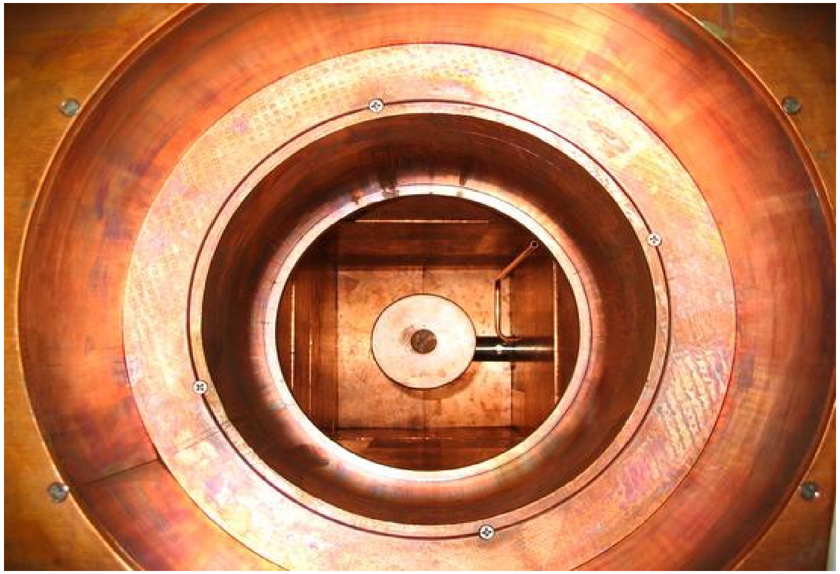
Low Background Counting Techniques At SNOLAB

Ian Lawson
SNOLAB Research Scientist

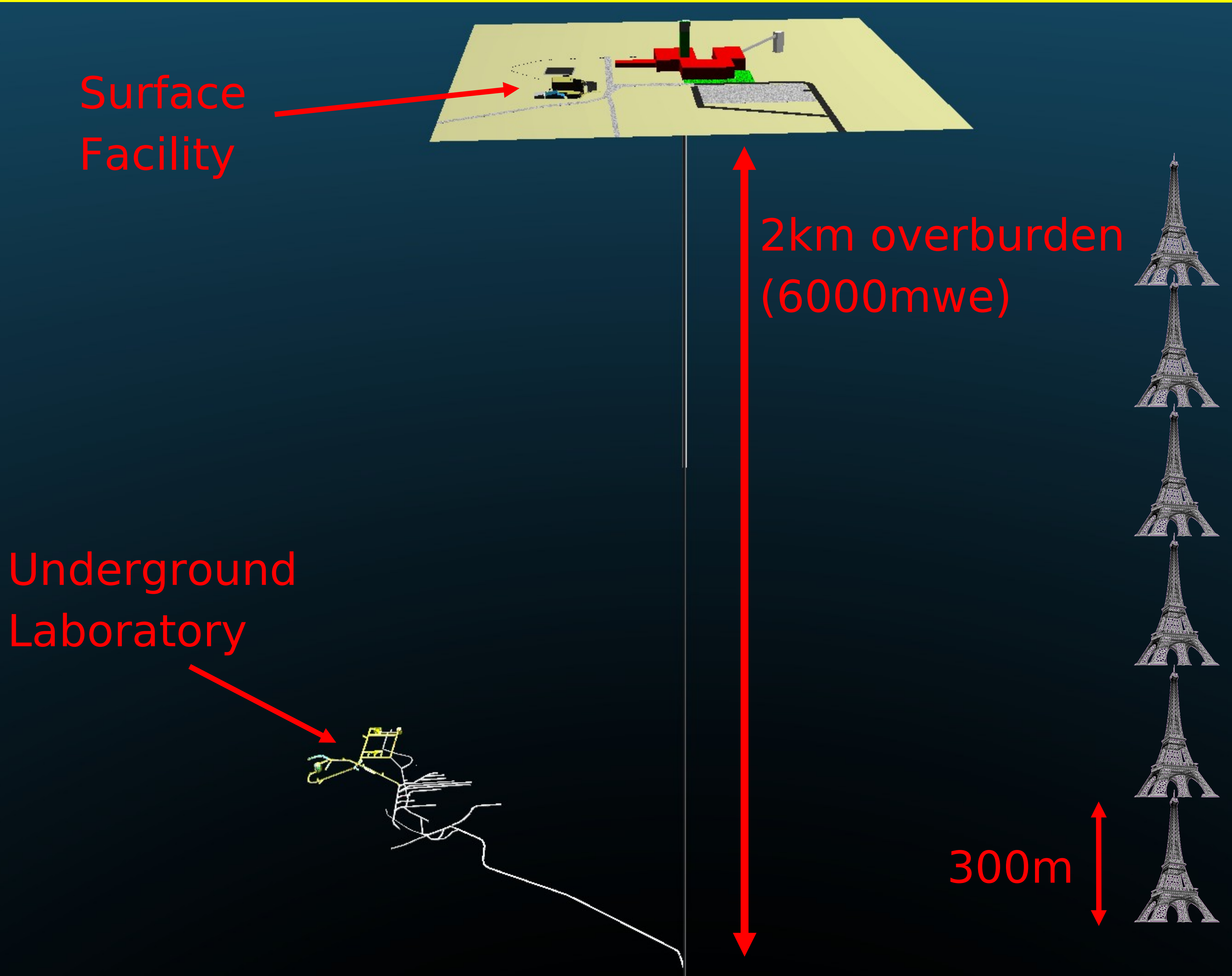
FNAL Research Technical Seminar



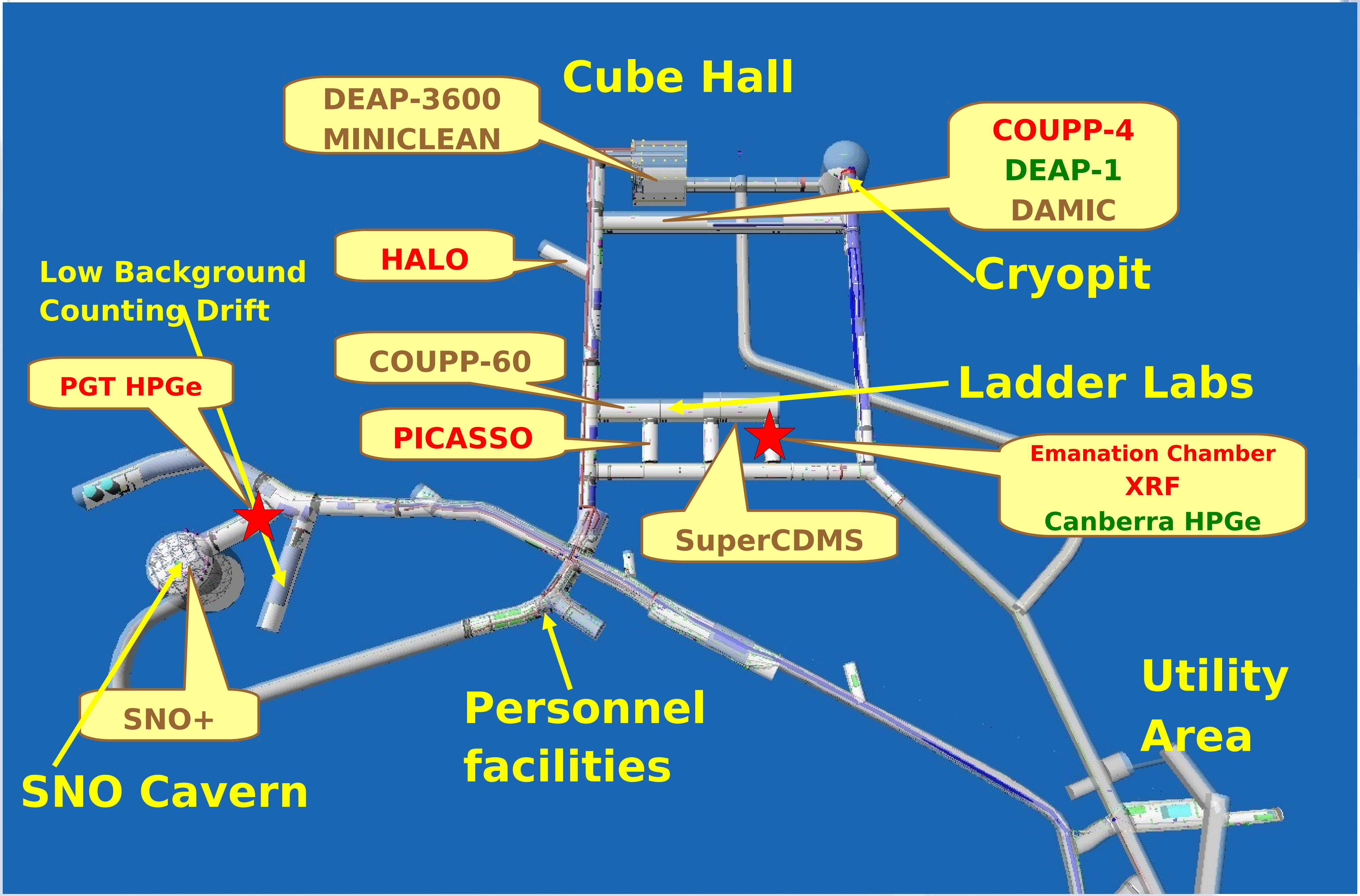
Outline

- Background Information
- Description of the SNOLAB Low Background Counting System, Including Results
- Electrostatic (ESC) Counters
- Alpha/Beta Counting System
- Underground Radon Levels at SNOLAB and How to Reduce These Levels
- Future Low Background Counting Facilities: Includes the new Canberra Well Detector Now Operational

SNOLAB


Surface
Facility
2km overburden
(6000mwe)
Underground
Laboratory
300m

SNOLAB



Cube Hall
DEAP-3600
MINICLEAN
COUPP-4
DEAP-1
DAMIC
HALO
Cryopit
Low Background
Counting Drift
COUPP-60
Ladder Labs
PGT HPGe
PICASSO
Emanation Chamber
XRF
Canberra HPGe
SuperCDMS
Utility
Area
SNO+
Personnel
facilities
SNO Cavern

Low Background Techniques Motivation

- Many of the experiments currently searching for dark matter, studying properties of neutrinos or searching for neutrinoless double-beta decay require very low levels of radioactive backgrounds both in their own construction materials and in the surrounding environment.
- These low background levels are required so that the experiments can achieve the required sensitivities for their searches.
- SNOLAB has several facilities which are used to directly measure these radioactive backgrounds.
- The backgrounds in question are on the order of 1 mBq or 1 ppb for ^{238}U, ^{232}Th and ^{235}U and 1ppm for 40K, or less.
- The problem backgrounds can include gammas, alphas and neutrons
- The goal is to measure these backgrounds and then to reduce them to be as low as reasonably achievable.

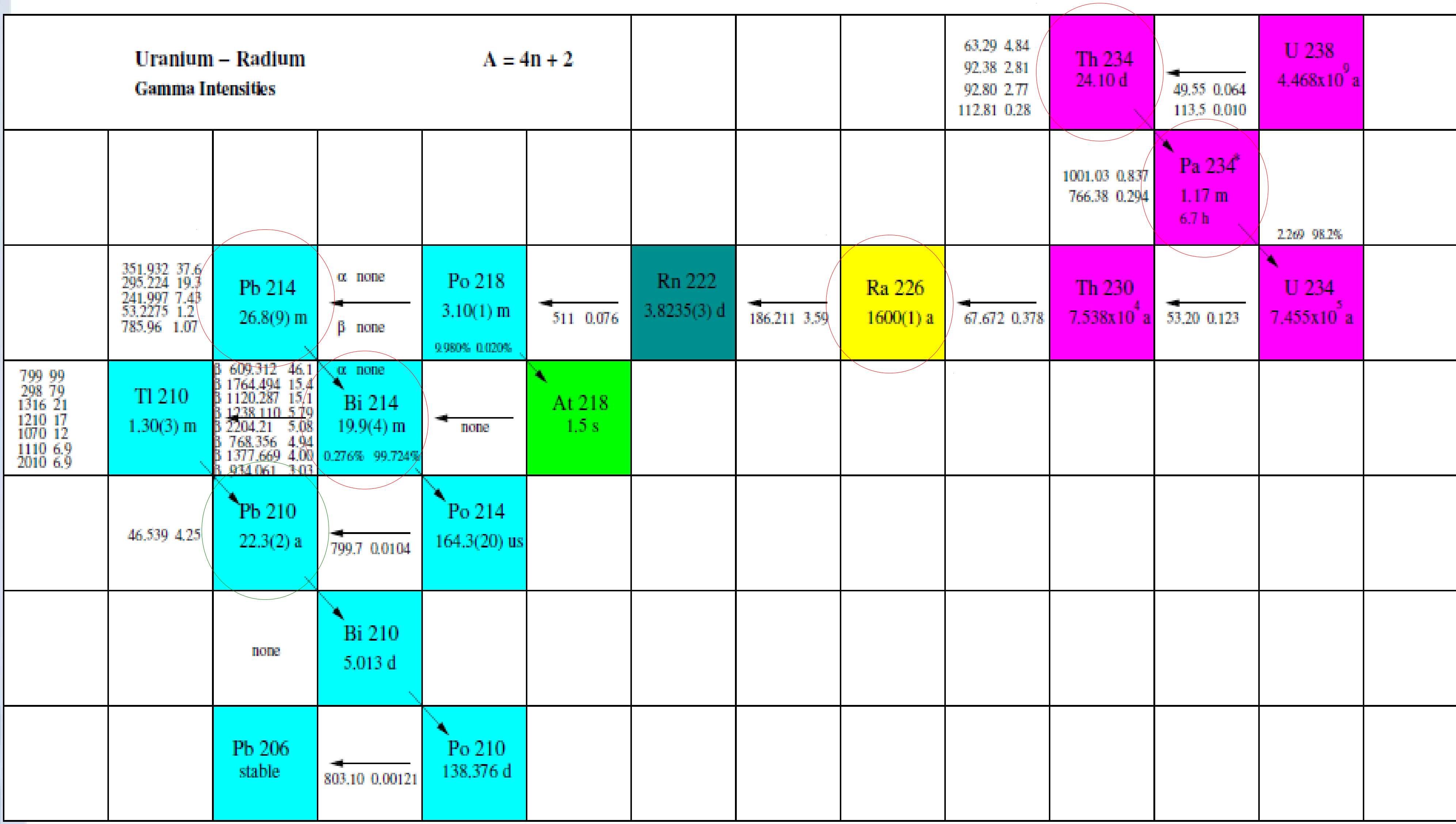
Key R&D Topics

- Development and strengthening of the ultra low background facilities and instrumentation in the UG labs
- measurement and monitoring of the background components in the underground Labs – Development of background simulation codes
- application of low background techniques to interdisciplinary fields
- R&D on radiopurity of materials and purification techniques.

