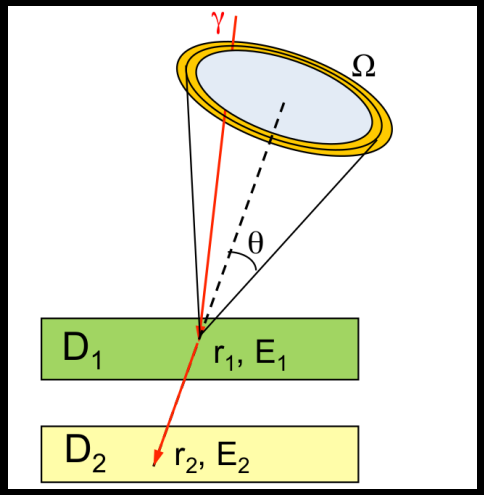
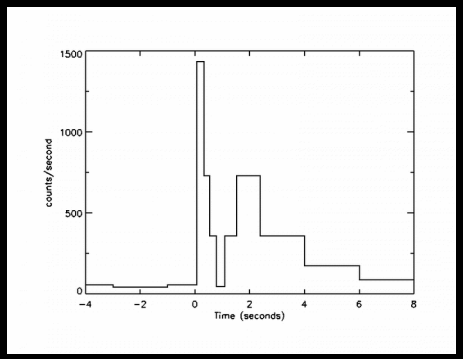
Development of an advanced Compton telescope prototype for MeV-range gamma-ray astronomy





Adrien LAVIRON
Université Paris-Sud / CSNSM, CNRS IN2P3
JRJC 2019

$$E = \frac{E_0}{\left(1 + E_0/m_e c^2 (1 - \cos\theta)\right)}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{KN} = \frac{r_e^2 \epsilon^2}{2}\left(\epsilon + \epsilon^{-1} - 2\sin^2\theta\cos^2\phi\right)$$

UNIVERSITÉ PARIS SUD
Comprendre le monde, construire l'avenir
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CENTRE DE SCIENCES NUCLÉAIRES ET DE SCIENCES DE LA MATIÈRE

Development of an advanced Compton telescope prototype for MeV-range gamma-ray astronomy

First part:

- What phenomena ?
- What observables ?

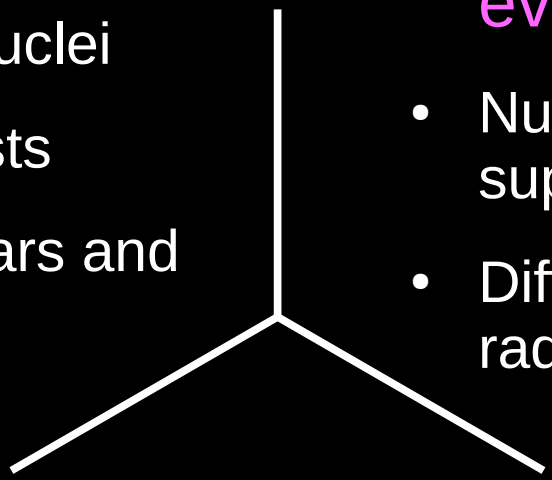
Second part:

- How to observe ?
- What are the challenges ?
- What am I really working on ?

MeV range gamma-ray astronomy : a wide range of phenomena

Astrophysical jets

- Active galactic nuclei
- Gamma-ray bursts
- Magnetars, pulsars and X-ray binaries



Nucleosynthesis and chemical evolution of the universe

- Nuclear lines in novae and supernovae
- Diffuse emission of long-lived radioactive isotopes

Cosmic rays physics

- Propagation of cosmic rays in the galaxy
- Effect of low-energy cosmic rays in the interstellar medium

MeV range gamma-ray astronomy : a wide range of phenomena

Astrophysical jets

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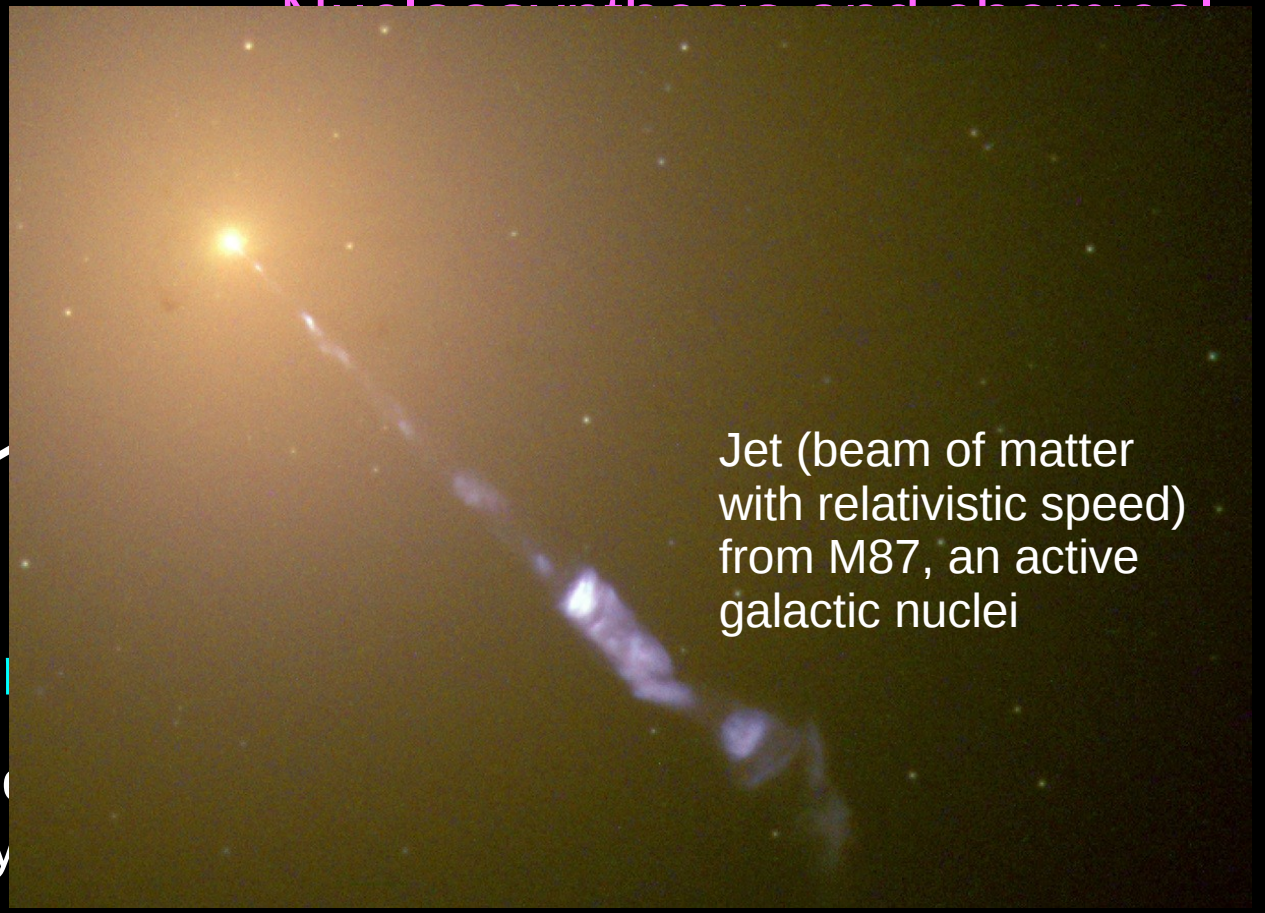

Jet (beam of matter with relativistic speed) from M87, an active galactic nuclei

Cosmic r

- Propagati
  the galaxy
- Effect of low-energy cosmic rays in the interstellar medium

MeV range gamma-ray astronomy : a wide range of phenomena

Astrophysical jets

- Active galactic nuclei
- **Gamma-ray bursts**
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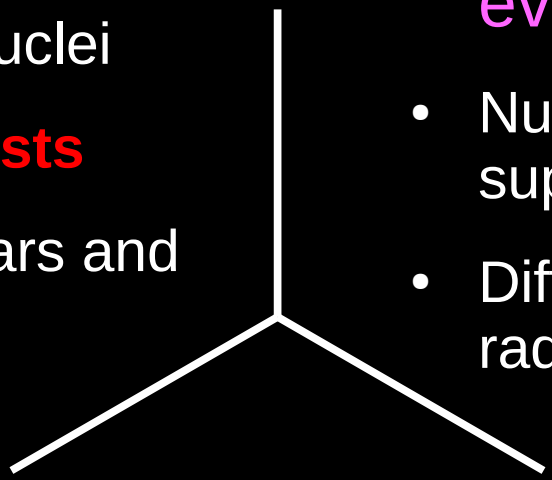

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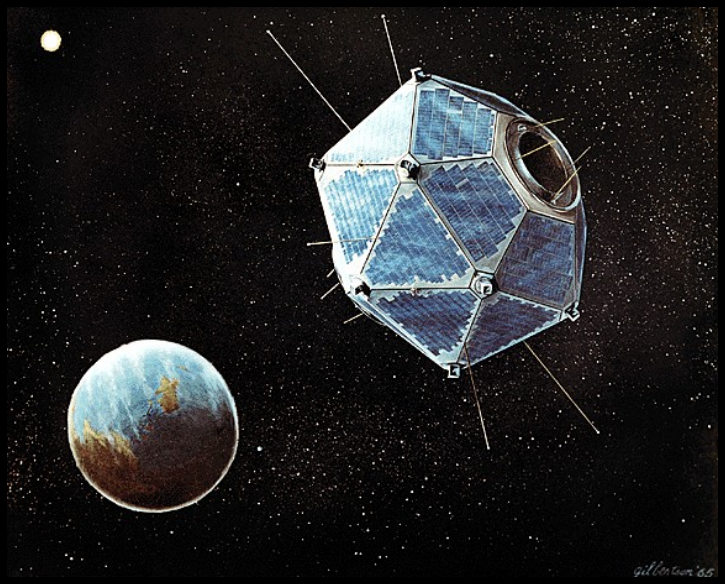
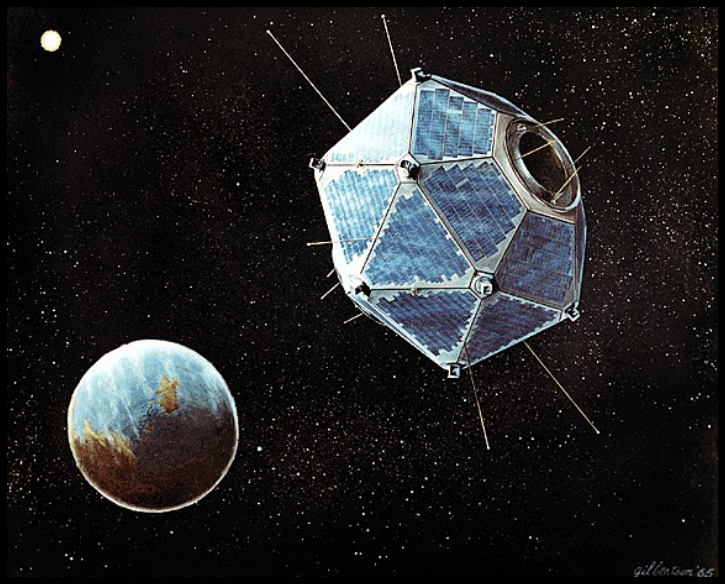
Gamma-ray bursts (GRBs)



Vela 5B (source : nasa)

August 1963: Nuclear test ban treaty
October 1963: First Vela 1A and 1B satellites launch

Gamma-ray bursts (GRBs)



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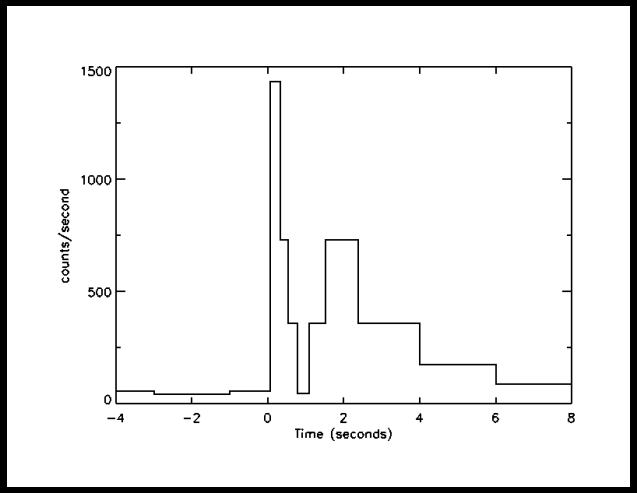

