High-resolution γ-ray spectroscopy at the Legnaro National Laboratories

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for the GALILEO collaboration

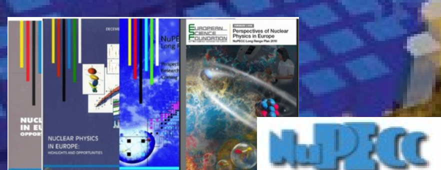
Outlook

- Introduction
- γ-ray spectroscopy at LNL
- AGATA tracking spectromter
- The GALILEO project
- PANDORA synergy

Motivations

Nuclear physics at the frontier

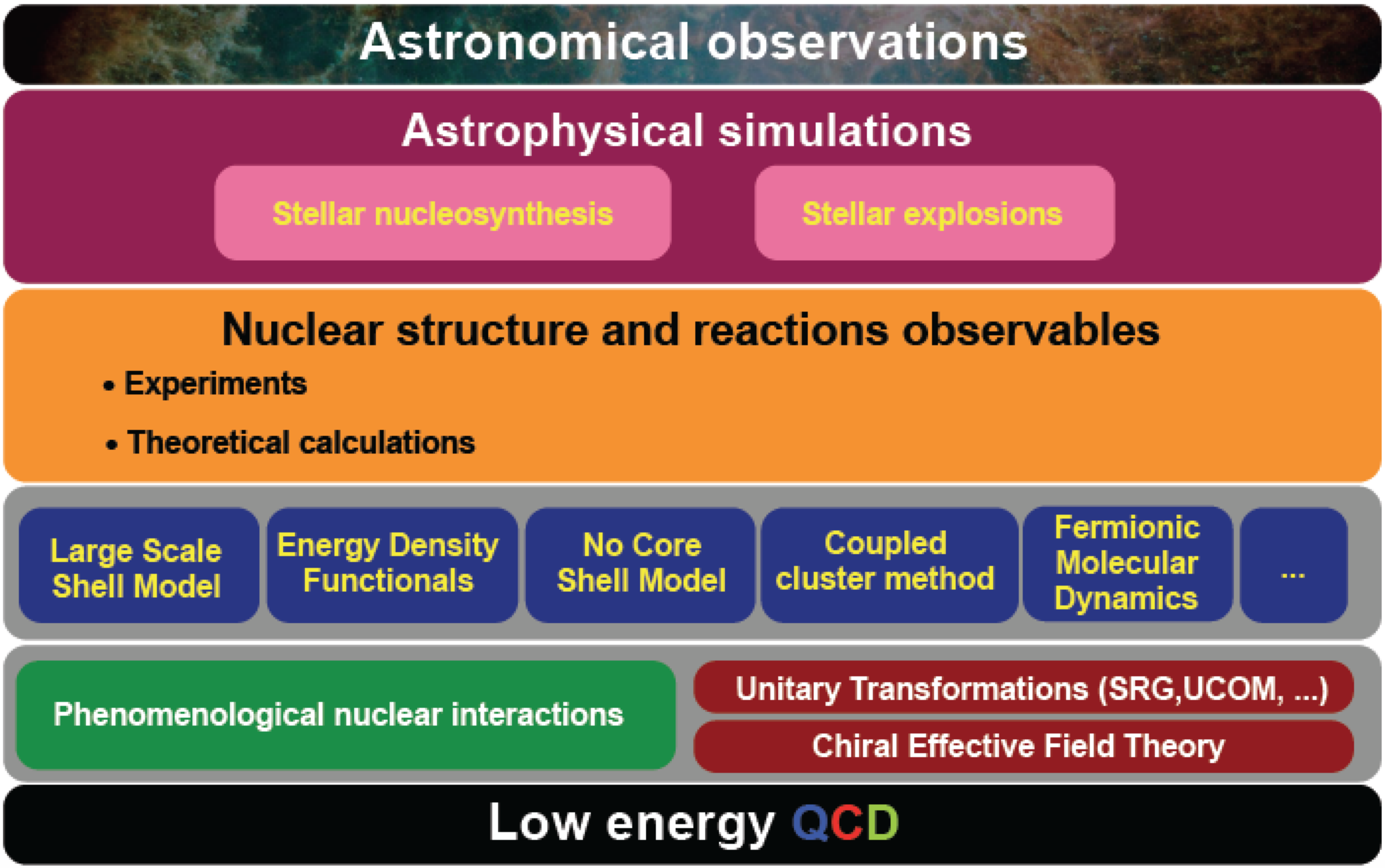
- How did visible matter come into being and how does it evolve?
- How do NNN forces impact structure and reaction properties of nuclei ?
- How does subatomic matter organize itself and what phenomena emerge?
- What is the origin of simple patterns in complex nuclei?




exotic beams for science

RIKEN FRIB FAIR ISOLDE Spiral2

The quantum ladder

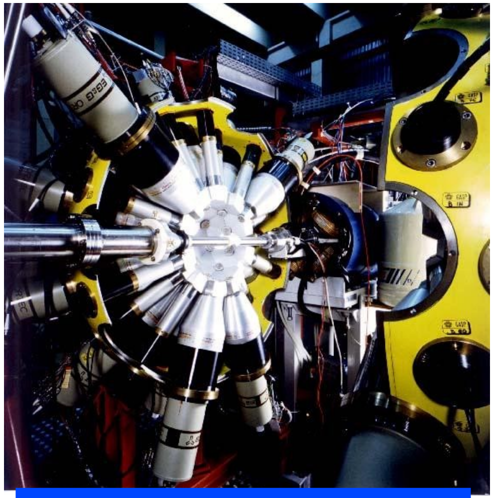


γ-ray spectroscopy at LNL

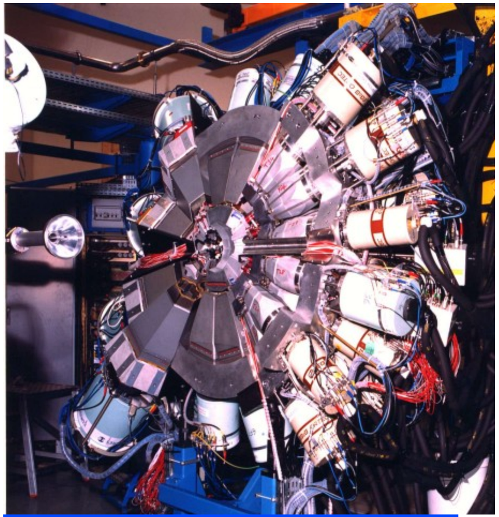
Legnaro National Laboratoy – INFN
Where

Accelerator complex: TANDEM, LINAC, SC RFQ and soon RIBS

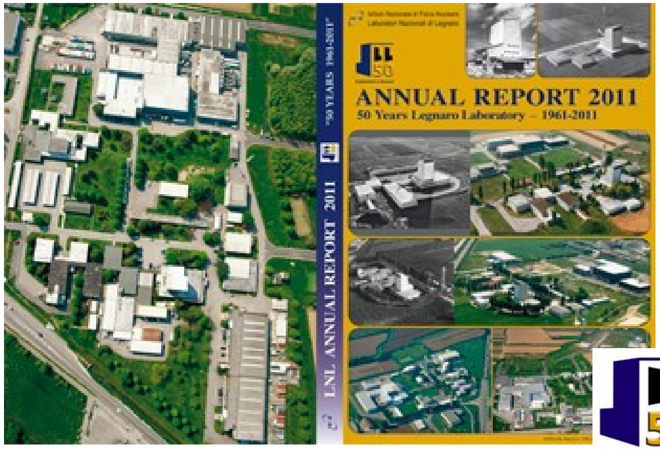
Long-standing activity

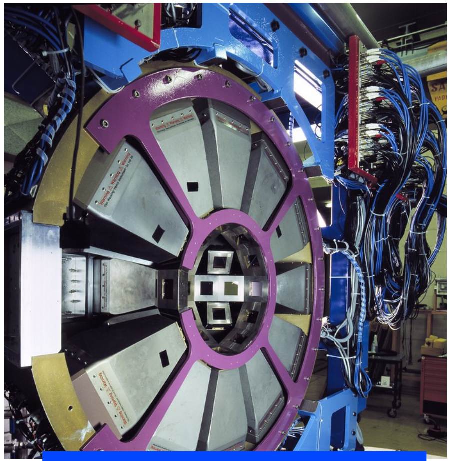


GASP 1992



EUROBALL 1998





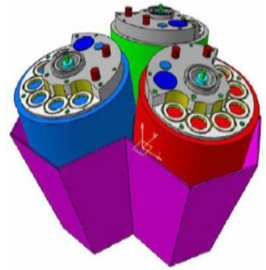
CLARA 2004

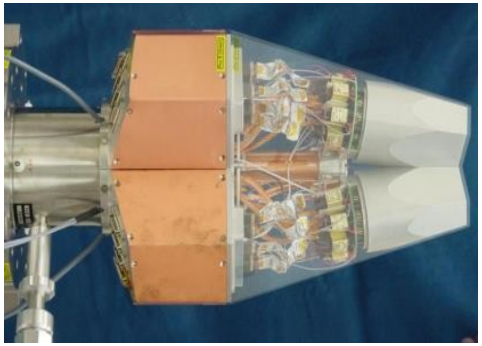
AGATA 2008

- **80% nuclear physics research**
- **50% γ-ray spectroscopy**
- **Proton- and neutron-rich nuclei**

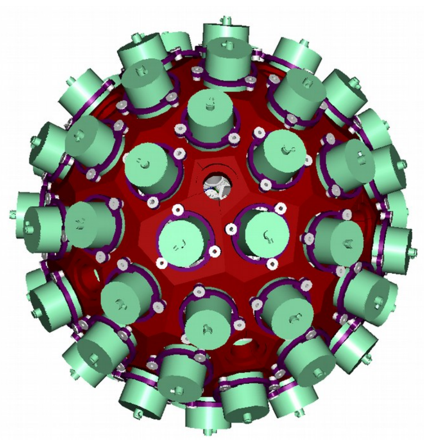
SPES
exotic beams for science

The AGATA project

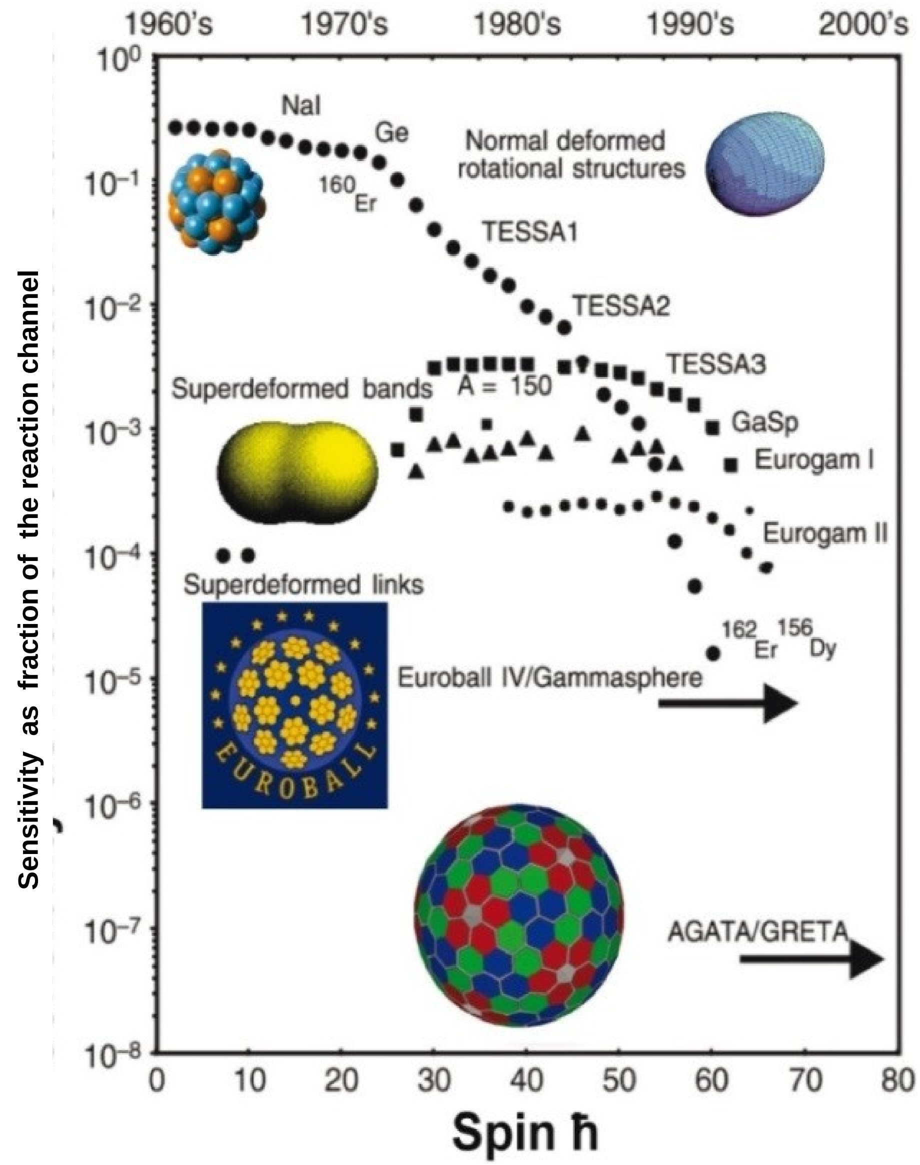




- segmented detector
- pulse-shape analysis
- tracking the γ rays
- digital electronics



- 180 (60 triple-clusters) 36-fold
- Amount of germanium: 362 kg
- Solid angle coverage: 82 %
- Singles rate >50 kHz
- Efficiency: 43% (M_γ=1) , 28% (M_γ=30)
- Peak/Total: 58% (M_γ=1), 49% (M_γ=30)
- Angular Resolution: ~1º

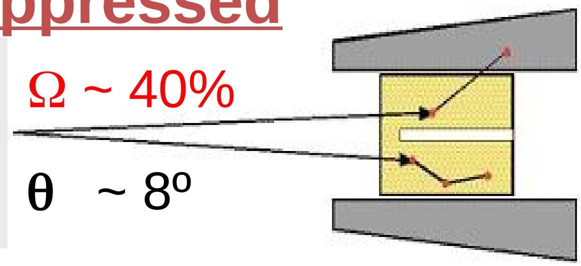


Calorimetric → Position Sensitive

Compton Suppressed

ε_{ph} ~ 10%

N_{det} ~ 100

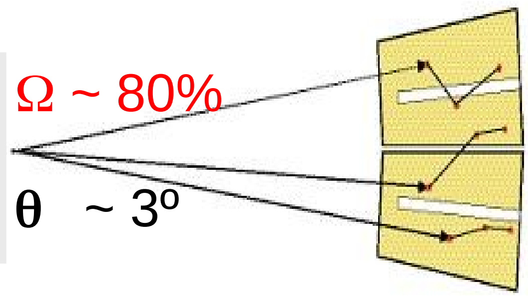


- 50% of solid angle taken by the AC shields
- large opening angle
  poor energy resolution at high recoil velocity

Ge Sphere

ε_{ph} ~ 50%

N_{det} ~ 1000

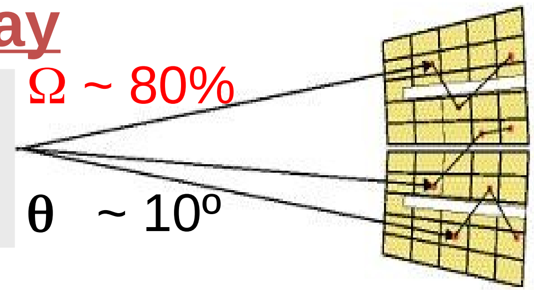


- too many detectors needed to avoid summing effects
- opening angle still too big for very high recoil velocity

Tracking Array

ε_{ph} ~ 50%

N_{det} ~ 100



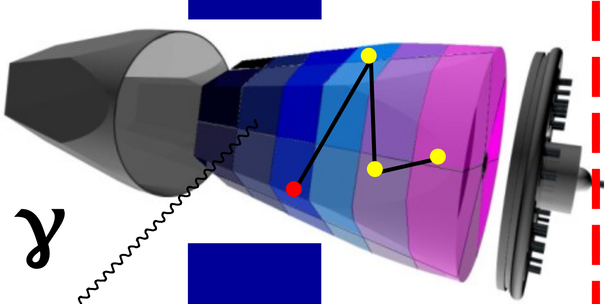
Pulse Shape Analysis
Gamma-ray Tracking
→
θ_{eff} ~ 1º
N_{eff} ~ 10000

Smarter use of Ge detectors

- segmented detectors
- digital electronics
- timestamping of events
- analysis of pulse shapes
- tracking of γ-rays

γ-ray tracking concept

Highly segmented HPGe detectors



Synchronized digital electronics to digitize (14 bit, 100 MS/s) and process the 37 signals generated by crystals

Readout Raw Data (10 kB/evt/crystal)

HARDWARE

Event building time-stamped data

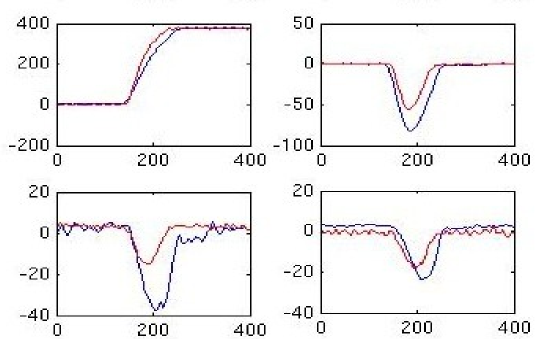
Global level

Local level

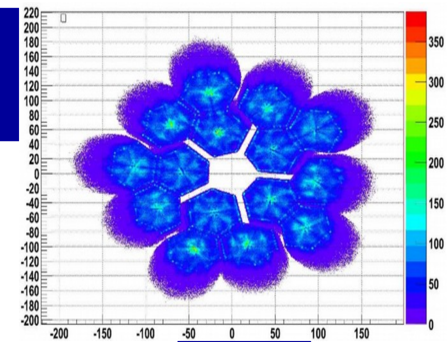
Energies, times, interaction points

$(x,y,z,E,t)_i$

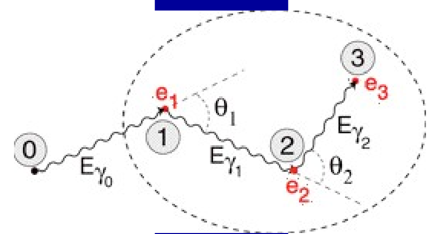
Pulse Shape Analysis of the recorded waves



