Advance Gamma Tracking Array
AGATA

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Part 1: Review of AGATA

Part 2: Data Processing

EGAN school 2011, December 5 - 9, 2011, Liverpool

Challenges in Nuclear Structure

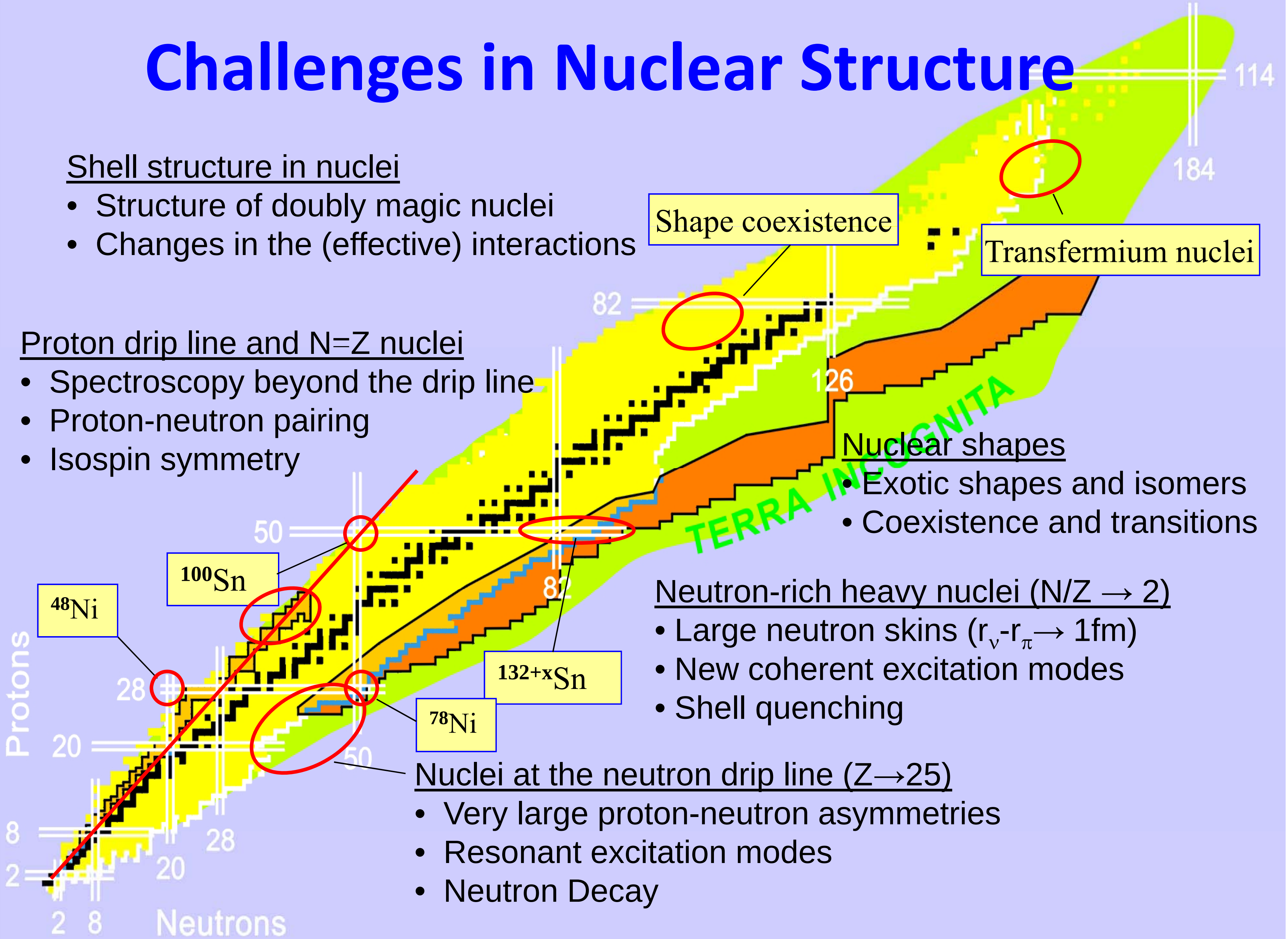
<u>Shell structure in nuclei</u>
- Structure of doubly magic nuclei
- Changes in the (effective) interactions

<u>Proton drip line and N=Z nuclei</u>
- Spectroscopy beyond the drip line
- Proton-neutron pairing
- Isospin symmetry

<u>Nuclear shapes</u>
- Exotic shapes and isomers
- Coexistence and transitions

<u>Neutron-rich heavy nuclei (N/Z → 2)</u>
- Large neutron skins (r_ν-r_π → 1fm)
- New coherent excitation modes
- Shell quenching

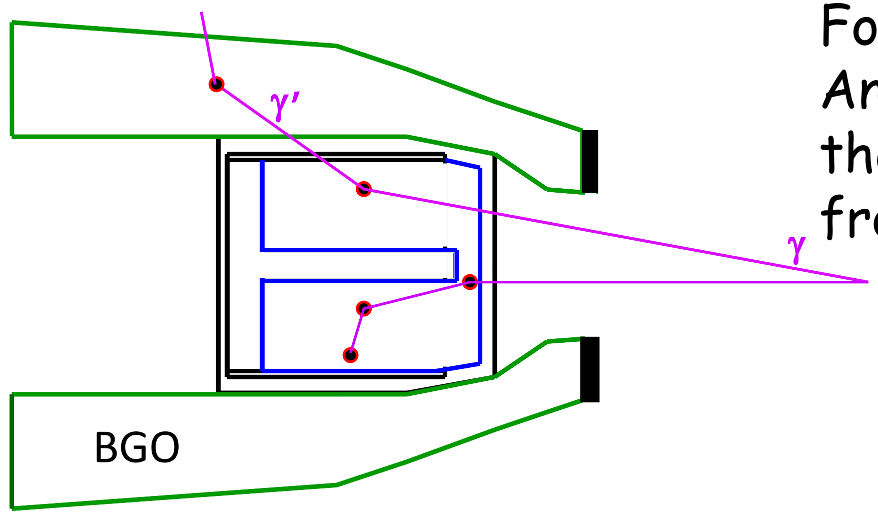
<u>Nuclei at the neutron drip line (Z→25)</u>
- Very large proton-neutron asymmetries
- Resonant excitation modes
- Neutron Decay



Requirements for the gamma detectors

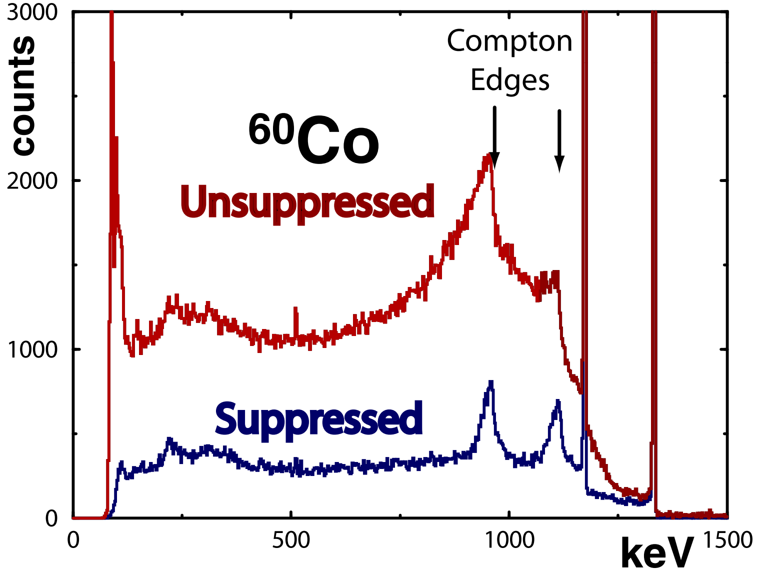
1. Best possible energy resolution in the range 10 keV – 10 MeV to disentangle complex spectra
   - Germanium detectors are the obvious choice
2. Good response function to maximize the number of good events
   - Large-volume Germanium detectors have at most 20%
   - Compton background suppression via BGO shields
3. Best possible effective energy resolution
   - Most experiments detect gammas emitted by nuclei moving at high speed (β ~5÷10% ➔ 50%)
   - Energy resolution dominated by Doppler broadening if the velocity vector and the emission angle of the γ-ray are not well known
4. Good high solid angle coverage to maximize efficiency, ideally 4π
5. Good granularity to reduce multiple hits on the detectors in case of high γ-ray multiplicity events
6. The individual crystals should be as big as possible to avoid dead materials that could absorb radiation
7. High counting rate capability

2. Response function
Escape-Suppressed Ge-detectors



For large-volume Ge crystals the Anticompton shield (AC) improves the Peak_to_Total ratio (P/T) from ~20% to ~60%

$\gamma 1 \setminus \gamma 2$	P	B
P	PP	PB
B	BP	BB

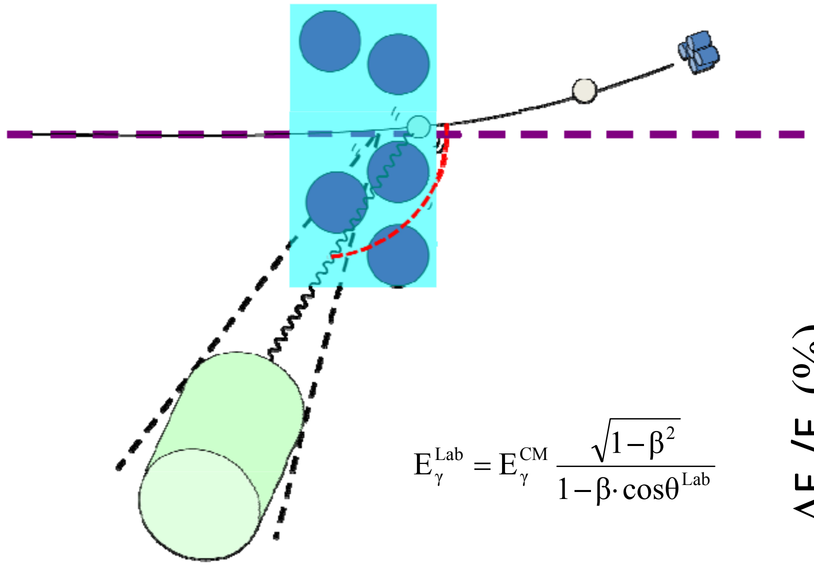


In a γ–γ measurement, the fraction of useful peak-peak coincidence events grows from 4 % to 36%

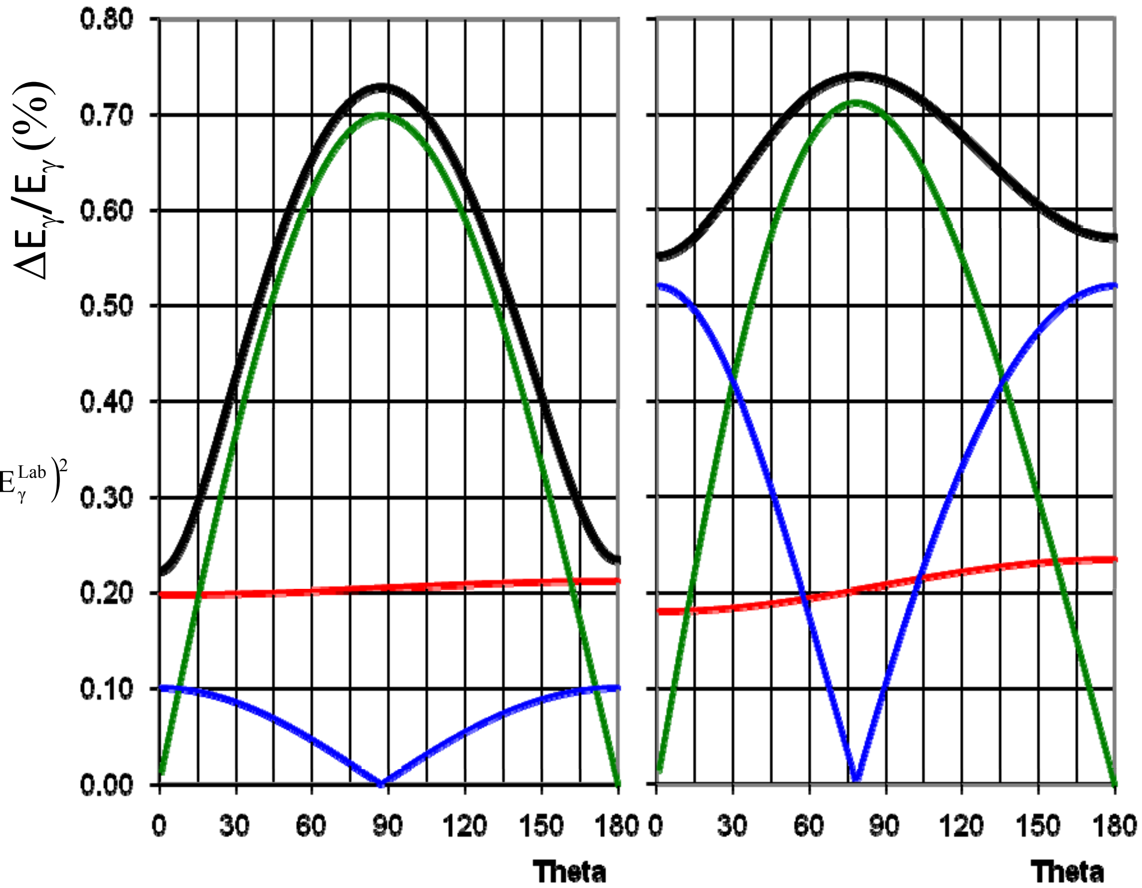
For high fold (F) coincidences the fraction of useful coincidences is

$$P/T^{F}$$

3. Effective Energy Resolution
➔ Doppler Broadening



E_γ	1 MeV	
ΔE_{lab}	$\sqrt{(1.2+0.003*E_{lab})}$	
$\beta(\%)$	5±0.01	20±0.005
$\Delta\Theta$(deg)	8	2



$$E_\gamma^{Lab} = E_\gamma^{CM} \frac{\sqrt{1-\beta^2}}{1-\beta\cdot\cos\theta^{Lab}}$$

$$E_\gamma^{CM} = E_\gamma^{Lab} \frac{1-\beta\cdot\cos\theta^{Lab}}{\sqrt{1-\beta^2}}$$

$$\left(\Delta E_\gamma^{CM}\right)^2 = \left(\frac{\partial E_\gamma^{CM}}{\partial\theta^{Lab}}\right)^2 \left(\Delta\theta^{Lab}\right)^2 + \left(\frac{\partial E_\gamma^{CM}}{\partial\beta}\right)^2 (\Delta\beta)^2 + \left(\frac{\partial E_\gamma^{CM}}{\partial E_\gamma^{Lab}}\right)^2 \left(\Delta E_\gamma^{Lab}\right)^2$$

$$\left(\frac{\Delta E_\gamma^{CM}}{E_\gamma^{CM}}\right)^2 = \left(\frac{\beta\cdot\sin\theta^{Lab}}{1-\beta\cdot\cos\theta^{Lab}}\right)^2 (\Delta\theta)^2 + \quad \text{Opening}$$

$$\left(\frac{\beta-\cos\theta^{Lab}}{\left(1-\beta^2\right)\left(1-\beta\cdot\cos\theta^{Lab}\right)}\right)^2 (\Delta\beta)^2 + \quad \text{Recoil}$$

$$\left(\frac{\Delta E_\gamma^{Lab}}{E_\gamma^{Lab}}\right)^2 \quad \text{Intrinsic}$$

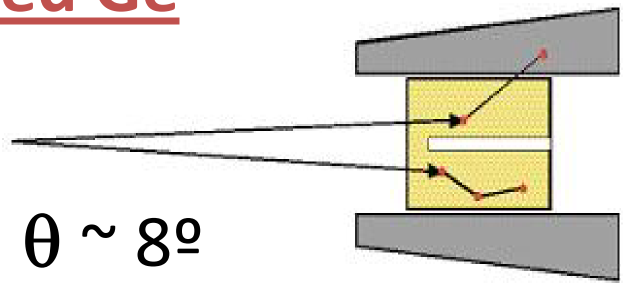
How to improve our γ-detection systems
➔ Idea of γ-ray tracking

Compton Shielded Ge

ε_{ph}	~ 10%
N_{det}	~ 100

Ω ~40%

$\theta \sim 8^{\circ}$

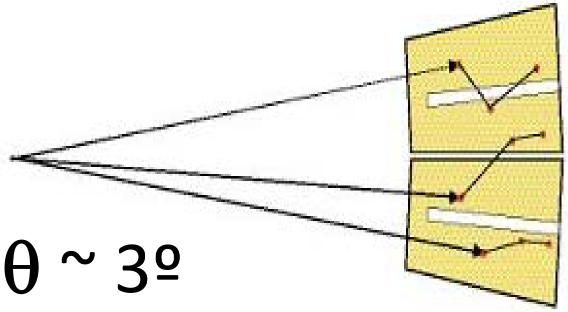


large opening angle means poor energy resolution at high recoil velocity

Ge Sphere

ε_{ph}	~ 50%
N_{det}	~ 1000

$\theta \sim 3^{\circ}$



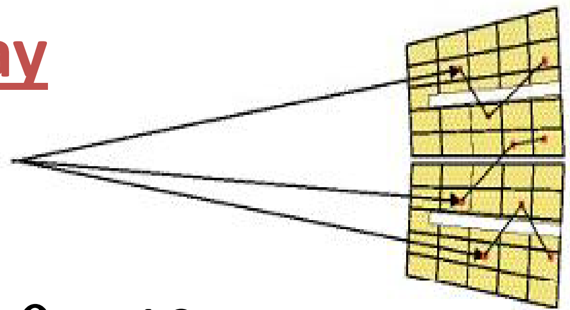
too many detectors are needed to avoid summing effects

Ge Tracking Array

ε_{ph}	~ 50%
N_{det}	~ 100

Ω ~80%

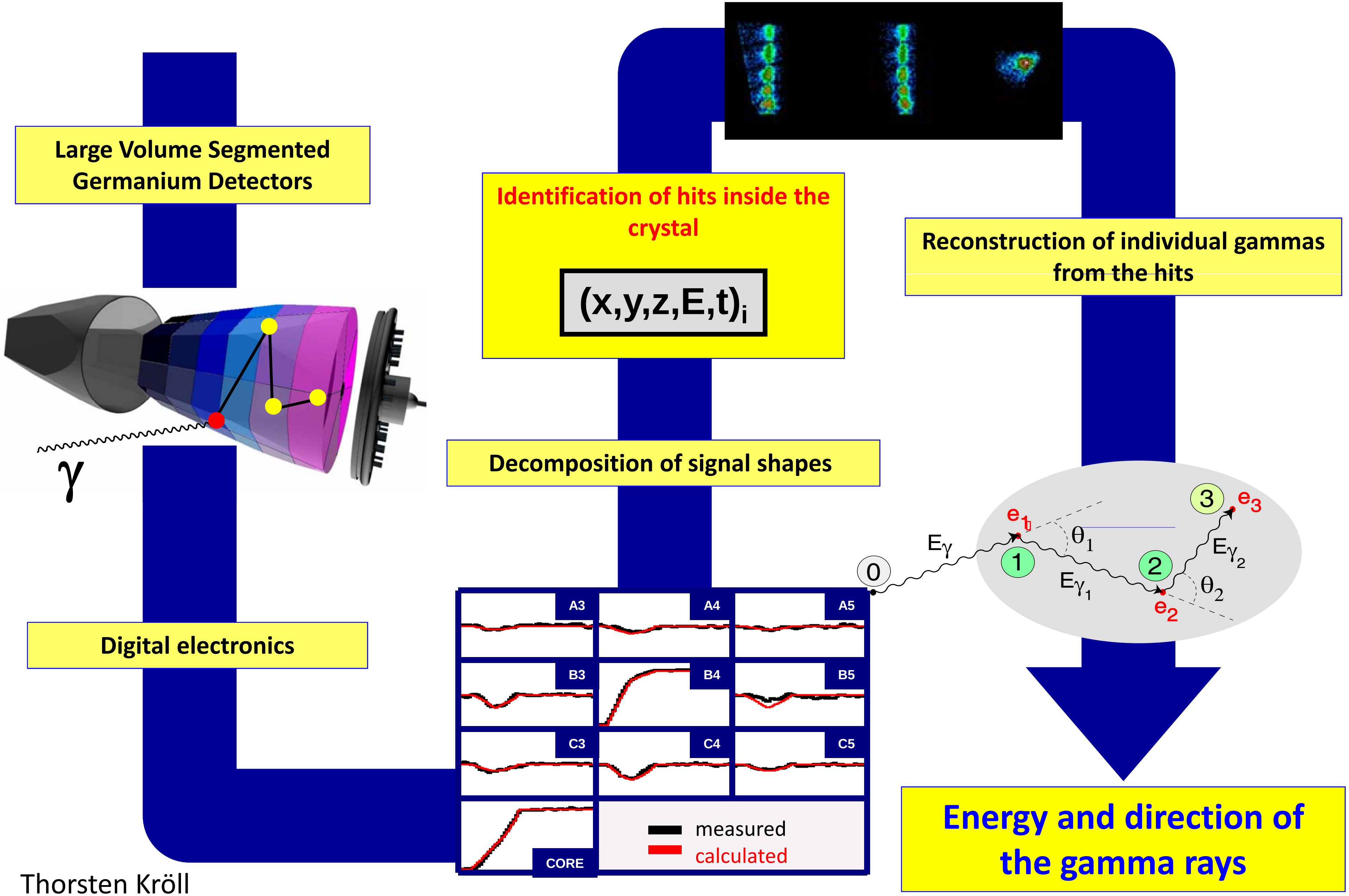
$\theta \sim 1^{\circ}$



Combination of:

