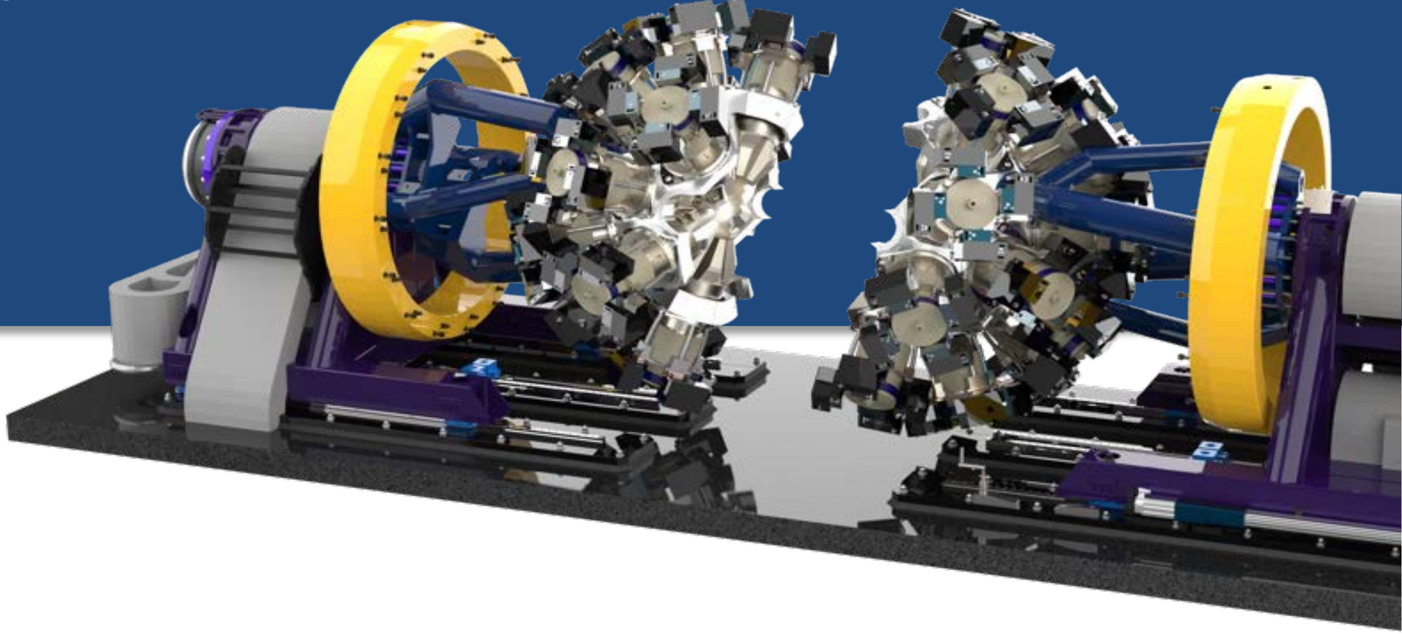
High Resolution Gamma Ray Detection and Tracking in HPGe Detectors

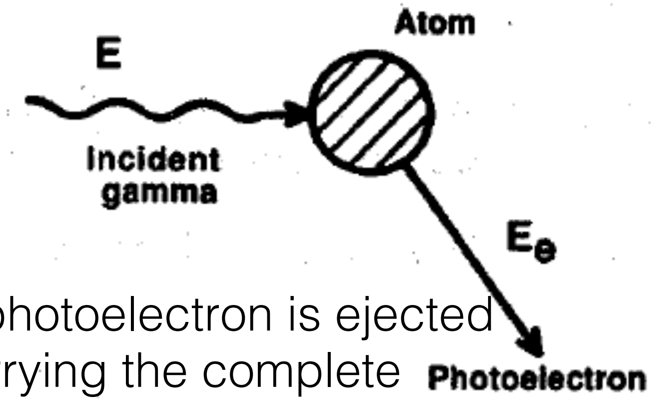


Heather Crawford

Nuclear Science Division
Lawrence Berkeley National Laboratory

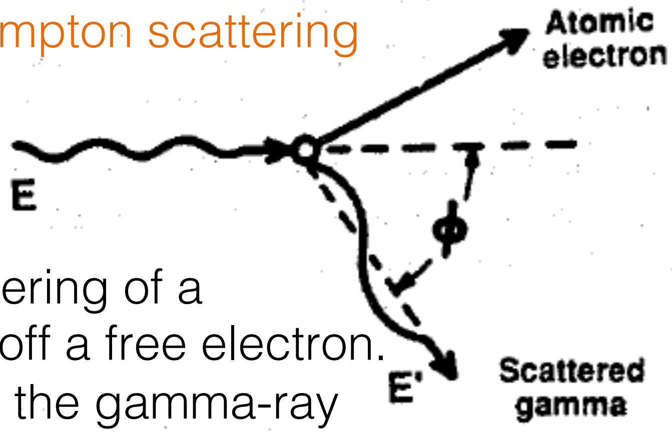
Interaction of Gamma-Rays with Matter

Photoelectric effect



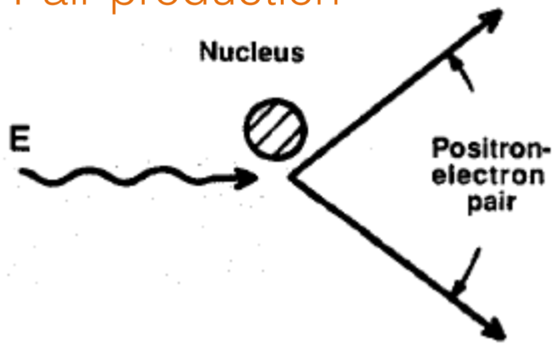
A photoelectron is ejected carrying the complete gamma-ray energy (- binding)

Compton scattering



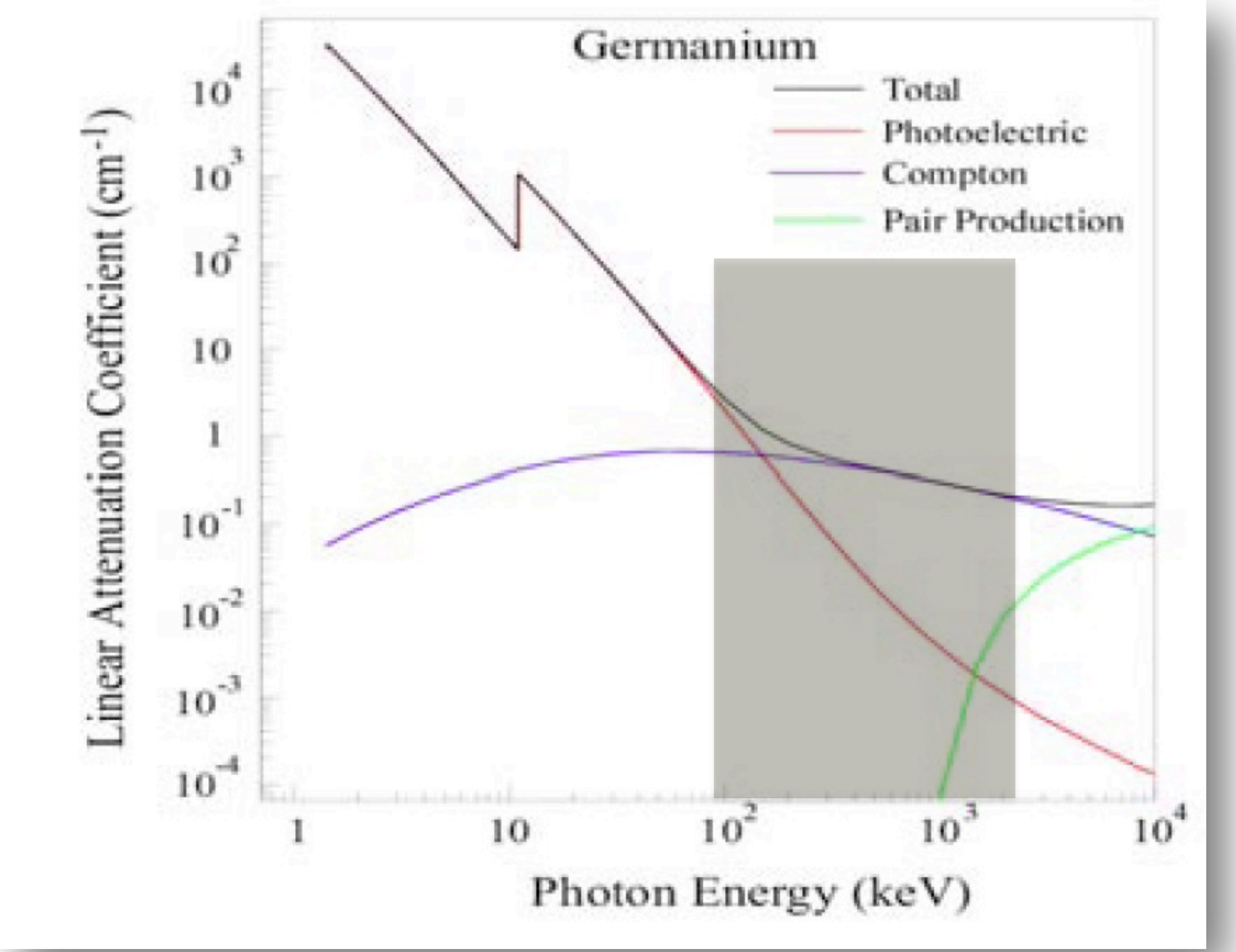
Elastic scattering of a gamma ray off a free electron.
A fraction of the gamma-ray energy is transferred to the Compton electron

Pair production



If gamma-ray energy is >> 2 $m_o c^2$ (electron rest mass 511 keV), a positron-electron can be formed in the strong Coulomb field of a nucleus.
This pair carries the gamma-ray energy minus 2 $m_o c^2$.

Gamma-Ray Interactions with Matter



100 keV – 3 MeV gamma-ray energies are typical in nuclear structure studies

⟹ Compton scattering dominates, with a scatter sequence always eventually terminating in photoelectric energy deposition

Gamma-Ray Detection: Basic Principles

- Fundamentally, we can detect a gamma-ray if it can leave energy in our detector that we can collect
- Gamma-rays primarily interact with electrons – most detectors therefore high Z
- Methods for measuring energy transferred to electrons vary… but we worry about 3 basic performance parameters:

- Efficiency
- Energy resolution
- Peak-to-total (P/T) – probability that a *detected* gamma-ray actually makes it into the peak

The science reach of a γ-ray tracking array can be expressed in terms of the effective resolving power (RP), which depends on these three quantities.

$$RP = \left(\left(\frac{\Delta E_\gamma}{\delta E} \right) \left(\frac{P}{T} \right) \right)^{F_{opt}}$$

Efficiency

- Efficiency is typically discussed as photopeak efficiency -- defined as the fraction of emitted gamma-rays that are detected with their full energy
- Two components – geometric and intrinsic

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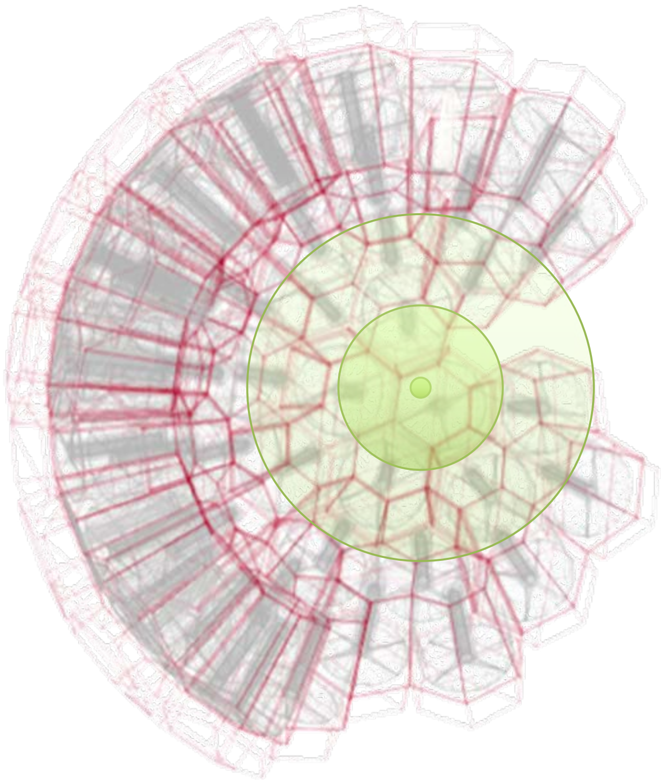

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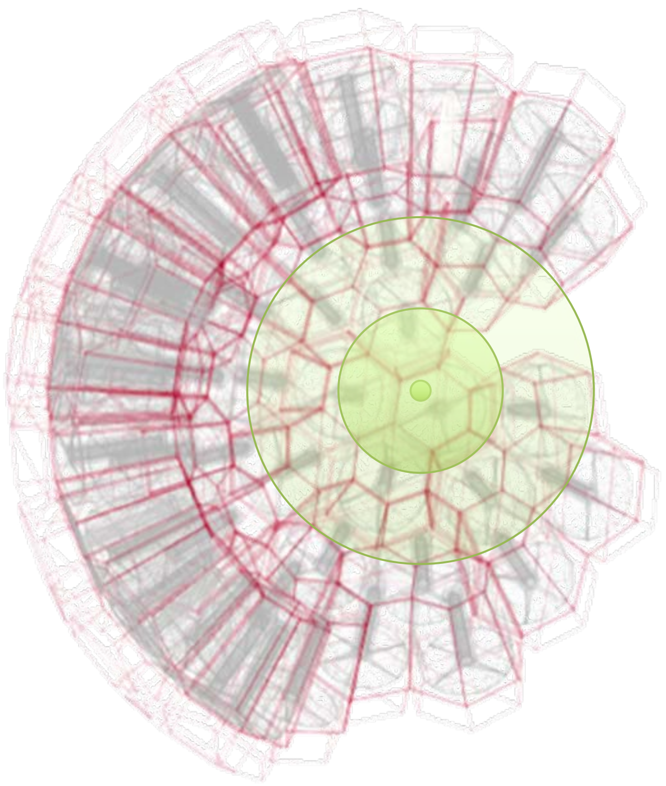
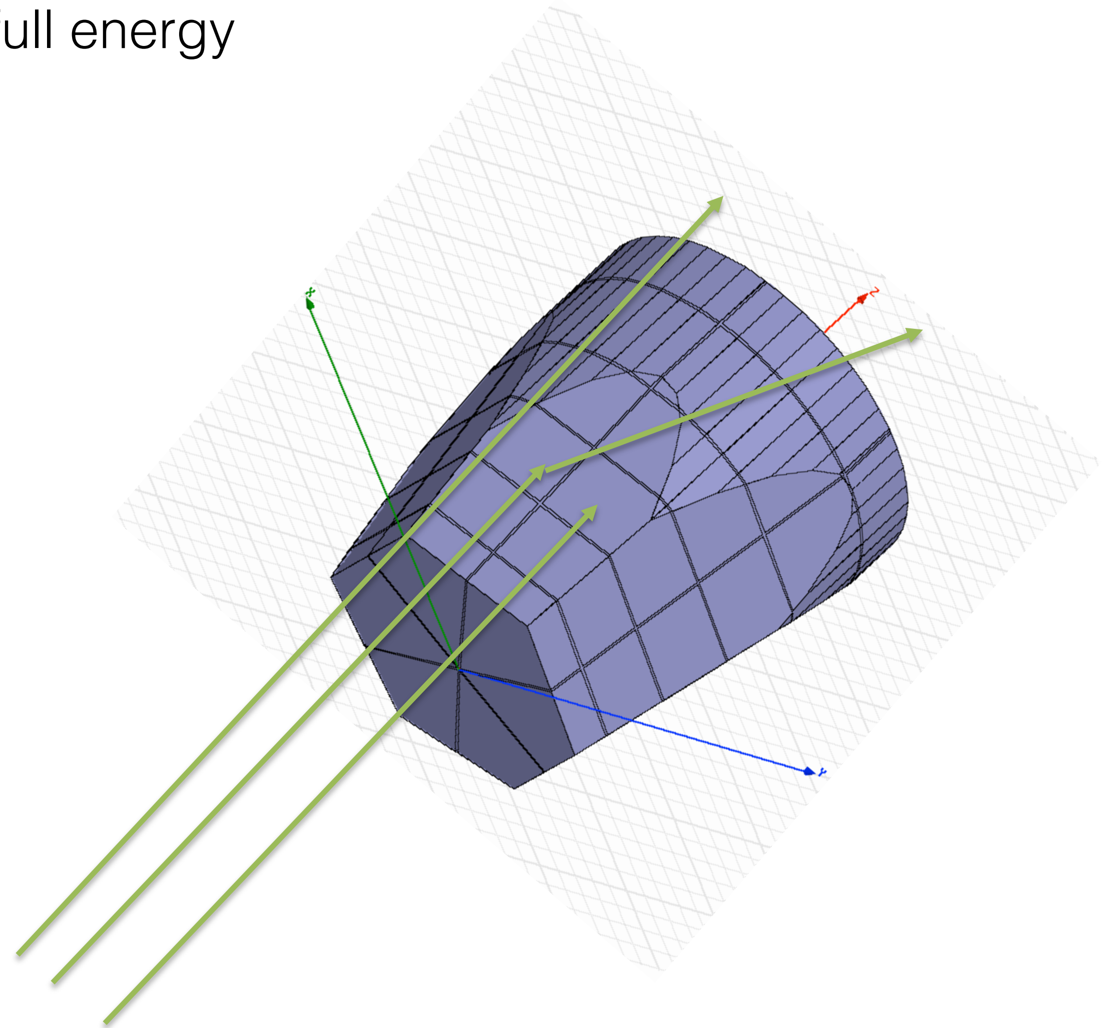
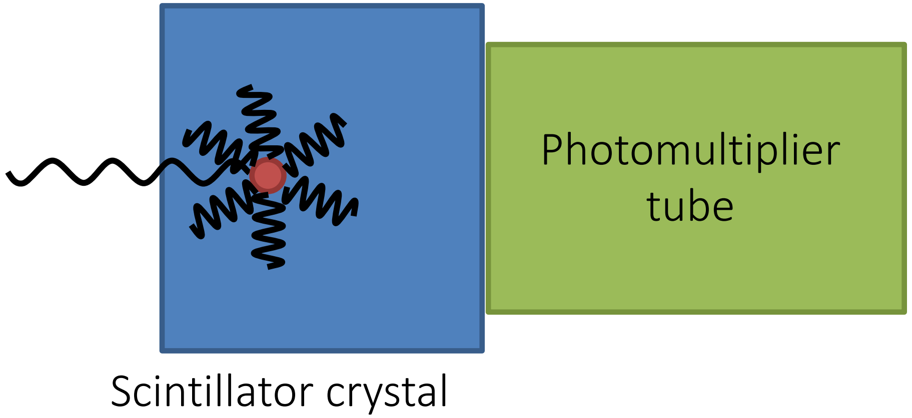
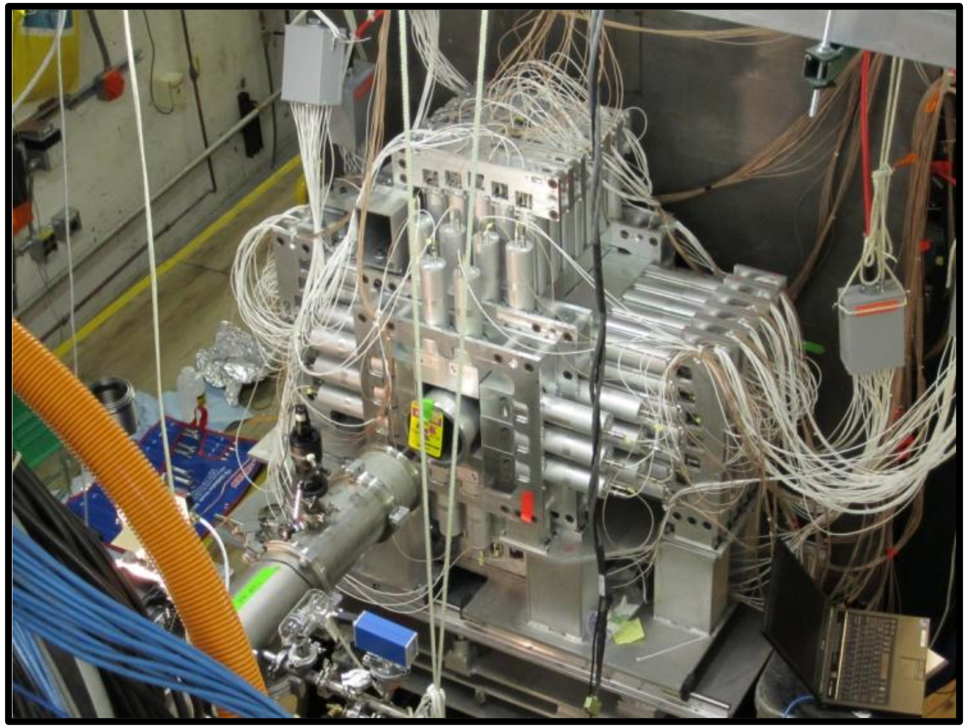