First GRB detected by Vela 4 in 1967, Klebesadel *et al.* 1973

August 1963: Nuclear test ban treaty
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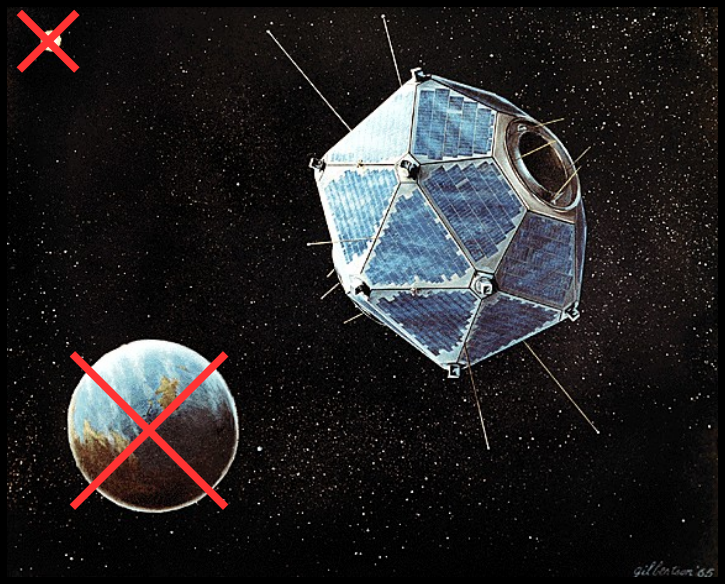
Gamma-ray bursts (GRBs)



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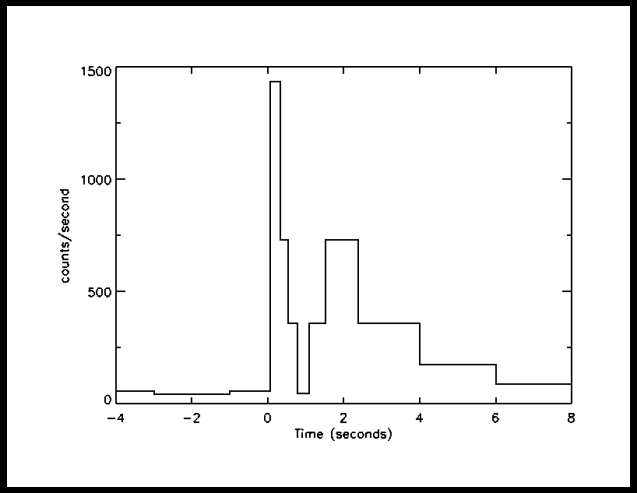
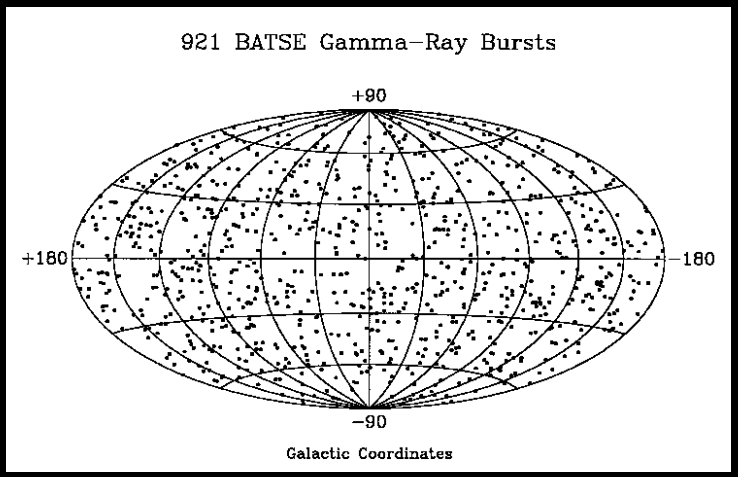
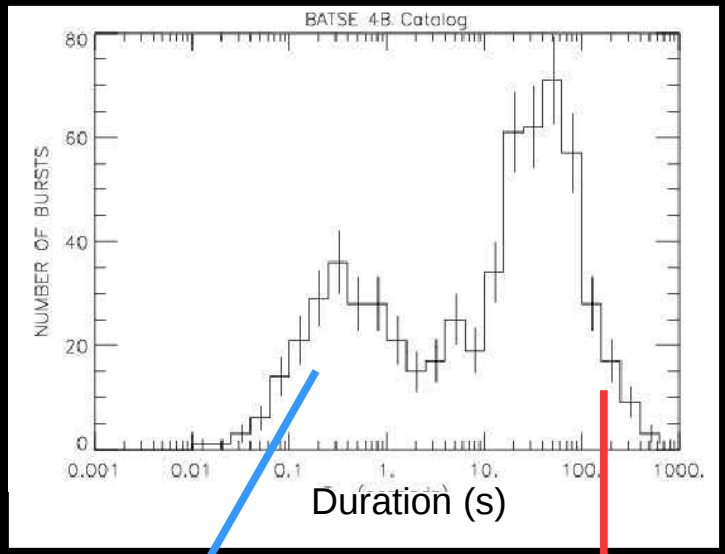


First GRB detected by Vela 4 in 1967, Klebesadel *et al.* 1973

August 1963: Nuclear test ban treaty
October 1963: First Vela 1A and 1B satellites launch
July 1967: First GRB detection
1990's: GRB distribution is isotropic



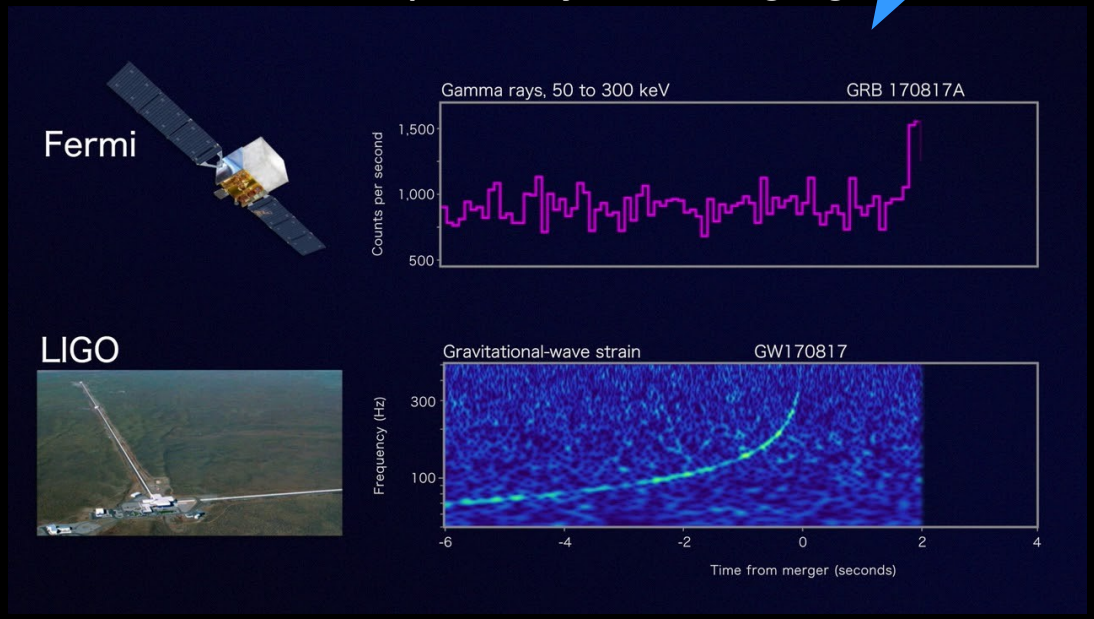
Gamma-ray bursts (GRBs)