SOFTWARE

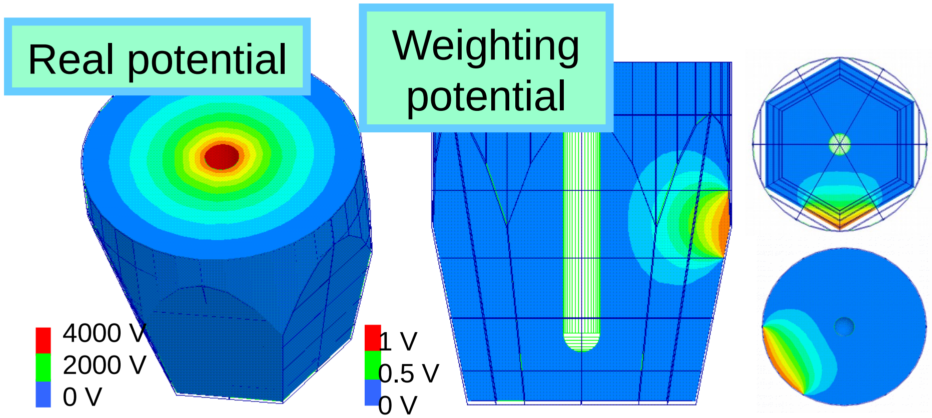


Reconstruction of γ-rays from the hits



Analysis & correlation with other detectors

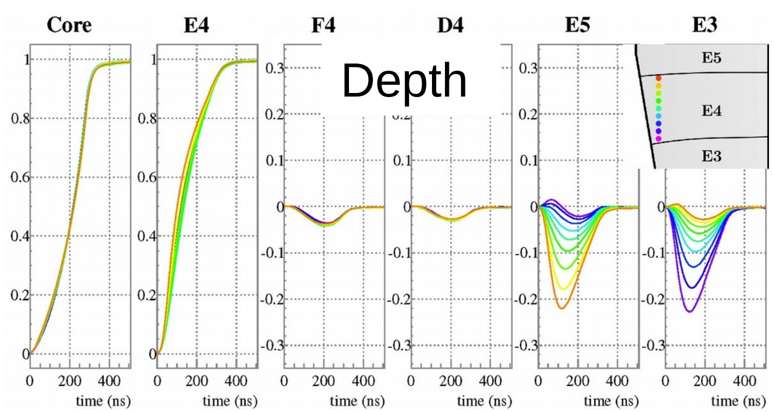
1 mm position resolution → 1 deg

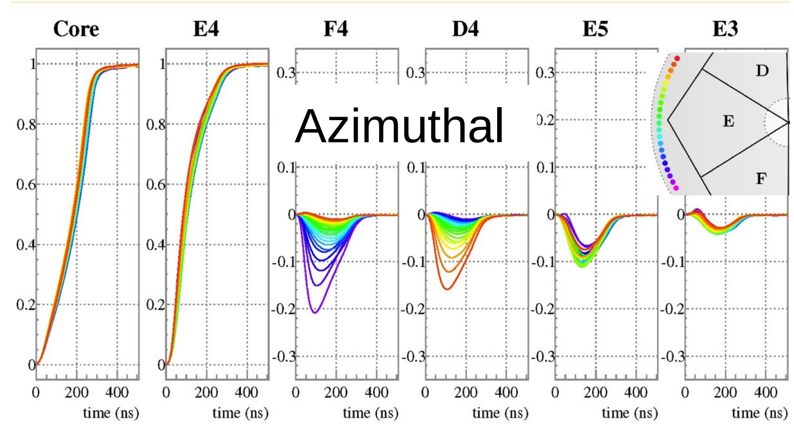


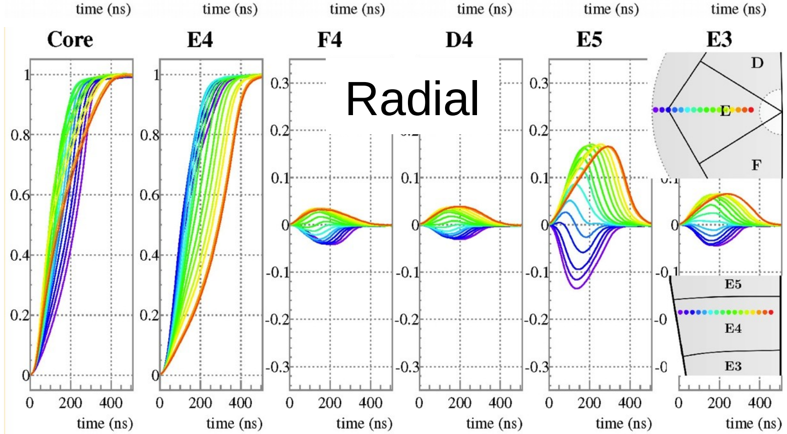
Induced current Ramo Theorem

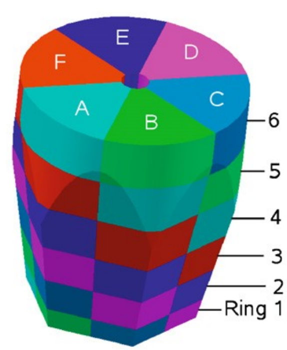
$$i_k = -qv \cdot \nabla\phi_k(r_q)$$

E. Gatti, et al. NIM 193 (82) 651



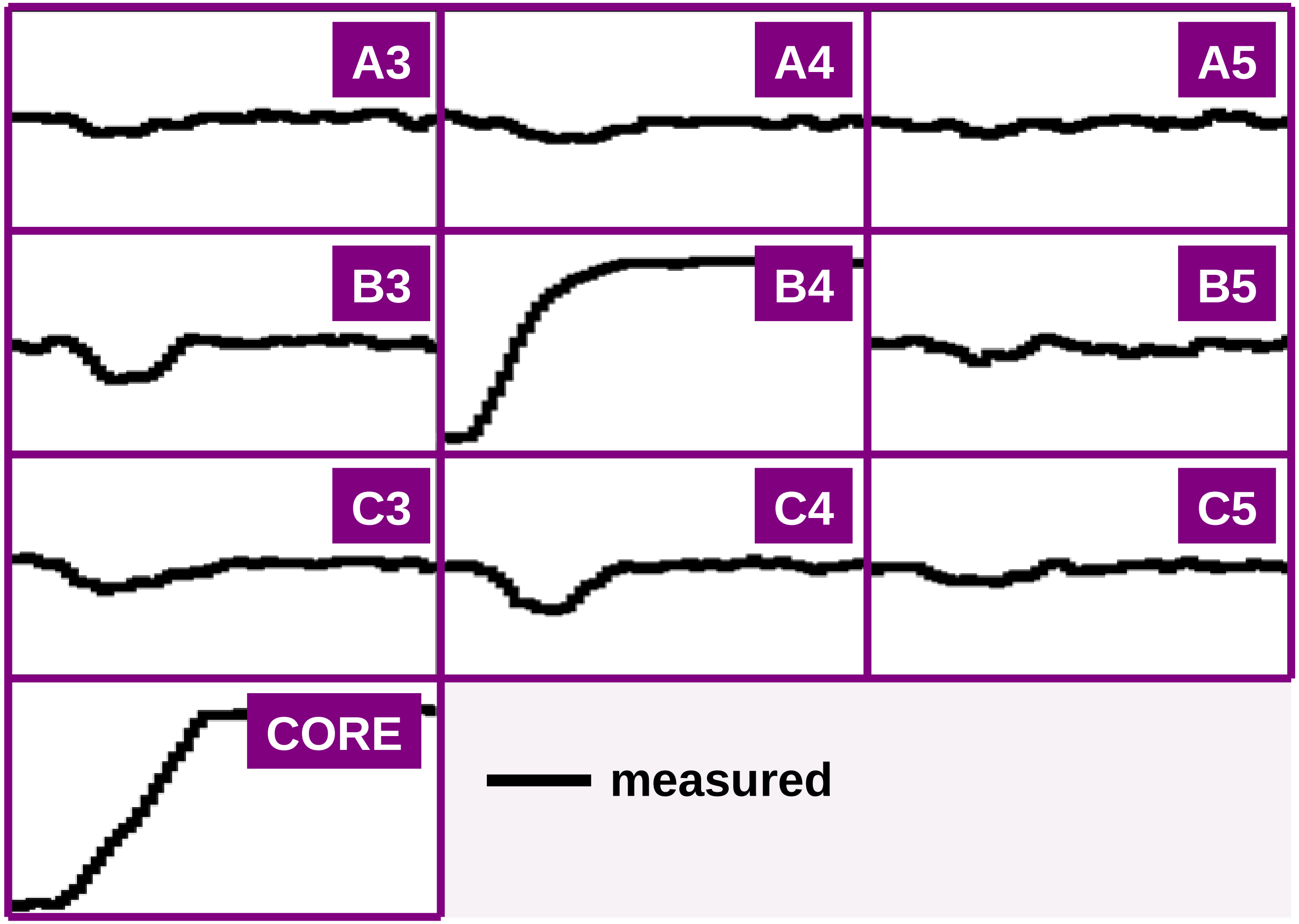






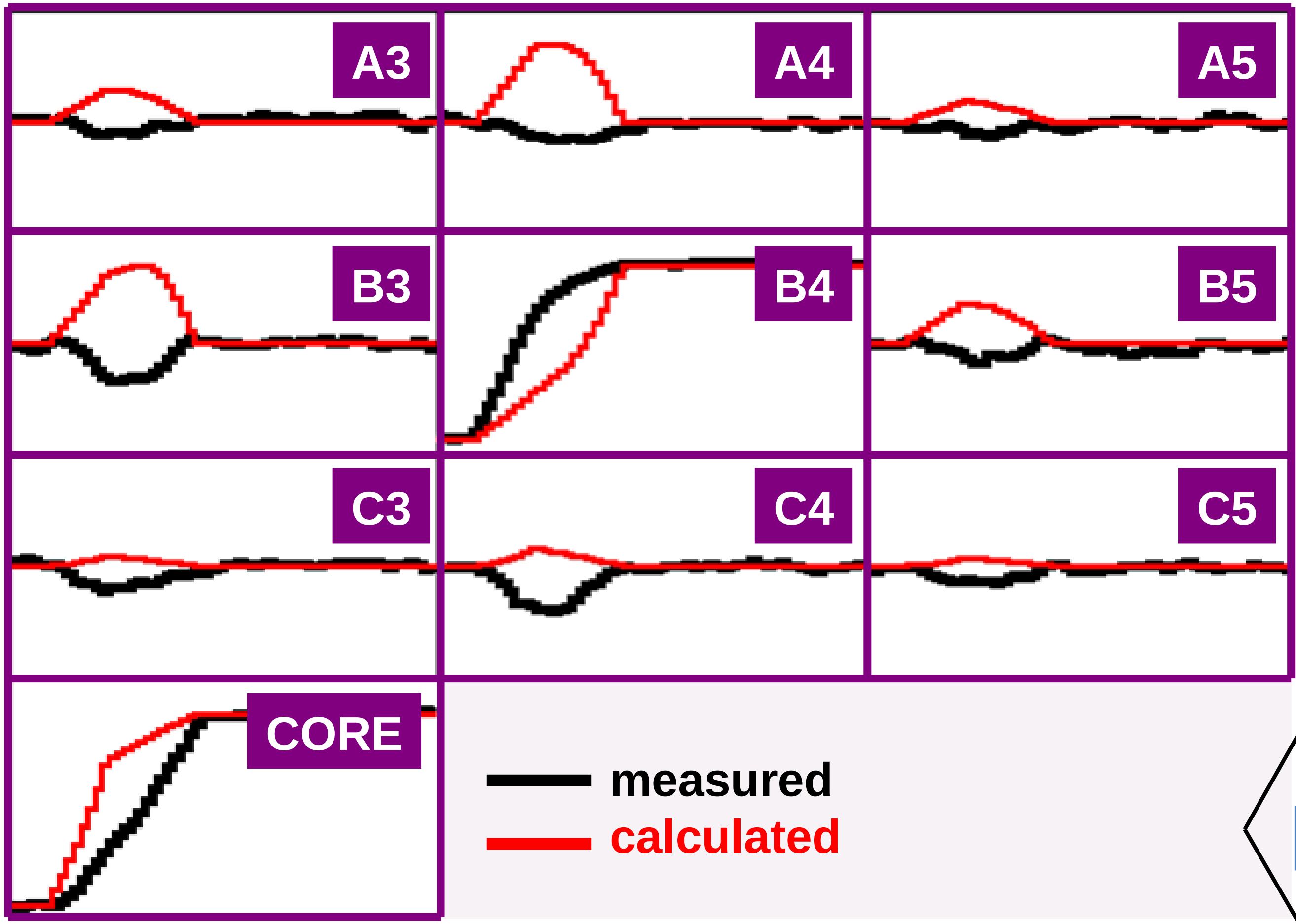
Credits M.Ginsz, et al.,
IPHC Strasbourg

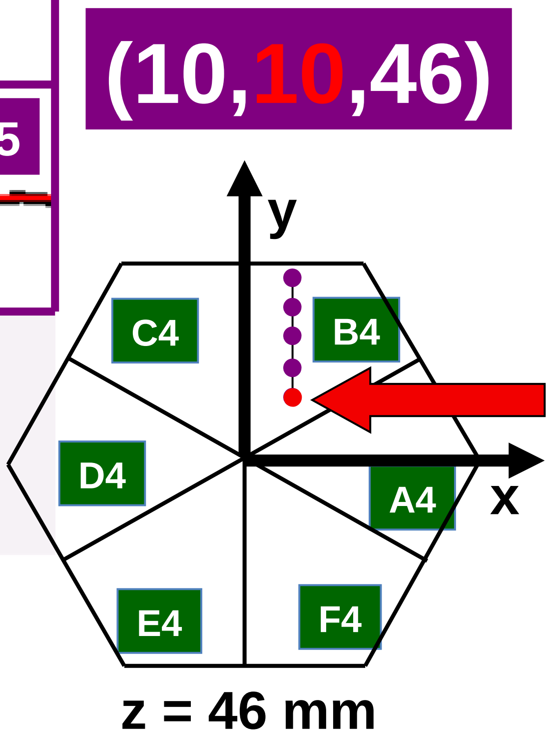
Pulse Shape Analysis concept



791 keV deposited in segment B4

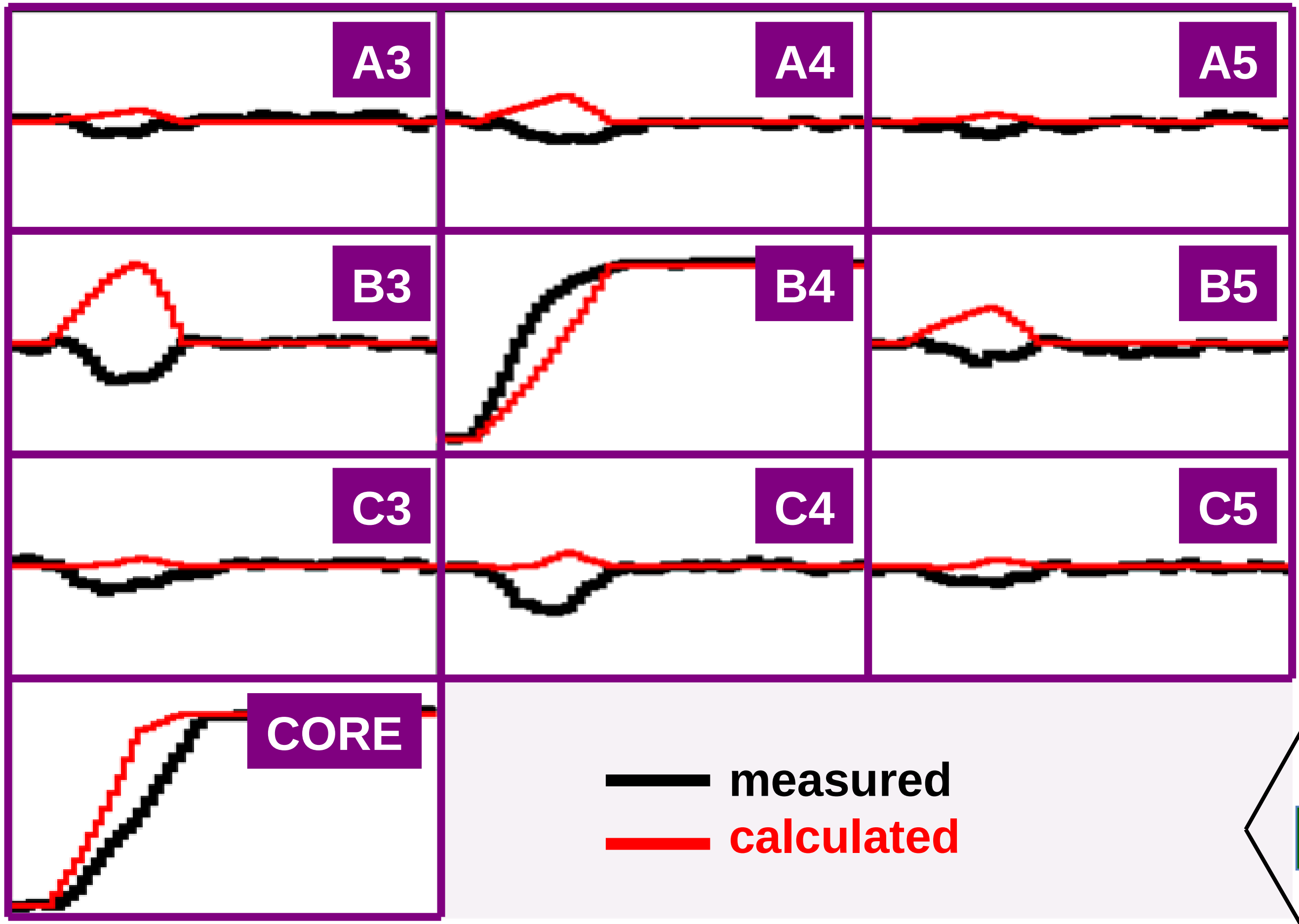
Pulse Shape Analysis concept





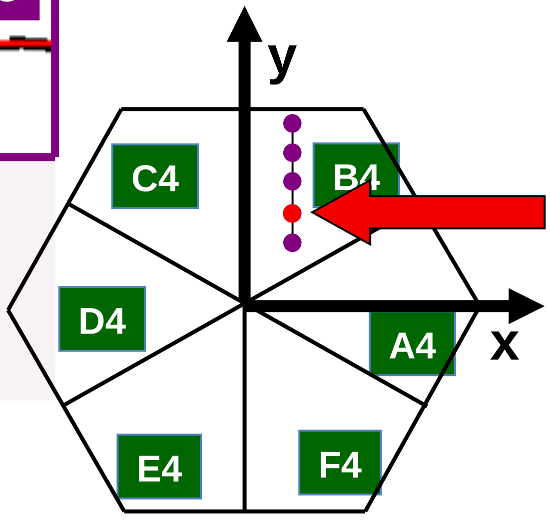
791 keV deposited in segment B4

Pulse Shape Analysis concept

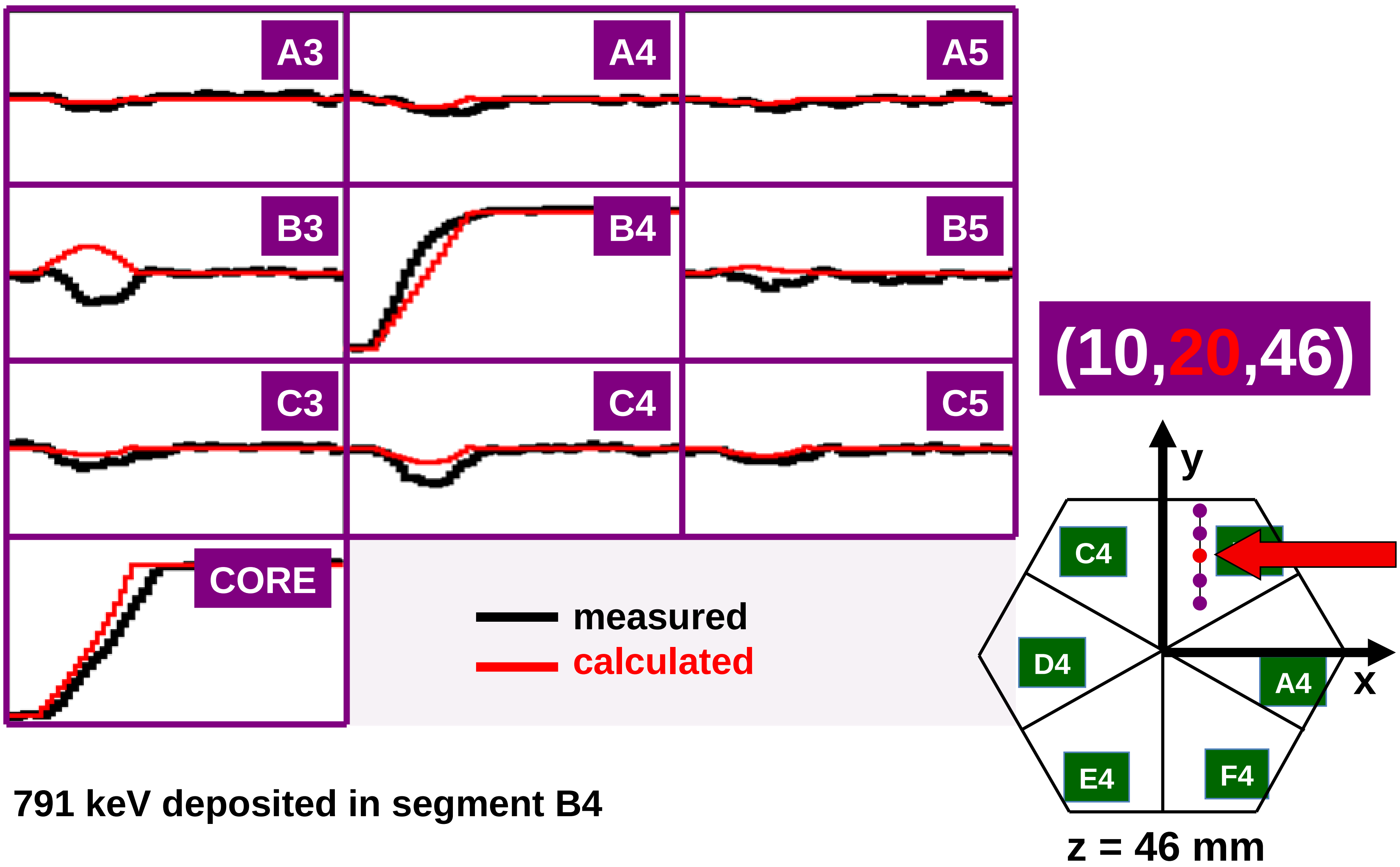


791 keV deposited in segment B4

(10,15,46)

