EXO material screening programme

AARM collaboration meeting
David Auty
University of Alabama
Fermilab 19th March 2013

Overview

- Overview of EXO-200 and nEXO
- Methods used for counting materials
- Counting at UA
  - NAA
- nEXO

The EXO-200 Collaboration

University of Alabama, Tuscaloosa AL, USA - D. Auty, T. Didberidze, M. Hughes, A. Piepke, R. Tsang

University of Bern, Switzerland - S. Delaquis, G. Giroux, R. Gornea, T. Tolba, J-L. Vuilleumier

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

Carleton University, Ottawa ON, Canada - V. Basque, M. Dunford, K. Graham, C. Hargrove, R. Killick, T. Koffas, F. Leonard, C. Licciardi, M.P. Rozo, D. Sinclair

Colorado State University, Fort Collins CO, USA - C. Benitez-Medina, C. Chambers, A. Craycraft, W. Fairbank, Jr., T. Walton

Drexel University, Philadelphia PA, USA - M.J. Dolinski, M.J. Jewell, Y.H. Lin, E. Smith, Y.-R Yen

Duke University, Durham NC, USA - P.S. Barbeau

IHEP Beijing, People's Republic of China - G. Cao, X. Jiang, L. Wen, Y. Zhao

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

Indiana University, Bloomington IN, USA - J. Albert, S. Daugherty, 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 - B. Cleveland, A. Der Mesrobian-Kabakian, J. Farine, B. Mong, U. Wichoski

University of Maryland, College Park MD, USA - C. Davis, A. Dobi, C. Hall

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

University of Seoul, South Korea - D.S. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA - M. Breidenbach, R. Conley, A. Dragone, K. Fouts, R. Herbst, S. Herrin, A. Johnson, R. MacLellan, K. Nishimura, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen

Stanford University, Stanford CA, USA - J. Bonatt, T. Brunner, J. Chaves, J. Davis, R. DeVoe, D. Fudenberg, G. Gratta, S.Kravitz, D. Moore, I. Ostrovskiy, A. Rivas, A. Schubert, D. Tosi, K. Twelker, M. Weber

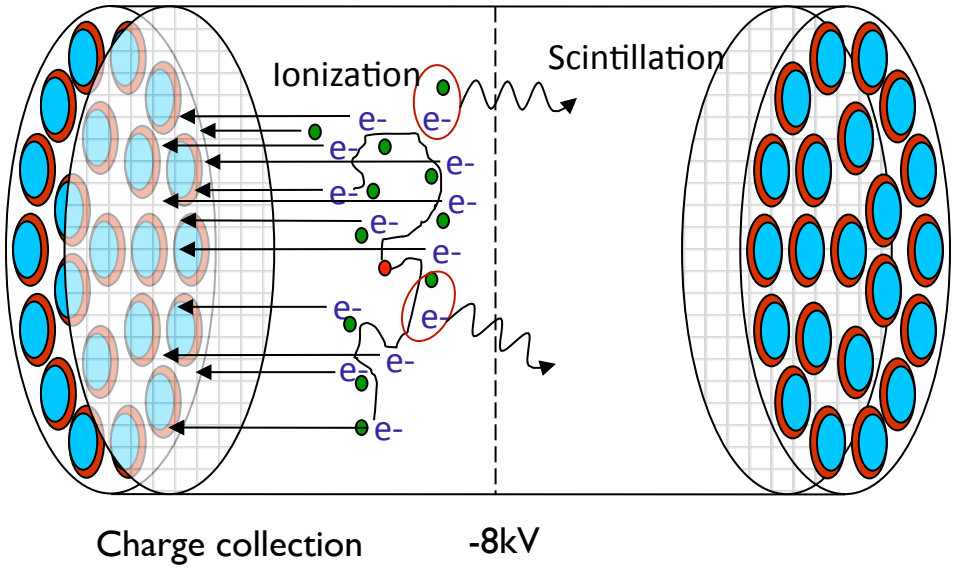
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

TRIUMF, Vancouver BC, Canada – J. Dilling, R. Krucken, F. Retière, V. Strickland

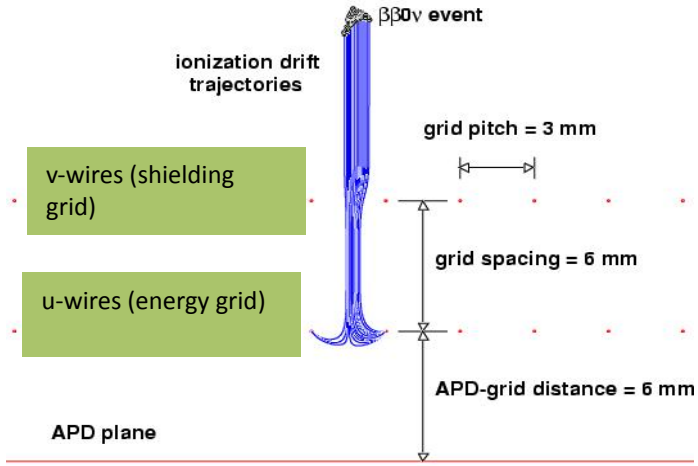
Overview of the physics of EXO

- Double beta decay
  - where two neutrons turn into two protons
  - Only allowed for nuclei where beta decay is energetically forbidden or highly suppressed due to a large angular momentum difference
- $2\nu\beta\beta$ decay half-life's are on the order $10^{18} – 10^{24}$ years
  - ^{136}Xe was measured by EXO-200 for the first time, which is the slowest directly measured decay
    - $T_{1/2} = 2.165 \pm 0.016(\text{stat}) \pm 0.059(\text{sys}) \cdot 10^{21}$ years (**Phys.Rev. C89 (2014) 015502)**
- No measurement of $0\nu\beta\beta$ decay
  - only happens if neutrinos are Majorana
  - B-L is violated
  - only limits been set
    - $1.1 \cdot 10^{25}$ years at 90% C.L. (**arXiv:1402.6956**)

EXO-200 Time Projection Chamber (TPC) Basics



TPC Schematics



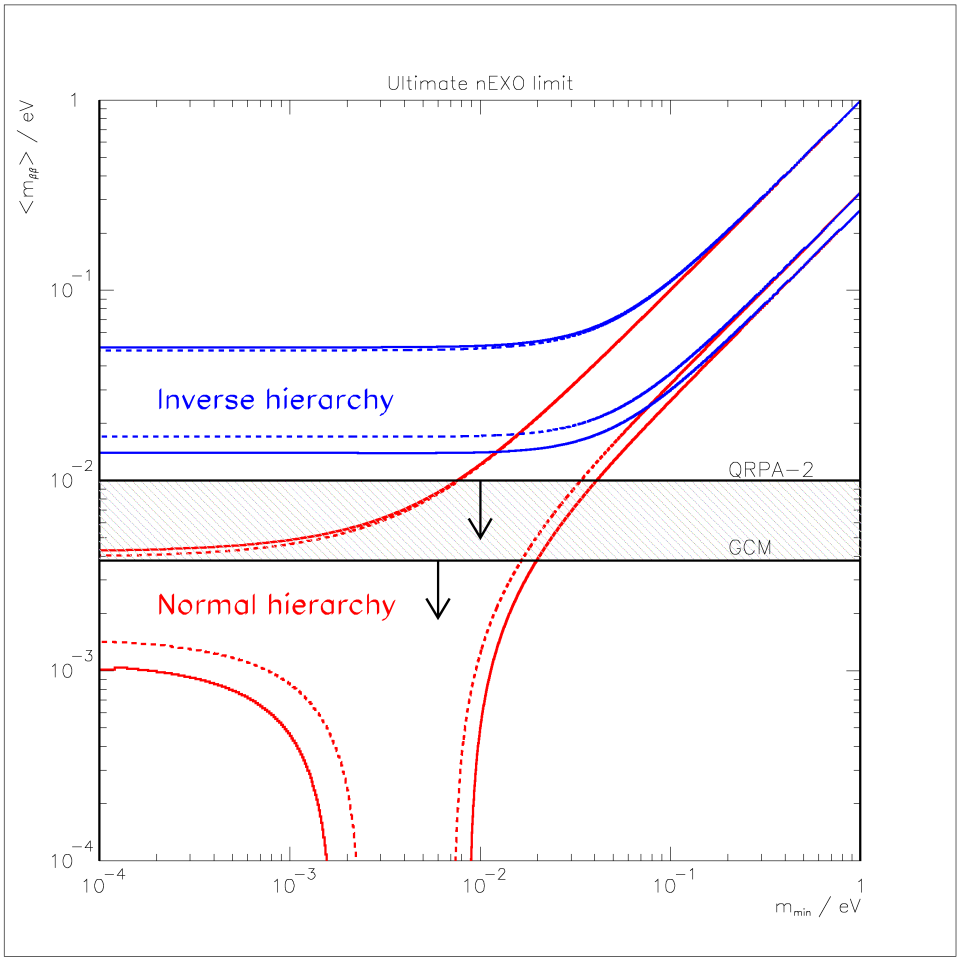
Simulation of Charge Drift

- Uses 200kg of liquid ^{136}Xe
- Two TPC modules with common cathode in the middle.
- APD array observes prompt scintillation for drift time measurement.
  - From which the Z-position can be calculated
- V-position given by induction signal on shielding grid.
- U-position and energy given by charge collection grid.

nEXO

- Next Enriched Xenon Observatory
- will be a tonne scale detector
  - ~5 tonne Xe experiment
  - initially without Ba tagging
    - but remaining an option in the future
- Assume
  - 4 tonnes active ^{enr}Xe (80% or higher)
  - 1.4% (σ) energy resolution
  - observed EXO-200 backgrounds minus the Rn in the shield
  - $\beta\beta$-scales like the volume, the background like the surface are
    - assumes equal materials and thickness

EXO-200 and nEXO projected sensitivities



Neutrino parameters: Forero et al. 1205.4018v4, 95%CL.