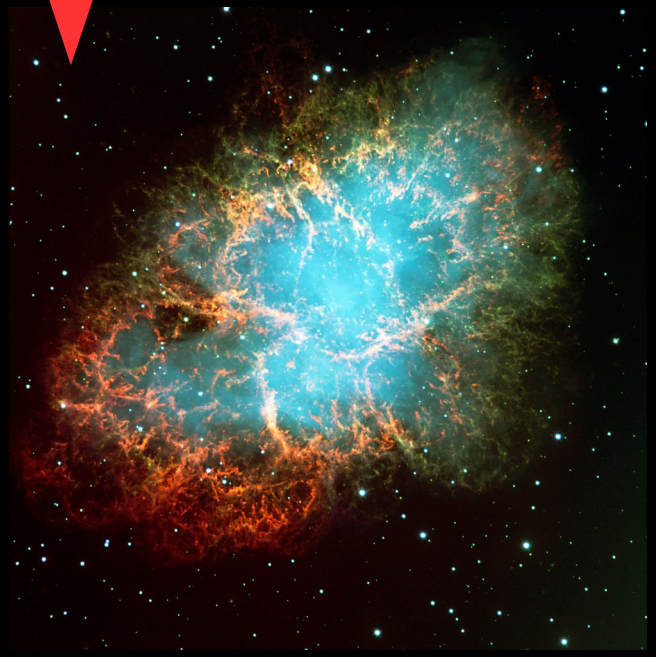


4th BATSE GRB Catalog, Pacesias *et al*., ApJS 1999

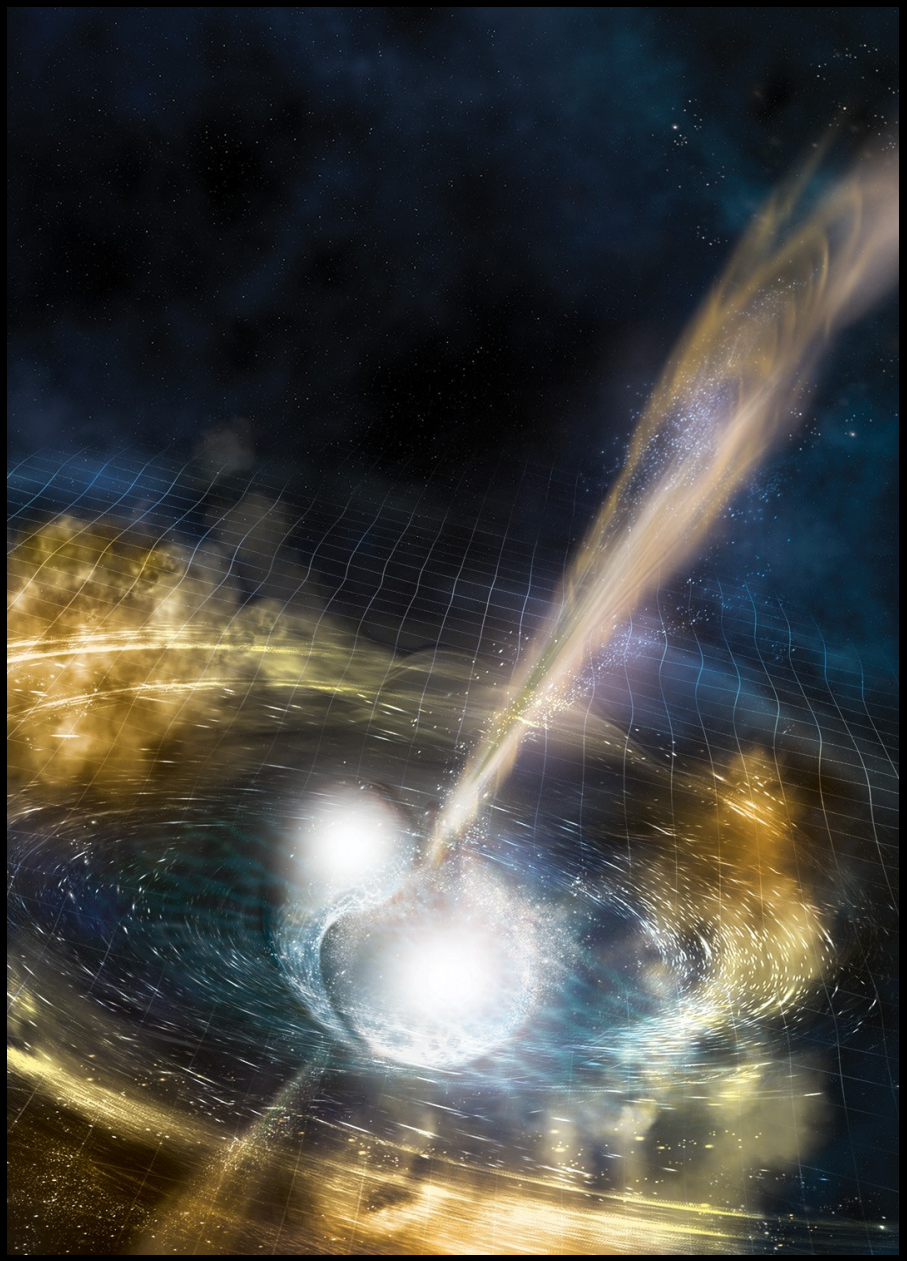
Short GRBs: compact objects merging

Long GRBs: supernovae

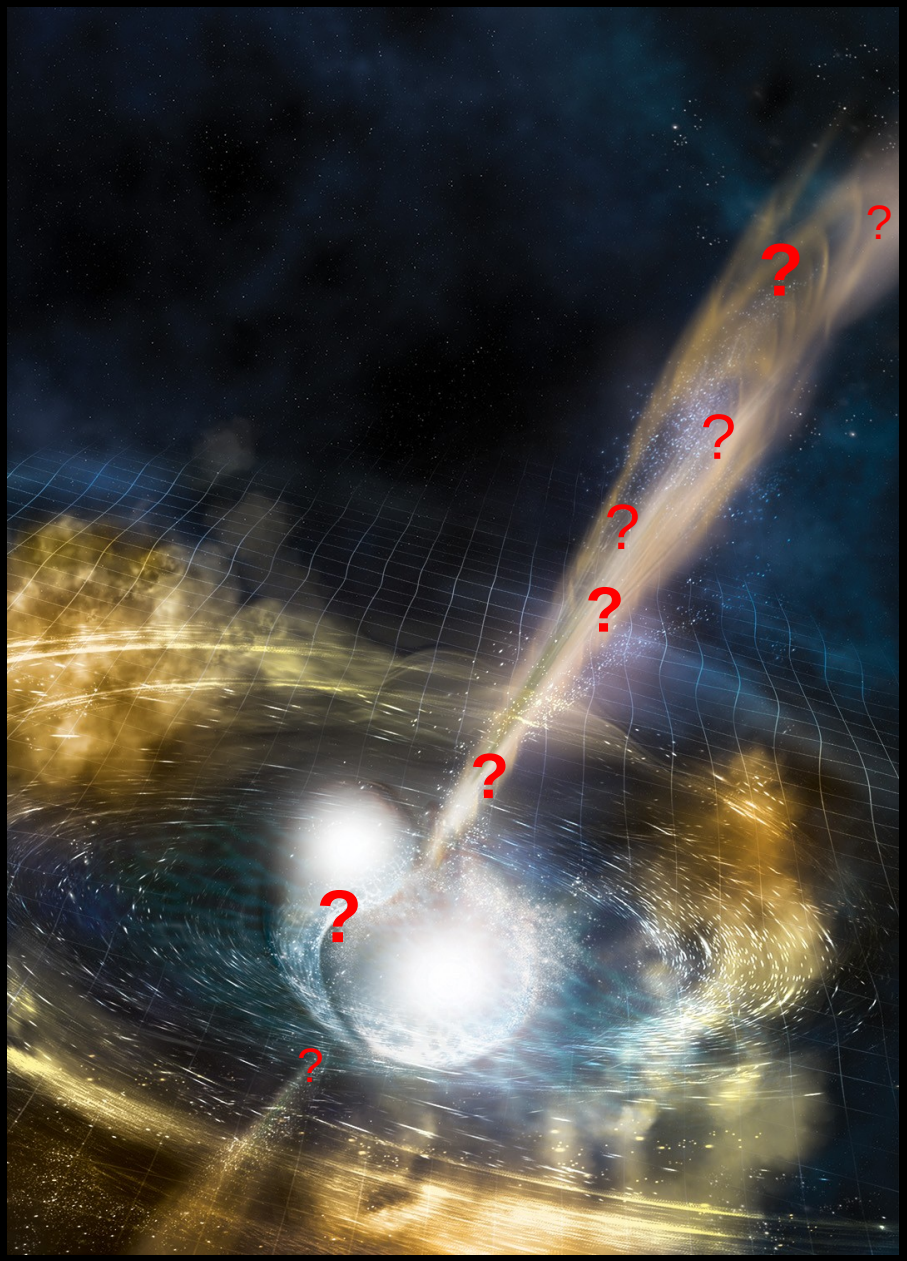




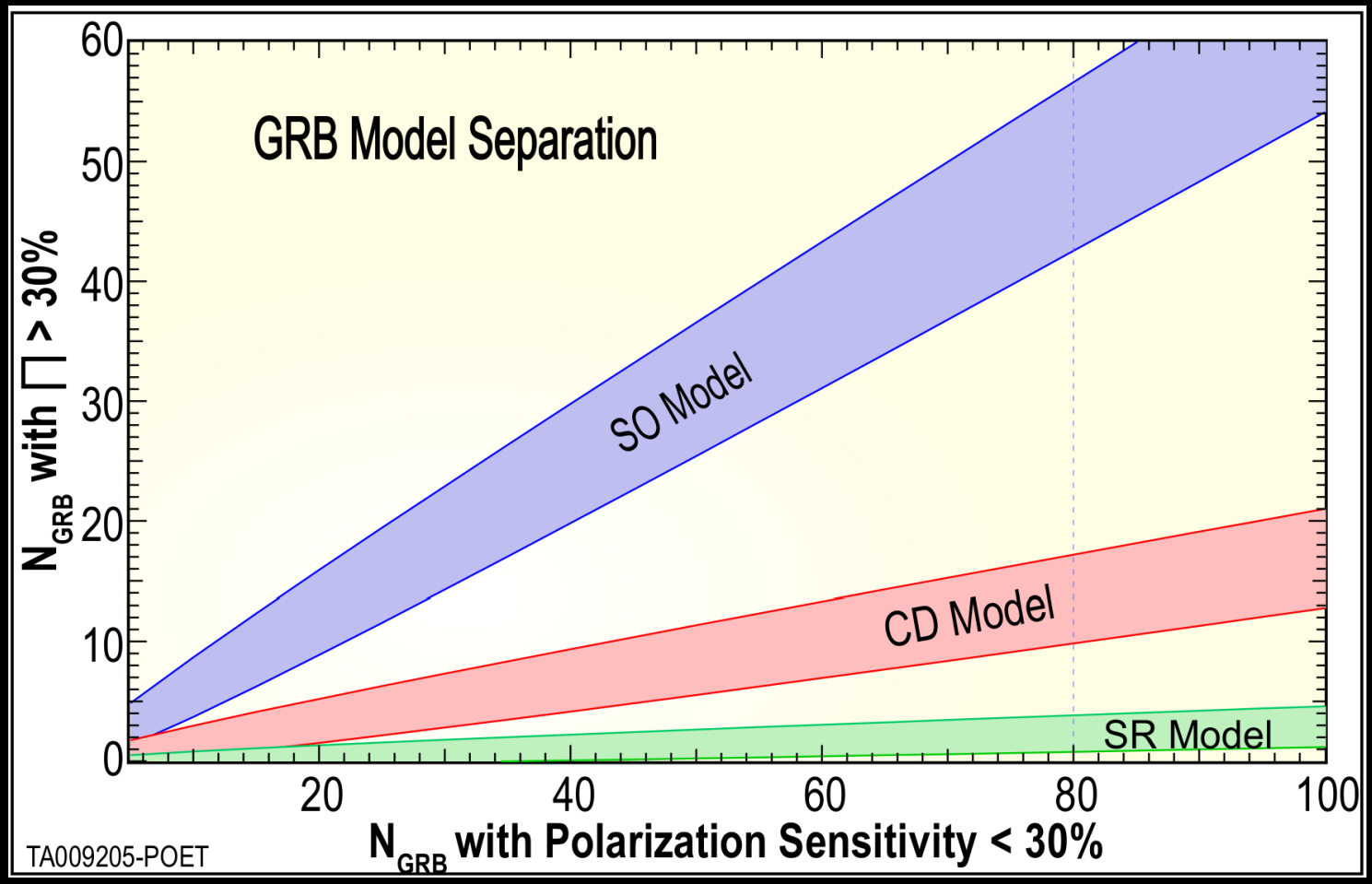
Gamma-ray bursts jets



Gamma-ray bursts jets



Polarization in GRBs

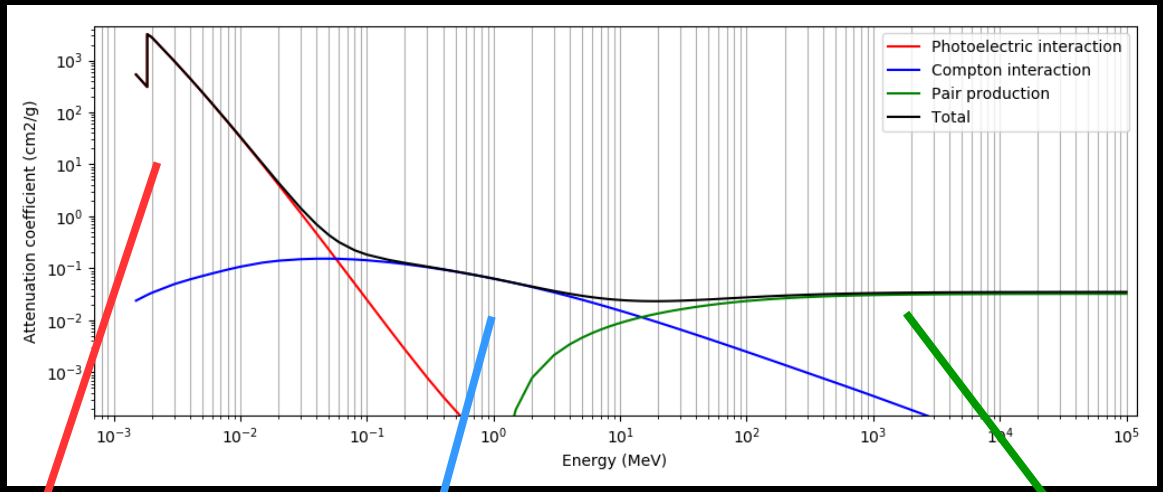


Mark McConnell, 8th Huntsville GRB symposium, 2016

SO : Synchrotron with ordered magnetic field
CD : Compton drag
SR : Synchrotron with random magnetic field (shocks)

Measuring the polarization will rule out some models. It gives a better understanding of the jet mechanism, that points to the physics of the progenitor.

Gamma-ray astronomy : What observables ?



Low energy

Focusing lens or mirrors

Medium energy

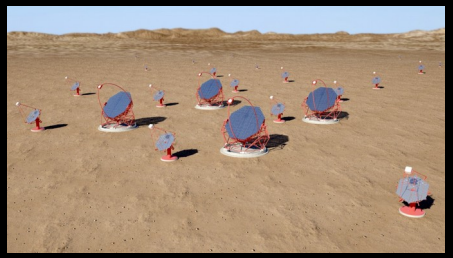
Coded mask imaging

Compton imaging

High energy

e^+-e^- pair tracking

Very high energy

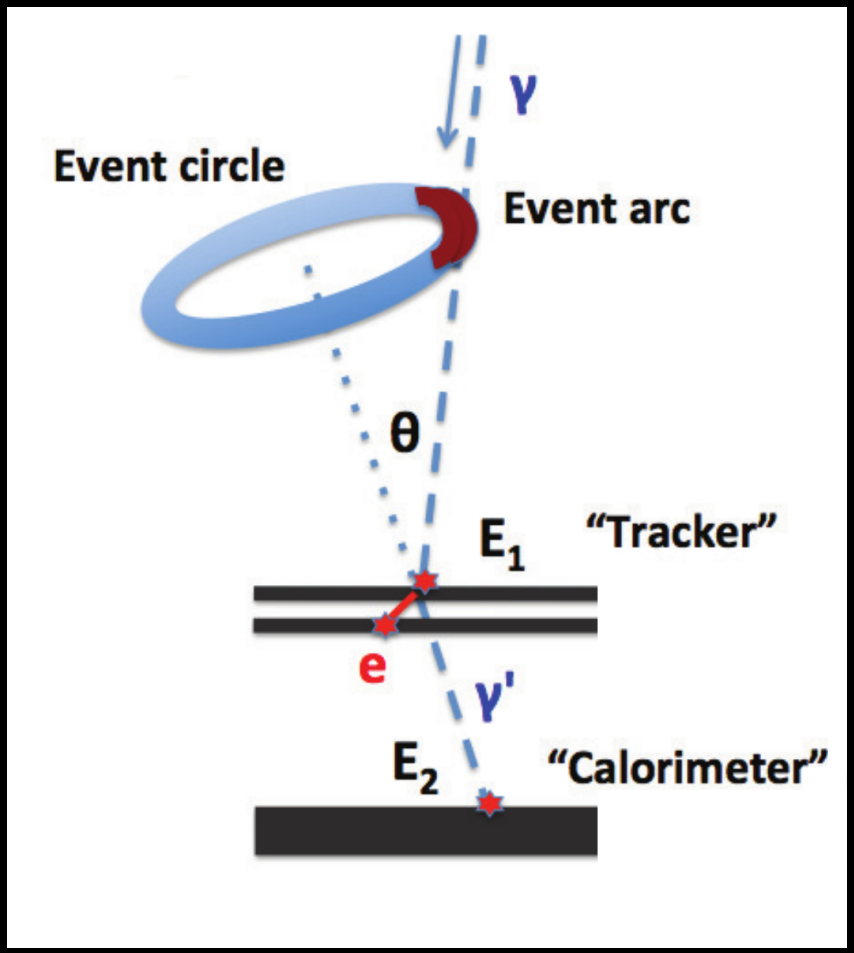


Earth atmosphere as a calorimeter

We always want to measure the energy of a gamma ray and the direction it comes from.