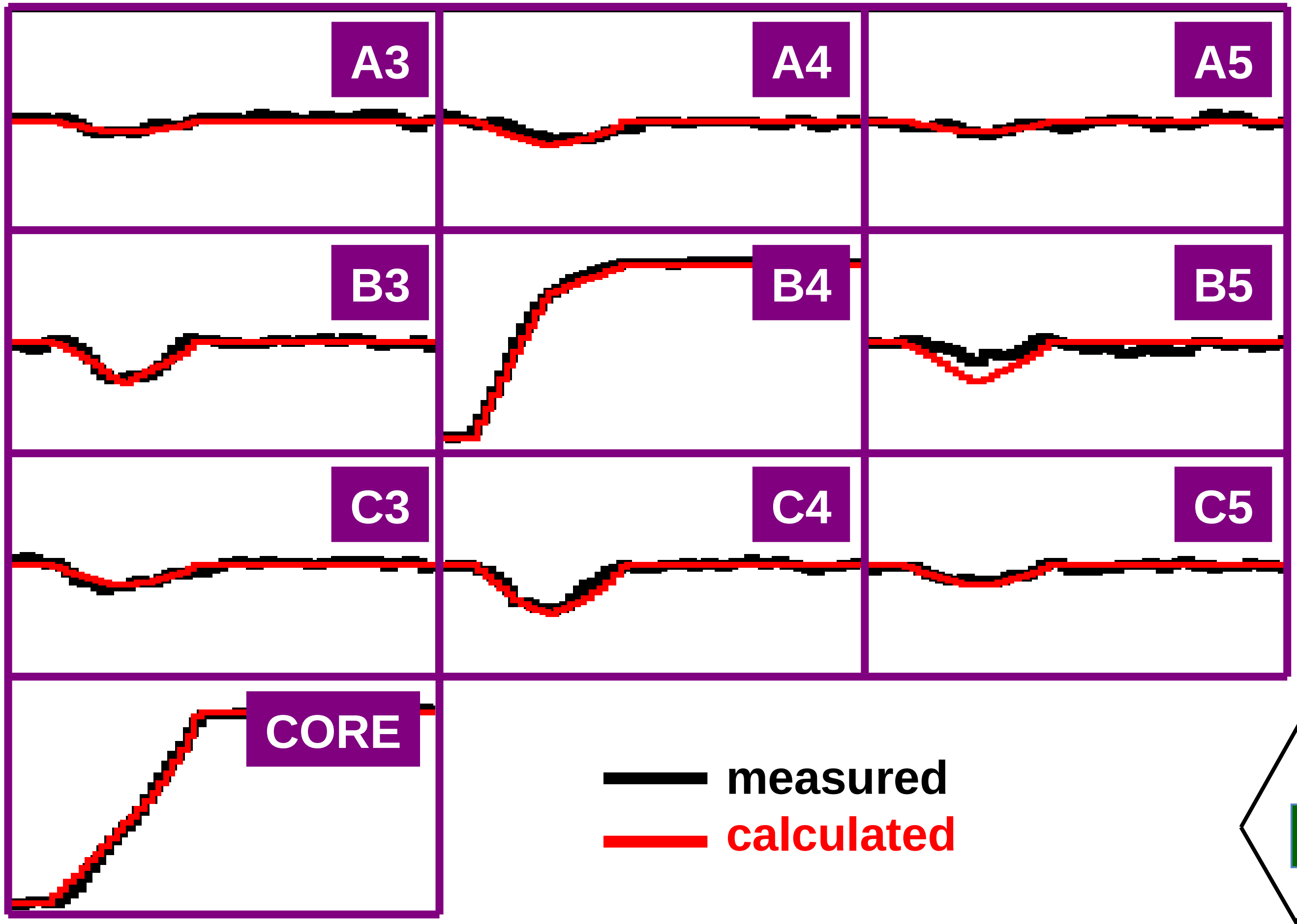


Pulse Shape Analysis concept

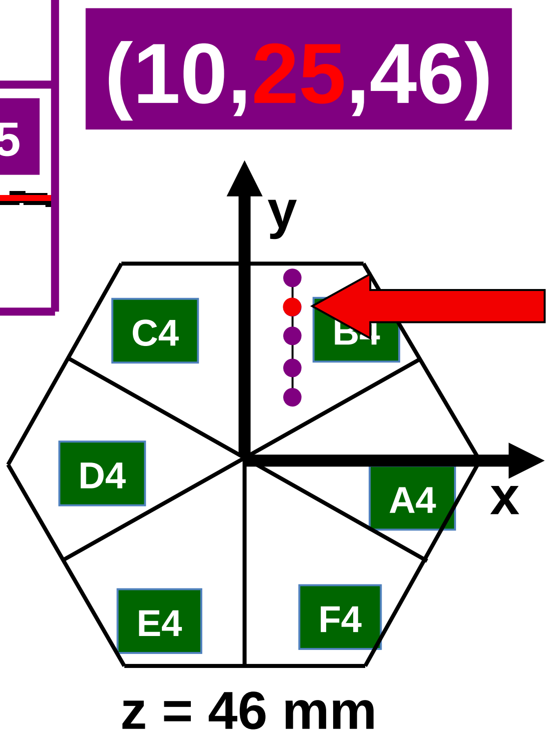


791 keV deposited in segment B4

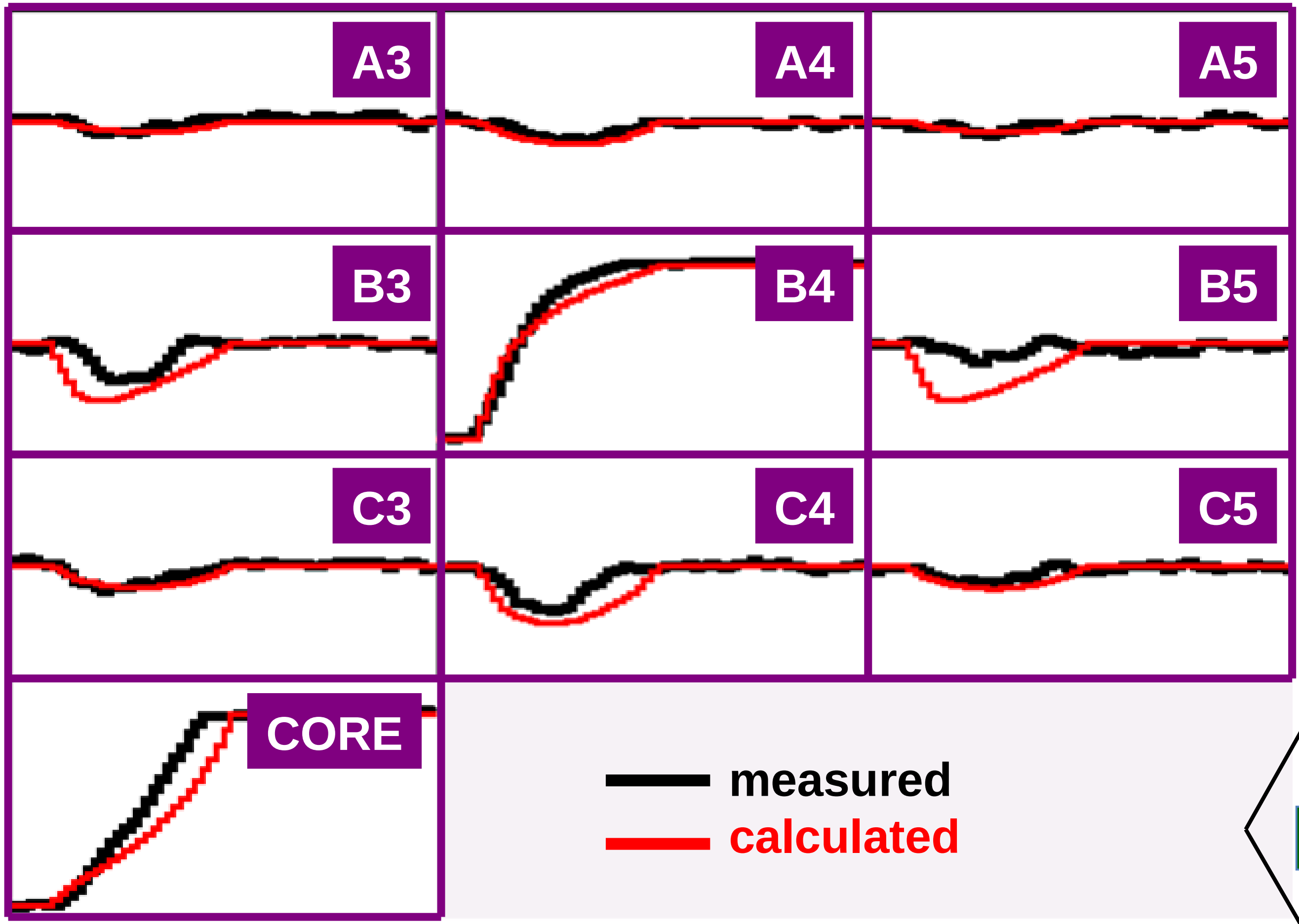
Pulse Shape Analysis concept

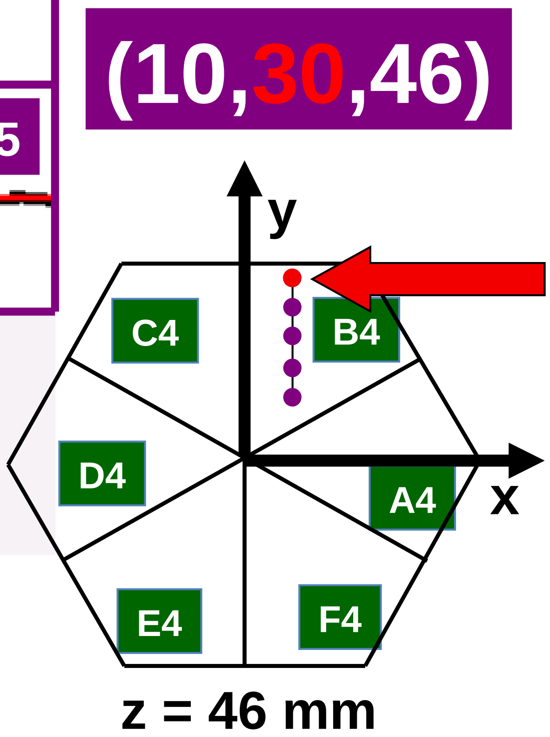


791 keV deposited in segment B4



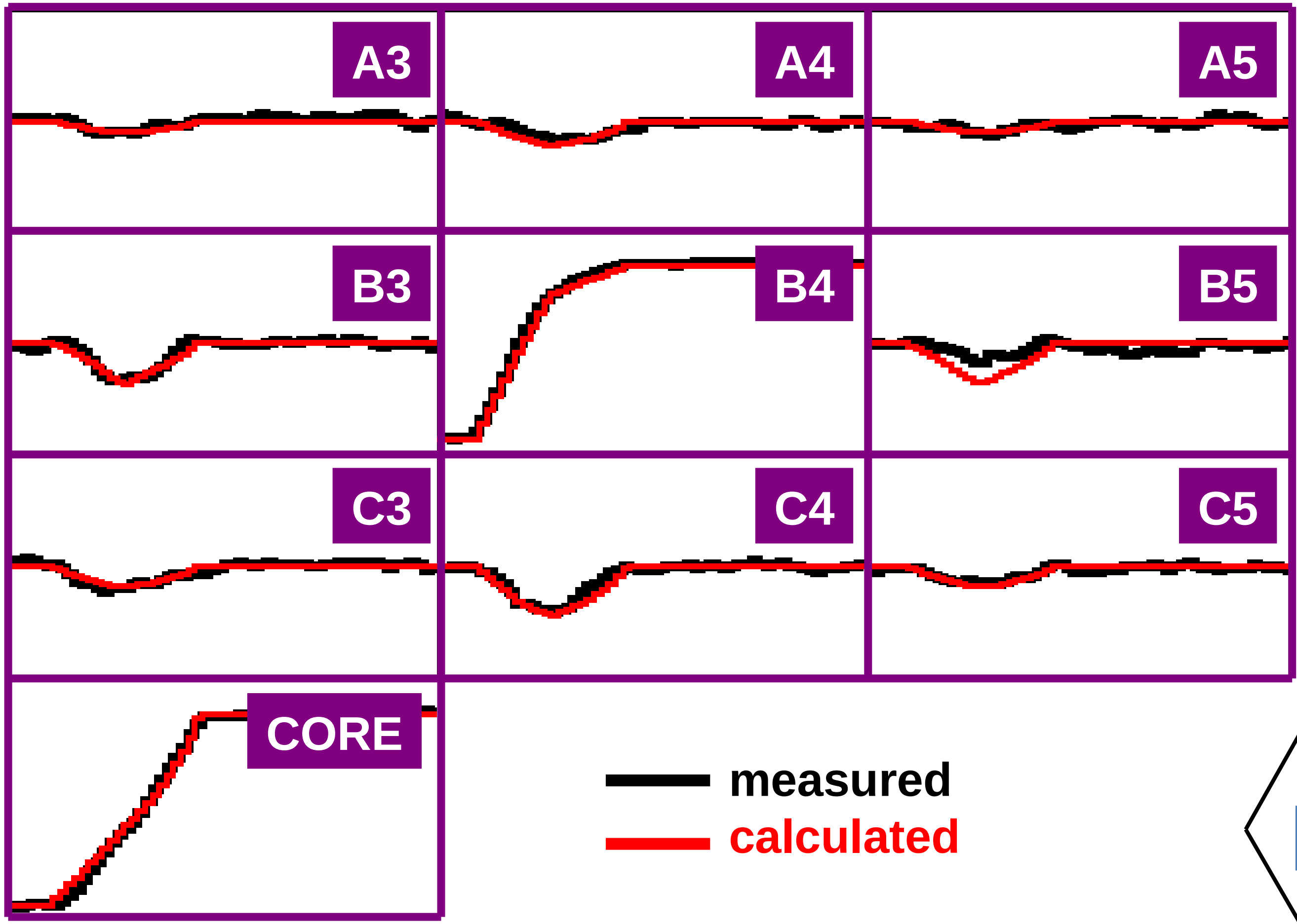
Pulse Shape Analysis concept





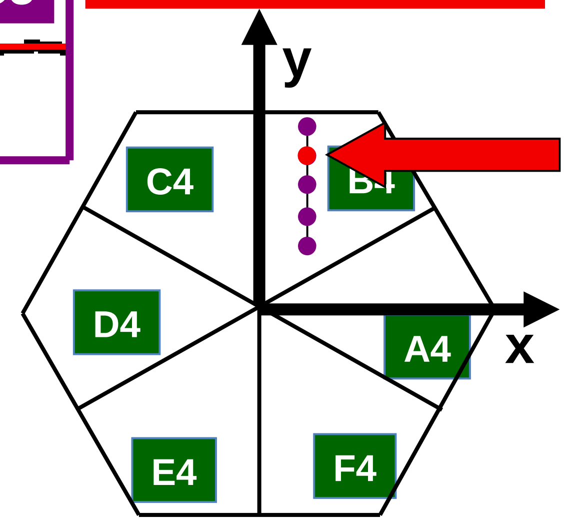
791 keV deposited in segment B4

Pulse Shape Analysis concept



Result of *Grid Search* Algorithm

(10,25,46)



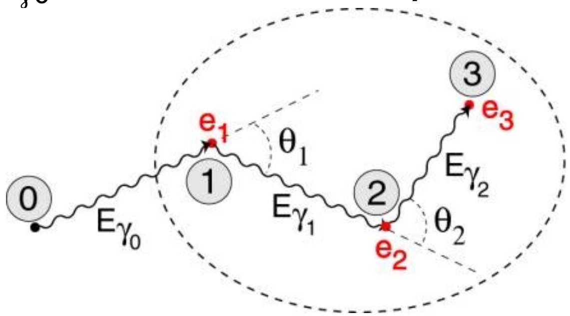
z = 46 mm

791 keV deposited in segment B4

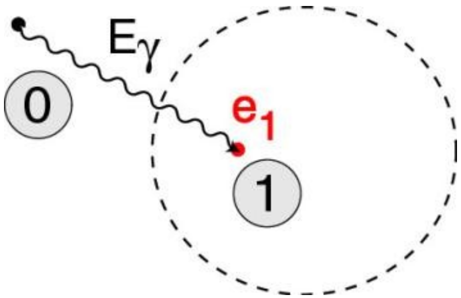
Forward tracking implemented in AGATA

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

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



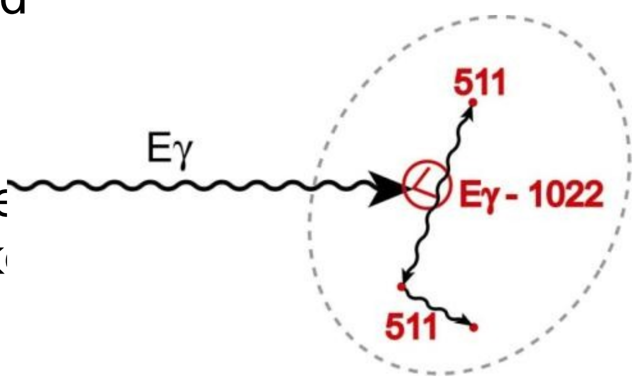
   2. does the interaction satisfy **photoelectric** conditions (e_1,depth,distance to other points) ?



   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 groupe
in two subsets with energy ~ 511 k

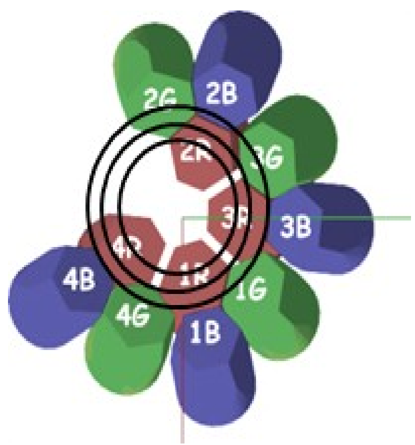


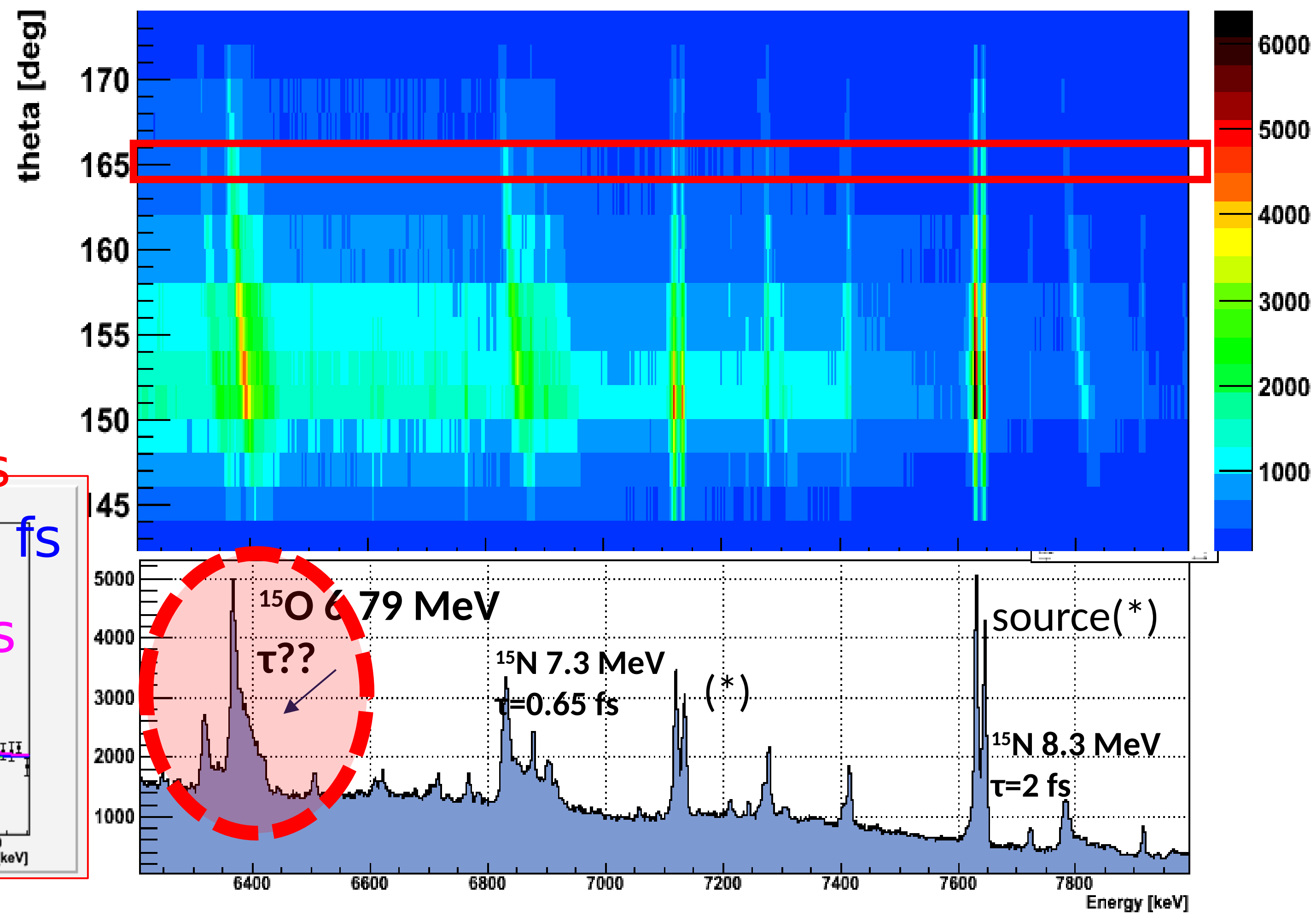
3. Select clusters based on χ^2

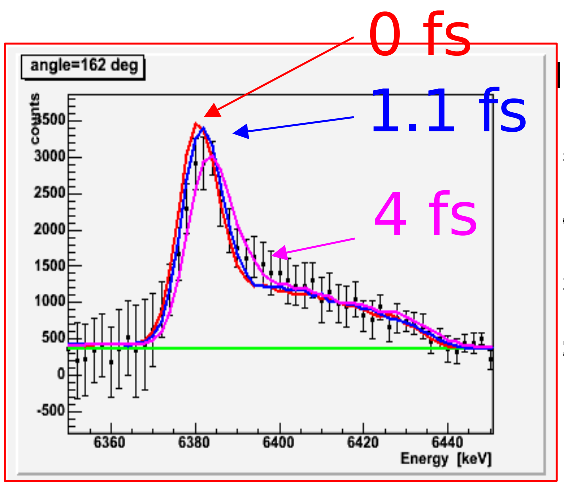
Lifetime measurement of 6.79 Mev in ^{15}O

