Title: Status of EXO-200

Date: Jun 06, 2008 09:00 AM

URL: http://pirsa.org/08060092

Abstract: Searches for neutrinoless double beta decays could determine if neutrinos are Majorana particles and could measure their absolute mass scale. The initial stage of the Enriched Xenon Observatory project, EXO-200, will look for two-neutrino and neutrinoless double-beta decays of Xe-136 in a liquid-xenon time-projection chamber. By combining the ionization signal with detection of the scintillation light collected in Large Area Avalanche Photodiodes (LAAPDs), an energy resolution of about 1.4% at the decay energy can be achieved. All construction materials have been systematically selected to minimize naturally-occurring radioactive impurities. An active muon veto is presently under construction. Using these background reduction techniques and the available 200 kg of isotopically enriched xenon (80% in Xe-136), EXO-200 will be soon able to test present constraints on the effective Majorana-neutrino mass. It will also serve to demonstrate the potential performance of a larger-scale EXO experiment which will further reduce backgrounds by detecting the residual Ba ion produced in the decay. Installation of the EXO-200 detector is now in progress at the Waste Isolation Pilot Plant (WIPP) in New Mexico.

# Motivation

Discovery of neutrino flavor oscillations showed that neutrinos are massive. Oscillation observed with:

- Solar and reactor neutrinos and anti-neutrinos:
- $\Delta m^2_{21}$, $m_1 < m_2$, $\sin^2\Theta_{12}$

- Atmospheric and accelerator neutrinos: $\Delta m^2_{23}$, $\sin^2\Theta_{23}$

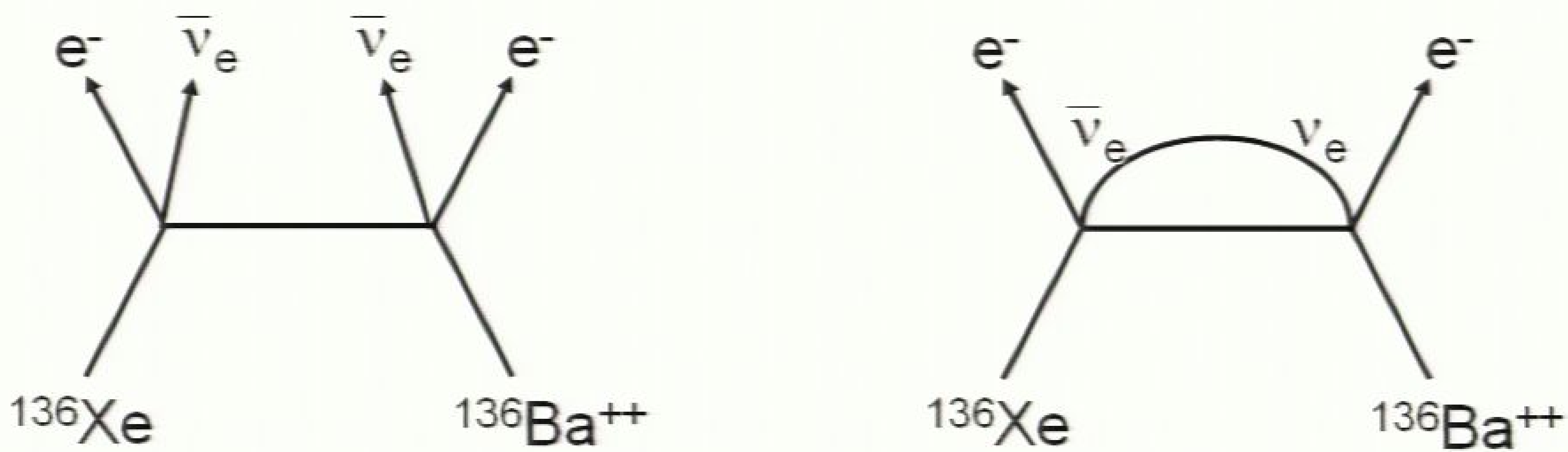
- LSND oscillation evidence not observed in MiniBooNE

Small number of parameters describe variety of experiments using different methods and energies.

# Double Beta Decay

- $\beta\beta$ is a second order weak process:
  **Very rare!**
  **$T_{1/2} > 10^{19}$ y (much higher for neutrinoless decays)**
- Signal is overwhelmed by standard β decay (if it occurs).
- Neutrinoless $\beta\beta$ provides information about:
  -Majorana nature of neutrino.
  (Is a neutrino it's own anti-particle?)
  -Absolute mass of neutrinos. (Effective mass actually; oscillation experiments only sensitive to mass differences)
  -To some extent the mass hierarchy.

# Two types of double beta decay




- $\Delta L_e = 0$
- standard second order process observed in multiple isotopes

- lepton number violation ($\Delta L_e = 2$)
- $m_\nu \neq 0$
- $\nu = \bar{\nu}$ ("Majorana neutrinos")

# Effective Neutrino Mass

Measure → $\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_\nu \rangle^2$ ← Calculate

CP-phases: ±1
(Can cause cancellations!)

# Effective Neutrino Mass

Measure → $\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_\nu \rangle^2$ ← Calculate

$$\langle \mathrm{m}_\nu \rangle^2 = \left| \sum_i \eta_i \, \mathrm{U}_{ei}^2 \, \mathrm{m}_i \right|$$

CP-phases: ±1
(Can cause cancellations!)

Elements upper
row of MNS-matrix

Neutrino masses

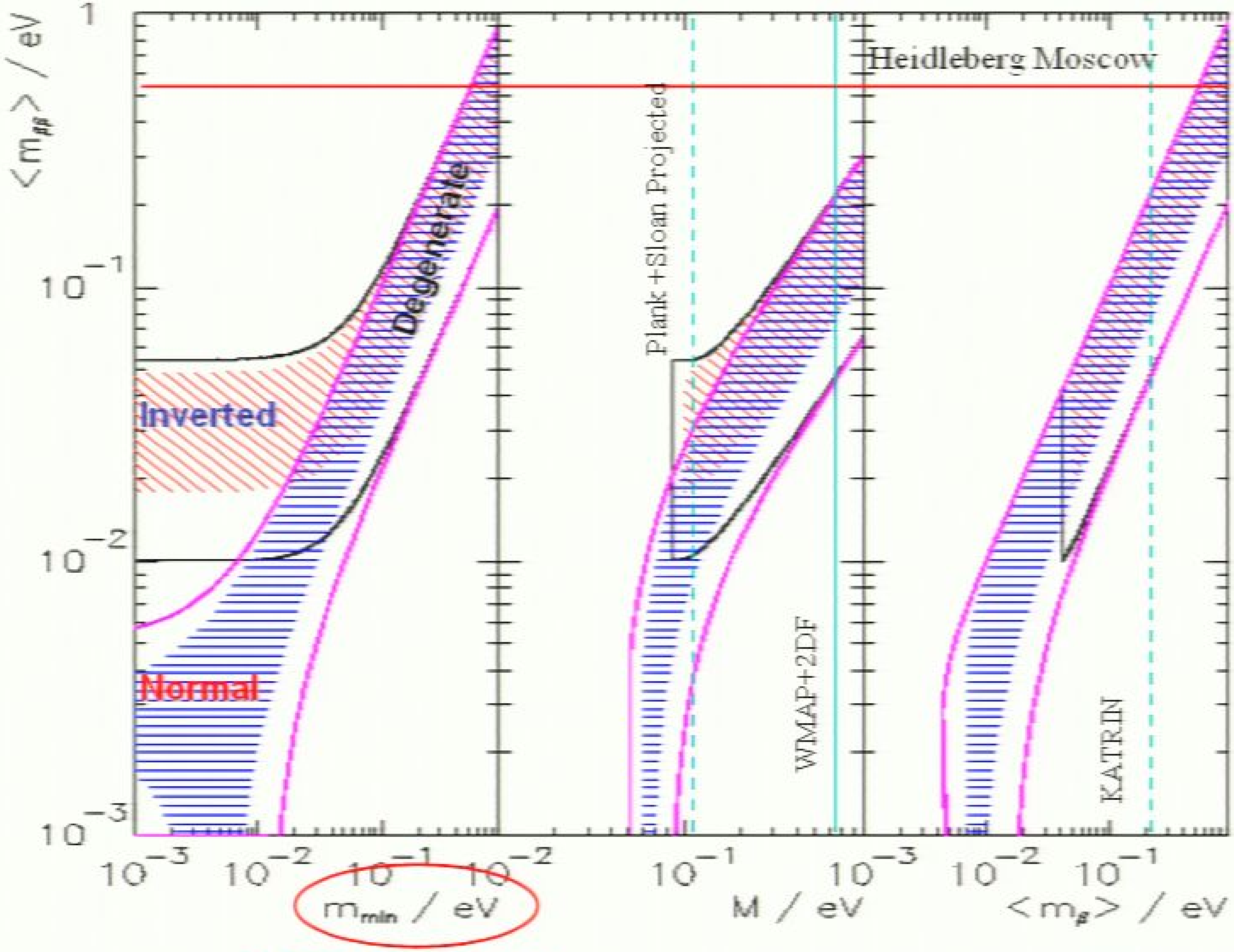
# Mass estimates from oscillations

Hierarchical | Inverse hierarchical


$\langle m_\nu \rangle$ driven by solar splitting 5 meV | by atmospheric splitting 50 meV

Provided CP phase +1. LSND left out.

# What can we Really Measure?

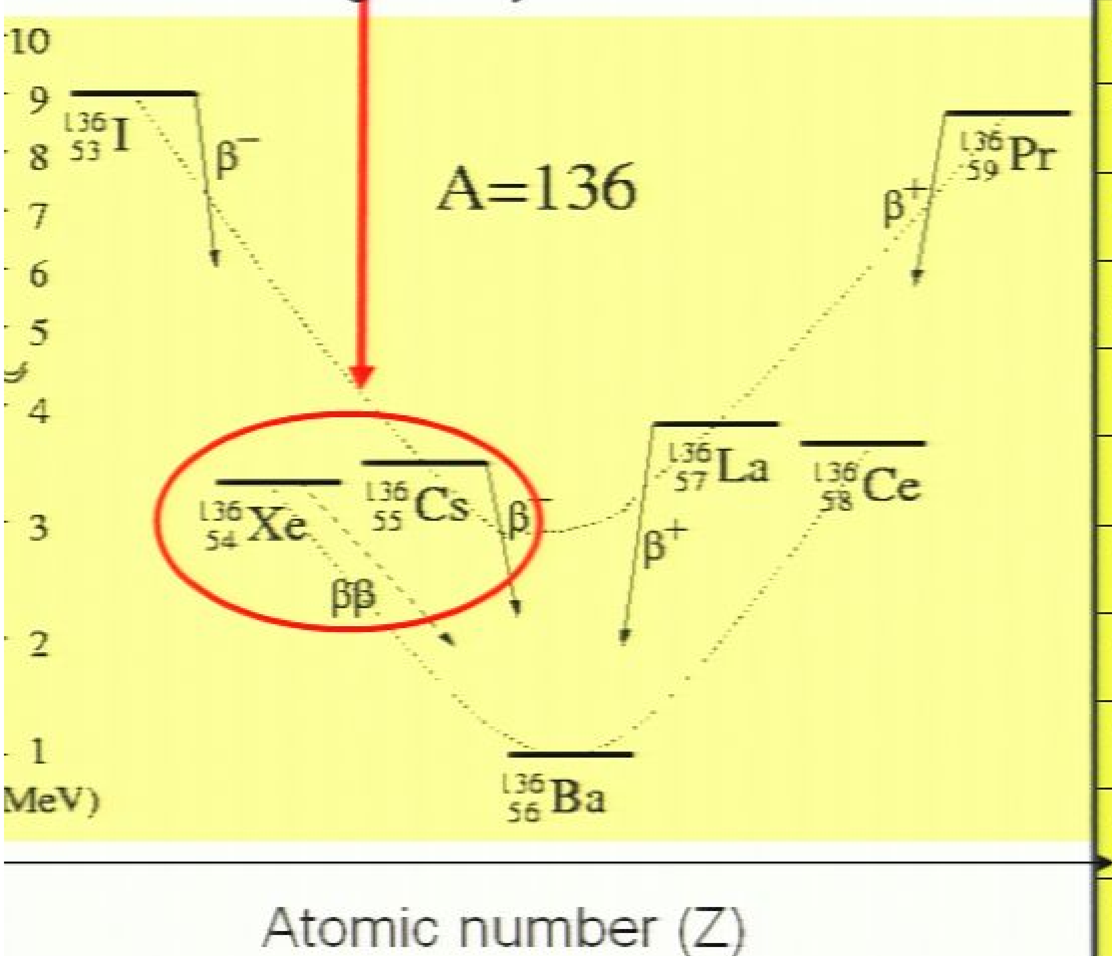



Not Observable!

(values may be out of date)

# Double-beta decay:

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




## Candidate nuclei with Q>2 MeV

| Candidate | Q (MeV) | Abund. (%) |
|---|---|---|
| $^{48}Ca \rightarrow ^{48}Ti$ | 4.271 | 0.187 |
| $^{76}Ge \rightarrow ^{76}Se$ | 2.040 | 7.8 |
| $^{82}Se \rightarrow ^{82}Kr$ | 2.995 | 9.2 |
| $^{96}Zr \rightarrow ^{96}Mo$ | 3.350 | 2.8 |
| $^{100}Mo \rightarrow ^{100}Ru$ | 3.034 | 9.6 |
| $^{110}Pd \rightarrow ^{110}Cd$ | 2.013 | 11.8 |
| $^{116}Cd \rightarrow ^{116}Sn$ | 2.802 | 7.5 |
| $^{124}Sn \rightarrow ^{124}Te$ | 2.228 | 5.64 |
| $^{130}Te \rightarrow ^{130}Xe$ | 2.533 | 34.5 |
| $^{136}Xe \rightarrow ^{136}Ba$ | 2.479 | 8.9 |
| $^{150}Nd \rightarrow ^{150}Sm$ | 3.367 | 5.6 |

# Key Xenon Advantages

- Reasonable Q-value, **2457.8±0.4 keV**

(M. Redshaw, J.McDaniel, E. Wingfield and E.G. Myers, to be submitted to Phys. Rev. C )

- (Relatively) easy to enriched
  (8.9% natural abundance even without enriching).
- Can be purified and re-purified.
- Reusable.
- Can be used in both liquid and gas phase with different advantages
- Has no long-lived isotopes to activate.
- bb-decay product atom remains charged → opens possibility of Ba removaland final state tagging through Ba single ion detection

## The decay rate:

$$R = \frac{N_0}{\tau} = \frac{N_0 \cdot \ln 2}{T_{1/2}}$$

## The decay rate:

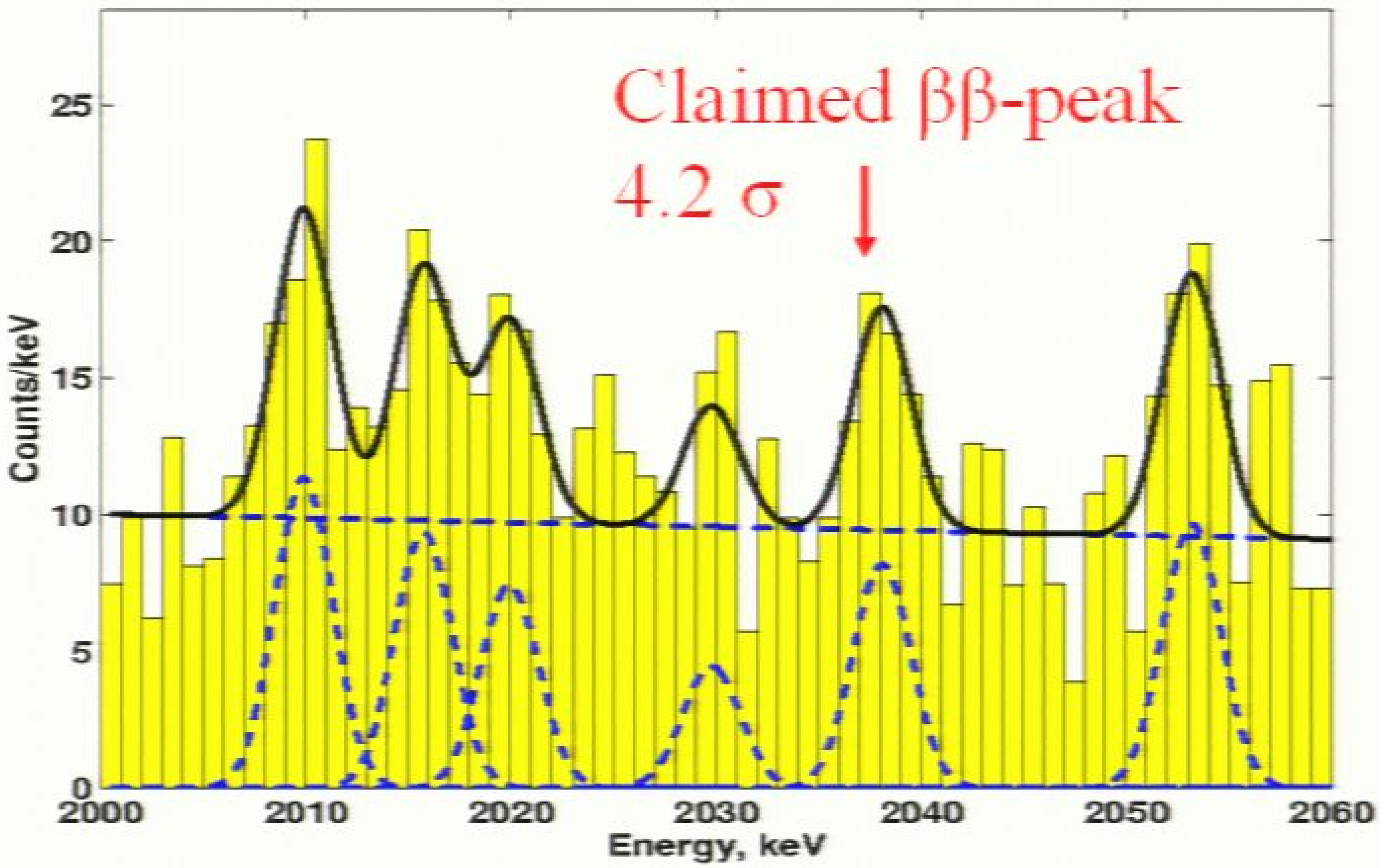
$$R = \frac{N_0}{\tau} = \frac{N_0 \cdot \ln 2}{T_{1/2}}$$

To achieve a decay rate of 5 $y^{-1}$ for a neutrino mass of 30 meV (in middle of allowed band):

8300 kg of Xe enriched to 80% in 136Xe is needed!

