Detection And Study of Medium-Low Energy Gamma-Rays With Novel Spaceborn Detectors

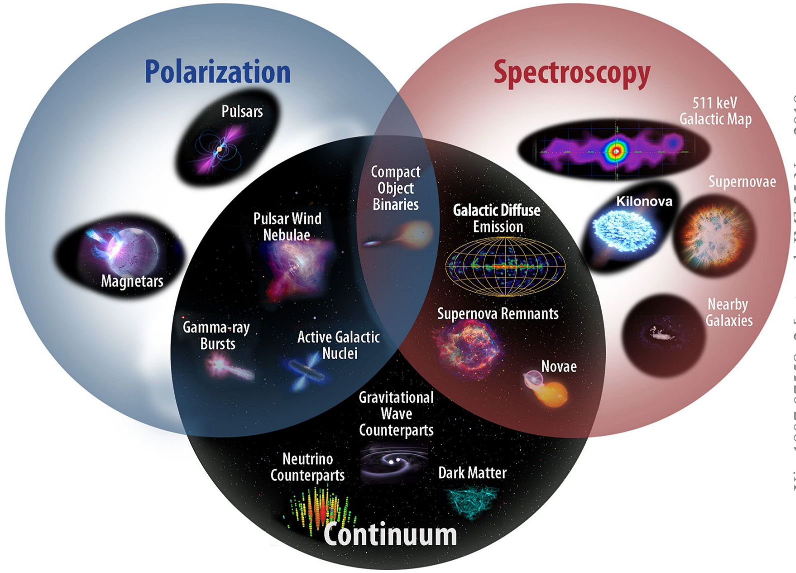
Ph.D. candidate: Aleksei Smirnov
Advisor: Felicia Carla Tiziana Barbato

20/10/2023

THE MEDIUM/LOW ENERGY GAMMA RANGE

Wonderful experiments and results in the hard X-ray/low energy gamma ray range (**E ~10-200 keV**) and high energy gamma rays range (**E > 1 GeV**)

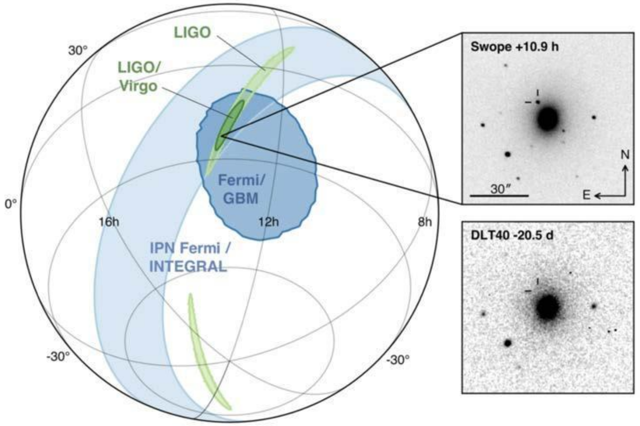
Medium energies still under-explored (**E ~ MeV**)



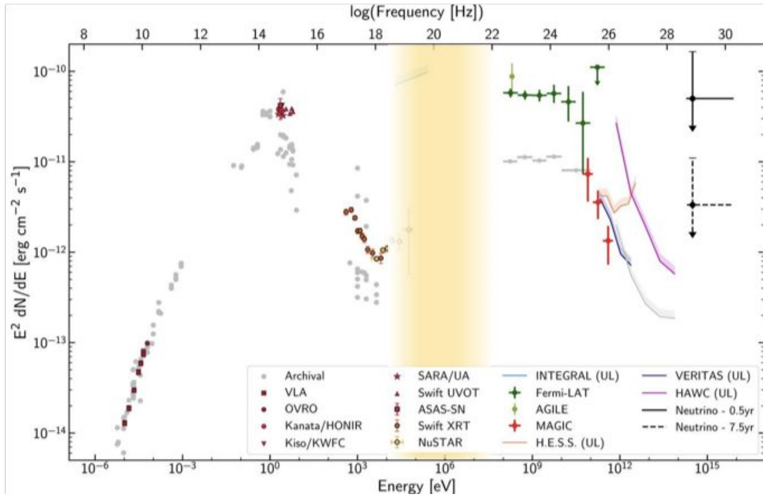
arXiv:1907.07558v2 [astro-ph.IM] 25 Nov 2019

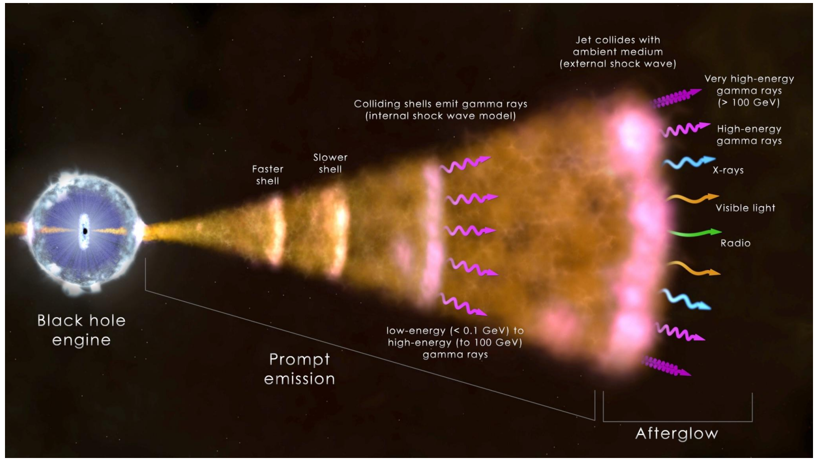
Powerful probes for the extreme Universe

