A one-page tutorial on coherent ν-N scattering

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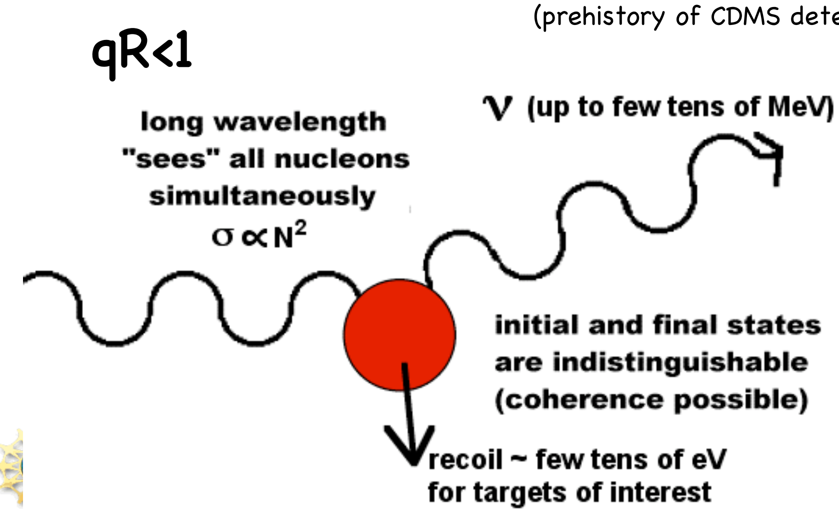
- Large enhancement in cross-section for E_ν < few tens of MeV ($\sigma \propto N^2$, possible only for neutral current)
- However, not yet measured… detector technology has been missing.

Detector mass must be at least ~1 kg (reactor experiment) + *recoil* energy threshold << 1keV

(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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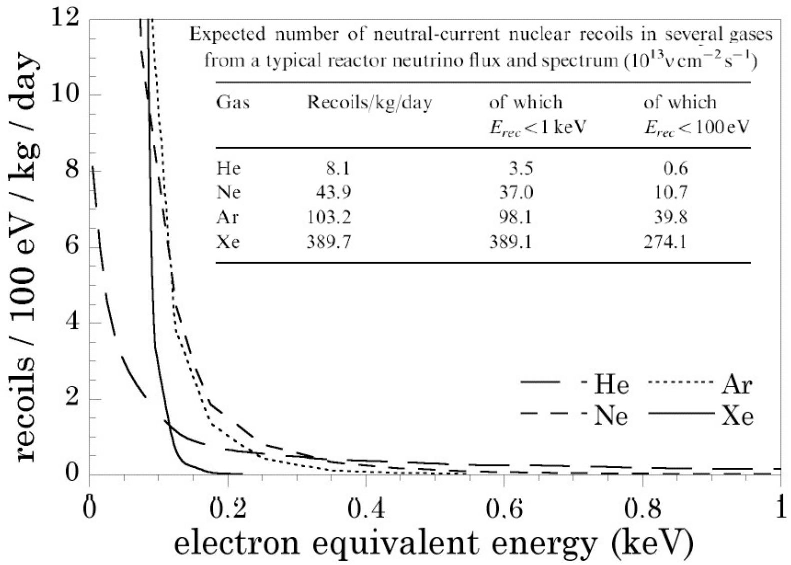

Gas	Recoils/kg/day	of which $E_{rec} < 1$ keV	of which $E_{rec} < 100$ eV
He	8.1	3.5	0.6
Ne	43.9	37.0	10.7
Ar	103.2	98.1	39.8
Xe	389.7	389.1	274.1

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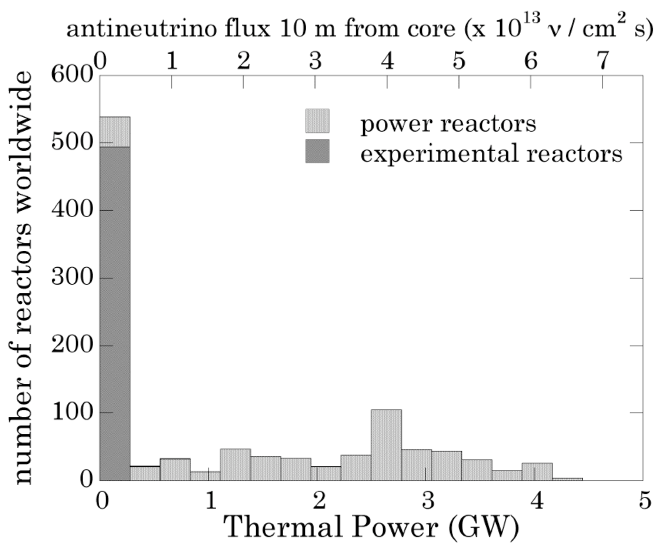

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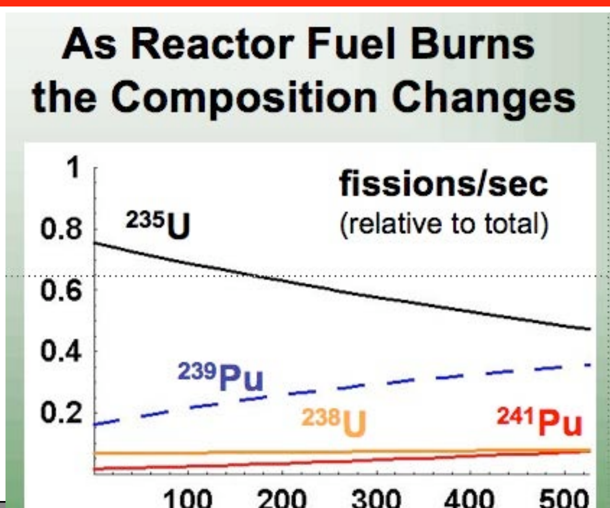

D. Reyna (ANL)

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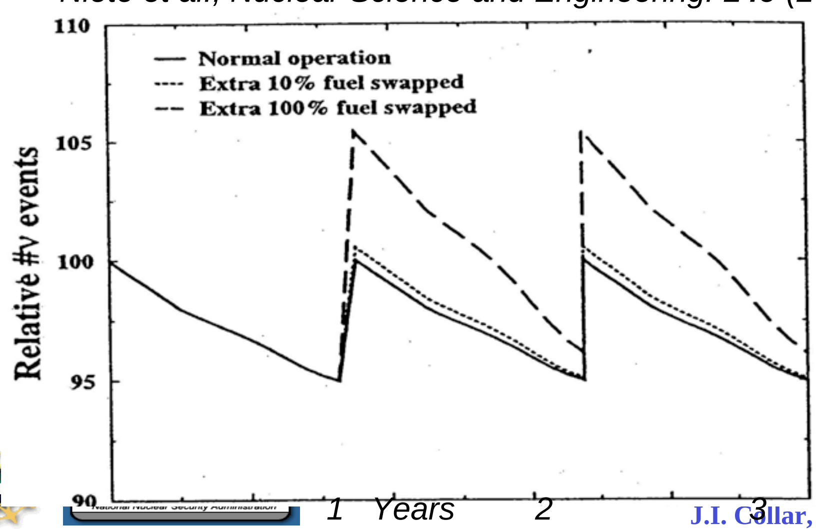
Nieto et al., Nuclear Science and Engineering: ***149*** *(2005)*



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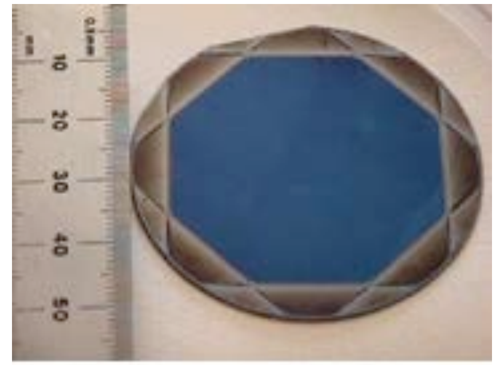
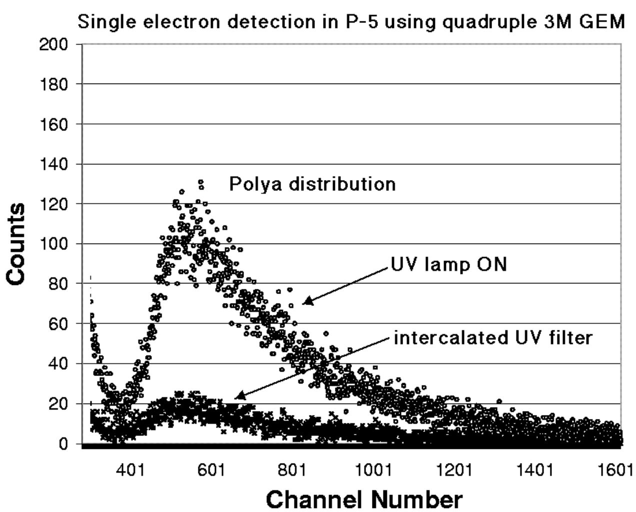
Three legged stool needed: mass, threshold, background

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

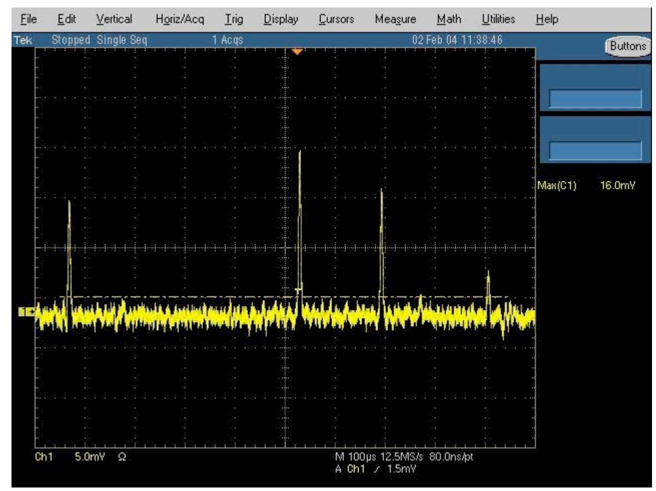


13 cm^2 APD on a 2 inch diameter silicon wafer



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)



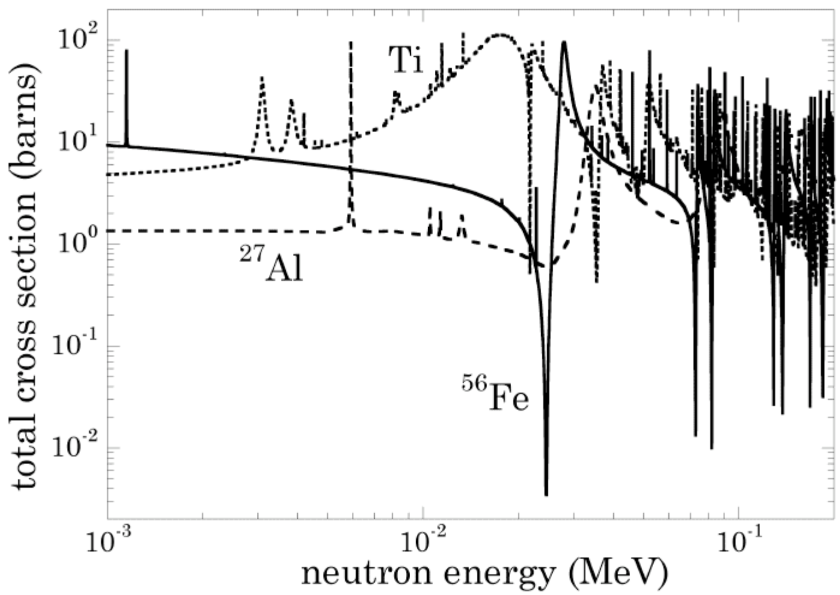
Mass-produced 3M-UoC GEM and single-electron signals from quadruple GEM

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

The Kavli Foundation

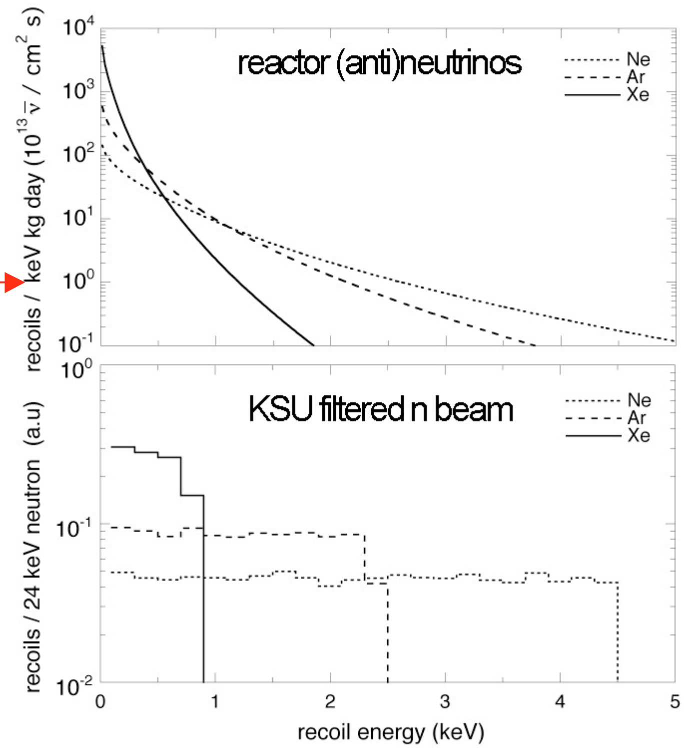
Start with the foundations: ultra low-energy recoil calibrations at KSU reactor

