Liquid Xenon Time Projection Chamber for EXO-200

Doug Leonard
University of Alabama

Enriched Xenon Observatory

EXO

for double beta decay

Collaborators

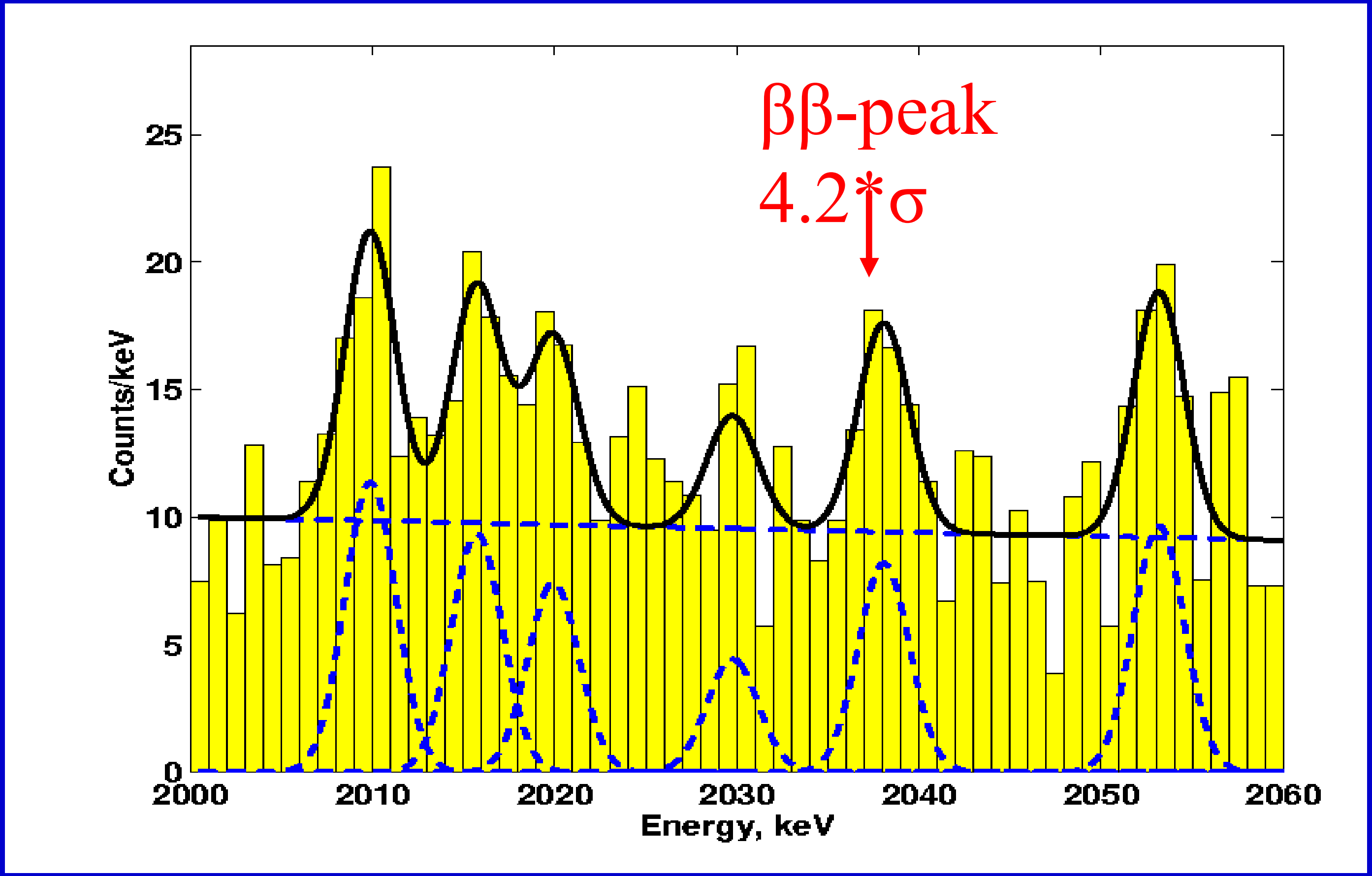
(Slightly out of date)

Z.Djurcic, D.Leonard, A.Piepke
Physics Dept, University of Alabama, Tuscaloosa AL
P.Vogel
Physics Dept Caltech, Pasadena CA
A. Bellerive, M. Dixit, C. Hargrove, D. Sinclair
Carleton University, Ottawa, Canada
W.Fairbank Jr., S.Jeng, K.Hall
Colorado State University, Fort Collins CO
M.Moe
Physics Dept UC Irvine, Irvine CA
D.Akimov, A.Burenkov, M.Danilov, A.Dolgolenko, A.Kovalenko, D.Kovalenko, G.Smirnov, V.Stekhanov
ITEP Moscow, Russia
J. Farine, D. Hallman, C. Virtue
Laurentian University, Canada
M.Hauger, F.Juget, L.Ounalli, D.Schenker, J-L.Vuilleumier, J-M.Vuilleumier, P.Weber
Physics Dept University of Neuchatel, Neuchatel Switzerland
M.Breidenbach, R.Conley, C.Hall, A.Odian, C.Prescott, P.Rowson, J.Sevilla, K.Skarpaas, K.Wamba,
SLAC, Menlo Park CA
E.Conti, R.DeVoe, G.Gratta, M.Green, T.Koffas, R.Leon, F.LePort, R.Neilson, Y.Uchida, S.Waldman, J.Wodin
Physics Dept Stanford University, Stanford CA

Double Beta Decay

- ββ is a second order weak process:
  Very rare!
  $T_{1/2} > 10^{19}$ y
- Signal is overwhelmed by standard β (if it occurs).
- Can emit two neutrinos, but possibly 0 neutrinos as well.
- Neutrino-less ββ is 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.

Heidelberg Evidence:



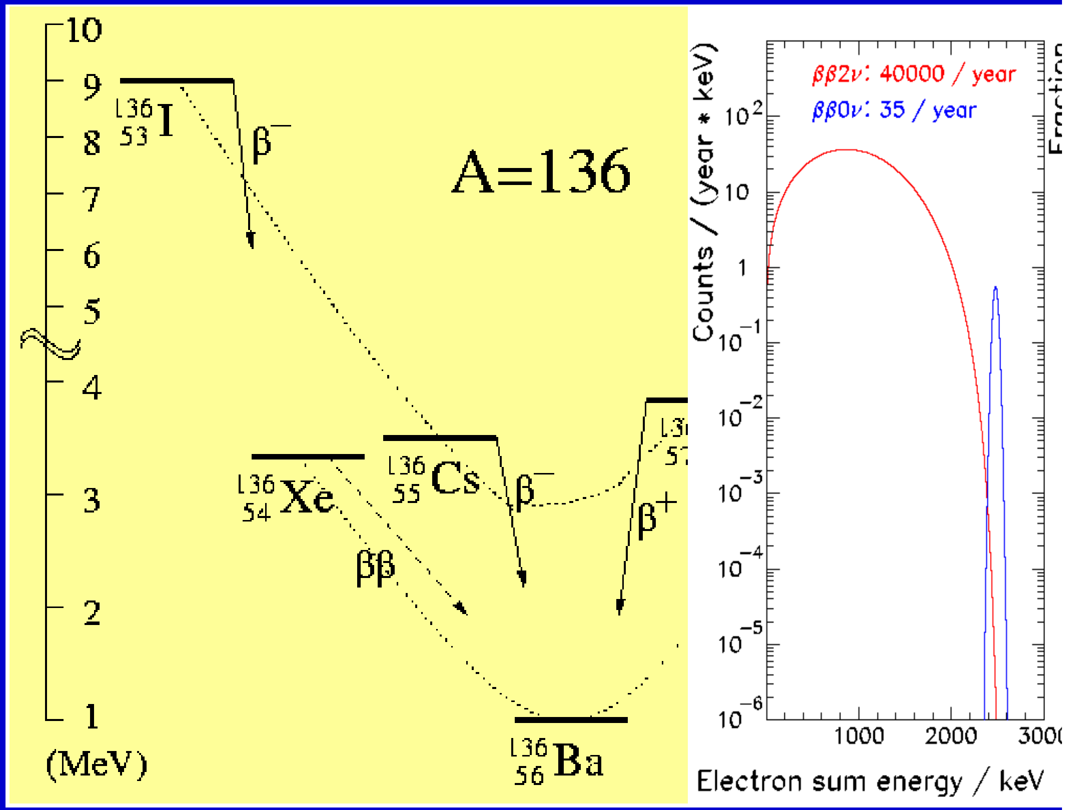
-Used 10.9 kg of Ge enriched to 86% in 76Ge.

