Development of a 3D-Imaging Calorimeter in $LaBr_3$ for Gamma-Ray Space Astronomy

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7th New Developmeants In Photodetection, Tours, France, 2014

Introduction: Gamma-ray instruments

GROUND BASED:

- ENERGY RANGE **E > GeV**
- INTERACTION IN ATMOSPHERE
- ELECTROMAGNETIC CASCADES
- FLASHES OF CHERENKOV LIGHT
- WIDE AREA OF DETECTION

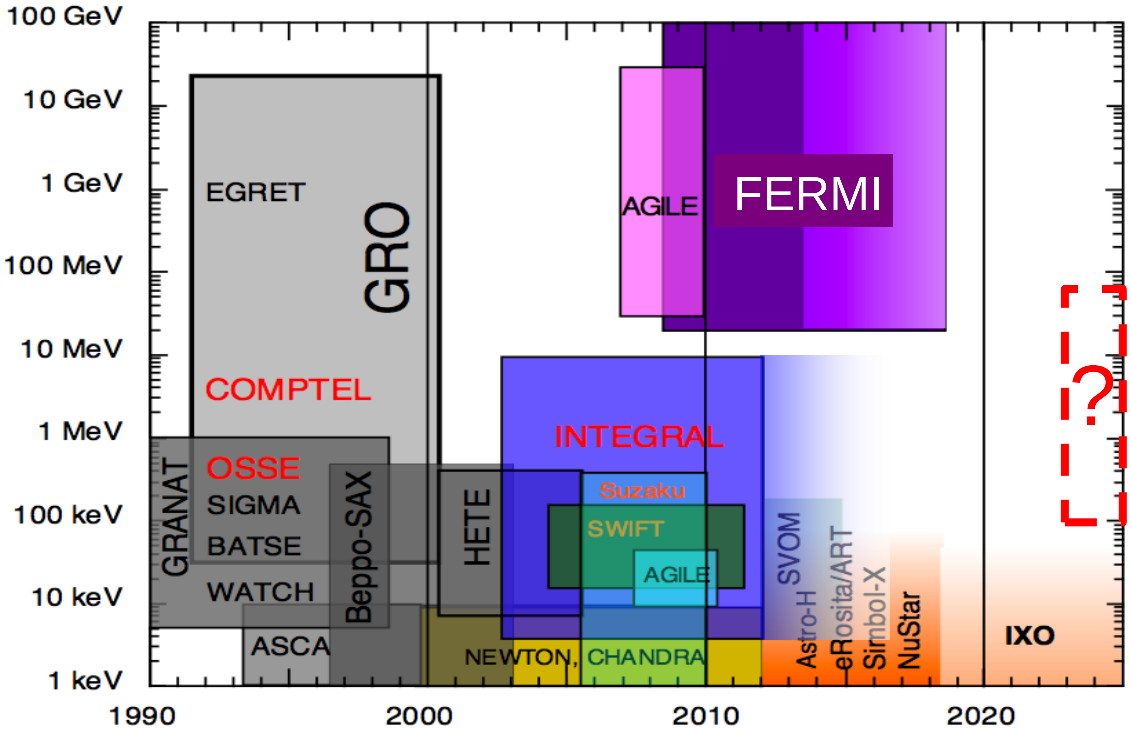
H.E.S.S. - **H**igh **E**nergy **S**tereoscopic **S**ystem

INTEGRAL - **INTE**rnational **G**amma-**R**ay **A**strophysics **L**aboratory

SPACEBORNE:

- ENERGY: **keV – TeV**
- DETECTION ABOVE THE ATMOSPHERE
- BALLOONS AND SATELLITES
- **PAIR PRODUCTION TELESCOPES, COMPTON, CODED MASK, GAMMA-RAY LENSES**

Motivation: Gamma-ray astronomy and ESA's Cosmic Vision



- Prepare a new γ-ray space telescope operating in the MeV range

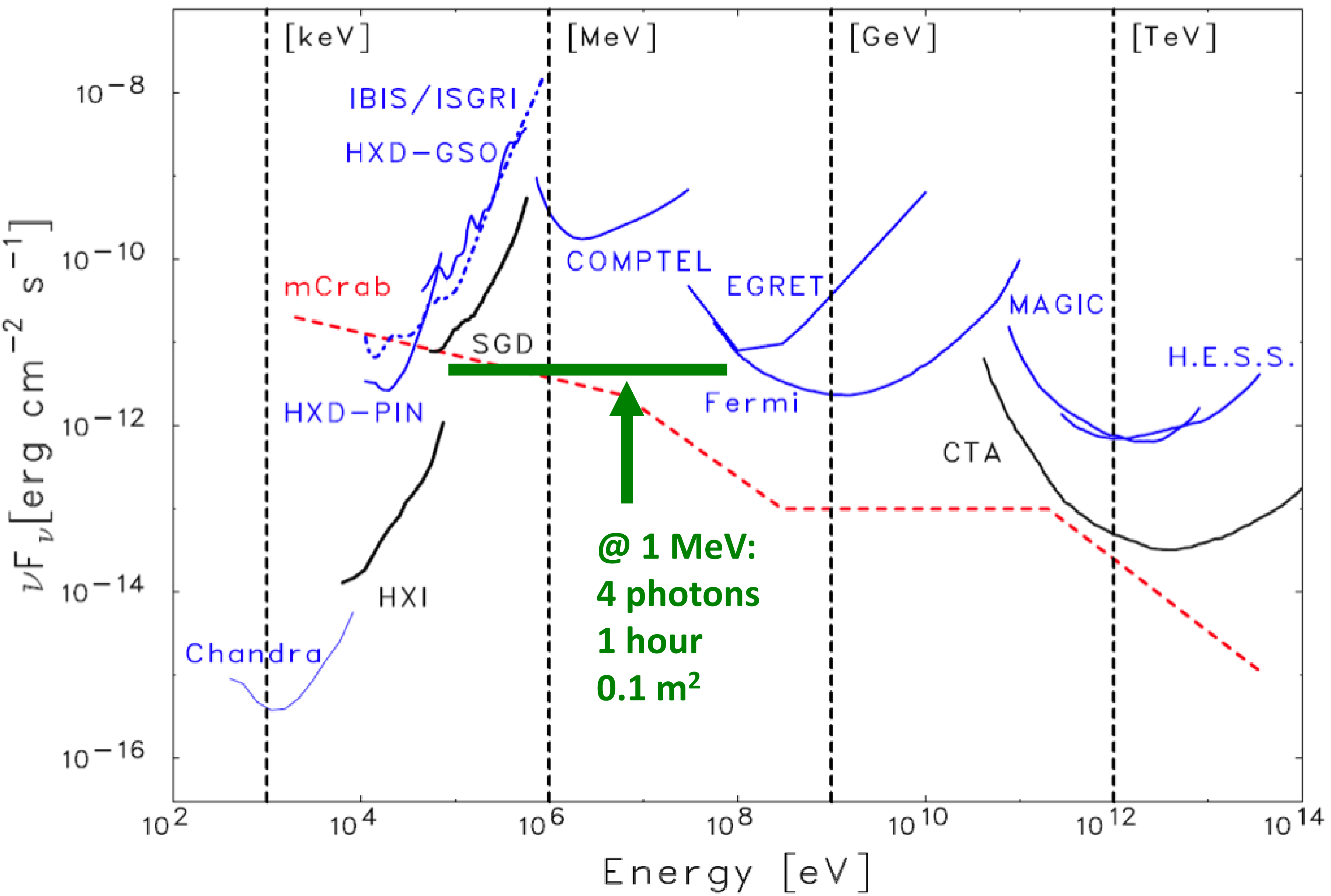
⇒ nucleosynthesis (γ-ray radioactivities), low-energy cosmic-ray physics, high-energy solar physics
+ active galactic nuclei, physics of neutron stars and stellar black holes…

- European proposals in response of ESA's call (2010) for a third Medium-size mission (program "Cosmic Vision 2015-2025"):

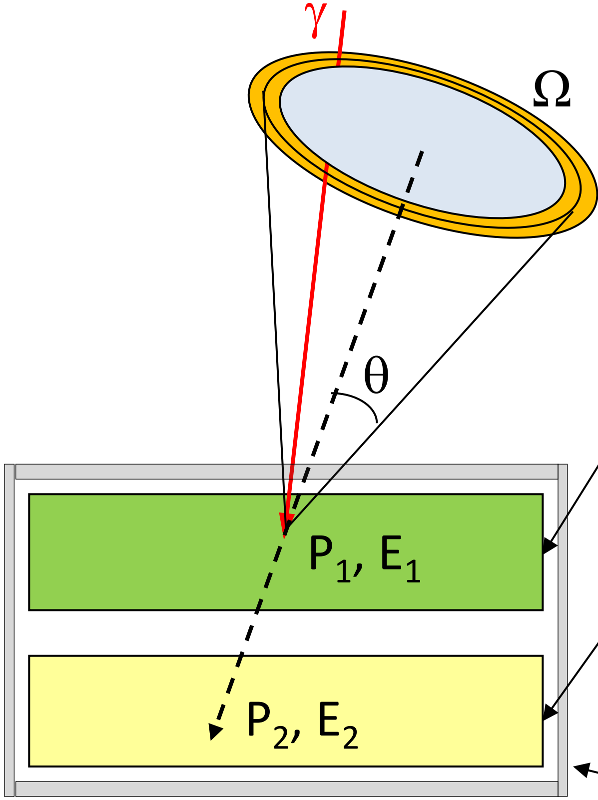
– DUAL (PI: CESR Toulouse): a Laue lens + a Compton telescope in Germanium
– GRIPS (PI: MPE Garching): a Compton telescope in Si (tracker) and $LaBr_3$
– CAPSiTT (PI: APC Paris): a Compton telescope in Si (no calorimeter)

A single proposal for ESA's next call (M4 in 2014) !