# Competition

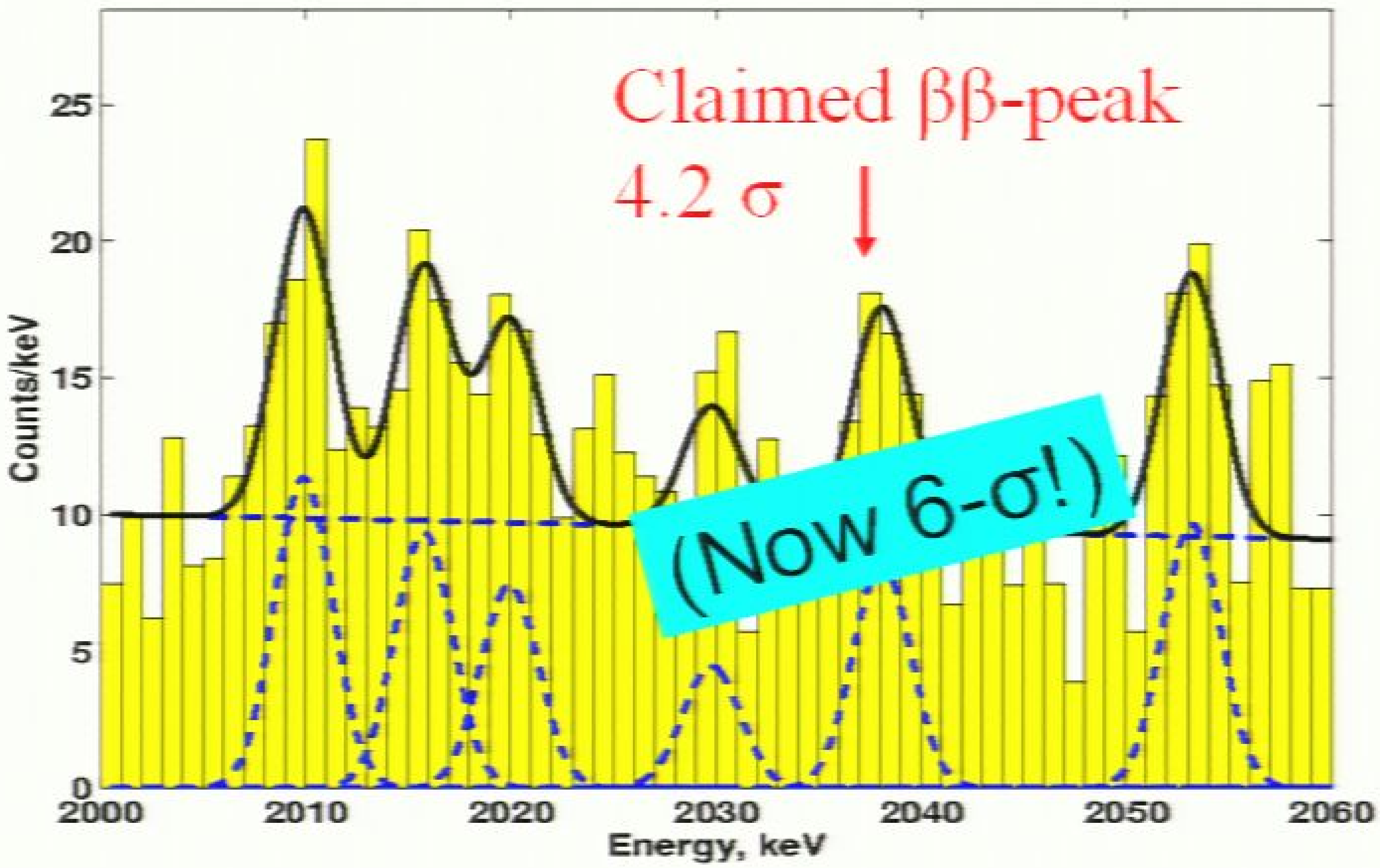
# Heidelberg Evidence:




-Used 10.9 kg of Ge enriched to 86% in 76Ge.

-Full data set Nov 1990 - May 2003. 71.7 kg*y, no PSD.

# Heidelberg Evidence:




-Used 10.9 kg of Ge enriched to 86% in 76Ge.

-Full data set Nov 1990 - May 2003. 71.7 kg*y, no PSD.

# Higlighted Results

- Cuoricino, 11.8 Kg*years of $^{130}Te$ data
  **$\langle m_{\beta\beta} \rangle$ < ( 0.19 – 0.68 eV )**

- Part of H-M, 71.7 kg*years of $^{76}Ge$ data
  **$\langle m_{\beta\beta} \rangle$ ~ 0.24- 0.58 eV**

- EXO-200 aims to reach **0.13 to 0.19 eV**
  in about 2 years (~ 200 to 400 kg*yr).

BUT!!... These all measure different isotopes. Multiple measurements are needed check the nuclear physics.

We expect 5*σ sensitivity to Ge result even with worst-case Matrix elements.

# Primary Measurement Techiniques:

- Lots of decay material (Expensive, 10 tons of xenon costs about $100M)
- Reduction of intrinsic radioactivity by finding clean materials (VERY DIFICULT).
- Control cosmogenic activition of materials.
- Passive shielding of cosmic ray showers. (go underground)
- Passive shielding of external radioactivity (ex: lead)
- Active shielding, especially for muons, usually scintillator layers.
- High resolution Calorimetry
  - Includes ionization, scintillation and bolometers.
  - With low Backgrounds and no other event discrimination, resolution typically needs to be below a couple of percent
- Spatial tracking:
  - Good single-site discrimination alone can reduce backgrounds significantly.
  - Several techniques ranging from high-resolution wire chambers to coarse segmentation.
- Residual nucleus identification (EXO-Full)
- Major Distinctions from other experiments:
  - Source is Detector? (Improves intrinsic background, but less versatile)
  - Good tracking vs. good calorimetry

# EXO Technical Preparation

Build and operate a smaller scale TPC to demonstrate that required energy resolution and background can be achieved. Demonstrate feasibility of large scale enrichment of $^{136}Xe$.

Ba extraction, transfer and single ion detection being developed in the lab in parallel.

After successful completion of these parallel research thrusts, preparation of full proposal.

Proof of principle does not require the funding of a very costly large experiment up front

# EXO-200

Scientific goals:

1) Measurement of yet unobserved $\beta\beta2\nu$ decay of $^{136}Xe$.
mportant background for full EXO.

# EXO-200

Scientific goals:

1) Measurement of yet unobserved $\beta\beta 2\nu$ decay of $^{136}Xe$.
Important background for full EXO.

2) Test of the Heidelberg evidence for $\beta\beta 0\nu$ decay.

# EXO Facts

**EXO-200:**

- 200 kg of Isotopically enriched liquid $^{136}Xe$ (80%)
  - $Q_{\beta\beta}$ **2457.8±0.4 keV**. (M. Redshaw, J.McDaniel, E. Wingfield and E.G. Myers, to be submitted to Phys. Rev. C)
  - Semi-cryogenic (-115 °C, small liquid range)
- Tracking (Time Projection Chamber):
  - LXe drift chamber detects ionization track on x and y wire grid. (~50 $e^-$/keV @ 3keV/cm )
  - Scintillation from recombination (175nm, ~25ph/keV @3kev/cm) gives timing "start" for z axis position reconstruction.
  - Resolution will be about 1 cm^3.
- Calorimetry: Ionization + Scintillation give ~ 1.4% resolution at $Q_{\beta\beta}$.
- Shielding: Multi-layer passive+ plastic scintillator active veto.

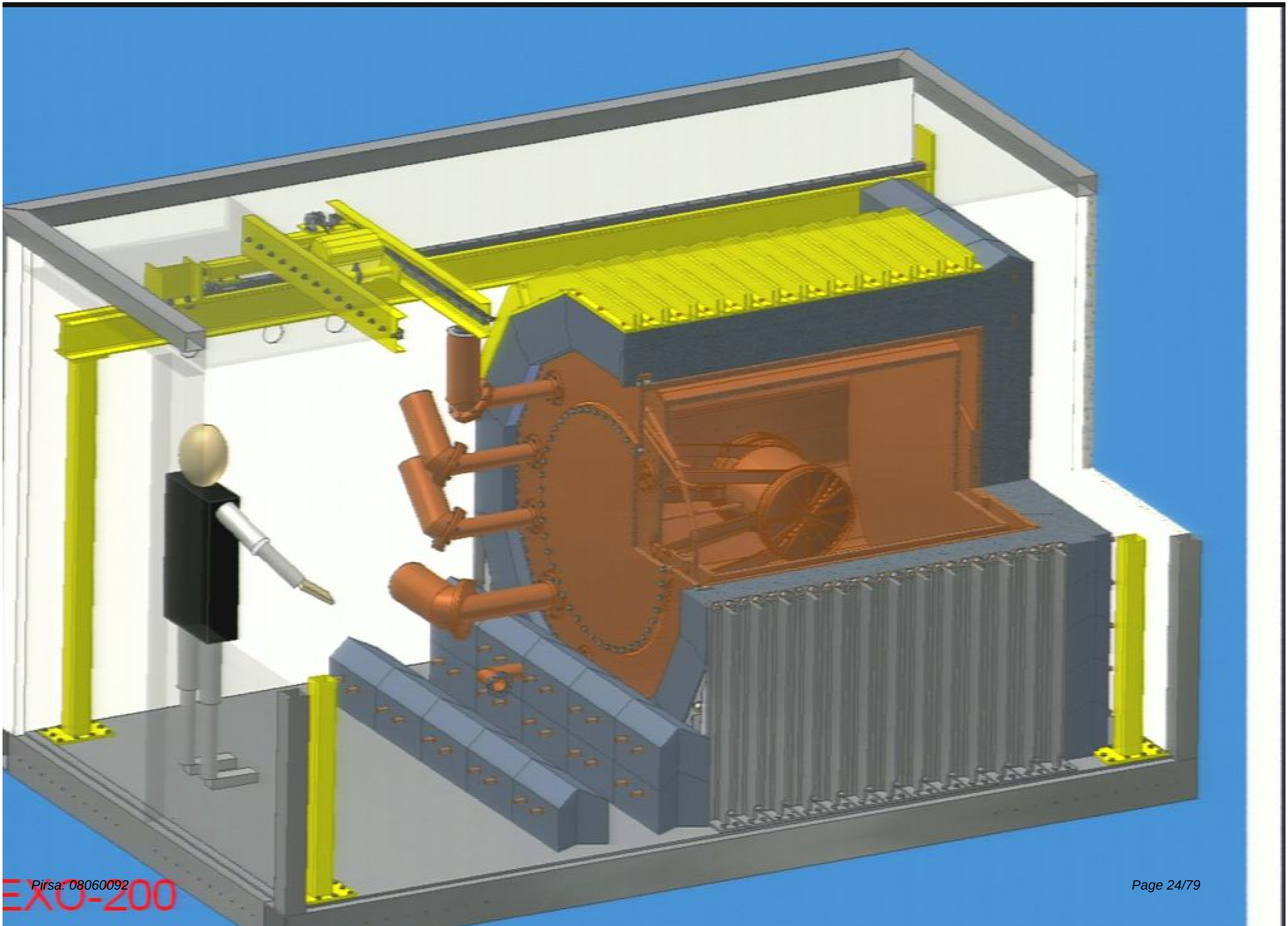
**Full EXO:**

- Mass: 1-10 tons
- Identify residual Ba ions!

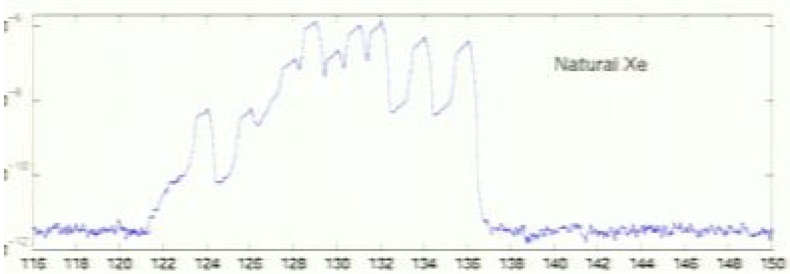
# Components (from outside to inside):

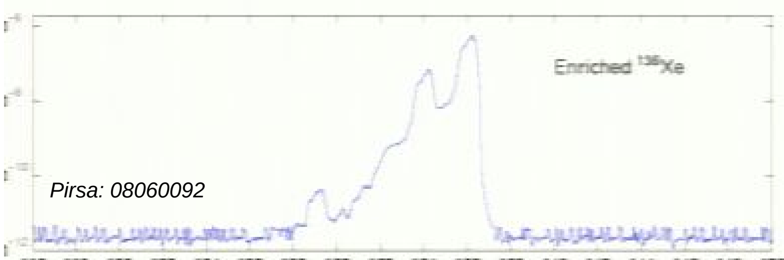
- Space to put things (without many muons)
- An Active Veto System
- Cleanrooms
- Lead Shield
- A Cryostat
- A Detection Chamber
- Xenon

Everything needs to be made from clean materials.


EXO-200

# 200 kg $^{136}$Xe test production completed spring '03 (enr. 80%)

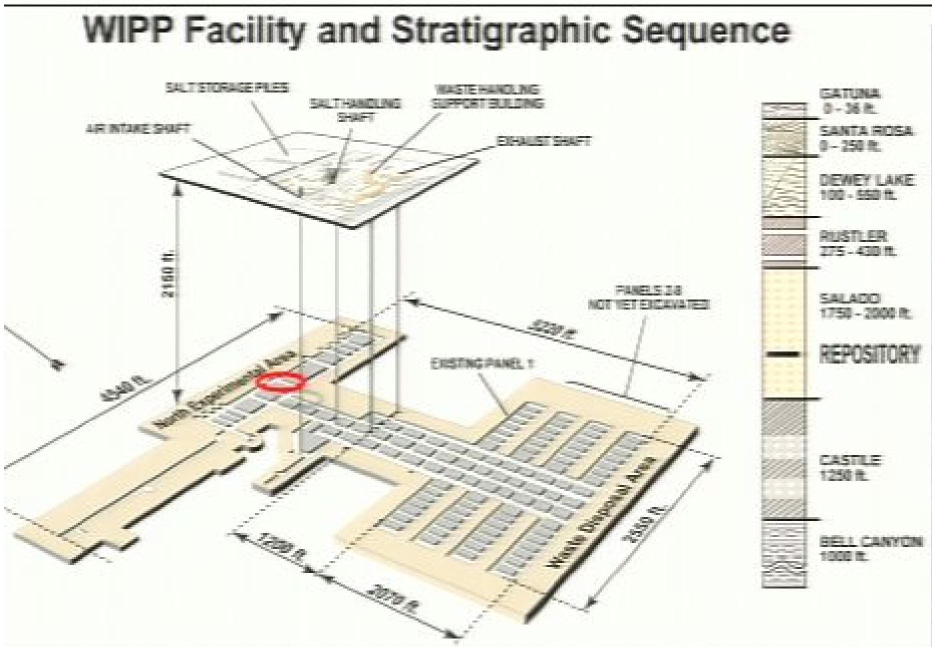


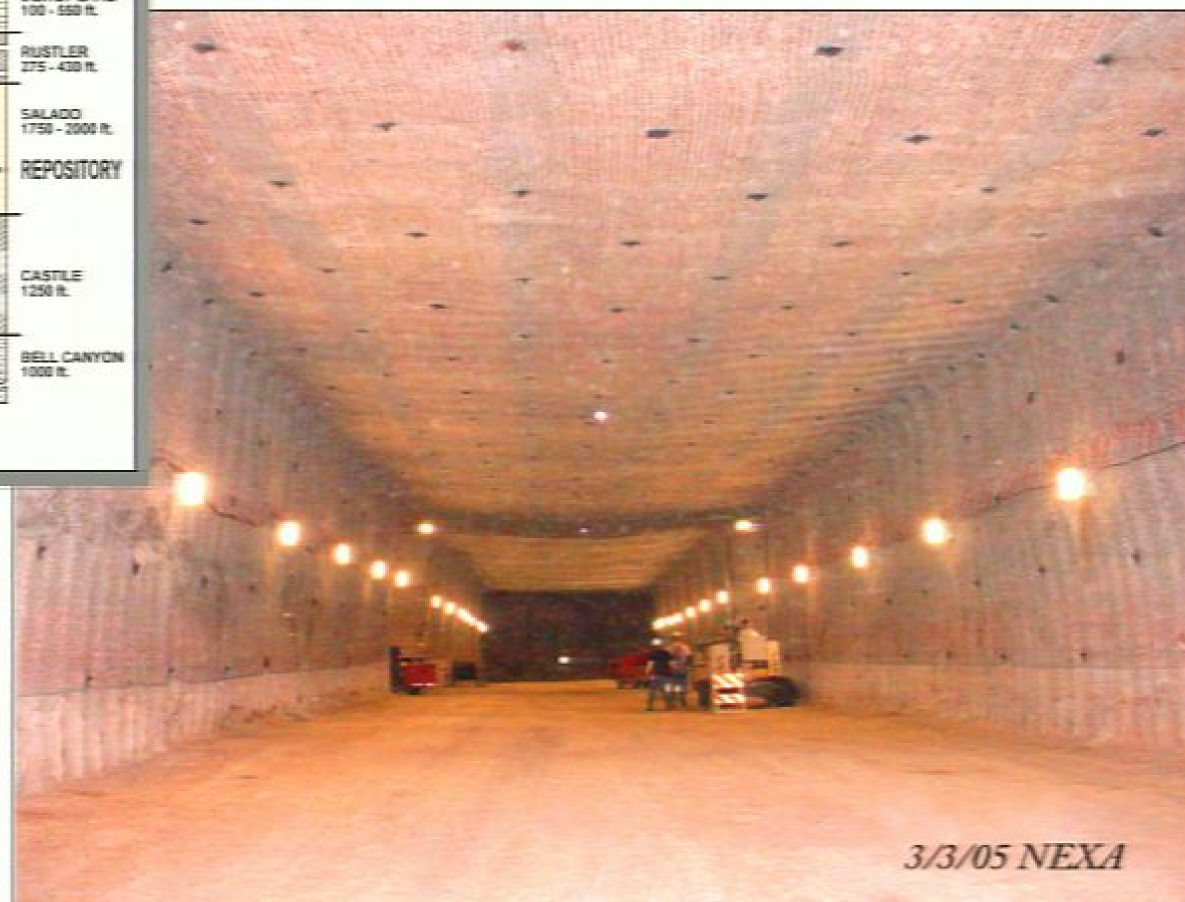




- Largest highly enriched stockpile not related to nuclear industry
- Largest sample of separated $\beta\beta$ isotope (by ~factor of 10)

