# A Compton camera in a CubeSat to measure GRB prompt emission polarization

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# Outline

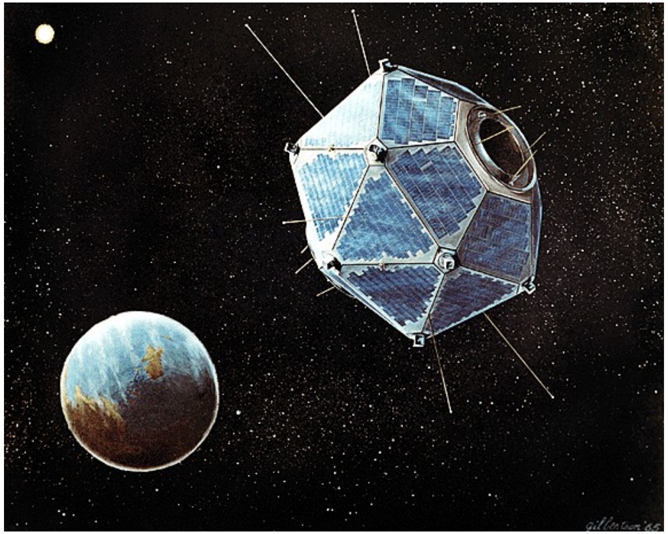
Introduction to Gamma-ray bursts

The COMCUBE instrument and simulated performances

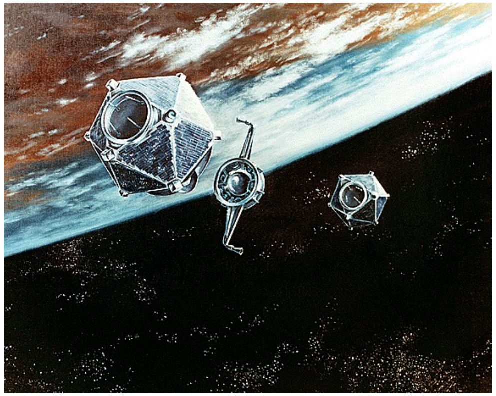
Current status of the COMCUBE prototype

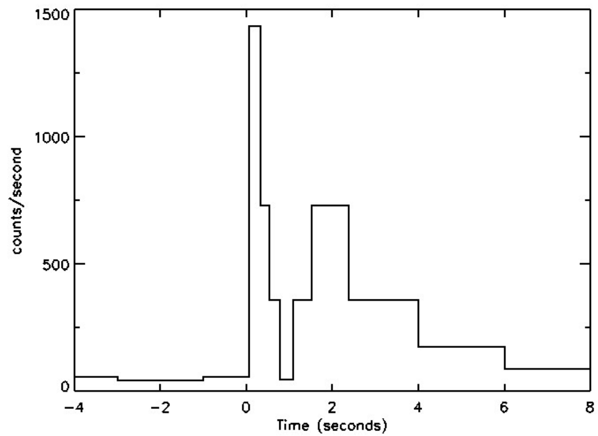
Conclusions and future prospects

# The discovery of GRBs



Vela 5B in Low Earth orbit (top) and Vela 5A and 5B in-orbit separation (bottom), from heasarc.gsfc.nasa.gov

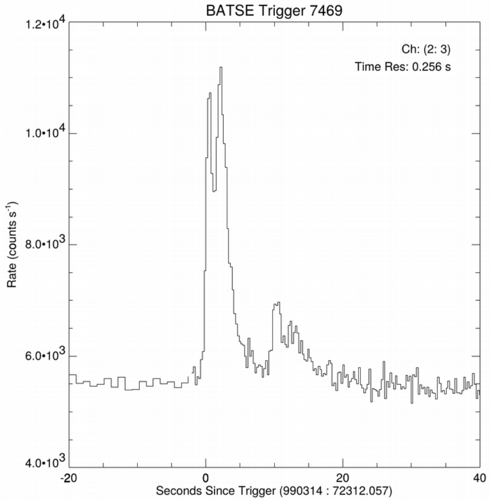


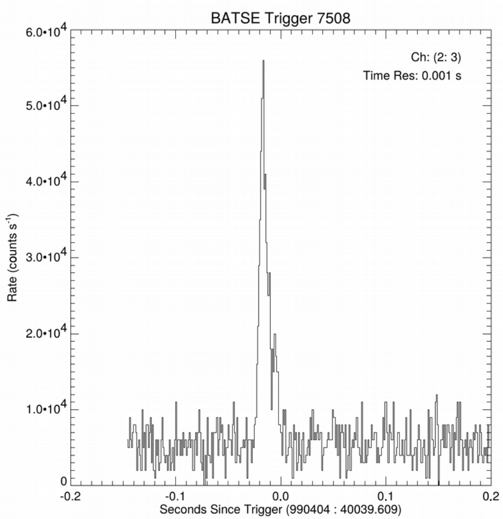


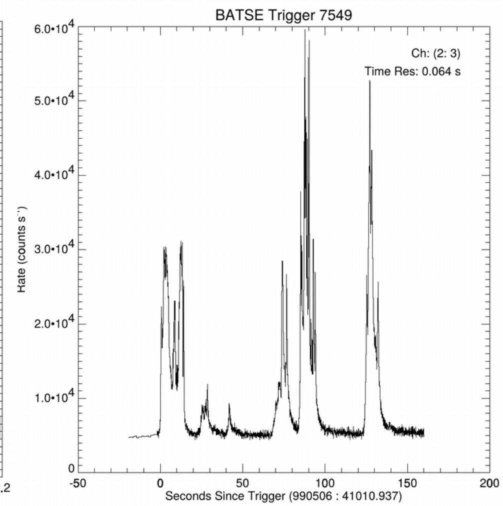

First GRB detected by Vela 4A in 1967

- Vela observed flashes of gamma rays
- Earth and sun were ruled out by geometric arguments

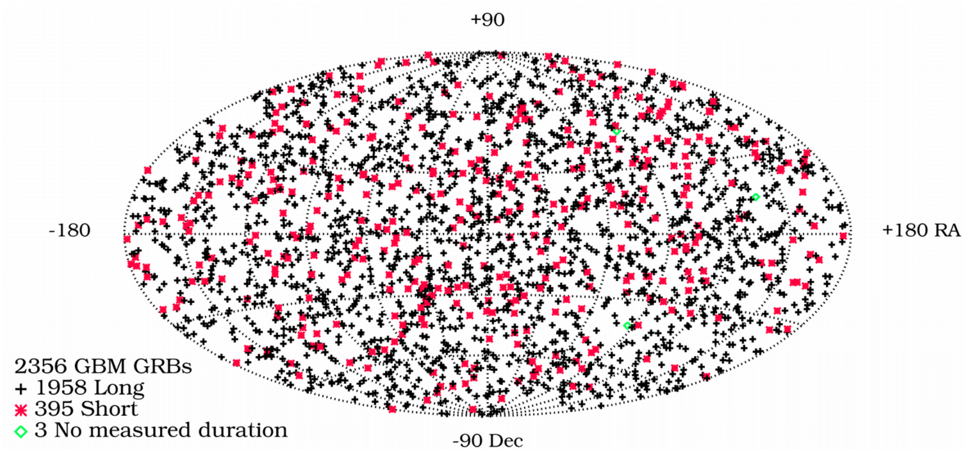
# Observation of GRBs



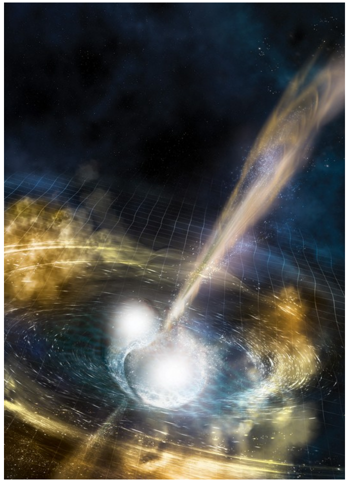

Three examples of GRB lightcurves in the 50-300 keV energy band, from the 4th BATSE GRB Catalog, Pacesias *et al*., ApJS 1999




Sky distribution of GRBs in the GBM 10-year catalog, von Kielin *et al.* (2020)

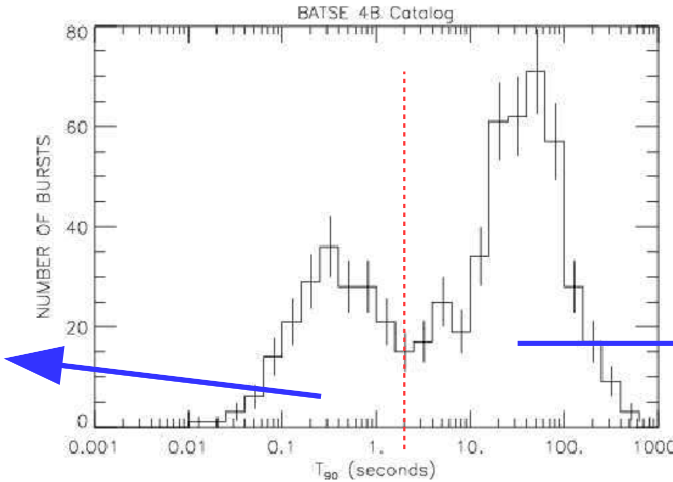
- Quick variability points at physically small sources
- Isotropic distribution points at cosmological distances