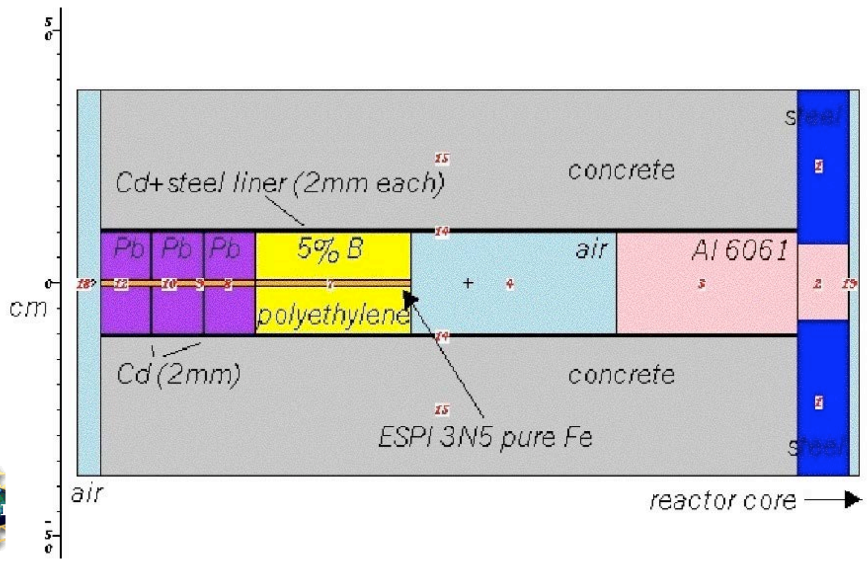
Kavli Institute for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO



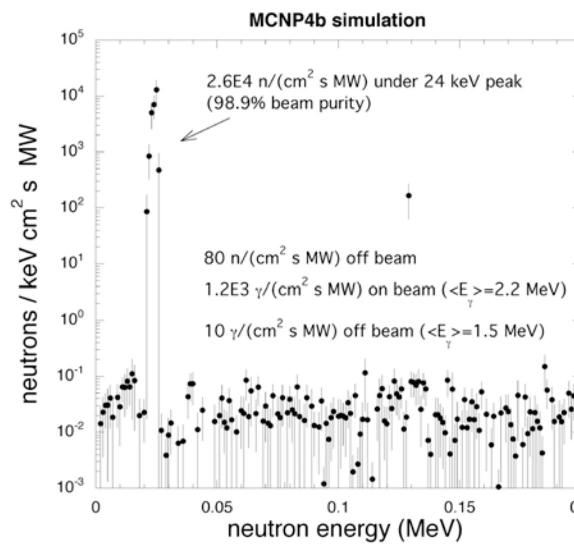
Fe-Al filter + Ti post-filter

24 keV n's mimic reactor ν's





MCNP filter design



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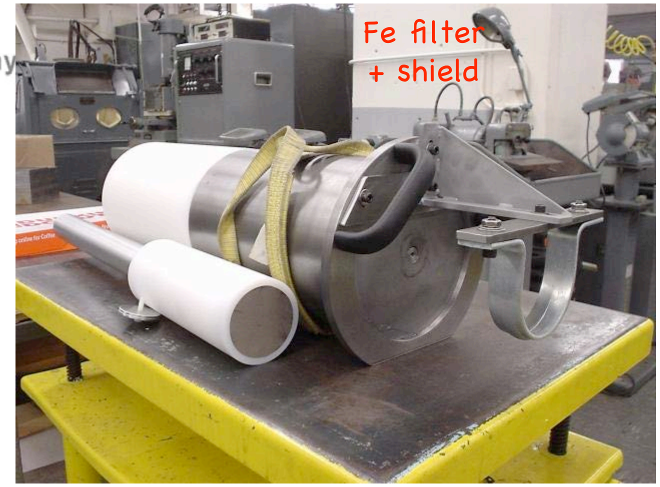
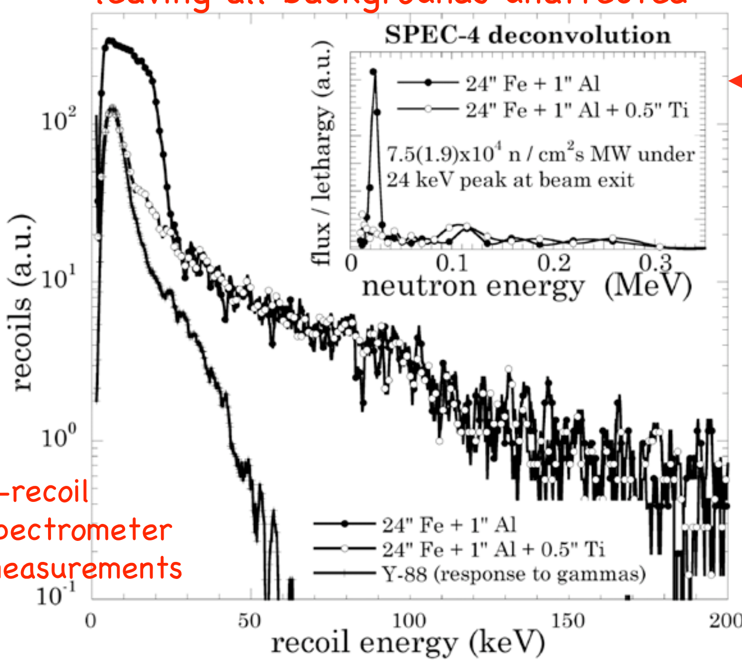


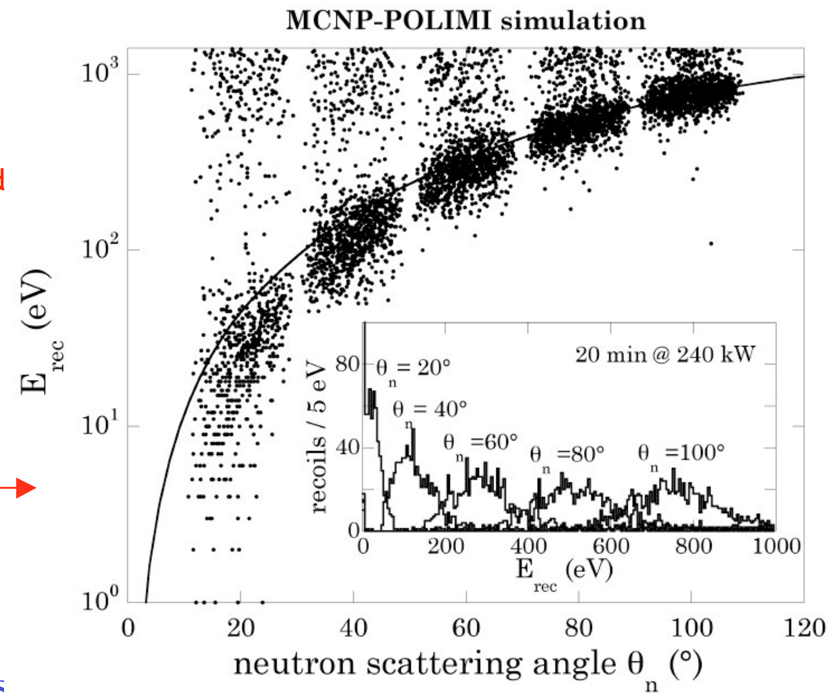
Ti post-filter "switches off" the recoils,
leaving all backgrounds unaffected



p-recoil
spectrometer
measurements

← Beam characterization studies completed 2005 (submitted to Phys. Rev. C)

Ideal to explore sub-keV recoil region →



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

IEEE Transactions on Nuclear Science, Vol. 36, No. 1, February 1989
P. N. Luke, F. S. Goulding, N. W. Madden and R. H. Pehl
LOW CAPACITANCE LARGE VOLUME SHAPED-FIELD GERMANIUM DETECTOR

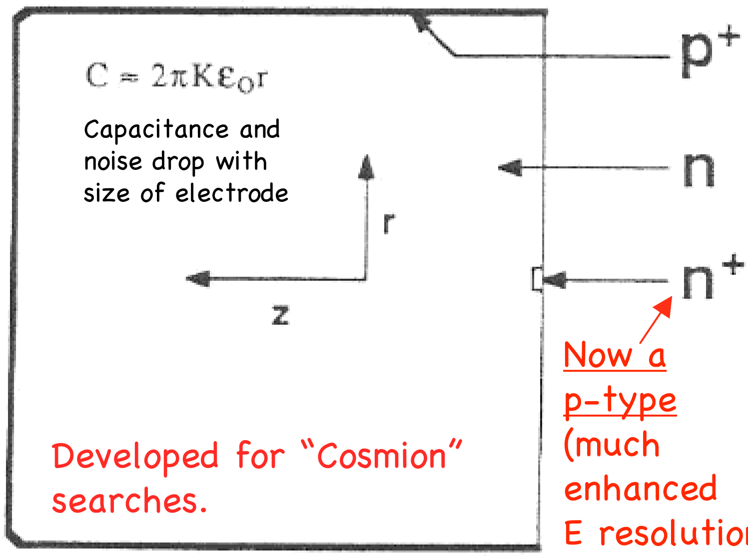

Fig. 3. Structure of the shaped-field detector.

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/$\sqrt{Hz}$
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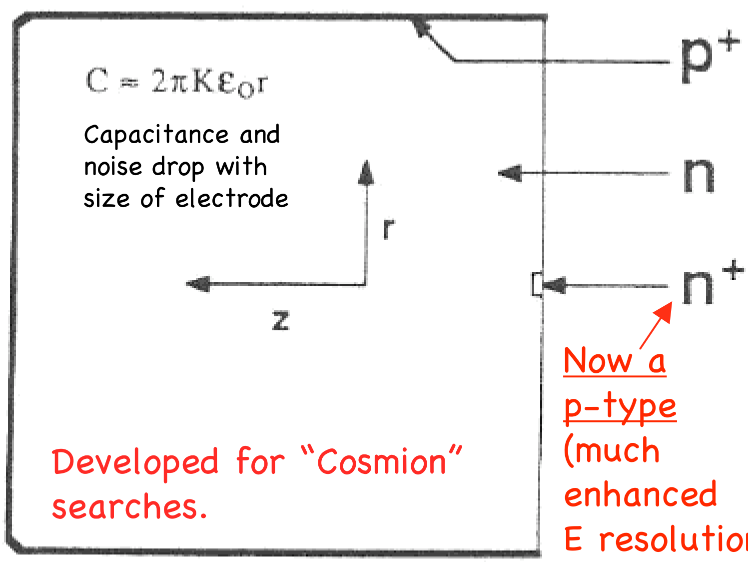

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The energy resolution and large mass of a HPGe plus the noise and threshold of a tiny x-ray detector???