$^{14}N(^{2}H,n)^{15}$**O** and $^{14}N(^{2}H,p)^{15}N$ reactions @ 32 MeV (XTU LNL Tandem)

Direct lifetime measurement with 4 ATCs at backward angles (close to the beam-line)

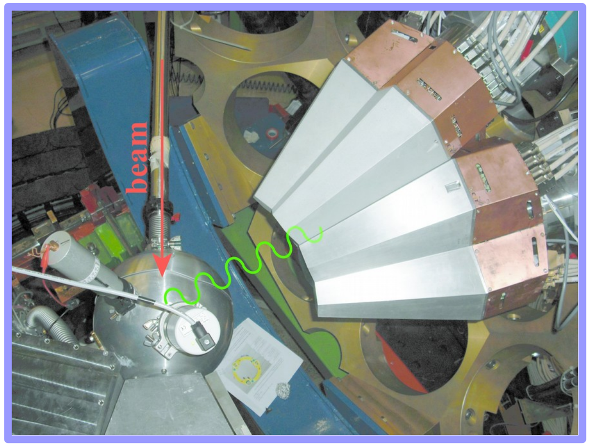


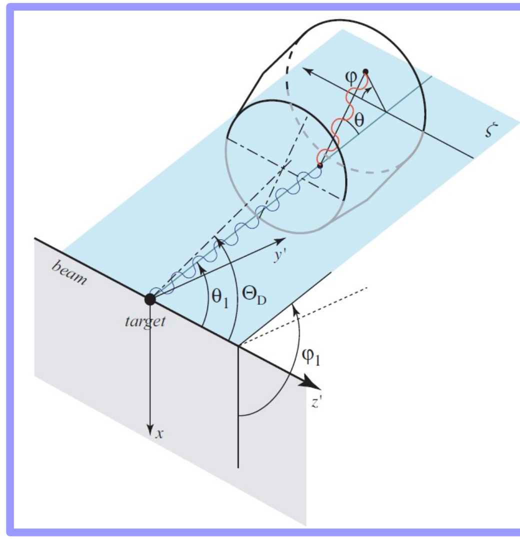




Compton polarimeters

Partially-polarized 555.8-keV and 433.9-keV lines in 104Pd and 108Pd [+unpolarized 137Cs source].

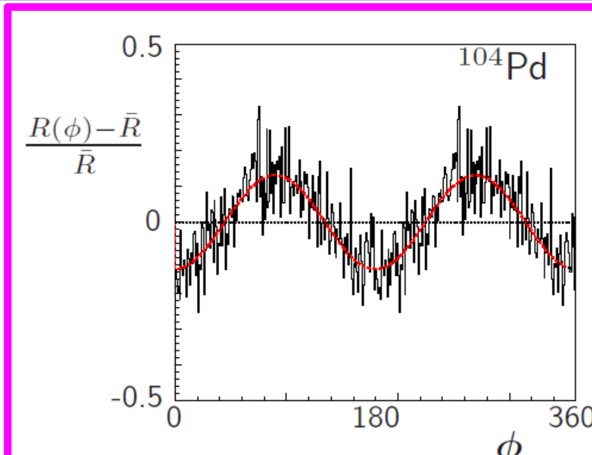




$$\bar{\sigma}_C(\theta,\varphi) = \frac{r_0^2}{4}\left(\frac{E'_\gamma}{E_\gamma}\right)^2 \left[\frac{E_\gamma}{E'_\gamma} + \frac{E'_\gamma}{E_\gamma} - \sin^2\theta \, (1 + P\cos 2\varphi)\right]$$

GOSIA

$$\frac{dN}{d\varphi} = a_0 + a_2 \cos(2\varphi) \, .$$



Analyzing power: 6x10-3

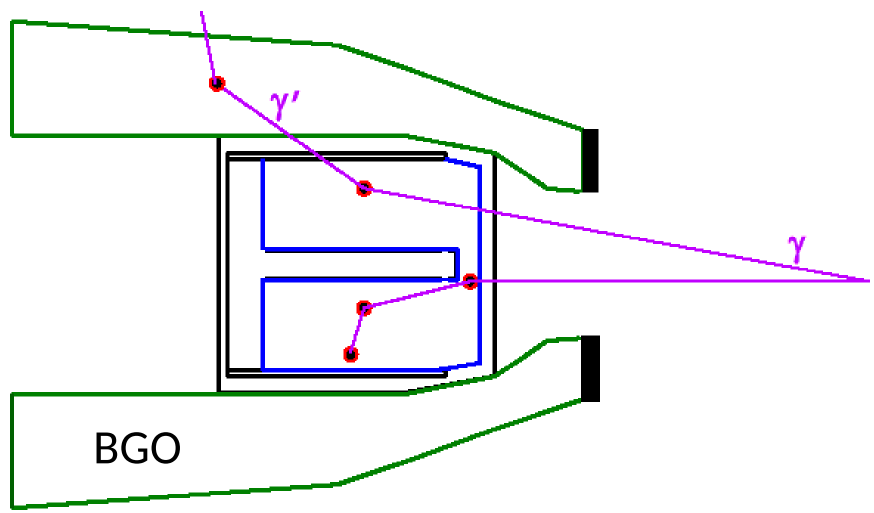
GALILEO

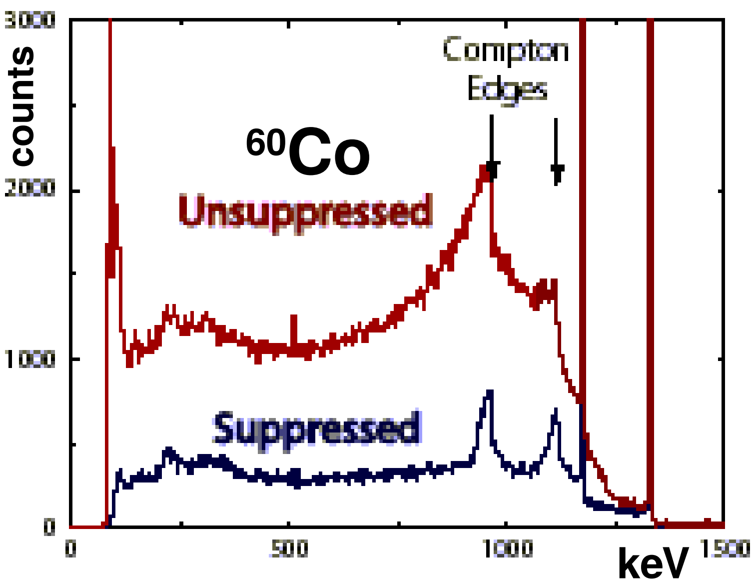
✔ Resident array at LNL

HPGe

- 25 HPGe detectors GASP type
- @ 22.5cm; ~ 2.4% eff @1332.5
- 25 BGO
- FWHM@1332.5 keV < 2.4 keV; with experimental shaping: 17 mounted
- Completely digital DAQ:
  - ✔ 4 μs rise time, 1μs flat top energy stored
  - ✔ initial part of the signal taken
  - ✔ BGO slave of HPGe
  - ✔ very low noise
  - ✔ recover time information from the signal

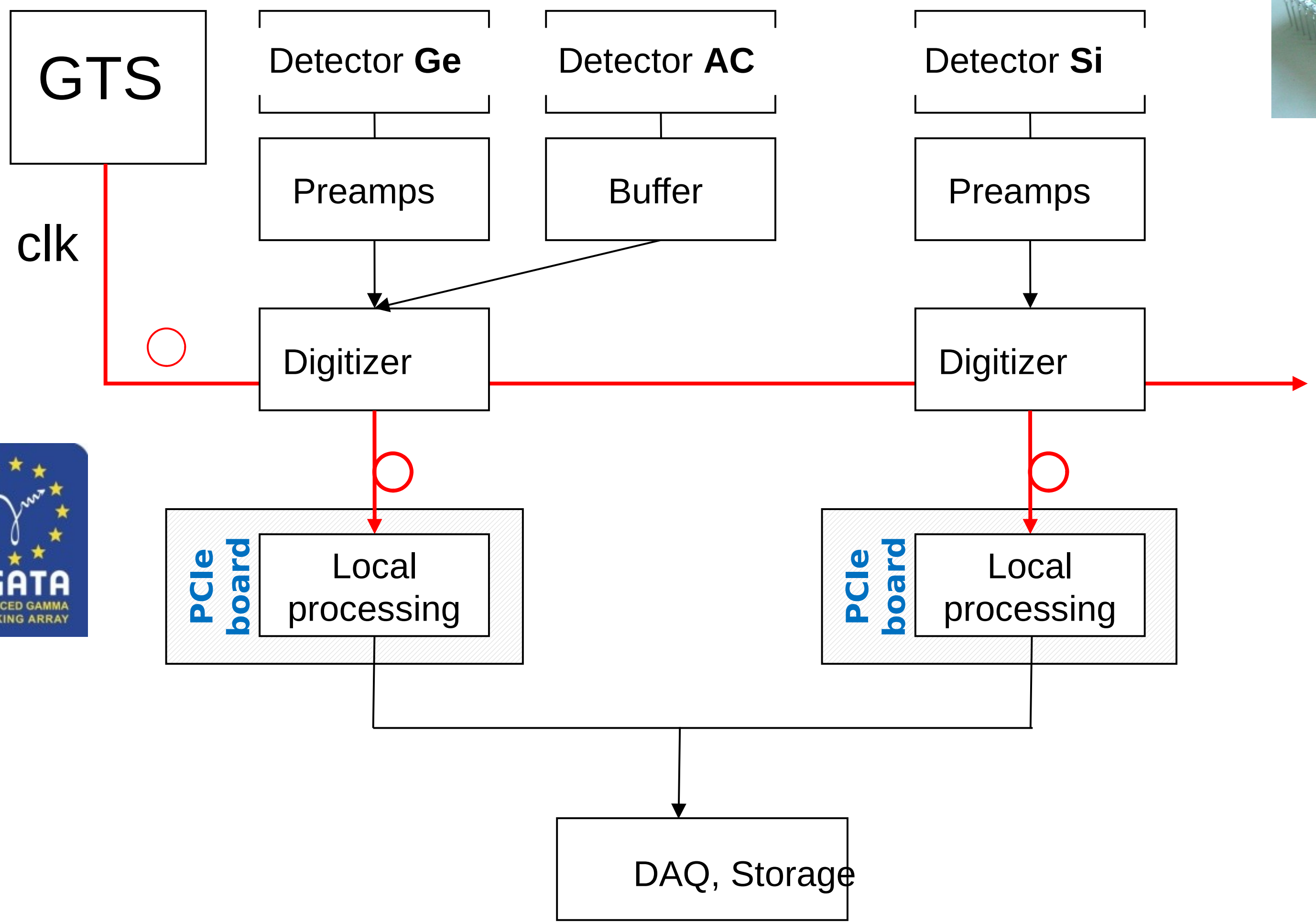
Compton shield

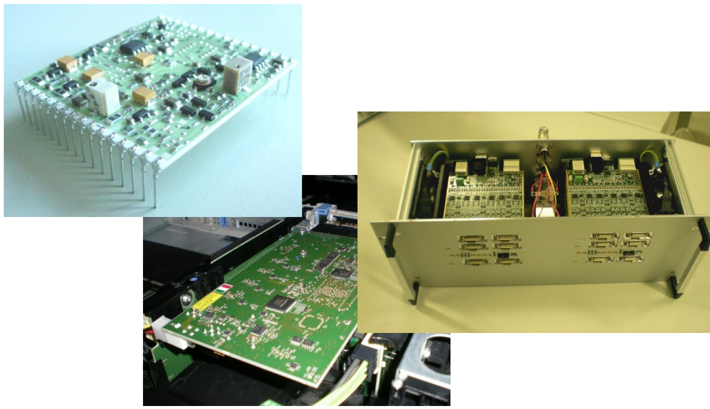




- For large-volume Ge crystals the Anticompton shield (AC) improves the Peak_to_Total ratio (P/T) from ~20% to ~60%
- In a g-g measurement, the fraction of useful peak-peak coincidence events grows from 4 % to 36%
- For high fold (F) coincidences the fraction of useful coincidences is: P/T^{F}

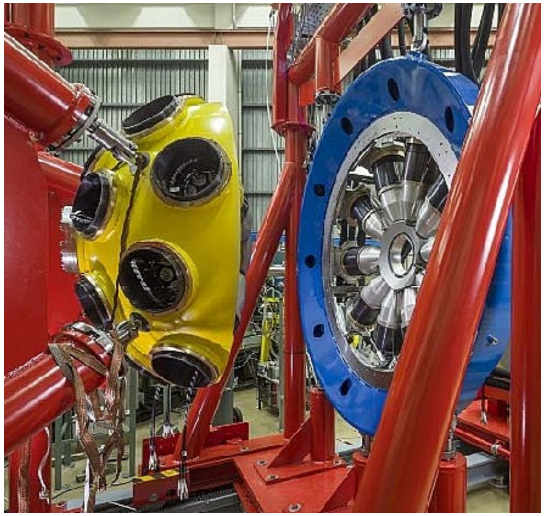
GALILEO – Digital electronics

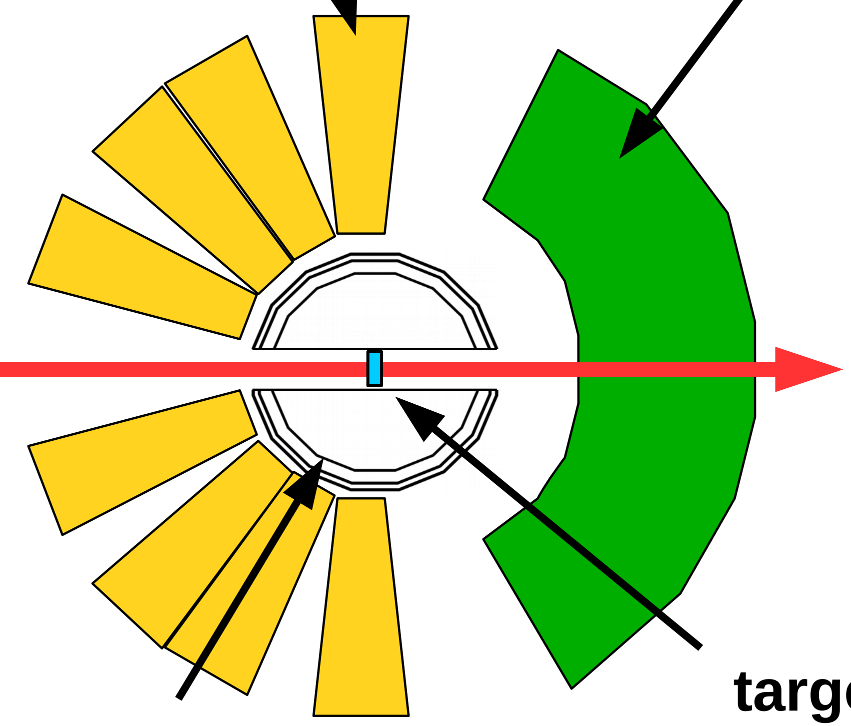


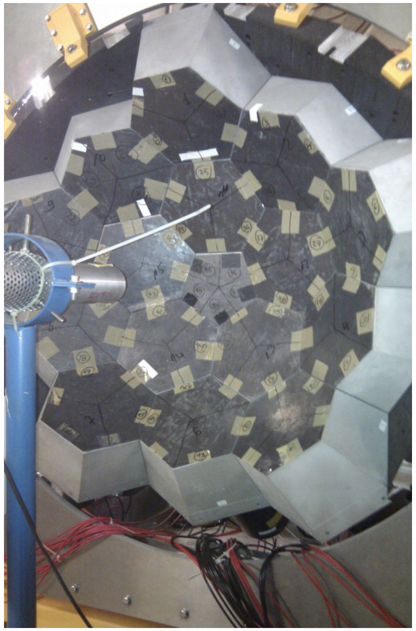


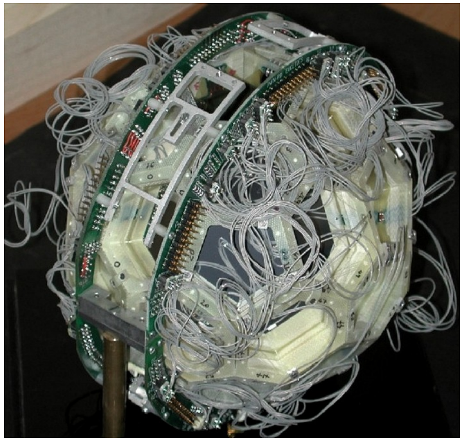
- HPGe,AC, Anc. digitized
- Branches are sync by GTS.
- Trigger-less operation
- 240 channels available
- Typical rate ~ 20 kHz/det
- Max rate ~ **50 kHz/det**

GALILEO –
ν deficient science campaign



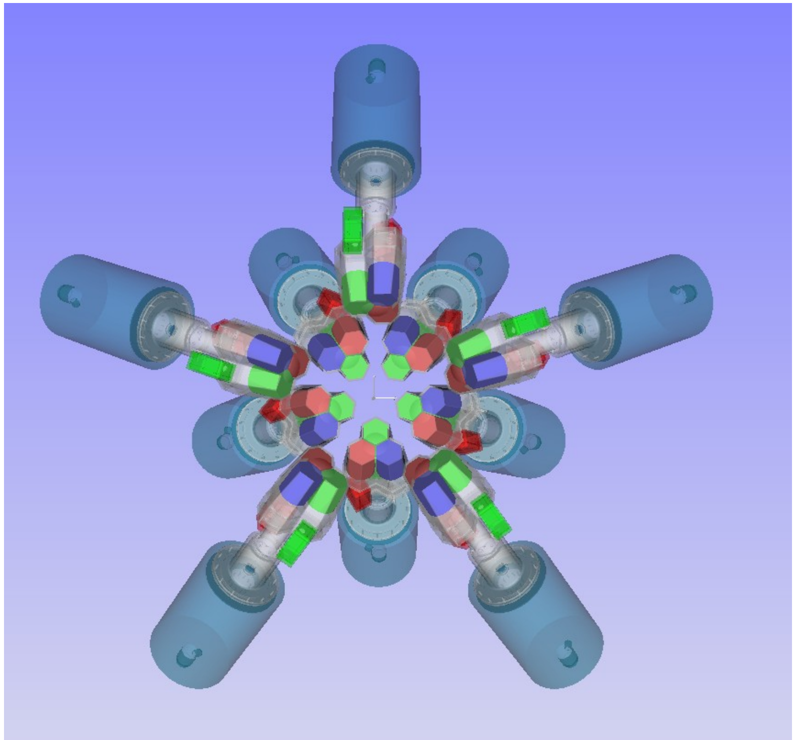




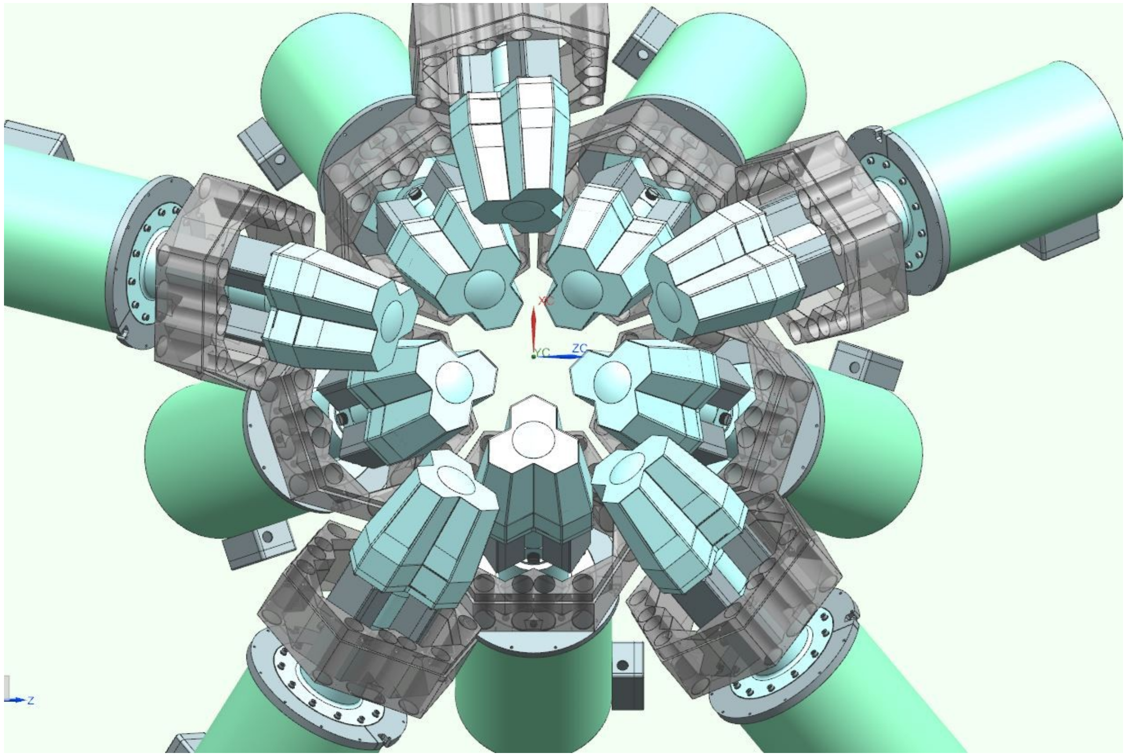


GALILEO – Phase 2

- Physics program driven configuration: 10 GTC @ backward angles
- Efficiency ~ 7.5%