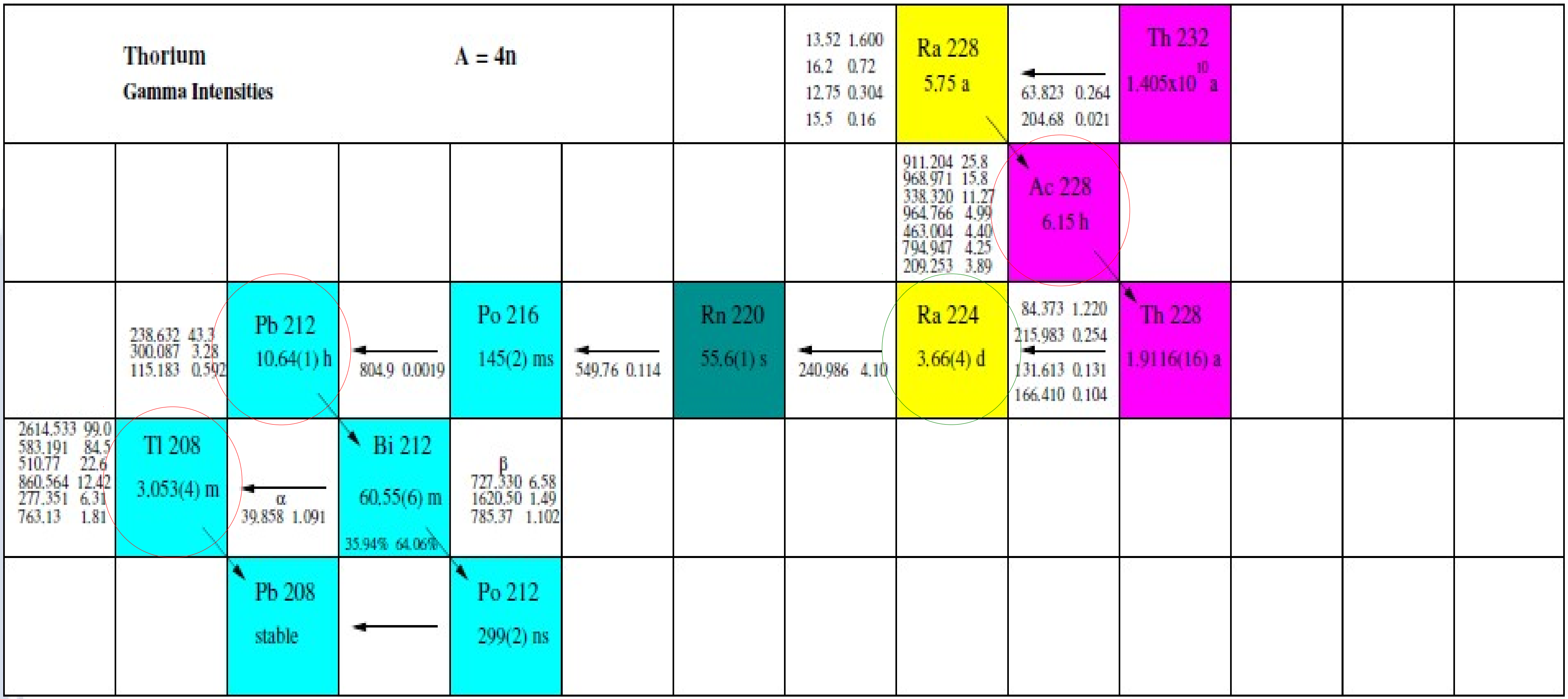
Support (from groups such as AARM):

- personnel
- travel money
- contribution to equipment and consumables for selected specific activities codes

^{238}U Decay Chain



^{232}Th Decay Chain



^{235}U Decay Chain

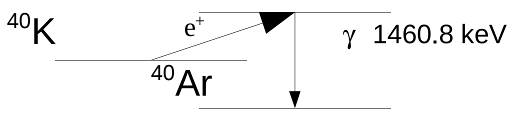
Actinium **Gamma Intensities**				A = 4n + 3					25.64 14.5 84.214 6.6	Th 231 1.0633 d	185.715 57.2 143.76 10.96 163.33 5.08 ← 205.311 5.01 109.16 1.54 202.11 1.08	U 235 7.028×10^8 a	
		293.54 1000 271.23 55 517.63 19 833.00 14 563.70 13 401.81 10	Bi 215 7.6 m	α none ← β none	At 219 56 s ~97% ~3%	α none β 50.13 36.0 β 79.72 9.1 ← β 234.81 3.0 β 49.89 2.7	Fr 223 21.8 m 0.006% 99.994%	α 160.26 0.0059 ← β none	Ac 227 21.773(3) a 1.380% 98.620%	27.36 10.29 300.07 2.47 302.65 2.19 ← 283.69 1.70 330.06 1.40 19.00 0.374	Pa 231 3.276×10^4 a		
	404.853 3.78 832.01 3.52 427.088 1.76	Pb 211 36.1(2) m	← 438.8 ~0.040	Po 215 1.781(4) ms	← 271.23 10.8 401.81 6.37	Rn 219 3.96(1) s	269.459 13.70 154.21 5.62 323.871 3.93 ← 144.232 3.22 338.281 2.79 445.031 1.27	Ra 223 11.435(4) d	235.971 12.3 50.13 8.26 256.25 7.01 ← 329.85 2.69 300.00 2.32 286.12 1.53	Th 227 18.72(2) d			
897.80 0.260 569.702 0.00159 328.12 0.00140	Tl 207 4.77 m	α 351.059 12.91 ← β none	Bi 211 2.14(2) m 99.724% 0.276%										
		Pb 207 stable	← 897.80 0.561 569.702 0.5	Po 211 516 ms									

Other Interesting Isotopes

Usually Present:

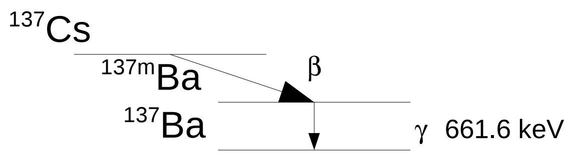
- ^{40}K

  1460.83 keV

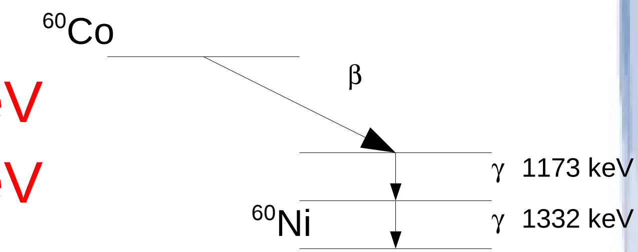


- ^{137}Cs

  661.66 keV



- ^{60}Co
  - 1173.2 keV
  - 1332.5 keV

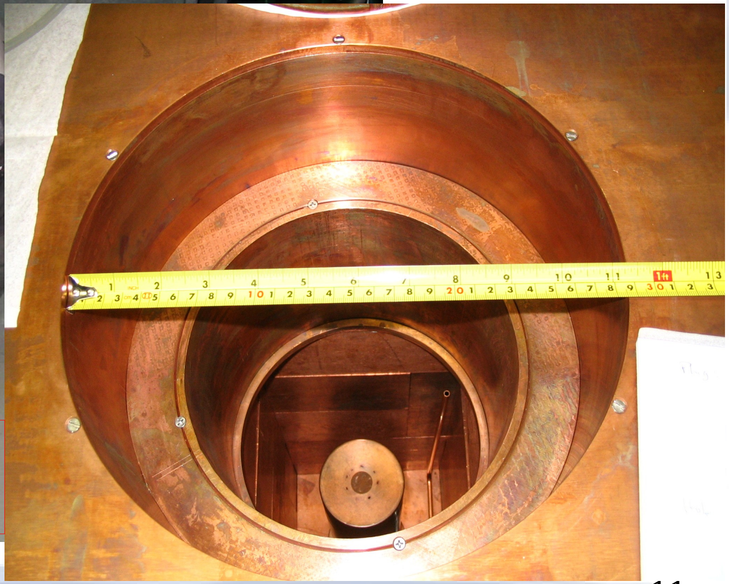


Occasionally Present:

- ^{54}Mn at 834.85 keV — Observed in Stainless Steel and other metals
- ^{7}Be at 477.60 keV — Observed in Carbon based materials, due to neutron activation, samples are particularly affected after long flights.
- ^{138}La and ^{176}Lu — Observed in rare earth samples such as Nd or Gd.

SNOLAB HPGe Counter

Additional lead used to dampen microseismic activity

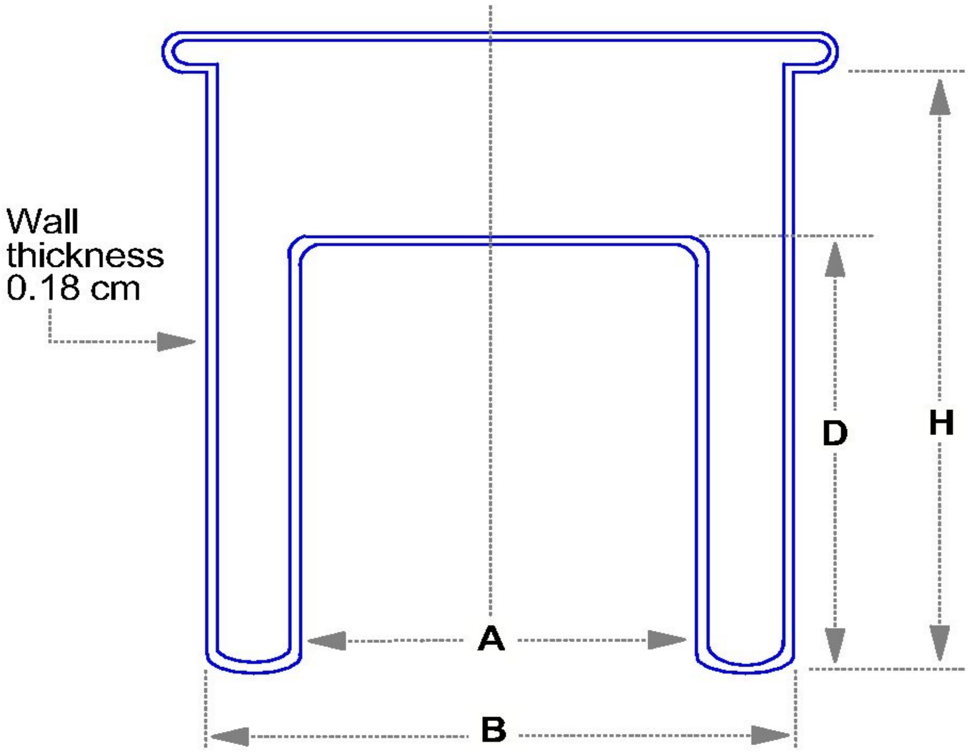


SNOLAB HPGe Detector Specifications

- Establishment of the Low Background Gamma Facility @ SNOLAB in 2005.
- Motivation
  - Survey materials for new, existing and proposed experiments (to be) located @ SNOLAB, such as SNO, SNO+, DEAP/CLEAN, PICASSO, EXO, ... Also survey materials for the DM-ICE experiment.
- Constructed @ SNOLAB from an HPGe detector and its associated shielding located underground at 4600 ft level since 1997.
  - Counter manufactured by PGT.
  - Endcap diameter 83 mm.
  - Relative Efficiency is 55% wrt a 7.62 cm dia x 7.62 cm NaI(Tl) detector.
  - Resolution 1.8 keV FWHM.
- Shielding
  - 2 inches Cu + 8 inches Pb
  - Nitrogen purge at 2L/min to keep radon out.

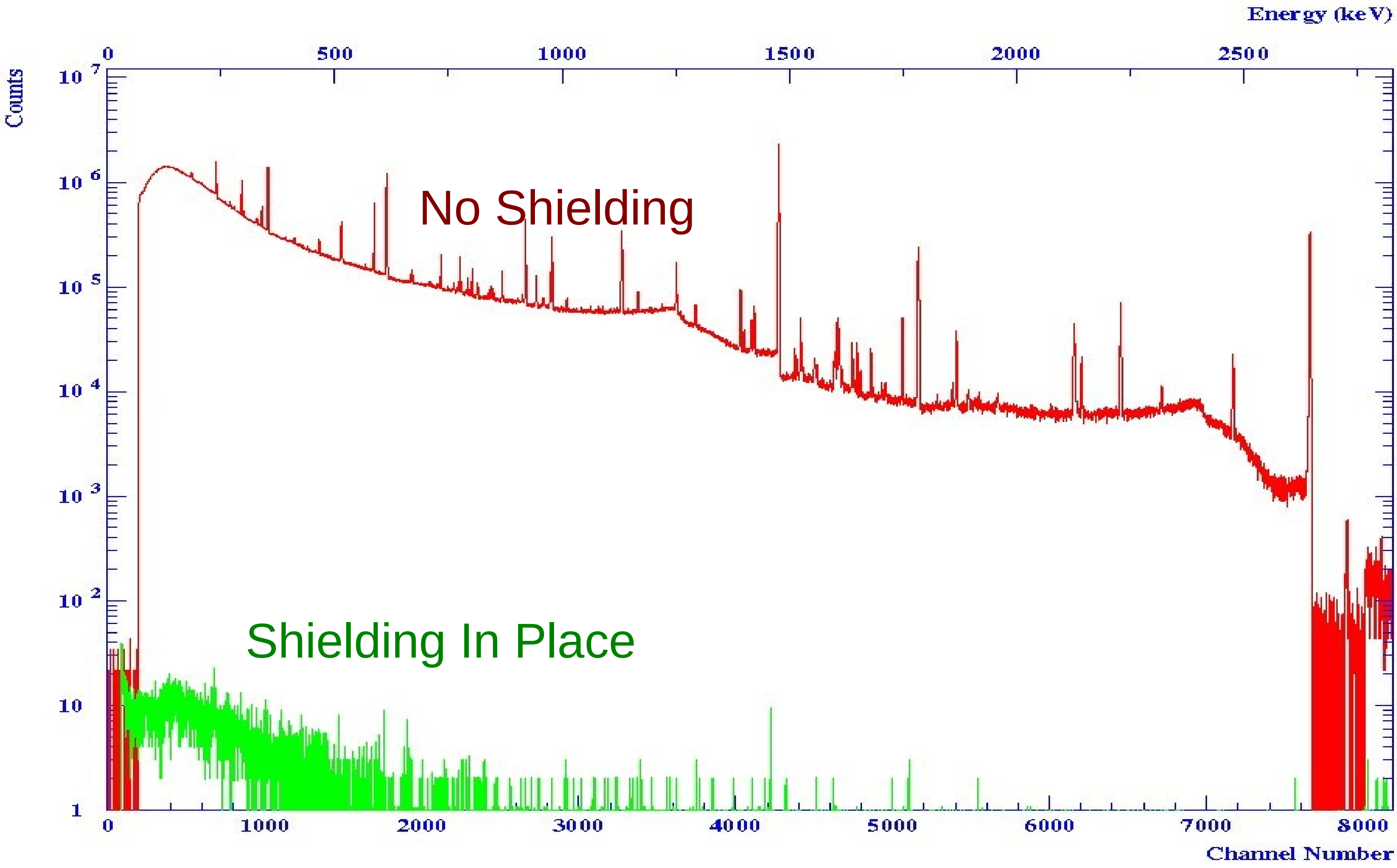
Sample Preparation

Marinelli Beaker



-The current beakers have a volume of 1 L.
-The beakers are made out of polyethylene.
-We have smaller beakers that are 250mL. These can be used for small and/or expensive samples.
-Samples should be made to fit into the beaker so that as much of the sample as possible is near the counter, it is preferable to crush the sample if possible.
-Samples can also be placed directly on top of the crystal.