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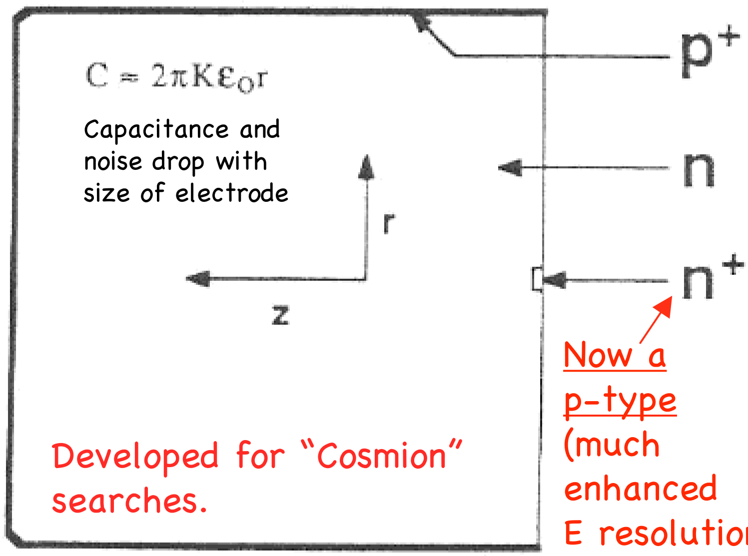

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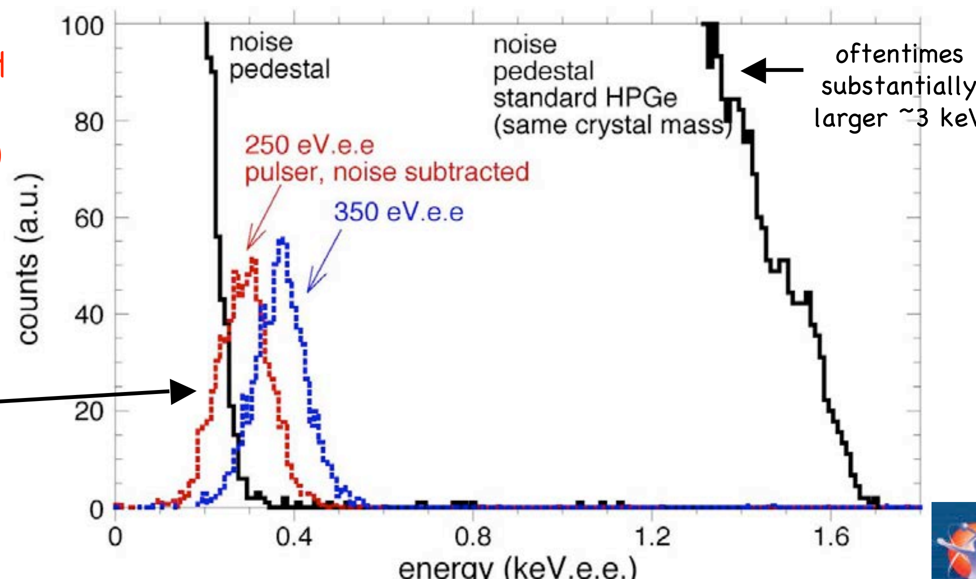
~x10 less noise than conventional HPGe of same mass (475 g) (threshold equivalent to 5 g x-ray detector)



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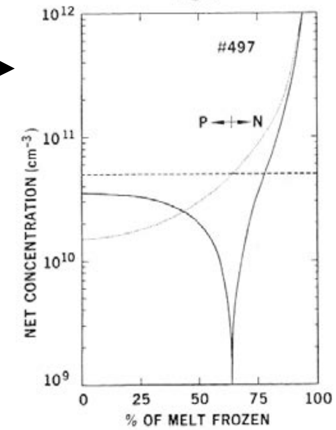
Precise gradient of charged impurities along the axis needed to compensate for small electrode

98 E. E. Haller *et al.* Adv. in Phys. 30(81)93

Fig. 1



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.

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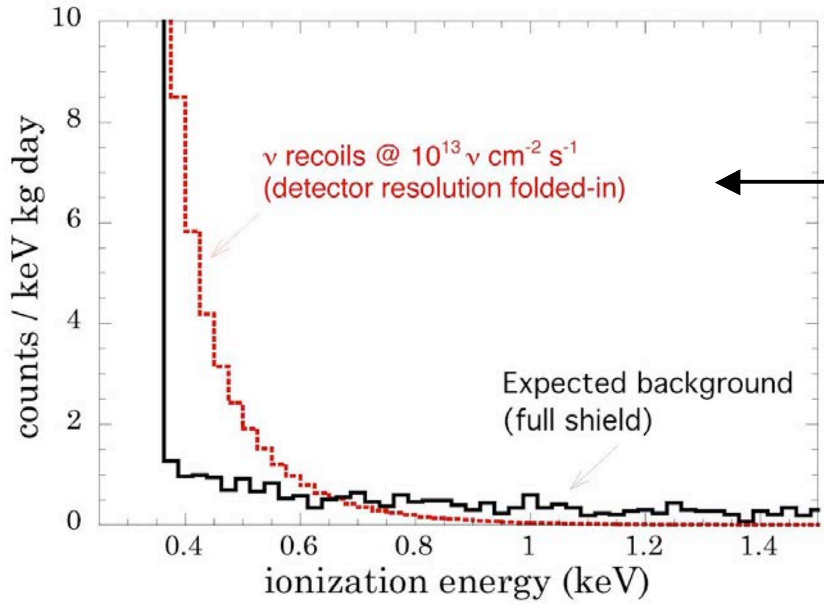
Mass and threshold in place for reactor experiment, background… almost there (anti-Compton shield & Al part replacement underway)

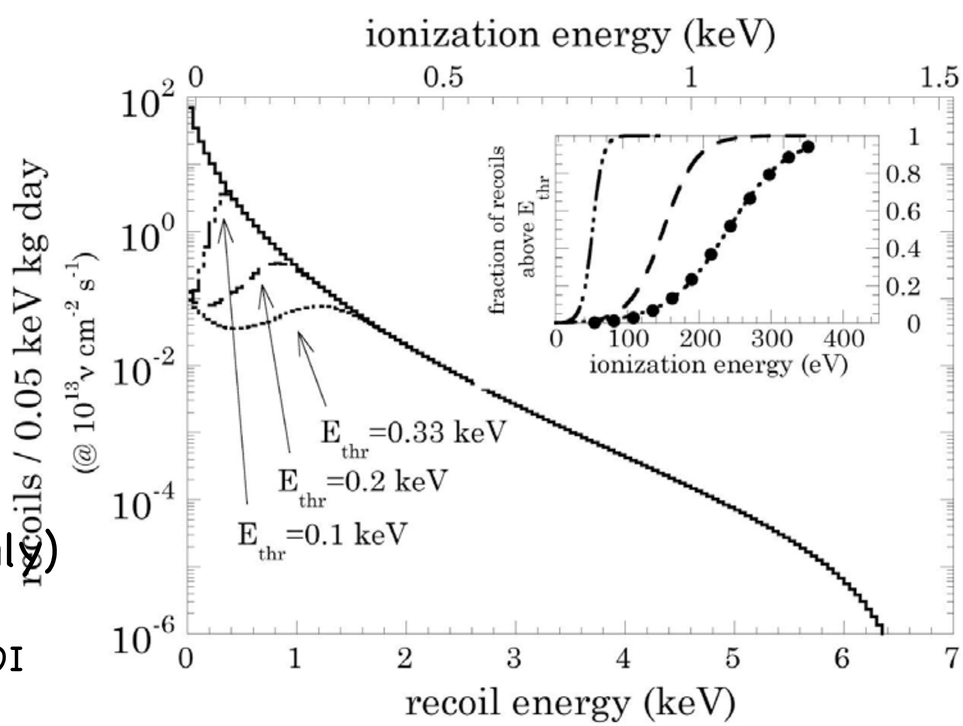


Expected antineutrino signal in reactor experiment with present detector. Background goal shown (scaled down from present status)

Presently 2.5 ν recoils/kg-day expected

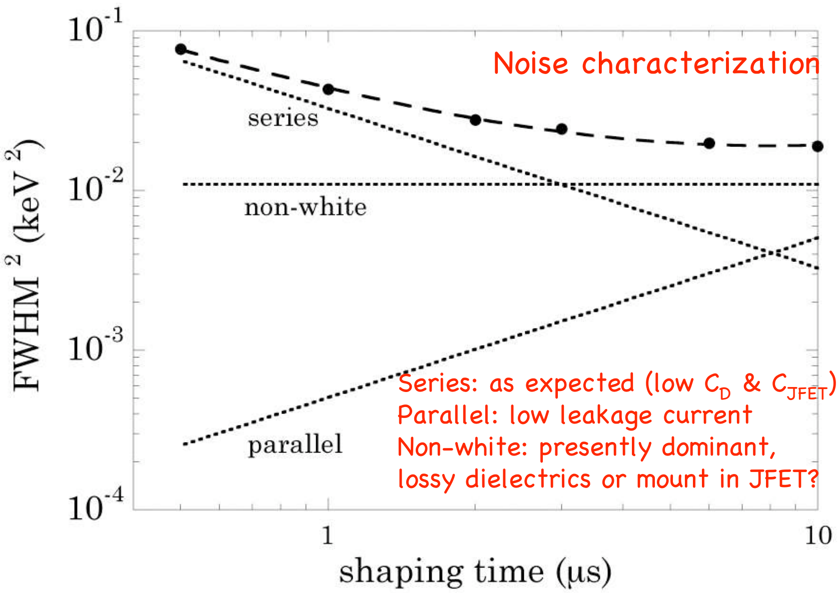
Work on non-white noise can increase this to >30 ν recoils/kg-day

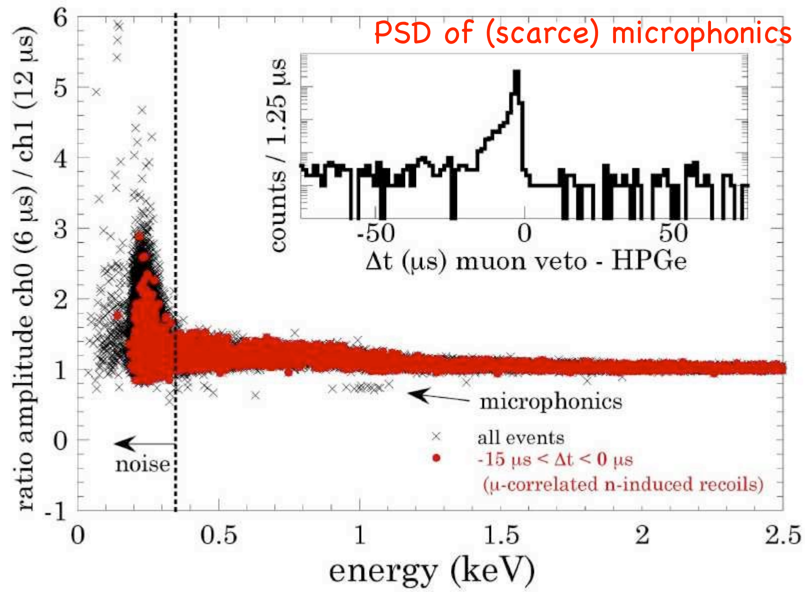
(limited by state-of-the-art JFET noise only)

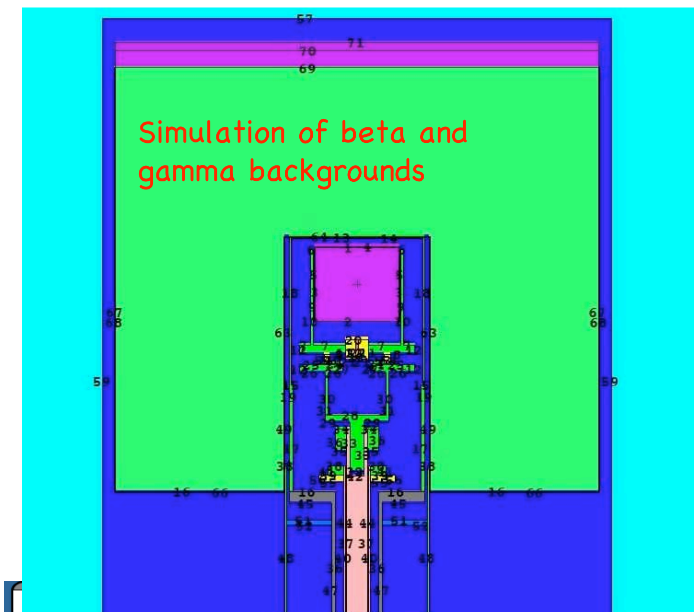


Silver lining: all of the signal concentrated in small ROI

Extensive detector characterization early 2006
(submitted to Phys. Rev. C)







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

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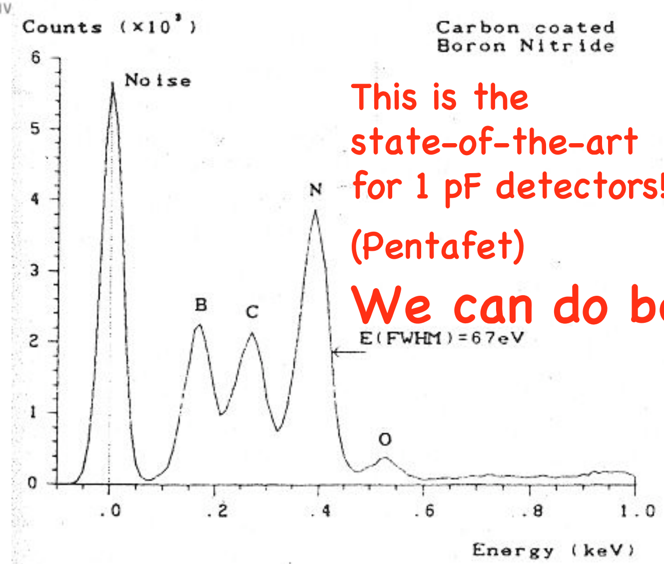