The horizontal bands represent the envelopes of the 90% CL limits expected (or obtained For the top-most) assuming various NME calculations and assuming that no signal as detected

The EXO-200 "Present limit" is from PRL 109 (2012) 032505

The EXO-200 "Ultimate" sensitivity: 4 yrs livetime with new analysis & Rn removal.

The "Initial nEXO" band refers to a detector directly scaled from EXO-200, including its measured background and 10yr livetime.

The "Final nEXO" band refers to the same detector and no background other than 2v

Controlling backgrounds

Most of the materials assay was done between the years 2002 and 2008, in a seven year period

The following methods were employed:

1. ICPMS: K 50 ppb Th/U ppt sensitivity, fast turn around (~1 week per sample), interpretation of data requires chain equilibrium assumption. Suited for metals or substances soluble in acids, small sample size order 1 g.
2. GDMS: K 5 ppb, Th/U 10 ppt sensitivity, fast turn around (~1 week per sample), relies on equilibrium assumption, suited for metals with good conductivity, small sample size order 1 g.

3. NAA: K 1 pb, Th/U 1 to sub ppt sensitivity, slow turn around (~1 month per three to four samples), requires equilibrium assumption, suited for non-metals or those metals with low neutron capture cross section of short half lives, small sample size (order 1 g) destructive.

4. Underground Ge counting: K 150 ppb, Th/U 50 ppt sensitivity, slow turn around (~1 month per sample and per screening detector available), no equlibrium assumption needed, suited for all materials, non-destructive, for good sensitivity needs large sample of order hundreds of g to kg.

5. Above ground Ge: K 1 ppm, Th/U 1 ppb sensitivity. Faster turn around of ~2 weeks per sample and detector.

6. Radon release counting: 5 ^{222}Rn atoms/day sensitivity, no equilibrium assumptions needed, not very fast, needs large samples.

•Total number of sample measurements performed in support of EXO-200 design and construction: about 420.

– about 59.1 sample runs per year.

•In addition we performed about 80 alpha spectroscopic measurements of various lead samples and 28 ^{222}Rn emanation measurements.

Relative loads for different methods:

ICPMS: 49%

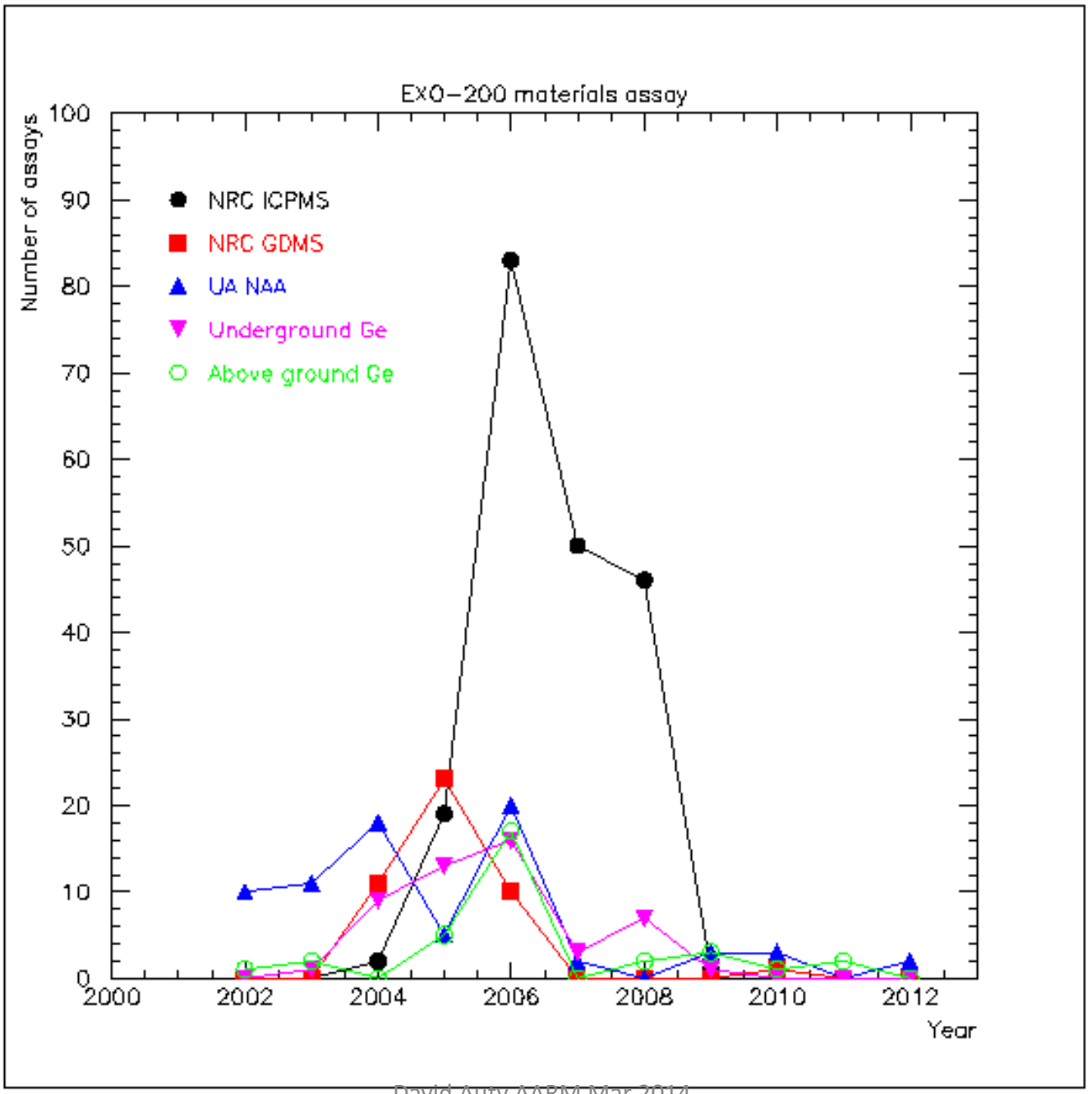
GDMS: 11%

NAA: 19%

UG Ge: 9%

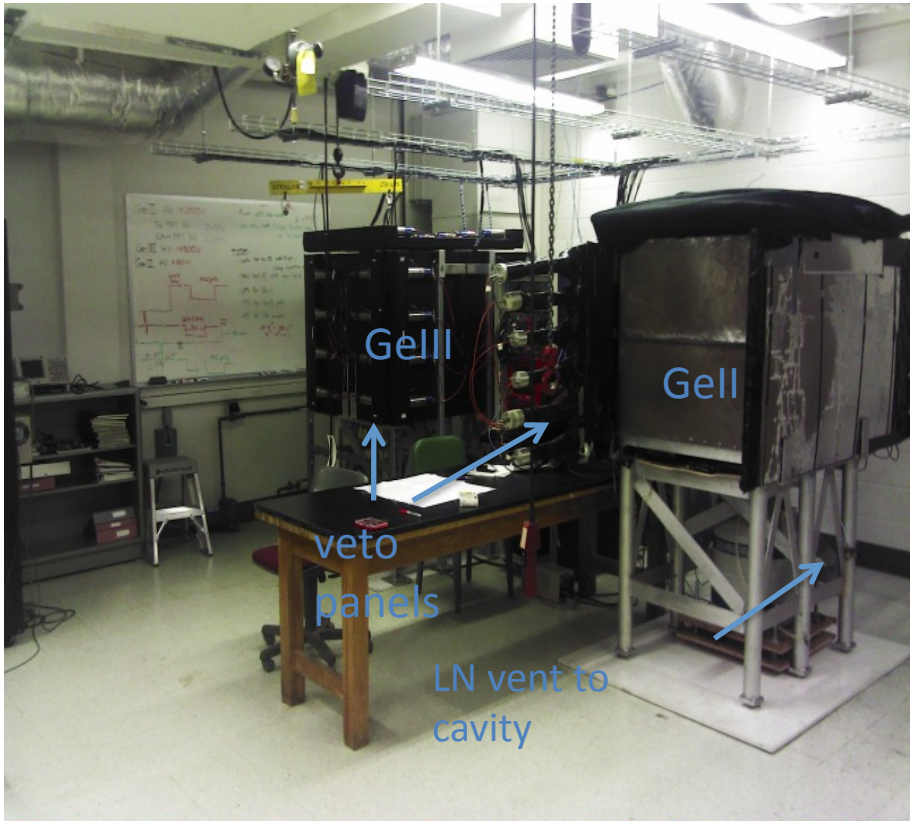
AG Ge: 8%

Other: 4%


EXO−200 materials assay
Number of assays
Year
NRC ICPMS
NRC GDMS
UA NAA
Underground Ge
Above ground Ge
0
10
20
30
40
50
60
70
80
90
100
2000
2002
2004
2006
2008
2010
2012