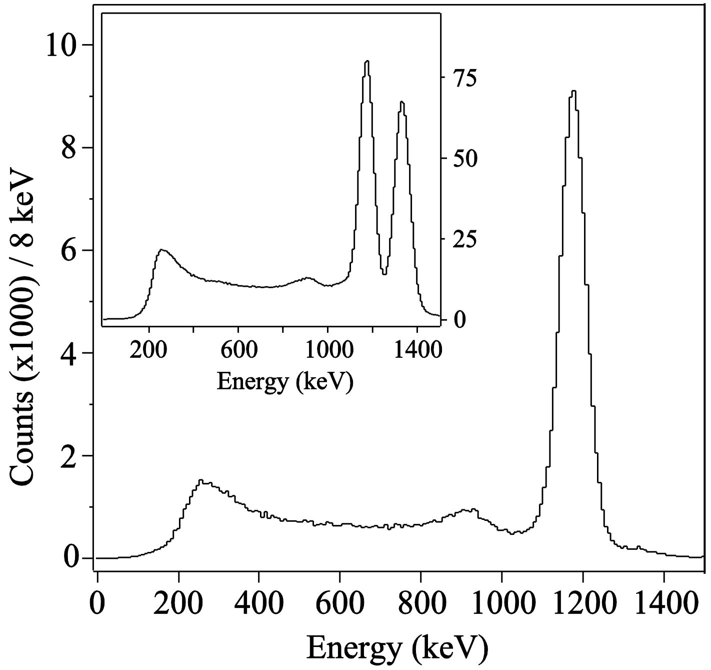


Scintillators



- High efficiency up to ≃ 40%
- Intrinsic energy resolution dominated by statistics of photoelectrons in the PMT – for scintillators, resolutions ≃ 6-7%





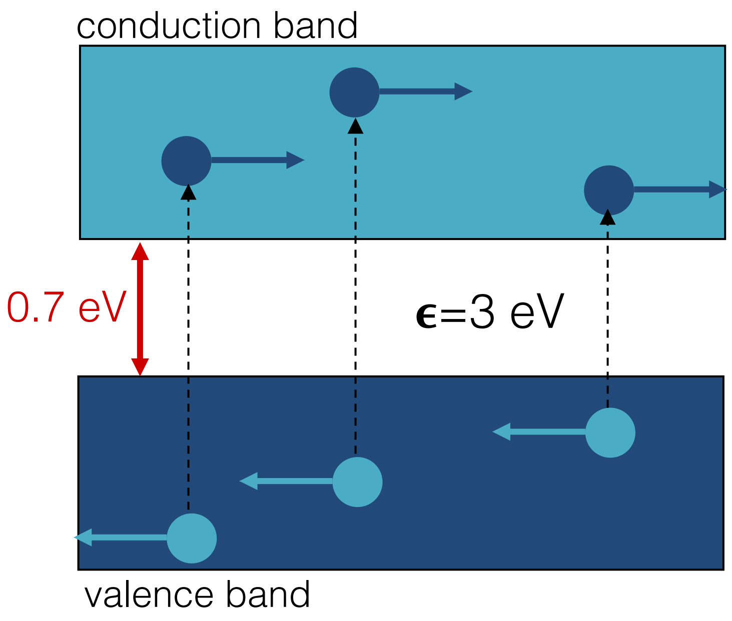
Resolution in Scintillators

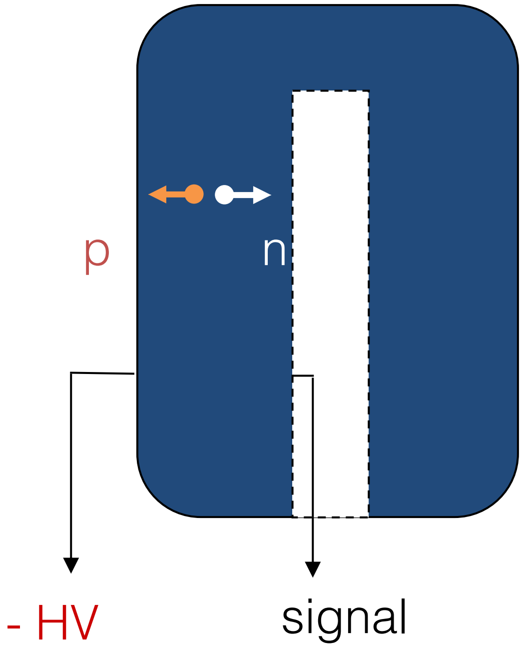
- Energetic particle traveling through a detector (i.e. electron from gamma-ray interaction). Per length traveled dx, this particle may produce scintillation photon, which may make it to the photo-cathode, be converted to a photo-electron and contribute to a signal
  - CsI(Na) yields 38,000 photons / 1 MeV gamma†
  - Light collection + PMT efficiency = 15%
  - 5700 photons collected on average -- $\sigma = \sqrt{6000} = 75$
  - FWHM = 178 → dE/E = 3%

†I. Holl, E. Lorenz and G. Mageras. "A Measurement of the Light Yield of Common Inorganic Scintillators". *IEEE Transactions on Nuclear Science* **35**, 105-109 (1988).

Semi-conductors

- Semiconductors (like HPGe) provide a gold standard for gamma-ray energy resolution
- Energy required to excite electron into the conduction band ≃ 3 eV, many more electron-hole pairs than photons for a scintillator (compare to effectively ~175 eV per detected scintillation photon)





Thermal Excitations

- Thermal energy is shared by electrons in a semi-conductor crystal – it is possible for a valence electron to gain enough energy to move into the conduction band
- Probability per unit time for a thermal electron-hole pair to be created:

$$p(T) = CT^{3/2} exp(-\frac{E_g}{2kT})$$

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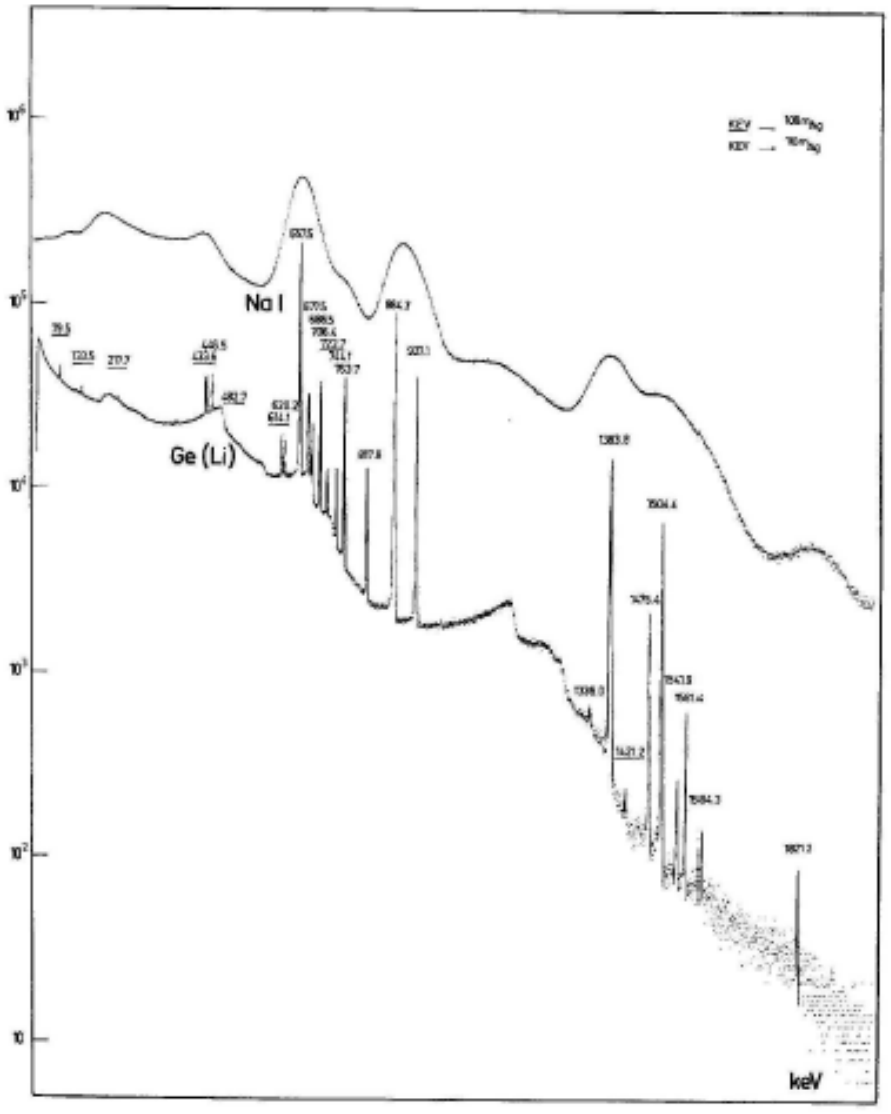
- Semiconductors must be operated cooled – HPGe typically operated at 77 K (LN_2 temperature)

Energy Resolution in HPGe



- Energy resolution for Ge is » order of magnitude better than scintillators
- So what are the downsides?
  - Very expensive (> $10K)
  - Smaller than scintillator crystals usually
  - Require cooling (LN_2)
  - Slower response (timing Ge 5-10ns; scintillator << 1 ns)

Detector Resolution

- Intrinsic resolution ∝ $N^{1/2}$ must be adjusted by the so-called Fano factor (F), which is introduced to quantify deviation of observed statistical fluctuations from Poisson statistics
- Fano factor results from the fact that the processes that give rise to formation of individual charge carriers are not independent (further deviation from Poisson statistics)

$$\sqrt{N} \rightarrow \mathrm{FWHM}_{\mathrm{intrinsic}} = 2.35\sqrt{F E_{\gamma} \epsilon}$$

- Observed detector resolution folds in contributions from intrinsic resolution, and electronic noise, the two largest contributors:

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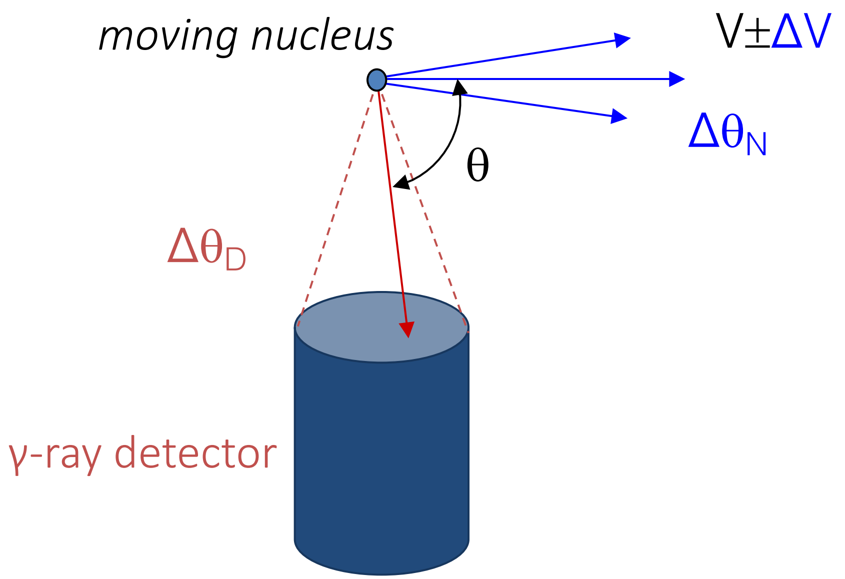
- Is there anything else that can affect energy resolution?

Doppler Correction

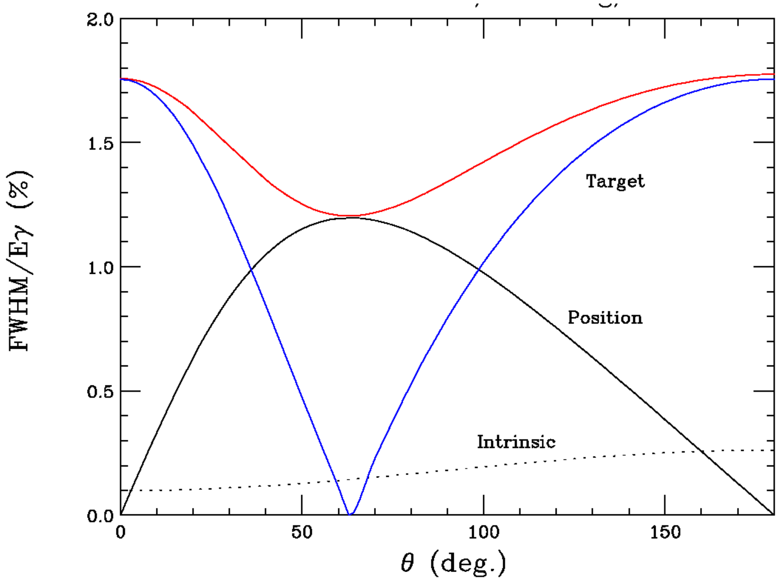


Doppler shift

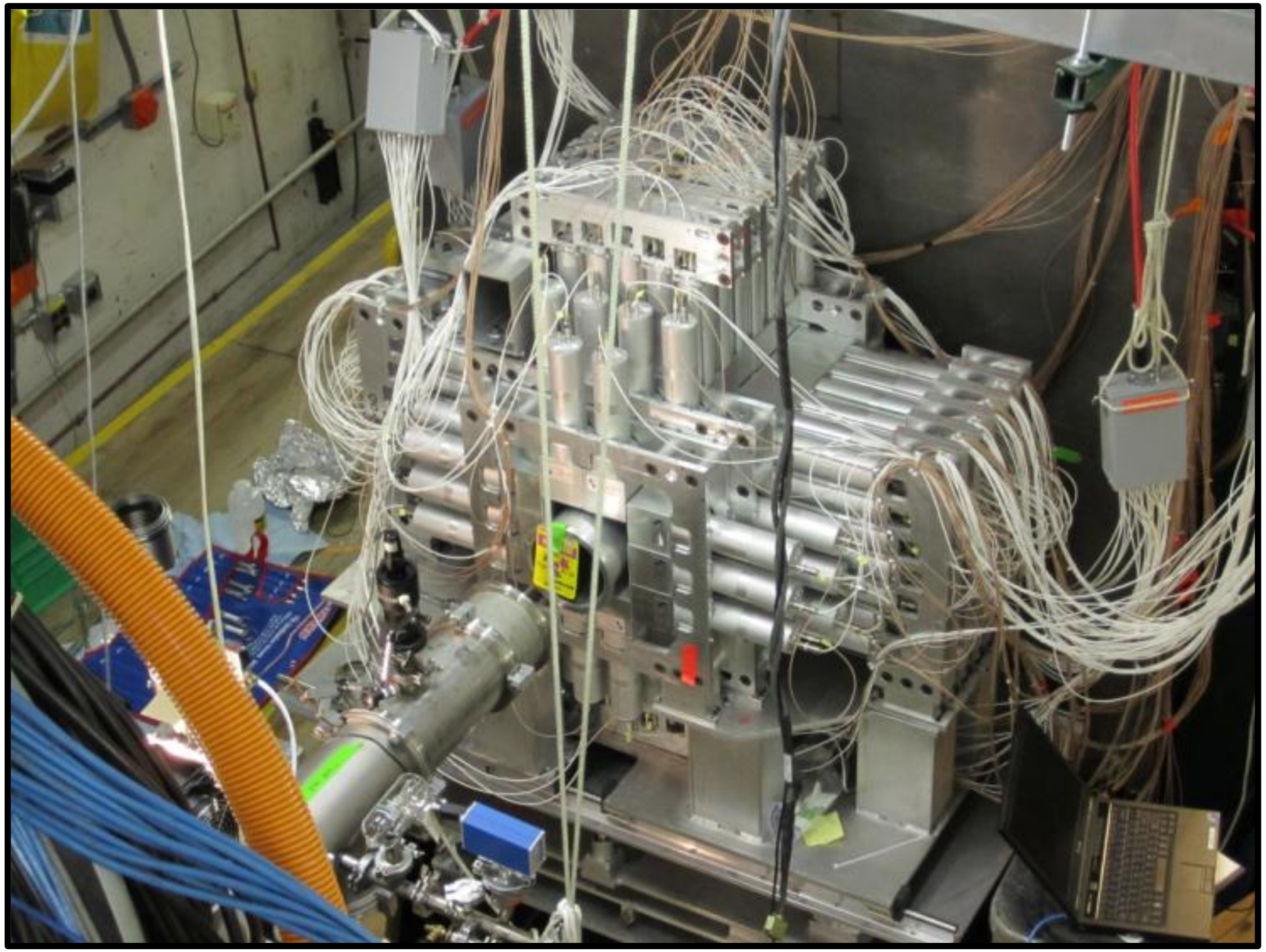
$$E_\gamma = E_\gamma^0 \frac{\sqrt{1-\frac{v^2}{c^2}}}{1-\frac{v}{c}\cos\theta}$$

