# From the ANL-Notre Dame BGO Array to the Ultimate Compton Suppression

CELEBRATING THE CAREER AND CONTRIBUTIONS OF ROBERT V. F. JANSSENS

David Radford

ORNL

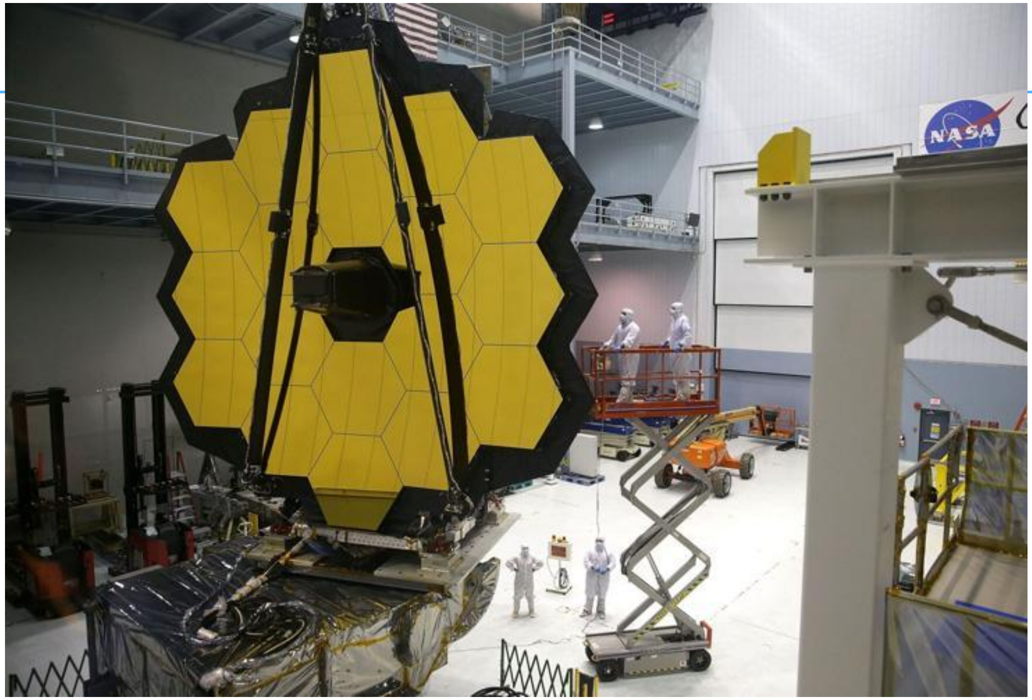
Sept 19, 2025

Oak Ridge National Laboratory

U.S. Department of Energy | Office of Science

# New Tools bring New Discoveries

- The Lens: 7th century BCE
  - Eyeglasses: 13th century
  - Microscope: 1590
  - Telescope: 1608
  - HST and JWST

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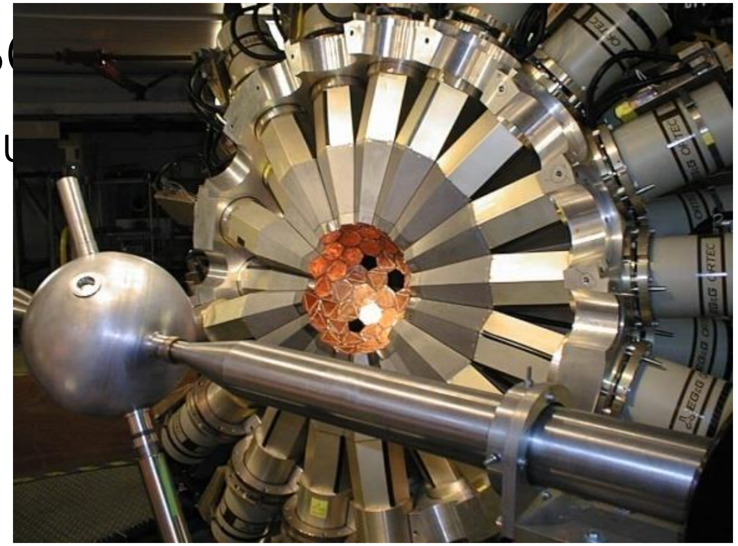
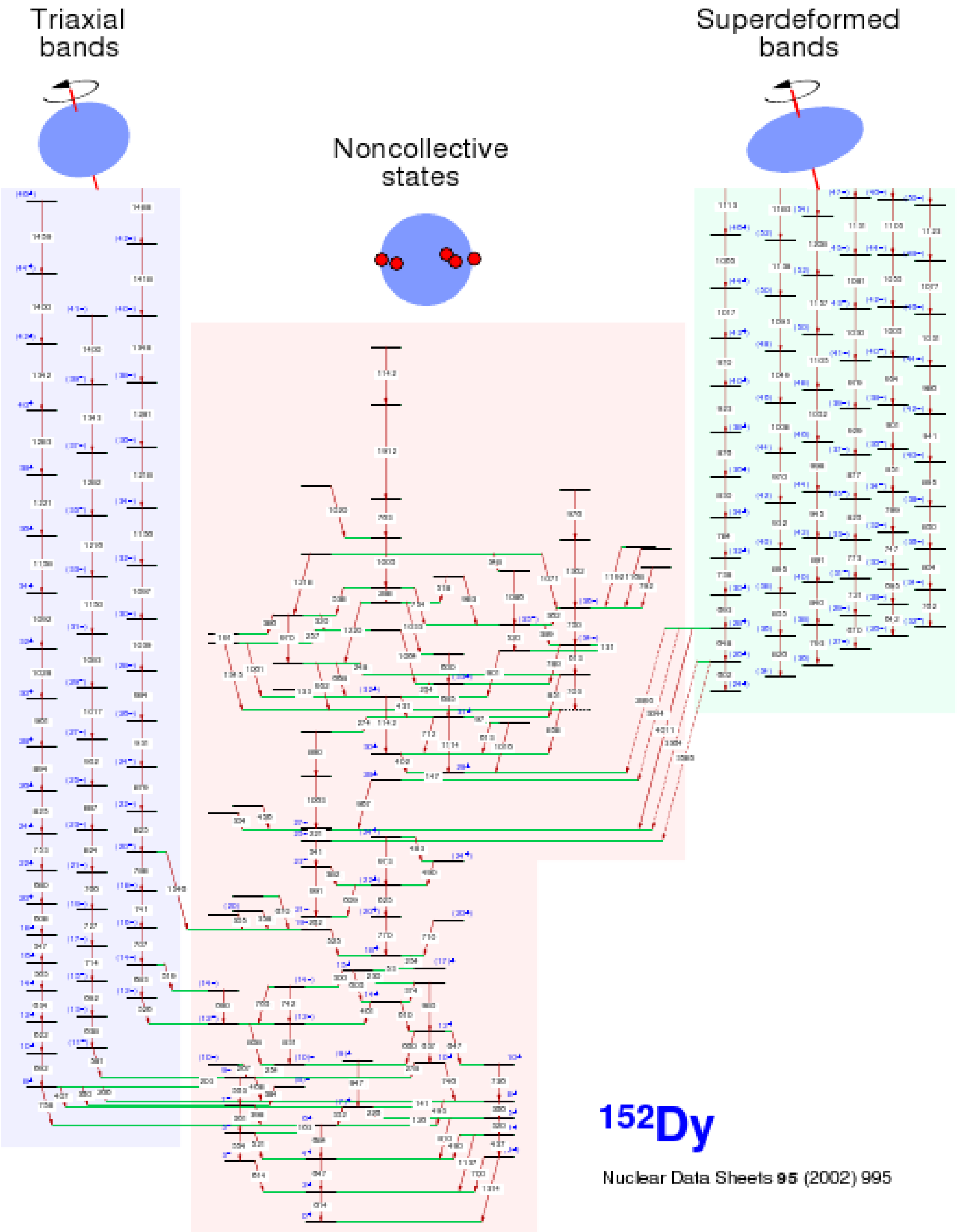
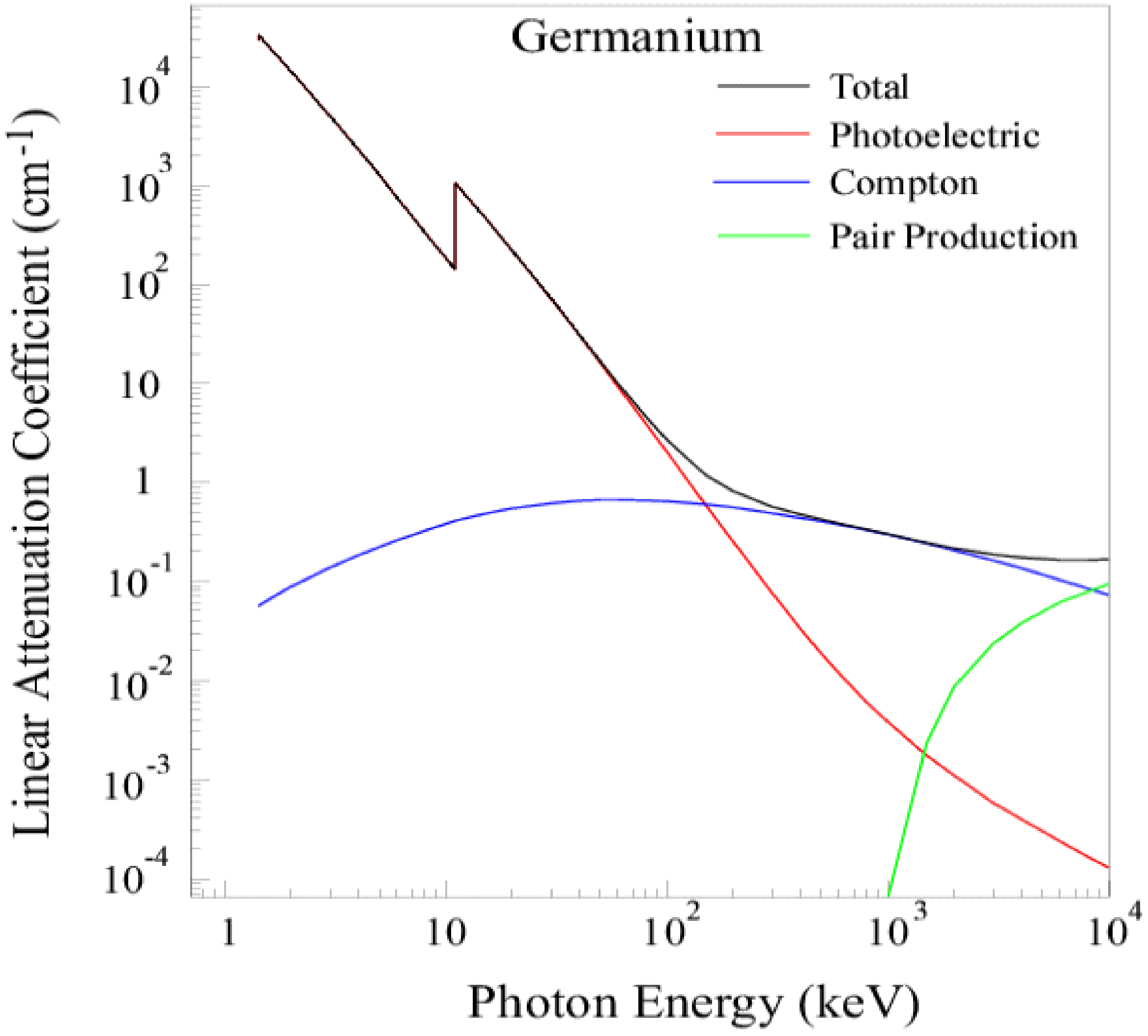


- First Ge diode 1946
- First transistor (Ge) 1947
- First Ge(Li) detectors 1960s
- First HPGe detectors late 1970s
- First Compton-suppressed arrays early 1980s