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

-$\langle m_\upsilon \rangle$=0.44 eV +/-

ββ decay in Xenon

- ^{136}Xe β-decay does not occur.
- Xe makes good ionization/drift chamber. (gas and liquid)
- Liquid Xe has high scintillation yield (175 nm, VUV).
- ββ0v at ~2448 keV, about 35 events per year in 200 kg.



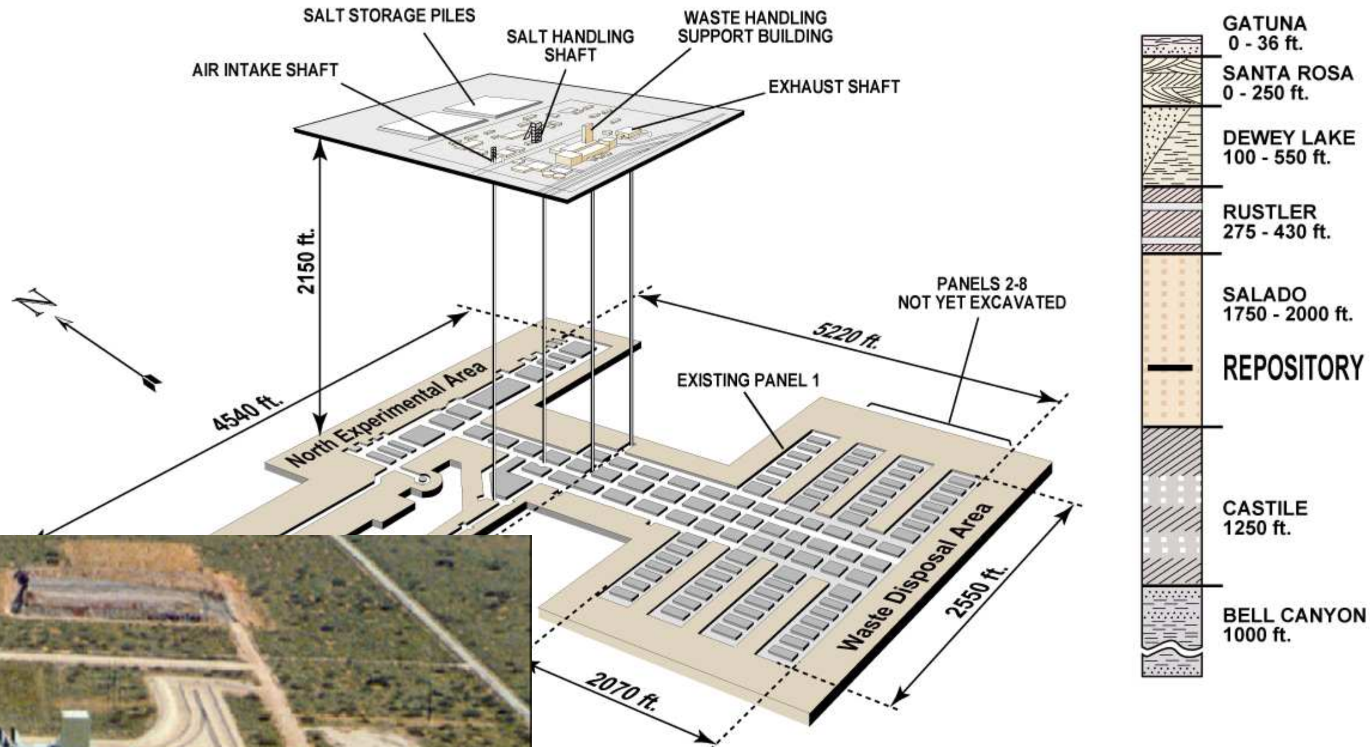
- ββ2v continuum <2448 keV, about 40,000 decays per year in 200 kg.
- All ββ decays are single site events.

Xe is ideal for a large experiment

- No need to grow crystals
- Noble gas: easy(er) to purify.
- Can be re-purified during the experiment
- No long lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- ^{136}Xe enrichment easier and safer:
  - noble gas (no chemistry involved)
  - centrifuge feed rate in gram/s, all mass useful
  - centrifuge efficiency ~ Δm. For Xe 4.7 amu
  - Much cheaper than Ge.
- A 200 kg Xe ββ detector is already being built! (EXO 200 of course).

200 kg prototype to be installed at DoE's WIPP, NM

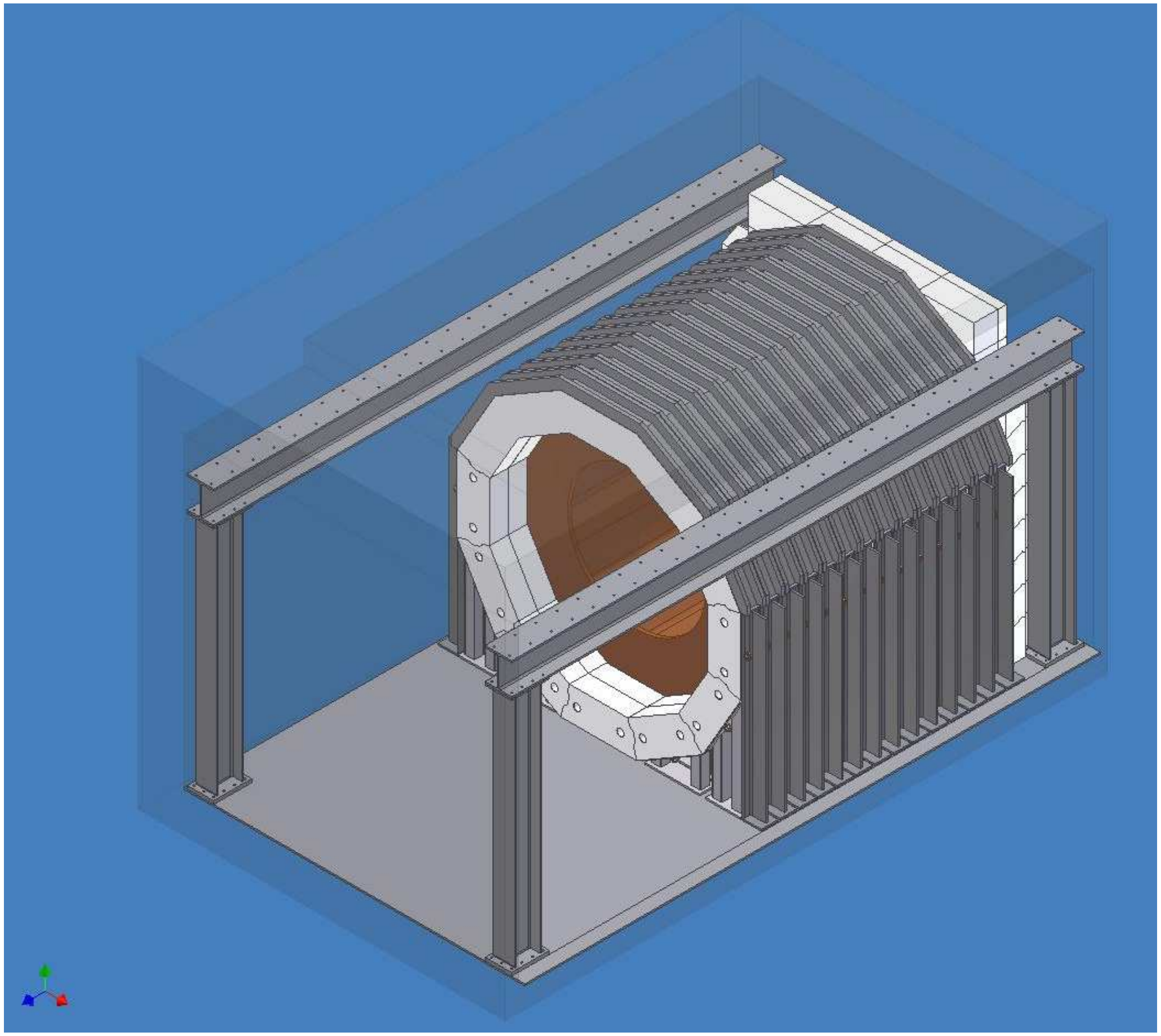
shielding depth
~2.5 km w.e.



