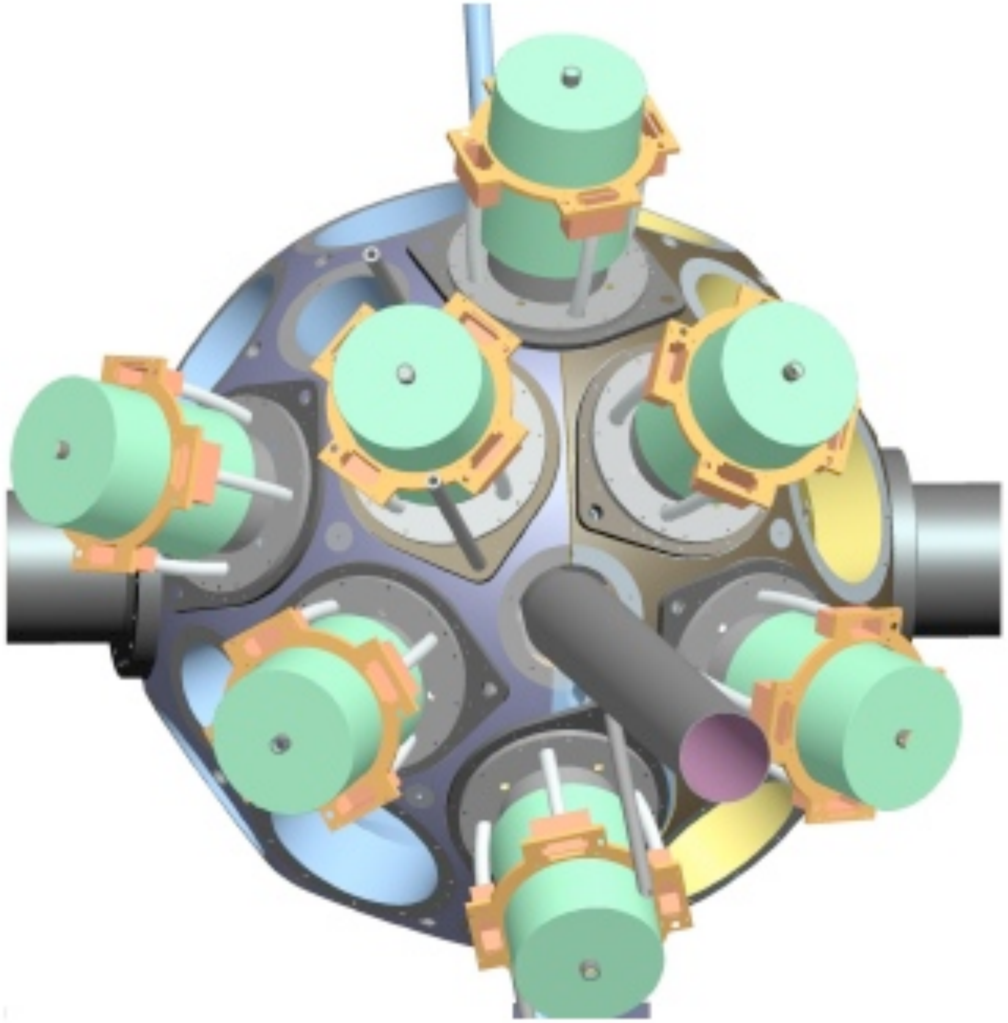
Gamma Ray Spectroscopy



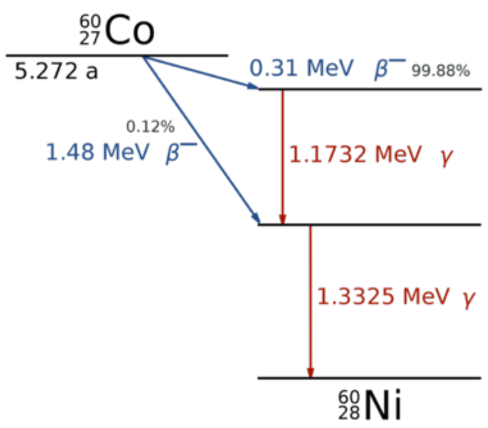
Mario Cromaz, LBNL

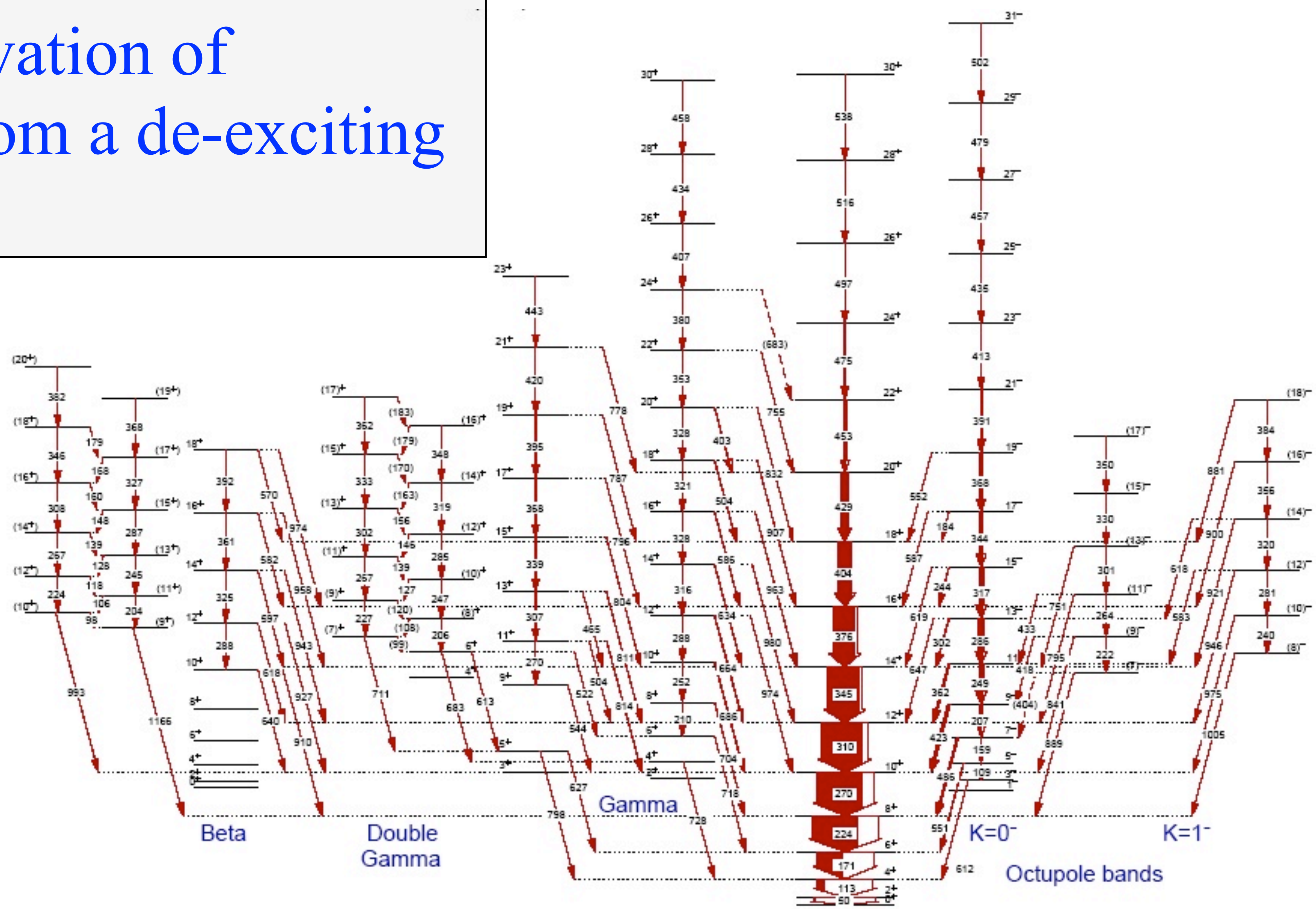
Outline

- basics
- a bit of history, motivation
- gamma-ray tracking spectrometers
  - they're new! just operational in last 2 years
  - large-scale, general purpose devices
  - GRETINA (US), AGATA (Europe)
- practicalities
- summary

The Basic Experimental Idea

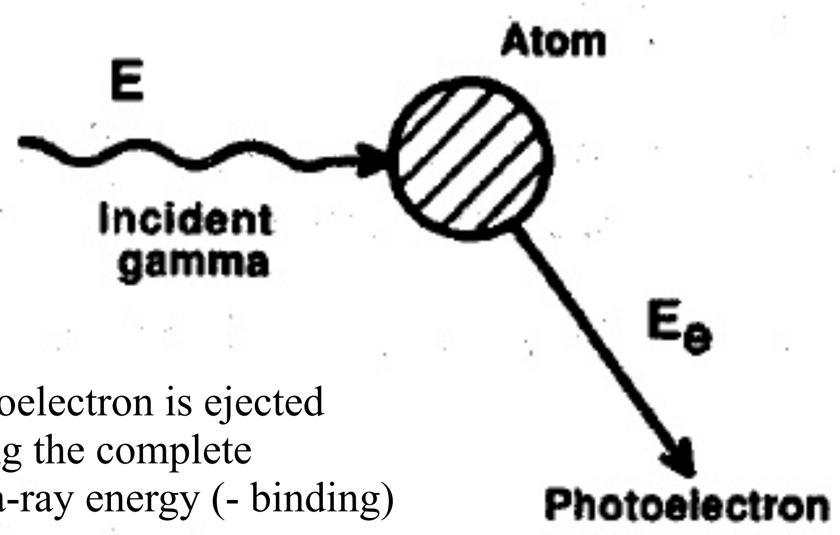
infer nuclear level schemes from the observation of gamma-rays from a de-exciting nucleus





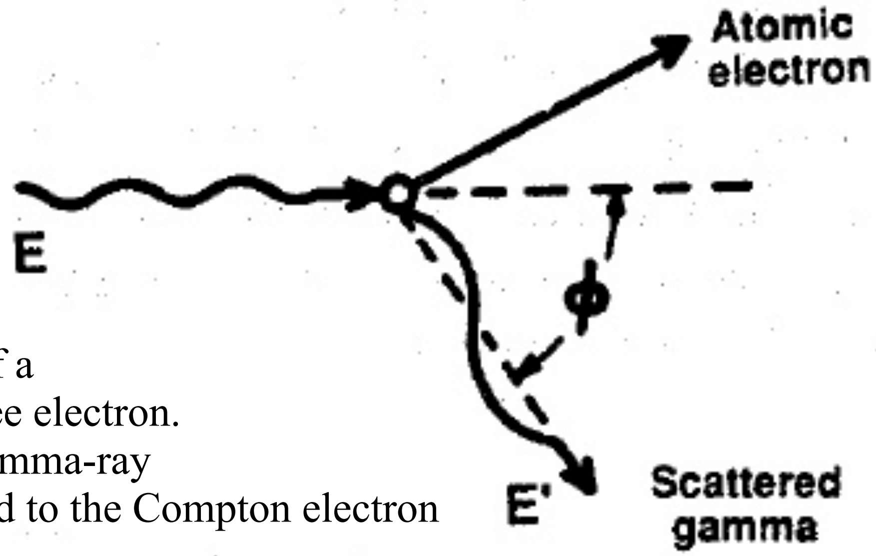
Interaction of Gamma-Rays

Photo effect



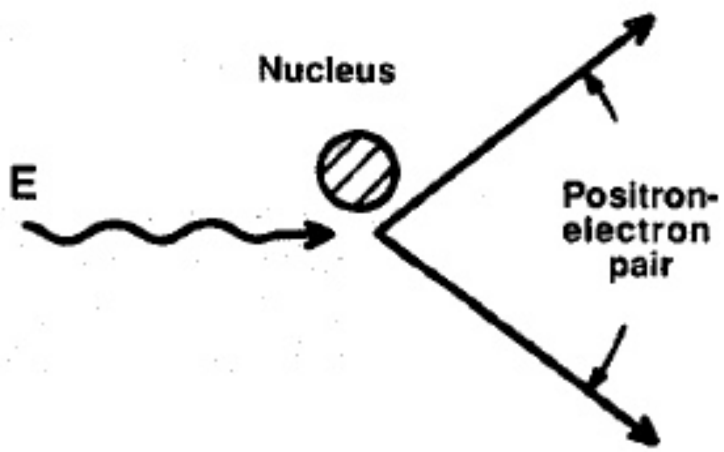
A photoelectron is ejected carrying the complete gamma-ray energy (- binding)

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

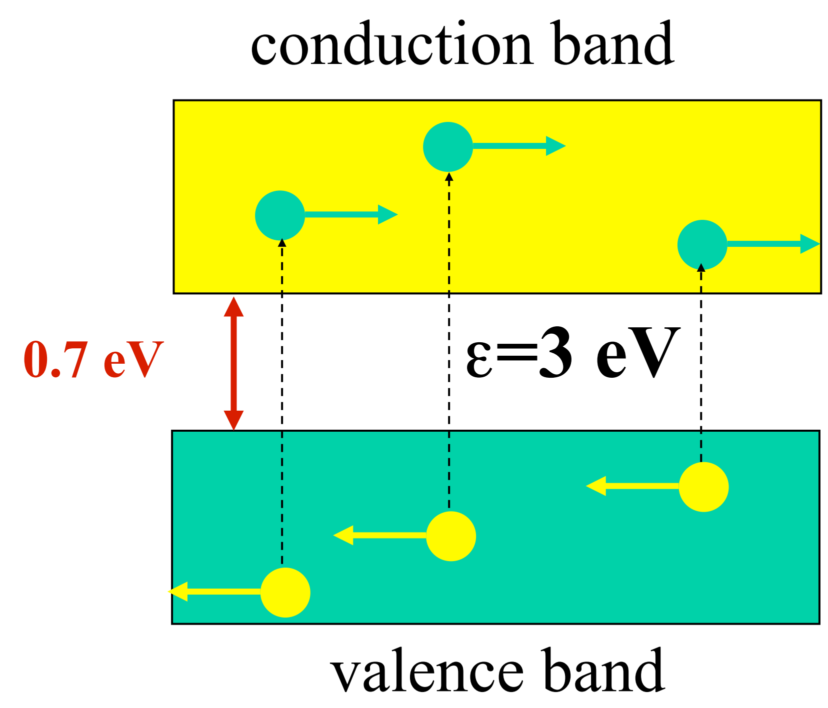
Pair production

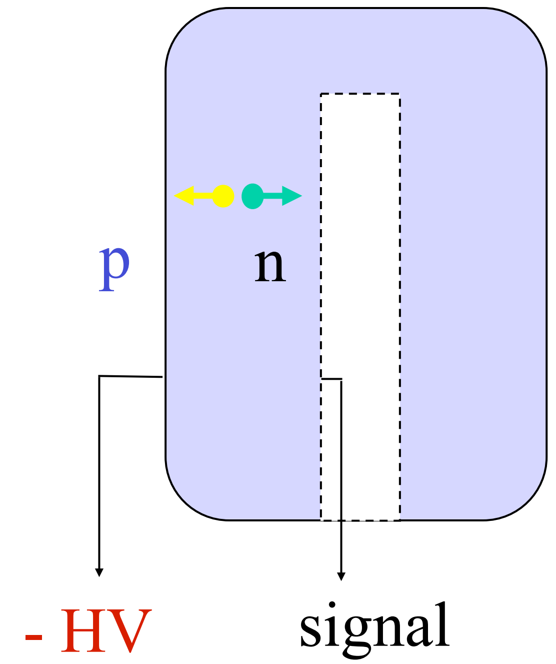


If gamma-ray energy is >> 2 m_oc^2 (electron rest mass 511 keV), a positron-electron can be formed in the strong Coulomb field of a nucleus. This pair carries the gamma-ray energy minus 2 m_oc^2 .

Ge Detectors

- high-purity Ge crystal operated as a reverse-biased diode
- **excellent** energy resolution due to small bandgap:
  - large number of charge carriers
  - low statistical fluctuations
  - high energy resolution (2 keV @ 1 MeV)
- but ...
  - expensive
  - Z=32 (medium stopping power), medium volume
  - requires cryogenics





Ge Detector Performance

1. energy resolution
2. efficiency
3. peak/total

excellent!

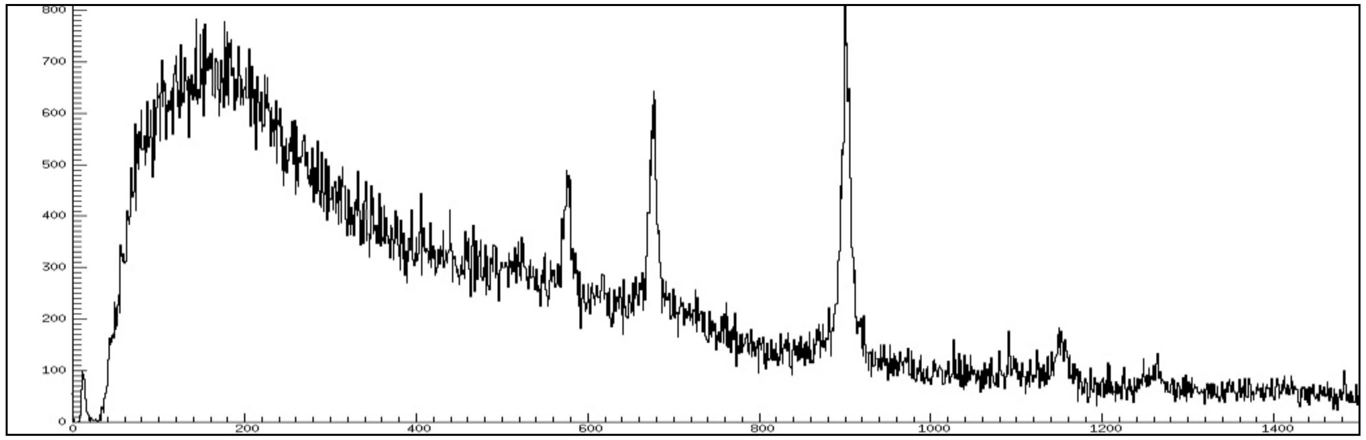
- low-to-moderate (dependent on crystal size, position)
- addressed by constructing detector arrays with singles efficiency Nε