Unshielded and Shielded Spectra



Background Comparison

Unshielded Versus Shielded Activity

Isotope	Activity Unshielded Crystal(Bq)	Activity Shielded Crystal (Bq)
^{238}U	70.11 ± 1.64	0.00128 ± 0.00016
^{232}Th	36.99 ± 1.21	0.00131 ± 0.00015
^{40}K	1723.33 ± 88.02	0.0189 ± 0.0017
^{137}Cs	1.00 ± 0.15	0.0020 ± 0.0002
^{60}Co	0.023 ± 0.052	0.00036 ± 0.00005

Unshielded Measurements done by Yoram Nir-EL

PGT HPGe Standard Detector Sensitivity
(for a standard 1L or 1 kg sample)

Isotope	1 Bq/kg	1 ppb	Sensitivity for Standard Size Samples	Typical for Earth's Crust
^{238}U	81 ppb	12 mBq/kg	~ 1 mBq/kg ~ 0.1 ppb	37 Bq/kg 3 ppm
^{232}Th	246 ppb	4.1 mBq/kg	~ 1.5 mBq/kg ~ 0.3 ppb	45 Bq/kg 11 ppm
^{40}K	32 ppm	0.031 mBq/kg	~ 21 mBq/kg ~ 0.7 ppm	800 Bq/kg 2.5 %

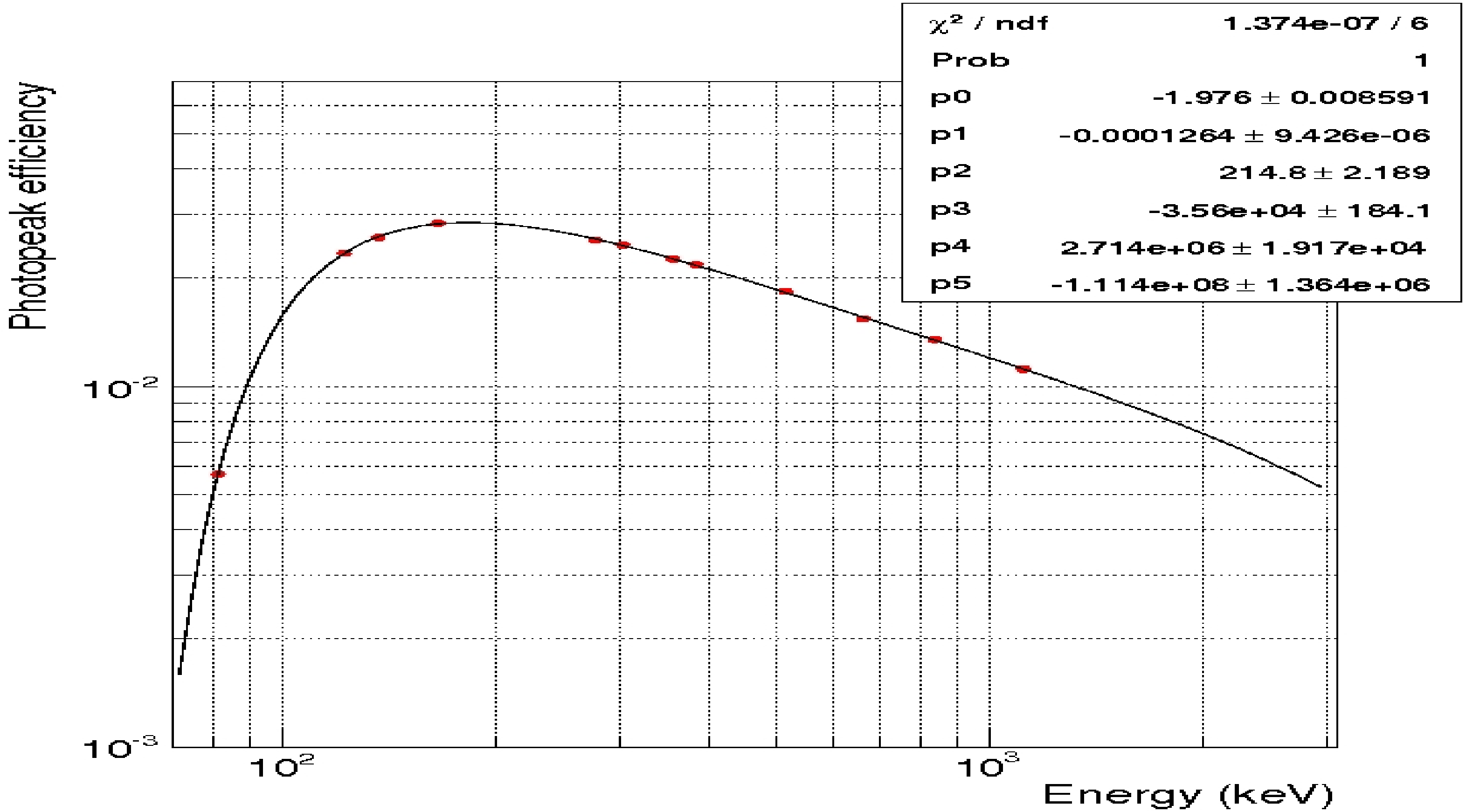
Better sensitivities have been achieved for specialized very large samples combined with an extremely long counting period:

^{238}U: 0.009 ppb,
^{232}Th: 0.02 ppb,
^{40}K: 87 ppb

Sensitivities of SNOLAB Compared to Some Other Facilities

Isotope	SNOLAB	SOLO	LBCF Surface Facility	LBCF Underground Facility
^{238}U	1 mBq/kg 0.1 ppb	1 mBq/kg 0.1 ppb	9 mBq/kg 0.5 ppb	0.9 mBq/kg 0.05 ppb
^{232}Th	1.5 mBq/kg 0.3 ppb	0.5 mBq/kg 0.05 ppb	12 mBq/kg 2 ppb	1.2 mBq/kg 0.2 ppb
^{40}K	21 mBq/kg 0.7 ppm	10 mBq/kg 0.25 ppm	32 mBq/kg 1 ppm	3.2 mBq/kg 0.1 ppm

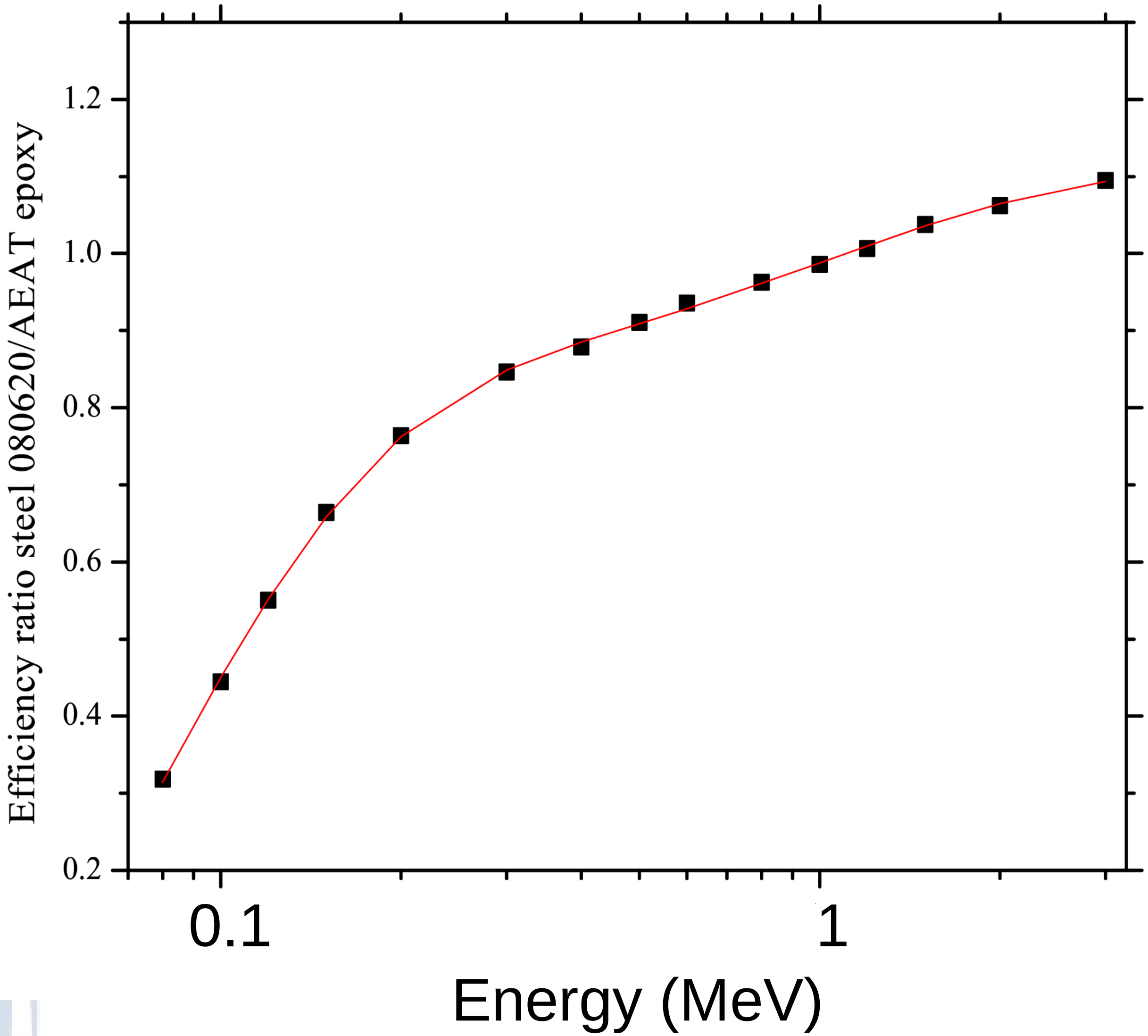
Detector Efficiency From A Mixed Calibration Sample



Plot by James Loach

The efficiency is scaled to individual samples using GEANT 4.9.4 which takes into account the sample components, to account for the density difference between the calibration source and the sample, and the sample geometry.

Typical Efficiency Correction

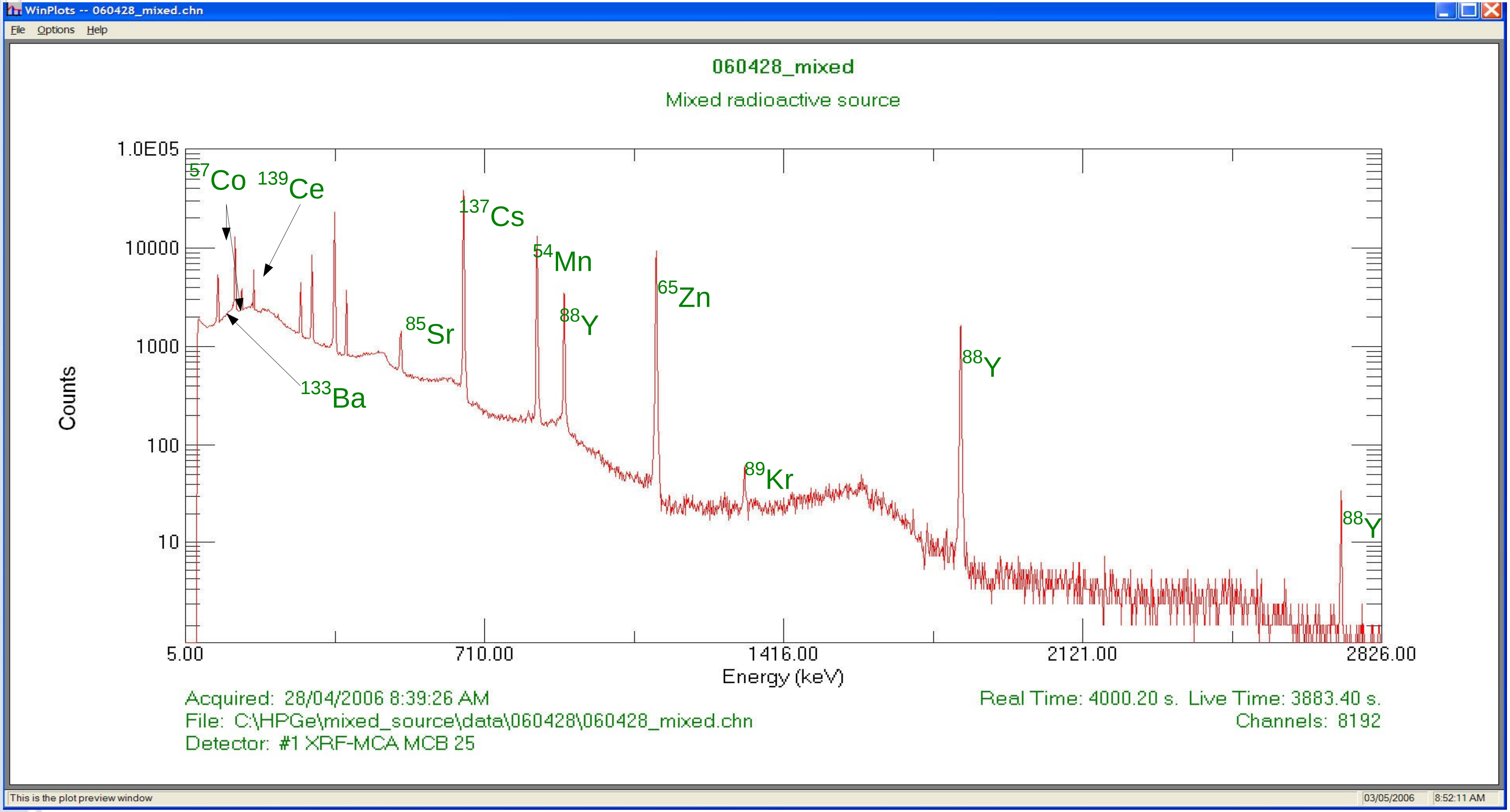


Efficiency correction for steel sample.

Use GEANT4.9.4, simulate detector with 5 million events at each energy.

Extrapolate between energy bins with a polynomial fit.

Calibration Spectrum



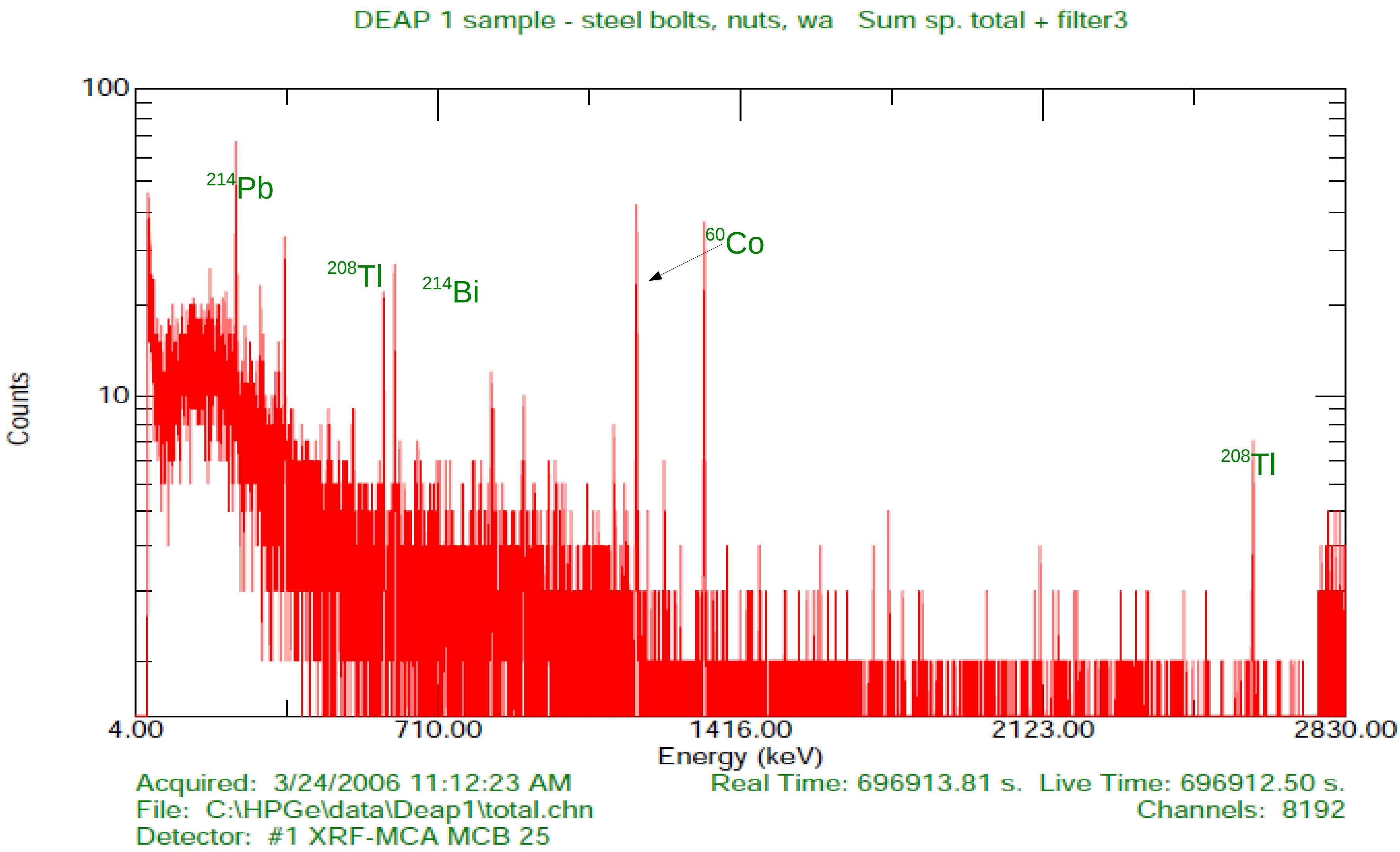
New calibration standards are being proposed which have much longer half-lives to allow the calibration sample to be used for several years unlike most commercial multigamma calibration samples. Would be used to cross-calibrate PGT and Canberra detectors.