# Gammas in Germanium

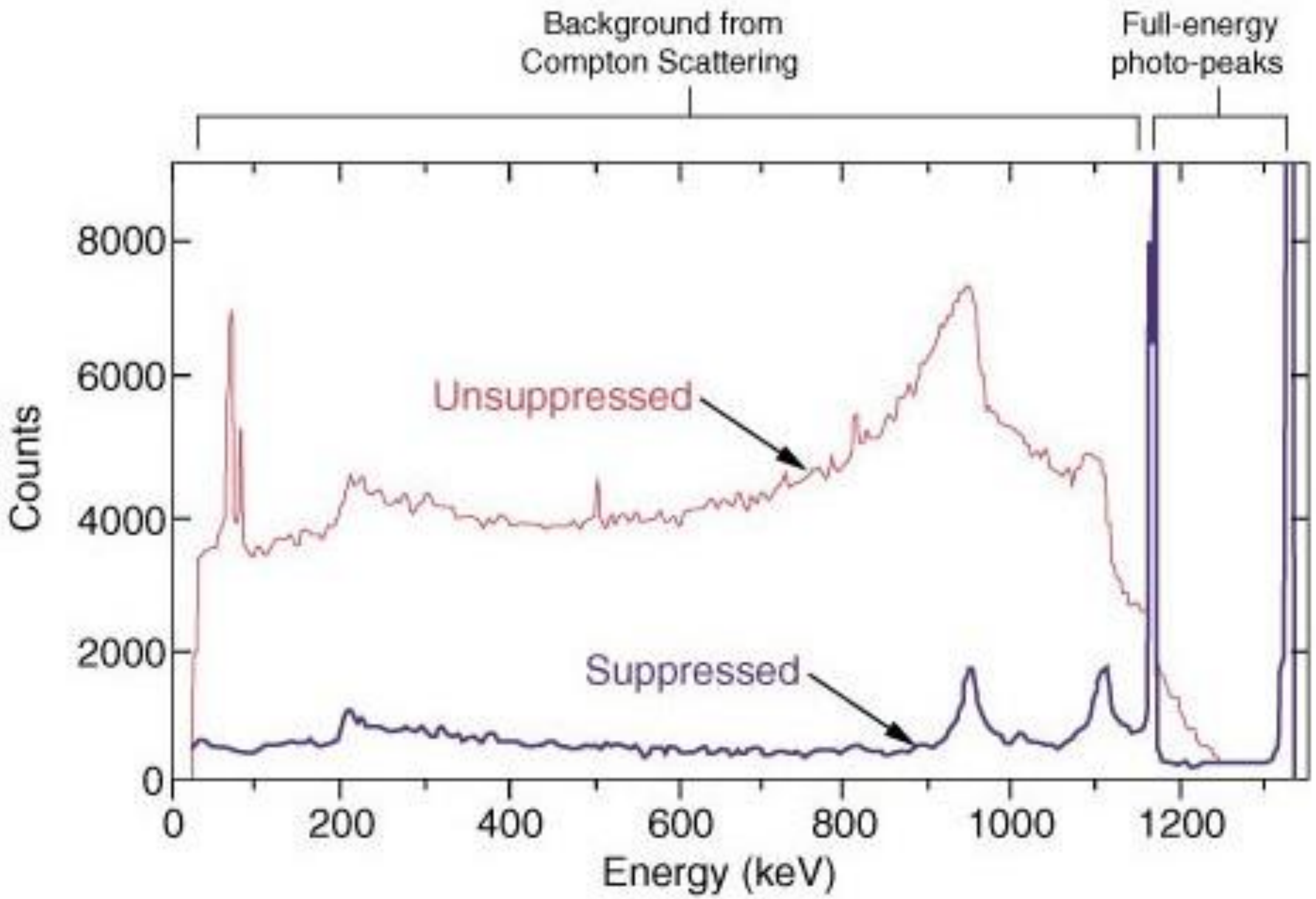



## Compton Scattering

- Important for gamma-ray detection
  - Higher-energy gamma rays generally scatter inside the detector, losing energy until low enough for a photoelectric event
- But also leads to *background* in gamma-ray spectra
  – Gamma rays can enter a detector and Compton-scatter out without being fully absorbed

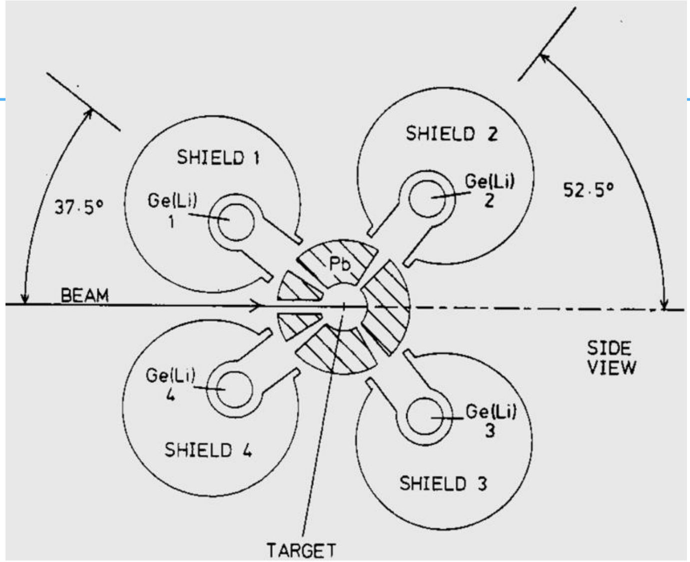
# Compton Suppression

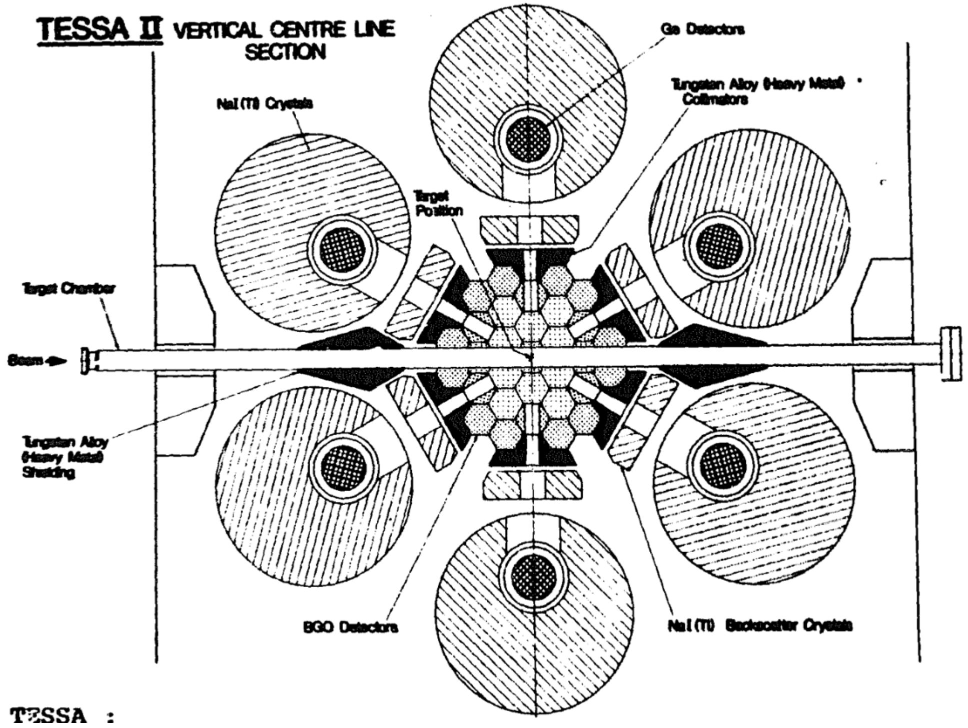
- Surround Ge by high-density scintillator for use as a veto shield
  - Peak/Total improves from ~ 0.2 to ~ 0.55 ($^{60}Co$)



# TESSA (Daresbury)

- TESSA I:
  - Four Ge detectors with NaI Compton-suppression shields
- TESSA II:
  - Six Ge detectors with NaI Compton suppressors
  - An inner array of 63 BGO crystals
- TESSA3
  - 12 Compton-suppressed detectors



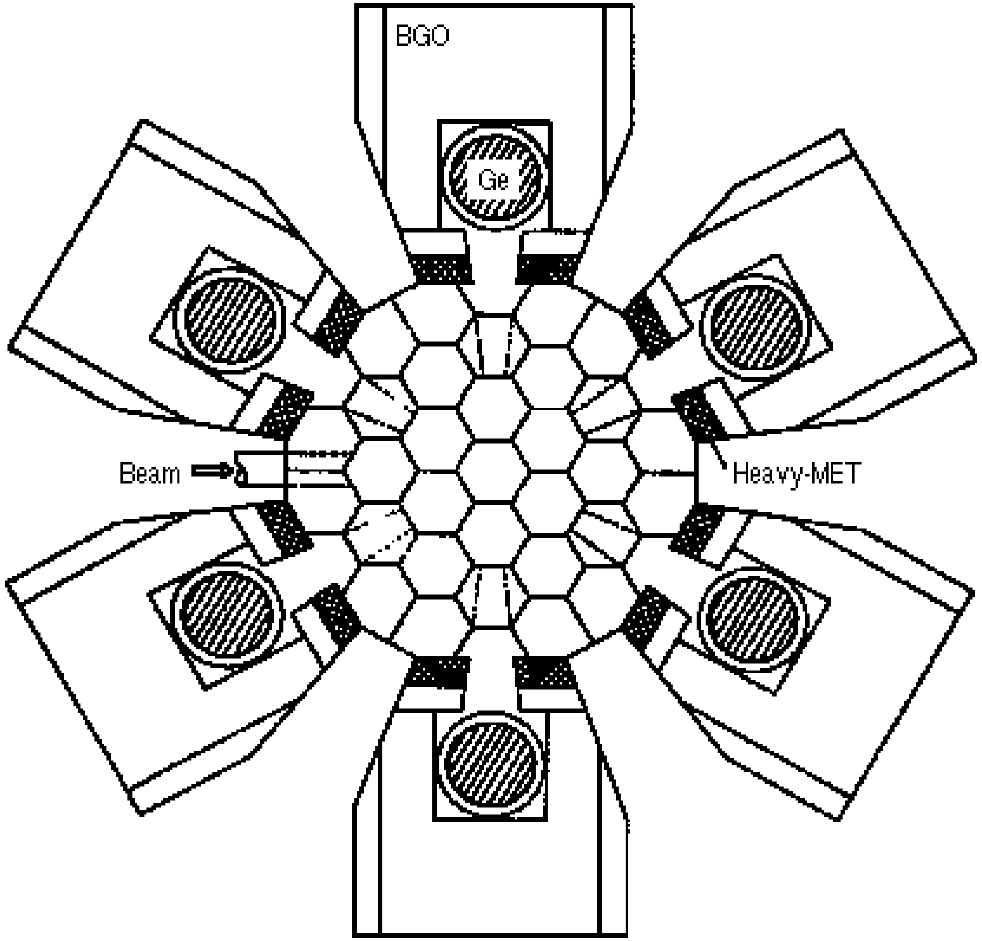



# The Argonne-Notre Dame BGO Gamma-Ray Facility

1983: My first exposure to designing and building a Compton-suppressed HPGe array

– With Robert, Teng-Lek, and Umesh

- An outer ring of 12 high-resolution Compton-suppressed Ge spectrometers
  - – Excellent energy resolution
  - – BGO suppressors provide good peak-to-background ratio
- An inner array of 50 BGO crystals with high gamma-ray stopping power and detection efficiency
  - – Total gamma energy emitted in reaction
  - – Gamma multiplicity, related to spin




Horizontal section of detector assembly. A central BGO array of 50 detectors is surrounded by two rings, each accommodating up to 6 Compton suppressed Ge detectors, located 20° above and below the equatorial plane. The array can also be used on a stand-alone basis, with additional elements on the outermost ring, for a full complement of 56. The diameter of the BGO array is < 25 cm.