Advanced Compton telescope

Incoming photon



Compton imaging:

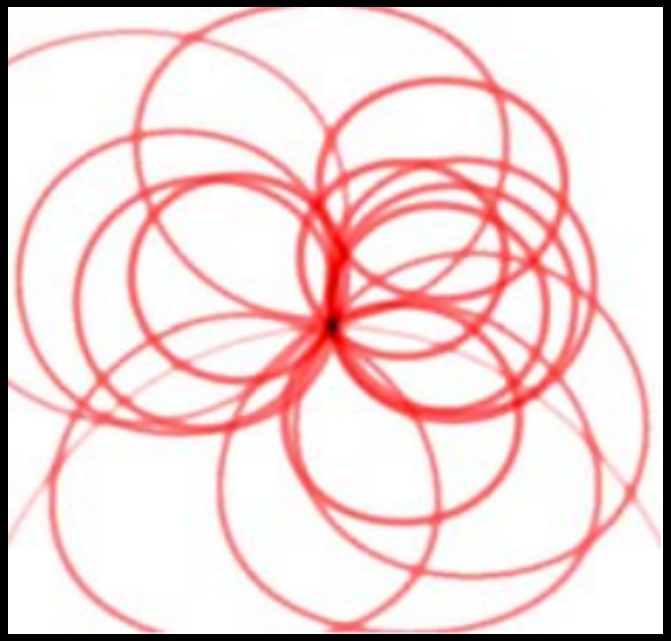
$$\theta = \arccos\left(1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2}\right)\right)$$

Advanced Compton imaging:

Electron tracking constrain the event circle to an event arc

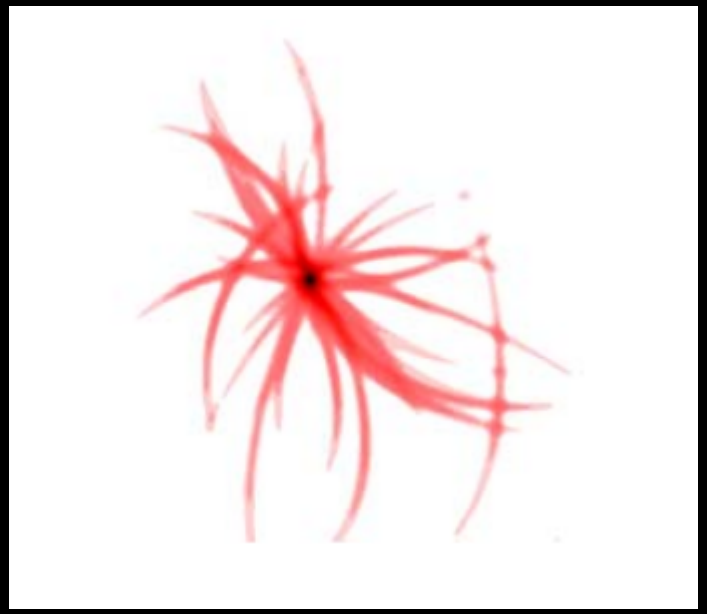
Advanced Compton telescope

Compton telescope



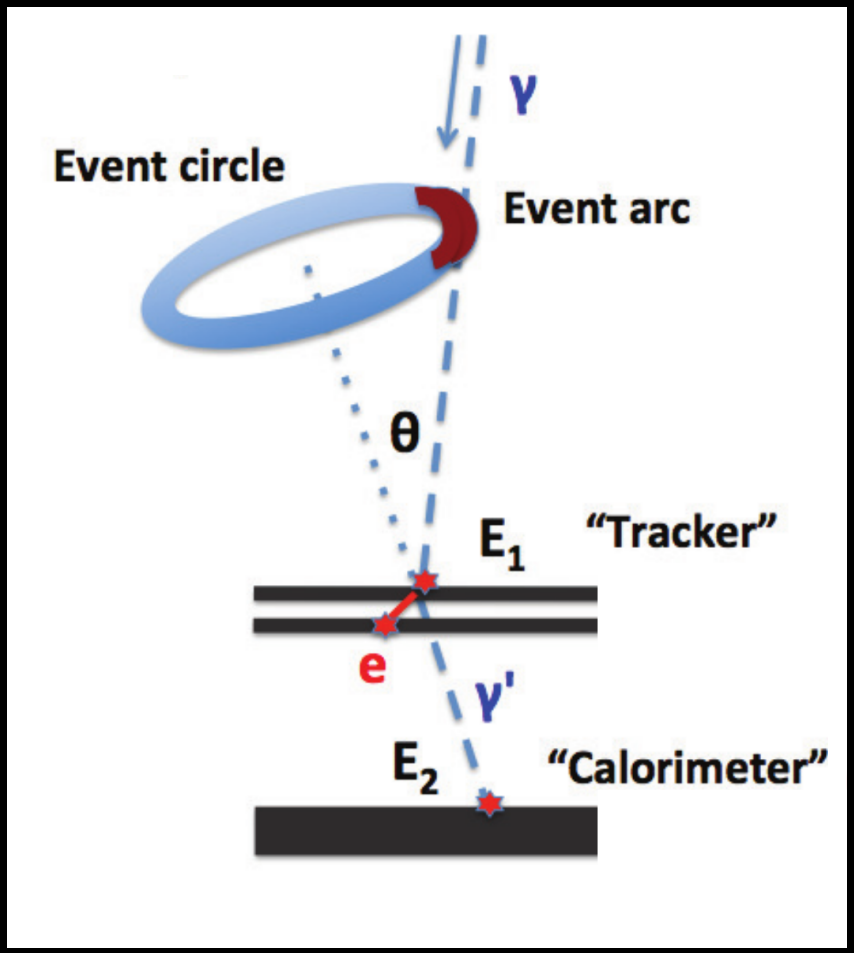
Compton image of one source
(Zoglauer, 2006)

Advanced Compton telescope



Compton image of one source with an advanced Compton telescope
(Zoglauer, 2006)

Advanced Compton telescope

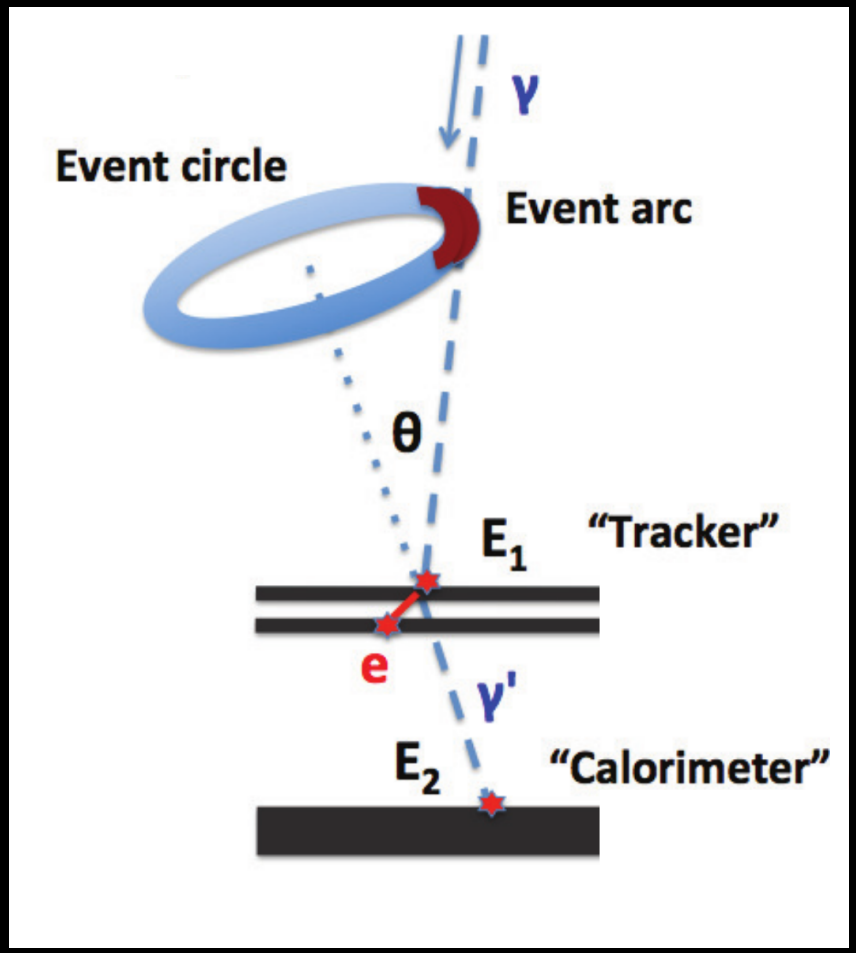


$$\left(\frac{d\sigma}{d\Omega}\right)_{KN} = \frac{r_e^2 \epsilon^2}{2}\left(\epsilon + \epsilon^{-1} - 2\sin^2\theta\cos^2\phi\right)$$

$$\text{with} \quad \epsilon = \frac{E}{E_0}$$

Advanced Compton telescope

Incoming photon



Sensitivity to linear polarization !

$$\left(\frac{d\sigma}{d\Omega}\right)_{KN} = \frac{r_e^2 \epsilon^2}{2}\left(\epsilon + \epsilon^{-1} - 2\sin^2\theta\cos^2\phi\right)$$

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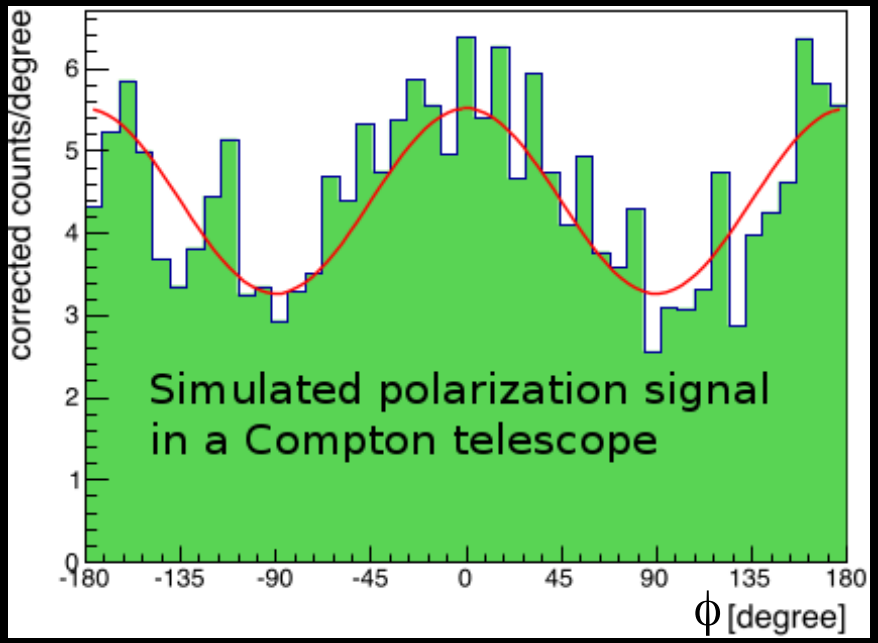
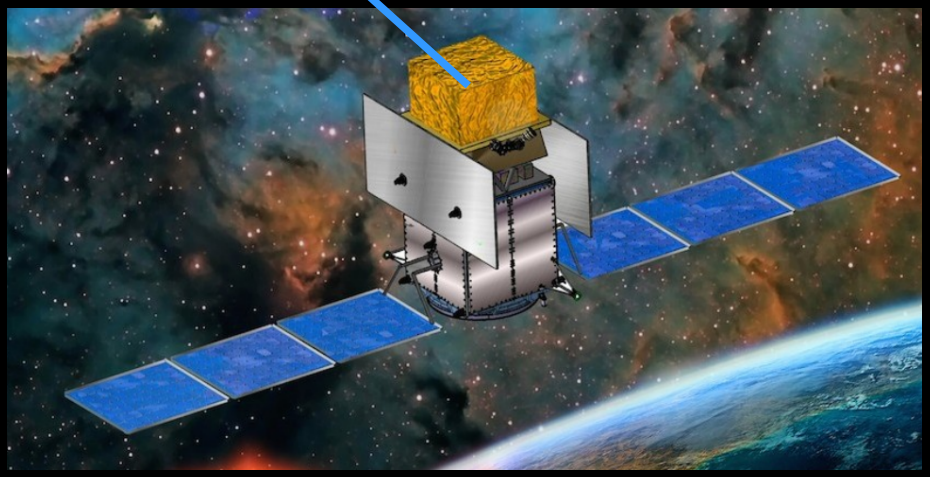