Detectors at UA

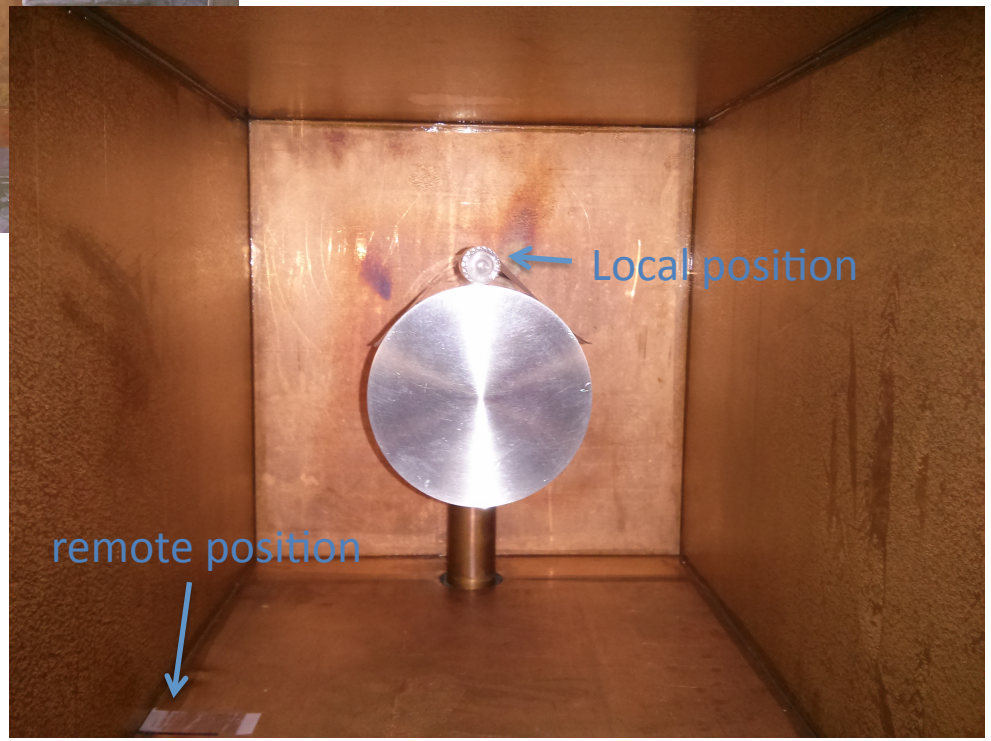
- We have three high resolution Ge detectors at UA
  - GeI, GeII, GeIII
- Two of them have plastic muon veto panels around them
  - GeII, GeIII
- One of them has 360° coverage veto coverage
  - GeIII
    - Veto completed in summer 2013
- Two have the LN vent to the cavity
  - GeII, GeIII
  - this drives out Rn


GeIII
GeII
veto
panels
LN vent to
cavity


GeI
GeII

- Smaller samples are placed in the local position (shown) higher activity sample are placed in the remote position (where the tape is)

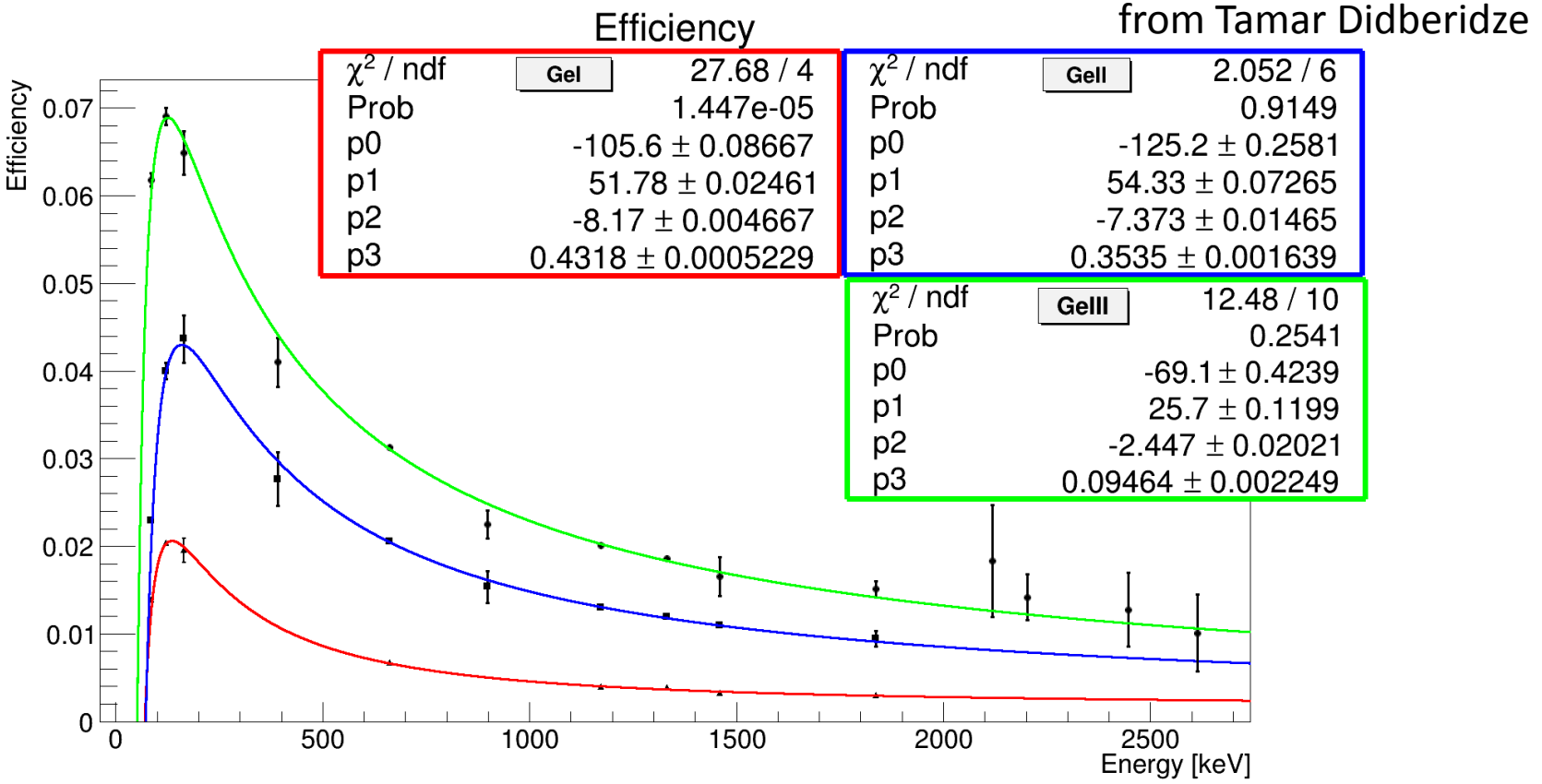
- Larger, low activity, samples are placed in front of the face of the detector



Efficiency of detectors in the Face position

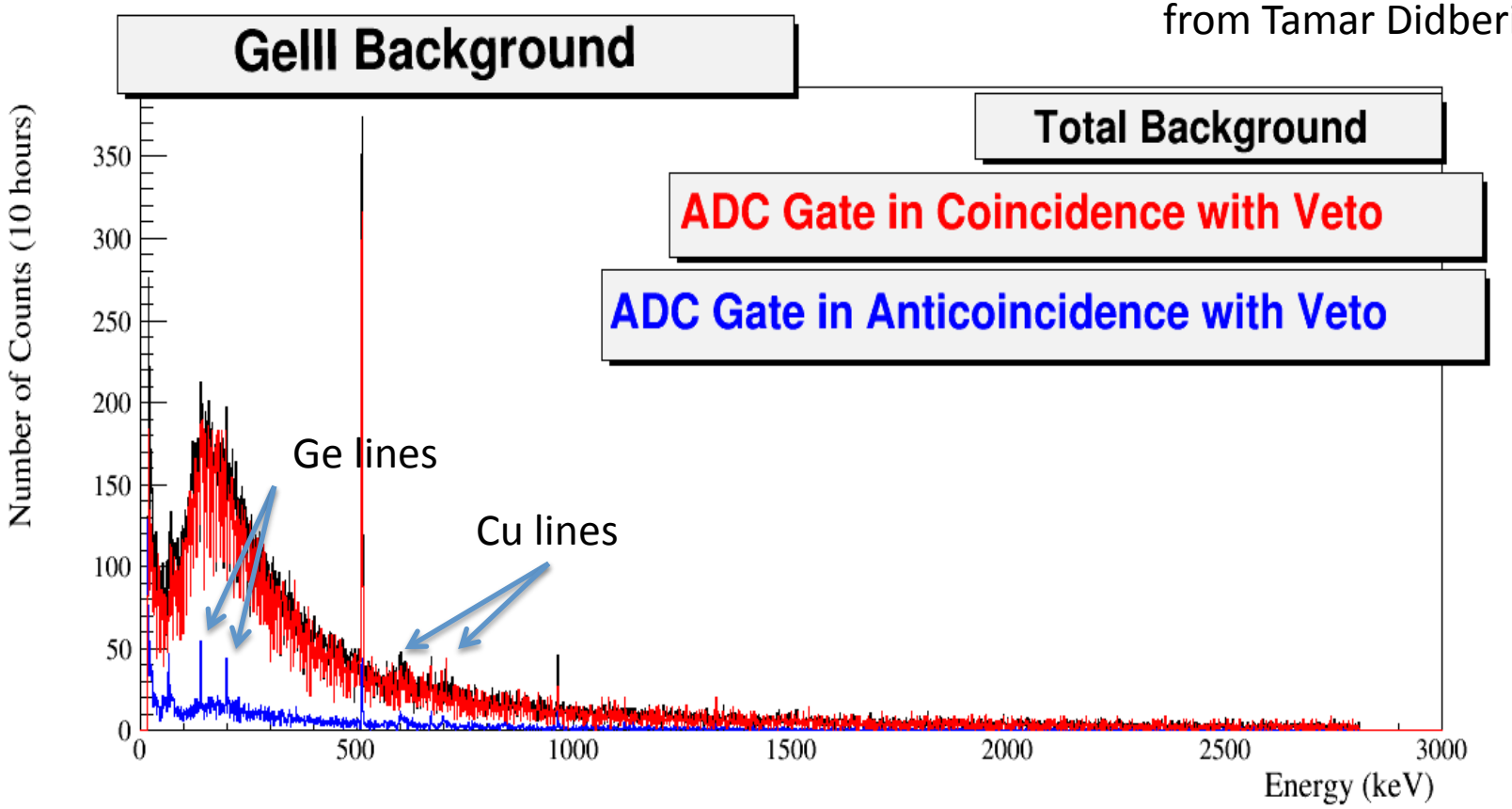
$$\varepsilon(\mathrm{E}_\gamma) = \frac{1}{\mathrm{E}_\gamma}[p0 + (p1)ln(\mathrm{E}_\gamma) + (p2)ln^2(\mathrm{E}_\gamma) + (p3)ln^3(\mathrm{E}_\gamma)]$$