- segmented detectors
- digital electronics
- pulse processing
- tracking the γ-rays

Gamma-Ray Tracking Paradigm



Thorsten Kröll

Aim of gamma-ray tracking

- From the deposited energies and the positions of all the interactions points of an event in the detector, reconstruct individual photon trajectories and write out photon energies, incident and scattering directions
- Discard events corresponding to incomplete energy release

Doppler correction

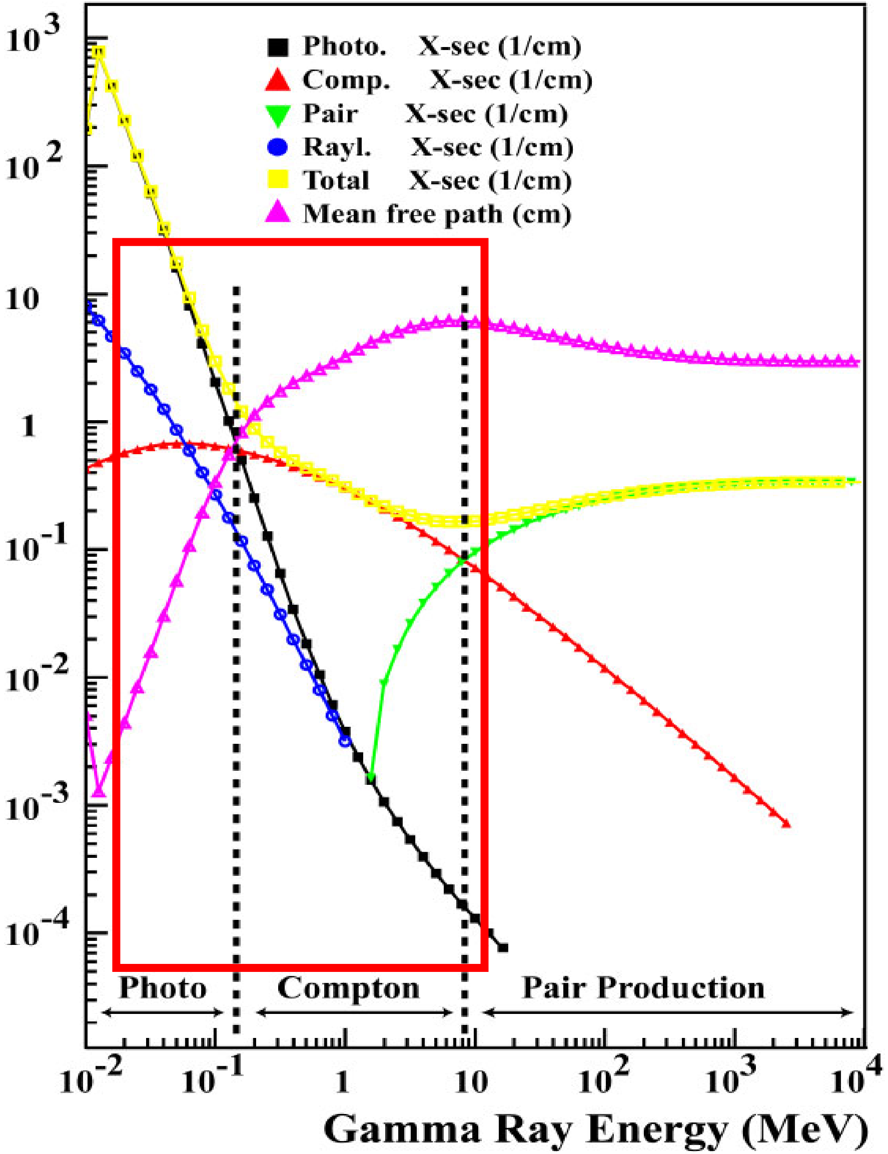
Linear Polarization

e_1, x_1, y_1, z_1
e_2, x_2, y_2, z_2
……………………
e_n, x_n, y_n, z_n

$\rightarrow$

$E_1, (\theta,\phi)_{inc,1}, (\theta,\phi)_{sc,1}.$ …
$E_2, (\theta,\phi)_{inc,2}, (\theta,\phi)_{sc,2}.$ …
………………………………
$E_i, (\theta,\phi)_{inc,i}, (\theta,\phi)_{sc,i}$

Interaction of photons in germanium



Mean free path determines size of detectors:

λ(10 keV)	~ 55 μm
λ(100 keV)	~ 0.3 cm
λ(200 keV)	~ 1.1 cm
λ(500 keV)	~ 2.3 cm
λ(1 MeV)	~ 3.3 cm
λ(2 MeV)	~ 4.5 cm
λ(5 MeV)	~ 5.9 cm
λ(10 MeV)	~ 5.9 cm

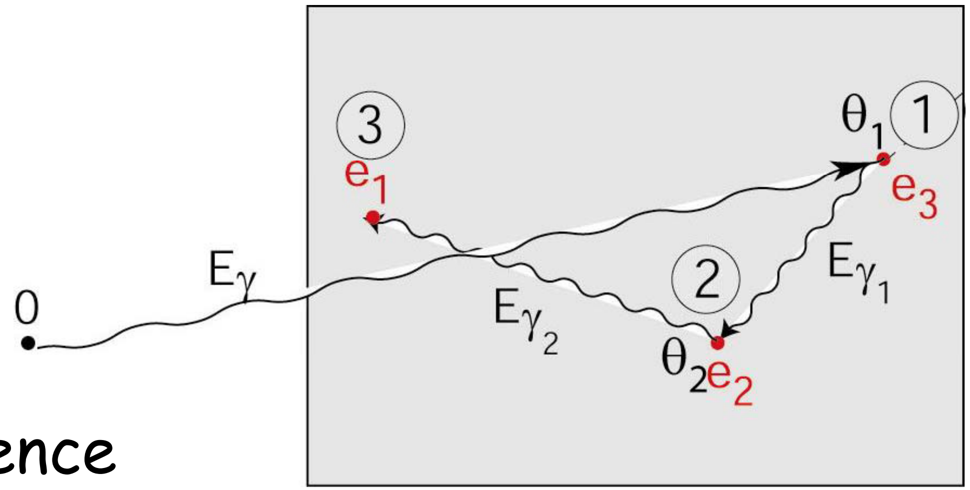
Tracking of Compton Scattered Events

Source position is known

Questions :

1) Is the event complete

2) What is the right sequence



$$E_{\gamma}^{E} = \sum_{i=n}^{N-1} e_i \qquad E_{\gamma'}^{E} = \sum_{i=n+1}^{N-1} e_i$$

$$\cos\theta^{P} = \frac{\overrightarrow{01}\cdot\overrightarrow{12}}{\left|\overrightarrow{01}\right|\cdot\left|\overrightarrow{12}\right|} \quad \Rightarrow \quad E_{\gamma'}^{P} = \frac{E_{\gamma}^{E}}{1+\frac{E_{\gamma}^{E}}{m_0c^2}\left(1-\cos\theta^{P}\right)}$$

$$\chi_n^2 = \left(\frac{E_{\gamma'}^{E} - E_{\gamma'}^{P}}{\sigma}\right)^2 \quad \Rightarrow \quad \chi^2 \approx \sum_{n=1}^{N-1} \chi_n^2$$

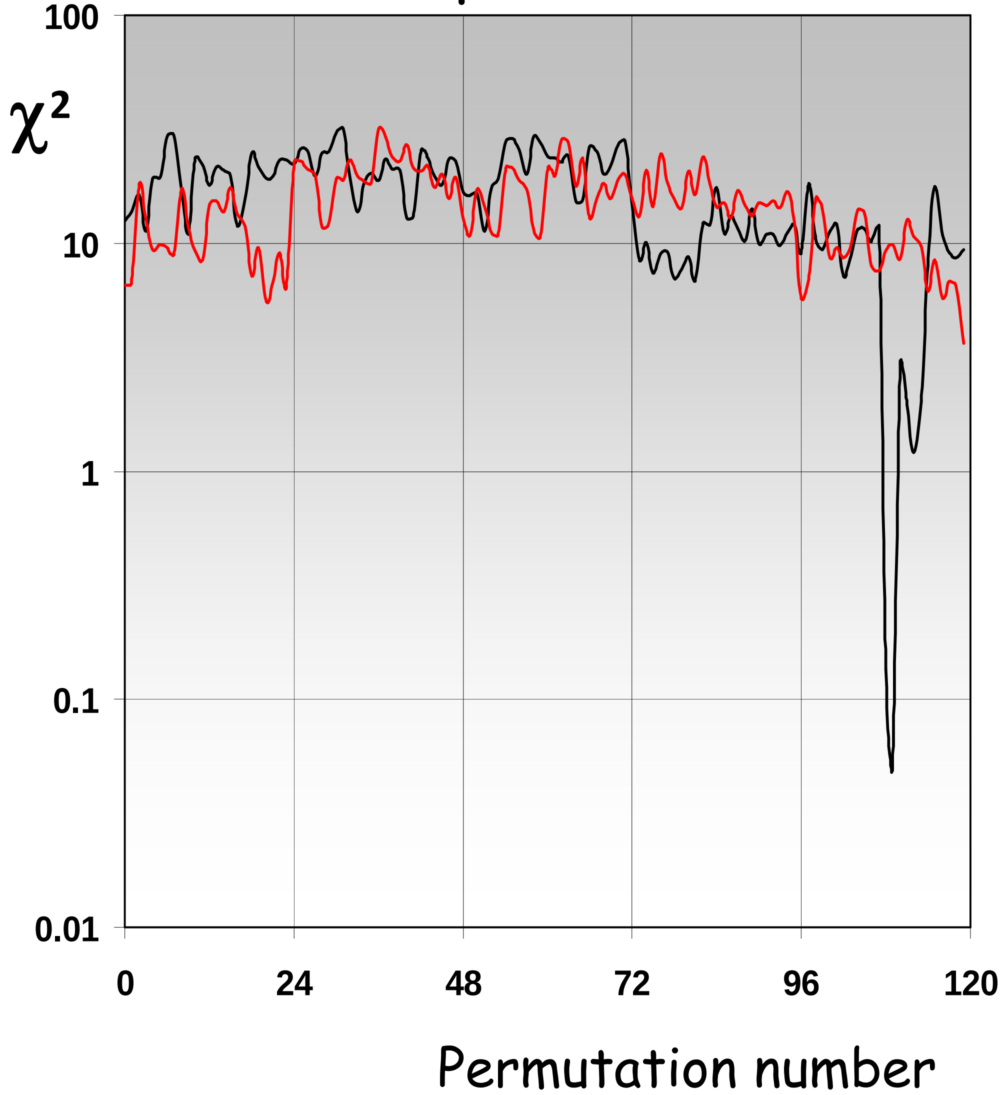
Tracking of Compton Scattering Events

Find χ^2 for the N! permutations of the interaction points

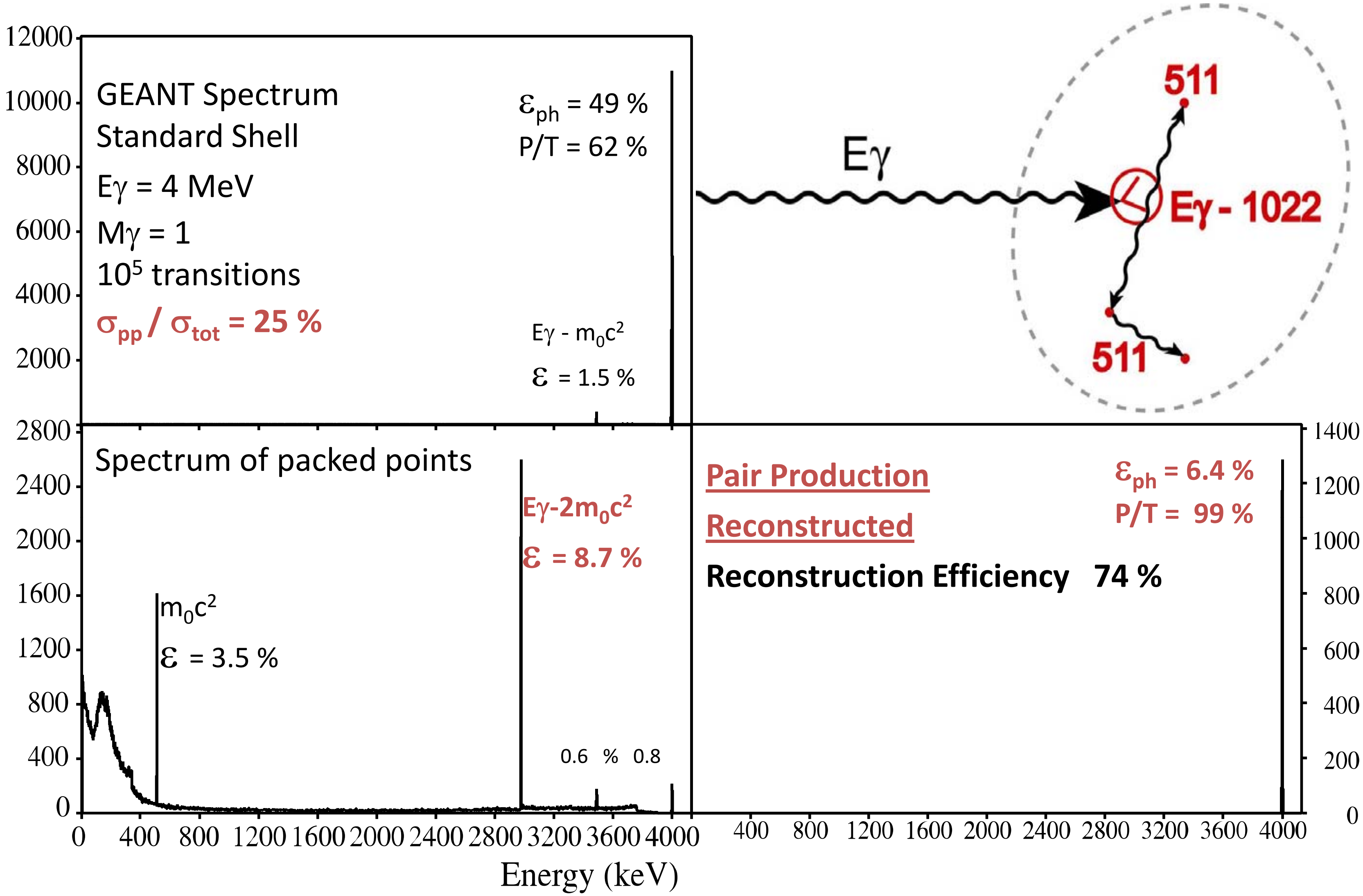
Fit parameter is the permutation number

Accept the best permutation if its χ^2 is below a predefined value

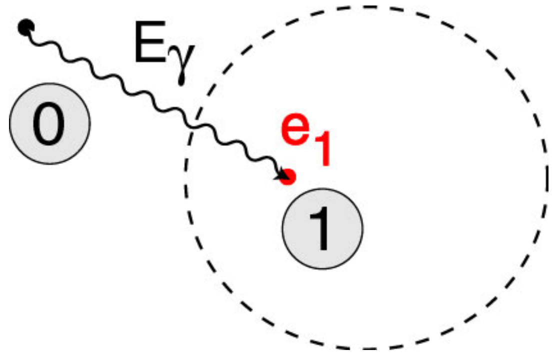
Two 5-point events



Reconstruction of Pair-Production Events
based on recognition of first hit

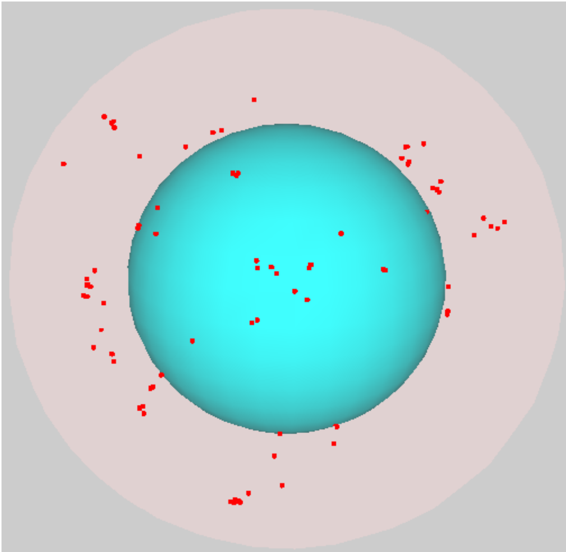


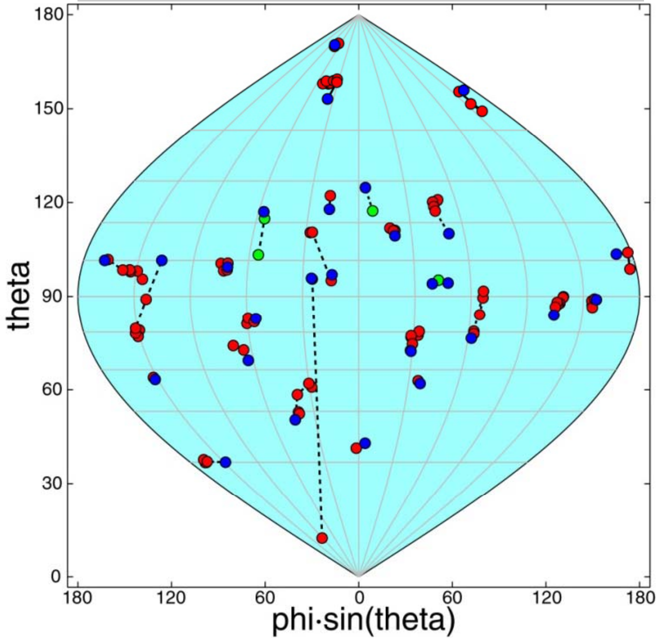
Reconstruction of single interaction events



- There is not much we can do
- Acceptance criterion is probabilistic: **depth < k·λ(e_1)**

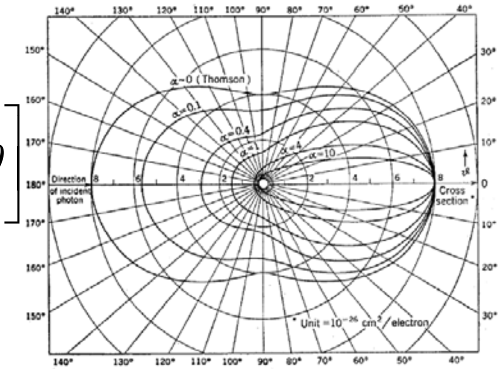
Reconstruction of multi-gamma events





- Analysis of all partitions of measured hits is not feasible:
  Huge computational problem
  (~10^{23} partitions for 30 points)
  Figure of merit is ambiguous → the total figure of merit of the "true" partition not necessarily the minimum
- Forward peaking of Compton scattering cross-section implies that the hits of one gamma tend to be localized along the emission direction

$$\frac{d\sigma_{KN}}{d\Omega} = Z\frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E}+\frac{E}{E'}-\sin^2\theta\right]$$

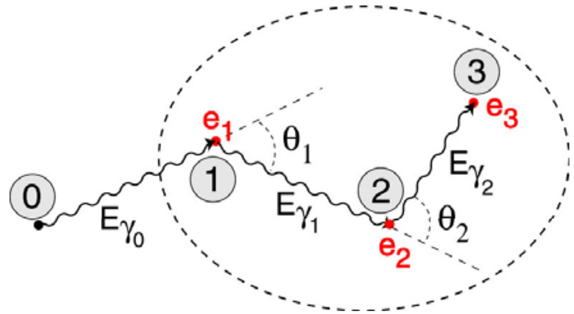


- The most used algorithm (G.Schmid et al. NIMA 430 1999, GRETA) starts by identifying clusters of points which are then analyzed as individual candidates gammas, accepted as said before

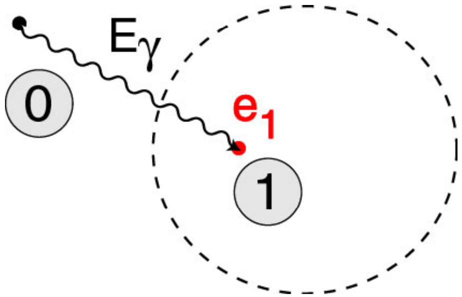
Forward Tracking implemented in AGATA

1. Create cluster pool => for each cluster, $E_{\gamma 0} = \sum$ cluster depositions
2. Test the 3 mechanisms
   1. do the interaction points satisfy the **Compton** scattering rules ?

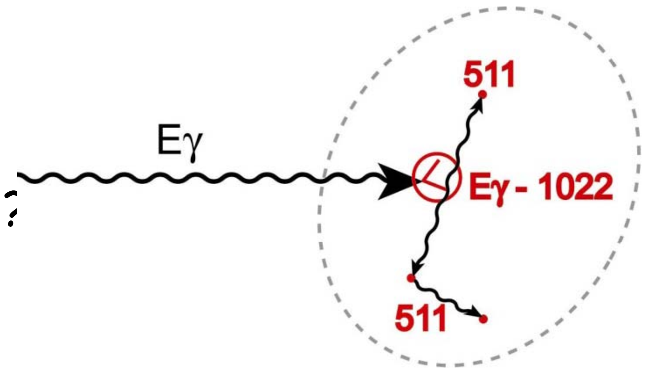
$$\chi^2 \approx \sum_{n=1}^{N-1} W_n \cdot \left(\frac{E_{\gamma'} - E_{\gamma'}^{Pos}}{E_\gamma} \right)_n^2$$



   2. does the interaction satisfy **photoelectric** conditions (e_1,depth,distance to other points) ?



