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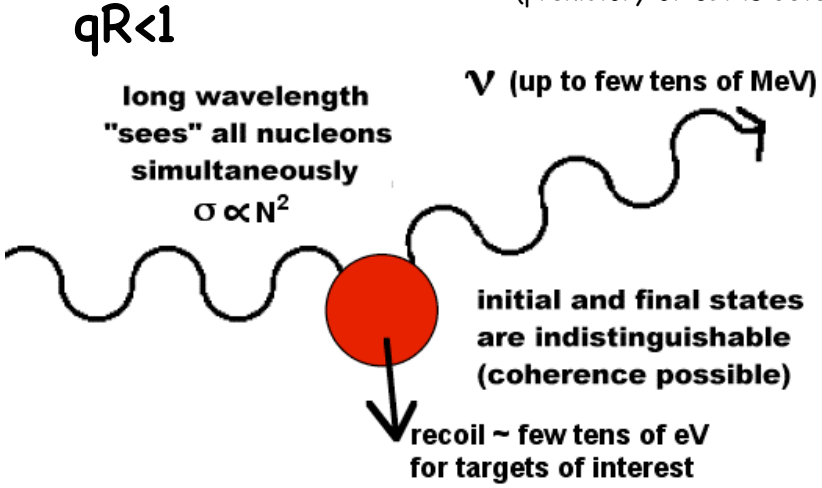
(low-E recoils lose only 10-20% to ionization or scintillation)

- Cryogenic bolometers and other methods proposed, no successful implementation yet

Cabrera, Krauss & Wilczek
Phys. Rev. Lett. 55, 25-28 (1985)
(prehistory of CDMS detectors)



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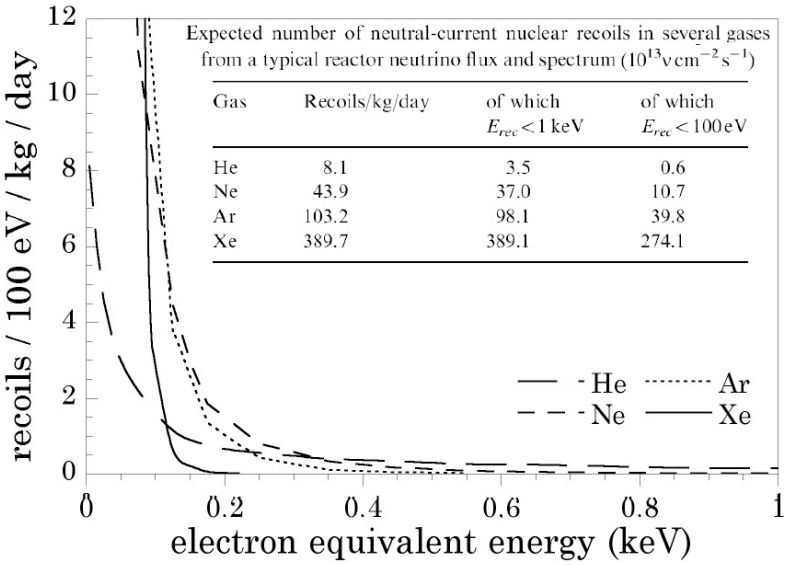

Expected number of neutral-current nuclear recoils in several gases from a typical reactor neutrino flux and spectrum ($10^{13}\nu\,cm^{-2}s^{-1}$)

Gas	Recoils/kg/day	of which $E_{rec}<1$ keV	of which $E_{rec}<100$ eV
He	8.1	3.5	0.6
Ne	43.9	37.0	10.7
Ar	103.2	98.1	39.8
Xe	389.7	389.1	274.1

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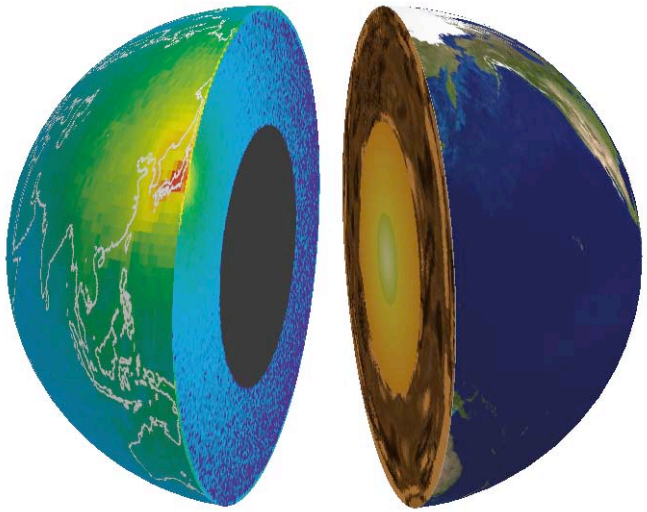

2005: Geoneutrinos detected.

Dawn of the applied neutrino physics era?

Applied Anti-Neutrino Physics Workshop
http://www.llnl.gov/neutrinos/workshop/aap2006.html

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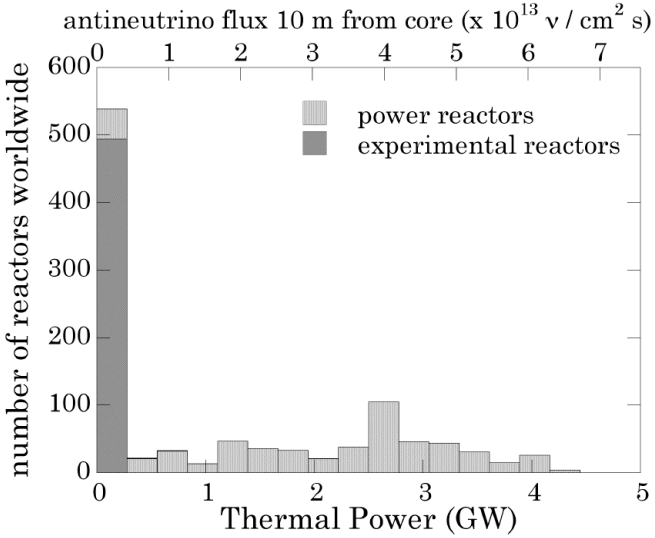

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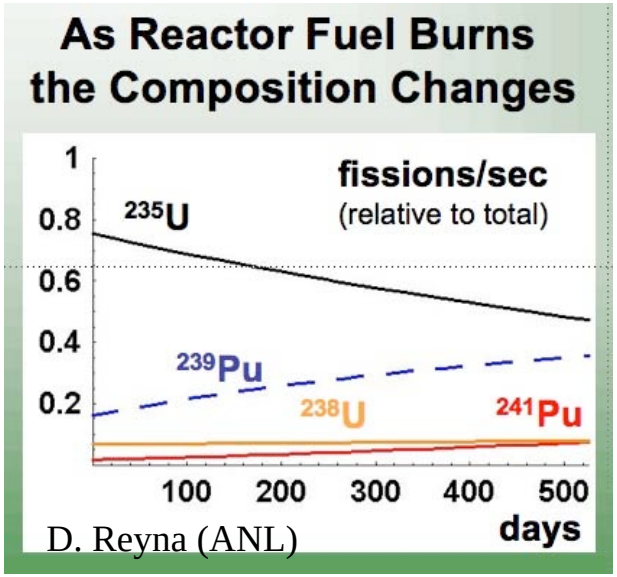

D. Reyna (ANL)

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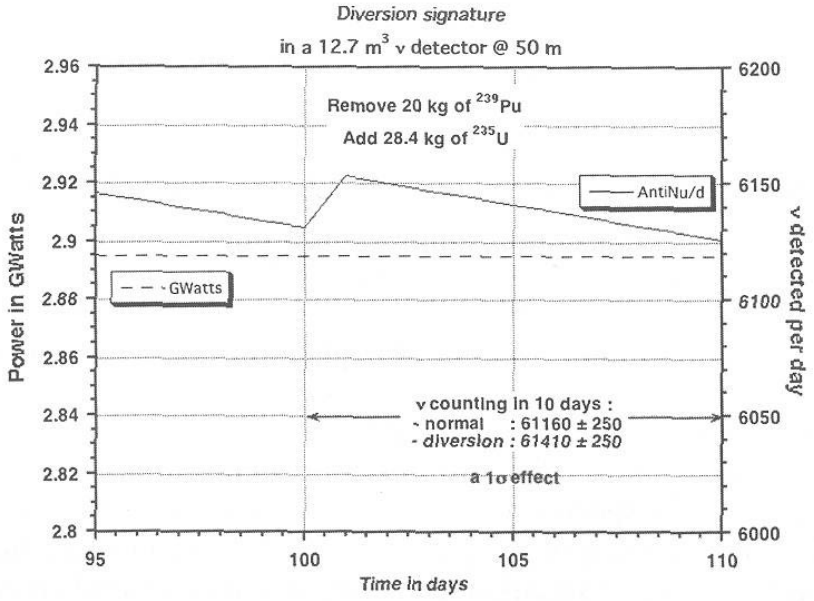

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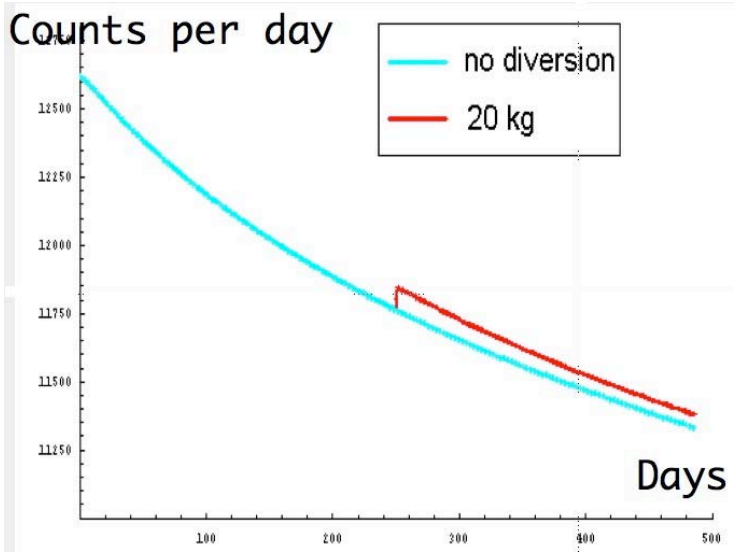

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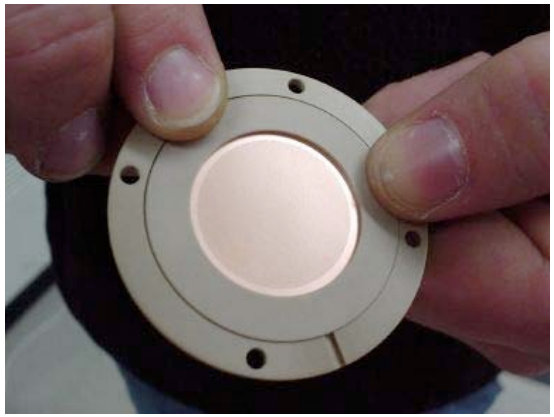
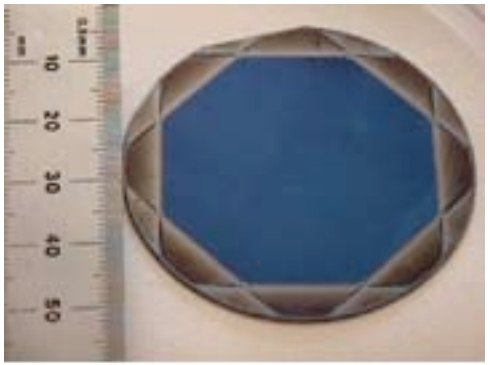
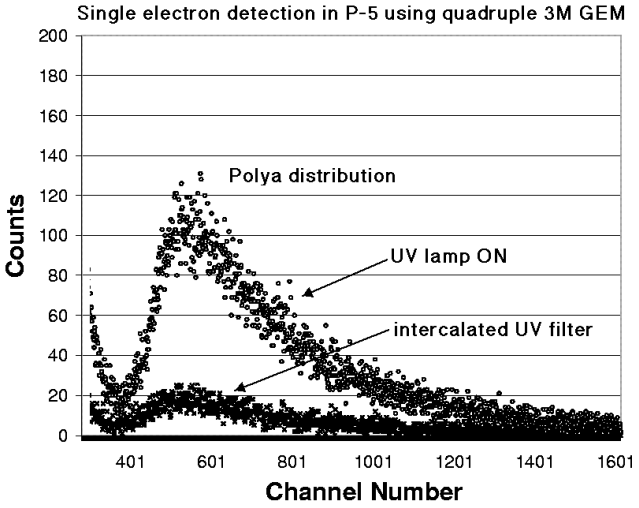
Three legged stool needed: mass, threshold, background



No "light-bulb" moment:
5 years of R&D at UC

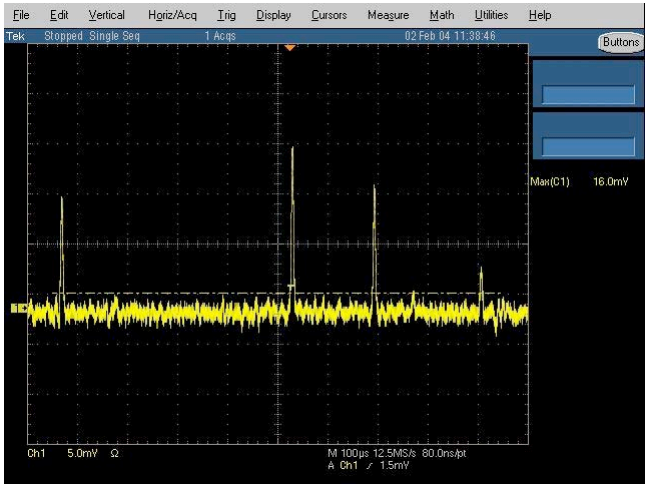


13 cm^2 APD on a 2 inch diameter silicon wafer



name-of-the-game:
detection of << 1 keV recoils with large (> 1 kg) detectors

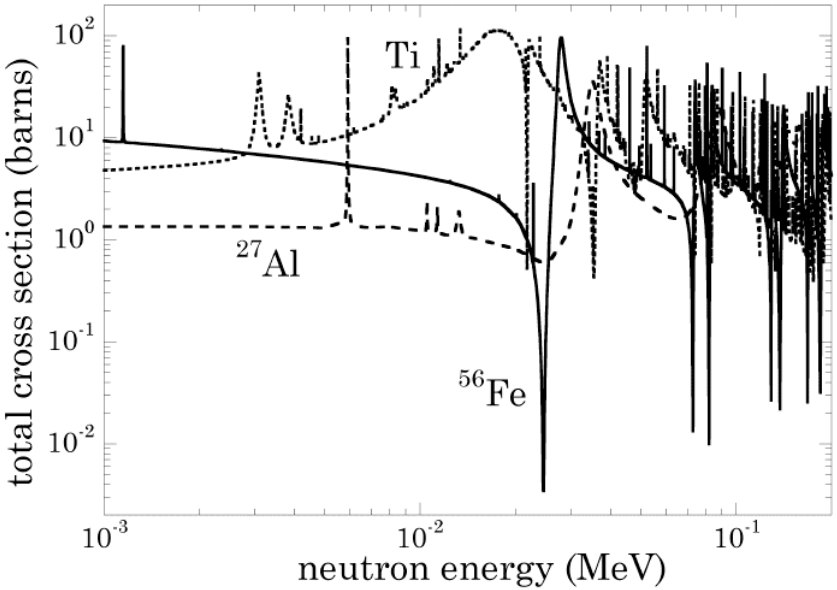
(25 y and counting... must use new technologies or at least alterations)



Mass-produced 3M-UoC GEM and single-electron signals from quadruple GEM

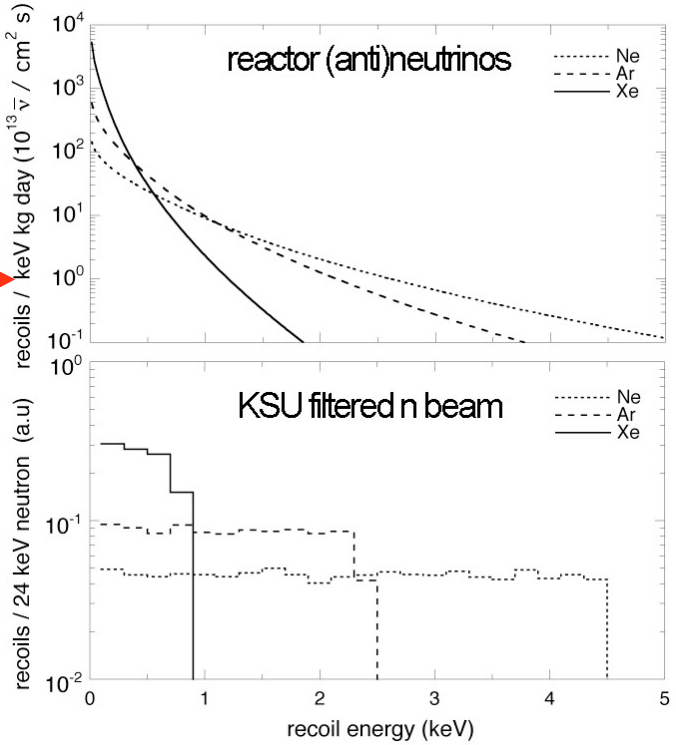
Single-photon pulses using LN_2 cooled LAAPDs (high QE)

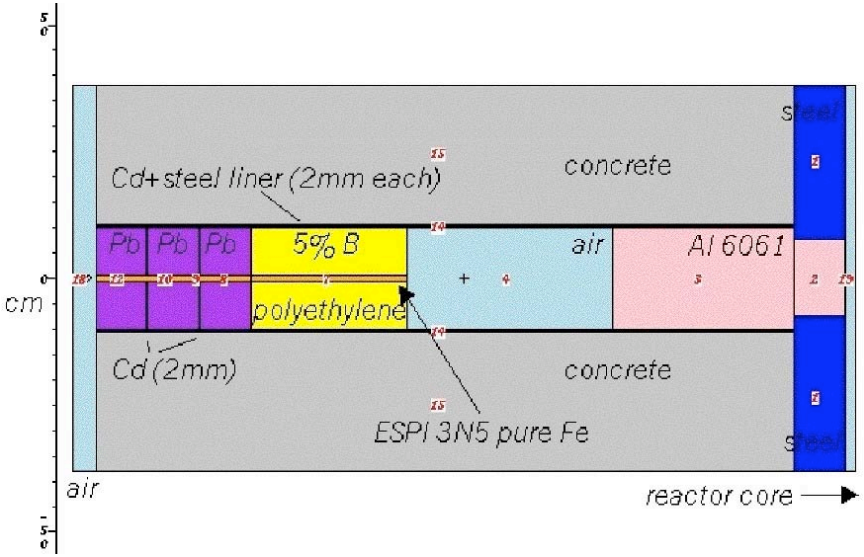
Start with the foundations:
ultra low-energy recoil calibrations at KSU reactor