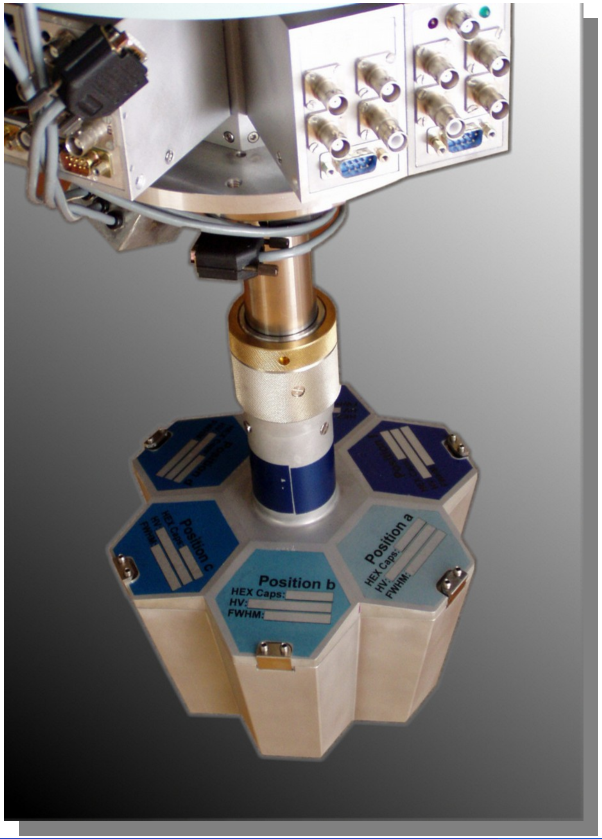
GEANT4 Simulation by Alain Goasduff

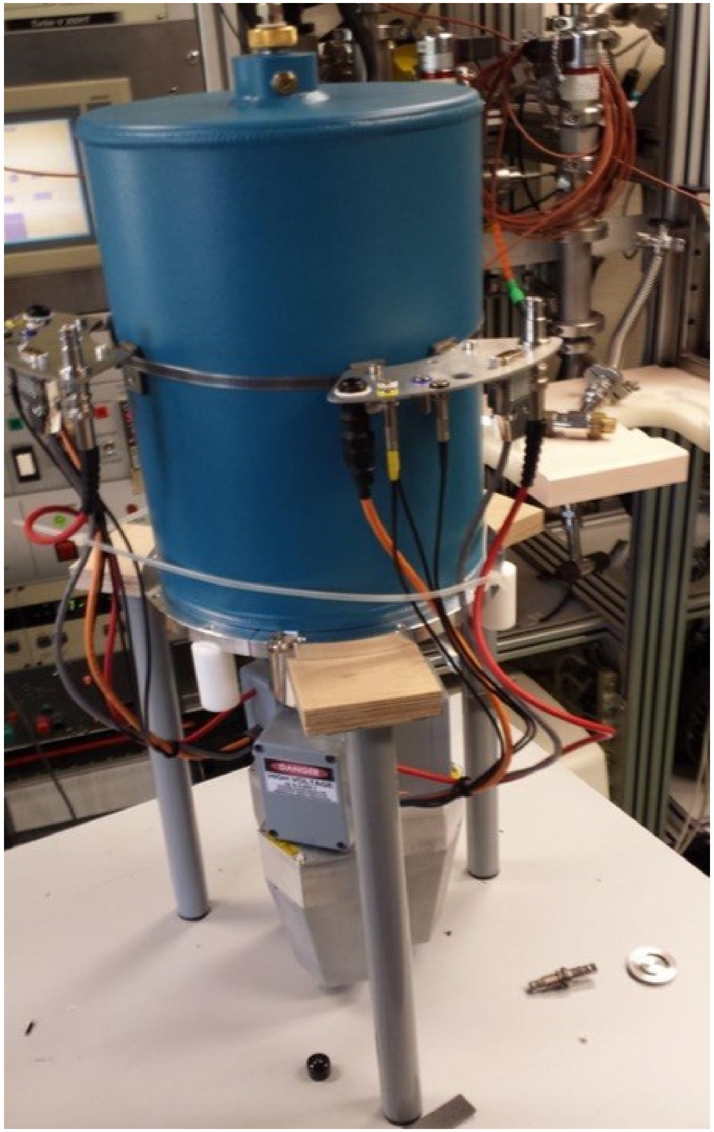


Mechanical project by INFN Padova

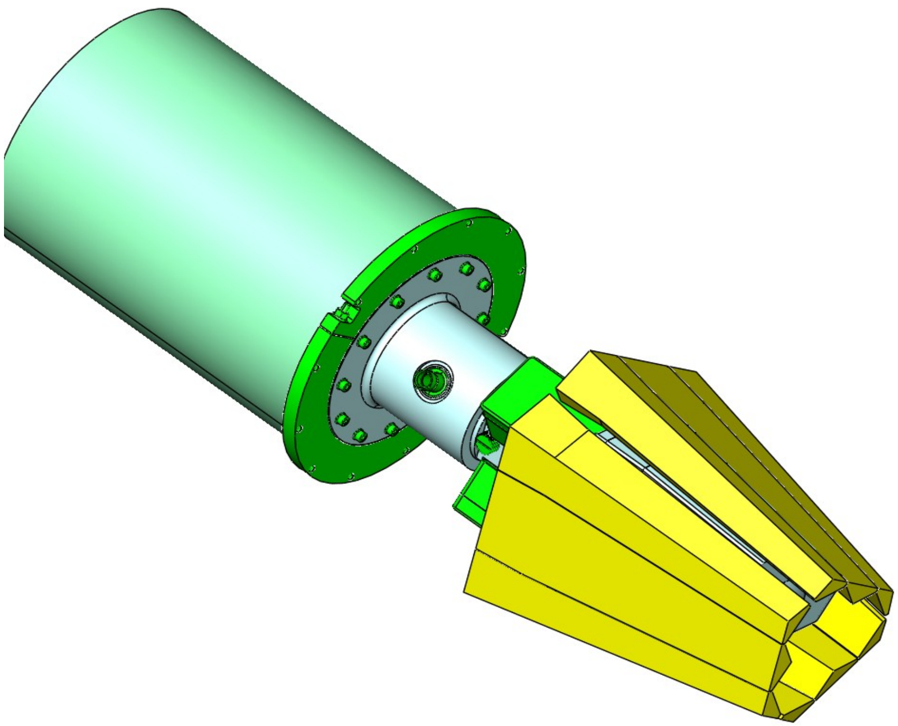
GALILEO triple cryostat

- New triple cryostat out of the EUROBALL capsules.

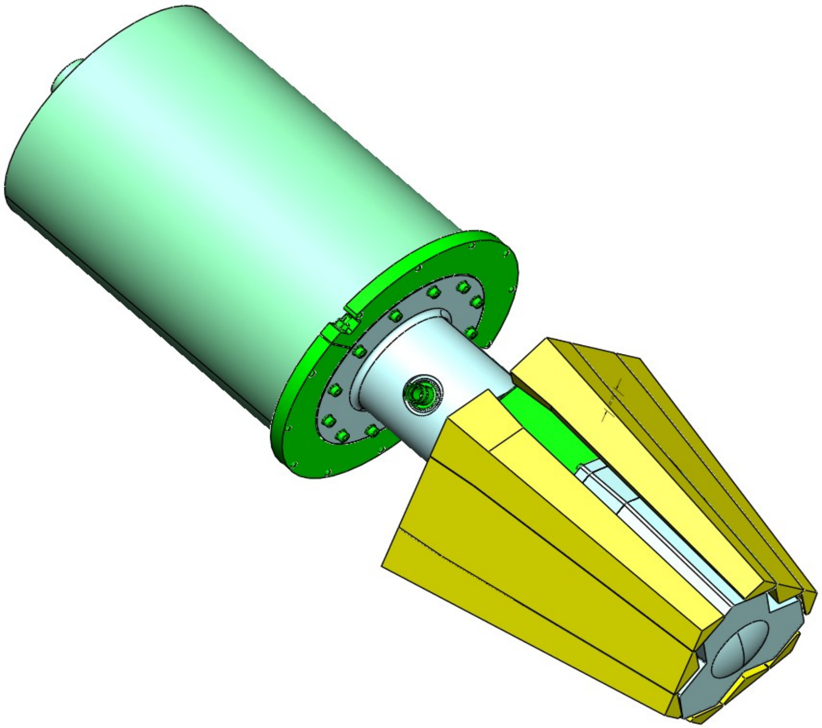




GTC + AntiCompton shields



Standard configuration GTC
crystals at ~ 5 cm from the
BGO front face

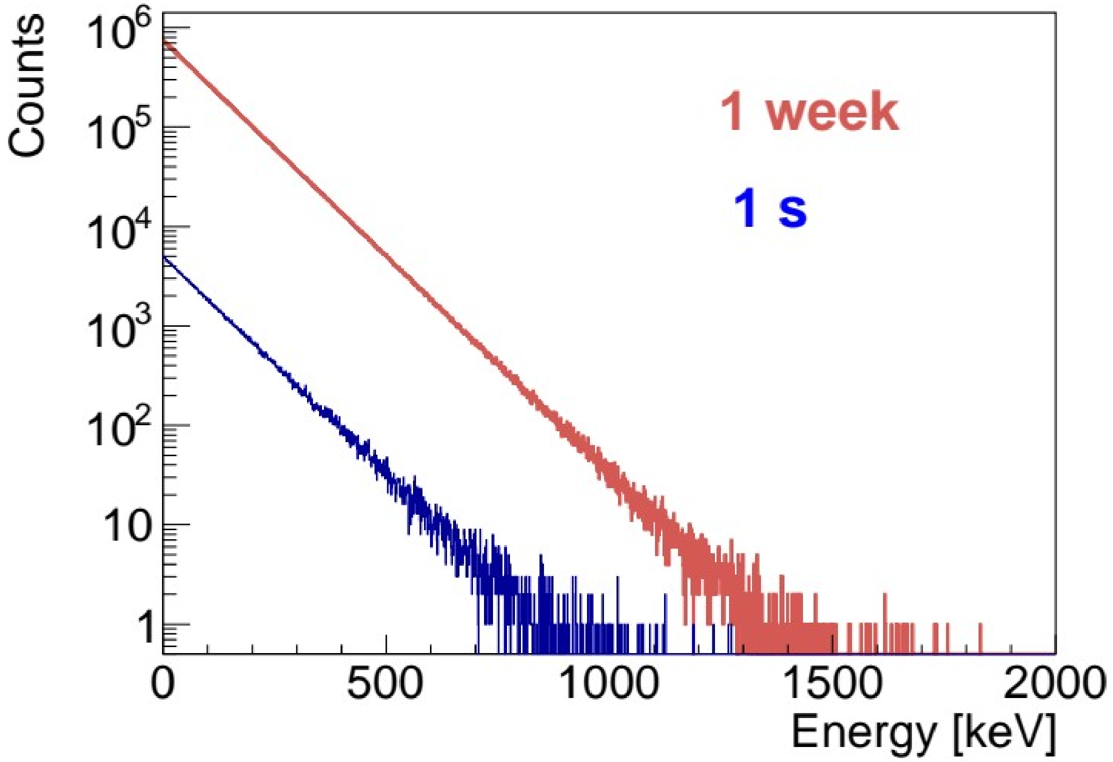


Close configuration
GTC crystals aligned to the
BGO front face

PANDORA

- ✔ Some considerations as γ-ray spectroscopist

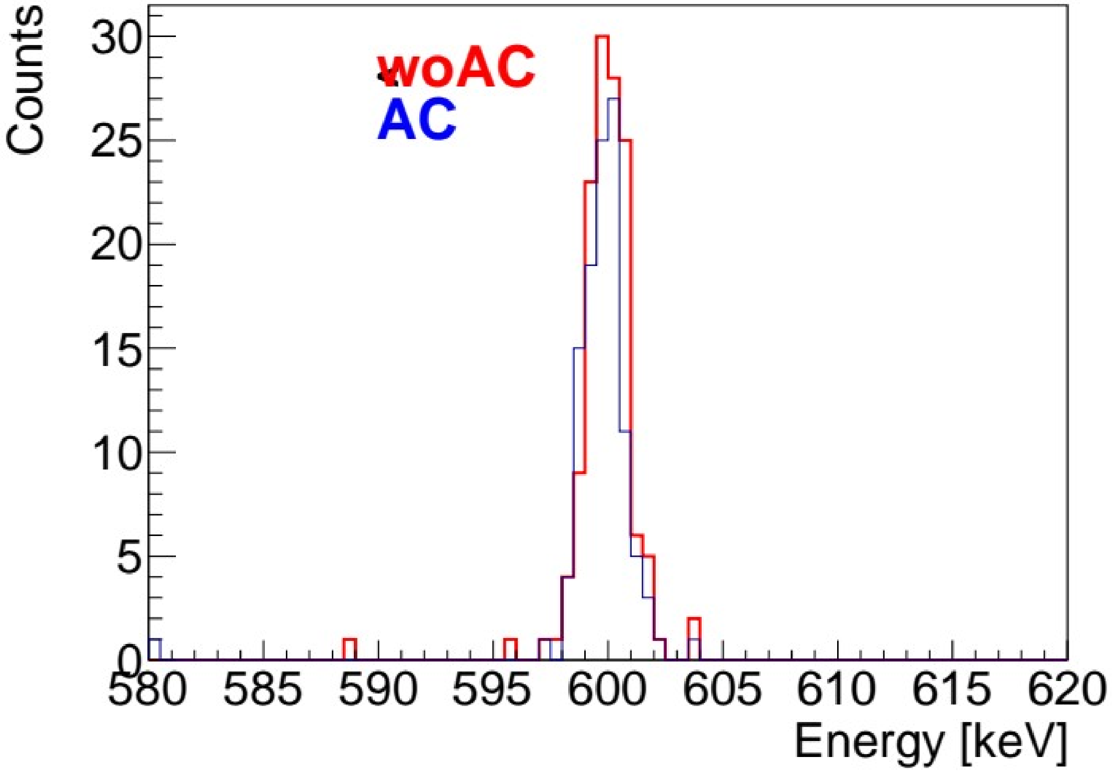
Background (from TDR)



- Back ground: $5000 \times e^{(-E/100keV)}$
- Integral: pps 500k –> ~50kHz det
- Hist populated with random numbers

- Shield to be considered
- Likely at the edge of a counting det for spectroscopy purposes (at *sustainable* cost)

w/o AC



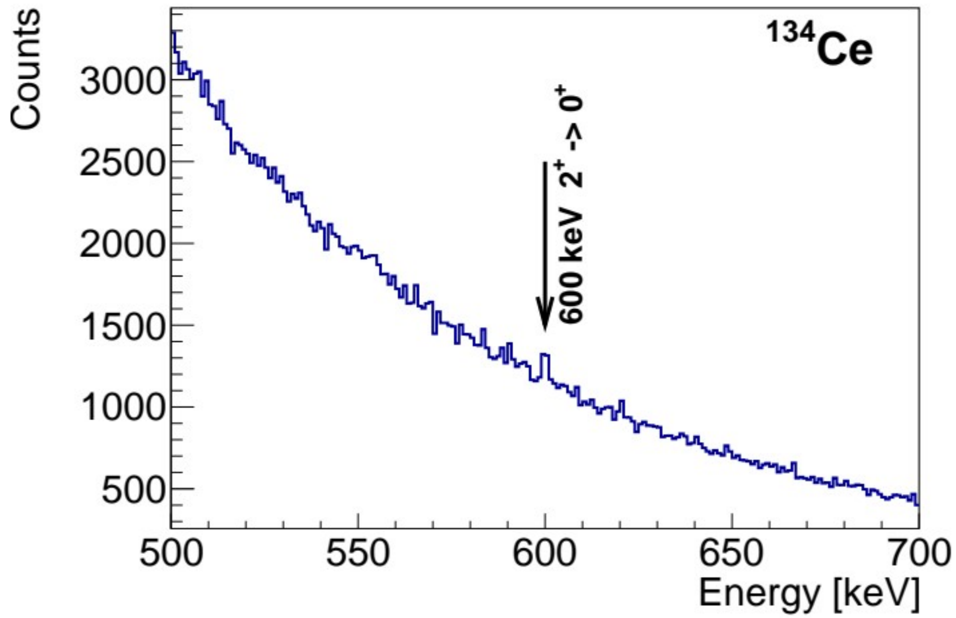
Ingredients:

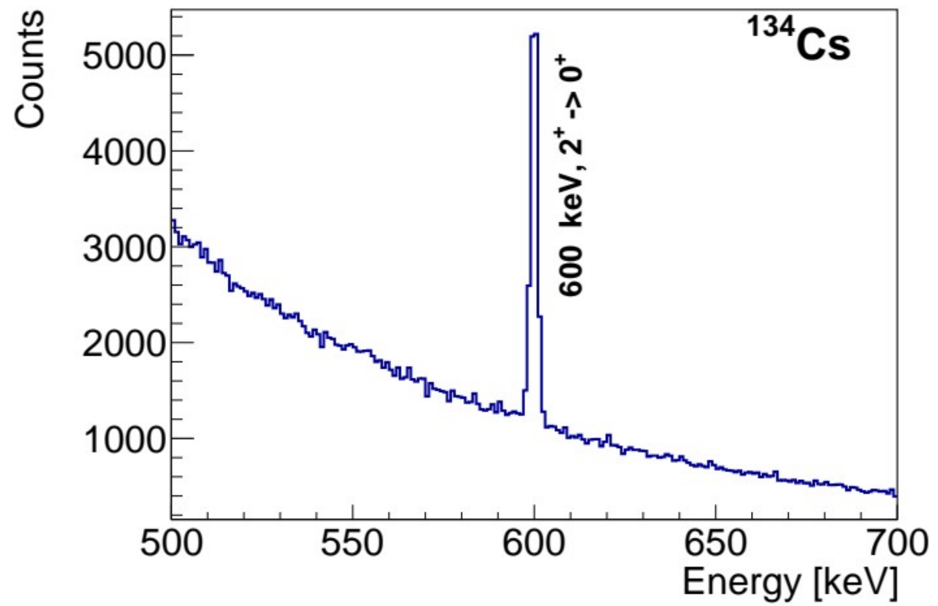
- 1 week
- 1 cps (short lifetime)
- No background
- Source at rest

No significant difference in single

$\gamma\gamma$ not investigated so far [PT^{Fold}] → depending on the activity a coincidence might be useful to resolve the (lower-energy transition)

Simulations (quick&dirt)