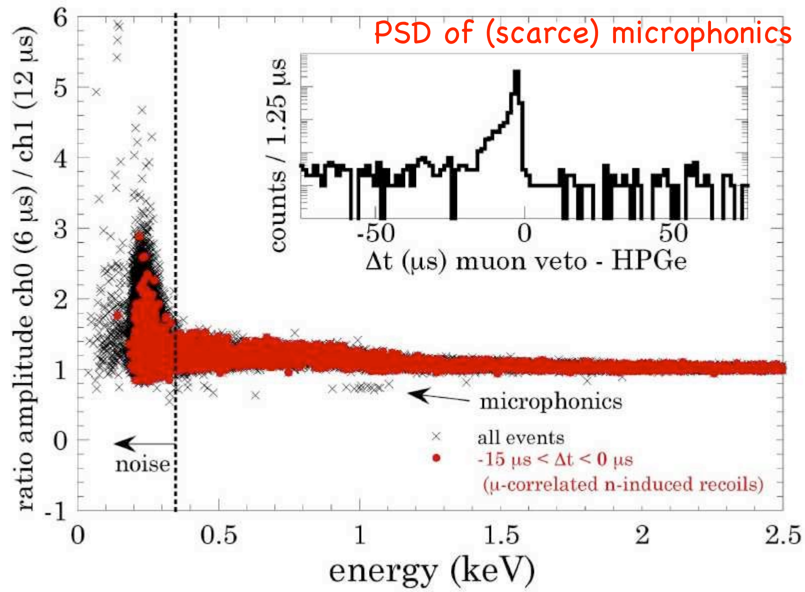

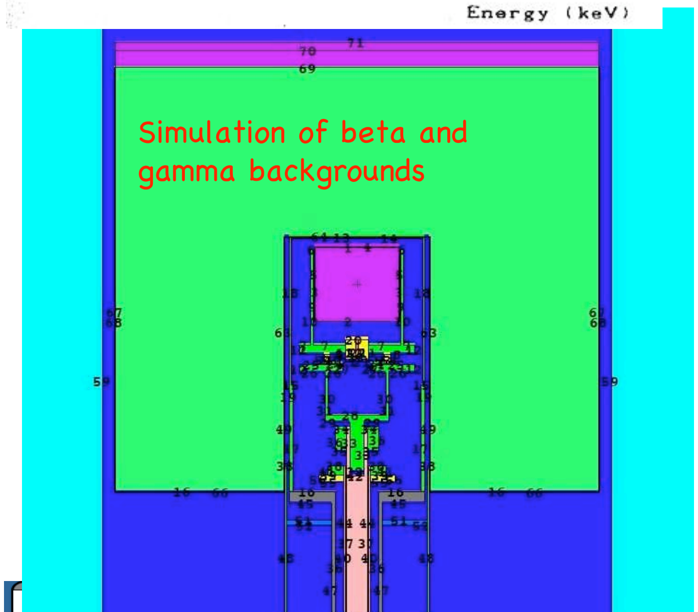

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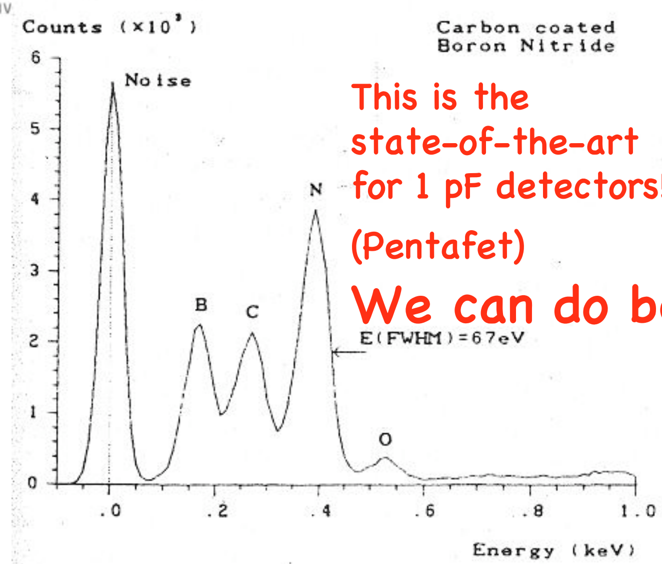
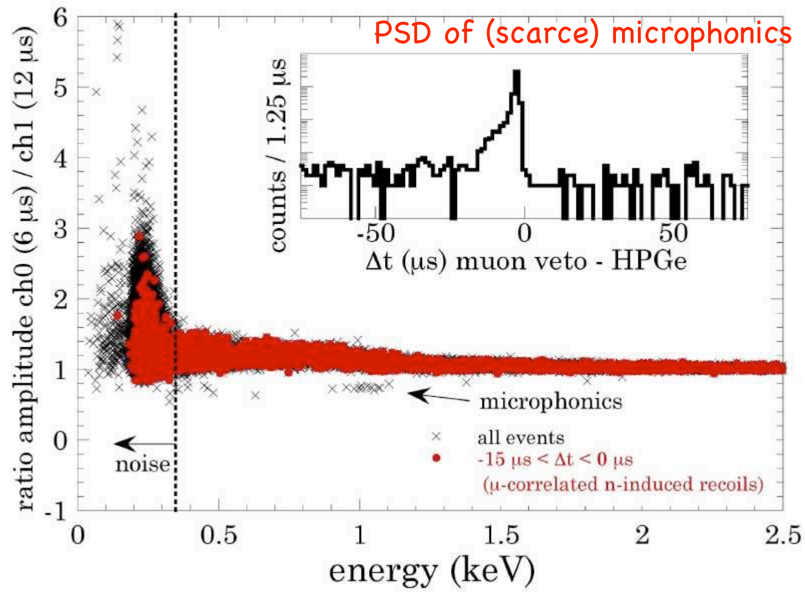
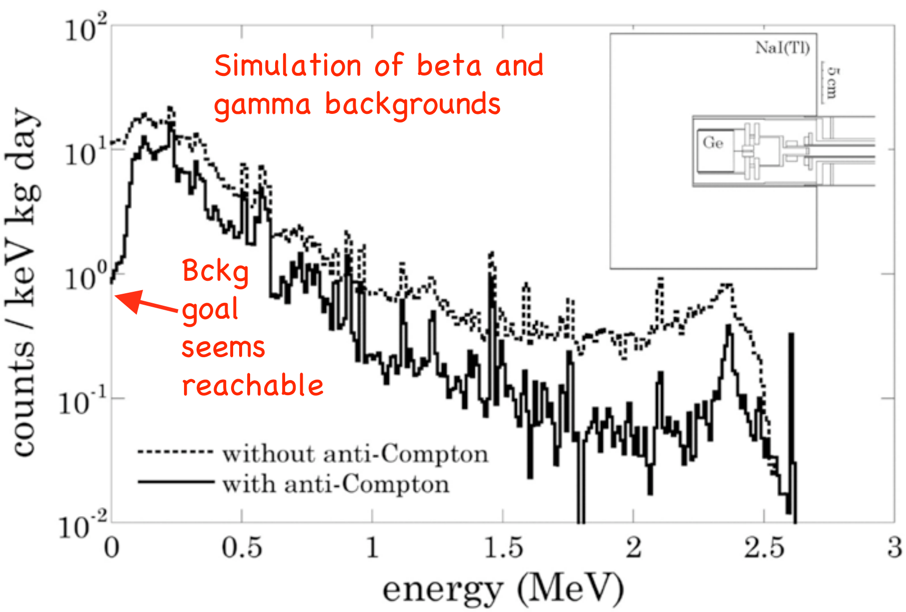


This is the state-of-the-art for 1 pF detectors!

(Pentafet)

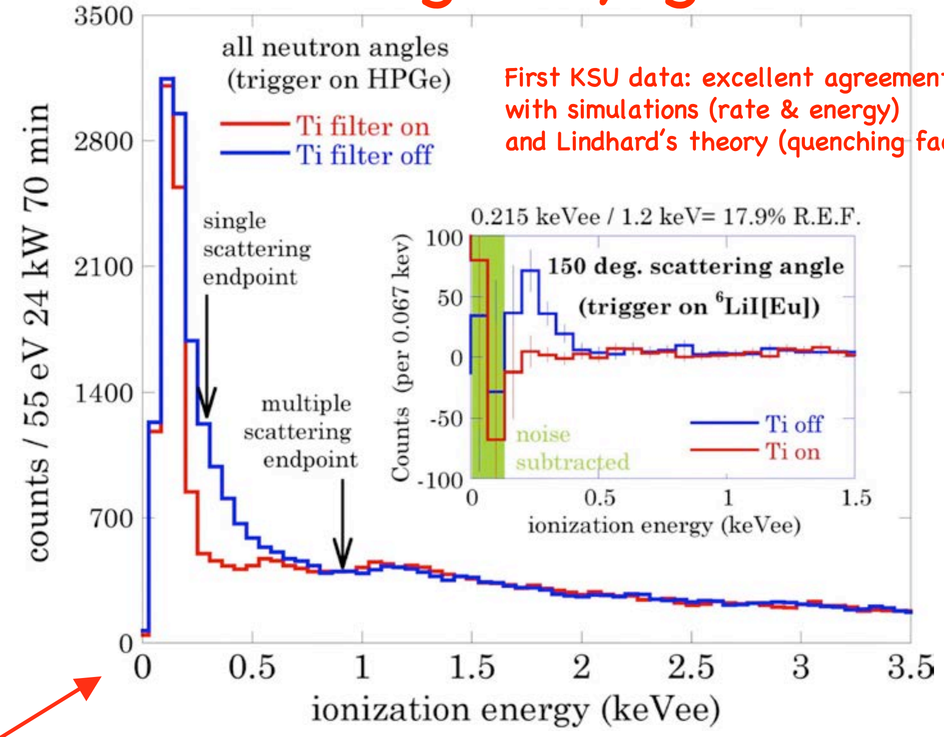
We can do better



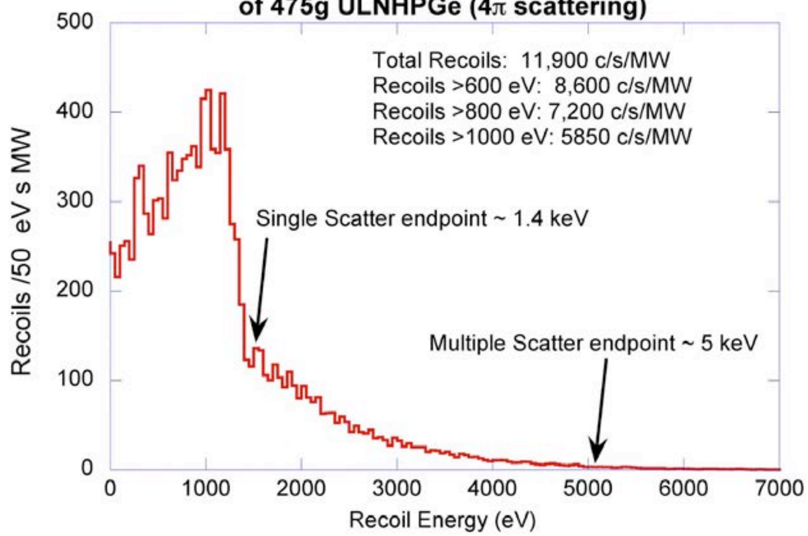


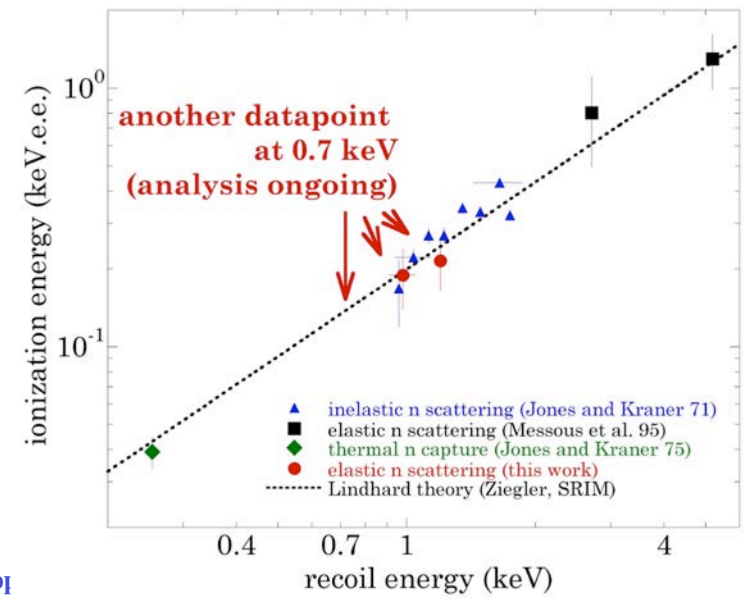
Some recent news: looking very good...