from Tamar Didberidze



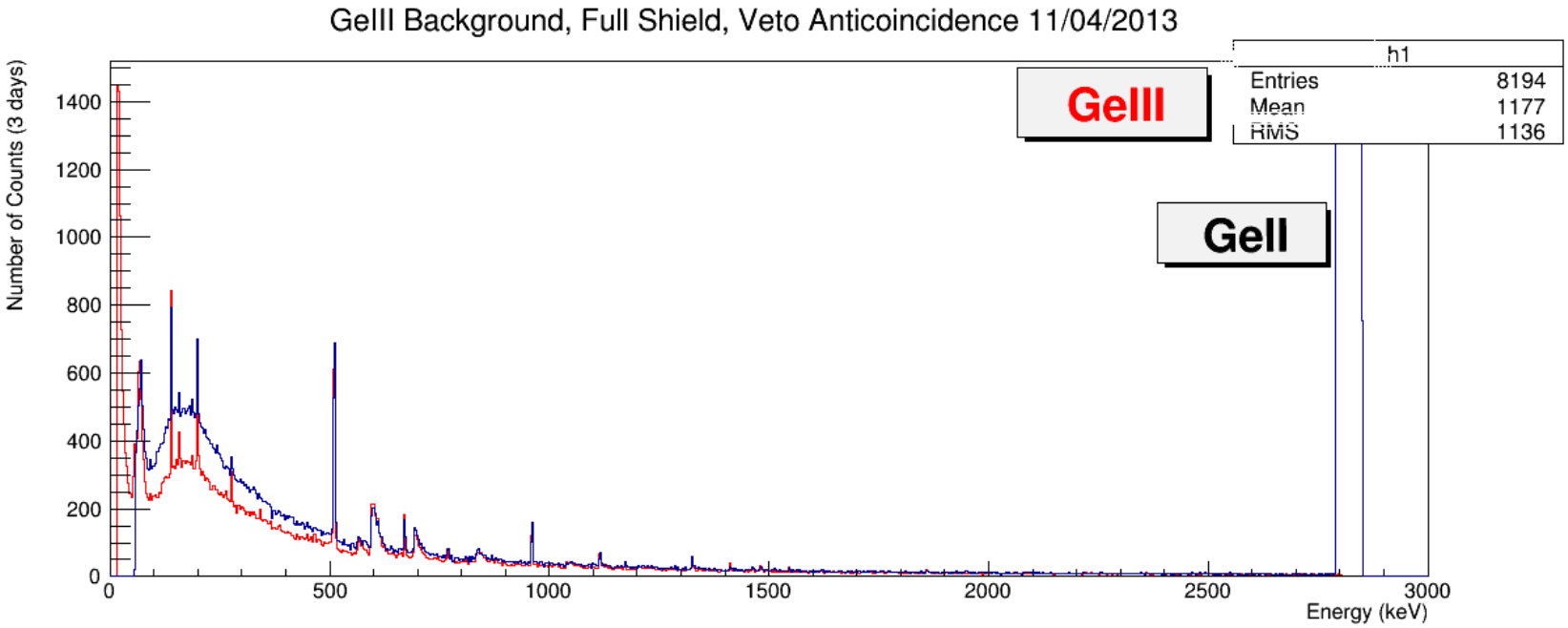
Veto panel power

from Tamar Didberidze



Comparing background GeII and GeIII

from Tamar Didberidze

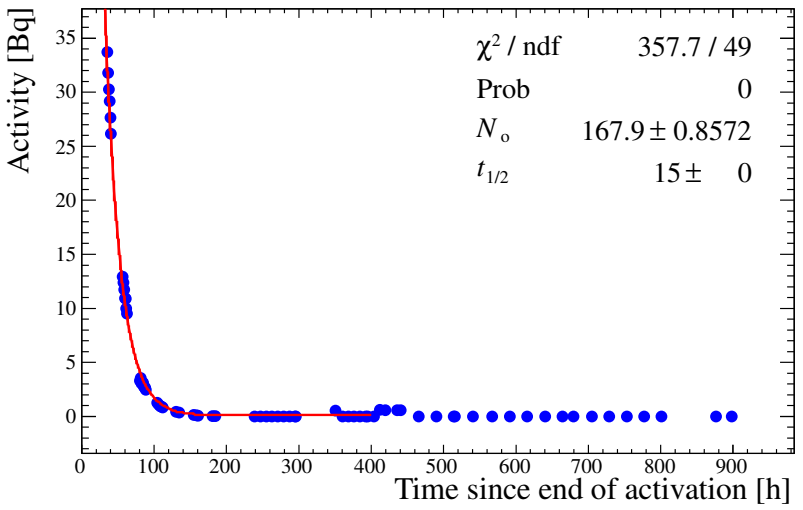


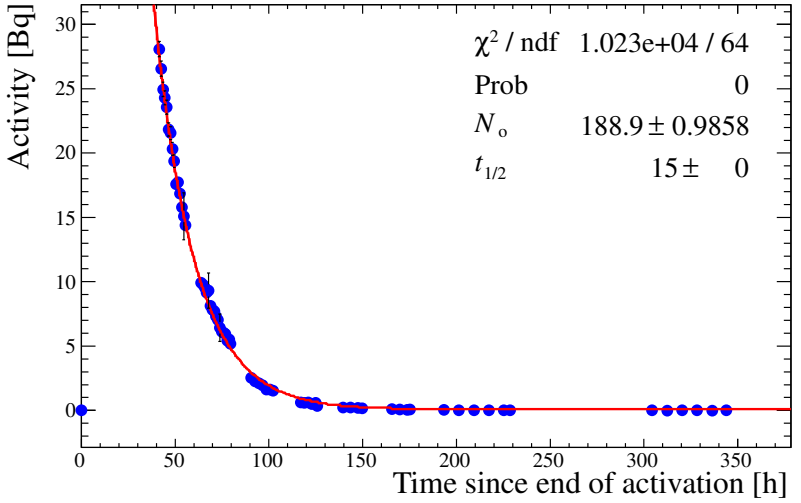
NAA analysis

- We prepare a calibrated fly ash sample to be activated with the sample to get an accurate neutron flux in the reactor
- Neutron activation analysis achieves sensitivities (K, Th, U) of 10-9 and 10-12/10-13 g/g for straight γ-counting of g-size samples following activation at a research reactor. At UA we work with the reactor at MIT
  - This involves typically a one day delay for initial cool-down and next day shipping by UPS/FEDEX
  - This technique is only applicable to matrix materials with low neutron capture cross section
  - Many metals are unsuited
  - High sensitivity analysis can take up to one month due the long half life of the Th activation product ^{233}Pa.
- For EXO 200 we have also utilised the high flux reactor at ORNL.

- Preparation of samples in class 500 clean room
- All containers etched with ultra pure acid
- Rinsed with purified water
- Depending on t_i and type of sample use small PE bottle or miniature quartz vial. Both melted shut before irradiation.
  - (for the current nEXO analysis we no longer use quartz vials)

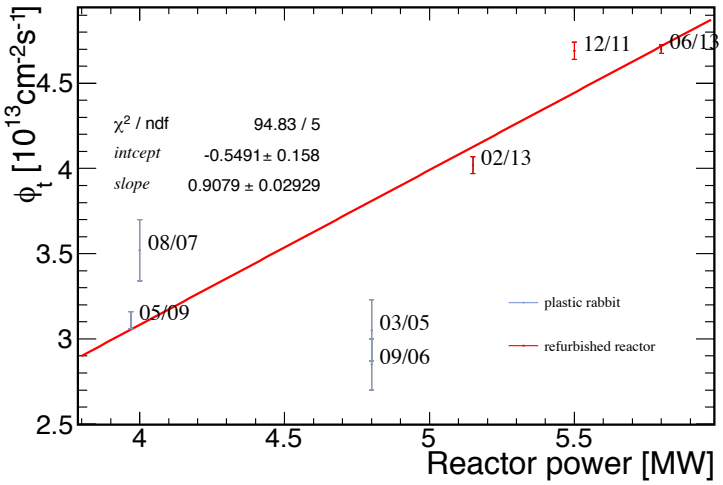
- We perform a time series analysis to find the initial activity
- To get the amount of initial substance in material the initial activities are adjusted for neutron cross-section and neutron flux as found by the fly ash sample