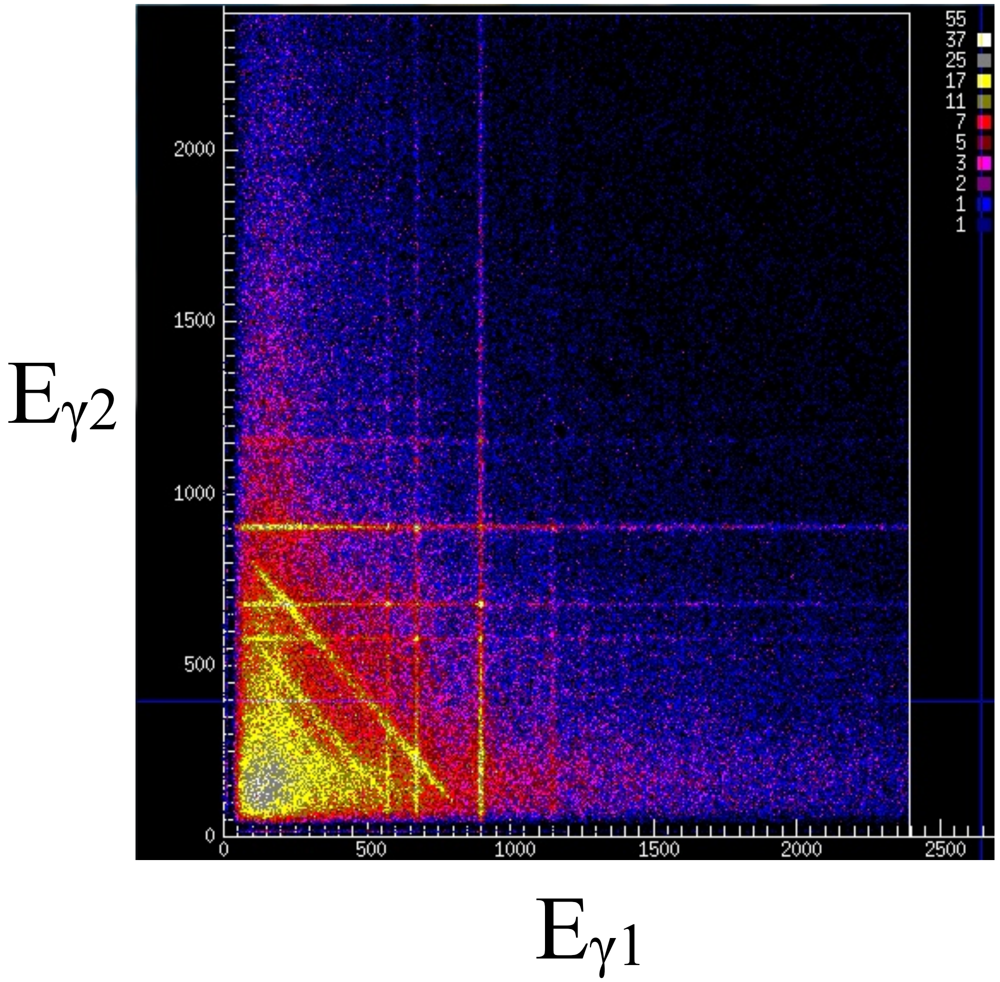
- low
- statistical fluctuations in background limit sensitivity to weak branches
- Compton scattering of γ-ray results in partial energy deposition

consider also:
- average level spacing
- gamma-ray multiplicity

Background

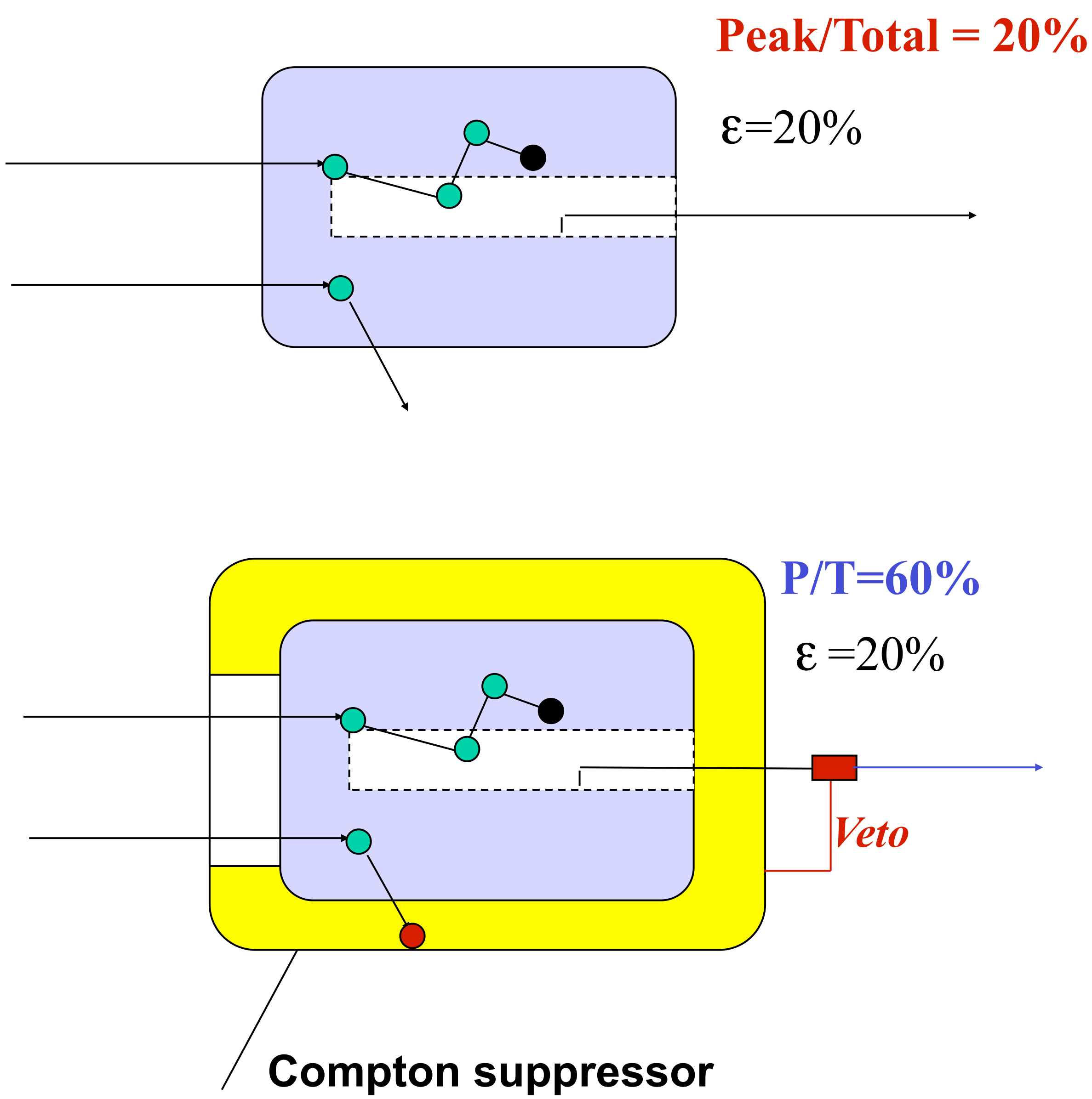
- several potential sources:
  - contaminant reactions
  - neutrons on Ge, Al, ...
  - decay products
  - room background
  - **Compton background**
- in Ge spectrometers the primary background is usually Compton background
- P/T ~ 0.2 for std. Ge detectors
- background is highly correlated

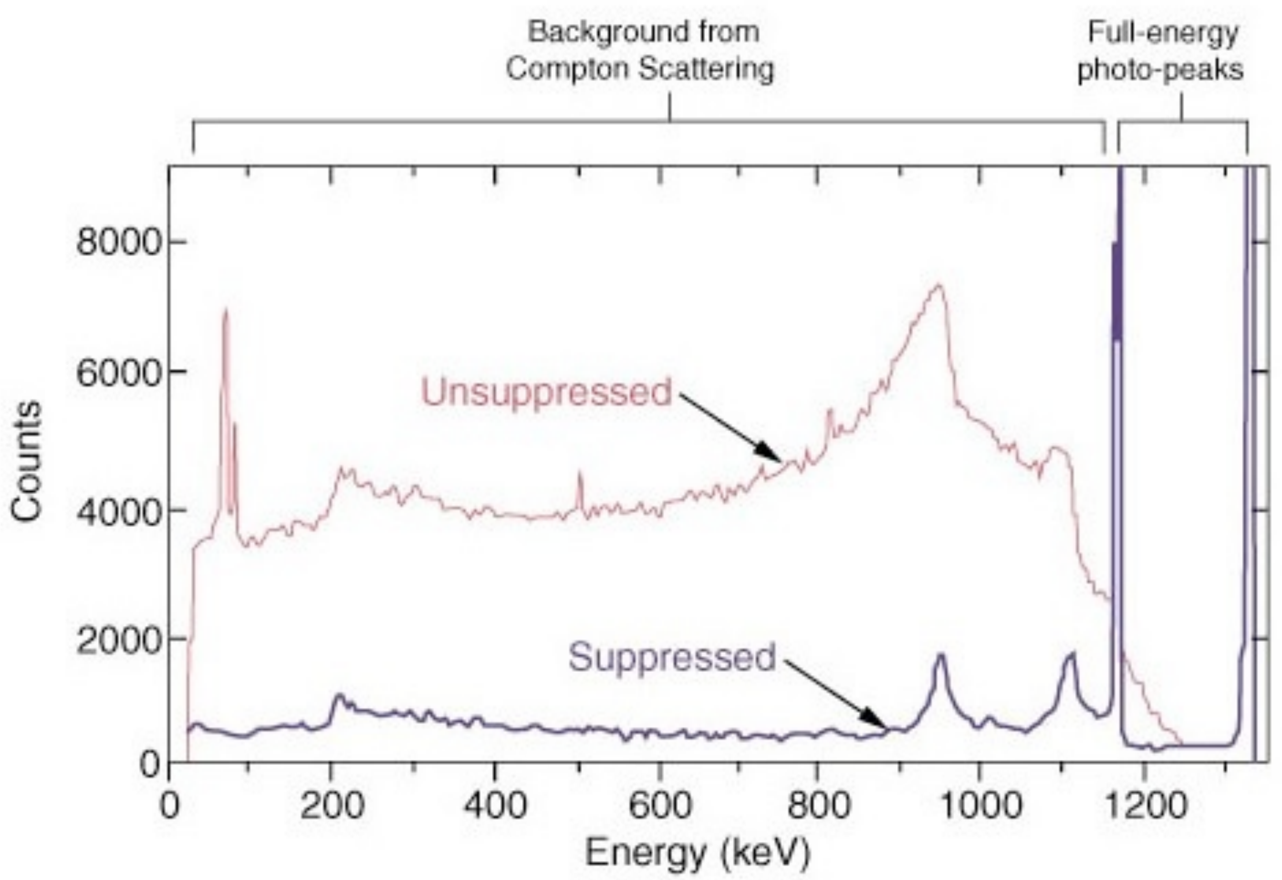




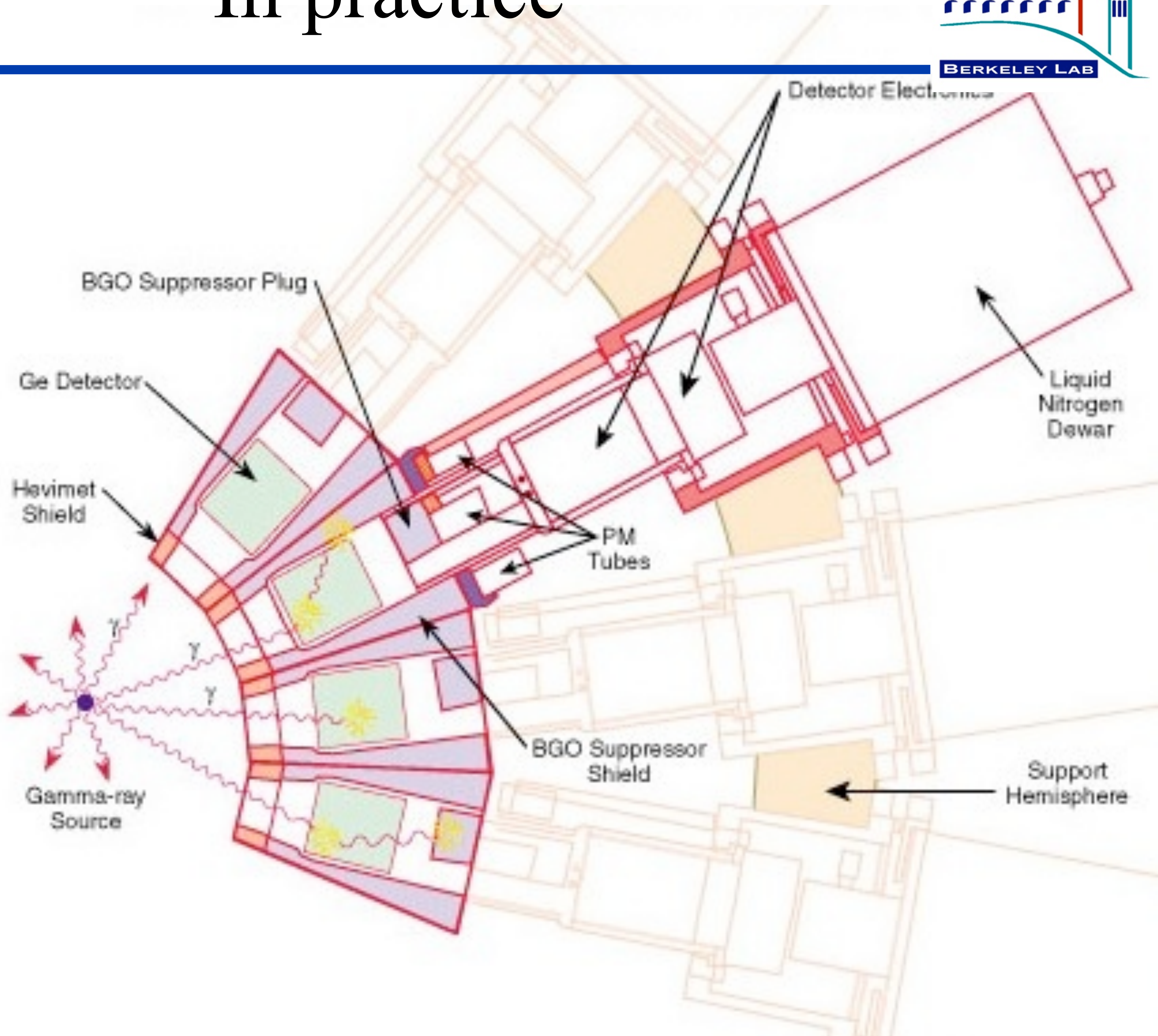
Gretina ^{64}Ge untracked - H. Crawford

Suppressors - Improving P/T





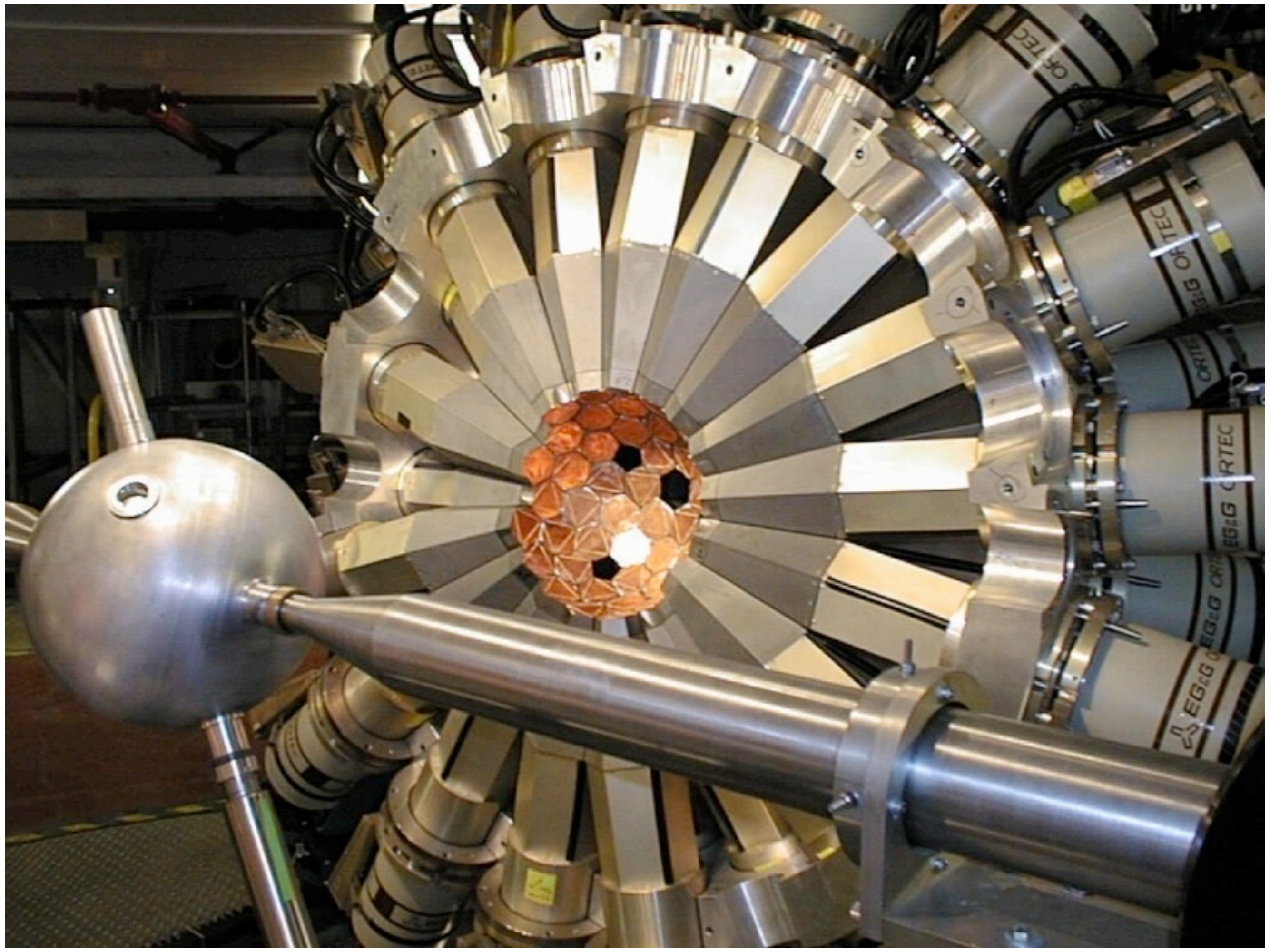
In practice



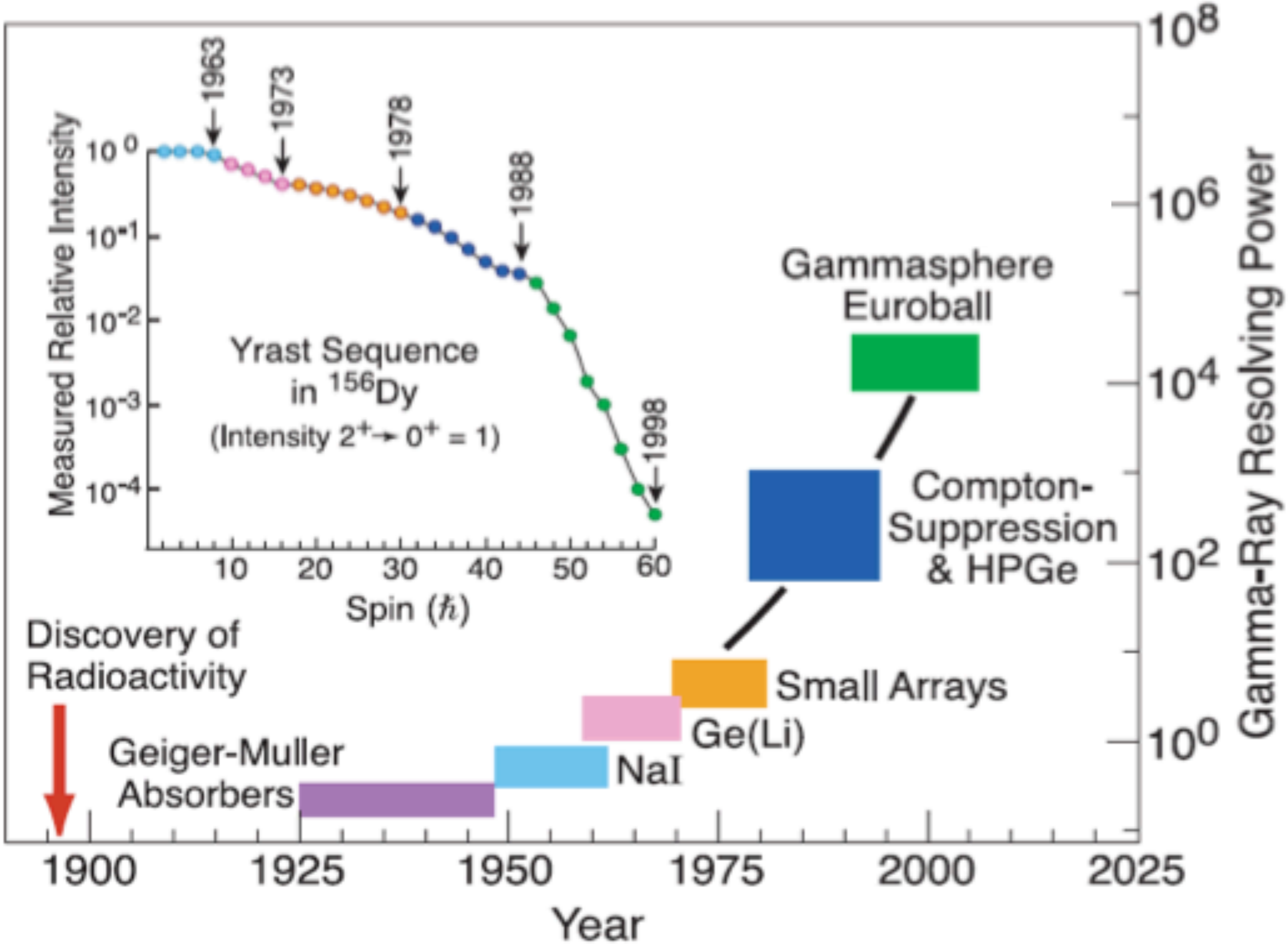
Detector Elect
BGO Suppressor Plug
Ge Detector
Hevimet Shield
γ
γ
γ
Gamma-ray Source
PM Tubes
Liquid Nitrogen Dewar
BGO Suppressor Shield
Support Hemisphere

Gammasphere

- 4π Compton-suppressed spectrometer:
  - 110 detectors (nominal)
  - ~10% efficiency @ 1MeV (prev. arrays ~ 1%)
- large number of detectors maintains efficiency while reducing summing
- high peak/total (60%) achieved by using Compton suppressors for each Ge detector
- solid angle coverage: 1/2 Ge, 1/2 BGO suppressor