Measurements To Date For Each Experiment

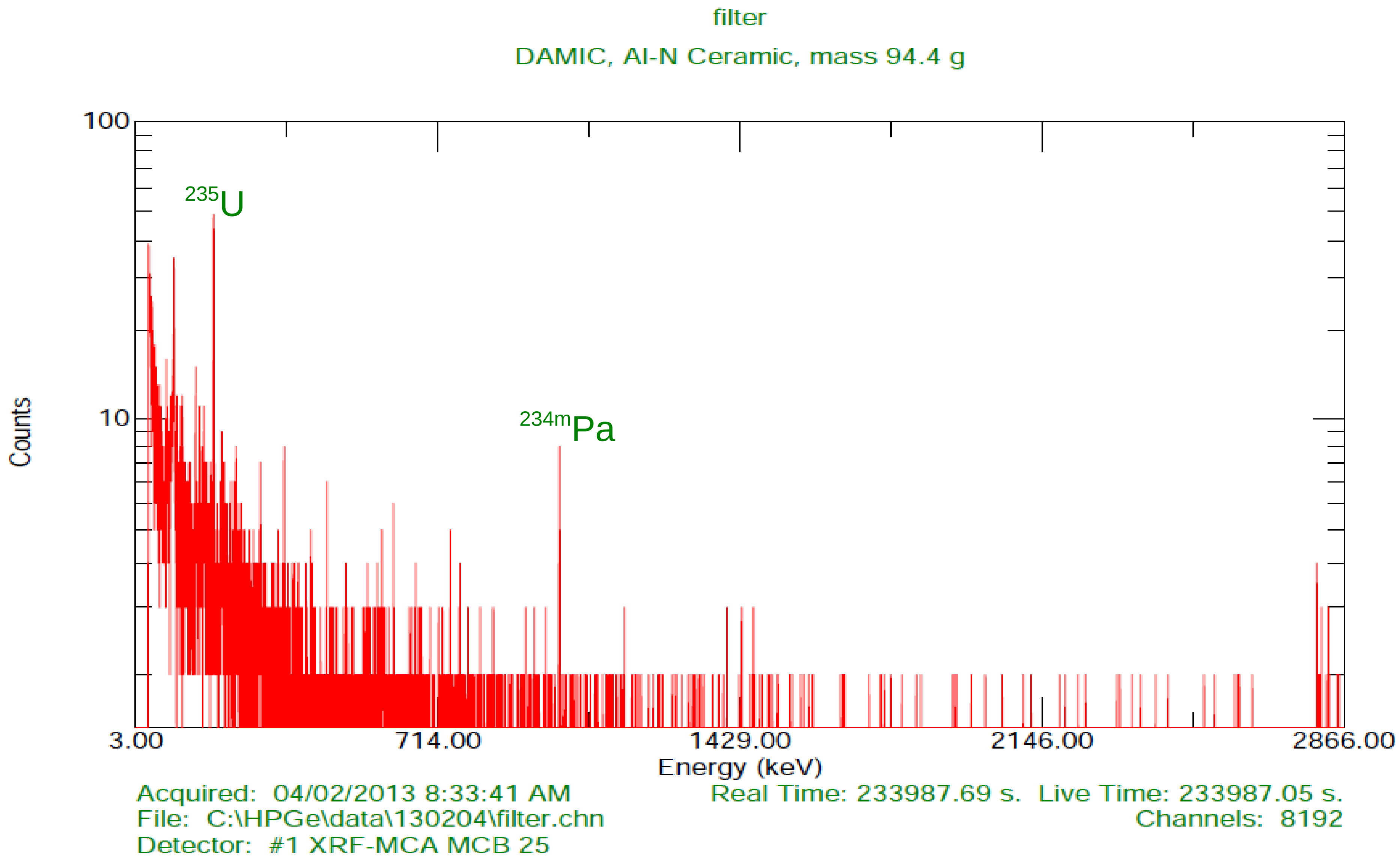
Experiment	2006	2007	2008	2009	2010	2011	2012	Total
SNO	2	7	0	2	0	0	0	11
SNO+	0	2	18	14	15	35	5	89
SNOLAB	7	3	0	0	9	6	17	42
EXO	1	1	0	0	2	1	0	5
MiniCLEAN	5	1	9	18	8	3	7	51
DEAP	8	8	12	10	8	15	18	79
HALO	0	0	0	2	3	1	1	7
PICASSO	1	1	4	3	0	0	0	9
DM-ICE / DRIFT	--	--	--	--	9	9	5	23
COUPP	--	--	--	--	1	15	17	33
DAMIC	--	--	--	--	--	--	1	1
Total	24	23	43	49	34	85	71	350
Calibrations &Tests	30	34	14	9	4	3	11	105

Samples in Detector Queue: - 10, which means up to 10 weeks or more of counting time!
- the queue keeps getting longer, so the new counters are very important.

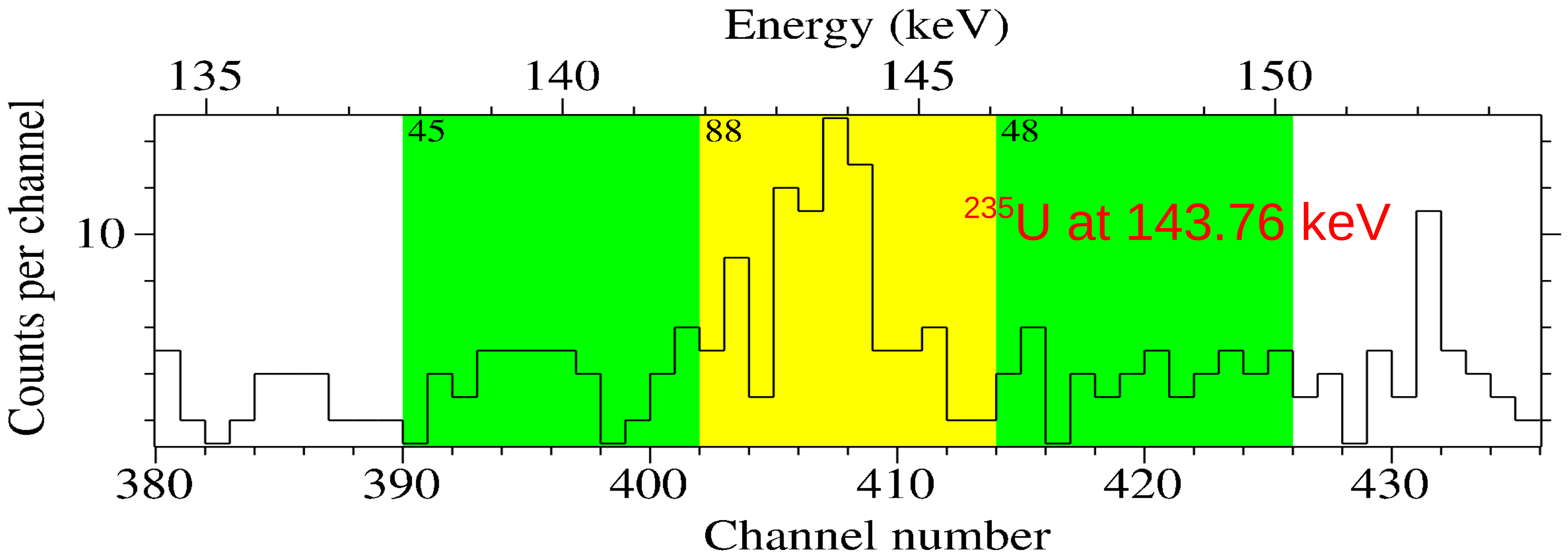
Typical Stainless Steel Spectrum

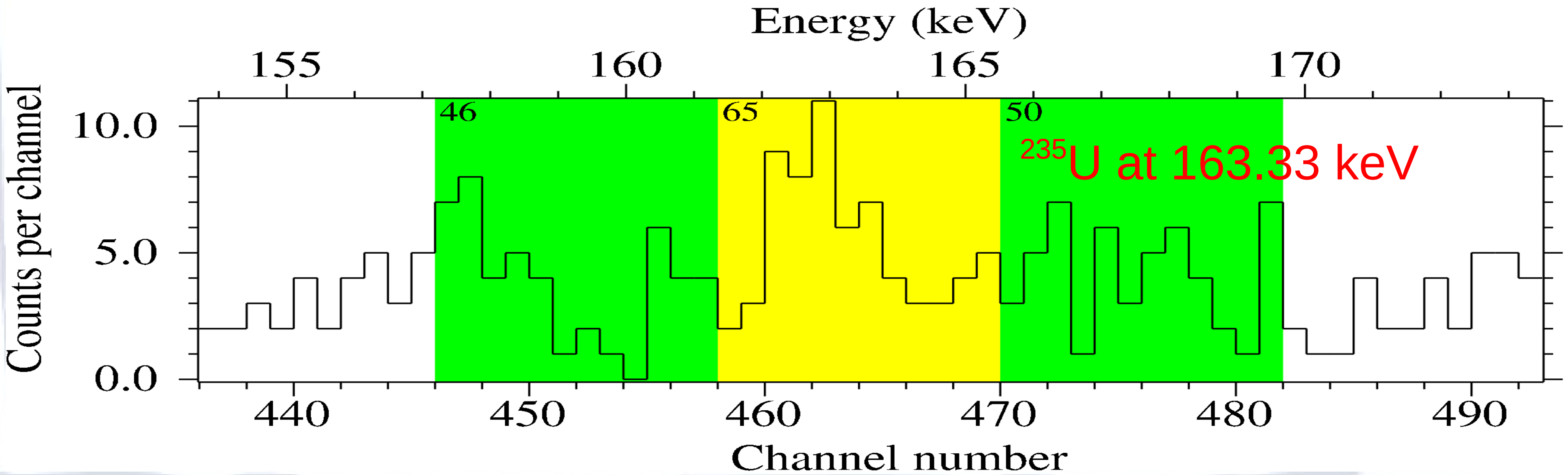


DAMIC Ceramic Spectrum

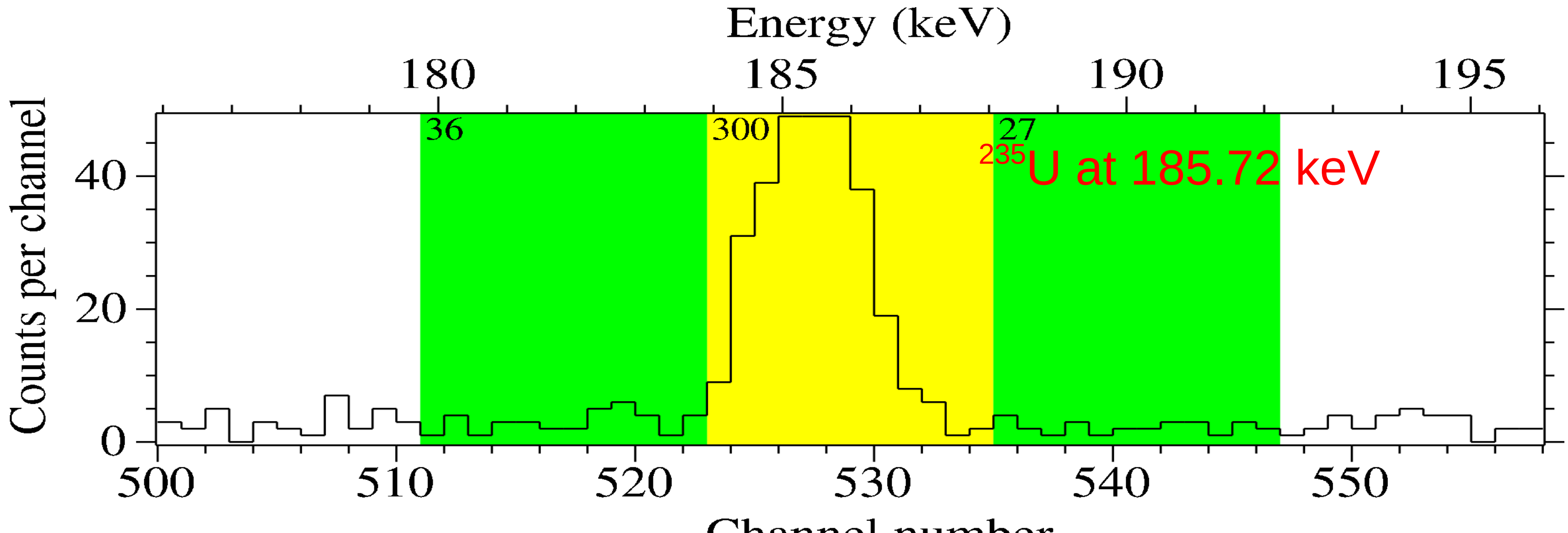


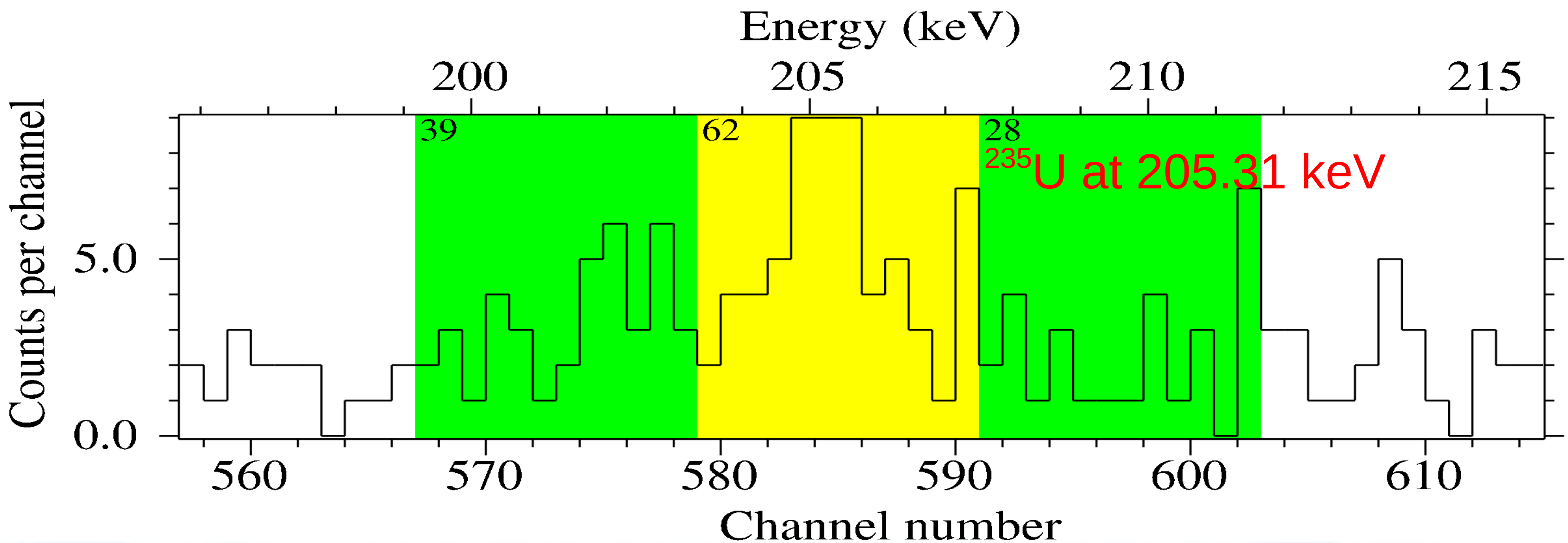
Analysis Techniques
(^{235}U Chain)





Analysis Techniques
(^{235}U Chain)





Analysis Techniques
(How the rate is calculated)

Calculate Rate: $$\text{Rate} = \frac{(N_p - N_{ab} - N_{pb})}{(\text{Eff} \times \text{Int} \times T_L)}$$

where N_p is the number of peak events

N_{ab} is the average number of events from the two background bands, if there are peak interferences then only one band may be used.

N_{pb} is the intrinsic detector background in the peak window

Eff is the detector efficiency at the peak energy

Int is the gamma intensity at the peak energy, sometimes referred to as the branching fraction, this is corrected to give the rate of the parent in the decay chain.