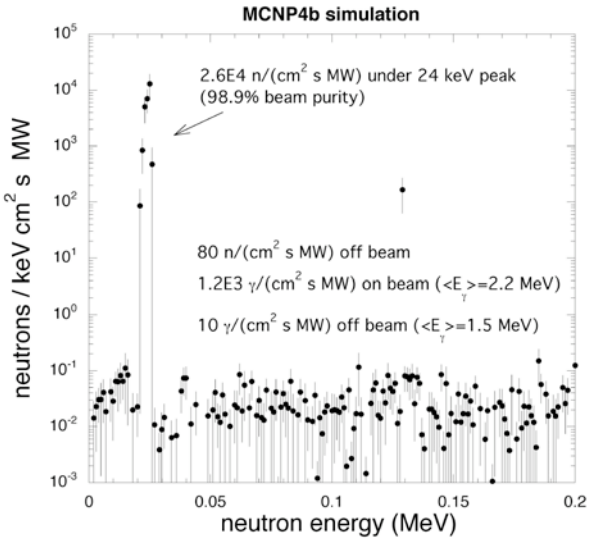
24 keV n's mimic reactor ν's

Fe-Al filter + Ti post-filter





MCNP filter design



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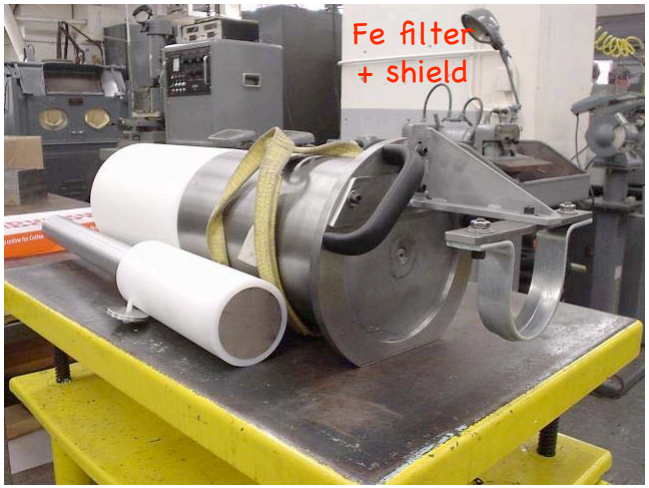
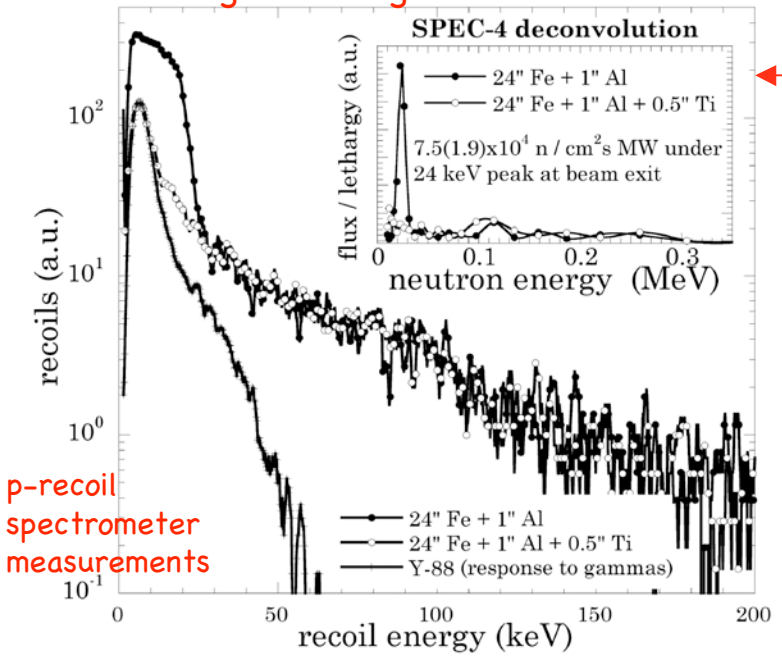


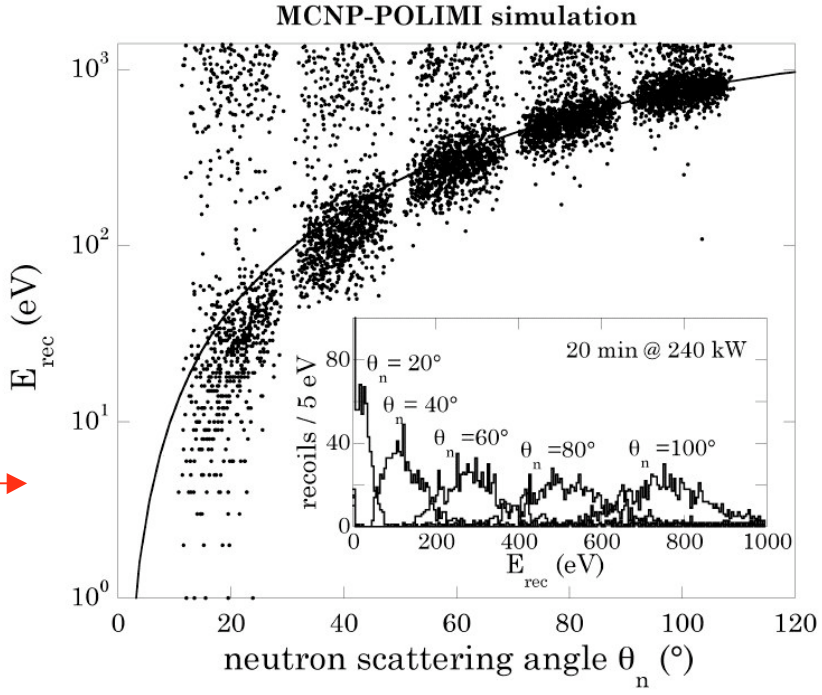
Ti post-filter "switches off" the recoils,
leaving all backgrounds unaffected



p-recoil
spectrometer
measurements

Beam
characterization
studies completed
2005
(nucl-ex/0701011)

Ideal to explore
sub-keV
recoil region



Modified-electrode p-type HPGe: A new tool in astroparticle & neutrino physics

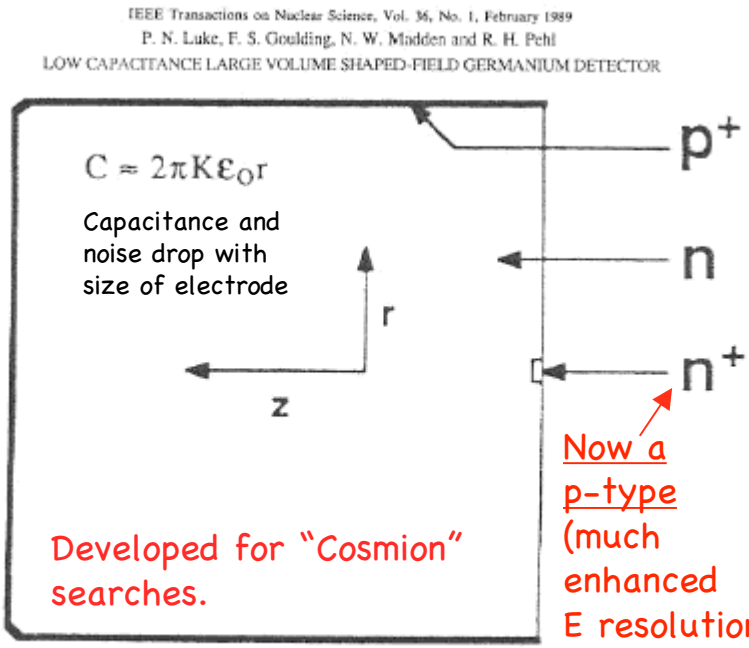


Fig. 3. Structure of the shaped-field detector.

Now a p-type (much enhanced E resolution, less sensitivity to low-E backgrounds)

1989 state-of-the-art in large HPGe noise:
300 eV FWHM (even with modified electrode)

The idea: we have gone a long ways in JFET technology

2005: (factor x10 improvement in JFET C_F and V_n)
~50 eV FWHM (same as C_D~1 pF x-ray detectors)

$$FWHM_{Ge} = 40.7\ eV \cdot V_n (C_F + C_D)/\sqrt{\Delta t}$$

~1985 **(TI 2N4416)** $C_F = 4.2$ pF, $V_n = 2$ nV/$\sqrt{Hz}$

2005 **(EuriFET ER105)** $C_F = 0.9$ pF, $V_n = 1.6$ nV/$\sqrt{Hz}$

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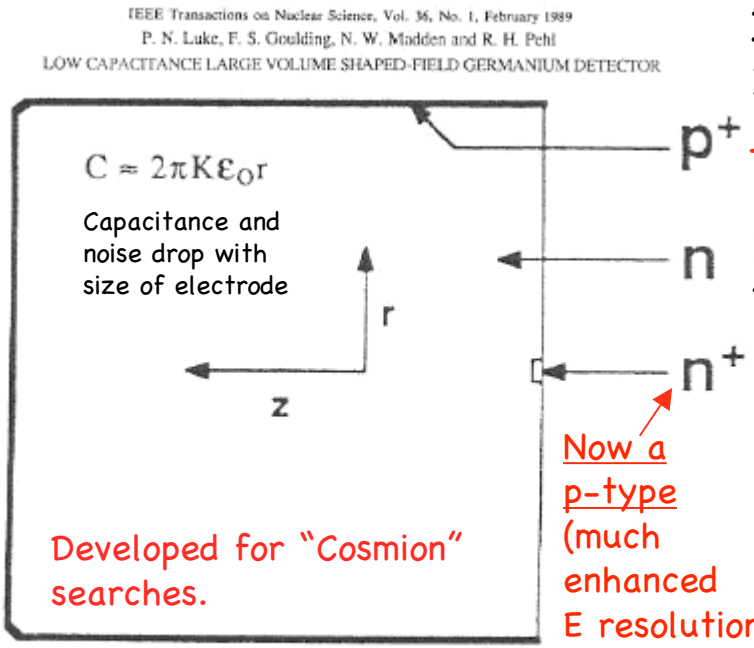

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Developed for "Cosmion" searches.

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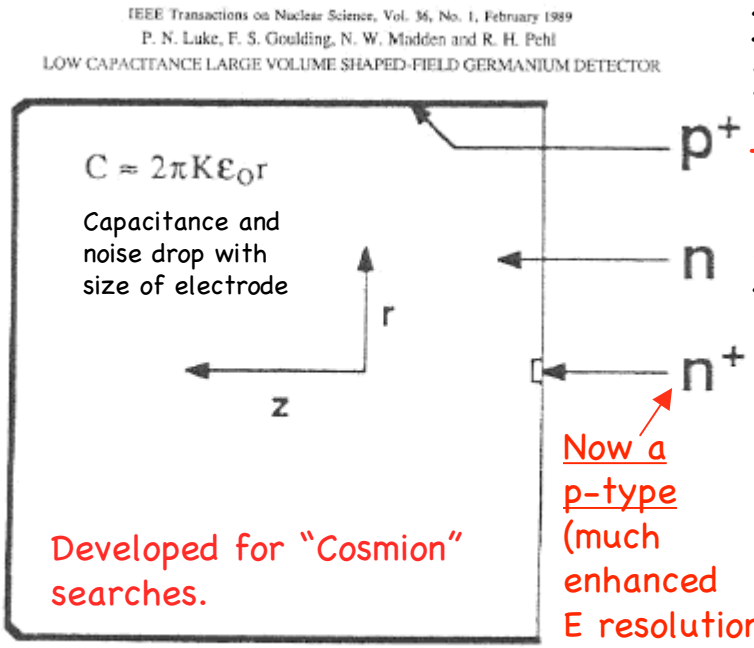
The energy resolution and large mass of a HPGe plus the noise and threshold of a tiny x-ray detector???

Modified-electrode p-type HPGe: A new tool in astroparticle & neutrino physics



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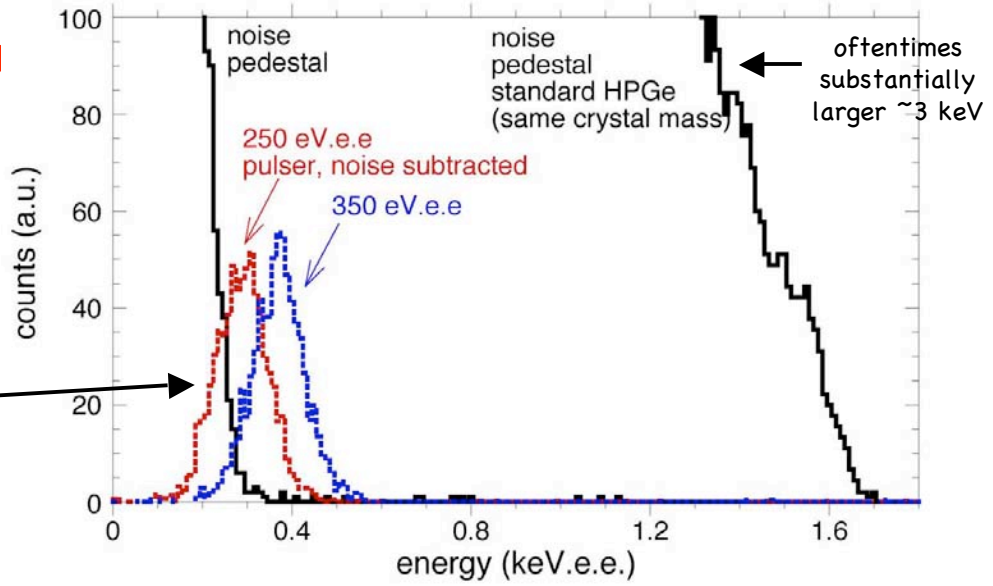
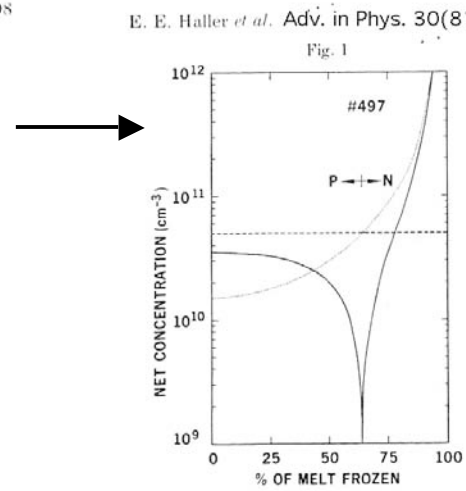
~x10 less noise than conventional HPGe of same mass (475 g) (threshold equivalent to 5 g x-ray detector)



Precise gradient of charged impurities along the axis needed to compensate for small electrode



Net-shallow level concentration $|N_A - N_D|$ along the growth axis of an ultra-pure germanium single crystal. At the seed end (0% of melt frozen) the aluminium acceptor dominates, yielding the crystal p-type. Near the tail end the phosphorus concentration exceeds the aluminium concentration. $|N_A - N_D|$: continuous curve; aluminium concentration: dashed curve; phosphorus concentration: dotted curve.

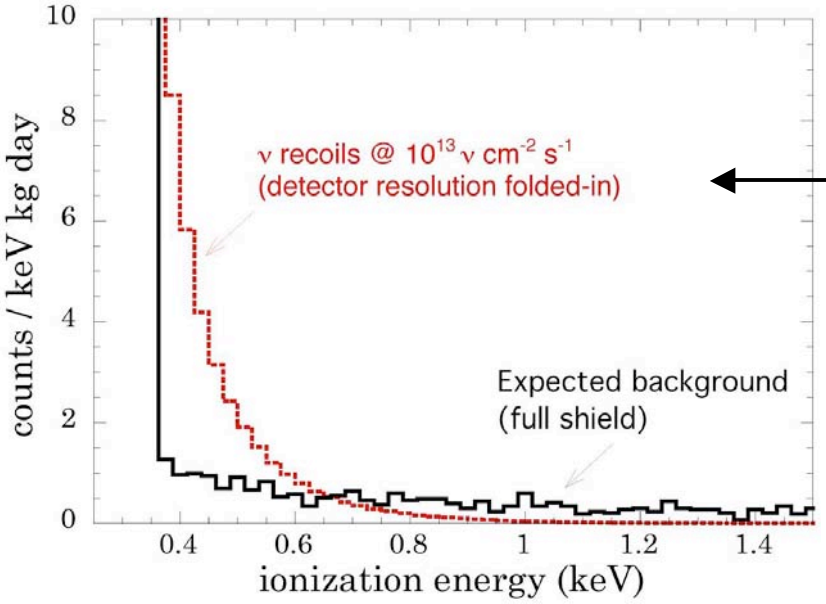
Delivered-To: collar@cfcp.uchicago.edu
Subject: Re: update?
From: otench@canberra.com
To: "Juan I. Collar" <collar@uchicago.edu>
Date: Sat, 3 Dec 2005 16:41:10 -0500
X-Uchicago-PMX-Id: 192.153.25.189: jB3LtheQ001154 [Sat Dec 3 15:55:44 2005]
X-Uchicago-Spam: Gauge=XXI, Probability=21%

Hello Juan,
We just got the first results in and they seem to be outstanding. The pulse resolution is about 160eV(FWHM) and Co-60 is well under 2.0 KV(FWHM). The detector should be shipping from France soon- in time for Christmas. It is too late now to change hardware but this mignt be done in future.

Best regards, Orren

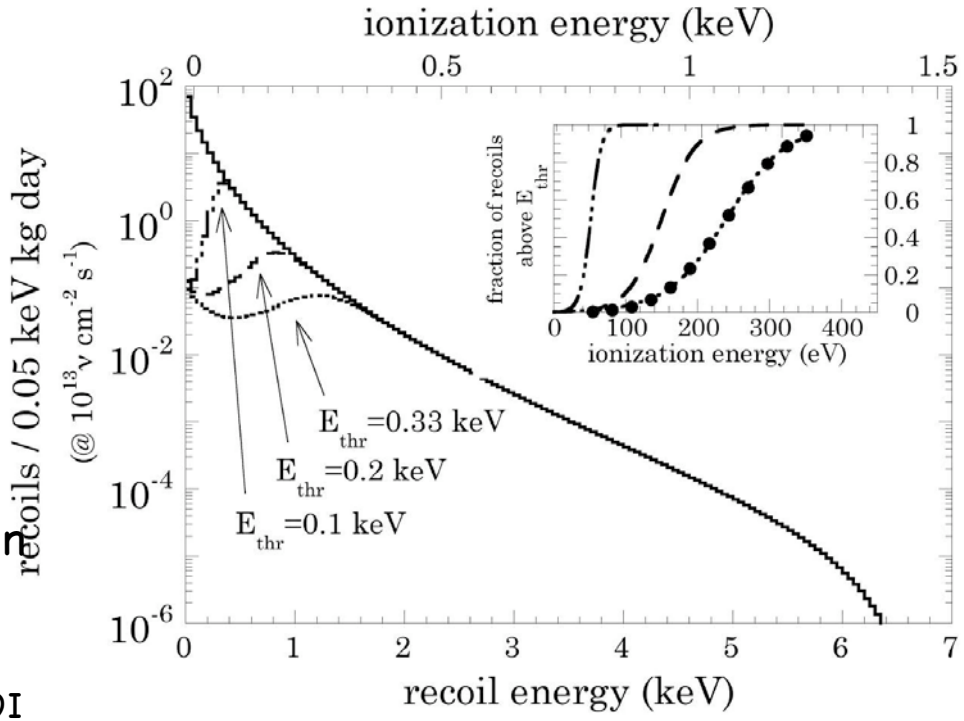
Developed during 2005
by CANBERRA/EURYSIS
(the one of three contacted companies up to the challenge)
Funded by NNSA.