Broadening of detected gamma-ray energy due to:

- Spread in speed ΔV
- Distribution in direction of velocity $\Delta\theta_N$
- Detector opening angle $\Delta\theta_D$



Doppler Correction – Arrays with many individual elements



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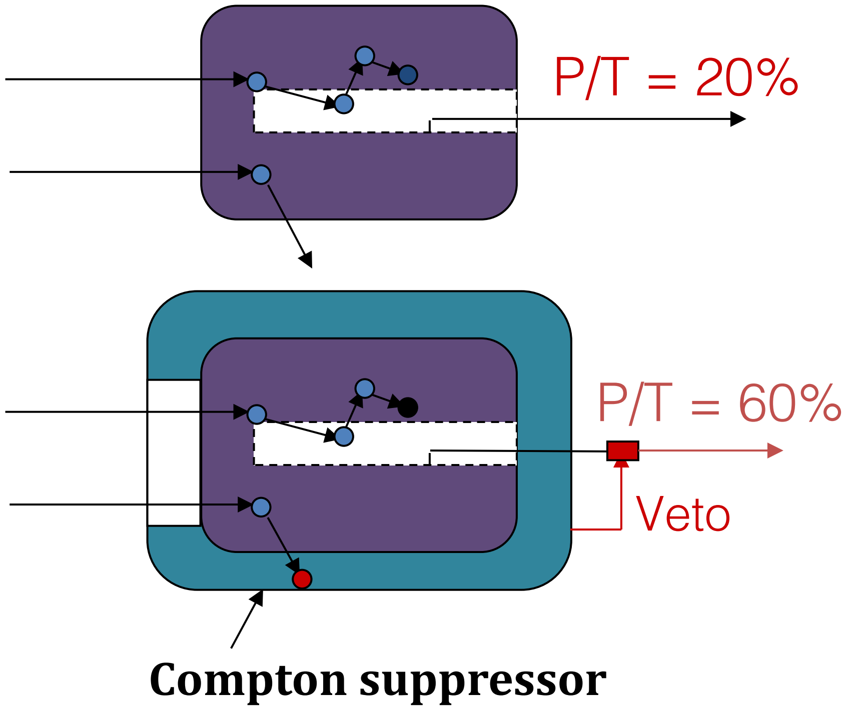
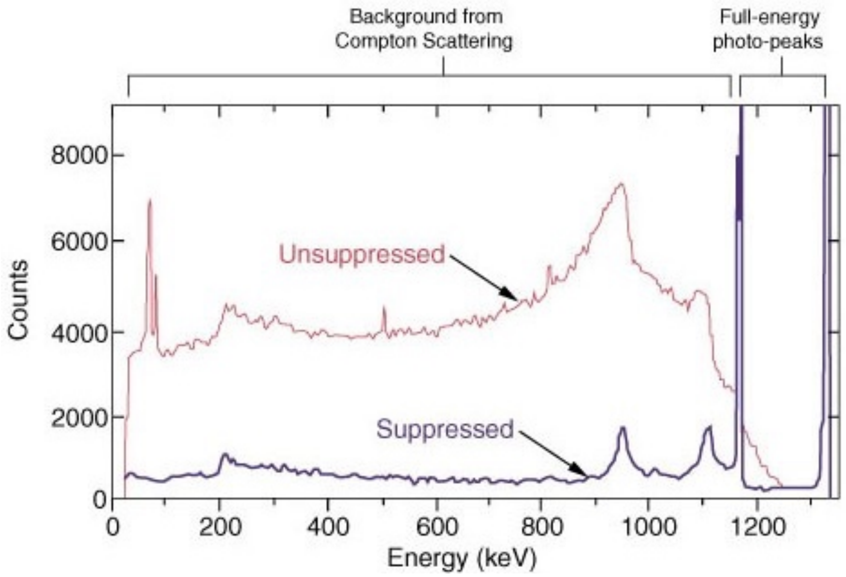
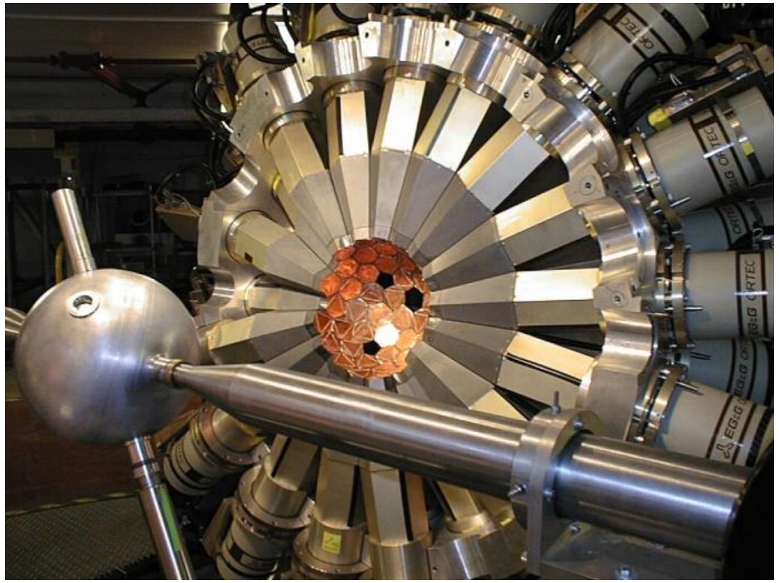
Compton Suppression – Enhancing P/T

- Eliminate contribution from Compton-scattered gamma-rays, which contribute to background, by vetoing these events using a high-efficiency scintillator surrounding the Ge crystal





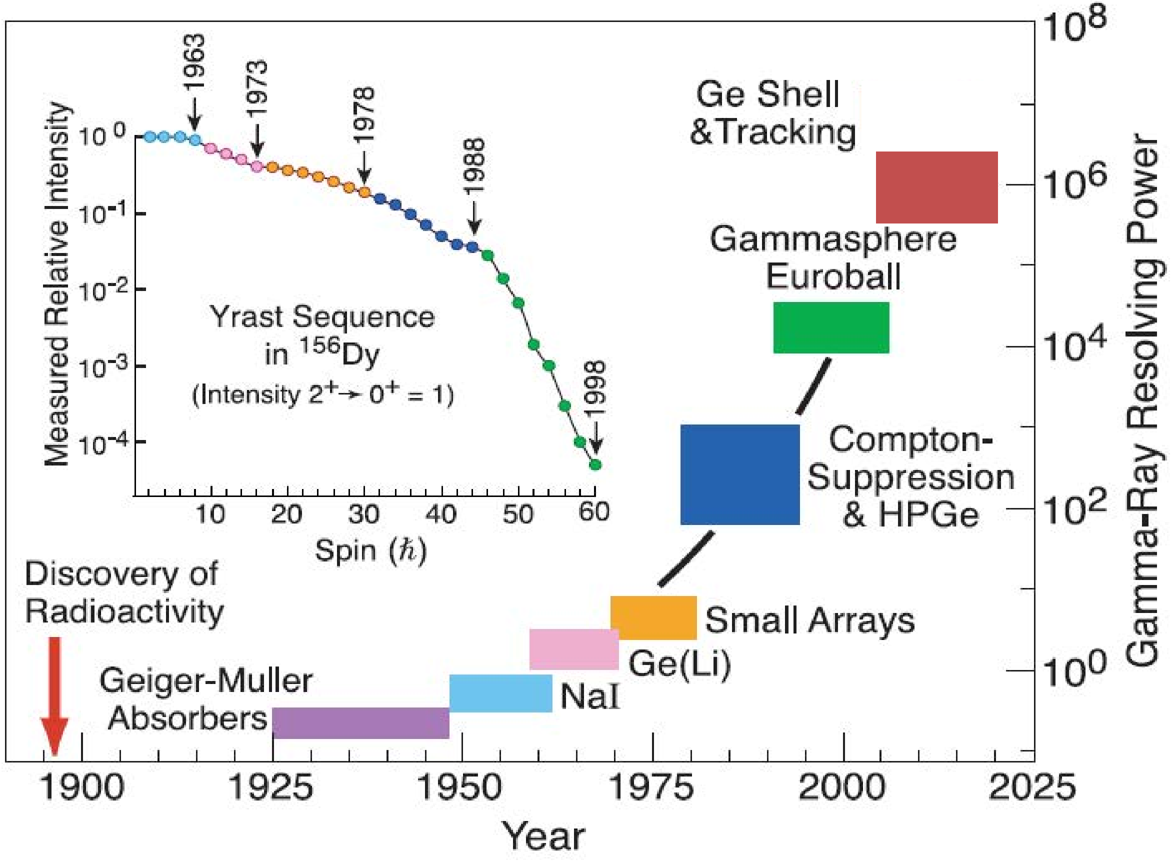


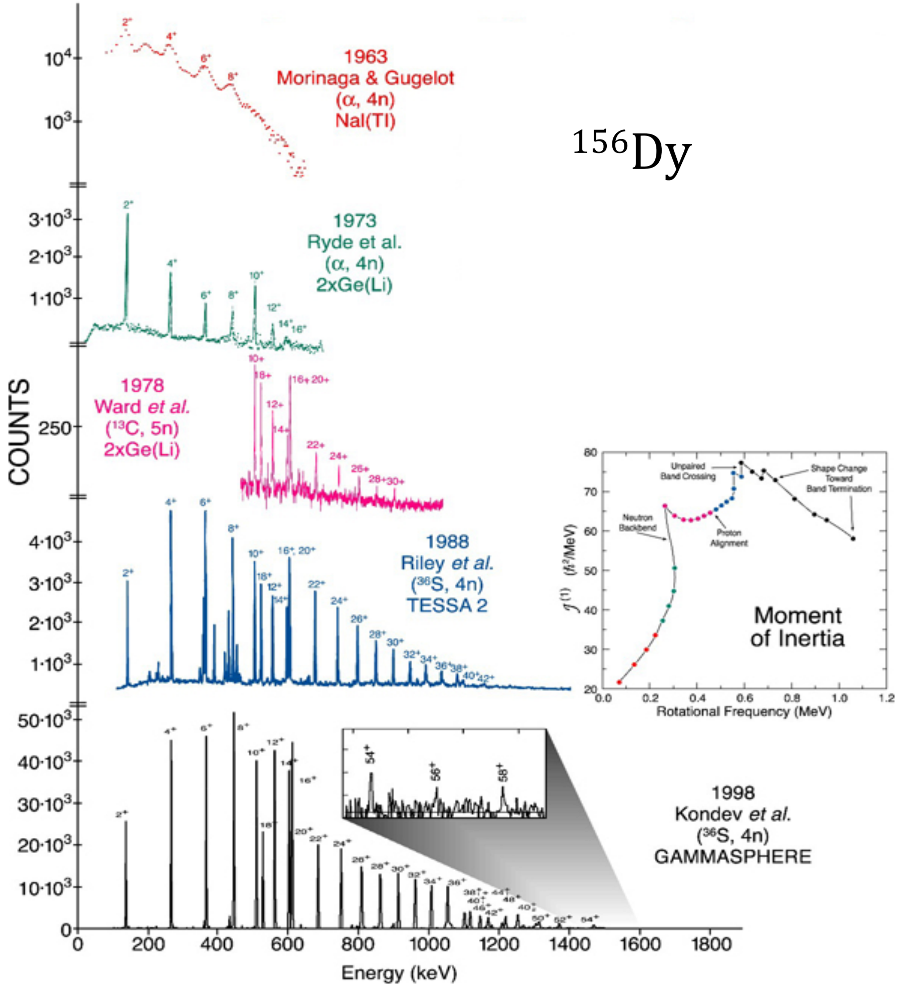
Resolving Power is a Quantitative Measure of Array Performance

The science reach of a γ-ray tracking array can be expressed in terms of the effective resolving power (RP)

Depends on Efficiency (ε); Peak-to-Total (P/T); Resolution (δE)

Resolving Power = Science





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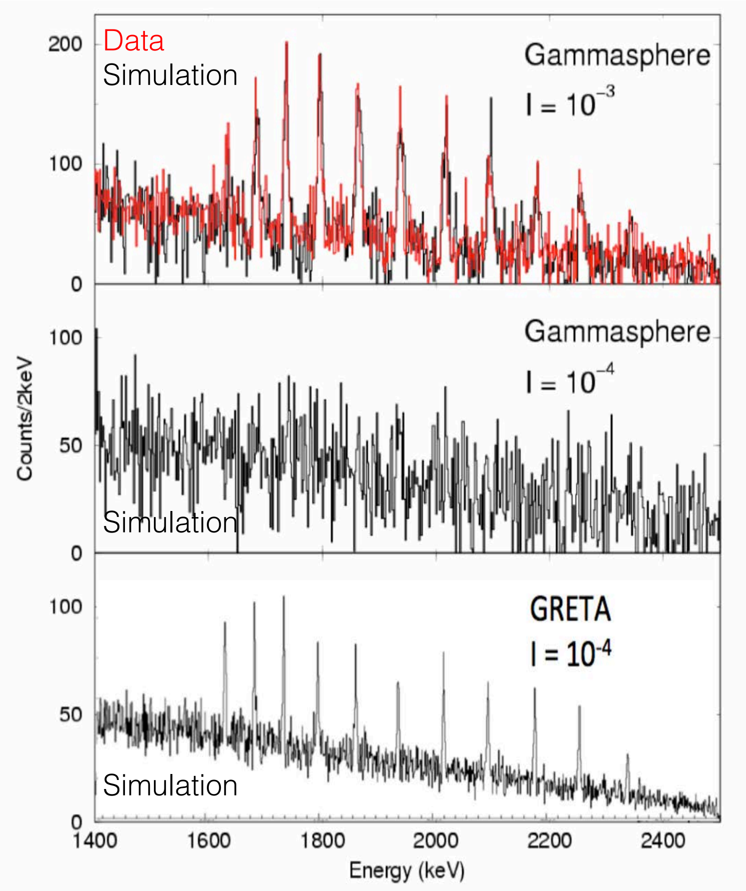

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Efficiency alone over another HPGe array gives GRETA an order of magnitude higher sensitivity for the weakest branches – goes as ~ ε^f for high fold

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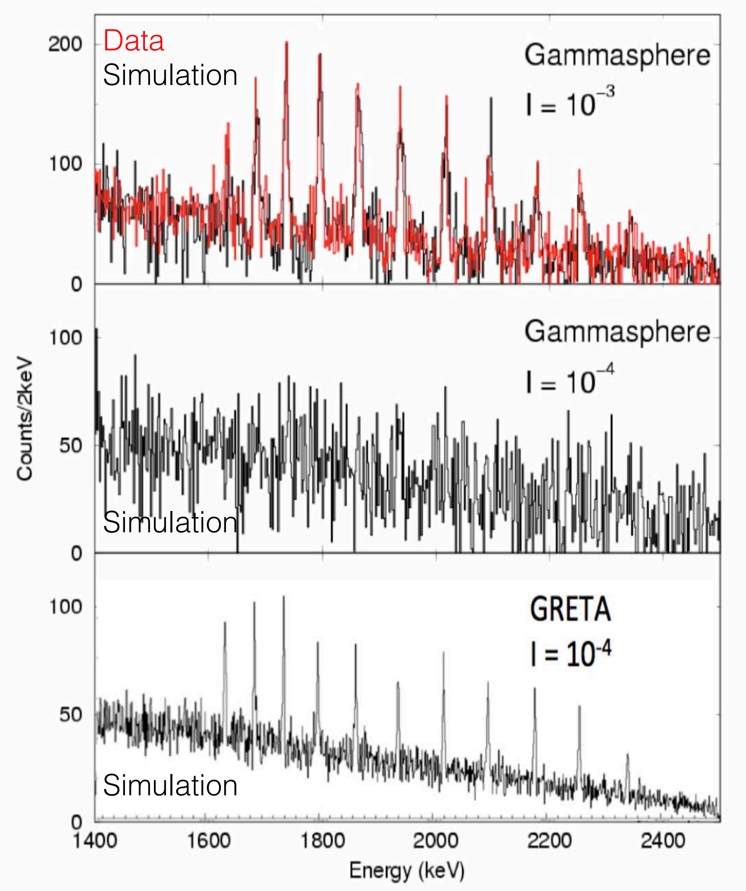

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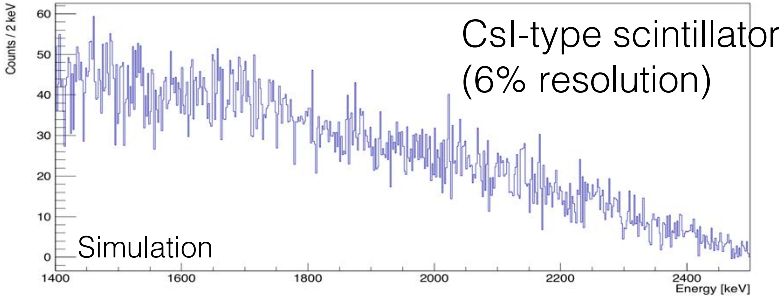
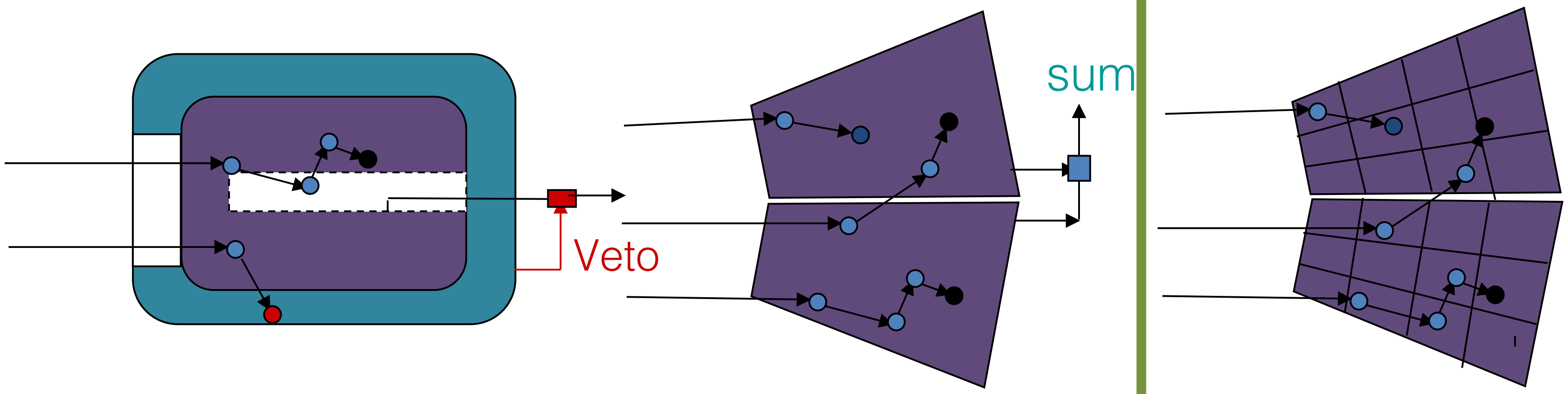
Resolution gives P/T as compared to scintillators with comparable efficiency.