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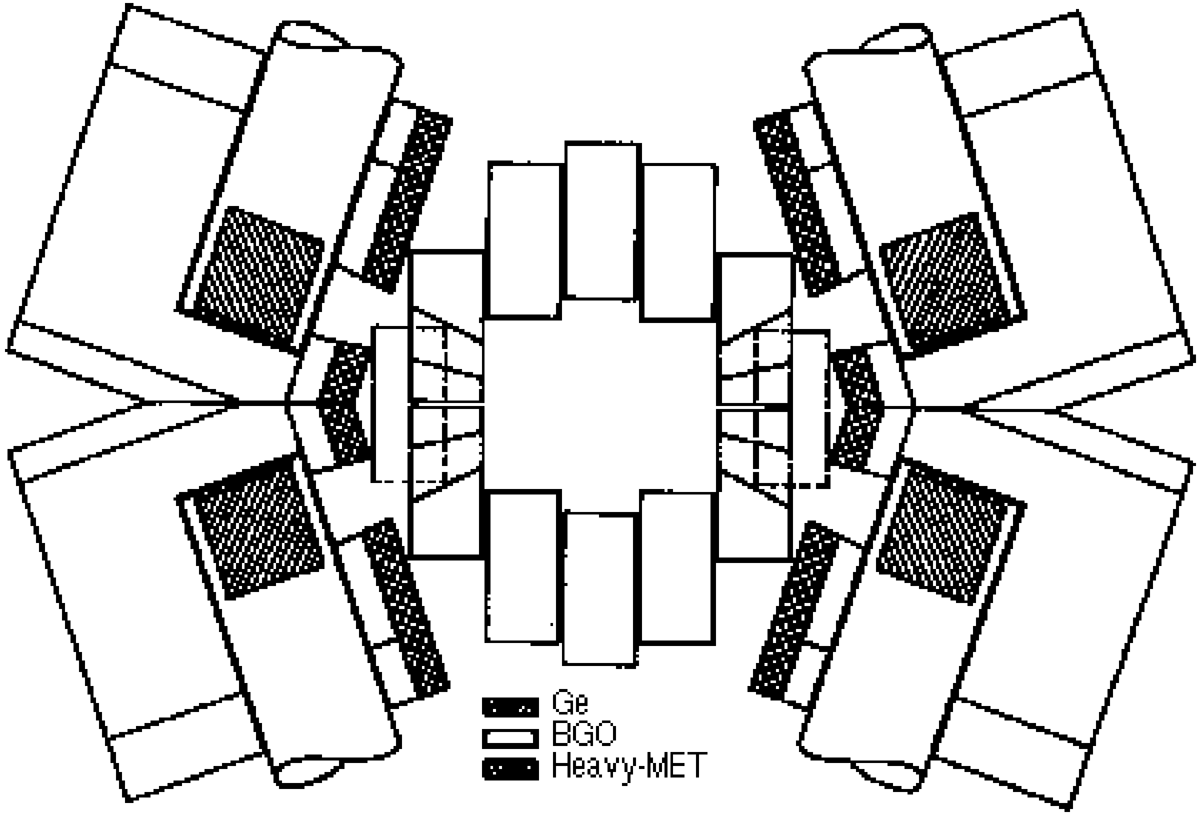
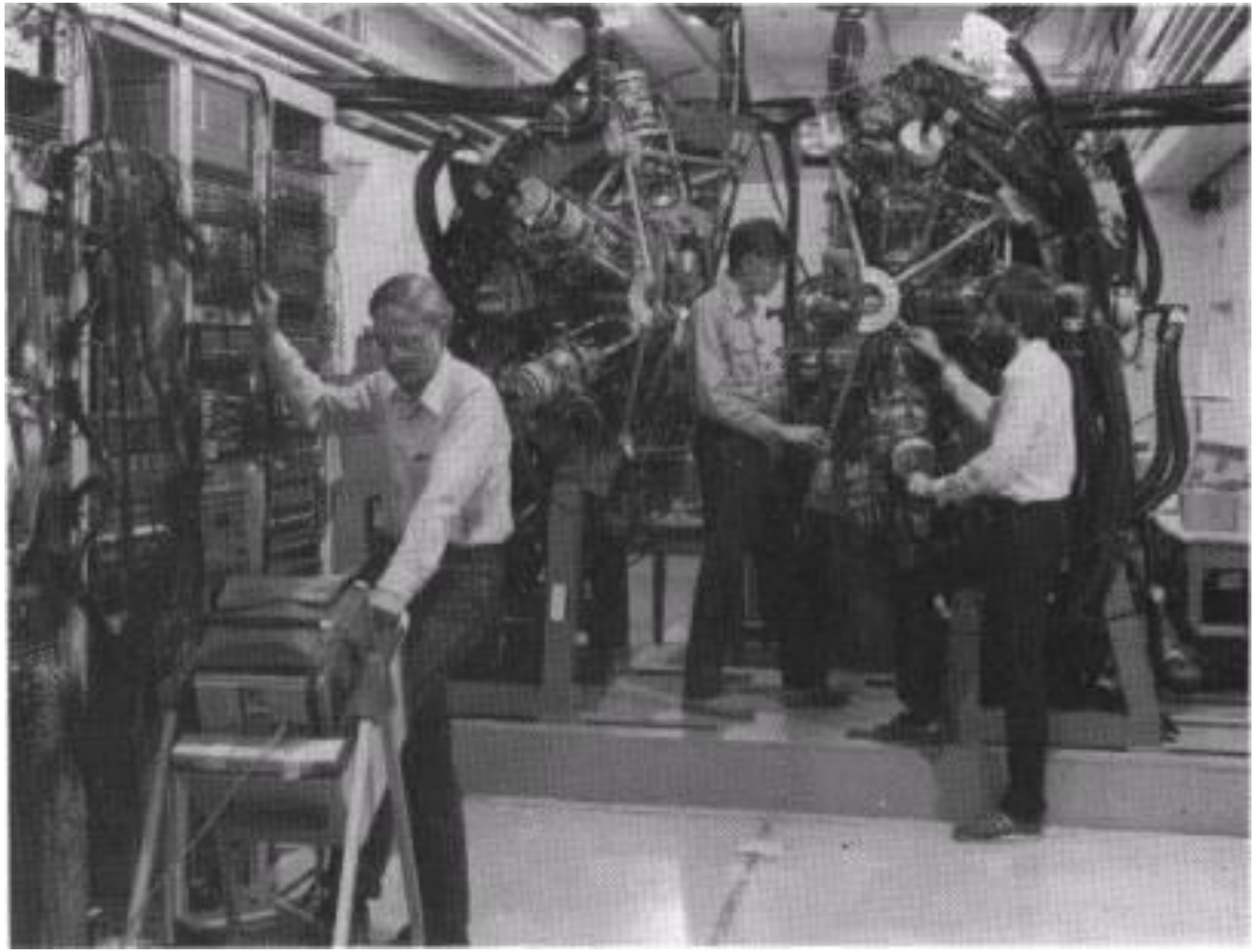



Vertical section of detector assembly in a plane defined by the target and the center of a Ge crystal. Four Compton-suppression spectrometers are shown around the BGO array. The internal space within the array could accommodate a chamber (or other apparatus) of 11.5 cm diameter and 8 cm height.

# The 8pi Spectrometer at Chalk River

- BGO ball
  - 72 detectors (60 hexagons, 12 pentagons)
  - 20 viewing ports for the Ge detectors
- HPGe array
  - 20 25% HPGe detectors
  - BGO Compton suppressors



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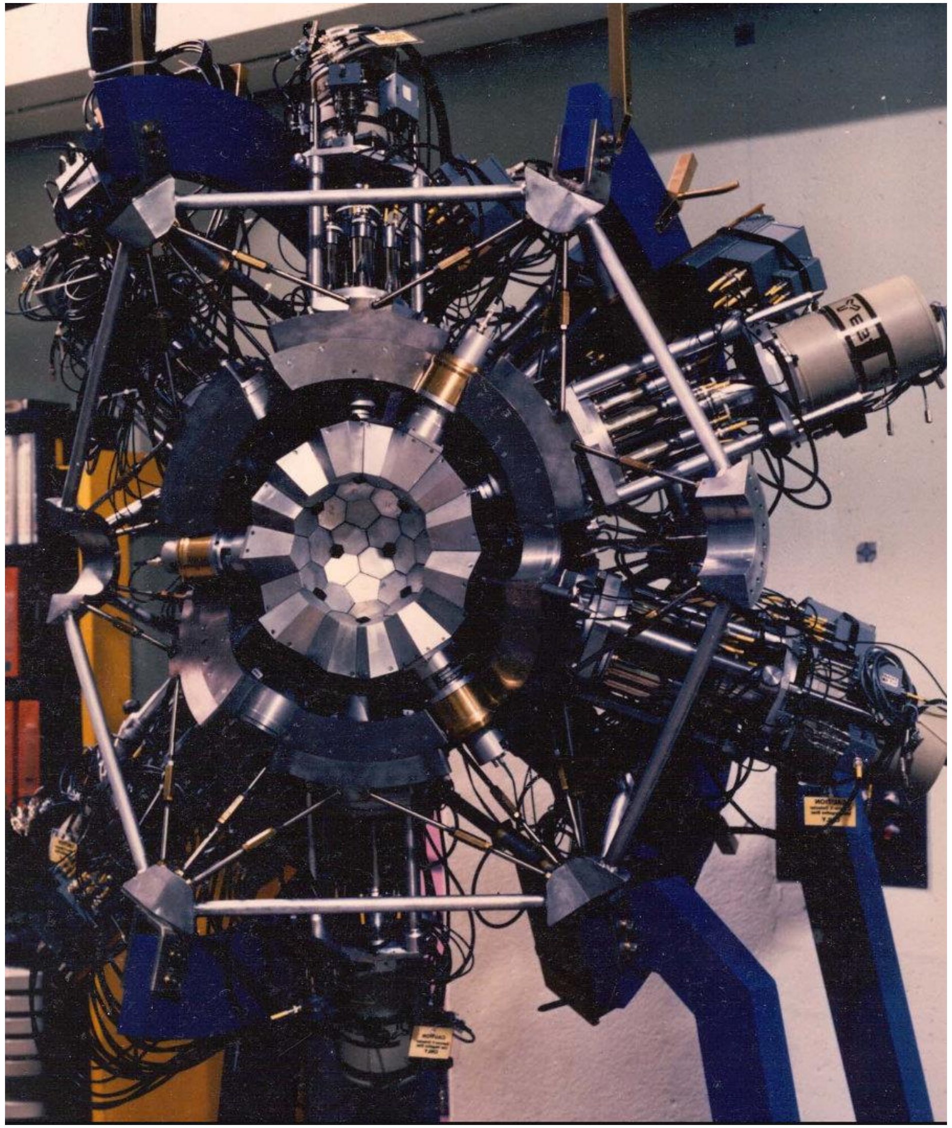

# Compton Suppressed Arrays Show their Power

- Example: The search for nuclear Superdeformation at high spin
  - Elongated prolate nuclear shape, axis ratio 2:1
  - First seen as fission isomers in actinide nuclei

# First SDB: $^{152}$Dy

- TESSA3
- 1986

VOLUME 57, NUMBER 7 PHYSICAL REVIEW LETTERS 18 AUGUST 1986

**Observation of a Discrete-Line Superdeformed Band up to 60ℏ in $^{152}$Dy**

P. J. Twin, B. M. Nyakó,[a] A. H. Nelson, and J. Simpson
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M. A. Bentley, H. W. Cranmer-Gordon, P. D. Forsyth, D. Howe, A. R. Mokhtar, J. D. Morrison, and J. F. Sharpey-Schafer
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and

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*Niels Bohr Institute, Risø, Roskilde, DK-2100 Copenhagen, Denmark*

(Received 5 May 1986)

