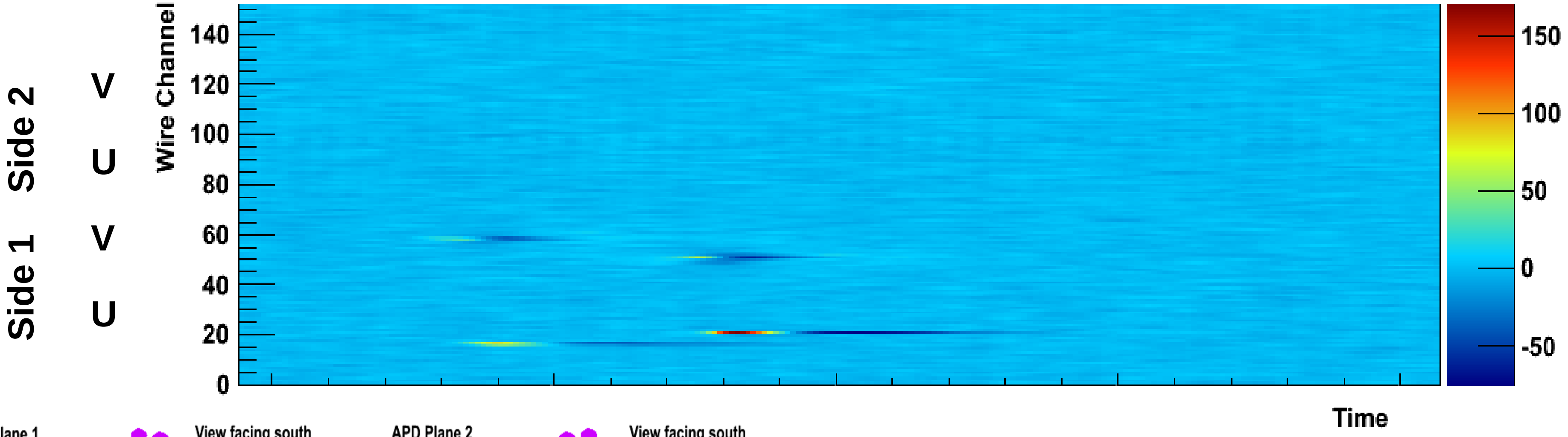


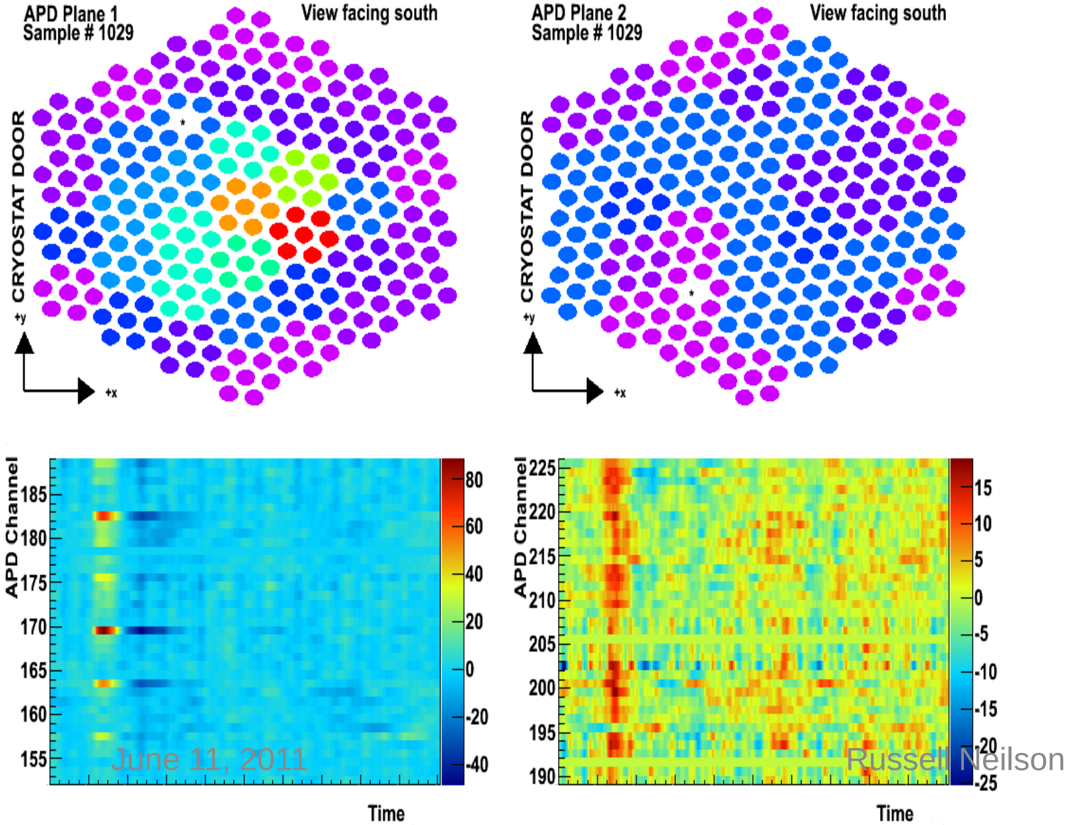
Scintillation light is seen from both sides, although more intense and localized on side 2, where the event occurred.

Small depositions produce induction signals on more than one V wires
but are collected by a single U wire.
V signal always comes before U.

Light signals precede in time the charge ones

Two-site Compton scattering event

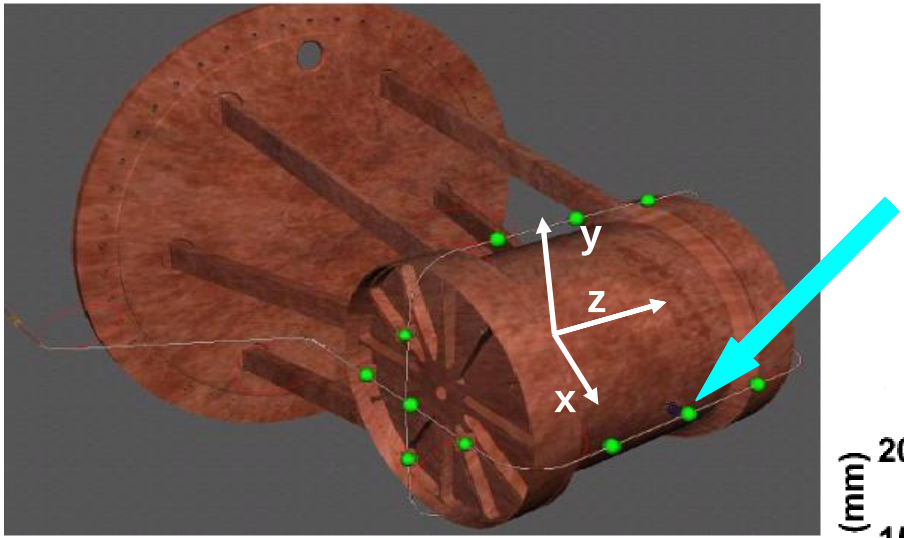




All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

The scintillation light is brighter and more localized on Side 1 where the scattering occurs