Mass and threshold in place for reactor experiment,
background… almost there
(anti-Compton shield & Al part replacement underway)



Expected antineutrino signal in reactor experiment with present detector.
Background goal shown
(scaled down from present status)

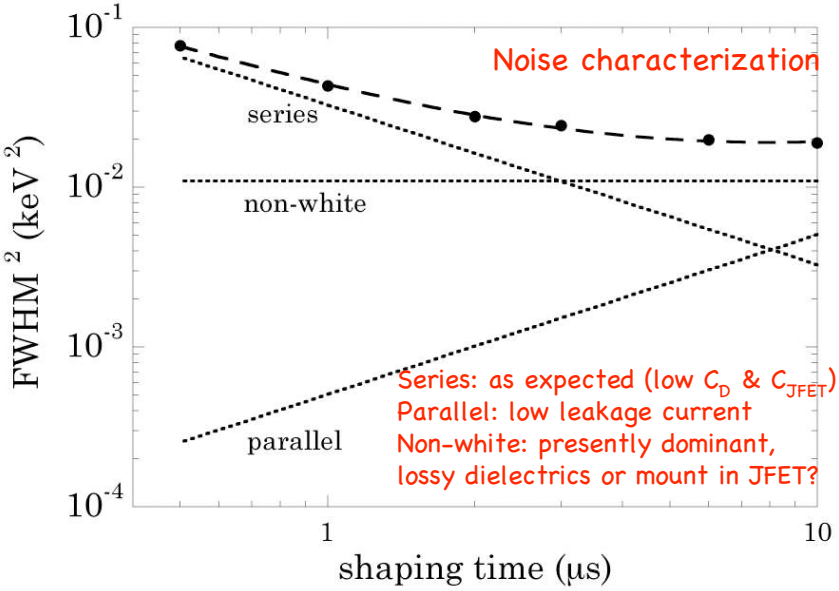
Presently 2.5 ν recoils/kg-day expected
Work on non-white noise can increase this to >30 ν recoils/kg-day
(limited beyond that by state-of-the-art in JFET noise only)

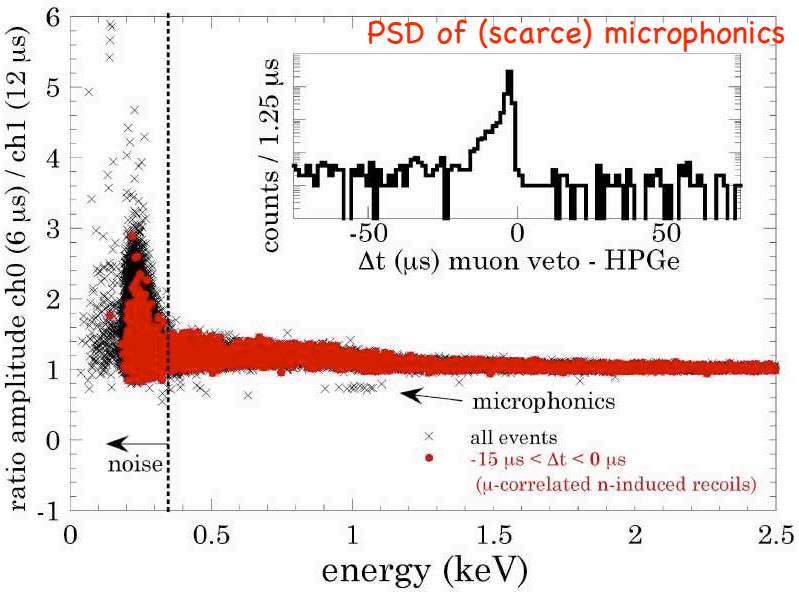


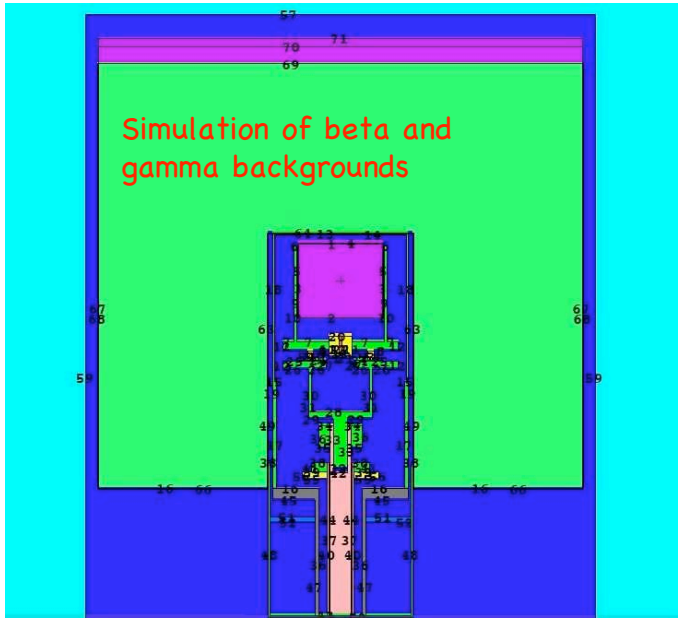
Silver lining: all of the signal concentrated in small ROI

Extensive detector characterization early 2006

(nucl-ex/0701012)





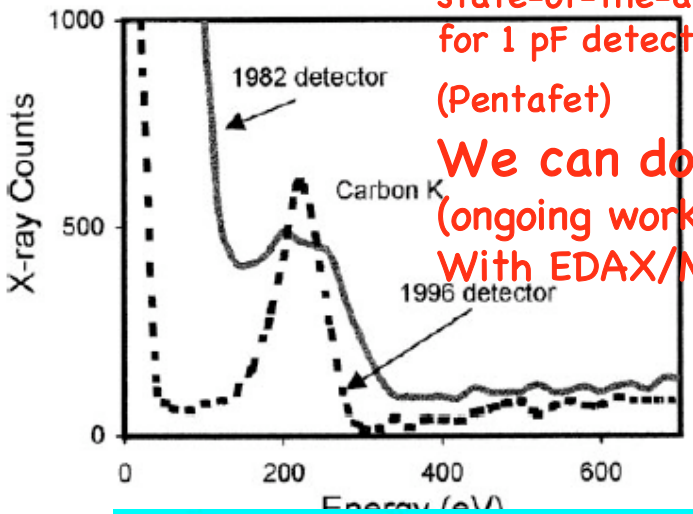


Shielding studies at 6 m.w.e. (comparable to reactor site)

FNA

Extensive detector characterization early 2006

(nucl-ex/0701012)

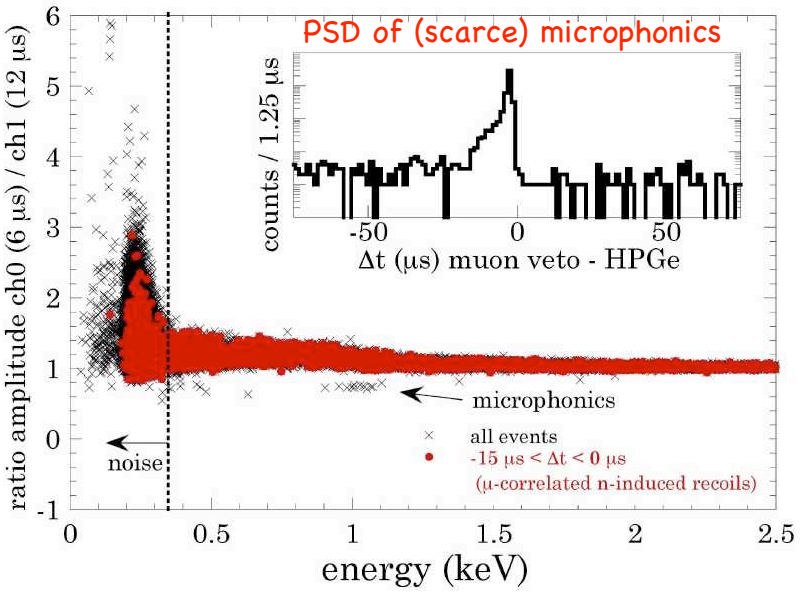


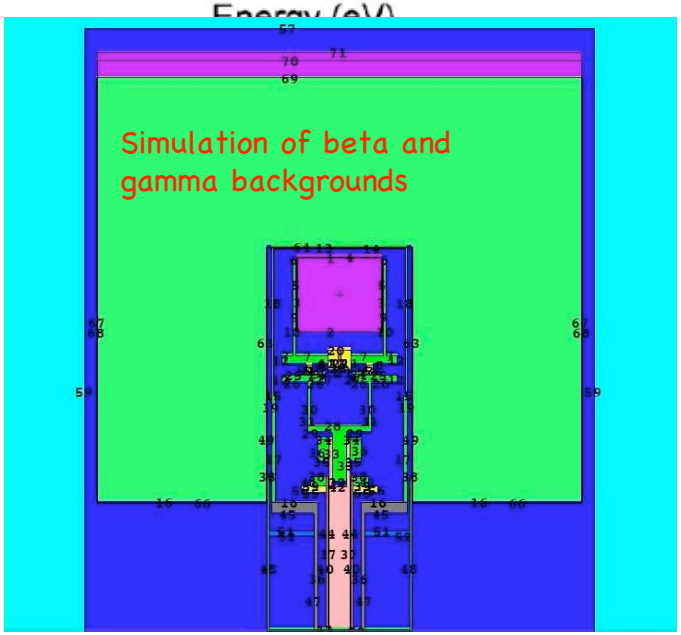
This is the state-of-the-art for 1 pF detectors!

(Pentafet)

We can do better!

(ongoing work With EDAX/Moxtek/ANL)



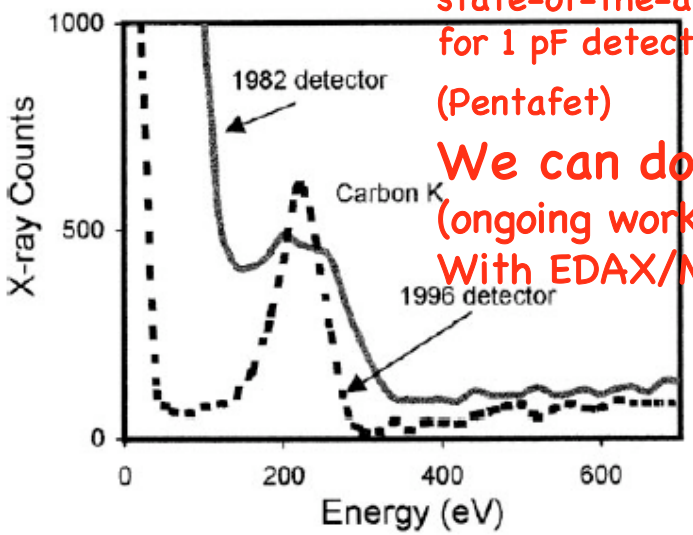


Shielding studies at 6 m.w.e. (comparable to reactor site)

FNA

Extensive detector characterization early 2006

(nucl-ex/0701012)



This is the state-of-the-art for 1 pF detectors!

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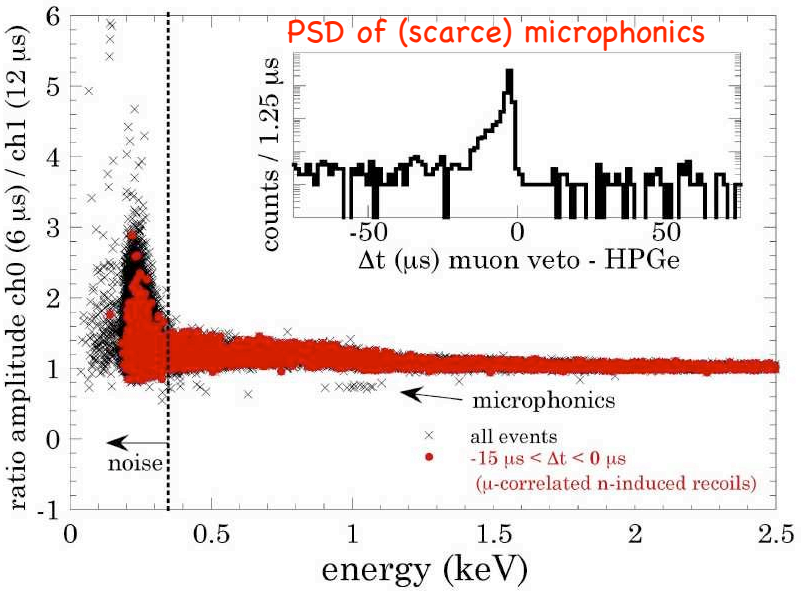
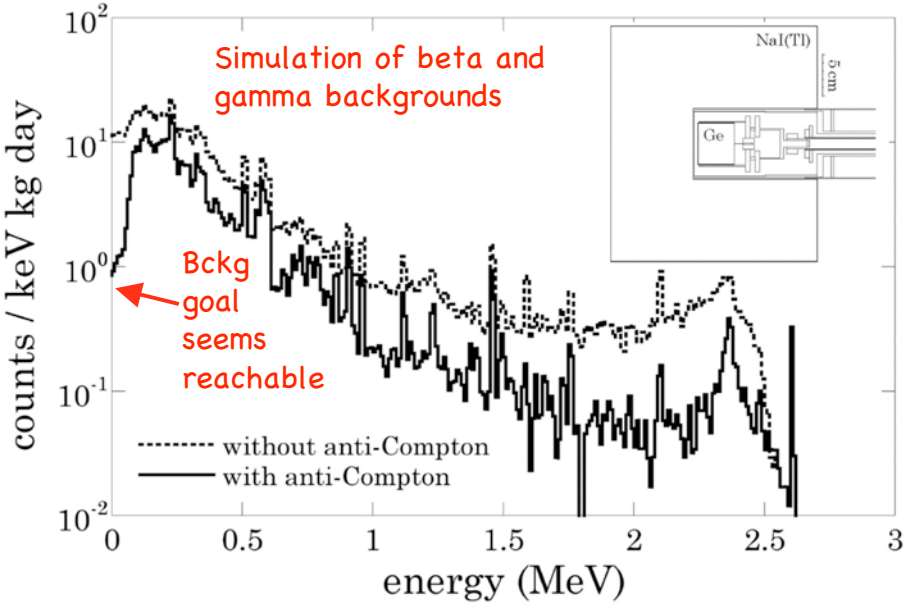
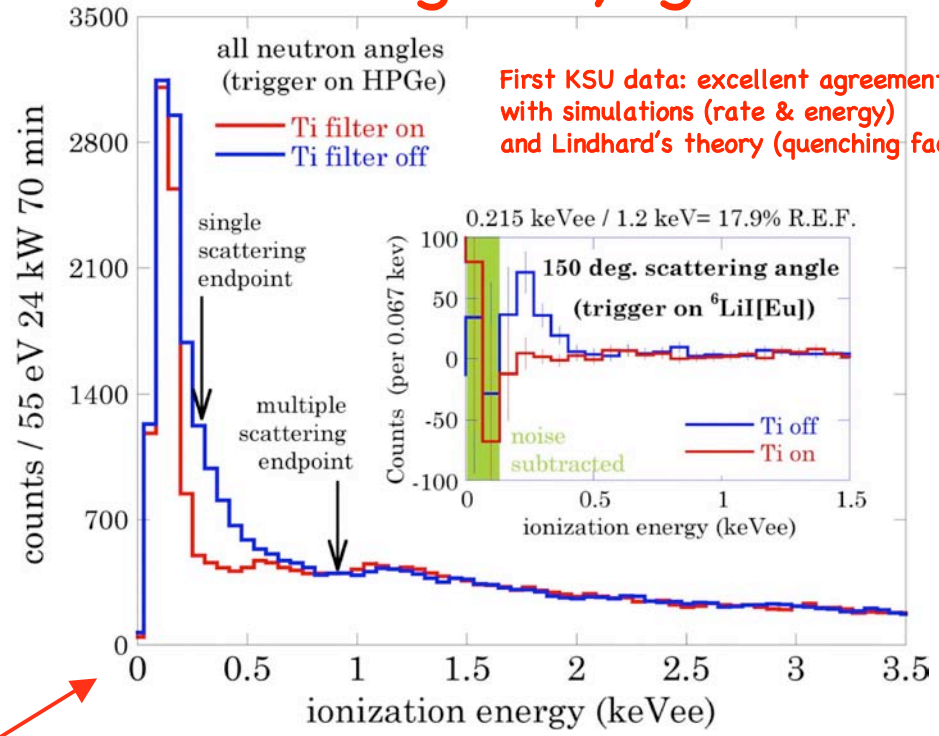


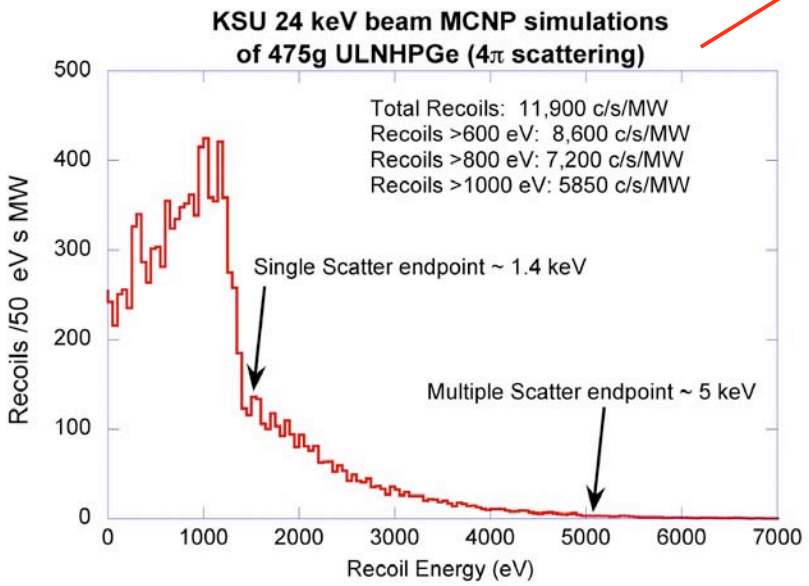


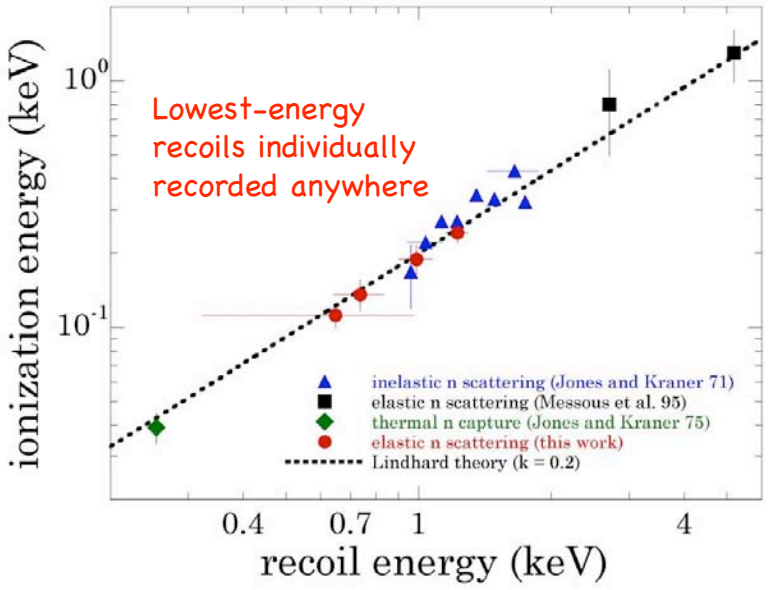
Shielding studies at 6 m.w.e. (comparable to reactor site)

Some recent news: looking very good...