GW170817



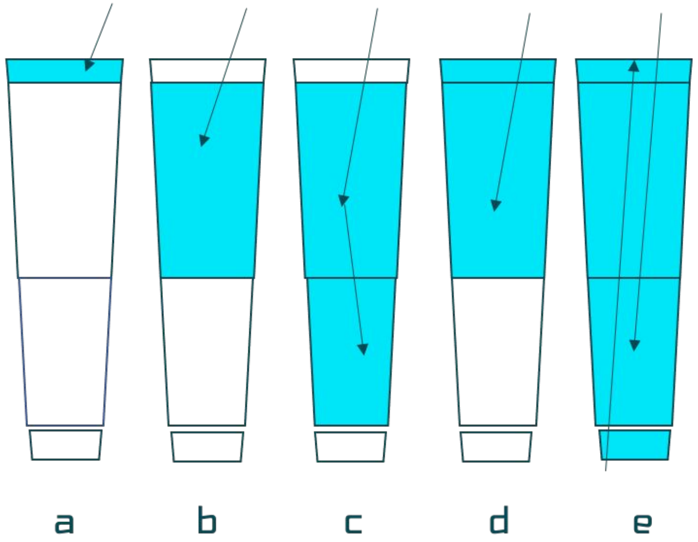
TXS 0506+056



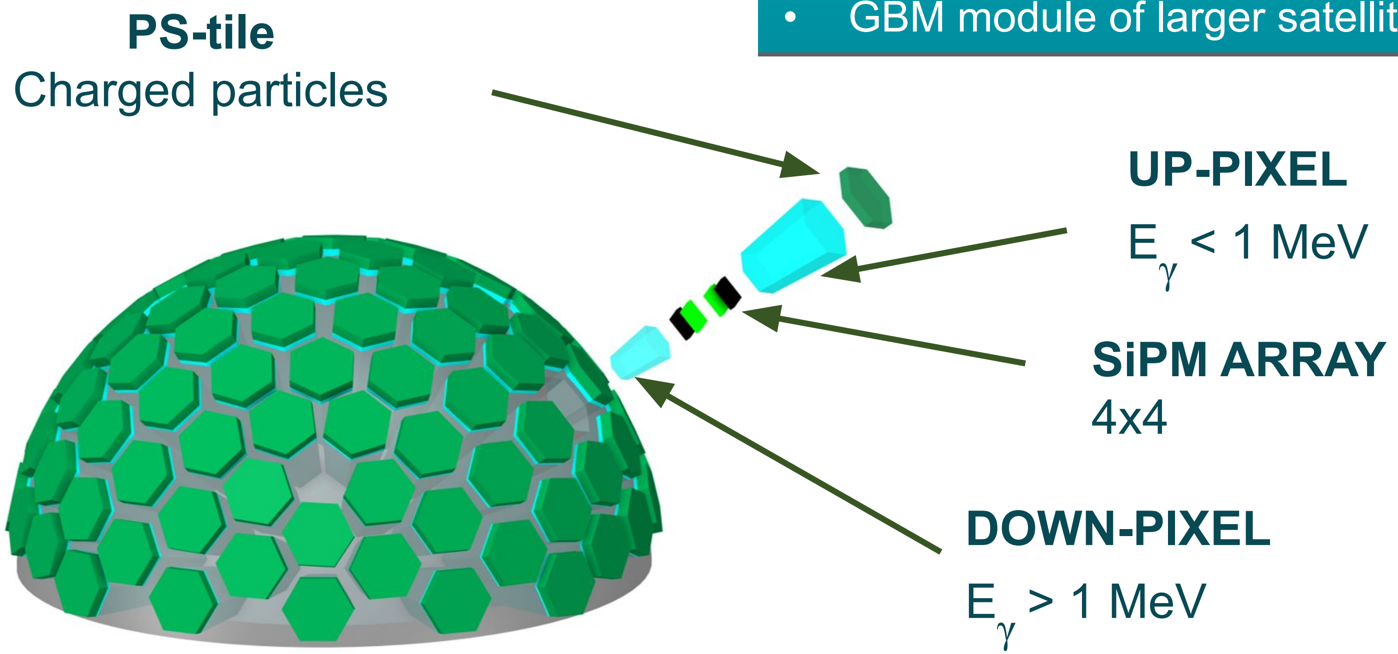


THE CRYSTAL EYE METHOD

Radius: 14.5 cm
Energy range: 10 keV - 30 MeV
Material: LYSO/GAGG
Photodetectors: SiPM
FOV: 6 sr
Effective area: ~ 600 cm^2 @ 1 MeV



A. Down-going hard X-ray
B. Down-going LE γ-ray
C. Down-going ME γ-ray
D. Down-going LE charged particle
E. HE charged particle



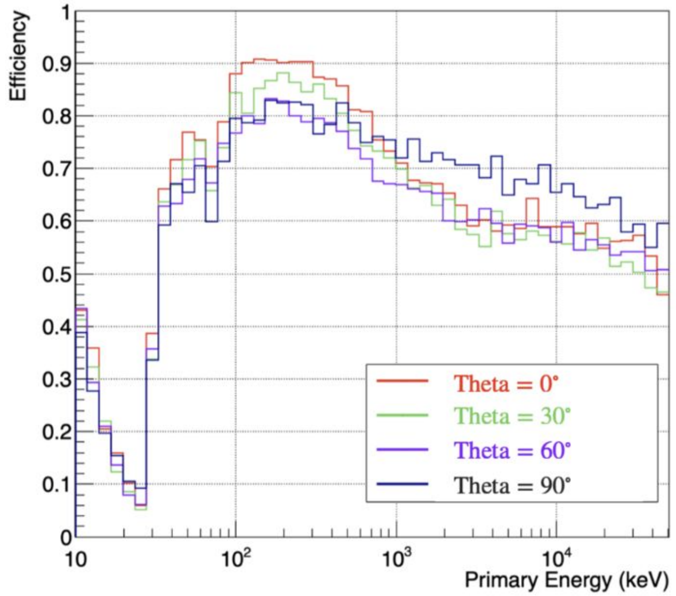
BORN TO BE:

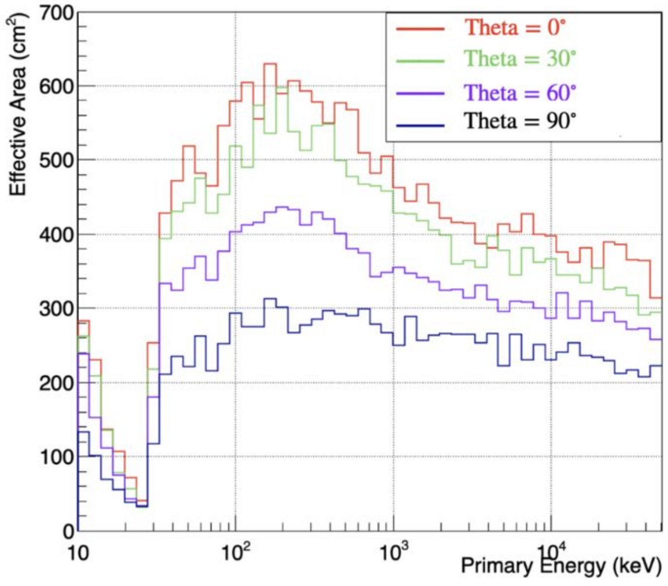
- Free-flyer
- Onboard of space stations
- GBM module of larger satellites