# Introduction to GRBs

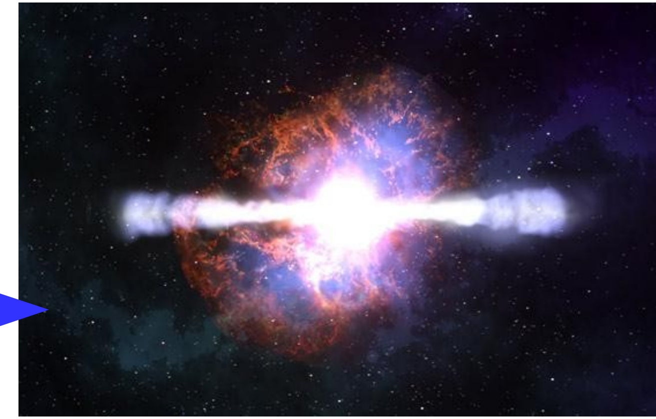


NSF/LIGO/Sonoma state university/A. Simonnet

Binary neutron star mergers
Associated GRB emission peaks typically around 300 keV




GRB duration distribution,
from the 4th BATSE GRB Catalog,
Pacesias *et al.*, ApJS 1999



NASA/GSFC/Dana Berry

Supernovae
Associated GRB emission peaks typically around 100 keV

NASA's Goddard Space Flight Center/S. Wiessinger

Magnetar giant flares could also contribute with a softer spectrum

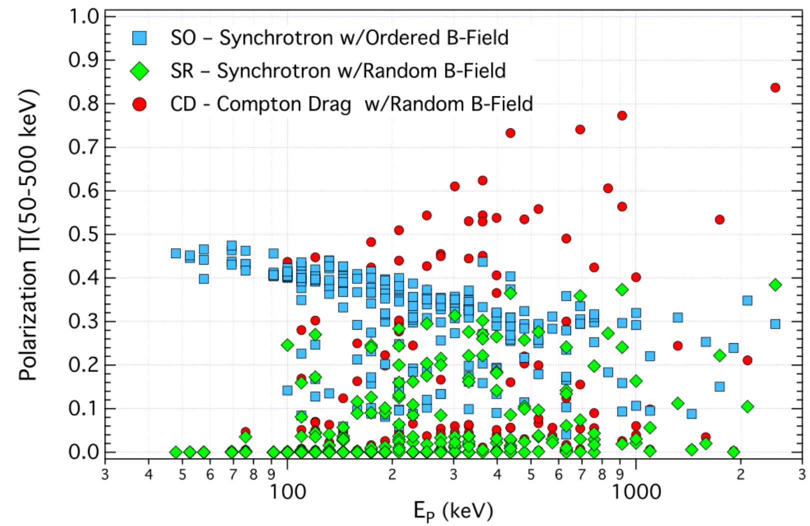
- Gravitationnal collapse of an object/system generates an accretion disk and an ultra-relativistic jet
- The interaction of the jet with the interstellar medium generate an afterglow emission visible in a wide range of energy, from radio waves up to several TeV.

# GRB prompt emission polarization

- Nature and characterization of the progenitors
- Physics of the central engine and jet

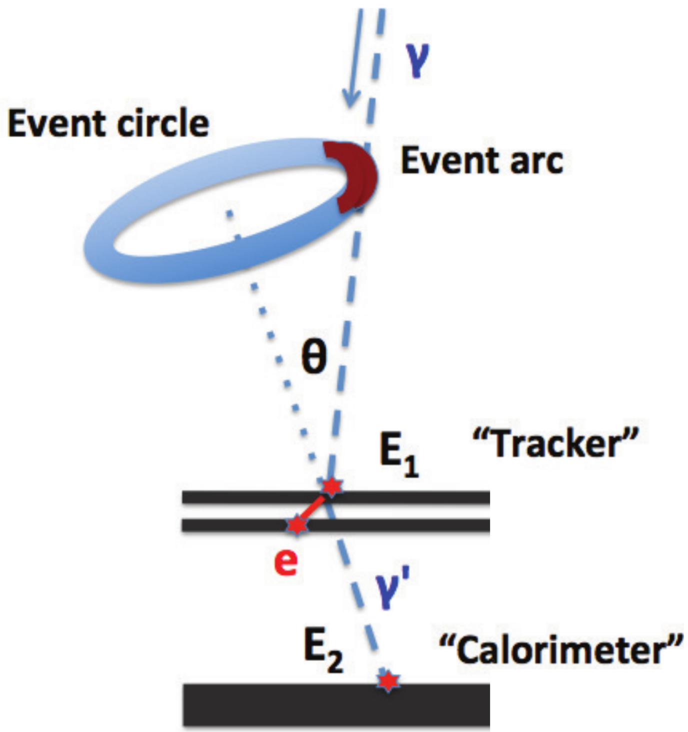
Measuring the polarization will rule out some models. It gives a better understanding of the jet mechanism, that points to the physics of the progenitor.

It also allows searching for Lorentz invariance violations.




Distribution of polarization fractions in the 50-500 keV energy range, predicted for three models as a function of the peak energy, from McConnell 2017, adapted from Toma *et al*. 2009

# Compton telescope




- A Compton telescope reconstructs the energy and direction of an incoming gamma ray by reconstructing a Compton interaction
- With enough gamma rays, we can make an image of the source
- The Compton interaction is sensitive to the linear polarization of incoming gamma rays, and so is the Compton telescope

# Compton polarimetry

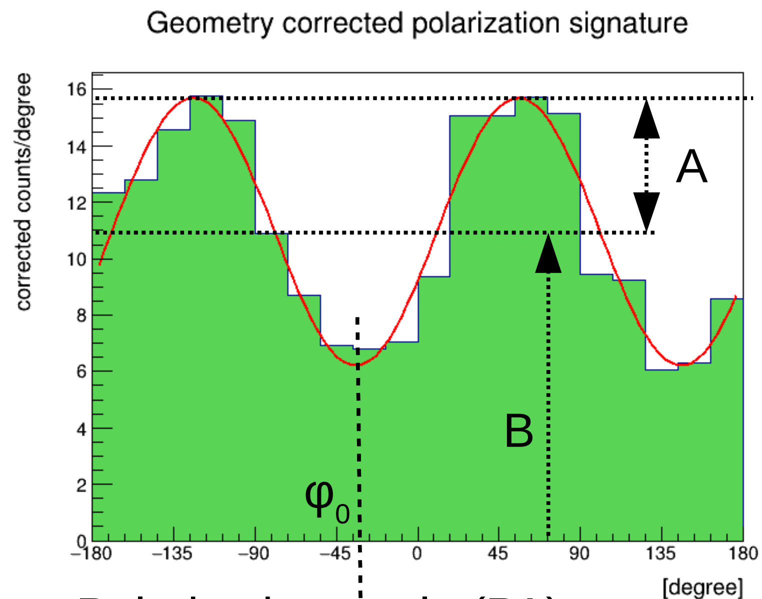
Klein-Nishina differential cross-section for polarized photons:

$$\frac{d\sigma_{KN}}{d\Omega} = \frac{1}{2} r_e^{\,2} \left(\frac{E_\gamma'}{E_\gamma}\right)^2 \left[\frac{E_\gamma'}{E_\gamma} + \frac{E_\gamma}{E_\gamma'} - 2\sin^2\theta \cos^2\phi\right]$$

- The polarization angle is given by a minimum of the fitted modulation
- The polarization fraction Π is given by

$$\Pi = \frac{\mu}{\mu_{100}} \text{ where } \mu = \frac{A}{B}$$

and $\mu_{100} < 1$ the modulation of a 100% polarized source seen by our instrument.

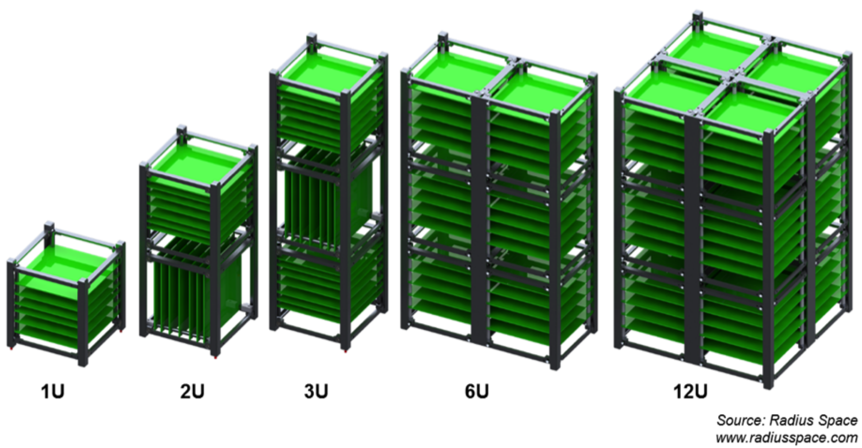


Polarization angle (PA)

# Designing COMCUBE

COMCUBE is a CubeSat mission project

- 1U is one unit of CubeSat
  - 10x10x10 cm³
  - ~ 1.3 kg
- Missions can have larger sizes