How To Go Beyond Compton Suppressed HPGe Arrays

- Compton Suppressed Ge
- Ge Sphere
- Gamma Ray Tracking

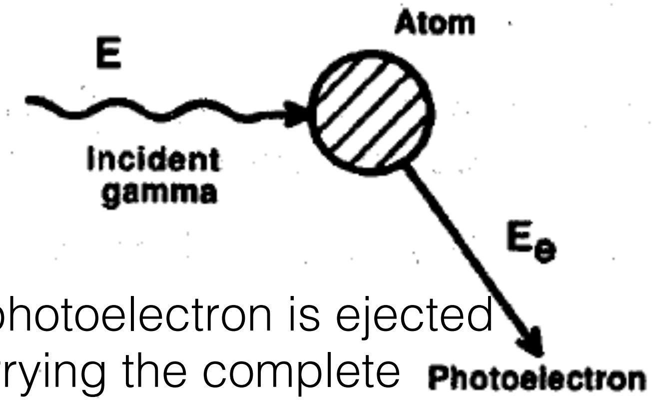


Compton Suppressed Ge	Ge Sphere	Gamma Ray Tracking
N = 100	N = 1000 (summing)	N = 100
NΩ e = 0.1	NΩ e = 0.6	NΩ e = 0.6
Efficiency limited	Too many detectors	Segmentation

Build a 4π sphere of Ge, using highly-segmented detectors
Gamma-ray tracking allows rejection of Compton scattering events,
Signal decomposition allows sub-segment position resolution

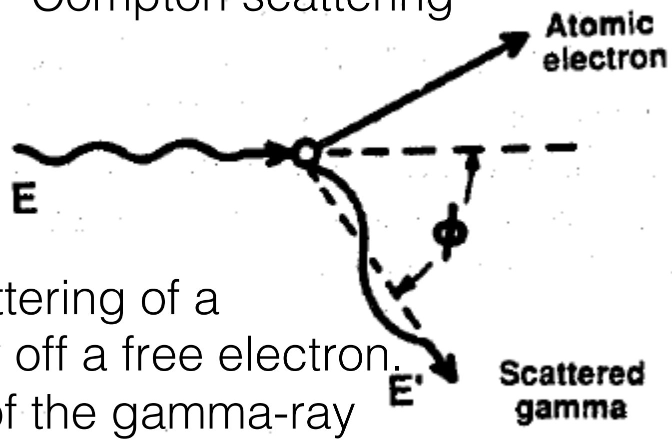
Interaction of Gamma-Rays with Matter

Photo effect



A photoelectron is ejected carrying the complete gamma-ray energy (- binding)

Compton scattering



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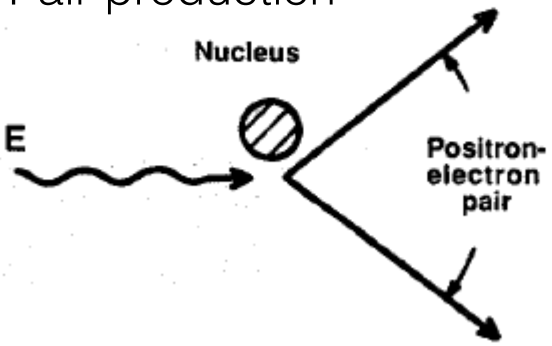
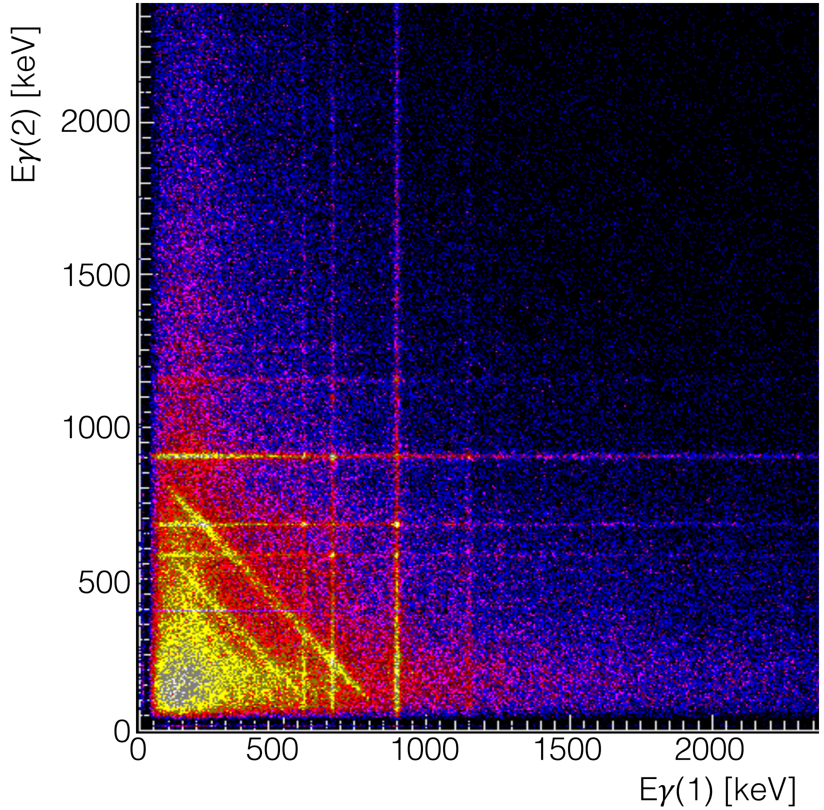
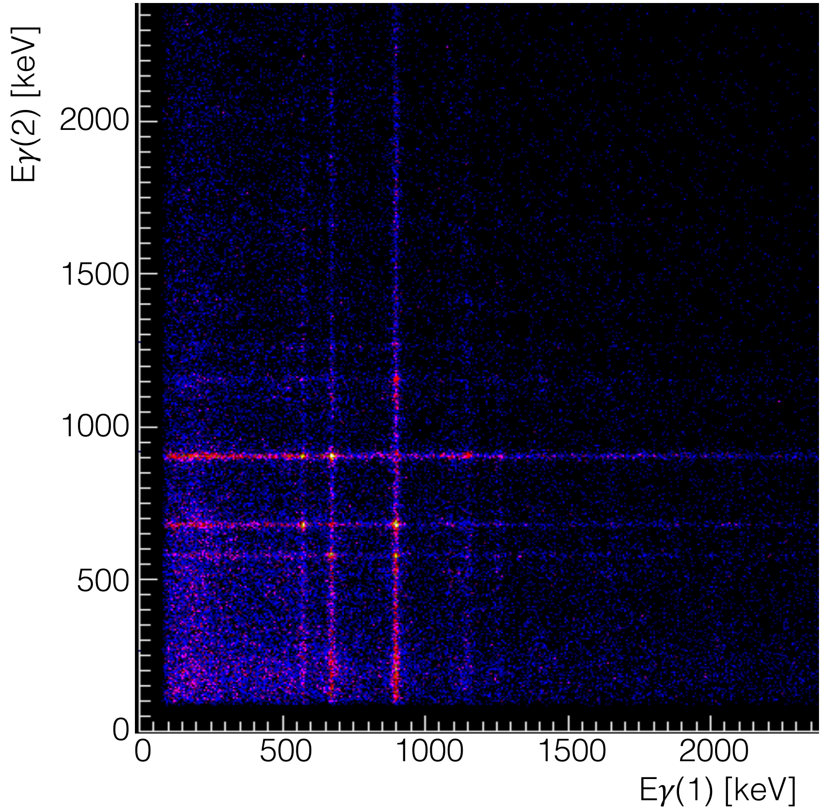


If gamma-ray energy is >> 2 m_oc^2 (electron rest mass 511 keV), a positron-electron can be formed in the strong Coulomb field of a nucleus.
This pair carries the gamma-ray energy minus 2 m_oc^2 .

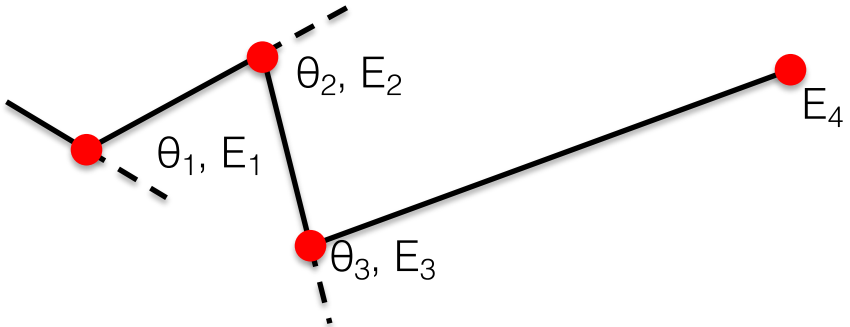
Tracking: Compton Rejection





^{64}Ge populated in knockout from ^{65}Ge

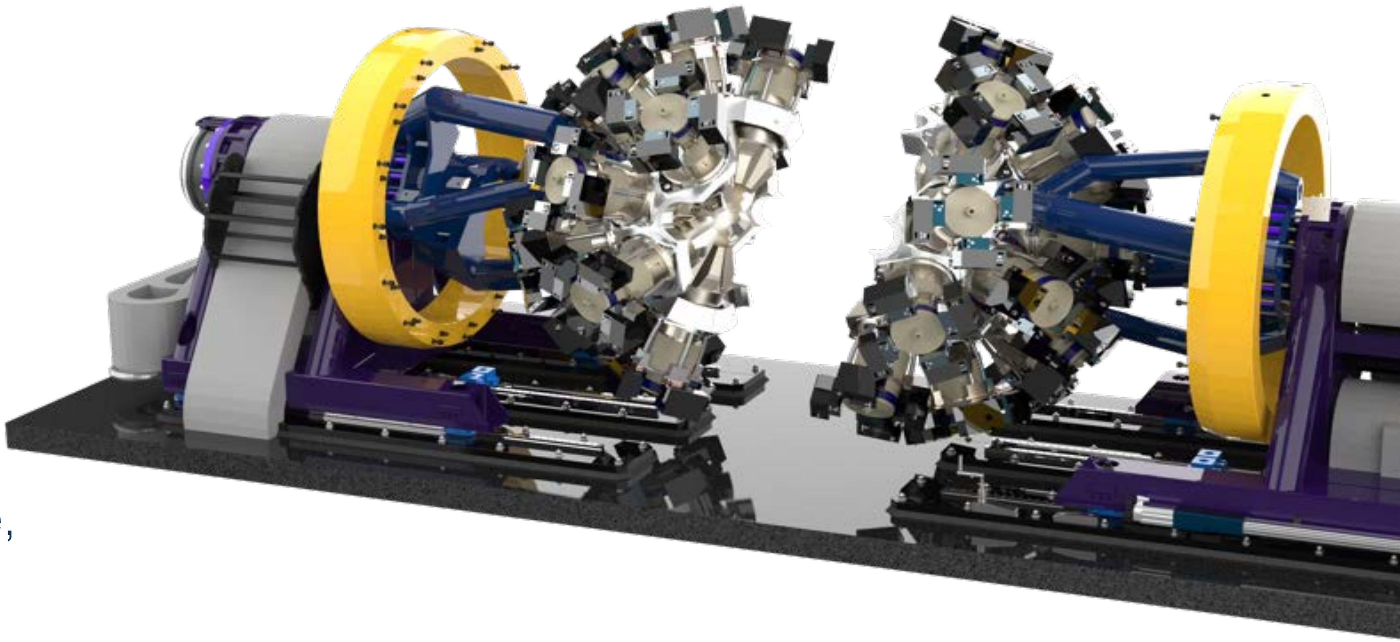
Reduction of Compton background by tracking allows spectral quality comparable to arrays with anti-Compton shields.



The Gamma-Ray Energy Tracking Array: GRETA

GRETA is a 4π tracking detector capable of reconstructing the energy and three-dimensional position of γ-ray interactions

Provides an unprecedented combination of
- full solid angle coverage and high efficiency
- excellent energy and position resolution
- good background rejection (peak-to-total)



LBNL-led project funded by DOE Office of Science, Office of Nuclear Physics and in collaboration with contributions from ANL, NSCL and ORNL

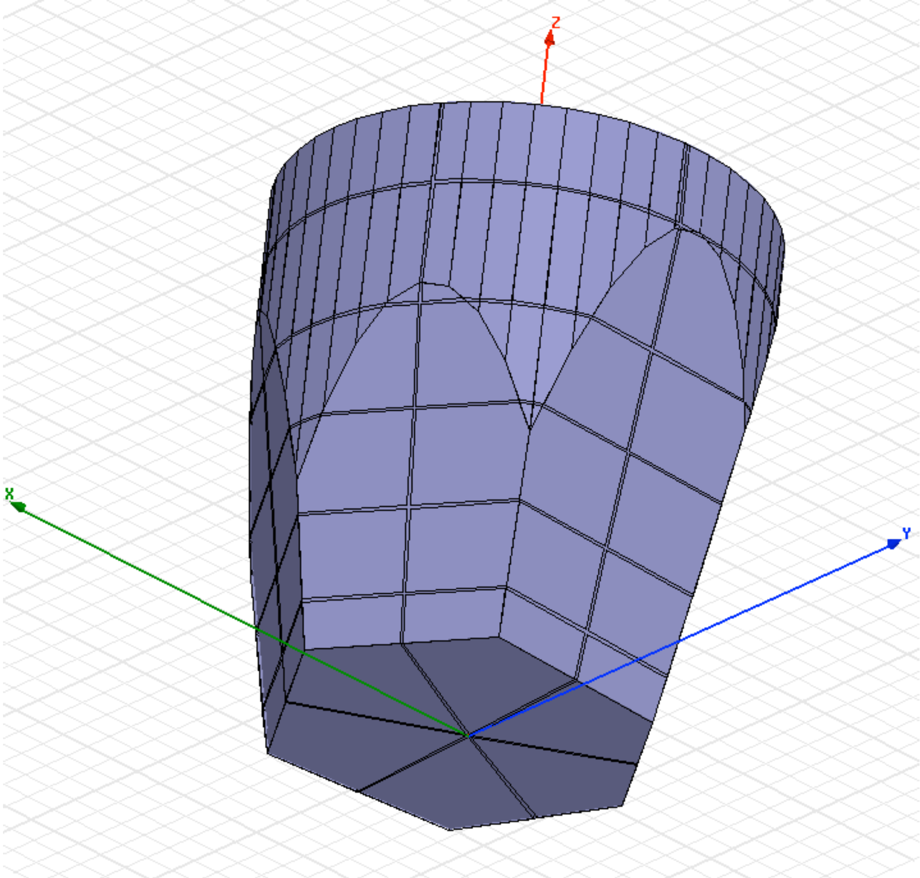
GRETA builds directly off of the success of GRETINA, which has been operating for physics since 2012, with 4 campaigns completed

"GRETA will play a central role by adding significant new capabilities to existing facilities, such as ATLAS, NSCL, and ARUNA facilities, and as a centerpiece at FRIB for the physics opportunities with both fast-fragmentation and reaccelerated beams. … the community is eagerly anticipating a full 4π GRETA array."