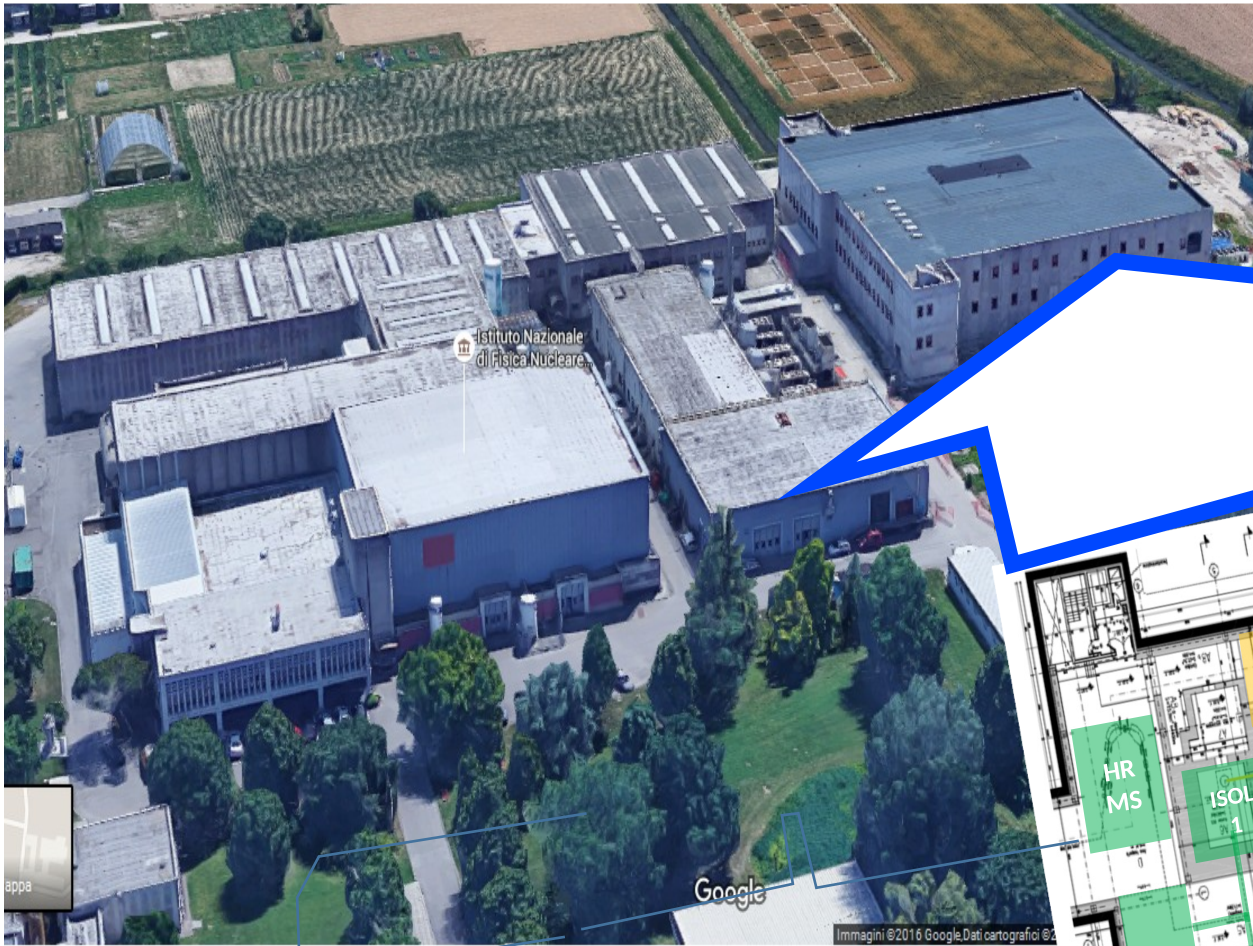


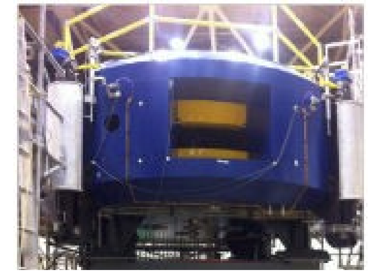
- 1 week of beam(*live*) *time* → *statistical precision to be address*
- Signals: 1 cps *vs* 100 cps [τ: 10^7 - 10^5]
- Source at rest, Ions velocity?
- HPGe: 20 cm distance (sphere) → ~2% ε_{ph}
- 2.5x5 cm^2 Pb collimator
- AC included but γγ not investigated (...useful)

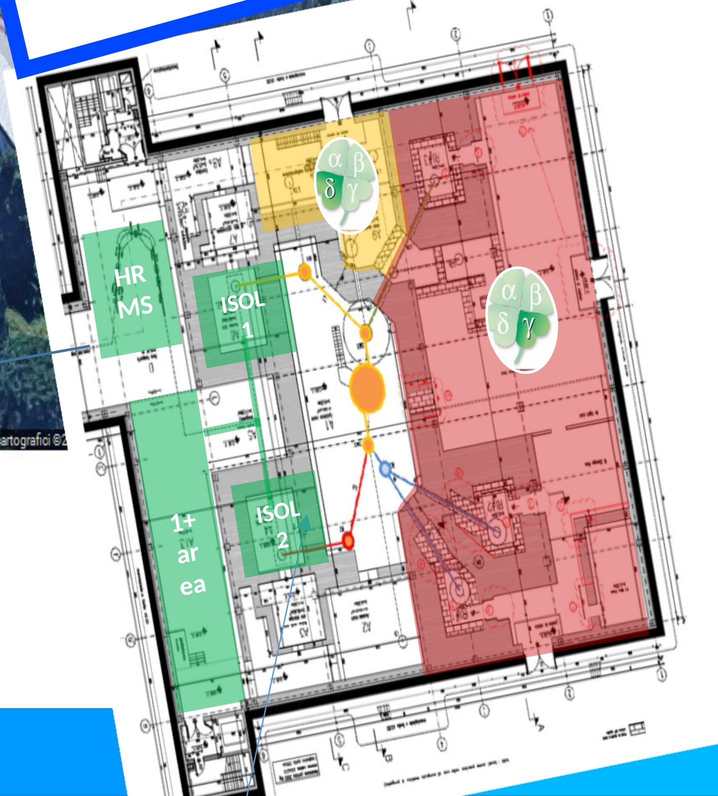
Summary and Conclusions

- Long-standing tradition in γ-ray spec. at LNL - INFN
- Principle of tracking and AC γ-ray spec.
- Simple simulations with PANDORA
- Synergies to be considered harmonizing the use of resources
- Human resources and expertises to be considered

SPES facility



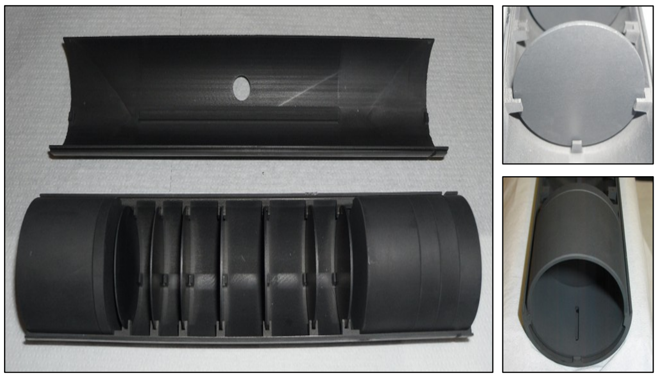


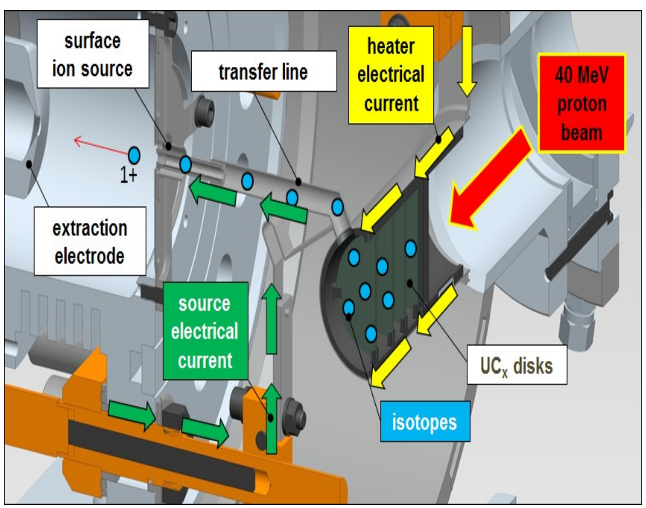


- 2nd generation ISOL facility:pure ad intense beam
- 10^{13} fissions/s

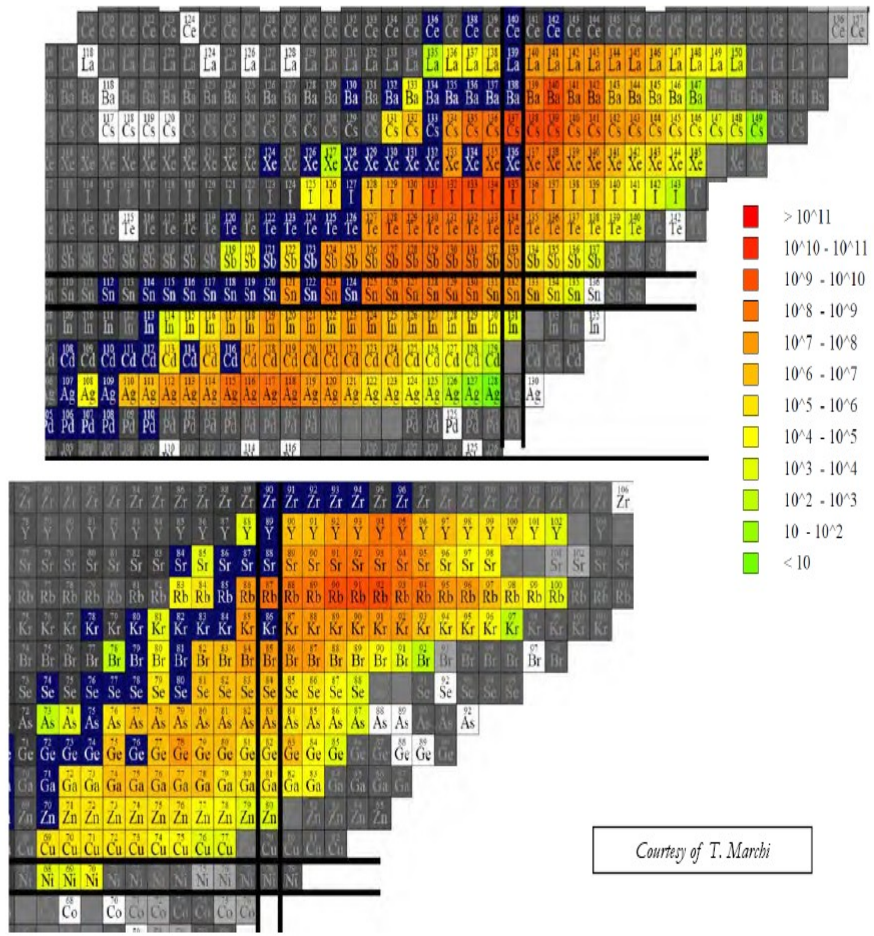
Fission fragments

- UCx Target
  (… + not fissile also foreseen)



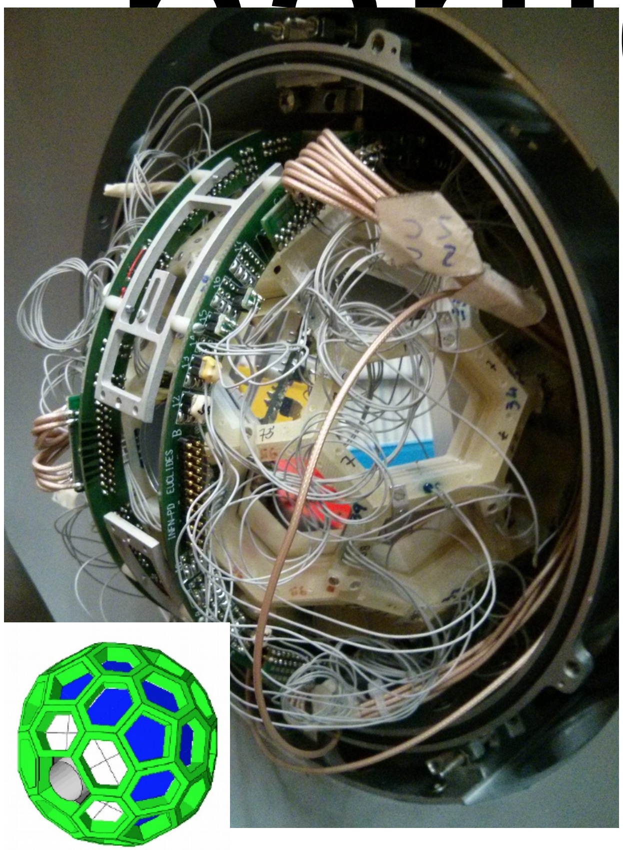


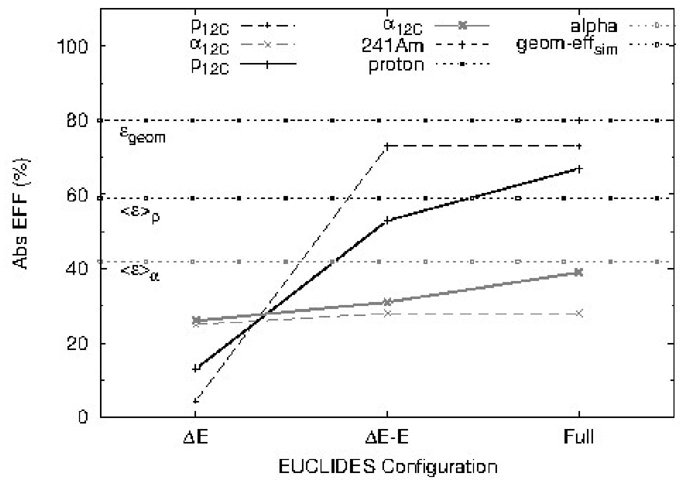
- Expected intensity for reaccelerated beams

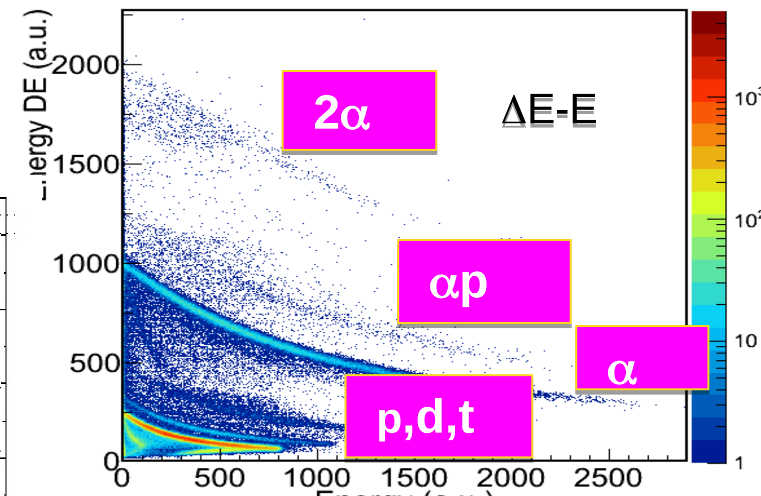


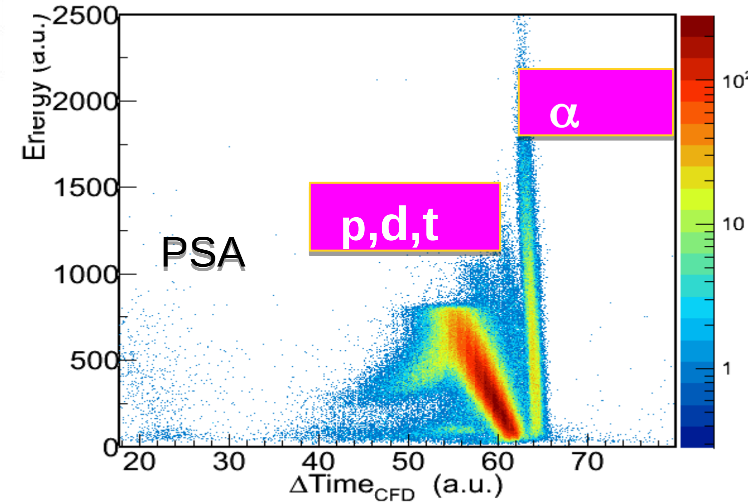
- **MCNPX Calculation**
- **BERTINI – ORNL** (FF cross-sections)
- **Release** & **ionization efficiency** in agreement and re-scaled on **HRIBF experimental values** and **currents** (200μA/5μA)

EUCLIDES particle de



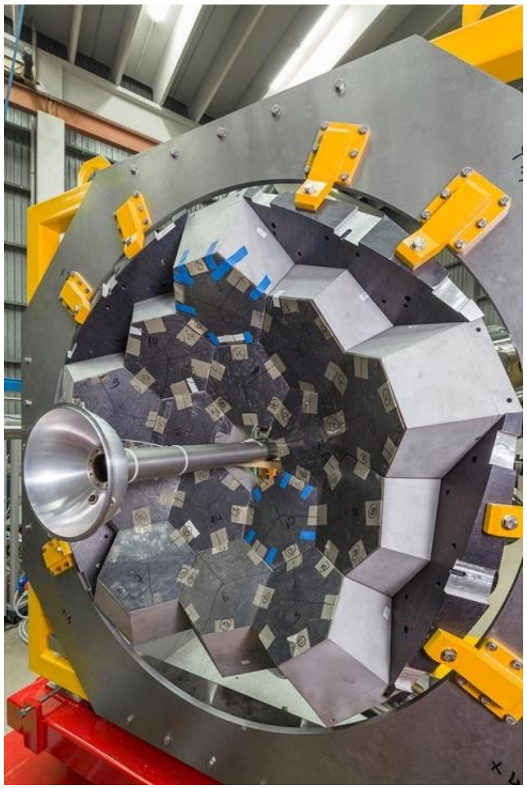


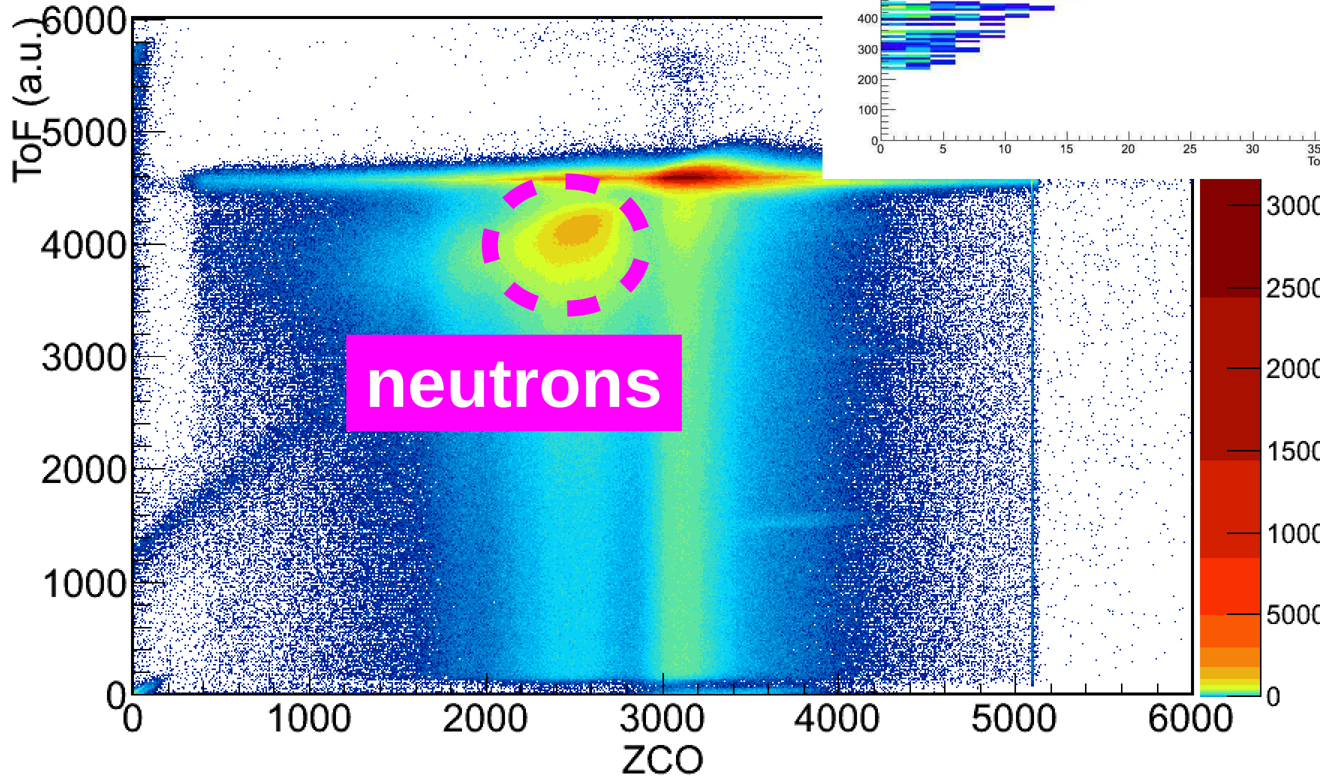


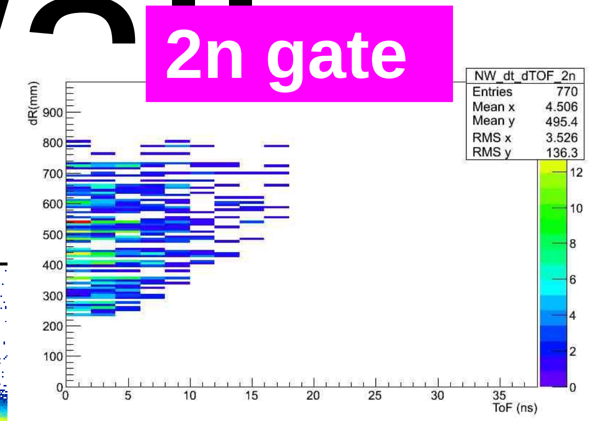


- 110 Silicon detectors (80%4π)
- New compact electronics
- Trigger less operation
- Telescope technique (DE-E and ...PSA)
- Efficiency highly depends on experiment