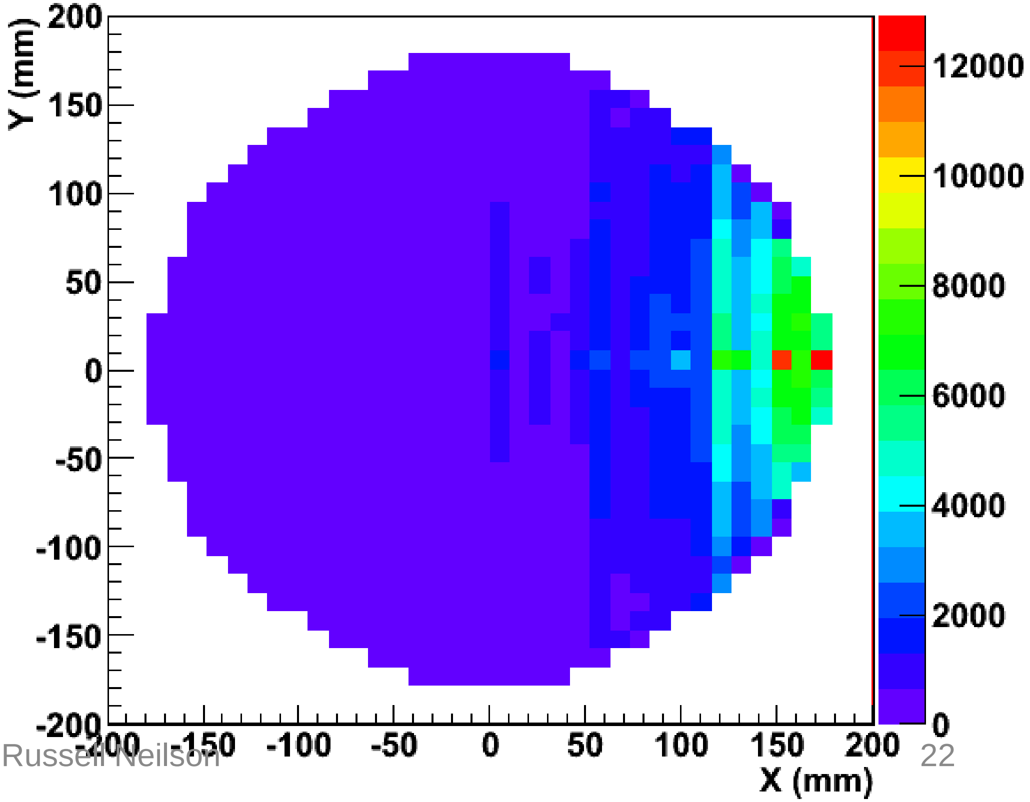
Calibration source run



^{60}Co

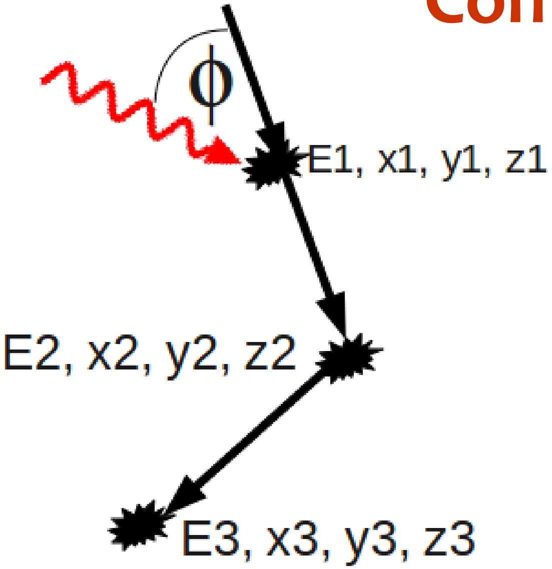
source

Various calibration sources can be brought to several positions just outside the detector