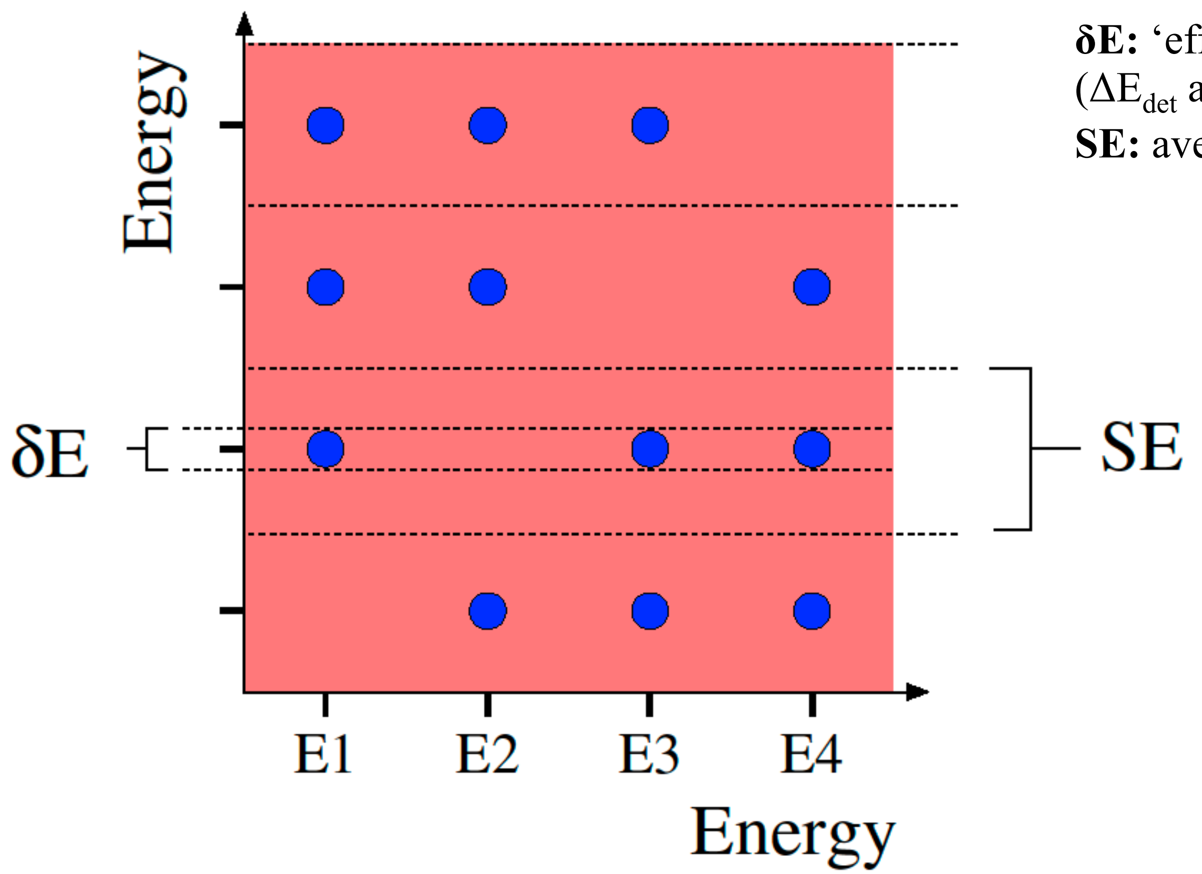


improvements in rp

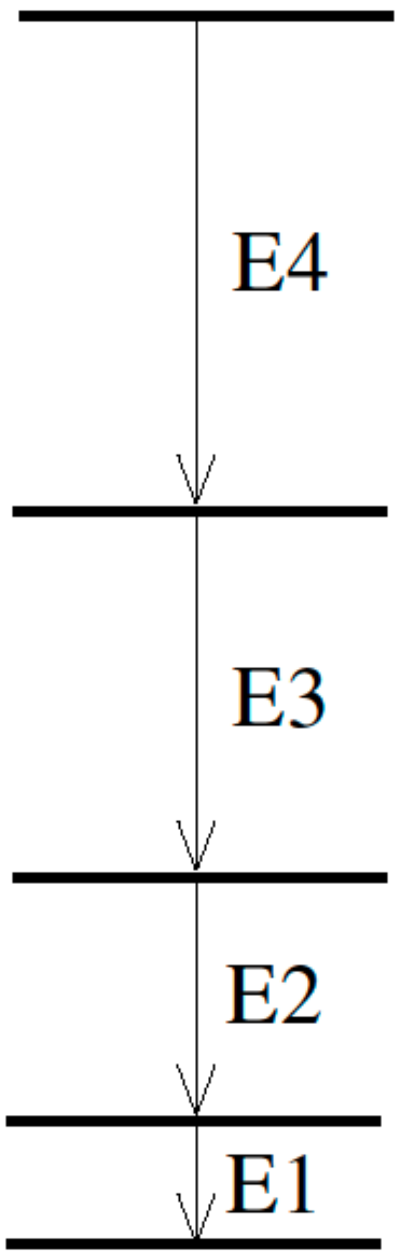


Coincidence Spectroscopy

…using F-fold coincidences (here 'matrix': F=2)



δE: 'effective' E-resolution (ΔE_{det} and $\Delta E_{Doppler}$)
SE: average energy spacing



→ E_x-E_y coincidences go into peak (blue)

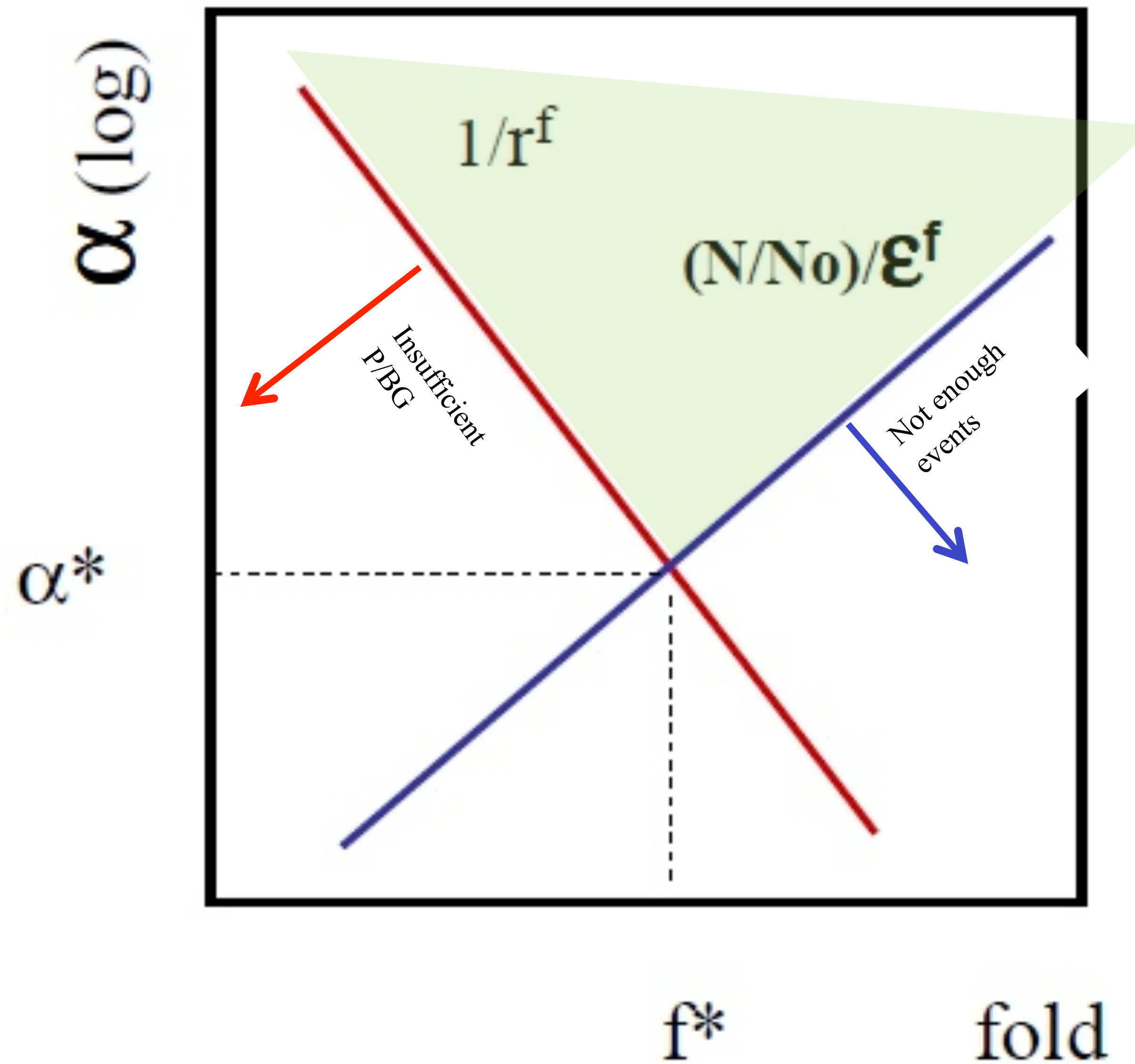
→ "everything else" spread over red area, as it isn't coincident with any E_x

Optimal Fold

- resolving power - weakest observable branch
- optimal fold - # of gates which minimizes background but retains sufficient counts in peaks
- 8pi, HERA ($\varepsilon \simeq 1\%$) - $f_{opt} = 2$
- Gammasphere ($\varepsilon \simeq 10\%$) - $f_{opt} = 3,4$

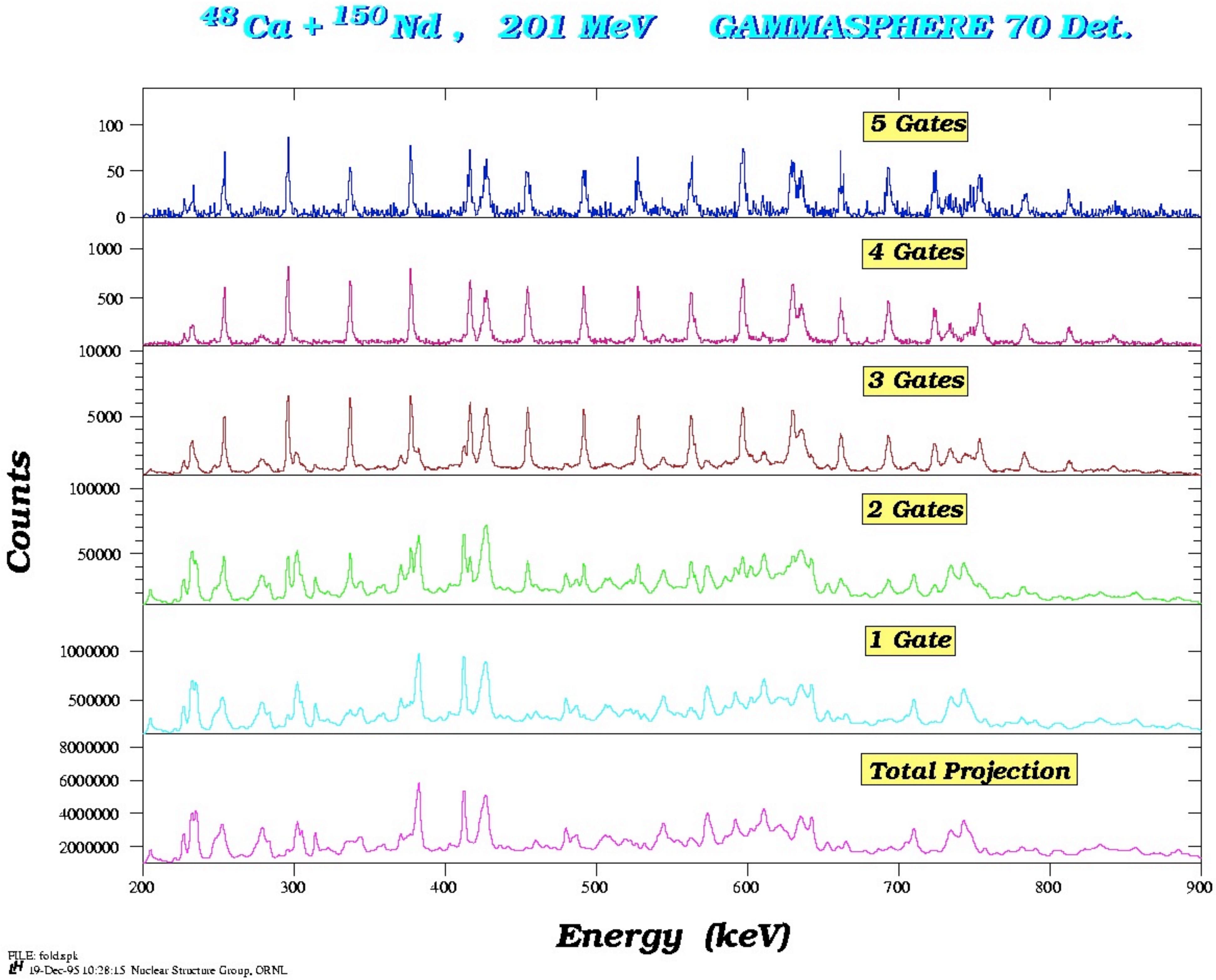
$$RP = 1/\alpha^* = r^{f^*}$$
$$r = 0.76(\Delta E/E_{res})(P/T)$$

Note: R>1, ε<1



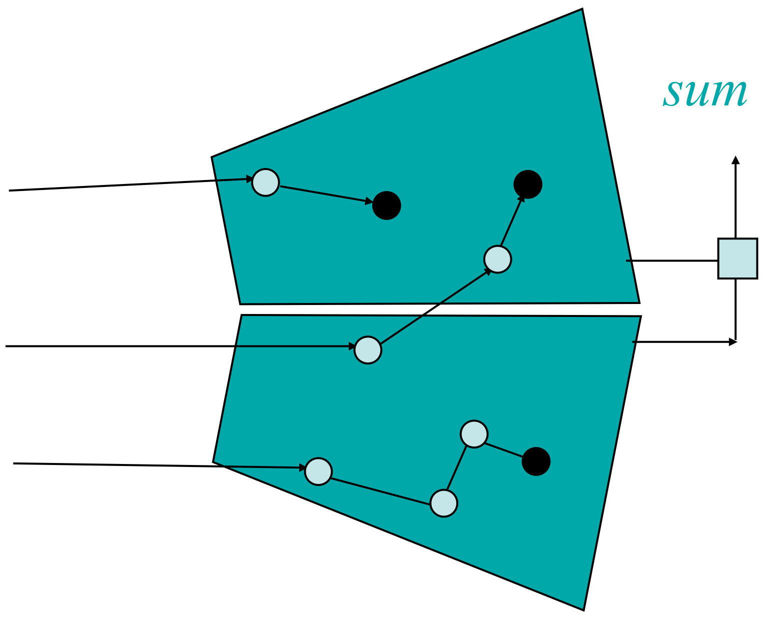
from A.O.Macchiavelli

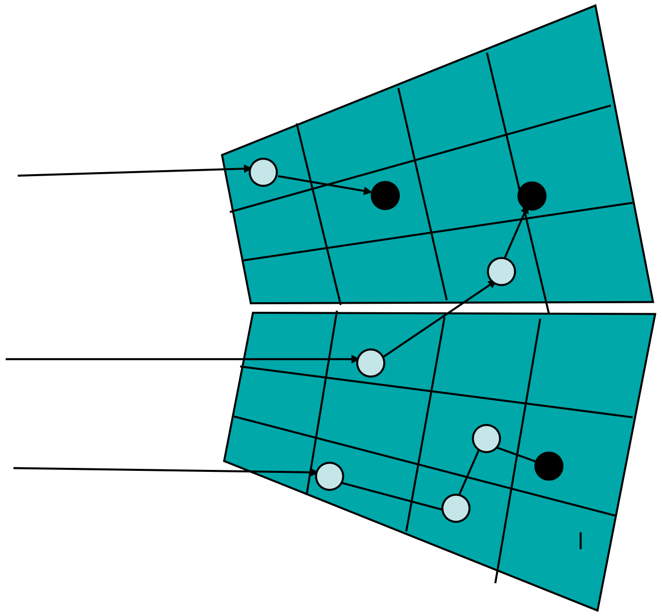
high-fold example



The Ge shell

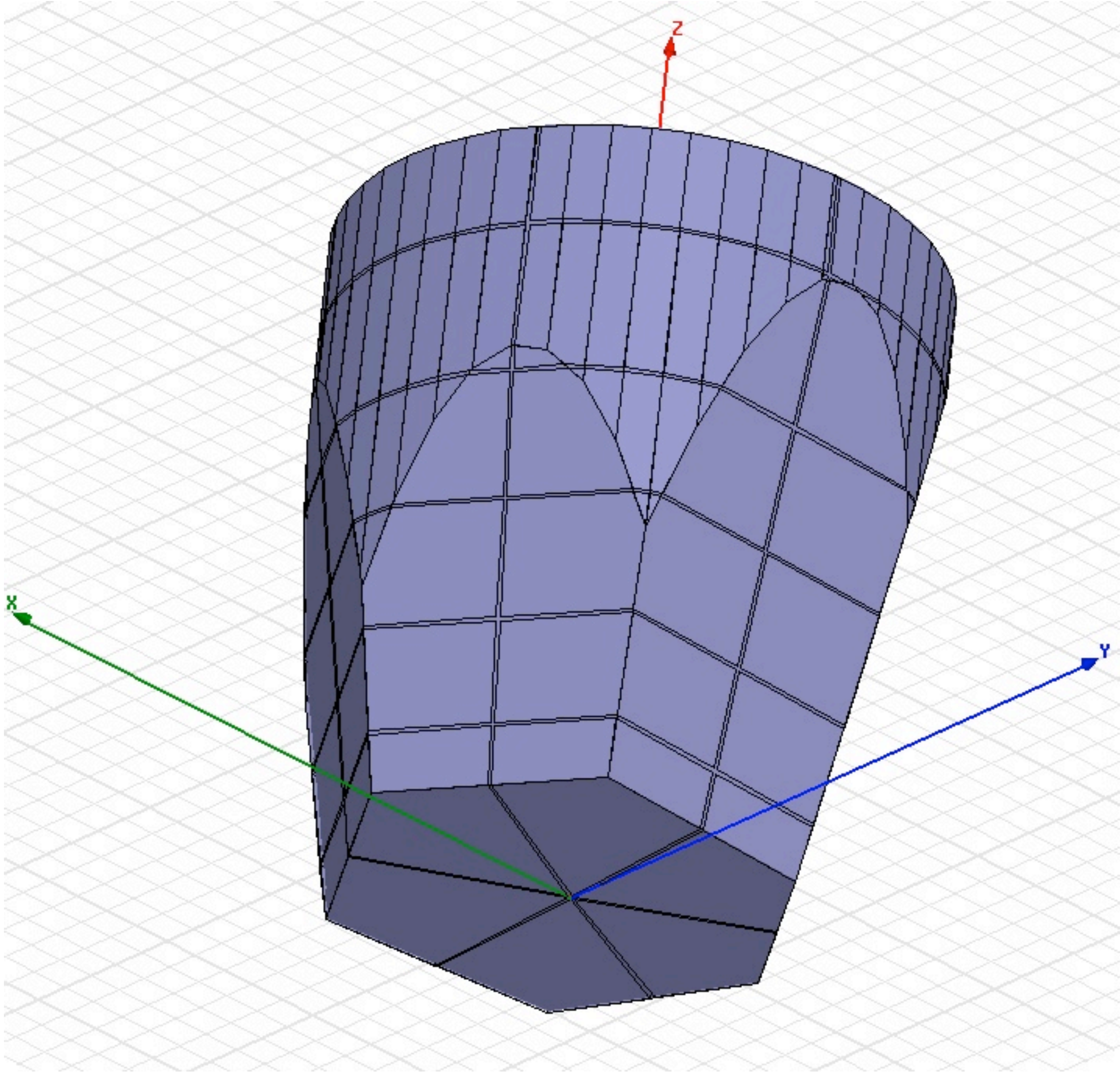
- Want more efficiency!
- BGO suppressors are effectively dead material from a spectroscopic point of view
- Why not tile a sphere with solid Ge? Break through 10% singles efficiency
- **problem - summing** gamma-ray scatters in multiple detectors - cannot recover energy
  - **sol'n 1**: many detectors (>1000)
  - **sol'n 2**: many "effective" detectors





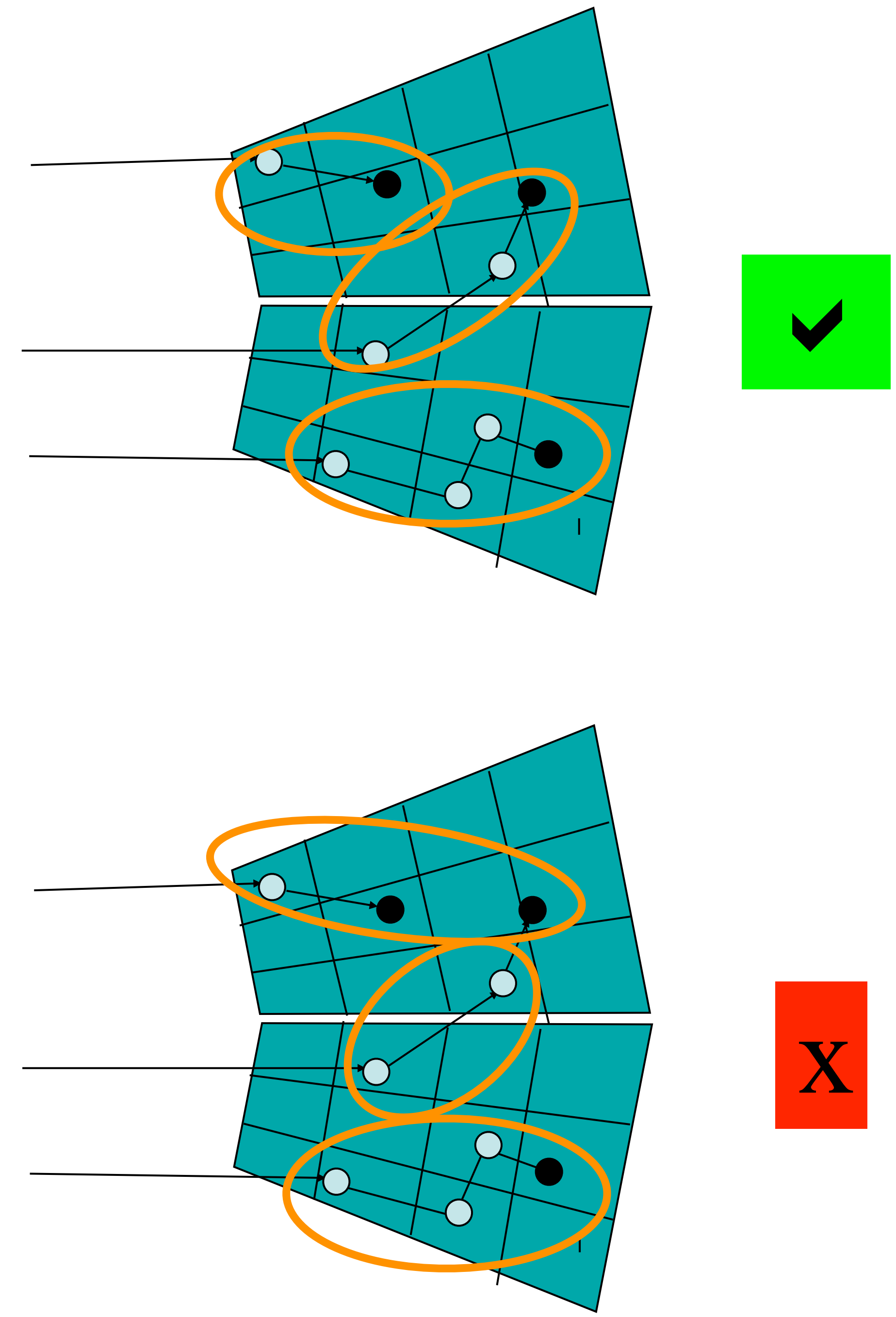
Segmented Coaxial Ge Detectors

- electrically segment outer contact of N-type Ge detector
- large HPGe crystal (9cm long, 8cm diameter)
- hit segment identified by presence of net charge
- each crystal is 36-way segmented, 6 longitudinal and 6 azimuthal segments
- for ~100 crystals → ~4000 "effective" detectors



but ...