T_L is the detector live time.

Analysis Techniques
(^{235}U Chain)

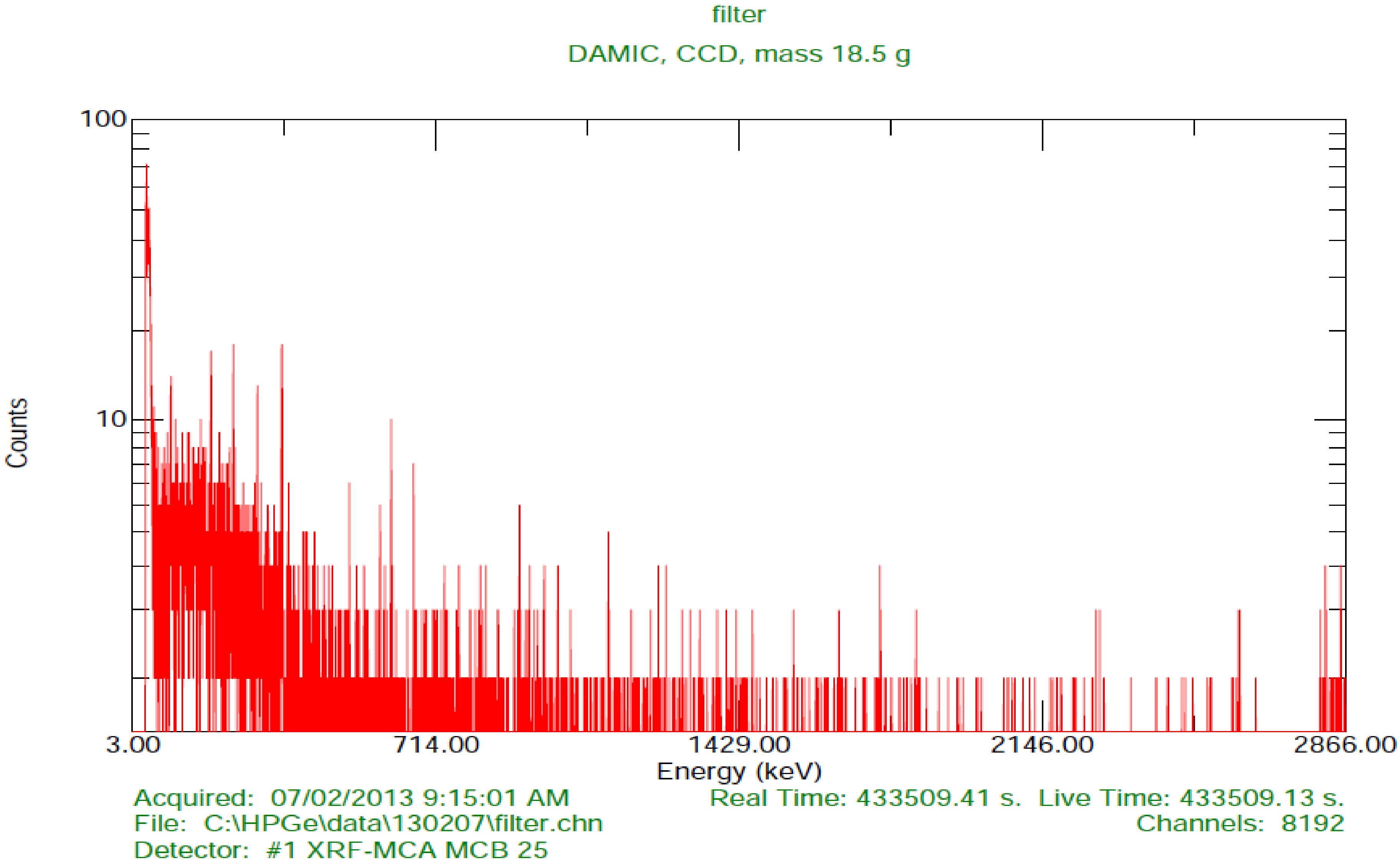
If the decay chain is in equilibrium the results from each peak are combined to give the overall background for the parent isotope.

Energy	N_p	N_{ab}	N_{pb}	N	Int (%)	Eff (%)	Rate (mBq)
143.76	88 ± 9.4	46.5 ± 4.8	0 ± 0	41.5 ± 10.5	10.96 ± 0.14	6.095 ± 0.457	26.6 ± 7.0
163.33	65 ± 8.1	48.0 ± 4.9	0 ± 0	17.0 ± 9.4	5.08 ± 0.06	6.216 ± 0.466	23.0 ± 12.9
185.715	300 ± 17.3	31.5 ± 4.0	0 ± 0	268.5 ± 17.8	57.20 ± 0.80	6.147 ± 0.461	32.6 ± 3.3
205.311	62 ± 7.9	33.5 ± 4.1	0 ± 0	28.5 ± 8.9	5.01 ± 0.07	6.001 ± 0.450	40.5 ± 13.0

Live Time: 233987.0 sec
Sample Mass: 94.4 g
Average Rate: 31.53 ± 2.84 mBq
333.958 ± 30.063 mBq/kg
587.767 ± 52.911 ppb

DAMIC CCD

(Note that the CCD is attached to a thin wafer)



Results from DAMIC Aluminium Nitride Ceramic and CCD

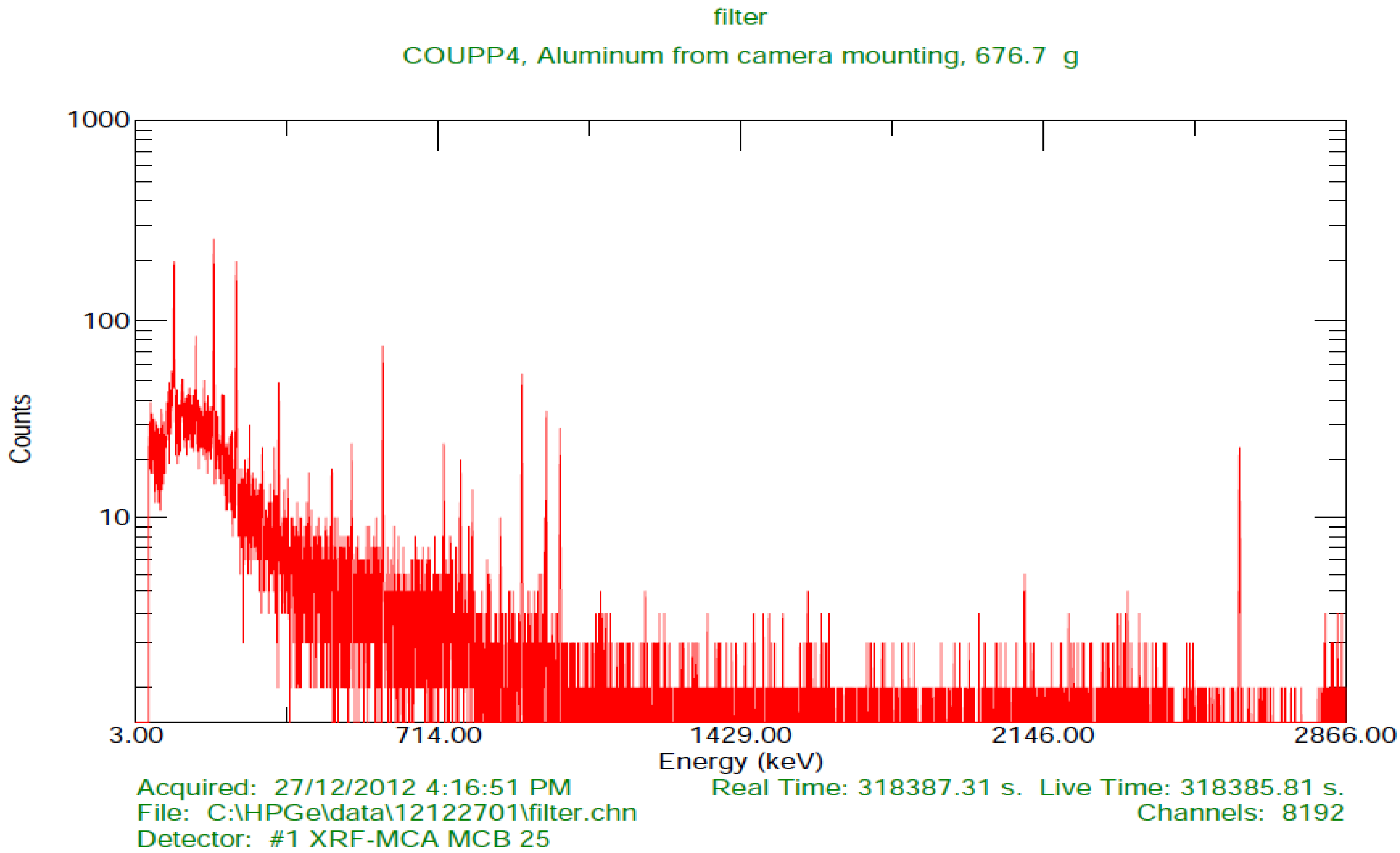
Ceramic (94.4 g)

^{238}U from ^{226}Ra	^{238}U from ^{234}Th	^{235}U	^{232}Th	^{40}K
42.16 +- 9.25 mBq/kg	4109.85 +- 530.95 mBq/kg	333.96 +- 30.06 mBq/kg	32.10 +- 8.61 mBq/kg	45.55 +- 66.74 mBq/kg
3.42 +- 0.75 ppb	332.90 +- 43.01 ppb	587.77 +- 52.91 ppb	7.90 +- 2.12 pb	1471.29 +- 2155.61 ppb

CCD (18.5 g)

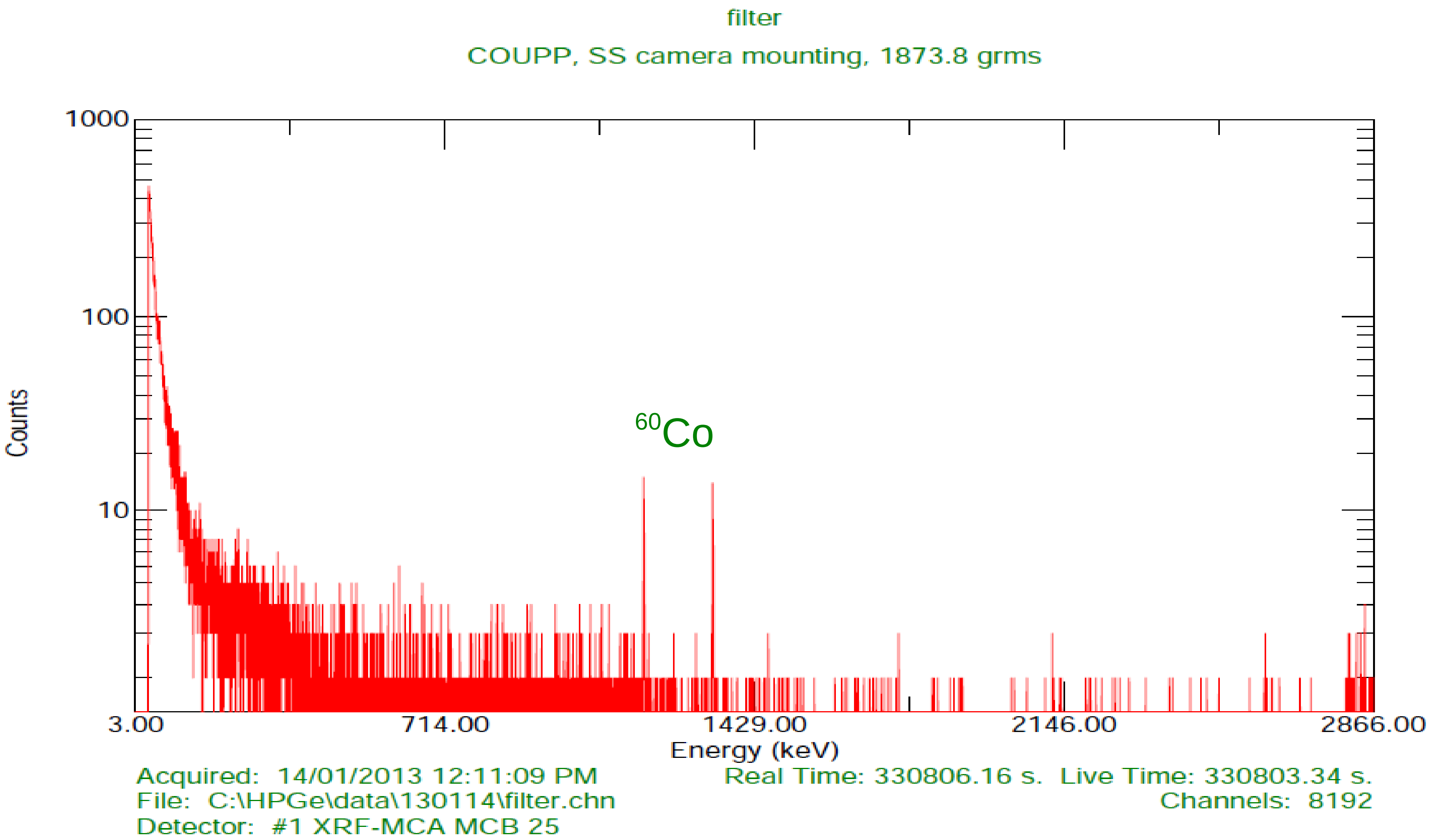
429.95 +- 47.05 mBq/kg	2017.87 +- 702.85 mBq/kg	227.27 +- 41.40 mBq/kg	209.10 +- 31.80 mBq/kg	<110.45 mBq/kg
34.83 +- 3.81 ppb	163.45 +- 56.93 ppb	399.99 +- 72.86 ppb	51.44 +- 7.82 ppb	<3.57 ppm

COUPP Sample, Aluminium Camera Mount From COUPP-4



Lots of peaks from ^{235}U and ^{232}Th, and ^{238}U above ^{226}Ra.

COUPP Sample, New Stainless Steel Camera Mount For COUPP-4



Only observable background is from ^{60}Co, which is expected to be present in stainless steel.

SNOLAB Data Repository

SNOLAB maintains a database in a spreadsheet format for each experiment.

The data is shown in units of mBq/kg or pp(b or m).

The table shows data from the standard gamma searches: ^{238}U, ^{235}U, ^{232}Th, ^{40}K ^{137}Cs, ^{60}Co.

While searching for the above gammas, we also search for any other peaks in the spectrum between 100 keV and 2800 keV, For example, ^{54}Mn is usually observed in steel. These are also included in the spreadsheet for each sample.

The database is available to all SNOLAB users and can be made available to others upon request as it is password protected, contact Ian.Lawson@snolab.ca or Bruce.Cleveland@snolab.ca.

Other Background Results

Several rock, shotcrete and concrete samples have been assayed from the new laboratory using a Ge counter at U. of Guelph and ICP-MS methods. Each area of SNOLAB has several measurements.

Ge Detector Results

Material	^{232}Th	^{238}U	^{40}K
	(ppm)	(ppm)	(%)
Average rock results	5.56 ± 0.57	1.11 ± 0.15	1.01 ± 0.12
Shotcrete	15.24 ±0.14	2.46 ± 0.09	1.78 ± 0.05
Concrete	15.38 ±0.40	2.41 ± 0.03	1.75 ± 0.05

Comparison of Ge Counting and ICP-MS

Element	Rock Sample 8		Rock Sample 11	
	Ge	ICP-MS	Ge	ICP-MS
K (%)	1.09 ± 0.01	0.97	1.08 ± 0.03	1.02
U (ppm)	1.24 ±0.16	1.21	1.09 ± 0.03	1.14
Th (ppm)	5.44 ±0.37	5.54	5.72 ± 0.05	5.19

Element	Shotcrete Sample 15		Concrete Sample 14	
	Ge	ICP-MS	Ge	ICP-MS
K (%)	1.78 ± 0.05	1.76	1.75 ± 0.05	1.61
U (ppm)	2.46 ±0.09	2.56	2.41 ± 0.03	2.38
Th (ppm)	15.24 ±0.14	14.90	15.38 ± 0.40	13.10

Electrostatic Counting System

Measures ^{222}Rn, ^{224}Ra and ^{226}Ra levels.