x-y distribution of events clearly shows excess near the source location

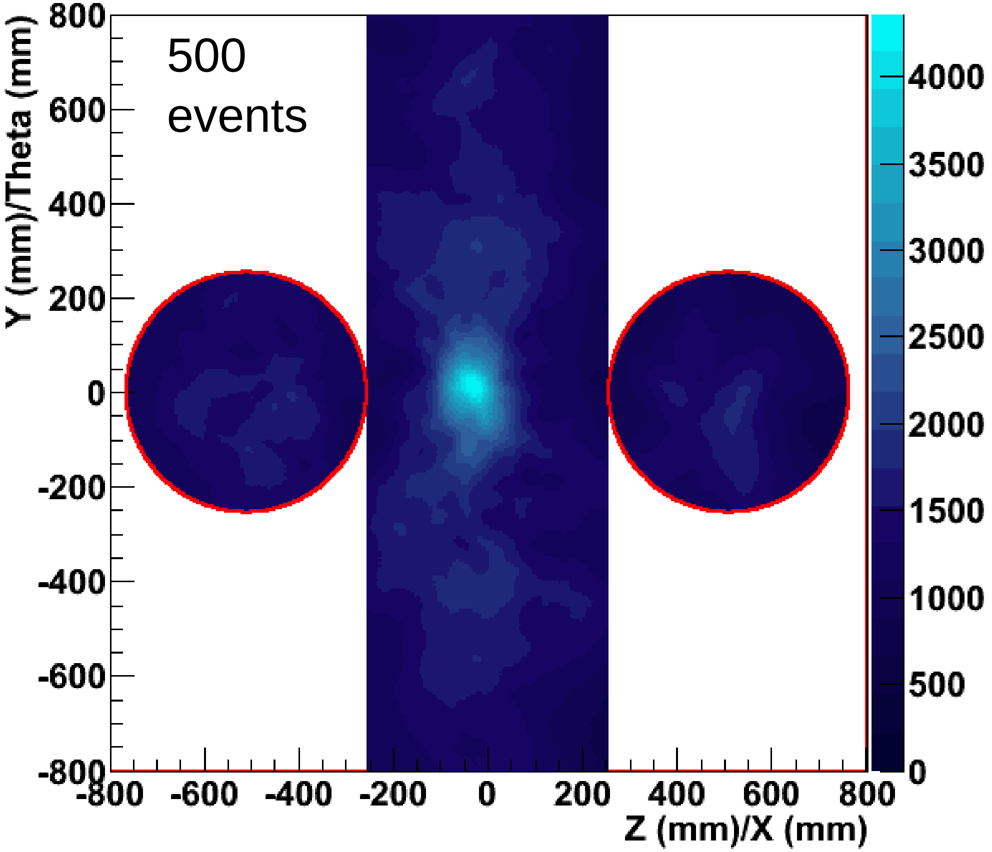
Compton telescope



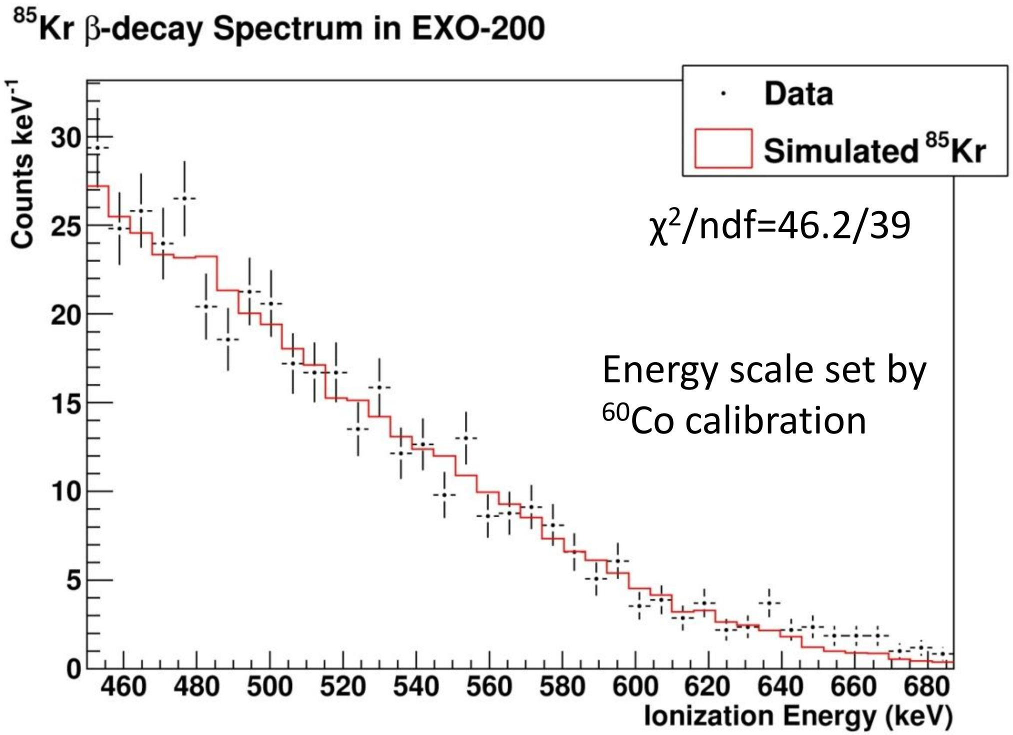
- Detector measures E, x, y, z for each site
- Use scattering formula

$$\phi = arccos\left[1 - m_e c^2 \cdot \left(\frac{1}{E_\gamma - E_1} - \frac{1}{E_1}\right)\right.$$

- From each site a cone is drawn and adding up these cones produces the image to the right