A salt mine to store the military radioactive waste…

…and perform low background physics experiments

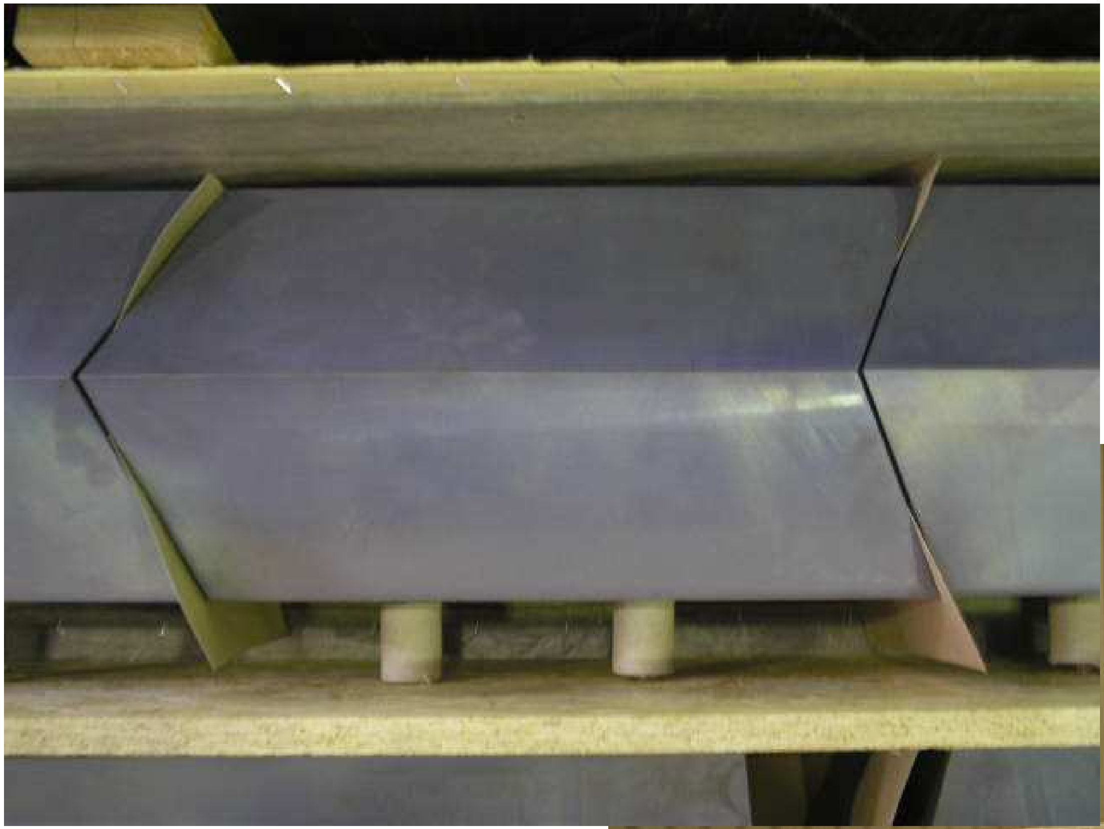
EXO Clean Rooms (now at Stanford)



Lead Shielding

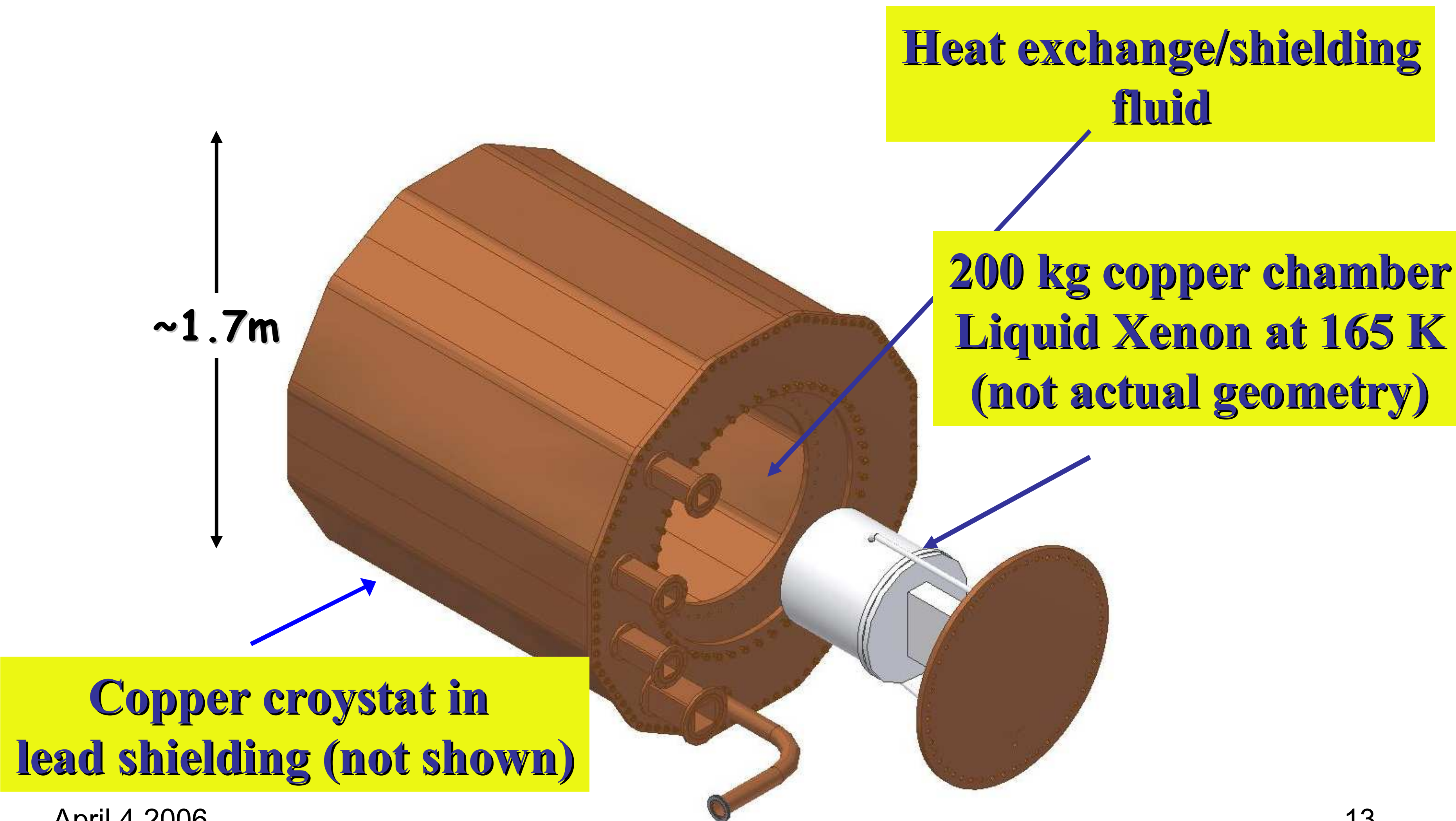
- Low-activity lead
  - U,Th, and K concentrations measured by ICPMS.
  - Alpha activity measured by direct alpha counting (=> low ^{210}Pb content).
- Interlocking blocks for structure and improved shielding.

Interlocking Lead Shielding Bricks



Interlocking Lead Shielding Arches (in Production)

The EXO-200 is an ultra-low background cryogenic apparatus

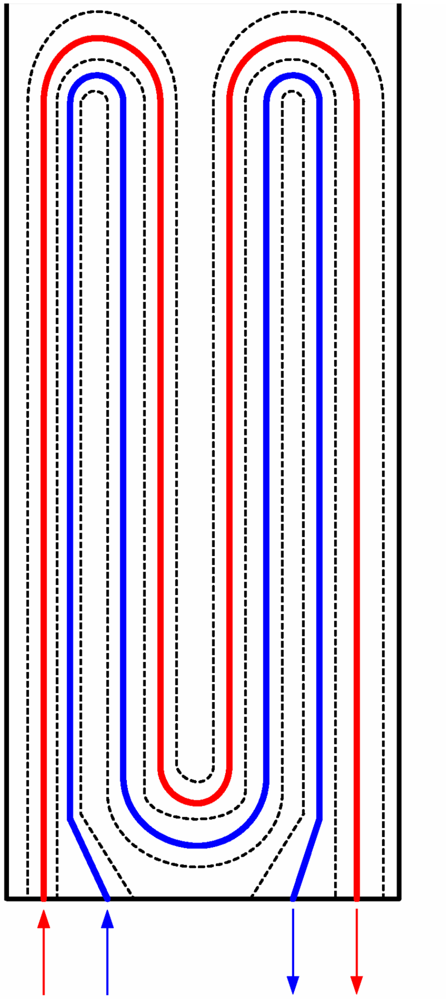


Outer Cryostat

Outer Vessel

Inner Cryostat

Heat Exchanger



Cooling loops fed by 3 external refrigerators.

200 kg xenon production completed in spring ’03

Already the largest highly enriched (80%) stockpile
not related to nuclear industry

EXO-200 Background Reduction

- Low background/ high discrimination detector.
- Over 40 individual background sources have been simulated by Monte Carlo.