The minimum detectable polarization MDP at the 99% confidence level quantifies the sensitivity to linear polarization:

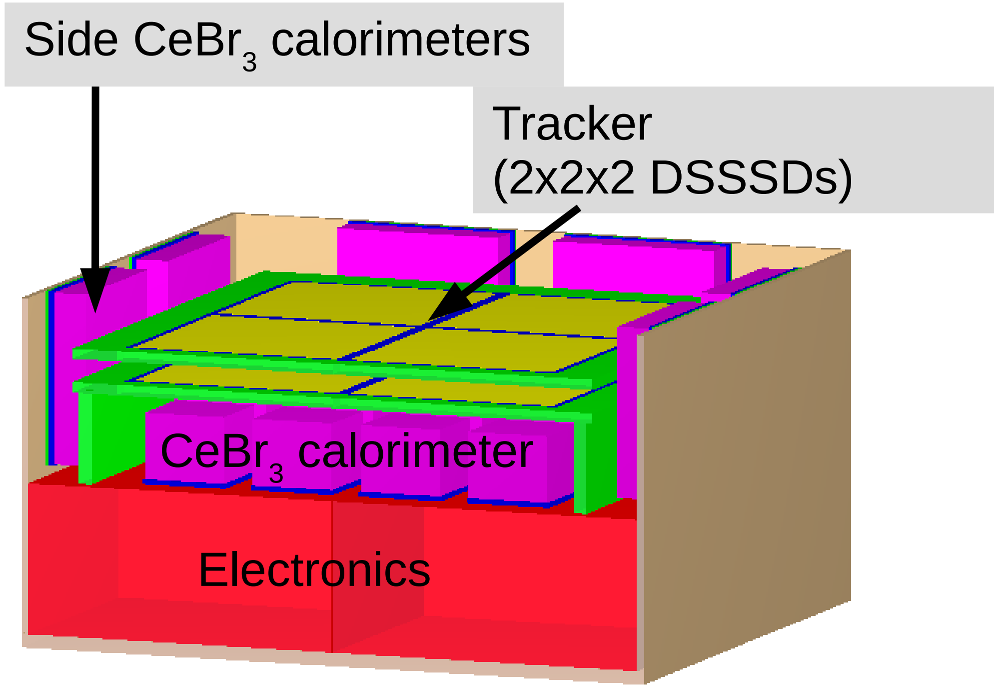
$$MDP_{99\%} = \frac{4.29}{\mu_{100} S} \sqrt{S+B}$$

See e. g. Weisskopf 2010

Where B is the number of triggers due to background and S is the number of photons from the source.

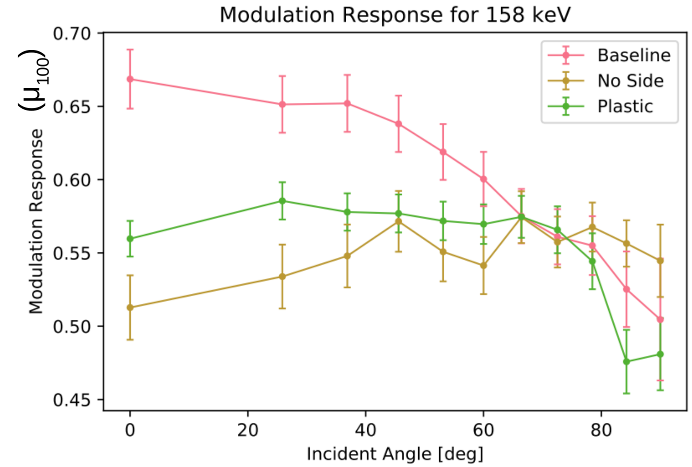
We want to maximize S (proportionnal to the effective area of the instrument) and $\mu_{100}$.

# COMCUBE's scientific payload




Current design
4U instrument (20 x 20 x 10 cm³)
6U spacecraft (30 x 20 x 10 cm³)

This instrument could detect up to 204 long GRBs and 35 short GRBs per year.



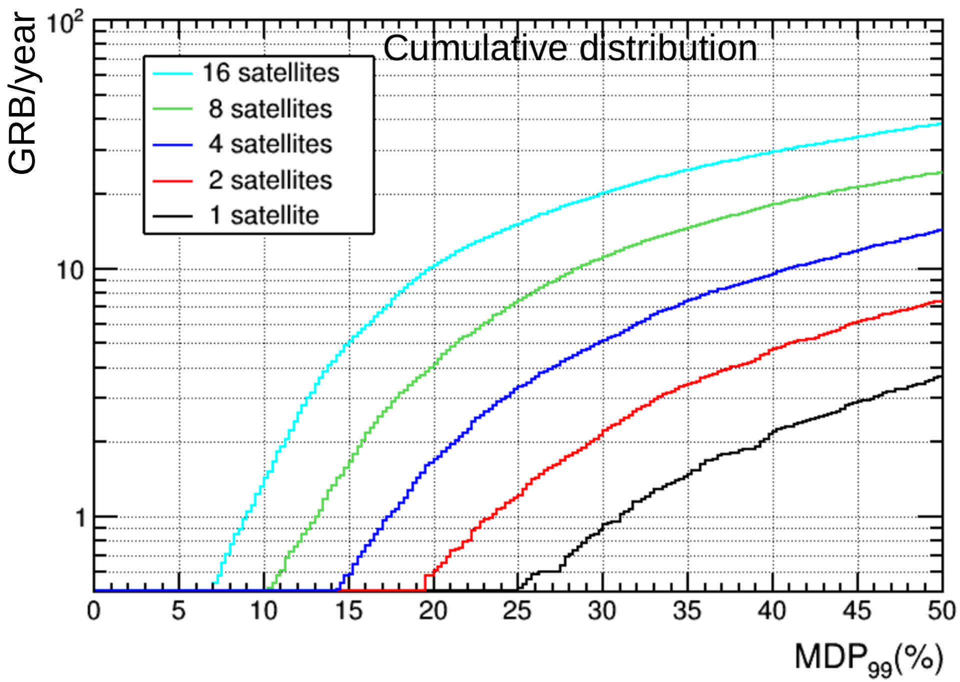
# Preliminary sensitivity to polarization

Simulations using the BATSE or GBM catalog, the MEGAlib background generator and 7 altitude sky bins of equal solid angle.

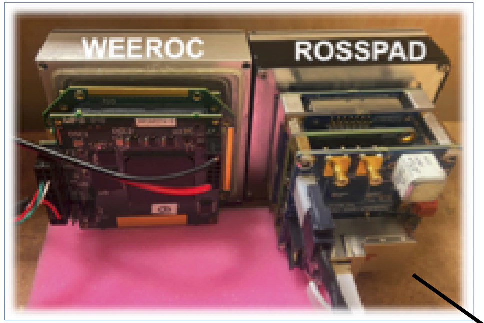
A single spacecraft can detect one GRB per year with $MDP_{99\%} < 31\%$

Observation of the same GRB on several instruments can be combined to perform a more precise analysis.

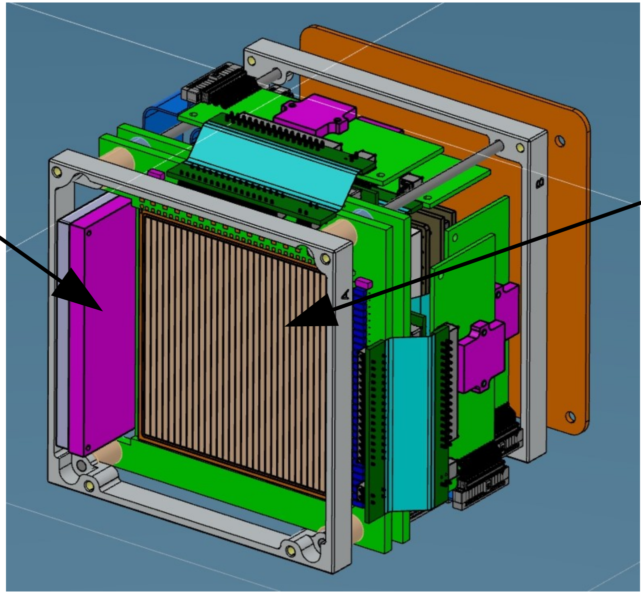
4 satellites in orbit would detect ~5 GRBs/year with a $MDP_{99}$<30 %



# The COMCUBE prototype




A first scientific payload should be tested during a stratospheric balloon flight in 2023.



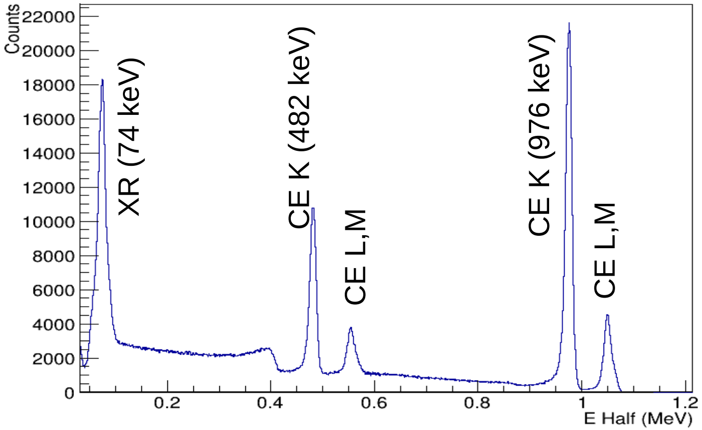
Side detectors and calorimeter are made of $CeBr_3$ monolithic scintillating crystals coupled to SiPM arrays.