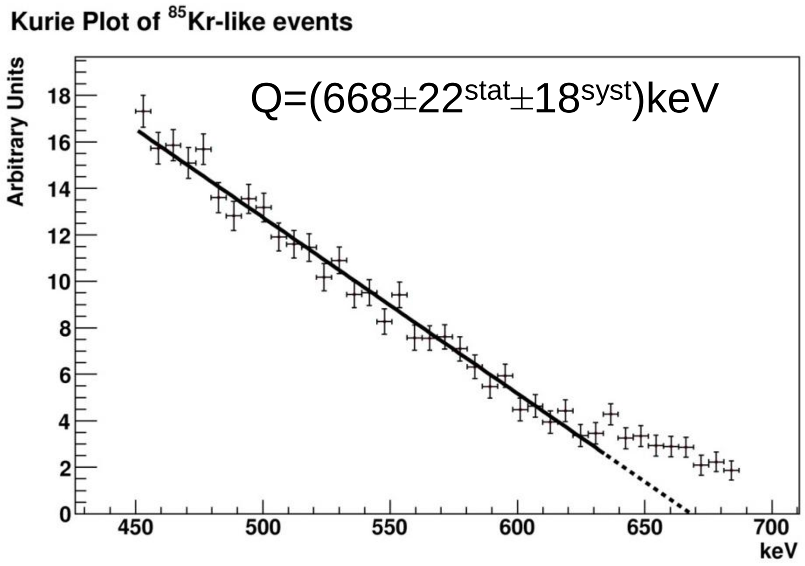


^{85}Kr in natural xenon



χ^2/ndf=46.2/39

Energy scale set by ^{60}Co calibration



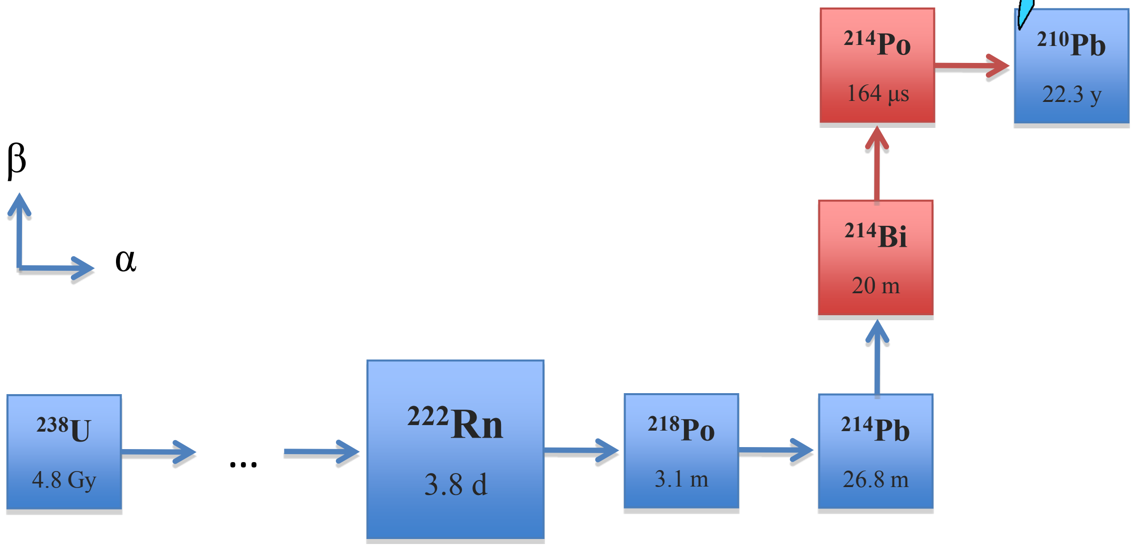
Q=(668±22^{stat}±18^{syst})keV

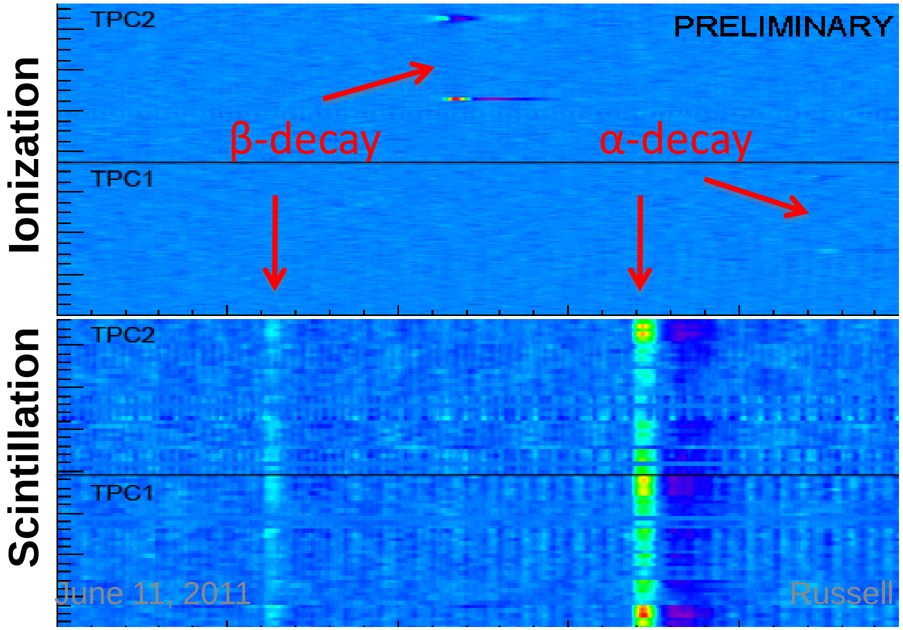
Fit ^{85}Kr simulation to match the data in the integral from 450keV to the Q value (687keV)

→ Consistent with Mass Spec result assuming standard ^{85}Kr/Kr concentration of ~10^{-11}

^{214}Bi – ^{214}Po co-incidences

^{214}Bi undergoes β-decay into ^{214}Po which then undergoes α-decay with a half life of 164 µs.





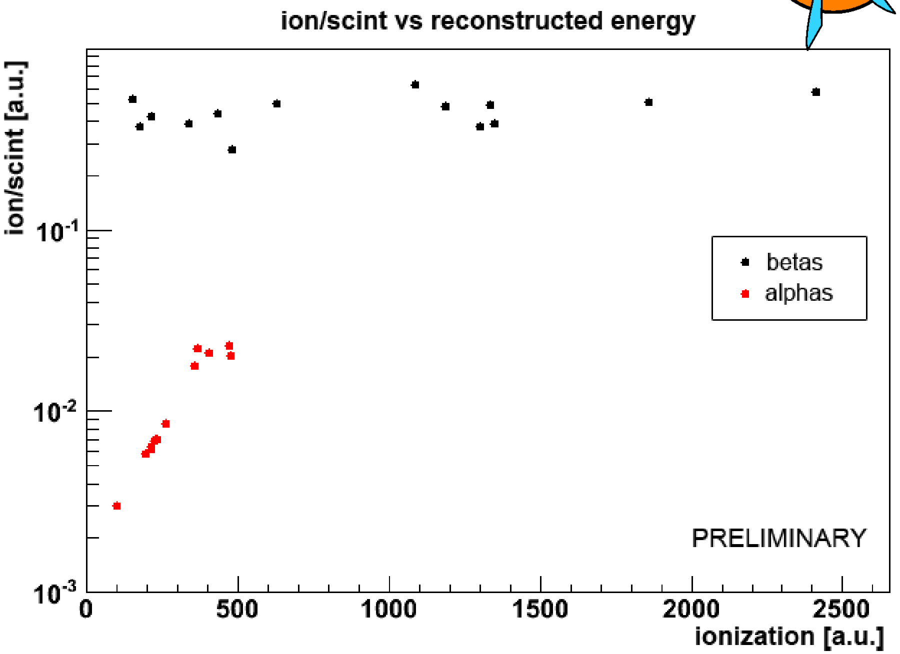
Bi-Po events are identified by their characteristic event topology which has a high probability to be detected in a single trigger window.