Reaching for the Horizon
The 2015 Long Range Plan for Nuclear Science

GRETA concept for a shell of closely packed Ge crystals

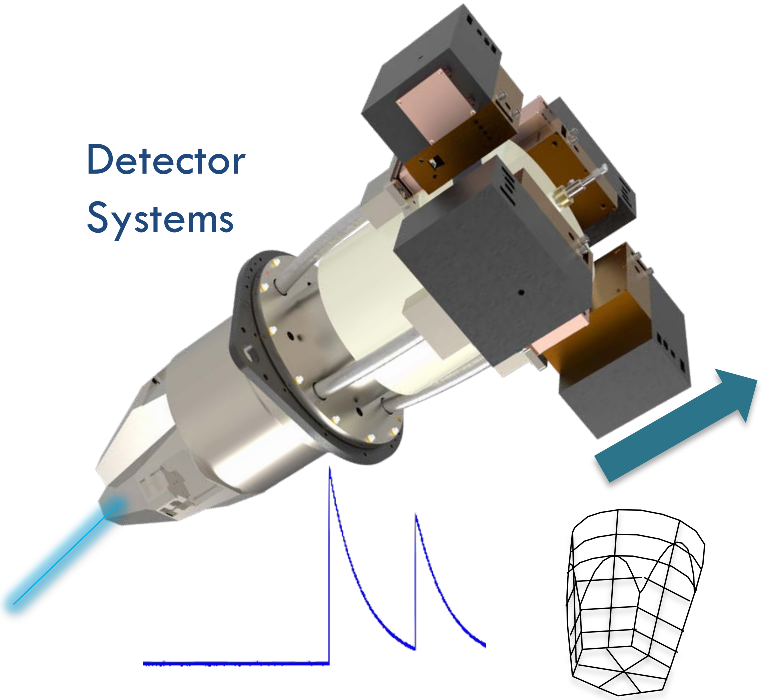
- Combines highly segmented, hyper-pure germanium crystals with advanced digital signal processing techniques
- Identify the position and energy of γ-ray interaction points within a compact "shell" of detectors
- Track γ-ray path both within and between detector elements, using the angle-energy relation of the Compton scattering process



Maximizes and Optimizes
- Efficiency, Energy Resolution, Peak-to-Total

Integrating the Subsystems of GRETA

Detector Systems



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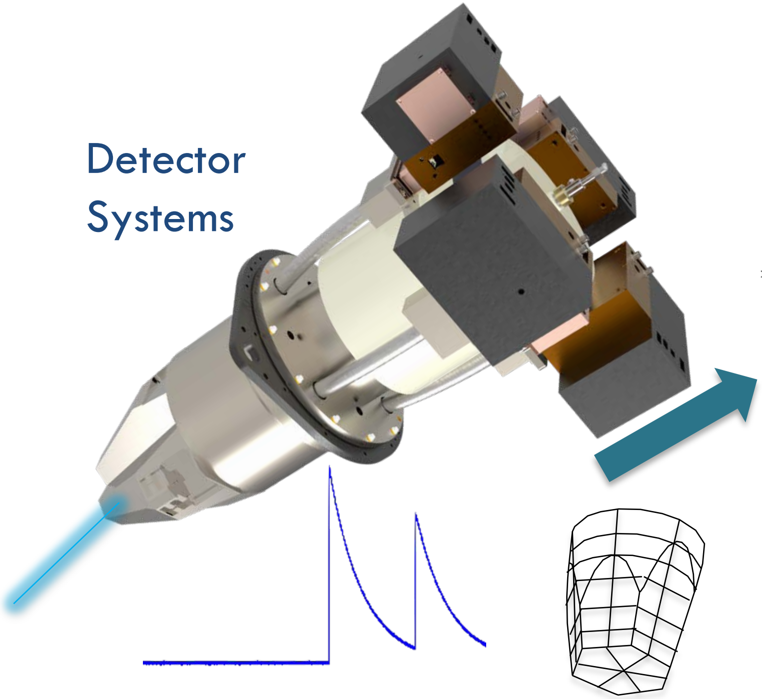

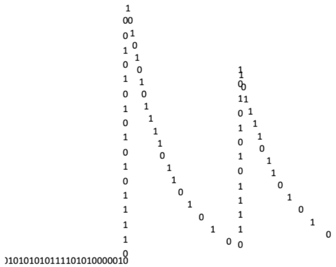

- Continuous 100MHz digitization of **40** preamplifier signals **per crystal**

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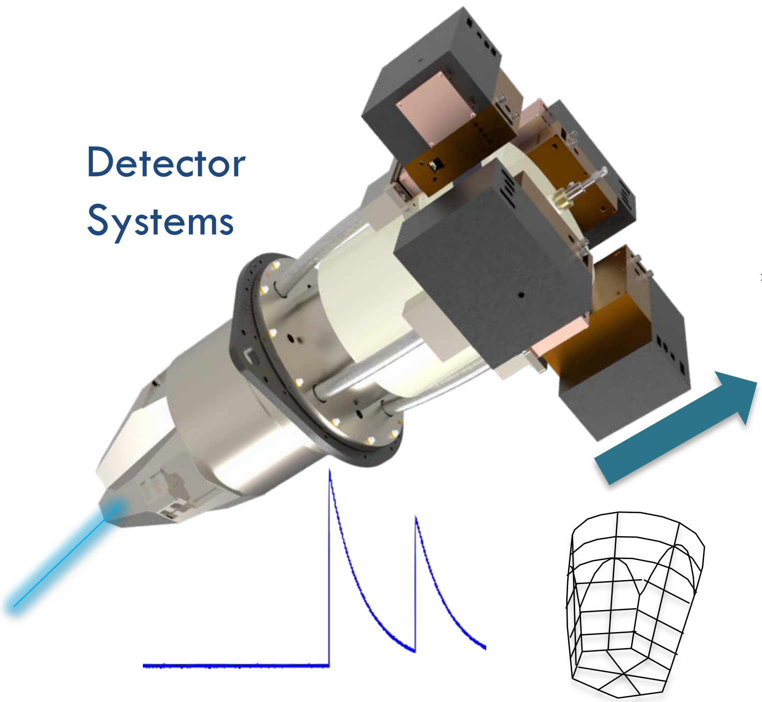

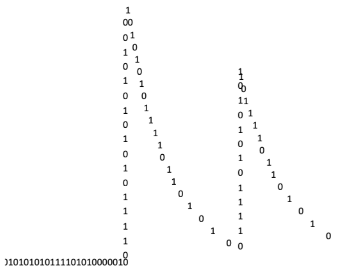

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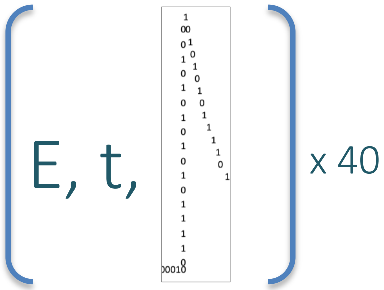
Electronics Systems



- FPGA-based energy filters, event selection in response to physics triggers

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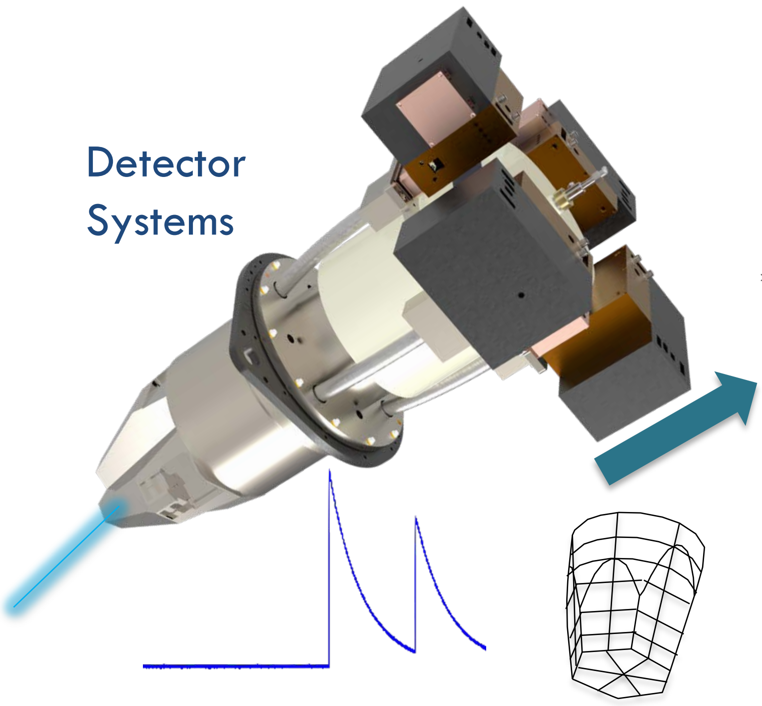

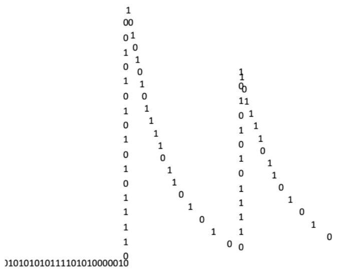

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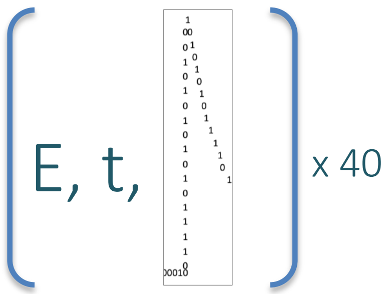

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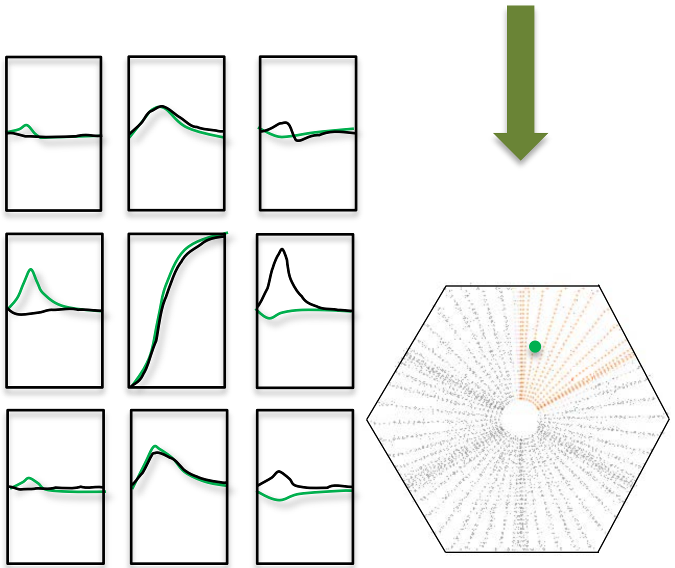

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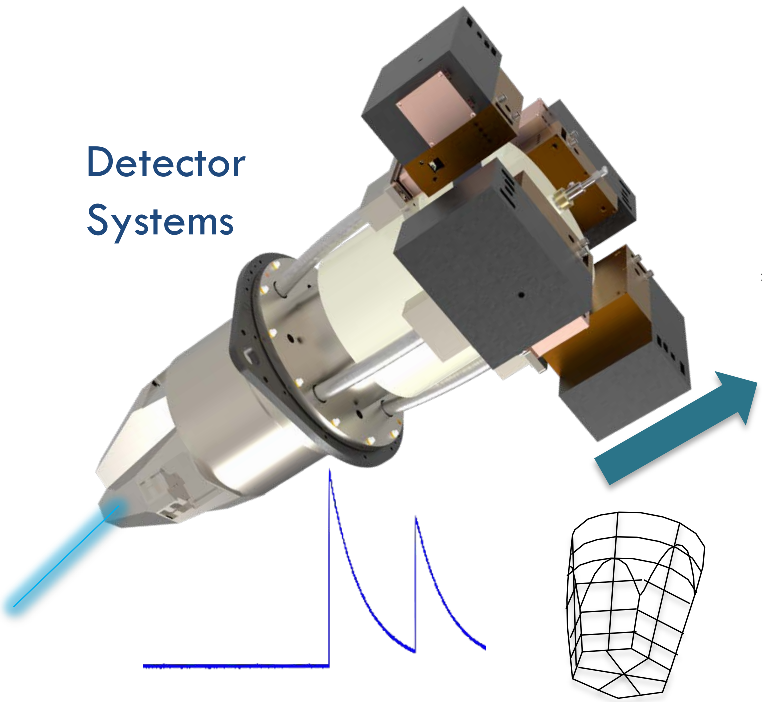

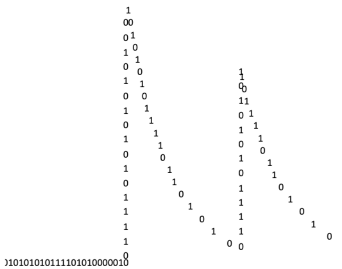

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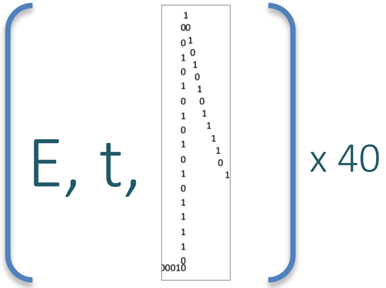

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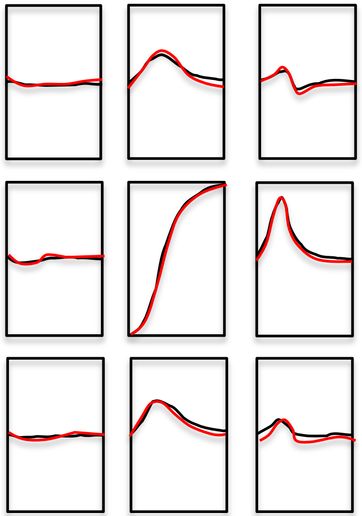
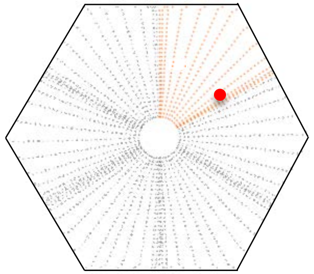
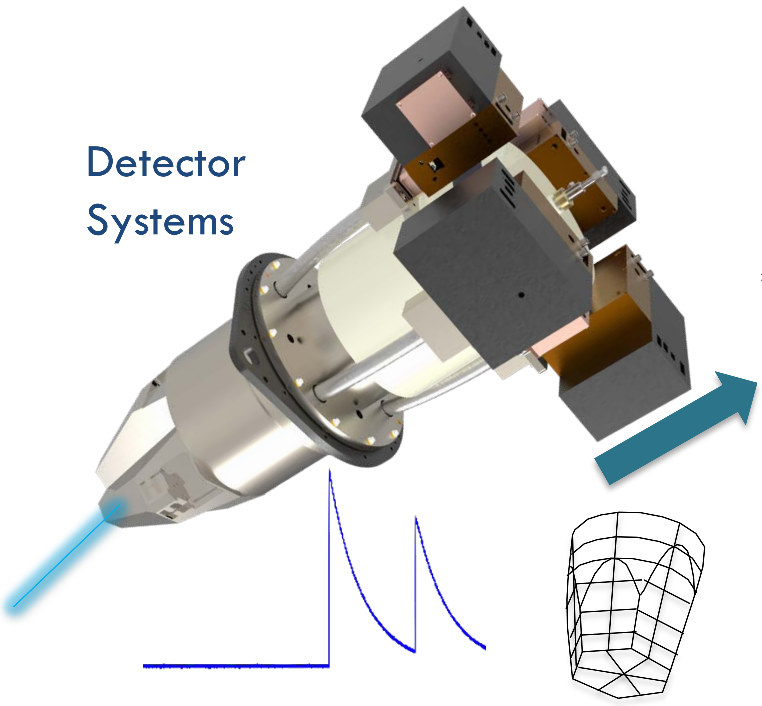
Computing Systems

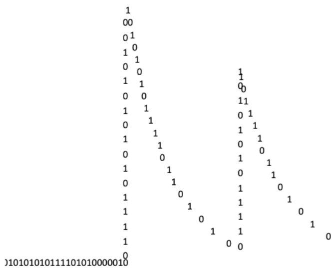




Integrating the Subsystems of GRETA

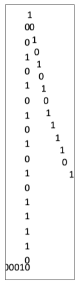
Detector Systems



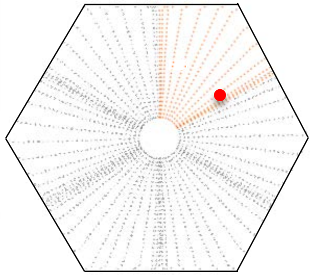


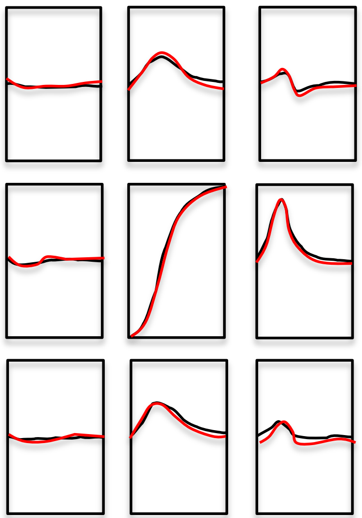
- Continuous 100MHz digitization of **40** preamplifier signals **per crystal**

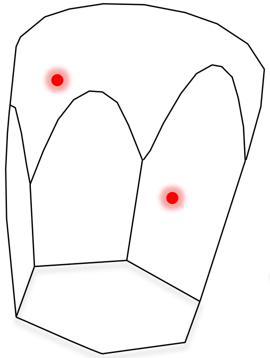
Electronics Systems

$\left[E, t, \right.$  $\left. \right]$ x 40

- FPGA-based energy filters, event selection in response to physics triggers



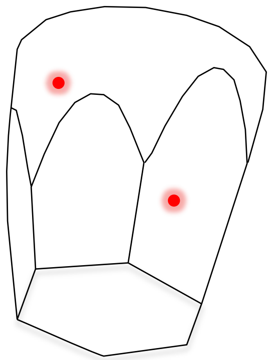




Computing Systems

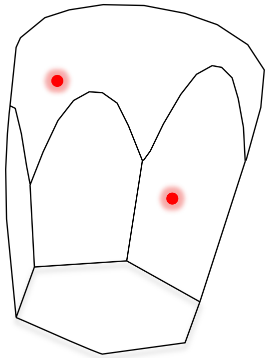
$\left[E, t, (x, y, z)_{crystal}\right]_n$

Integrating the Subsystems of GRETA

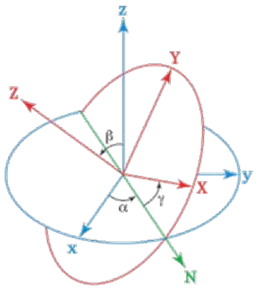


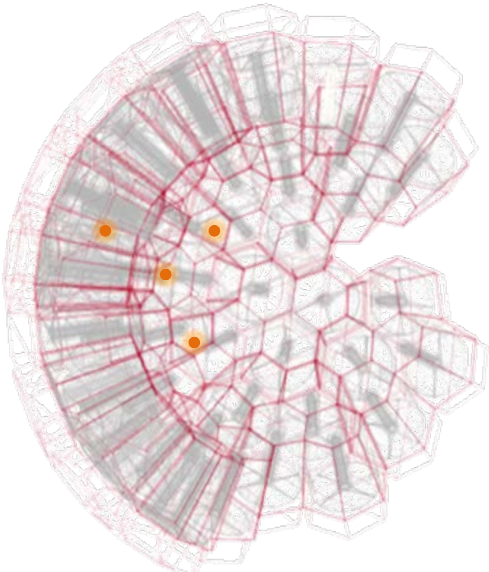
$\left[E,\ t,\ (x,\ y,\ z)_{crystal}\right]_n$