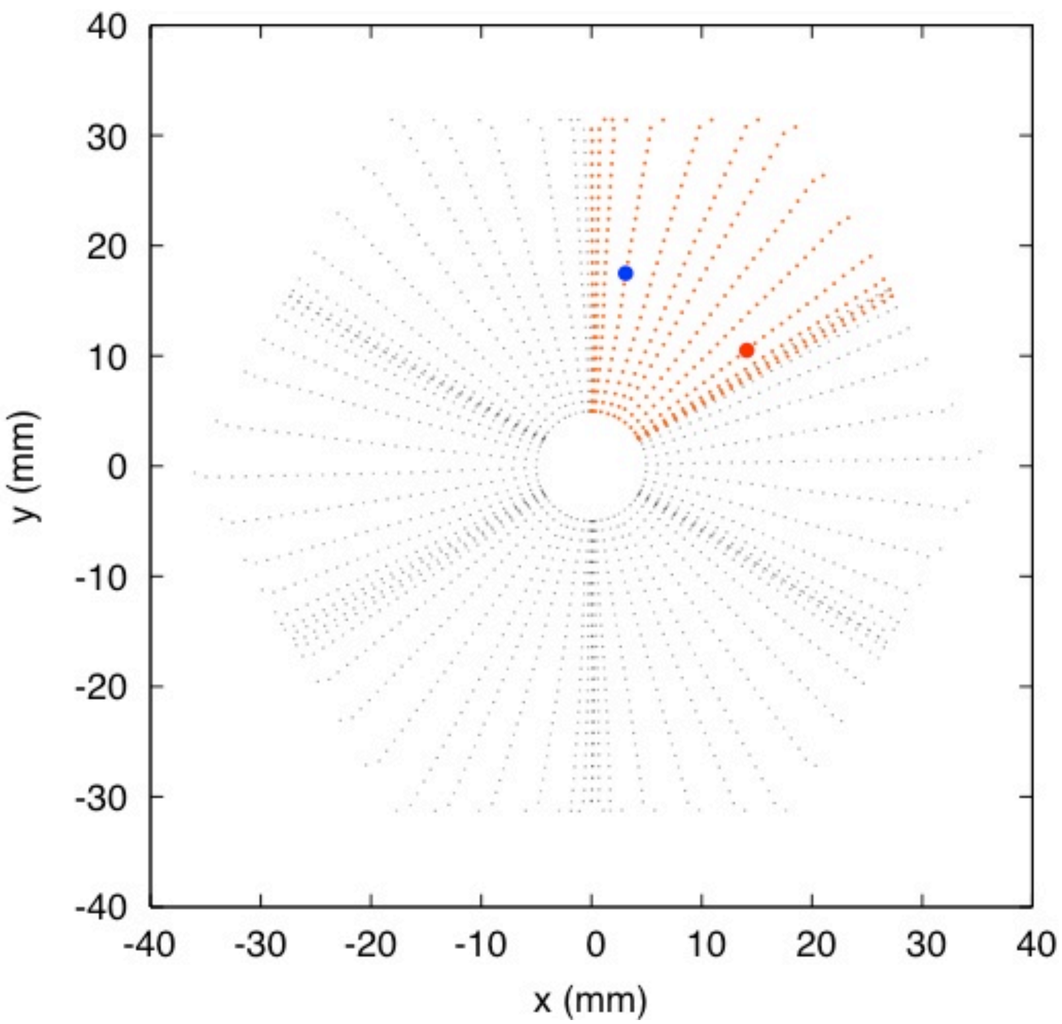
- these effective detectors are small (few cm^3)
- simple clustering not sufficient to assign hit segments to individual gamma-rays - recovered energies by summing not reliable
- need to additional components to make this work:
  - **Compton tracking**
  - **sub-segment position resolution of individual interaction points**

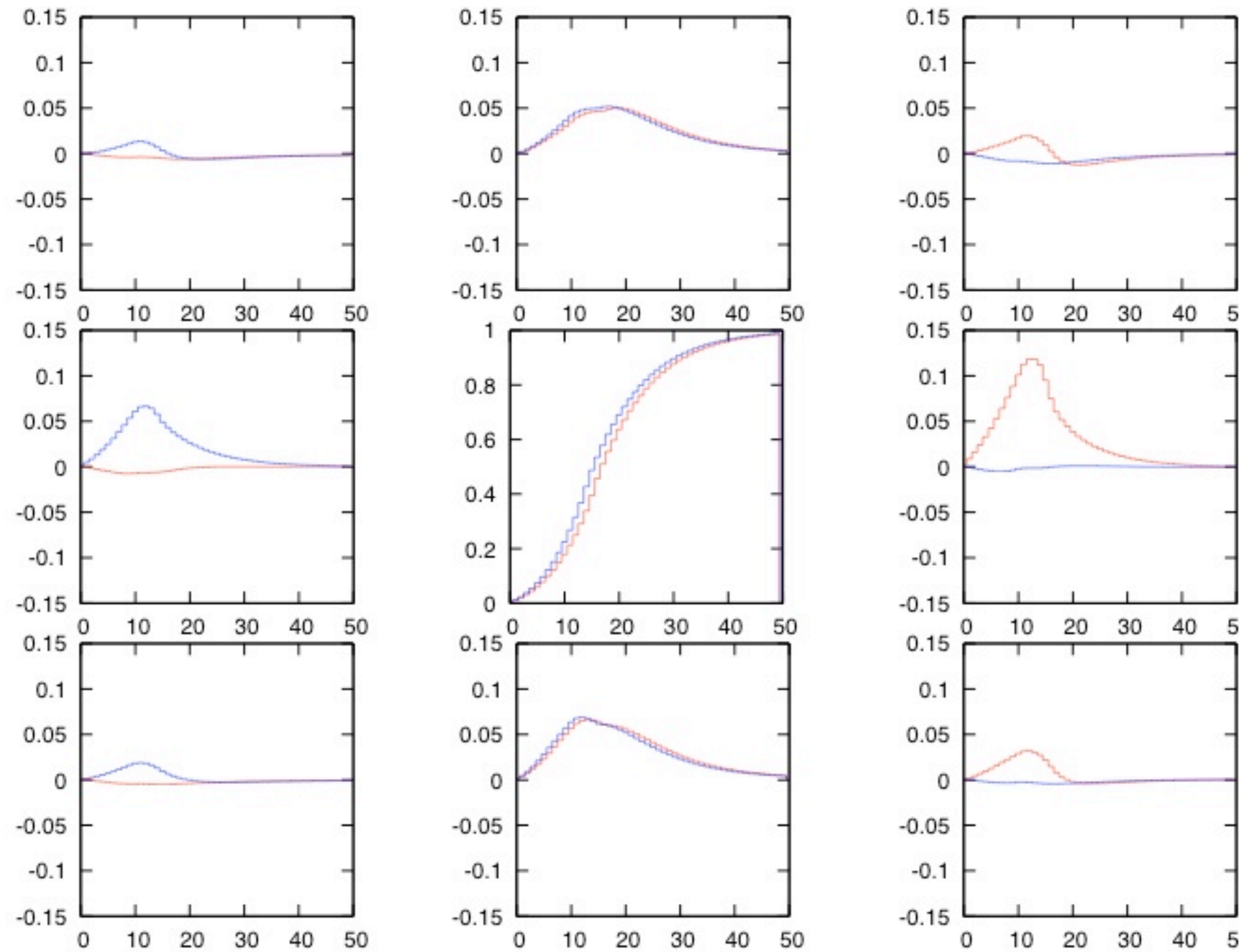


2 of 3 γ-ray energies incorrect

Sub-Segment Resolution

net and induced signals allow sub-segment position determination of interaction points





(14.1, 10.5, 30.7)
(3.1, 17.5, 30.8)

amplitude of induced signals ~5% of net charge signals

Compton Tracking

$$E_\gamma = E_{e1} + E_{e2} + E_{e3}$$

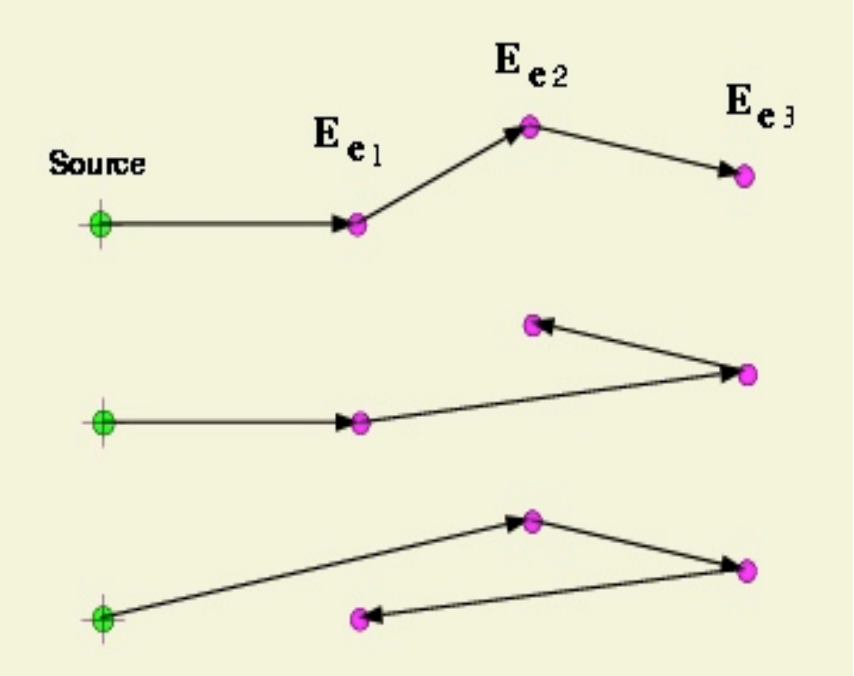
$$\cos\theta_C = 1 + \frac{0.511}{E_\gamma} - \frac{0.511}{E'_\gamma}$$

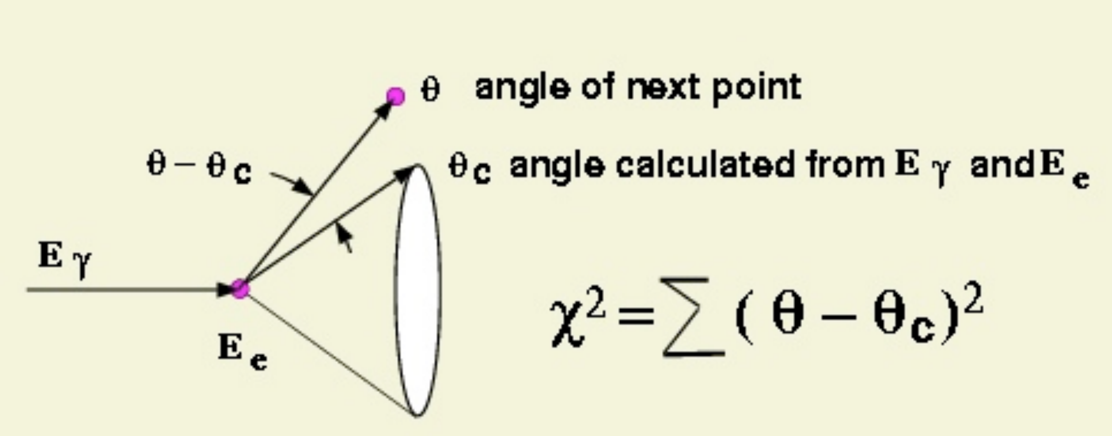
1.group interaction points likely to belong to a given gamma-ray

2. fit all permutations of positions and energies of interaction points against the Compton scattering formula
3. choose permutation with lowest $\chi 2$ to give most probable scattering sequence

$$\chi^2 = \frac{1}{N-1}\sum_{i=1}^{N-1}\left(\frac{\theta^i - \theta_C^i}{\sigma_\theta^i}\right)^2$$

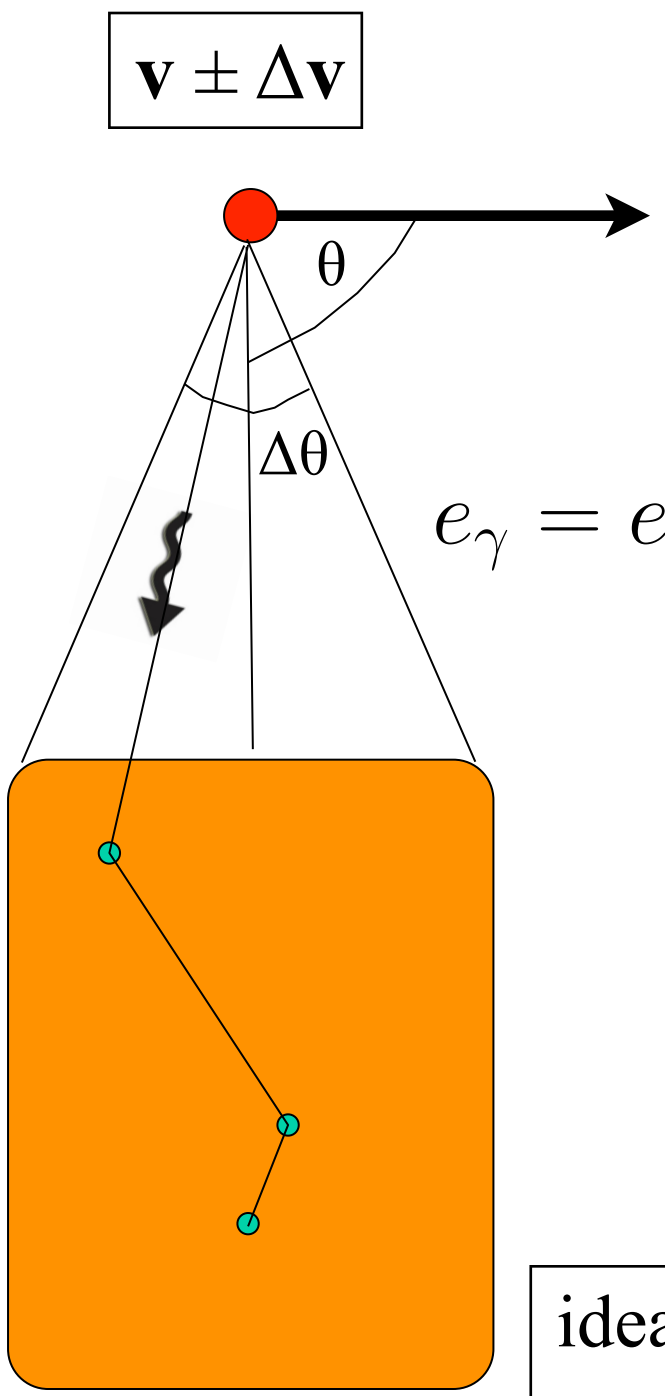
4. apply a FOM cut (eff. vs P/T)
   - if χ^2_{min} > FOM regroup points
   - reject event if re-grouping fails (Compton escapes, not target-like)





Advantages of Tracking

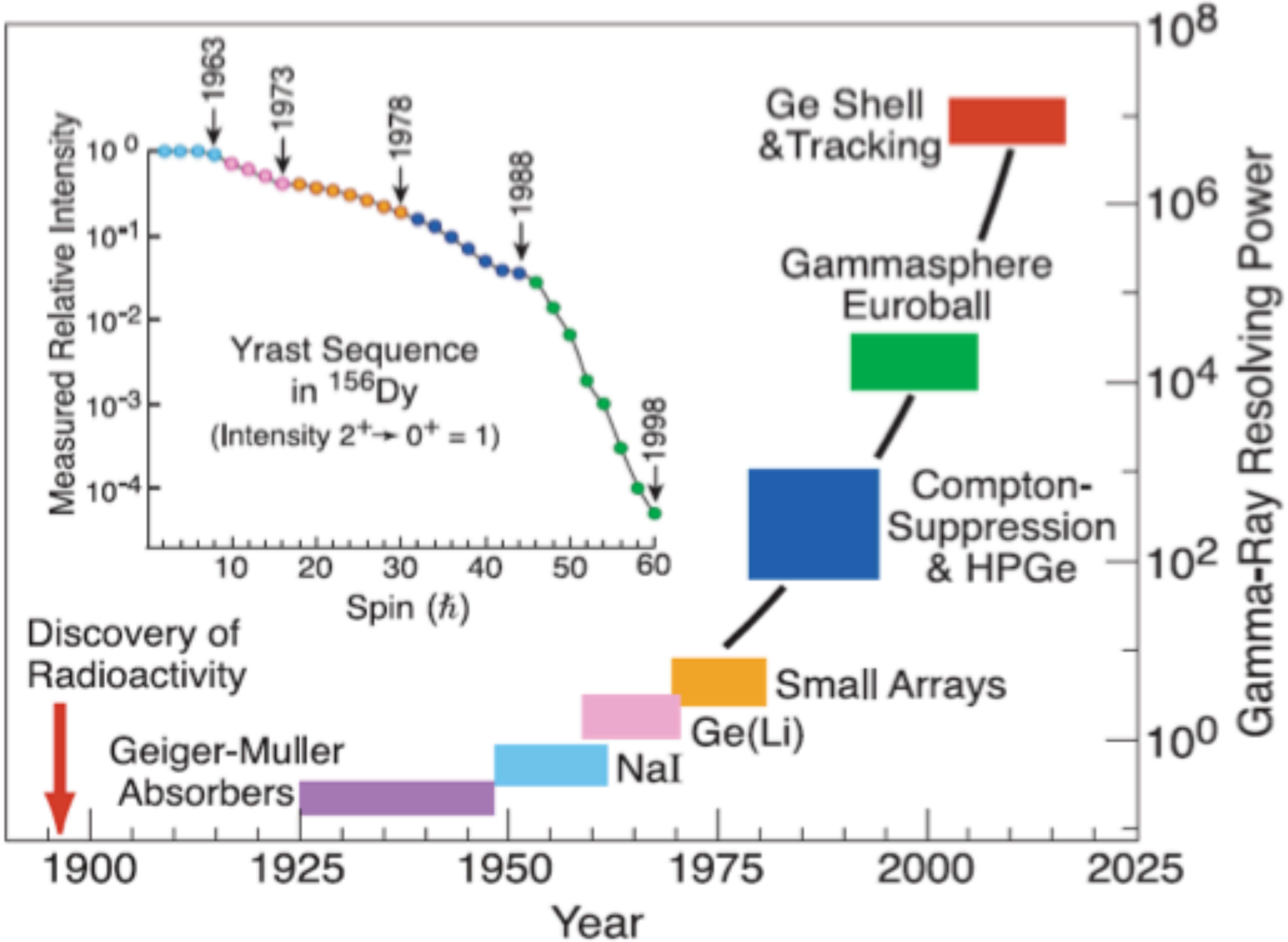
- high efficiency
- gamma-ray is rejected if it fails to track (your entire active volume is your suppressor)
- *event-by event Doppler correction, critical for fast beams* *
  - for high-velocity residues, energy resolution dominated by detector opening angle
  - tracking gives first interaction point, angle with precision
- polarimetry
- counting rate



$$e_\gamma = e_\gamma^0 \left(\frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta} \right)$$