Part II

Current instrumental developments

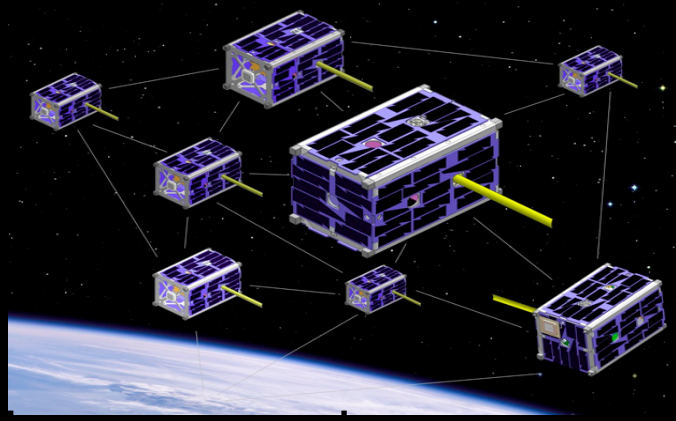
Space mission concepts

Array of tracker+calorimeter modules



Big, very sensitive instrument

One tracker+calorimeter module per nanosatellite

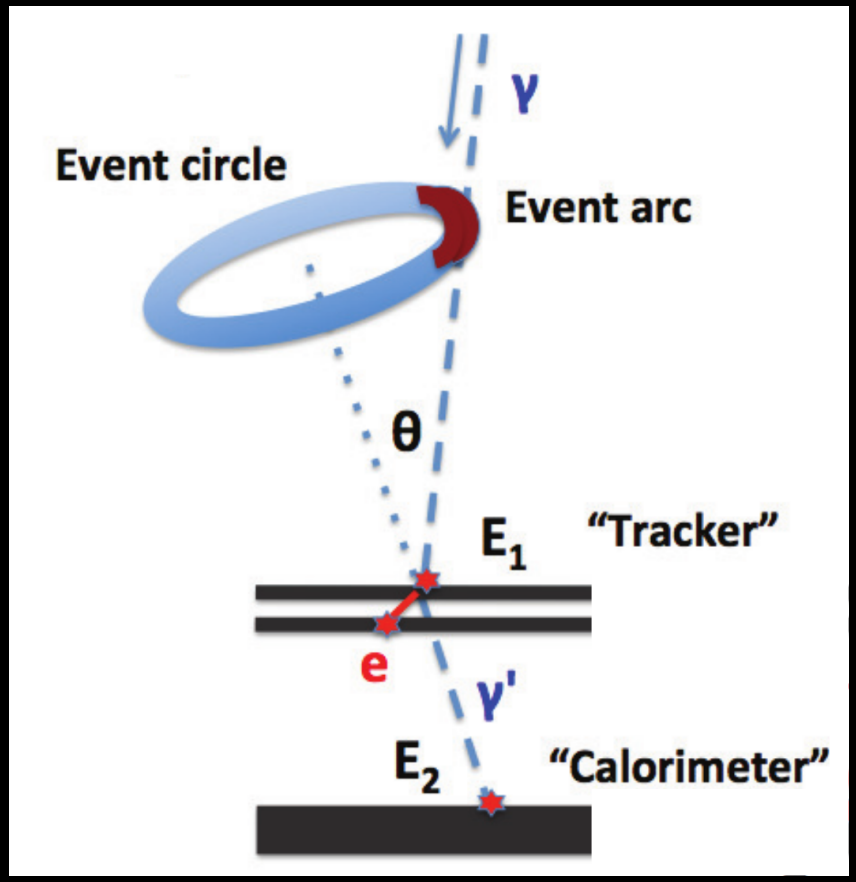


Constellation of nanosatellites for all-time full-sky coverage

Great for studying GRBs

Current instrumental developments

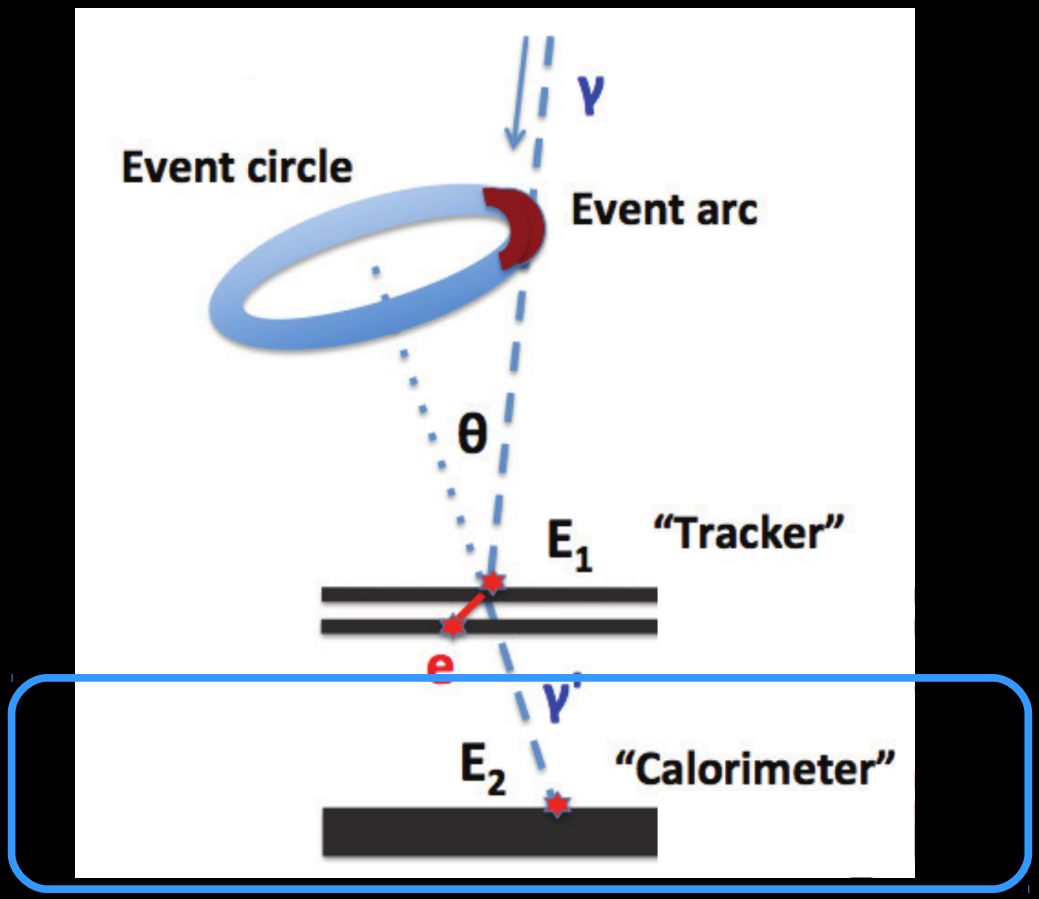
Incoming photon



Build a module prototype
for a nanosatellite

Current instrumental developments

Incoming photon



Main task of the CSNSM research team

Build a module prototype for a nanosatellite

The calorimeter

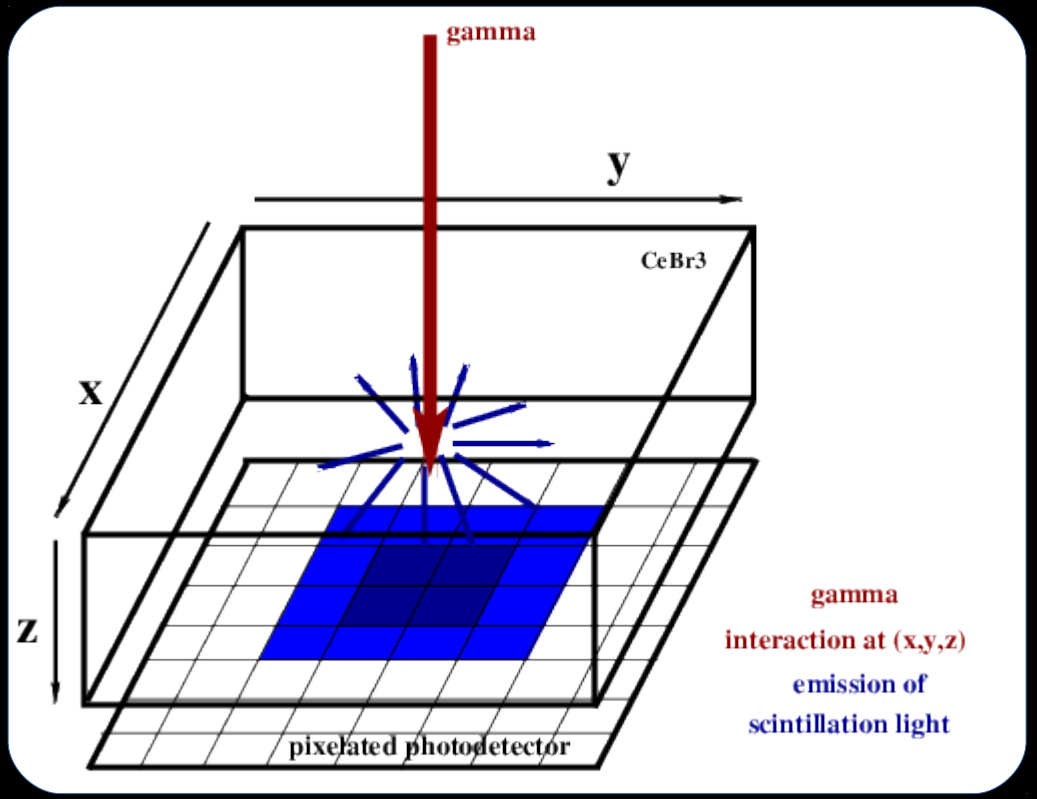
The goals:

- High stopping power
- High spectral resolution
- High spatial resolution

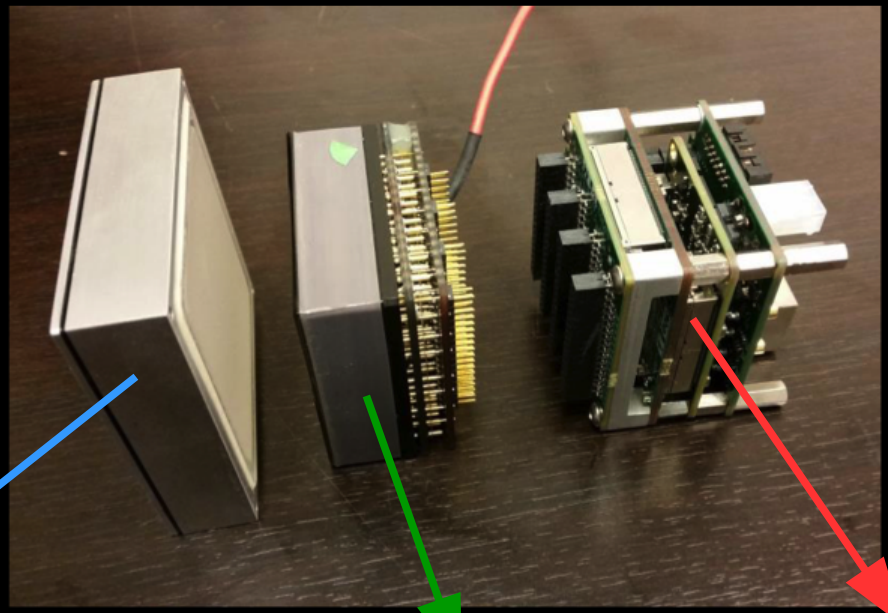
The calorimeter

The goals:

- High stopping power
- High spectral resolution
- High spatial resolution



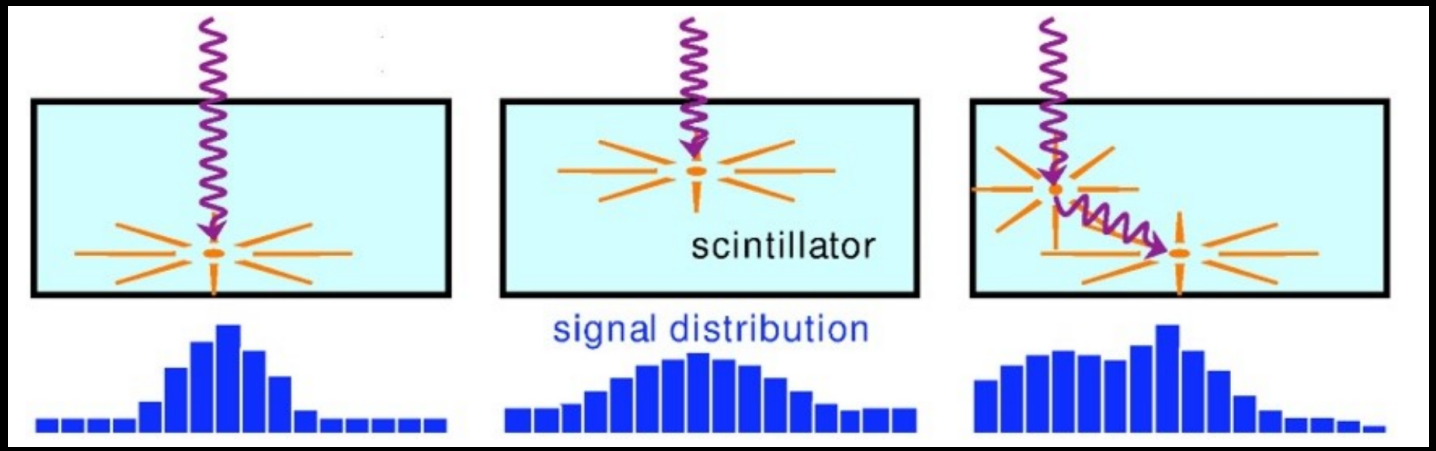
The calorimeter



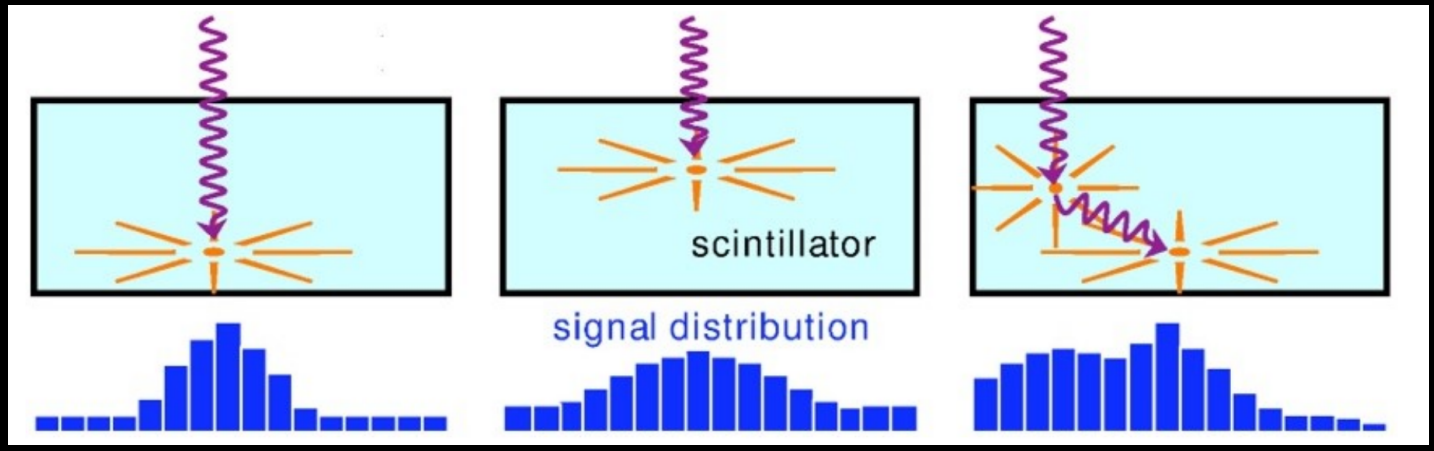
Monolithic, inorganic $CeBr_3$ scintillator