Tracker will be composed of two Micron BB7 double-sided silicon stripped detectors (DSSSD) with custom compact PCB.

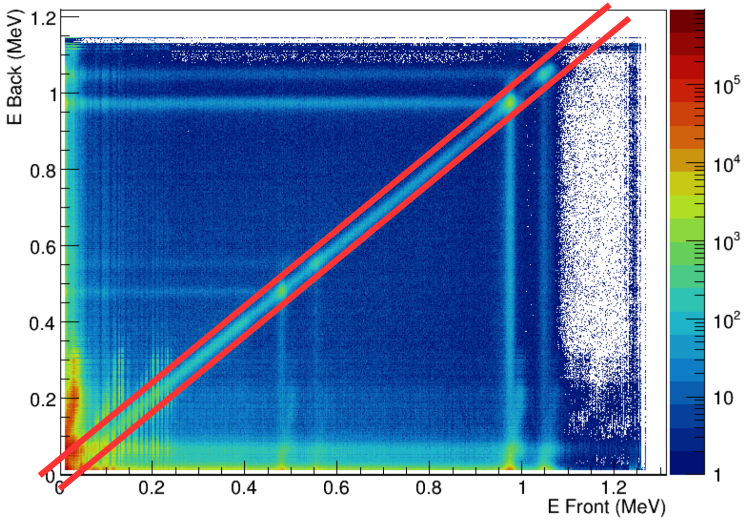
# Detectors for the COMCUBE prototype: The tracker

- 64 x 64 x 1.5 mm³ sensitive volume, 32 strips per side
- Custom low-noise readout electronics based on VATA or IdefX ASICs
- 12 keV FWHM energy resolution
- 30 keV low-energy threshold

$^{207}$Bi calibration spectrum



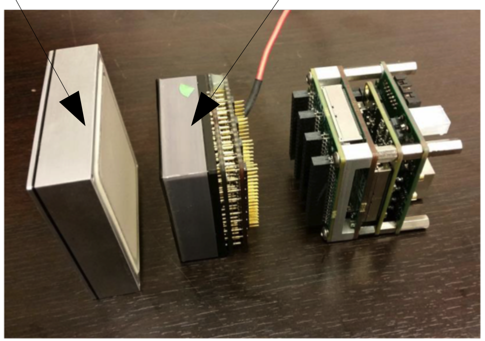

Front-Back energy correlation

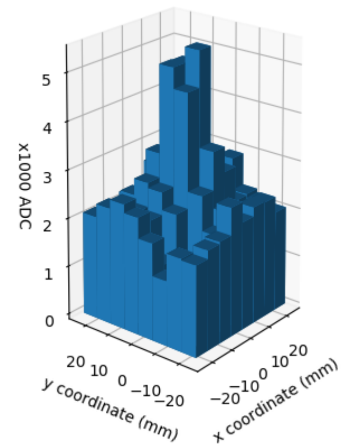


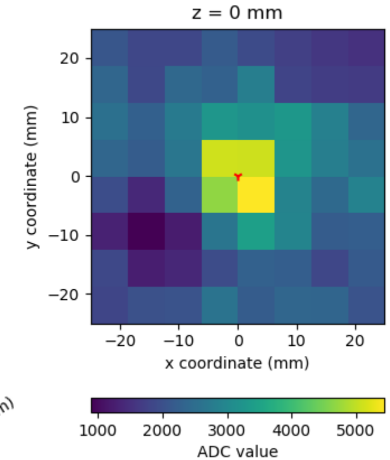
# Detectors for the COMCUBE prototype: The calorimeter

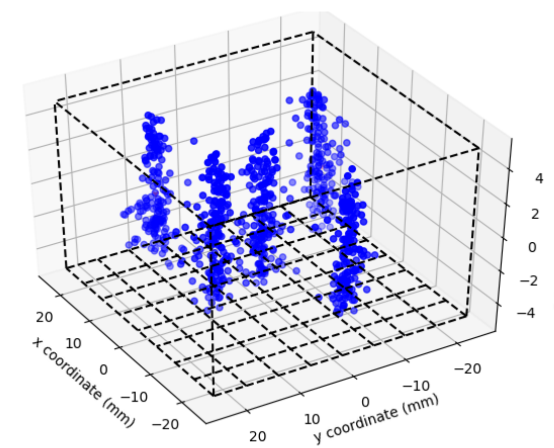
$CeBr_3$ monolithic scintillator $51x51x10\ mm^3$

64-channel multi-anode PMT, will be replaced by an SiPM array





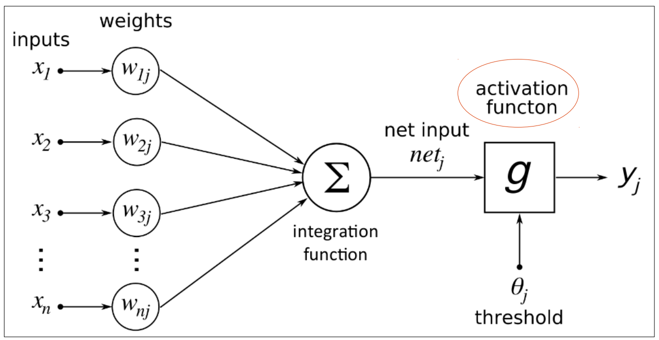



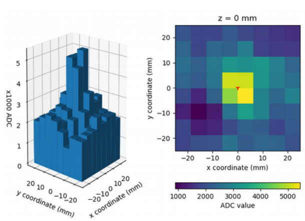

- Monolithic $CeBr_3$ scintillator read by a pixelated photo-detector
- 3D position reconstruction is based on machine learning algorithms (see Laviron *et al*, 2021)

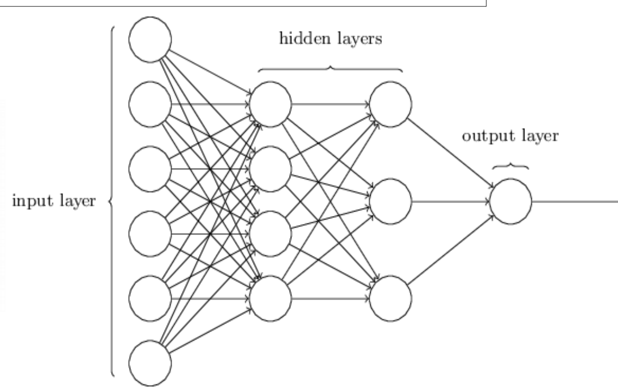
# Artificial neural networks for calorimeter modules data analysis

- We use multi-layer perceptrons
- How many layers and how many neurons do we need ?