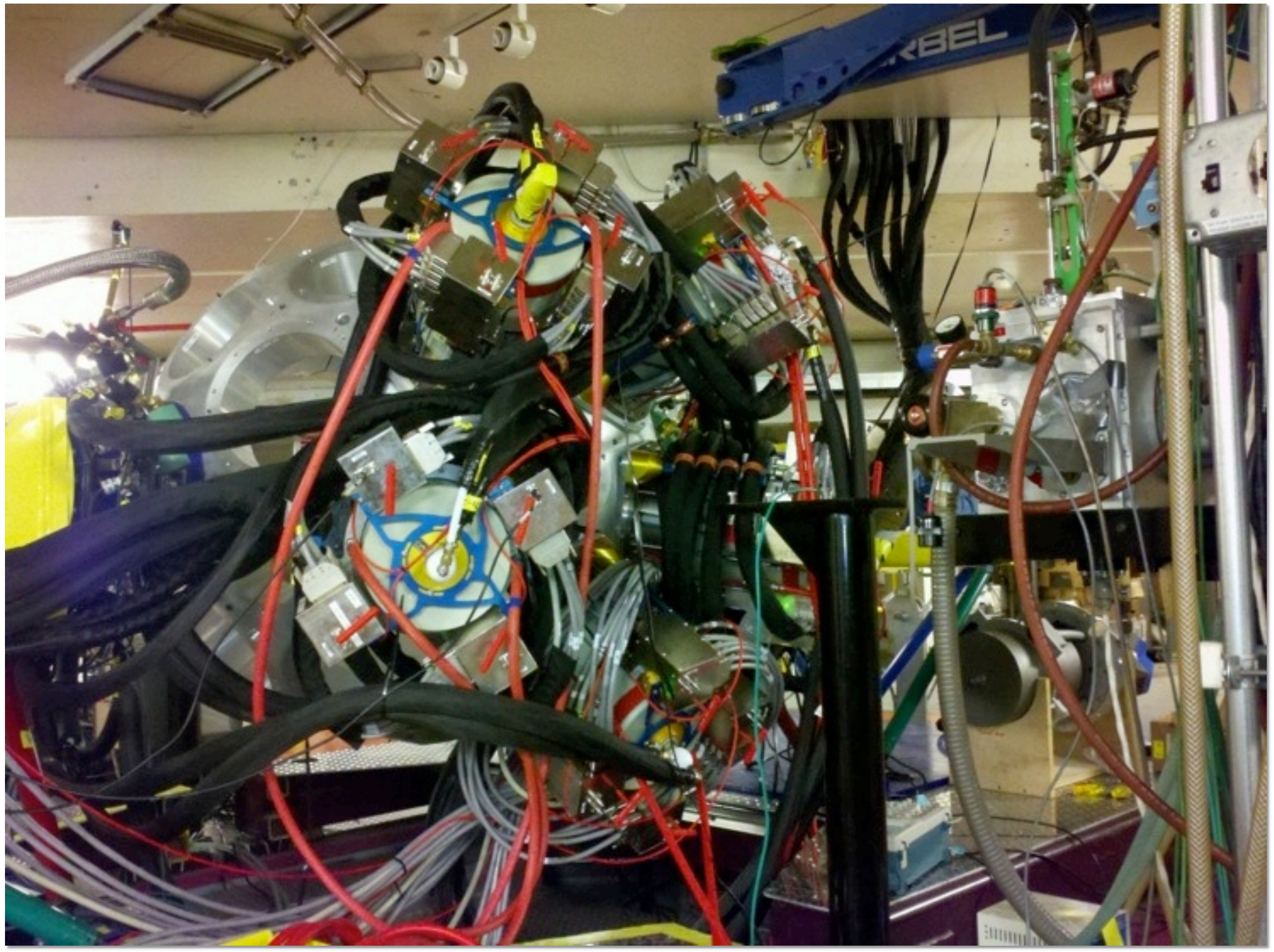
ideally ...
$res_{\Delta v} \ll res_{\Delta\theta}$

ge tracking shell rp



The Gretina Spectrometer

- partial shell covering 25% of available solid angle (scalable to full 4π coverage)
- consists of seven 4-crystal modules (quads)
- similar in scope to the AGATA demonstrator
- singles efficiency ~6%
- peak/total ~55%
- 2mm position resolution
- data processing rate ≥ 20,000 γ/s

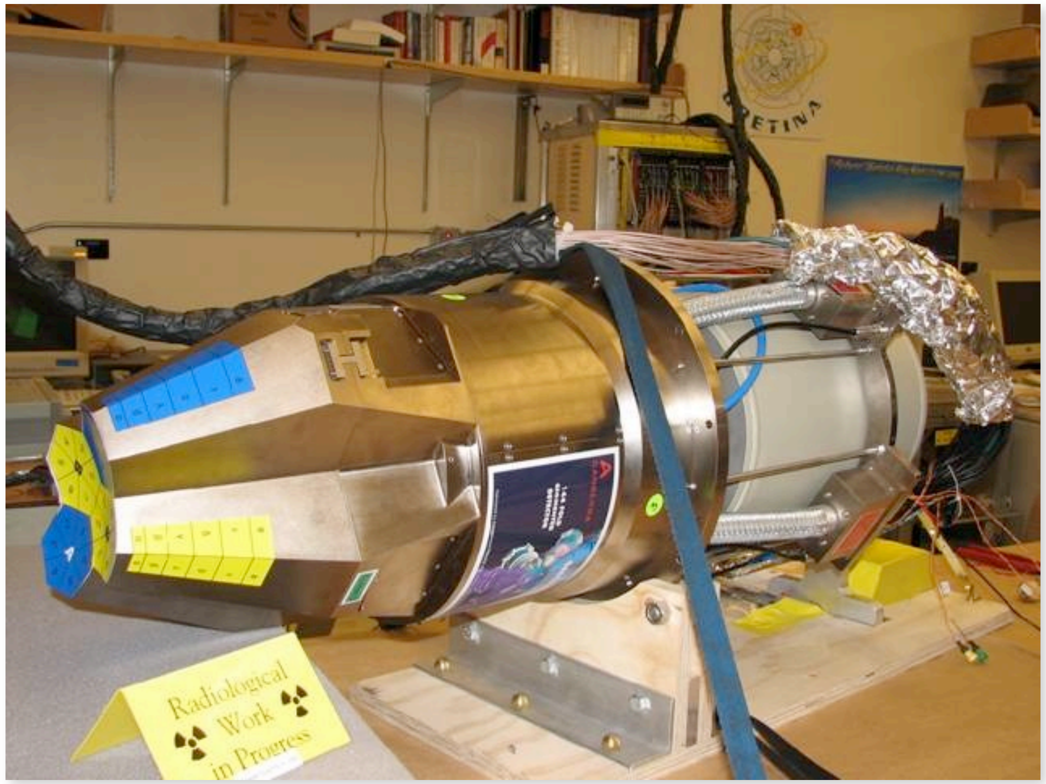


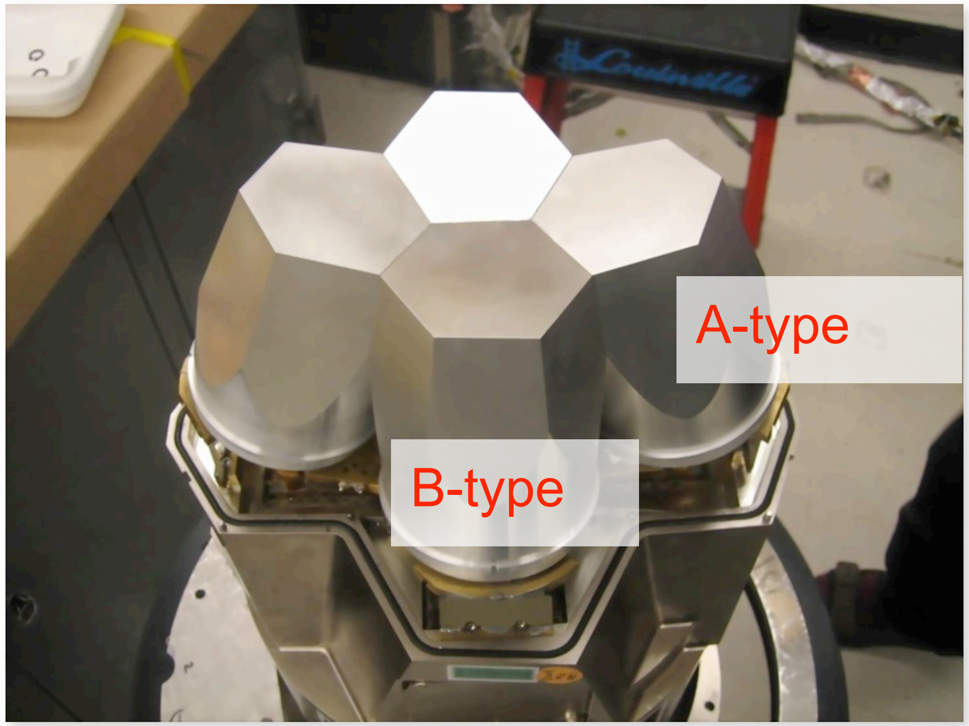
Technical Challenges

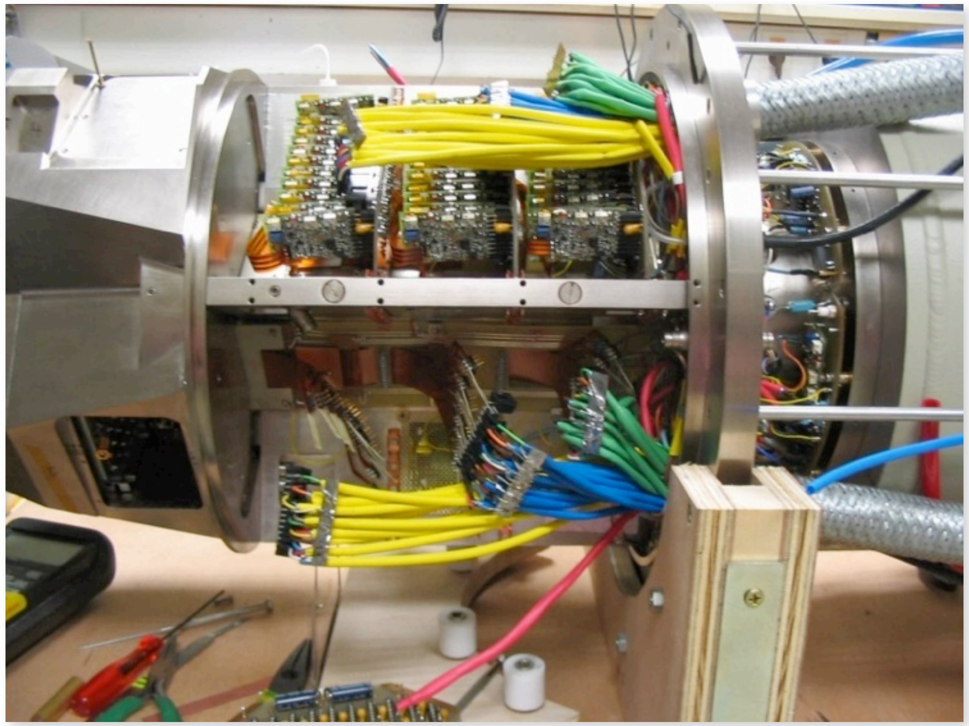
- very highly segmented HPGe detectors required
- efficient algorithms to determine scattering locations in the crystal (signal decomposition)
  - $\sigma_x, \sigma_y, \sigma_z \leq 2$ mm
- completely digital signal-processing chain
- computing required for real-time data processing
- four major subsystems:
  - detector
  - mechanical
  - electronics
  - computing, algorithms

Detector Module (quad)

– 4 encapsulated crystals in a single cryostat
– 2 types of irregular hexagons allow for spherical packing
– segments have warm FETs, central contacts have cold FETs
– 148 pre-amps/module

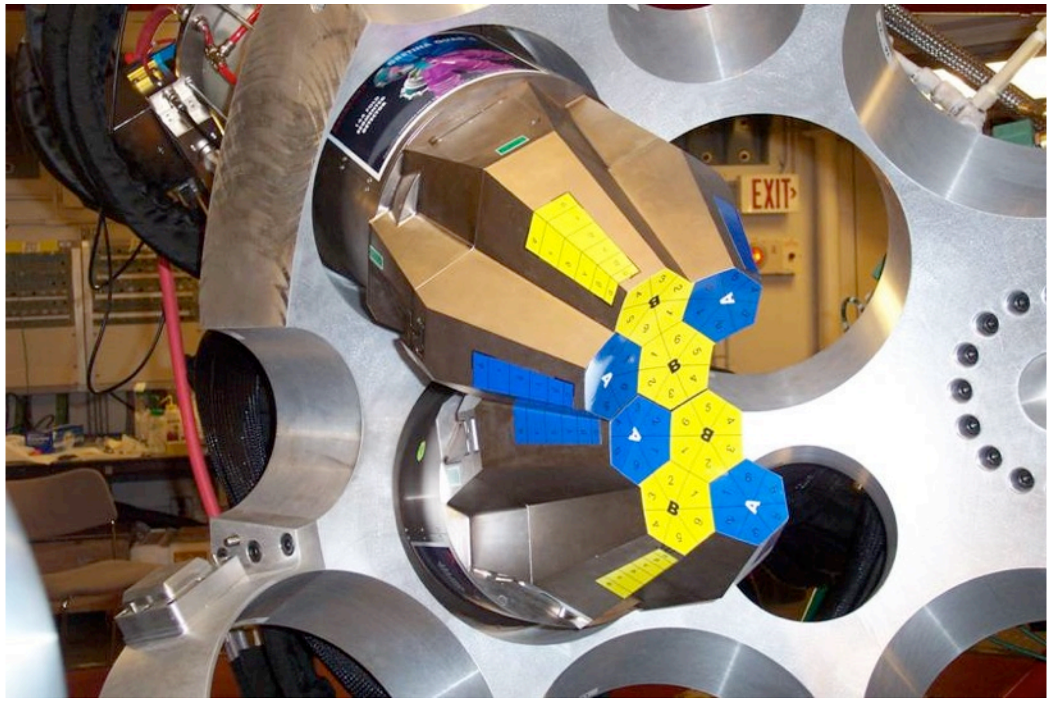






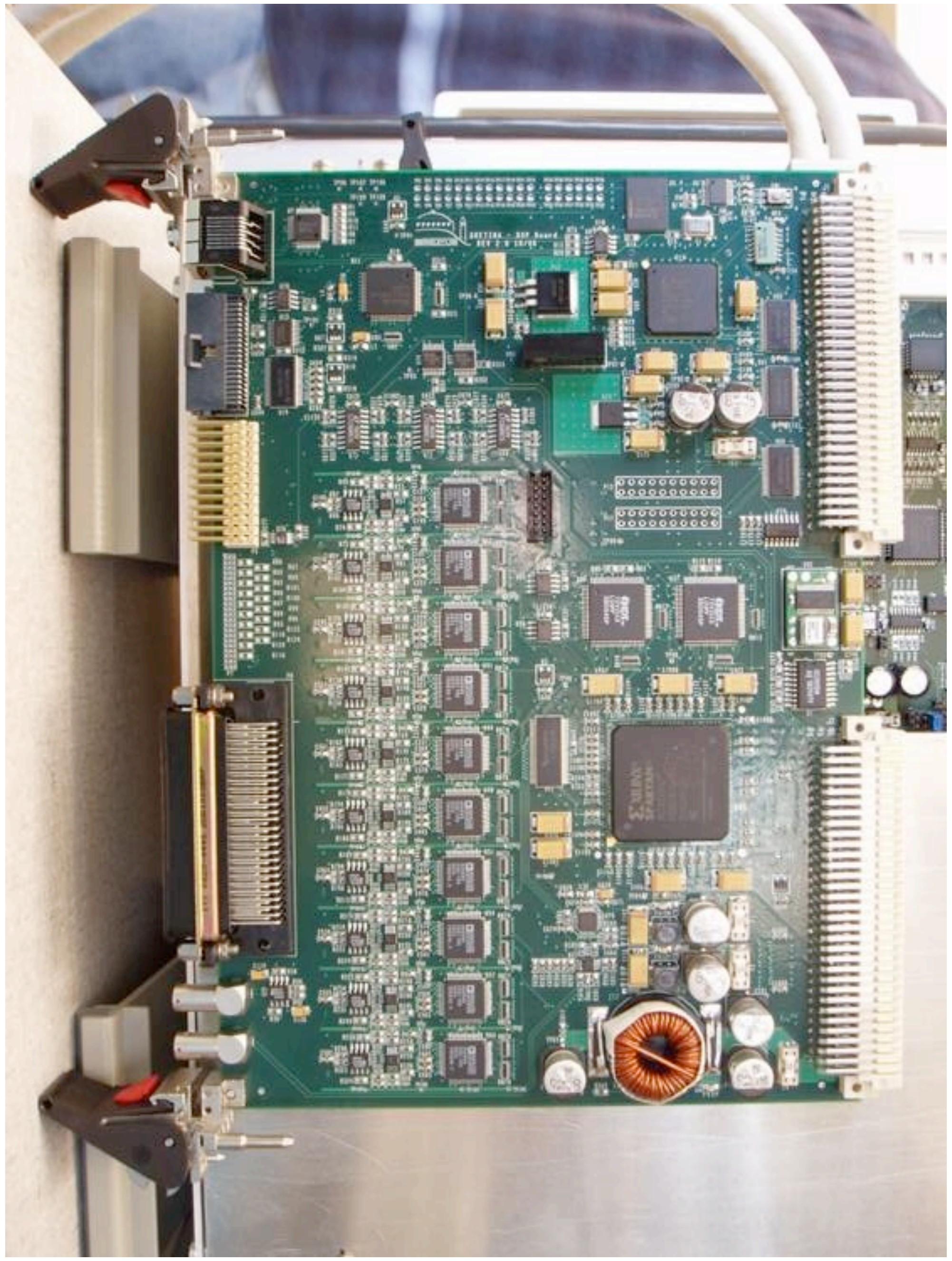
Mechanical Structure

- two "quarter" spheres
- exceptionally rigid
- can be rotated to remove detectors
- very high precision necessary to avoid interference
  - frame, wedge plates
  - detector cryostat



Digital Electronics

- tracking arrays require
  - energy (segments, cc)
  - time (physics, event building)
  - trace of charge on segments, cc
- need for trace for sub-segment position resolution, channel density requires digital electronics
- approx. 1000 channels
- employ VME-based digitizers constructed at LBNL:
  - 10 ch, 14-bit, 100 MHz
  - extract trace information and provide energy, LED, CFD,