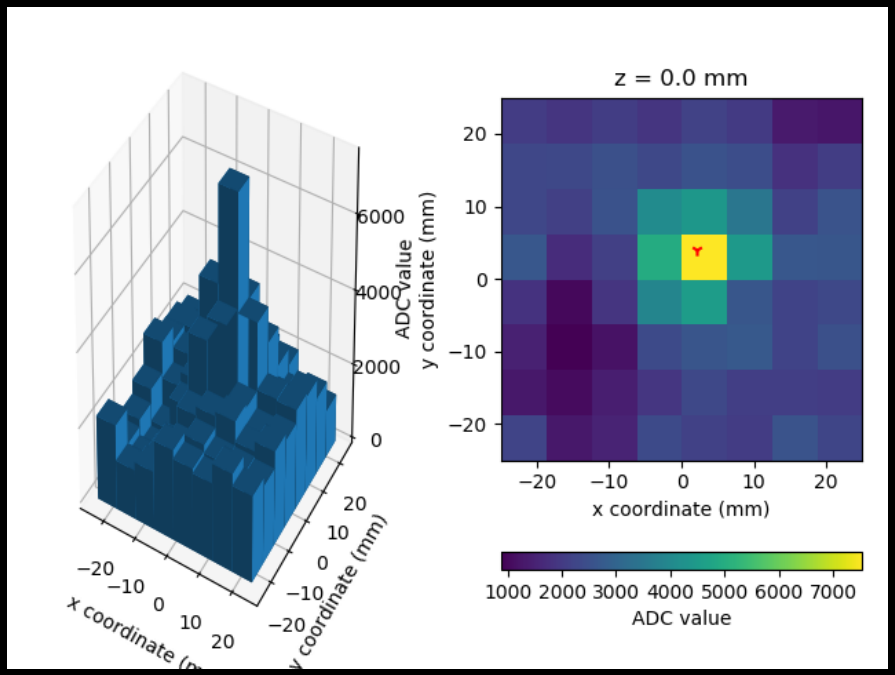
Pixelated photodetector (SiPM matrix or multi-anode PMT)

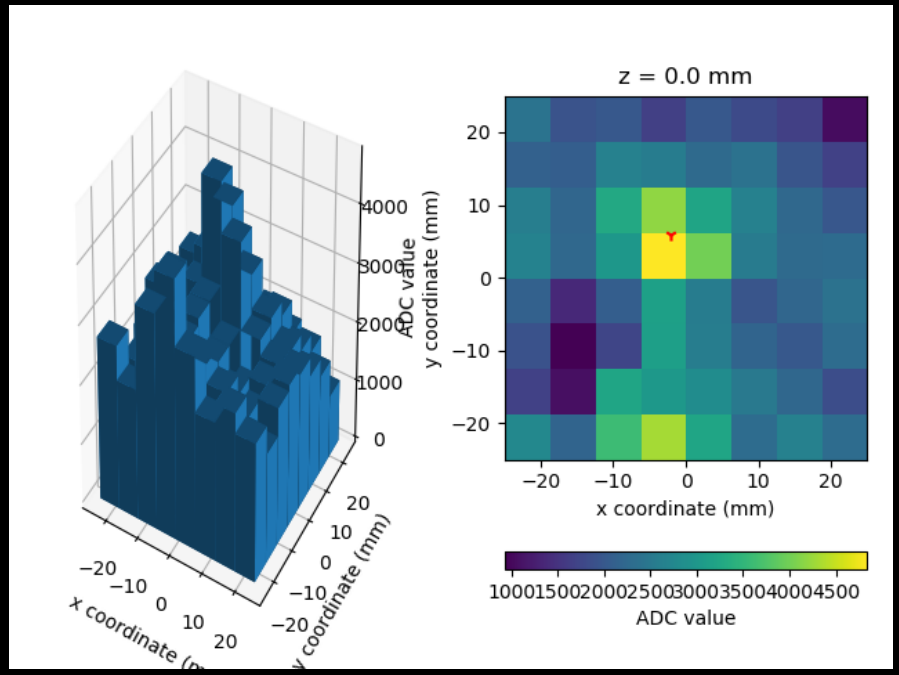
Integrated electronics



Interaction position determination



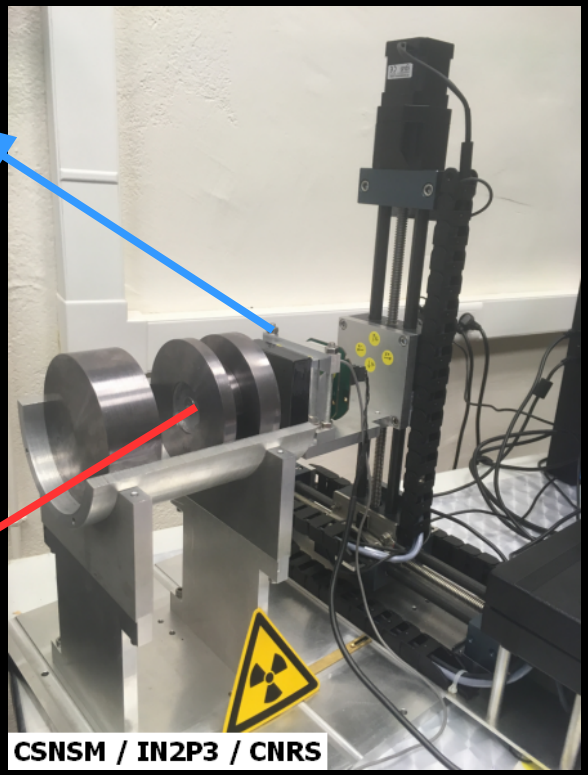




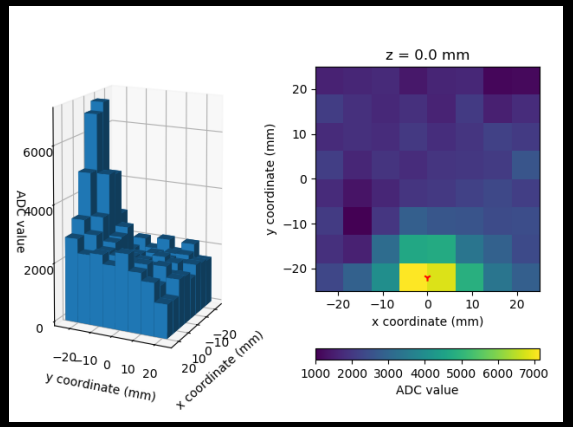
Experimental setup

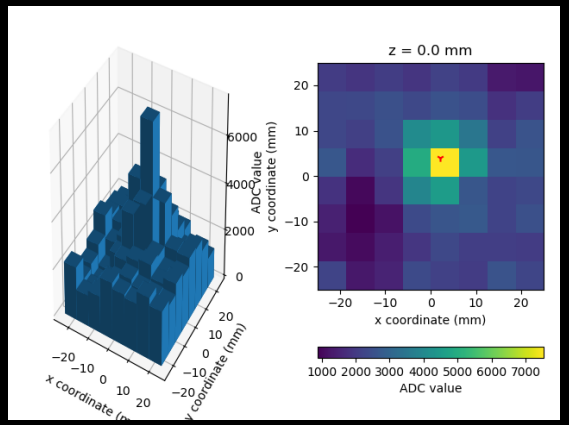
The module can move to span all possible positions of interaction

Radioactive source and collimator generate a gamma-ray beam



Module in position 1

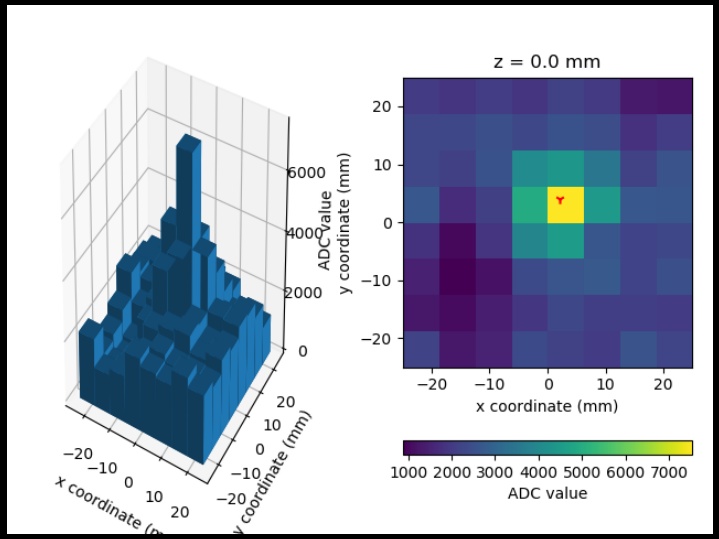


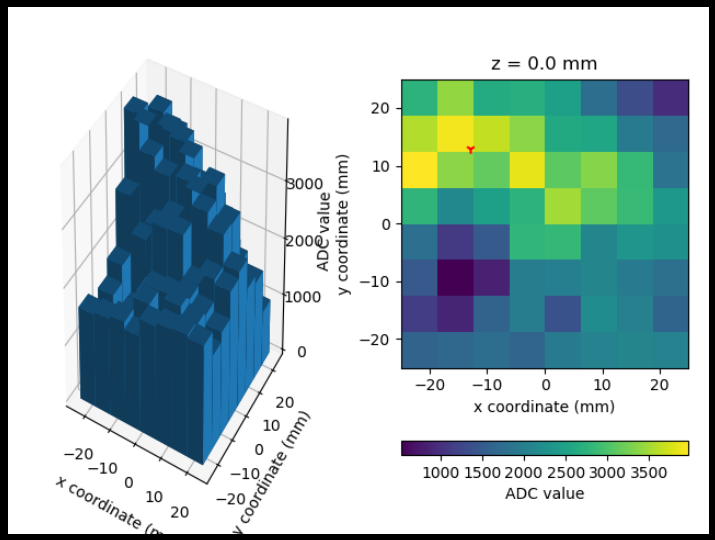


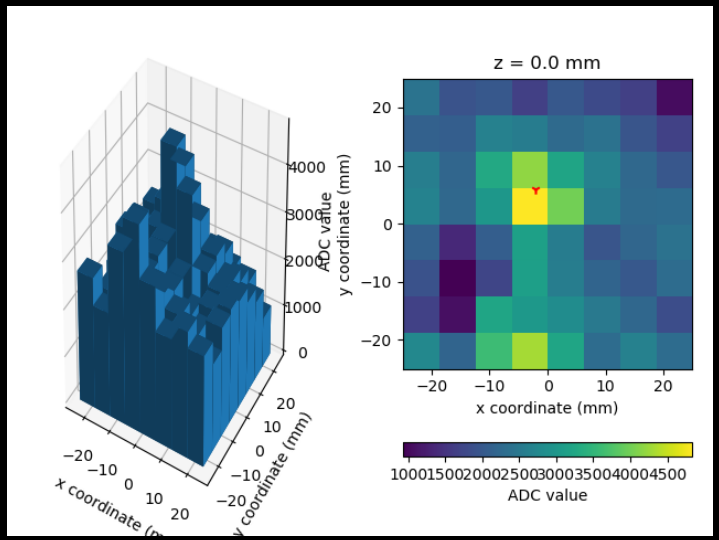
Module in position 2

Data characterization

- Events can have different morphologies
- Peaked morphologies are easier to use for position reconstruction