Motivation: Sensitivity of current and previous instruments



Conceptual design of an Advanced Compton Telescope



$$E_\gamma = E_1 + E_2$$
$$\cos\theta = 1 + m_e c^2[1/(E_1+E_2)-1/E_2]$$

Tracker. Low-Z material for Compton scattering and minimum Doppler broadening $\Rightarrow$ Si

Calorimeter. High-Z material for an efficient absorption of the scattered photon

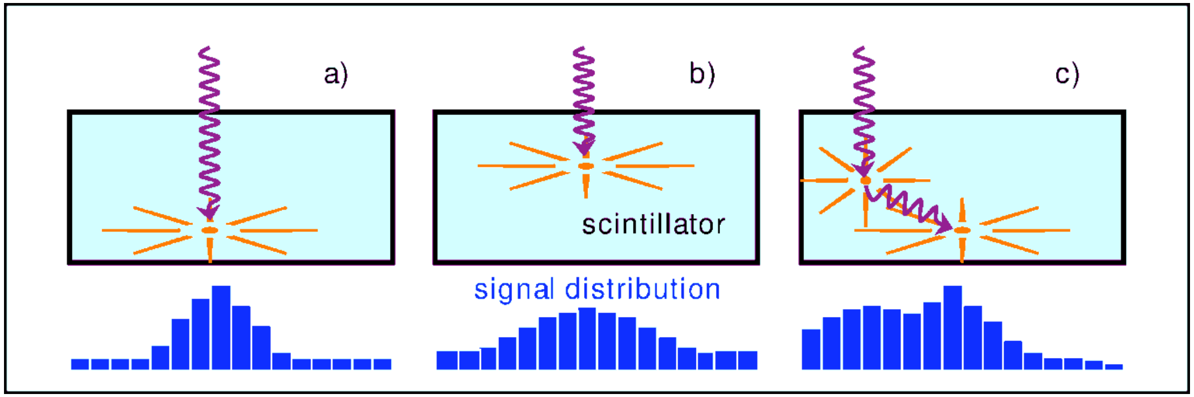
Anticoincidence detector to veto charged-particle induced background

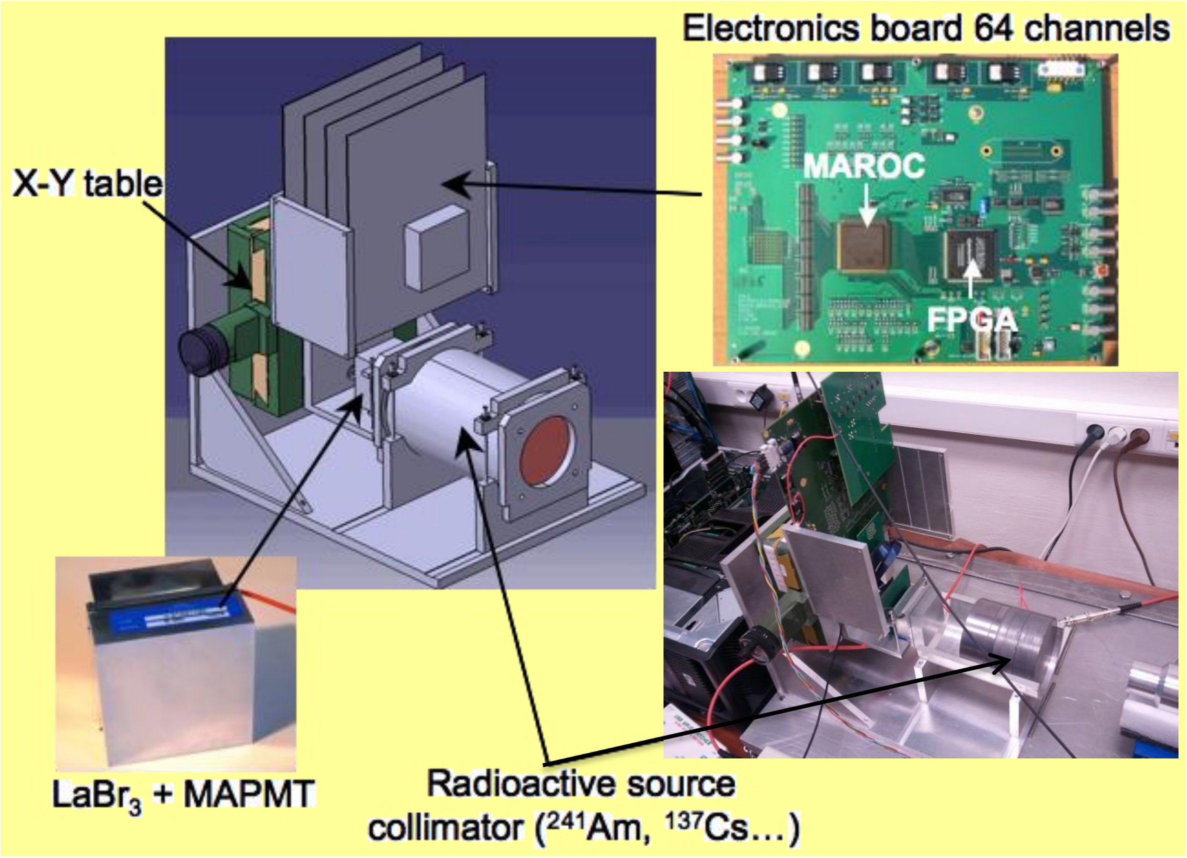
Optimize background rejection (sensitivity), perform Compton imaging and **polarization** studies:

- ✓ Fine **3-D position resolution** (~1 mm^3) ➔ **Si DSSD** (tracker)
- ✓ Good **energy resolution** ➔ **$LaBr_3$:Ce scintillator** (calorimeter)

3D - Imaging calorimeter in $LaBr_3$:Ce

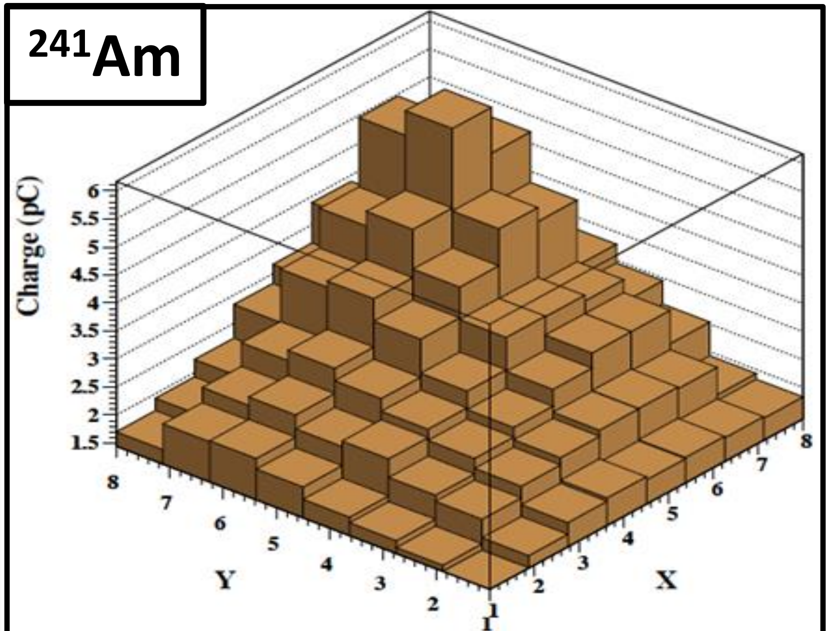
- **$LaBr_3$:Ce** scintillator : good energy resolution, high stopping power, very fast response
- **3D position** resolution Anger-camera-like module
- **Coupling** of $LaBr_3$:Ce crystals (St Gobain) to a multianode PMTs (Hamamatsu)
- Dedicated **test bench** (mechanics, electronics)