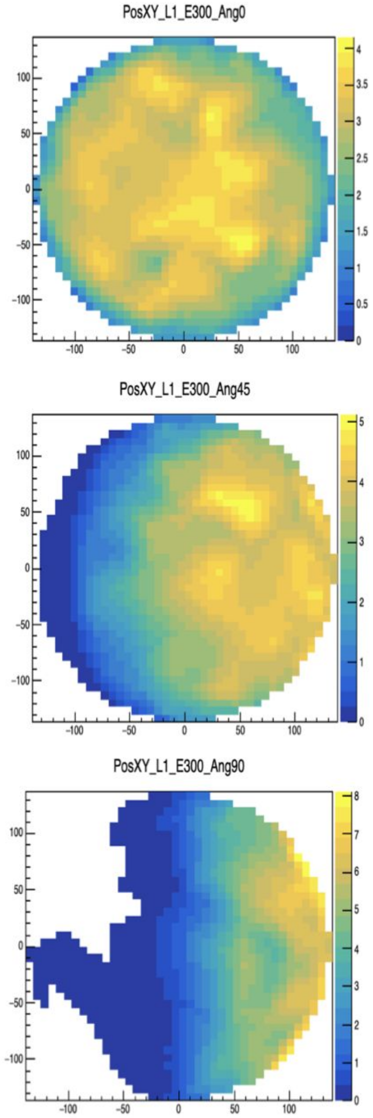
SMART CONFIGURATION:

- Compactness
- Symmetry
- Thermal protection of the SiPMs

FULL DETECTOR SIMULATIONS: CRYSTAL EYE PERFOMANCE



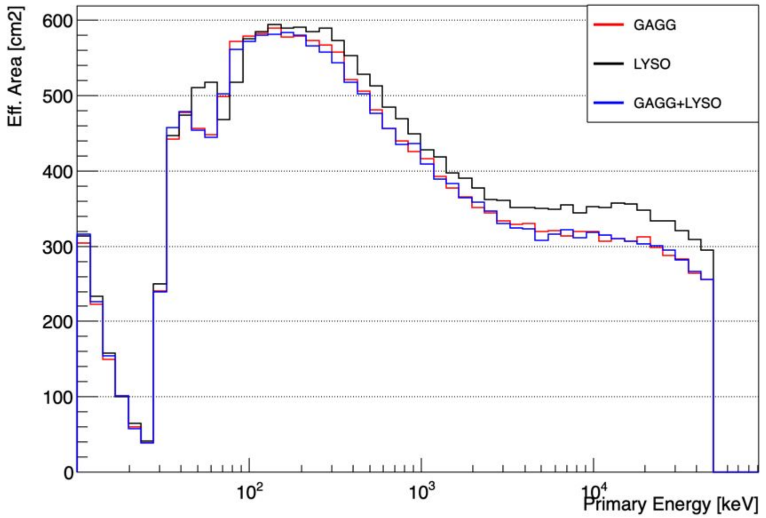


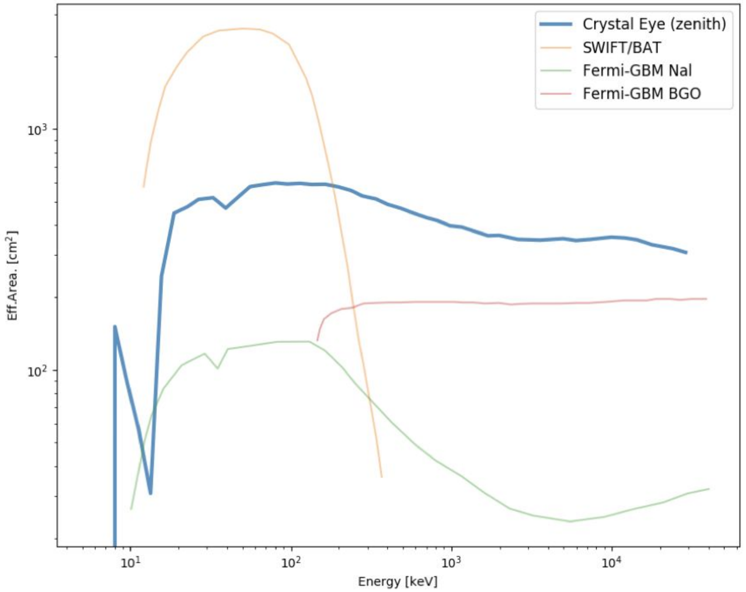


0°

45°

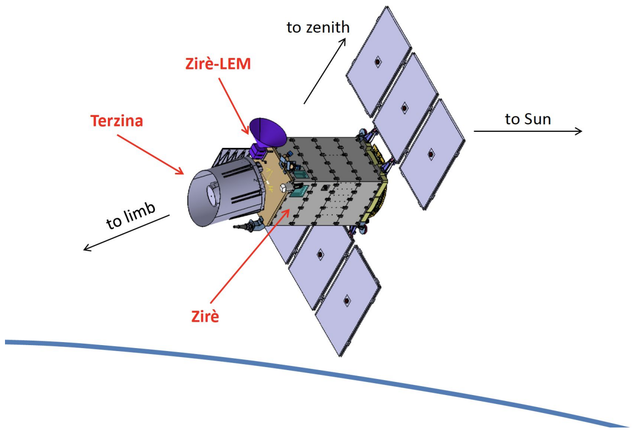
90°





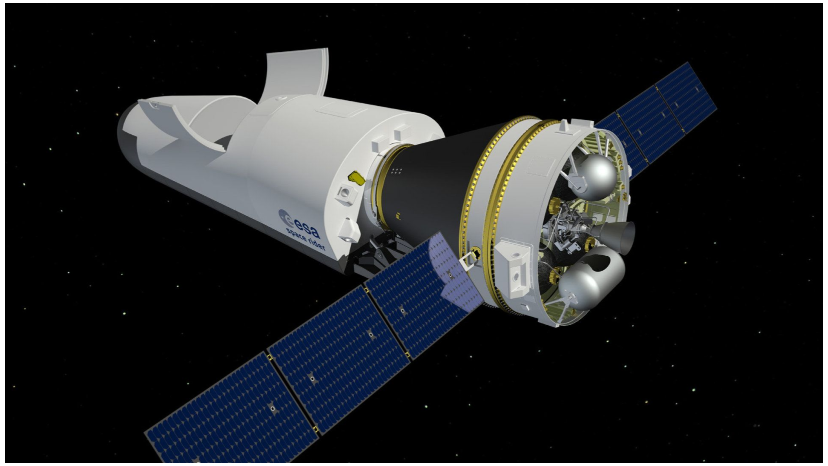
THE GAMMA-RAY MISSION

NUSES/Zirè



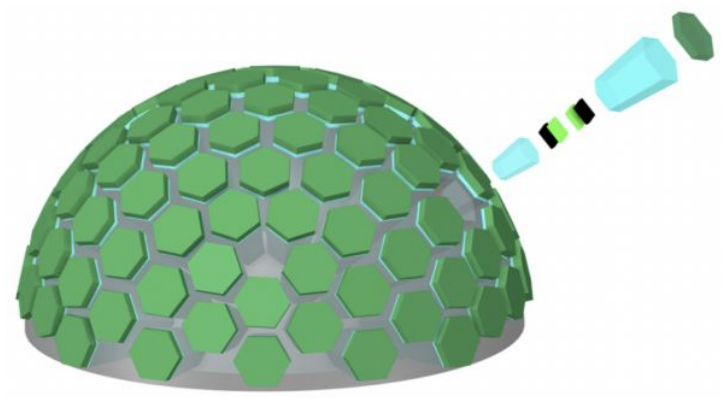
- Different crystal material check
- Test beam