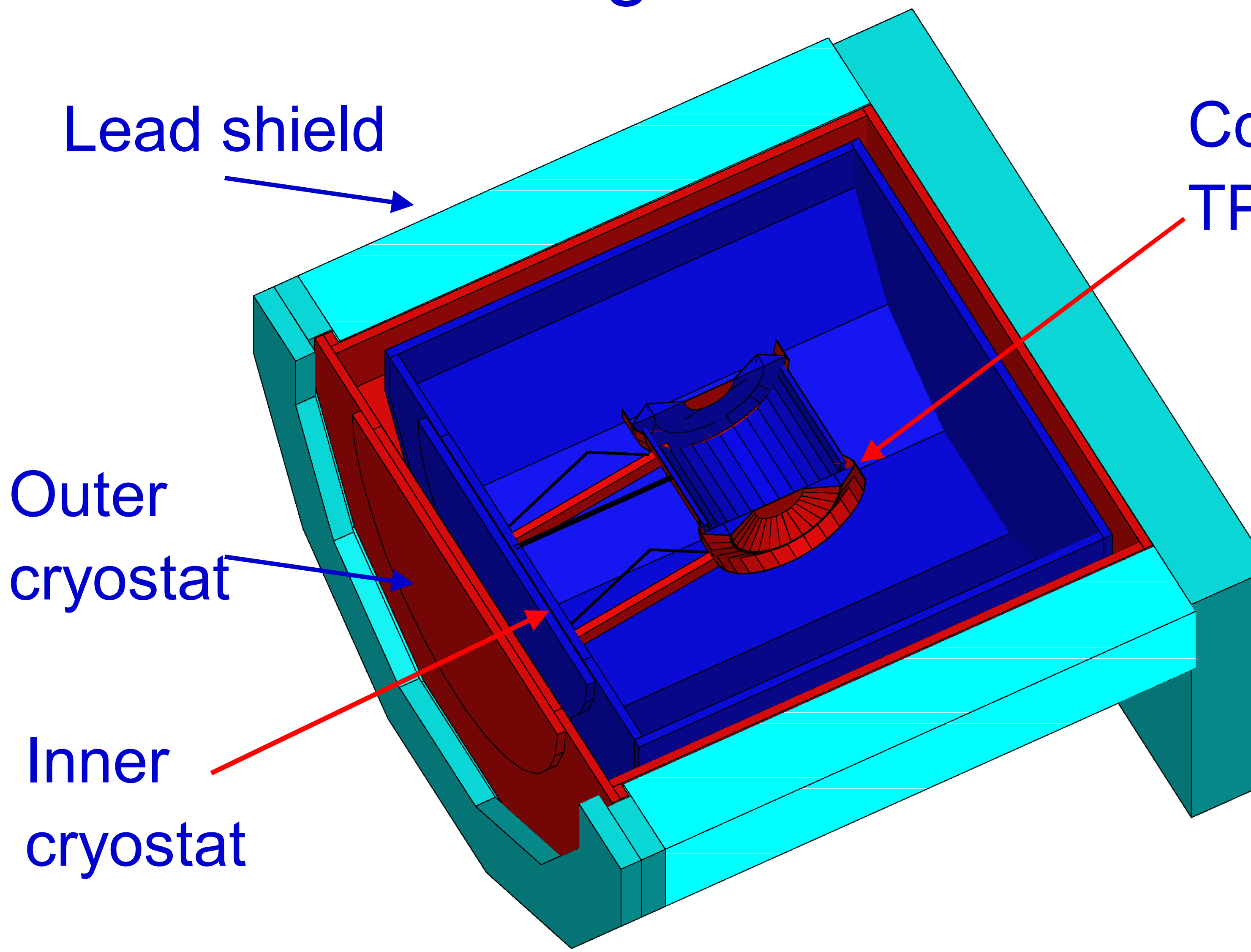
  ^{232}Th (in salt walls) , ^{40}K, ^{232}Th and ^{238}U (everywhere),

  ^{222}Rn,^{210}Pb, Cosmogenic isotopes in copper cryostat

  Muon bremsstrahlung.
- Clean materials have been selected along with implementation of an active veto in order to achieve VERY low background rates (about 40 per year in ββ0v window).
- But detector performance is crucial !!!
- Energy resolution (~1.4%) and tracking (~1-2 cm resolution) are very important.

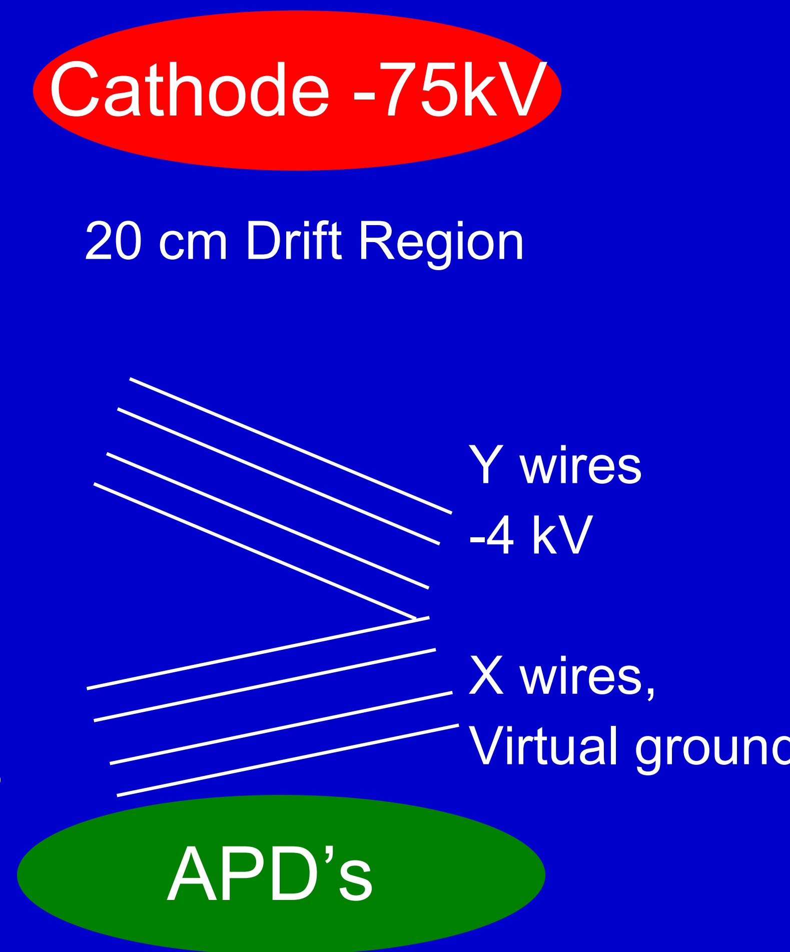
  (tracking reduces background by > 10 times)

Realistic Monte Carlo Geometry for Background Studies.