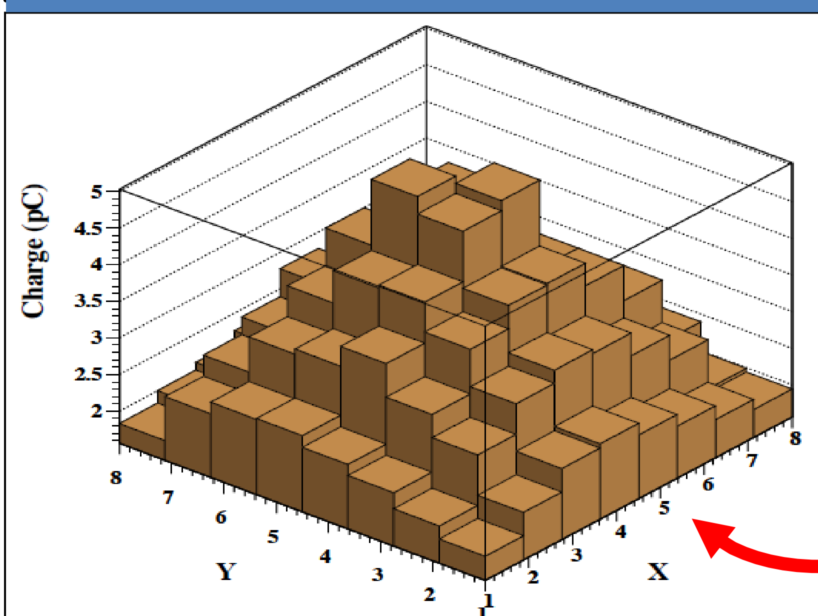




Measurement of scintillation signal distributions

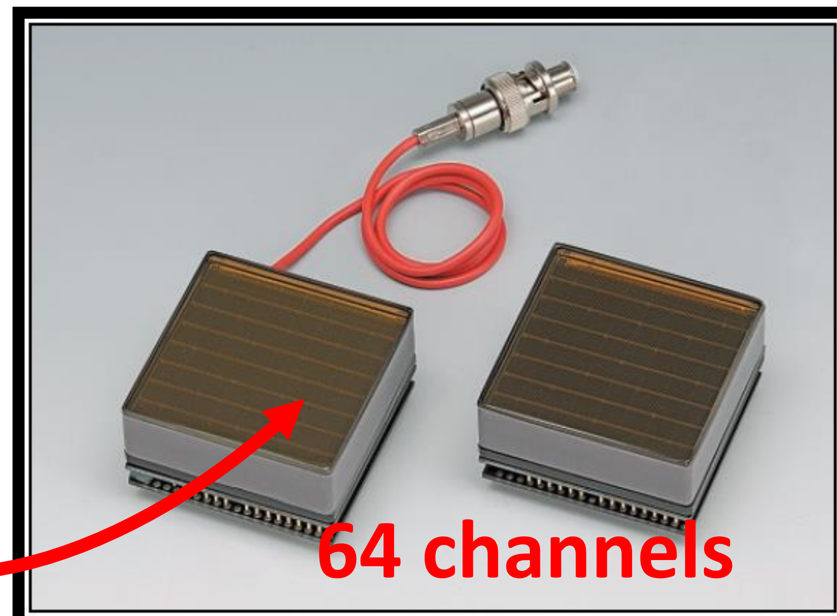
E X P E R I M E N T A L D A T A





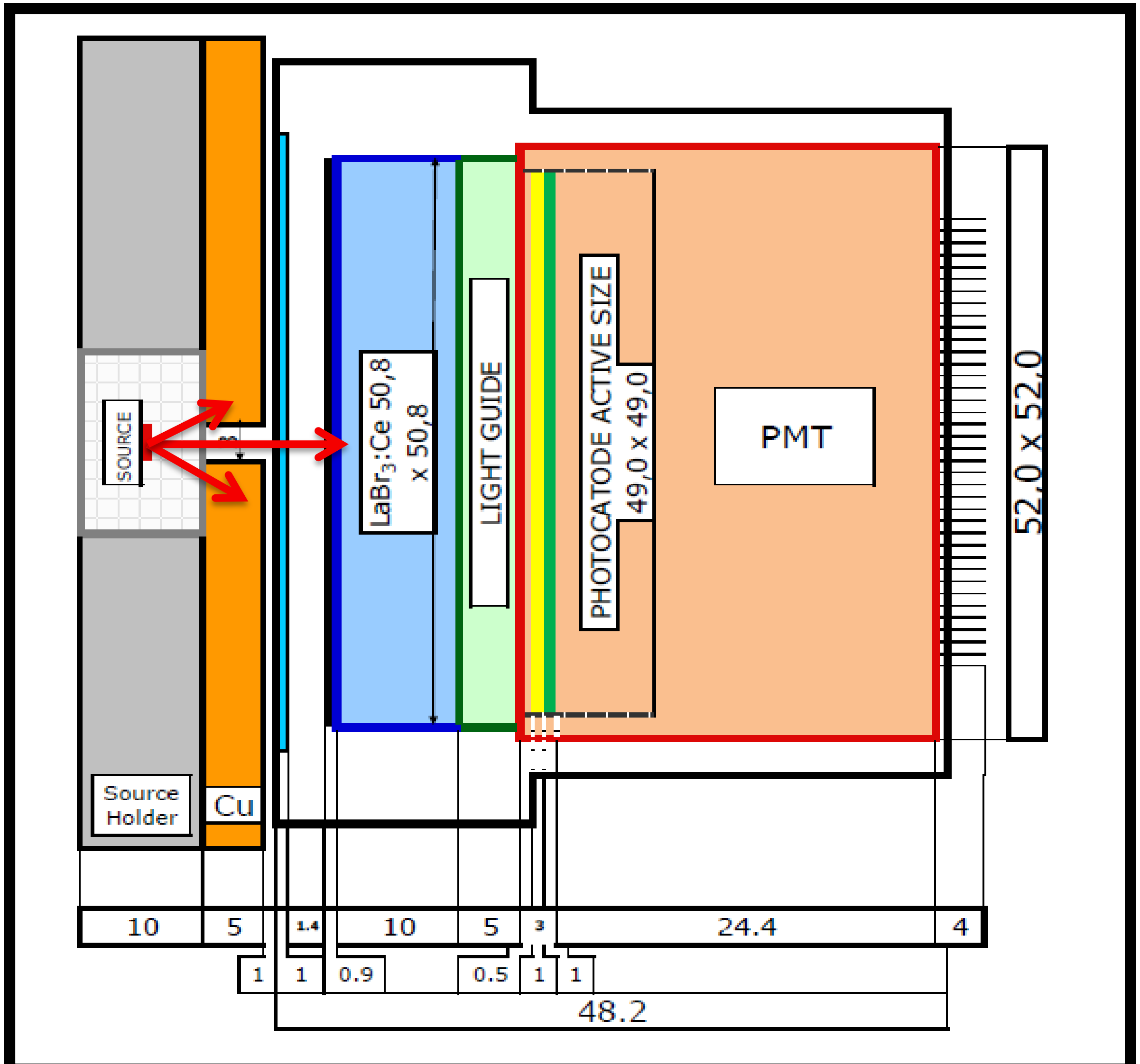
- TOTAL COLLECTED CHARGE
- DISTRIBUTED IN 8 x 8 GRID
- 1 BIN : 1 MAPMT CHANNEL
- EXP. STATISTICS: 50k EVENTS
- 1 EVENT : 64 MATRIX

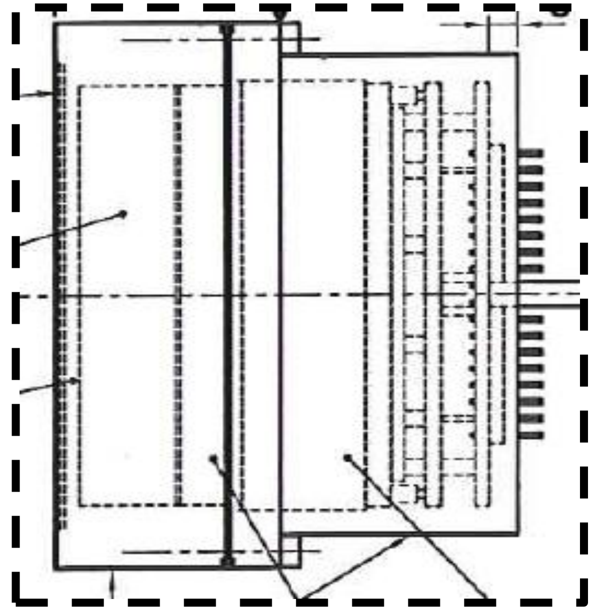
HAMAMATSU H8500C MULTIANODE PHOTOMULTIPLIER:

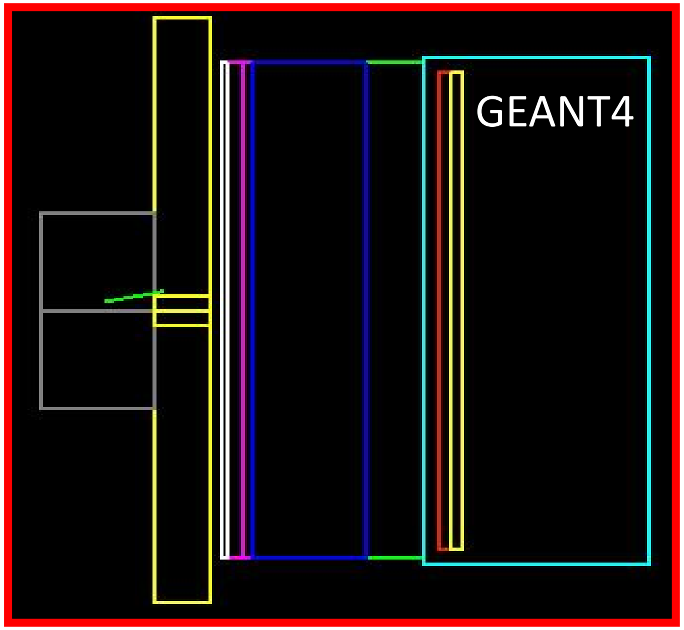


Detector module in detail

4 Volumes: SHIELD – CRYSTAL - GUIDE – PMT

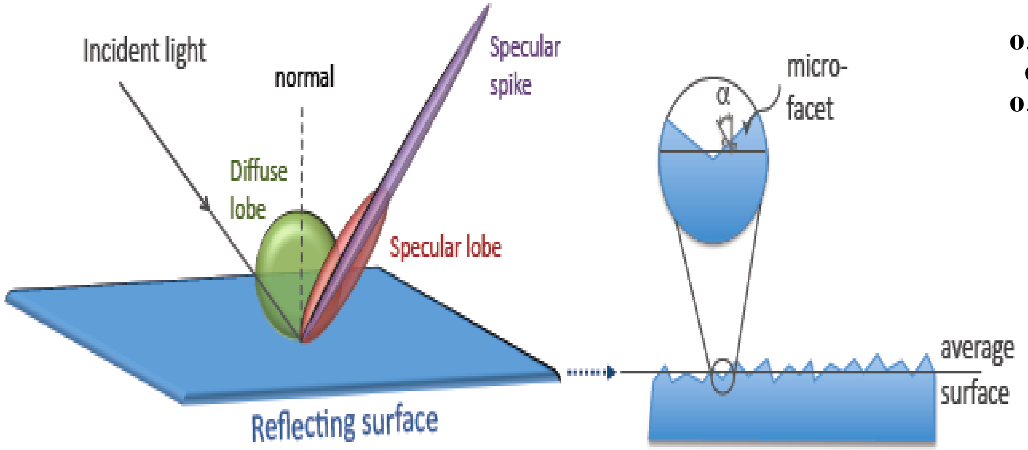


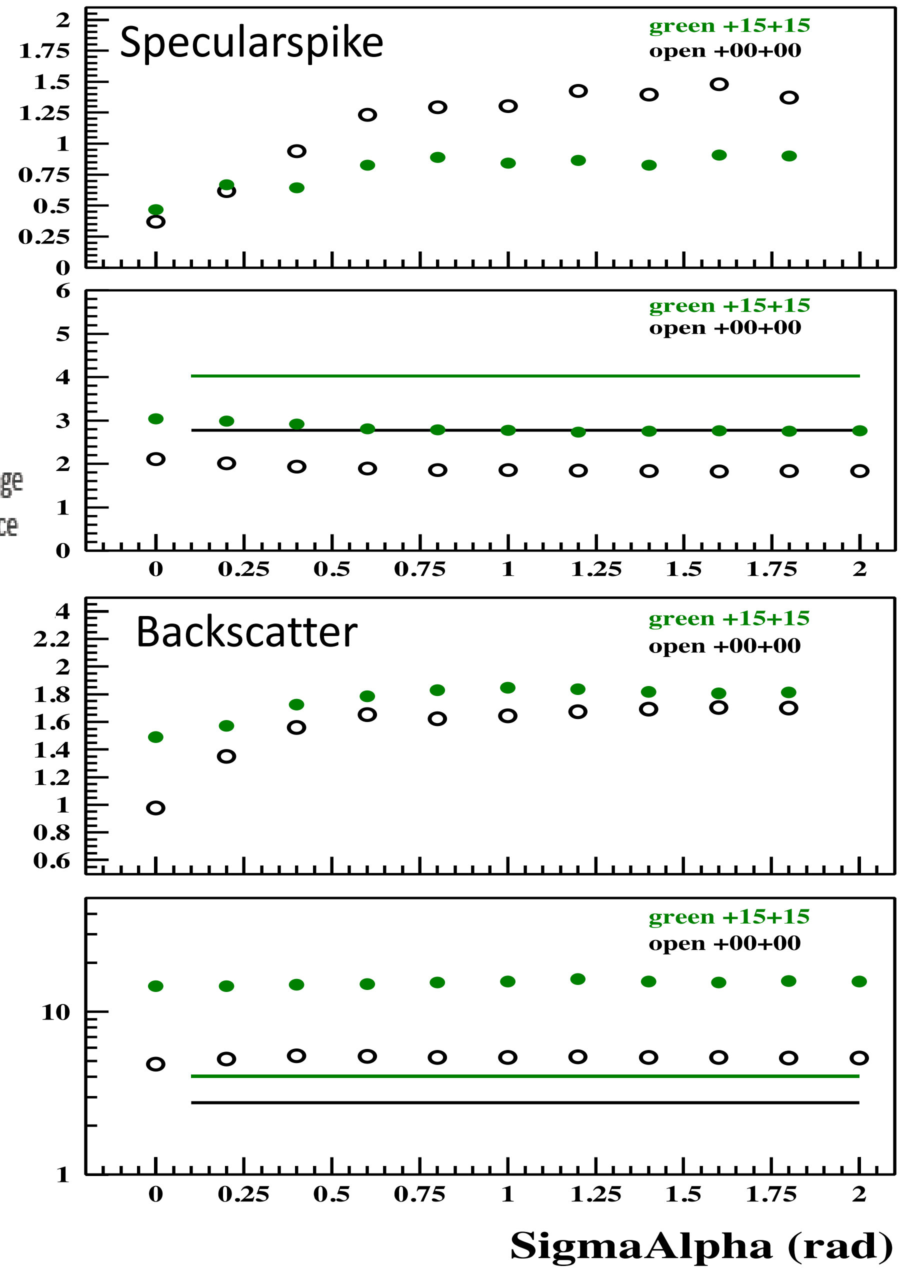


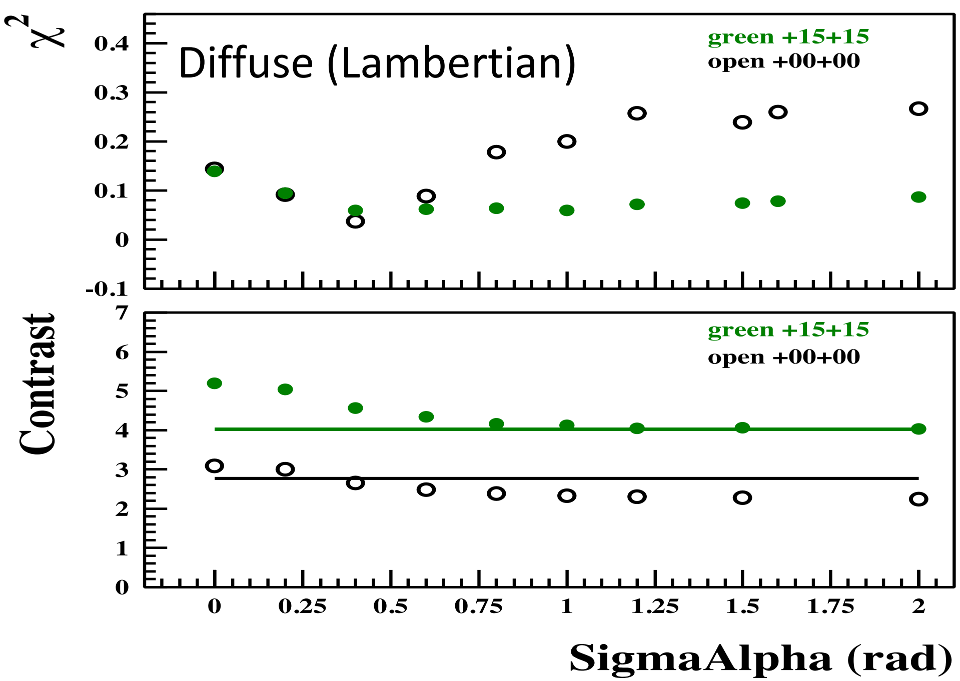


GEANT4 – UNIFIED model parameters

Adjusting simulated 64 channel output PROFILE
- Parameters of internal surfaces



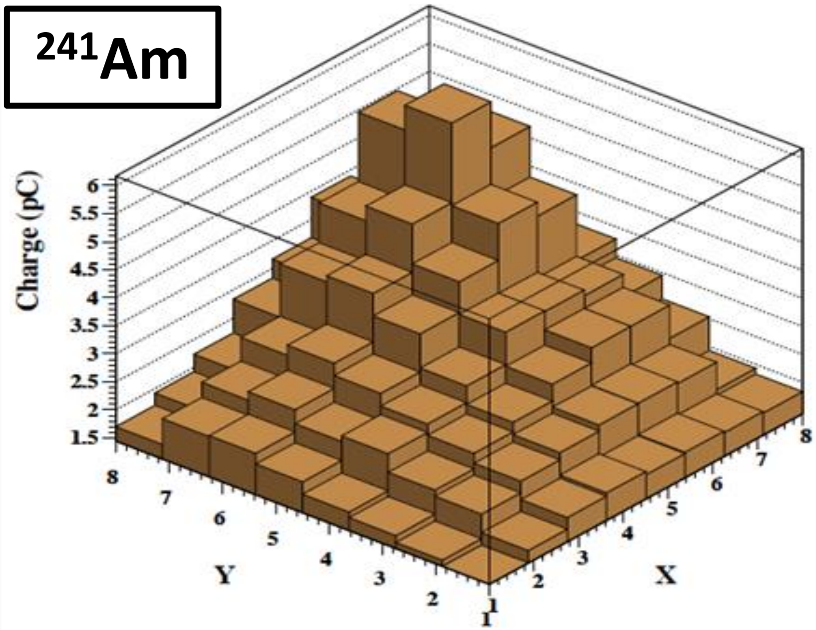


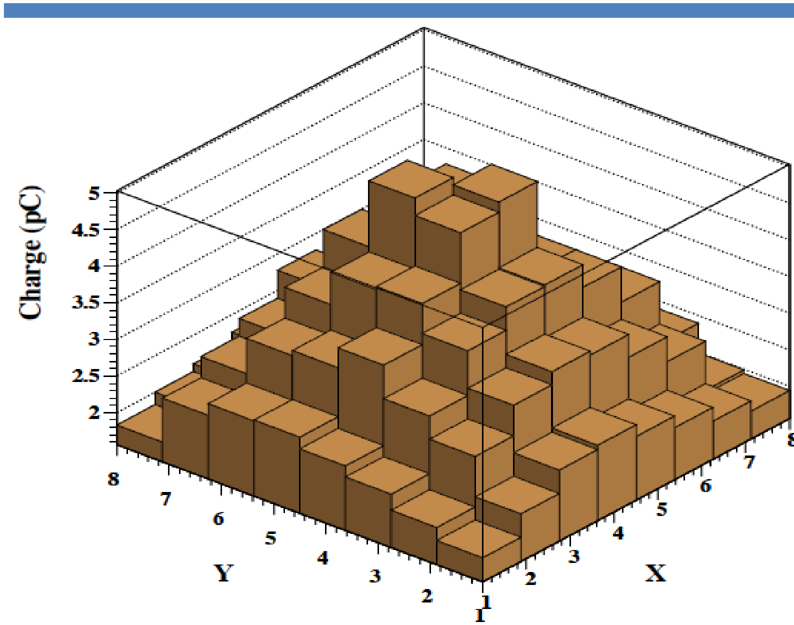


Results: measurements and simulation

E X P E R I M E N T A L D A T A

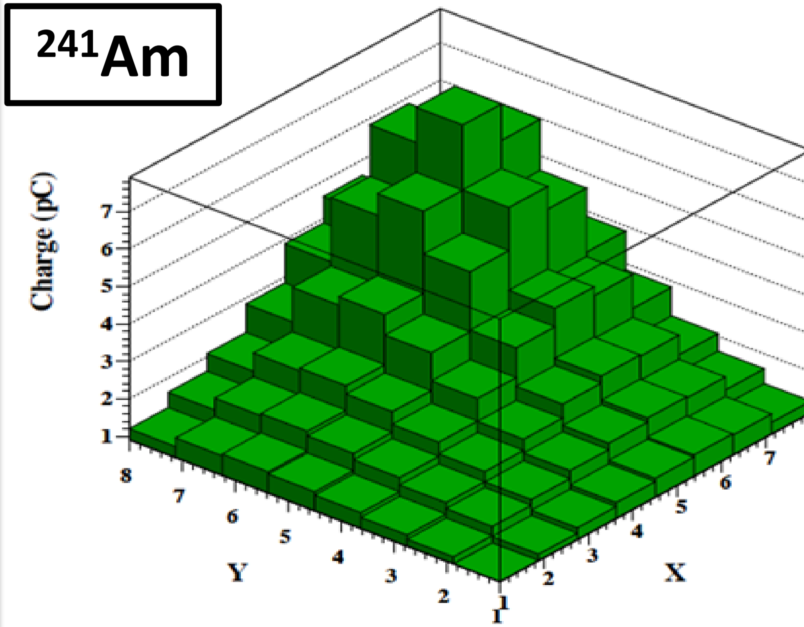
^{241}Am

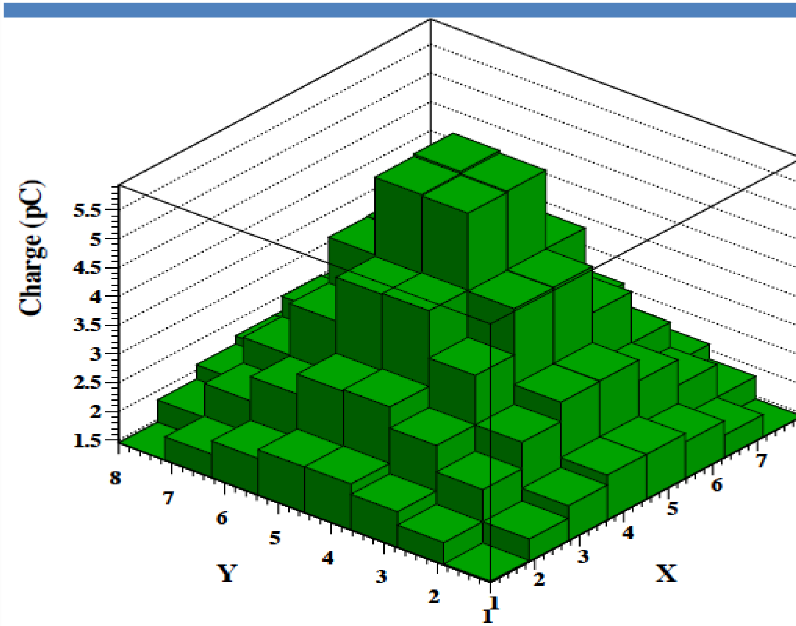




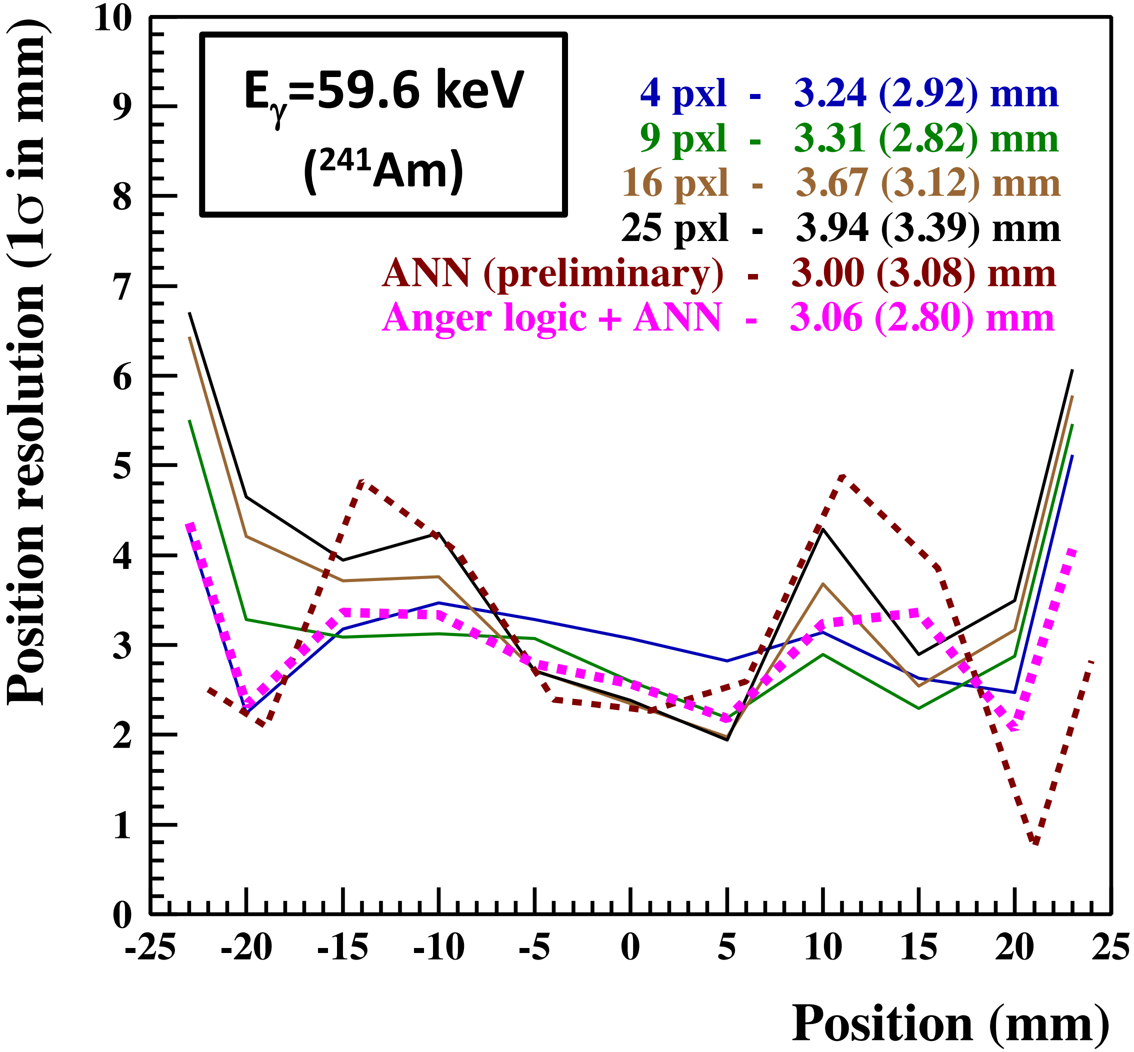