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



KSU 24 keV beam MCNP simulations of 475g ULNHPGe (4π scattering)





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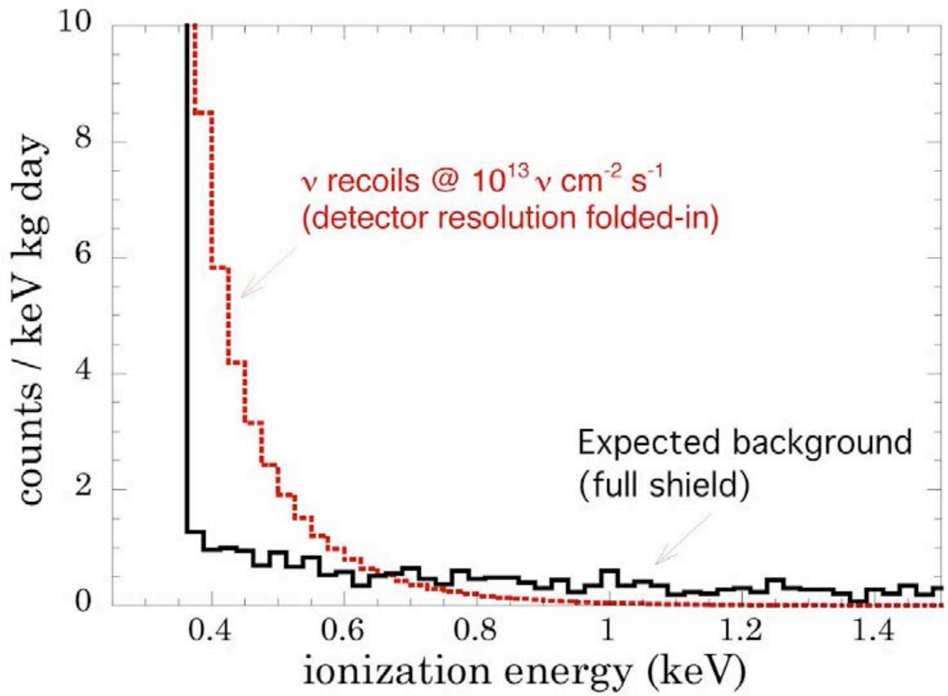
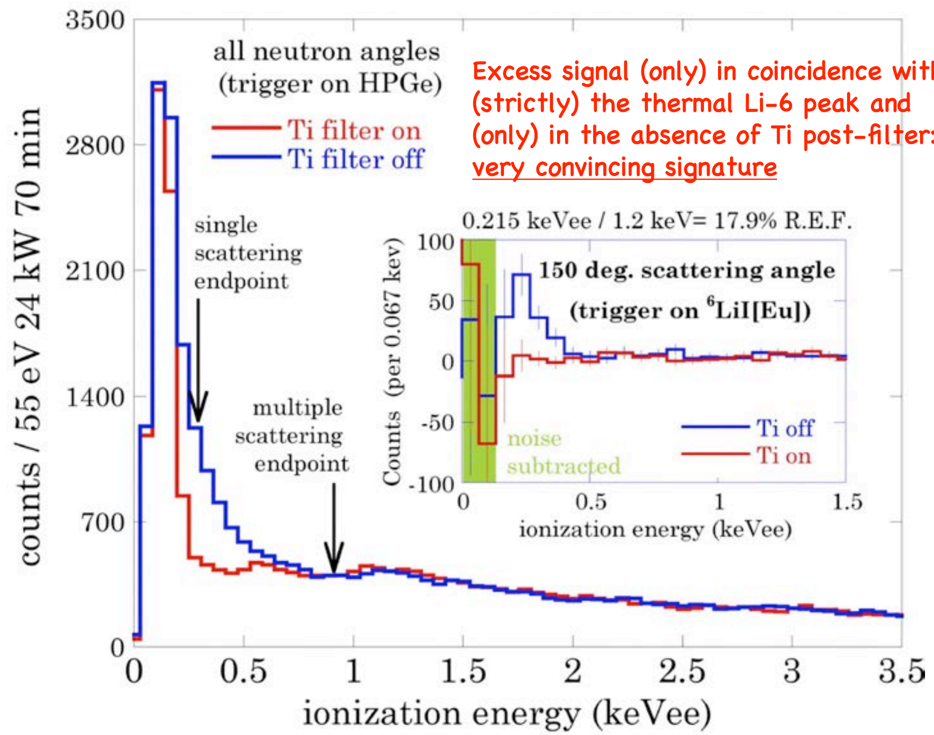
Some recent news: looking very good…

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…

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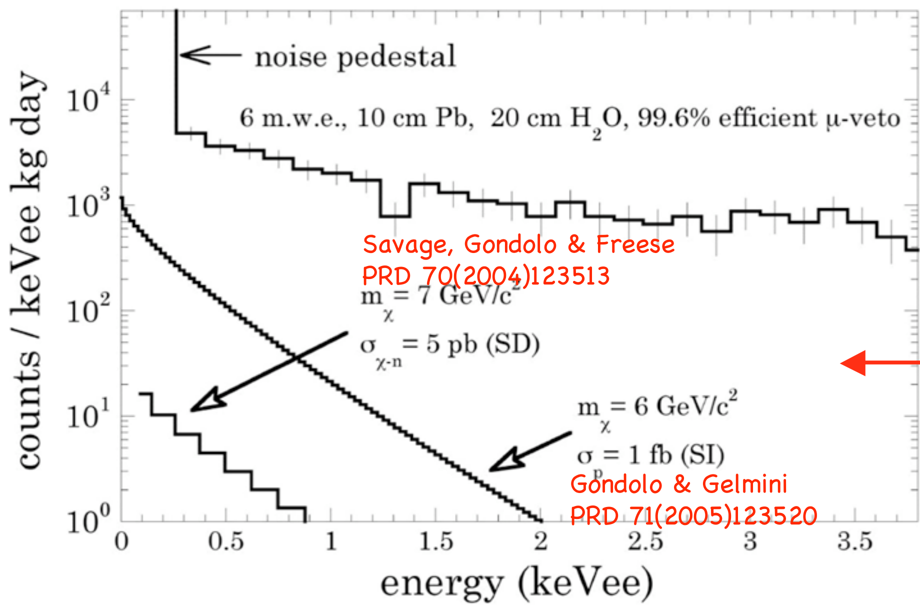
Definitive check on DAMA soon
X50 improvement from clean Al, x10 from anti-Compton



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! ☹)

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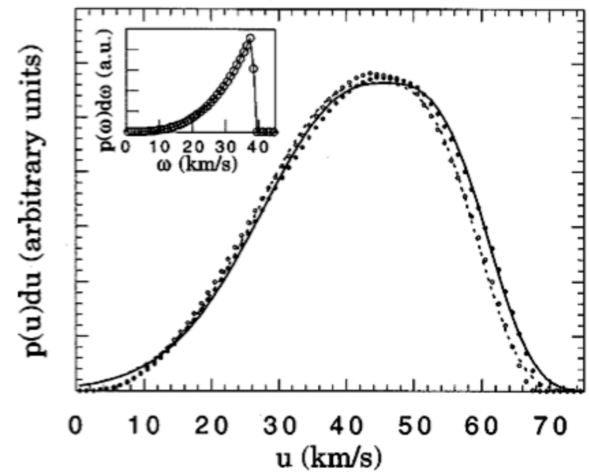
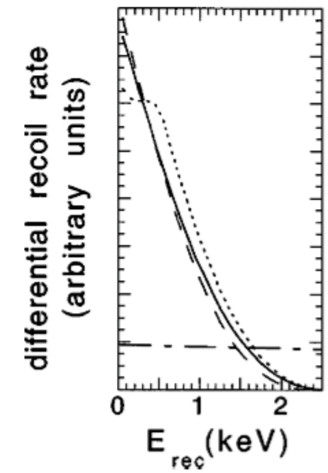
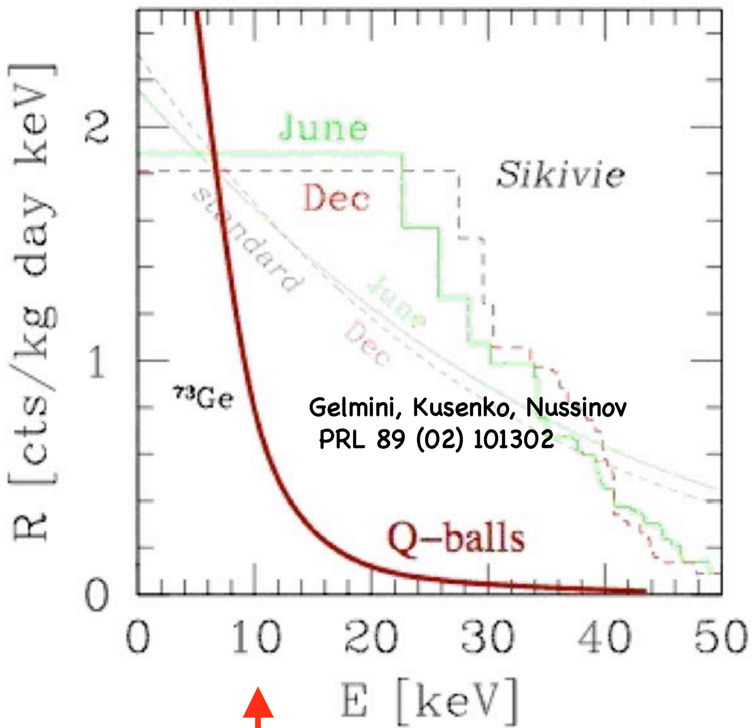
What else can you do with such a detector?

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

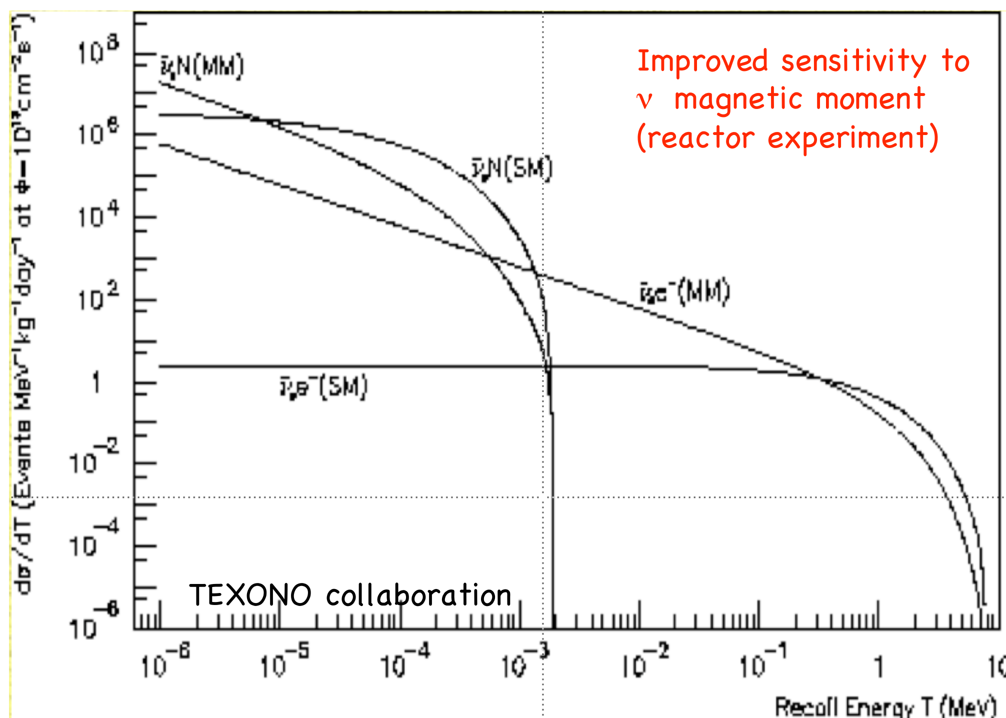
Solar-bound WIMPs:
deposit ~x100 less E_{rec}
than galaxy-bound,
concentrate all rate in narrow
spectral region (higher s/n)
Sub-keV threshold a must