# The Place

# EXO-200 WIPP SITE

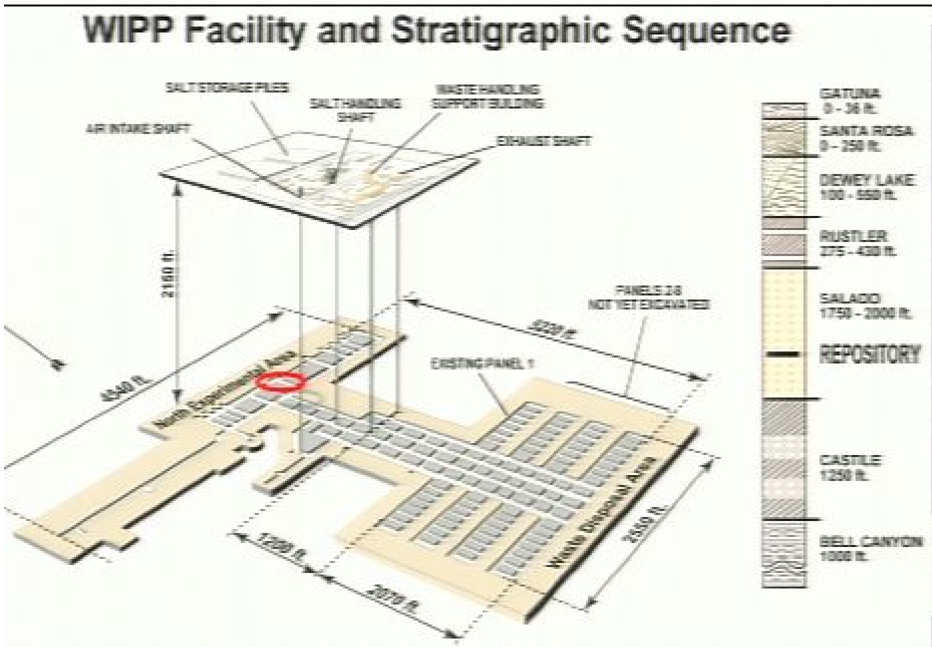


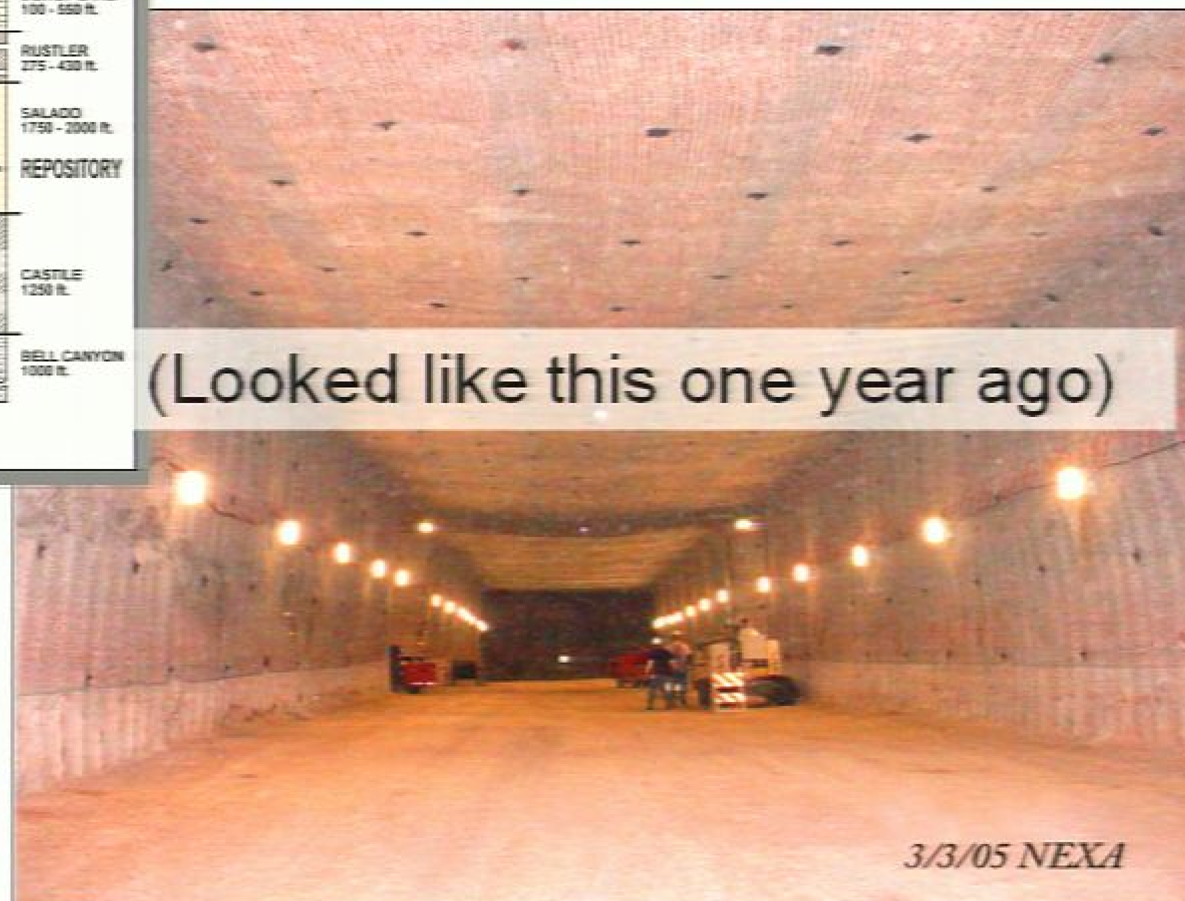




- 655 m underground (rock + salt), ~1600m.w.e
- vertical muon flux = $3.1 \times 10^{-7}\ s^{-1}\ cm^{-2}\ sr^{-1}$

(NIMA 538 (2005) 516)

# EXO-200 WIPP SITE




- 655 m underground (rock + salt), ~1600m.w.e
- vertical muon flux = $3.1 \times 10^{-7}\ s^{-1}\ cm^{-2}\ sr^{-1}$

(NIMA 538 (2005) 516)

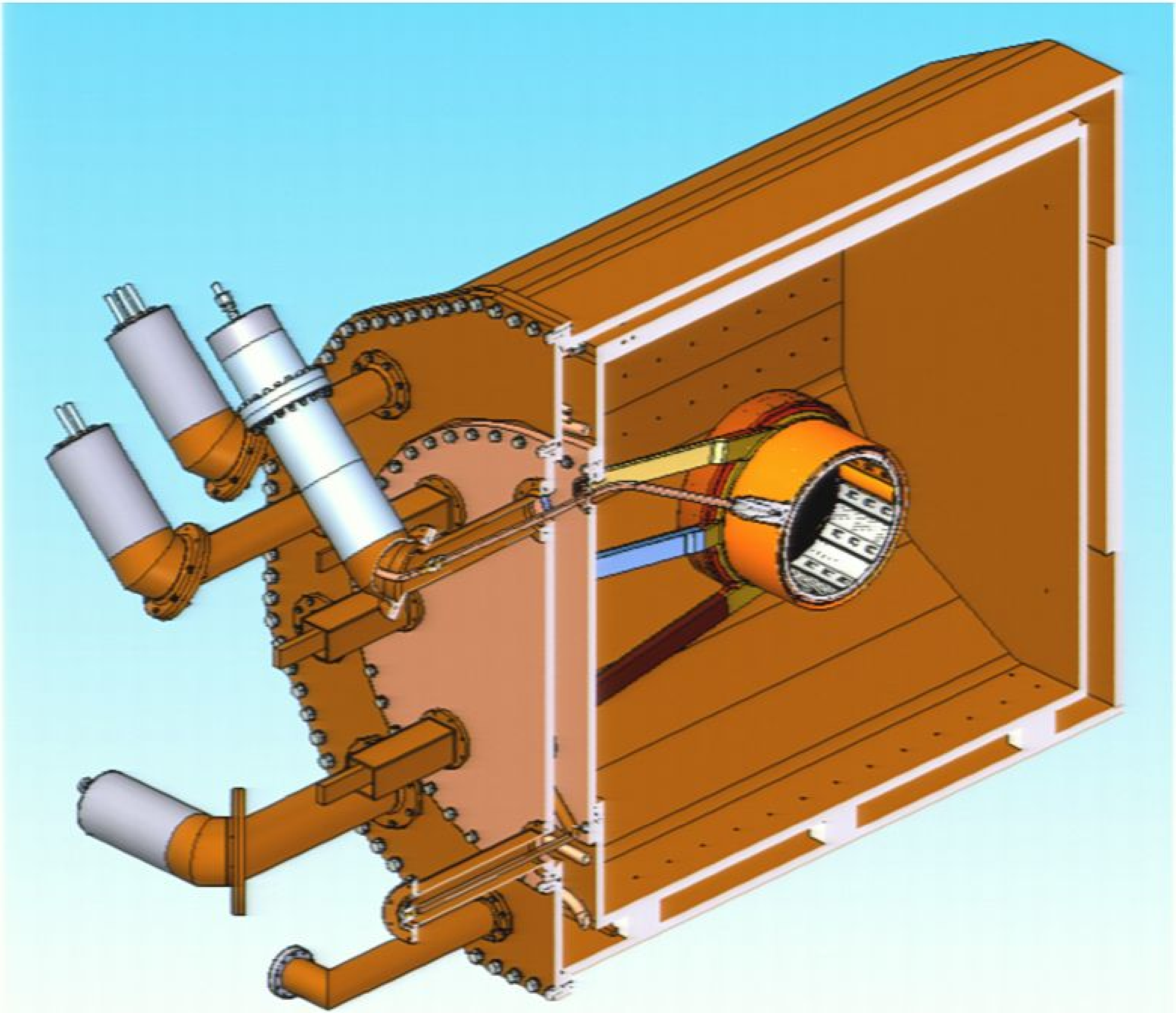

Adjustable supports

October 2007: clean-rooms and gowning area installed at WIPP.

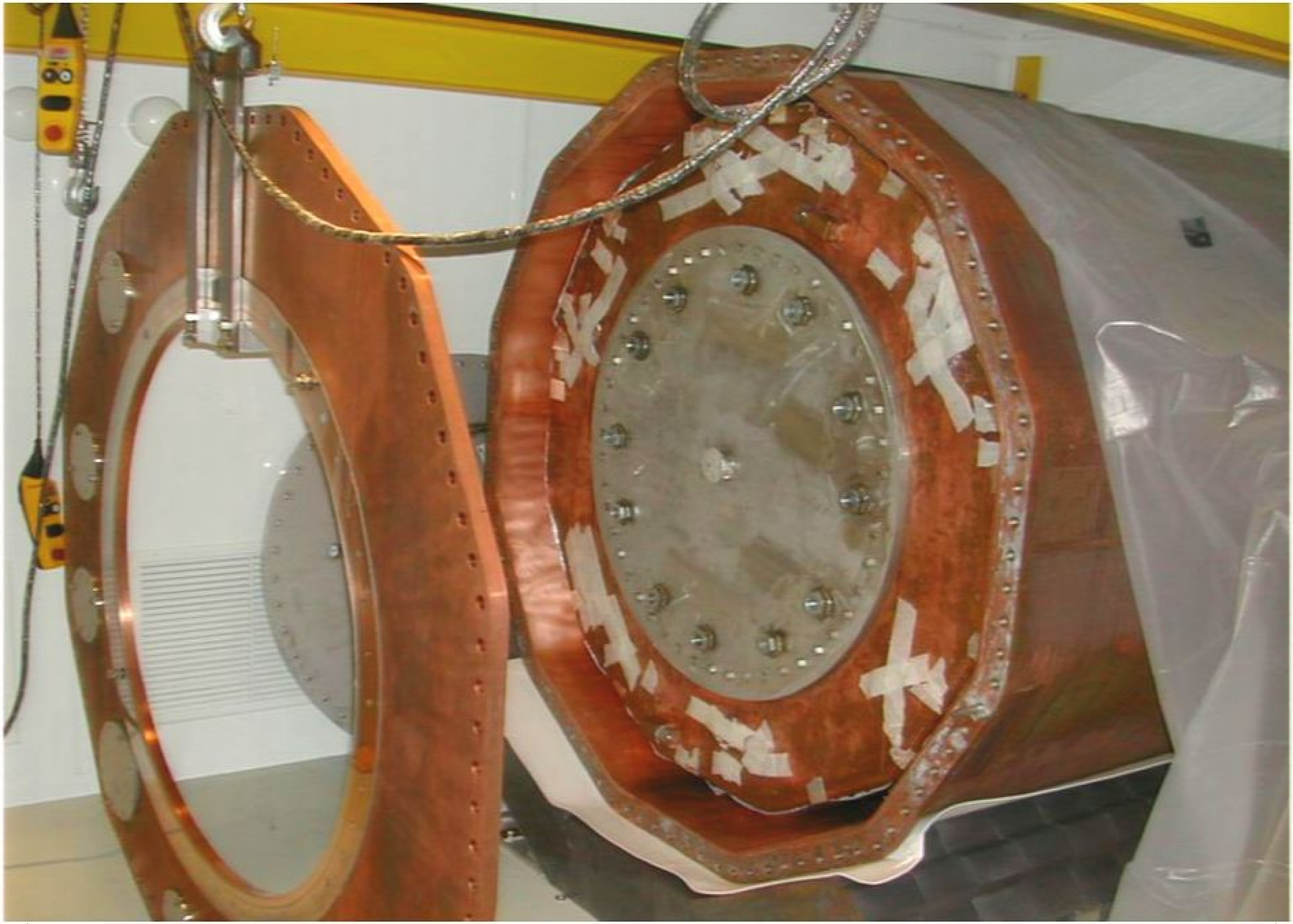
October 2007: clean-rooms and gowning area installed at WIPP.

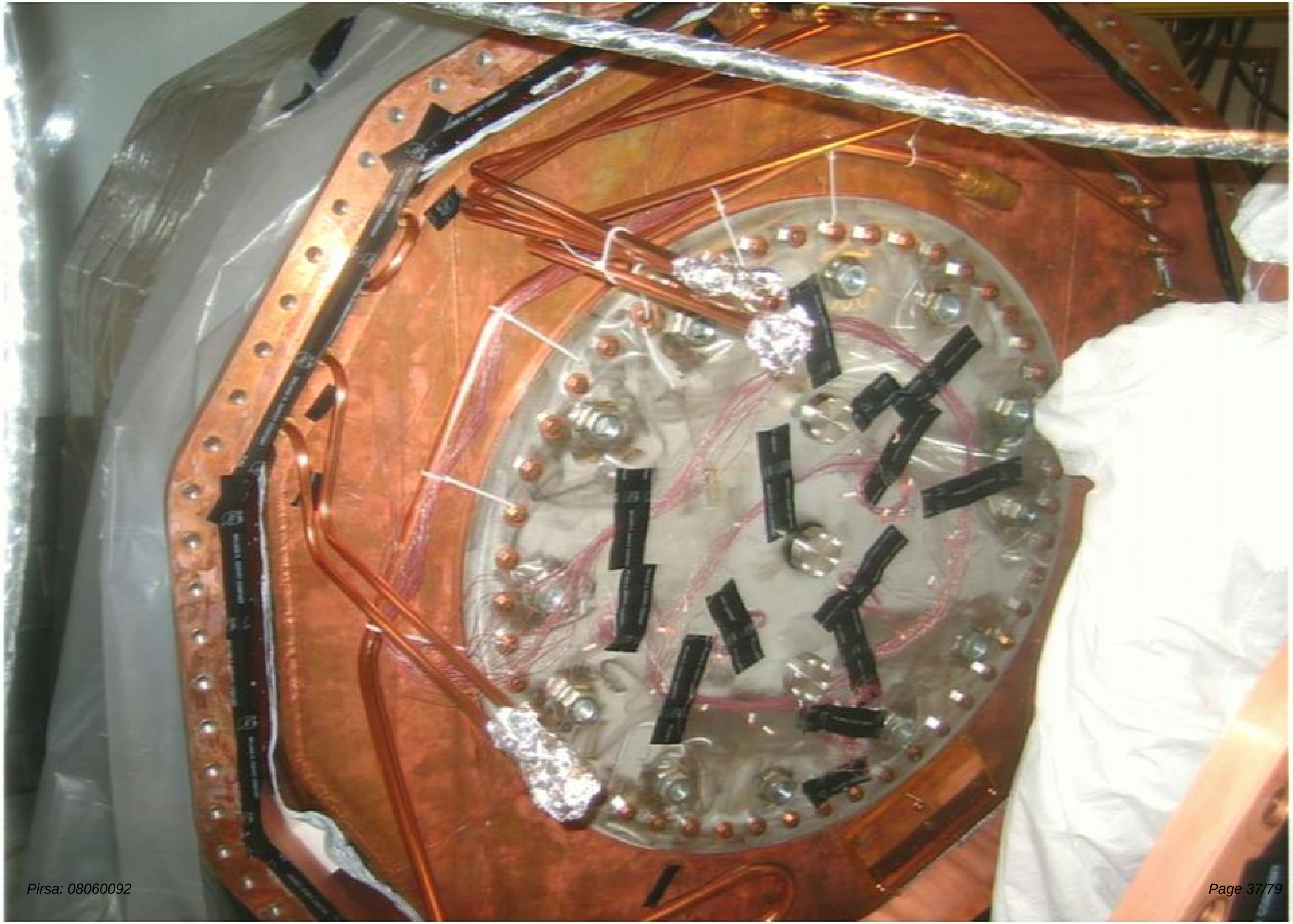
Staging container for component pre-cleaning installed at WIPP.