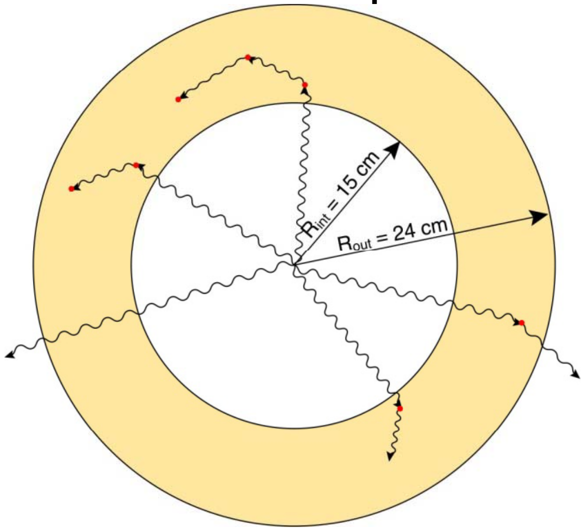
   3. do the interaction points correspond to a **pair production** event ?
      $E_{1st} = E_\gamma - 2\,m_e c^2$
      and the other points can be grouped in two subsets with energy ~ 511 keV ?



3. Select clusters based on χ^2

Performance of the Germanium Shell

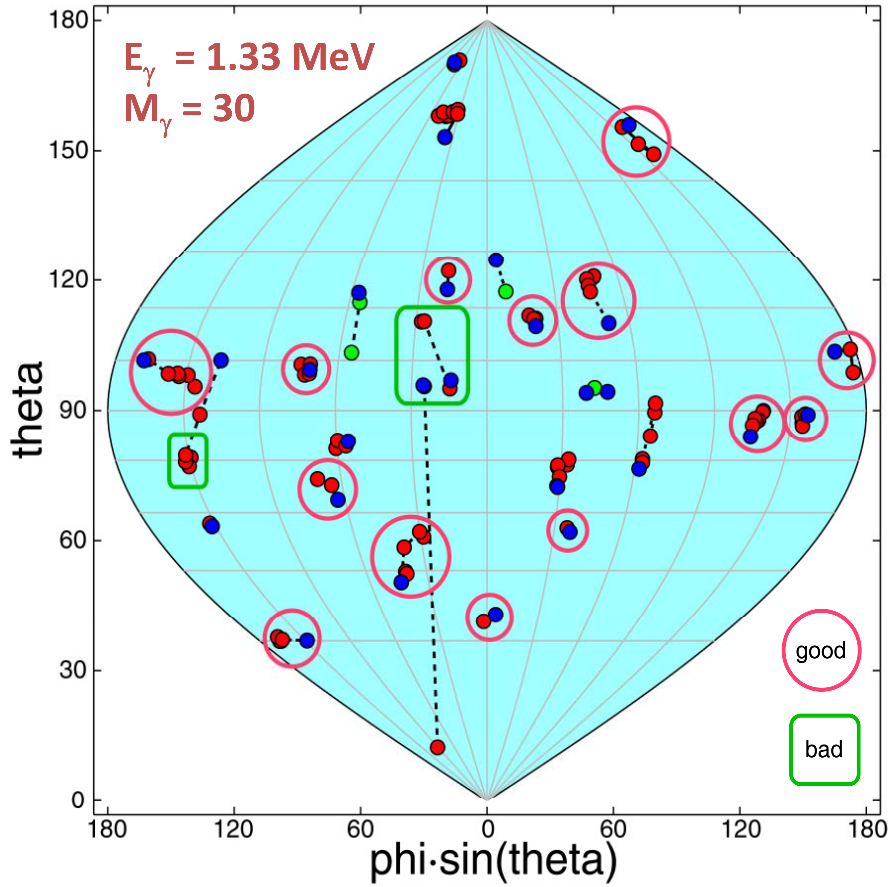
Idealized configuration to determine maximum attainable performance.



1.33 MeV	$M_\gamma = 1$	$M_\gamma = 30$
ε_{ph} (%)	65	36
P/T(%)	85	60

Reconstruction by Cluster-Tracking
Packing Distance: 5 mm
Position Resolution: 5 mm (at 100 keV)

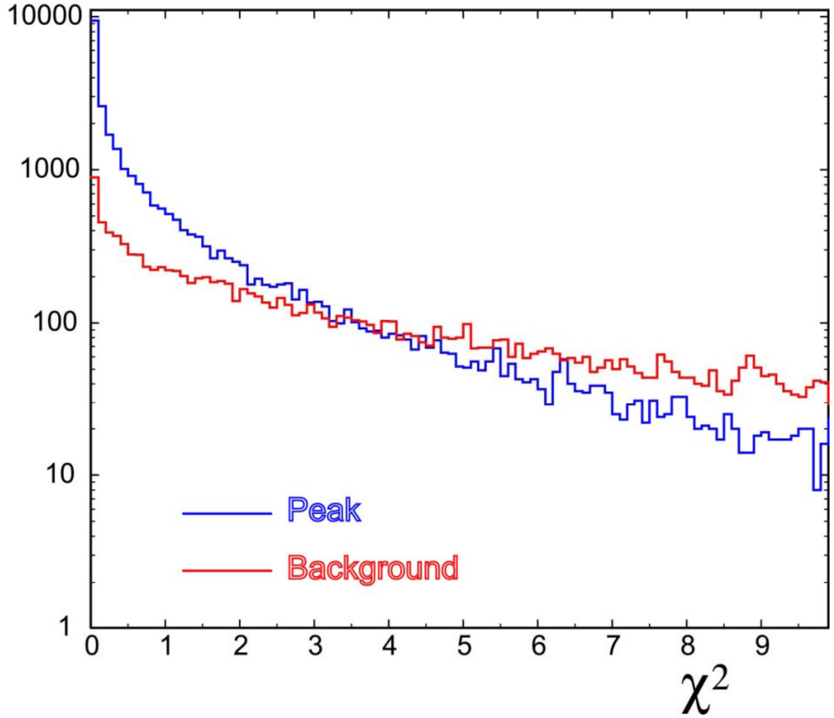
A high multiplicity event

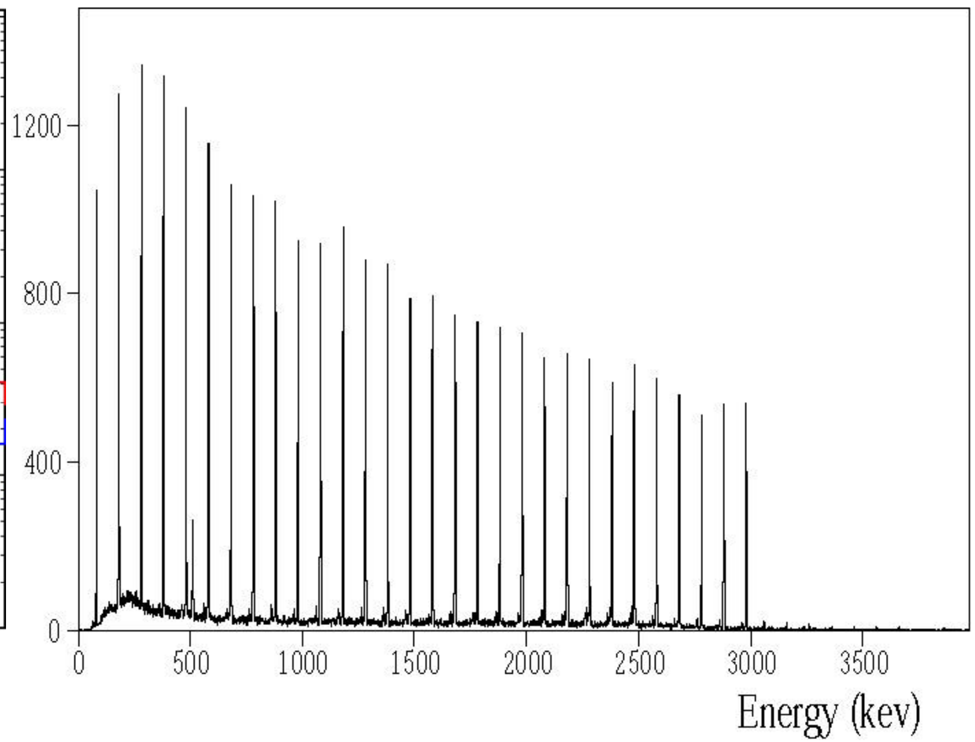


27 gammas detected -- 23 in photopeak
16 reconstructed -- 14 in photopeak

Identification is not 100% sure

➔spectra will always contain background



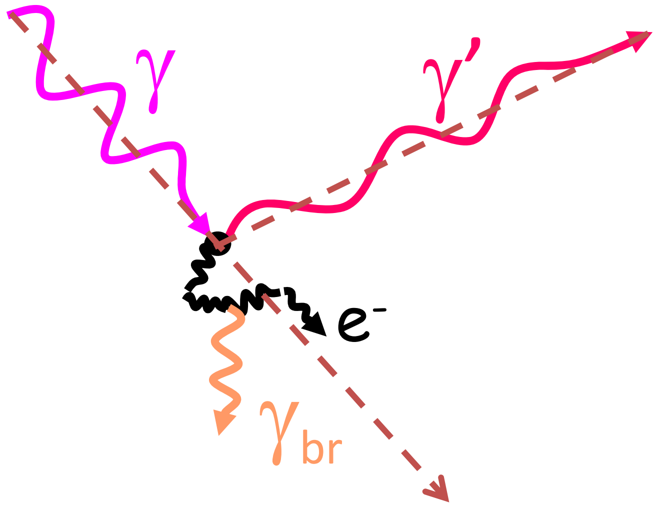


The acceptance value determines the quality (P/T ratio) of the spectrum

Often we use the **R = Efficiency•PT** to qualify the reconstructed spectra

Fundamental effects limiting the performance

- Interaction position $\neq$ position of energy deposition
- Bremsstrahlung

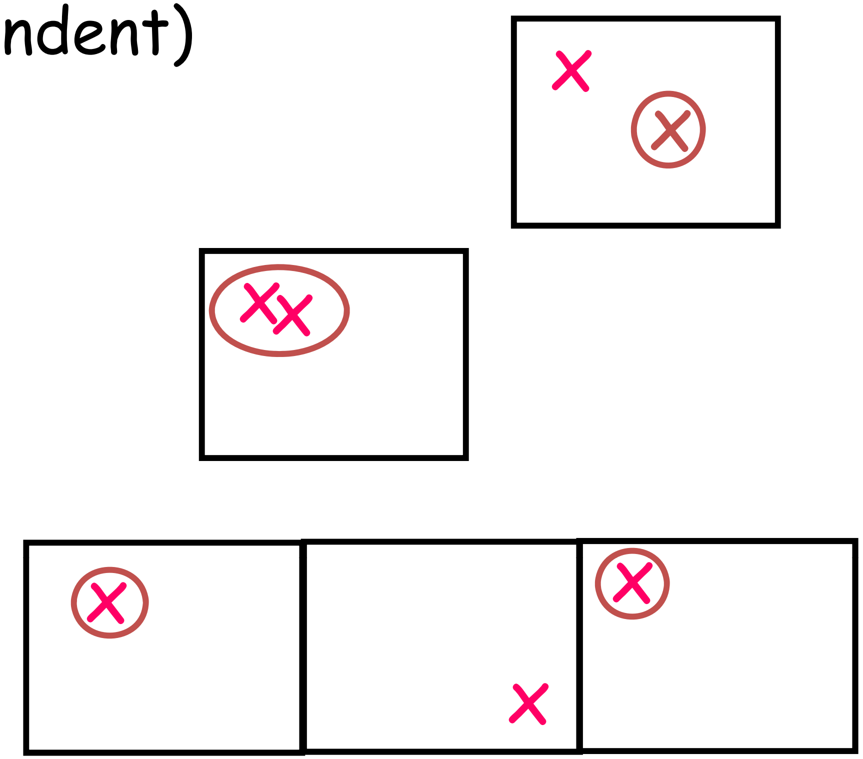


- Rayleigh scattering ➔ change incident direction (relevant at low energy & end of track)
- Momentum profile of electron ➔ change scattering direction (relevant at low energy & end of track)

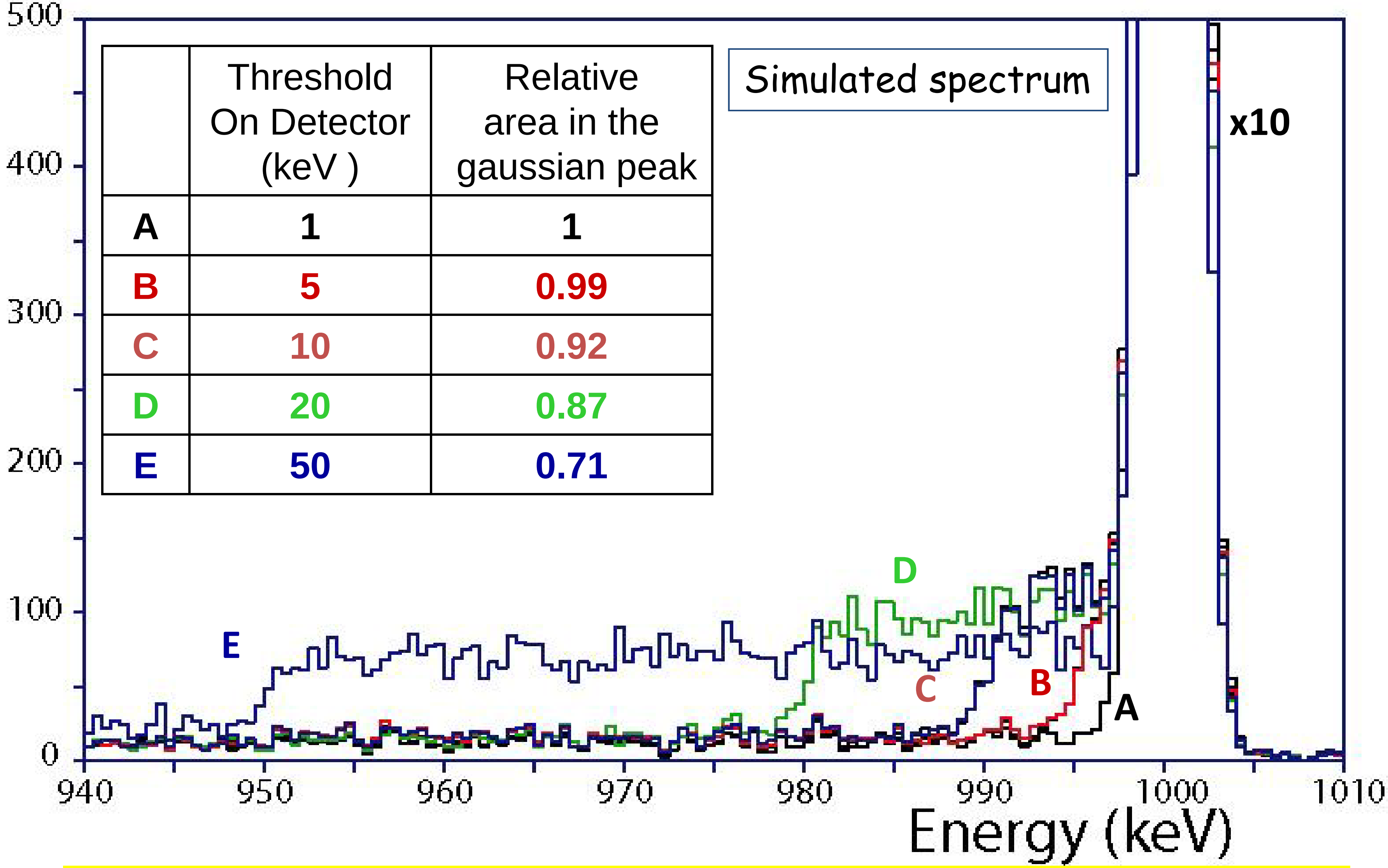
Fortunately (?) these effects are masked by the poor position resolution of practical Ge detectors

Practical Effects limiting the performance

- uncertainty in position of interaction:
  (position & energy dependent)
- position resolution
- energy threshold
- energy resolution
- dead materials ...



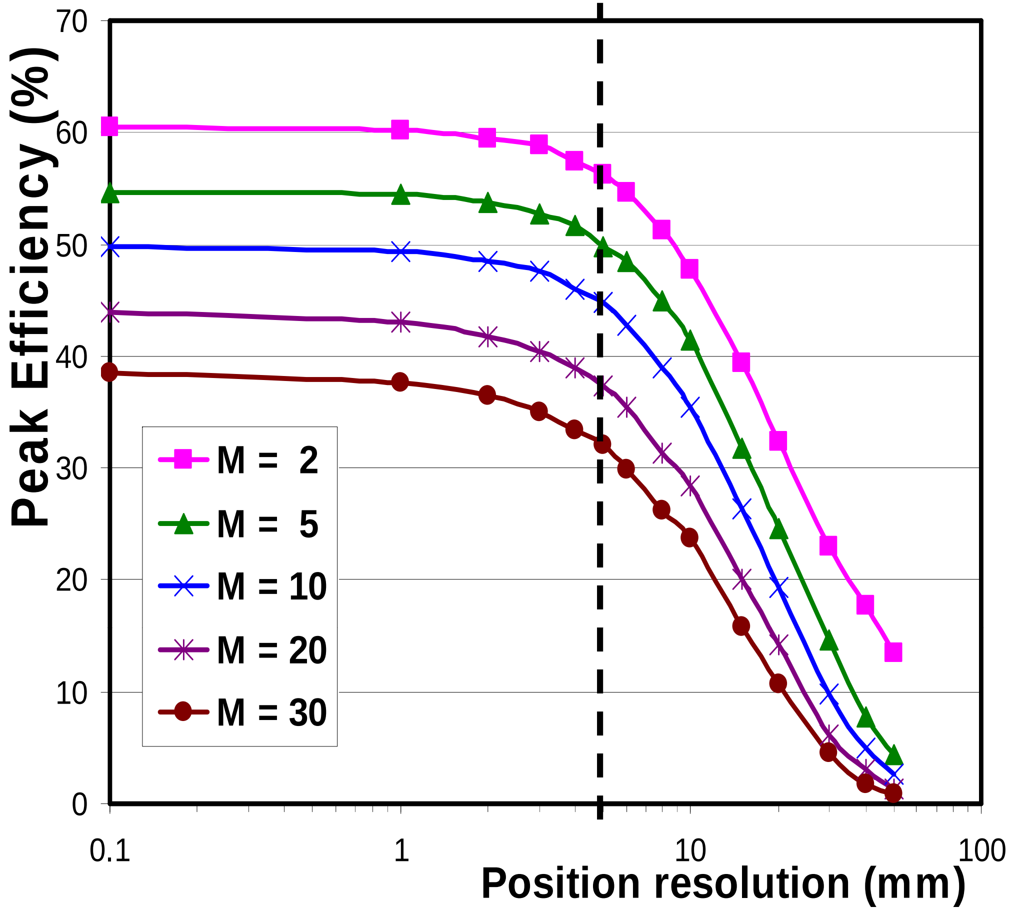
Effect of energy-threshold on tracking efficiency



	Threshold On Detector (keV)	Relative area in the gaussian peak
A	**1**	**1**
B	**5**	**0.99**
C	**10**	**0.92**
D	**20**	**0.87**
E	**50**	**0.71**

Effect completely removed, if all hits in a crystal are assigned to the same gamma

Efficiency of Standard Ge Shell vs. Position Resolution and γ Multiplicity



The biggest losses are due to multiplicity (mixing of points) not to bad position resolution

5 mm is the standard "realistic" packing and smearing assumption

Reminder: when quoting Position Resolution

AGATA uses FWHM

GRETA uses σ

If positions inside segments are not known, performance is "only" a factor 2 worse

Standard shell; E_γ = 1.33 MeV; Packing=Smearing; Energy independent smearing

Implementations of the concept

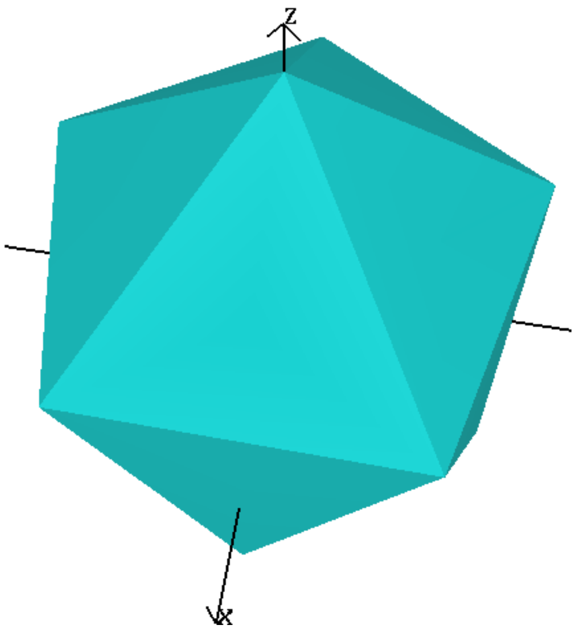
- Specs
- Configurations of 4π Arrays
- Monte Carlo
- The detectors
- Status