Integrating the Subsystems of GRETA



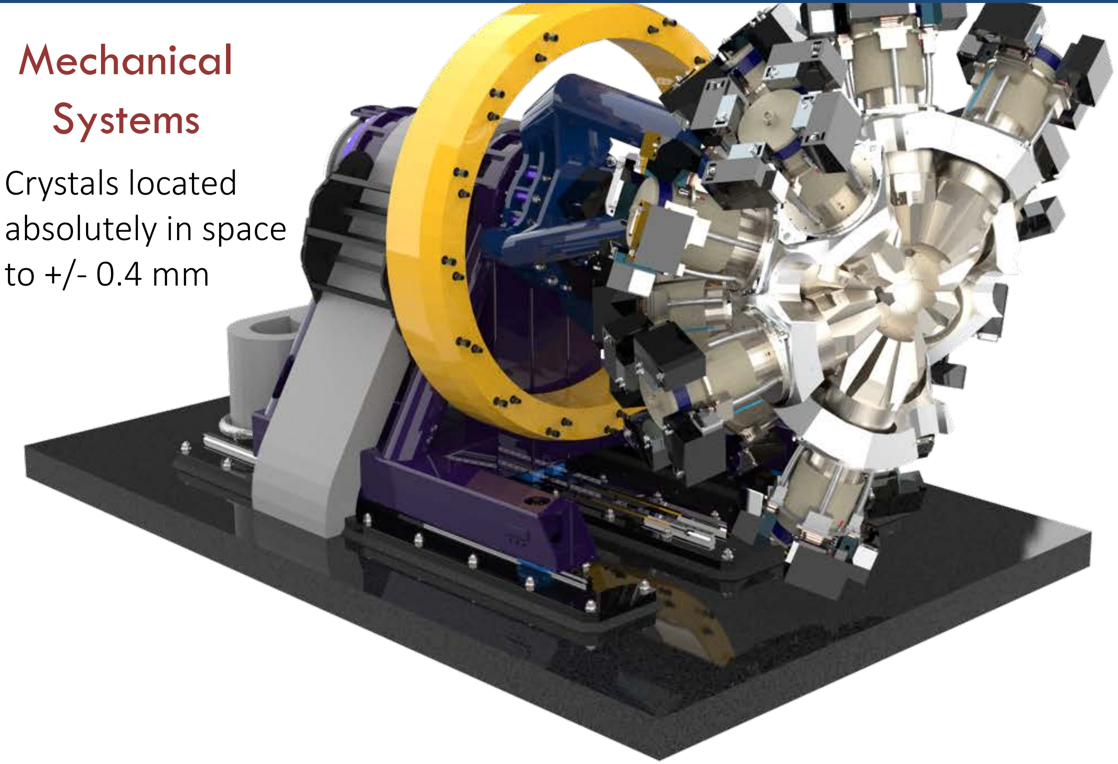
$$\left[E,\ t,\ (x,\ y,\ z)_{crystal}\right]_n$$



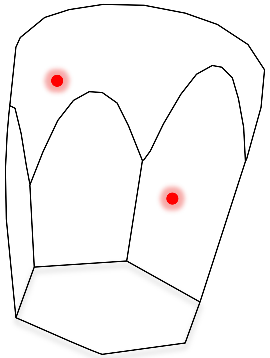


Mechanical Systems

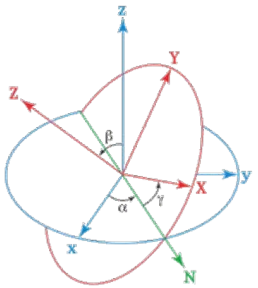
- Crystals located absolutely in space to +/- 0.4 mm



Integrating the Subsystems of GRETA



$$\left[E,\ t,\ (x,\ y,\ z)_{crystal}\right]_n$$



Mechanical Systems

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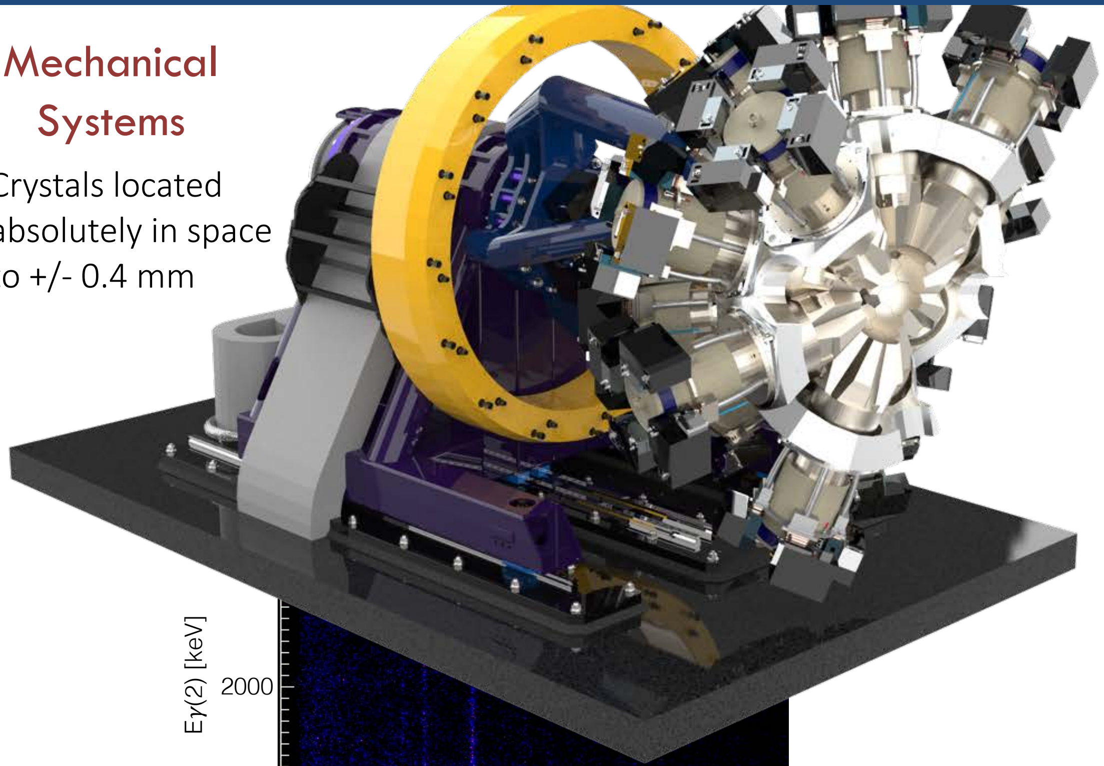
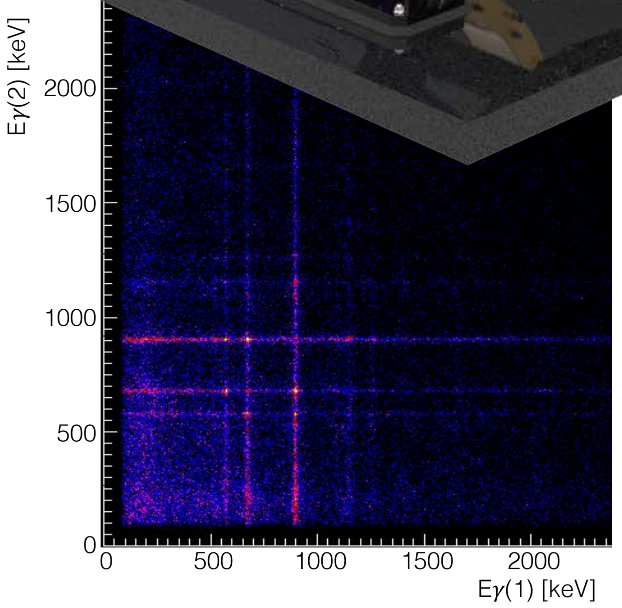
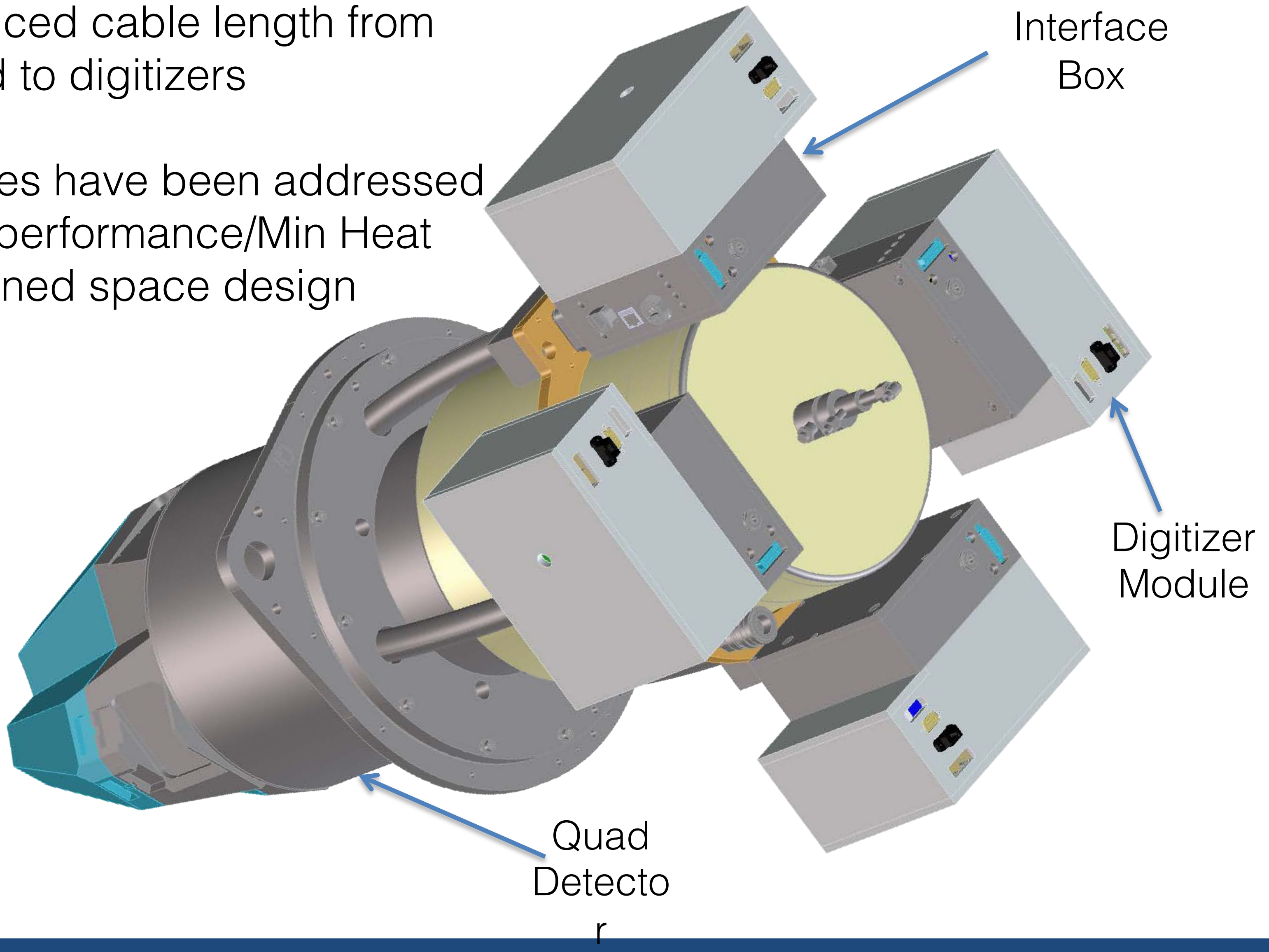


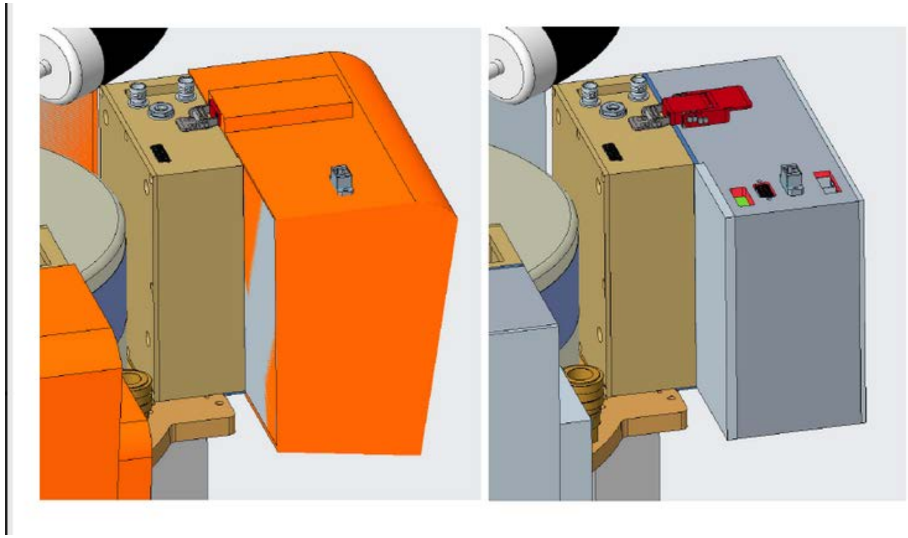


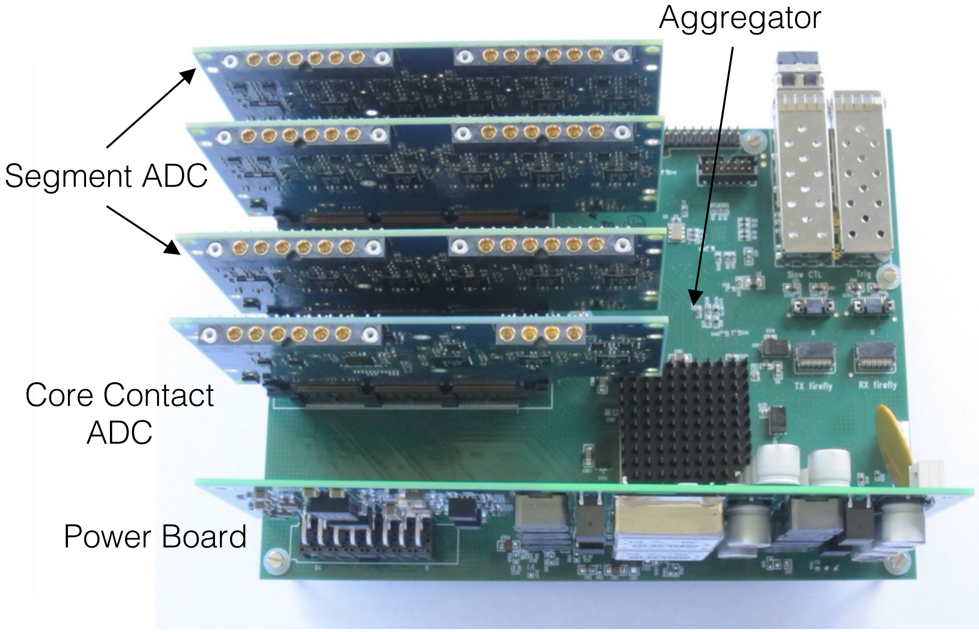
DIB & DM Mounted on the Quad Detector

- Benefits
  - Reduced cable length from Quad to digitizers
- Challenges have been addressed
  - Max performance/Min Heat
  - Confined space design

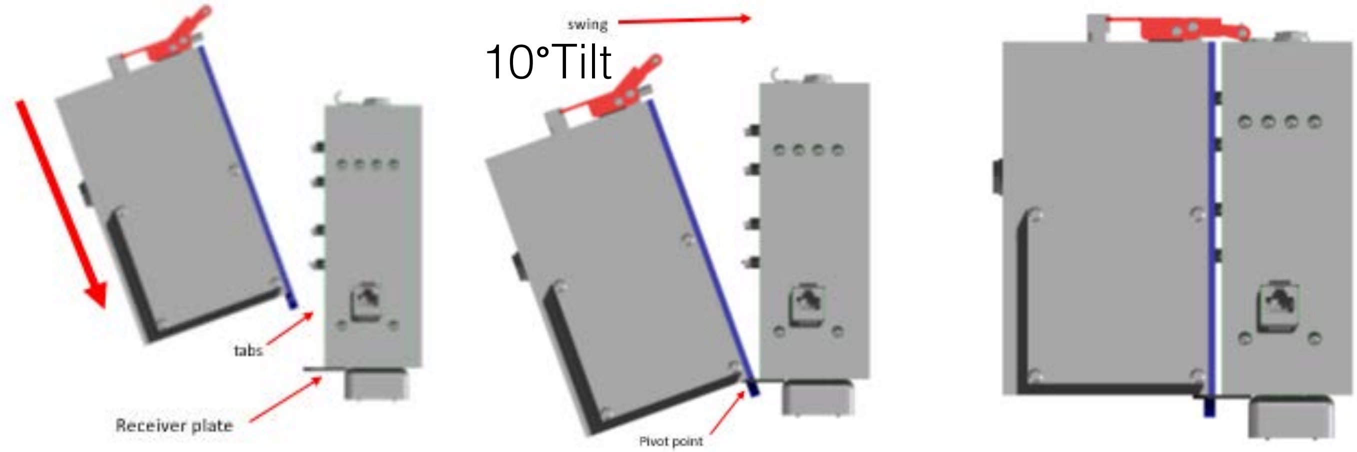


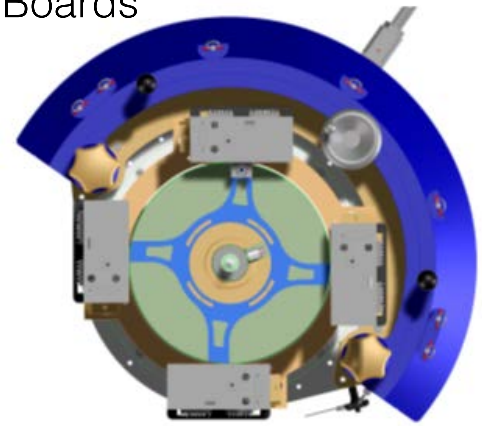
DM to DIB models and prototypes complete