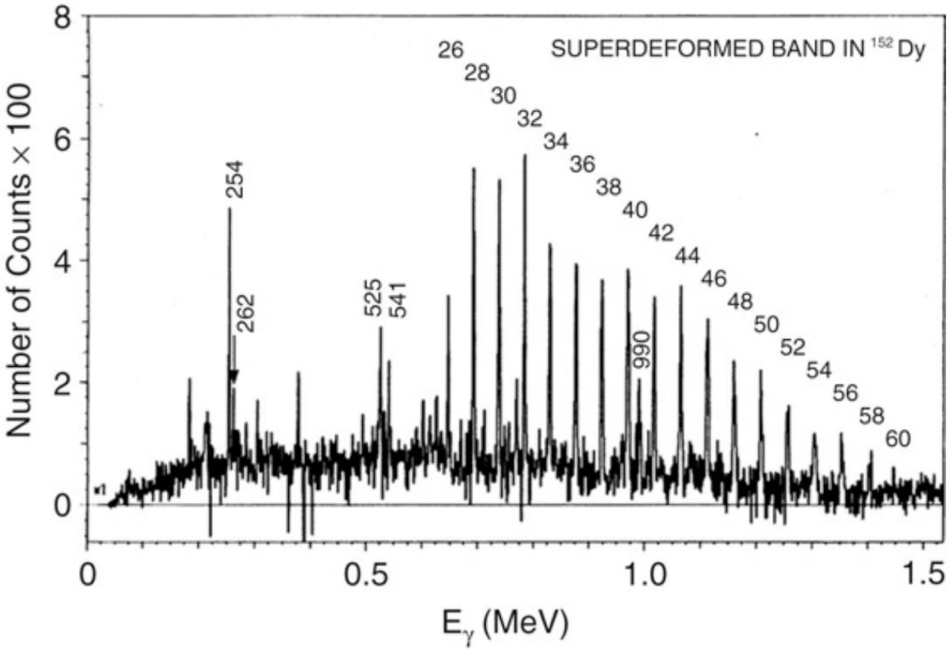
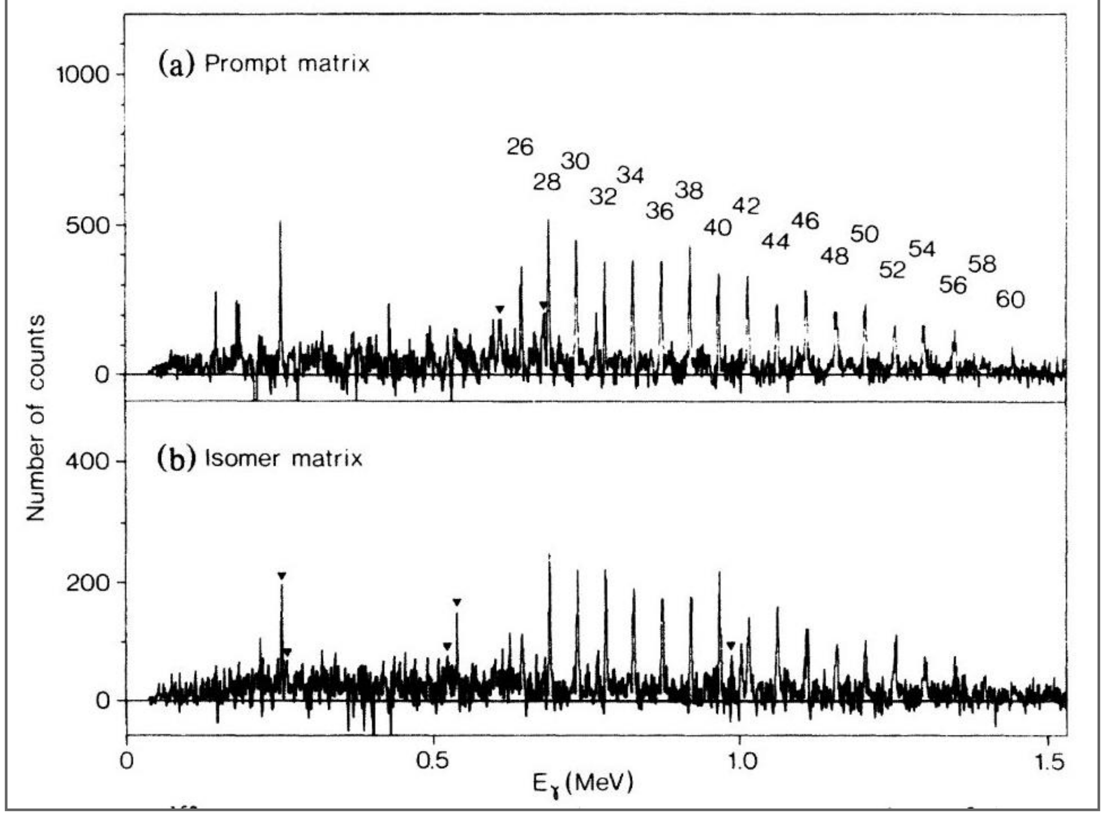



Fig. 10. Coincidence spectrum of the super-deformed band in $^{152}$Dy [41].



# Second SDB: $^{149}$Gd

- 8pi
- 1988

VOLUME 60, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1988

**Superdeformed Band up to Spin $\sim \frac{127}{2}$ in $^{149}$Gd**

B. Haas,[a] P. Taras, S. Flibotte, F. Banville, J. Gascon, S. Cournoyer, S. Monaro, N. Nadon, D. Prévost, and D. Thibault
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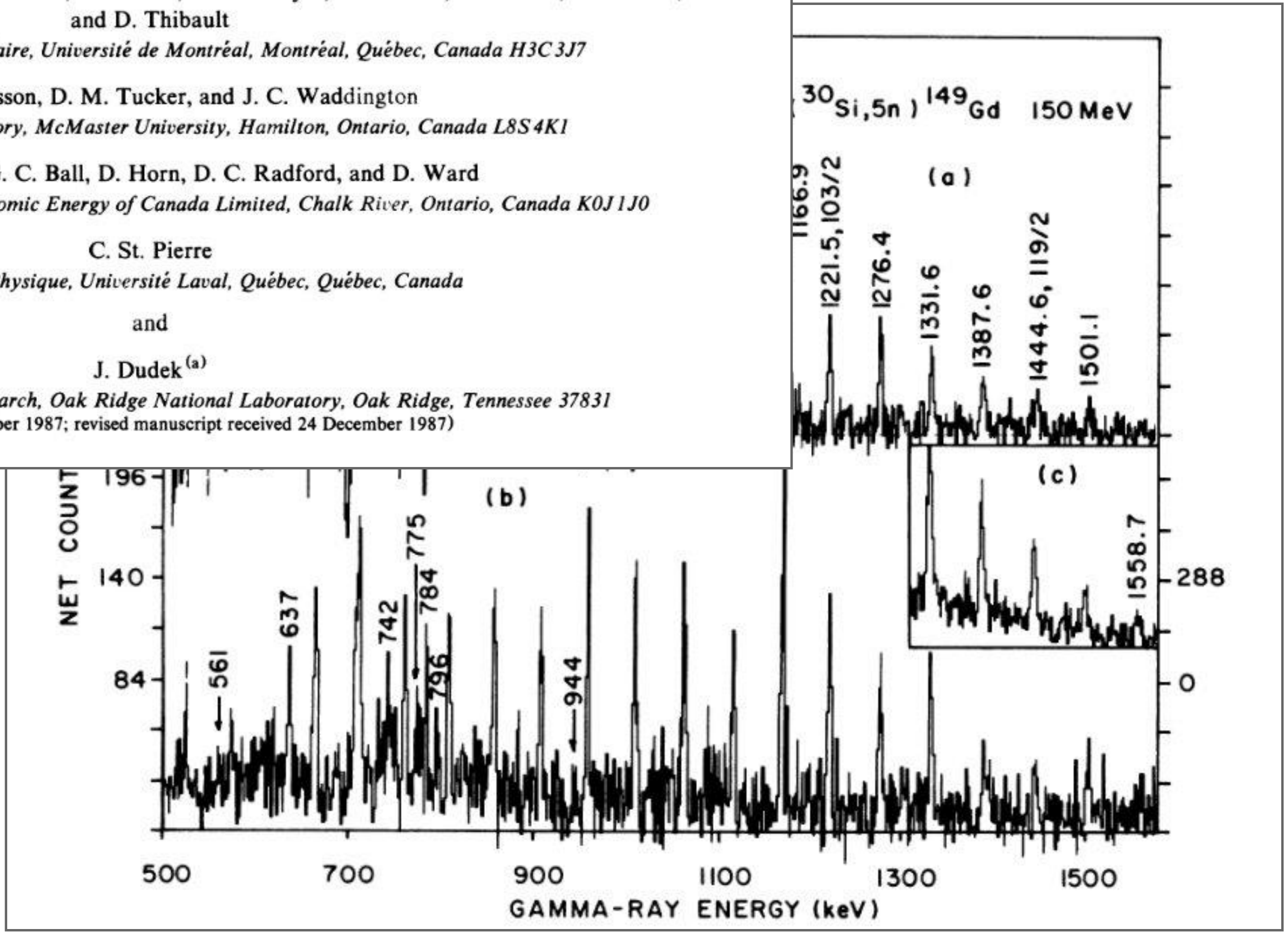
(Received 19 October 1987; revised manuscript received 24 December 1987)



# A new SD Region: $^{191}$Hg

- ANL-ND Array
- 1989

VOLUME 63, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JULY 1989

## Observation of Superdeformation in $^{191}$Hg

E. F. Moore, R. V. F. Janssens, R. R. Chasman, I. Ahmad, T. L. Khoo, and F. L. H. Wolfs
*Argonne National Laboratory, Argonne, Illinois 60439*

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(Received 8 March 1989)

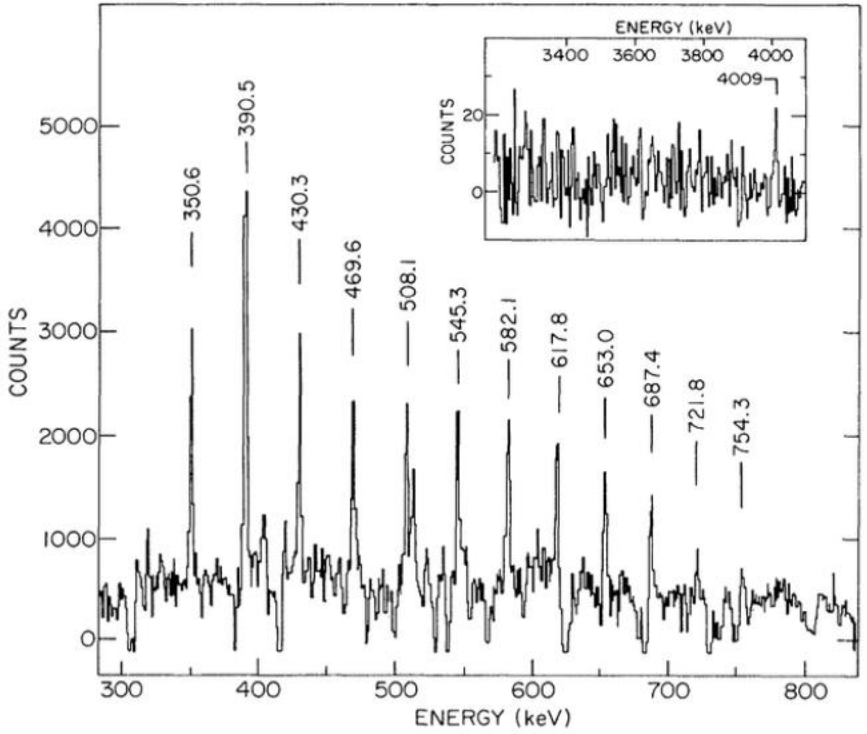



FIG. 1. $\gamma$-ray spectrum in $^{191}$Hg obtained by summing coincidence gates on selected transitions (351, 471, 508, 545, 582, and 653 keV). The $\gamma$ ray at 514 keV is an identified contaminant (seen only in the 508-keV gate). Inset: The high-energy end portion of this spectrum, with the 4009-keV line discussed in the text.