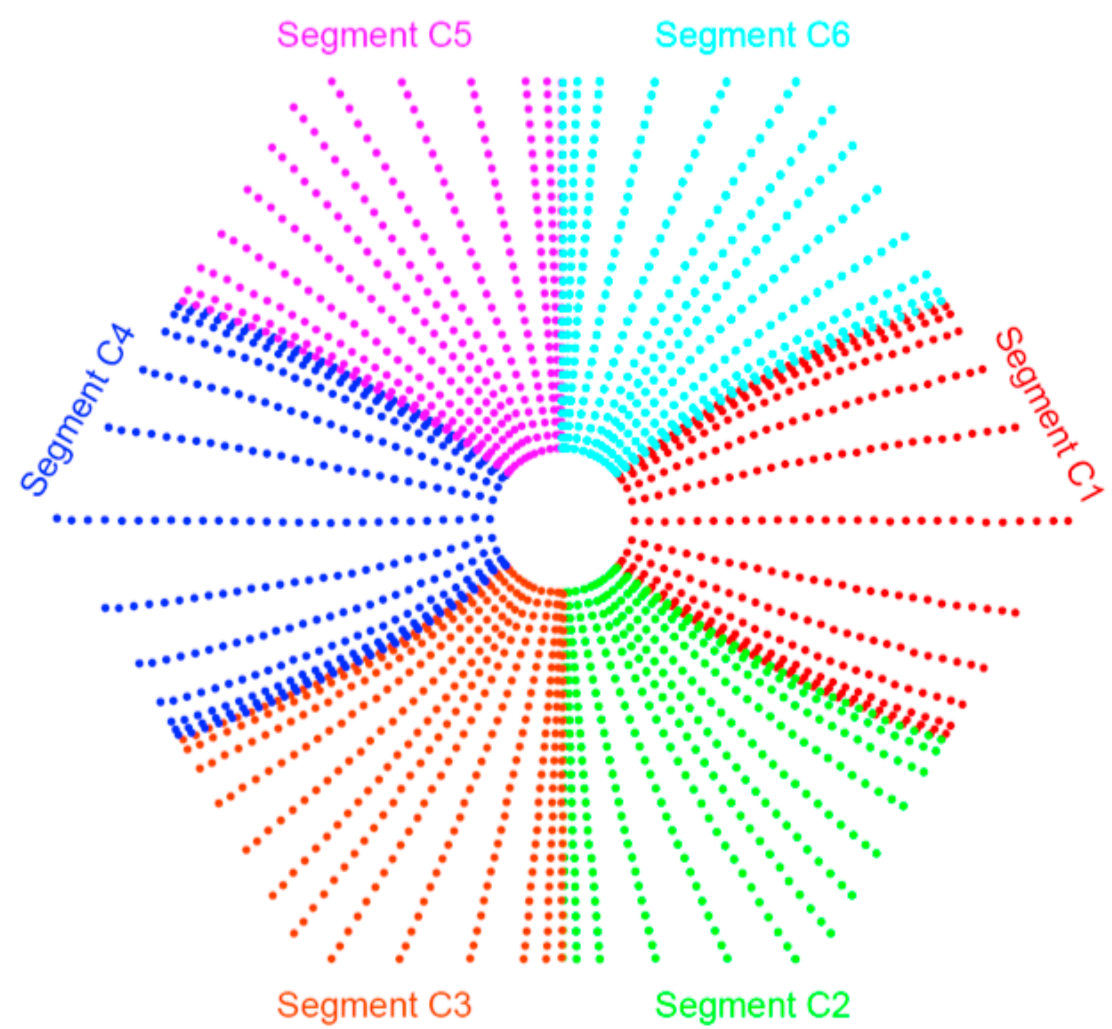


Gretina employs 100 digitizer boards requiring 4 racks

Locating Interaction Points

- calculate electric field, weighting potentials based on crystal geometry, bias voltage, impurity concentration of each crystal
- generate a grid and simulate charge collection on each segment pad for unit charge at each grid point
- compare simulated signals against those experimentally measured
- position of interaction point has the lowest χ^2

spacing is sensitivity weighted



Quasi-cylindrical grid
1 mm avg spacing
(D. Radford, K. Lagergren)

Challenging problem

- multiple interactions within a segment
- image charge signals can overlap with that of neighbors
- must fit linear combinations of simulated basis signals **s** experimental signals

$$\mathbf{s} = e_1\mathbf{s}_{r1} + e_2\mathbf{s}_{r2} + e_3\mathbf{s}_{r3} + \ldots.$$

$$\mathbf{s}_{rn} \equiv \mathbf{tr}_{net} \mid \mathbf{tr}_{n1} \mid \mathbf{tr}_{n2} \mid \mathbf{tr}_{n3} \mid \ldots$$

tr is 50 samples (500ns)

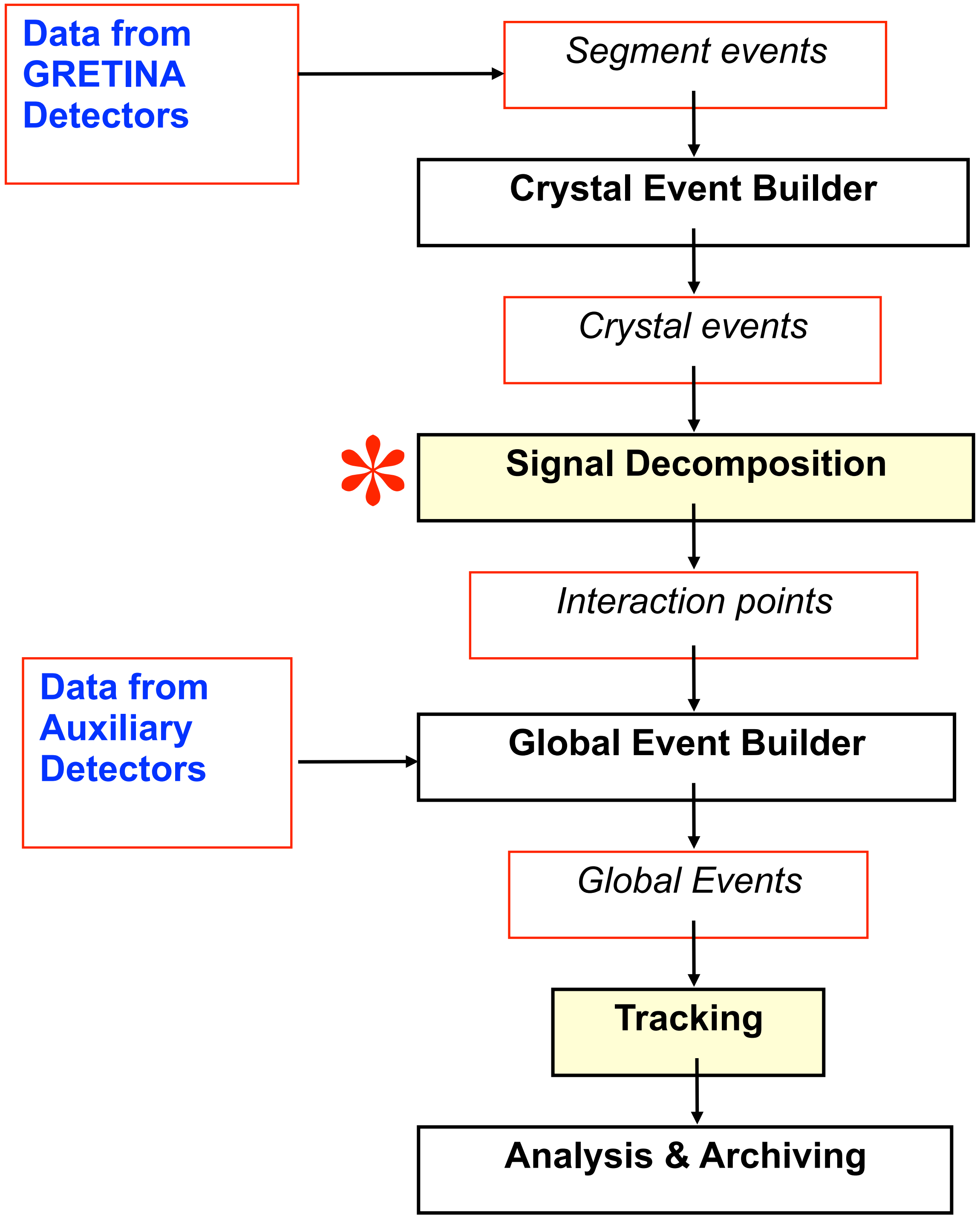
- roughly 230,000 basis elements $\mathbf{s}_{rn}$ per crystal, number of interaction points unknown apriori
- **... and you need to run in real time**
- this problem/process is known as **signal decomposition**

Signal Decomposition Algorithm

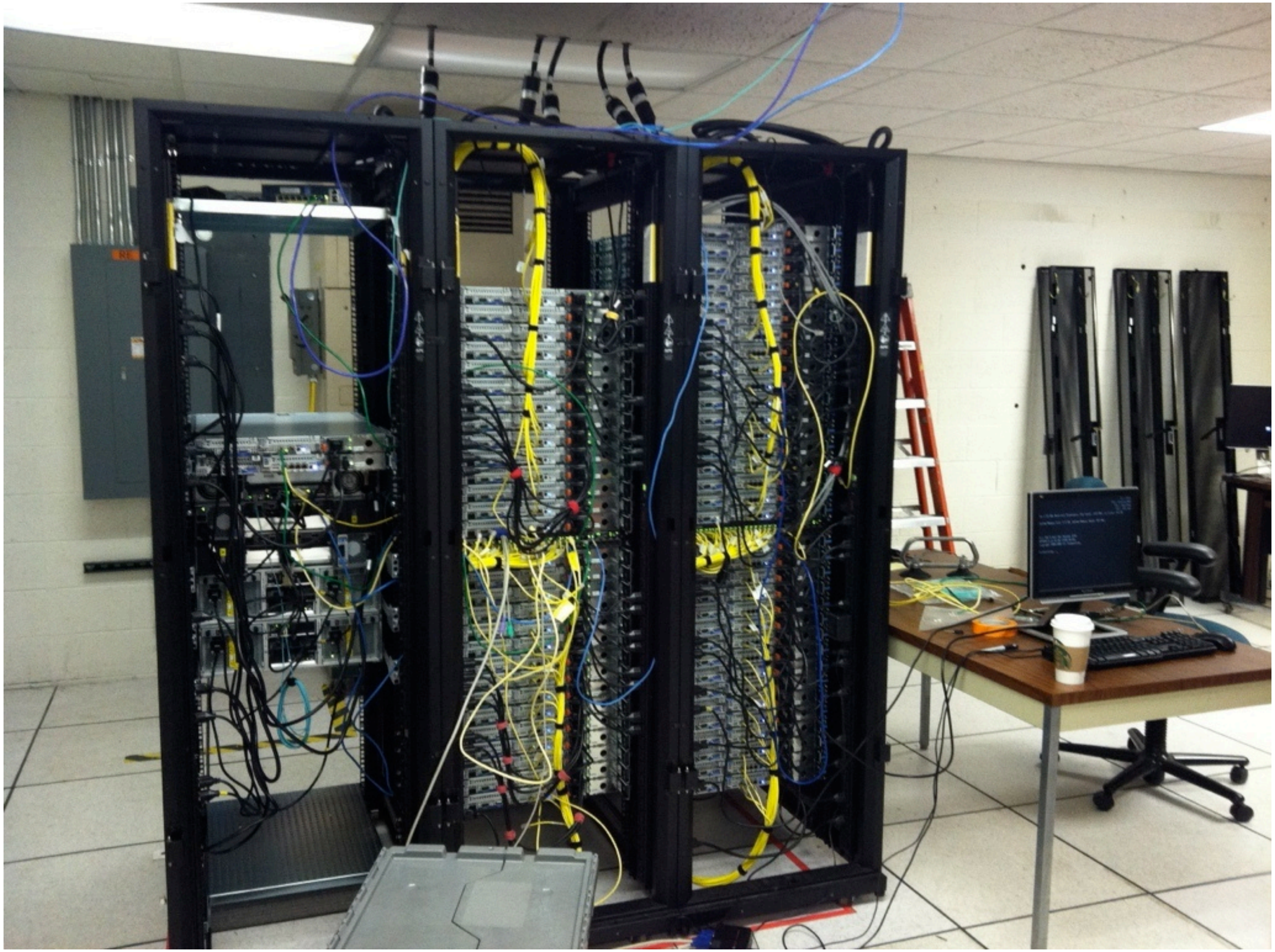
- **adaptive grid search**
  - net = 1
    - exhaustive search for 2 interaction points on course grid (600x600) followed by refinement on fine grid
  - net > 1
    - perform search on high energy segment, perform above search and subtract result from neighboring segments - search resultant signal in neighbors
- **non-linear fit (sqp)**
  - use starting positions from adaptive grid
  - fit t_0, allow interaction points to go off grid
- computationally efficient, works well in simulation

Keeping Up

- signal decomposition is the rate limiting step
- performance goal for Gretina is 20000 γ/s
  - **post trigger**
  - 20,000 mult. M=1 events
  - 4,000 mult. M=5 events
- implication:
  - 20,000 γ/s * 1.5 xtals/γ = 30,000 decomp/s
  - ~10 ms/decomp/cpu core
  - ~300 cpu cores

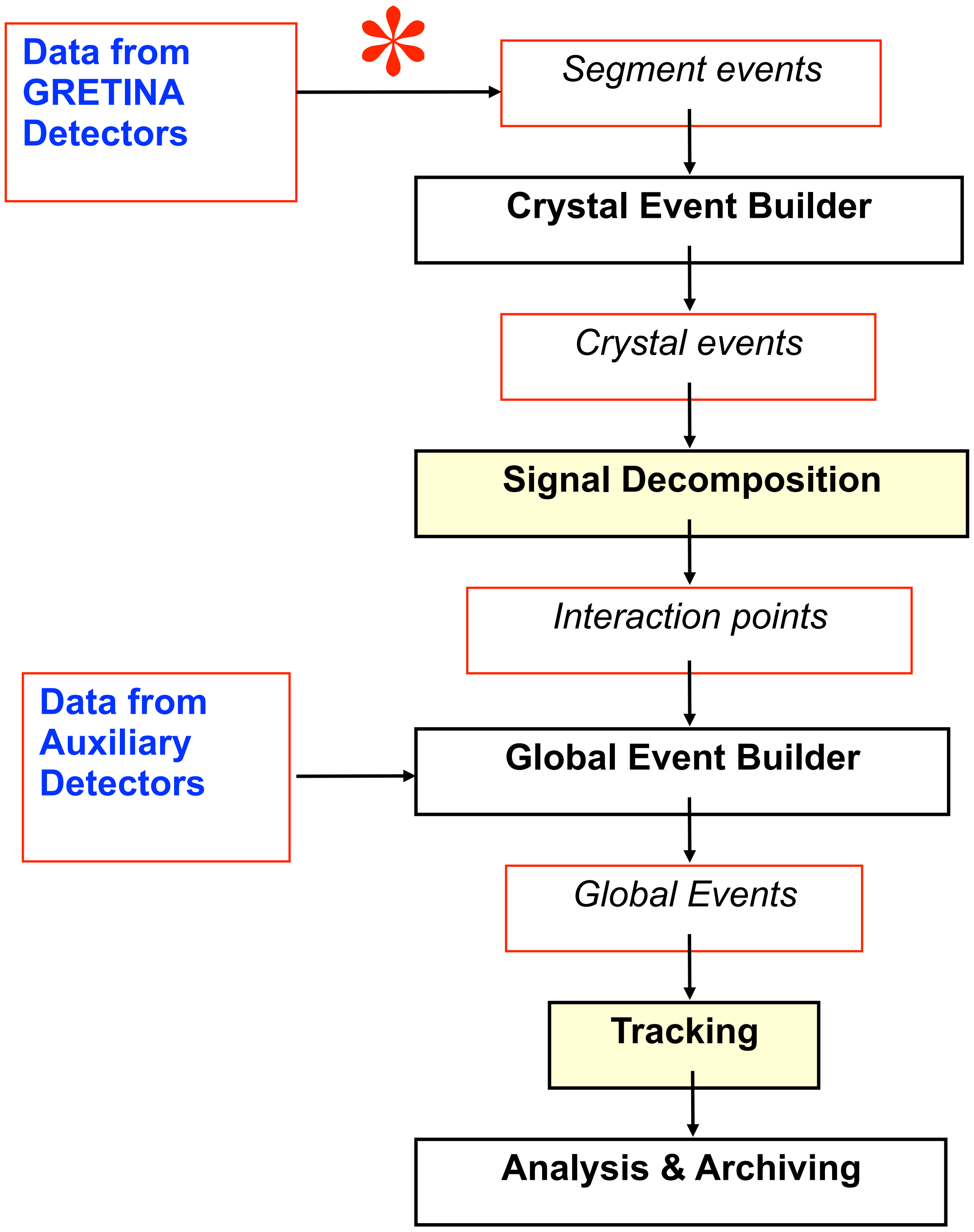


Gretina computing cluster



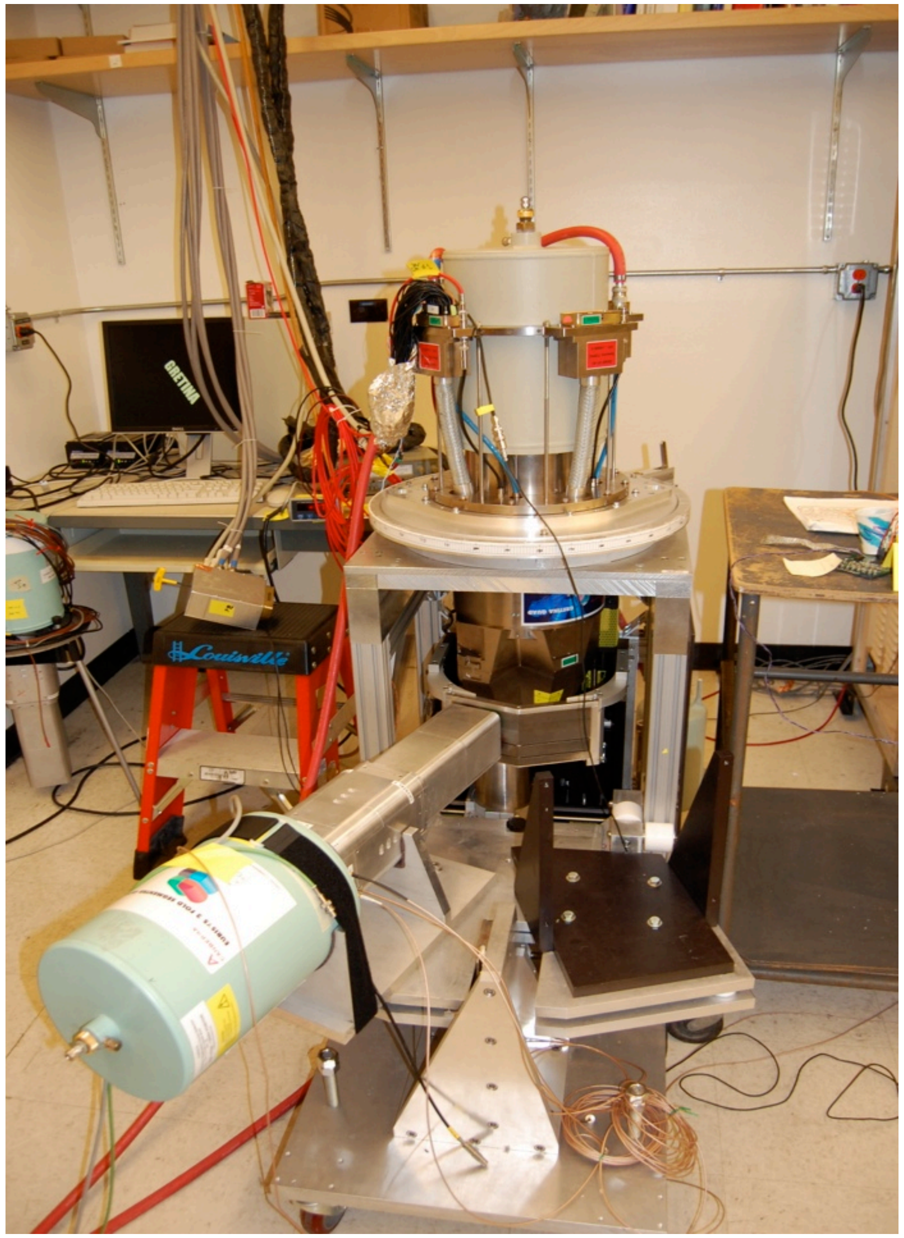
Readout

- readout is the second bottleneck
- 40 ch/xtal * 120 samples * 2 bytes /sample ≃ 10 kB
- 30,000 xtal/s * 10 kB = 300 MB/s (~10 MB/s/crate)
- average xtal readout rate - 1 kHz
- **Gretina requires a selective trigger so not to be overwhelmed by the shear size of trace data**