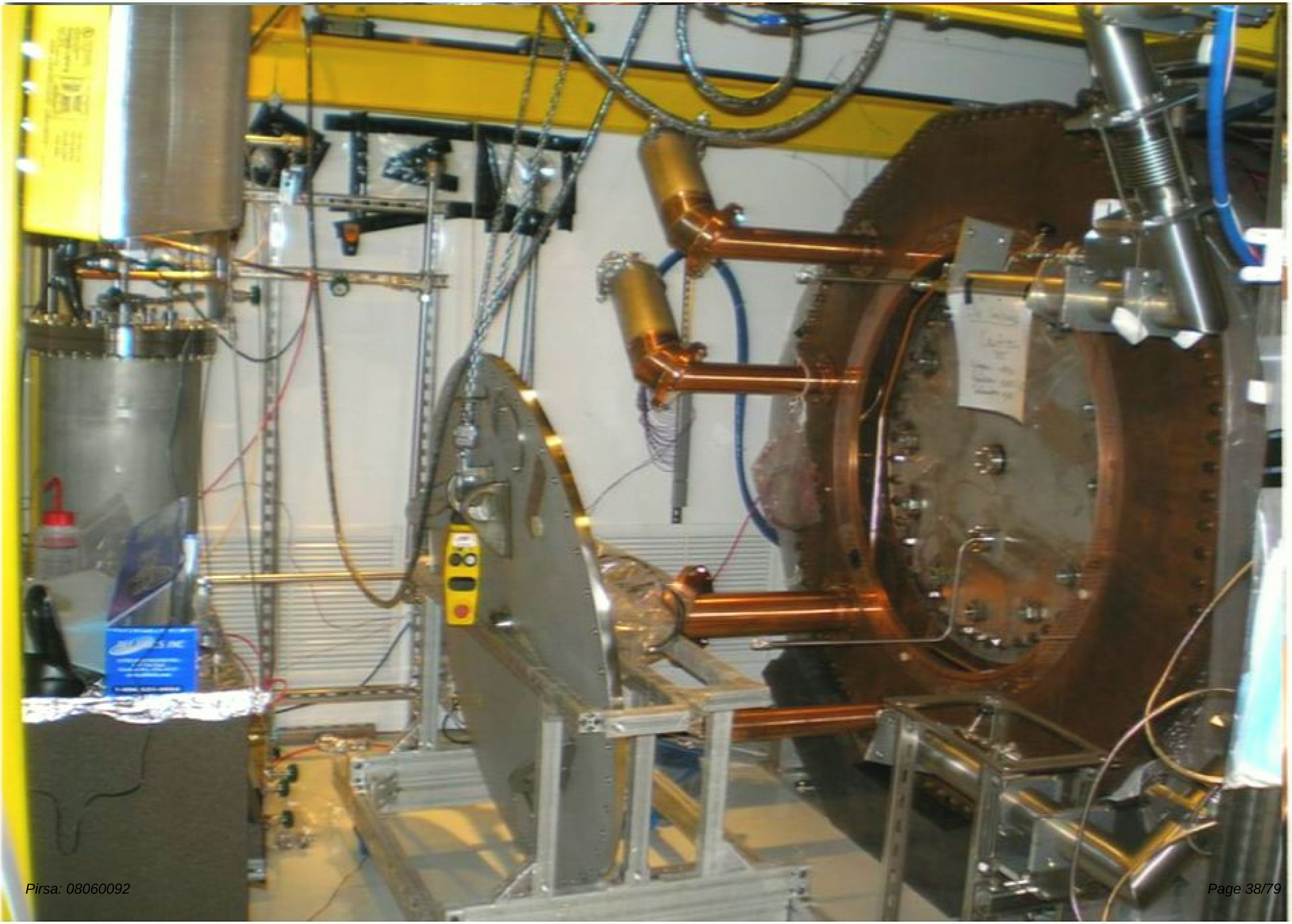
# The Cryostat



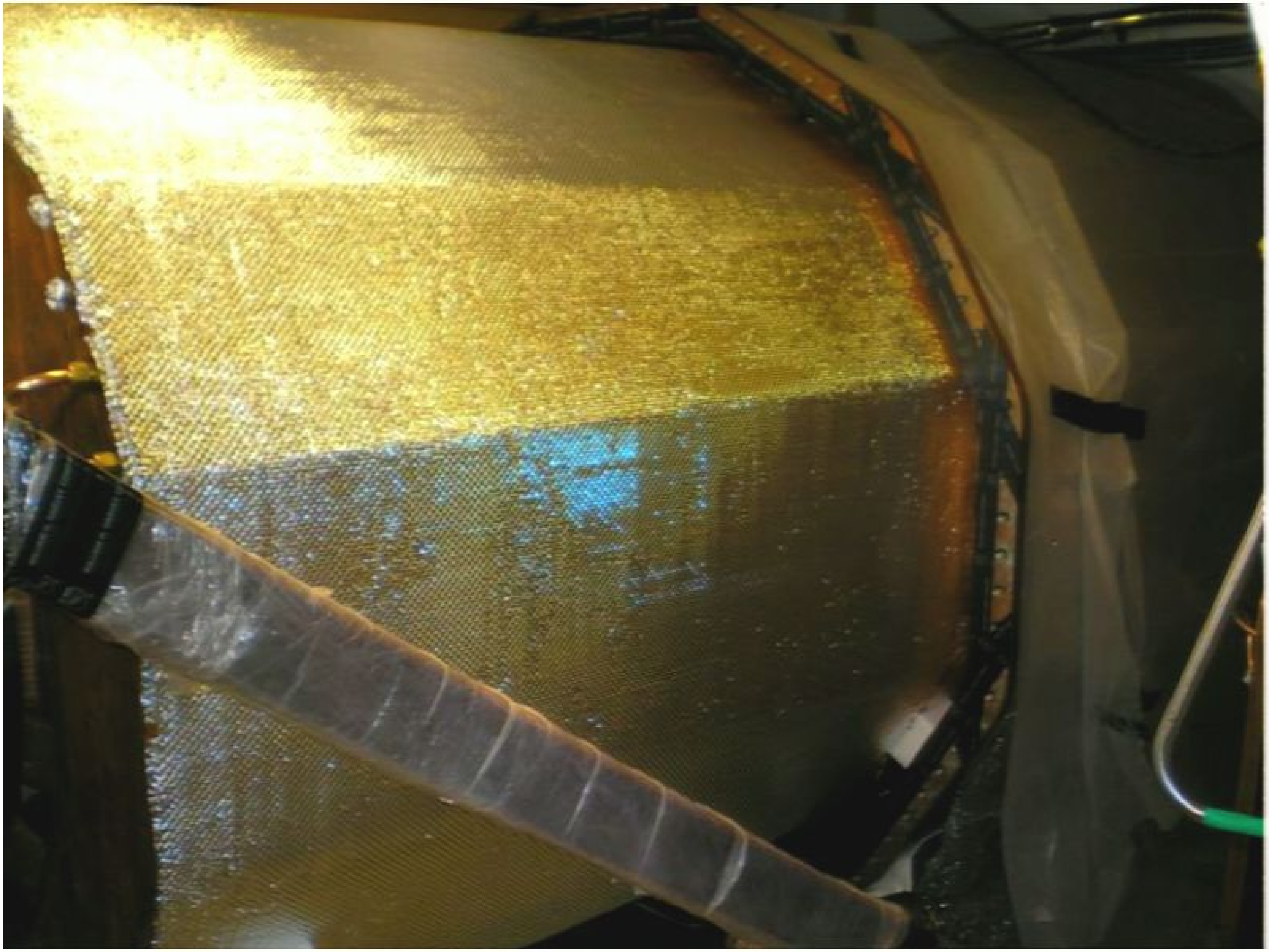
Etching with dilute $HNO_3$ after receipt in 2006.







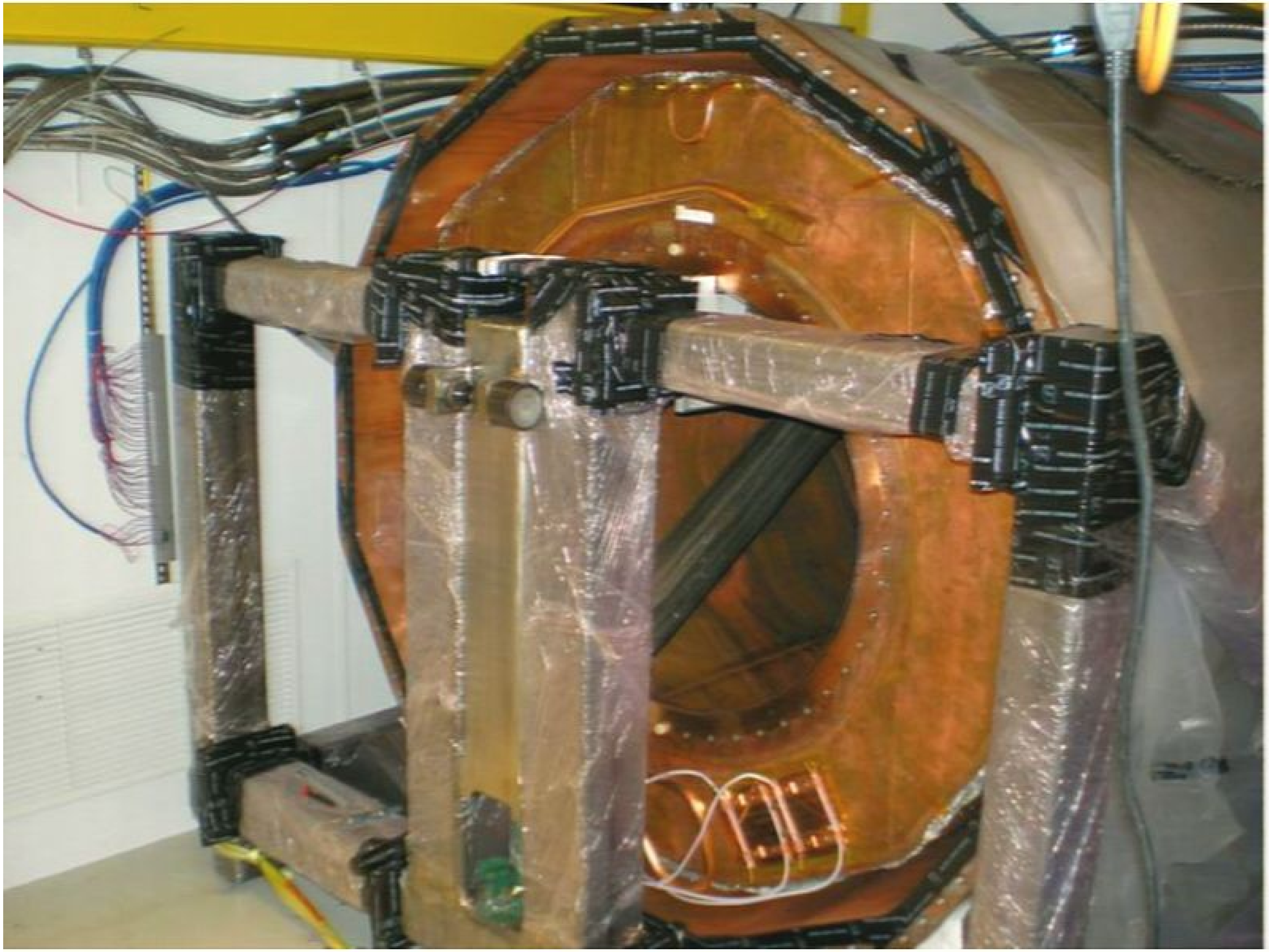
# Superinsulation



Application of new SI after it was found that original SI was too radio-active (2007).

Required design of a large extraction device.

# Superinsulation



Application of new SI after it was found that original SI was too radio-active (2007).

Required design of a large extraction device.

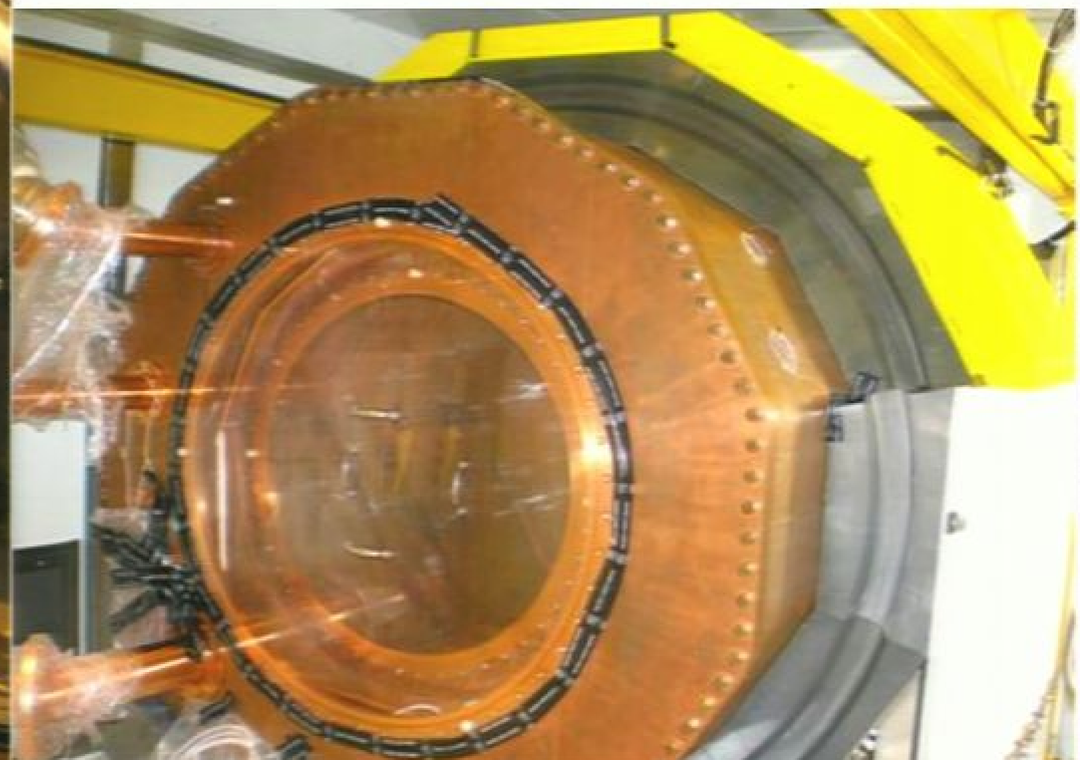
# Lead Shield

# Lead Shielding

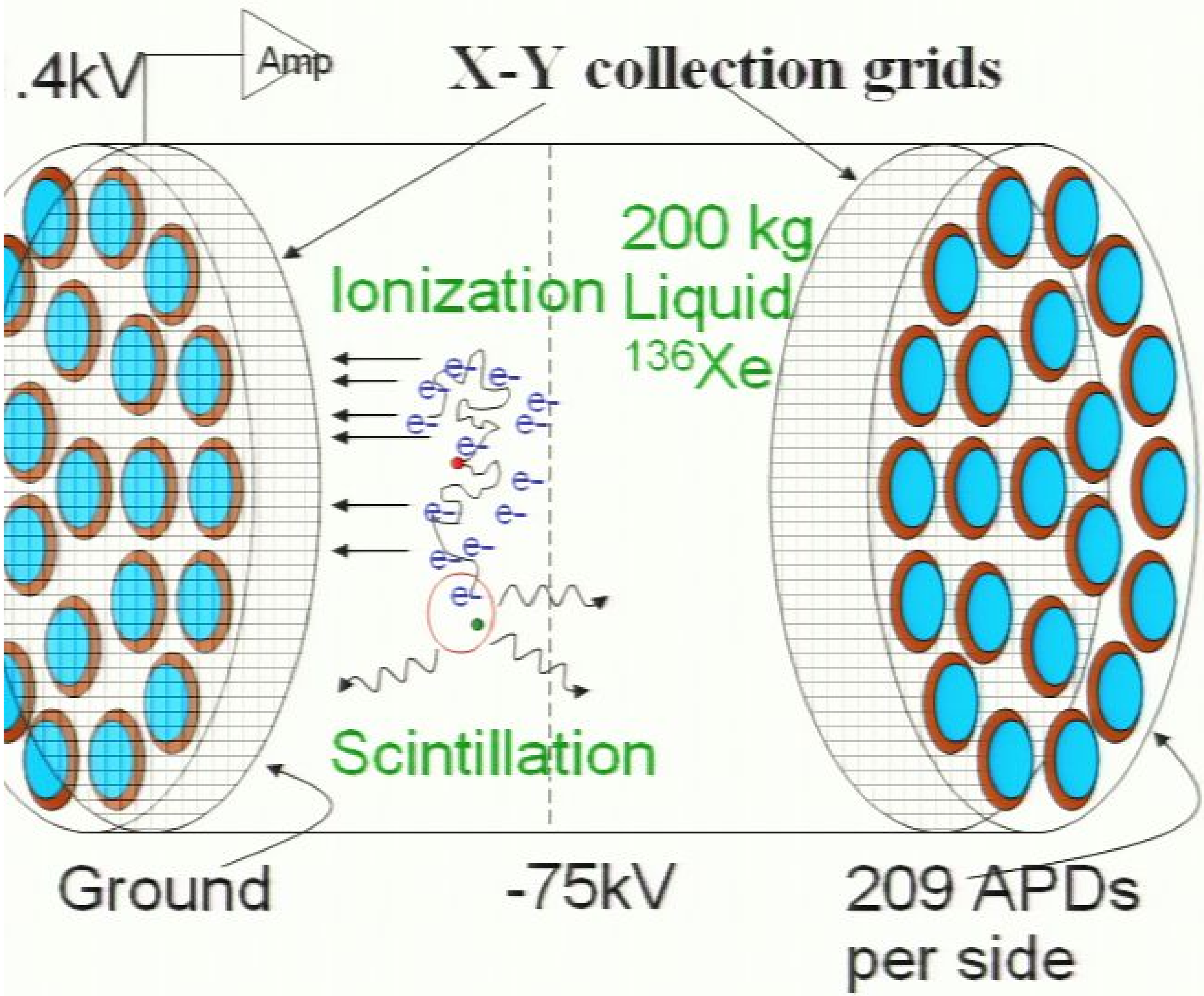

All Lead bricks interlock to avoid line-of-sight gaps in shielding.