Space Rider/WINK



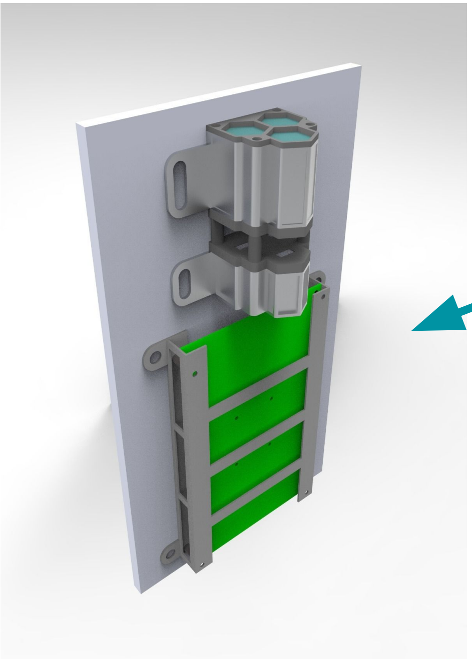
- Debugging & characterization
- Simulations

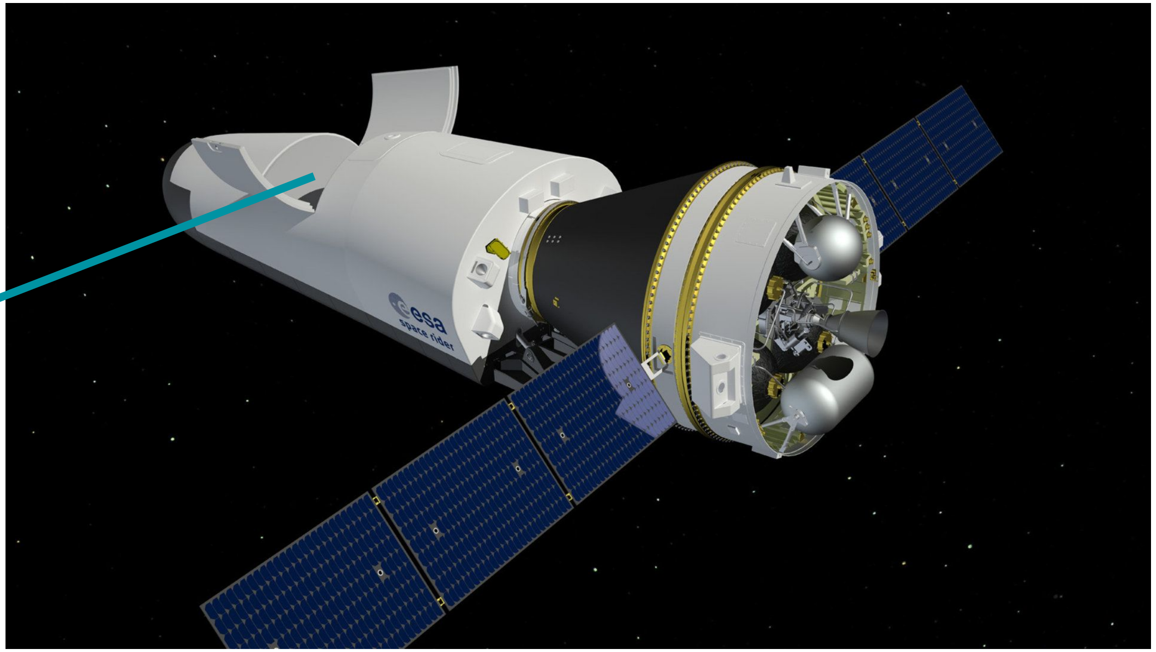
Full detector



- Full detector simulation
- Check different geometries

WINK: A PATHFINDER FOR THE SPACE RIDER FLIGHT





Technological pathfinder eligible for the Space RIDER launch by ESA in 2025

SCIENTIFIC GOAL : Background characterization

3 different type of LYSO scintillators:

1. Ground surfaces by EPIC
2. Polished surfaces by EPIC
3. Ground surfaces by OST

Number of pixels: 3
Material: LYSO
Photodetectors: 4x4 Hamamatsu MPPC 3x3 mm^2 50 μm
Weight: 1.5 kg
Power consumption: < 10 W
FOV: 30°

PRIN 2022
WINK: a pathfinder mission for the future Crystal Eye X and γ rays all sky monitor