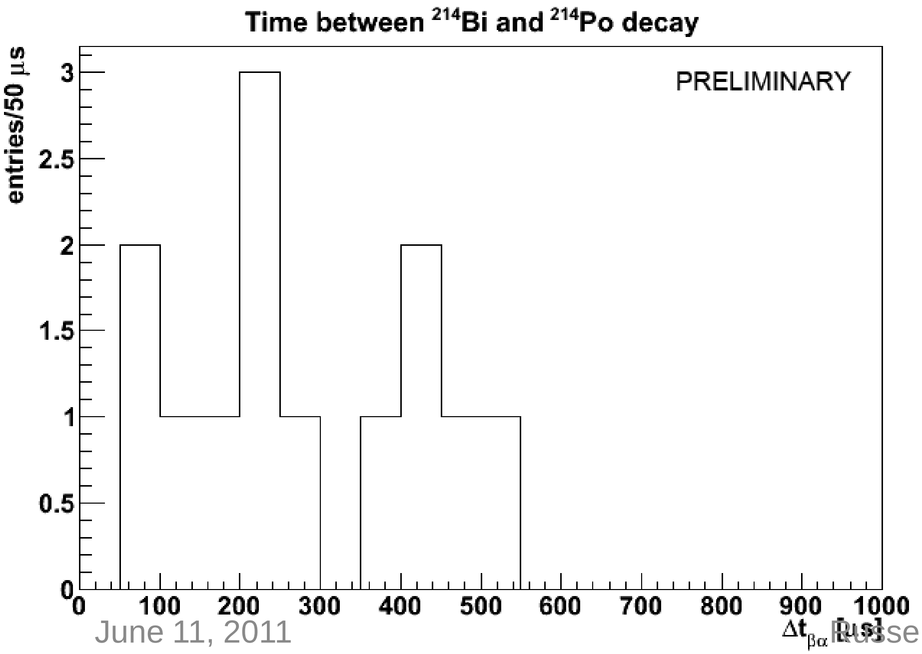
α: strong light signal, weak charge signal
β: weak light signal, strong charge signal

^{214}Bi – ^{214}Po co-incidences

α and β particles can be identified by their ionization/scintillation ratio (right plot).

- 15 Bi-Po events were found in a commissioning run.
- 6 of them occurred on or near the cathode whereas the others are located in the bulk of detector.





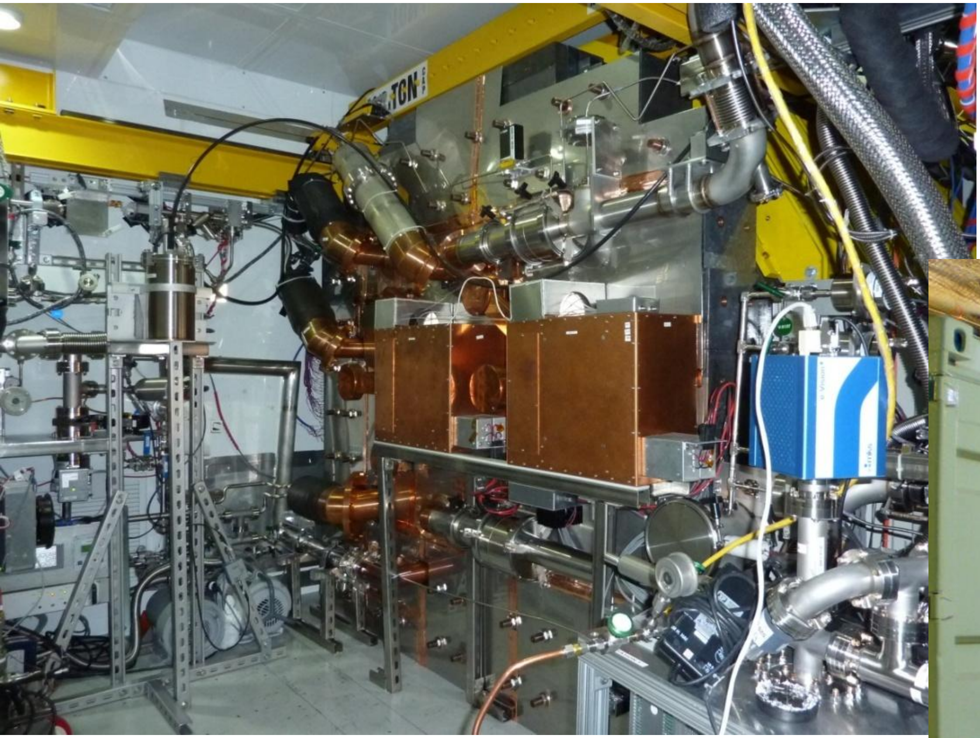
The average time between the β and α decay (left plot) is 242 μs which corresponds to τ = 271 μs.

Considering the low statistics, this is in good agreement with the true value of τ=237 μs.

^{214}Bi rate is consistent with expectation before the Rn trap is commissioned.

Low background run

Front shield & Rn enclosure



Veto counter installed and commissioned

Low background data taking with **200kg enriched Xe** started in spring 2011

Stay tuned!

EXO-200: sensitivity

2 year sensitivities for the EXO-200 $0\nu\beta\beta$ search.

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV)	
							QRPA[1]	NSM[2]
EXO-200	0.2	70	2	1.6*	40	6.4×10^{25}	109	135

[1] Simkovic et al., *Phys. Rev.* C**79**, 055501(2009) [g_A= 1.25]; [2] Menendez et al., *Nucl. Phys.* A**818**, 139(2009) [UCOM results]

EXO-200 will also search for $2\nu\beta\beta$ of ^{136}Xe, which has not been observed.

	$T_{1/2}^{2\nu}$ (yr)	Events/year (no efficiency applied)
Experimental limit		
Luescher et al, 1998	**$> 3.6 \times 10^{20}$**	**< 1.3 M**
Bernabei et al, 2002	**$> 1.0 \times 10^{22}$**	**< 48 k**
Gavriljuk et al, 2005	**$> 8.5 \times 10^{21}$**	**< 56 k**
Theoretical prediction [$T_{1/2}^{max}$]		
QRPA (Staudt et al)	**$= 2.1 \cdot 10^{22}$**	**= 23 k**
QRPA (Vogel et al)	**$= 8.4 \cdot 10^{20}$**	**= 0.58 M**
NSM (Caurier et al)	**$(= 2.1 \cdot 10^{21})$**	**(= 0.23 M)**

The EXO Collaboration

D. Auty, M. Hughes, R. MacLellan, A. Piepke, K. Pushkin, M. Volk

University of Alabama, Tuscaloosa AL

P. Vogel

California Institute of Technology, Pasadena CA

A. Coppens, M. Dunford, K. Graham, P. Gravelle, C. Hagemann, C. Hargrove, F. Leonard, K. McFarlane, C. Oullet, E. Rollin, D. Sinclair, V. Strickland