First KSU data: excellent agreement with simulations (rate & energy) and Lindhard's theory (quenching factor)

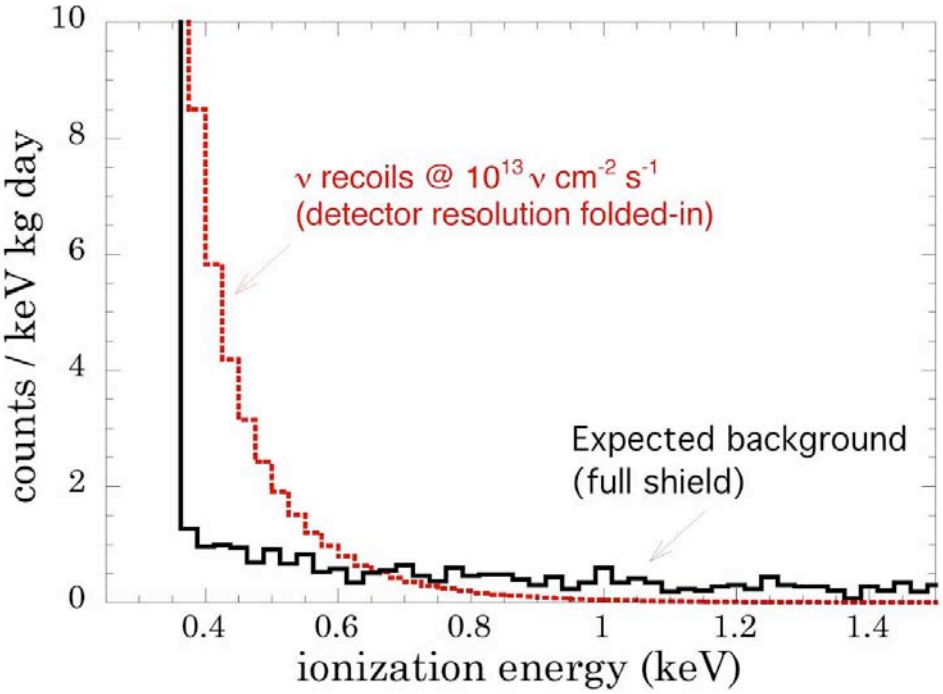


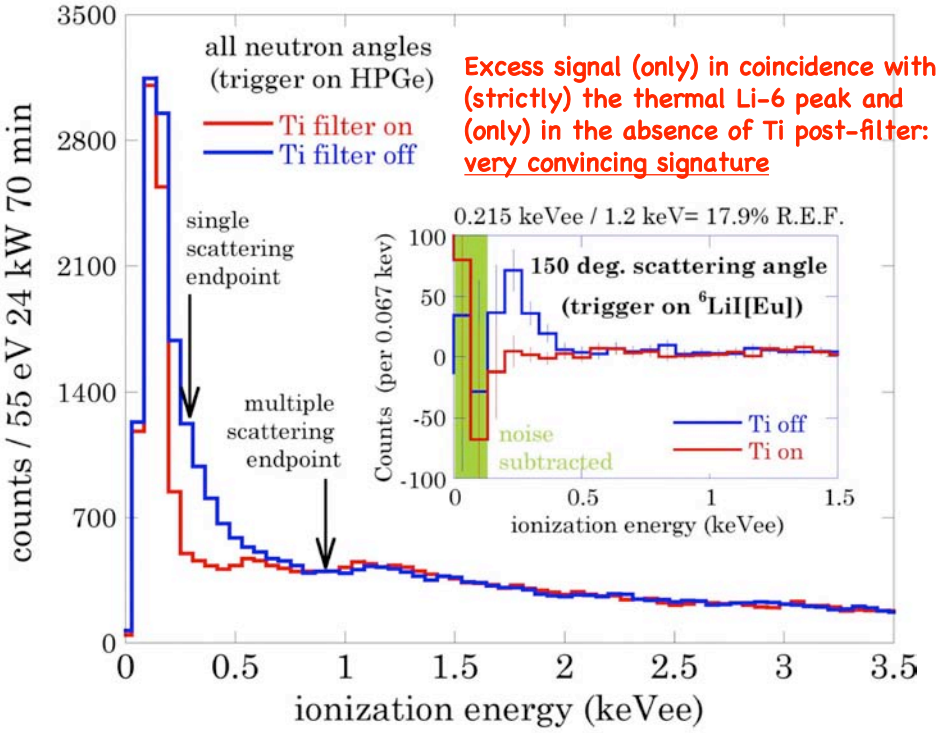


FNAL

Some recent news: looking very good…

Relevant ROI for power reactor experiment has been explored





Excess signal (only) in coincidence with (strictly) the thermal Li-6 peak and (only) in the absence of Ti post-filter: very convincing signature

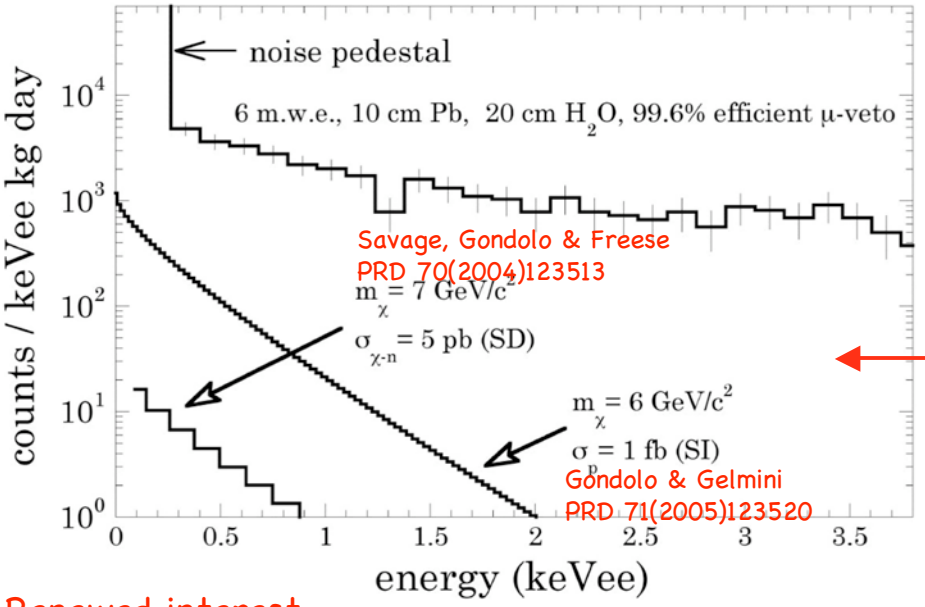
Mass √

Threshold √

Background… (on it)

Some recent news: looking very good...

Definitive check on DAMA soon
X50 improvement from clean Al, x10 from anti-Compton



Renewed interest
in <20 GeV/c^2
light dark matter particles ---> See also J.F. Gunion *et al.* hep-ph/0509024
B. McElrath hep-ph/0506151
F. Ferrer *et al.* PRD74 (06) 115007

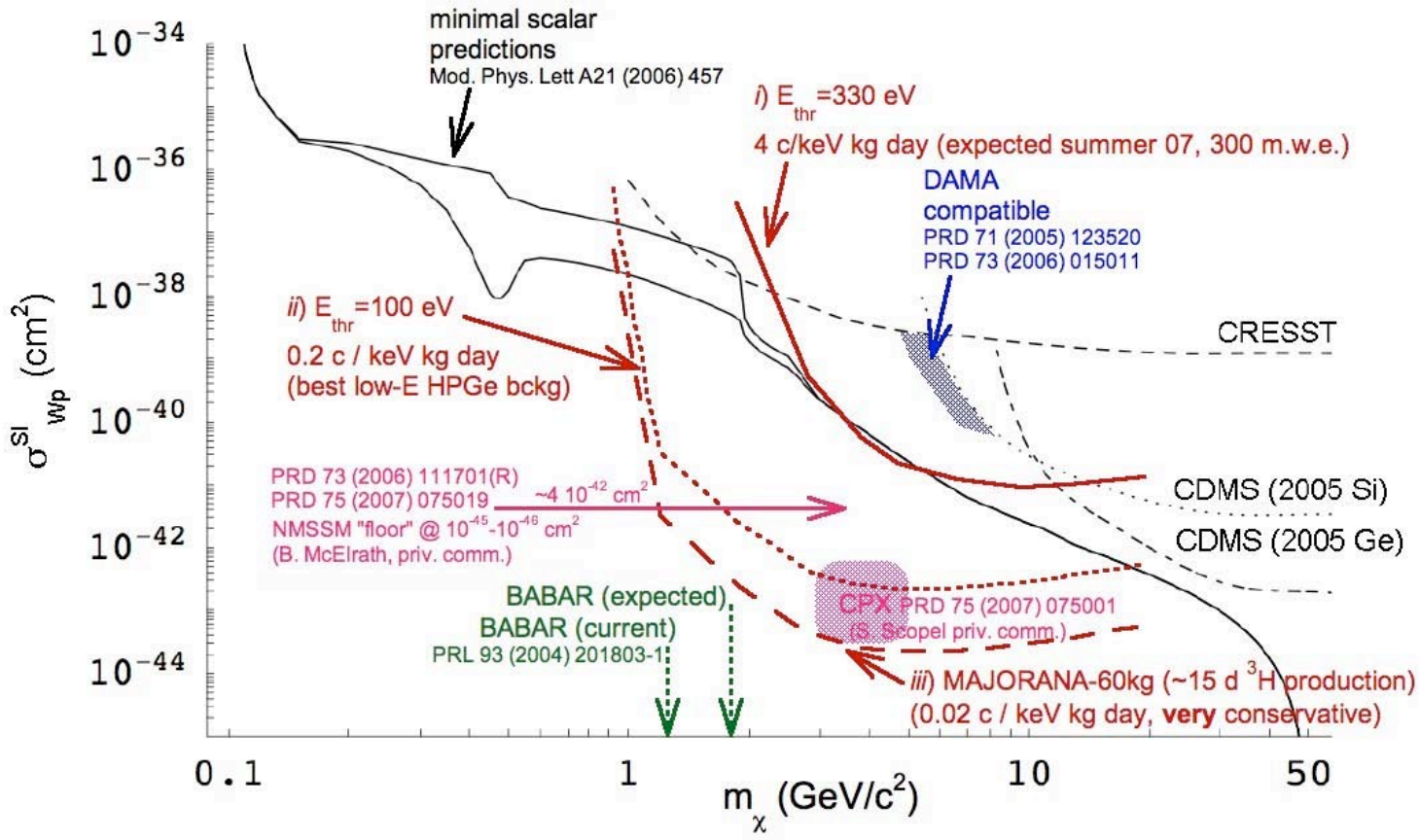
First Physics Results expected Fall 06:

These light WIMPs remain compatible with DAMA & all other searches (accelerator bounds are model-dependent)

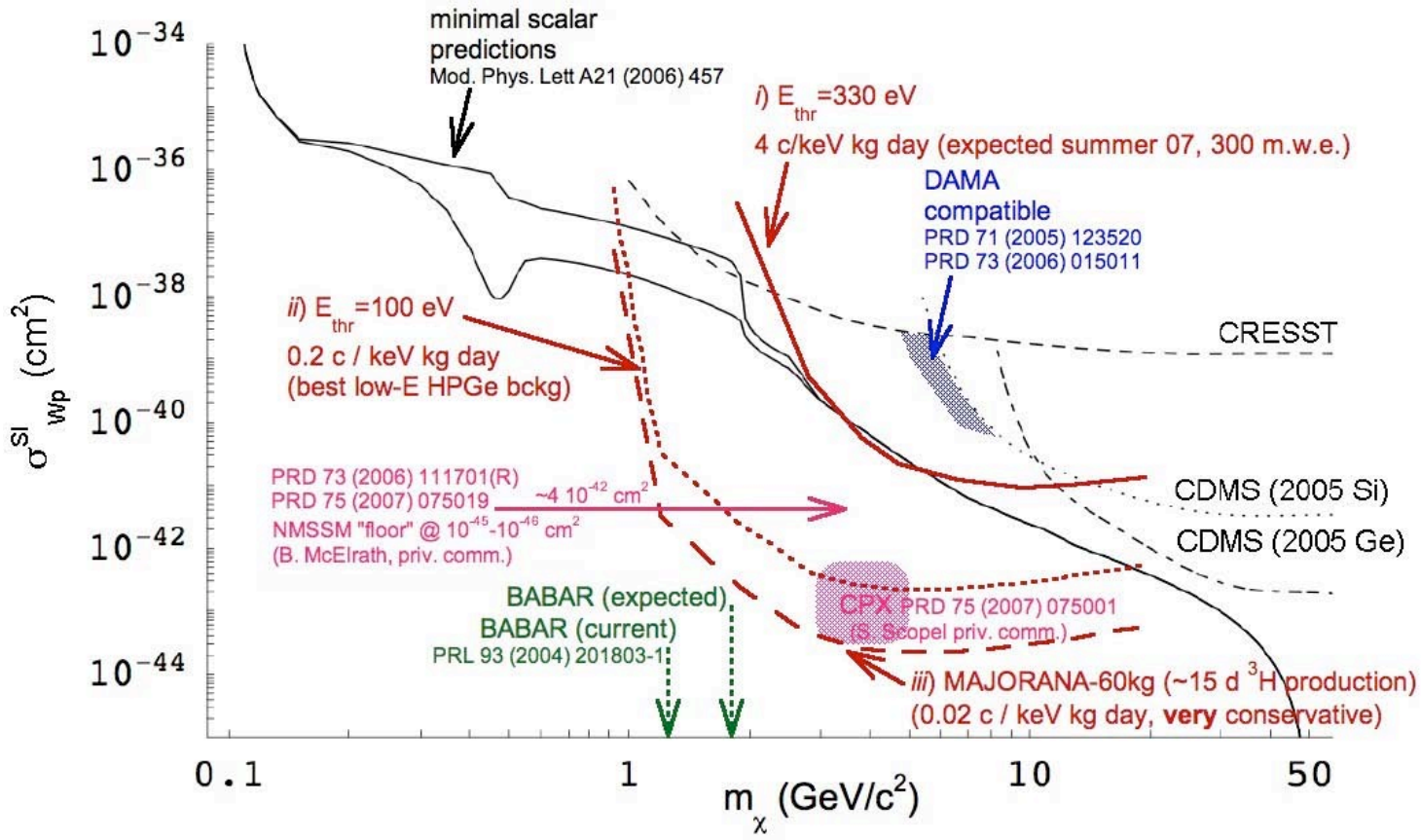
Next: replacement with <0.2 ppb U cryostat, develop low-bckg version of anti-Compton shield... and deploy to power reactor.

Nothing radioclean yet (need cash! ☹)

Some recent news: looking very good...



Some recent news: looking very good...

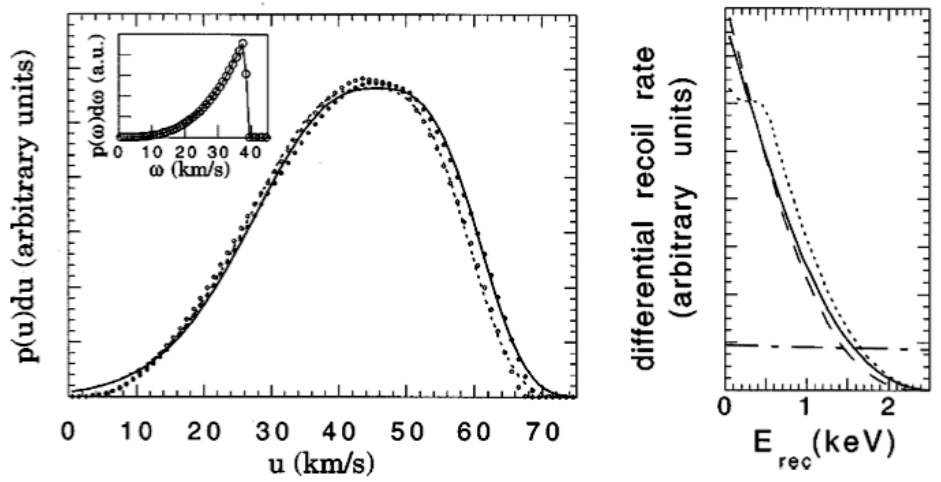


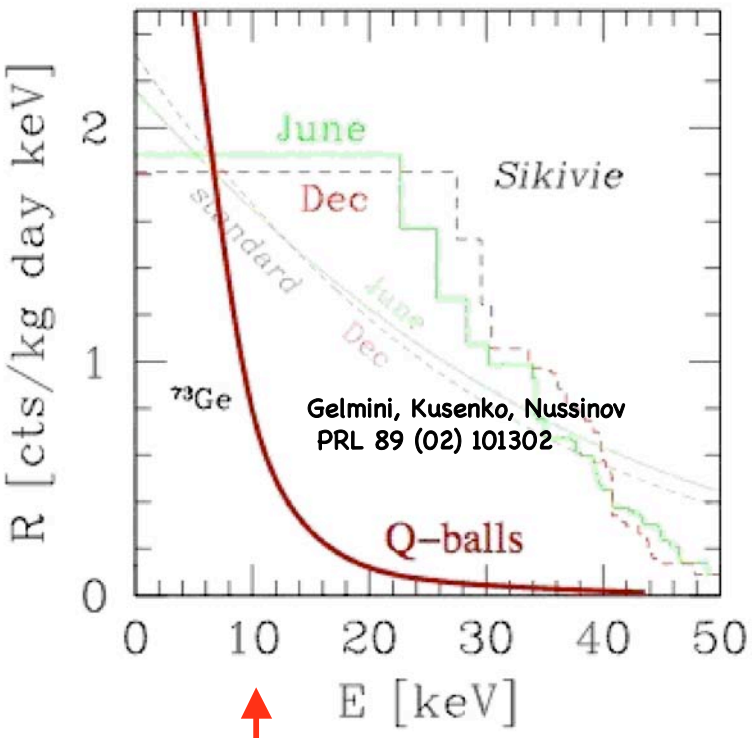
Both are vacations by the sea...

What else can you do with such a detector?