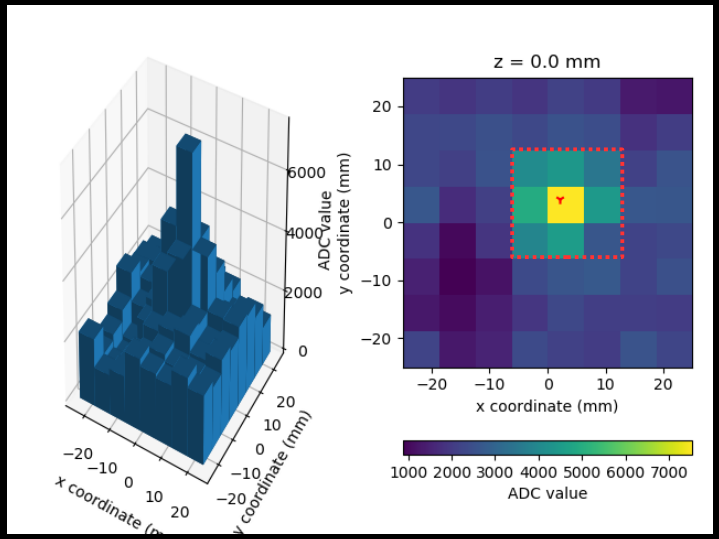


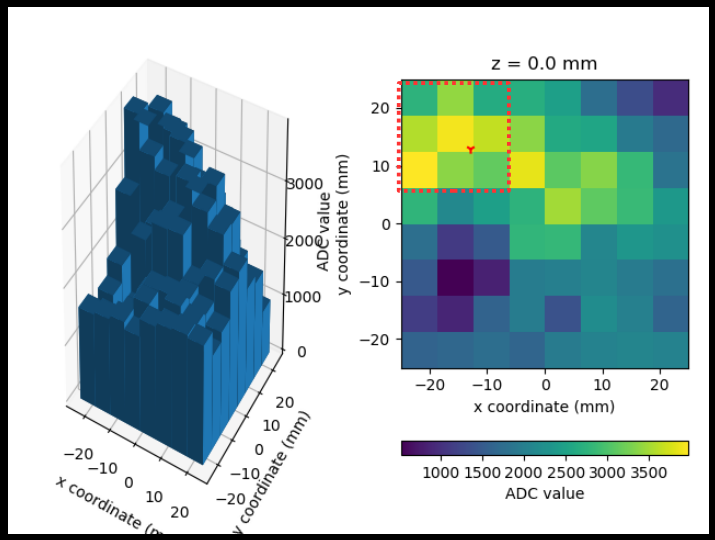


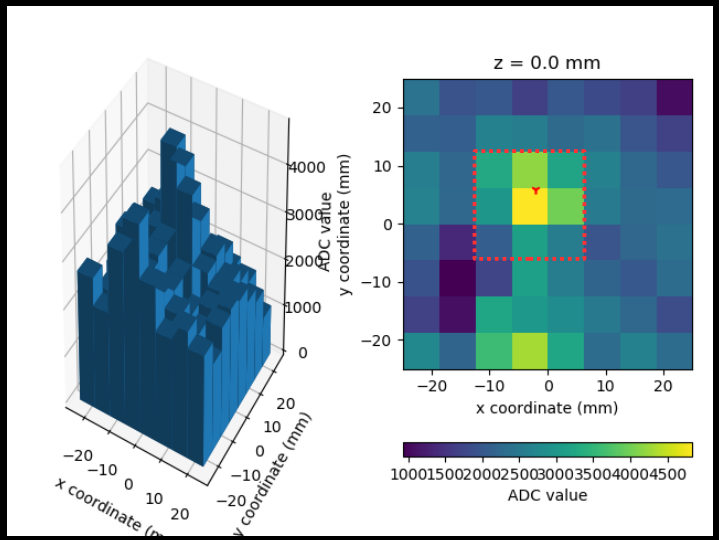


Data characterization

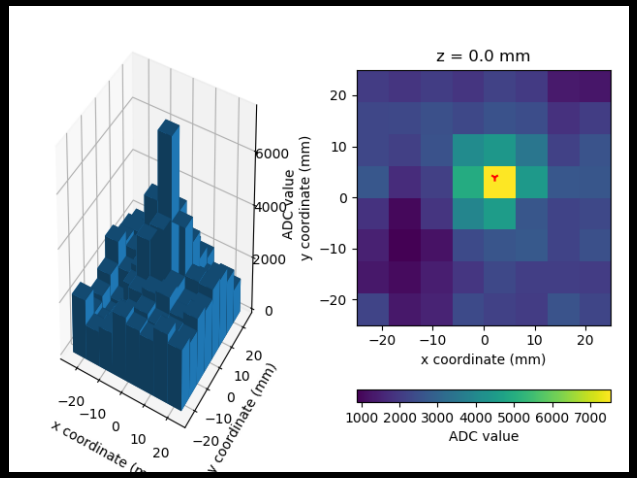
- Events can have different morphologies
- Peaked morphologies are easier to use for position reconstruction
- They can be sorted using a morphological cut
- Unusable data represent less than 15% of the datasets

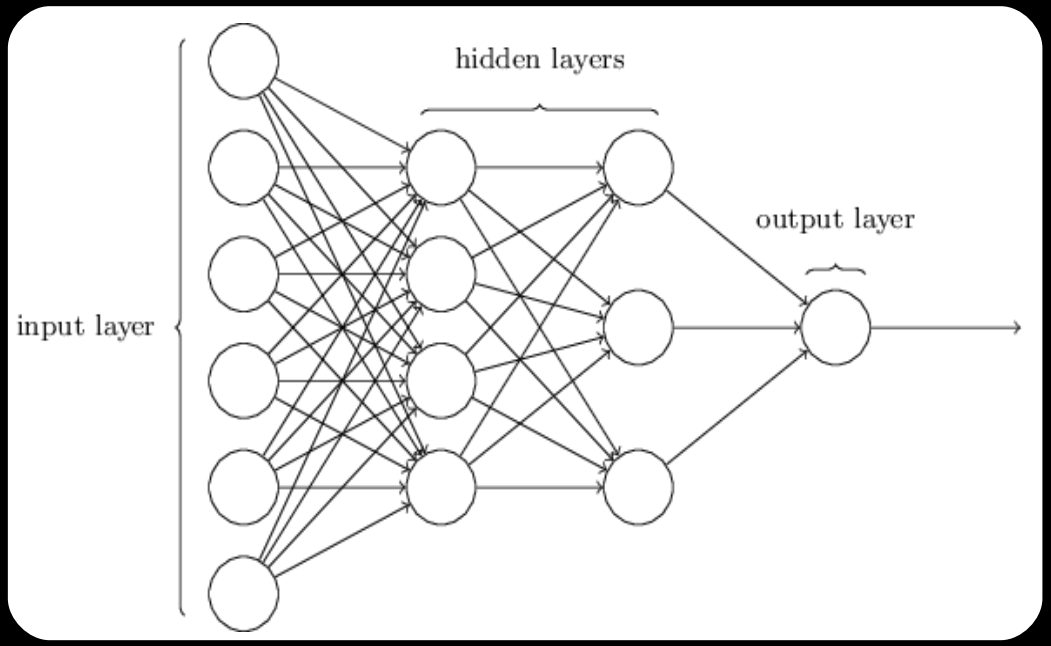






Artificial neural networks (ANNs)



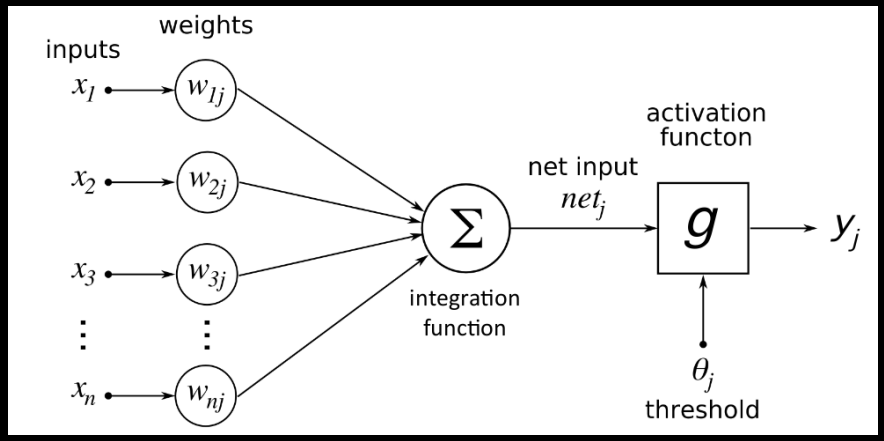


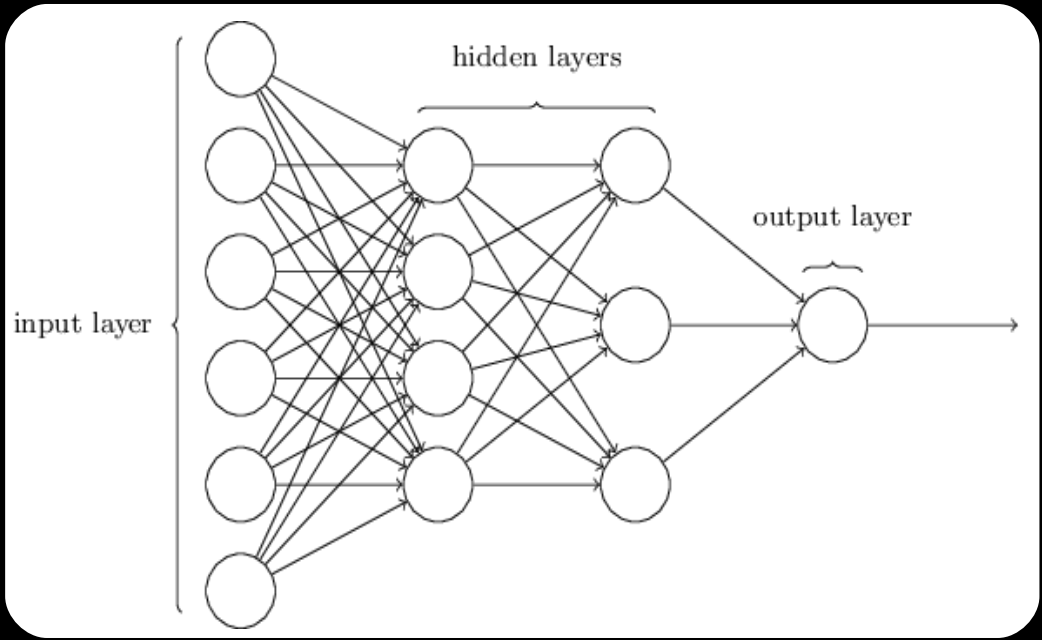
(x, y)

(z)

Artificial neural networks (ANNs)