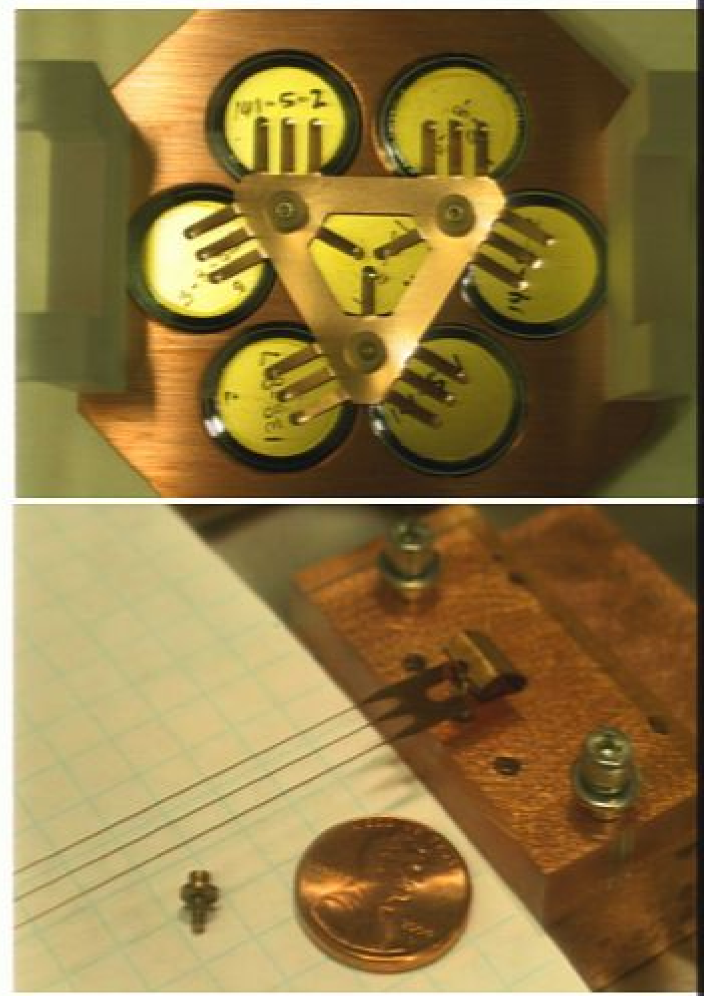
Lead selection was very strict.

May 2008: installation of the "barrel section" of the lead, at WIPP.

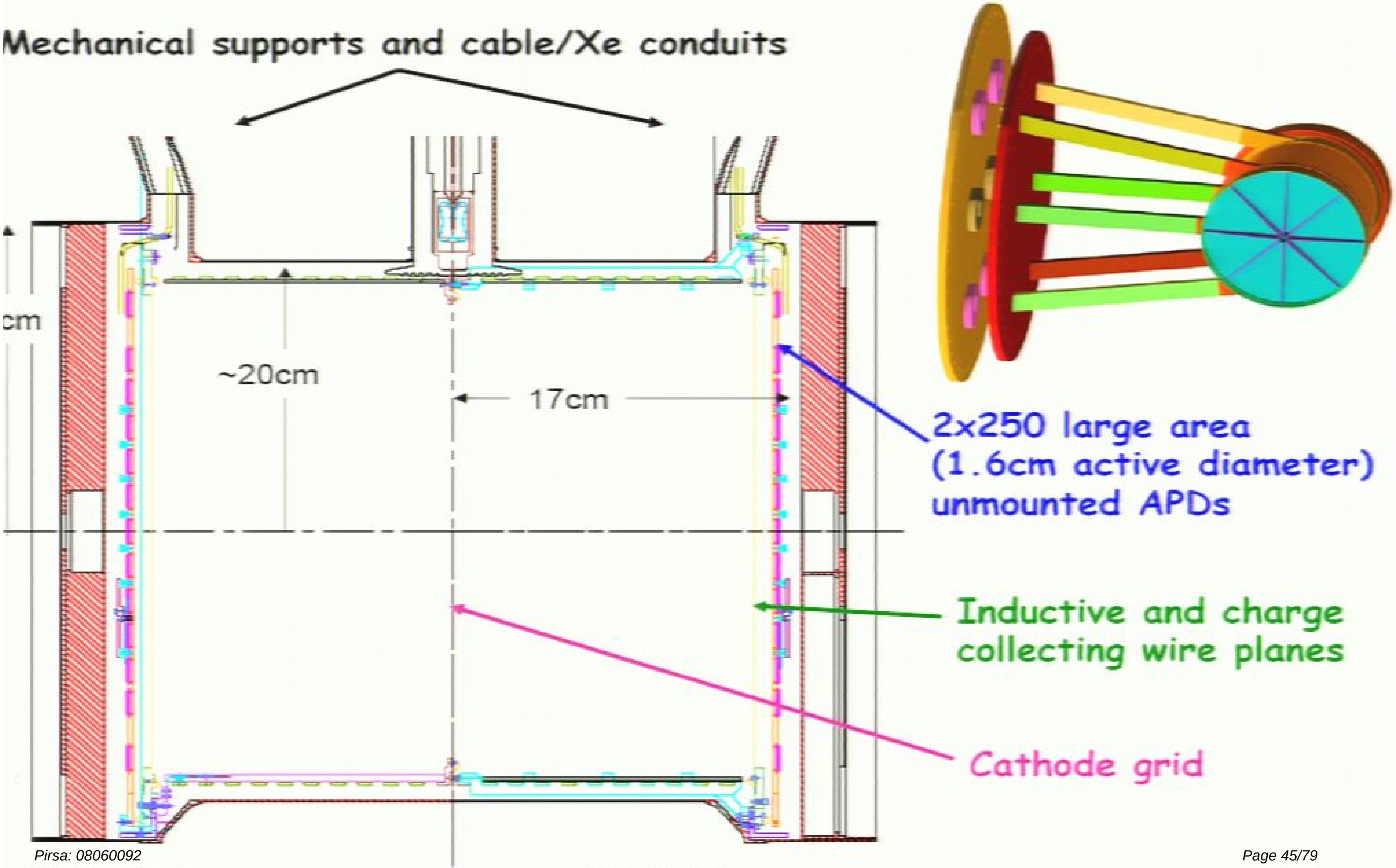


# EXO-200 Detector



# EXO chamber “hugs” the fiducial volume very closely!



# Charge Detection

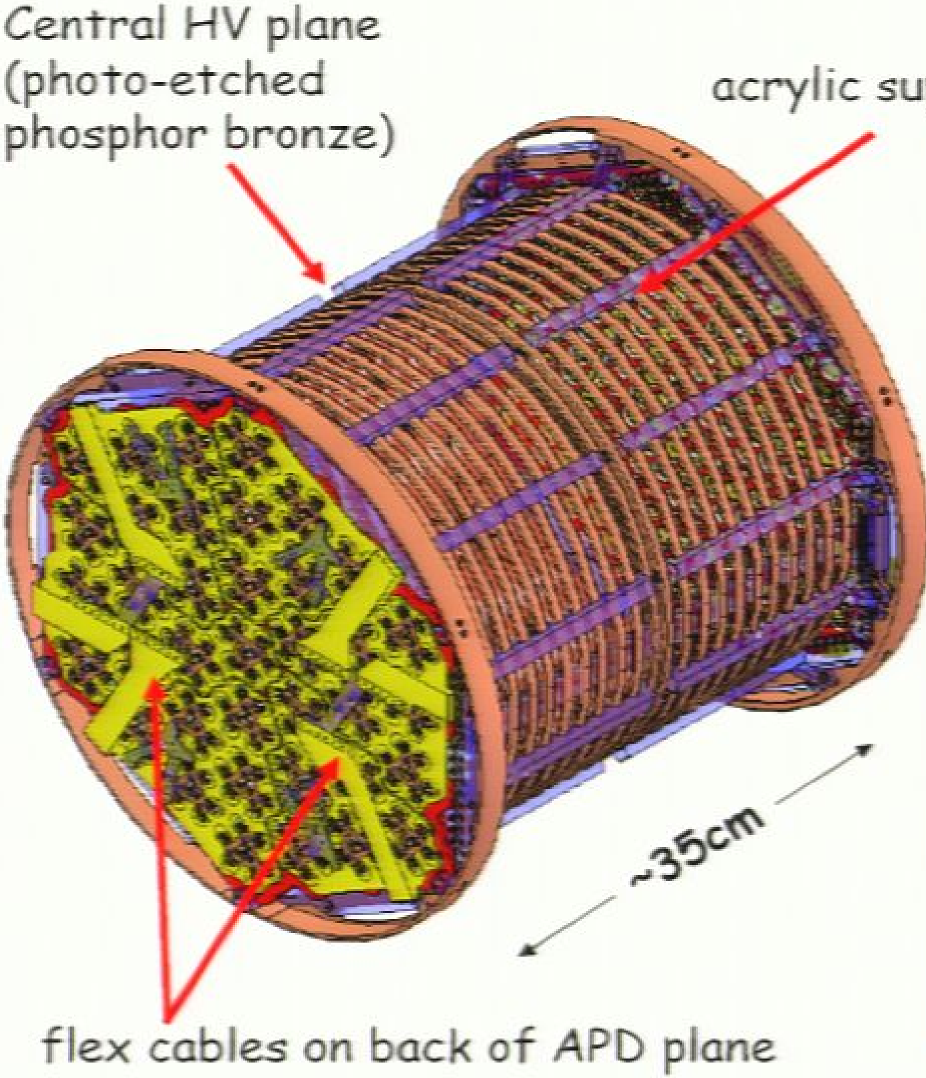
- Double-ended TPC chamber with ~20 cm drift regions
- Mid-plane cathode biased at -75 kV
- 38 Inductive “Y” wires per side at -4 kV, 100% charge transparent.
- 38 “X” wires at virtual ground to collect the charge.
- LXE electron mobility ~2000 $cm^2/(Vs)$
- Saturation velocity ~ 0.28*cm/μs
- Electron lifetime goal of 3ms

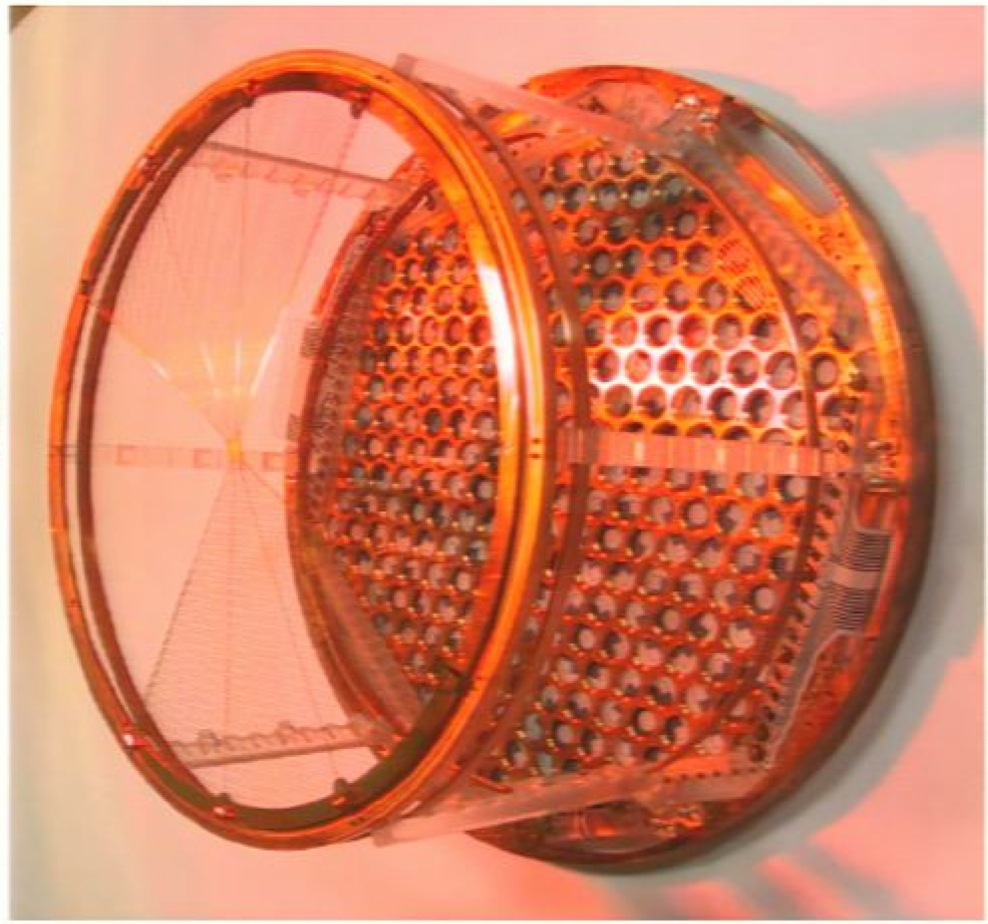
  => 2.4% loss at 20 cm.

# Light Detection

- 518 16mm APD's (Avalanche Photo Diodes) custom made with clean material stocks.
- Gangs of seven APD's
- Yield enhanced by reflective Teflon coatings in the TPC.
- 125pf each => 1000 pF per gang of seven.
- Low gain (compared to PMT's), roughly 200 electrons/photon.
- Clean materials, mostly refined silicon.
- QE measured at 129% at 175nm with 300V by comparison with NIST standard.
- Connections made by contact springs for easy maintenance.

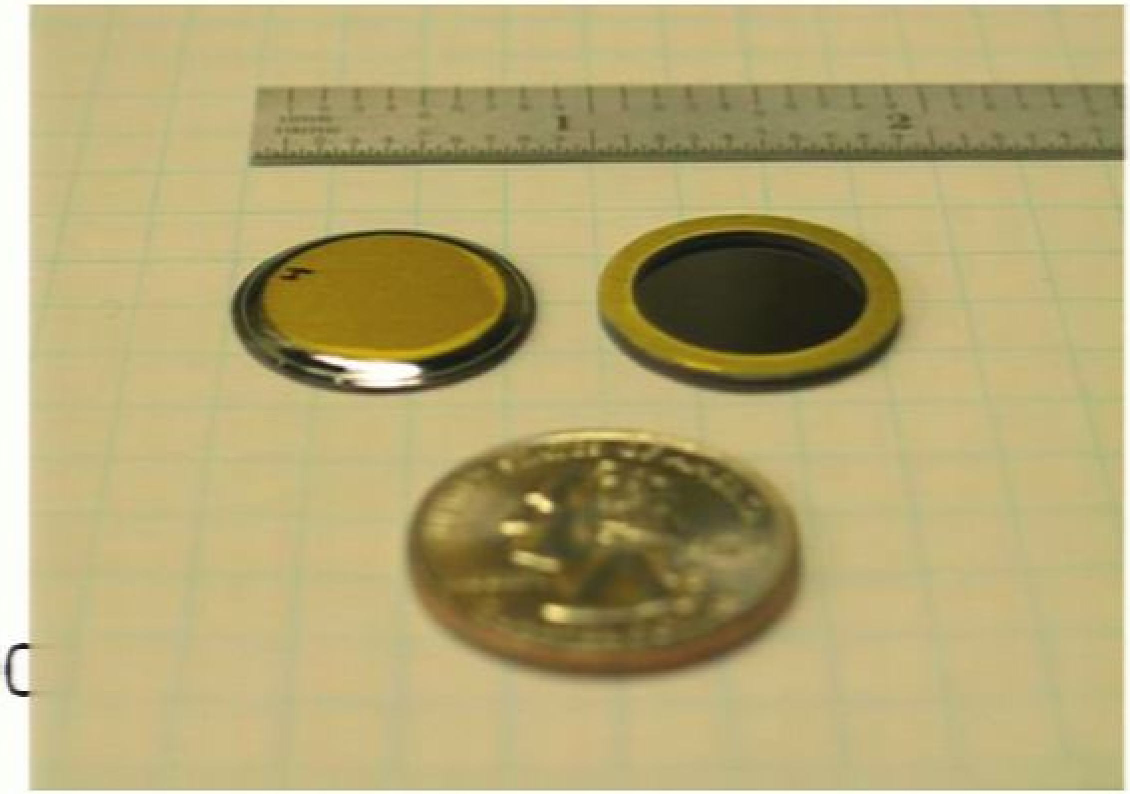
# EXO-200 LXe TPC field cage & readout planes