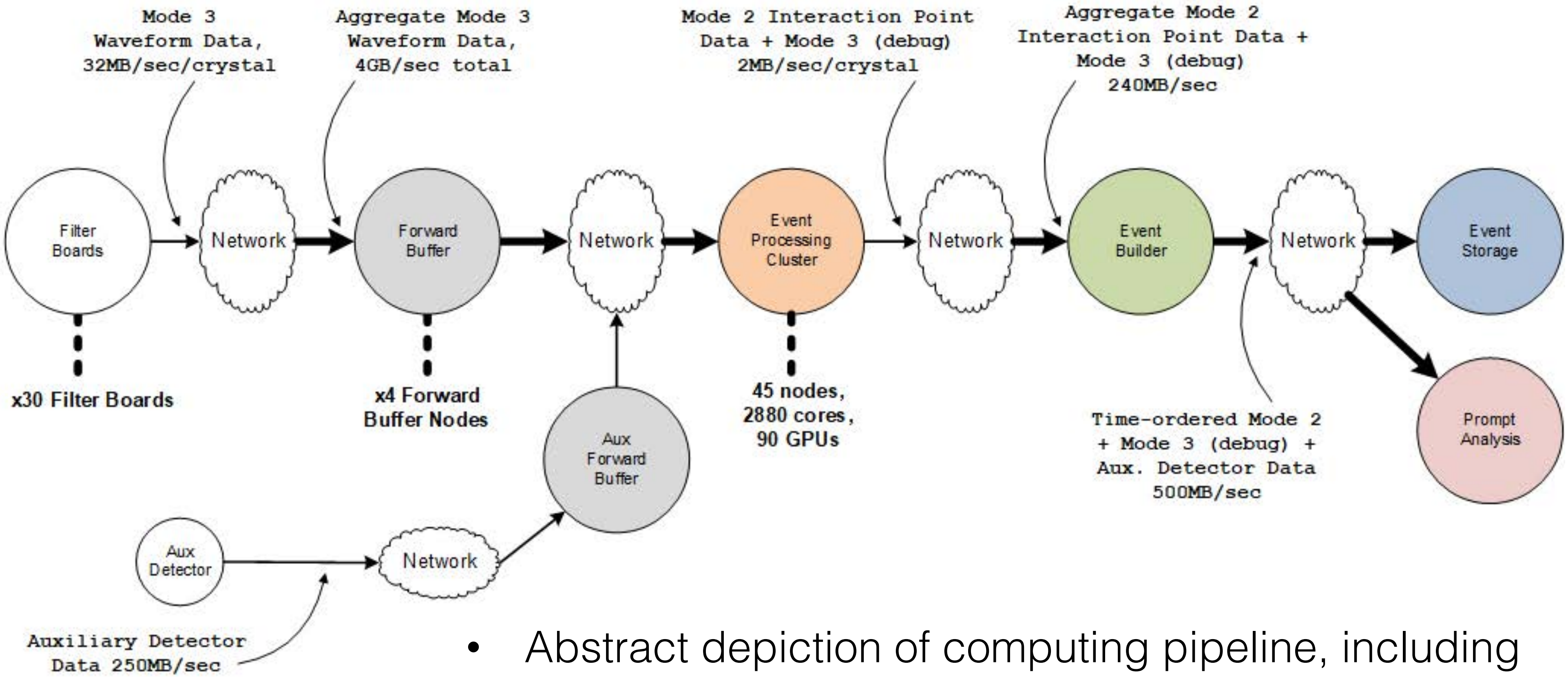


Digitizer Module Assembly - Internal Boards



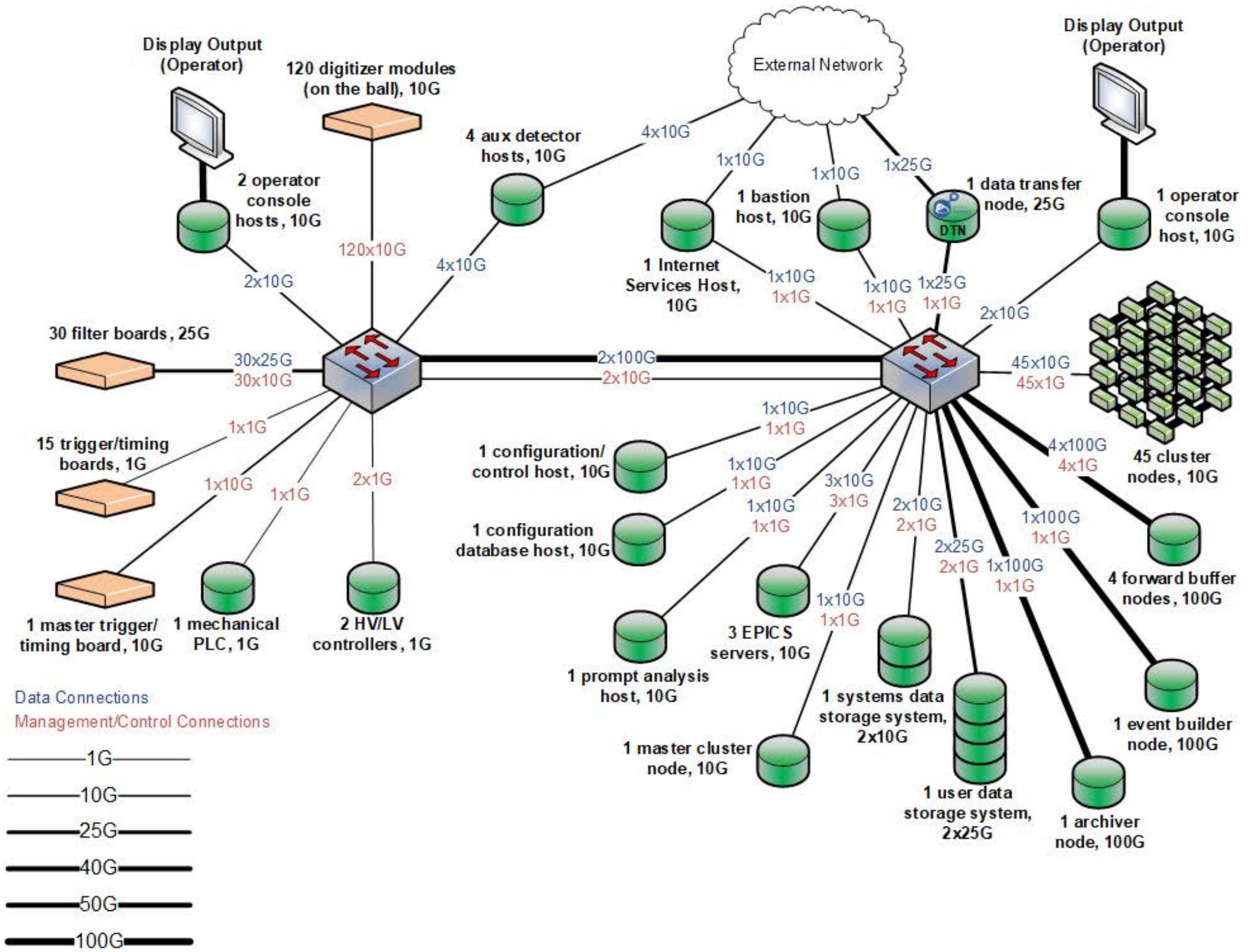


GRETA Computing Pipeline



- Abstract depiction of computing pipeline, including device counts and data rates
- Computing pipeline serves as a platform for data processing, from detector electronics on the left to visualization and storage on the right

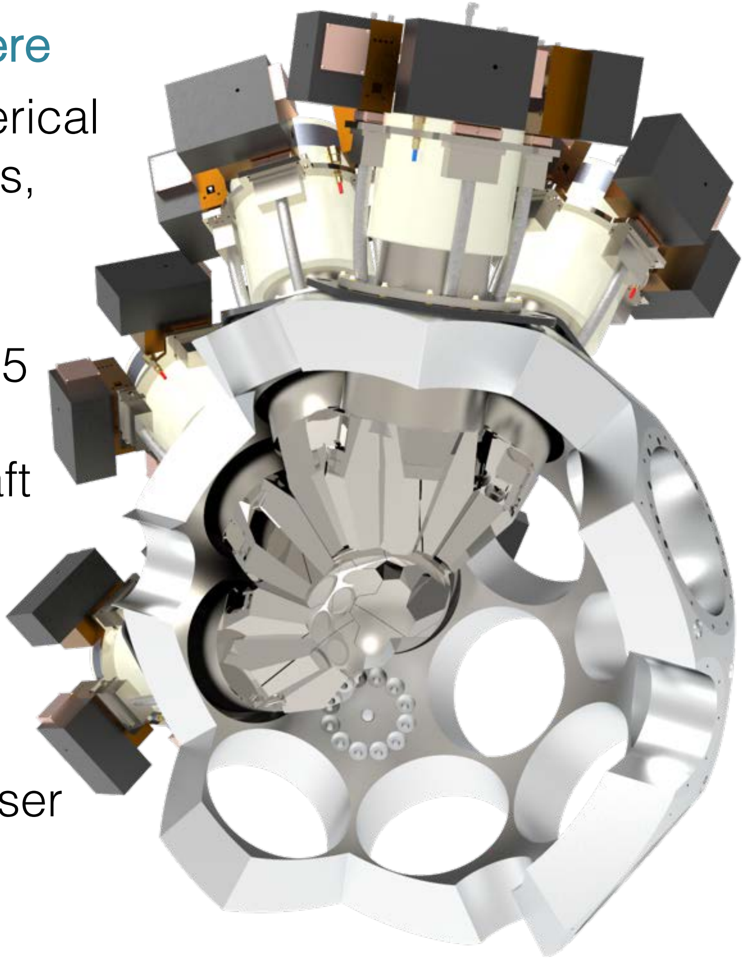
GRETA Network Diagram



Detector Array Sphere & Support Structure

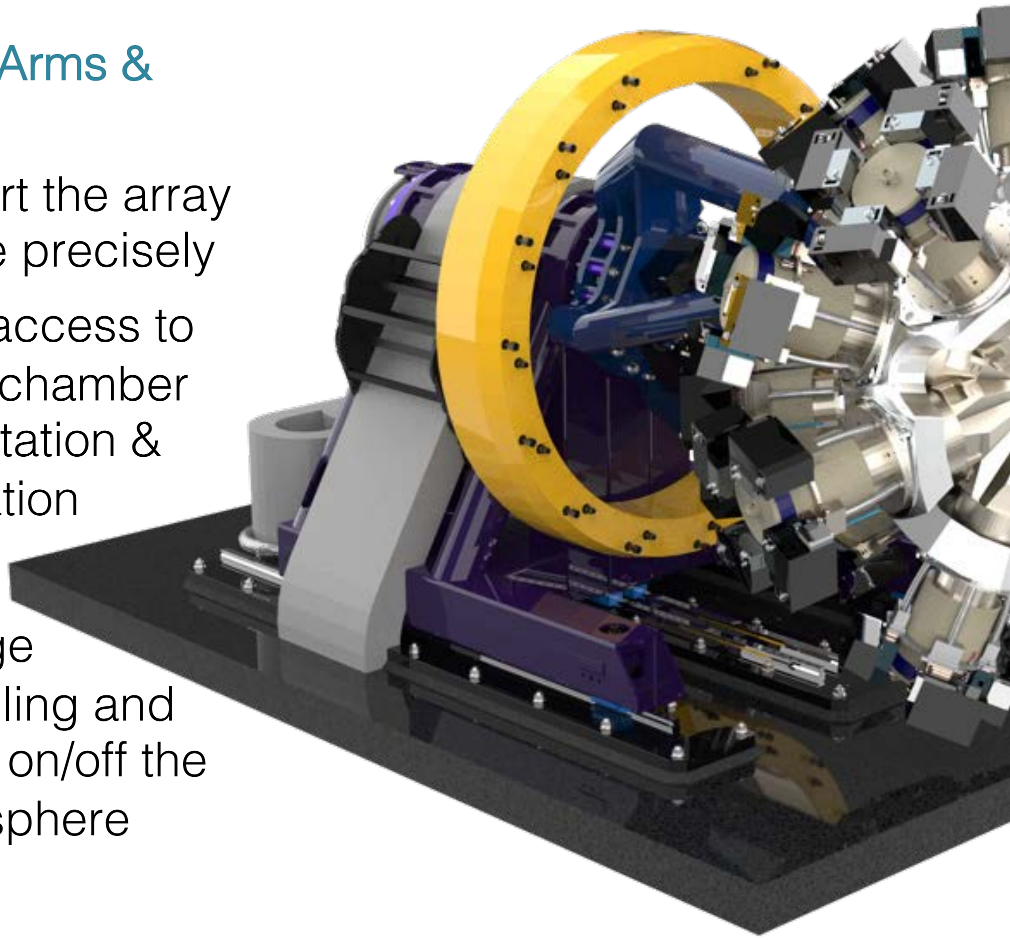
Detector Array Sphere

- Two 2π hemispherical support structures, **very similar to GRETINA**
- Ability to remove 5 Quad Module locations fore & aft along beam axis
- Quads mounted with electrical isolation
- Alignment with laser fiducials

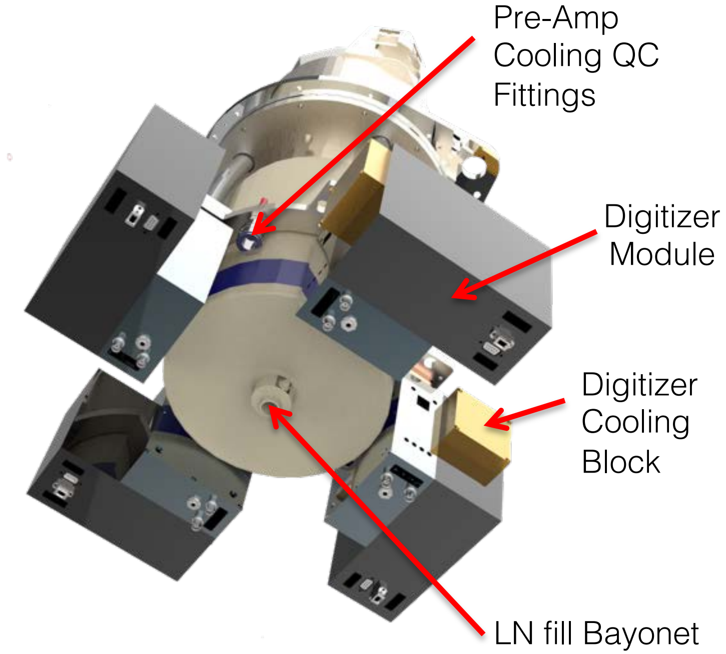


Detector Arms & Frame

- Support the array sphere precisely
- Allow access to target chamber with rotation & translation
- Manage all cabling and piping on/off the array sphere



Cooling Systems & Controls Systems

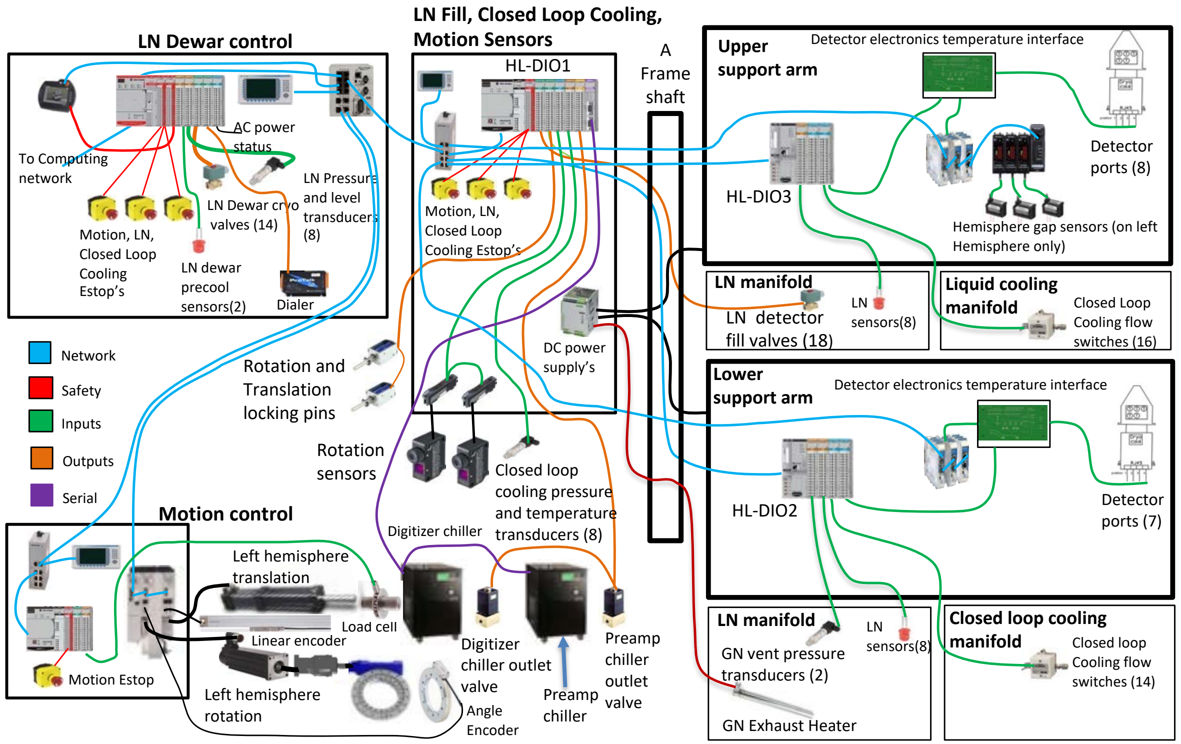


Cooling Systems

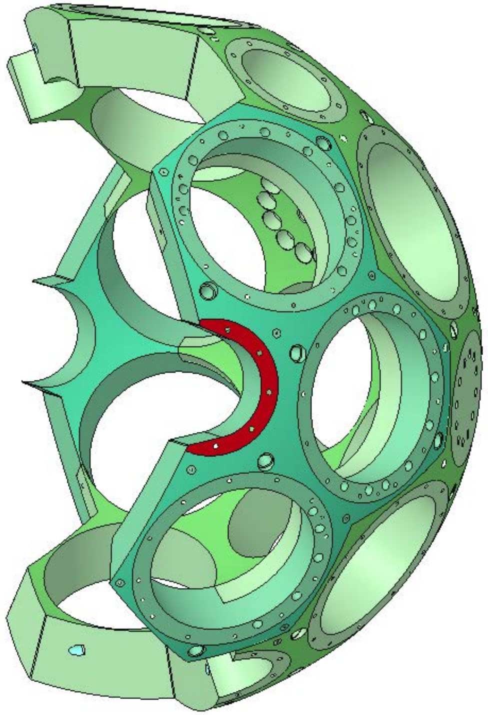
- Automated LN distribution via two large manifolds distributes to all 30 Quad modules
- Two independent closed-loop cooling systems hold Quad module preamplifiers and Digitizer modules at stable temperature points