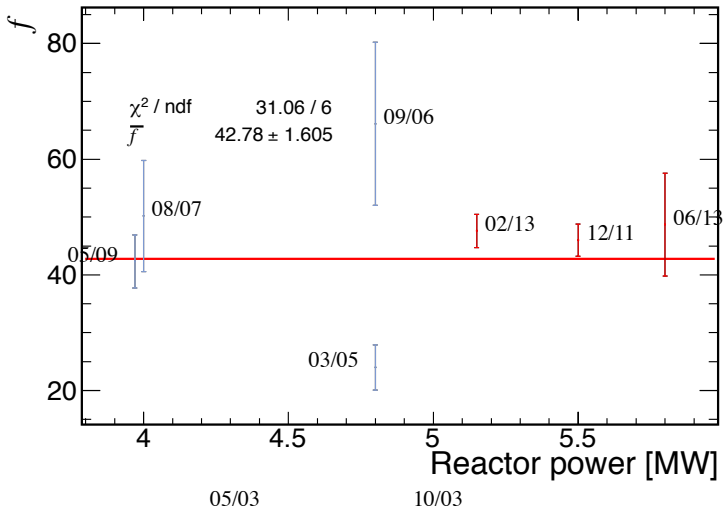


Neutron thermal cross-section and resonance integral flux at MIT

Thermal neutron capture cross section vs reactor power



Resonance integral vs reactor power



Backgrounds in EXO-200

- From material counting it was estimated that there would be 40 counts in 2 y in the ROI[2]
  - latest background result $(1.7 \pm 0.2) \cdot 10^{-3}\,\mathrm{keV}^{-1}\,\mathrm{kg}^{-1}$ [3]
- For the $\beta\beta$ decay papers backgrounds have been fitted to the data
  - we are now working on a background paper that will compare the predictions to what the counting measured

2) M. Auger et al.**, JINST, 7, P05010 (2012)**.
3) (**arXiv:1402.6956**)

nEXO counting

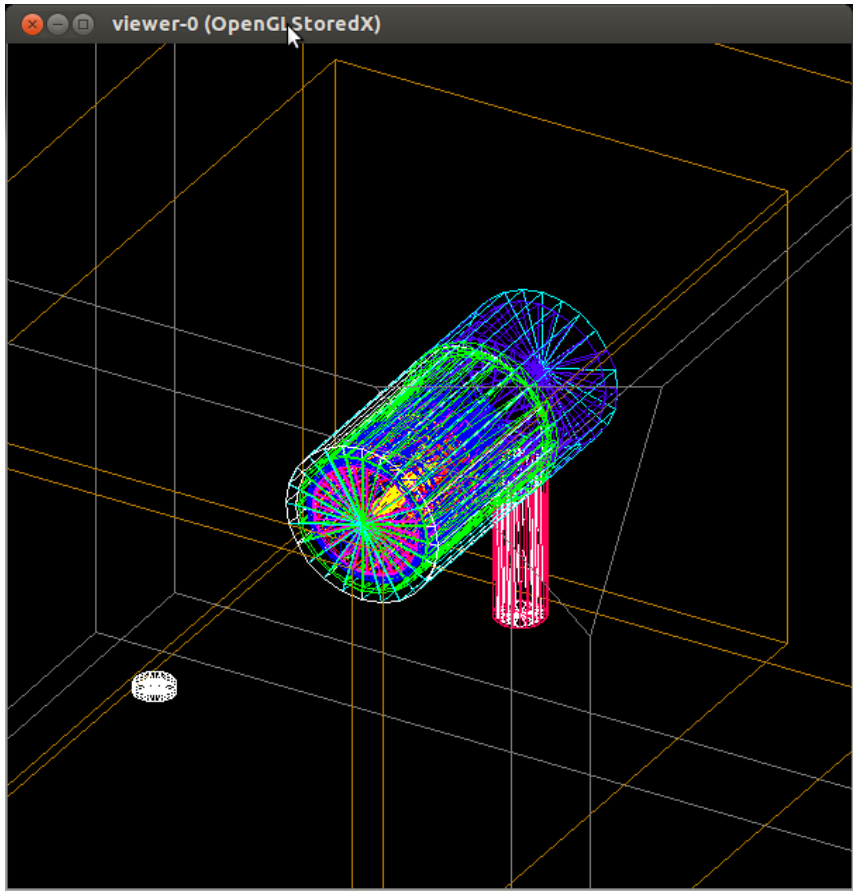
- nEXO should have the about the same number of samples to analysis
  - Although if the TPC is made from a plastic rather than Cu, then there will be more NAA samples
  - Although technical changes contemplated for nEXO relative to EXO-200: water shield instead of lead, removal of flat cables
- If development and construction takes 5 years a peak screening rate of 100/year
- Samples will be rescreened for nEXO
- Counting of nEXO material has started

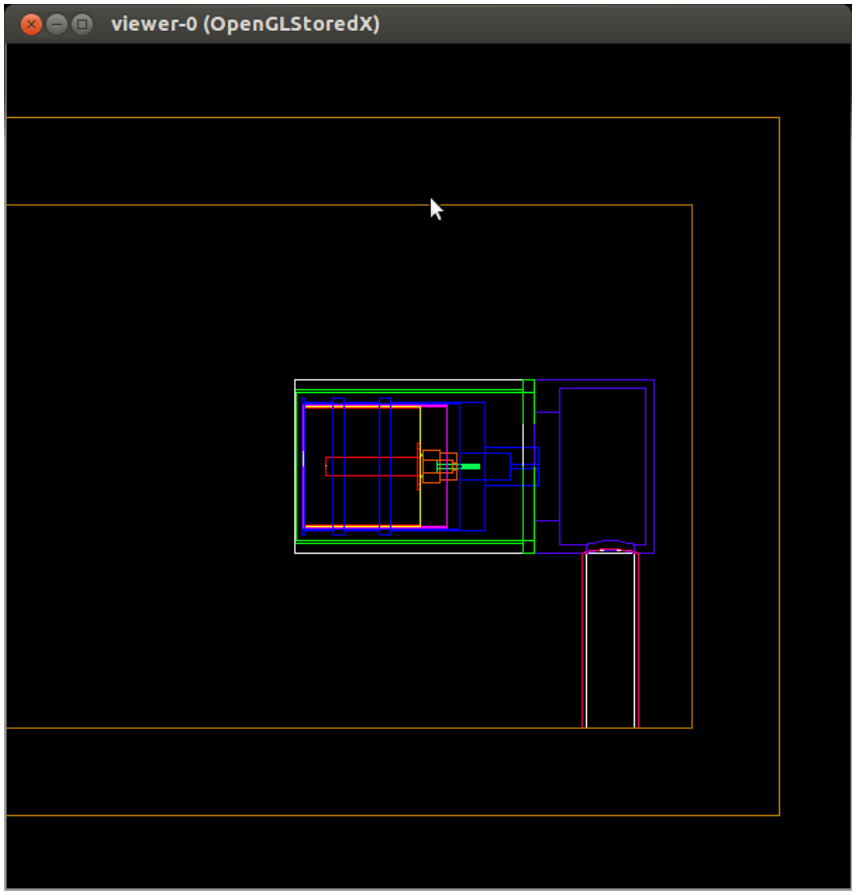
Improvements in NAA/UA setup

- In the last activation we tested a lower flux port
- For a 2/3 thermal neutron flux there was a two orders of magnitude drop in fast neutron flux
  - this will allow us to activate some metals that we weren't able to before
- We now have a Geant4 model of the detectors
  - We can model the efficiency for any setup