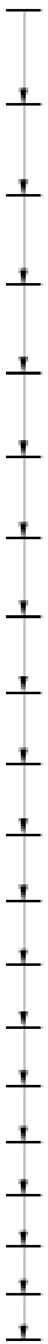
# An Aside: Super-Deformed Rotation

- A rotating quadrupole-shaped charge emits electromagnetic radiation

- When a level near the top of a $^{152}$Dy super-deformed band is populated in a reaction, the nucleus emits 20 gamma rays in about $10^{-13}$ s
  - 20 MeV in $10^{-13}$ s is 32 W (!) from a single nucleus
  - Average rotational frequency $\hbar\omega \cong 500$ keV

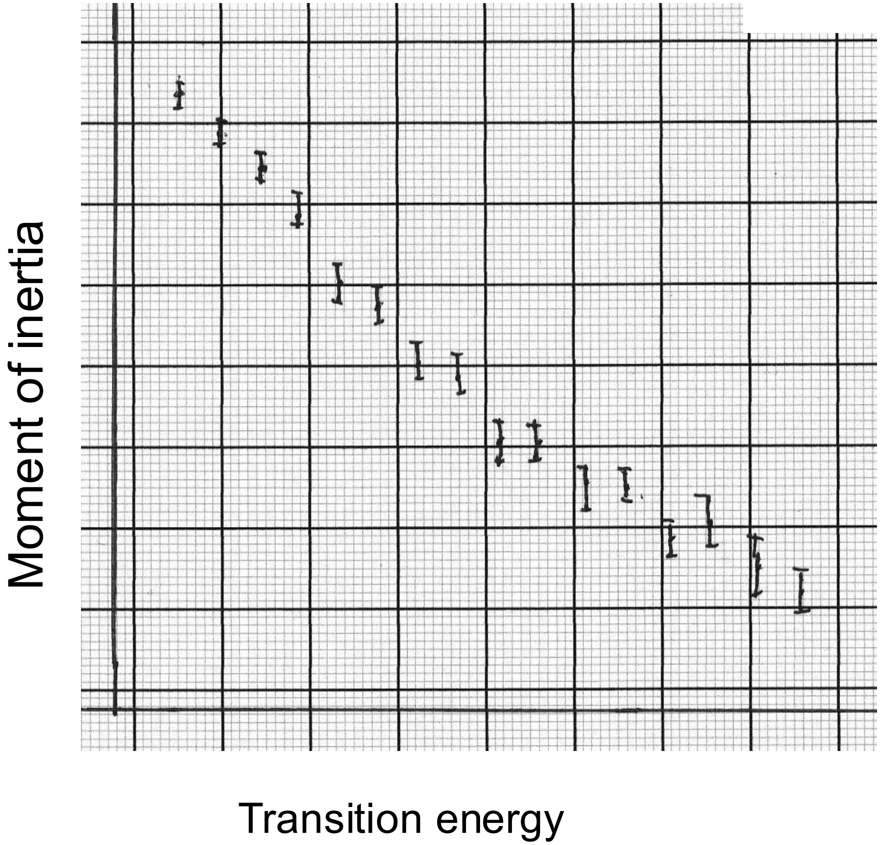
    $10^{7}$ rotations in $10^{-13}$ s, roughly the number of days in 30,000 years

- The decay to the ground state passes through a long-lived (86 ns) level
  - About $5 \times 10^{12}$ rotations, roughly the number of days in the age of the universe



# C4 Symmetry

- Eurogam phase I
- 1993




VOLUME 71, NUMBER 26 PHYSICAL REVIEW LETTERS 27 DECEMBER 1993

## ΔI=4 Bifurcation in a Superdeformed Band: Evidence for a $C_4$ Symmetry

S. Flibotte,[1,*] H. R. Andrews,[2] G. C. Ball,[2] C. W. Beausang,[3] F. A. Beck,[1] G. Belier,[1] T. Byrski,[1] D. Curien,[1] P. J. Dagnall,[3] G. de France,[1] D. Disdier,[1] G. Duchêne,[1] Ch. Finck,[1] B. Haas,[1] G. Hackman,[4] D. S. Haslip,[4] V. P. Janzen,[2,4] B. Kharraja,[1] J. C. Lisle,[5] J. C. Merdinger,[1] S. M. Mullins,[4] W. Nazarewicz,[6,7,†] D. C. Radford,[2] V. Rauch,[1] H. Savajols,[1] J. Styczen,[8] Ch. Theisen,[1] P. J. Twin,[3] J. P. Vivien,[1] J. C. Waddington,[4] D. Ward,[2] K. Zuber,[8] and S. Åberg[6,9]

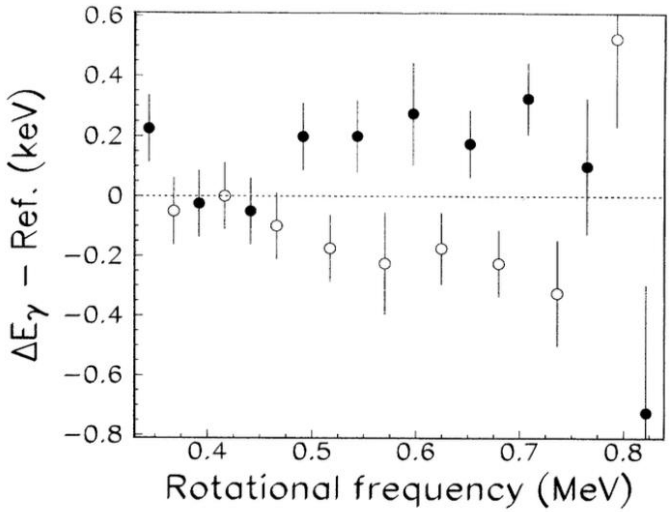



FIG. 3. Energy differences $\Delta E_\gamma$ between two consecutive $\gamma$-ray transitions of the superdeformed band in $^{149}$Gd as a function of rotational frequency after subtraction of a smooth reference given by $\Delta E_\gamma^{\mathrm{ref}}(I) = [\Delta E_\gamma(I+2) + 2\Delta E_\gamma(I) + \Delta E_\gamma(I-2)]/4$. Filled and empty symbols refer to different values of $\alpha_4$. The staggering effect sets in just above $\hbar\omega$=0.4 MeV, i.e., just after alignment of the $N$=6 proton pair.

# Identical SD Bands and C4 Symmetry

- An unresolved puzzle

PHYSICAL REVIEW C VOLUME 58, NUMBER 4 OCTOBER 1998

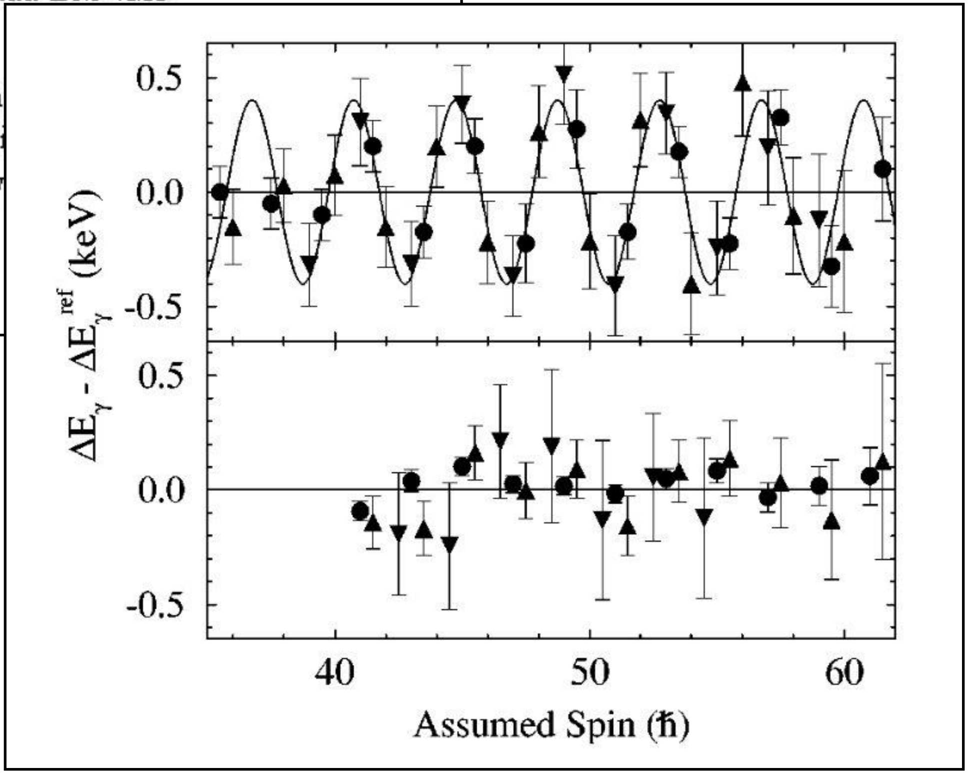
**Analysis of staggering patterns in identical superdeformed bands: Constraints on a $C_4$ Hamiltonian**

D. S. Haslip, S. Flibotte, C. E. Svensson, and J. C. Waddington
*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1*

(Received 28 July 1998)

The $\Delta I = 4$ bifurcation in three identical superdeformed rotational bands is compared with
the model of Hamamoto and Mottelson. A complete calculation of the tunneling amplitude
treatment of this model constrains the model's parameters to just three regimes, with very
scales. [S0556-2813(98)50510-9]

PACS number(s): 21.60.Ev, 21.10.Re, 23.20.Lv, 27.60.+j



# Time to Move On

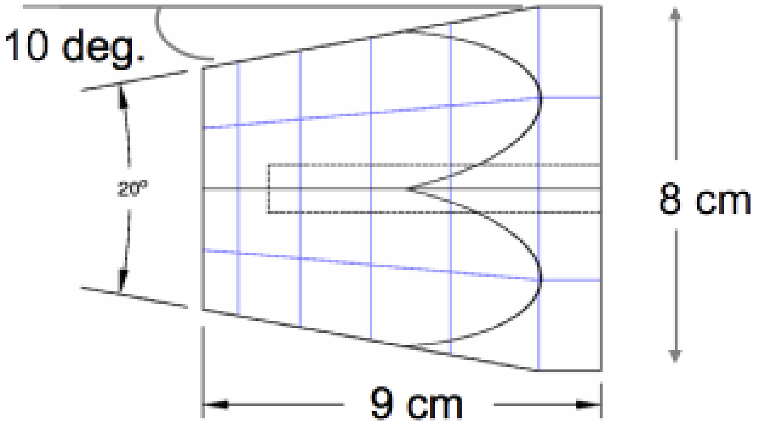
- TASCC facility closed in 1997

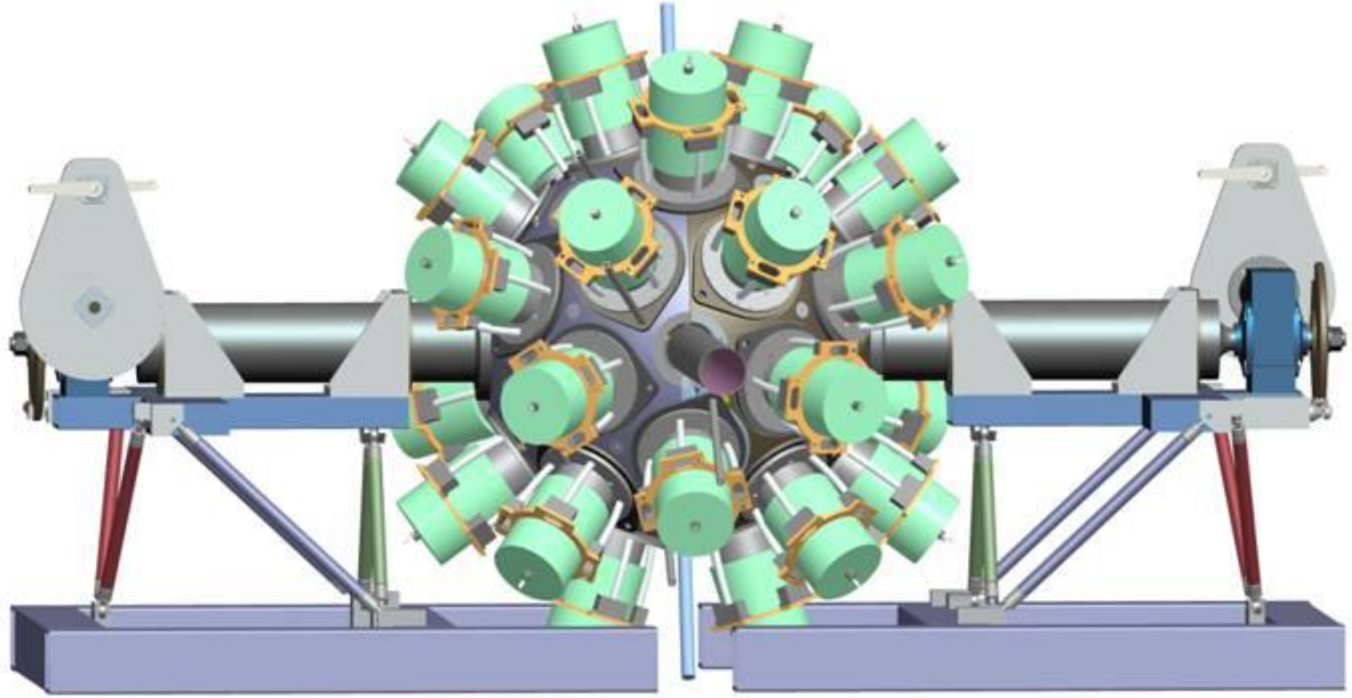
# Radioactive Beams: CLARION at the ORNL HRIBF