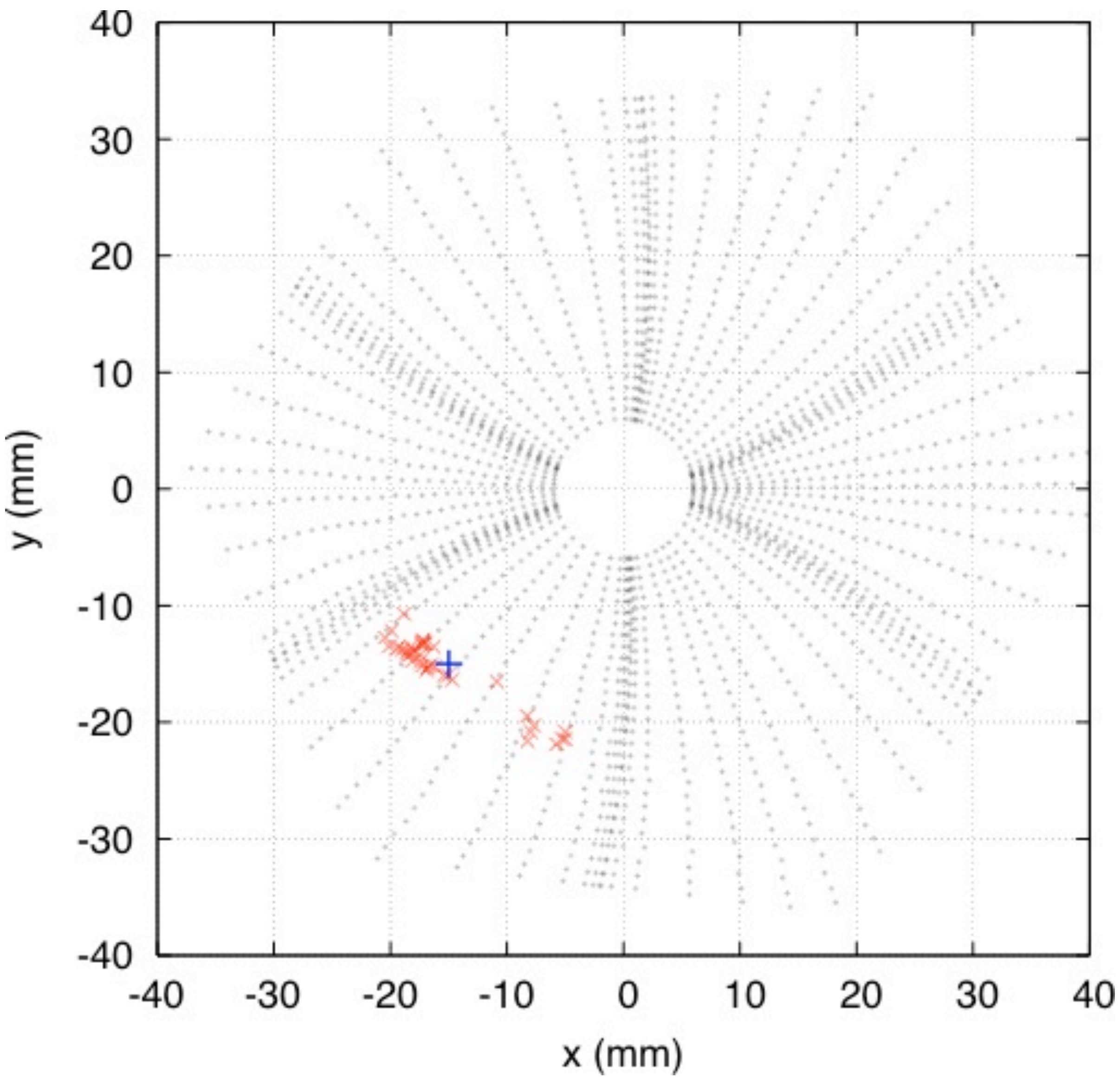
Measuring position resolution

- pencil beams:
  - primary tool for measuring position resolution
  - use collimated Cs source so that first interaction point of pencil defines a line through detector
  - gives 2D position resolution for a line through the crystal
- coincidence scans:
  - use second detector with collimator to tag on 90 deg scatters from pencil beam
  - very selective, low count rate

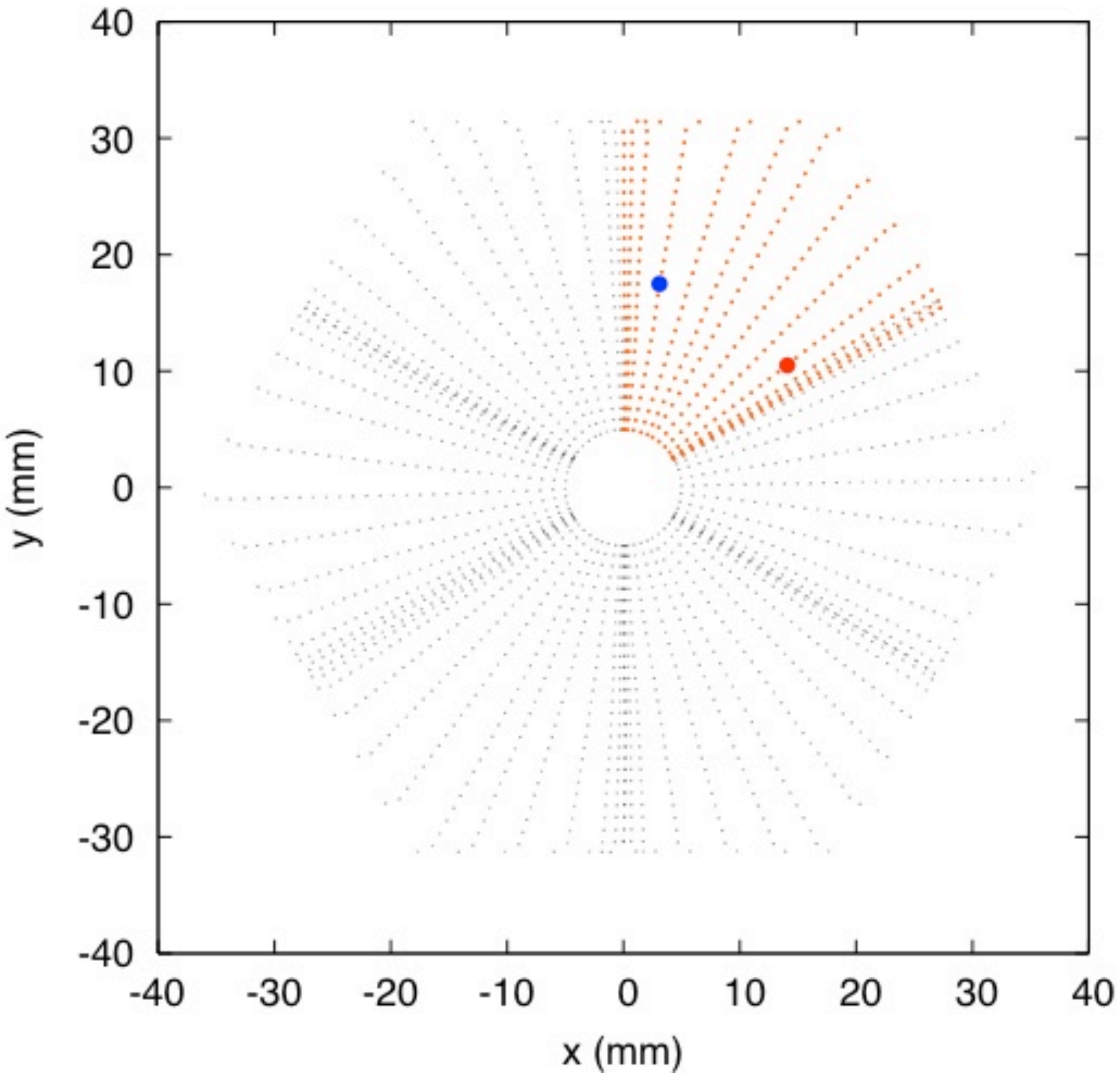


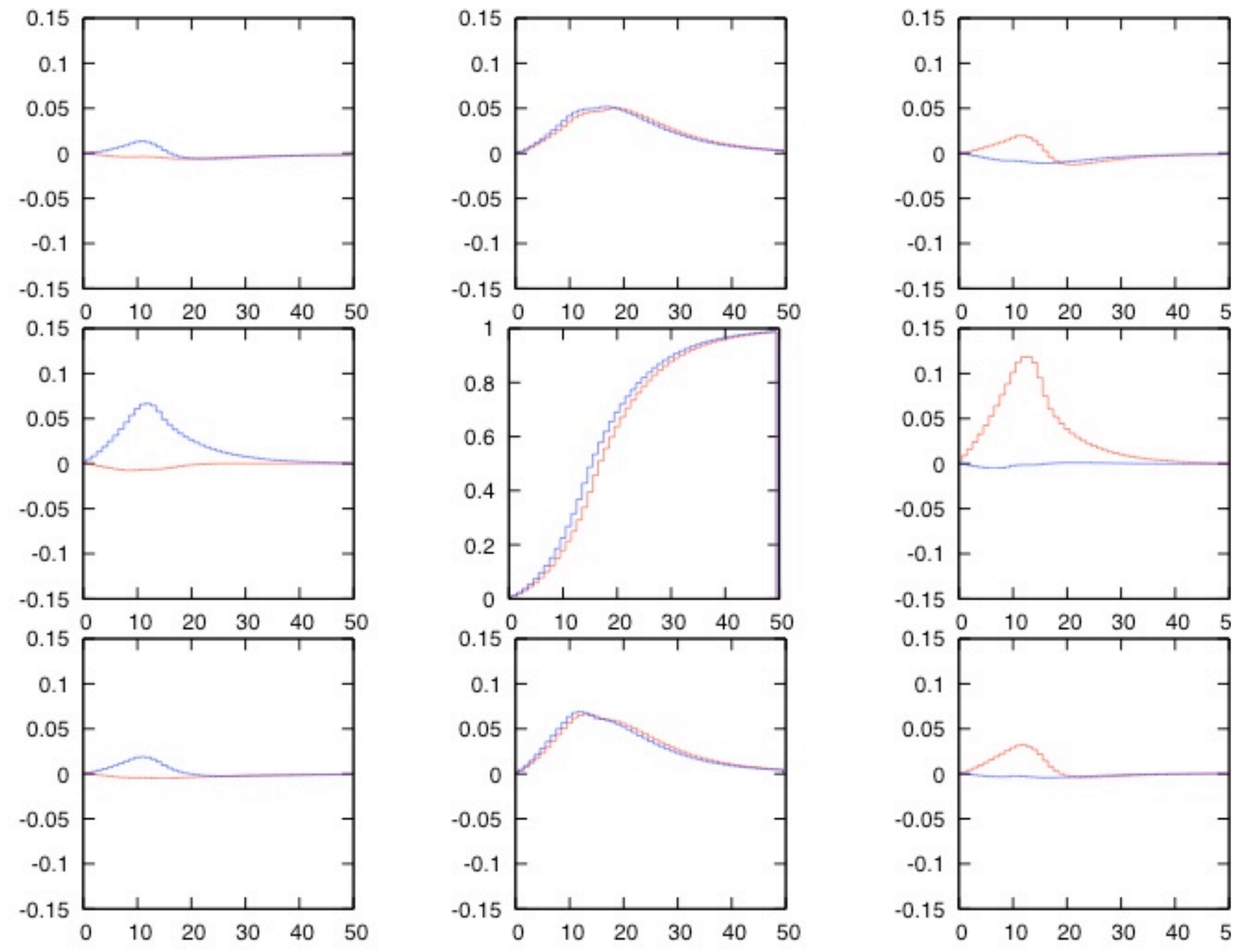
Bifurcation, Differential Crosstalk

- coincidence scans (single interaction) show two points rather than one
- culprit - differential crosstalk
- derivative of neighboring signals induced on signals of interest
- similar magnitude as induced signals which define (φ, z) of interaction points
- basis (simulated) signals no longer accurate - fitter will use multiple interactions to try to mock thing up



single interaction point coincidence measurement

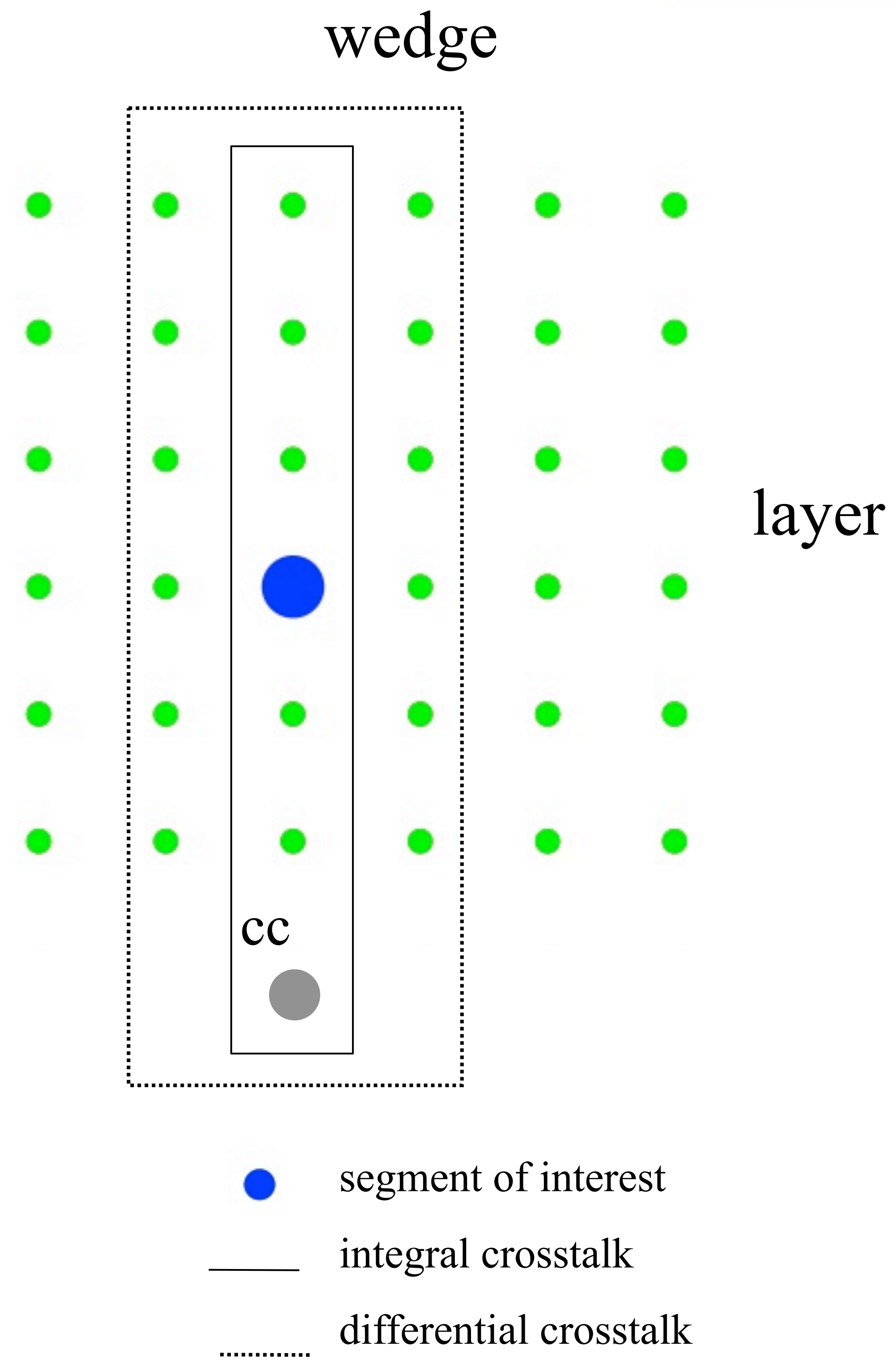




(14.1, 10.5, 30.7)
(3.1, 17.5, 30.8)

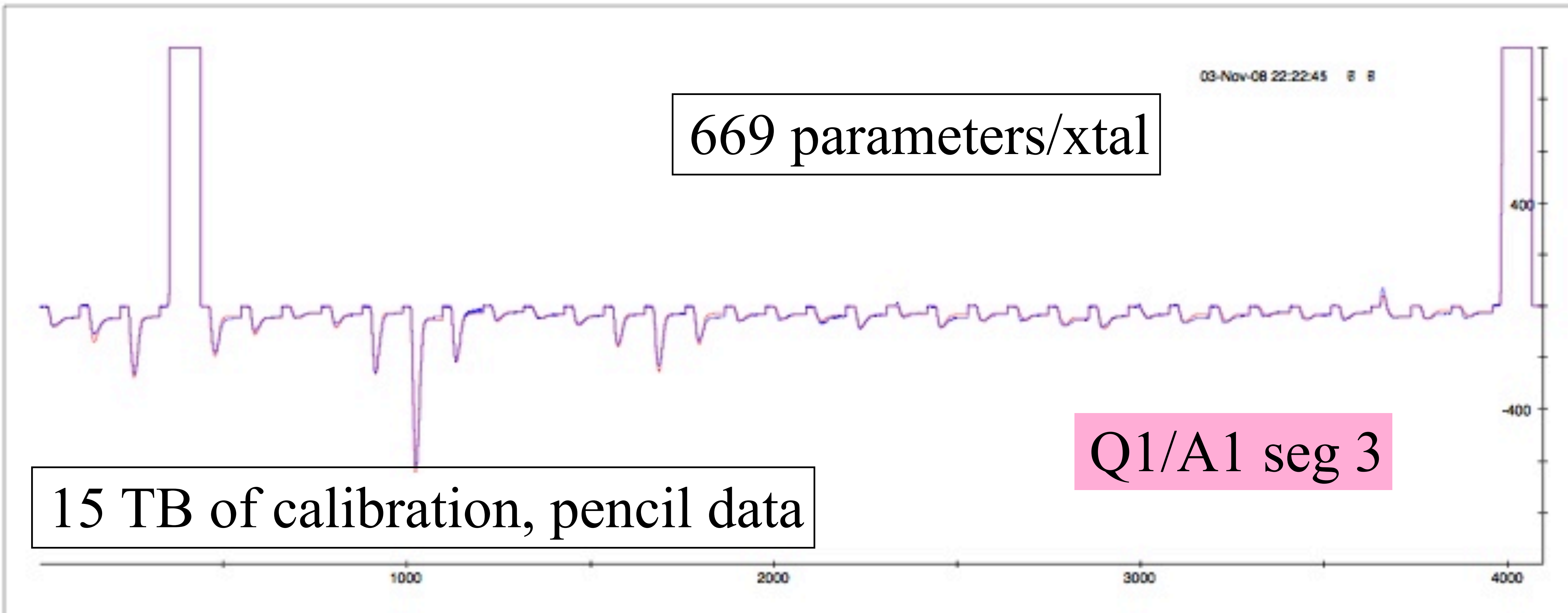
Electronics Response Corrections

- need to determine:
  - integral crosstalk
  - differential crosstalk
  - preamplifier shaping
  - delays between channels
- only a subset of all possible crosstalk parameters are required
- but still ... hundreds of parameters/xtal
- and many of these parameters, specifically differential crosstalk, you cannot directly measure ... :(

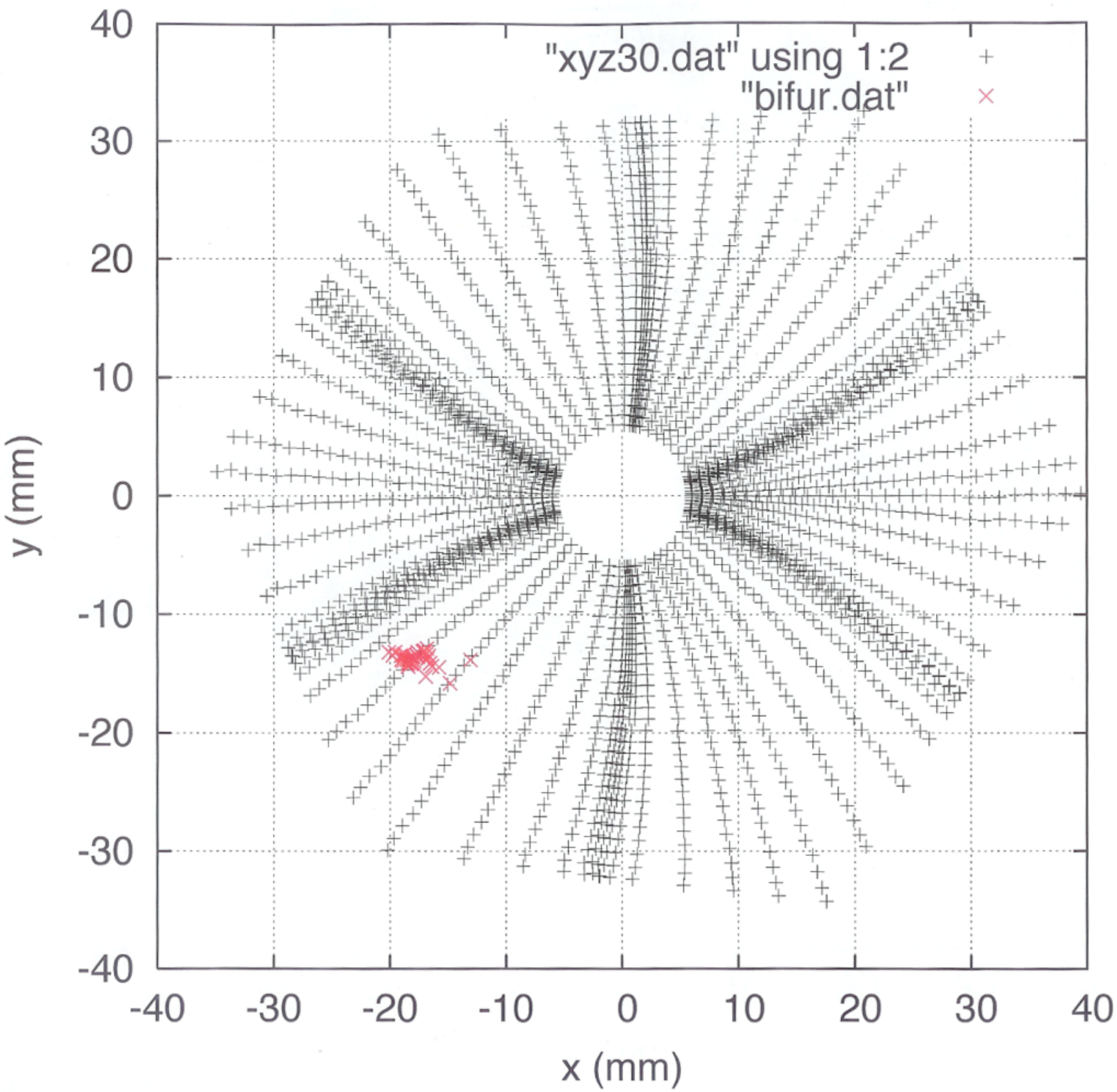


^{60}Co superpulse fits

- signals in each segment have same electronic crosstalk
- fit these parameters from averaged traces given proper weighting by simulation
- fits include integral and differential crosstalk, relative delays between channels and preamplifier shaping