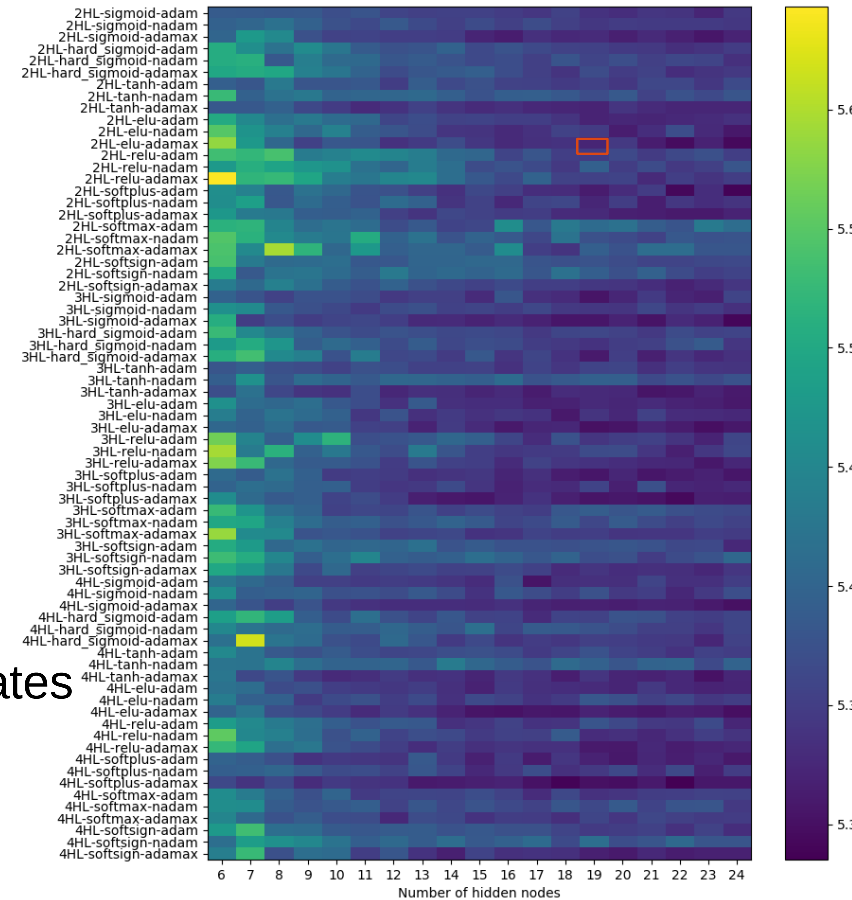



A single neuron

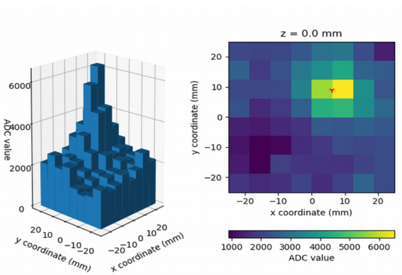



(x,y) coordinates
z coordinate

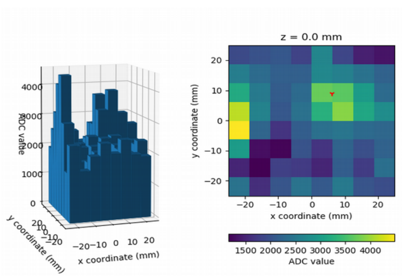


# Morphology of the scintillation light distribution

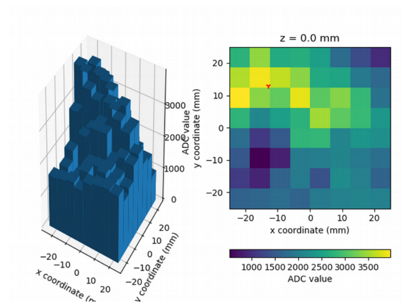



1 peak

2D rms position resolution : 2.6 mm




2 peak



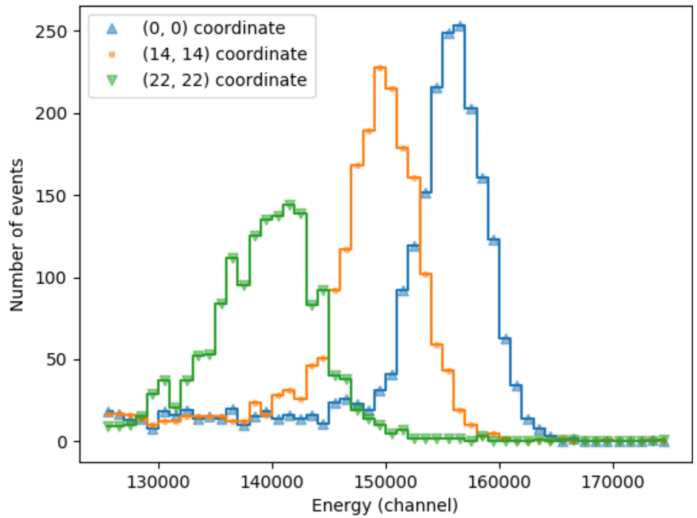

>2 peaks

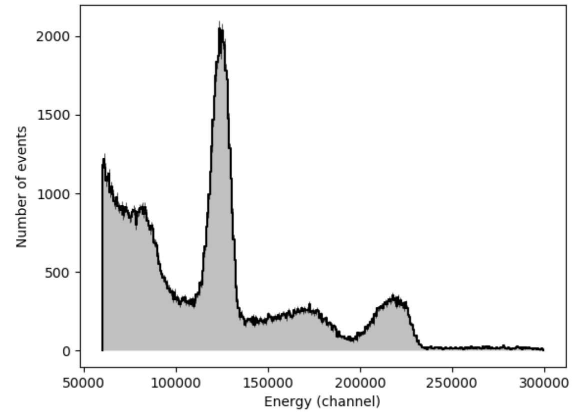
< 10 % of all events at 662 keV

2D rms position resolution : 3.9 mm

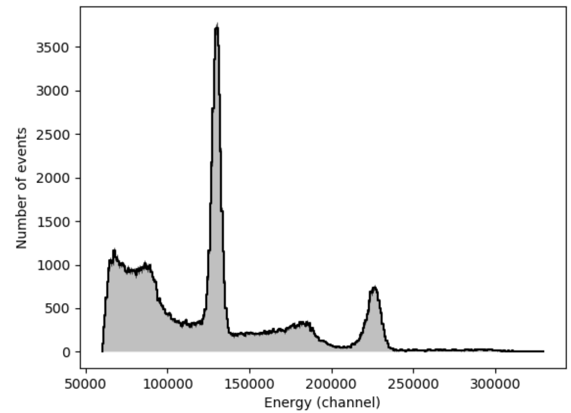
# Energy reconstruction

- Detector spectral response changes with the position of interaction



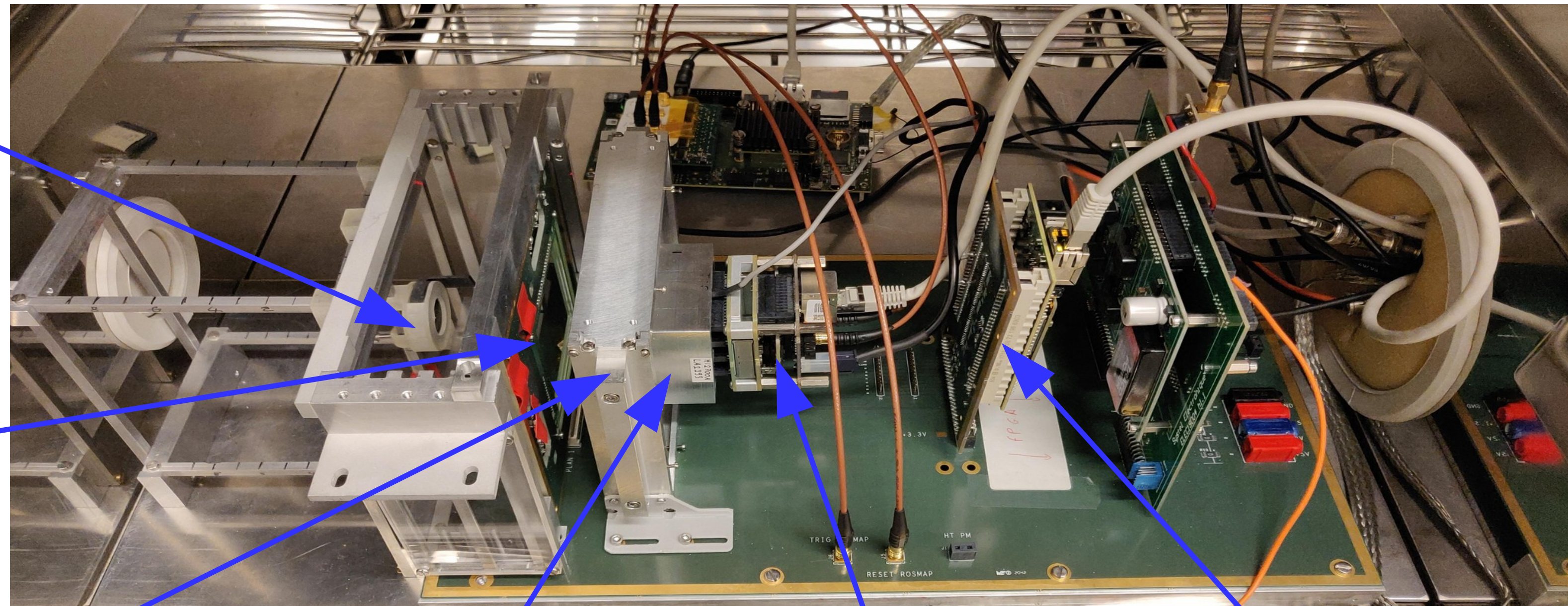




Before correction: 8.3 % FWHM at 662 keV




After correction: 4.7 % FWHM at 662 keV

# The COMCUBE prototype: Current status



Source holder

DSSSD
and its
FEE

$CeBr_3$
crystal
(inside)

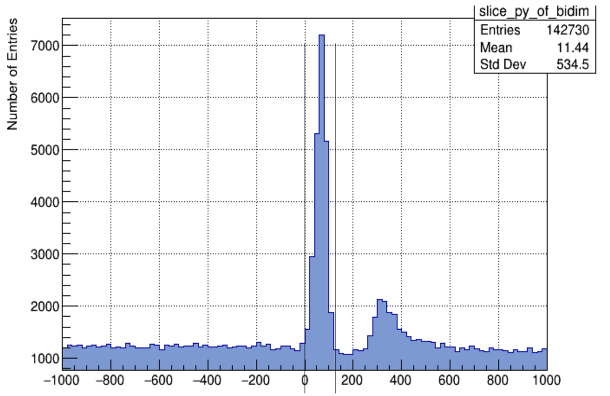
pixelated photo-sensor
(here a multi-anode PMT)