Carleton University, Ottawa ON, Canada

L.Kaufman

Indiana University

M. Moe

University of California, Irvine, Irvine CA

C. Benitez-Medina, S. Cook, W. Fairbank, Jr., K. Hall, N. Kaufold, B. Mong, T. Walton

Colorado State University, Fort Collins CO

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

ITEP Moscow, Russia

B. Beauchamp, D. Chauhan, B. Cleveland J. Farine, J. Johnson, U. Wichoski, M. Wilson

Laurentian University, Sudbury ON, Canada

C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

University of Maryland, College Park MD

J. Cook, T. Daniels, K. Kumar, P. Morgan, A. Pocar, B. Schmoll, C. Sterpka, D. Wright

University of Massachusetts Amherst, Amherst MA

D.Leonard

University of Seoul, Republic of Korea

M. Auger, D. Franco, G. Giroux, R. Gornea, M. Weber, J-L. Vuilleumier

Laboratory for High Energy Physics, Bern, Switzerland

W. Feldmeier, P.Fierlinger, M. Marino

Technical University of Munich, Garching, Germany

N. Ackerman, M. Breidenbach, R. Conley, W. Craddock, S. Herrin, J. Hodgson, D. Mackay, A. Odian, C. Prescott, P. Rowson, K. Skarpaas, M. Swift, J. Wodin, L. Yang, S. Zalog

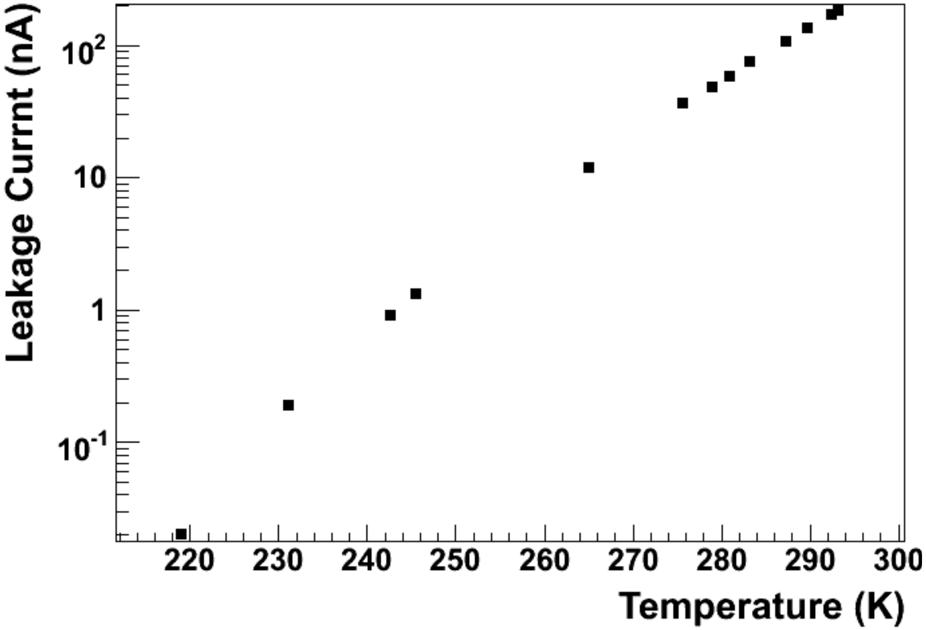
Stanford Linear Accelerator Center (SLAC), Menlo Park CA

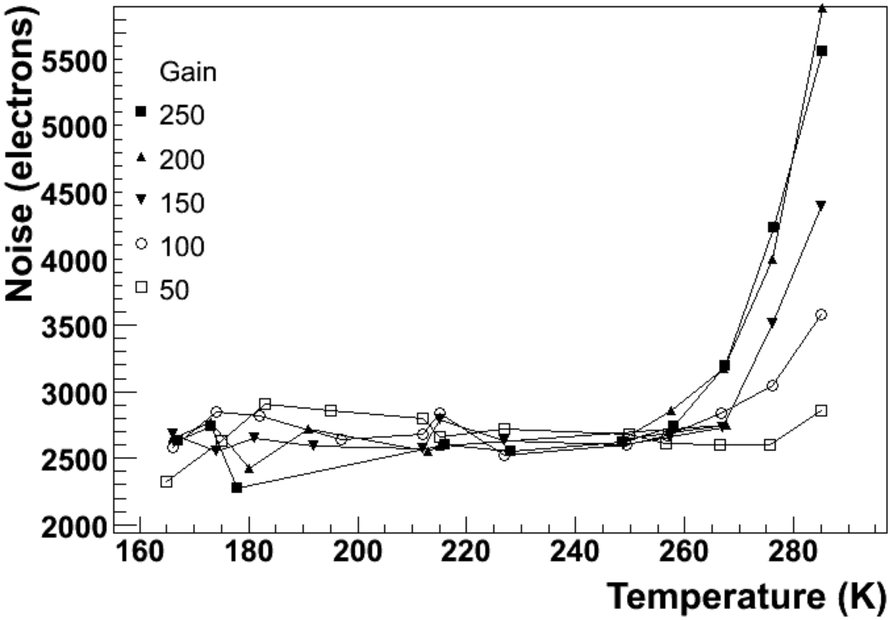
P. Barbeau, L. Bartoszek, J. Davis, R. DeVoe, M. Dolinski, G. Gratta, F. LePort, M. Montero-Diez, A.R. Muller, R. Neilson, K. O'Sullivan, A. Rivas, A. Saburov, D. Tosi, K. Twelker