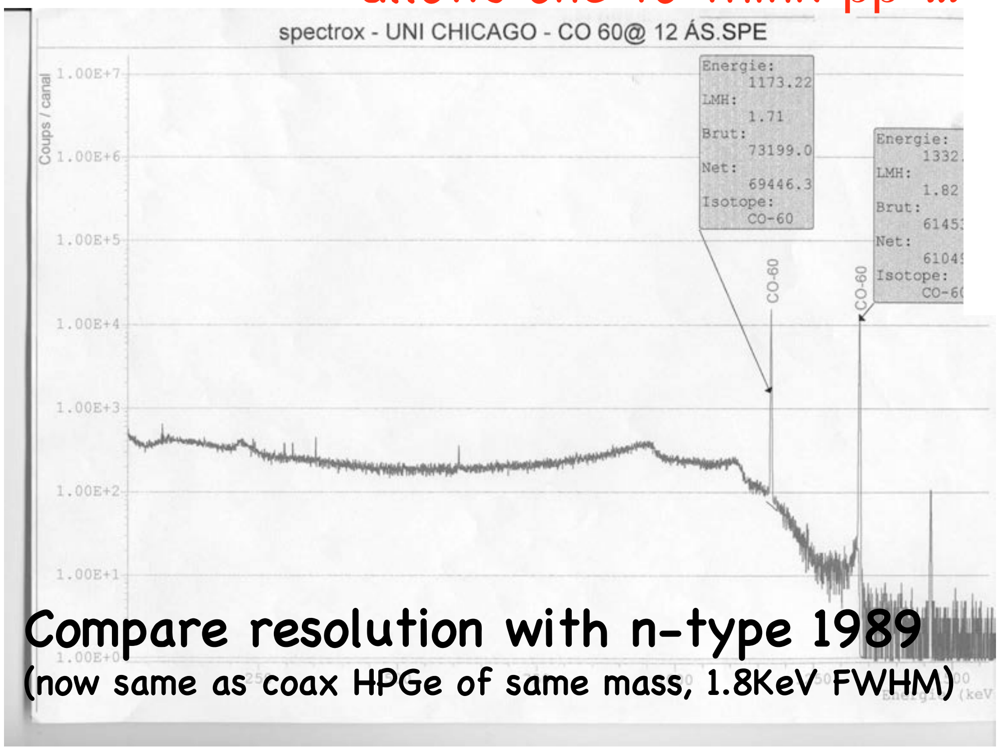


The neutralino is not the only supersymmetric
Dark Matter candidate. Non-pointlike DM
(Q-balls, Mirror matter, etc.) call for
ultra-low threshold detectors

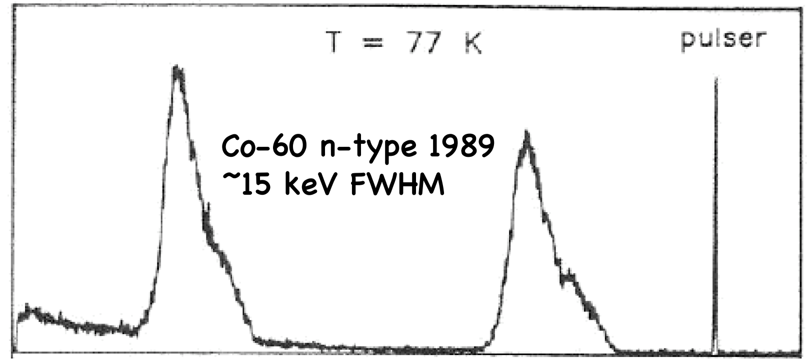


MAJORANA: can we avoid segmentation altogether?
(cost, speed, simplicity, much lower front-end backgrounds)
Does this device have anything to offer in a ββ context?

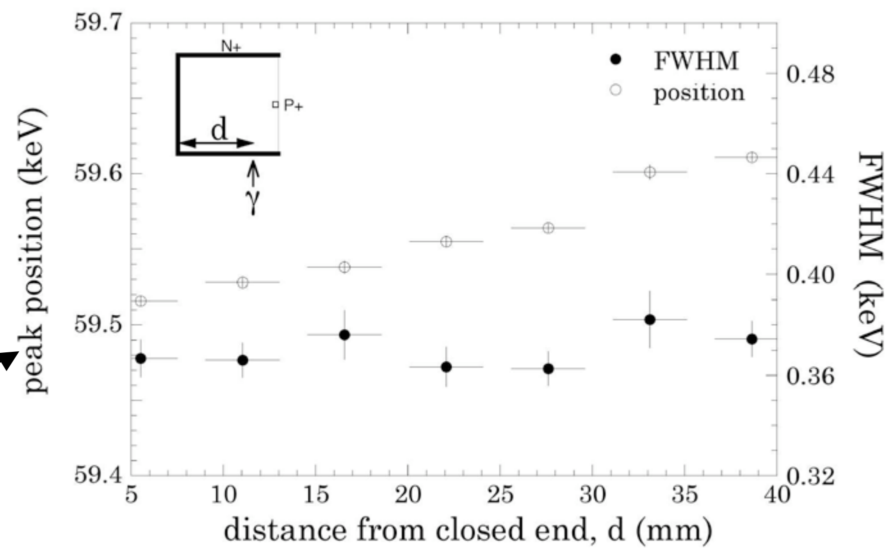
Optimal E-resolution
allows one to think ββ ...



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



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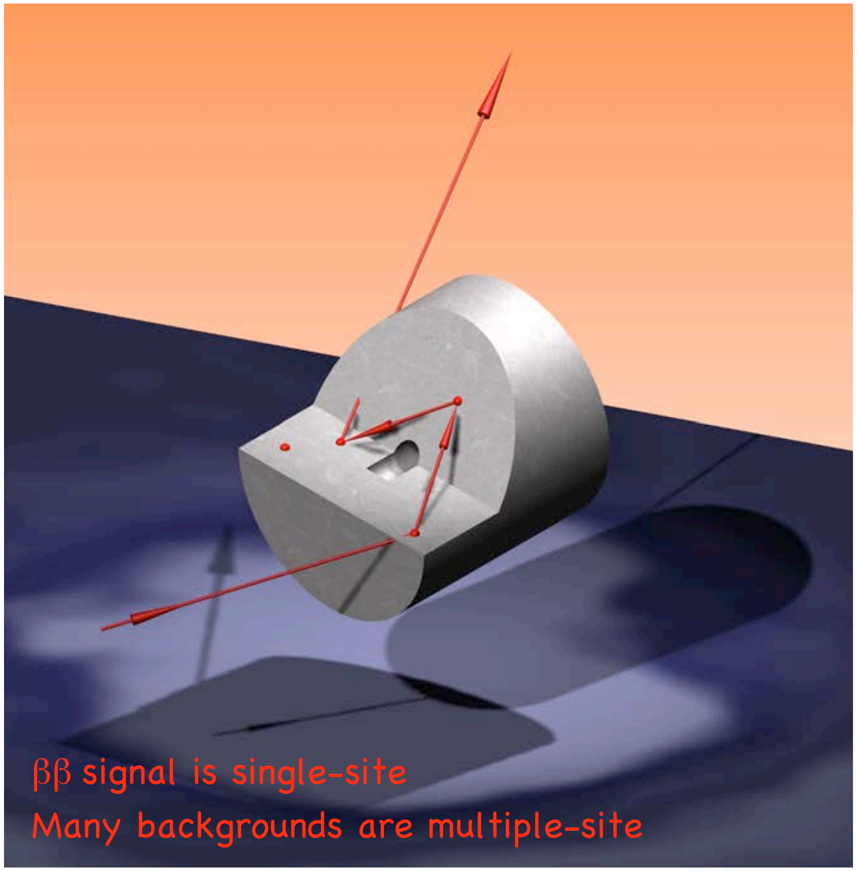
How does a multiple-site interaction look in a modified-electrode HPGe?



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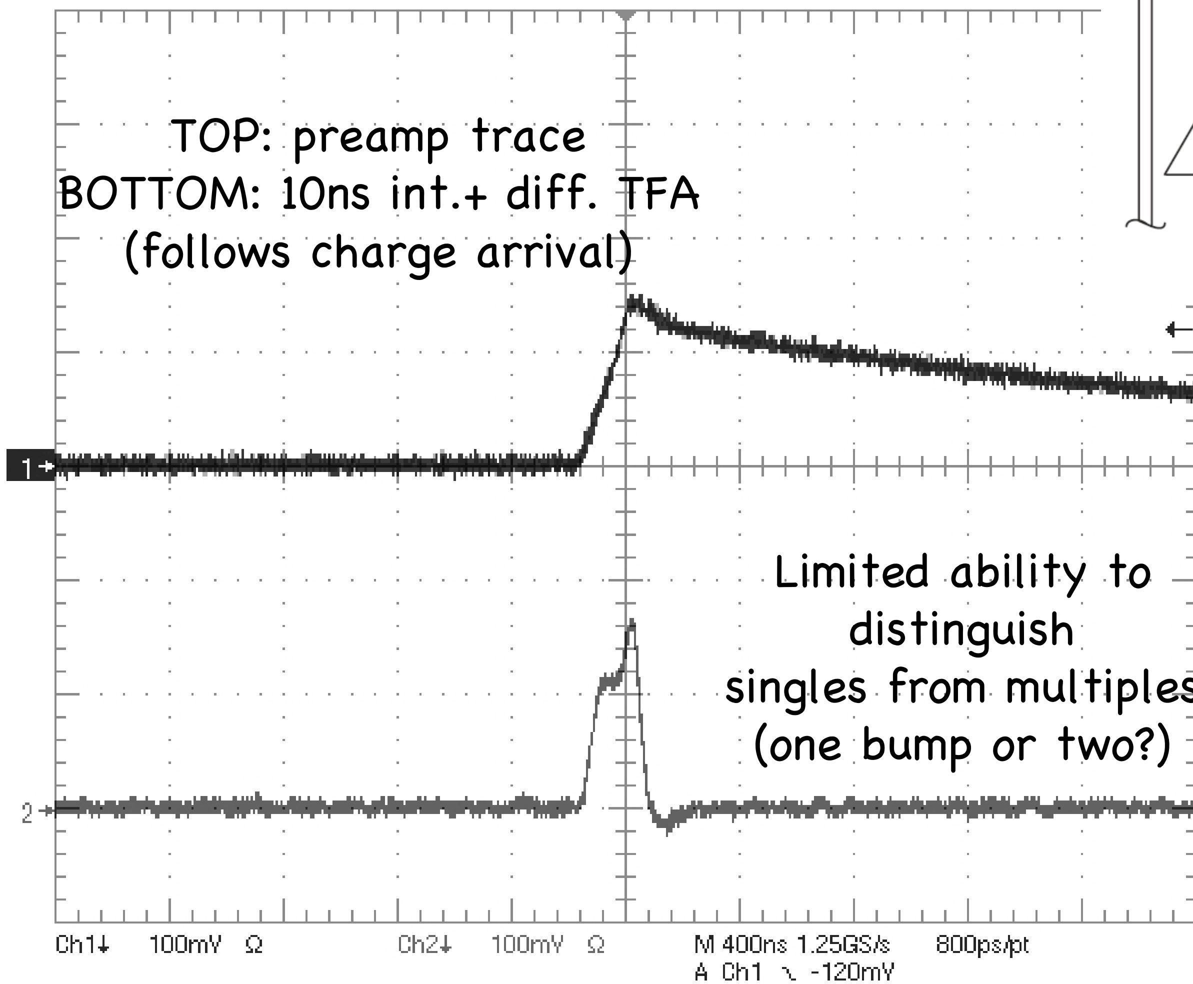
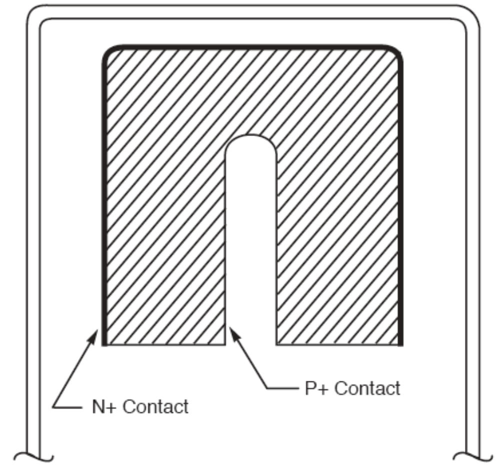
That was then…