J.I. Collar PRD 59 063514
Damour & Krauss PRL 81 5726

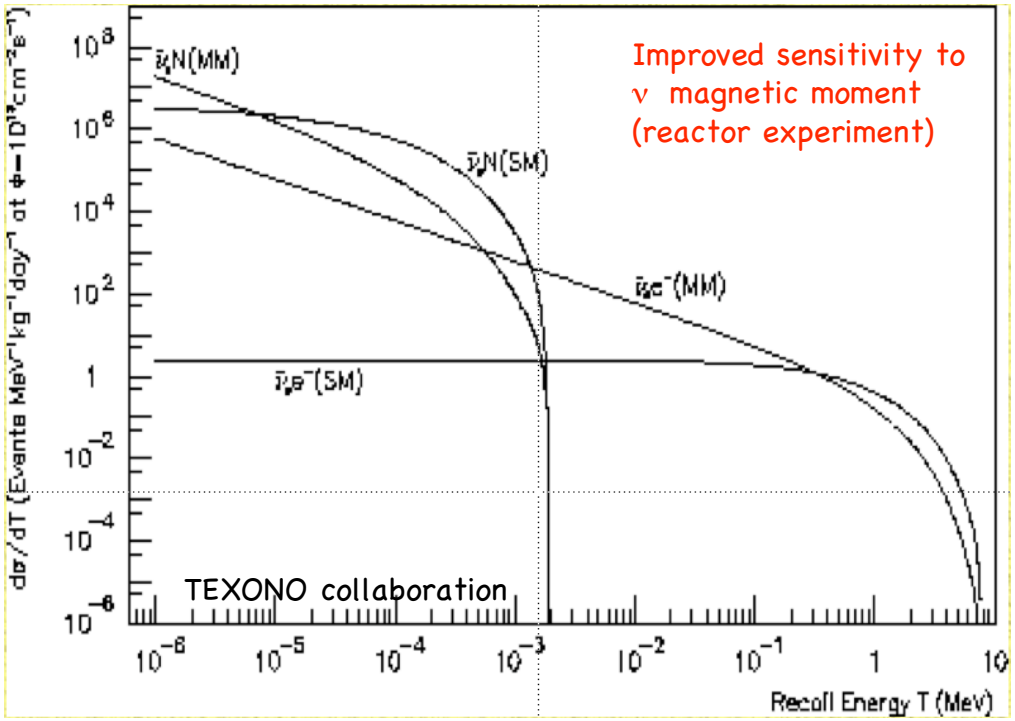
Solar-bound WIMPs: deposit ~x100 less E_{rec} than galaxy-bound, concentrate all rate in narrow spectral region (higher s/n) Sub-keV threshold a must





Gelmini, Kusenko, Nussinov
PRL 89 (02) 101302

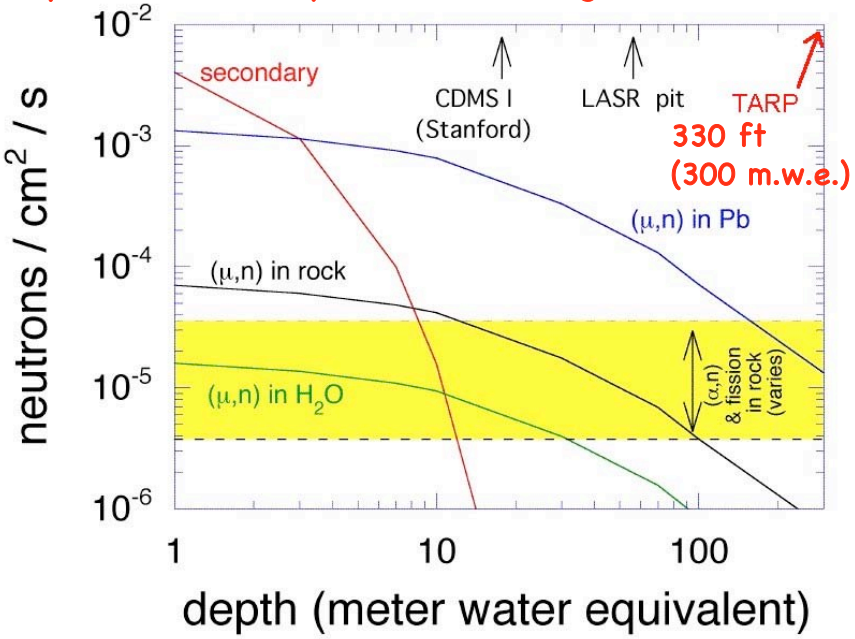
The neutralino is not the only supersymmetric Dark Matter candidate. Non-pointlike DM (Q-balls, Mirror matter, etc.) call for ultra-low threshold detectors

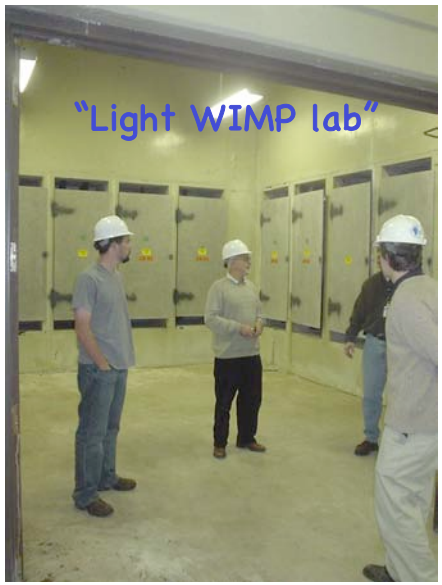


TARP: 5 minutes from ANL, 20 min from UC

permission to use until (at least) 2012: Big THANKS to Tom Economou

Equivalent of deeper site with a good muon veto

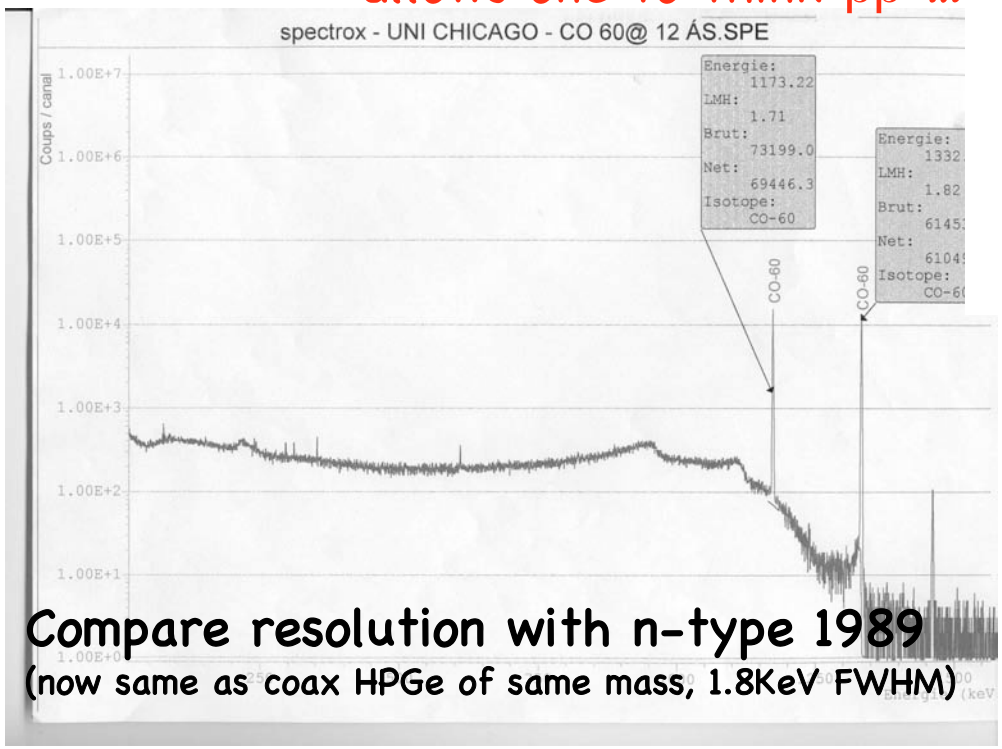




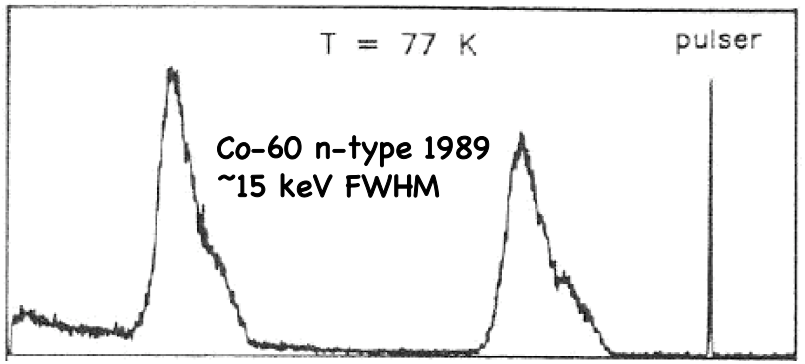
The city of Chicago lending a hand to local Dark Matter hunters...

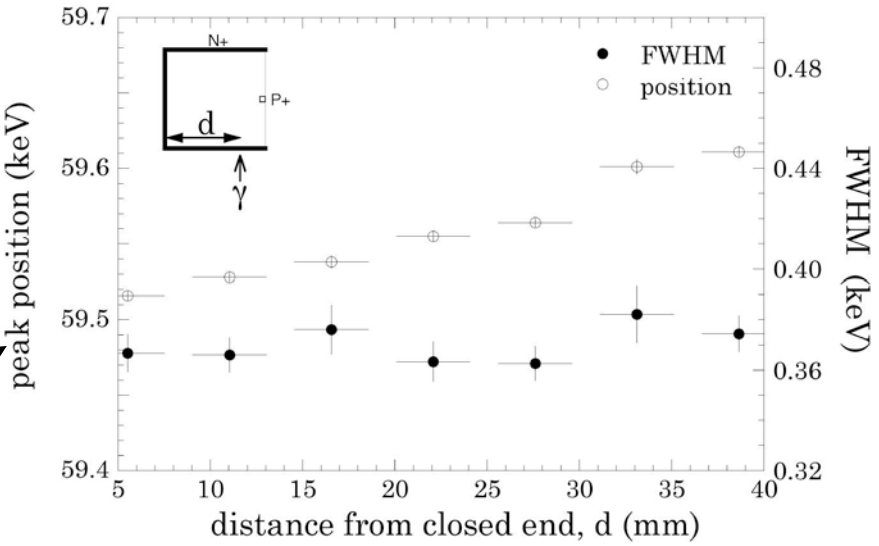
MAJORANA: can we avoid segmentation altogether?
(cost, speed, simplicity, much lower front-end backgrounds)
Does this device have anything to offer in a ββ context?

Optimal E-resolution
allows one to think ββ ...



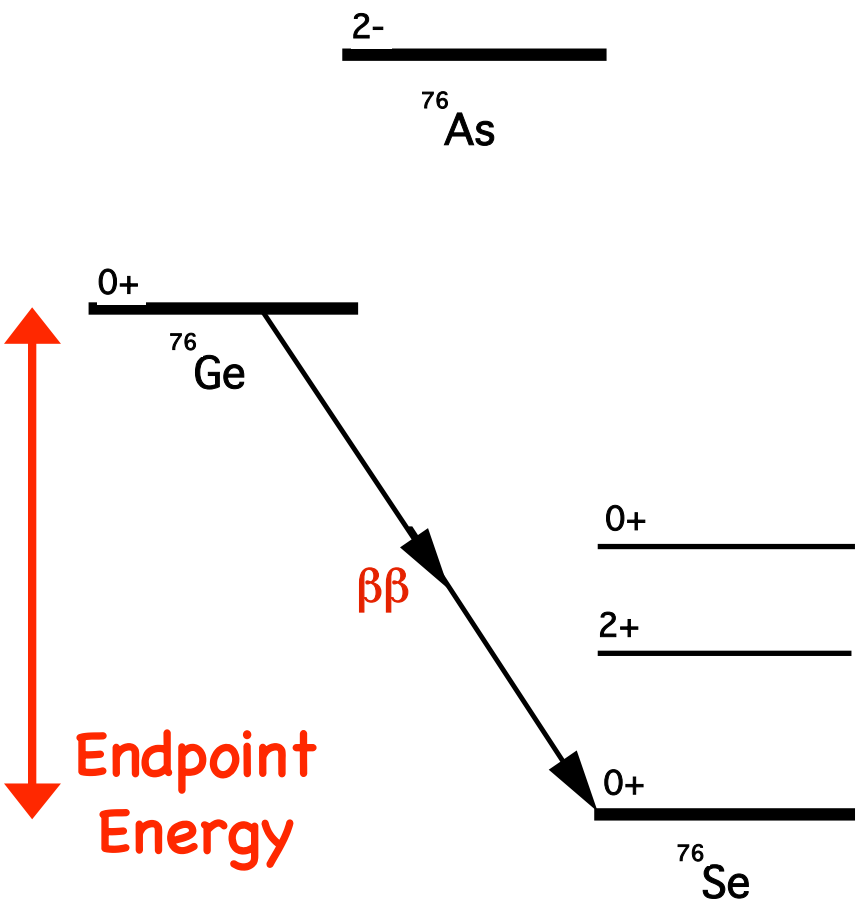
Compare resolution with n-type 1989
(now same as coax HPGe of same mass, 1.8KeV FWHM)

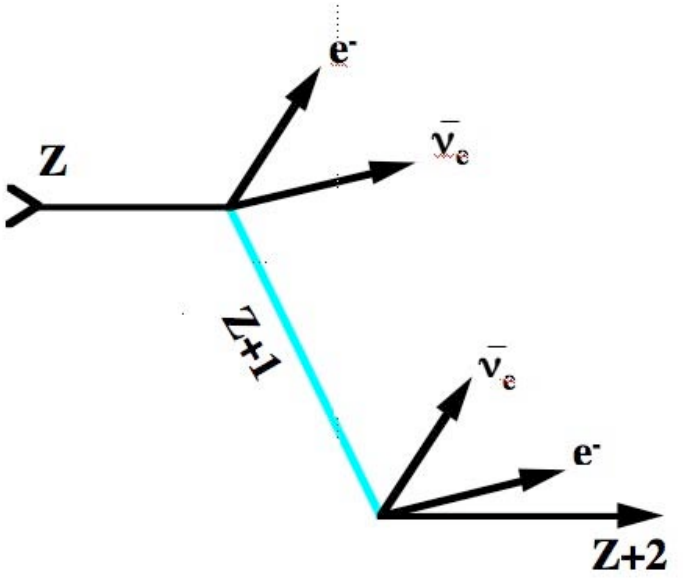


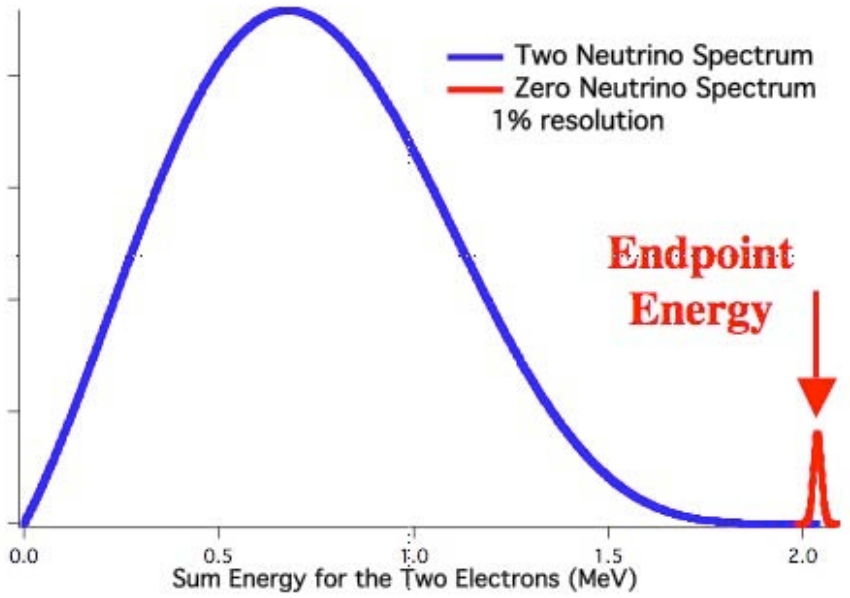


Also x20 improvement in
charge collection
in going to p-type

Quick and dirty intro to neutrinoless ββ decay



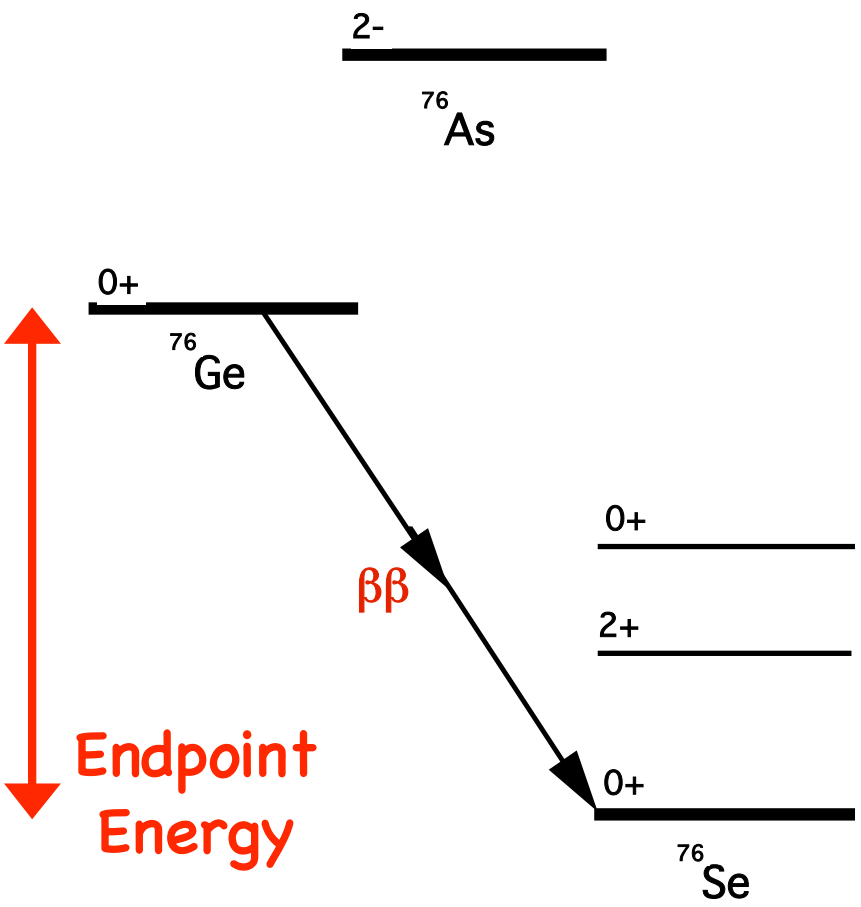


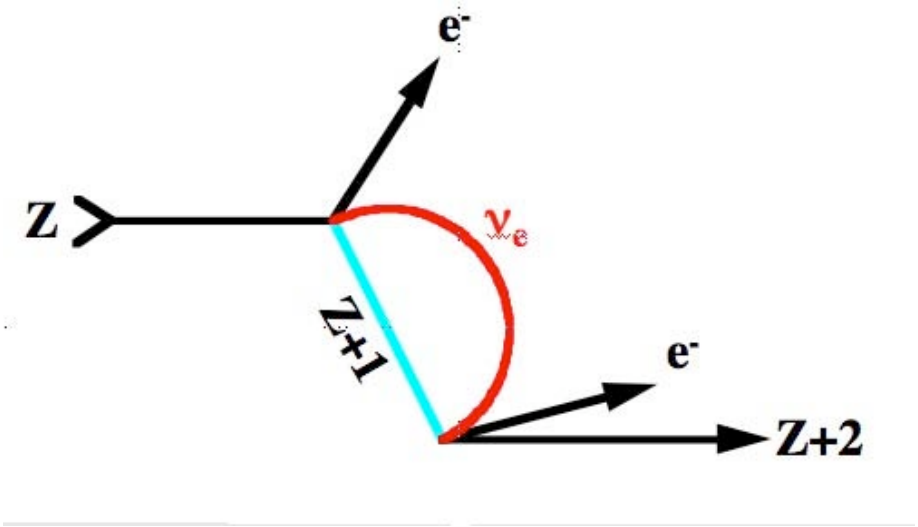


In many even-even nuclei, β decay is energetically forbidden. This leaves ββ as the allowed decay mode.