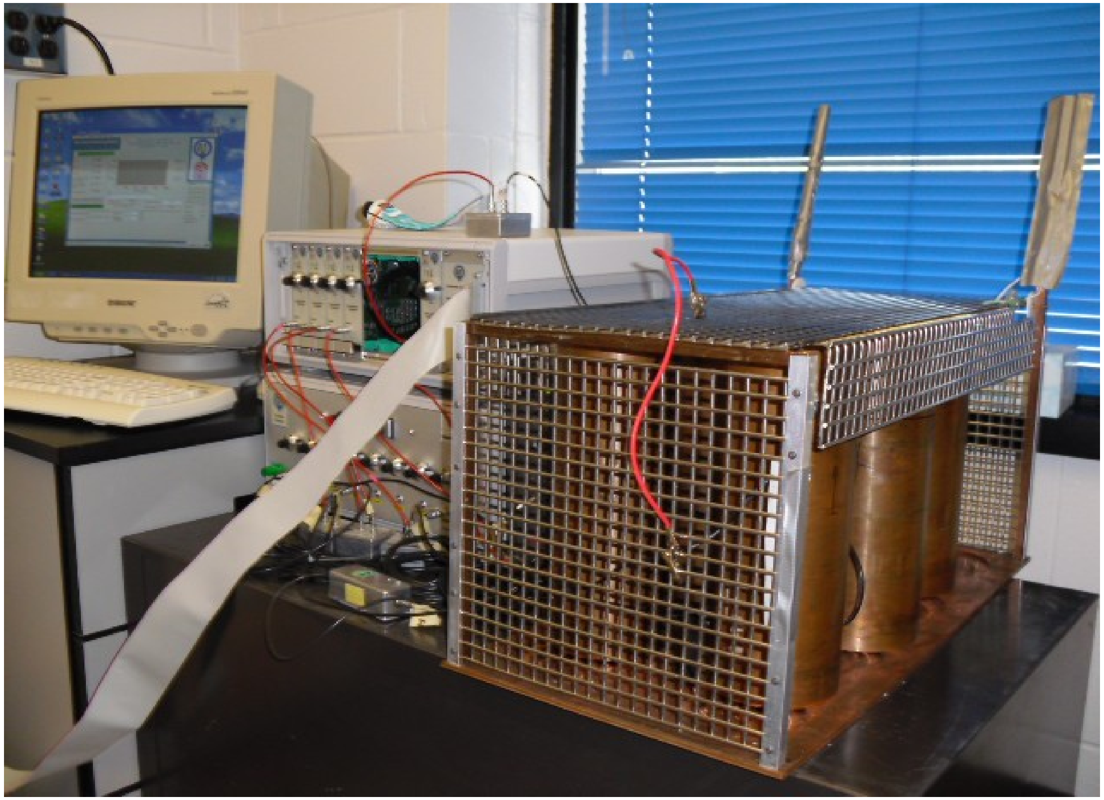
Sensitivity Levels are:

- ^{222}Rn: 10^{-14} gU/g
- ^{224}Ra: 10^{-15} gTh/g
- ^{226}Ra: 10^{-16} gU/g

Work is ongoing to improve sensitivity even further.

9 counters located at SNOLAB,
1 on loan to LBL,
1 on loan to U of A,
1 remains at U. of Guelph

Alpha Beta Counting System

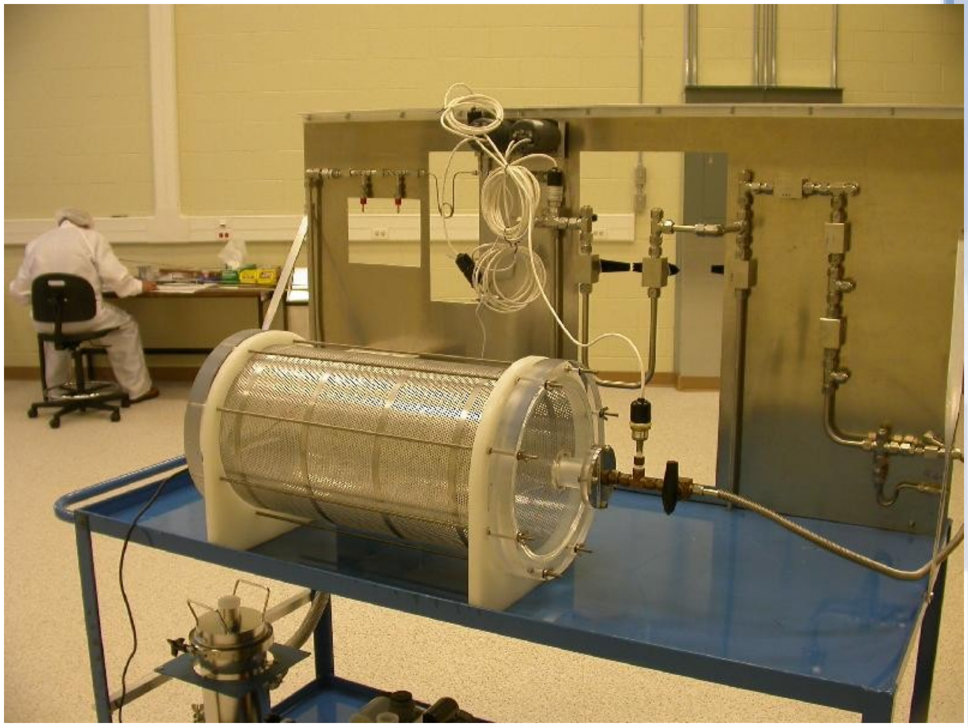


Currently located at the SNOLAB hot lab at LU so that spike sources can be measured.

Sensitivity for ^{238}U and ^{232}Th is ~ 1 mBq assuming that the chains are in equilibrium.

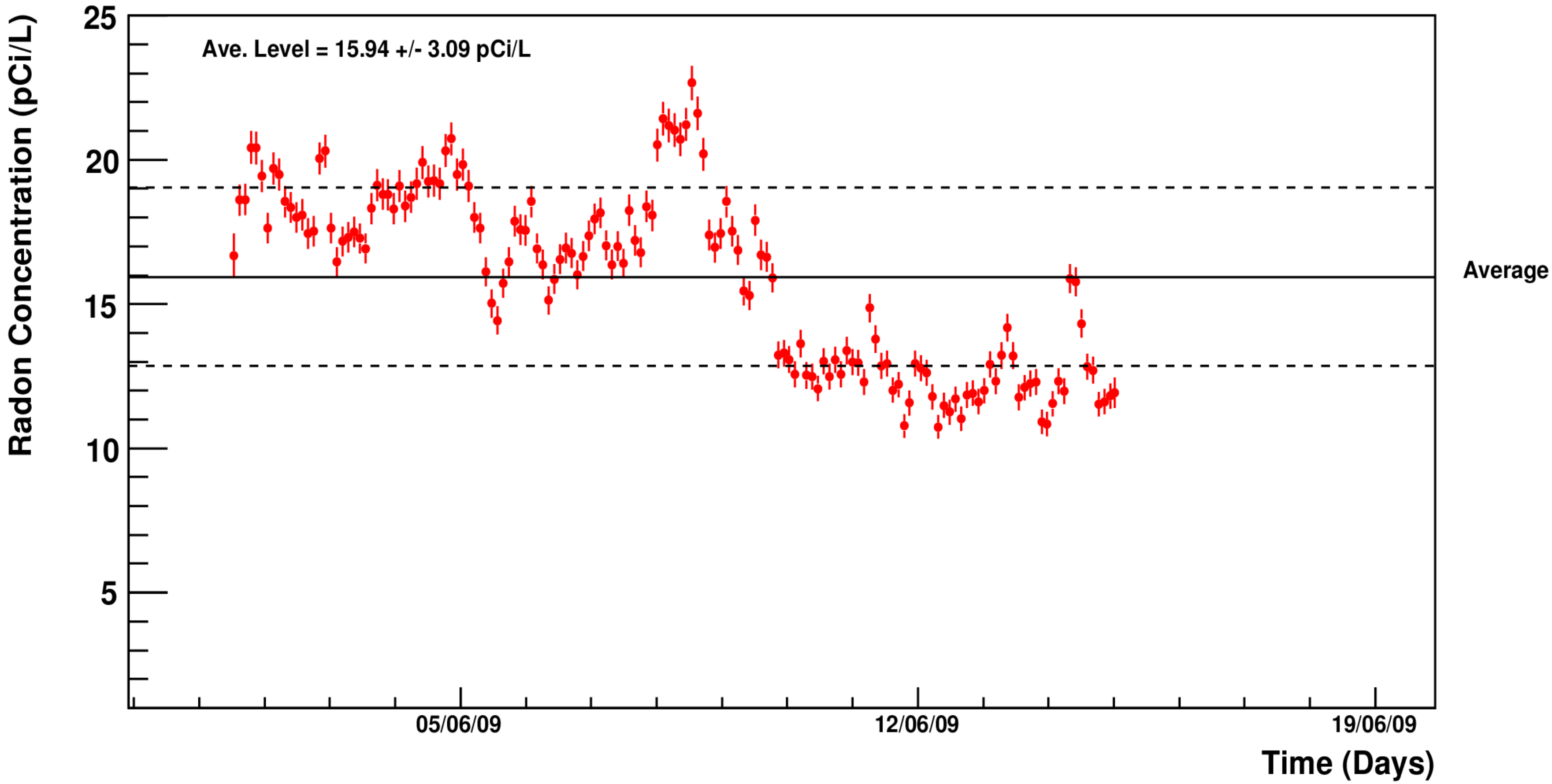
Material Screening

- **Radon Emanation Chambers**
  - Used extensively for counting materials used in the SNO ex-periment.
  - sensitivity ~50 decays per day.
- **ICP-MS**
  - Association with facility at NRC (National Research Council) ICP-MS facility in Ottawa and with GeoLabs in Sudbury.
  - NRC facility can be tuned to maximize sensitivity to U and Th at sub ppt levels. K limits to < 100 ppb.



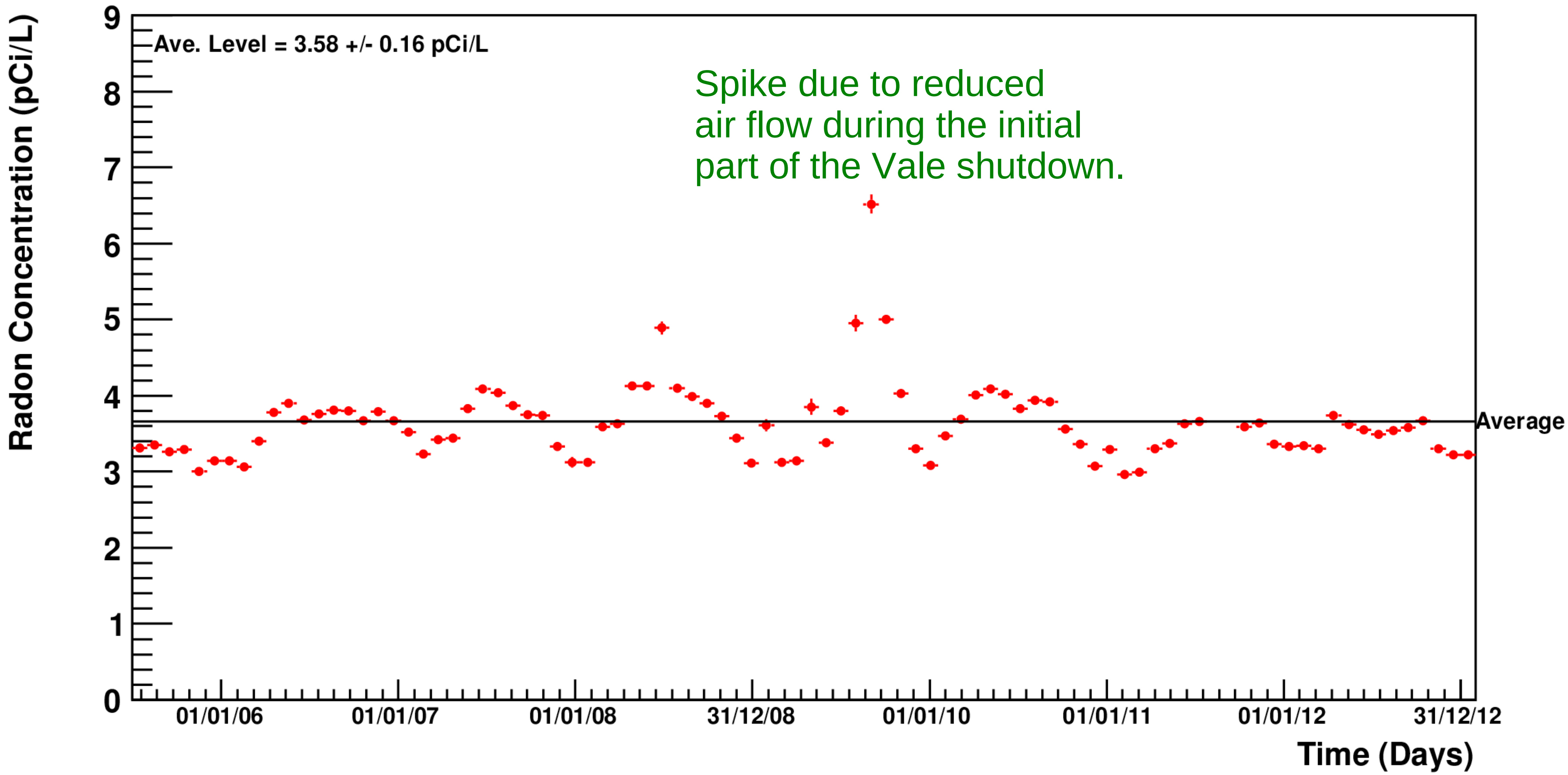
SNOLAB Radon Levels Without Fresh Air

Radon levels: 15.94 ± 3.09 pCi/L or 589.8 ± 114.3 Bq/m^3.

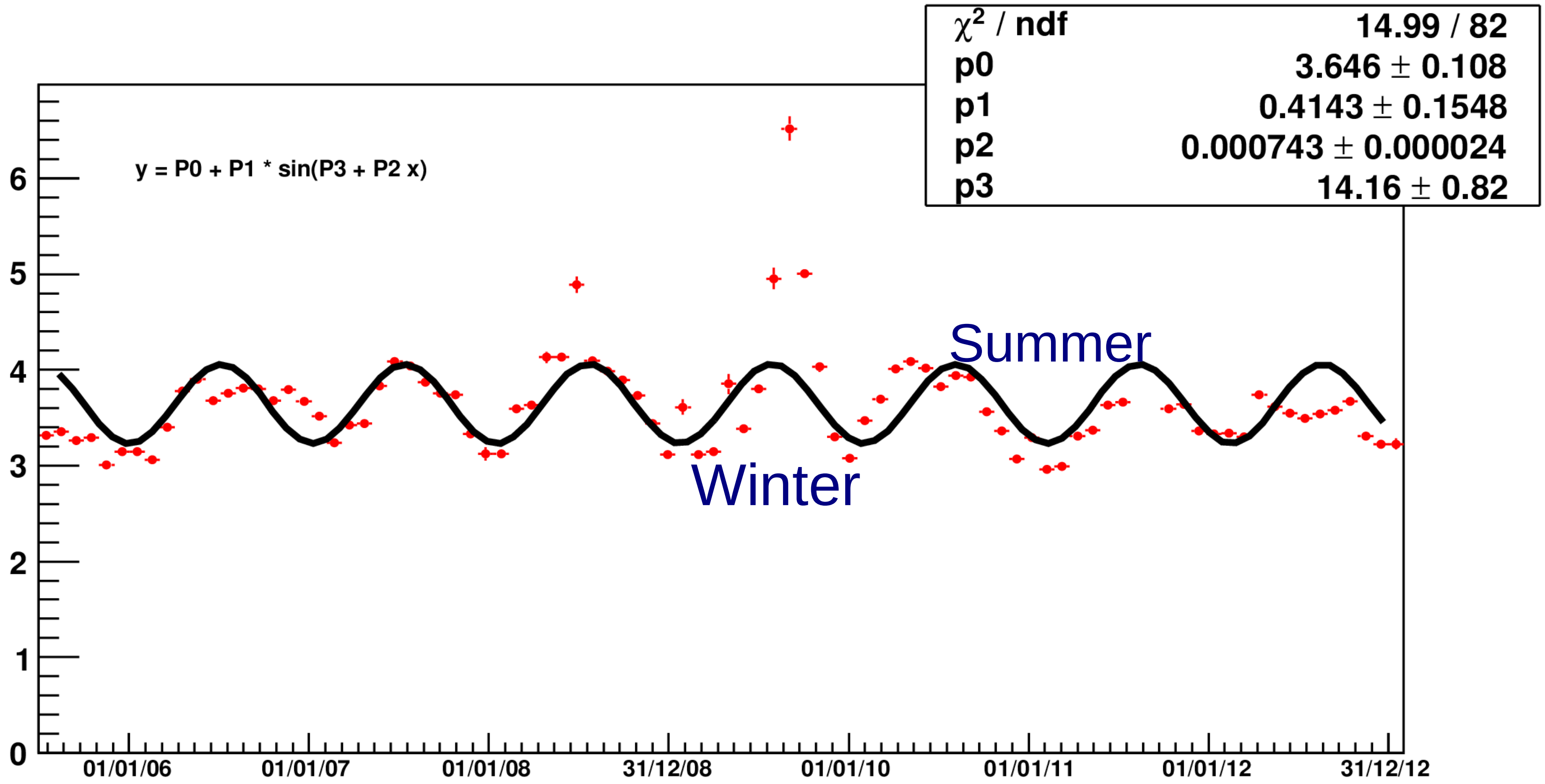


Radon Levels at SNOLAB With Fresh Air
(Normal Laboratory Operating Conditions)

Radon continuously monitored for the several years now.
Radon levels are: 3.58 ± 0.16 pCi/L or 129.5 ± 5.9 Bq/m^3.