Requirements for a Gamma Tracking Array

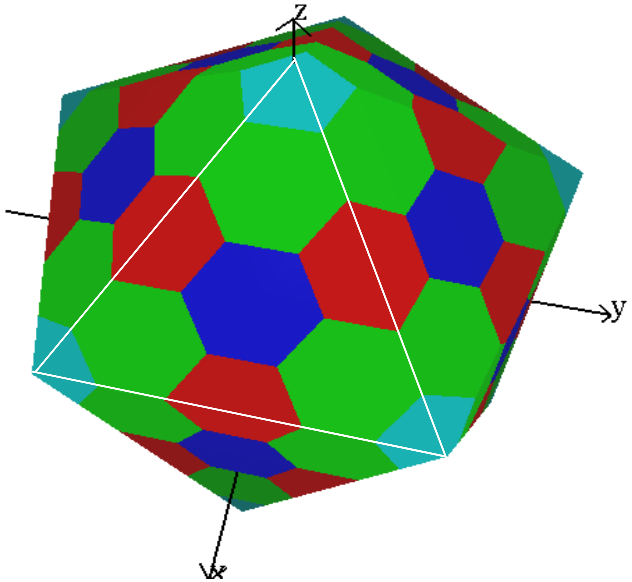
efficiency, energy resolution, dynamic range, angular resolution, timing, counting rate, **modularity**, angular coverage, inner space

Quantity	Target Value	Specified for
Photo-peak efficiency (ε_{ph})	**50 %** **25 %** **10 %**	E_γ = 1 MeV, M_γ = 1, $\beta < 0.5$ E_γ = 1 MeV, M_γ =30, $\beta < 0.5$ E_γ =10 MeV, M_γ = 1
Peak-to-total ratio (P/T)	**60 - 70 %** **40 - 50 %**	E_γ = 1 MeV, M_γ = 1 E_γ = 1 MeV, M_γ = 30
Angular resolution ($\Delta\theta_\gamma$)	**better than 1°**	for $\Delta E/E < 1\%$ at large β
Maximum event rates	**3 MHz** **300 kHz**	M_γ = 1 M_γ = 30
Inner diameter	**> 34 cm**	for ancillary detectors

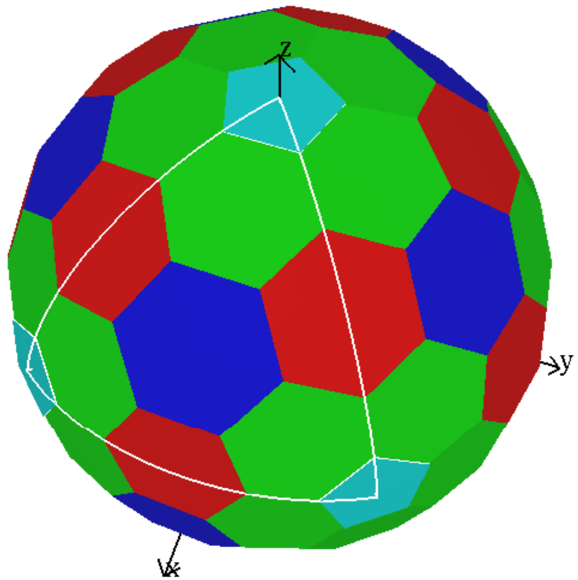
Building a Geodesic Ball (1)



Start with a platonic solid e.g. the icosahedron



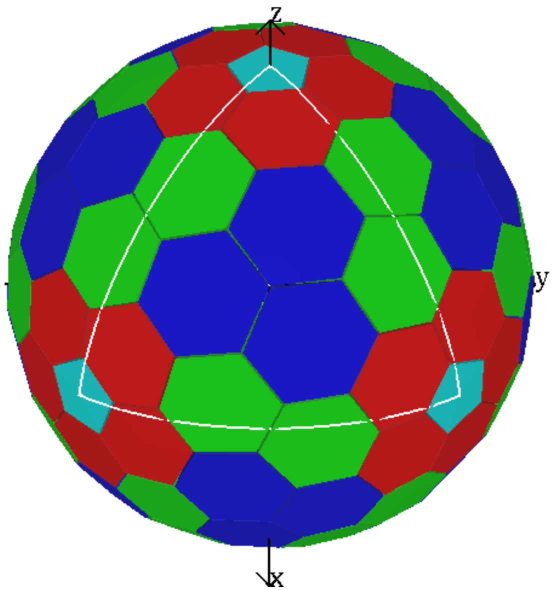
On its faces, draw a regular pattern of triangles grouped as hexagons and pentagons. E.g. with 110 hexagons and (always) 12 pentagons



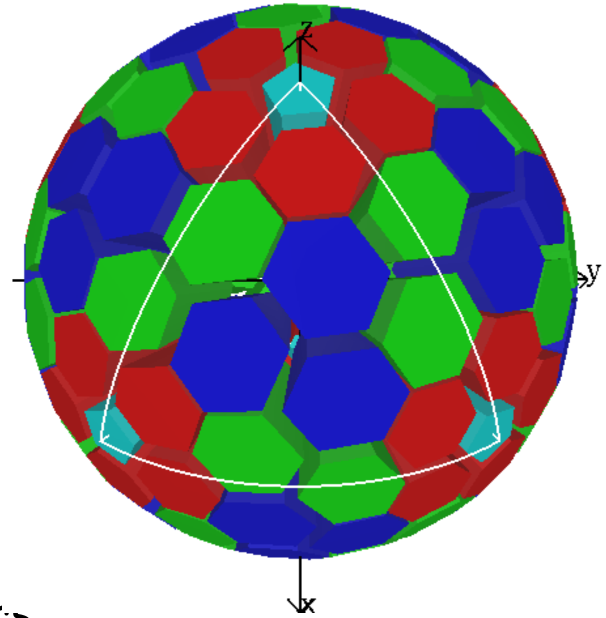
Project the faces on the enclosing sphere; flatten the hexagons.

Building a Geodesic Ball (2)

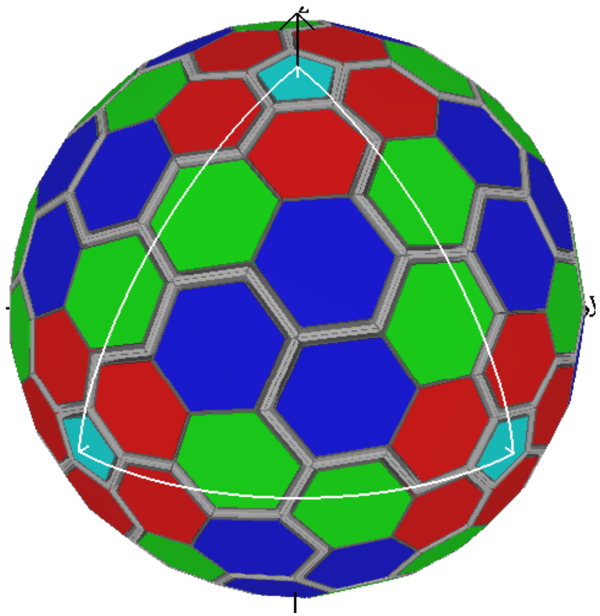
Al capsules	0.4 mm spacing	
	0.8 mm thick	
Al canning	2.0 mm spacing	
	1.0 mm thick	



A radial projection of the spherical tiling generates the shapes of the detectors. Ball with 180 hexagons.



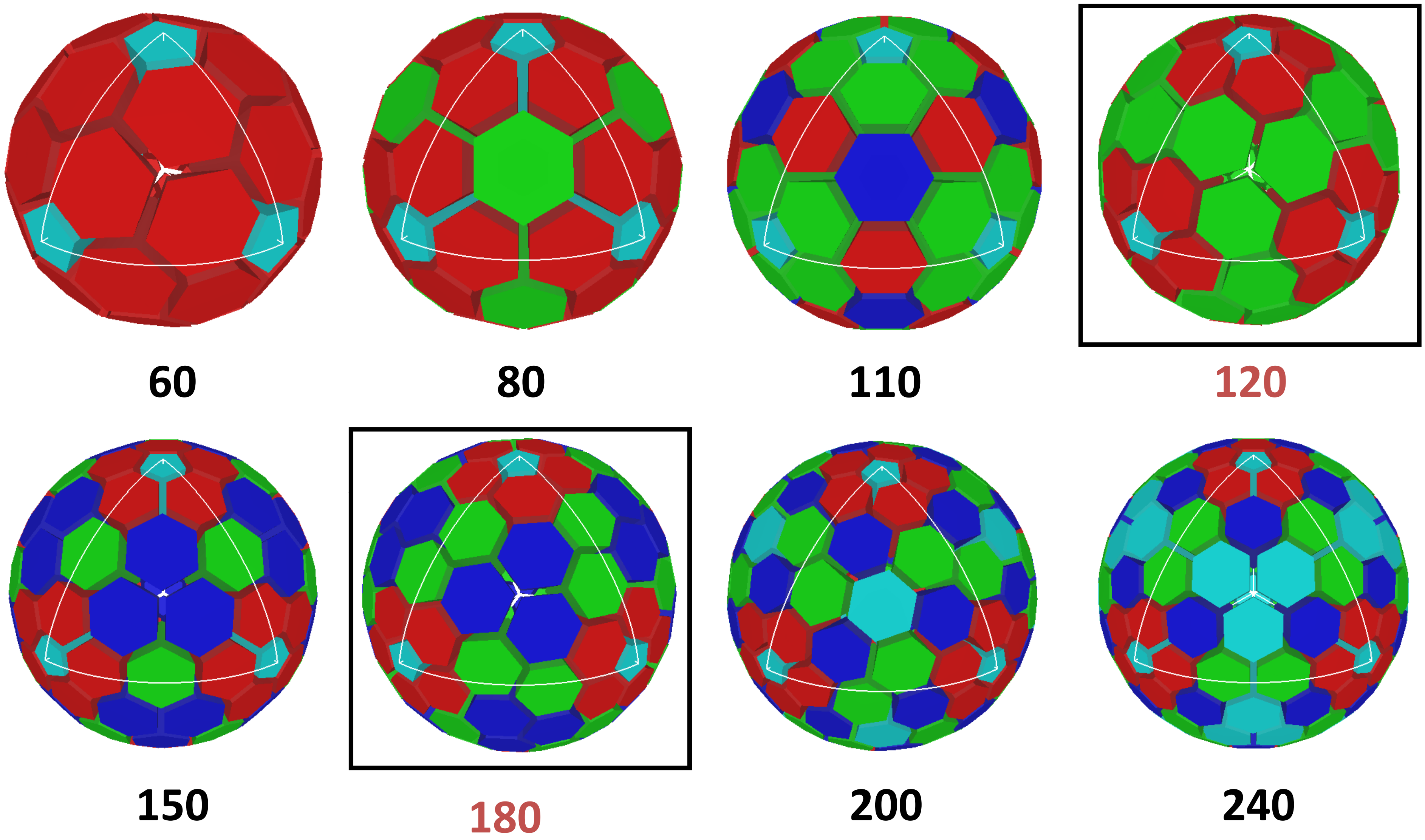
Space for encapsulation and canning obtained cutting the crystals. In the example, 3 crystals form a triple cluster



Add encapsulation and part of the cryostats for realistic MC simulations

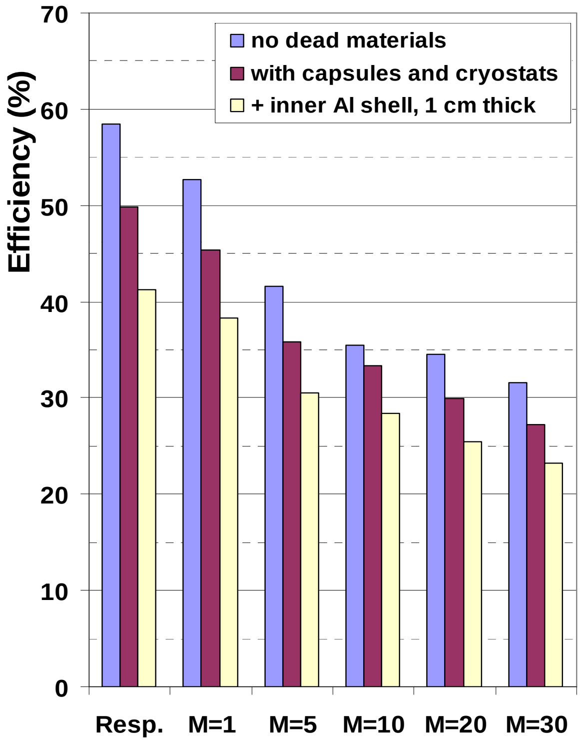
Geodesic Tiling of Sphere

using 60–240 hexagons and 12 pentagons

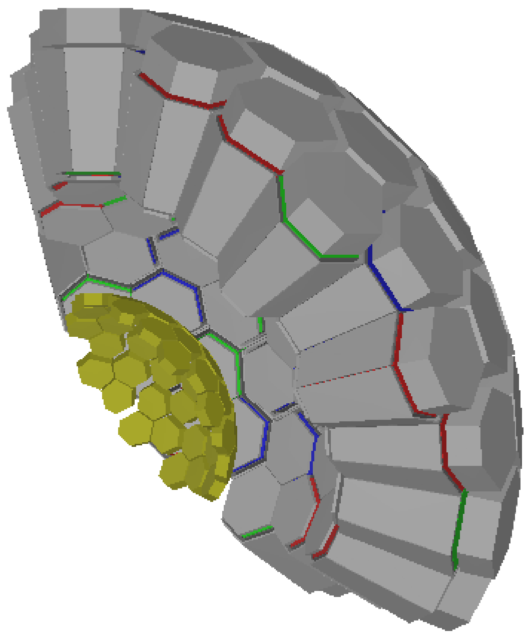


AGATA Monte Carlo Simulations

- Using the C++ package GEANT4, with extended geometry classes
- Geometry defined by an external program
- GEANT4 has good models of low energy interaction mechanisms of γ rays
- Simulations take into account dead materials and possible inner detectors
- Provides input to γ-ray tracking programs which performs further actions (packing and smearing) to make results as realistic as possible

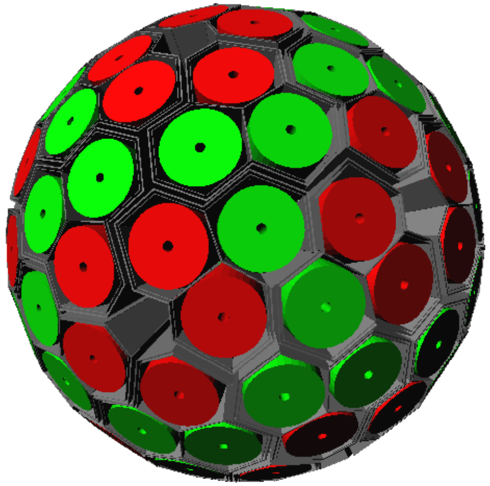


Thickness of	mm
Capsule side	0.8
Cryostat side	1.5
front	3.0
back	30
Inner "ball"	10

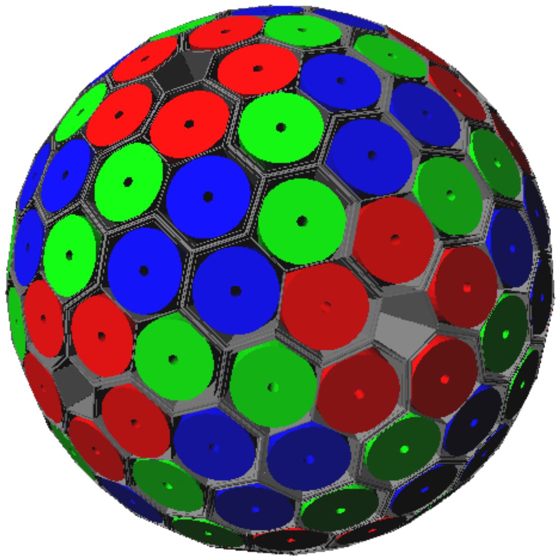


Package written by Enrico Farnea, INFN Padova

Performance of the 2 Configurations



120 crystals

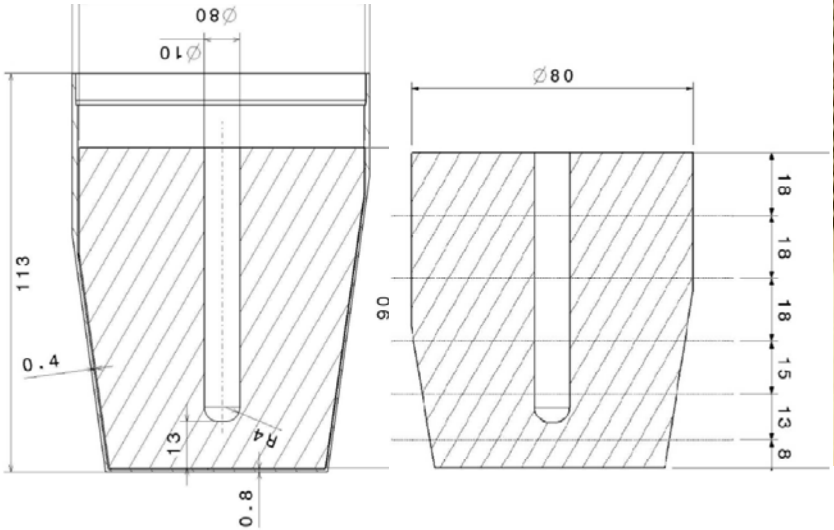


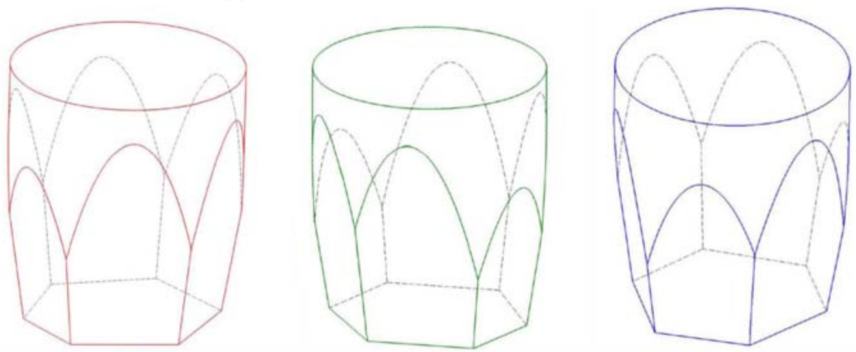
180 crystals

Configuration	A120	A120F	A120C4	A180
# of crystals / clusters	120 / 40	120 / 40	120 / 30	180 / 60
# of crystal / cluster shapes	2 / 2	6 / 2	2 / 1	3 / 1
Covered solid angle (%)	71.0	77.8	78.0	78.4
Germanium weight (kg)	232	225	230	374
Centre to crystal-face (cm)	19.7	18	18.5	23.5
Electronics channels	4440	4440	4440	6660
Efficiency at $M_\gamma = 1$ (%)	32.9	36.9	36.4	38.8
Efficiency at $M_\gamma = 30$ (%)	20.5	22.0	22.1	25.1
P/T at $M_\gamma = 1$ (%)	52.9	53.0	51.8	53.2
P/T at $M_\gamma = 30$ (%)	44.9	43.7	43.4	46.1

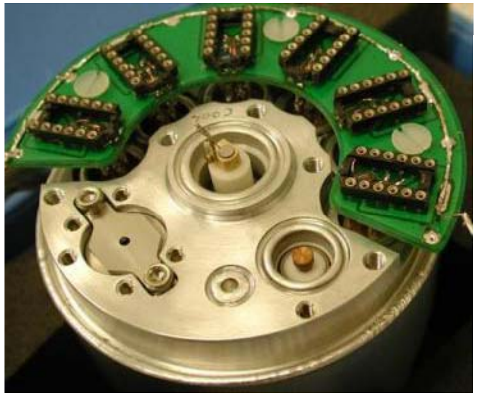
GRETA → 120 crystals packed in 30 4-crystal modules
AGATA → 180 crystals packed in 60 3-crystal modules