FN

Quick and dirty intro to neutrinoless ββ decay





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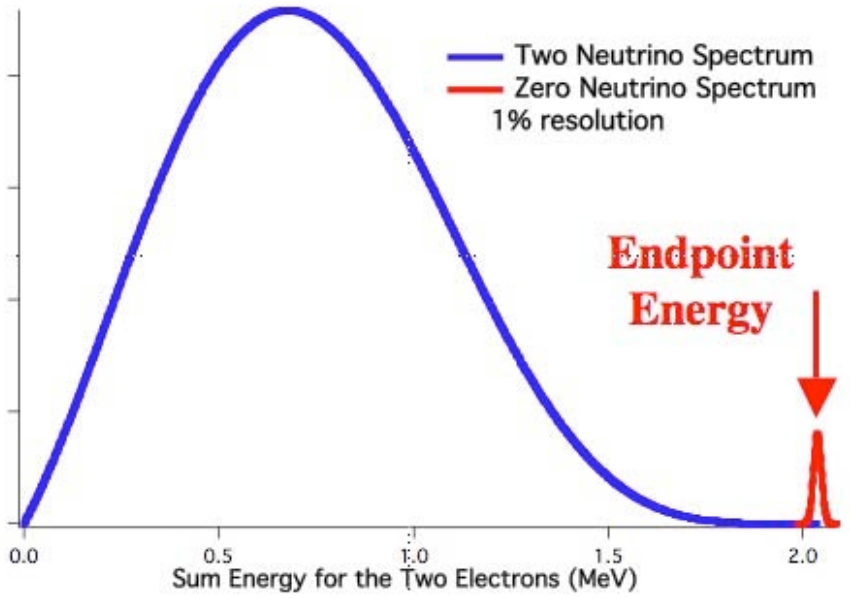
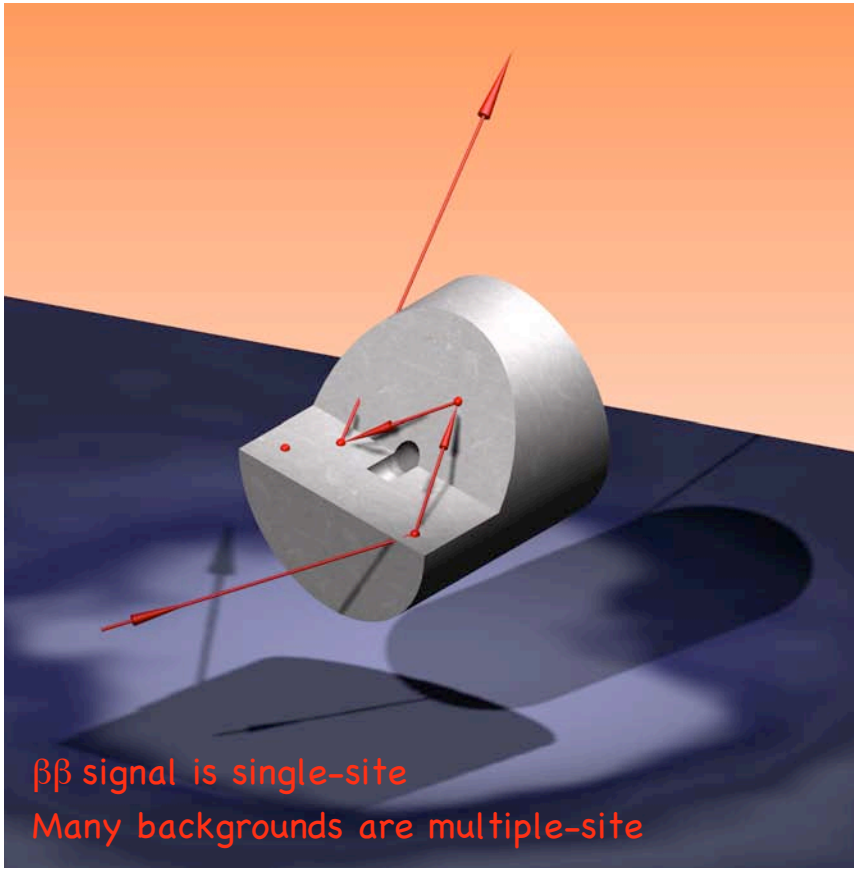
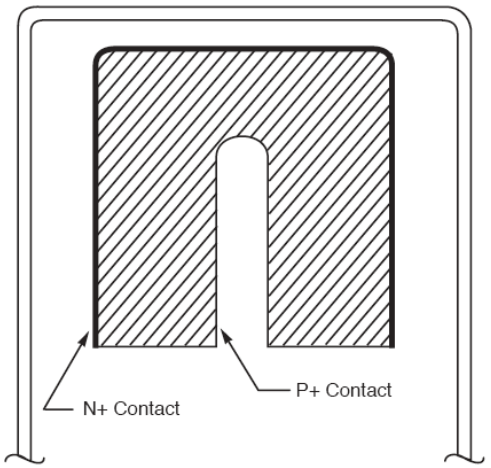


FN

How does a multiple-site interaction look in a modified-electrode HPGe?

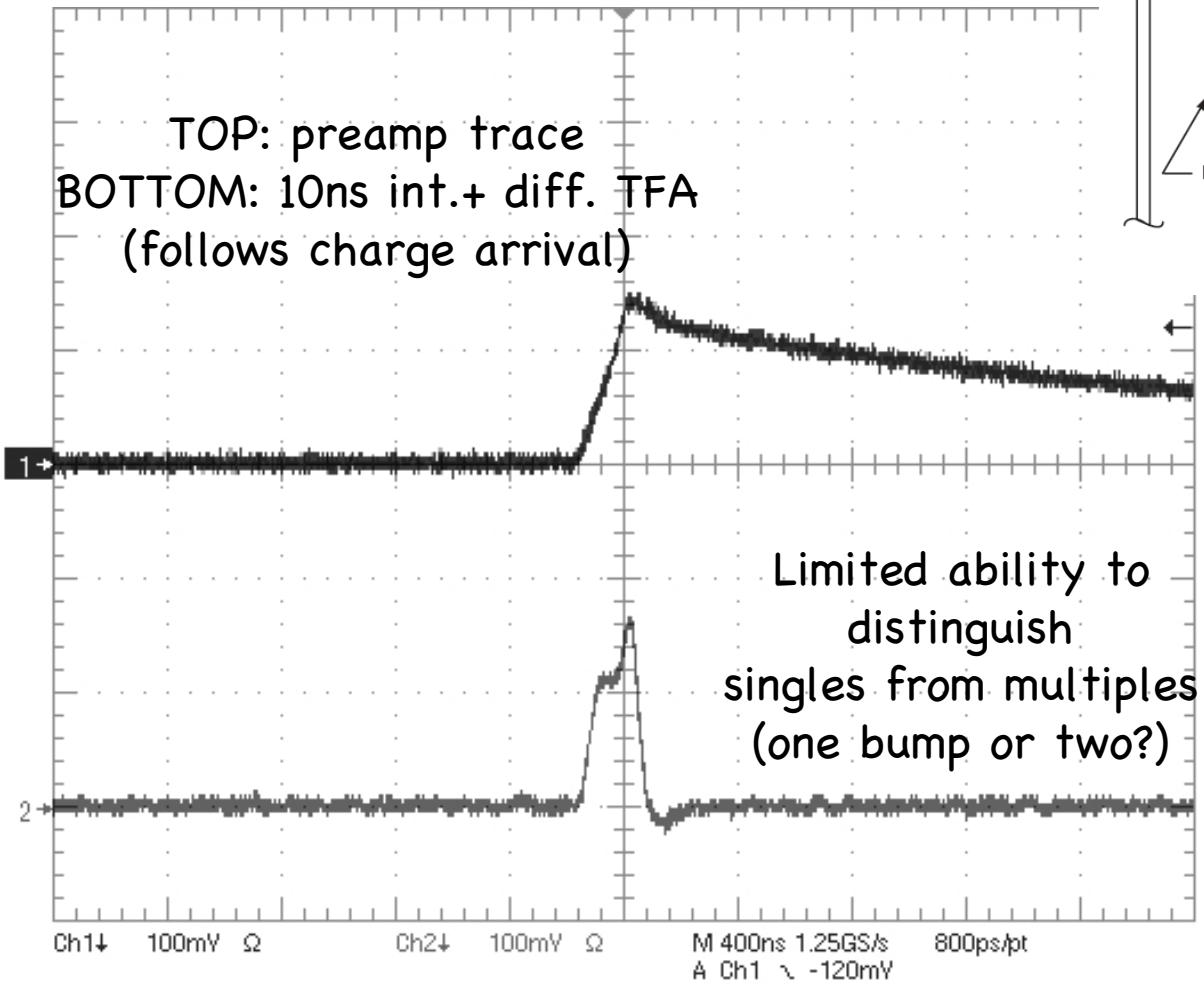


That was then...



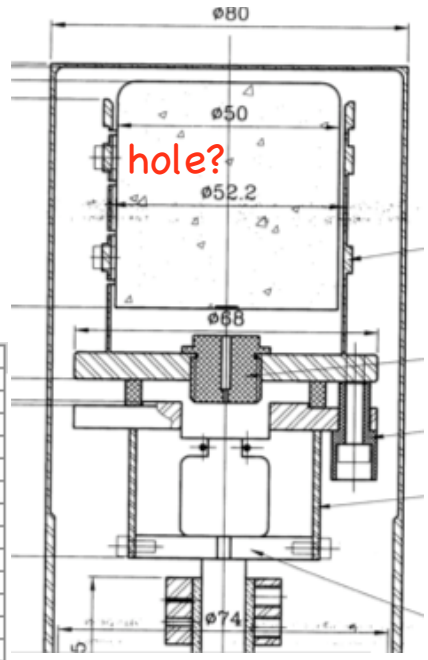
Coaxial Ge Detector Configuration

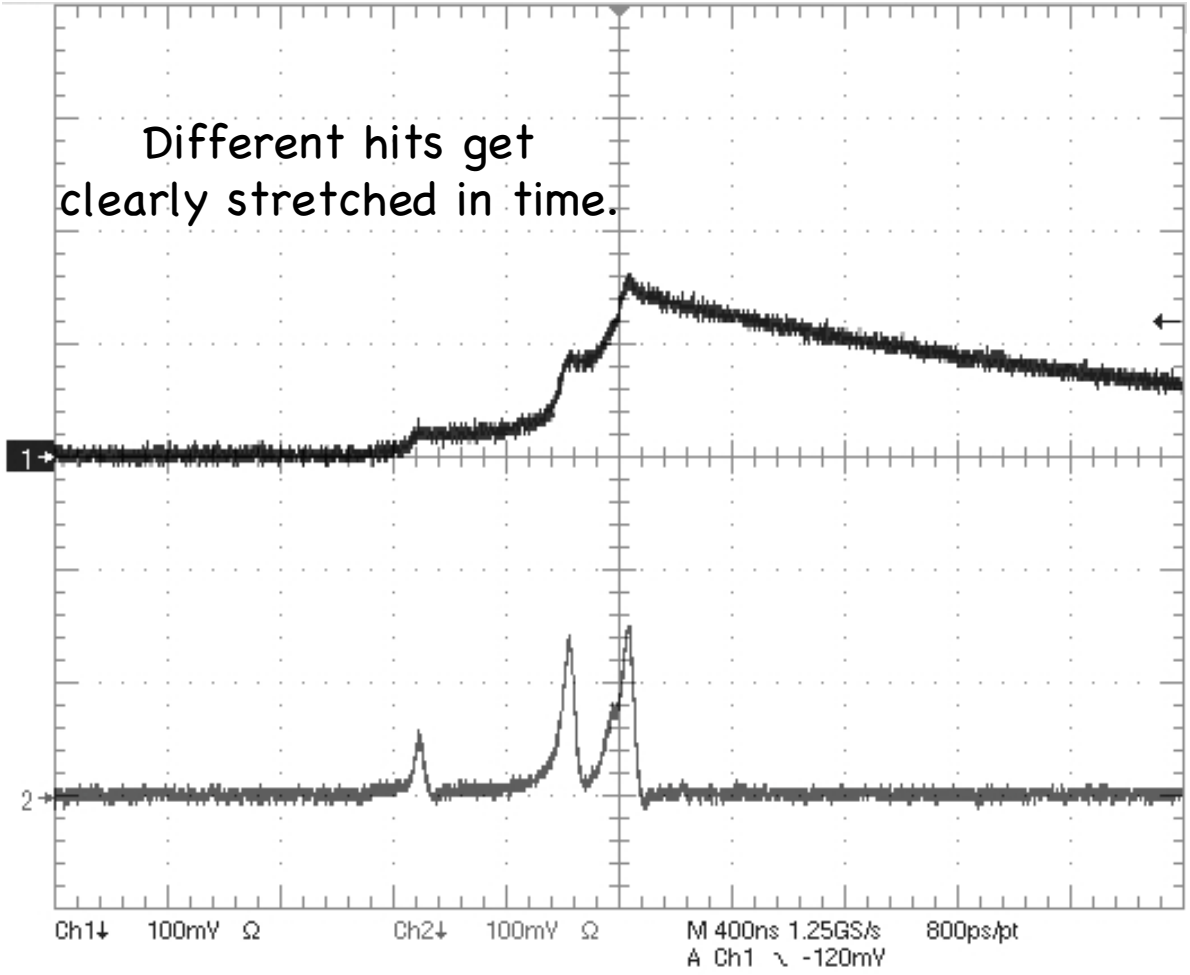
TOP: preamp trace
BOTTOM: 10ns int.+ diff. TFA
(follows charge arrival)



Limited ability to distinguish singles from multiples (one bump or two?)

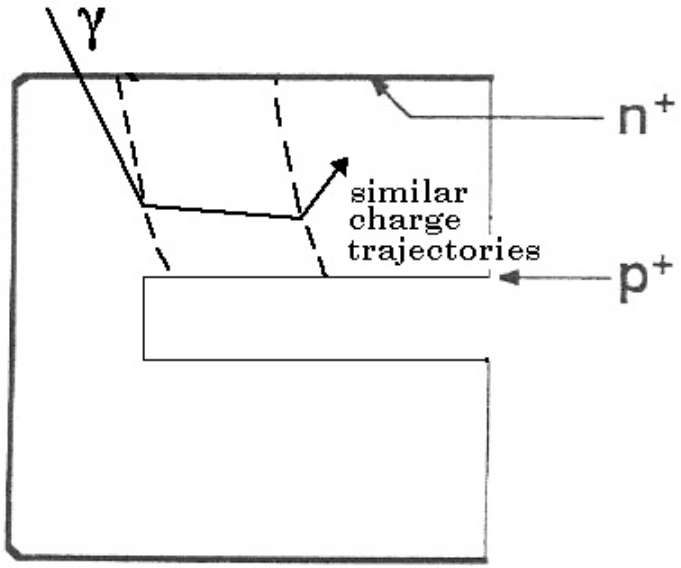
This is now.



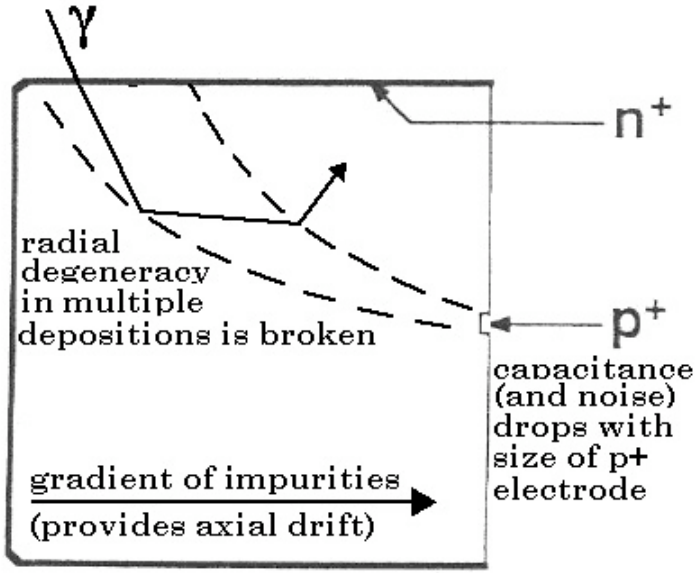


All this with optimal energy resolution and charge collection (and one channel)

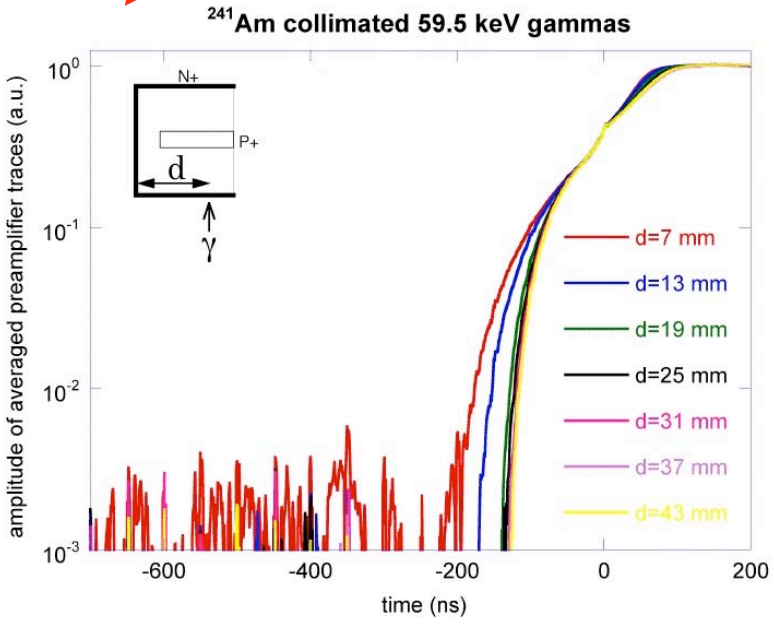
What is happening?