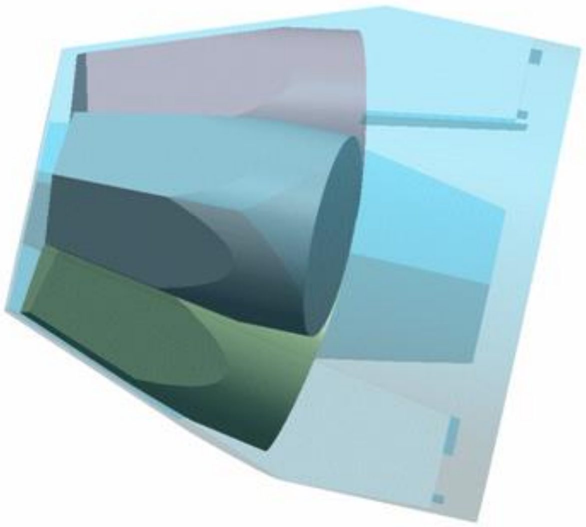

- 12 Compton-suppressed clover detectors, designed for RIB experiments
- Coulex
- Neutron transfer in gamma-ray coincidence

# GRETA (Gamma Ray Energy Tracking Array)

- 120 large volume 36-fold segmented Ge crystals in 30 quadruple-crystal modules
- Total efficiency (1332 keV): 25 - 40%
- Angular Resolution: ~1°
- Similar European instrument is AGATA

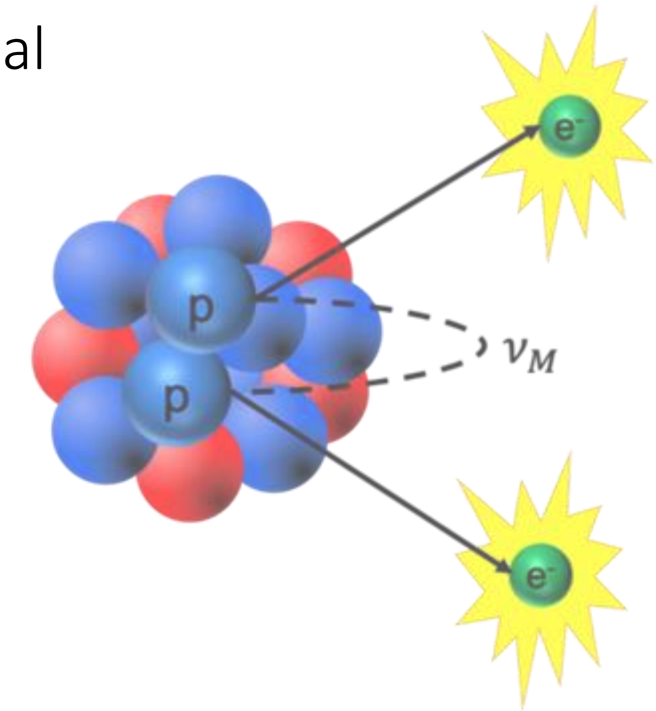




# A New Direction: Neutrinoless Double Beta Decay of $^{76}$Ge?

- Discovery of $0\nu\beta\beta$ decay would dramatically revise our foundational understanding of physics and the cosmos
  - Lepton number is not conserved (matter can be created without an equal amount of antimatter)
  - The neutrino is a fundamental Majorana particle (its own anti-particle)
  - There is a potential path for understanding the matter – antimatter asymmetry in the cosmos, through leptogenesis
  - The very small, nonzero neutrino mass can be explained




- MAJORANA DEMONSTRATOR (SURF, SD)
- LEGEND-1000 (LNGS, Italy)

# The LEGEND-1000 Discovery Sensitivity

- LEGEND-1000 is designed to discover 0νββ decay at a half-life beyond $10^{28}$ years
- A half-life of $10^{28}$ years is less than one decay per year per ton of $^{76}$Ge isotope
  - Need about $10^{28}$ atoms of $^{76}$Ge (one metric ton)
  - Need 10 years of data to get a few counts

One way to think of this:

- Build seven GammaSpheres out of enriched $^{76}$Ge
- Bury at least a km underground
- Run for 10 years
- Look for a peak with $< 5$ counts at 2039 keV

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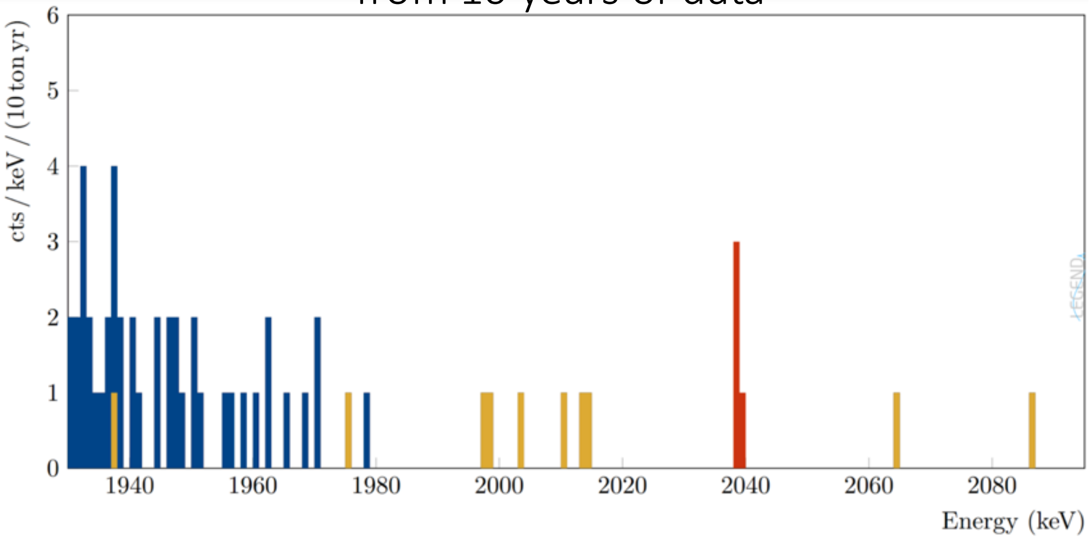
  - Need about $10^{28}$ atoms of $^{76}$Ge (one metric ton)
  - Need 10 years of data to get a few counts

- Need exceptional signal-to-background ratio to get statistical significance
  - *A very low background event rate*
  - The best possible energy resolution

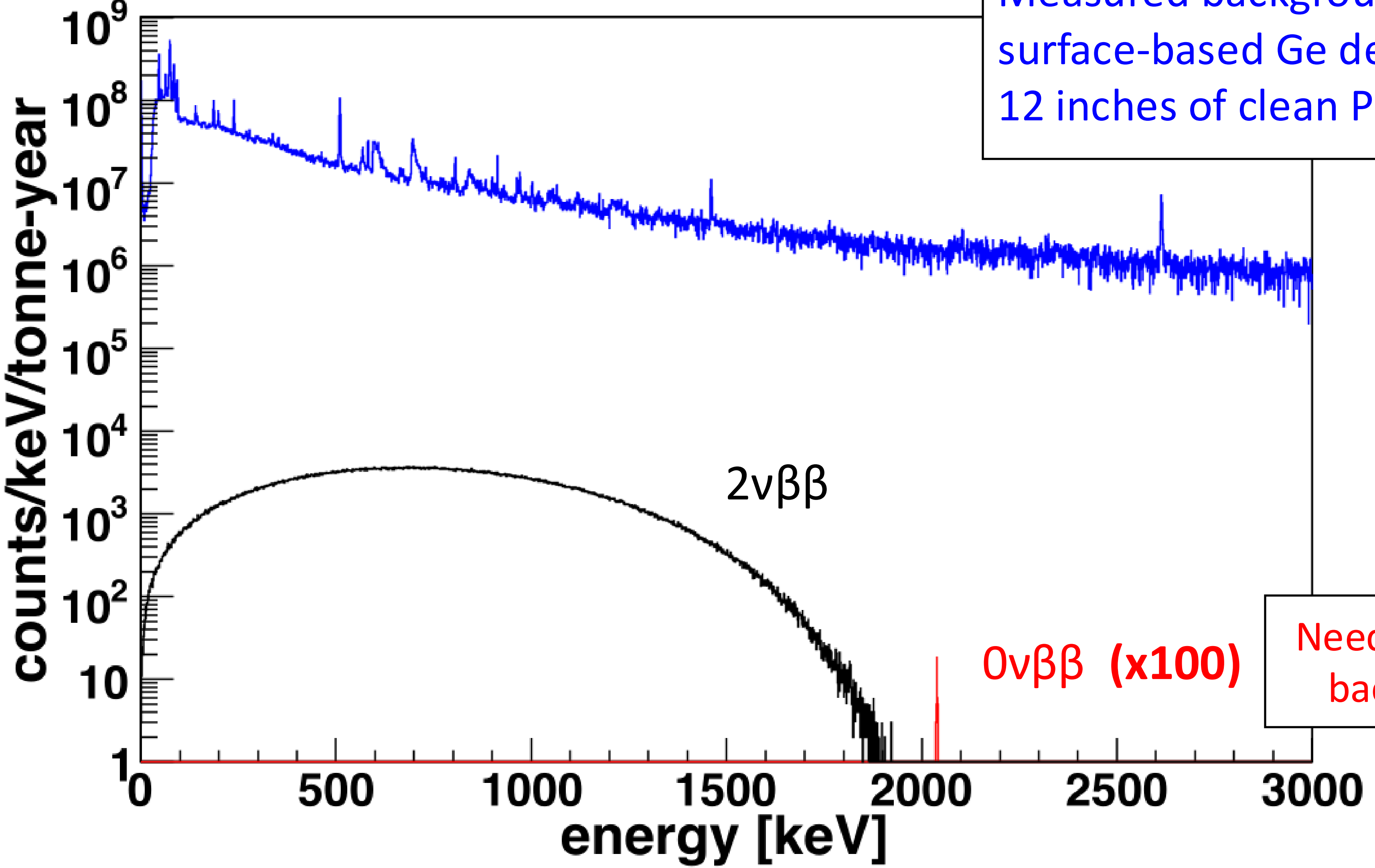
It's all about getting rid of the background
- "But U and Th are everywhere!"

  – Paddy Regan

Typical simulated example spectrum, after cuts, from 10 years of data



# Background Challenge




Measured backgrounds in typical 1 kg surface-based Ge detector shielded by 12 inches of clean Pb

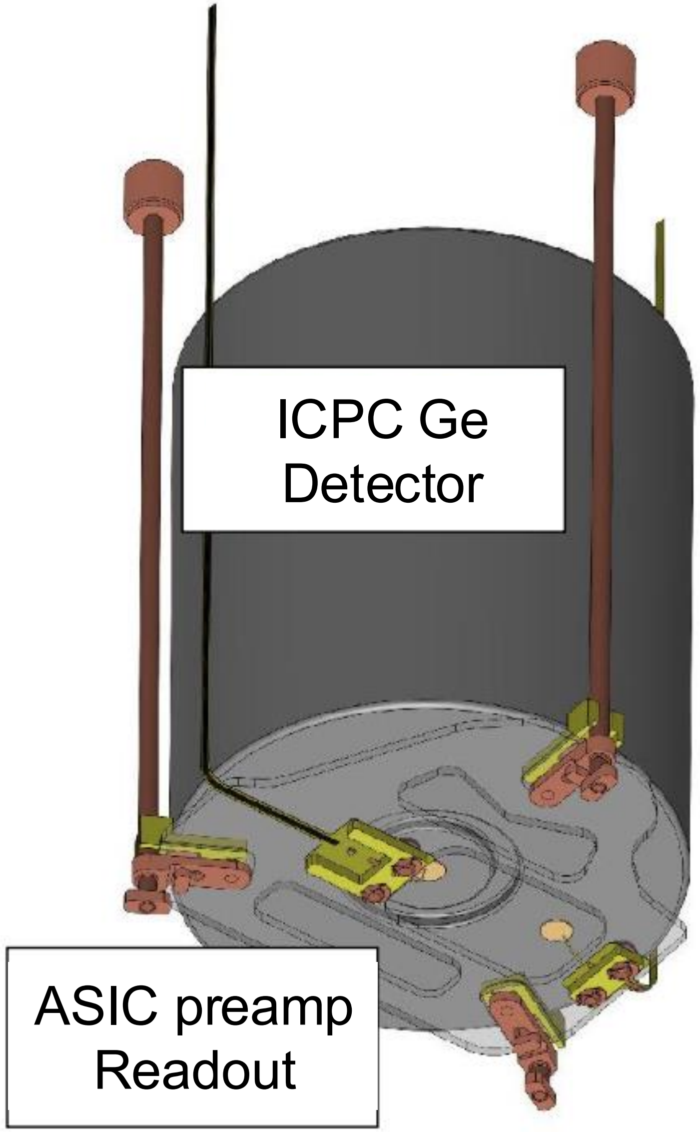
Need 9 orders of magnitude background suppression