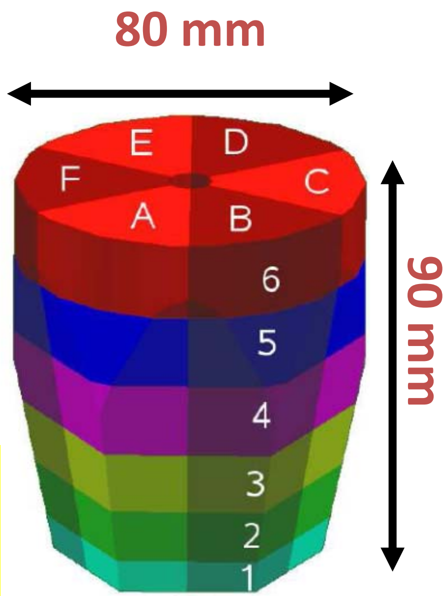
AGATA Crystals





(d) A - red (e) B - green (f) C - blue

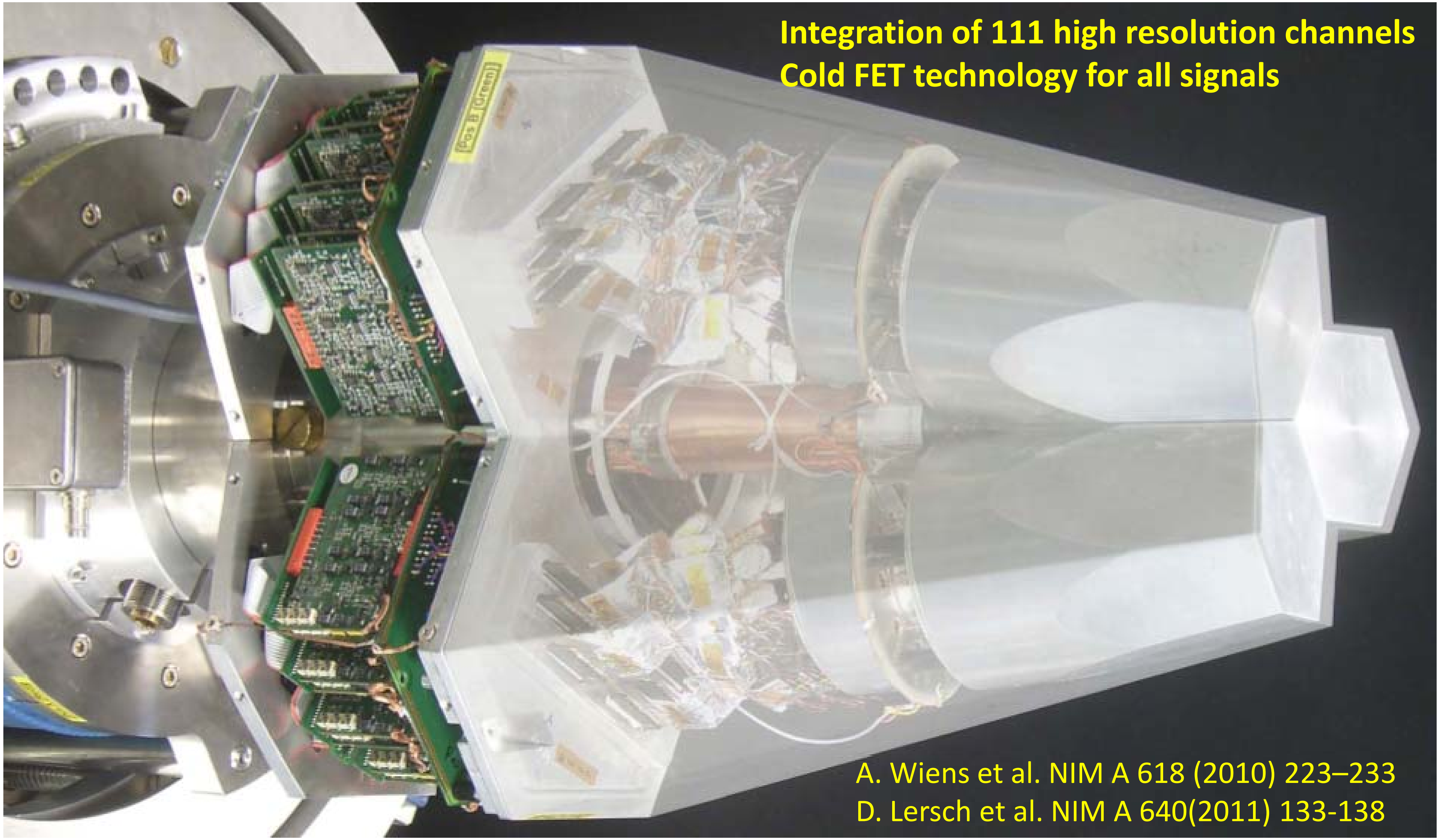




Volume ~370 cc Weight ~2 kg
(the 3 shapes are volume-equalized to 1%)

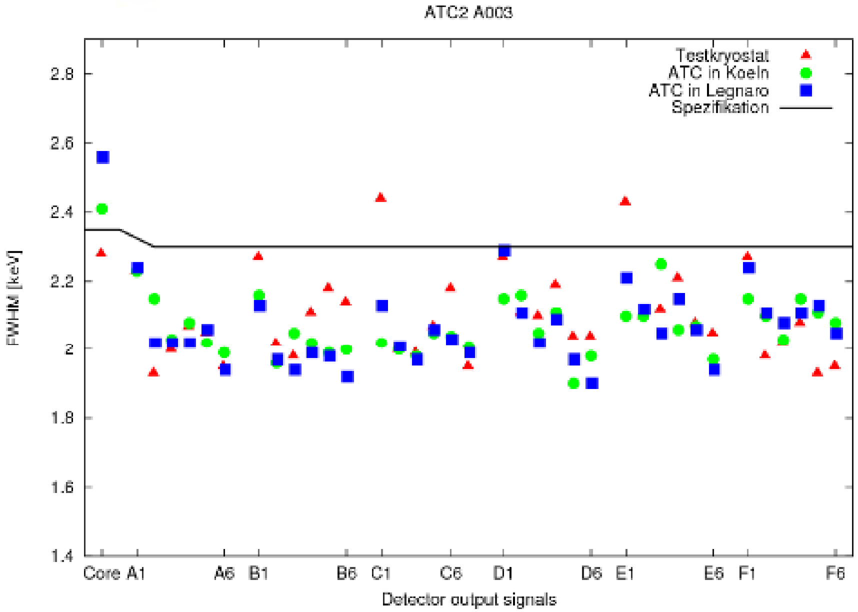
6x6 segmented cathode

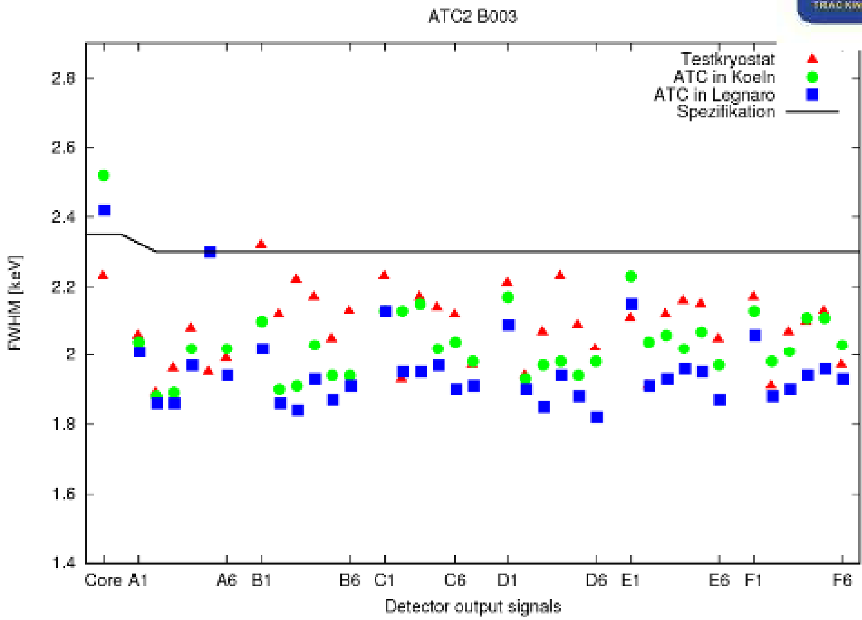
Agata Triple Cluster

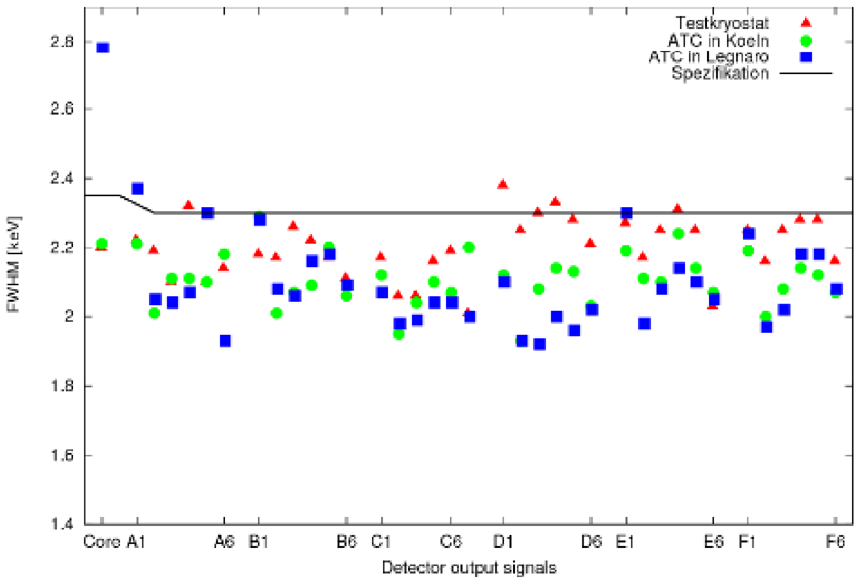


Courtesy P. Reiter

AGATA triple cluster ATC2







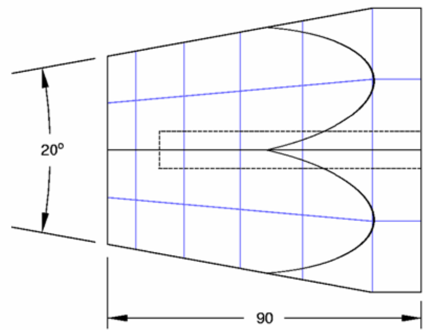
Measured at Köln and Legnaro

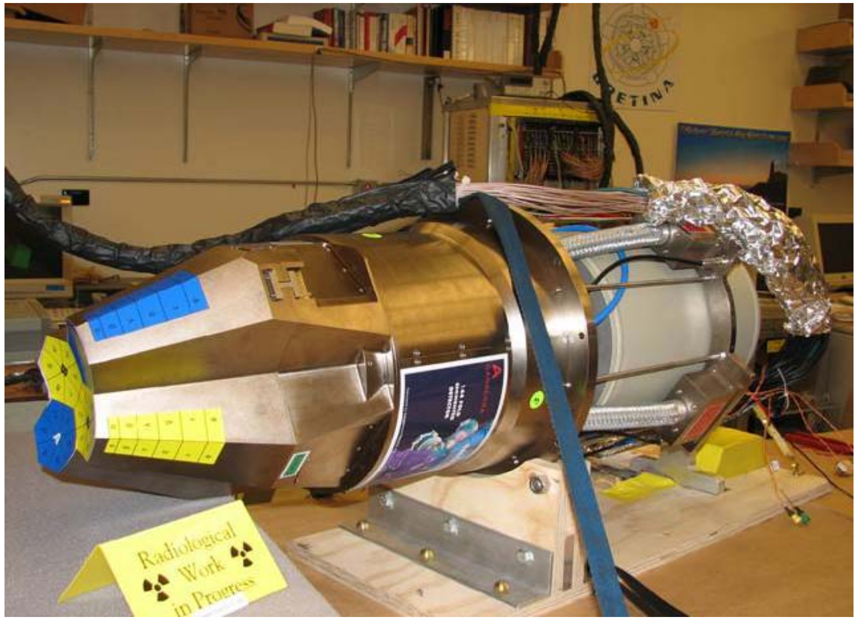
Mean values energy resolution segments at 1,3 MeV:

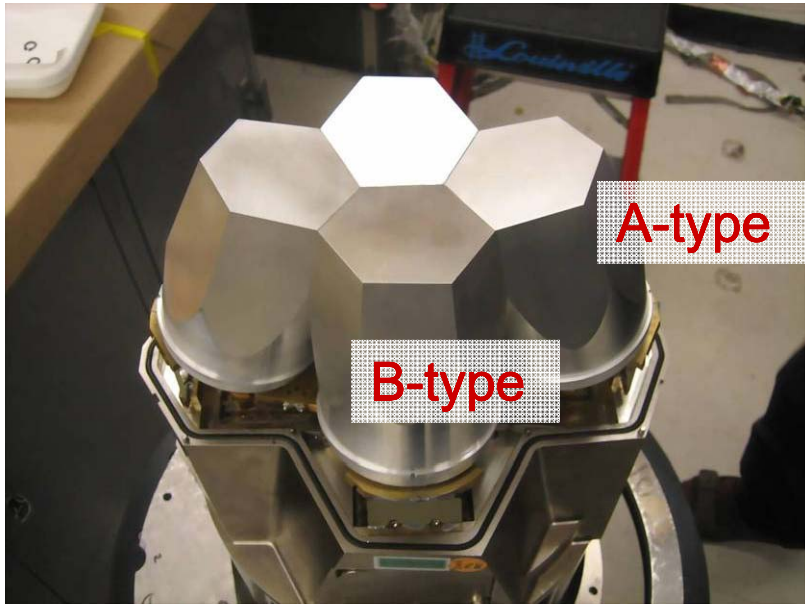
	IKP	/ Legnaro
A003:	2,06 keV	/ 2,06 keV
B003:	2,03 keV	/ 1,94 keV
C005:	2,11 keV	/ 2,08 keV

GRETINA Quadruple Cluster

4 crystals in one cryostat
36 fold segmented crystals
2 types of crystal shape
Cold FET for cores, warm for segments
148 high resolution channels per cluster







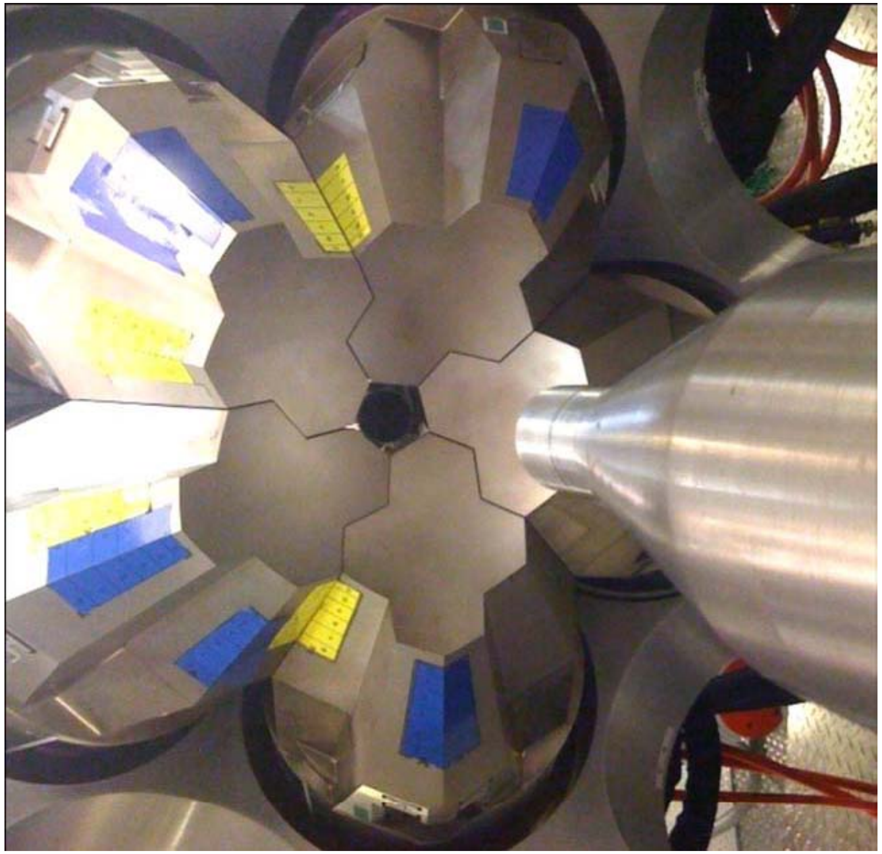
Courtesy I-Yang Lee

First implementations of the γ-ray tracking array concept

AGATA Demonstrator @ LNL

15 crystals in 5 TC
Commissioned in 2009 (with 3 TC)
Experiments since 2010 (mostly with 4 TC)
Completed with the 5th TC, May 2011
32 crystals ordered, ~ 18 accepted

GRETINA at LBNL

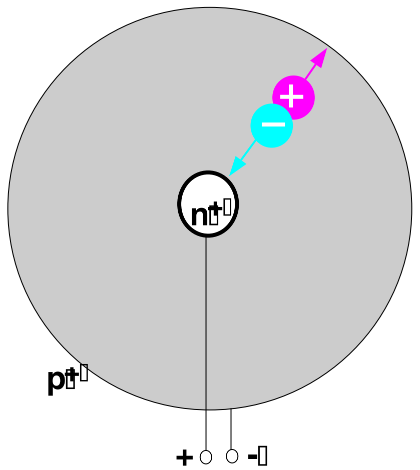


28 crystals (+2 spares) in 7 quads
Engineering runs started April 2011
Now taking data at LBNL, coupled the BGS

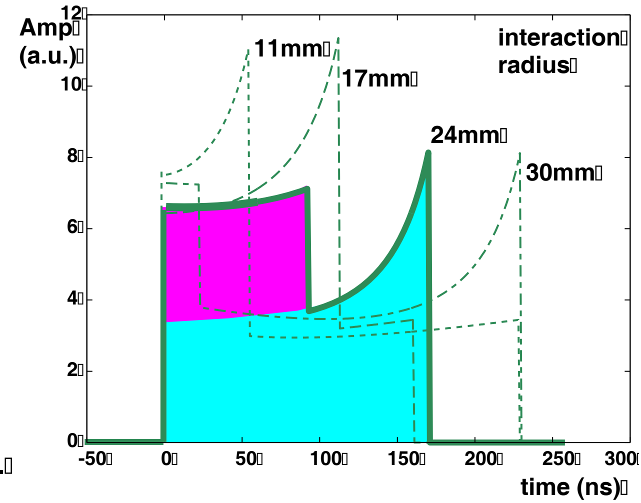
The big challenge: operating the Ge detectors in position sensitive mode

Pulse shapes in segmented detectors

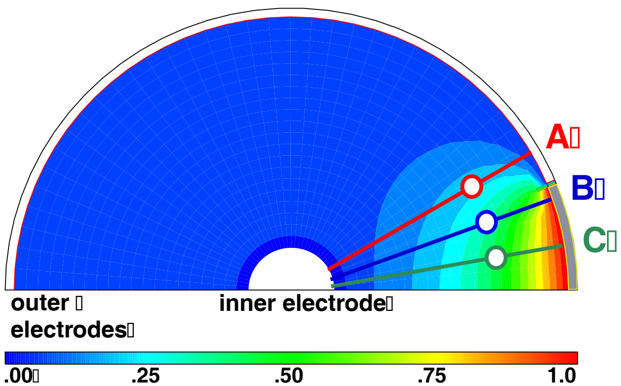
(very schematic)



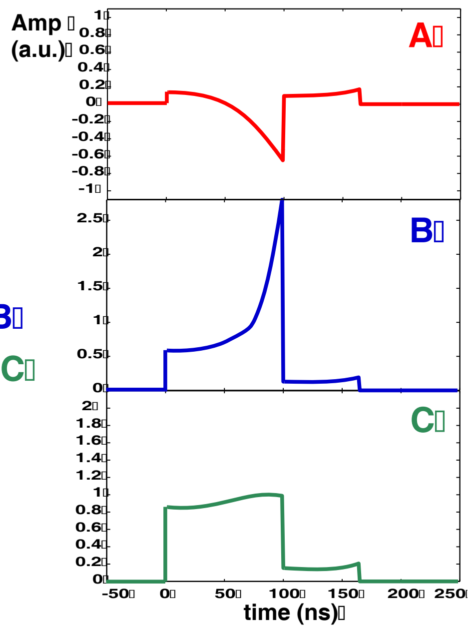
Cross section of a coaxial detector.



For a non-segmented “true” coax, the shape depends on initial radius



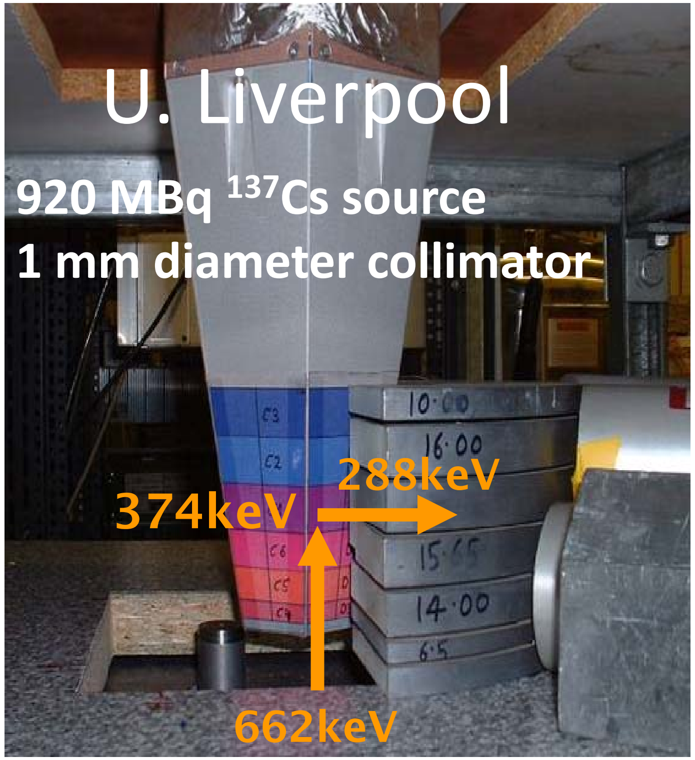
Weighting potential of a detector segment with 3 interactions at different angles

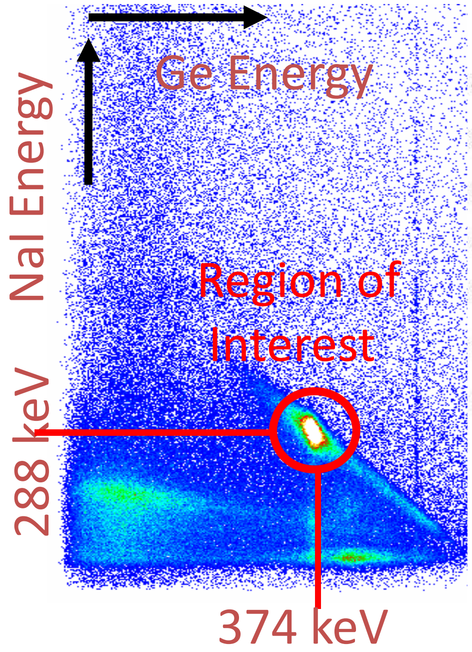


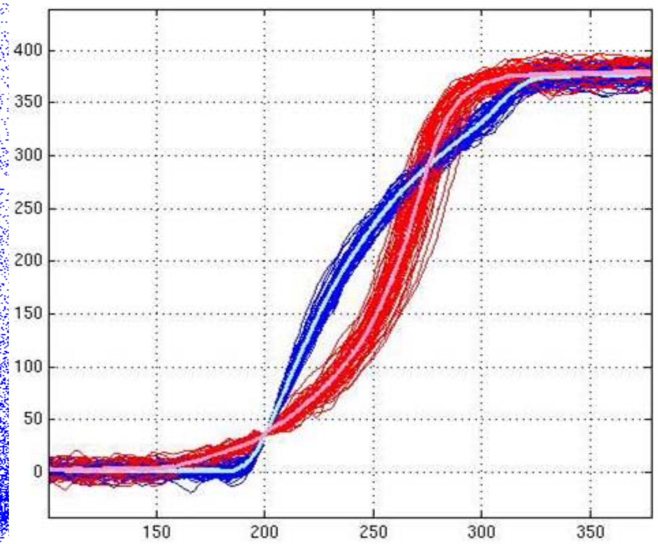
If cathode is segmented, “net” and “transient” shapes depend on the angular position of the interaction point