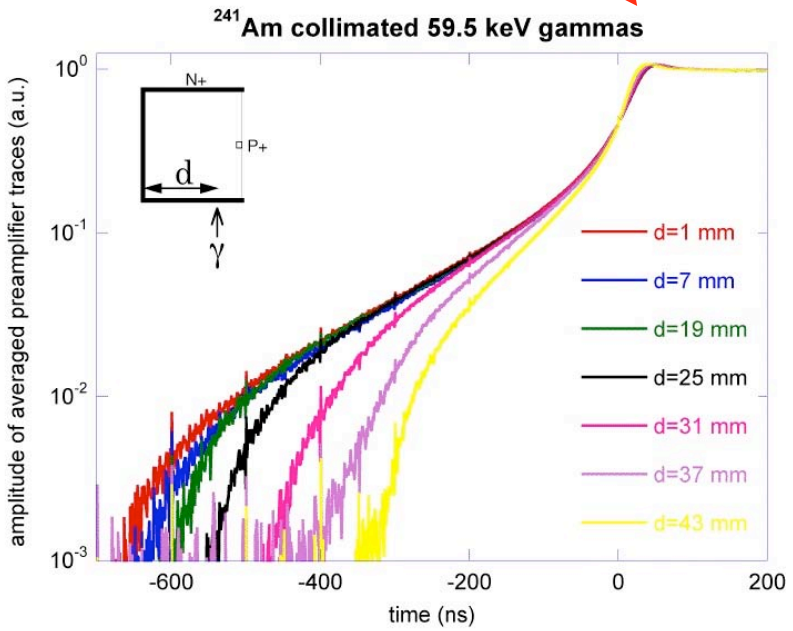


standard coaxial HPGe

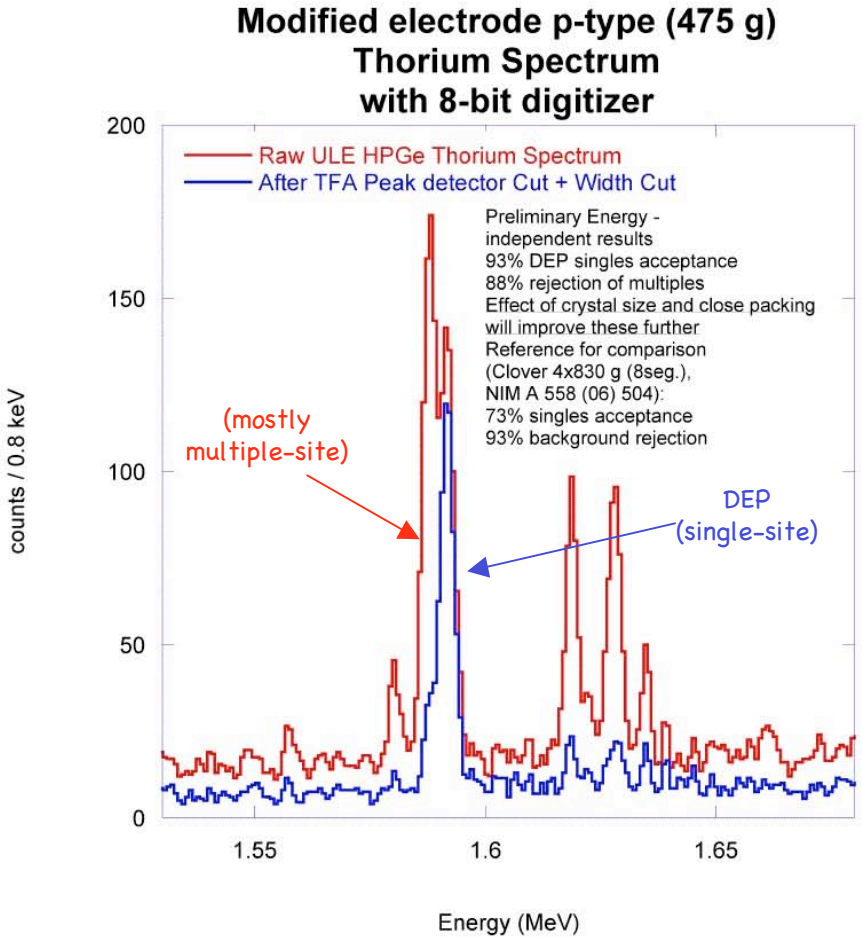


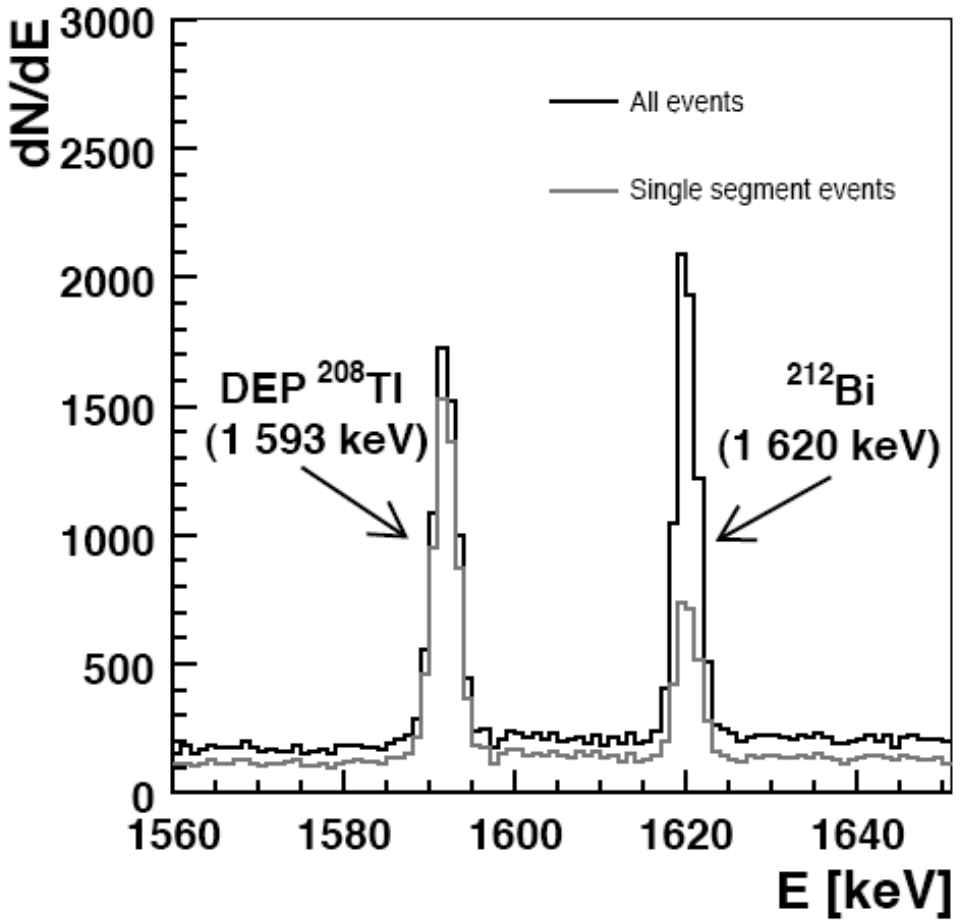
P-type modified electrode





Comparable or better signal acceptance / background rejection than an 8-segment clover HPGe (Majorana) or an 18-segment (Gerda) <u>all with a single-channel device</u>





LEFT: Natural Th, mod. electrode
93% SA, 88% BR (nucl-ex/0701012)

RIGHT: ^{228}Th, n-type 18-segment
92% SA, 65% BR (nucl-ex/0701005)

Advantages of single channel p-type modified electrode vis-à-vis segmentation for MAJORANA:

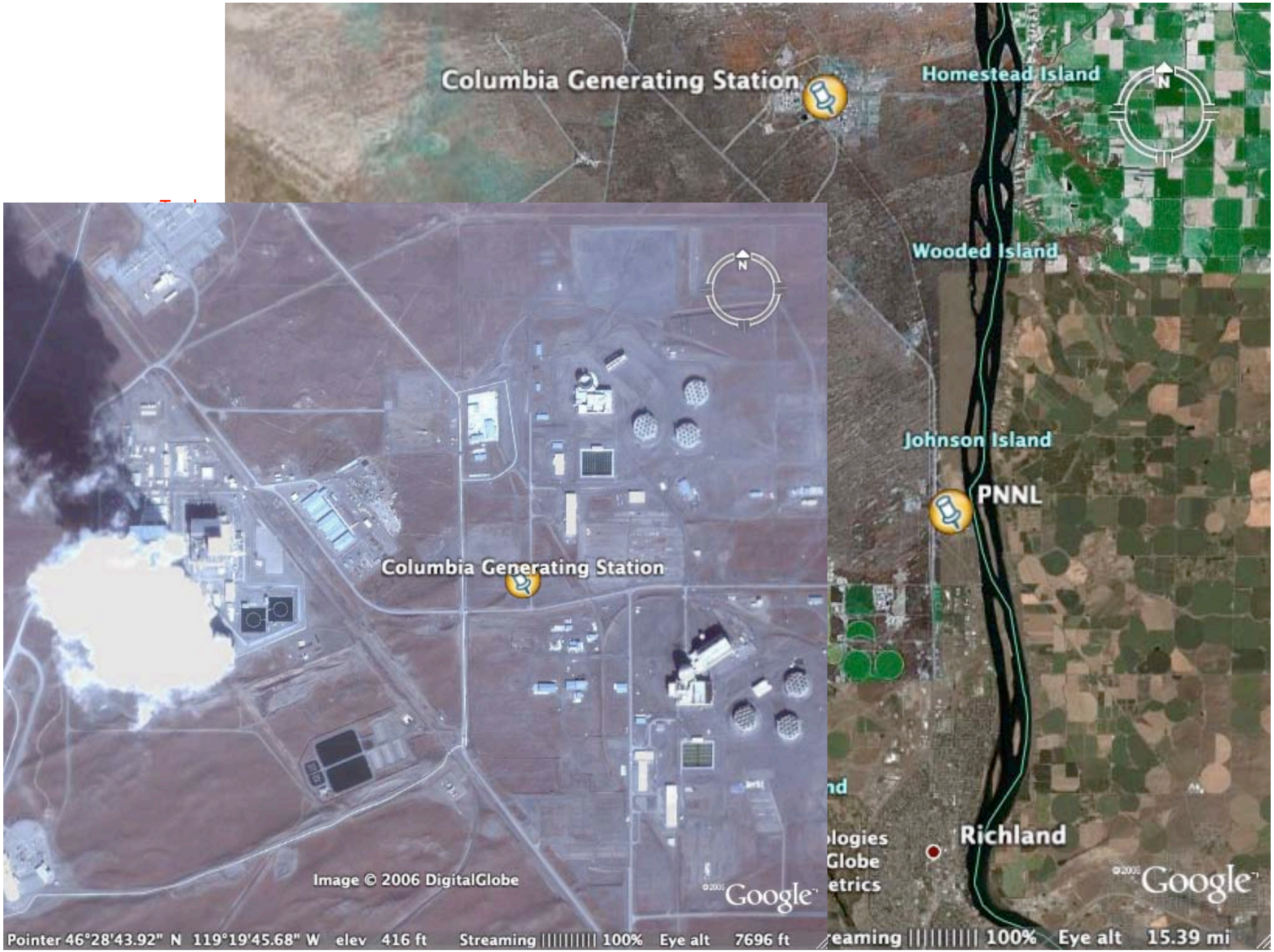
- Very efficient PSA rejection of multiples. All with one channel.
- Excellent energy resolution (1.8 keV Co-60, may drop some as noise is further improved)
- Increase speed of deployment/manufacture as long as... (is gradient of impurities reproducible? How important?)
- Increase simplicity of construction and analysis (one channel)
- Decrease cost (detectors and DAQ). Improve production time (cosmogenics)
- Decrease front end-associated radioactive backgrounds, thermal load, photon path.
- Increase stability (prototype performance stable for >5 continuous mo. and counting)
- Intrinsic to p-type: ruggedness (a must when arraying) and decreased sensitivity to surface contaminations.
- Several others (e.g., rejection of ALL alphas via PIXE -studies underway-)
- CANBERRA and PHDs Co. receptive to further fabrication (and further work on noise reduction).

Disadvantages:

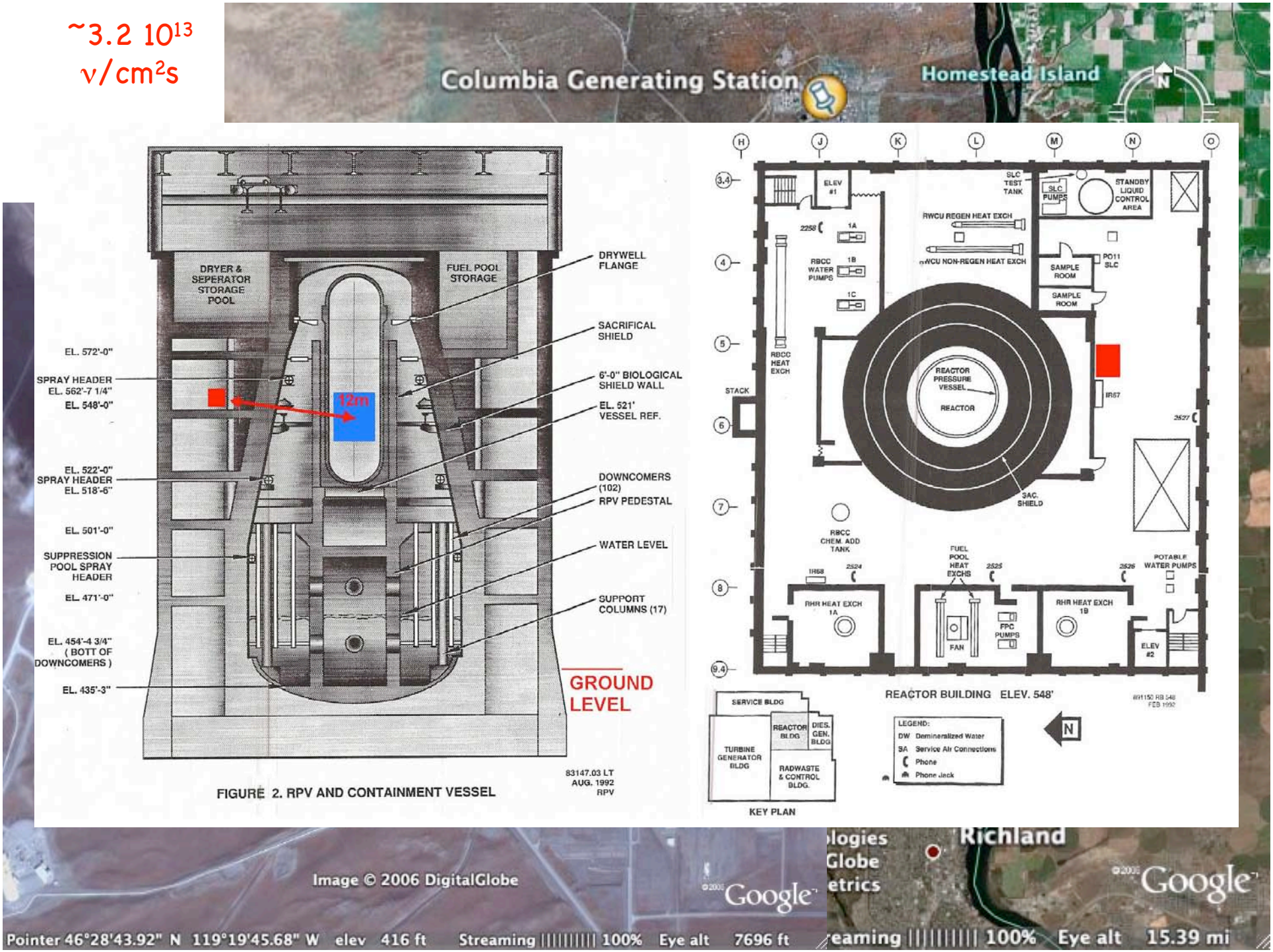
- Technology too new: too many unknowns in reproducibility, cost, speed of production, largest crystal size that can be produced, waste (important for $\beta\beta$), etc.
- Canberra's position: We need to build 6-10 more to know (they admit "lucking out". Hopefully this will not change).

Solution:

- This fits perfectly with planned coherent ν program. Recent NSF/DOE proposal centered around this theme <- Help from rest of MAJORANA collaboration to maximize **synergy**: PNNL already funded to build more of these, ORNL seeking funding.
- Several kg of modified-electrode p-type HPGe's built by 2007!
- GOAL: Be by early next year counting at the Columbia Generating Station (Richland, WA, 12 mi. from PNNL) and simultaneously further developing the technique (i.e., building more of these). San Onofre? (offers more depth)

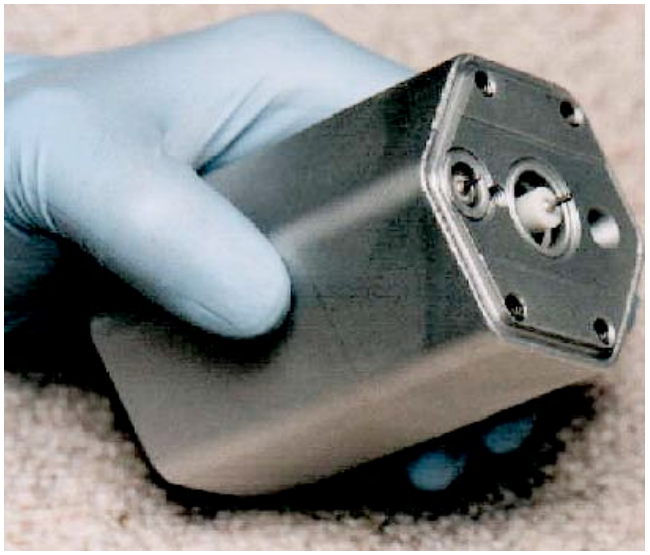

Columbia Generating Station
Homestead Island
Wooded Island
Johnson Island
PNNL
Richland
Columbia Generating Station
Image © 2006 DigitalGlobe
Google
Pointer 46°28'43.92" N 119°19'45.68" W elev 416 ft
Streaming 100% Eye alt 7696 ft
Google
100% Eye alt 15.39 mi

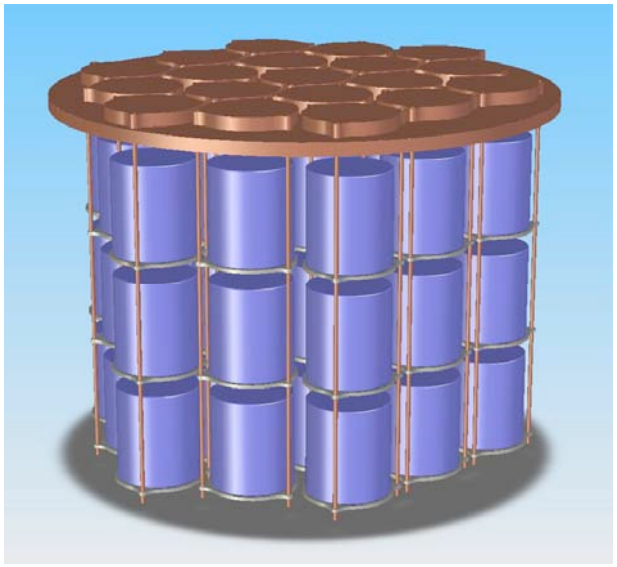
~3.2 10^{13} ν/cm^2s



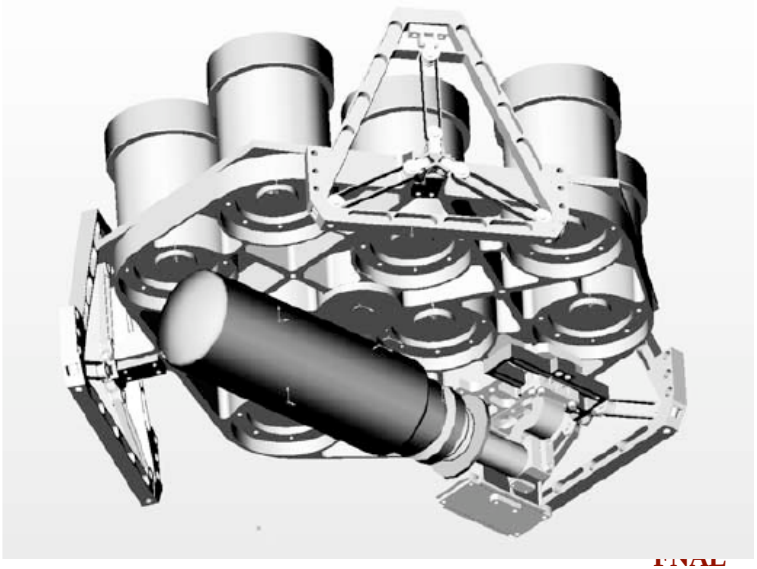
Reactor Monitoring: Right technological timing
(HPGe technology flourishing:
segmentation, encapsulation, arrays and (silent) mechanical cooling)