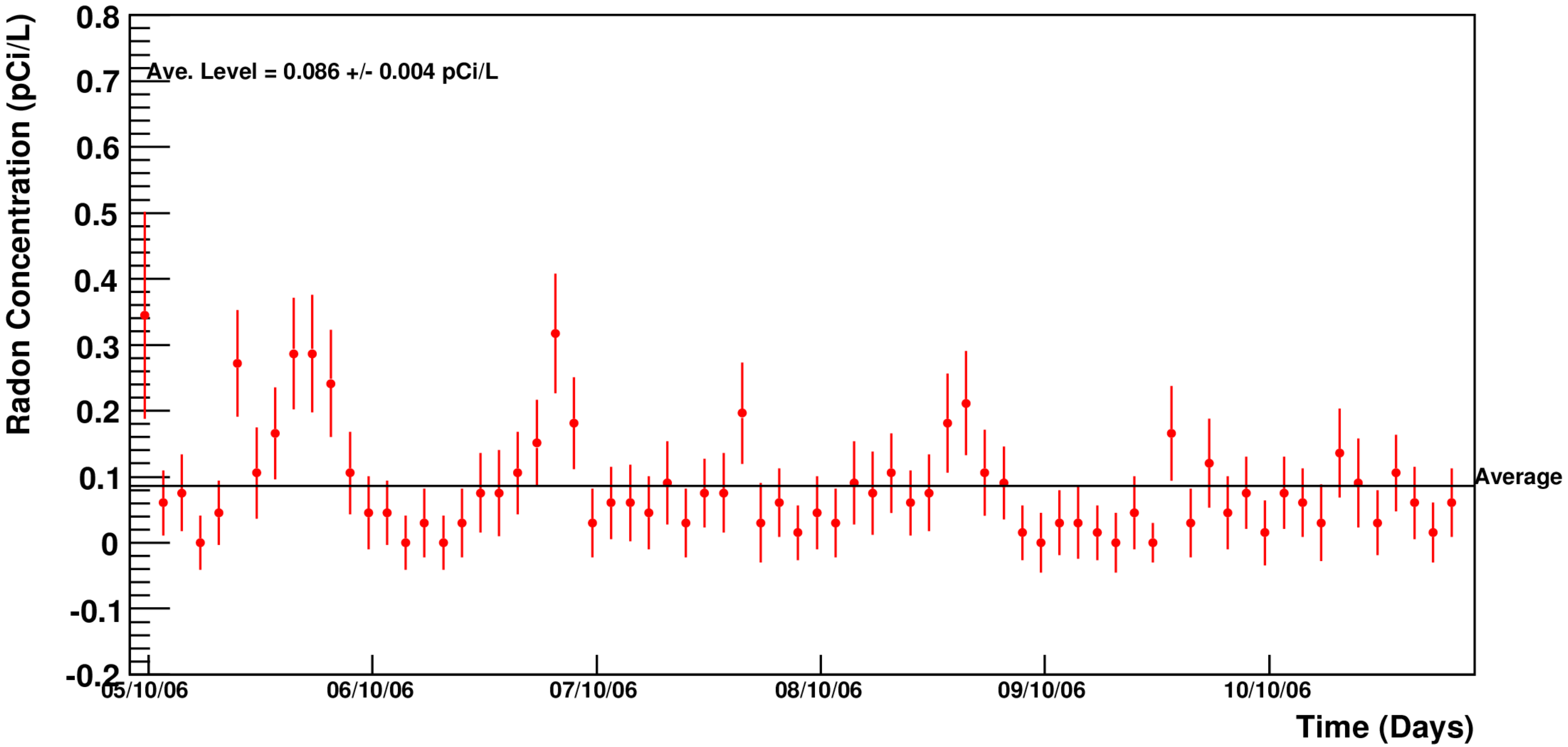
Radon Level Annual Cycle



The annual cycle corresponds to 363.21 +- 29.73 days, the expected cycle is one year.

Achievable Radon Levels
Using Compressed Air Supplied From Surface

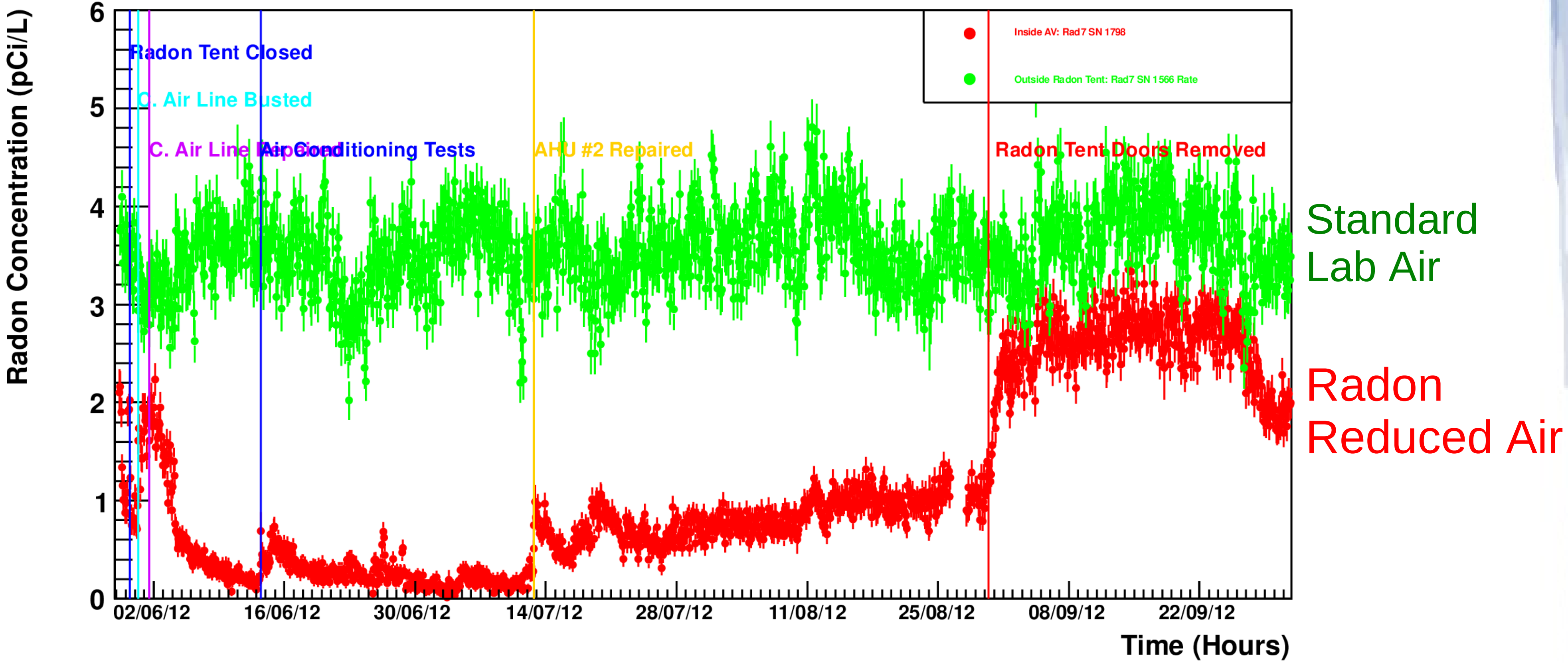
Radon levels: 0.086 ± 0.004 pCi/L or 3.18± 0.15 Bq/m^3.



To use this air, specialized filters have to be used to ensure that all particulate matter is removed from the air before it is used.

To achieve lower levels of radon, radon scrubbing systems would have to deployed.

Radon Reduction Room
(SNO+ Experiment)



With proper controls the radon levels can be reduced to that of the input compressed air.

Future Low Background Counting At SNOLAB

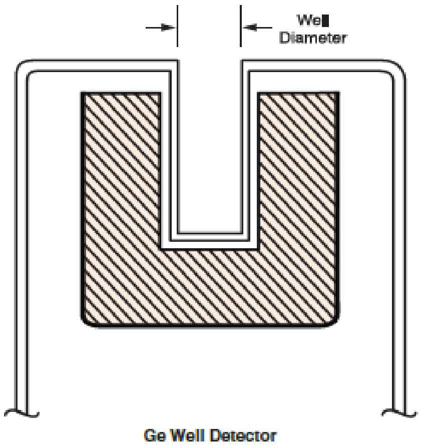
Two new low background high purity Ge Counters were ordered from Canberra

One counter is a p-type coaxial detector and the other is a well detector. Canberra also supplied a specially built shield for the well detector.

However, the well detector would not fit in the supplied shielding setup as the base of the well detector was too large for the copper disks and the vacuum tube connecting the dewar with the detector was too short for the shielding thickness.

The well detector was sent back to Canberra to be rebuilt to fit the shielding, the detector is now back at SNOLAB and being characterized.

The shielding was slightly modified to allow the coax detector to fit so that the coax detector could be tested.



Future Low Background Counting At SNOLAB

The well detector shielding was slightly modified to allow the coax detector to fit so that the coax detector could be tested.

The coax detector was then run inside the well detector shielding to characterize the backgrounds in the hope the detector has backgrounds less than the PGT detector, which we used as the basis for maximum background requirements.

However, it was determined that the coax detector is anything but low in backgrounds. It has substantial amounts of ^{232}Th and ^{235}U, the other backgrounds are similar to those observed from the PGT counter.

Future Low Background Counting At SNOLAB
Canberra Coax Detector

The background levels for a true ultra-low background detector should be no more than 100 counts/year from U and Th chain events.

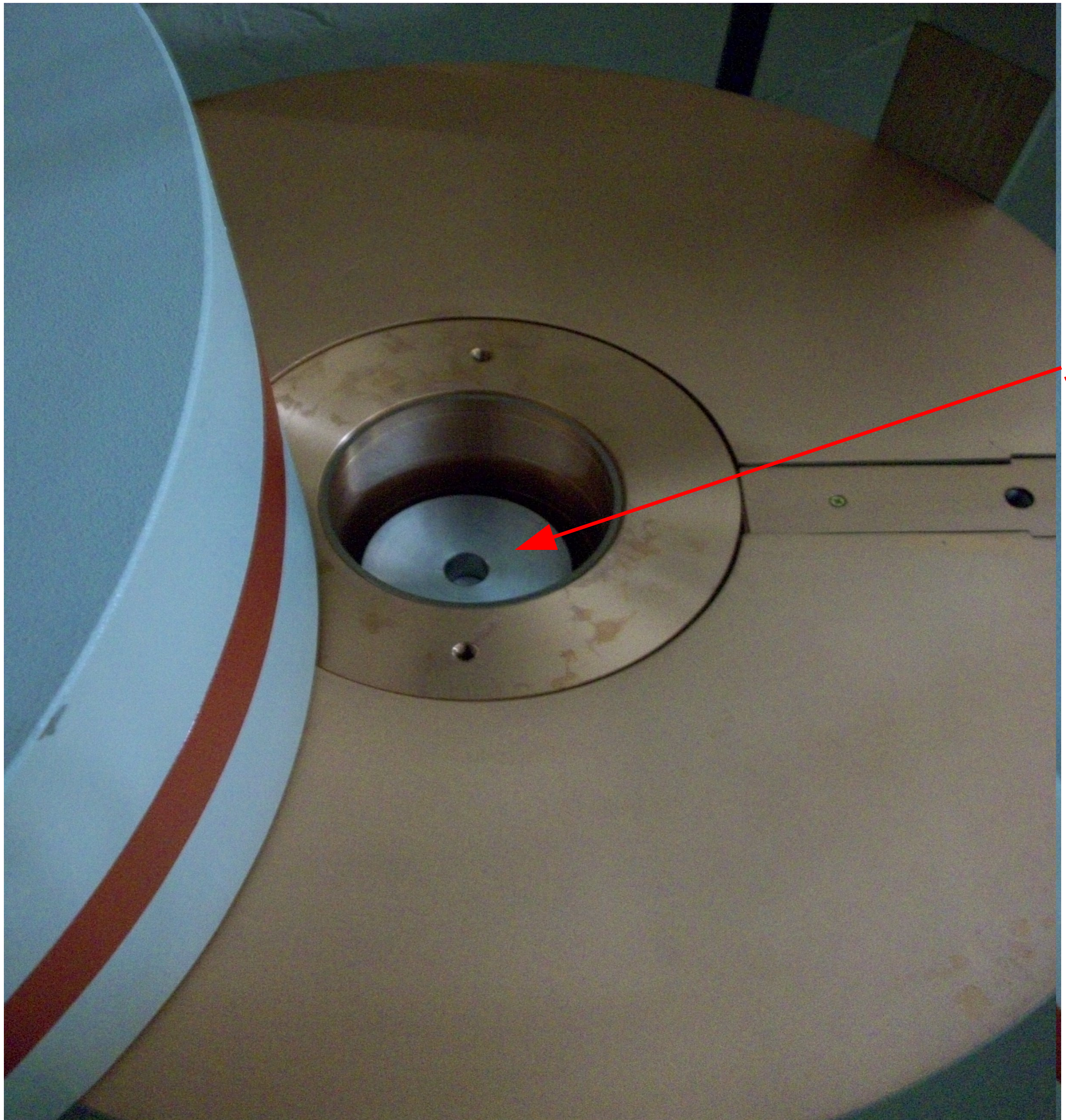
The activities present are:

- ^{228}Th progeny at 30 counts/day
- ^{228}Ra progeny at 30 counts/day
- ^{238}U progeny at 500-600 counts/day, although below ^{226}Ra the rate is only about 5 counts/day.
- ^{40}K at 18 counts/day

Canberra has sent SNOLAB many components to determine where this background is coming from, but so far there is no smoking gun. The Coax detector is now at Canberra being refurbished in a similar manner as the well detector.