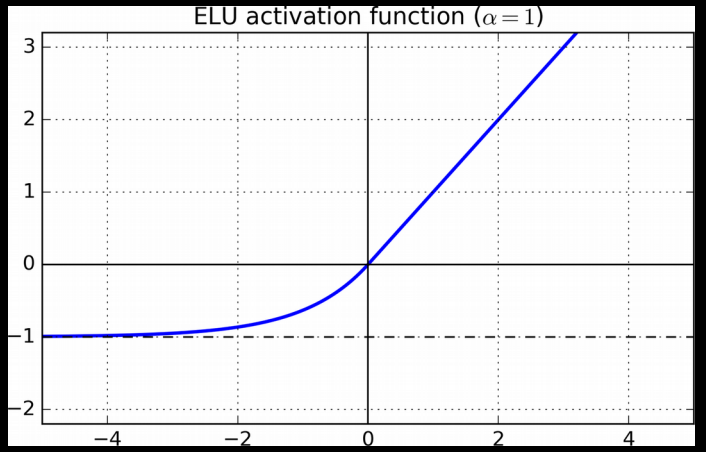
An artificial neuron



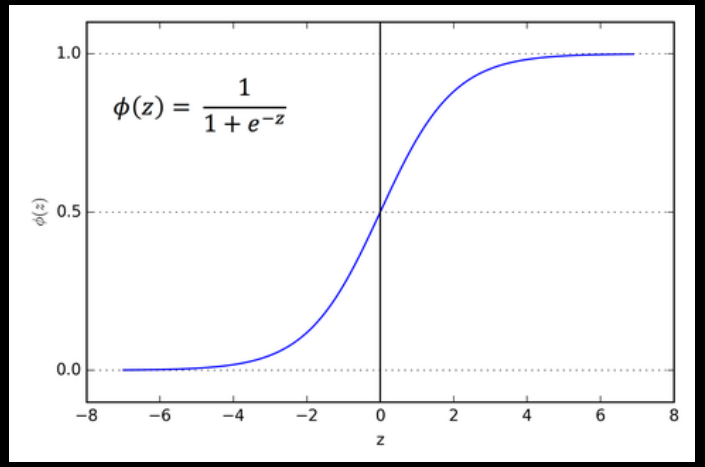


Some meta-parameters of ANNs

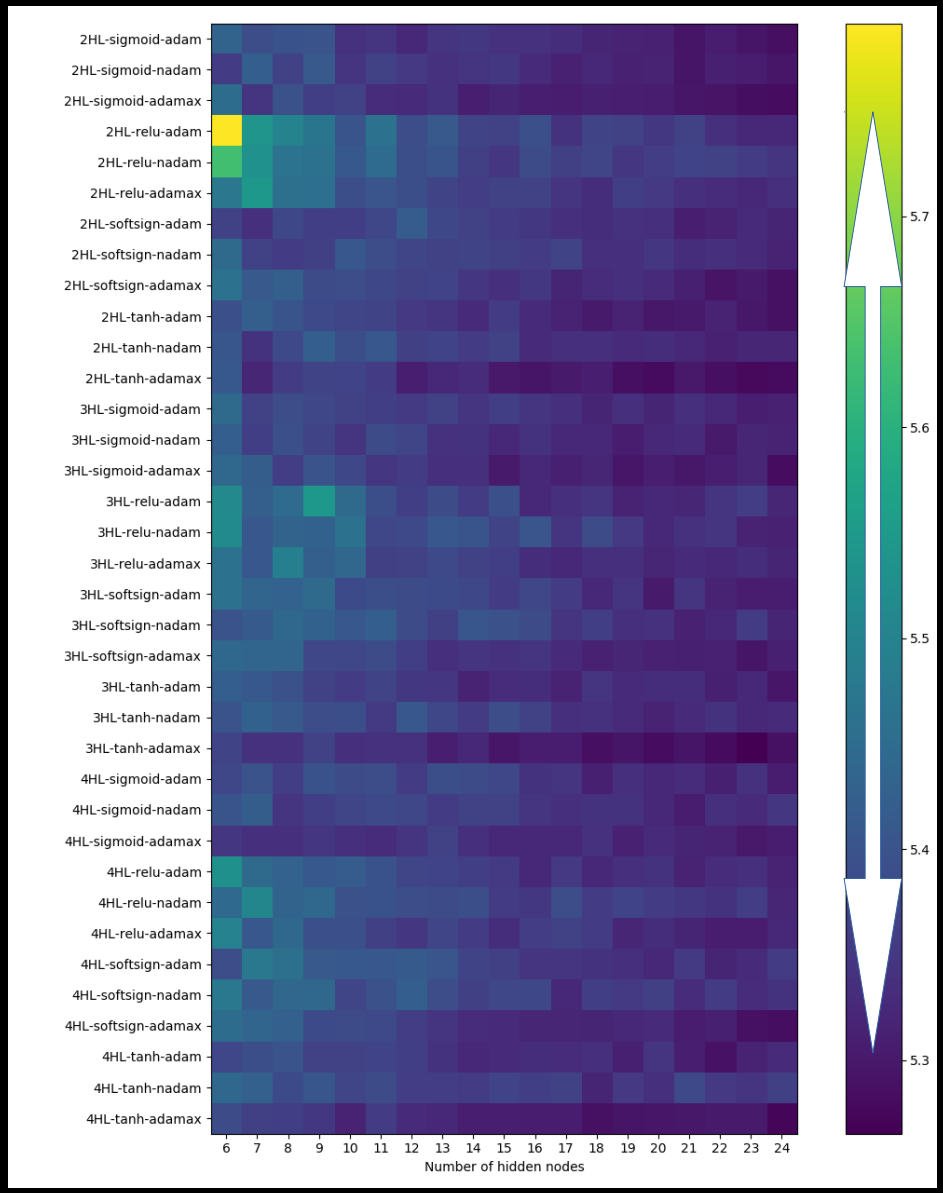
- Activation function
- Training algorithm
- Number of layers
- Number of neurons
- What datasets to use ?



Examples of activation function
(top: elu, bottom: sigmoid)

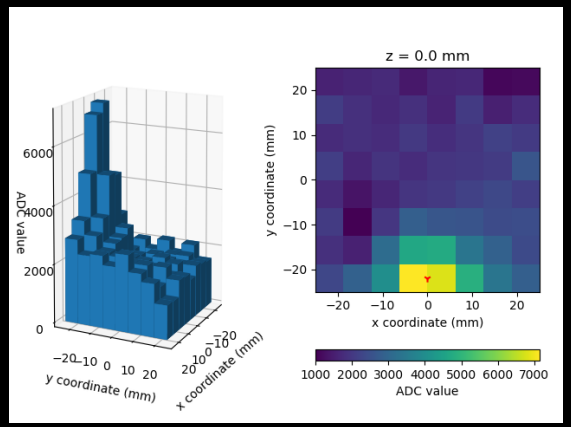


Systematic exploration of meta-parameters space

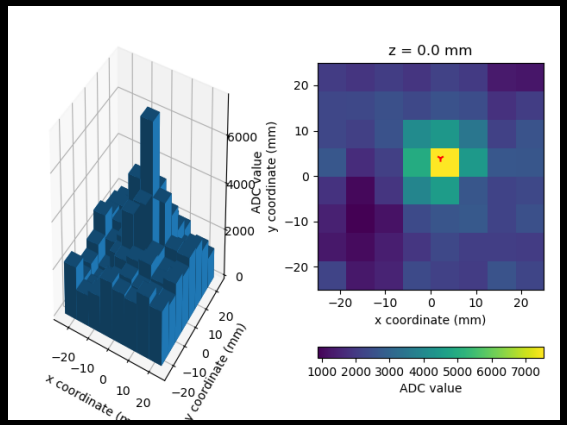


Reconstructing the z coordinate

Module in position 1

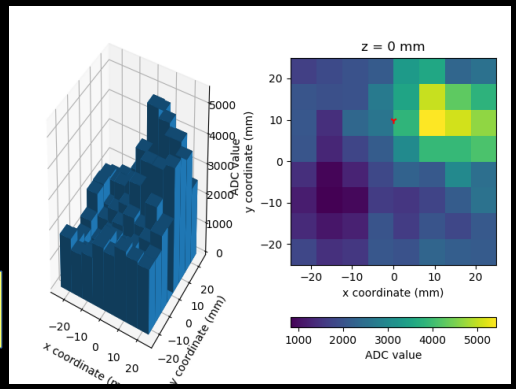


Module in position 2

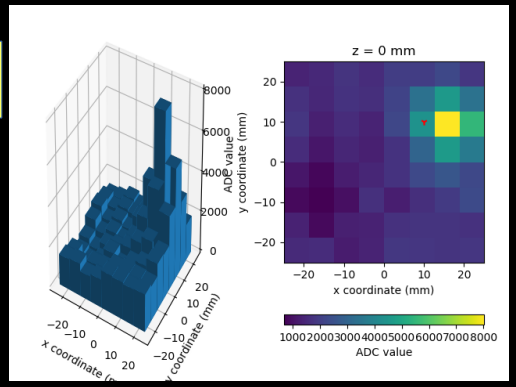


Gamma-ray beam

Module in position 3



Module in position 4

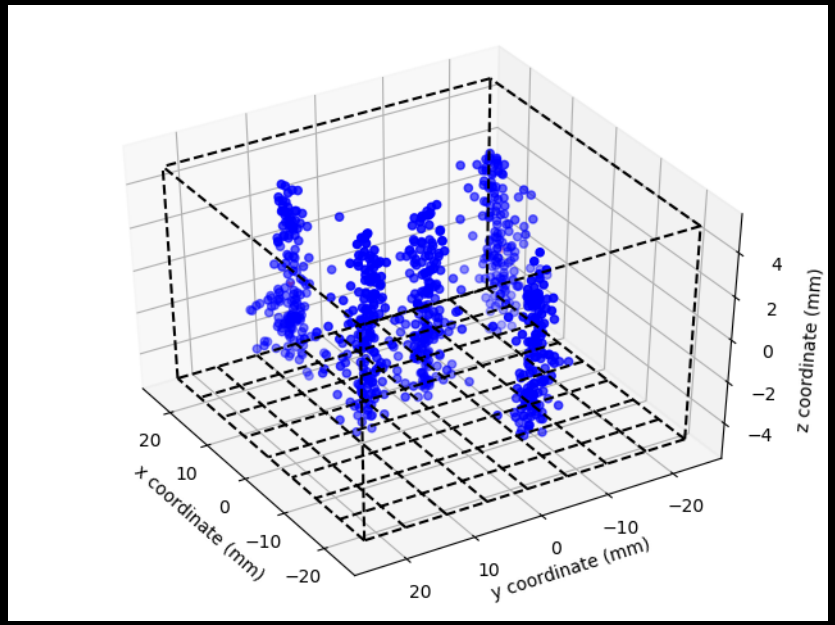


XY

Z

Some Results

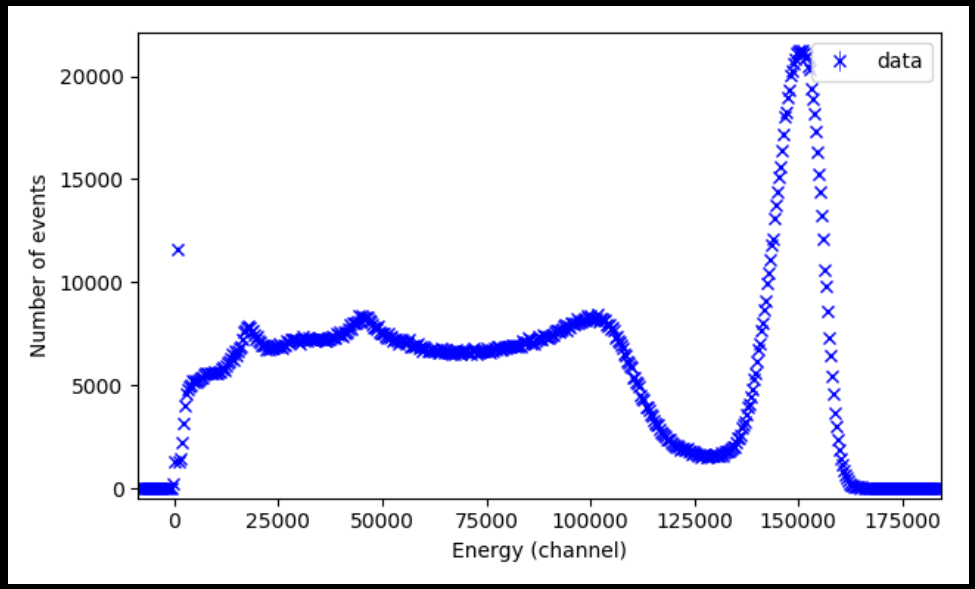
- For the x and y coordinates, an ANN with 2 hidden layers and 20 neurons per layer is a good complexity/performance compromise
- For the z coordinate, we need a more complex ANN (4 hidden layers, 80 neuron per layer)
- For each x, y and z
- coordinate we have a spatial
- resolution of ⟨σ ⟩≈2 mm

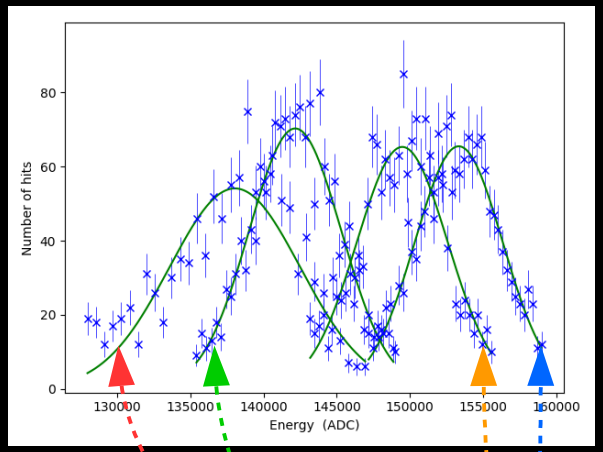


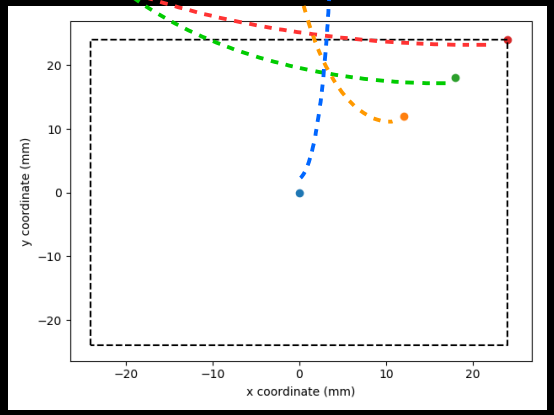
Laviron et al., in prep

$\langle \sigma \rangle \approx 2\,\mathrm{mm}$

Spectral resolution



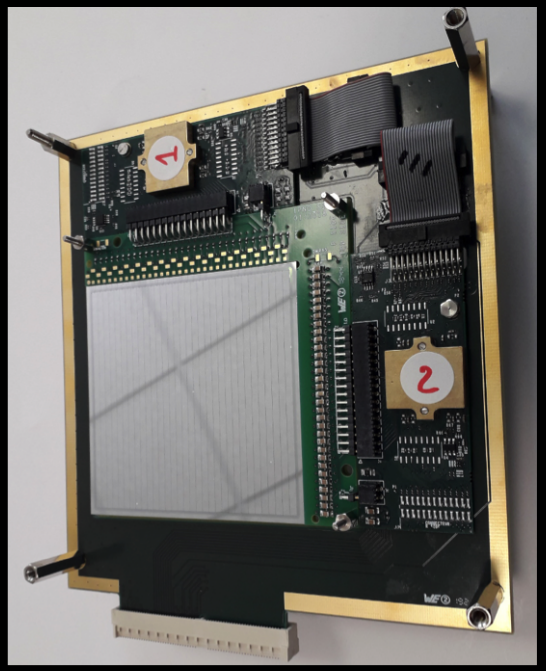


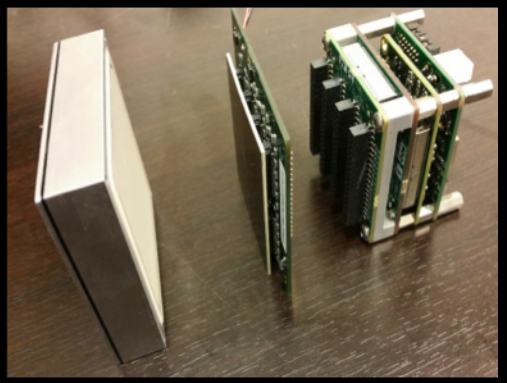


- Spectral resolution without corrections is about **9% @ 662 keV**
- Good spatial resolution and proper characterization of the detector allow for corrections and down to **4.5% @ 662 keV**

Upcoming work

- Integration of a calorimeter module and a silicon tracker into a working prototype
- Build a module using SiPMs instead of a multi-anode PMT
- Simulations of the actual performance of a nanosatellite
- Test measurements as part of a particle accelerator experiment or during a stratospheric balloon flight





Thank you for your attention