S I M U L A T I O N G E N E R A T E D

^{241}Am





Detector characterization (1): 2D Position resolution

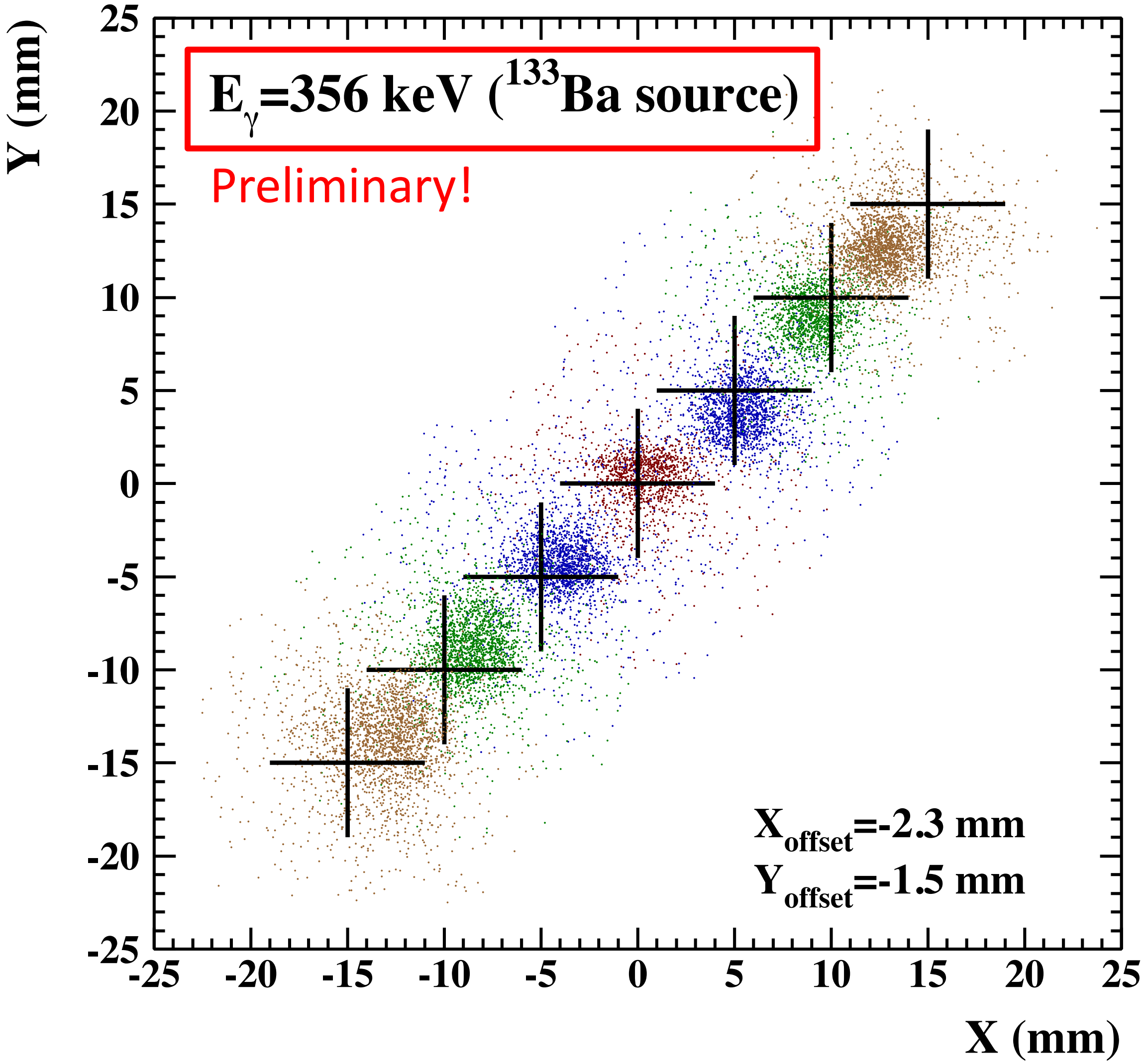


- Center of gravity - Anger logic
- 11 diagonal points with ^{241}Am source
- 4,9,16,25,36 channels (pixels) for different precision
- Artificial Neural Network (ANN)
- JETNET 3.0 package
- 10 Inputs: center of gravity values for X and Y
- 2 Outputs: X and Y positions of the 1st γ-ray hit

Final error on 2D position resolution: standard deviation corrected for beam spot size: $\sigma \approx 1.7$ mm (from GEANT4 simulation)

Detector characterization (2): 3D Position resolution