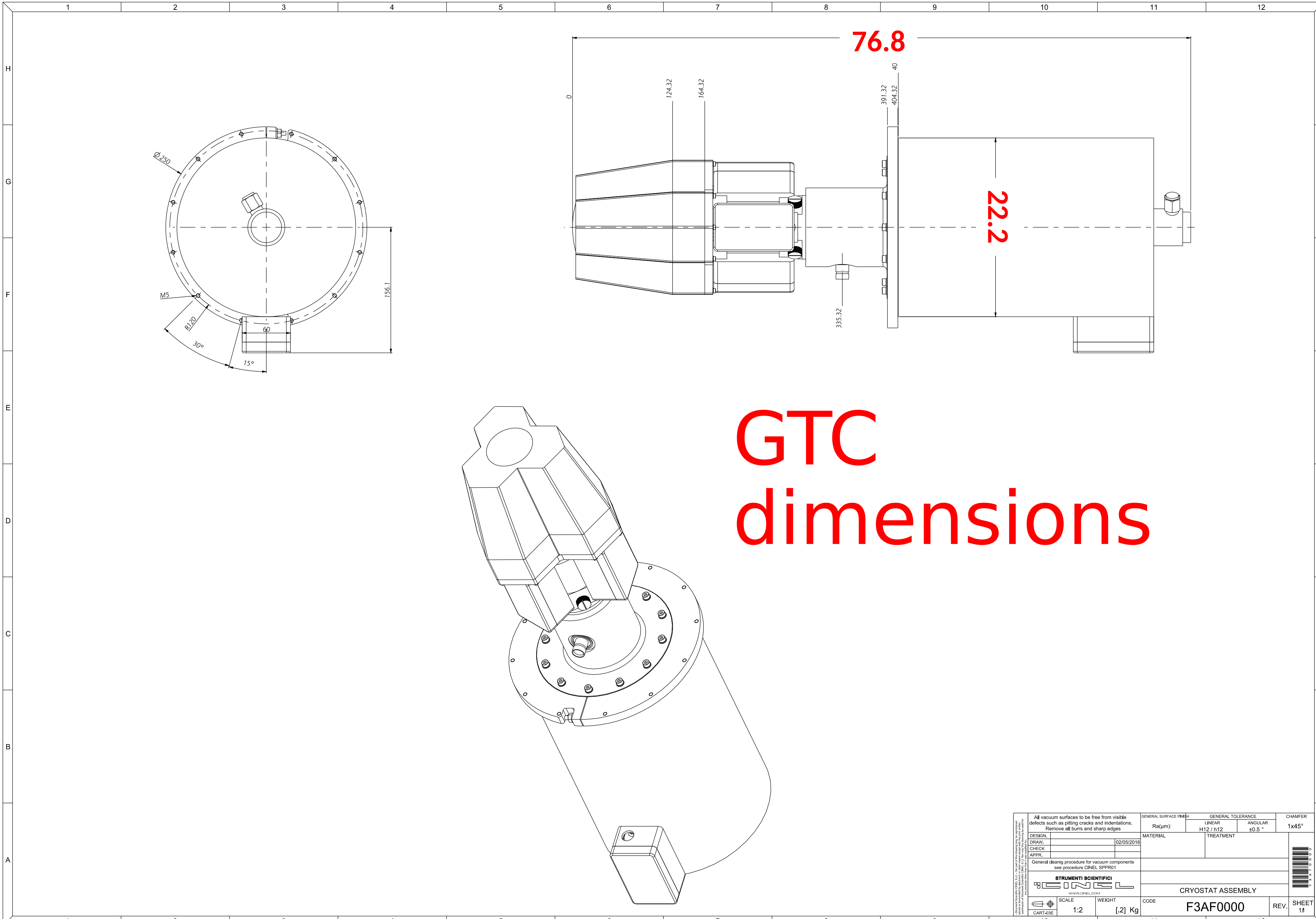
Neutron Wall







- 50 (45) detectors, organic scintillators [BC501A]
- Three types of signals for each of them: QVC, TOF, ZCO
- Preselected neutron condition provided to the trigger
- *s*(1n) = 23-27%; advantageous for identification of 2n channel
- VME electronics → going to digital (NEDA)

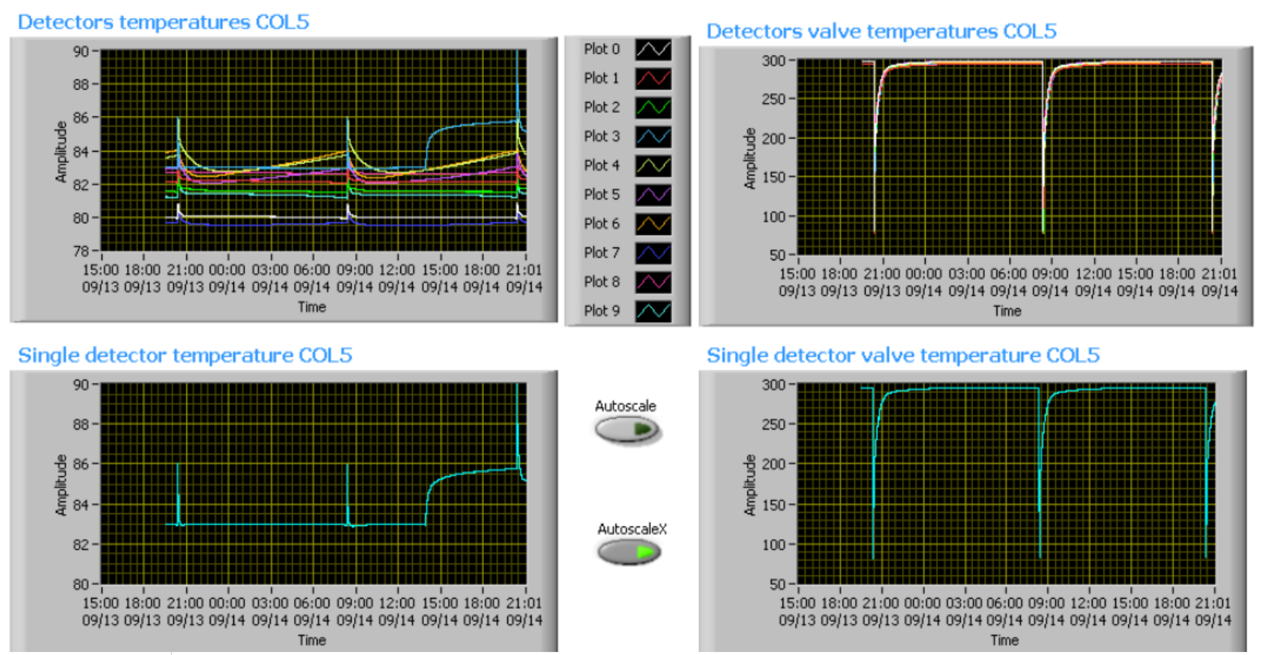


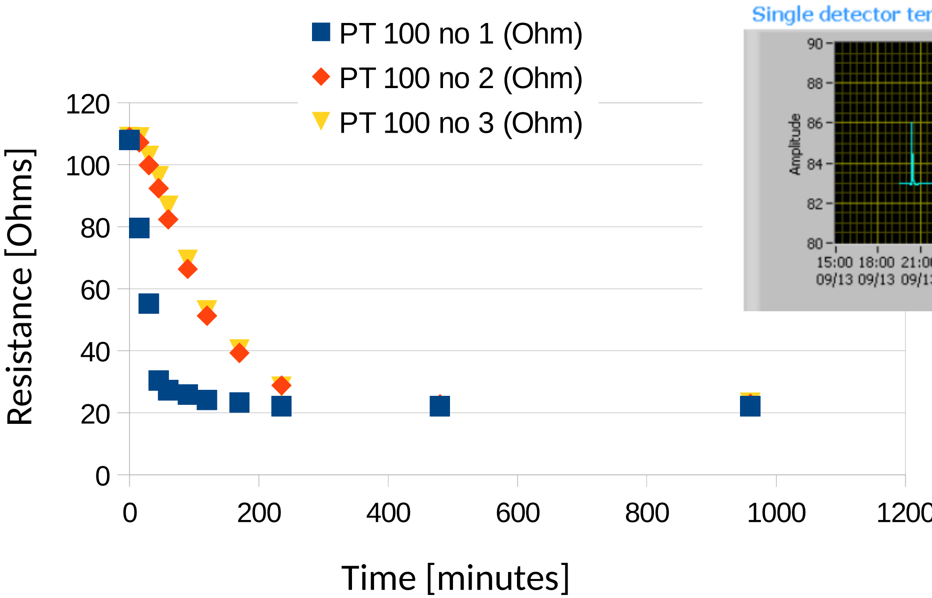
76.8
22.2
GTC dimensions
0
124.32
164.32
391.32
404.32
40
335.32
Ø250
M5
R120
30°
15°
60
156.1
All vacuum surfaces to be free from visible defects such as pitting cracks and indentations. Remove all burrs and sharp edges
GENERAL SURFACE FINISH
Ra(μm):
GENERAL TOLERANCE
LINEAR H12 / h12
ANGULAR ±0.5 °
CHAMFER 1x45°
DESIGN.
DRAW. 02/05/2016
CHECK
APPR.
MATERIAL
TREATMENT
General cleanig procedure for vacuum components see procedure CINEL SPPR01
STRUMENTI SCIENTIFICI
CINEL
WWW.CINEL.COM
CRYOSTAT ASSEMBLY
SCALE 1:2
WEIGHT [.2] Kg
CODE F3AF0000
REV.
SHEET 1/1
CART-03E
Pro/ENGINEER

GTC performances

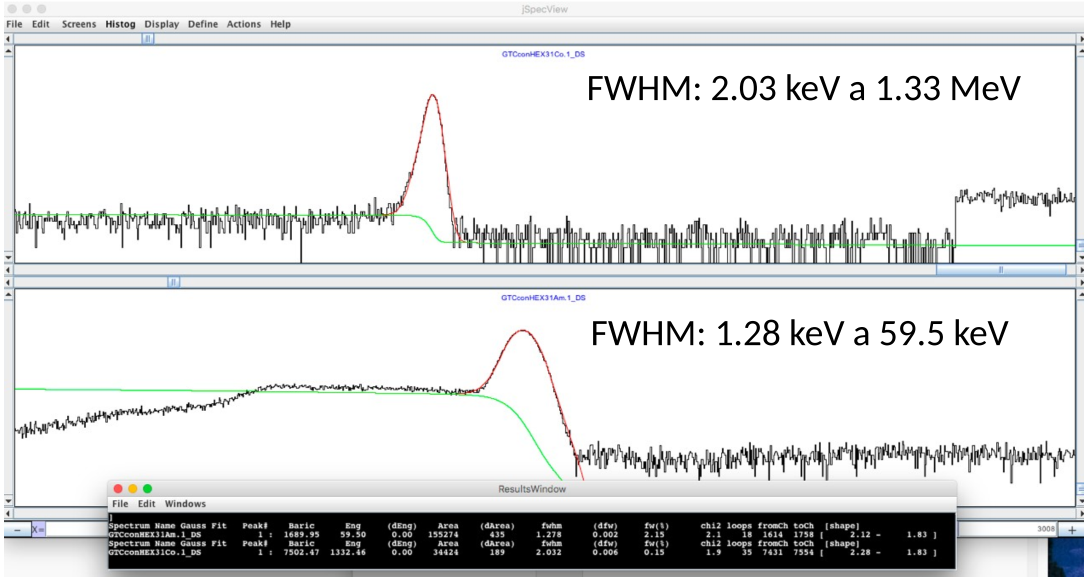
Prototype GTC

- 22 litres of LN_2 are needed to cool down the detector
- After ~ 4 hours the detector is ready to be connected to the automatic filling system
- No problems turning the detector upside-down: the temperature increases by ~ 3 °C
- Holding time > 32 hours





GTC status



Prototype GTC

- Delivered on August 29, 2016
- Positive acceptance test

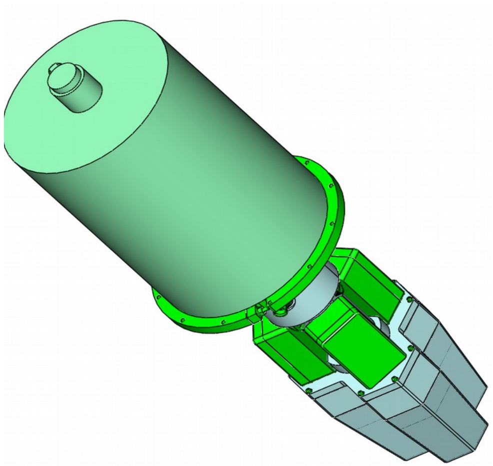
Production of 10 GTC

- Placed the order in 2017
- Expected delivery of first 2 cryostats on February 2018

Mechanics and electronics

- Production of new cold and warm preamplifiers (AGATA core type)
- Mounting flanges and adapters TBD

FWHM / Position	Data sheet	Measurements at GSI	Prototype results
Pos A: HEX130 AGATA CC	1.25 keV 2.21 keV	??? 2.02 keV	1.14 keV 1.95/2.04 keV
Pos B: HEX161 New CC	1.35 keV 2.30 keV	??? 2.04 keV	1.11 keV 1.94/2.01 keV
Pos C: HEX 31 Orig.CC w Test	1.00 keV 2.00 keV	??? 2.06 keV	1.35 keV 2.17/2.29 keV



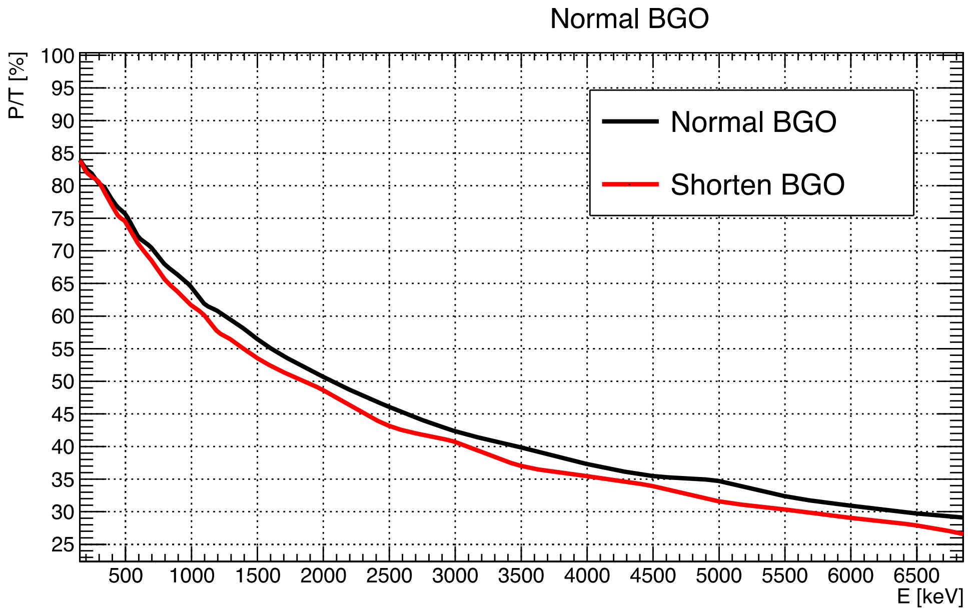
AC status

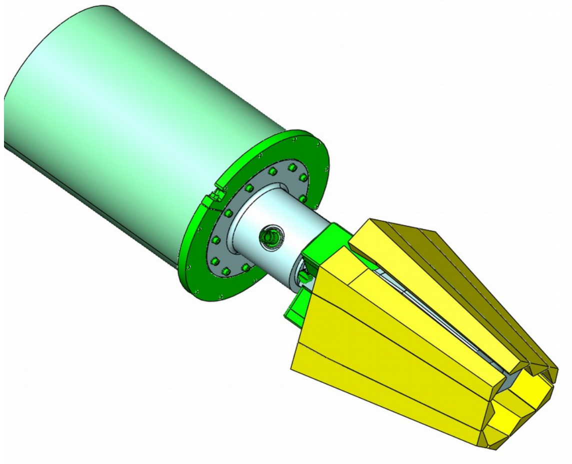
AC prototype

- Project definition and cost estimate with an AC from GSI (SCIONIX)
- Irreversible BGO crystal changes authorized by Gammapool (option under investigation)

Produzione 10 AC per GTC

- Funding request submitted in 2017. Estimated cost: ~ 130 k€ (IVA inclusa)

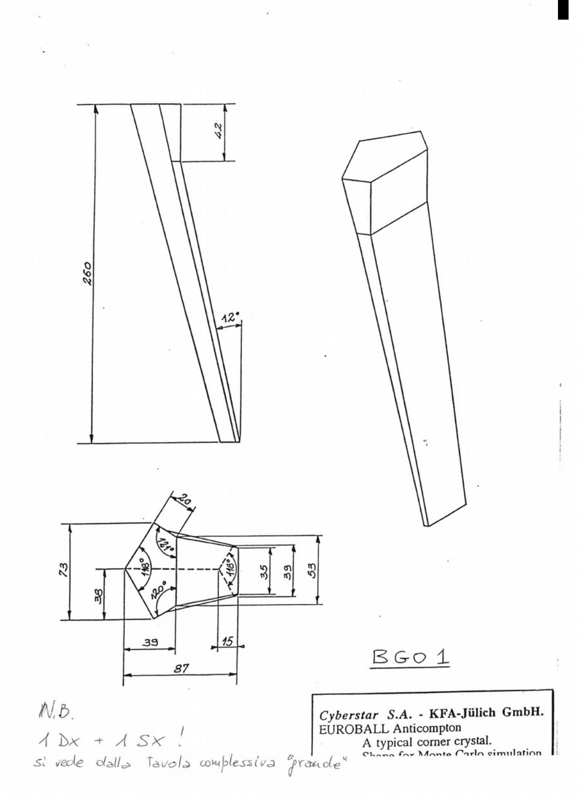




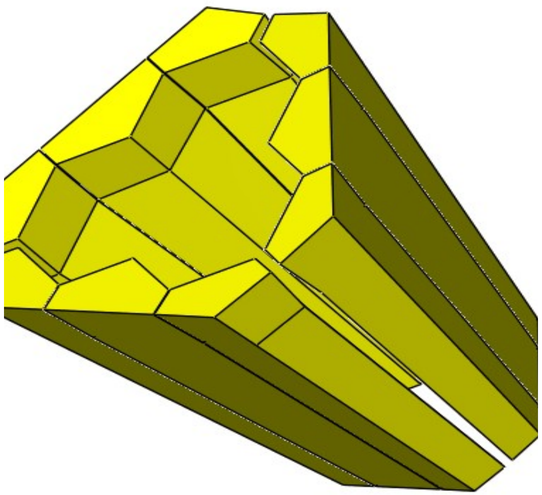
Standard configuration with GTC crystals at ~ 5 cm from the BGO front face

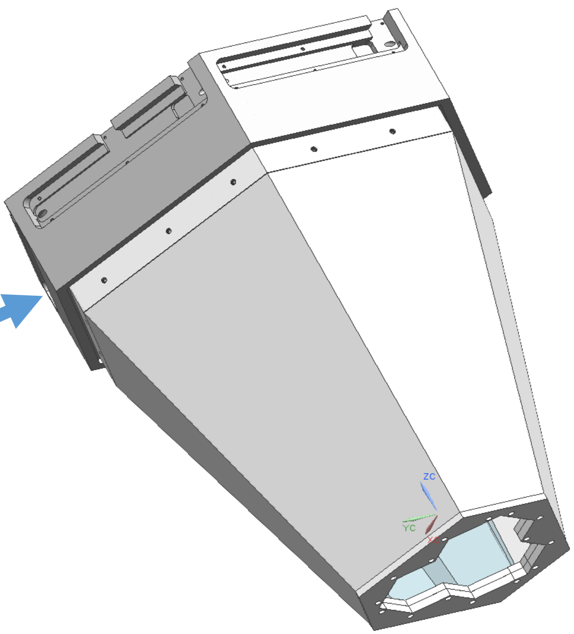
- Normal: original crystals used
- **Short**: crystals must be cutted (TBD)