calorimeter
FEE and BEE

DSSSD BEE and
coincidence electronics

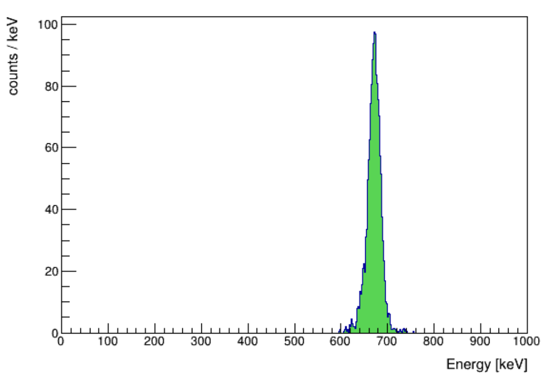
# Data acquired in coïncidence

Time difference histogram



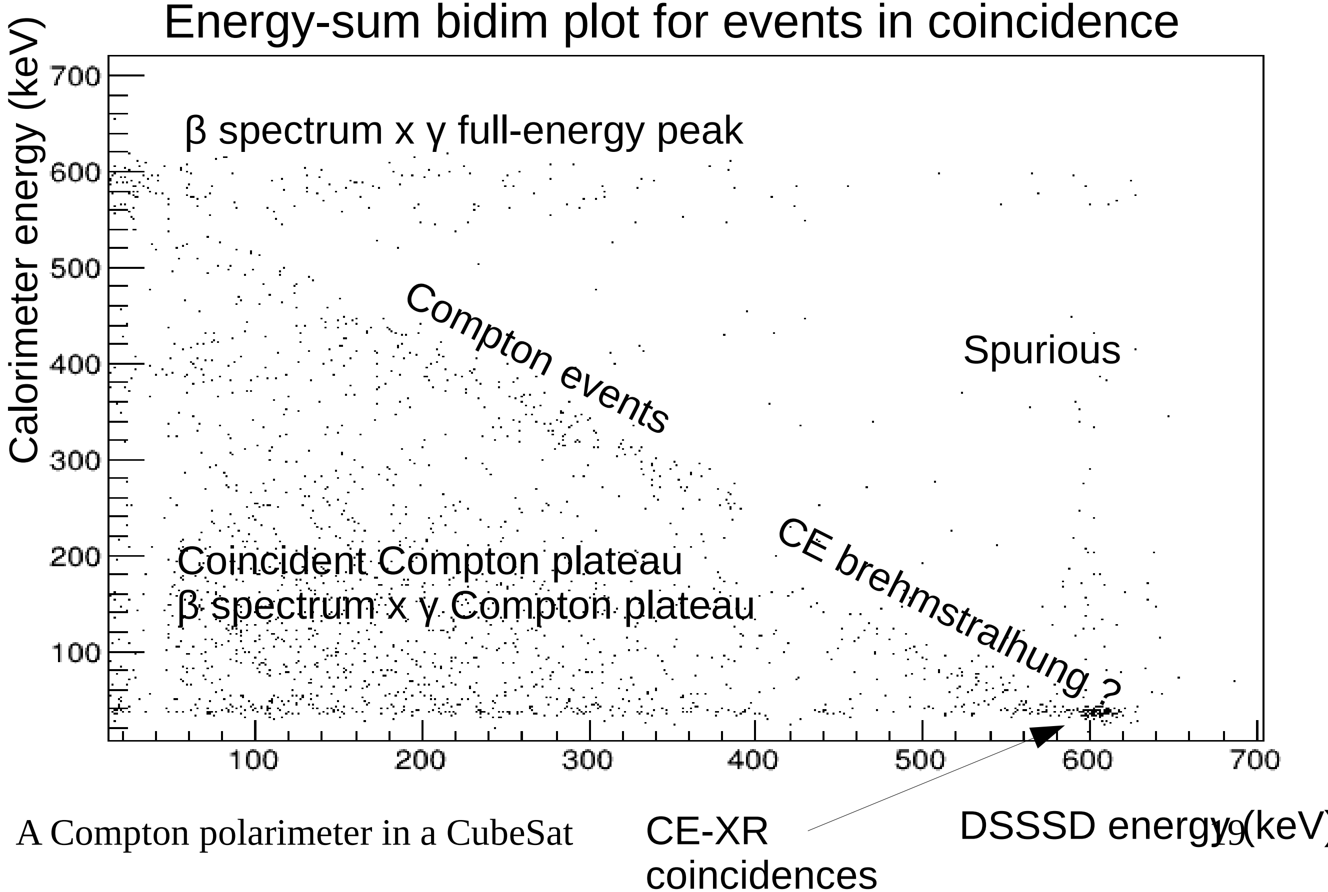

1 μs coincidence window $\Delta t / 10\,\mathrm{ns}$

Energy spectrum



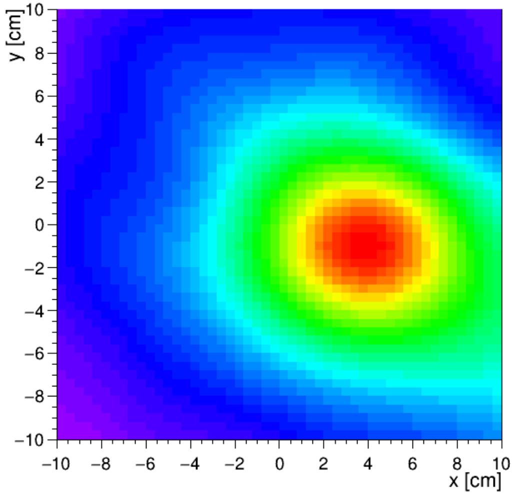

We use a $^{137}$Cs β-γ radioactive source

Energy-sum bidim plot for events in coincidence

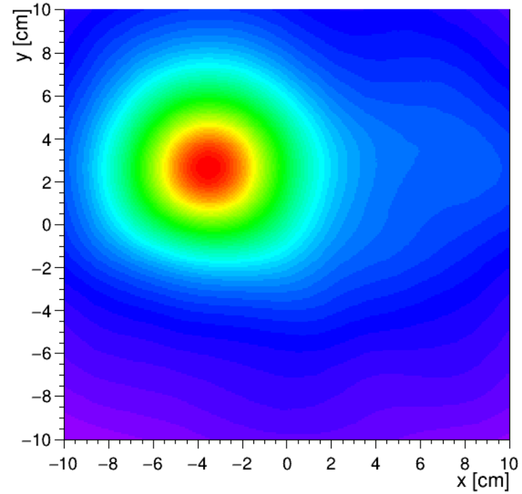


# COMCUBE’s first gamma-ray images

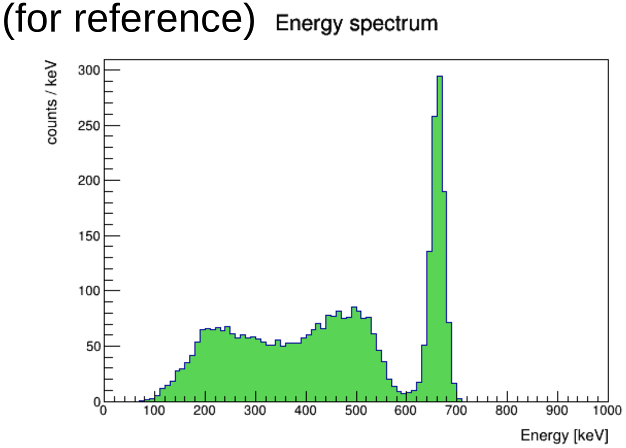
x, y = (36, -11) mm



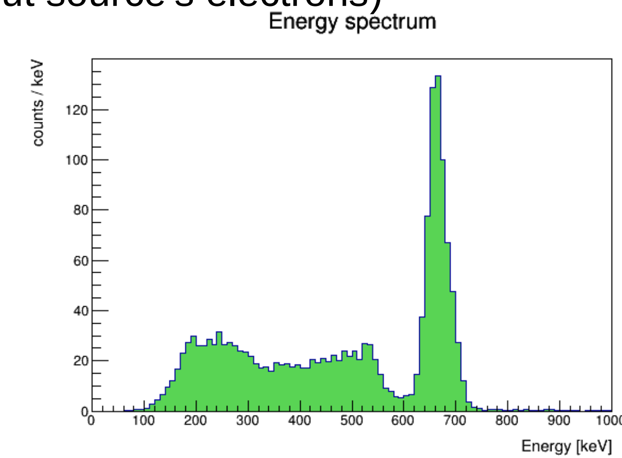

x, y = (-36, 23) mm




Simulation (for reference)

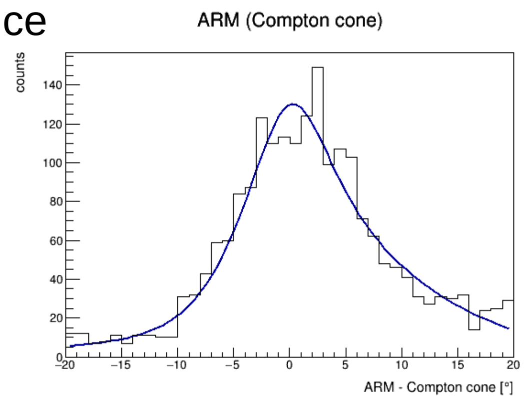



Data (without source’s electrons)