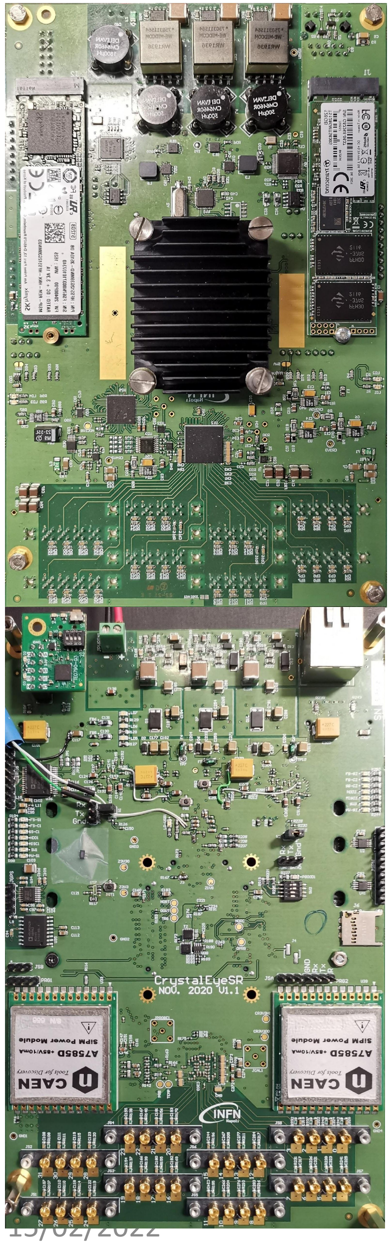
GS SI

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

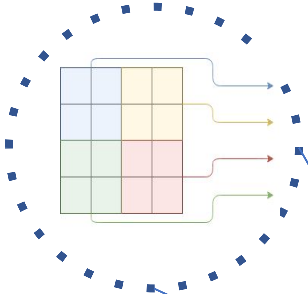
ALTEC

DAQ

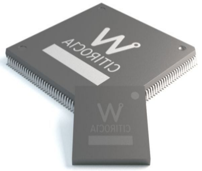
TOP VIEW



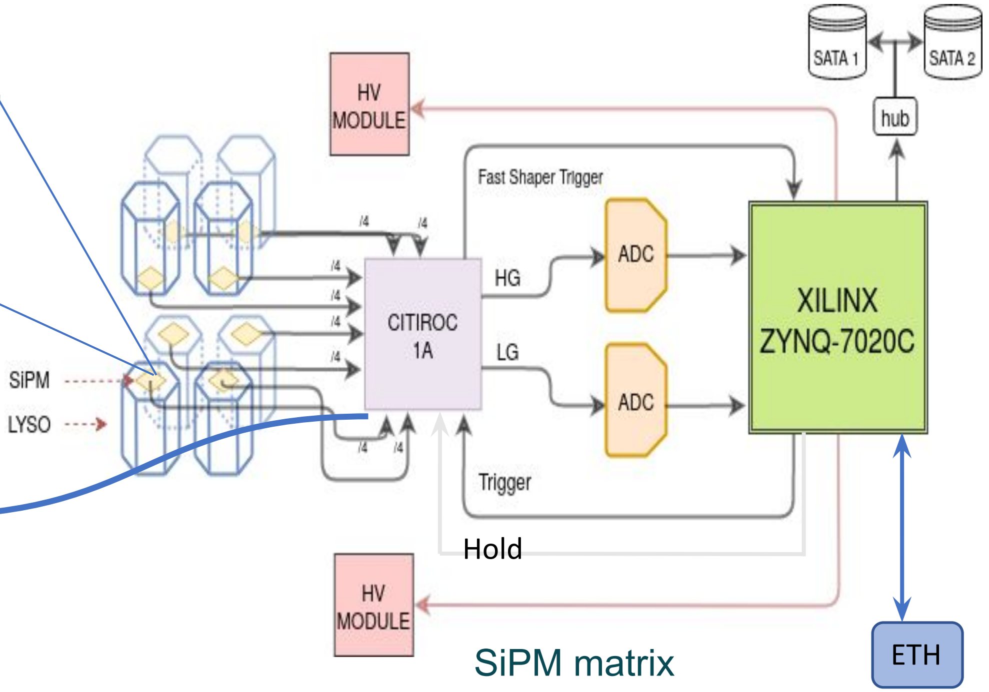
BOTTOM VIEW