# Background Challenge

- Go deep underground (cosmic muons)
- Use only the cleanest materials available
- Minimize the amount of those materials
- Minimize time for the Ge above ground
  - 2 radioactive atoms/day/kg!
- Pulse-shape discrimination to select only single-site events in the detector bulk
- Compton suppression!
  - Liquid argon

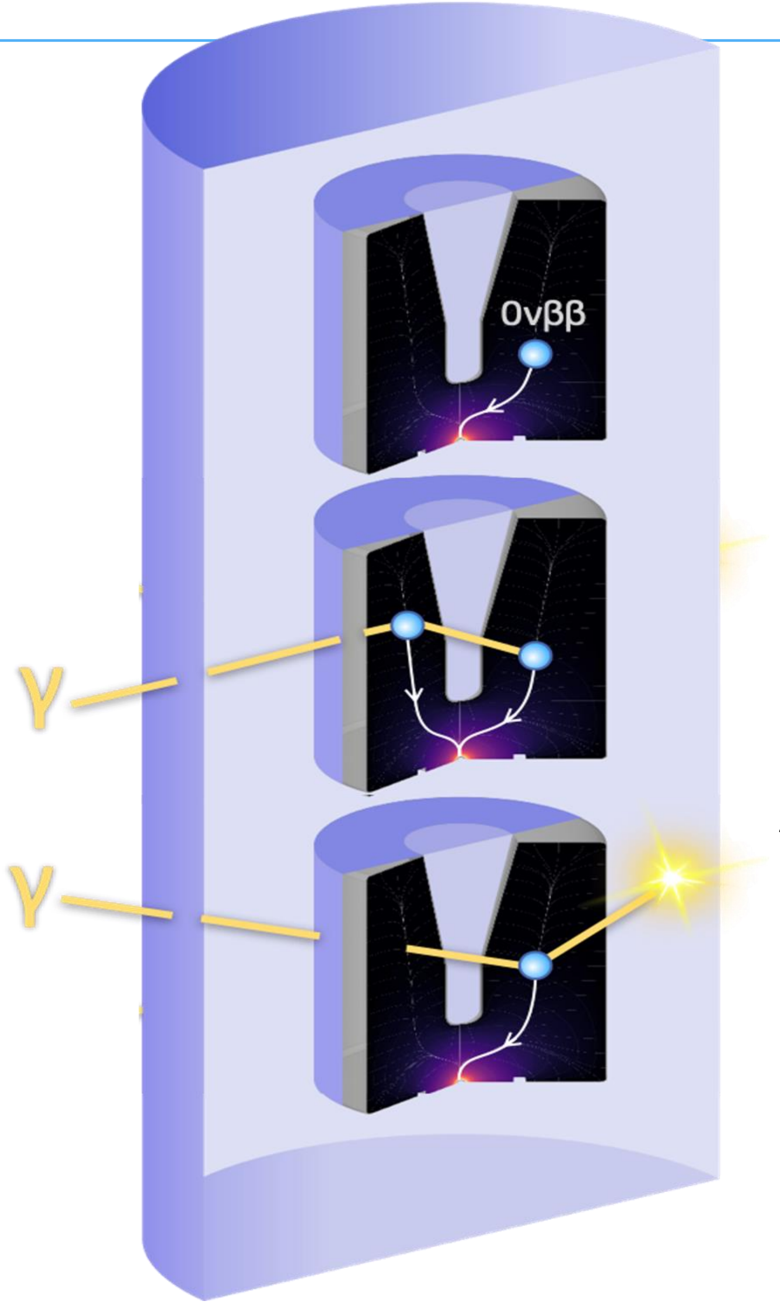
# LEGEND-1000: LAr

- Large "Inverted-Coaxial Point-Contact" HPGe detectors
  - Excellent performance demonstrated for masses up to 4 kg
- Minimum additional materials
  - Underground-electroformed copper
  - PEN plate
  - Ultra-pure Kapton cables
  - ASIC preamp



# LEGEND-1000: LAr

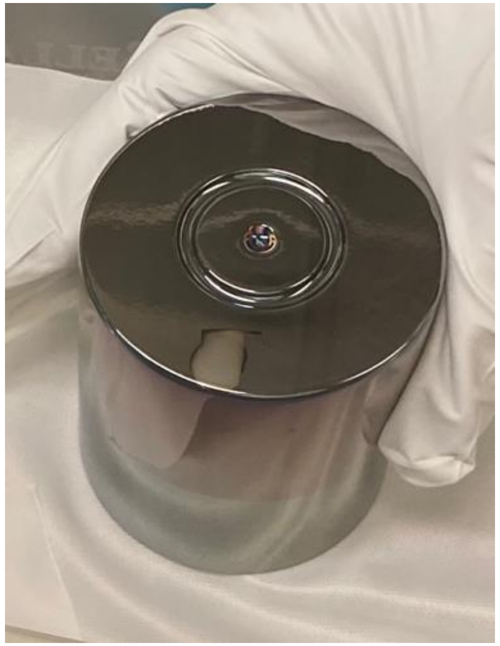
- Large "Inverted-Coaxial Point-Contact" HPGe detectors
  - Excellent performance demonstrated for masses up to 4 kg
- Liquid argon serves as both cryogen and active (scintillating) radiation shield
  - Low-background wavelength-shifting fibers and SiPMs for single-photon detection



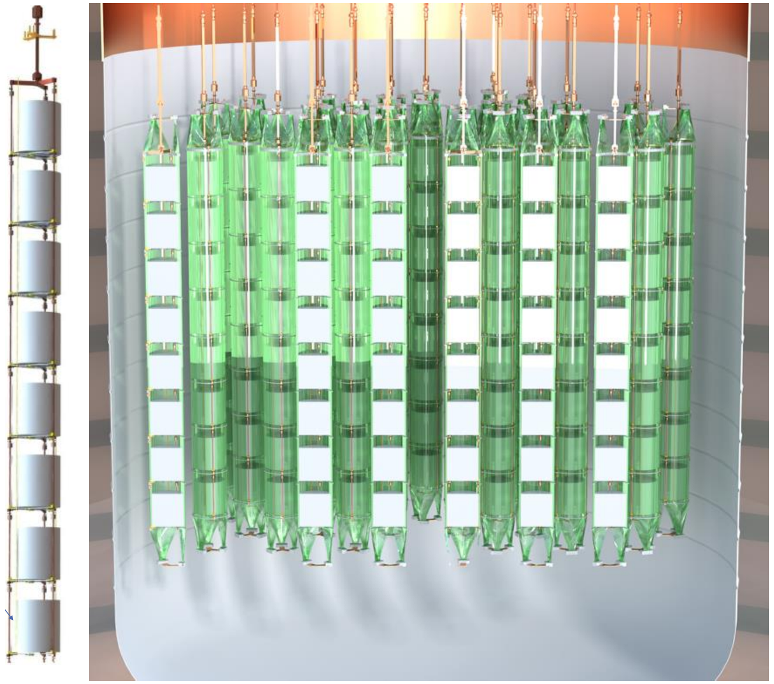

Pulse-shape analysis

Ar light anticoincidenc
e

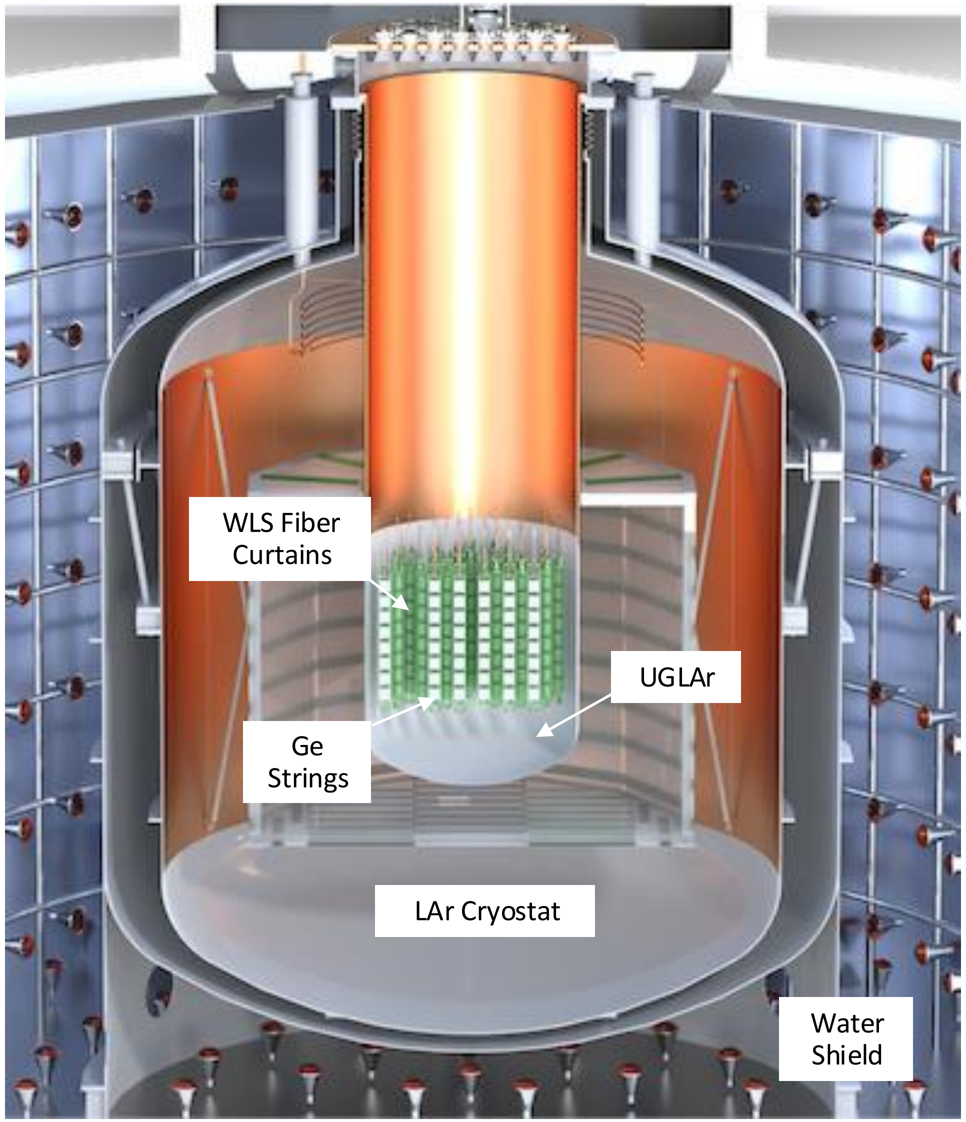
# LEGEND-1000 Concept



- Inverted-Coaxial Point Contact $^{76}Ge$ detectors
- Made from Ge enriched to >90% in $^{76}Ge$ isotope
- ~3kg each