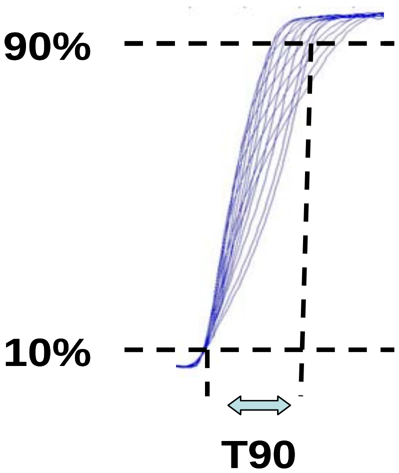
Characterization of Ge detectors

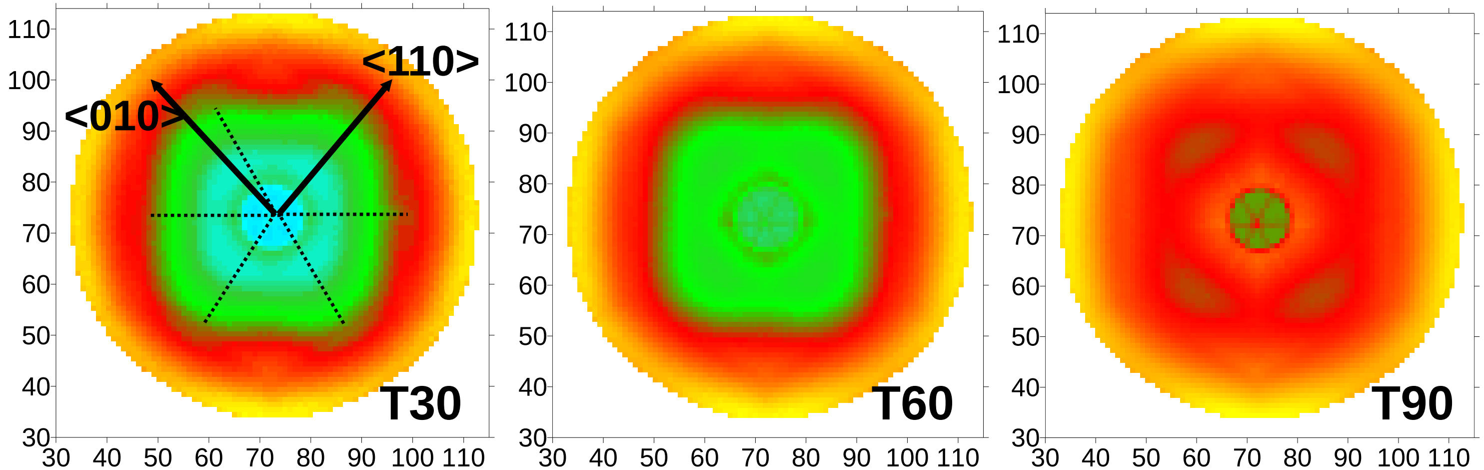
to validate calculated signals



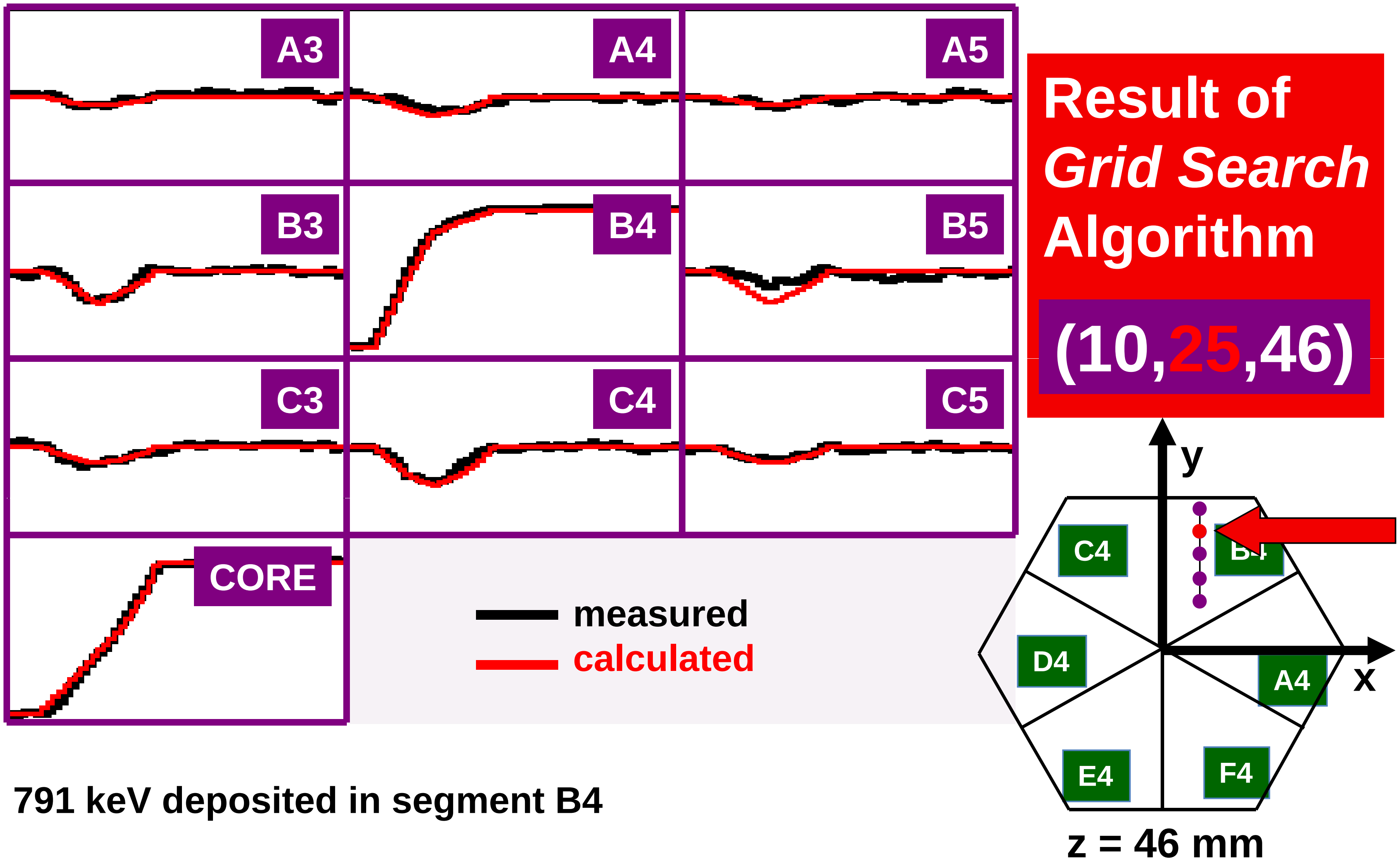








Pulse Shape Analysis concept



791 keV deposited in segment B4

Complications for PSA

- Theoretical
  - No good theory for mobility of holes ➔ must be determined experimentally
  - Mobility of charge carriers depends on orientation of collection path with respect to the crystal lattice ➔ shape of signals depends on orientation of collection path with respect to the crystal lattice
  - Detectors for a 4π array have an irregular geometry, which complicates calculation of pulse shape basis
  - Effective segments are defined by electric field and follow geometrical segmentation only roughly
  - Position resolution/sensitivity is not uniform throughout the crystal

- Practical/Computational
  - A basis calculated on a 1 mm grid contains ~ 400000 points, each one composed by 37 signals each one with > 50 samples (for a 10 ns time step)
  - Direct comparison of the experimental event to such a basis takes too much time for real time operation at kHz rate
  - Events with more than one hit in a segment are common, often difficult to identify and difficult to analyze
  - Low energy releases can easily end-up far away from their actual position

Position sensitivity

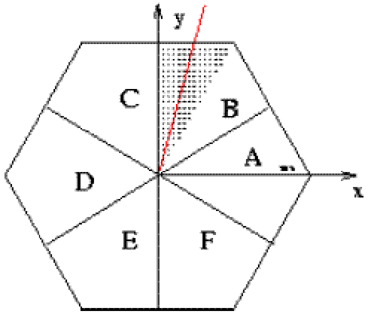
- Position sensitivity is the minimum distance at which difference in pulse shapes become distinguishable over the noise.
- It depends on the segmentation geometry, the segments size, the location within each segment and the direction.
- An interaction at position *i* is distinguishable from one at *j* if the **overall difference** in signal shapes is greater than that caused by the random fluctuation (noise).

$$\chi_{ij}^2 = \sum\sum \frac{\left(q_i(m,t) - q_j(m,t)\right)^2}{2\sigma^2}$$

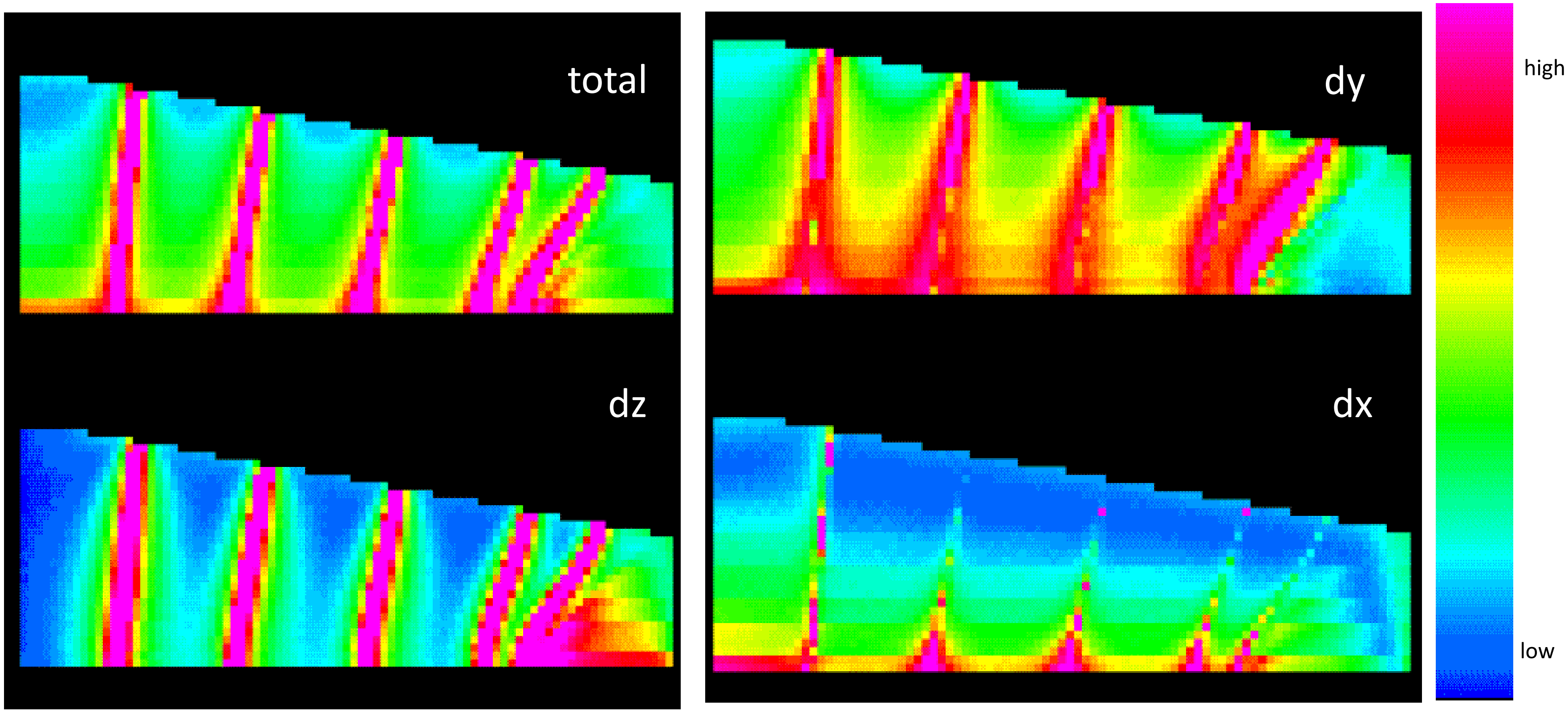
- Noise level assumed to be 5 keV
- $\chi^2 \sim 1$ → signals not distinguishable
- $\chi^2 > 1$ → signals are distinguishable

K.Vetter et al. NIMA 452(2000)223

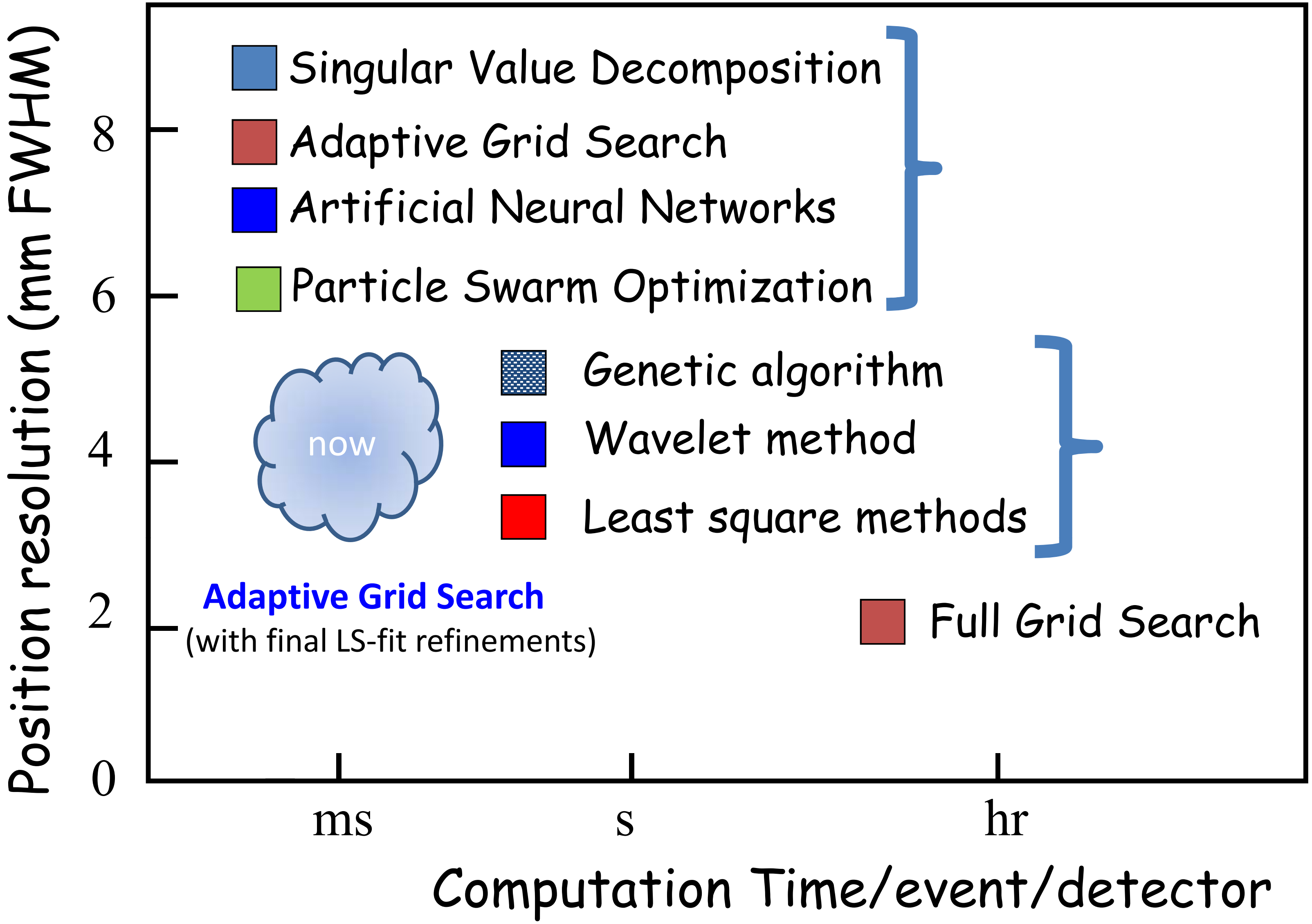
Sensitivity inside crystals



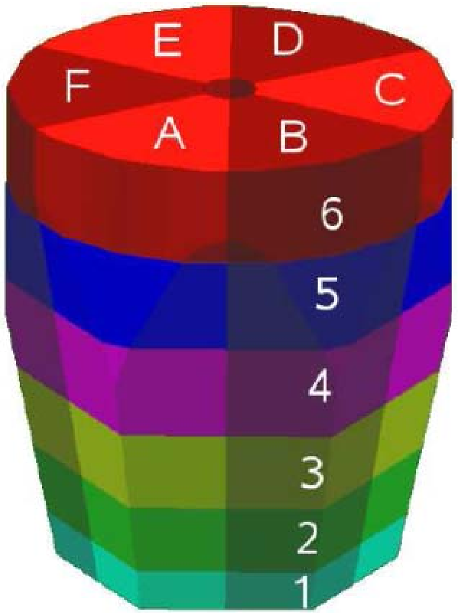
- Demonstration of sensitivity: the position sensitivity peaks at the **effective** segment borders. At the front, the deviation from the segmentation pattern is large.
- Regions near the outer surface between segment borders have the poorest sensitivity