Stanford University, Stanford CA

BACKUP SLIDES

LAAPD properties – leakage current

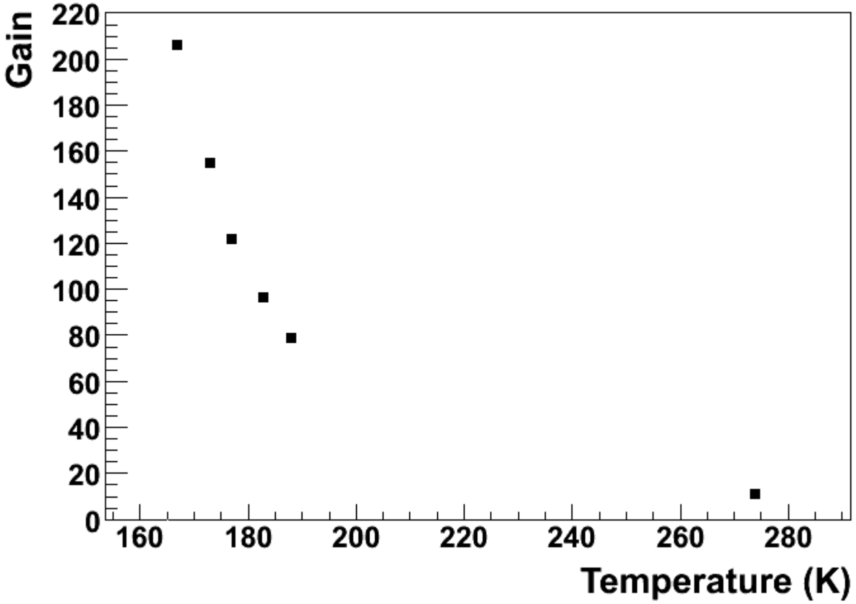


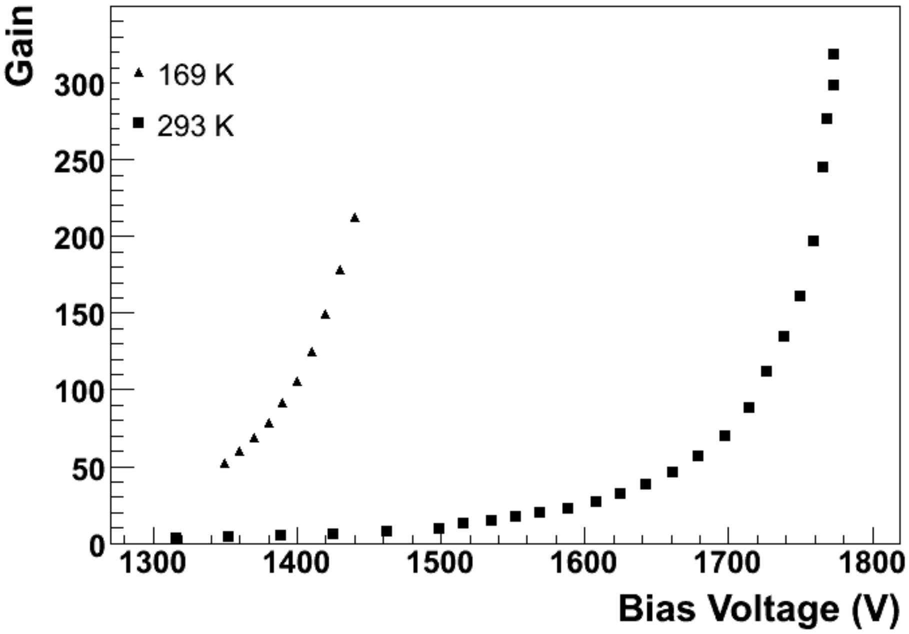


Leakage current drops by over 4 orders of magnitude from room temperature to liquid xenon temperature (169K).