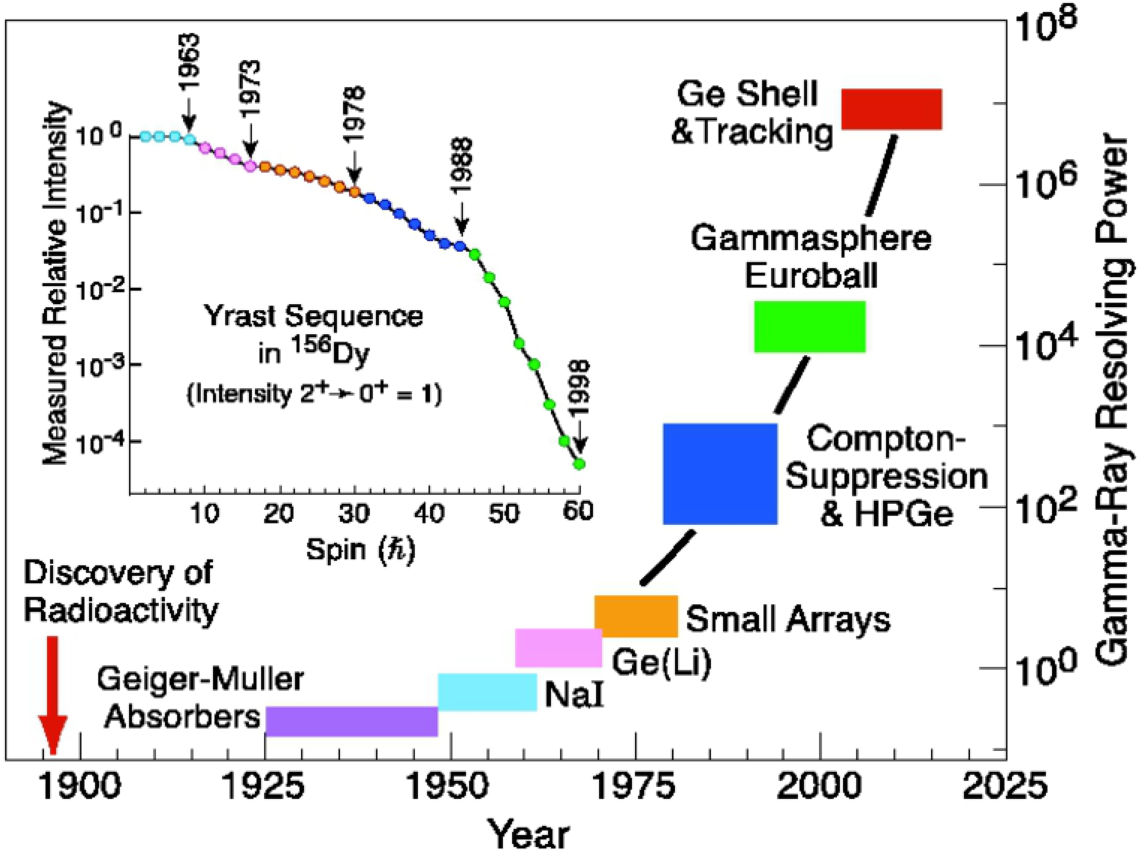
- 42 strings of 8 detectors each, surrounded by light readout fibers
- Immersed in 20 tons of underground liquid argon (low level of $^{42}Ar$)
- LAr is both active shield and cryogen




Installed in a large (~ 6 m) cryostat at LNGS (Italy)

# Conclusion

- My personal journey with Compton-suppressed Ge began with Robert at ANL
- As these tools were developed and refined, they gave us incredible, unimagined insights into the nucleus
- Robert has been a wonderful companion to all of us along this journey
- For me, this journey has culminated in the ultimate Compton-suppressed array, LEGEND-1000



# Thank You, Robert

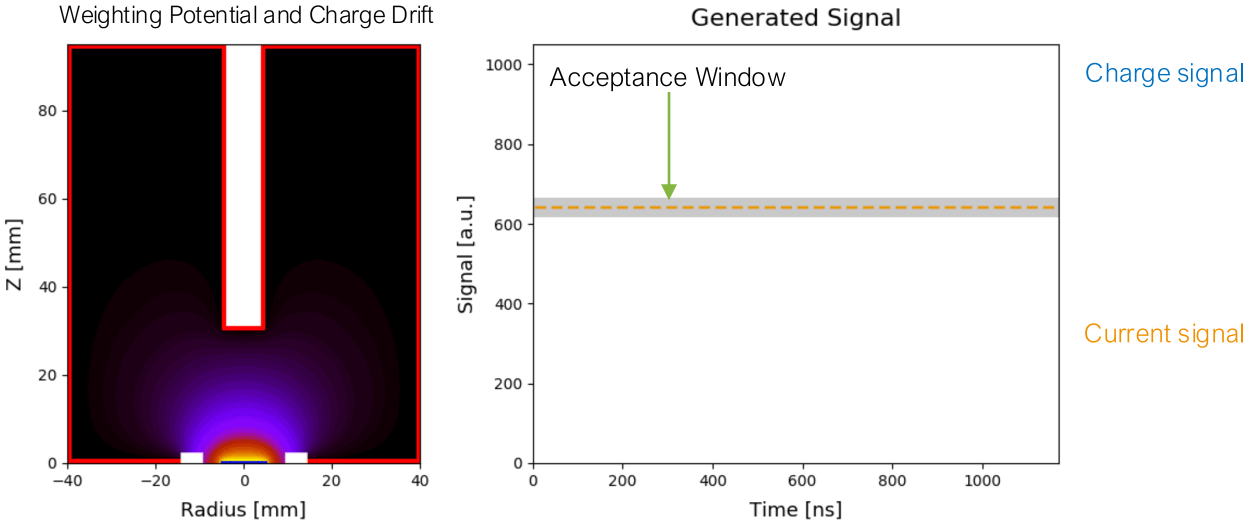
- Superb physicist
- Mentor and colleague
- Wonderful friend in a difficult time
- Best man


# Backup Slides

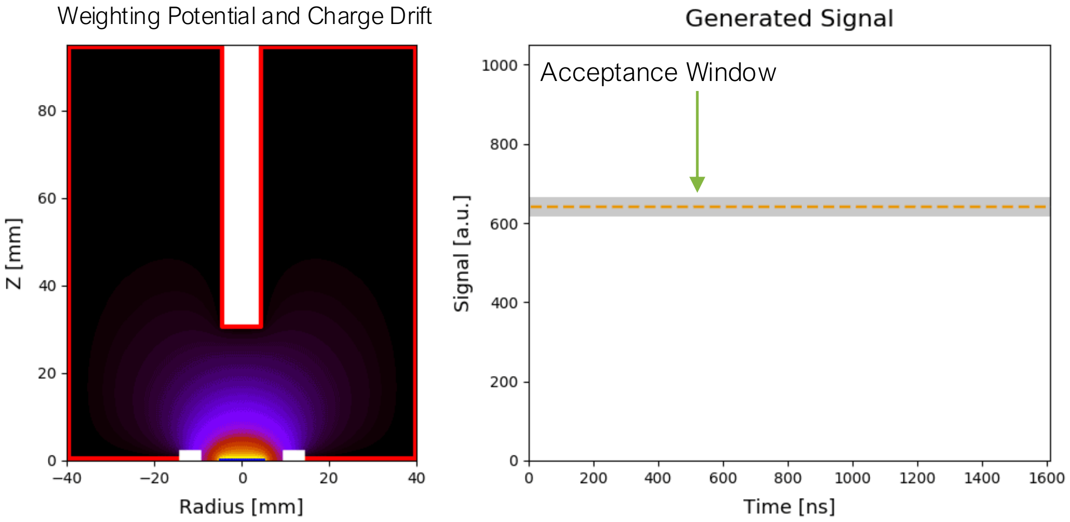
# ICPC Ge Detectors: Pulse Shape Analysis

- Event Topologies through Pulse-Shape Analysis

## $0\nu\beta\beta$ signal (single site)




## Gamma-ray background (multisite)




Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

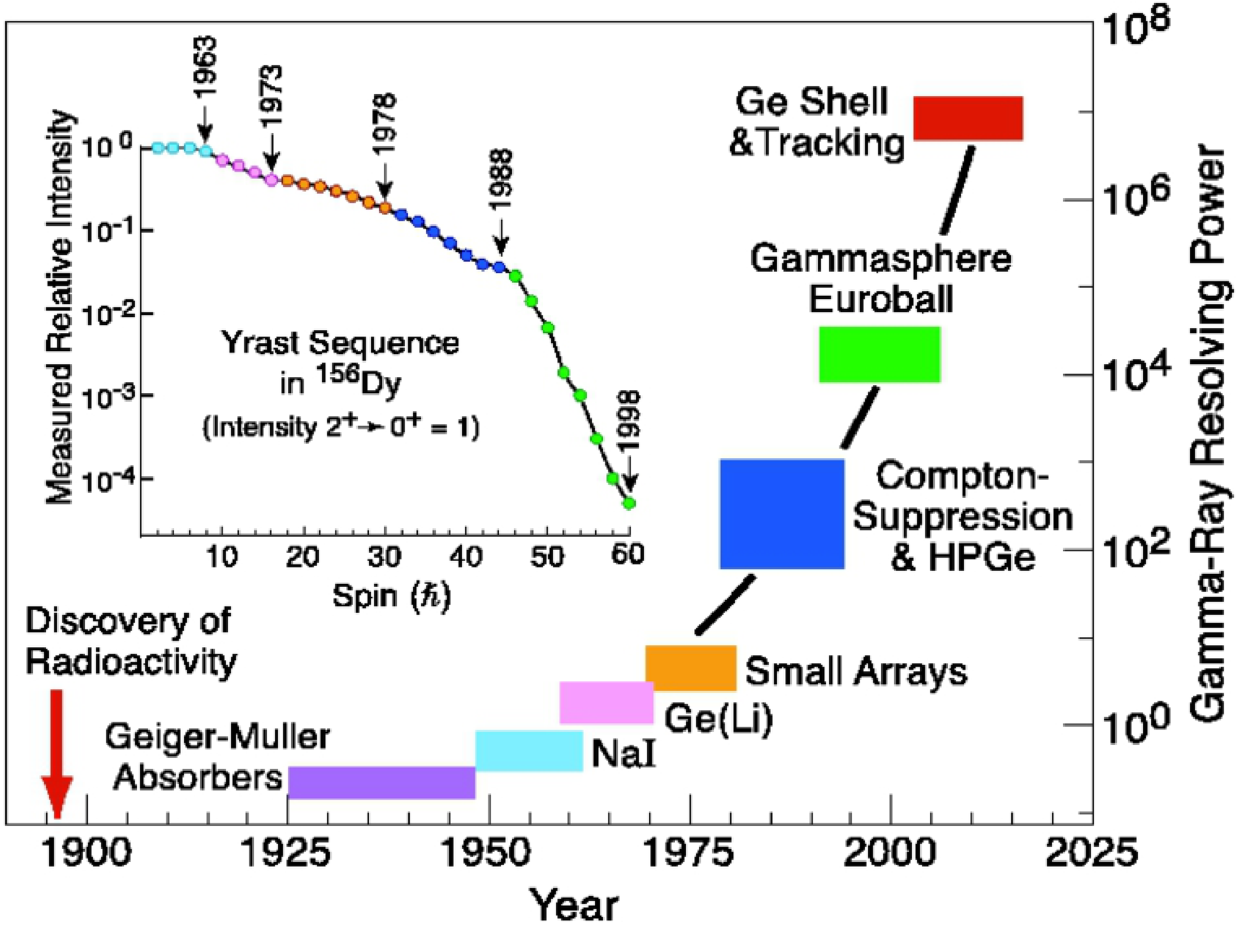
Weighting Potential: $\phi_w$

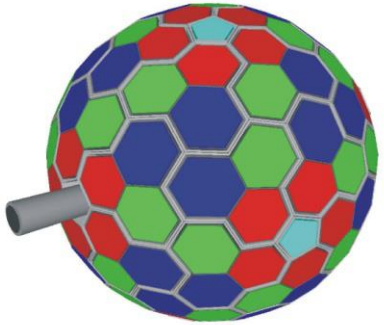
Animation only visible in pptx

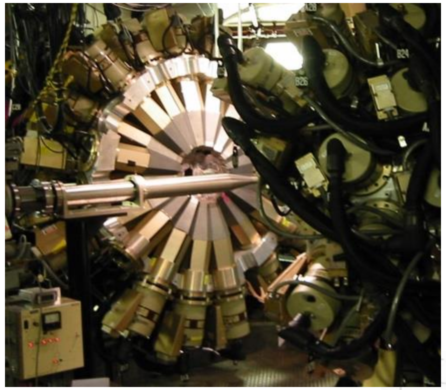
More details in presentation A05

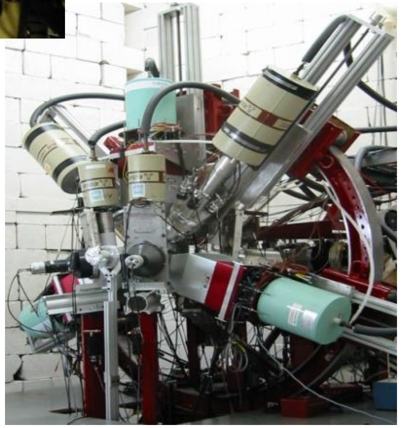
# Evolution of In-Beam Gamm-Ray Detection

- Resolving power:  The ability to observe weak gamma rays or cascades from rare and exotic nuclear states







Ge(LI)