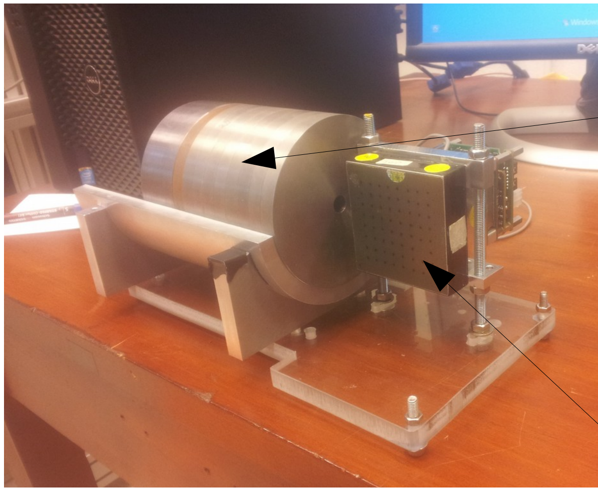



First data with a $^{137}$Cs source at a finite distance

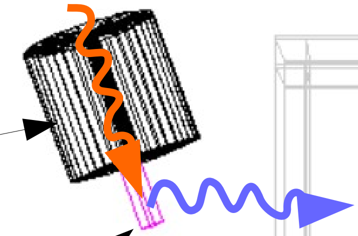
- Energy resolution: 5.68 % FWHM at 662 keV
- ARM FWHM ≈ 12°
- Source position is well reconstructed

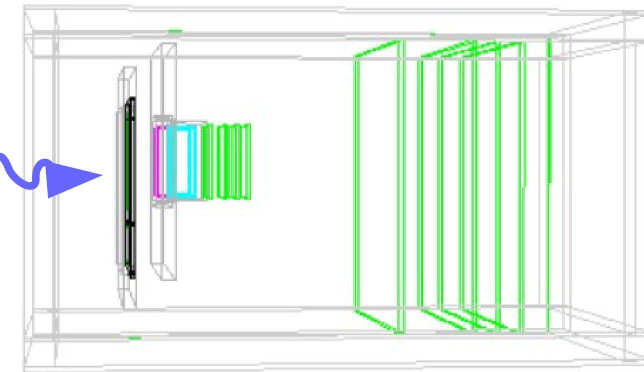


# Next experiment with a polarized source



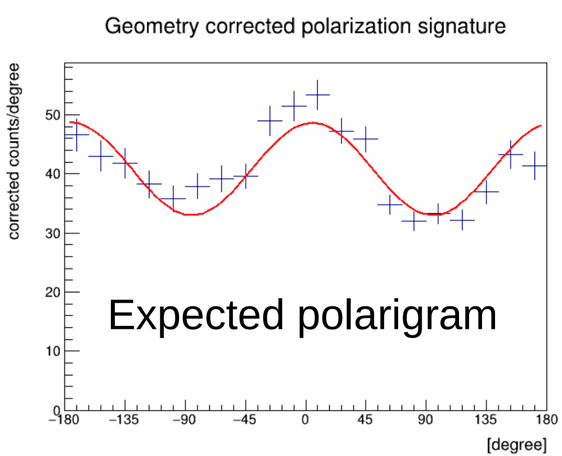
Collimator

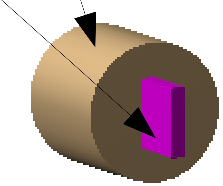


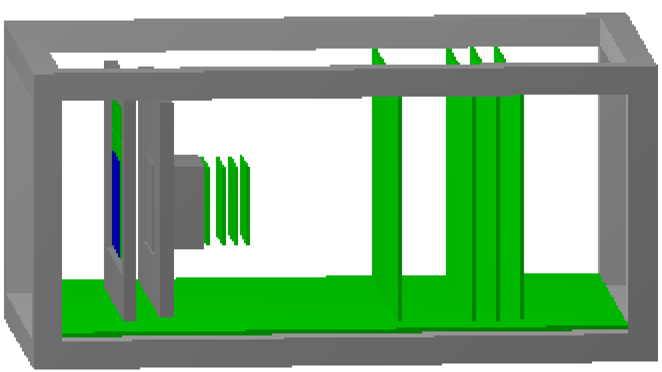


Initial 662 keV gamma-ray
Diffused, ≈60% polarised, 356 keV gamma-ray

Event-tagging detector





# Conclusion

- COMCUBE is a constellation of cubesats that will be able to detect several GRBs per week and measure the polarization of several GRB prompt emissions per year

- Prototype testing in laboratory with radioactive sources gave results in reasonable agreement with the simulation and polarized gamma ray sources are also scheduled

# Collaborators

I. Cojocari[2], N. de Séréville[1], G. Fernandez[3], C. Hamadache[1], L. Hanlon[4], P. Laurent[2], J. Lommler[5], S. McBreen[4], A. Morselli[3], D. Murphy[4], H. Neves[6], U. Oberlack[5], R. Silva[6], V. Tatischeff[1], A. Ulyanov[4], V. Vitale[3], P. von Ballmoos[7]

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(5) Johannes Gutenberg Univ., Mainz, Germany

(6) LIP, Coimbra, Portugal

(7) IRAP, Toulouse, France

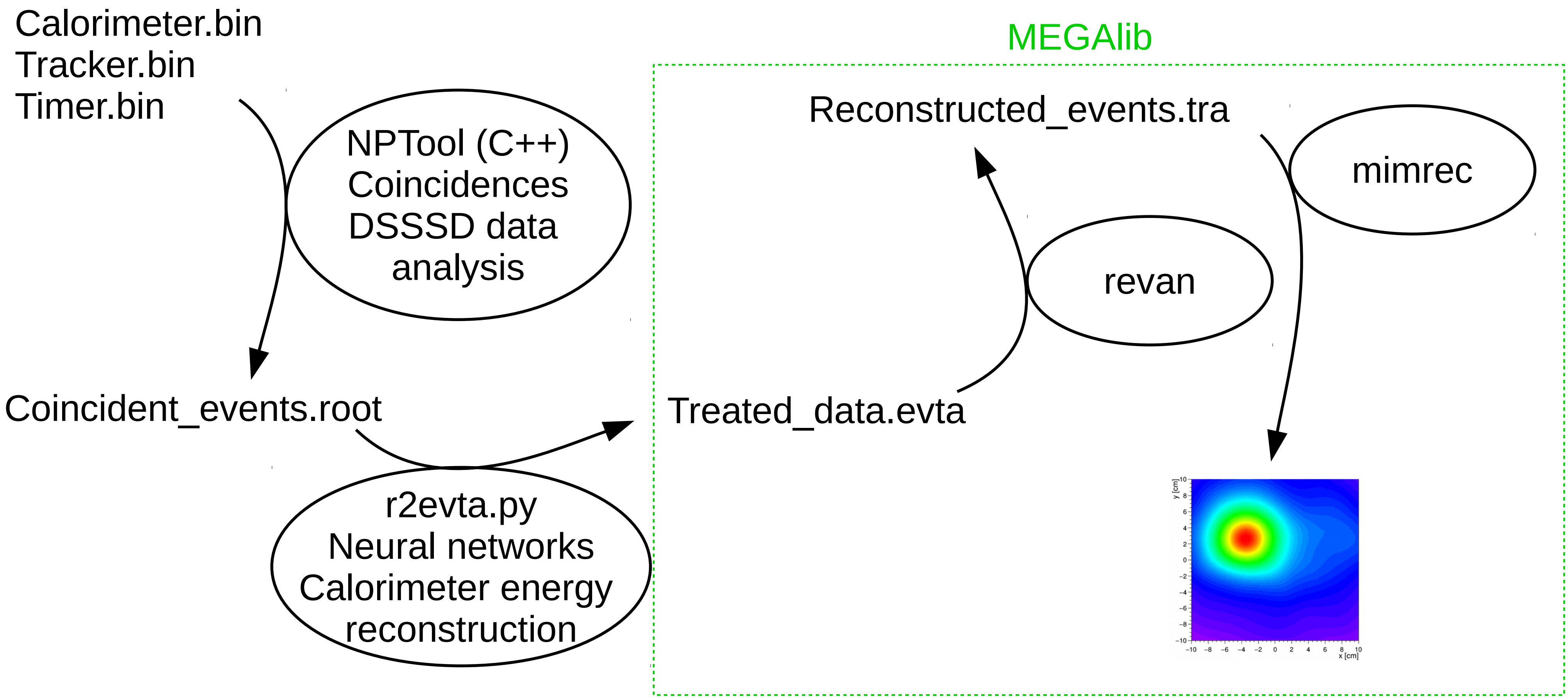
# MEGAlib

MEGAlib is a set of software tools which are designed to simulate and analyze data of gamma-ray detectors, with a specialization on Compton telescopes [Zoglauer *et al.* NewAR 50 (7-8), 2006]