Charge Detection

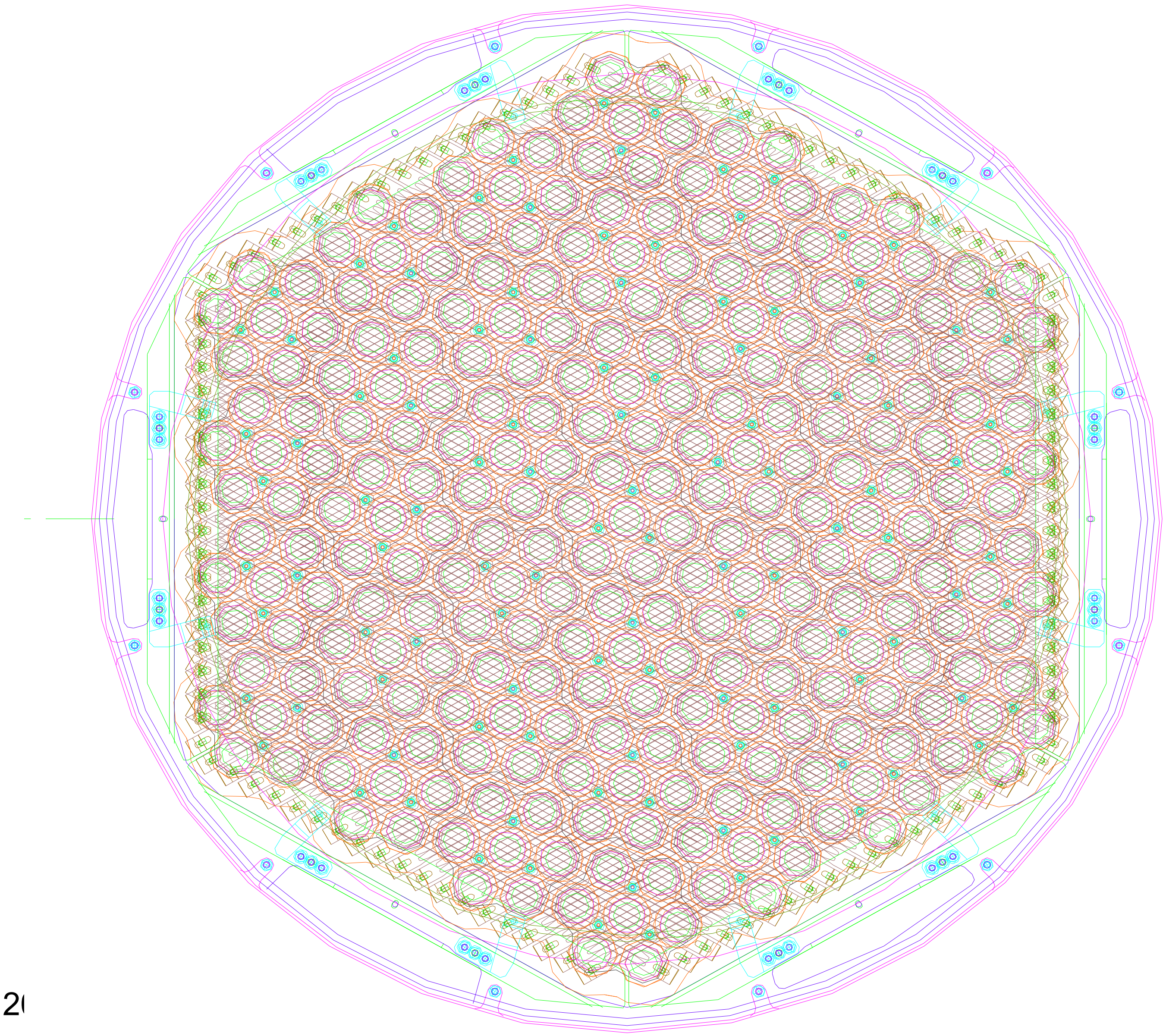
- Double-ended TPC chamber with ~20 cm drift regions
- Mid-plane cathode biased at -75 kV
- 38 Inductive "Y" wires per side at -4 kV, 100% charge transparent.
- 38 "X" wires at virtual ground to collect the charge.
- LXE electron mobility ~2000 $cm^2/(Vs)$
- Saturation velocity ~ 0.28*cm/μs
- Electron lifetime goal of 3ms
  => 2.4% loss at 20 cm.



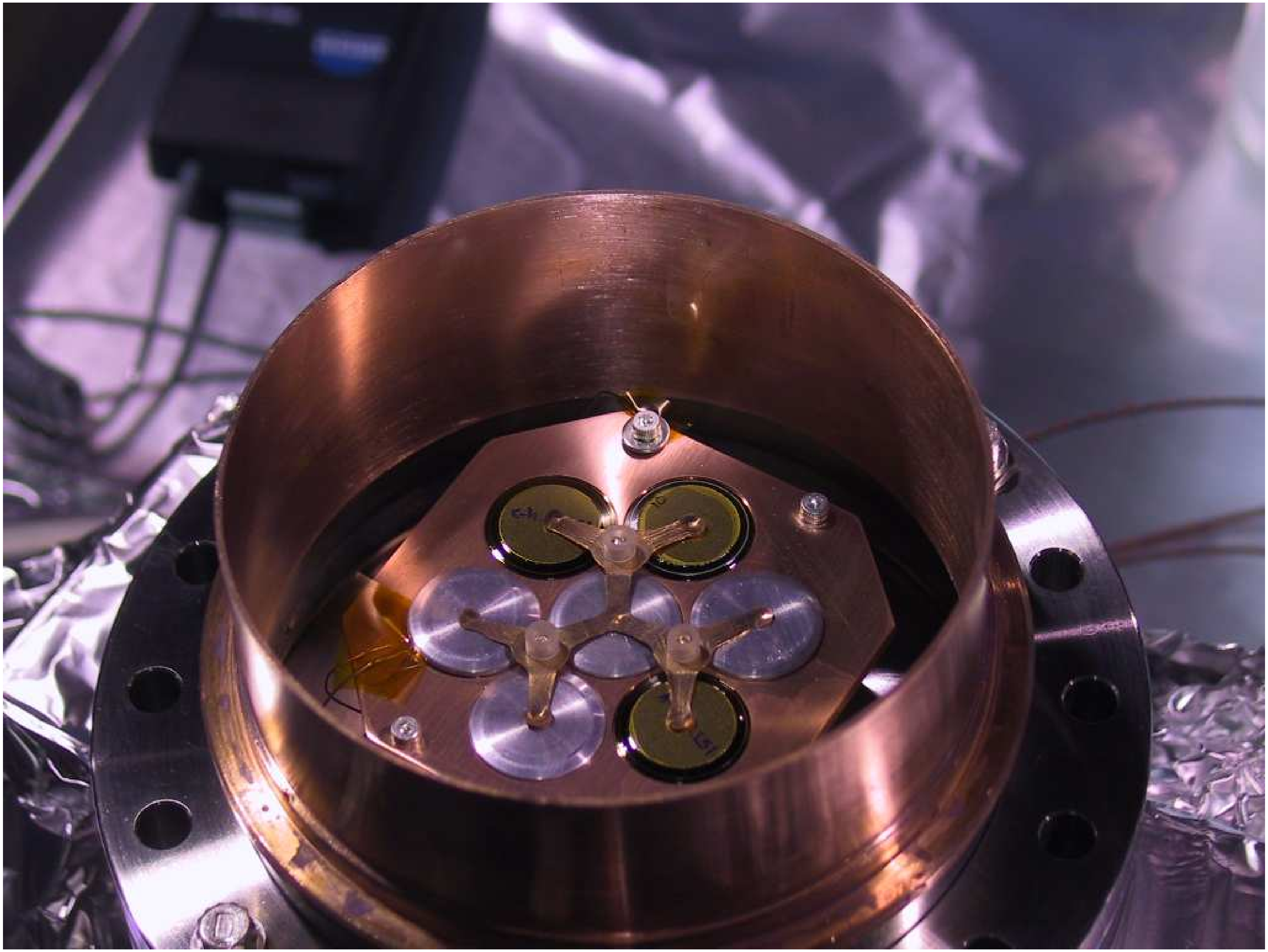
Light Detection

- 16mm APD's (Avalanche Photo Diodes)
- 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.