Canberra Well Detector at SNOLAB

Canberra Well Detector at SNOLAB

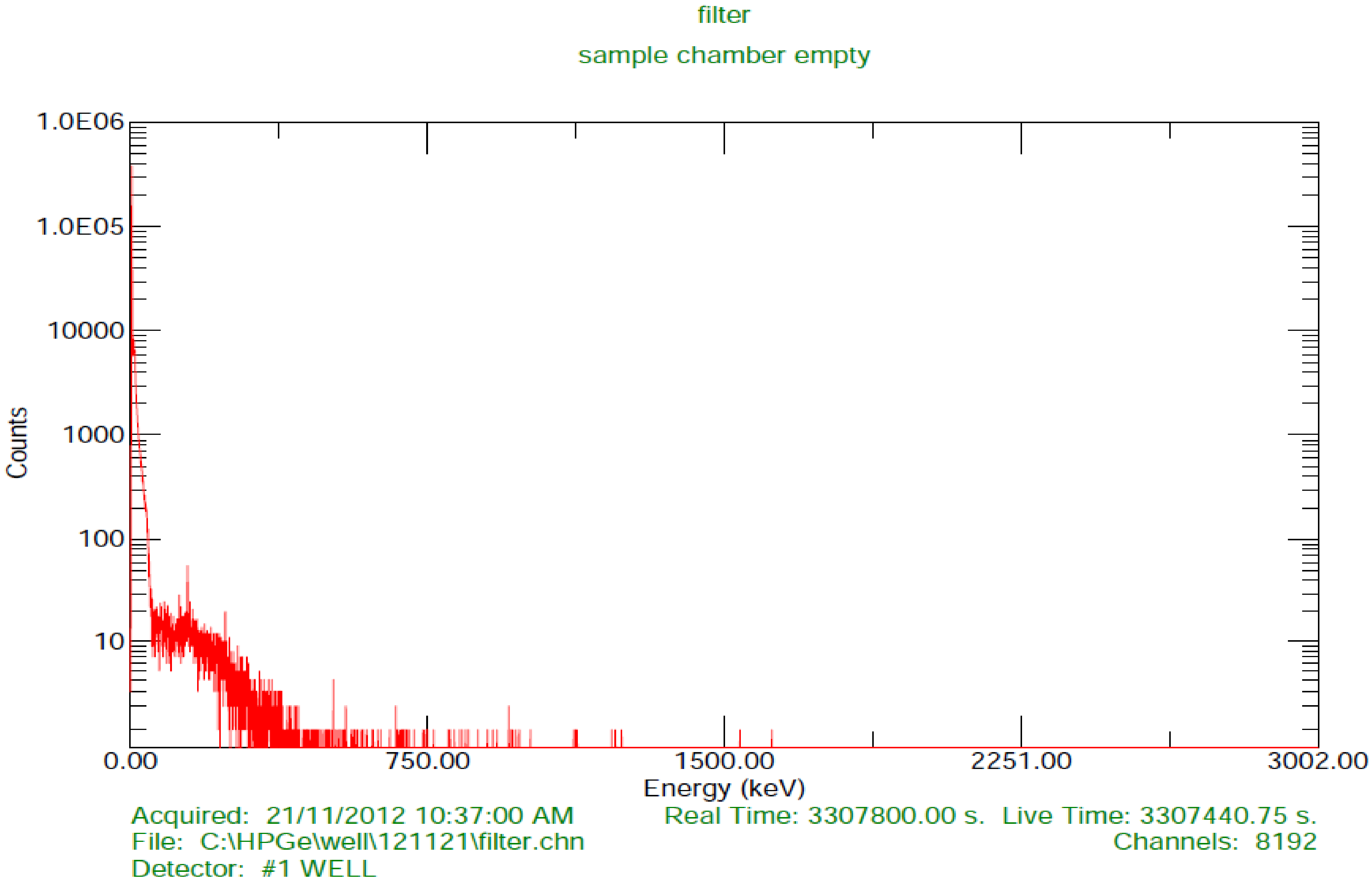


Sample Well

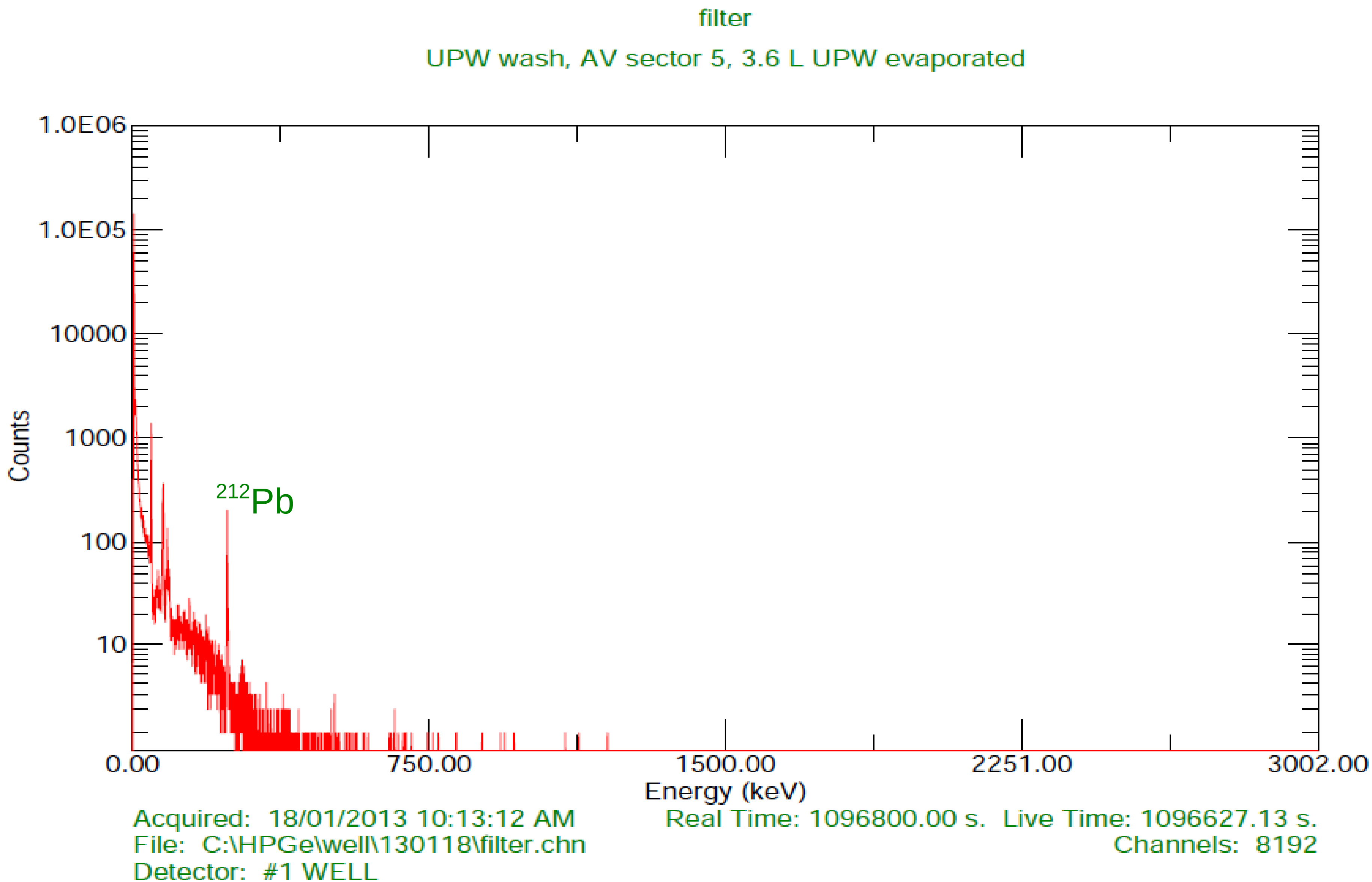
Sample Bottle

Volume is 3 ml

Well Detector Background Spectrum



Well Detector Example Spectrum
(Concentrated Water Sample from SNO+ Acrylic Vessel)



Canberra Well Detector Status

- Background run completed (38 days).

  ^{238}U 0.029 ± 0.058 decays per day (10.59 ± 21.17 decays per year)

  ^{232}Th 0.048 ± 0.063 decays per day (17.52 ± 23.00 decays per year)

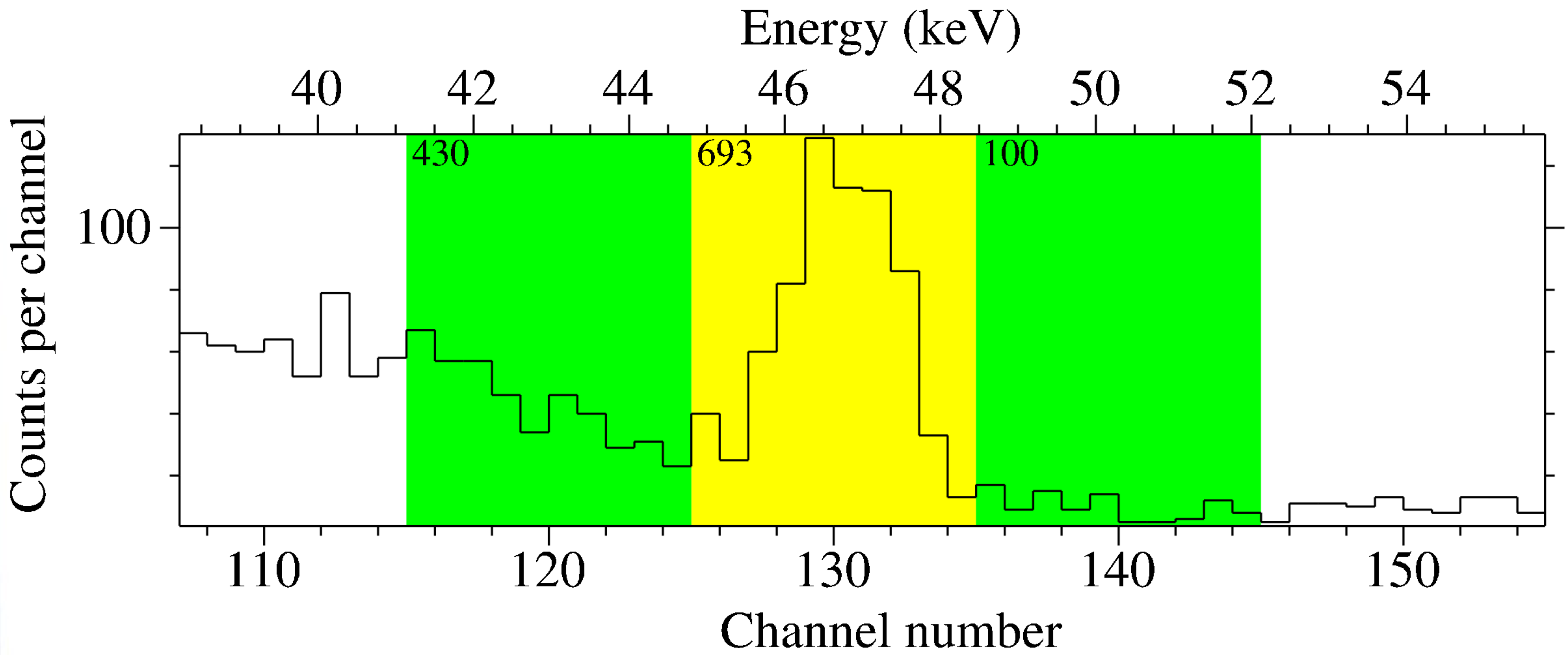
  ^{40}K 0.0 ± 0.02 decays per day (0.0 ± 7.3 decays per year)

  ^{210}Pb not observed

  Total backgrounds at the level of 30 counts / year.

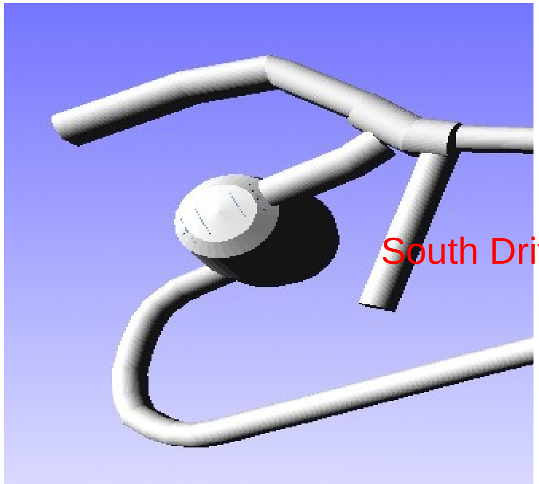
- Calibration source approval is nearly completed, therefore efficiency and background can be calculated for each gamma soon.
- Samples for SNO+ and DEAP have been counted, final results awaiting efficiency measurement.
- Ability to measure small samples, sensitive to gamma energies between 10 keV and 300 keV, therefore can measure several gammas from ^{238}U, ^{235}U and ^{232}Th but not very sensitive to ^{40}K.
- Ability to directly measure ^{210}Pb.

^{210}Pb Measurement



Concentrated sample of leachate from SNO+ Acrylic Vessel

SNOLAB Low Background Laboratory
(under construction)



A new dedicated space is being constructed at SNOLAB for a low background lab located in the South Drift (former refuge station).

This drift is somewhat isolated from other drifts and is inaccessible to large equipment (fork lift). This will help reduce micro-seismic noise which can effect Ge detectors.

Increased air flow and perhaps other radon reduction techniques will be used. It is known that the compressed air from surface has substantially less radon than the lab air and can be used to reduce radon levels from 135-150 Bq/m^3 to 1-5 Bq/m^3.

Space can accommodate 3-5 Ge detectors, XRF, radon emanation chamber and have room for other types of counters which would benefit from low-cosmic ray background.

Ongoing Improvements and R&D

- Improved neutron shields (detector response, spectrum)
- Improved material selection (more sensitive, better radiopurity e.g. PbWO4 with archaeological lead)
- Active shielding
- Going deeper underground
- Storage of freshly made construction materials underground
- Multisegmented crystals or multiple crystals
- Collaboration with producers (e.g. depleted Ge, crystal growing, Cu electroforming underground)
- The "ultimate" ultra-low background facility

Ongoing Improvements and R&D

- Future experiments need more sensitive screening techniques (< µBq/kg for 226Ra) ⇒ use of today's (e.g. CTF) or tomorrow's (e.g. GERDA) most sensitive detectors for screening.
- Future experiments need dedicated and highly sensitive screening and test techniques for measuring and monitoring surface contaminations (development and adaptation of existing techniques and methods to need, e.g. LA-ICP-MS).
- Reorganisation and optimisation of existing screening facilities is necessary, because they are costly and measurement times can be rather lengthy.
- Harmonisation of how to report data and intercomparison programs for ultra low-level measurement techniques.

Research Applications

- Ultra low-level chemistry
- Particle astrophysics (material and techniques applicable to rare events experiments)
- Space science (e.g. micro meteorites, Mars samples, cosmic activation products, comet tail samples)
- Atmospheric samples ((very) short lived isotopes, radionuclide composition, stratospheric samples)
- Ocean samples (e.g. deep ocean water - ^{60}Fe)
- In general application of low background techniques to interdisciplinary fields:
  - Low-level environmental radioactivity measurement and monitoring
  - Radiodating (extension of determined ages towards the past)
  - Geophysics (palaeoseismology, palaeogeology, sedimentation)

Common Database

- Currently each counting group has separate databases, some are public and some are very private.
- Common goal of low background counting groups is to have a common database assessable to anyone interested in low background studies, with as much data available as possible.
- Standardize units to mBq/kg.
- The AARM working groups meet regularly and it is expected that by LRT2013 that the database will be up and ready to add data.
- Ongoing work to determine what the best software is for the database, currently planning to use CouchDB.
- Database could be hosted by Cloudant with backup databases expected to be at SNOLAB with at least two other sites.

Summary

- SNOLAB PGT HPGe low background counting system has run continuously for the past since 2005 and has counted 350 samples so far.

  Counting queue is long at ~10 samples, this sometimes limits when samples can be counted in a timely manner.

  The counter(s) is available for all SNOLAB experiments and can be made available to non-SNOLAB experiments upon request (eg. DM-ICE).

- Two new Canberra Ge detectors were delivered to SNOLAB, but need refurbishing since they are not ultra-low background as expected.

  The new counters should allow much higher sensitivity, effort underway to ensure all materials are low background. The well detector will be used for very specialized small samples such as vapourized acrylic.

- Specialized counting can be done using the ESC or Alpha-Beta Counters and materials can be emanated for Radon.
- New low background counting lab is being constructed at SNOLAB, final preparations are now underway.