SiPM matrix
front-end

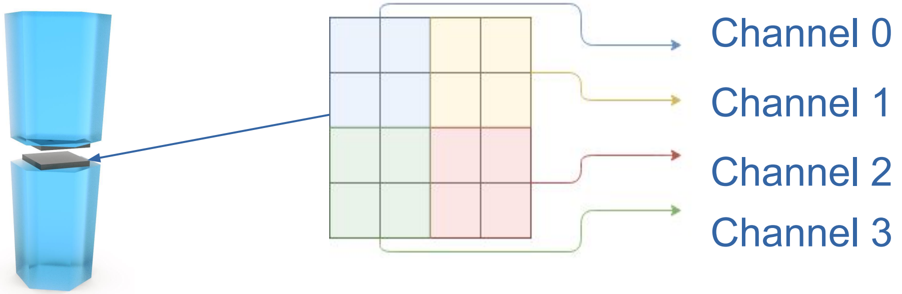


CITIROC-1
A



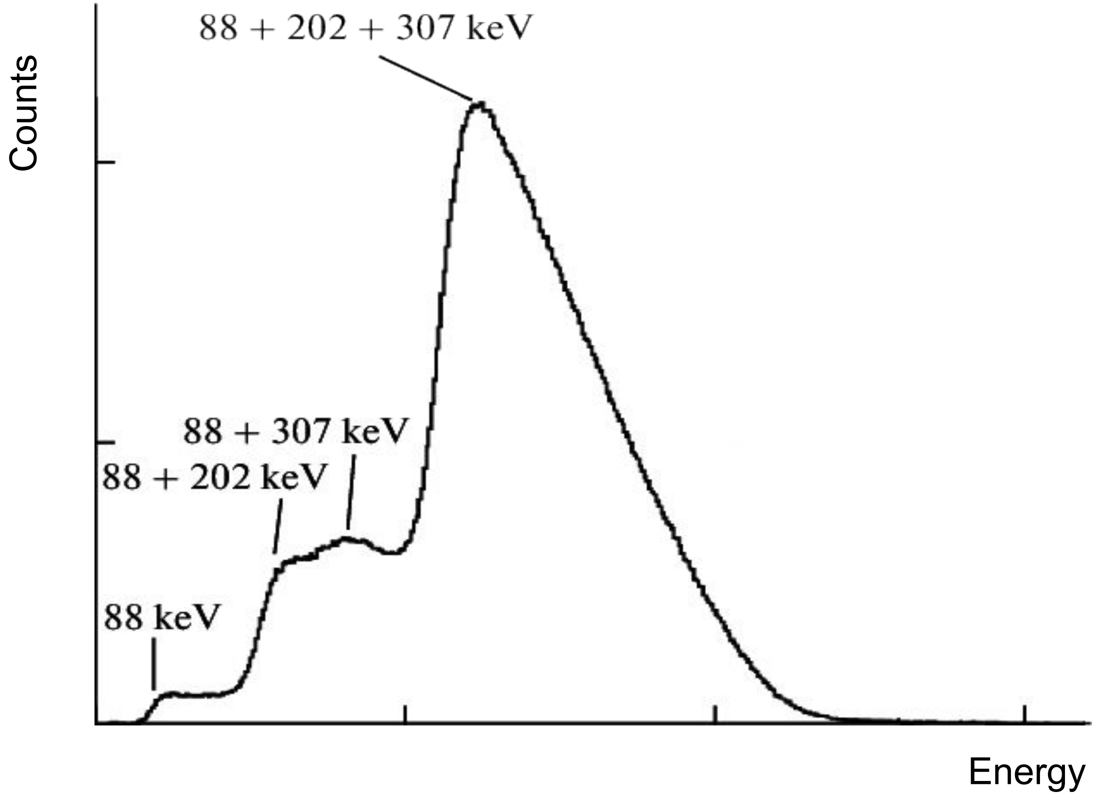
SiPM matrix
front-end

UP Pixel



Down Pixel

WHAT I DID FOR THE PROTOTYPE



Expected LYSO spectrum

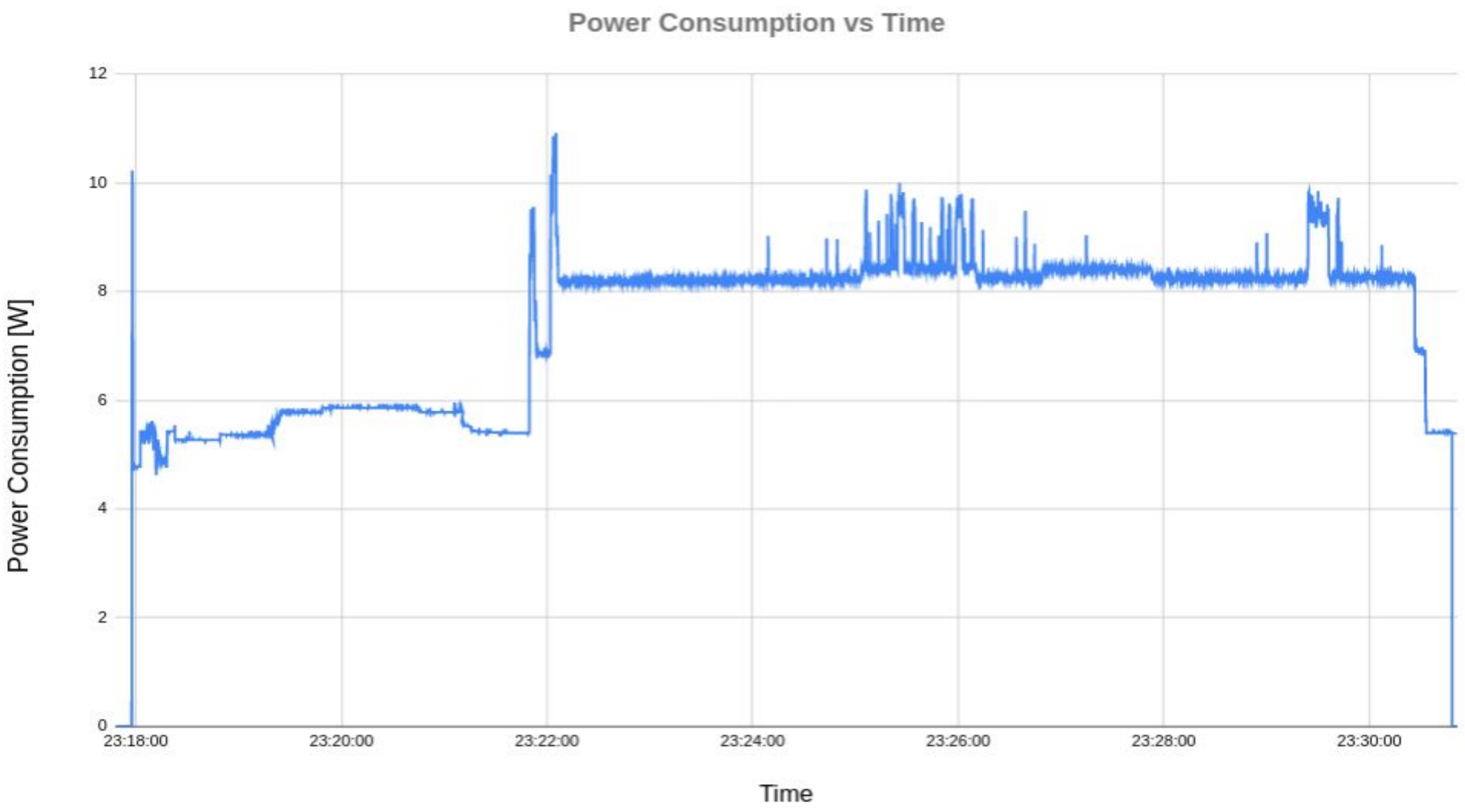