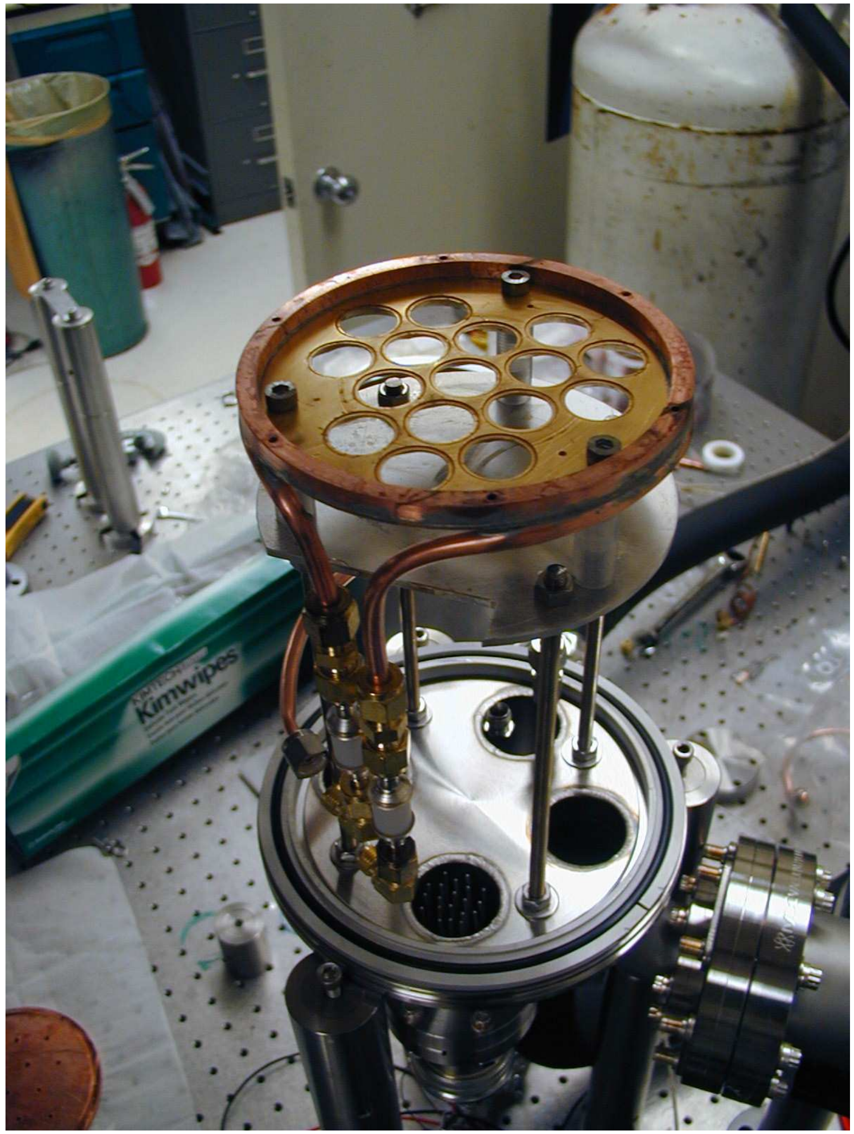
Preliminary APD layout



APD gang in weld test fixture



APD Scintilation Test Chamber



APD signal simulation

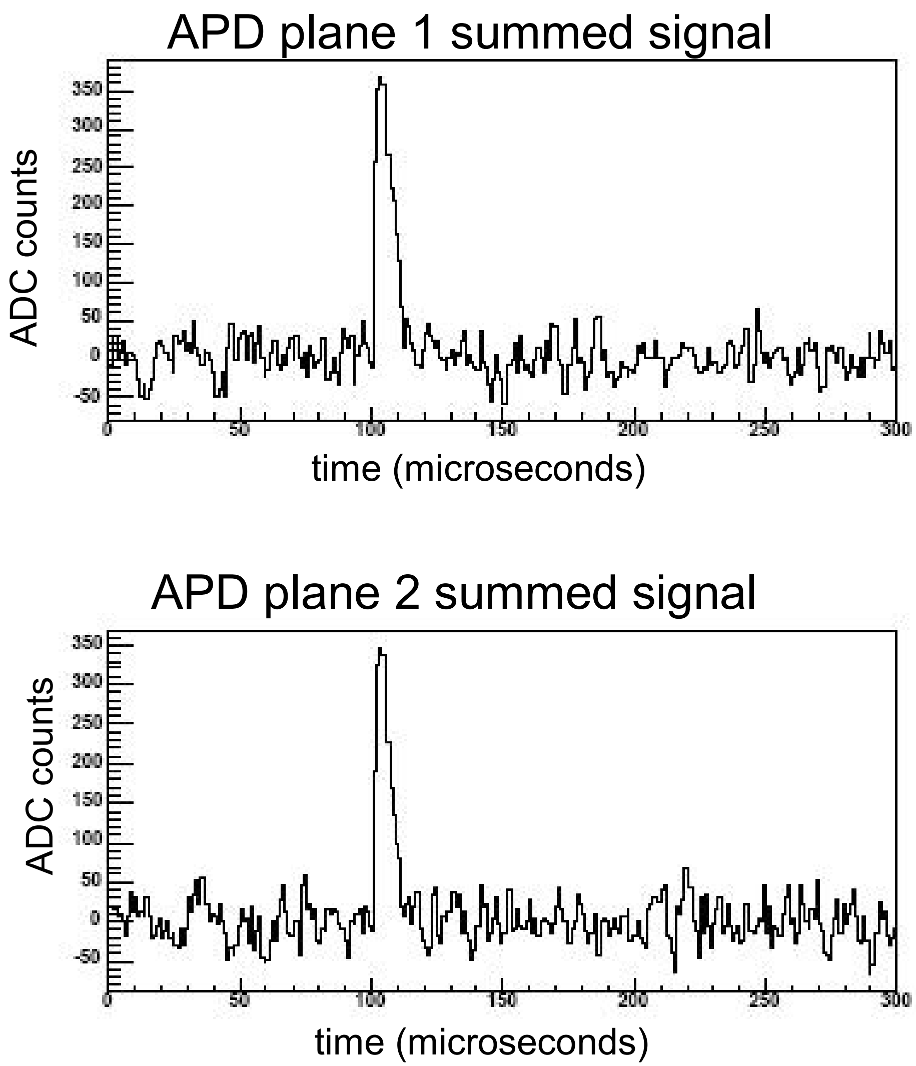
- GEANT4 APD simulation with 301 APD's per side (actual is 259 per side)

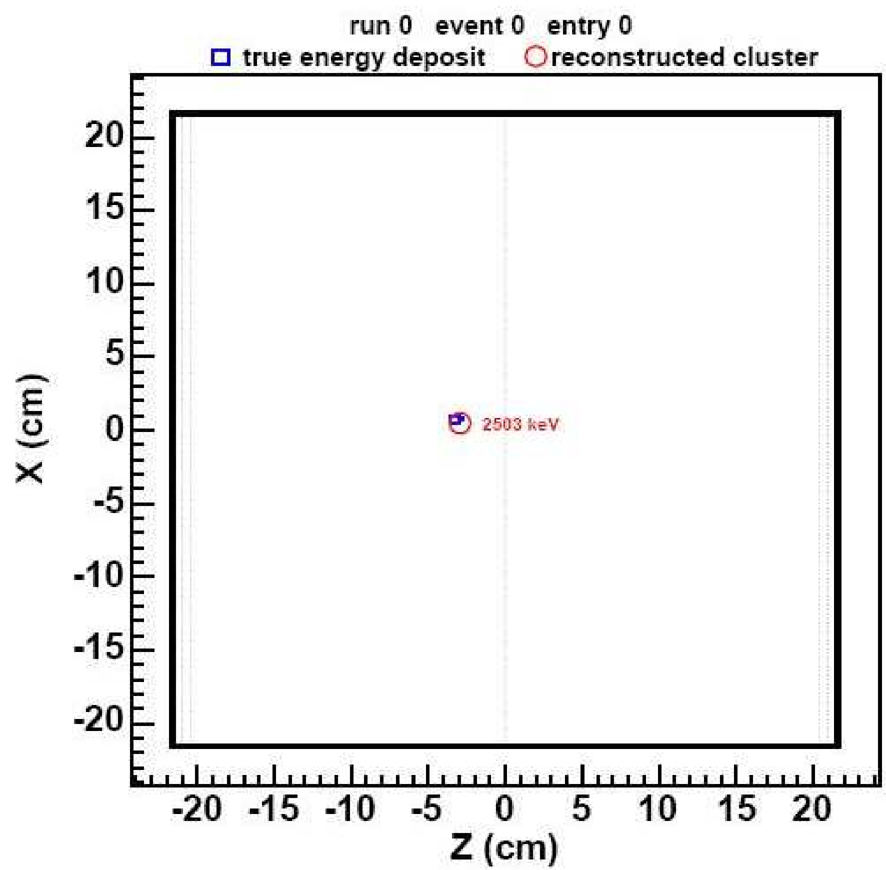
- APD signals calculated by assuming 200 electrons per photon, with 3 μs integration and differentiations times.

- 2000 electrons of noise (reasonable estimate given the integration time) added to each APD gang-of-seven signal trace.

- Realistic event reconstruction to determine t0 (and thus z), and scintillation energy

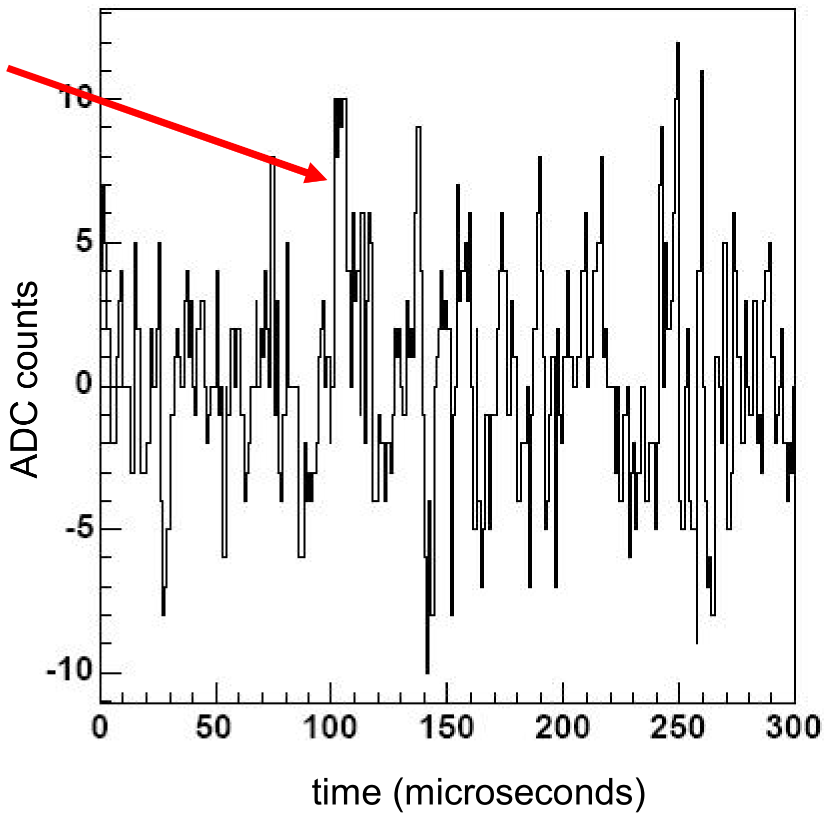
APD signals from a $\beta\beta0\nu$ event near the cathode