Electronic noise decreases with leakage current

LAAPD properties - gain

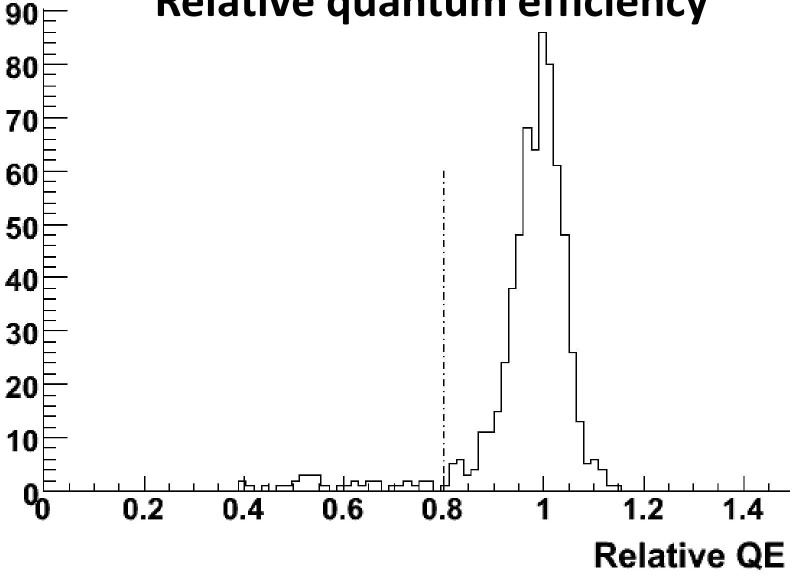




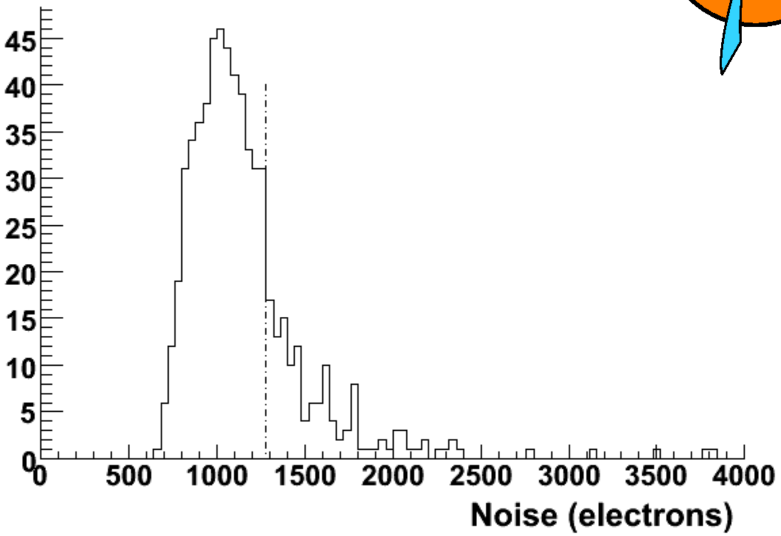
At 169K, gain changes by 5% K^{-1}

Gain increases by 1.5% V^{-1}

LAAPD selection cuts

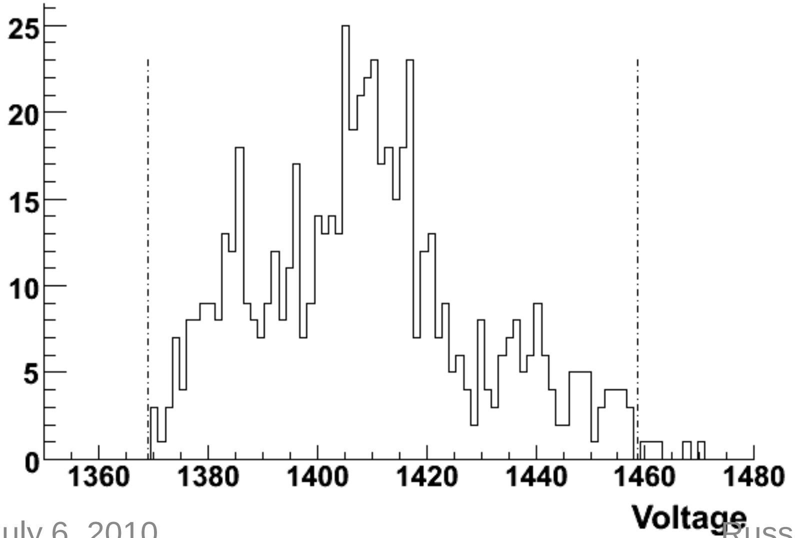


Relative quantum efficiency



Electronic noise

About 180 APDs had noise >> 4000 electrons and were immediately rejected.



Operating voltage for gain = 100

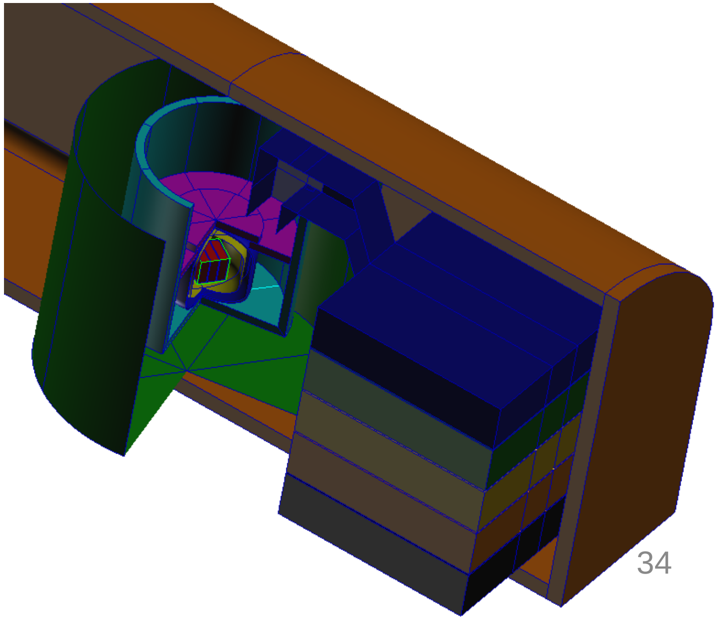
R. Neilson et al., NIM A, 608, 68-75

Sensitivity of ton-scale EXO with barium tagging

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	2νββ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV)	
							QRPA[1]	NSM[2]
Conservative	1	70	5	1.6*	0.5 (use 1)	$2*10^{27}$	19	24
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	4.3	5.3

1) Simkovic et al. Phys. Rev. C**79**, 055501(2009) [use RQRPA and g_A= 1.25]

2) Menendez et al., Nucl. Phys. A**818**, 139(2009), use UCOM results



Neutrino masses

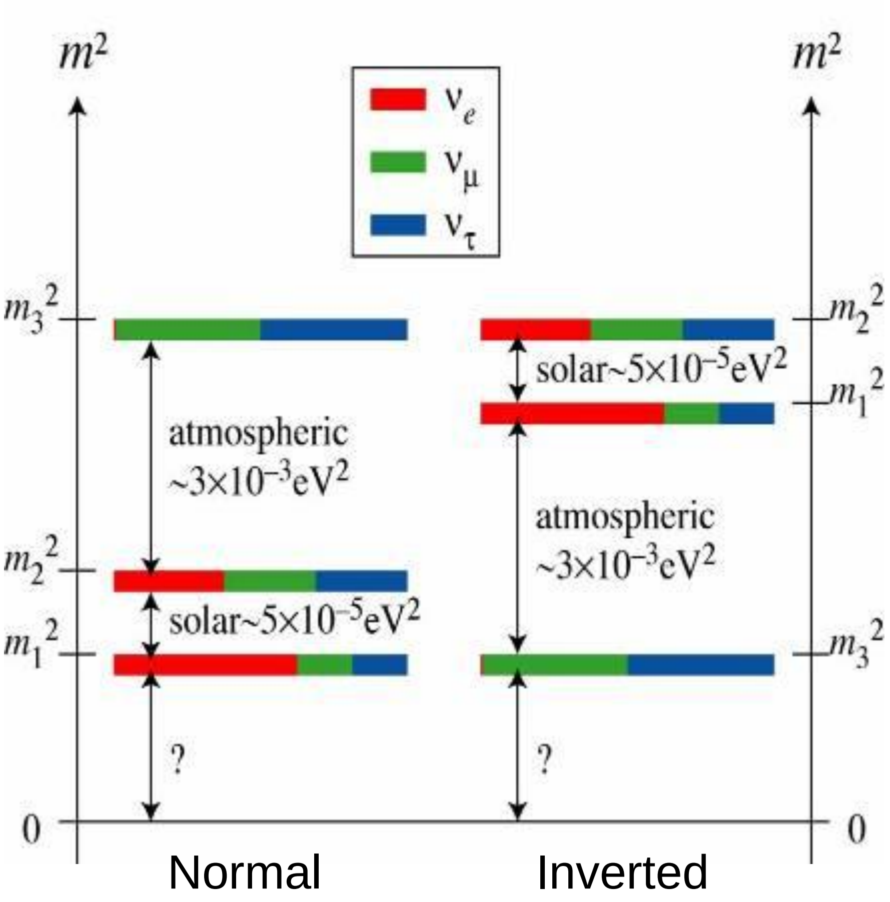
Enriched Xenon Observatory
EXO
for double beta decay

~0.3 eV

from $0\nu\beta\beta$ if ν is Majorana

~2 eV

from tritium endpoint (Mainz and Troitsk)



~1 eV

from cosmological observations (WMAP)

~10 eV

time of flight from SN1987A (PDG 2002)