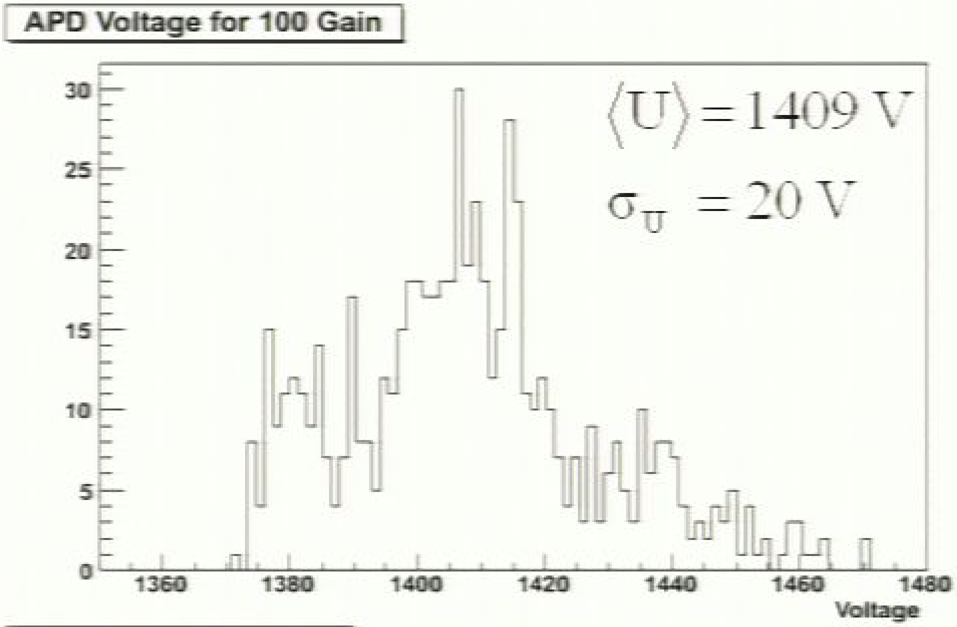


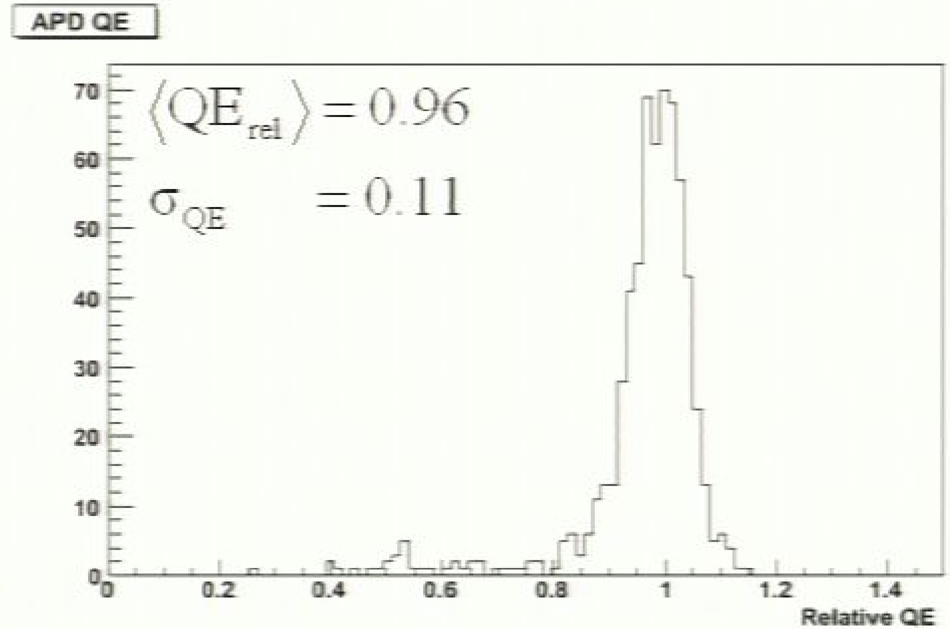



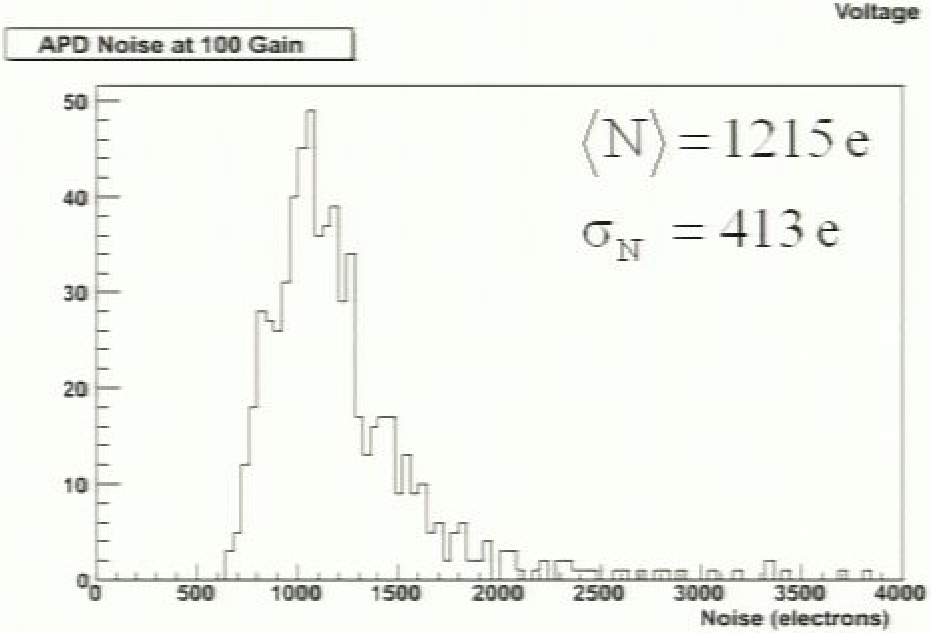
## APD delivery status

- 815 APDs delivered out of 849.
- 812 tested.
- 596 working (relative QE > 0.7, noise < 3000 electrons).
- 516 needed
  - 258 at each end
- 36 gangs of 7, one gang of 6.

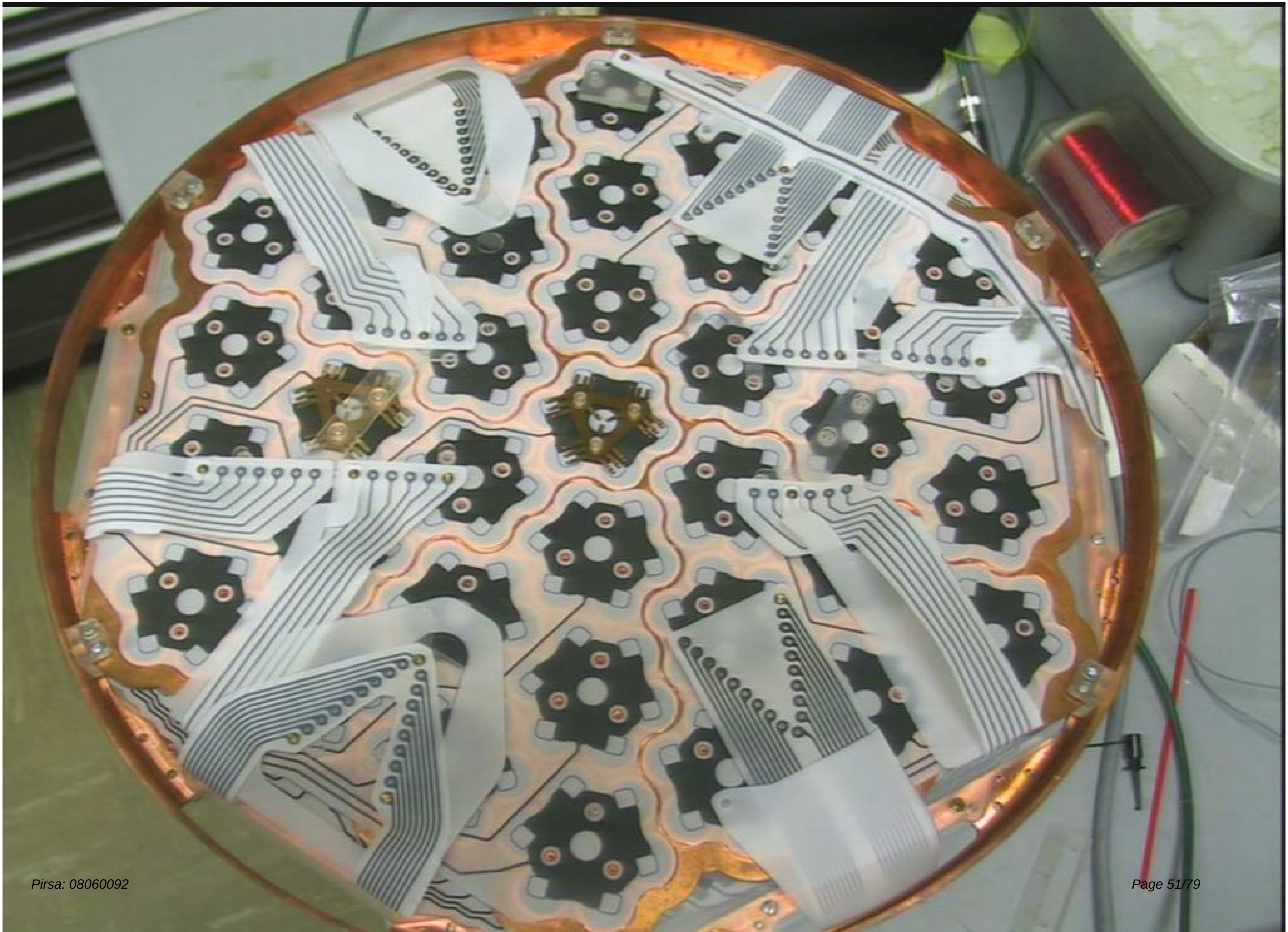




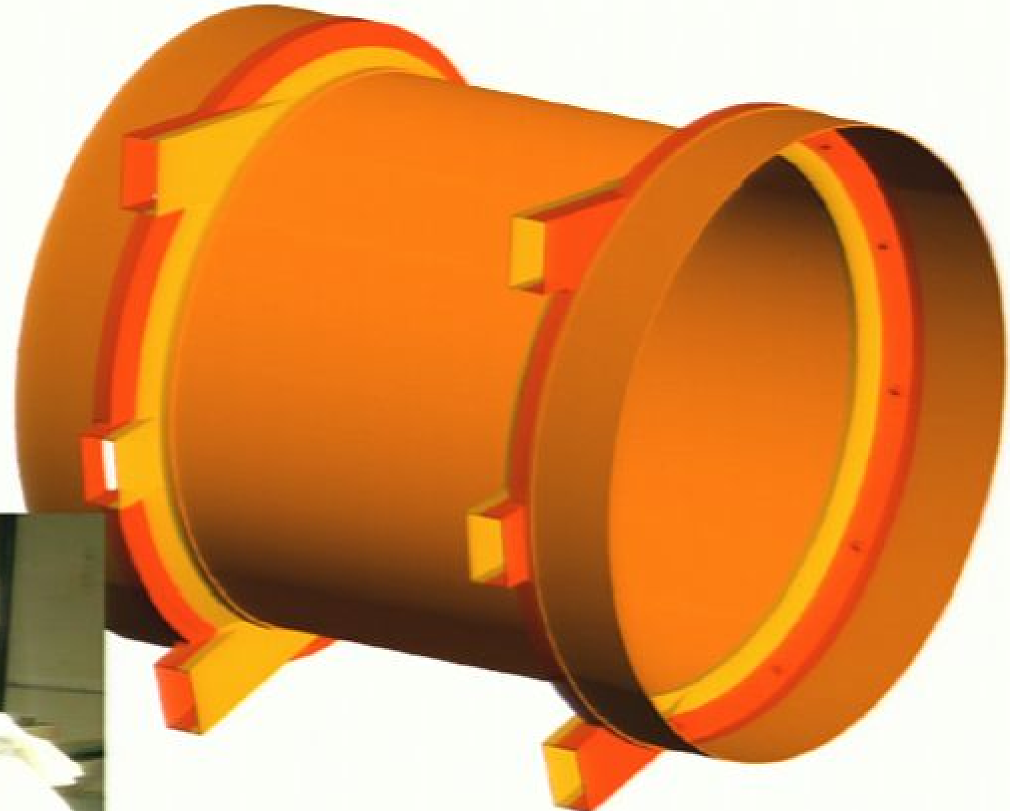




All tests done at liquid Xe temperature (-108° C).

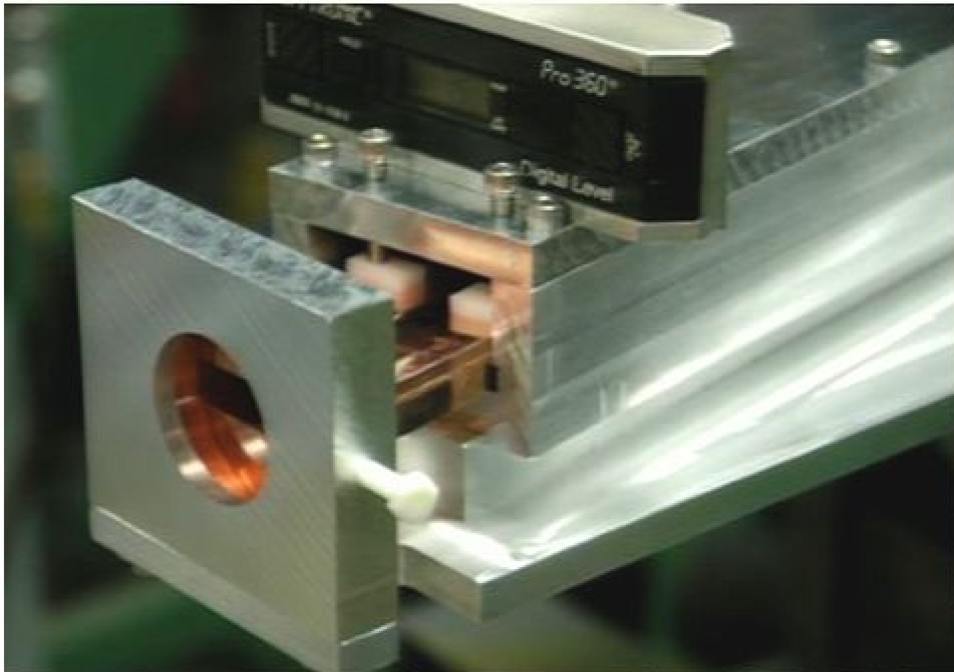


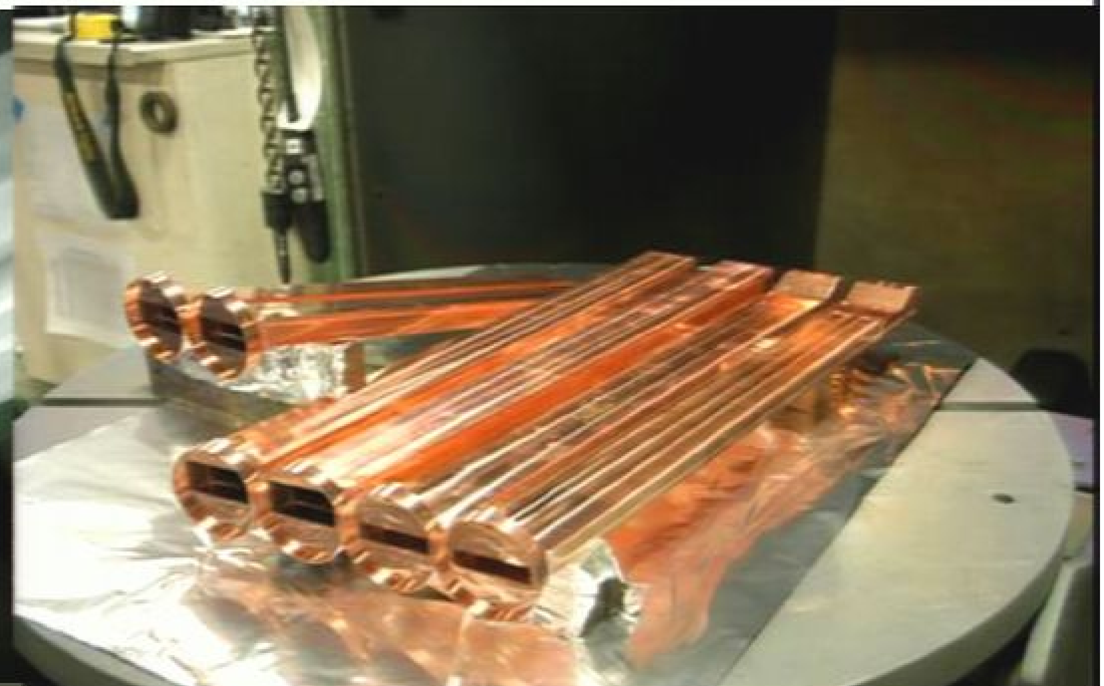
# ltra-low activity Cu vessel

- 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 under (shallow) shielding


Pro360
Digital Level



# EXO-200 Background Studies

- Impacts background sources have been studied by Monte Carlo simulation with realistic cuts:
  - $^{232}$Th in salt walls including leakage through realistic. construction joints
  - $^{40}$K, $^{232}$Th and $^{238}$U in all detector and shielding parts (nuts, bolts, o-rings, welds, residues, etc).
  - $^{222}$Rn in shielding joints, coolant system, Xenon.
  - $^{210}$Pb in lead shield and TPC walls
  - Cosmogenic isotopes in copper cryostat.
  - Muon bremsstrahlung

- We have now analyzed over 300 construction materials and parts via direct gamma counting, neutron activation, alpha counting, and mass spectroscopy.

D. S. Leonard et al. doi:10.1016/j.nima.2008.03.001

## Techniques:

**Gamma Counting:** Above and underground low background counting at UA and the University of Neuchatel (Switzerland).
Sensitivity (Th/U): 1 ppb at UA
7/16 ppt at Neuchatel
Advantage: test for background causing isotopes,
no assumptions on chain equilibrium needed.
Disadvantage: limited sensitivity, long analysis time, large samples. \

**ICPMS and GDMS** by the INMS (Canada).
Sensitivity (Th/U): 10 ppt with GDMS
1 ppt ICPMS
Advantage: high sensitivity, fast analysis, small samples.
Disadvantage: acid digestable materials only (ICPMS), needs assumption on chain equilibrium for background impact.

# EXO-200 Background Studies

- Impacts background sources have been studied by Monte Carlo simulation with realistic cuts:
  - $^{232}$Th in salt walls including leakage through realistic. construction joints
  - $^{40}$K, $^{232}$Th and $^{238}$U in all detector and shielding parts (nuts, bolts, o-rings, welds, residues, etc).
  - $^{222}$Rn in shielding joints, coolant system, Xenon.
  - $^{210}$Pb in lead shield and TPC walls
  - Cosmogenic isotopes in copper cryostat.
  - Muon bremsstrahlung

- We have now analyzed over 300 construction materials and parts via direct gamma counting, neutron activation, alpha counting, and mass spectroscopy.

  D. S. Leonard et al. doi:10.1016/j.nima.2008.03.001

## Techniques:

**Gamma Counting:** Above and underground low background counting at UA and the University of Neuchatel (Switzerland).
Sensitivity (Th/U): 1 ppb at UA
7/16 ppt at Neuchatel
Advantage: test for background causing isotopes, no assumptions on chain equilibrium needed.
Disadvantage: limited sensitivity, long analysis time, large samples. \

**ICPMS and GDMS** by the INMS (Canada).
Sensitivity (Th/U): 10 ppt with GDMS
1 ppt ICPMS
Advantage: high sensitivity, fast analysis, small samples.
Disadvantage: acid digestable materials only (ICPMS), needs assumption on chain equilibrium for background impact.

# Neuchatel (CH): Vue-des-Alpes

μ  ($200\ m^{-2}s^{-1}$)

220m (600mw.e.)

μ  ($0.2 m^{-2}s^{-1}$)


University of Neuchatel

# Neuchatel (CH): Vue-des-Alpes

μ $(200\ m^{-2}s^{-1})$

220m (600mw.e.)