Coaxial Ge Detector Configuration

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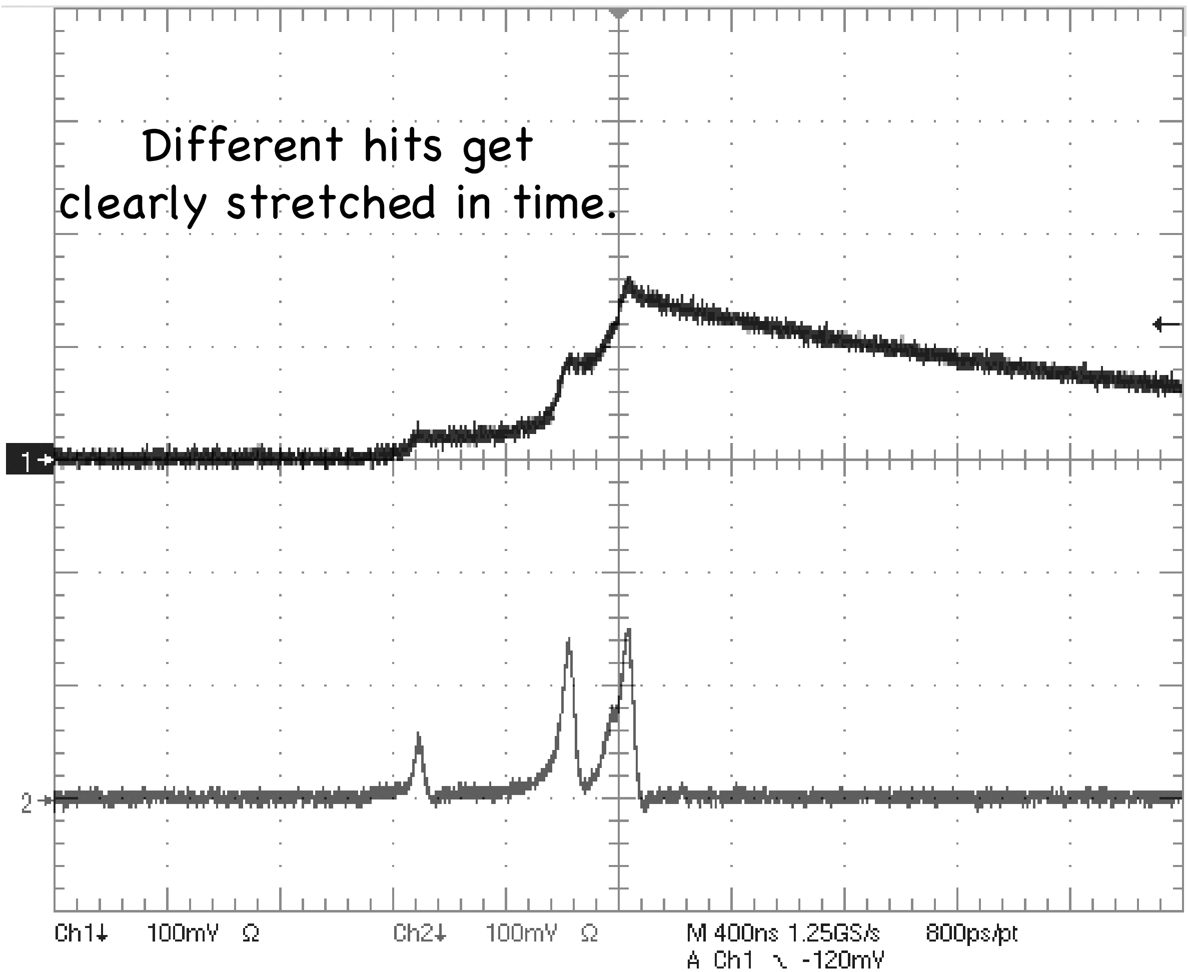
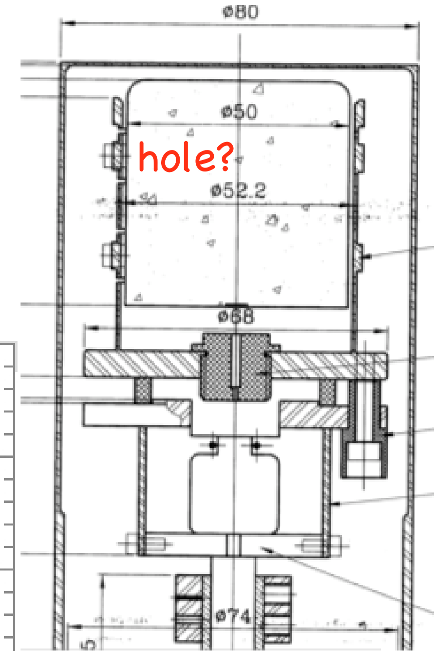
This is now.





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

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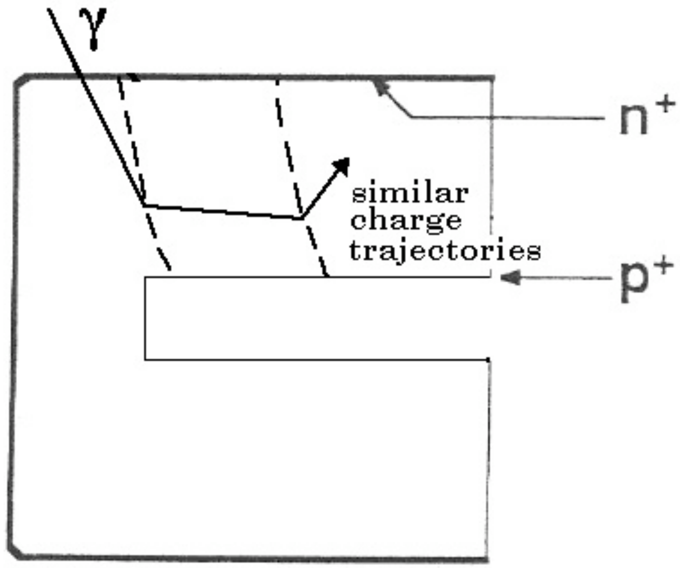
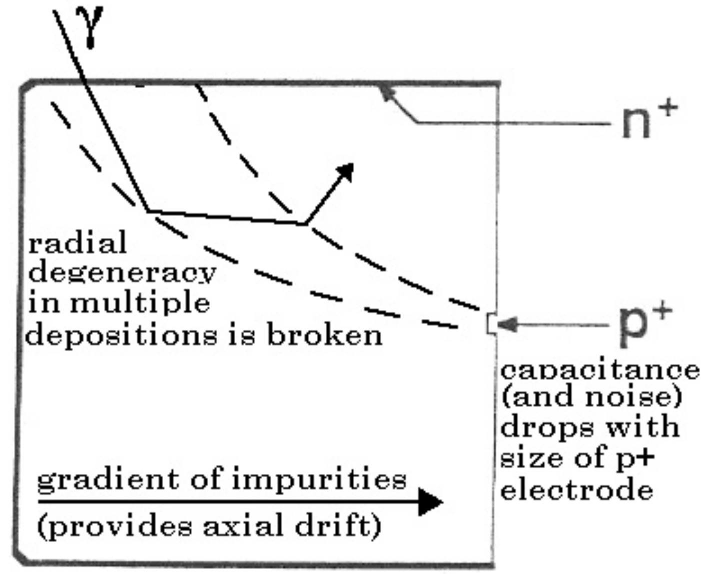
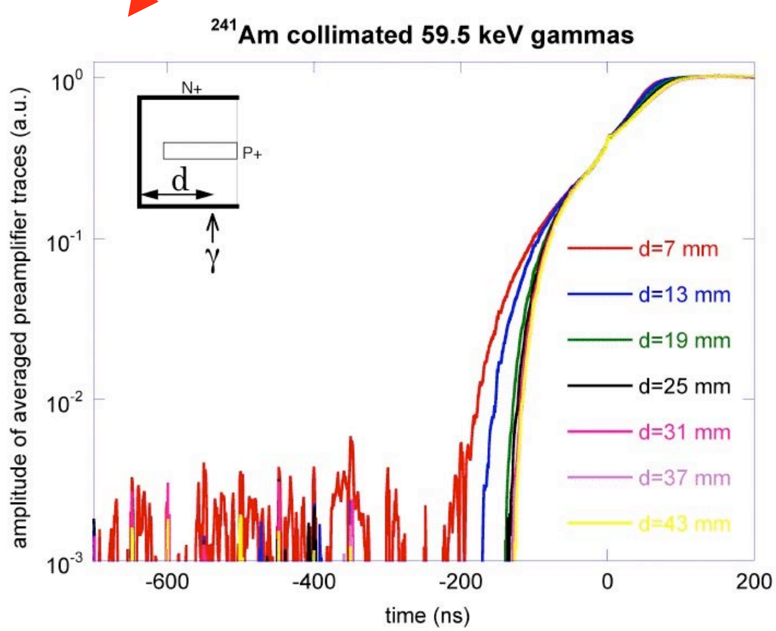
What is happening?

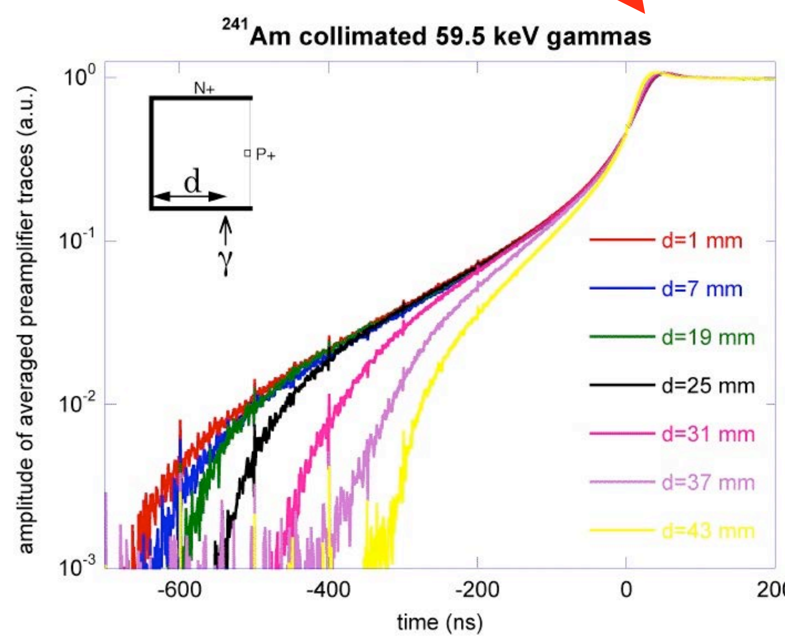


standard coaxial HPGe



P-type modified electrode





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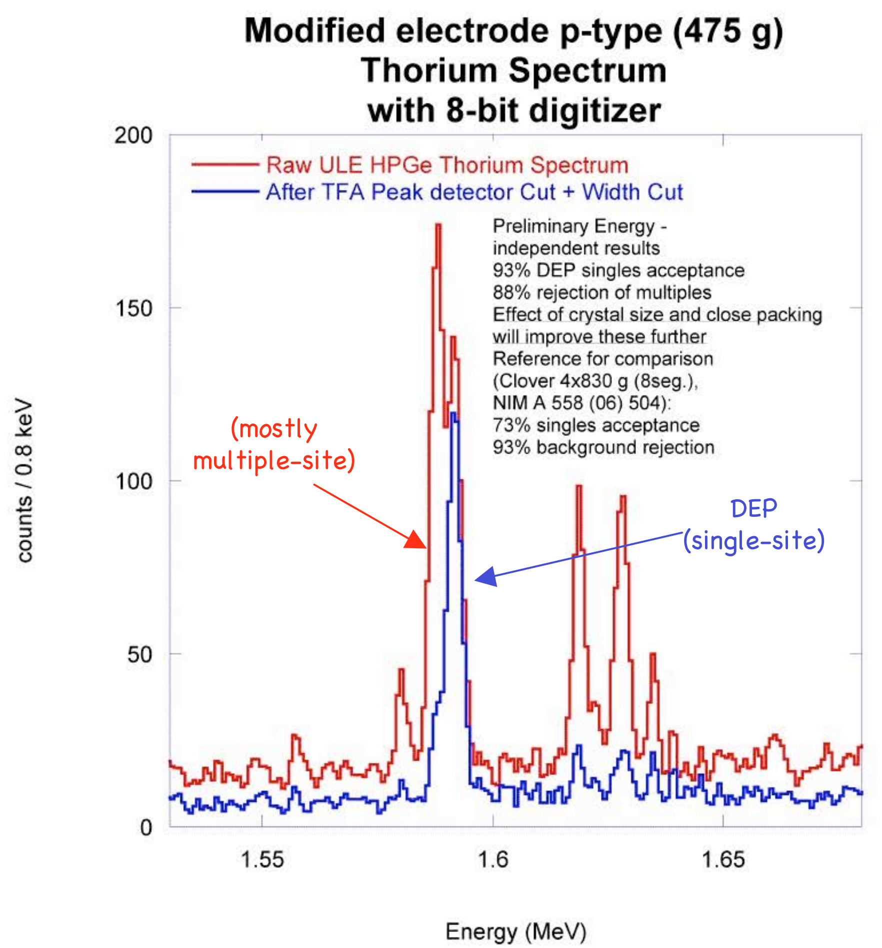
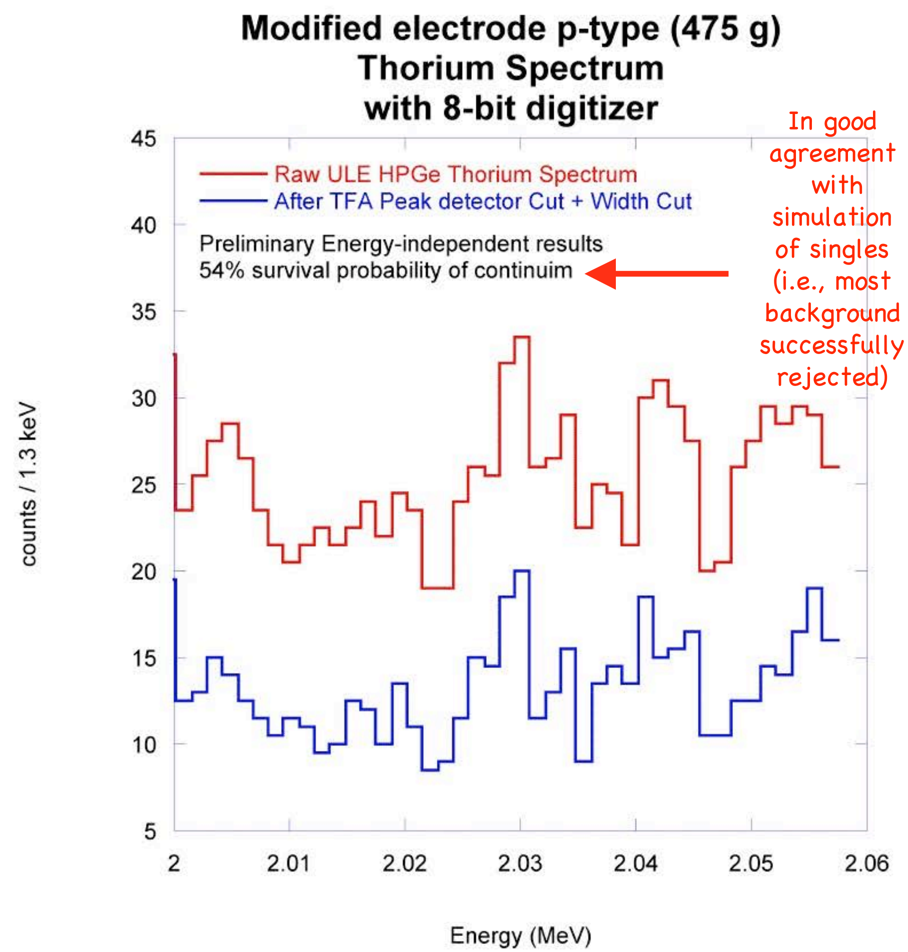
Better signal acceptance / background rejection than an 8-segment clover HPGe (even before close packing!) all with a single-channel device





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

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- 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).