Geant4 model

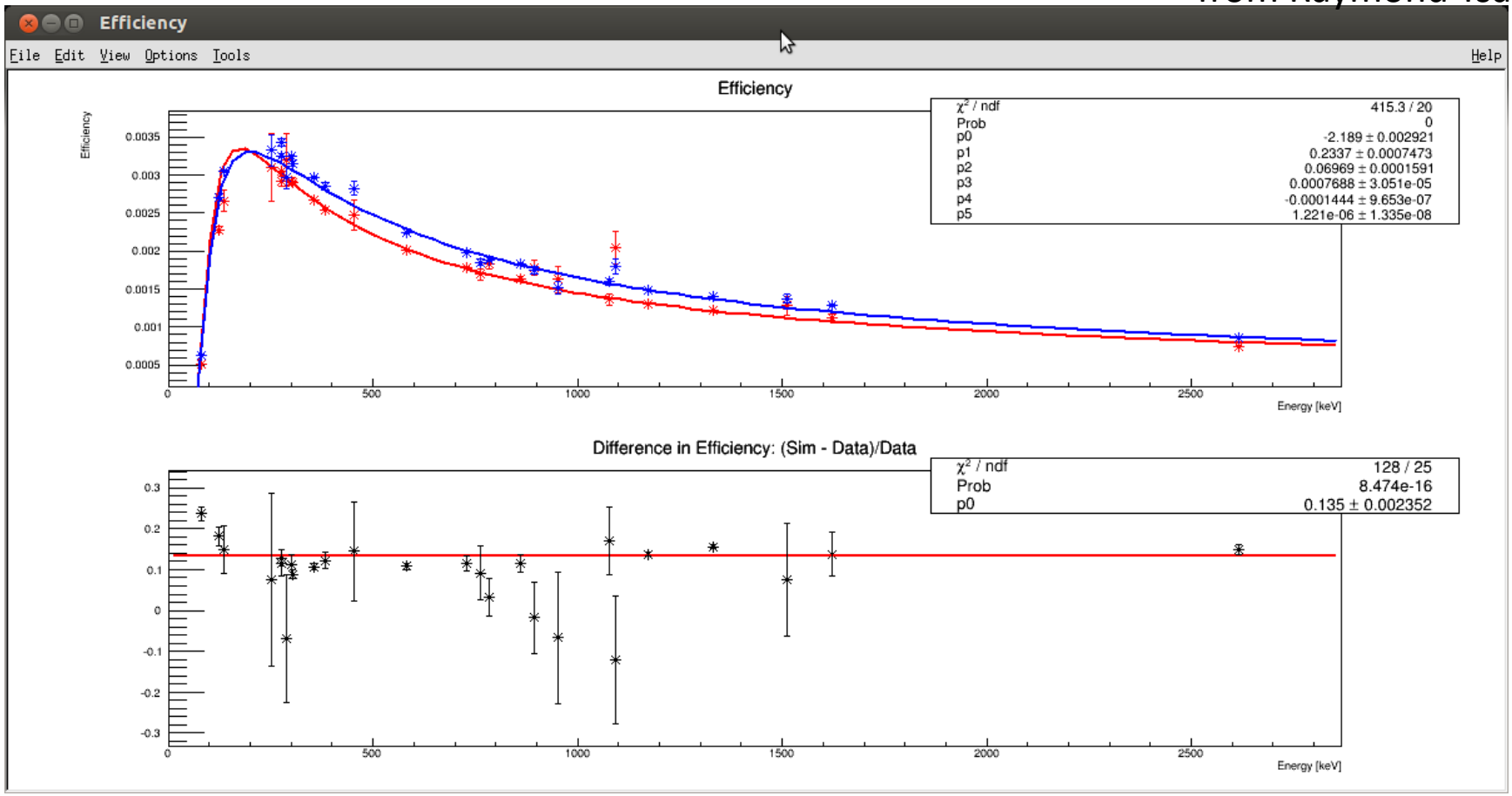
from Raymond Tsang





Compare simulation to data

from Raymond Tsang



Summary

- Measuring $0\nu\beta\beta$ decay tells us the neutrinos are the only fundamental Majorana particle and B-L is not conserved
- We were able to control the material background so only 1.3 counts/y in ROI
  - A EXO-200 background paper is being prepared
- EXO-200 counted ~500 materials over 7 years
- nEXO expects the same amount of counting
- For nEXO we can use NAA for more materials using a lower flux port
- Now have working MC for the Ge detectors at UA
- Have a new Ge detector with 360° coverage veto panel coverage

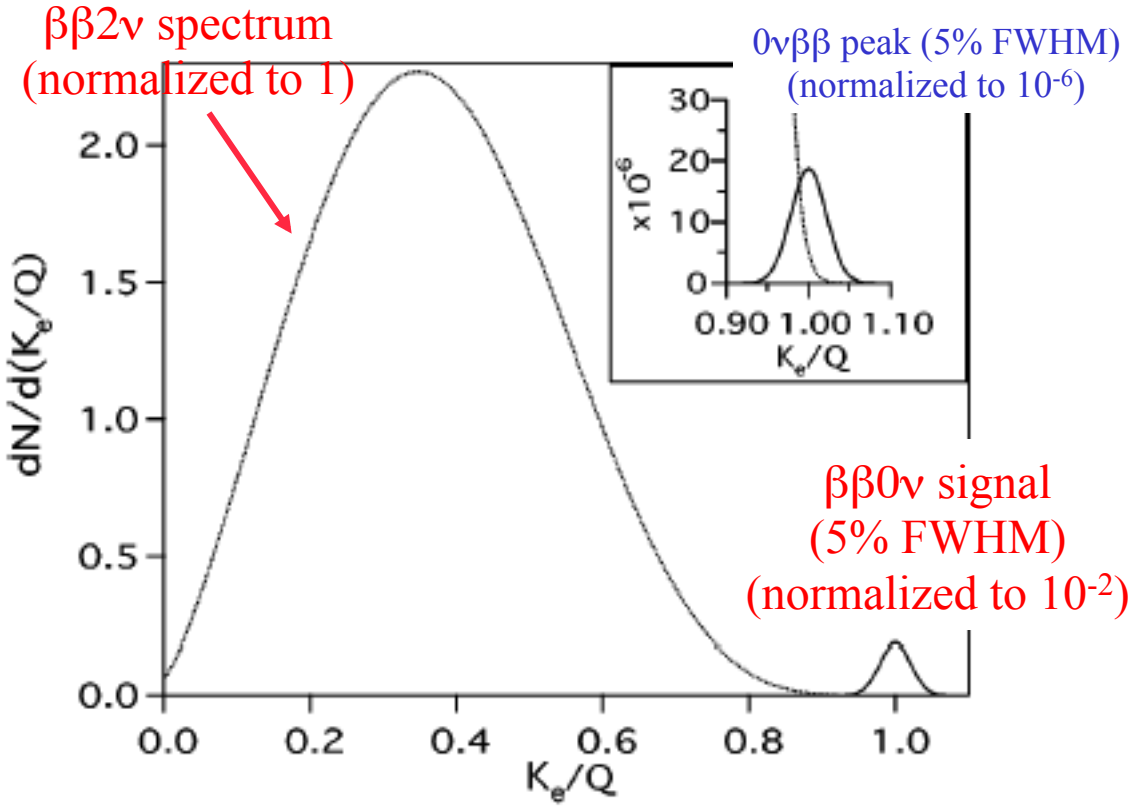
Table 3. Total radioactivity of the major components of EXO-200 and of the components internal to the TPC. Pb shielding does not include the outer front wall.
[†]Because the installed cables were not assayed for K contamination, these activities are derived from assays of similar materials.

		Radioactivity [mBq]			2ν background [counts/yr]			0ν background [counts/yr]	
Part/material	Quantity	K	Th	U	K	Th	U	Th	U
APDs	518 units	< 0.13	< 0.09	< 0.011	< 39	< 310	< 340	< 1.0	< 1.5
Bronze cathode	0.010 kg	< 0.019	0.00108 ± 0.00019	0.00364 ± 0.00021	< 340	28 ± 5	193 ± 11	0.0071 ± 0.0012	1.11 ± 0.06
Bronze wires	0.083 kg	< 0.16	0.0090 ± 0.0015	0.0302 ± 0.0017	< 50	32 ± 6	84 ± 5	0.110 ± 0.019	0.370 ± 0.021
Other bronze	0.314 kg	< 0.6	0.0176 ± 0.0027	0.107 ± 0.006	< 120	63 ± 10	295 ± 17	0.216 ± 0.033	1.30 ± 0.08
Flat cables									
in TPC	7406 cm^2	$< 0.9^{\dagger}$	< 0.07	0.43 ± 0.06	< 250	< 220	1080 ± 160	< 0.8	4.6 ± 0.7
in TPC legs	10825 cm^2	$< 1.4^{\dagger}$	< 0.07	0.76 ± 0.09	< 19	< 10	76 ± 9	< 0.07	0.262 ± 0.032
Teflon reflectors	1.530 kg	0.087 ± 0.010	< 0.0022	< 0.008	40 ± 4	< 12	< 60	< 0.034	< 0.32
Teflon behind APDs	3.375 kg	0.193 ± 0.021	< 0.005	< 0.017	51 ± 6	< 15	< 82	< 0.06	< 0.35
Acrylic spacers									
and insulators	1.460 kg	< 0.14	< 0.024	< 0.07	< 65	< 130	< 290	< 0.37	< 1.6
Field cage resistors	20 units	< 0.08	< 0.0006	< 0.0017	< 35	< 3.0	< 0.5	< 0.009	< 0.038
Cu TPC	32.736 kg	< 60	< 0.5	< 1.5	< 13000	< 1100	< 2600	< 5	< 12
Cu TPC legs	6.944 kg	< 12	< 0.11	< 0.33	< 170	< 13	< 33	< 0.10	< 0.11
HV cable	0.091 kg	< 5	< 0.036	< 0.6	< 160	< 12	< 150	< 0.07	< 0.6
Cu calibration									
tube	0.473 kg	< 8	0.016 ± 0.003	0.043 ± 0.001	< 1100	18.5 ± 3.8	45 ± 12	0.100 ± 0.021	0.18 ± 0.05
Cu wire calibration									
tube support	0.144 kg	< 11	0.027 ± 0.002	0.19 ± 0.06	< 700	16.7 ± 1.2	10 ± 3	0.097 ± 0.007	0.04 ± 0.01
Cu cryostat	5901 kg	< 72	< 19	< 58	< 9	< 29	< 46	< 0.4	< 0.19
HFE-7000									
cryogenic fluid	4140 kg	< 20	< 0.25	< 0.8	< 220	< 27	< 65	< 0.20	< 0.25
Pb brick paint	0.300 kg	< 8	< 0.17	3.00 ± 0.30	< 0.19			< 0.0015	< 0.004
Pb shielding	55000 kg	< 33000	< 2700	< 8300	< 40	< 60	< 85	< 0.9	< 0.5

Who's doing the counting

- Alabama (EXO-200 and nEXO): above ground Ge counting, NAA, alpha counting, and perhaps Rn counting.
- Bern (EXO-200 and nEXO): underground Ge counting
- Seoul (nEXO): ICPMS
- Duke (nEXO): underground Ge countig and NAA
- Laurentian (EXO-200 and nEXO): Rn counting

How do we Measure the Rate?