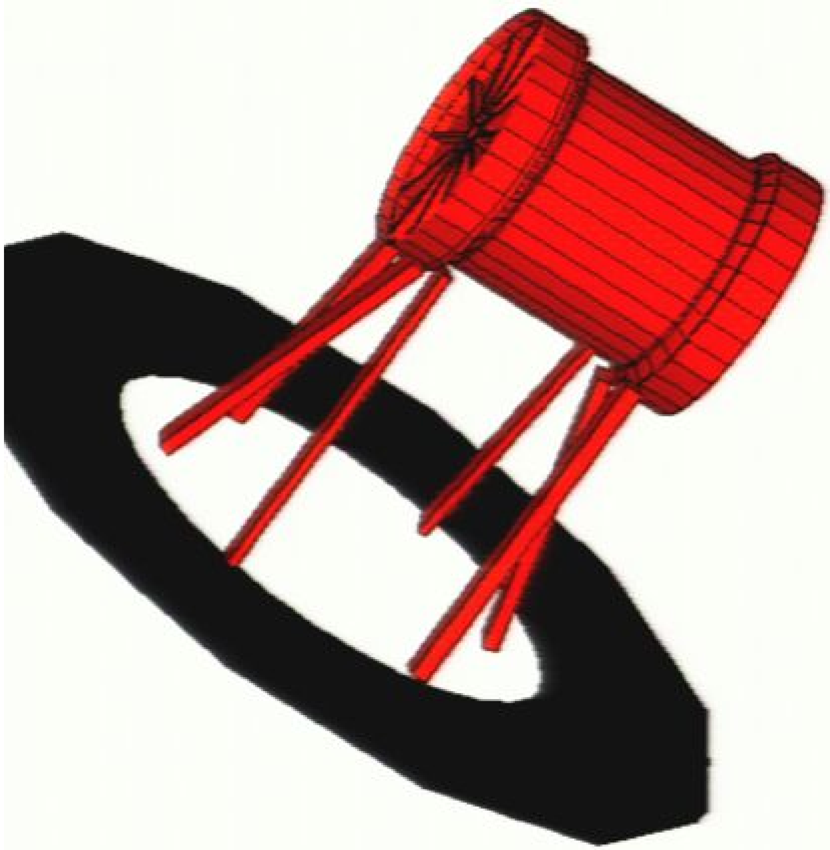
μ $(0.2m^{-2}s^{-1})$

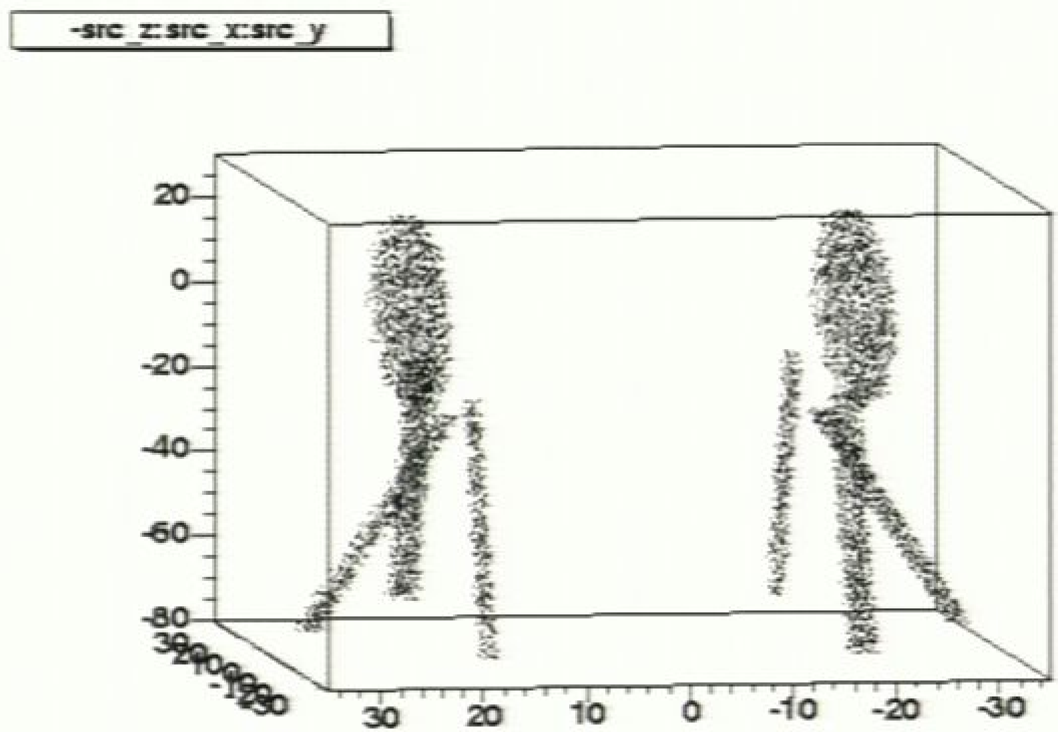

University of Neuchatel

# Facilities available at UA

Recent example: quantify background impact of flat cables used in quantity to bias APDs and transfer the signals.

Optimize production process until impacts of measured contamination was found acceptable.





Materials are only accepted for construction if

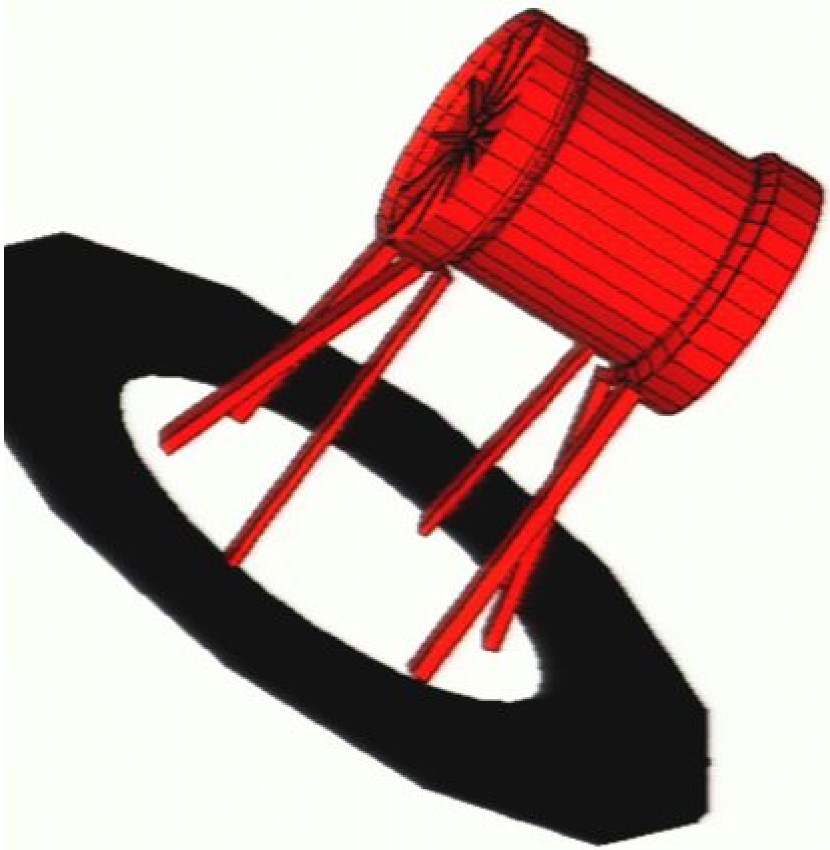
1) They have been tested for radioactivity and

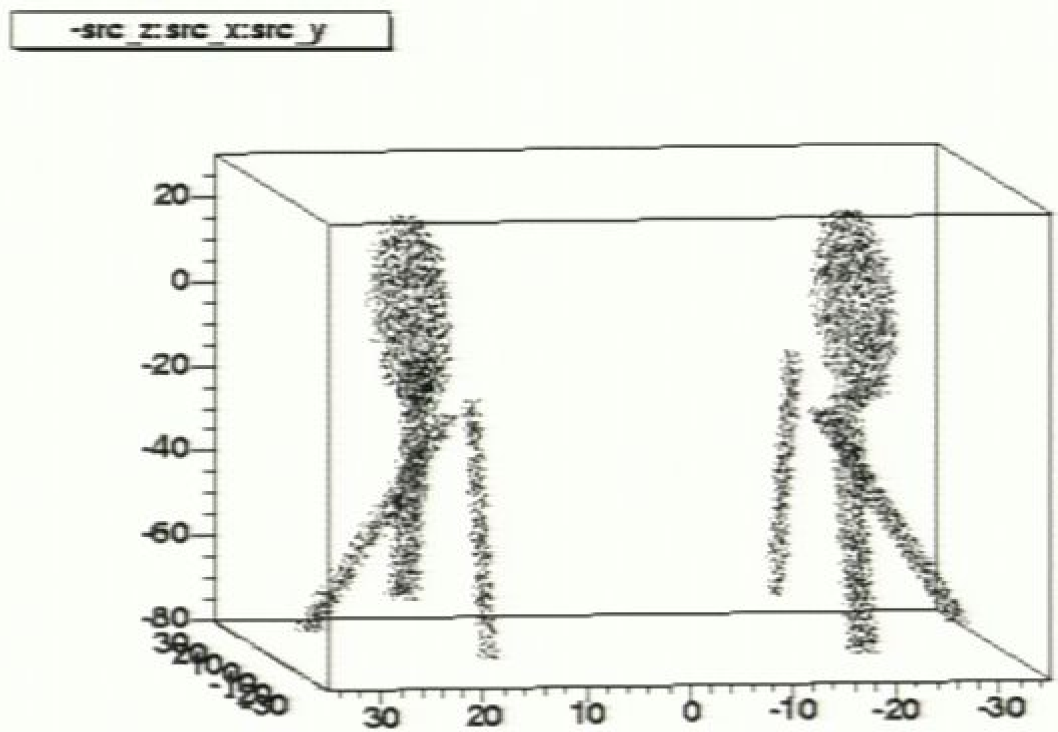
2) The background impact for each point of use has been found acceptable by Monte Carlo.

We keep a running log of all backgrounds during installation.

Recent example: quantify background impact of flat cables used in quantity to bias APDs and transfer the signals.

Optimize production process until impacts of measured contamination was found acceptable.





ea tr nsp rt in crete led

c er t press vatio

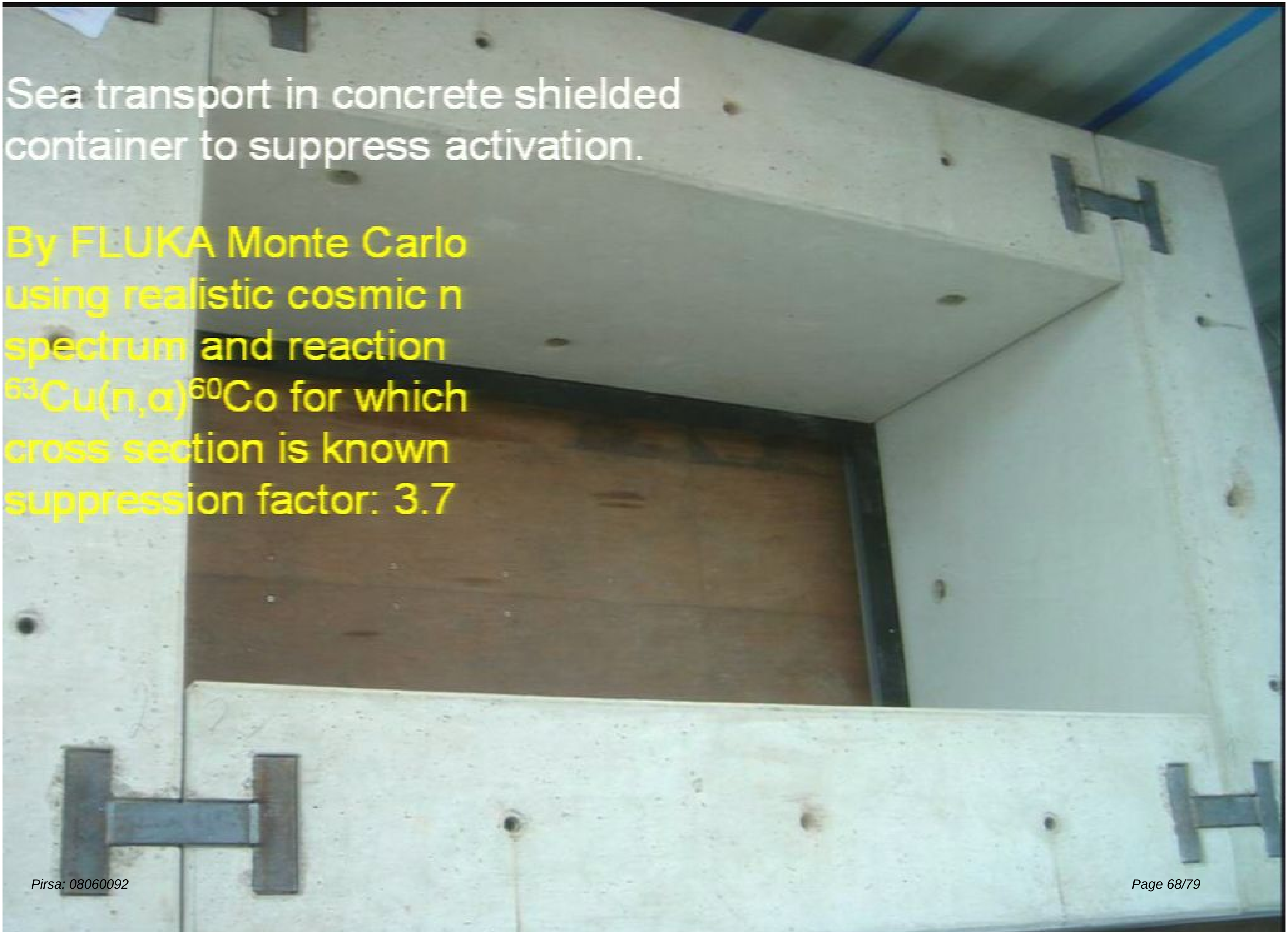
FL Mont lo

s im a actic

oss n is n

s ssio or: 3


.2 tons high purity
Cu freshly produced
n Germany 6/1/2006.
imited cosmics exposure
o avoid activation.
Shielding bunker at
DESY stored 6/2/2006
22
26



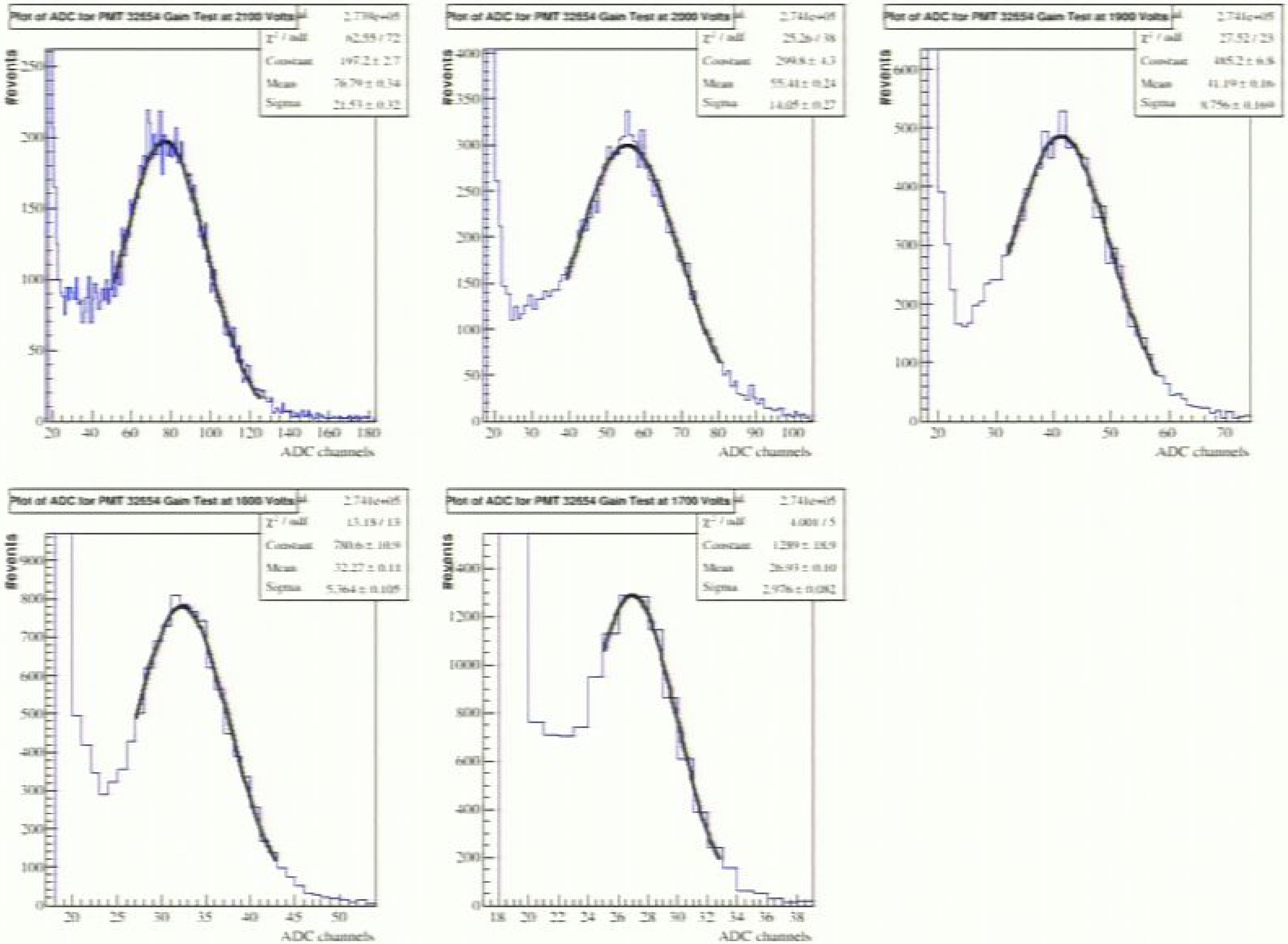
Sea transport in concrete shielded container to suppress activation.

By FLUKA Monte Carlo using realistic cosmic n spectrum and reaction $^{63}Cu(n,\alpha)^{60}Co$ for which cross section is known suppression factor: 3.7

31 large plastic scintillator panels, left over from the concluded KAREMEN neutrino oscillation experiment, have been acquired.

They are currently being refurbished, tested, and calibrated at UA. Includes gain matching of about 300 PMTs.