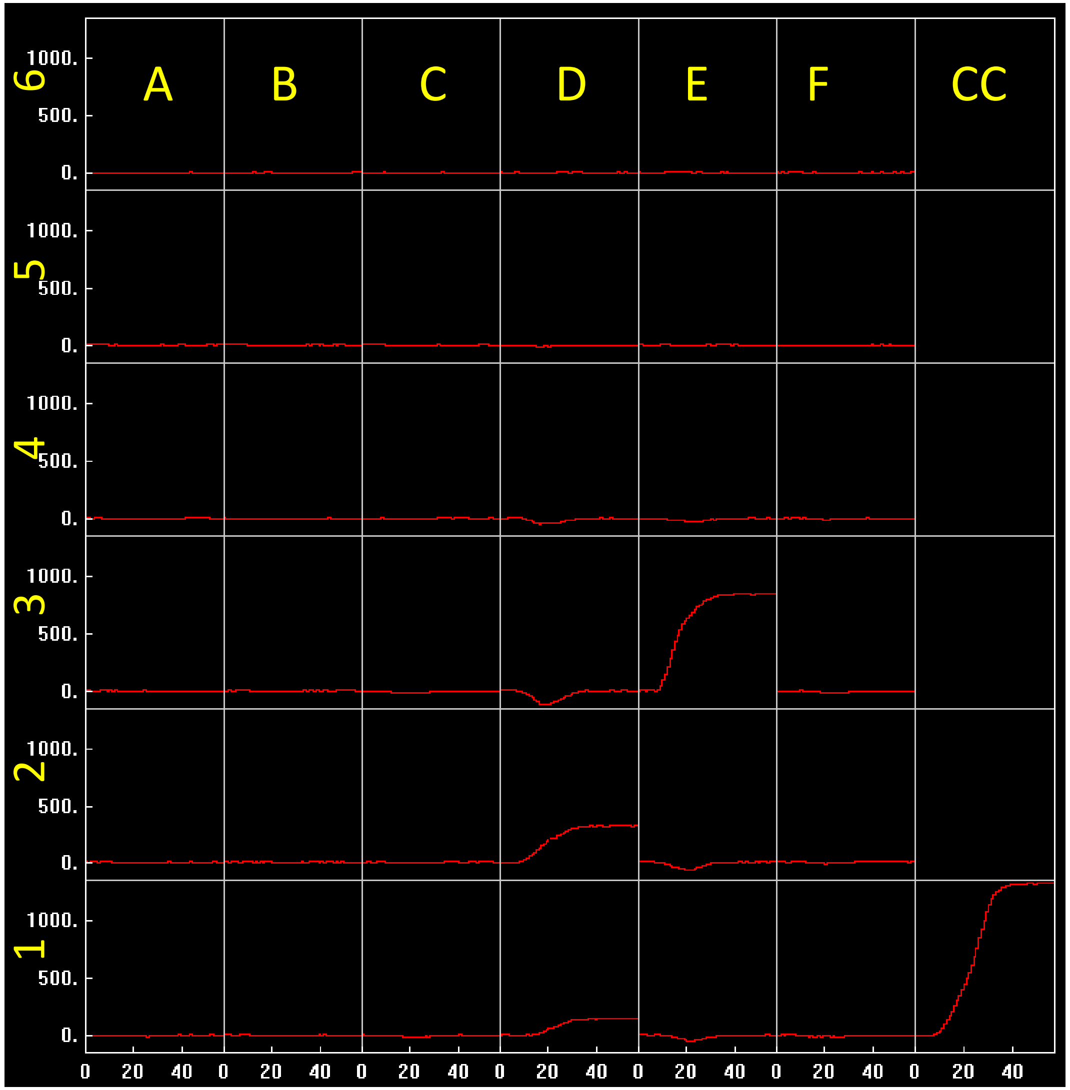


Pulse Shape Analysis algorithms

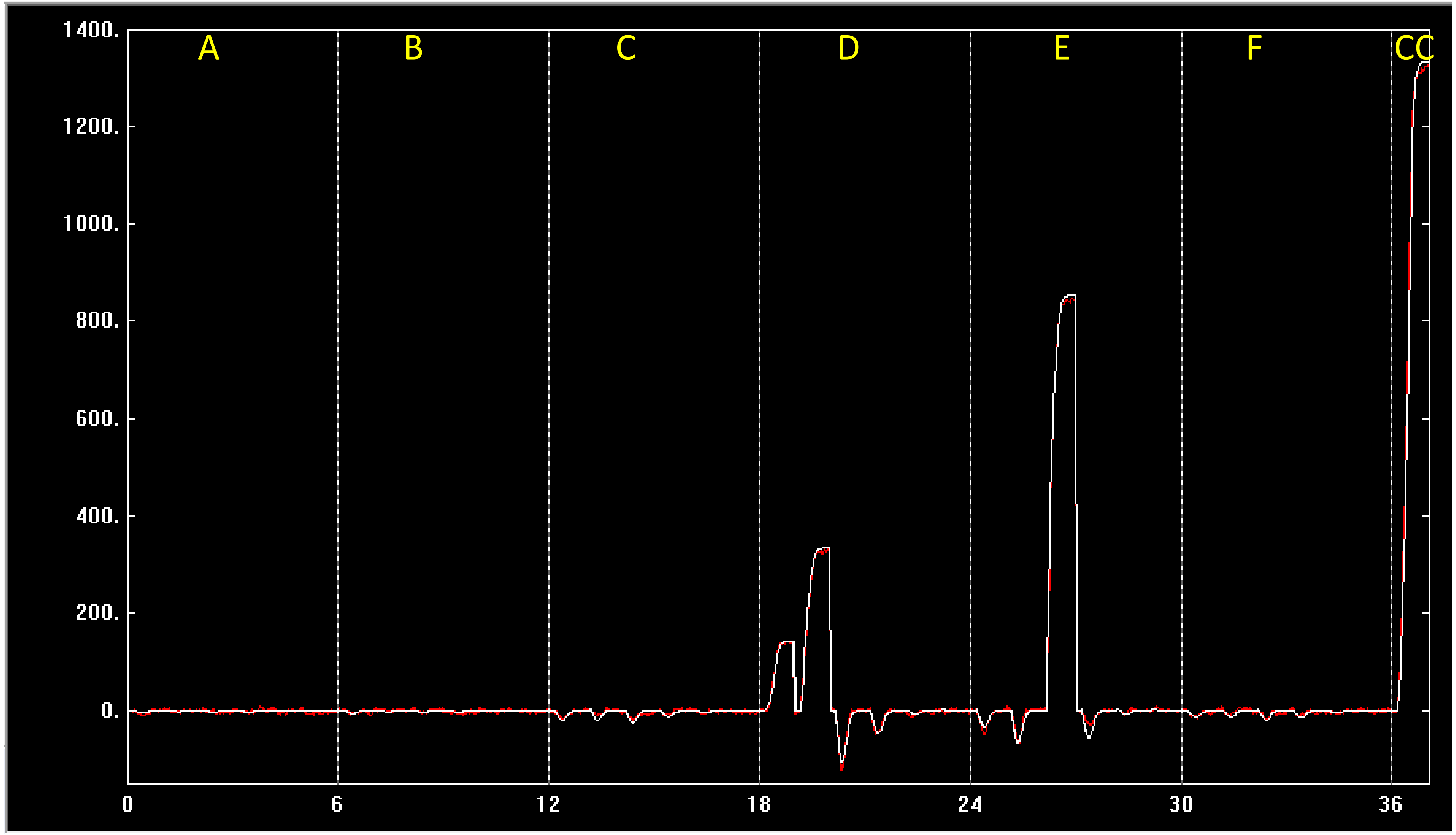


Adaptive Grid Search in action





Adaptive Grid Search in action



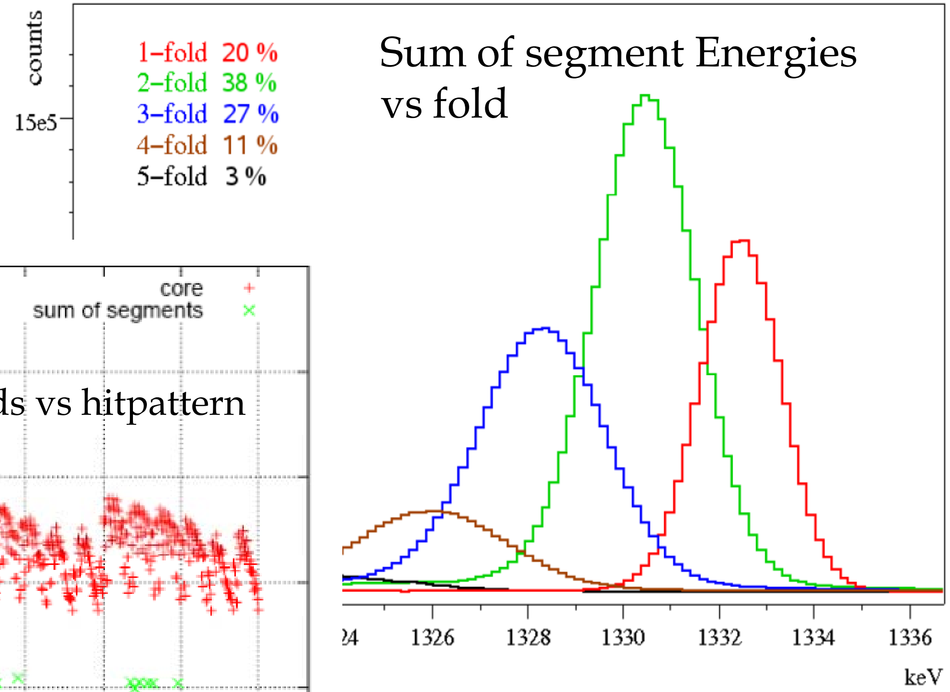
6 Final Result

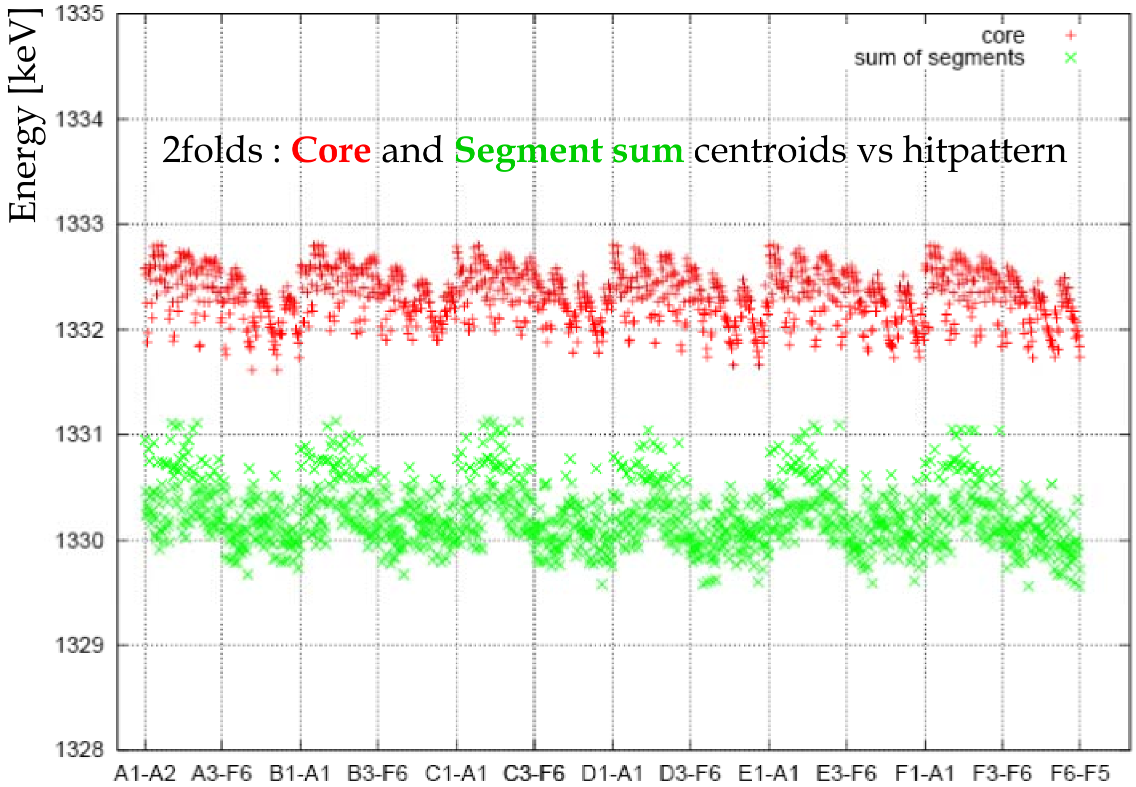
Performance of PSA

- Depends on the signal decomposition algorithm but of equal or more importance are:
- The quality of the signal basis
  - Physics of the detector
  - Impurity profile
  - Application of the detector response function to the calculated signals
- The preparation of the data
  - Energy calibration
  - Cross-talk correction (applied to the signals or to the basis!)
  - Time aligment of traces
- A well working decomposition has additional benefits, e.g.
  - Correction of energy losses due to neutron damage

Crosstalk correction: Motivation

- Crosstalk is present in <u>any</u> segmented detector
- Creates strong energy shifts proportional to fold
- Tracking needs <u>segment energies</u> !

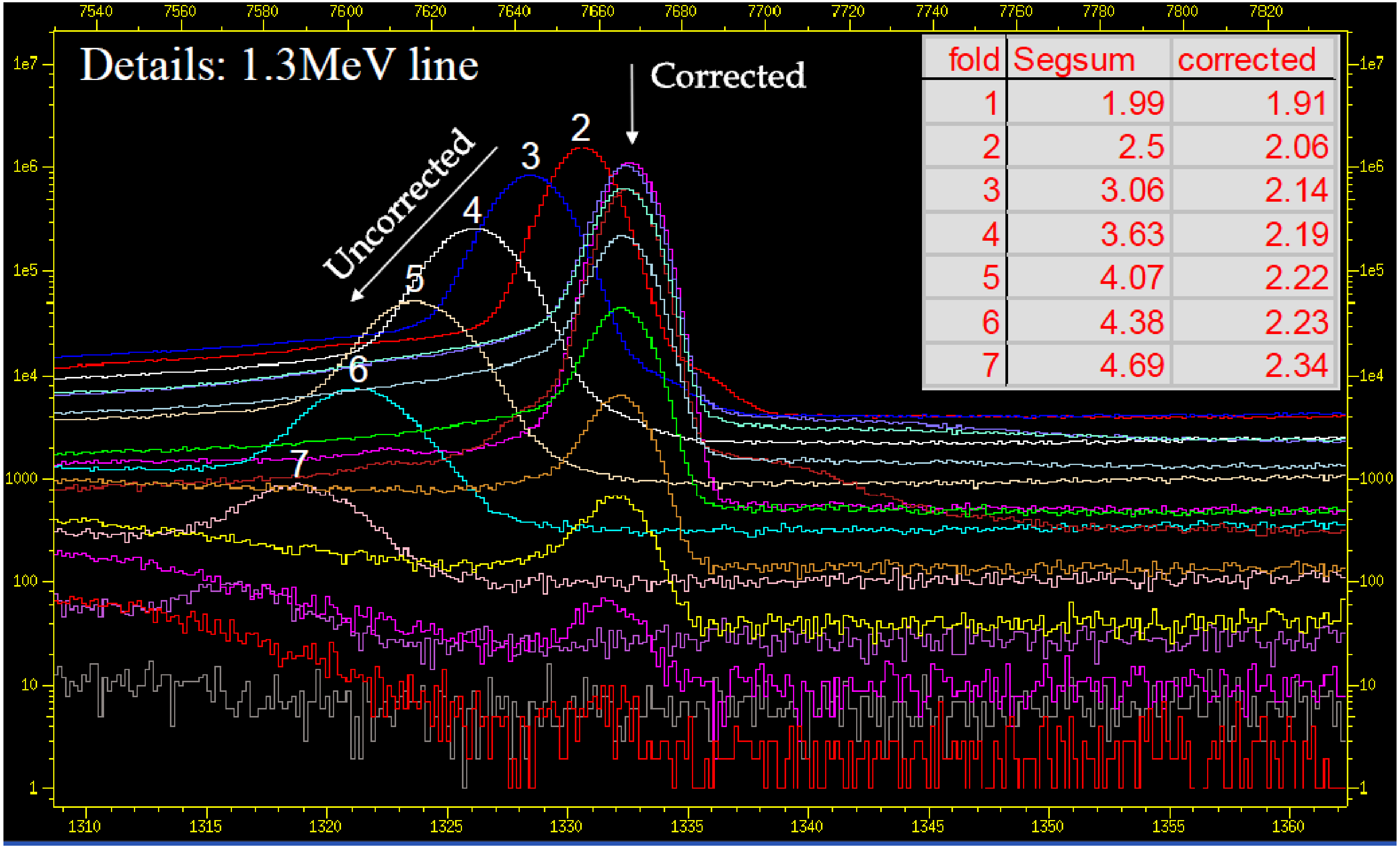




…All possible 2fold combinations

Cross talk correction: Results

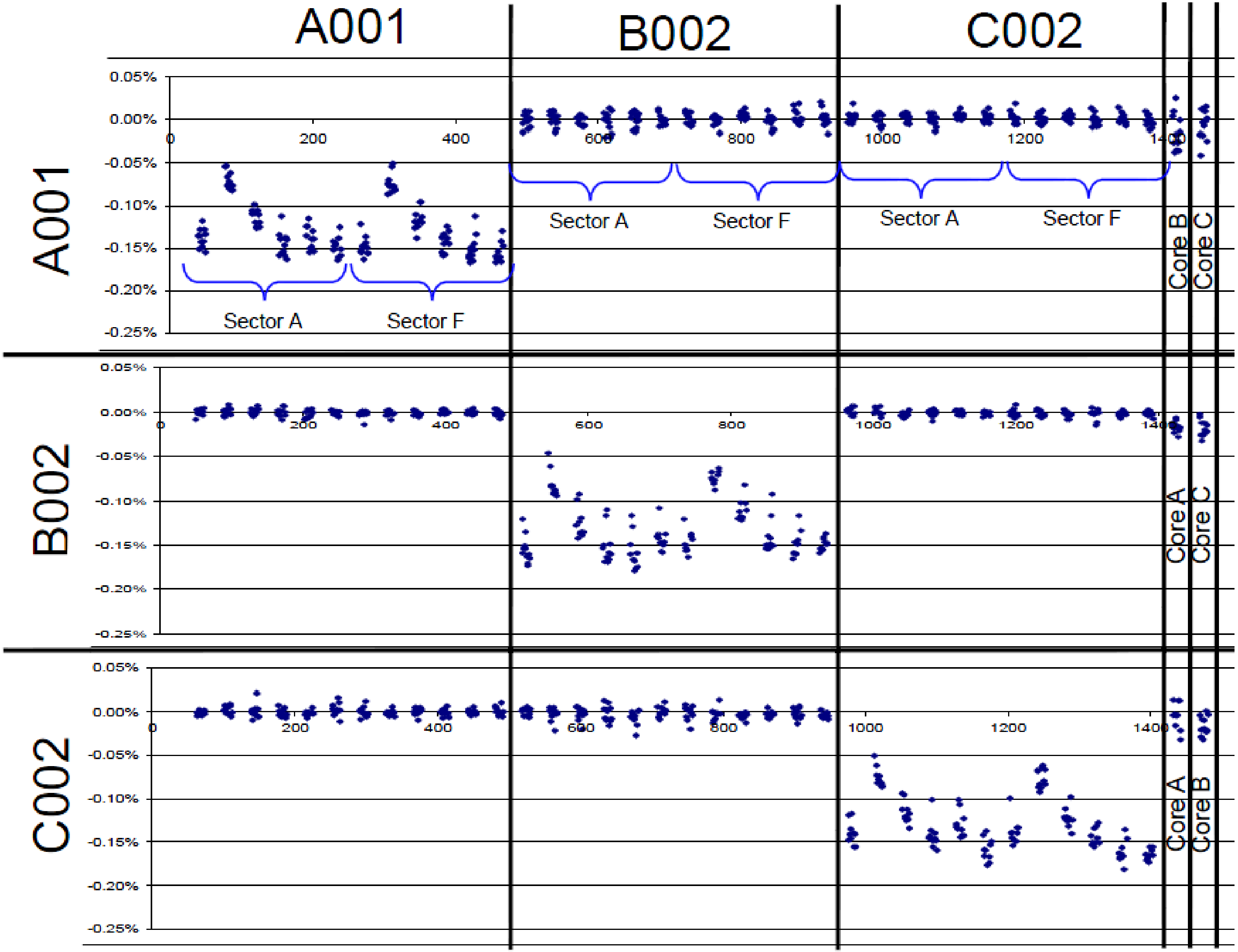
FWHM 60keV: 1.20 → 1.02 !



fold	Segsum	corrected
1	1.99	1.91
2	2.5	2.06
3	3.06	2.14
4	3.63	2.19
5	4.07	2.22
6	4.38	2.23
7	4.69	2.34

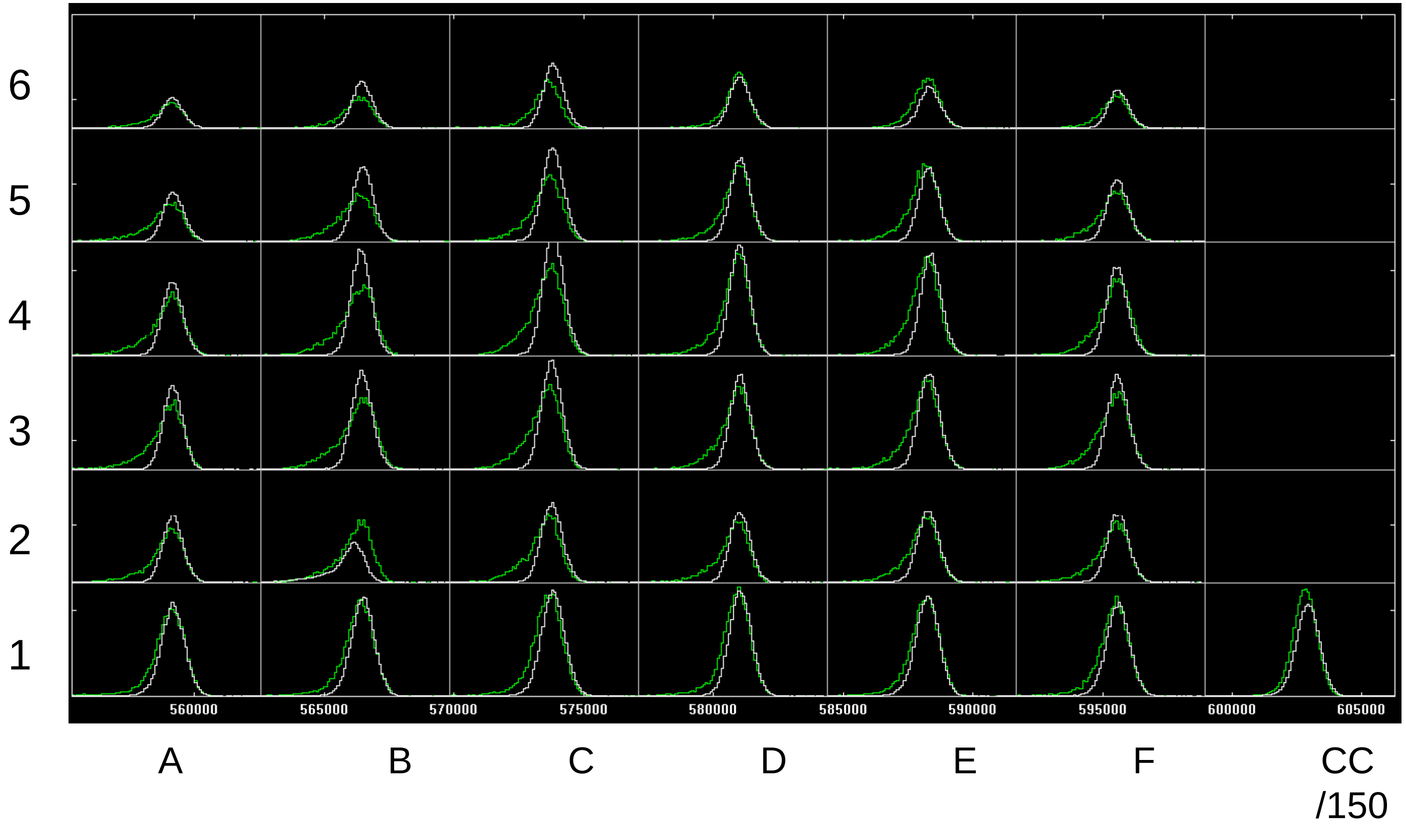
B. Bruyneel et al, Nucl. Instr. and Meth. A 608, (2009) 99