Elliot, S. et al., Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51

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

To maximize sensitivity:

- Large mass
- Low background
- High detection efficiency
- Good energy resolution

$$S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A} \left[\frac{MT}{B\Gamma} \right]^{1/2}$$

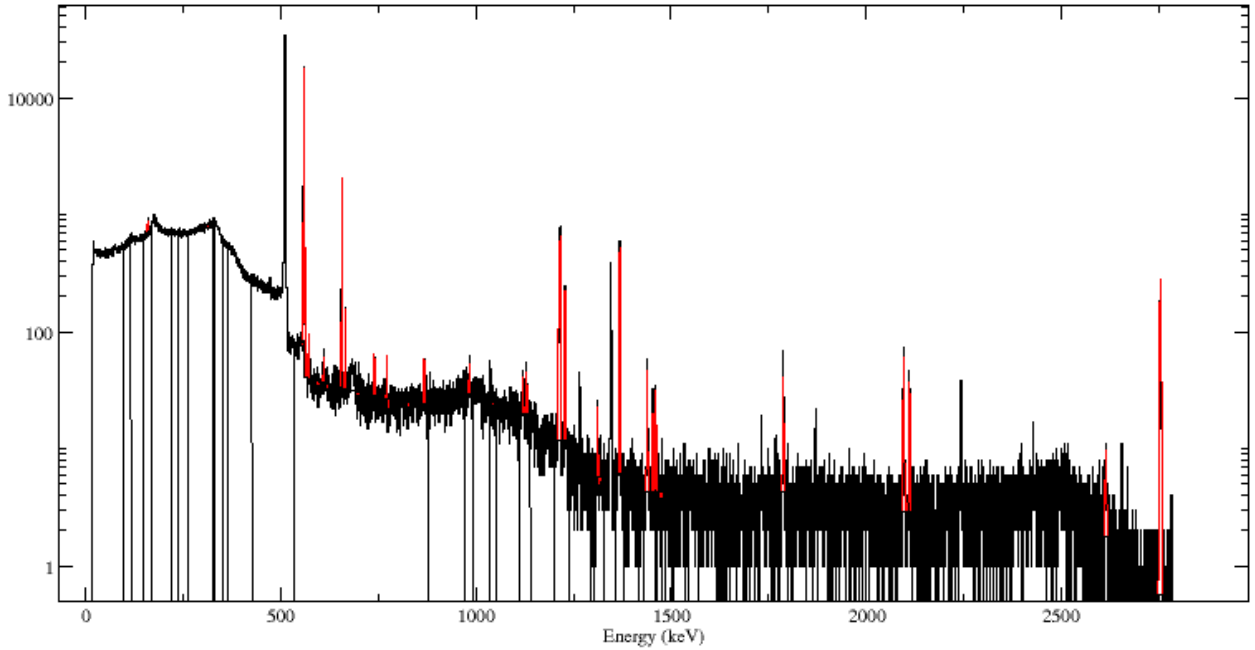
ε is efficiency
a is isotopic abundance
A is atomic mass
M is source mass
T is time
B is background
Γ is resolution

Analysing the samples

- Remove the samples from activation vial and place in PE counting vials as soon as we receive the samples
- Place vials on Ge detectors
  - Fly ash usually in GeI as it has high activity so doesn't need the extra sensitivity of GeII or GeIII
- We utilise a time series analysis so create a job script that counts for a set time
  - We can test the halflife of a γ-line as well as its energy
  - Short count times early longer count times later

Analysising the spectrum

- Use gdfit[1] to find the activity of the peaks
  - It uses all peaks and corrects for branching ratio



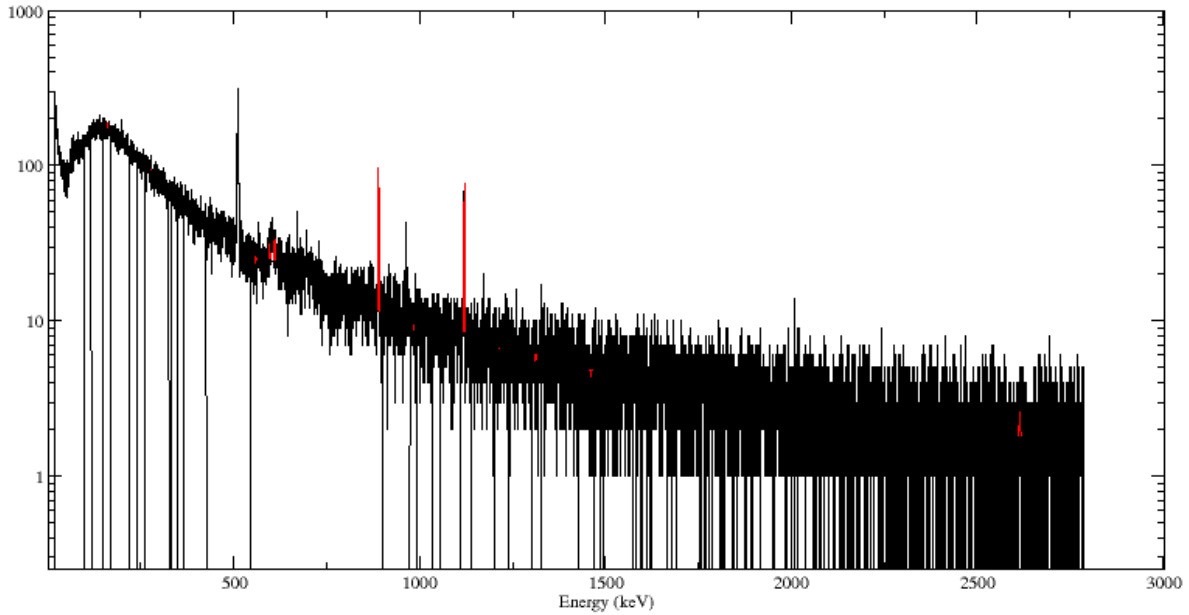
35 hours after activation

1 hour long run

1 (D.S Leonard et.al **Nucl.Instrum.Meth. A591 (2008) 490-509**.)

Analysising the spectrum

- Use gdfit[1] to find the activity of the peaks
  - It uses all peaks and corrects for branching ratio



848 hours after activation

24 hour long run

1 (D.S Leonard et.al **Nucl.Instrum.Meth. A591 (2008) 490-509**.)

What fraction of this effort was expended on which components?

Small parts:	36%
Plastics:	9%
Cu:	6%
Phosphor bronze:	10%
Silicon bronze:	3%
Lead:	18%
Flat cables:	9%
Heat transfer fluid:	3%
Other:	6%

- We perform a time series analysis to find the initial activity
- Pa-233 relates to Th and Np-239 relates to U
- To get the amount of initial substance in material the initial activities are adjusted for neutron cross-section and neutron flux as found by the fly ash sample

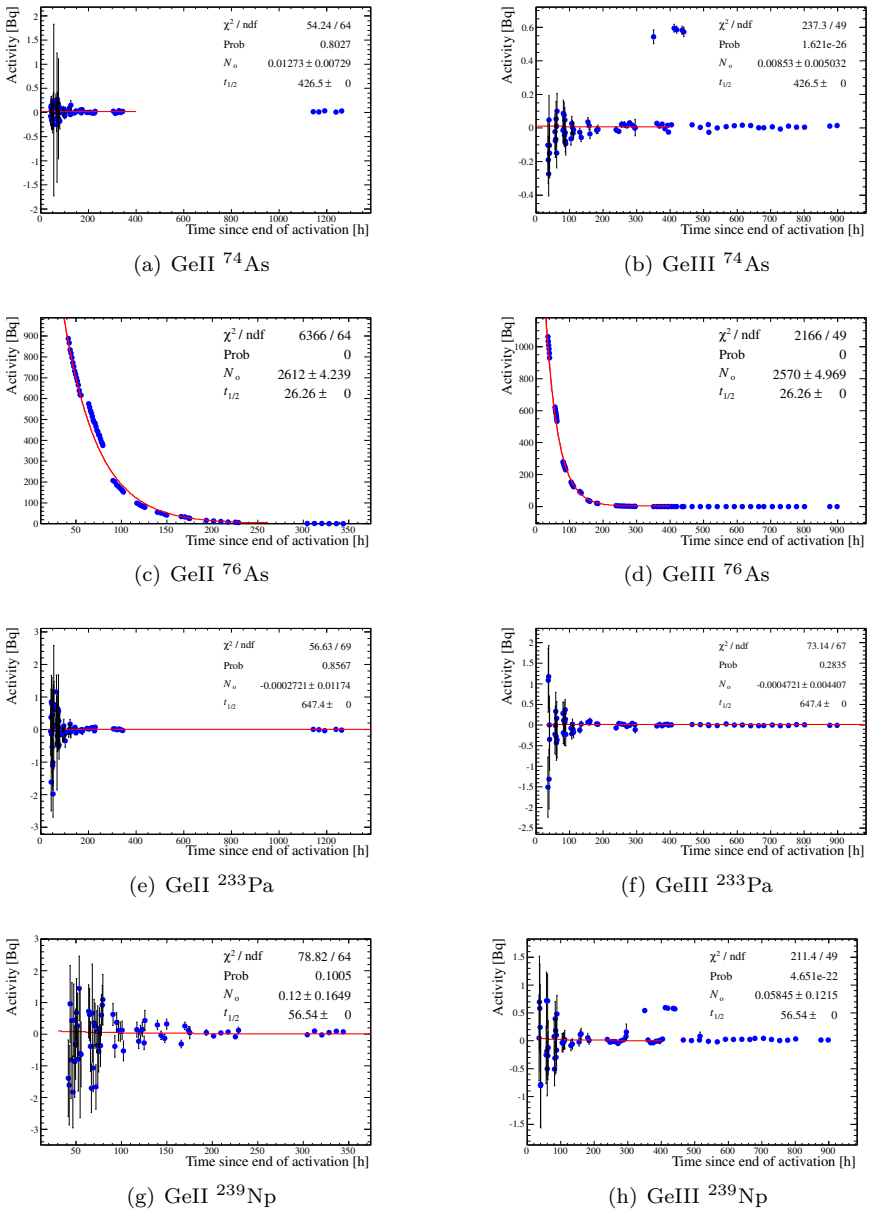
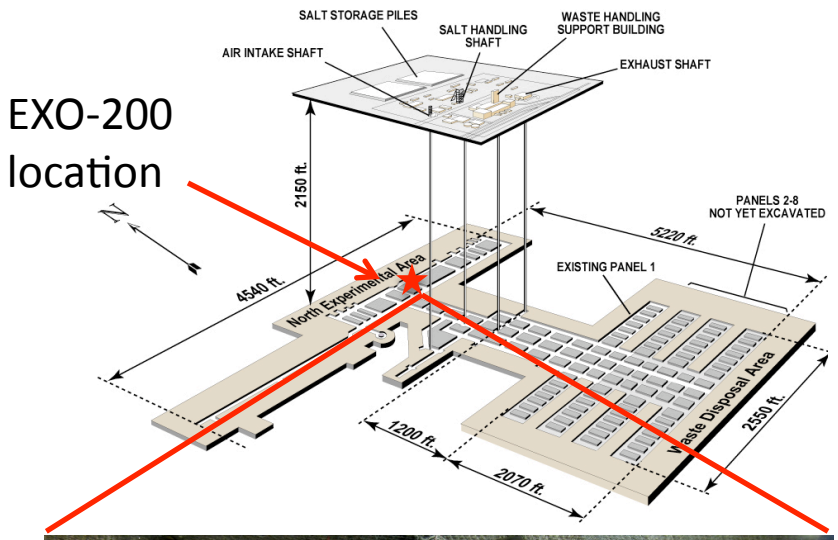