✓ **Measurement of power consumption**

Answers to ESA questions to design the Space Rider electrical interface

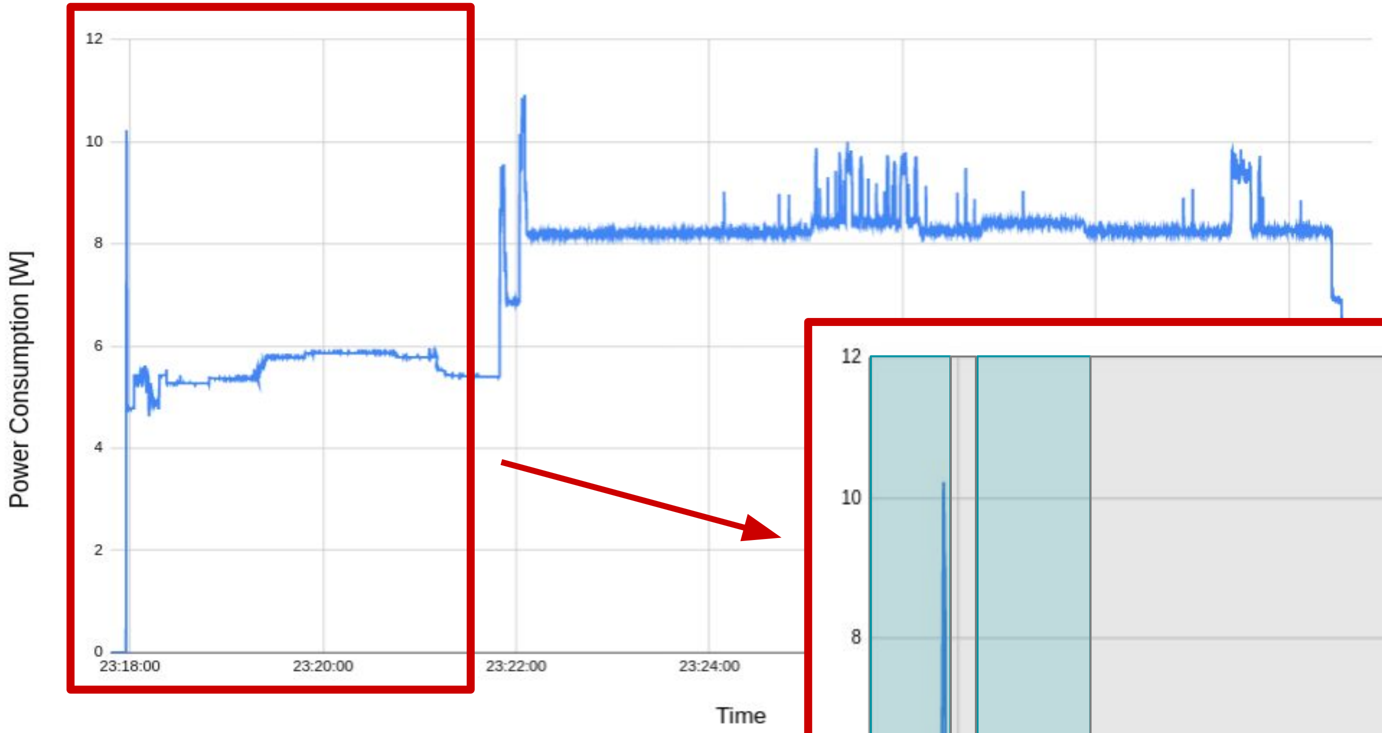
✓ **Measurement of background signal**

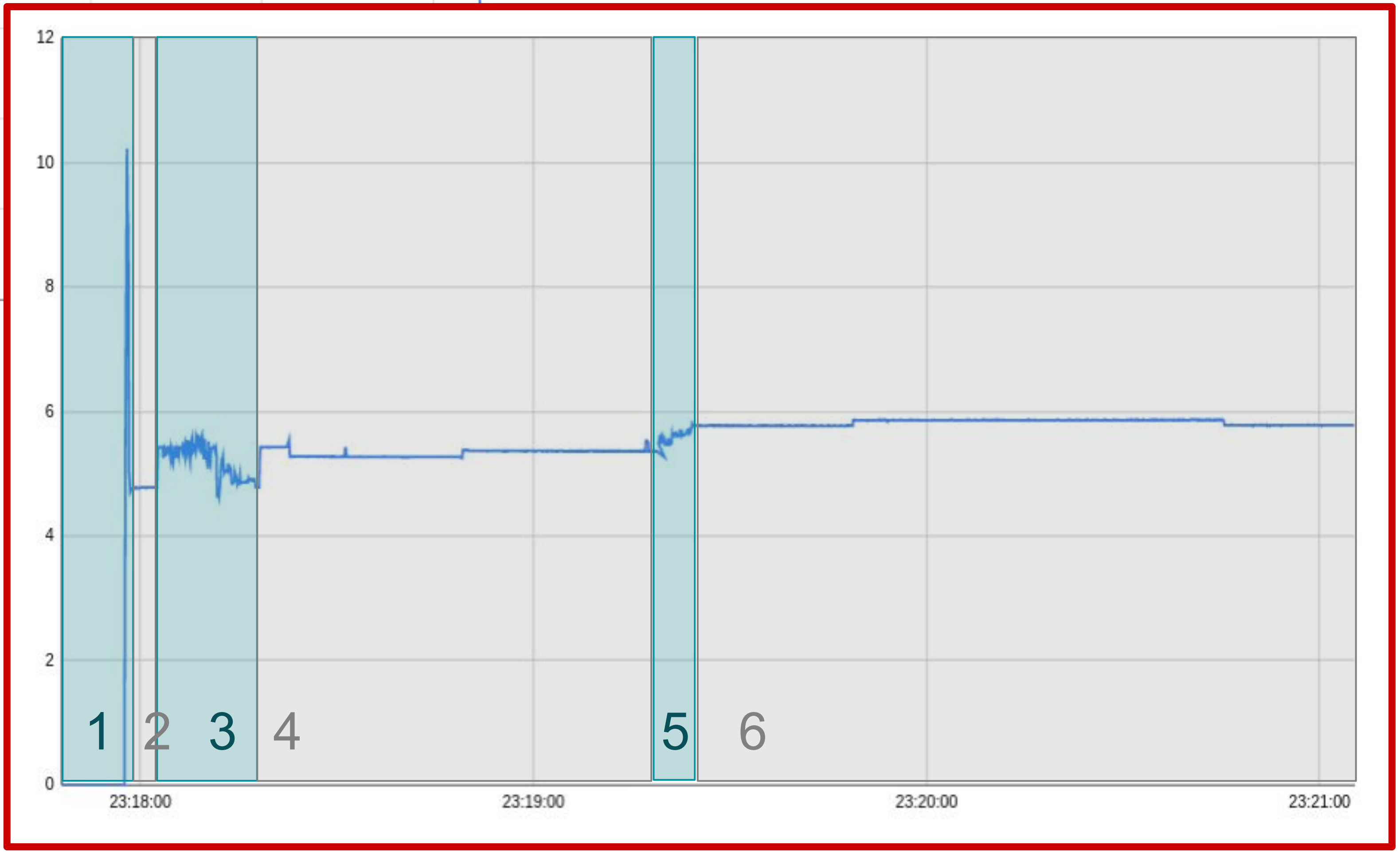
Study the LYSO Spectrum for trigger system