Experimental X/Y: -15 mm (step: +5) + 15 mm



Single Neural Network

- **Trained with 90k simulated events**
- **64 inputs: all channels normalized to 1**
- **3 outputs: X , Y , Z**
- **2 hidden layers, 10 nodes each**

X [mm]	Y [mm]	σ_x [mm]	σ_y [mm]
-13.2	-13.8	3.02	2.90
-8.62	-8.84	2.54	2.53
-4.14	-4.33	2.46	2.33
0.36	0.22	2.44	2.30
5.27	4.16	2.26	2.46
9.03	8.95	2.13	2.38
12.94	12.77	2.97	2.91

Detector characterization (3): 3D Position resolution

Deviations around the true values for 2D coordinates (experimentally known)

X, Y – front plane of the detector

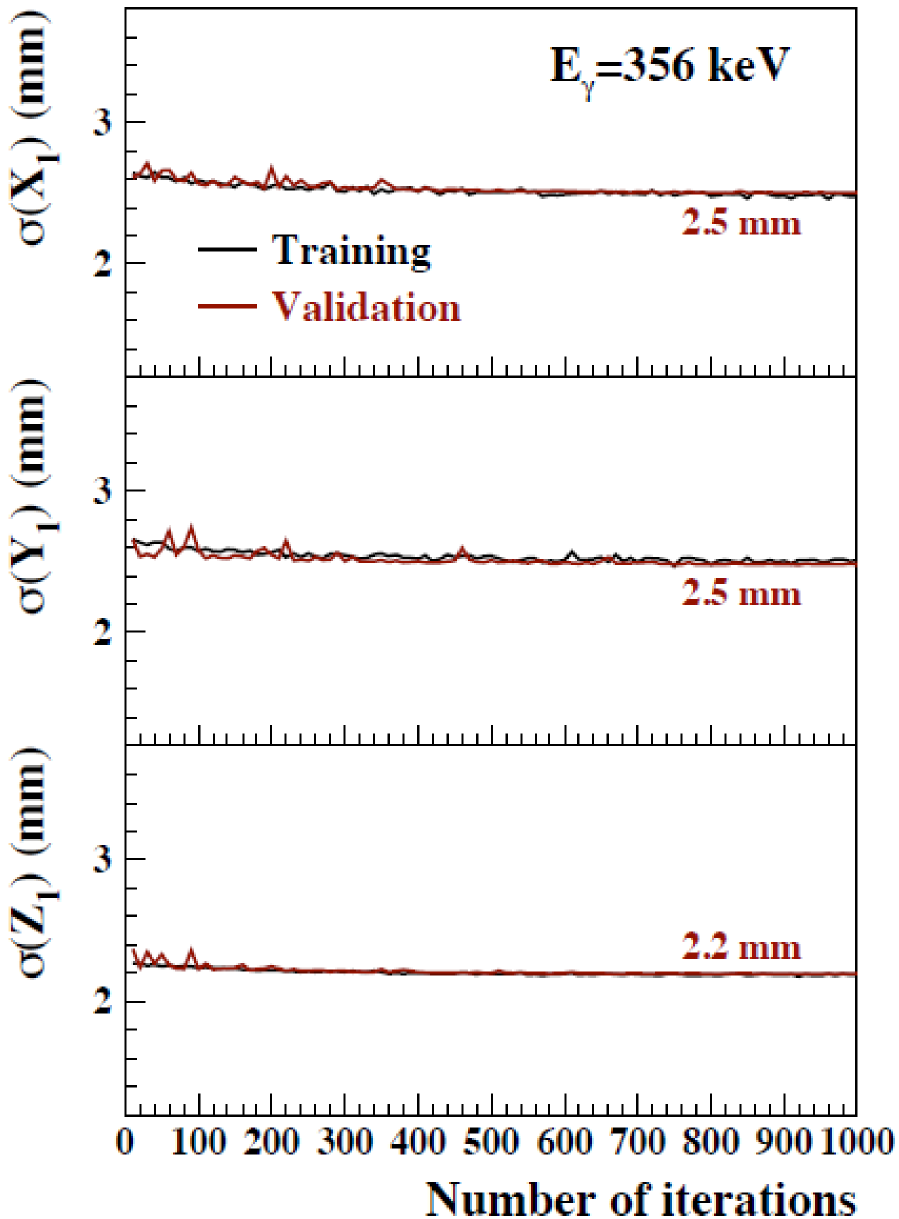
$\langle\sigma_{x\_true}\rangle \approx 2.5$ mm