Figure 12: *Exponential decay fits to the radionuclide activities, for UA241 on GeII and GeIII (continued).*

EXO-200 installation site: WIPP



- EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM
- 1600 mwe flat overburden (2150 feet, 650 m)
- U.S. DOE salt mine for low-level radioactive waste storage
- Cleanroom installed on adjustable stands to compensate salt movements.
- Salt "rock" low activity relative to hard-rock mine

$$\Phi_\mu \sim 1.5 \times 10^5\, yr^{-1} m^{-2} sr^{-1}$$

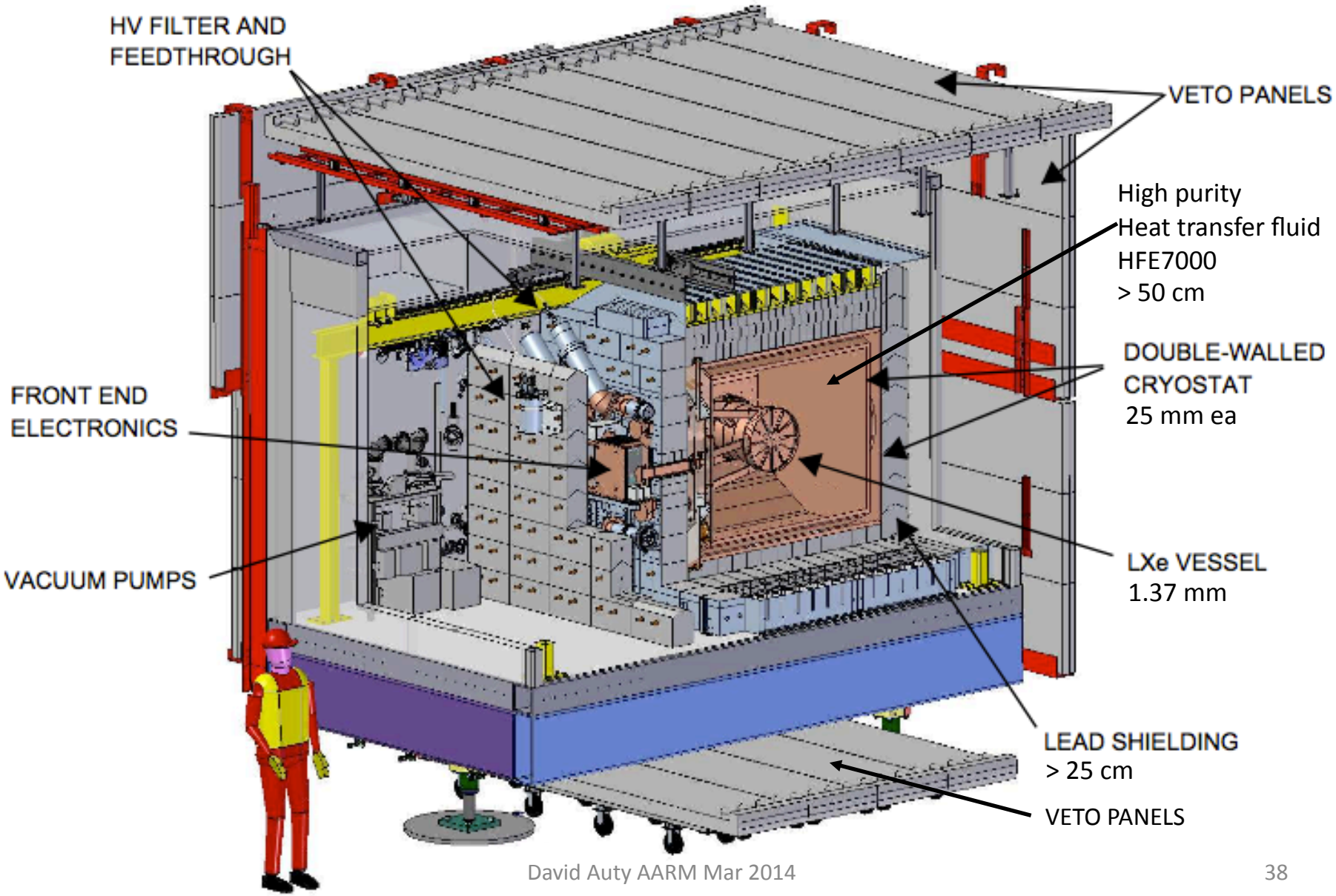
$$U \sim 0.048\, ppm$$

$$Th \sim 0.25\, ppm$$

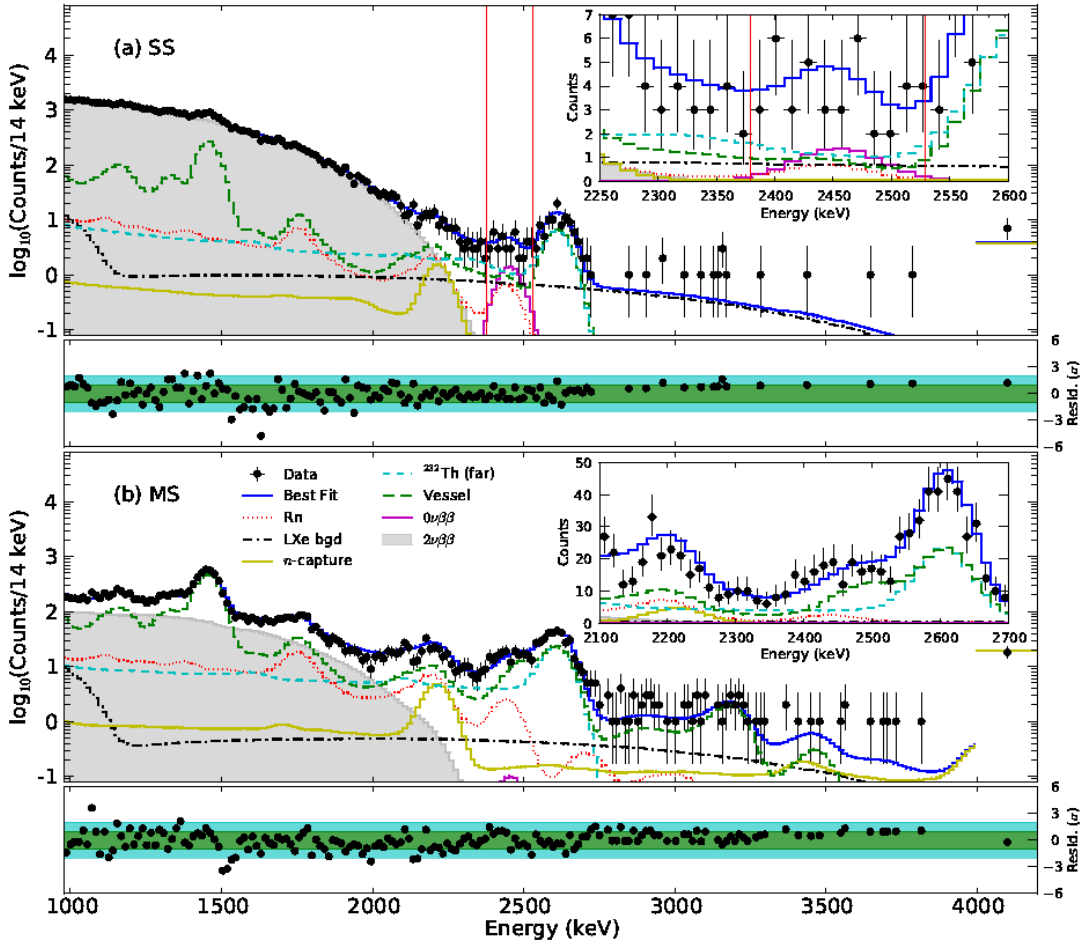
$$K \sim 480\, ppm$$

Esch et al., arxiv:astro-ph/0408486 (2004)

The EXO-200 Detector



Best fit results



0 ν comparition with Ge