CLUSTER





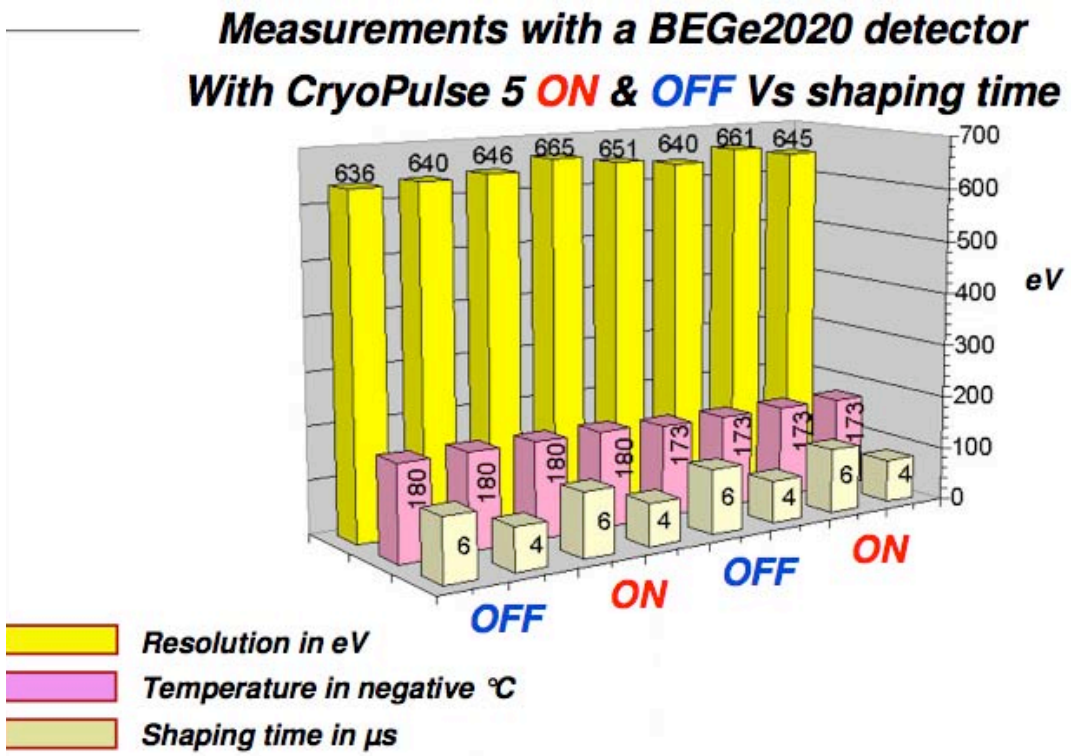
MAJORANA



RHESSI

GERDA

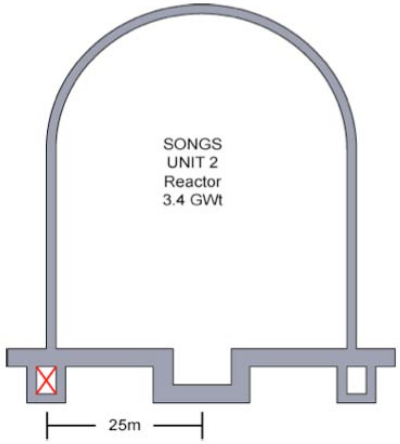
Reactor Monitoring: Right technological timing
(HPGe technology flourishing:
segmentation, encapsulation, arrays and (silent) mechanical cooling)



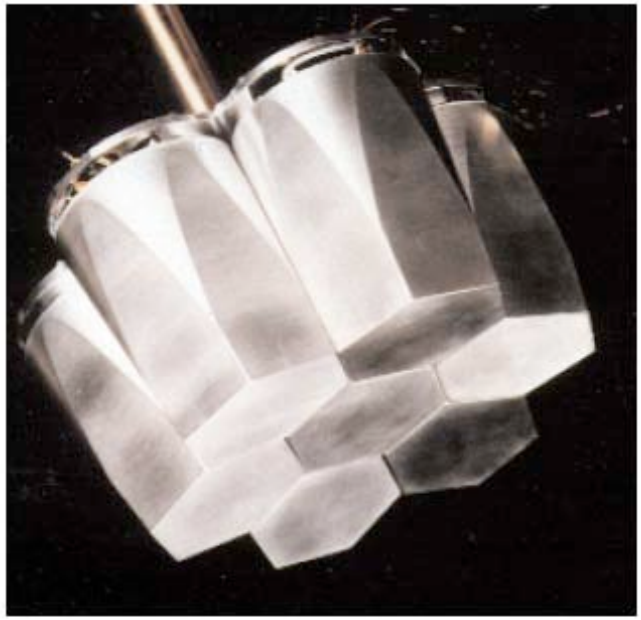
New generation of recondensing Dewars add
no microphonic noise and need topping (not refilling)
every ~ 1yr (can be filled from N2 gas cylinder!)
Ideal for reactor deployment.

11 kg,
encapsulated,
single cold finger
(CANBERRA)

A reality
fast approaching?



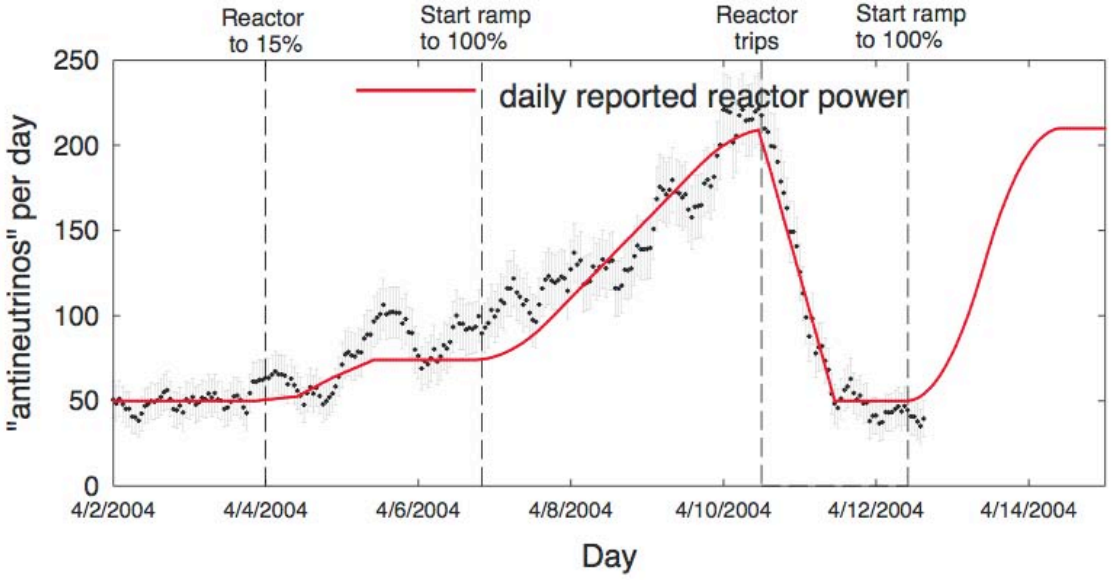
With 100 eV threshold,
the equivalent
of ~1 ton
liquid scintillator
(plus an additional
~x10 in rate beyond!)



CLUSTER array for EUROBALL
(7 encapsulated HPGe detectors)

Hexagonal tapering - diam.: 70 mm - height: 78 mm
FWHM resolution : ≤ 2.3 keV
Efficiency: ≥ 55%
Alu wall thickness: 0.7 mm
Cap-to-Ge distance: 0.7 mm.

SANDS Sees Reactor Turn-on in Detail
(Antineutrino Rate, Running Average)



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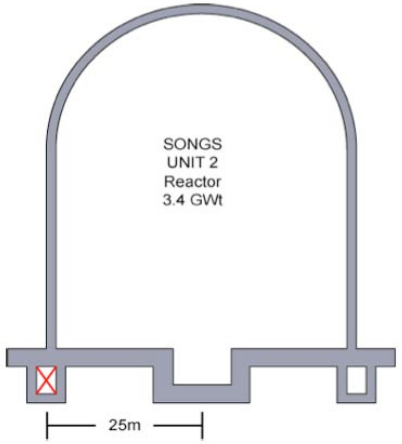

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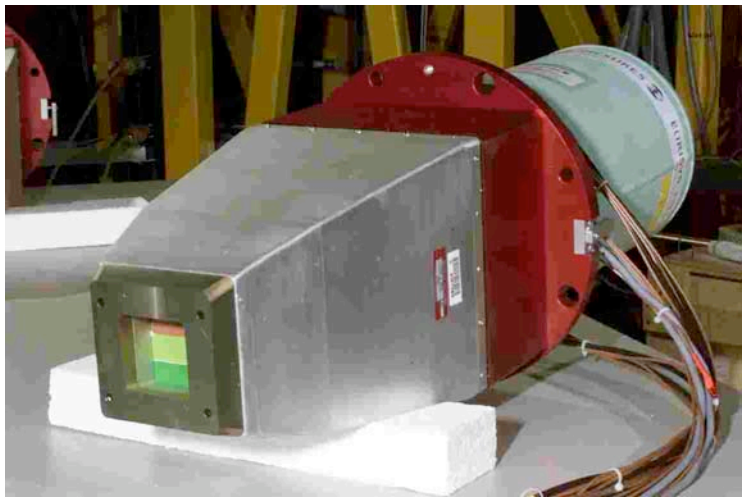
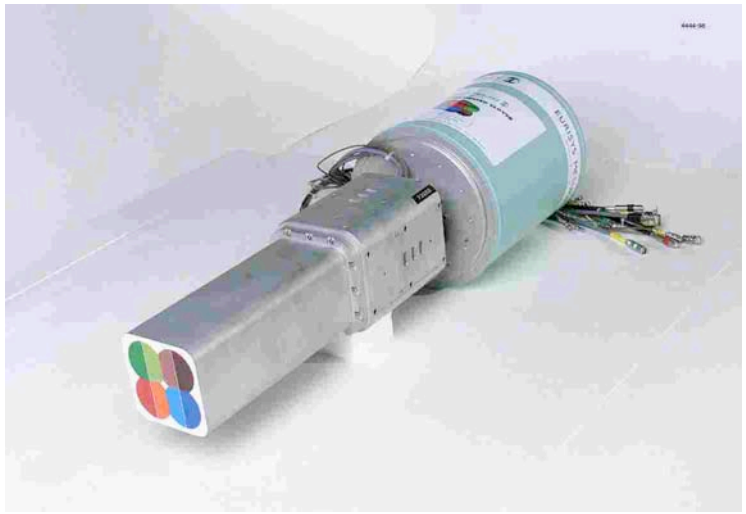
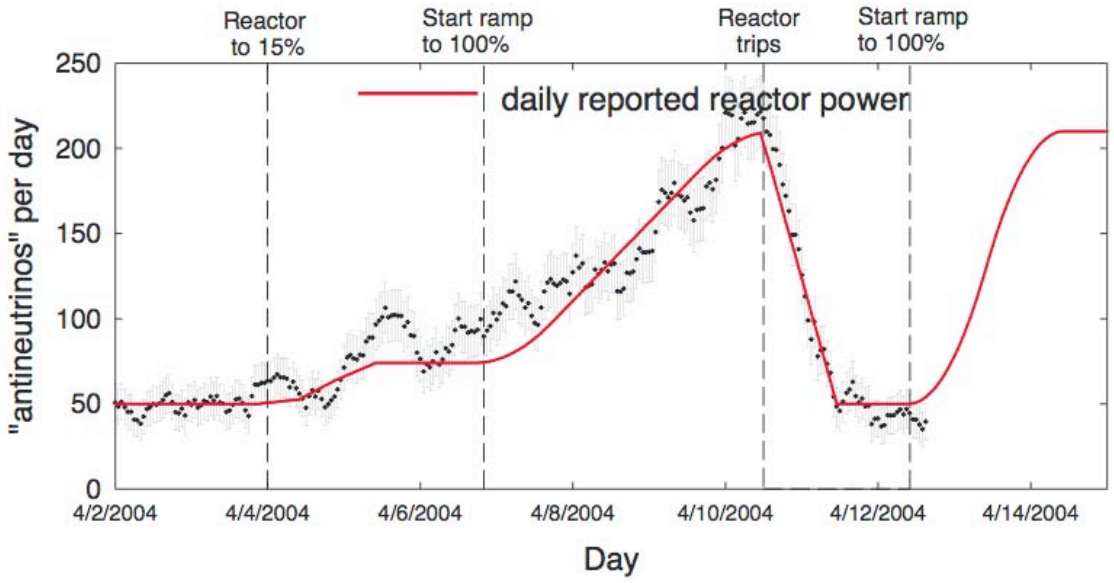




SANDS Sees Reactor Turn-on in Detail
(Antineutrino Rate, Running Average)



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A reality
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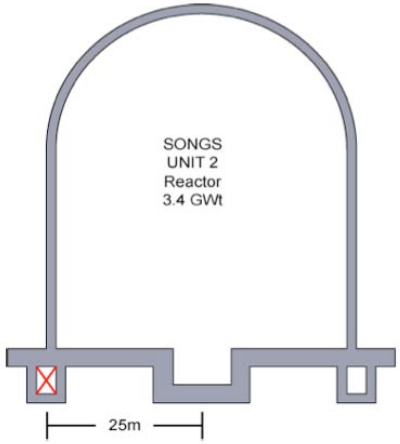

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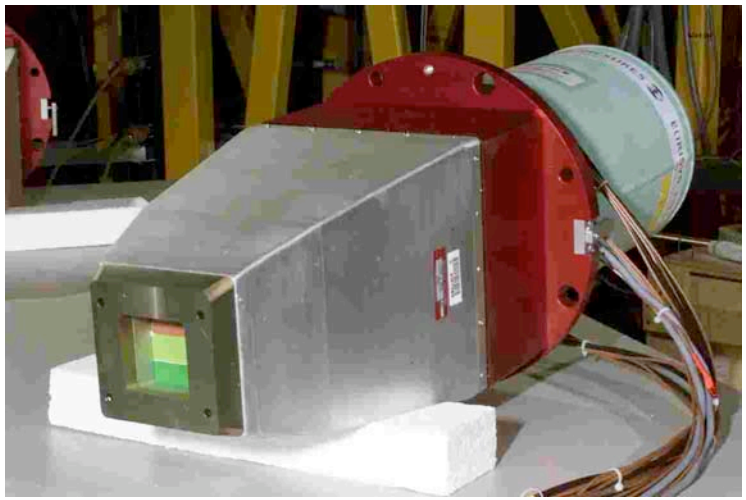

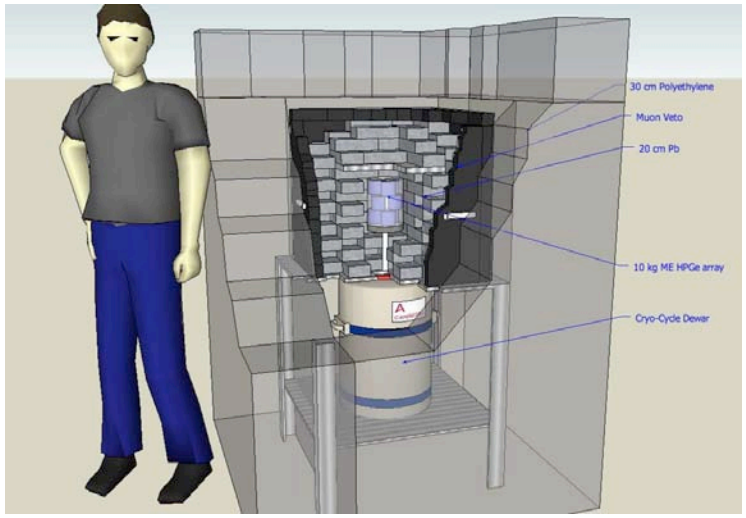

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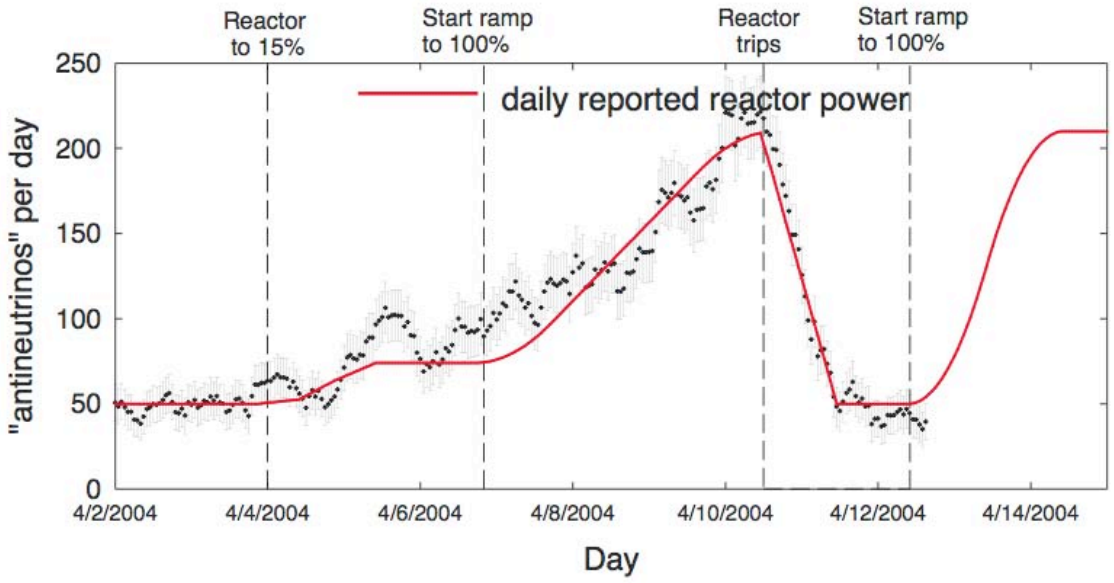
(Antineutrino Rate, Running Average)



Coherent neutrino detection:

I want to believe!