$\langle\sigma_{y\_true}\rangle \approx 2.5$ mm

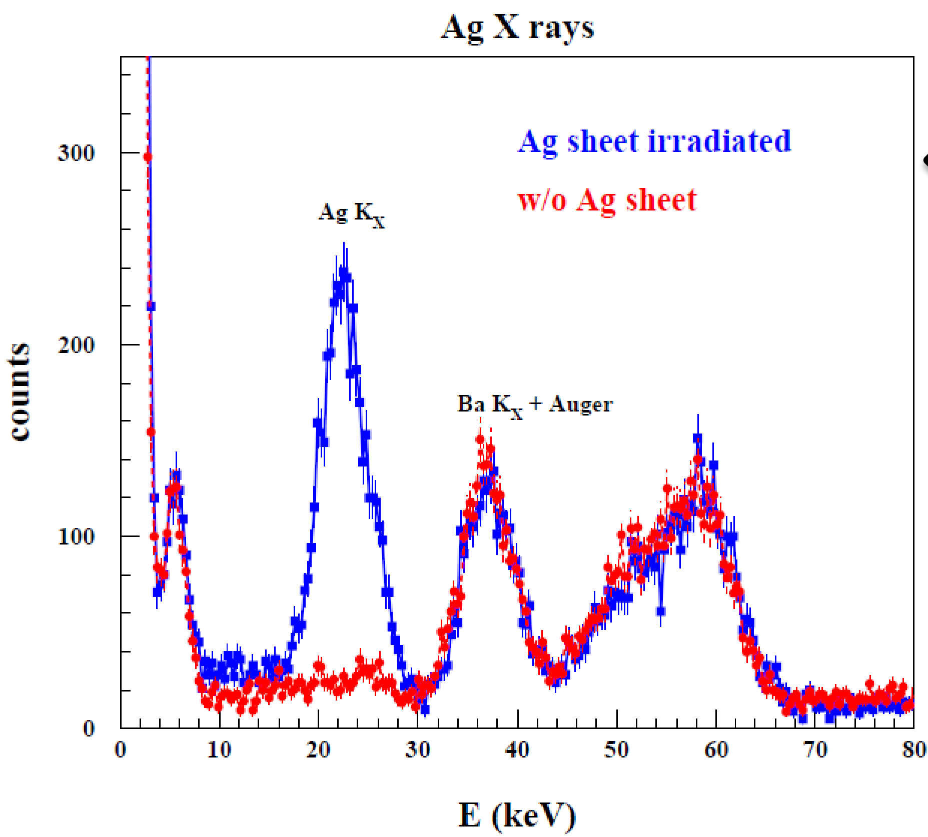
Deviation for the 3rd coordinate

Z – depth of interaction

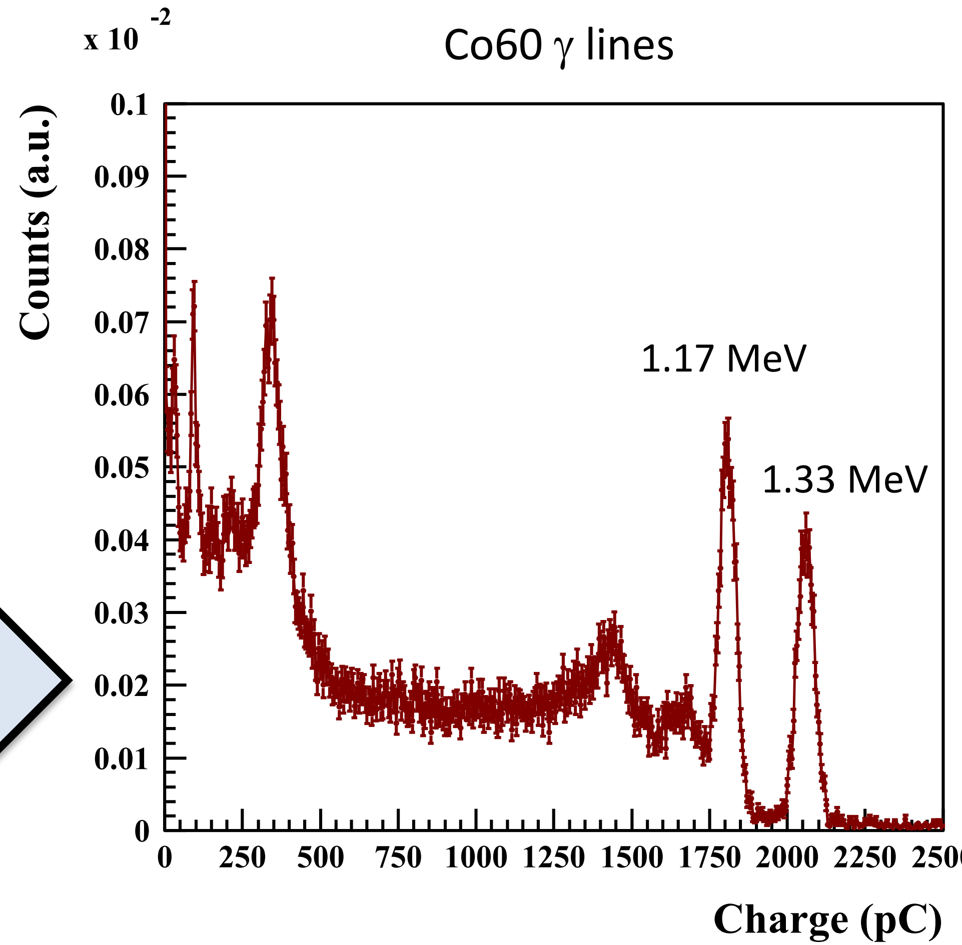
$\langle\sigma_{z}\rangle \approx 2.2$ mm



Detector characterization (4): E dynamic range

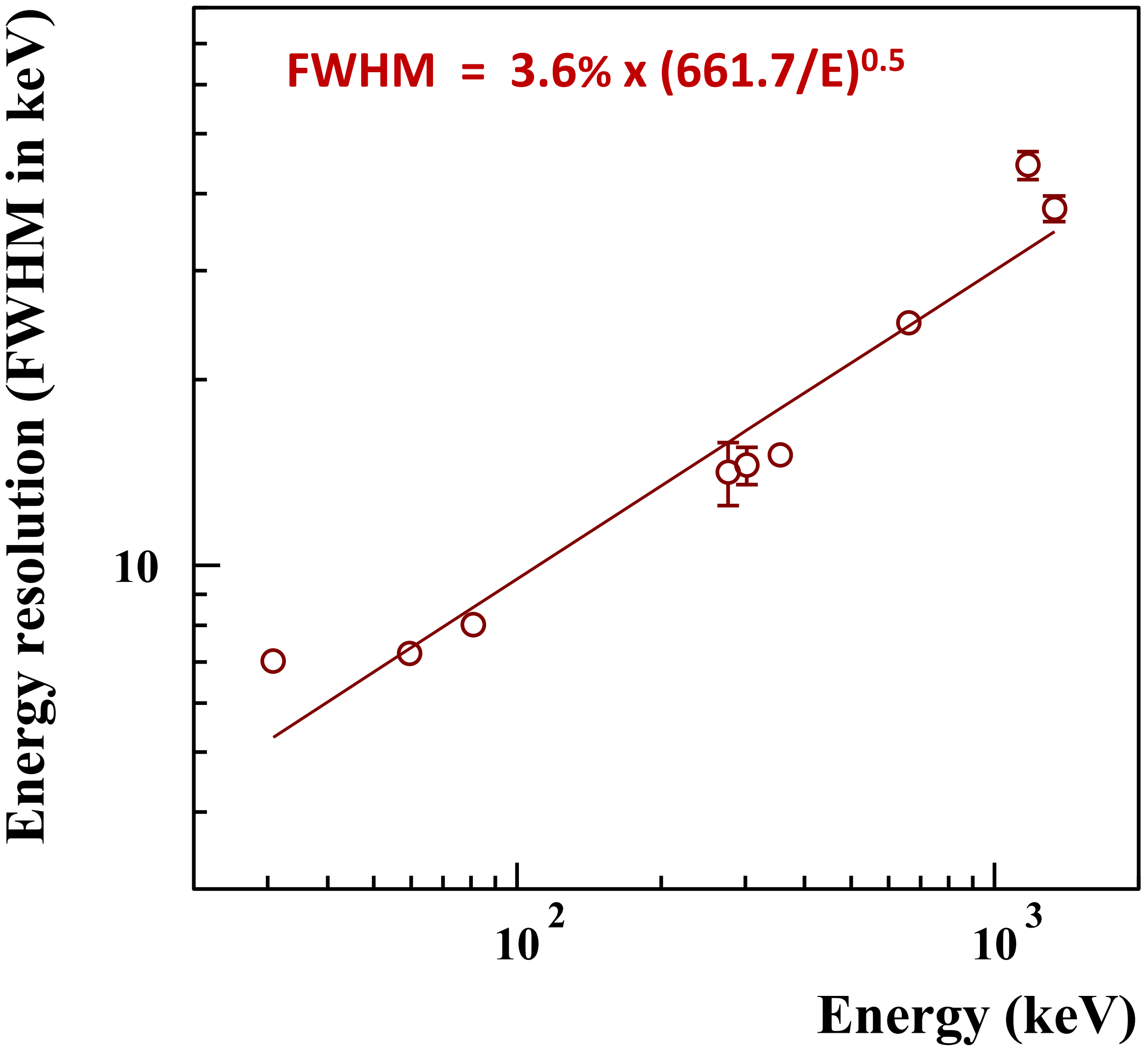


LOW-END: - X rays
- MIN energy: **22 keV**
- background + Ag K_X



HIGH-END: - gamma-rays
- MAX energy: **1.3 MeV**

Detector characterization (5): Energy resolution



LINES	E (keV)
Cs K_α X	30.85
γ ^{241}Am	59.5
γ ^{133}Ba	80.9
γ ^{133}Ba	276.4
γ ^{133}Ba	302.9
γ ^{133}Ba	356.0
γ ^{137}Cs	661.7
γ ^{60}Co	1173.2
γ ^{60}Co	1332.5