Anti Compton shield



Configuration compatible with GTC





Schematic drawing, not corresponding to final configuration

9 BGO crystals (6x type 1 + 3x type 2)
from the EUROBALL AC shields
Total weight ~ 35 kg

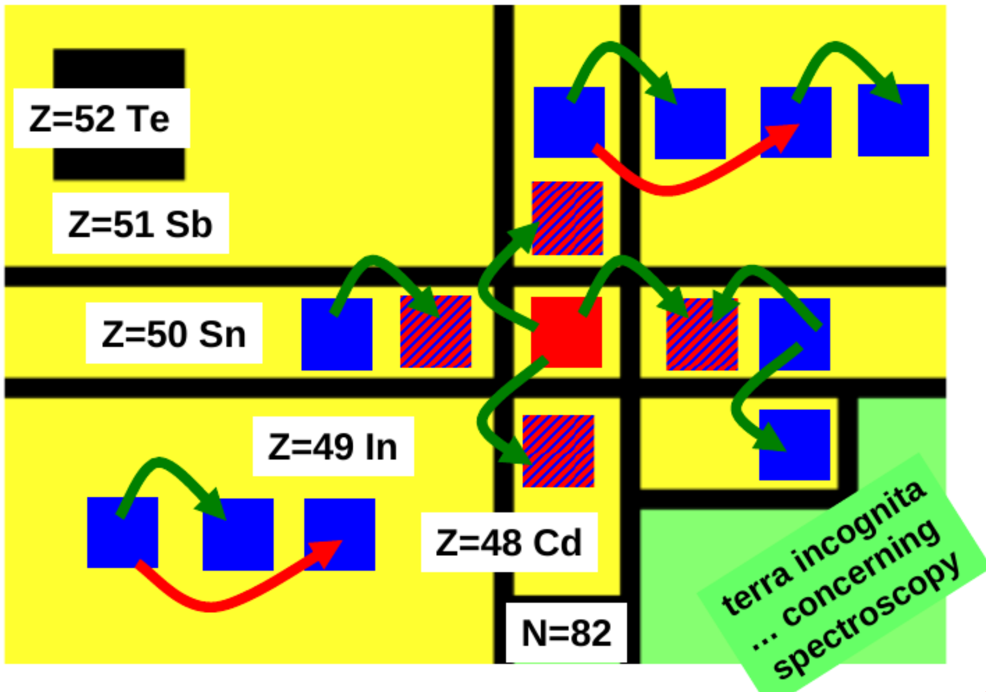
Top mounting flange

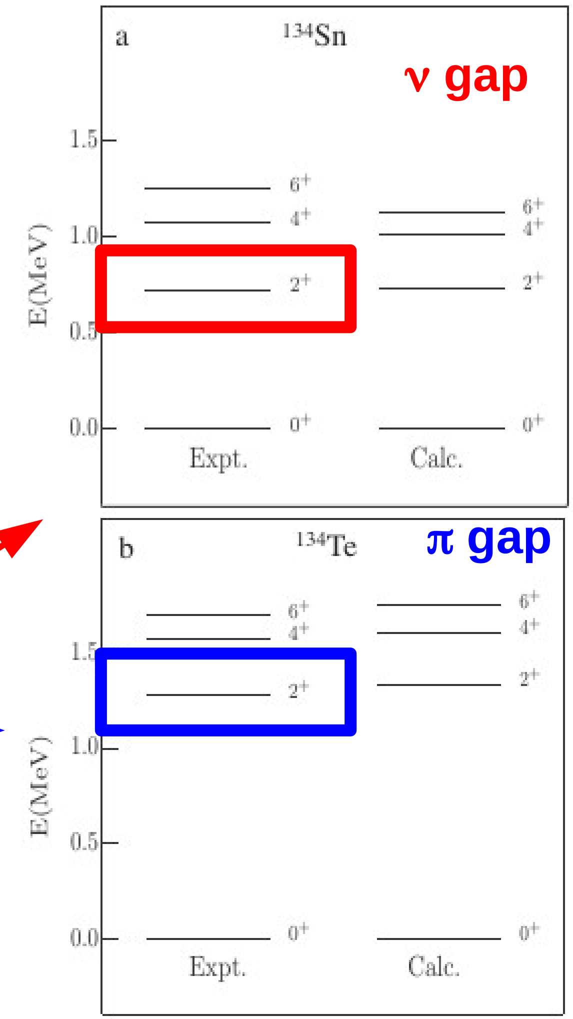
Project *evaluated/in preparation* by SCIONIX.
Mounting system to be confirmed

SPES

exotic beams for science

Probe of the nuclear effective interaction

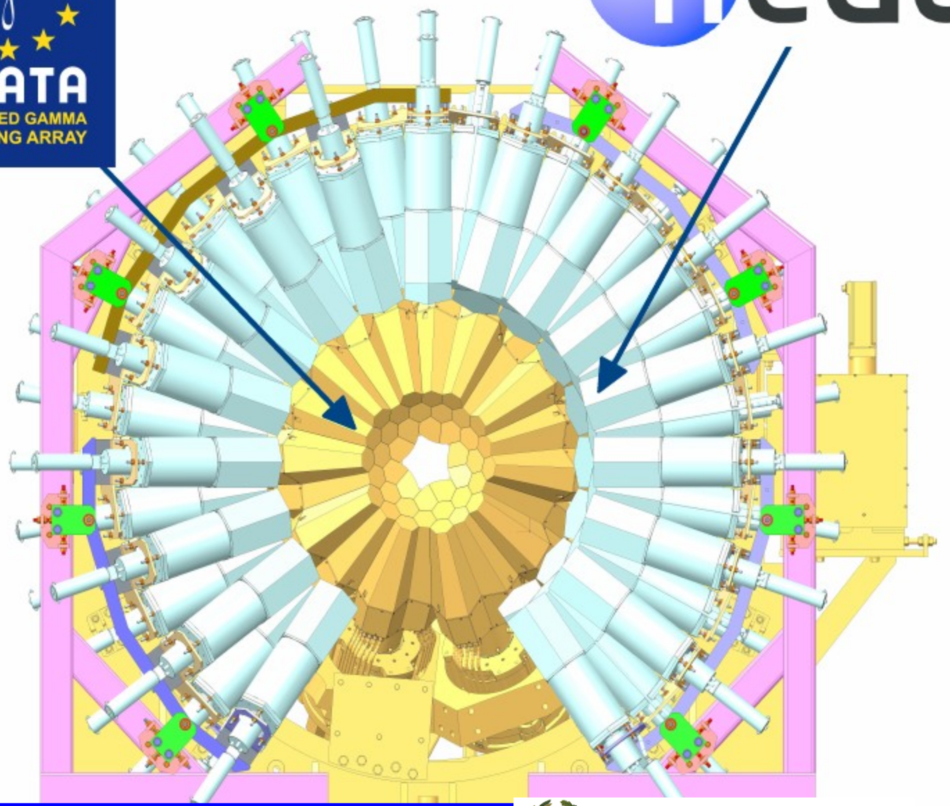




- SF → **single particle energies**
- 134Sn, 134Te → ππ, νν **pairing** term
- 137Xe → νπ **tensor force** tailoring
- Collective **excitation** from the **core**
- ν,π holes below 132Sn → erosion of shell closure? Island of inversion?
- 128Cd, 130In → trimmer the interaction ν,π holes configurations

NEDA

Nuclear structure by detecting neutrons

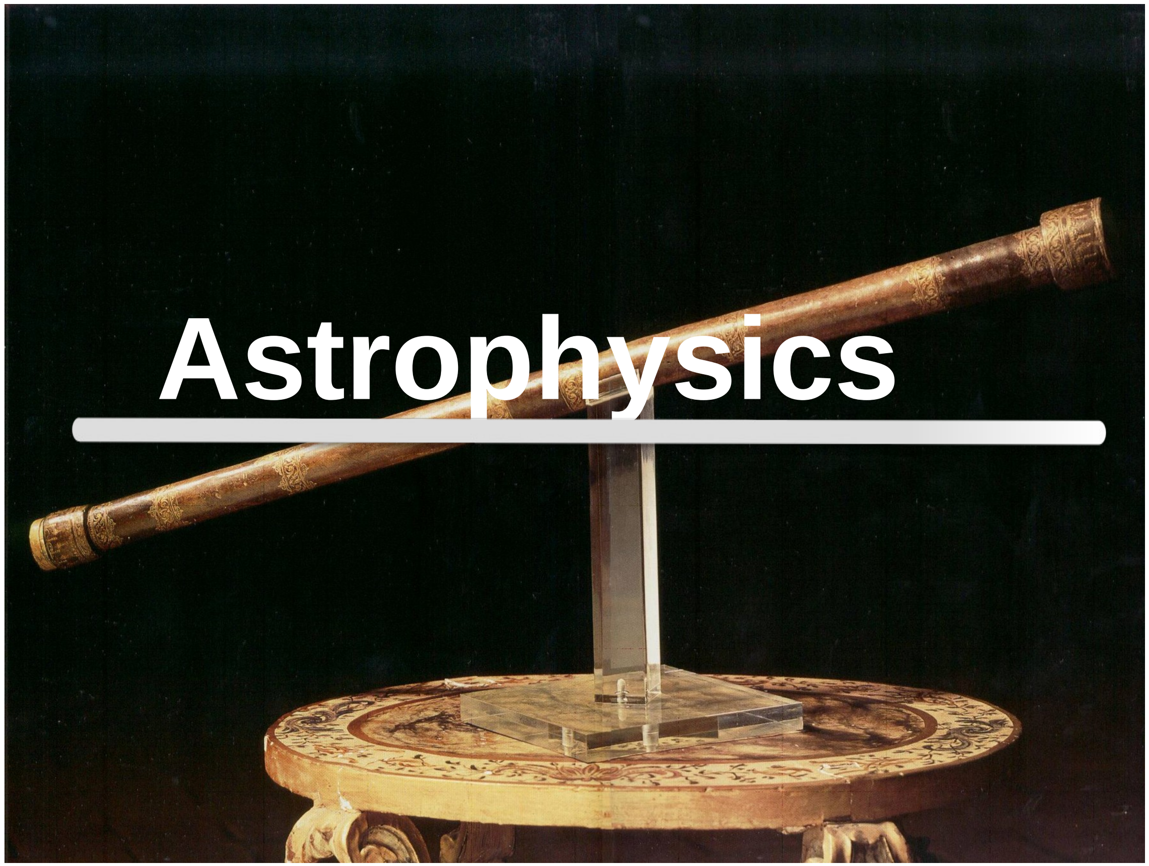


- FIRB 2010-2014
- Spiral2 – Prep.Phase
- INFN

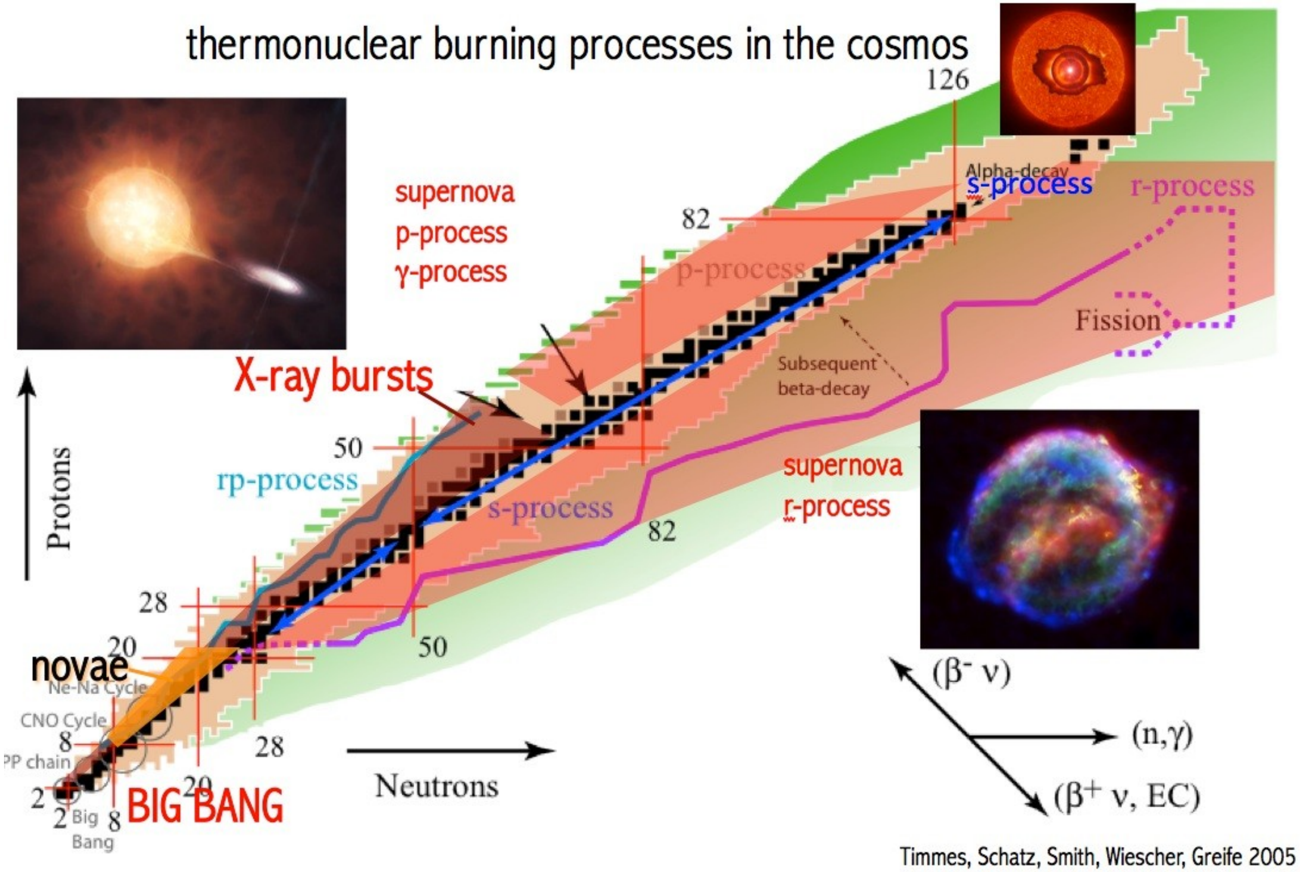
MINISTERO DELL' ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

- Science campaign with AGATA at GANIL

Astrophysics



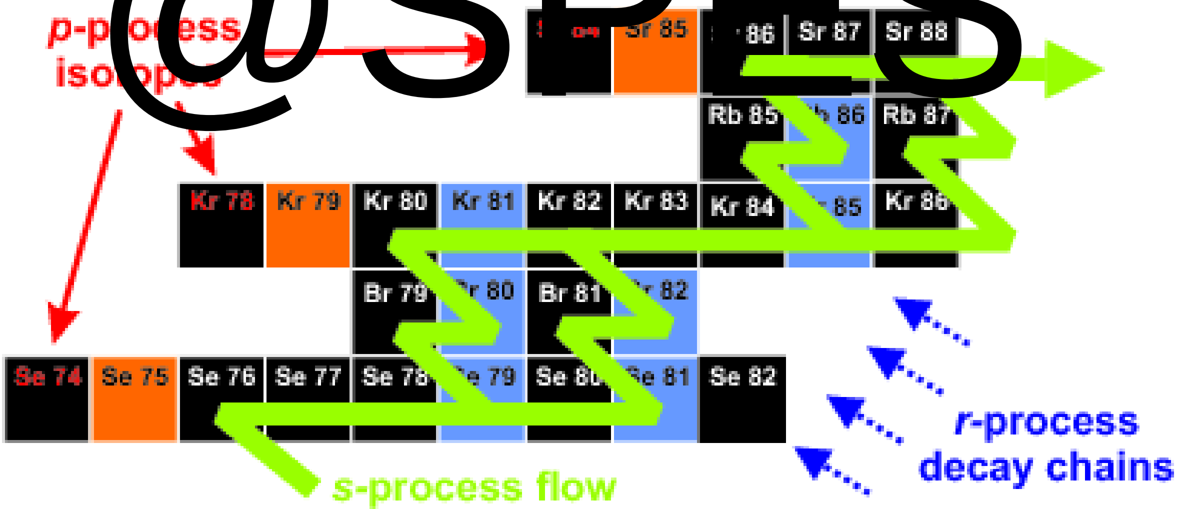
Basics of nucleo-synthesis processes



- The *s* and *r* processes produce almost all heavy elements (A>60)
- Processes are linked to stellar Evolution
- Abundance patterns predicted by models, require **nuclear physics input**

- Burbidge, Burbidge, Fowler, Hoyle, Rev. Mod. Phys. 29 (1957) 547
- A.G.W. Cameron, 1982

Fission products @SPES

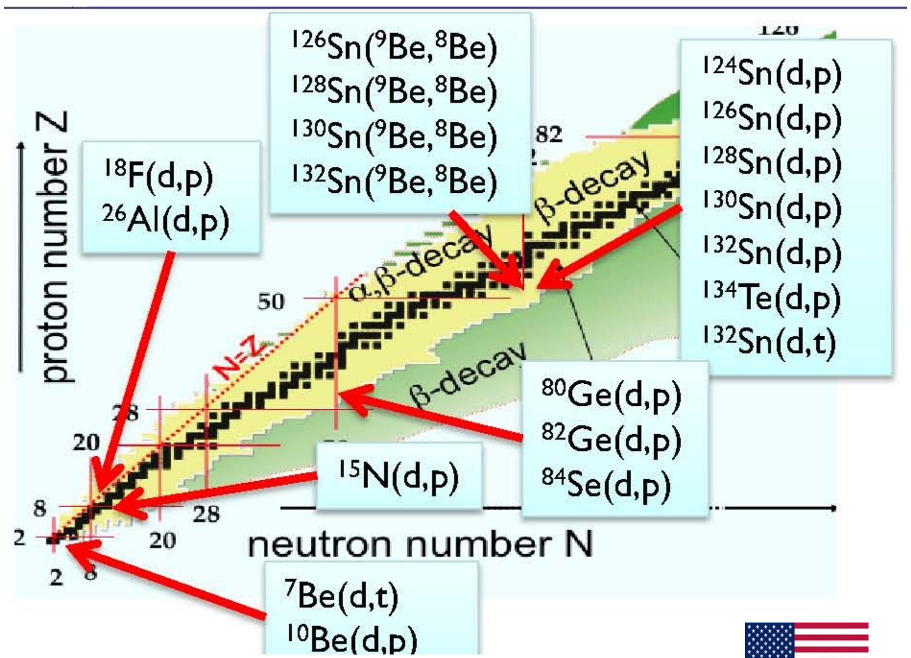


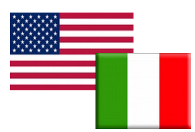
- β decay faster then n capture
- Neutron density 10^{6-7} n/cm^3
- Branching points: τ and n capture rate of the same order of magnitude
- key reaction: (n,γ)

- n capture faster than β decay
- Neutron density 10^{20} n/cm^3
- Dripline and waiting points: plenty of ... nuclear structure information needed
- τ, masses, energy levels, J^{π}, s.p. strengths, (n,γ)

- indirect methods for RIB (TH, SR, ANC)

one-nucleon and cluster transfer at the relevant astrophysics sites

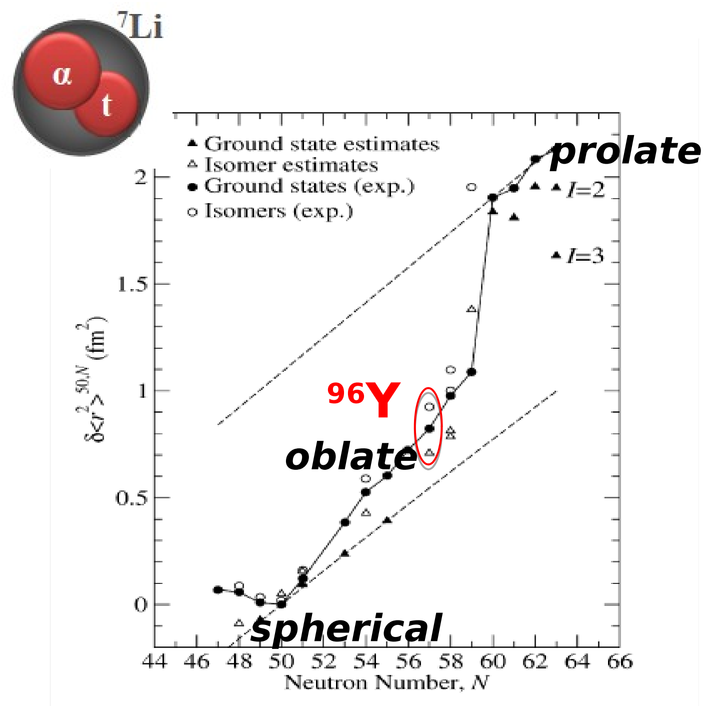




SPES LOI:

Search for deformed oblate structures in ^{96}Y by γ-spectroscopy and **cluster transfer** reactions with a ^{95}Sr SPES beam

B. Fornal, S. Leoni ..



SPES LOI:

Address uncertainties by the measurement of transfer reactions on neutron-rich nuclei

S.Pain, D.Mengoni et al

Complementariety