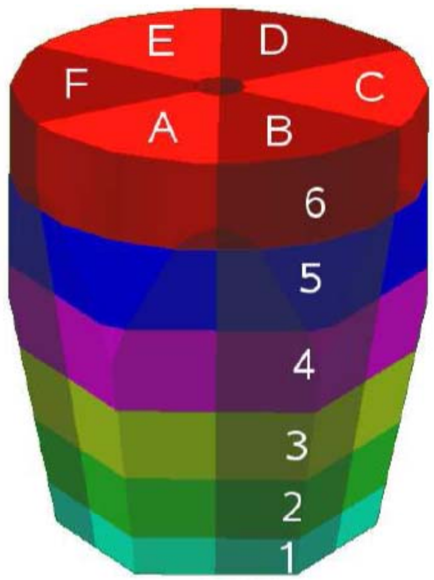
Cross talk in AGATA Triple Cluster



Radiation damage from fast neutrons

Shape of the 1332 keV line



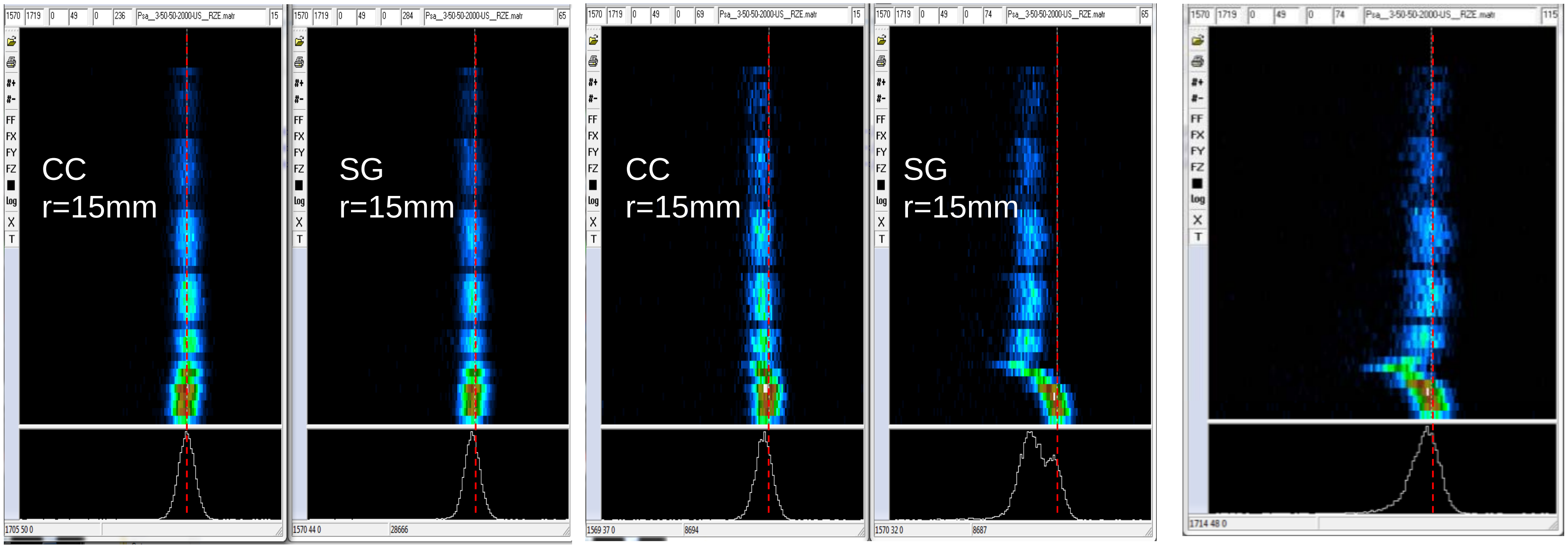


White: April 2010 → FWHM(core) ~ **2.3 keV** FWHM(segments) ~**2.0 keV**
Green: July 2010 → FWHM(core) ~**2.4 keV** FWHM(segments) ~**2.8 keV**
Damage after 3 high-rate experiments (3 weeks of beam at 30-80 kHz singles)

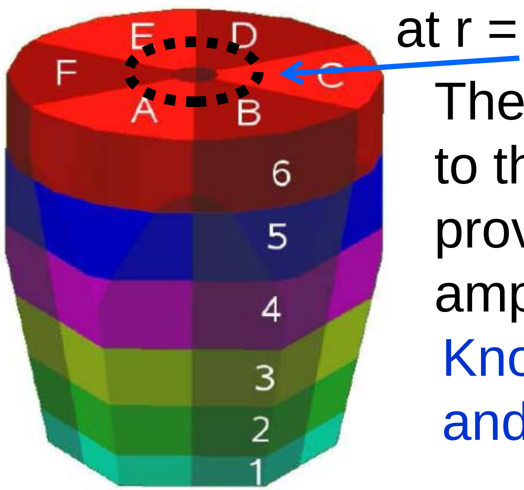
Worsening seen in most of the detectors; more severe on the forward crystals;
segments are the most affected, cores almost unchanged (as expected for n-type HPGe)

Crystal C002

April 2010 **July 2010** **→ corrected**



The 1332 keV peak as a function of crystall depth (z) for interactions at r = 15mm



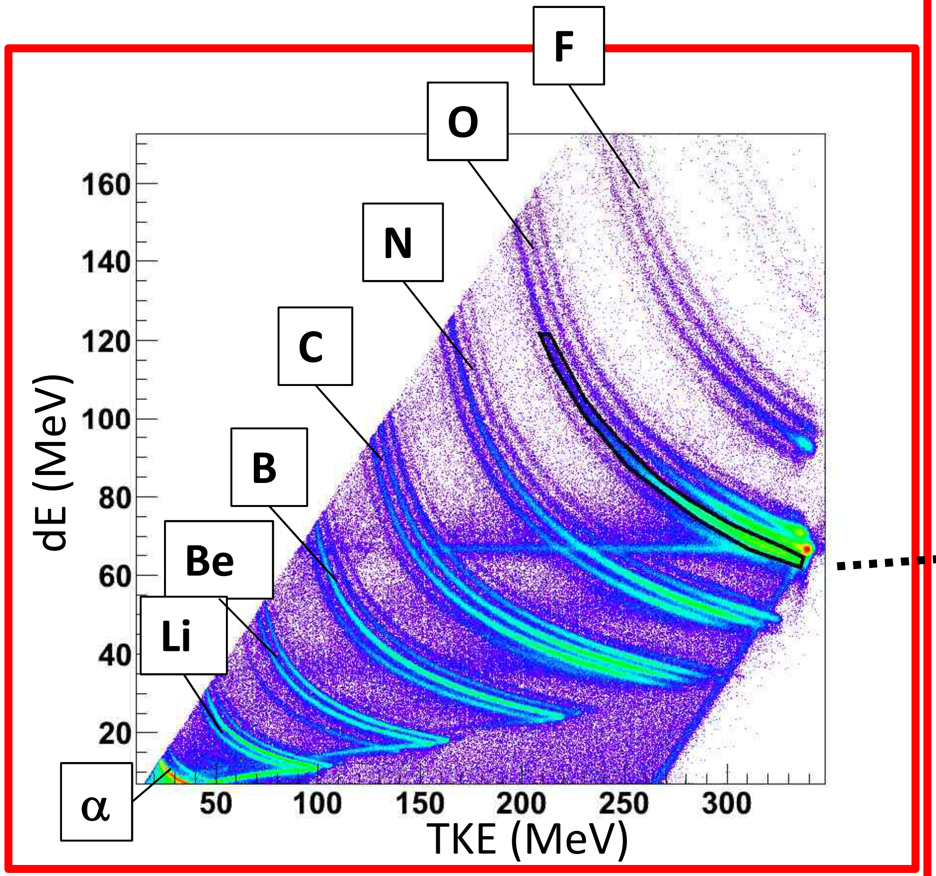
The charge loss due to neutron damage is proportional to the path length to the electrodes. The position is provided by the PSA, which is barely affected by the amplitude loss.

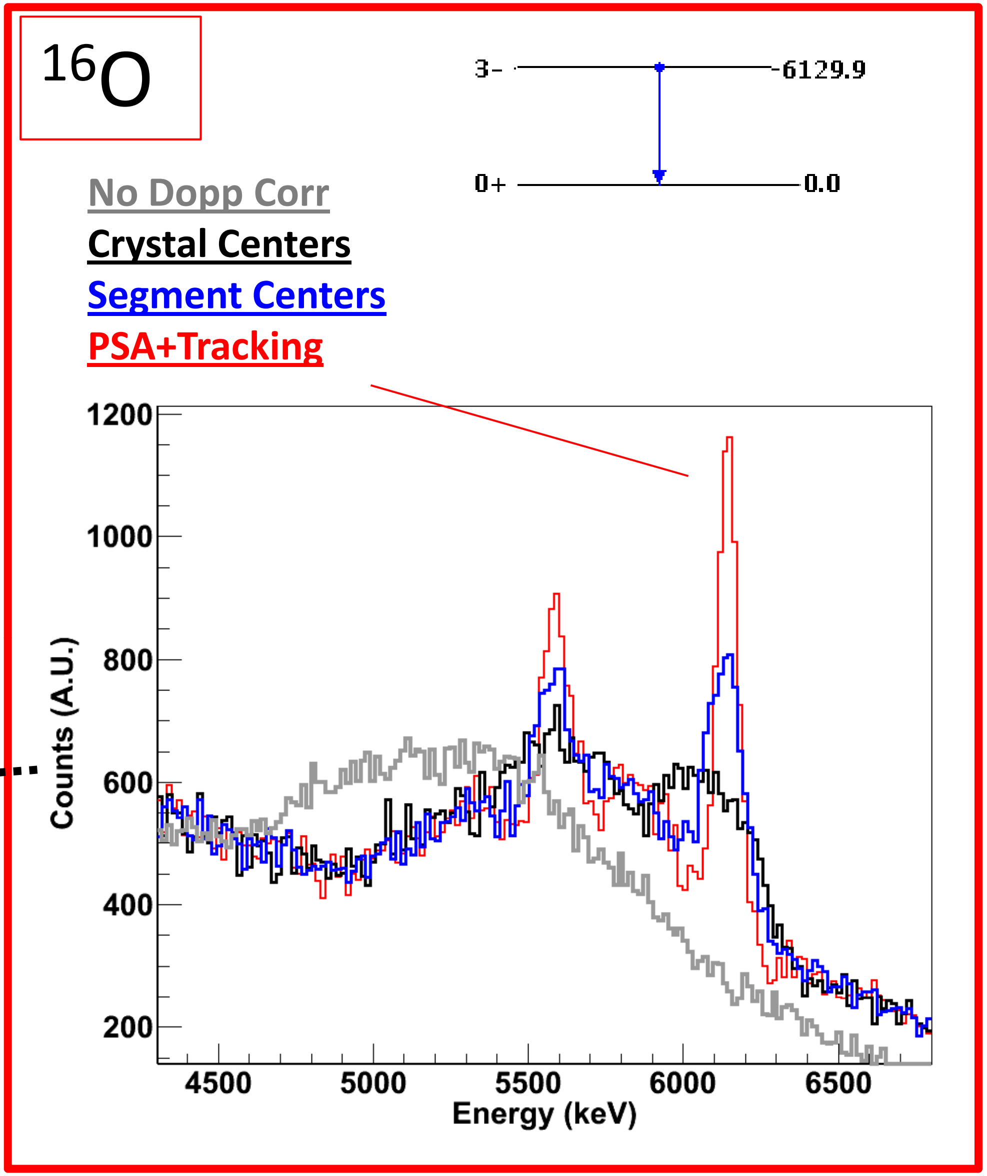
Knowing the path, the charge trapping can be modeled and corrected away (Bart Bruyneel, IKP Köln)

Some results

Doppler correction capabilities

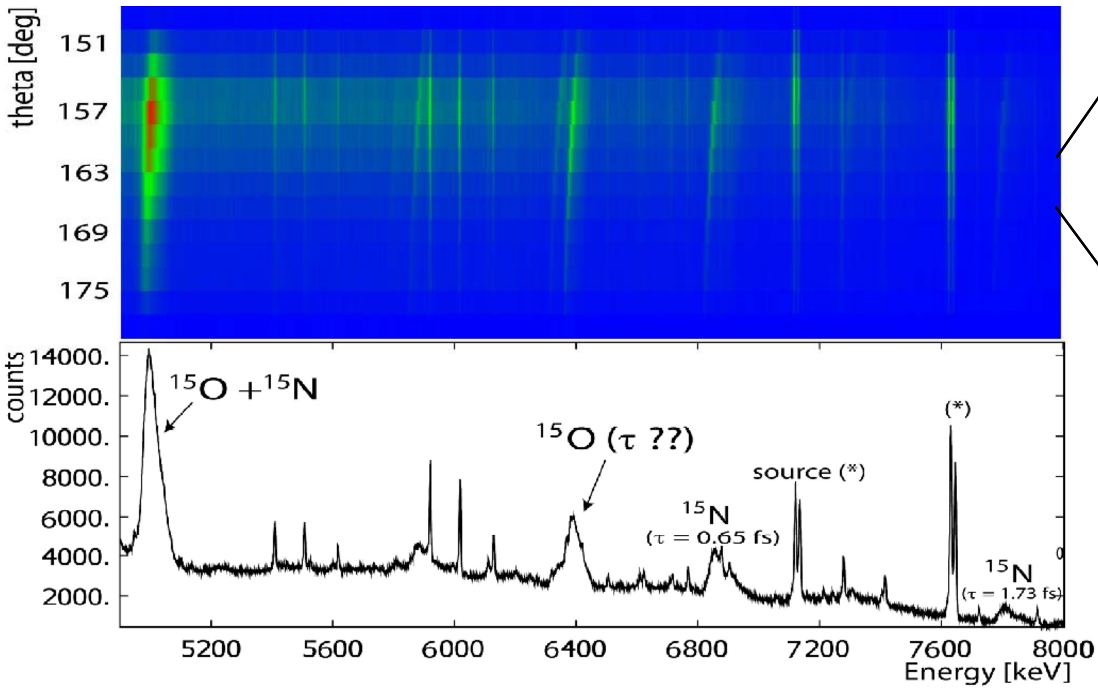
Inelastic scattering
^{17}O @ 20 MeV/u on ^{208}Pb

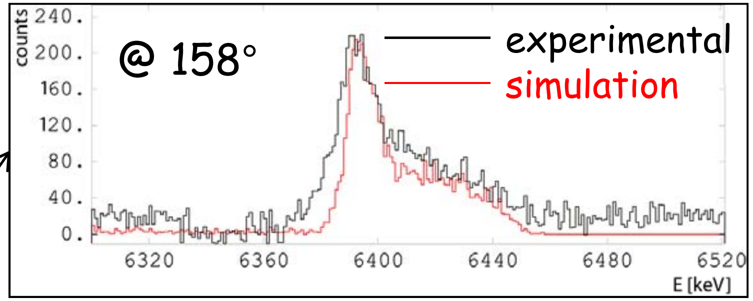


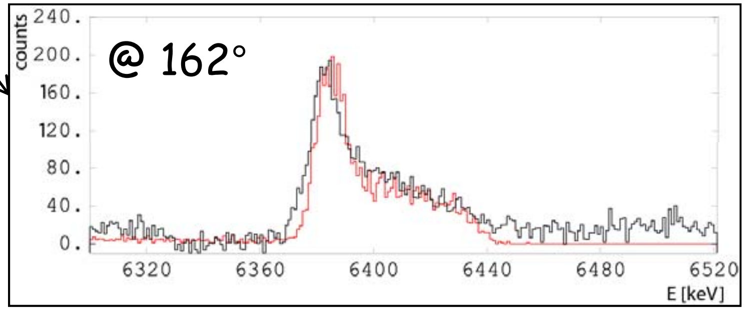


F.Crespi, Milano

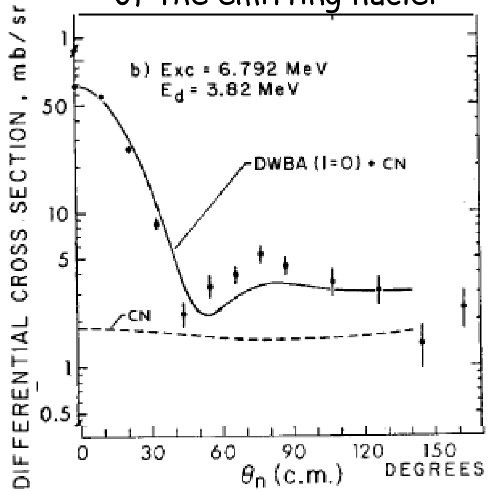
Lifetime measurement of the 6.79 MeV state in ^{15}O







CM angular distribution of the emitting nuclei



R.C. Ritter *et al.*, NPA 140 (1970) 609

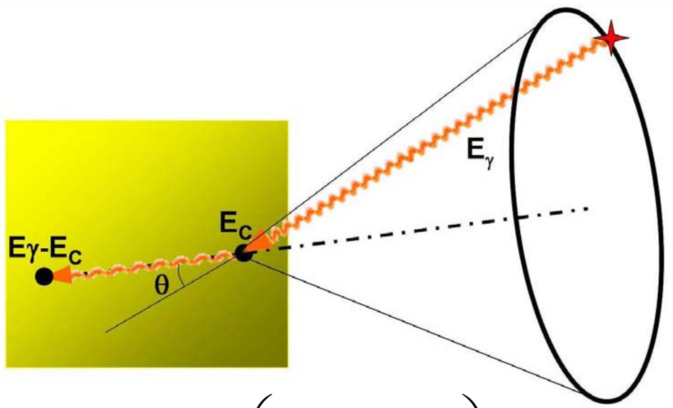
^{14}N(^{2}H,n)^{15}O and ^{14}N(^{2}H,p)^{15}N reactions @ 32 MeV
(XTU LNL Tandem)
4 ATCs at backward angles (close to the beam-line)
Direct lifetime measurement

The energy and angular resolution of the AD will allow for a lower upper limit in the lifetime of the level of interest (~fs), with respect to what was obtained in the past with the same technique (Gill et al., NPA 121 (1968) 209).

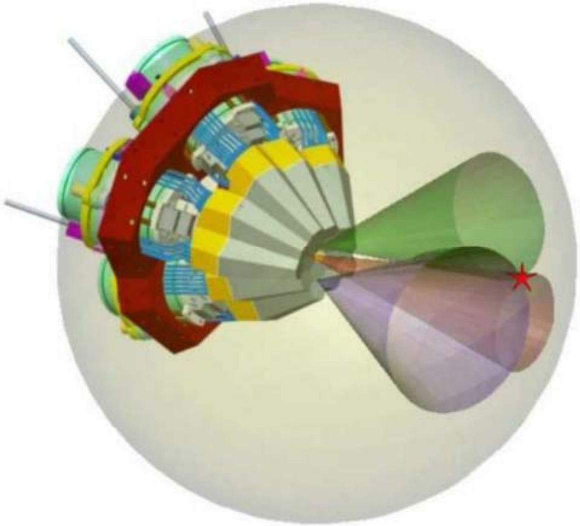
C.Michelagnoli, R.Depalo

Imaging of E_γ=1332 keV gamma rays

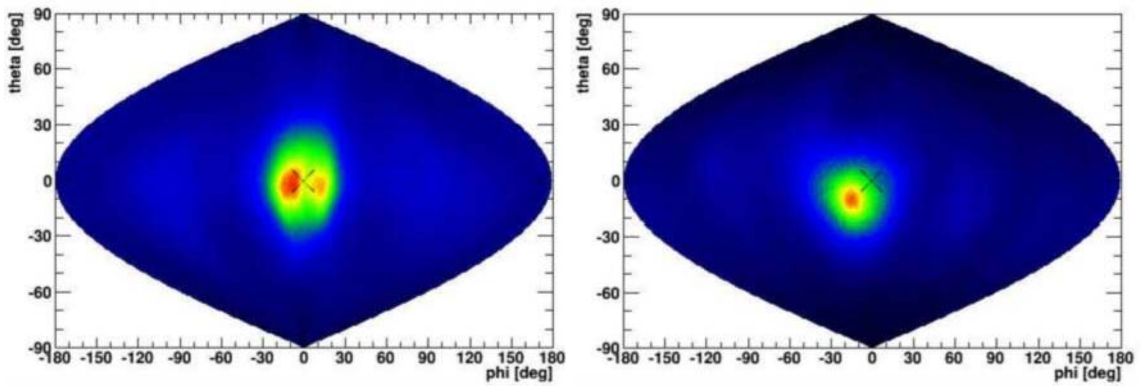
AGATA used as a big and exspensive Compton Camera



$$\cos\theta = 1 + \left(\frac{1}{E_\gamma} - \frac{1}{E'_\gamma}\right) m_0 c^2$$



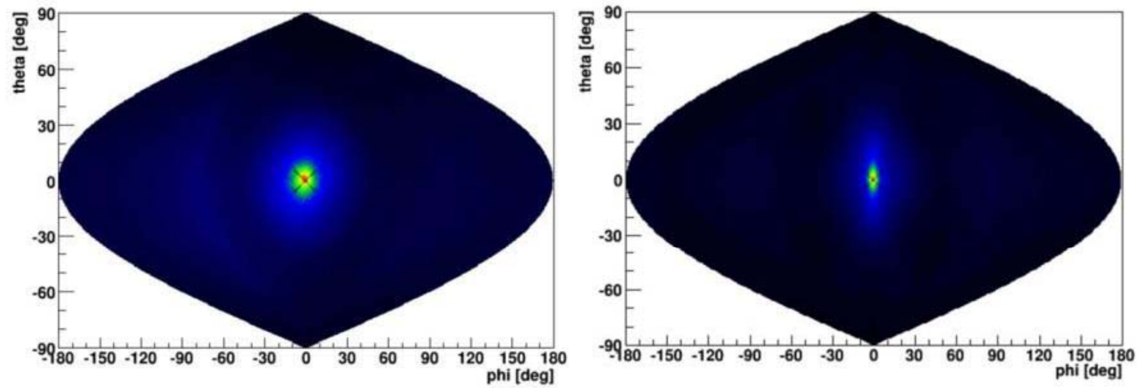
Far Field Backprojection



All 9 detectors

One detector

Near Field Backprojection



All 9 detectors

One detector

Source at 51 cm ➔ $\Delta x \sim \Delta y \sim 2$ mm $\Delta z \sim 2$ cm

Francesco Recchia

The Experimental Campaign at LNL