Compensated for different interaction locations (less charge detected closer to the detector border) => **4.9 % -> 3.6 %** at **662 keV**

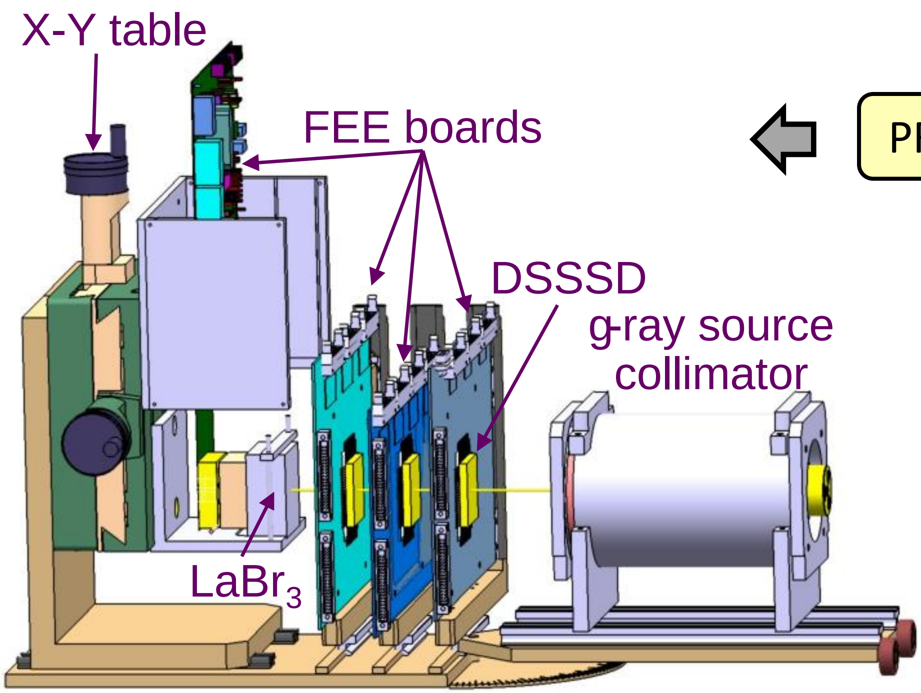
Overview

POSITION RESOLUTION

- Successful 2D (3D) pos. reconstruction
- $1\sigma \approx$ **2.5 mm** (< bin size)

DYNAMIC RANGE and E RESOLUTION

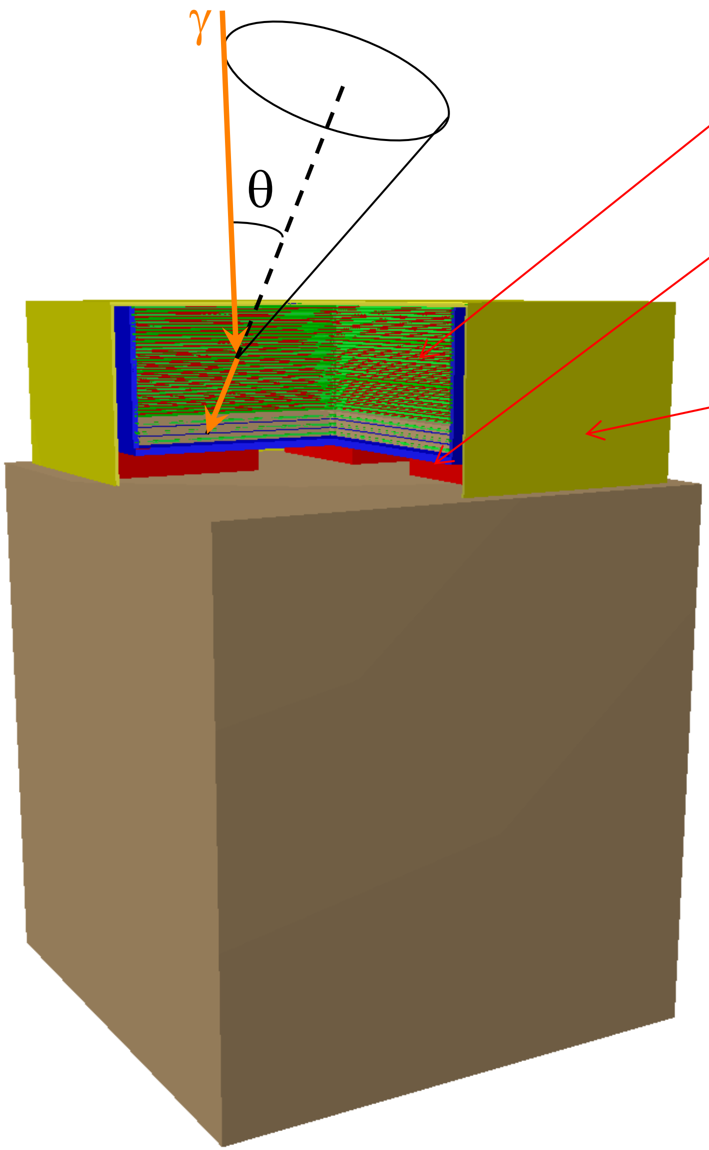
- Good range:
  covering **X** and **γ-rays**
- **< 22 keV – 1.3 MeV** (good for a Compton telescope)
- Good E resolution: only 20% above cylindrical crystal



PROTOTYPE & TESTING

- $LaBr_3$:Ce + 3 Si DSSD layers
- Coincidence mode
- New module: **$CeBr_3$ + SiPM**
- Aiming for the balloon mission
- Polarization of the Crab Nebula and the Crab Pulsar, in the range of 100–300 keV

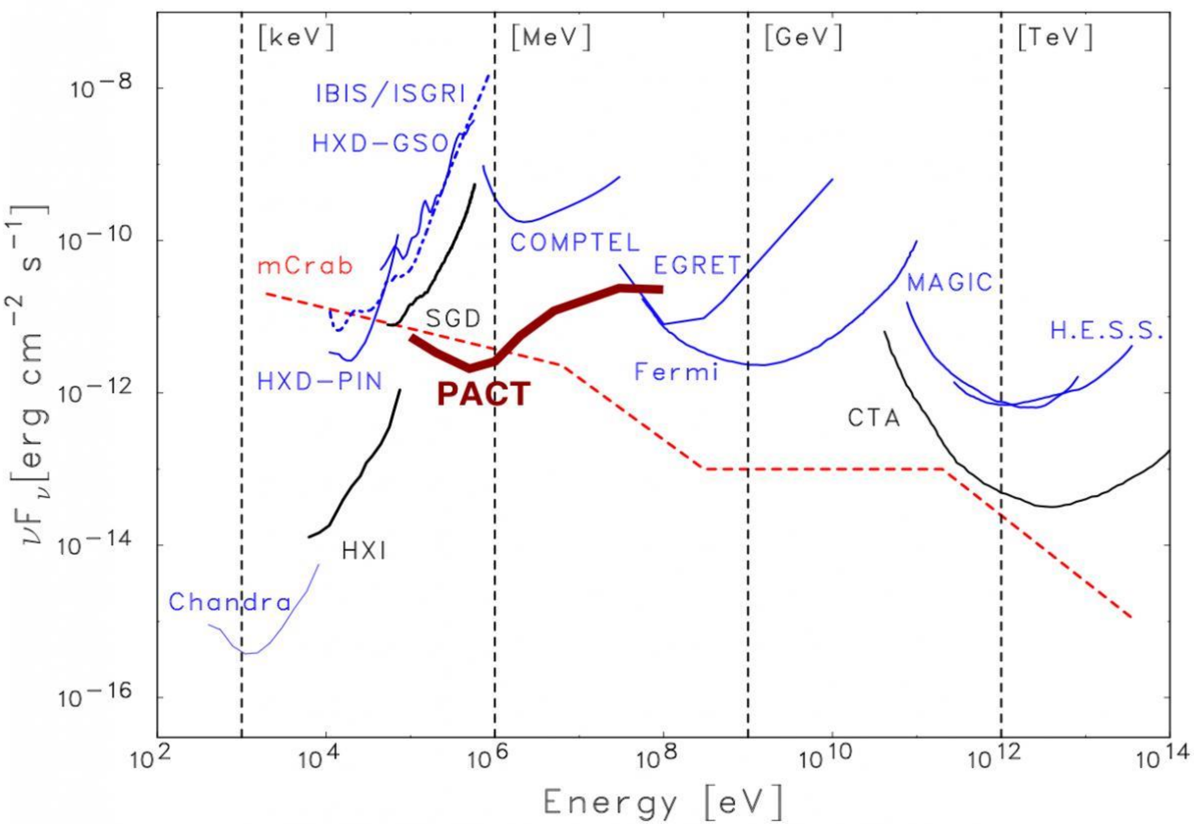
PACT: Pair And Compton Telescope



Tracker: Si DSSDs e.g. 30 layers of 12x12

Calorimeter: several layers of inorganic scintillator, crystal e.g. $CeBr_3$ or ceramics, coupled to an array of SiPMs

Plastic anticoincidence detector e.g. NE-110 ~ 1 cm thickness



More information at:

astromev.eu