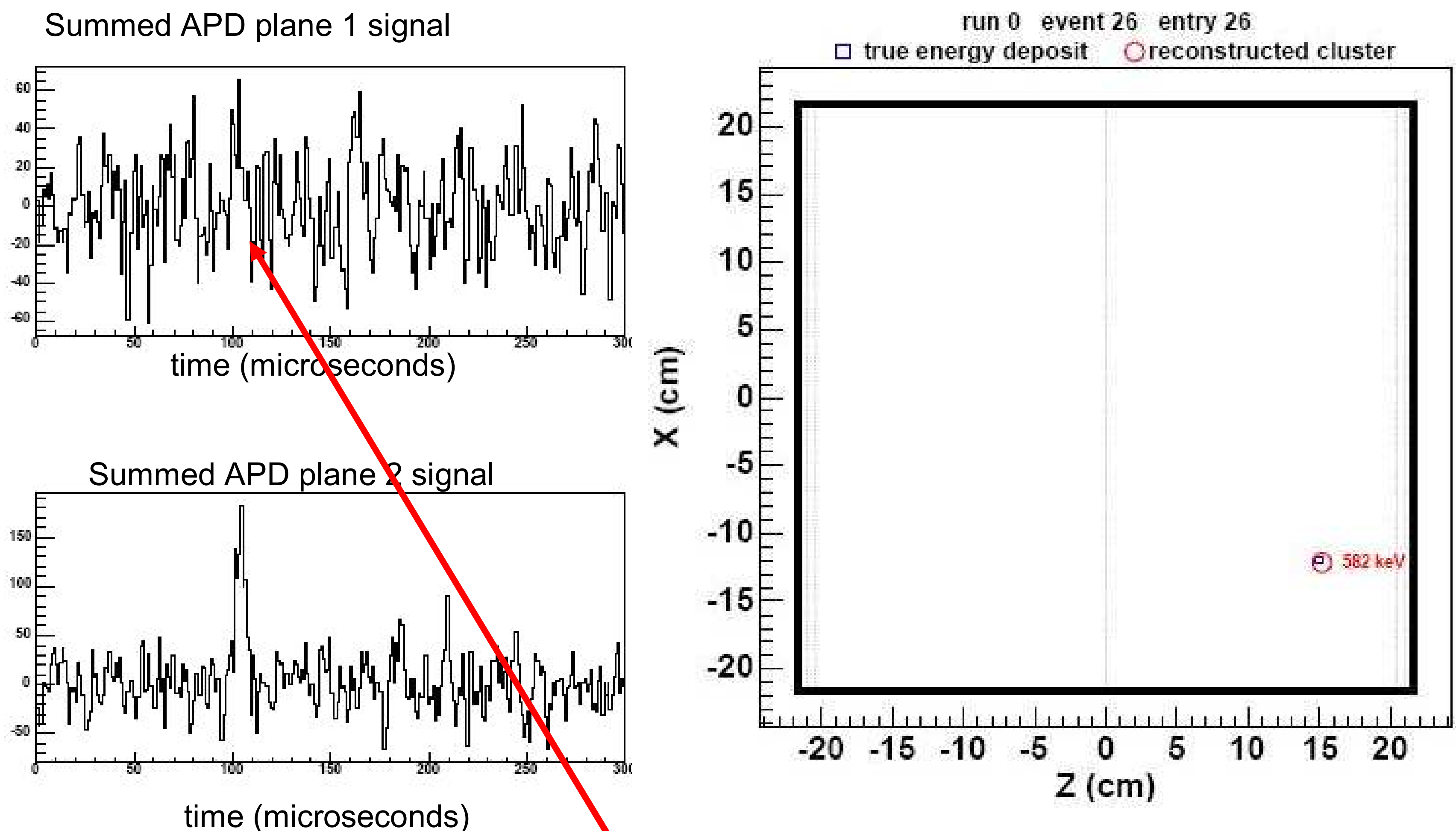
APD signal on one gang-of-seven, for the same ββ0ν event

the signal



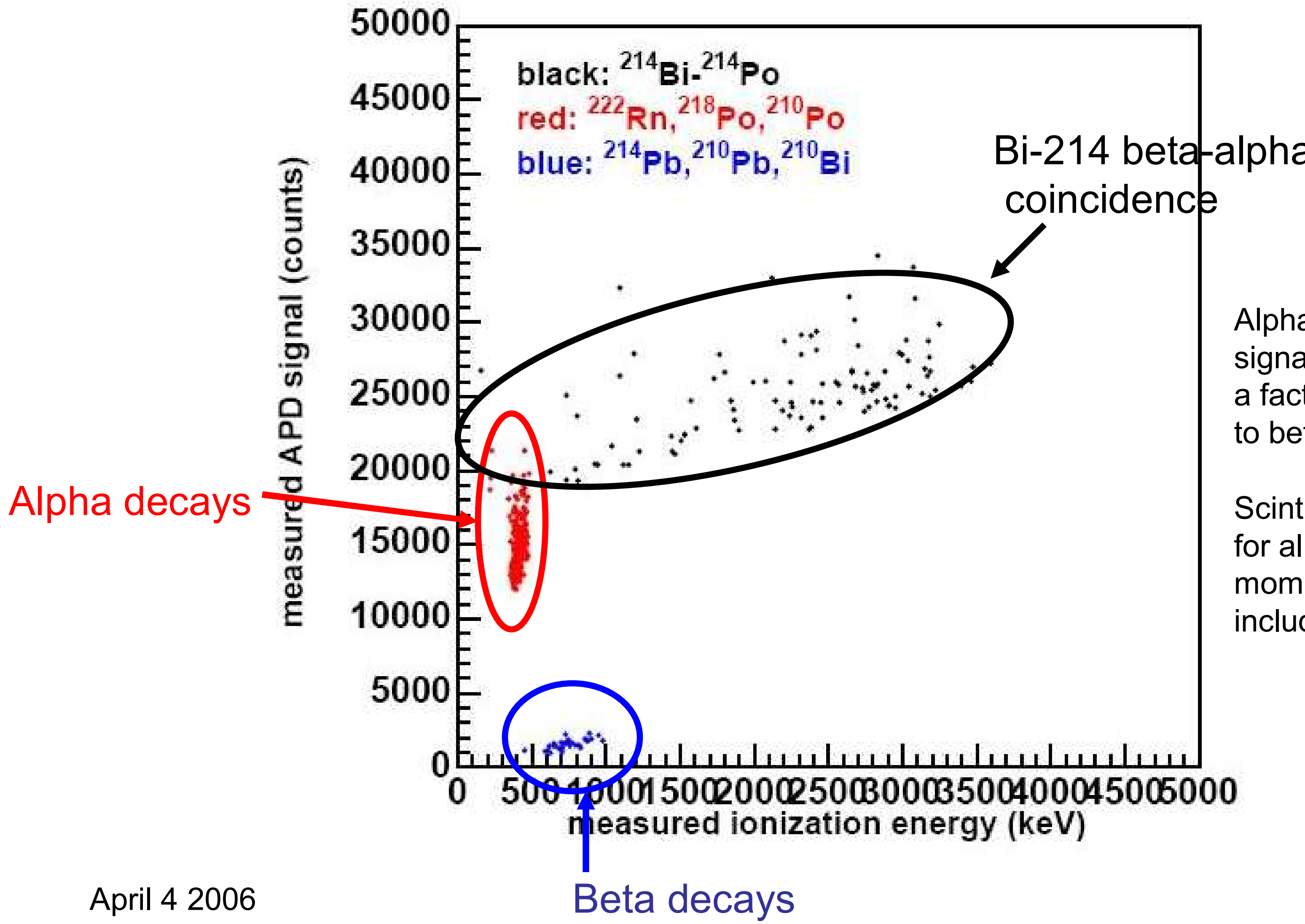
Assuming 2000 electrons of noise per gang-of-seven APDs.

APD signals from 582 keV ββ2ν event



APD signal on far side of detector lost in the electronic noise, assuming 2000 electrons of noise per gang-of-seven APDs.

Alpha rejection from scintillation-ionization comparison



Alpha ionization signal suppressed by a factor of 17 compared to betas.

Scintillation is enhanced for alphas, but at the moment that's not included in the simulation.