# Single PE peaks at various Voltages

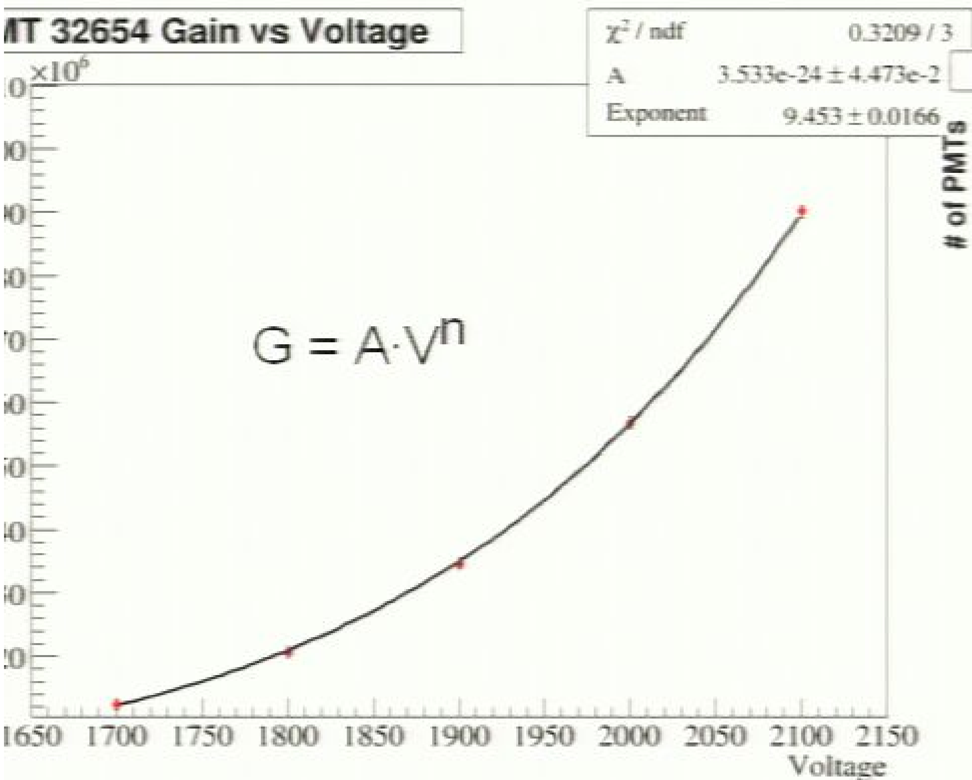


# Experimental Setup

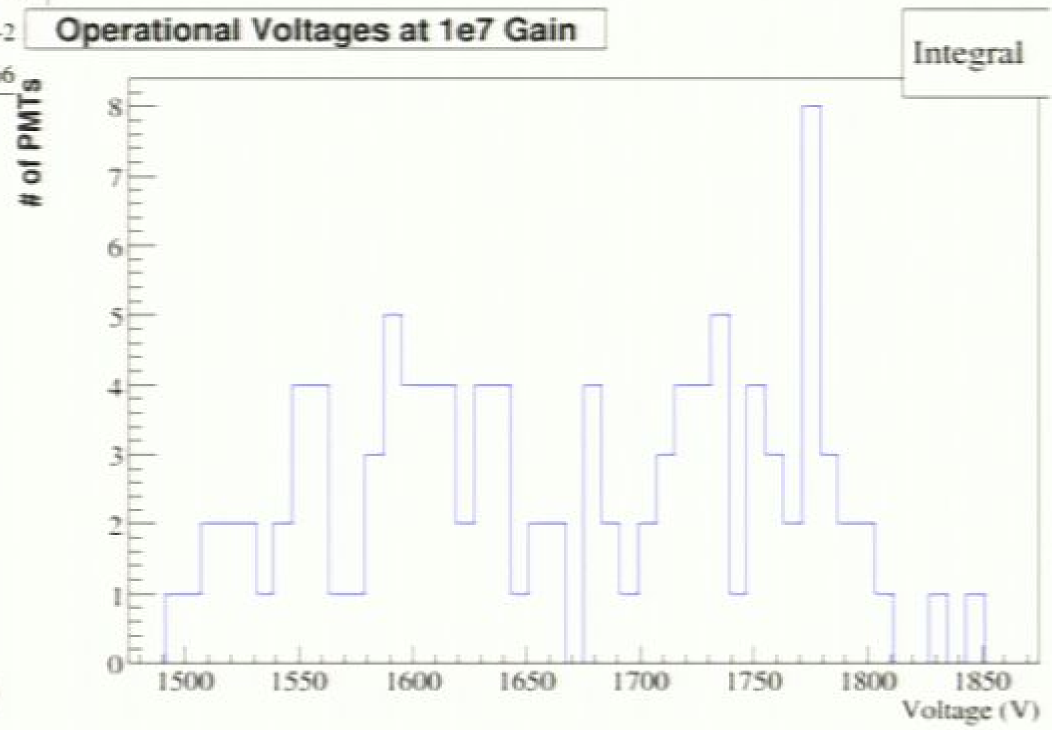
- Position determined by a muon telescope

Cumbersome clamp stands are now replaced with a wooden box for easier telescope placement.

# Gain vs. Voltage




# Operating Voltages

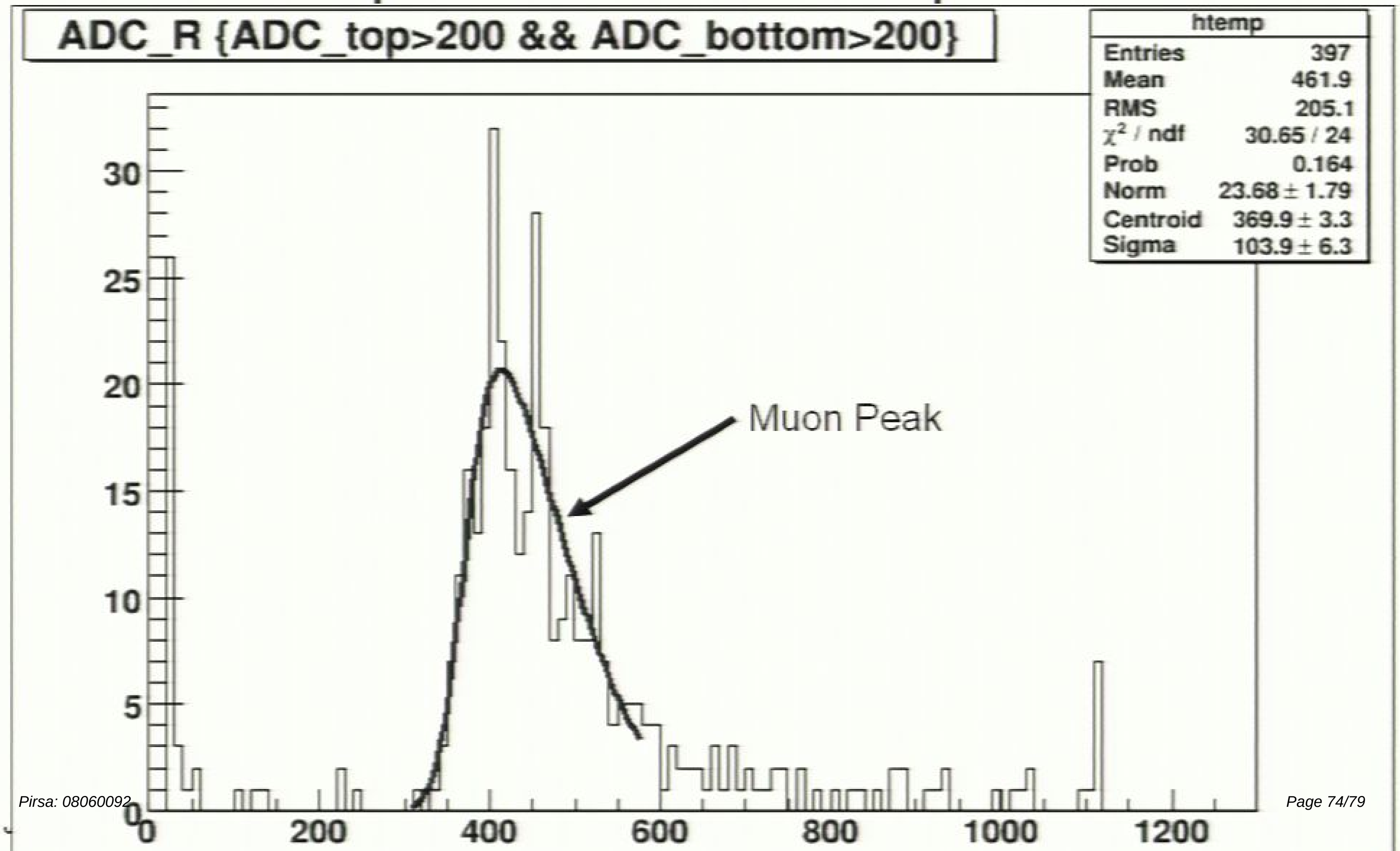


# Experimental Setup

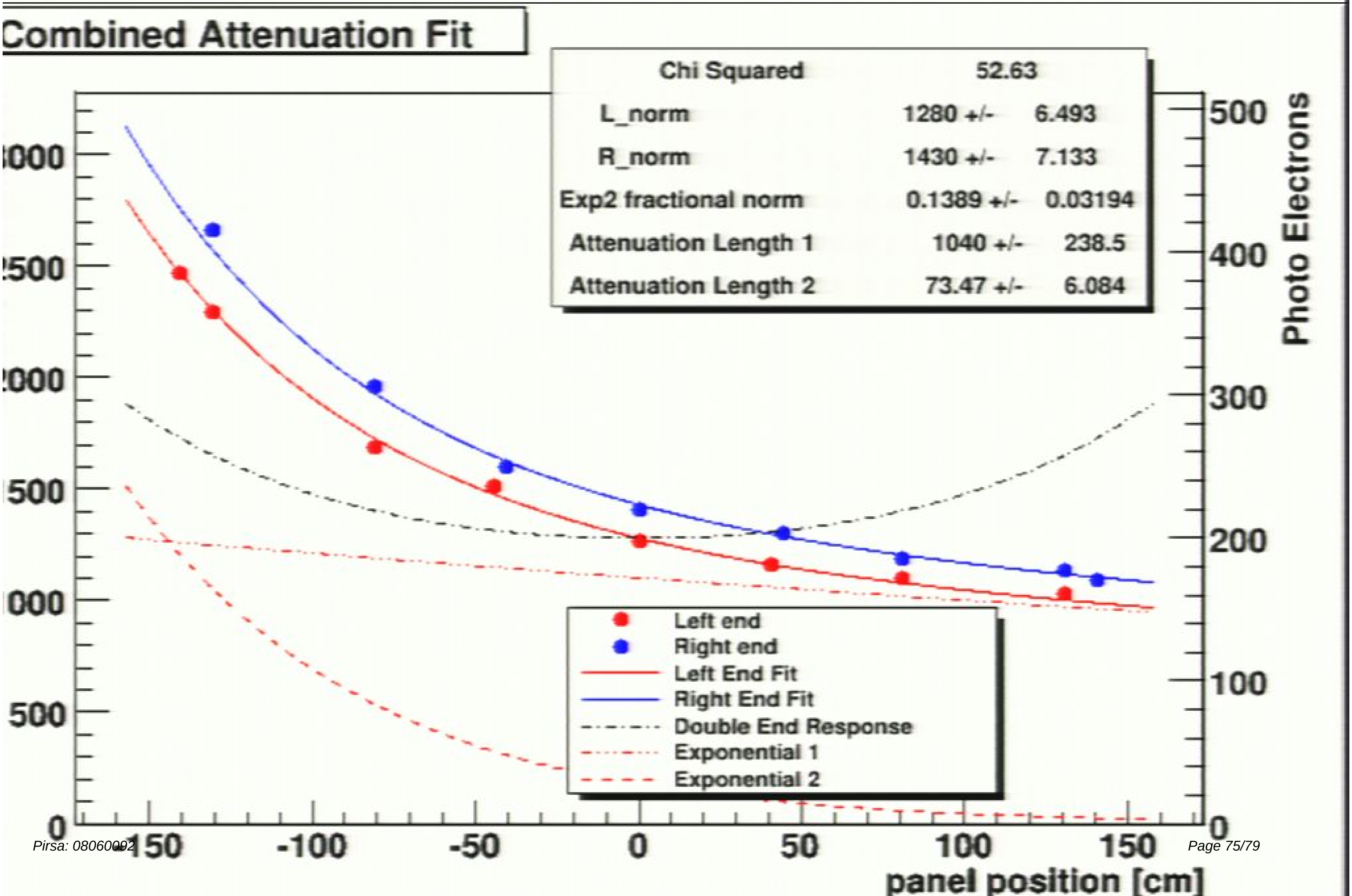
- Position determined by a muon telescope

Cumbersome clamp stands are now replaced with a wooden box for easier telescope placement.

# Panel end spectrum (Gang of 4 PMT's) with telescope coincidence requirement



# Panel S24



Combined Attenuation Fit
Chi Squared 52.63
L_norm 1280 +/- 6.493
R_norm 1430 +/- 7.133
Exp2 fractional norm 0.1389 +/- 0.03194
Attenuation Length 1 1040 +/- 238.5
Attenuation Length 2 73.47 +/- 6.084
Left end
Right end
Left End Fit
Right End Fit
Double End Response
Exponential 1
Exponential 2
Photo Electrons
panel position [cm]

# EXO-200 Majorana mass sensitivity

Assumptions:

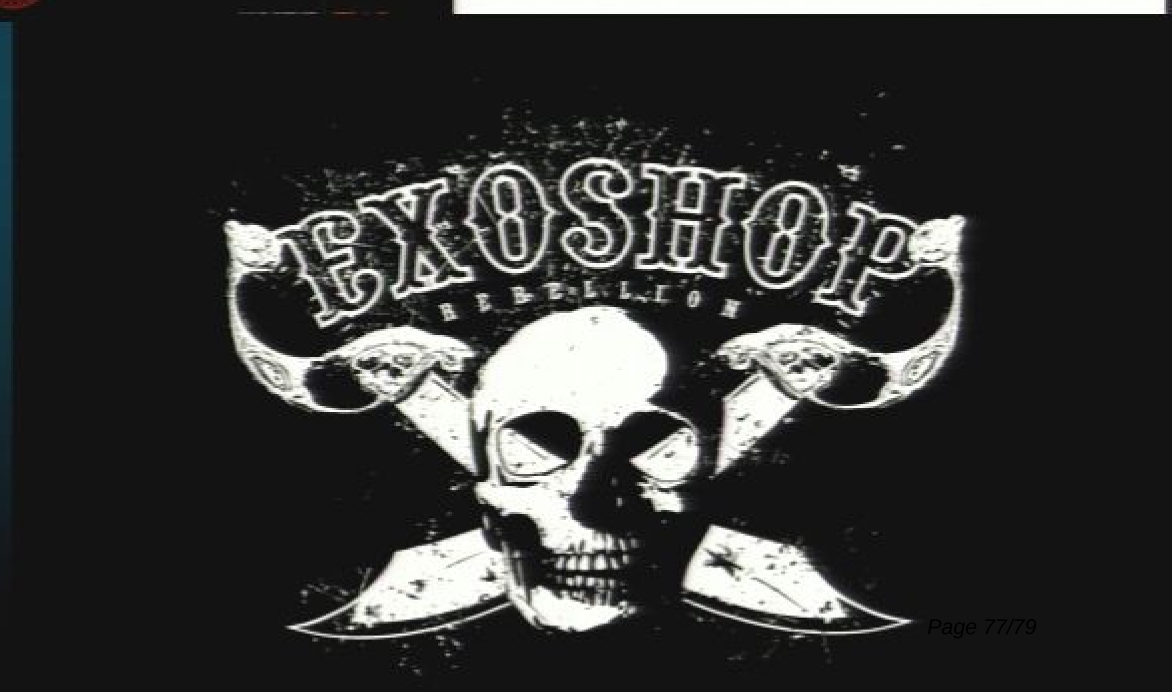
1) 200kg of Xe enriched to 80% in 136
2) $\sigma(E)/E$ = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
3) Low but finite radioactive background:
   20 events/year in the $\pm 2\sigma$ interval centered around the 2.46MeV endpoint
4) Negligible background from $2\nu\beta\beta$ ($T_{1/2}$>$1\cdot10^{22}$yr R.Bernabei et al. measurement)

| Case | Mass (ton) | Eff. (%) | Run Time (yr) | $\sigma_E/E$ @ 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 | $6.4\times10^{25}$ | 133 | 186 |

1) Rodin, *et. al.*, Nucl. Phys. A **793** (2007) 213-215
2) Caurier, *et. al.*, arXiv:0709.2137v2

# <u>NOT</u> our Collaboration





# he EXO Collaboration

rry, D.Leonard, E.Niner, A.Piepke *Physics Dept, University of Alabama, Tuscaloosa AL*
gel *Physics Dept Caltech, Pasadena CA*
ellerive, M.Bowcock, M.Dixit, C.Hargrove, E.Rollin, D.Sinclair, V.Strickland
*Carleton University, Ottawa, Canada*
enitez-Medina, S.Cook, W.Fairbank Jr., K.Hall, B.Mong *Colorado State University, Fort Collins CO*
loe *Physics Dept UC Irvine, Irvine CA*
kimov, I.Alexandrov, A.Burenkov, M.Danilov, A.Dolgolenko, A.Kovalenko, V.Stekhanov
*ITEP Moscow, Russia*
rine, D.Hallman, C.Virtue, U.Wichoski *Laurentian University, Canada*
euer, C.Hall, L.Kaufman, S. Slutsky, Y-R. Yen
*University of Maryland, College Park MD*
mar *U. of Massachusetts, Amherst*
uger, R.Gornea, D.Schenker, J-L.Vuilleumier, J-M.Vuilleumier
*Physics Dept University of Neuchatel, Switzerland*
ckerman, M.Breidenbach, R.Conley, W.Craddock, J.Hodgson, D.McKay, A.Odian, C.Prescott, P.Rowson,
kar... J.Wodin, L.Yang, S.Zalog *SLAC, Menlo Park CA*
nthony, L.Bartoszek, R.DeVoe, P.Fierlinger, B.Flatt, G.Gratta, M.Green, S.Kolkowitz, F.LePort,

# $Ba^+$ Tagging R&D