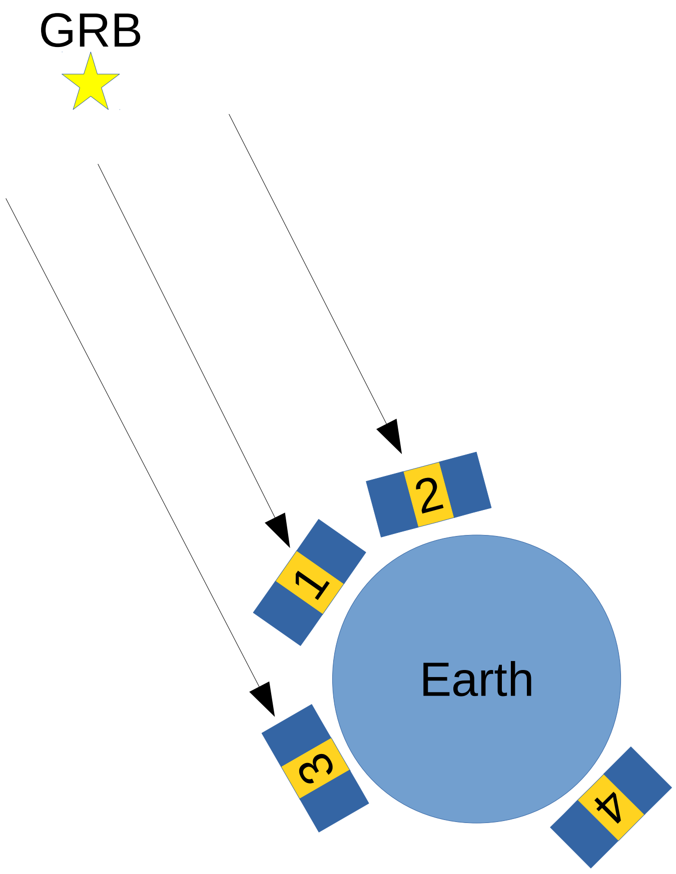
Geometry definition and simulations are based on Geant4 v. 10.02, plots are made using Root 6

We used MEGAlib 2.34 (former release version), then we updated to MEGAlib 3.01 (current release version)

# Prototype current data pipeline



# Polarimetry with several spacecrafts

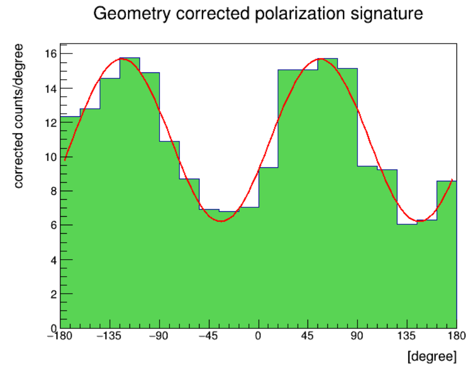


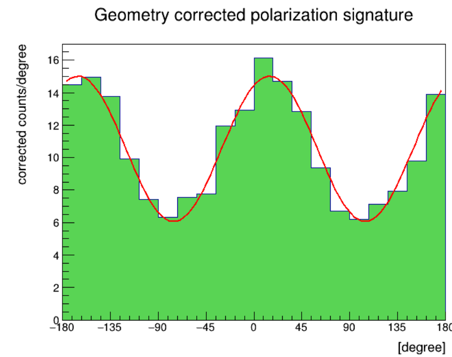

Several instruments see the same source

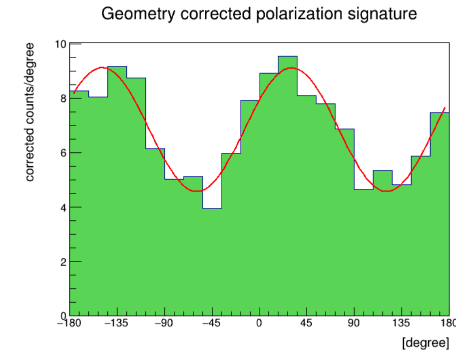
Each instrument sees the source at a position (θ, φ) in the sky and with a certain angle of rotation around the source direction (ψ, analogous to the polarization angle)

These **three** parameters define the satellite orientation

# Polarigrams for different satellite orientations







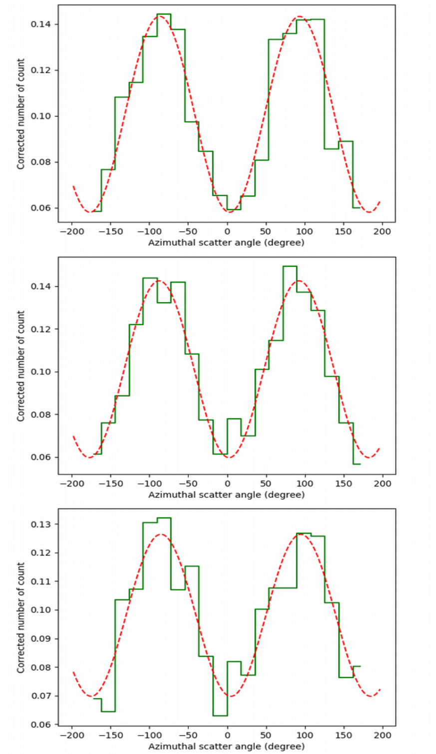

| Satellite | 1 | 2 | 3 |
|---|---|---|---|
| orientation (θ, φ, ψ) | (11°, -17°, 126°) | (35°, 51°, 147°) | (96°, 25°, 67°) |
| $\mu_{100}$ | 0.433 ± 0.098 | 0.425 ± 0.100 | 0.333 ± 0.122 |
| PA [°] | 146 ± 6 | 105 ± 6 | 121 ± 10 |

Both the polarization angle and the maximum modulation factor $\mu_{100}$ vary from one satellite orientation to another.

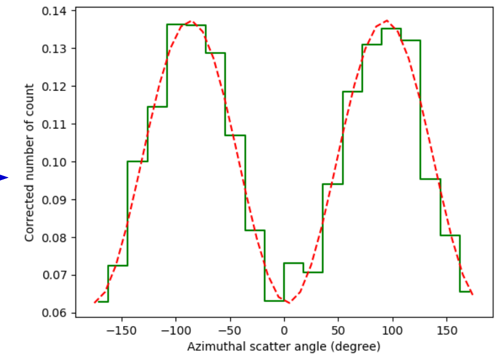
# Adding up polarigrams

Orientation correction must be done for each gamma ray. For that purpose, MEGAlib’s polarization analysis algorithm was re-implemented in python.

1
2
3




sum each bin



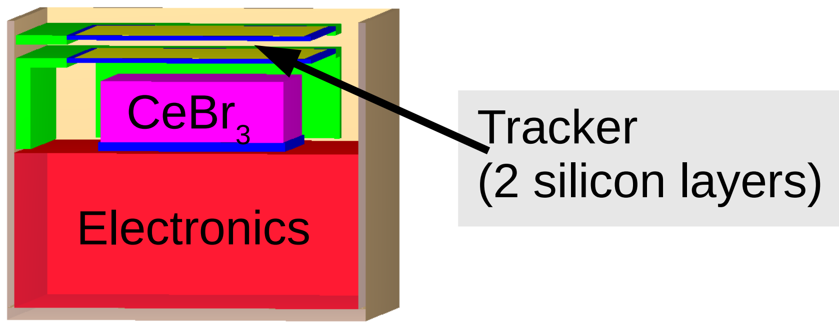

$\mu_{100}$ = 0.375 ± 0.014 ; PA = 3.5 ± 1.1°

The number of photons used is the sum of that of the summed distributions

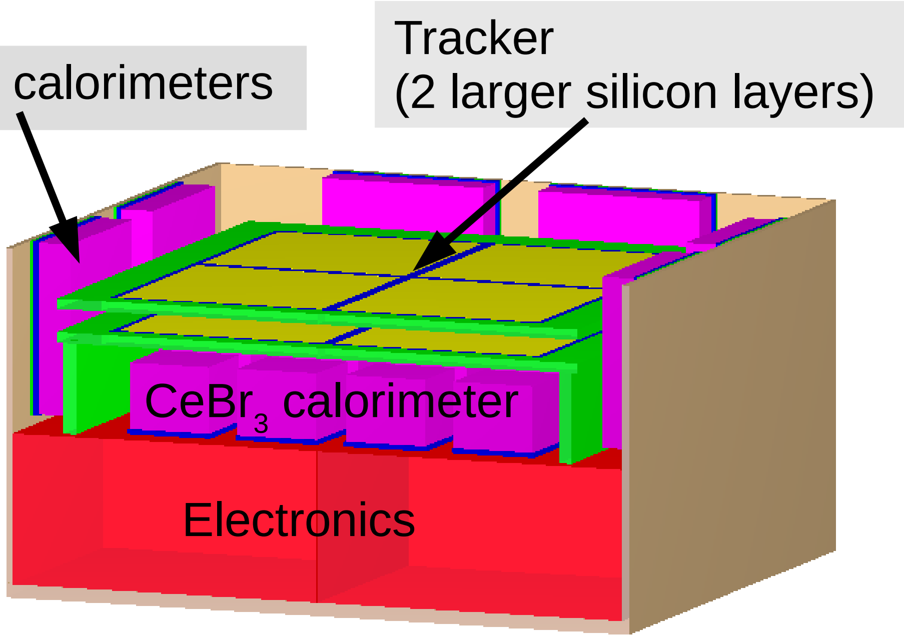
The modulation factor is the weighted mean of the modulation factors of the distributions summed

# Design of the scientific payload

Simulations were performed using MEGAlib (see [megalibtoolkit.com](megalibtoolkit.com)), a software toolkit based on Geant4




First idea (1U instrument)




Current design (4U instrument in a 6U spacecraft)

| Mass model | First | Current |
|---|---|---|
| Effective area 30° off-axis at 300 keV | 0.17 cm² | 8 cm² |
| Modulation factor $\mu_{100}$ on-axis | 0.44 | 0.43 |