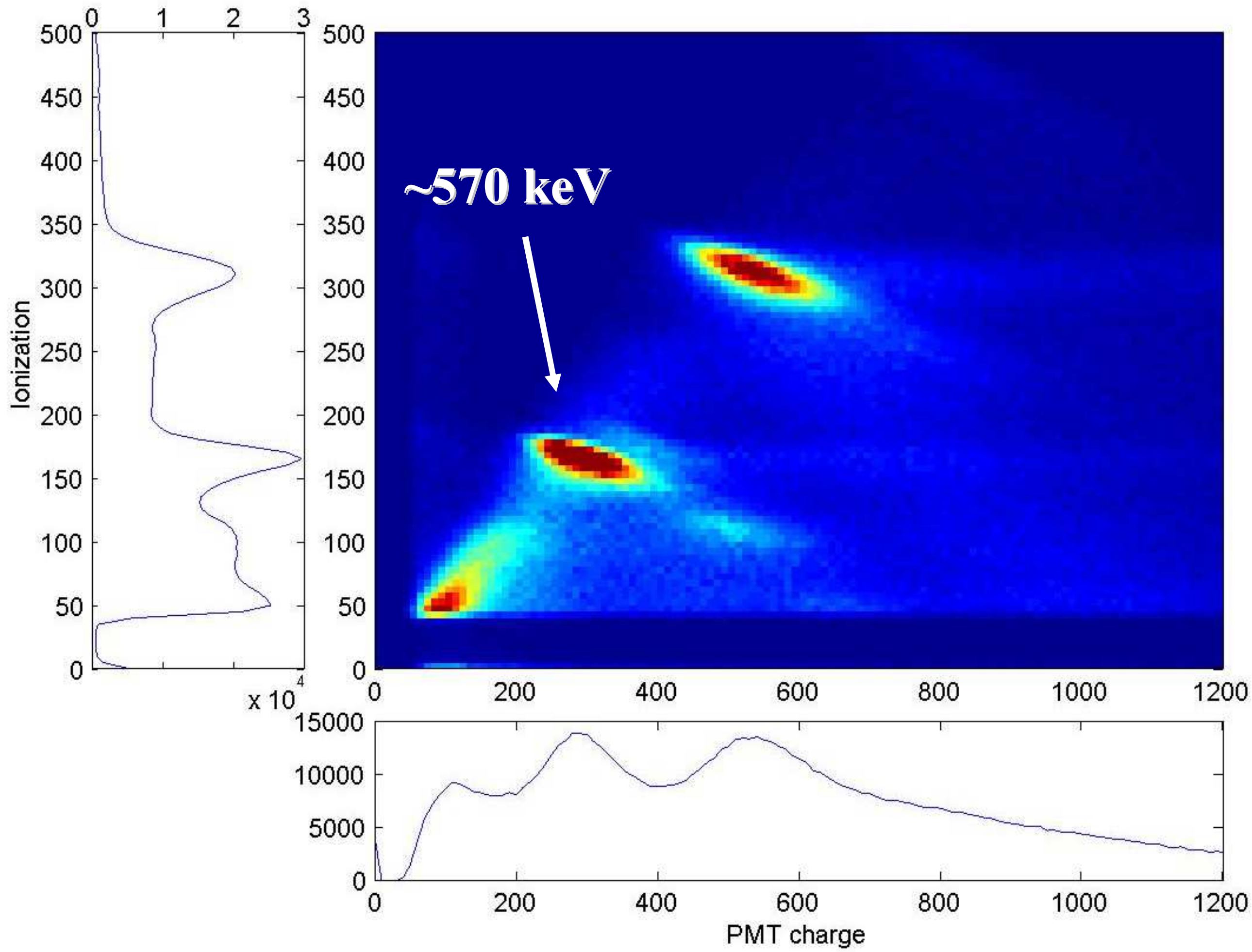
Light/Charge Correlations

$$\sigma_e = \sqrt{F_e N_e}$$

- Fano factor F_e characterizes noise in an ionization chamber.
- F_e depends on variation in energy per ionization AND on other loss mechanisms.
- For gaseous XE: F_e~.04
- But for LXE: F_e>20!
- Energy is lost by scintillation in liquid xenon.
- Scintillation can occur by recombination

  => scintillation and ionization are anti-correlated
- Our experiments verify this.

Found a clear (anti)correlation between ionization and scintillation



Ionization alone: 3.8% res. at 570 keV

Ionization & Scintillation: 3.0% at 570 keV

We expect 1.4% at $Q_{\beta\beta}$.

Conti et al. hep-ex/0303008
Phys. Rev. B 68 (2003) 054201.

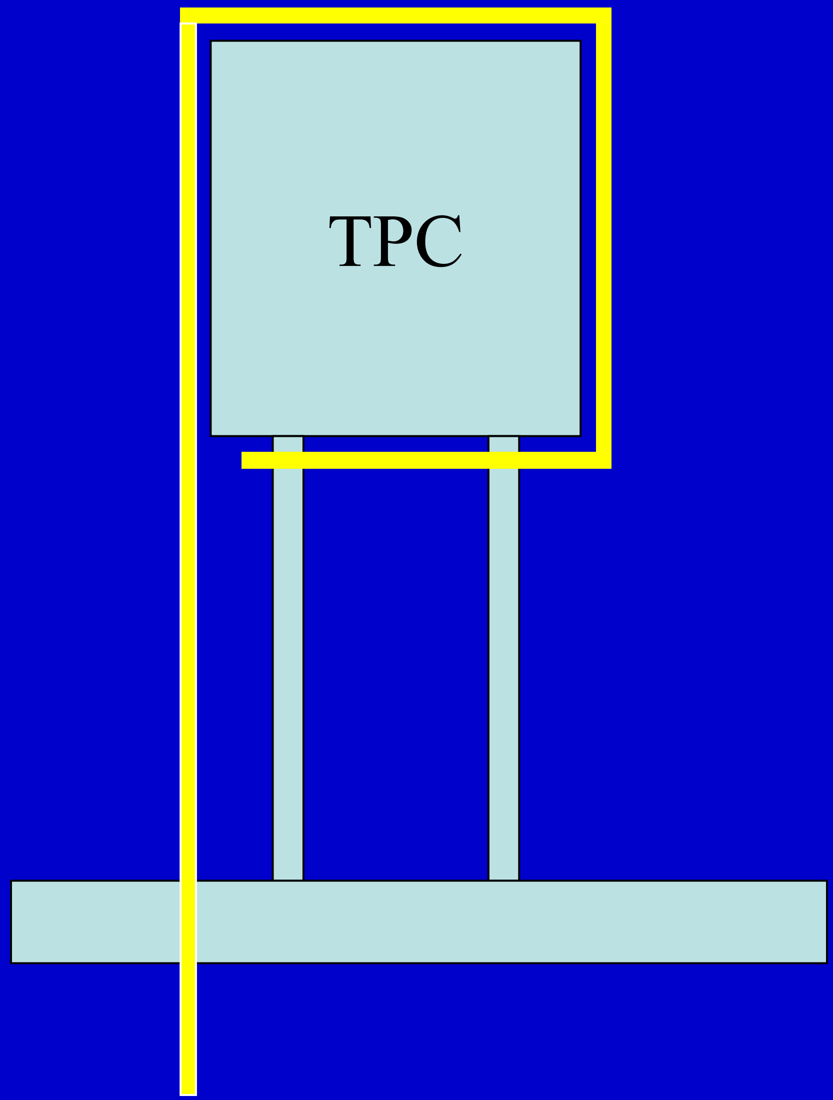
Calibration

- Want 0.1% energy resolution.
- Need ~ 50 volume elements and 1000 calibration events per volume element.
- Monte Carlo simulation with :

  ^{137}Cs (662 keV): line near detector threshold

  ^{60}Co (1173 and 1332 keV): lines near bb2n-maximum

  ^{228}Th (2615 keV): line near bb0nu endpoint:
- For external point source, with electronics saturated, some parts of the detector have rates too low.
- Must have a moveable source.



- 5 mm inner diameter tube, wrapped around chamber in one loop, closed at the end.
- Sources can be pushed in attached to wires.
- Full calibrations may take a few days.
- We will also install LED’s (probably removable) for APD calibration.

Summary and Prospects

- EXO-200 Status:
  - Fully funded by a combination of: DoE-OS, DoE-EM, Swiss Natl Science foundation, ITEP, NSERC (Canada) and private funding from the University of Alabama and Stanford University.
  - Installation scheduled for November 2006.
  - Expect spatial resolution of about 1-2 cm.
  - Using correlated signals, we expect energy resolutions of about 1.4%.
  - Expect background rates around 40/year for 0-ν and
    4000 per year for 2-ν (aprox. 400 to 2000 keV window)
  - Will test Heidleberg evidence,
    2 years run time => ~.3 eV Majorana sensitivity.
- Full 1 -10 tonne EXO will be designed as soon as the first technical data from EXO-200 will be available and the R&D on Ba tagging will be complete. (That's a different talk.)