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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. Upcoming NSF proposal (3 yr) will be 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)

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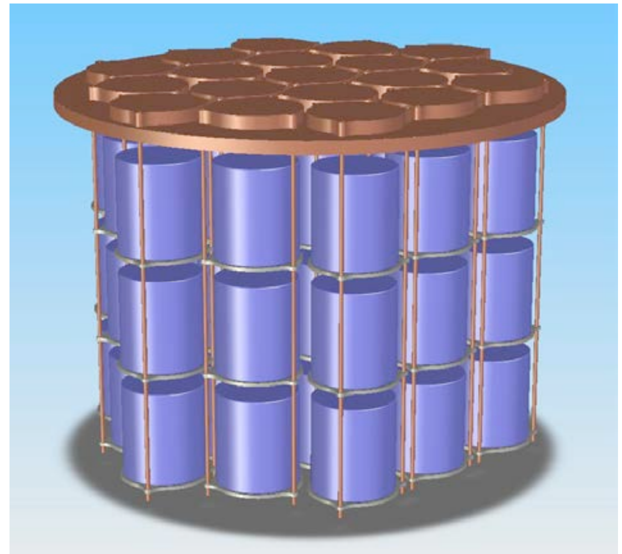
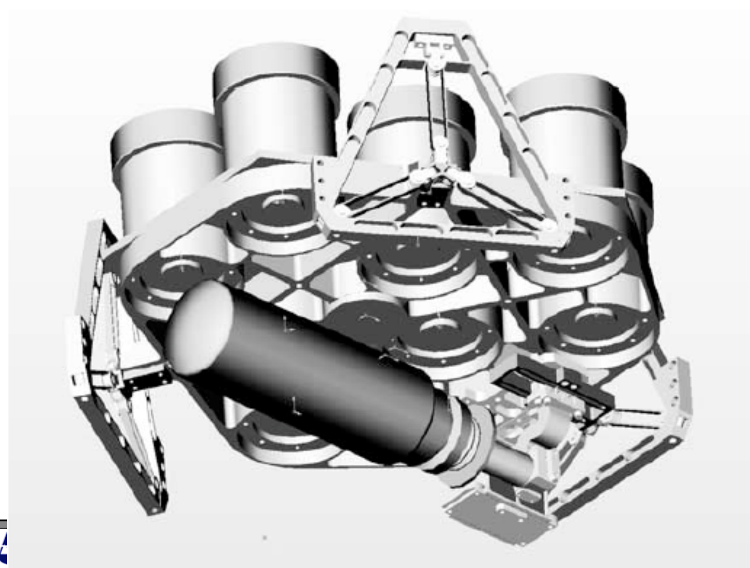
Reactor Monitoring: Right technological timing (HPGe technology flourishing: segmentation, encapsulation, arrays and (silent) mechanical cooling)

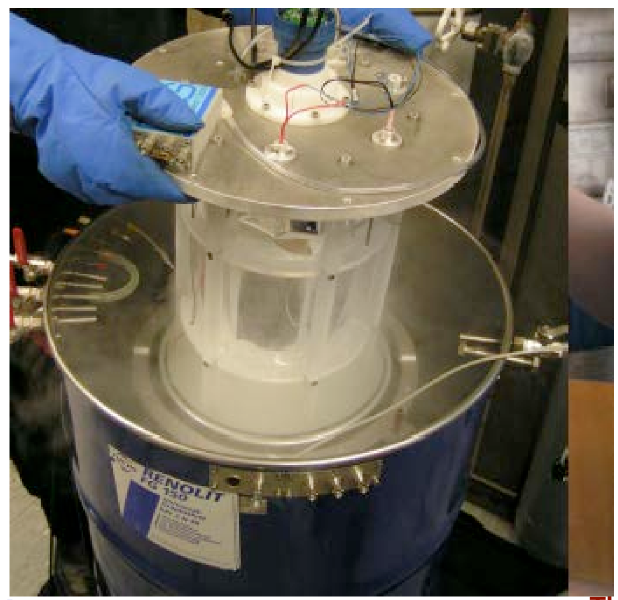
CLUSTER



MAJORANA

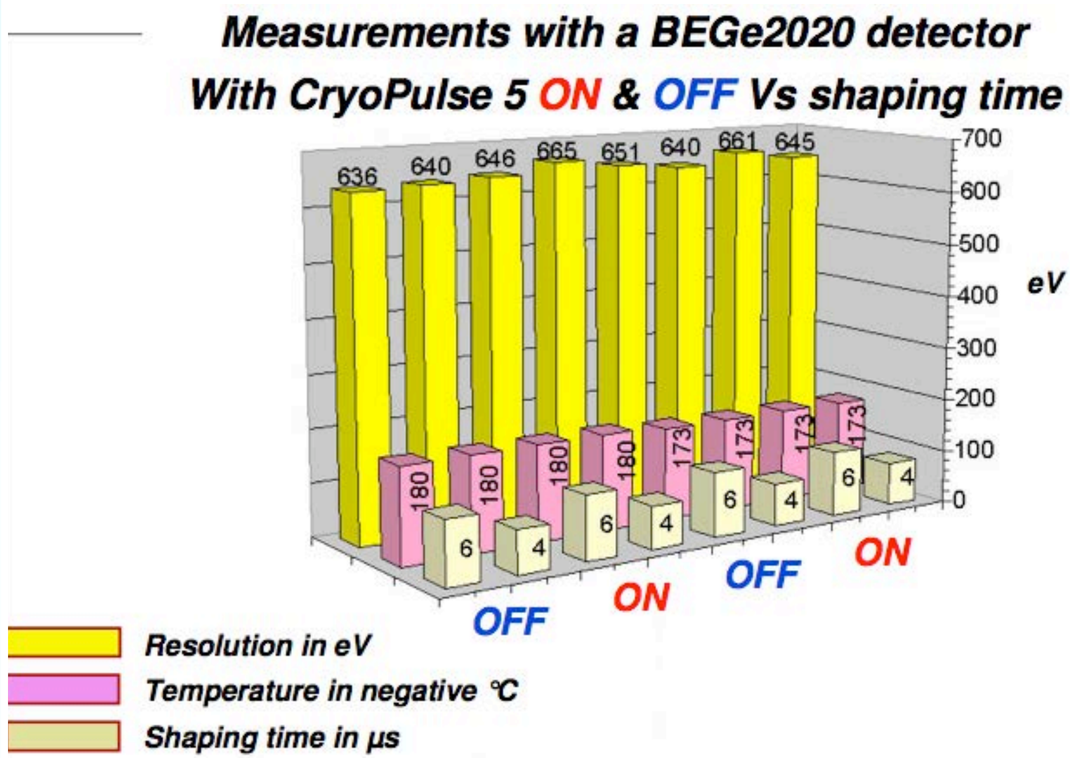


RHESSI



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.

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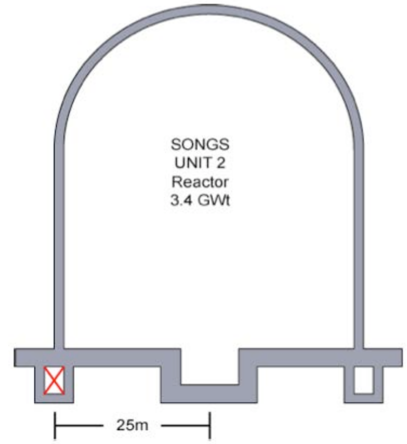
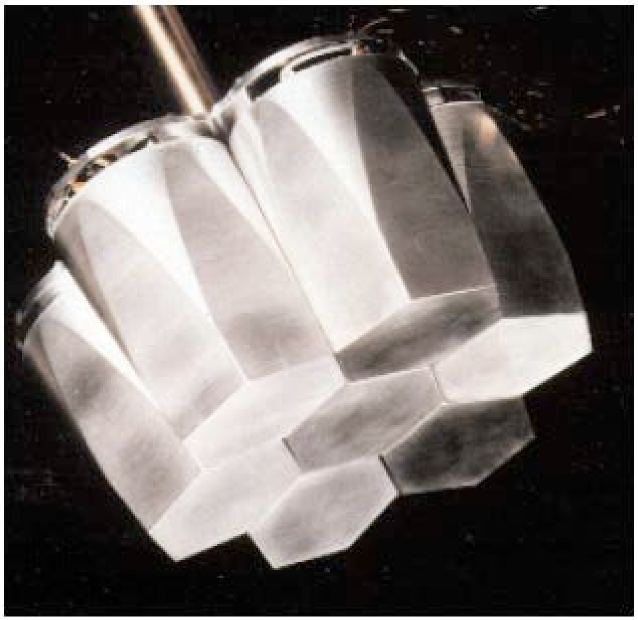
11 kg,
encapsulated,
single cold finger
(CANBERRA)

A reality
fast approaching?



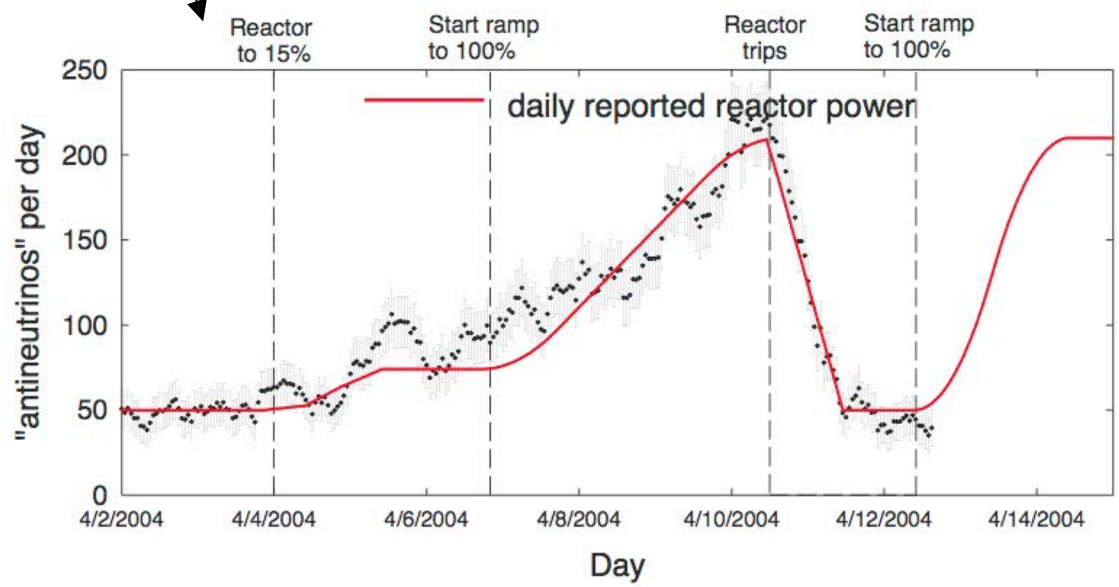
With 100 eV threshold,
the equivalent
of ~1 ton
liquid scintillator



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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Coherent neutrino detection:

I want to believe!

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