Coincidence data - q1a1

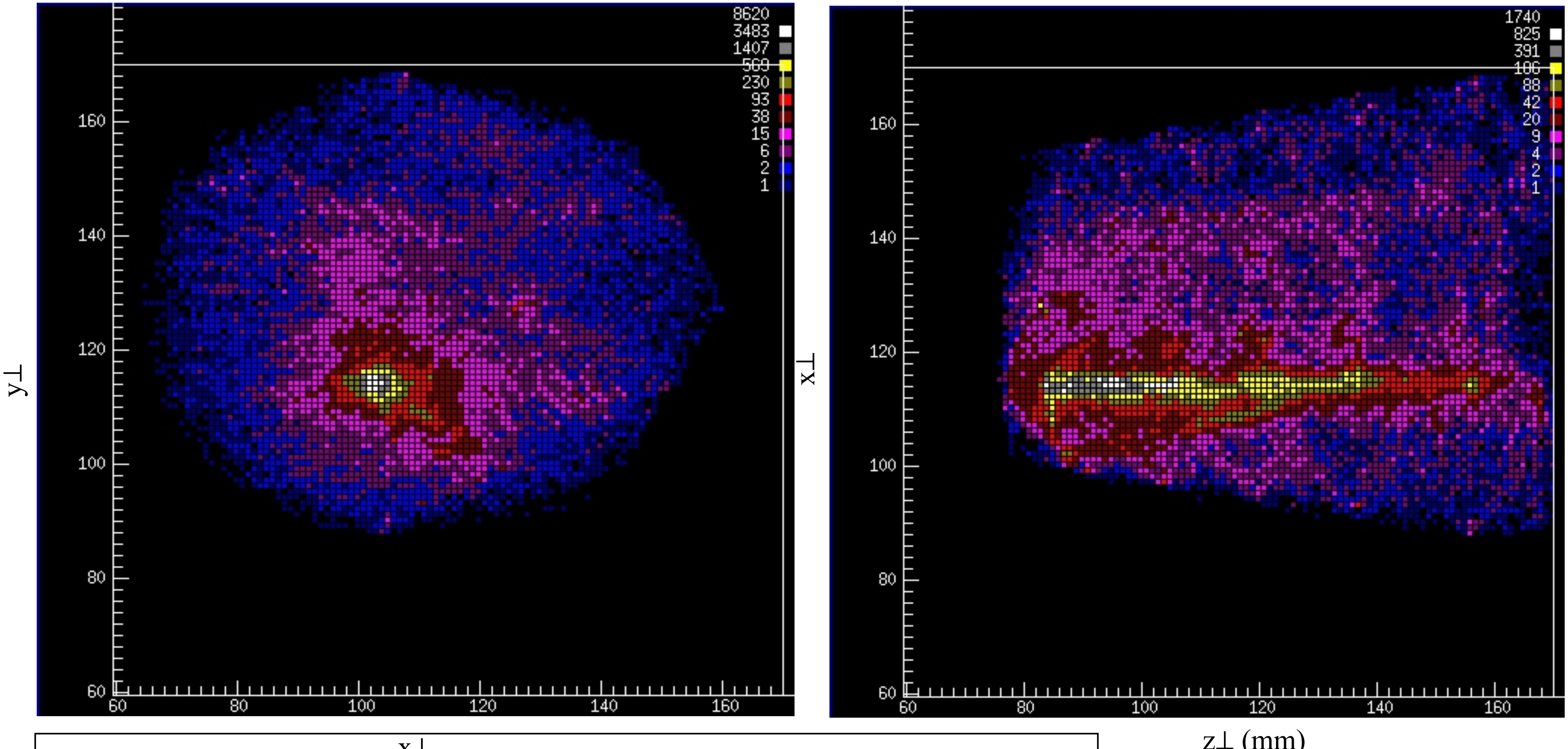


Cs coincidence, modified gdecomp (with penalty factors)

$\sigma_x, \sigma_y \sim 1$ mm

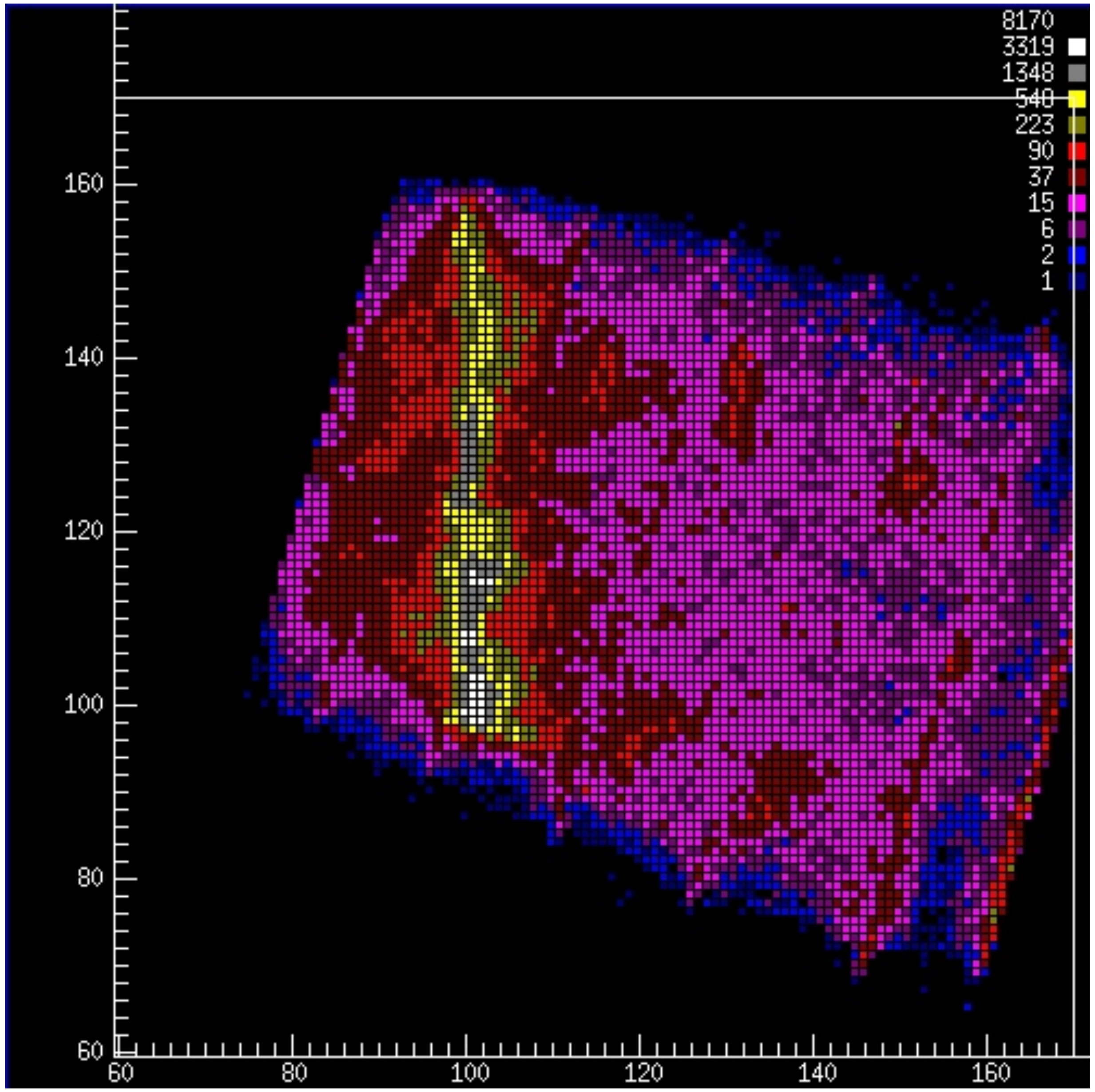
Q1A1, pencil

vertical Cs



-collimated source, no coincidence requirement
-decomposition, not simple lookup

Q2A6 - transverse pencil

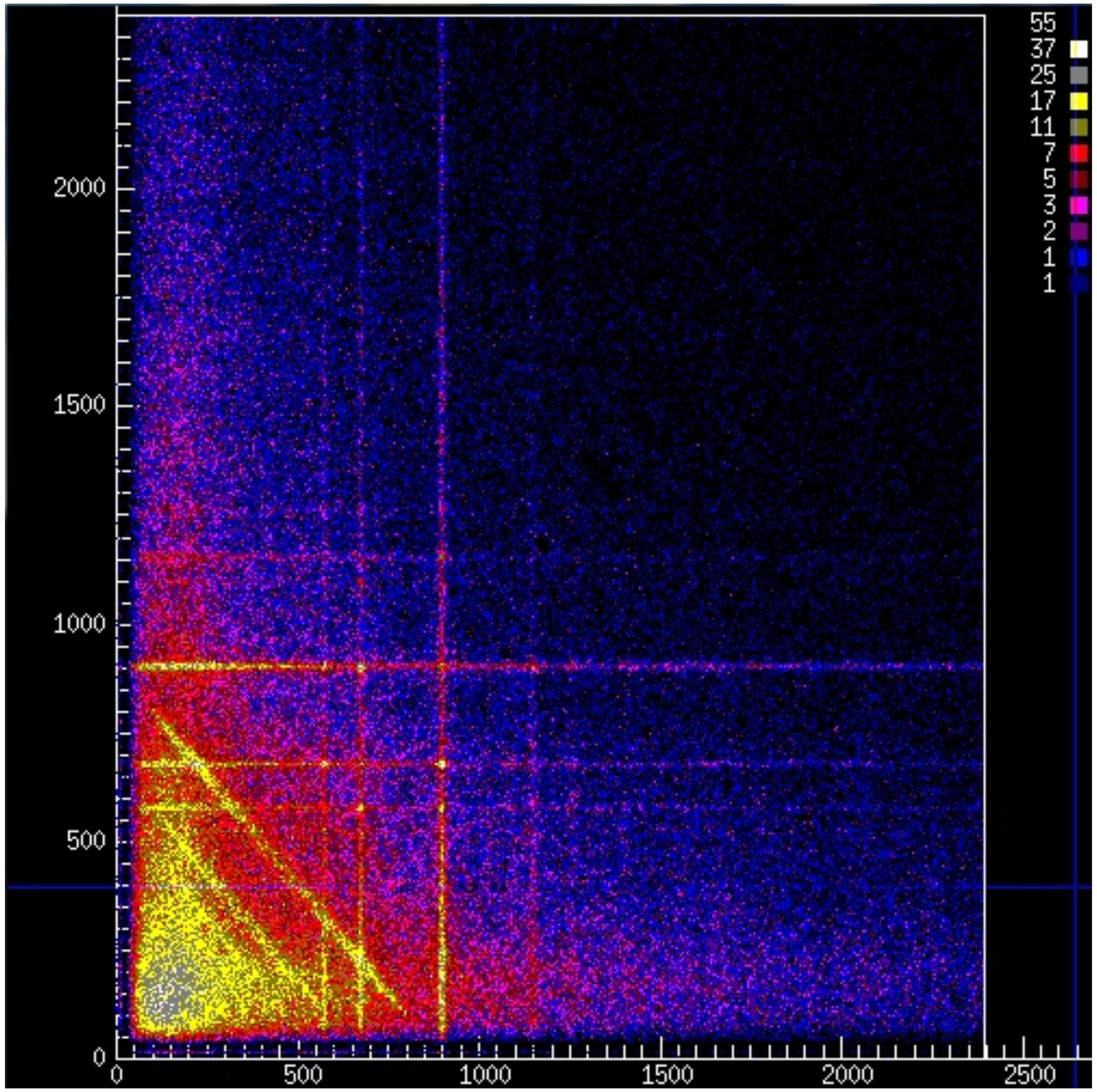


$\sigma_z = 1.54$ mm
$\sigma_y = 2.37$ mm

things are looking good!!

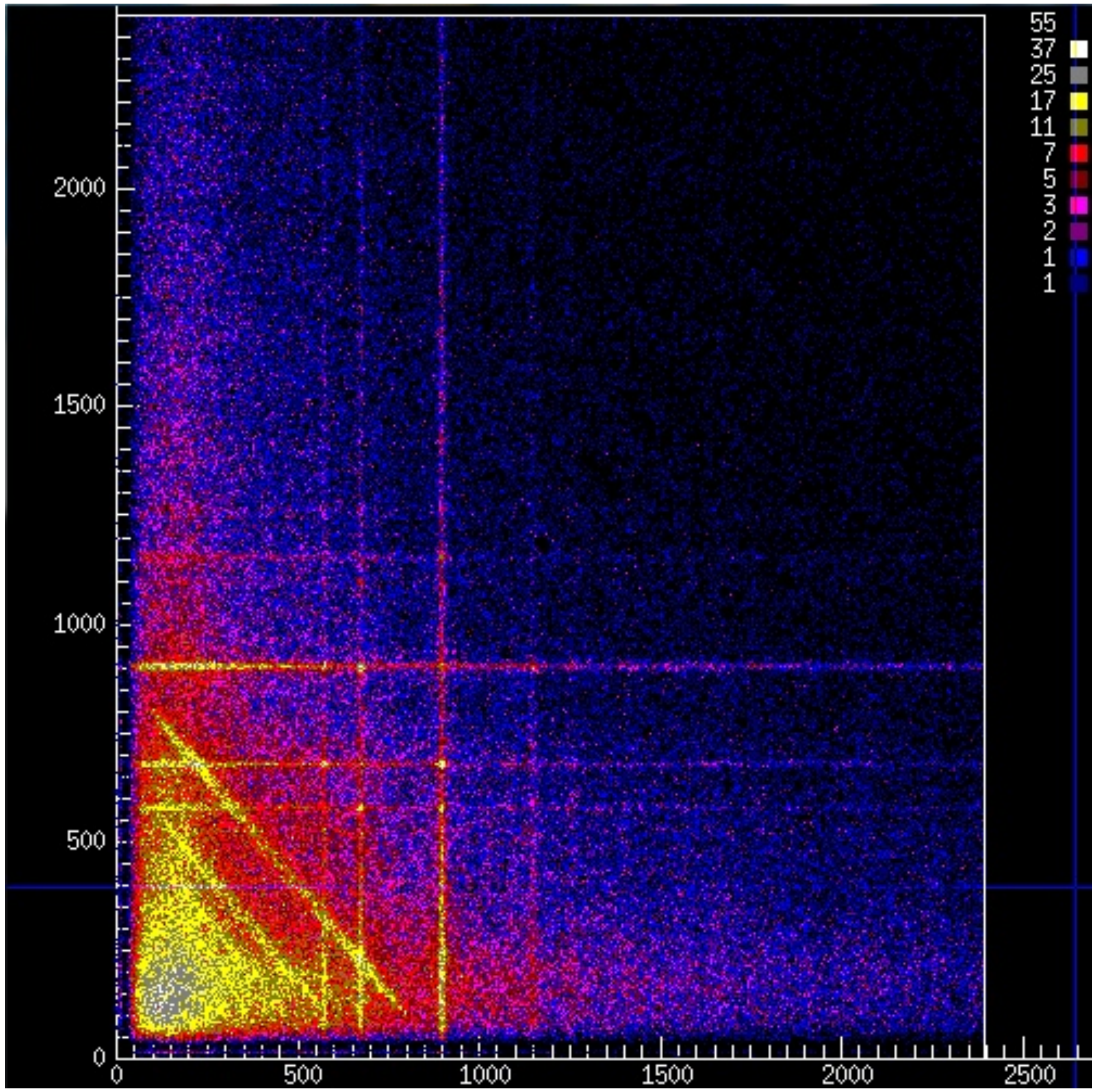
Timeline

- start construction - June 2005
- start operation - April 2011
- engineering and commissioning - May 2011
- operation at NSCL - July 2012
- operation at ANL - Jan 2014

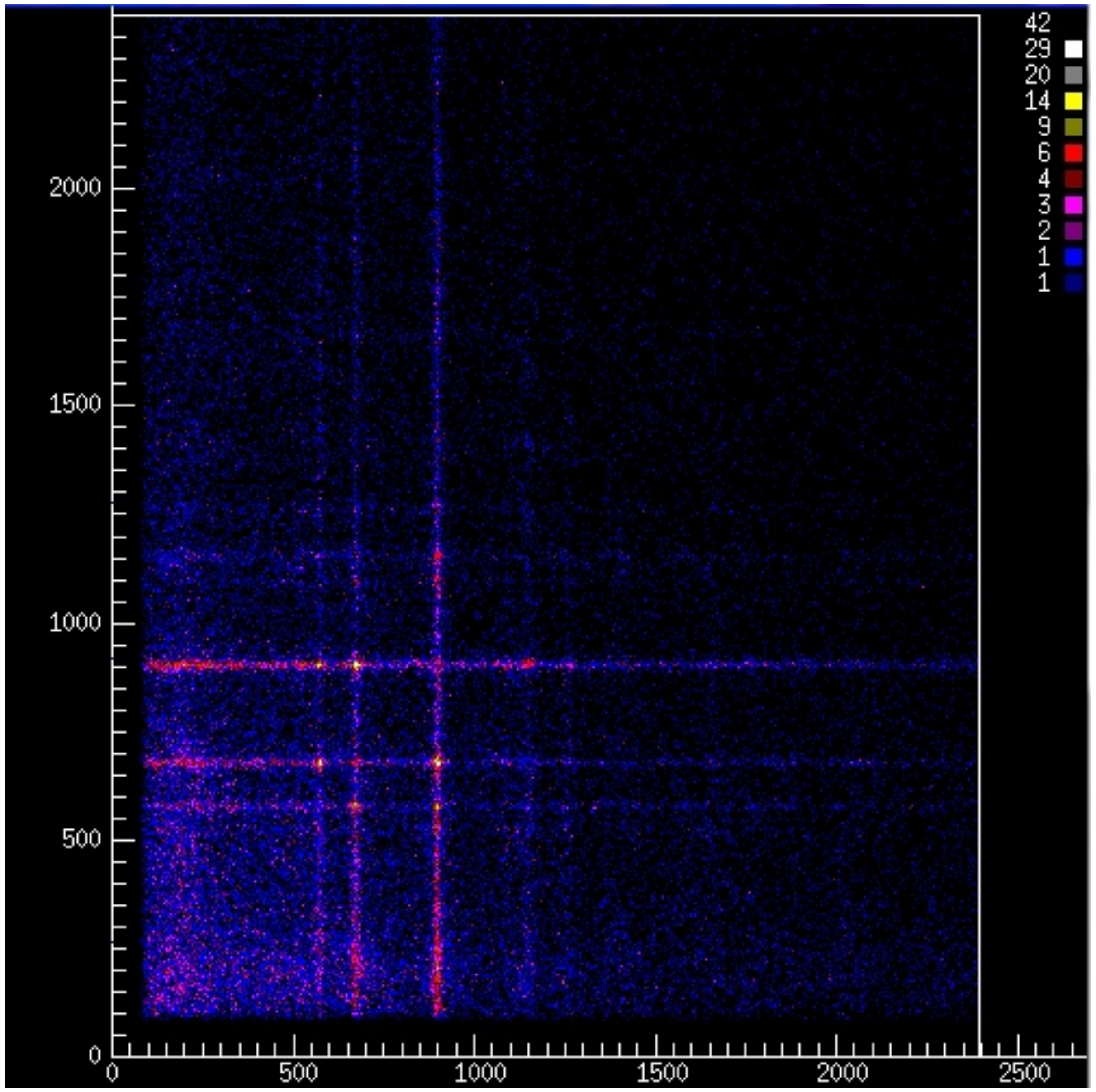


untracked

tracked



untracked



tracked

Summary

- γ-ray spectrometer technology continues to evolve
- capability to build a spectrometer based on a Ge shell has been developed
- very complex, large scale - requires significant resources, collaboration
- still in the early days - potential for higher performance (signal decomp, rate)
- Ge tracking arrays will extend the physics reach of both current and future exotic beam facilities

Thanks to the Gretina collaboration - especially Augusto Macchiavelli, I-Yang Lee, David Radford and Heather Crawford