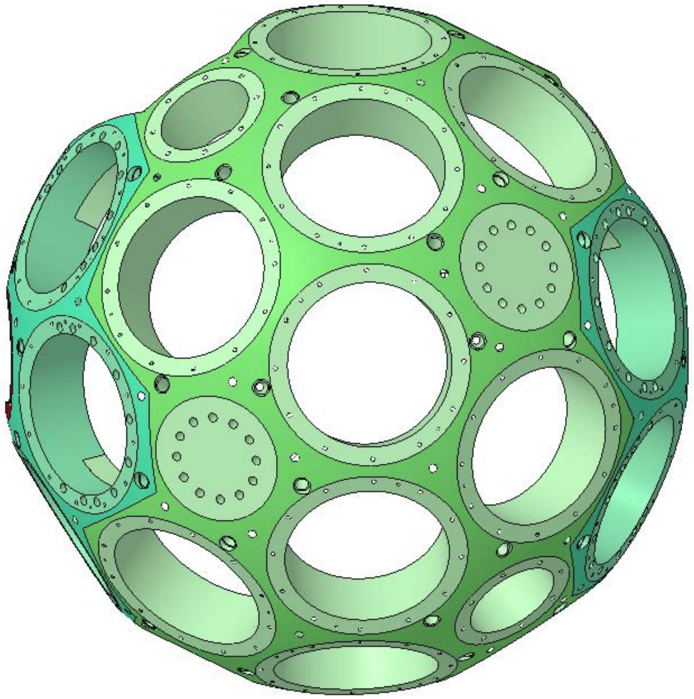
PLC-Based Controls Systems

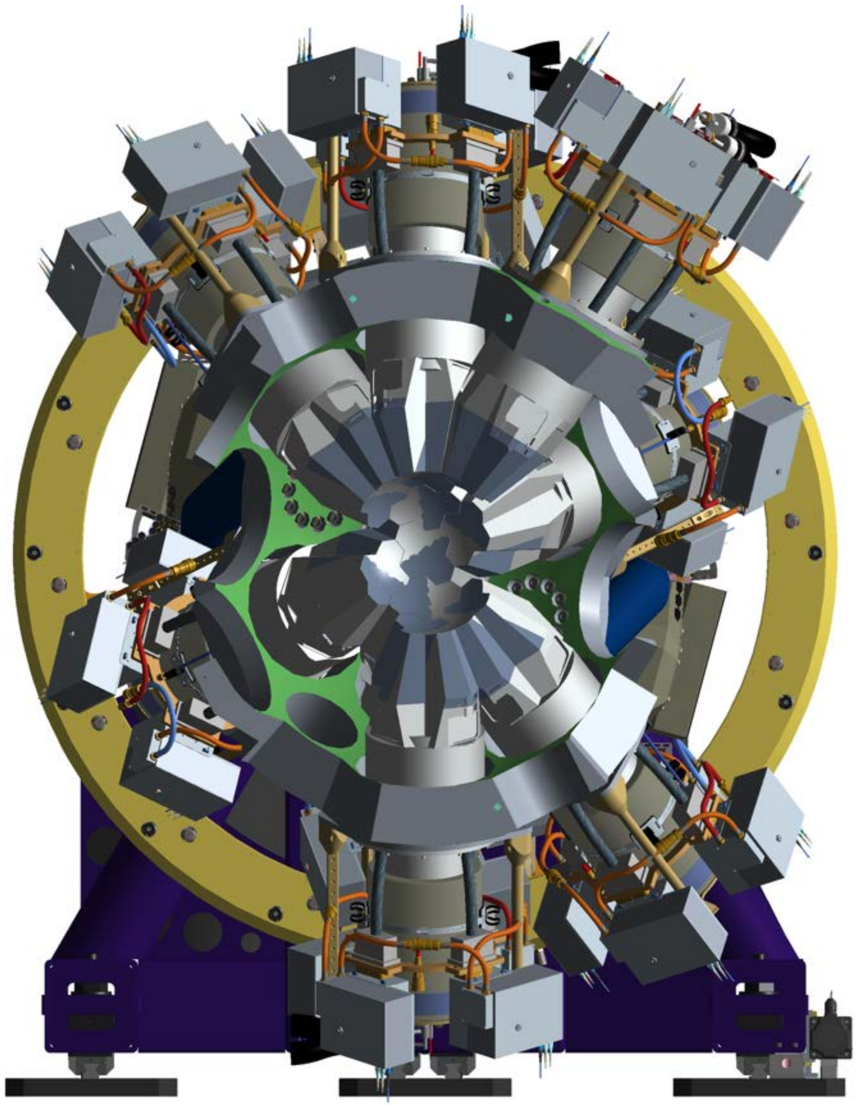
- 4-axis motion controls (rotation + translation for each hemisphere)
- LN and closed loop cooling controls
- Safety systems with warning indicators, E-stops



Removing the Forward or Aft Ring of Quad Modules

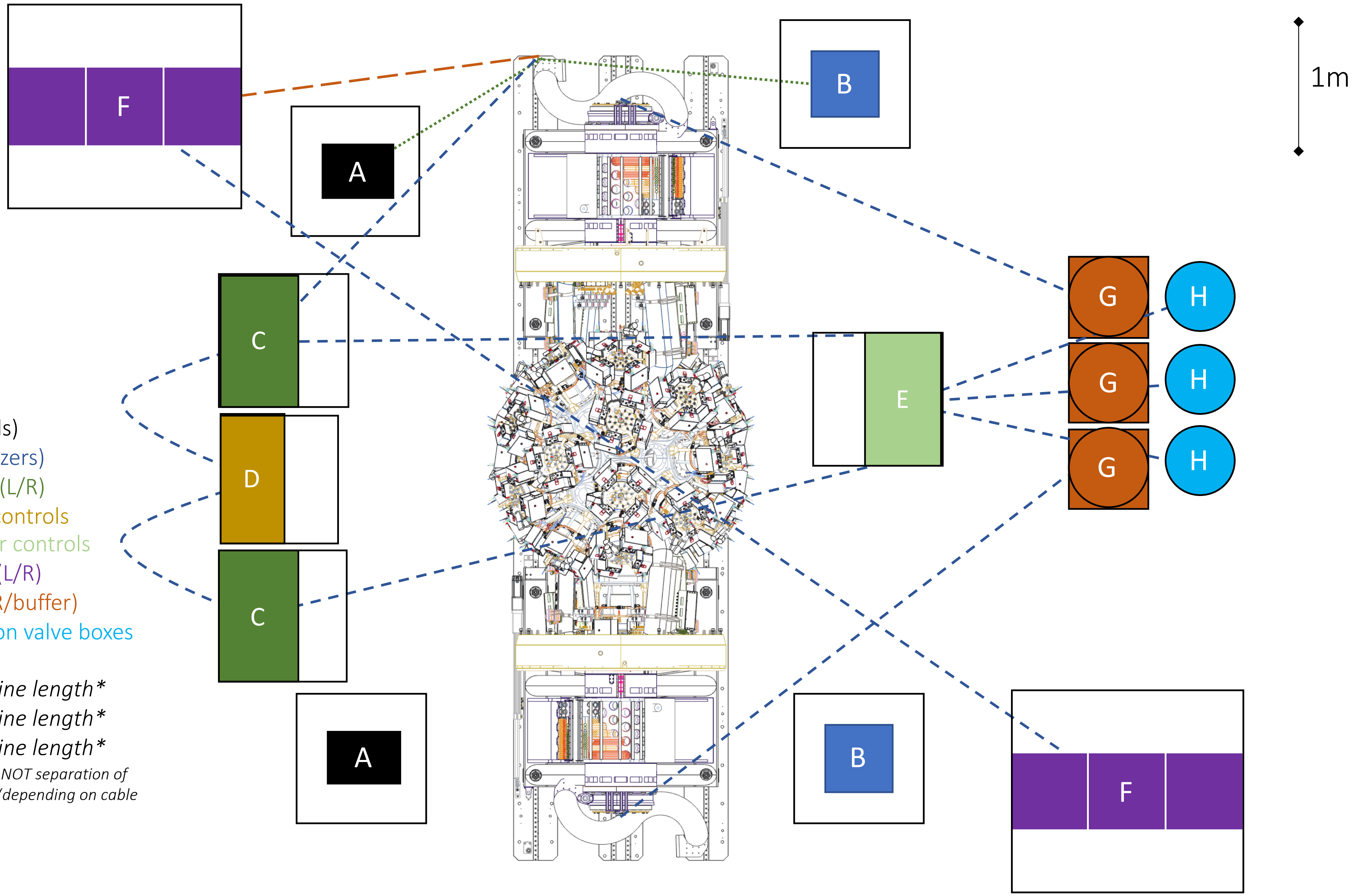






- GRETA frame offers the flexibility to remove the forward and/or aft rings of 5 Quad modules
- The width of the array along the beam direction is narrowed (from ~2.4 to 1.8m)
- Also opens space available for larger auxiliary detector systems

The Full GRETA Footprint



A. Chiller (Quads)
B. Chiller (Digitizers)
C. PLC controls (L/R)
D. PLC motion controls
E. PLC LN dewar controls
F. ES/CS Racks (L/R)
G. LN Tanks (L/R/buffer)
H. LN distribution valve boxes

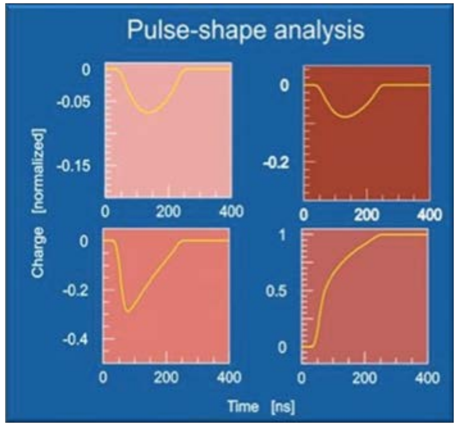
*50m max. line length**
*30m max. line length**
*15m max. line length**

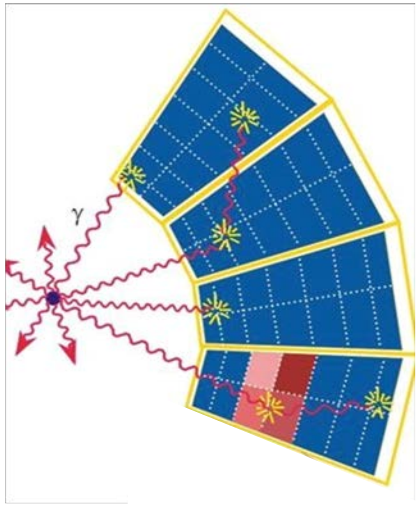
**length of cables/hoses, NOT separation of components necessarily (depending on cable routing path)*

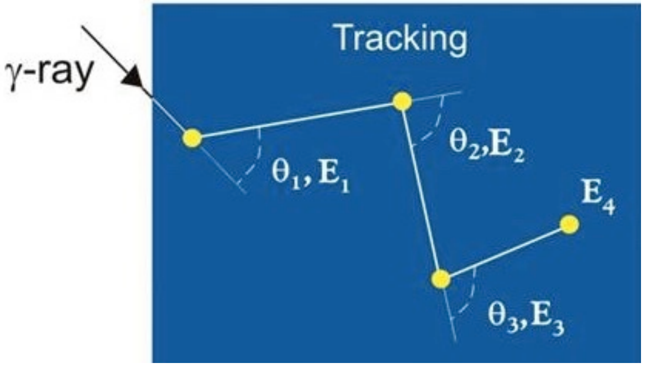
Questions?

GRETA concept for a shell of closely packed Ge crystals

- Combines highly segmented, hyper-pure germanium crystals with advanced digital signal processing techniques
- Identify the position and energy of γ-ray interaction points within a compact “shell” of detectors
- Track γ-ray path both within and between detector elements, using the angle-energy relation of the Compton scattering process



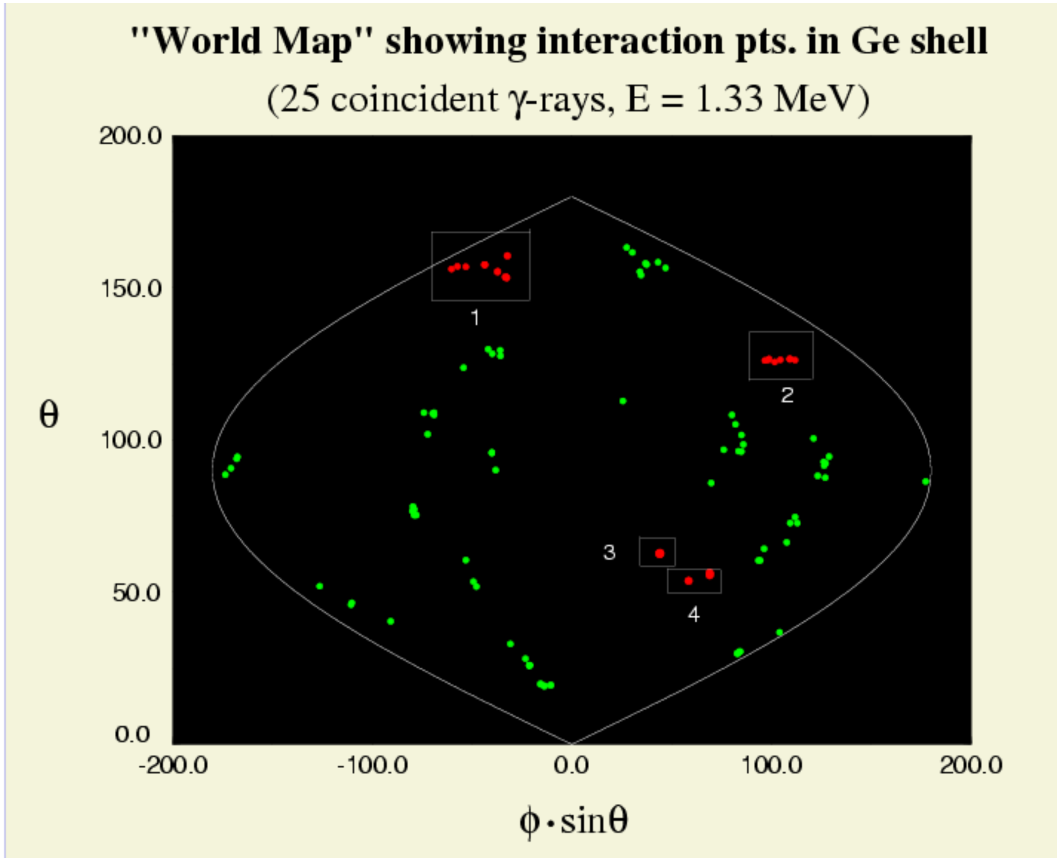


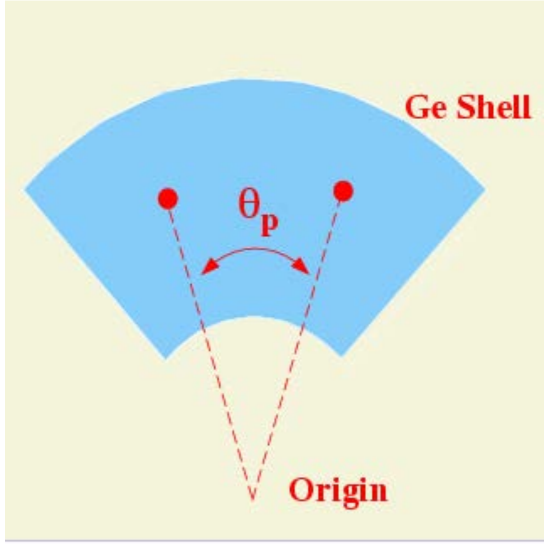


Maximizes and Optimizes

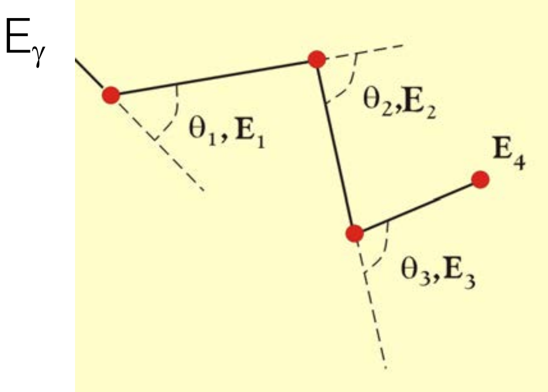
- Efficiency, Energy Resolution, Peak-to-Total

First step in tracking is to find clusters of interaction points which likely belong to a single γ-ray scattering in the detector – based on opening angle into the Ge shell





Any two points with $\theta < \theta p$ are grouped into the same cluster

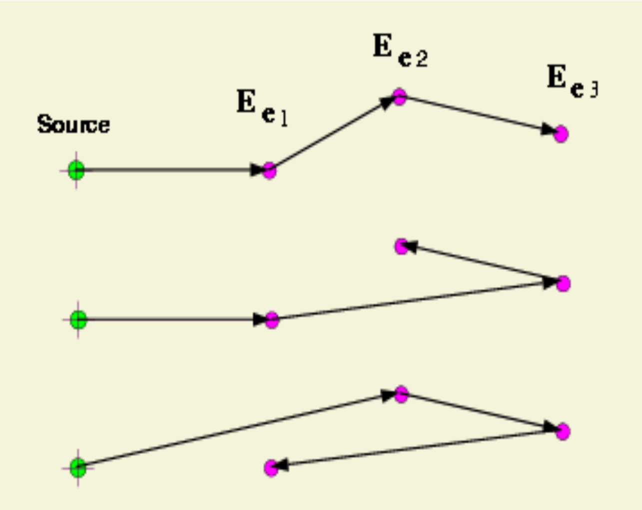


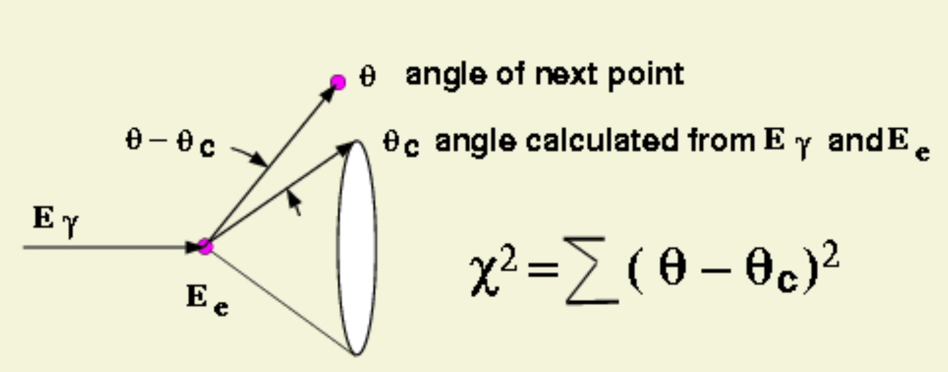
$$E_e = E_\gamma \left(1 - \frac{1}{1 + \frac{E_\gamma}{0.511}(1-\cos\theta)} \right)$$

Problem: 3!=6 possible sequences

Assume:

- $E_g = E_{e1} + E_{e2} + E_{e3}$
- γ-ray from the source





Sequence with the minimum $\chi^2 < \chi^2_{max}$

→ correct scattering sequence

→ rejects Compton and wrong direction

…Low-energy single interaction point γ-rays don't track