POWER CONSUMPTION



POWER CONSUMPTION





1 Switch on the board (spike)

2 IDLE mode

3 Autoboot

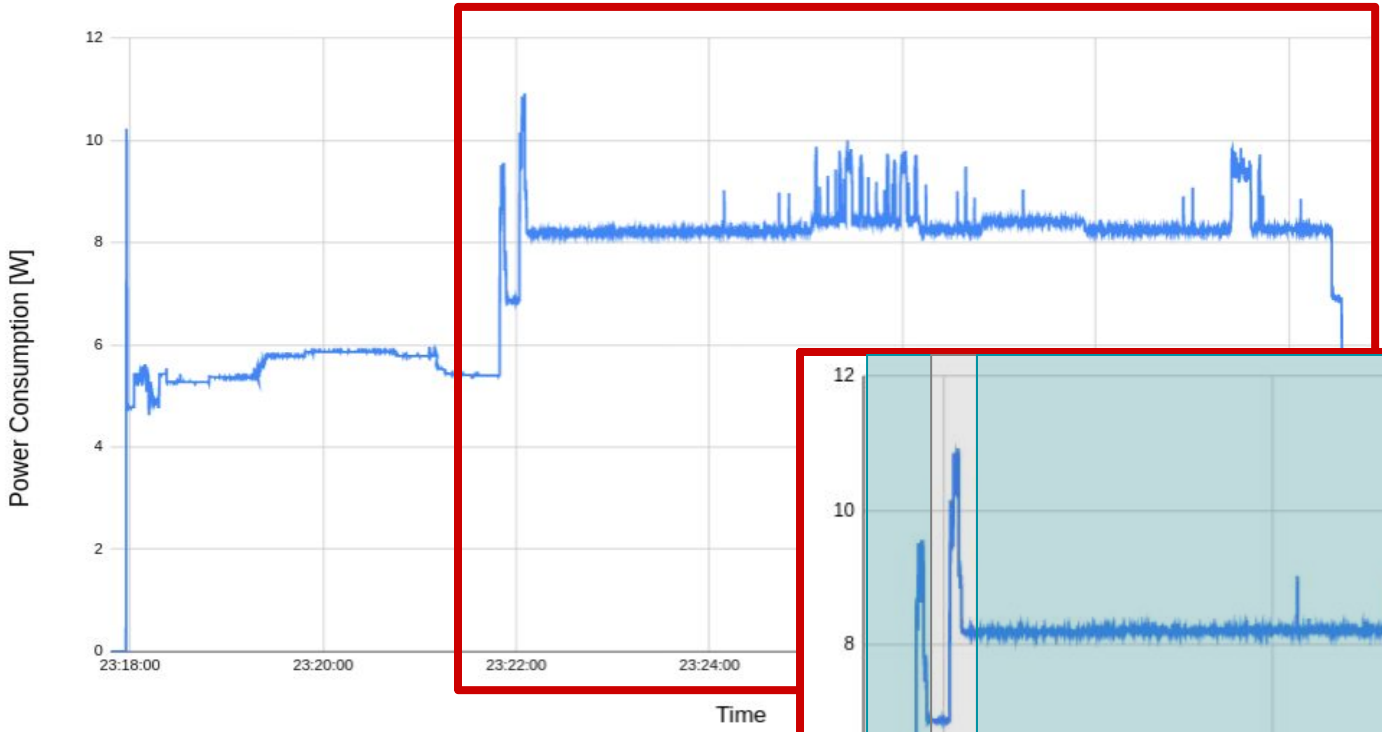
4 Boot

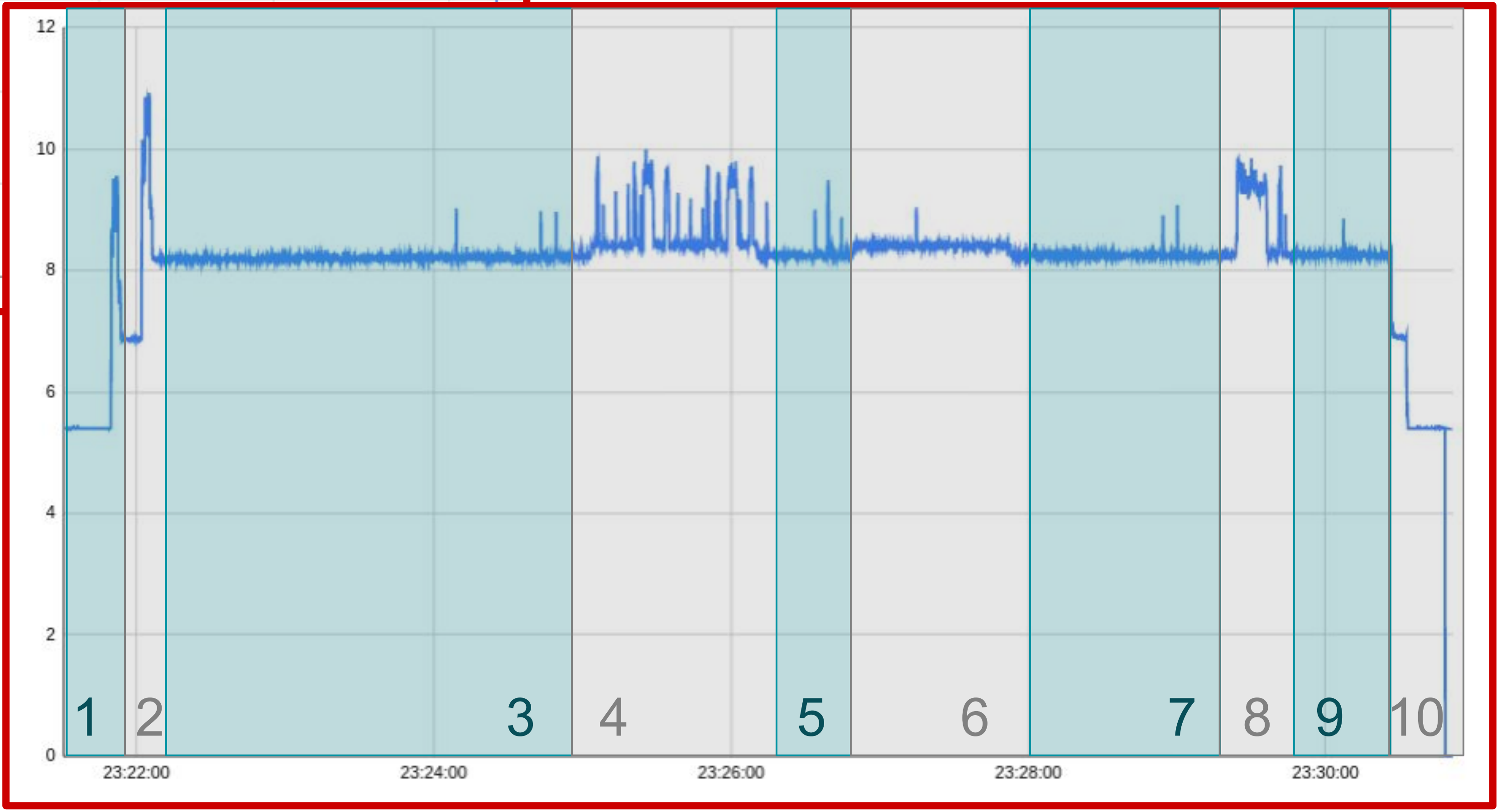
5 HV-SIPM ON

6 Data Acquisition

GSSI

POWER CONSUMPTION





1 Disk1 ON

2 Disk2 ON

3 IDLE

4 Writing on disk 1

5 IDLE

6 Writing on ZYNQ

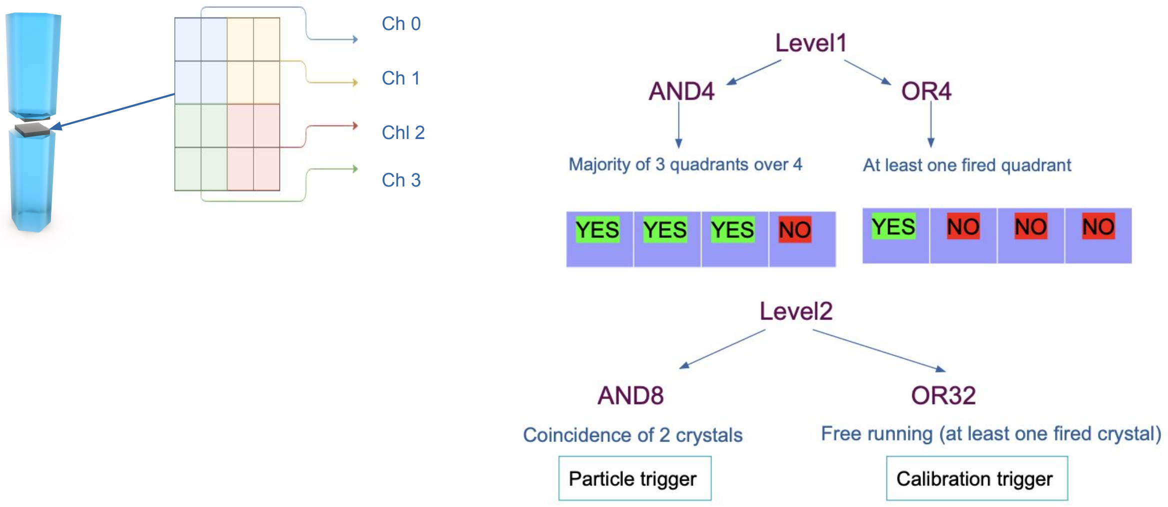
7 IDLE

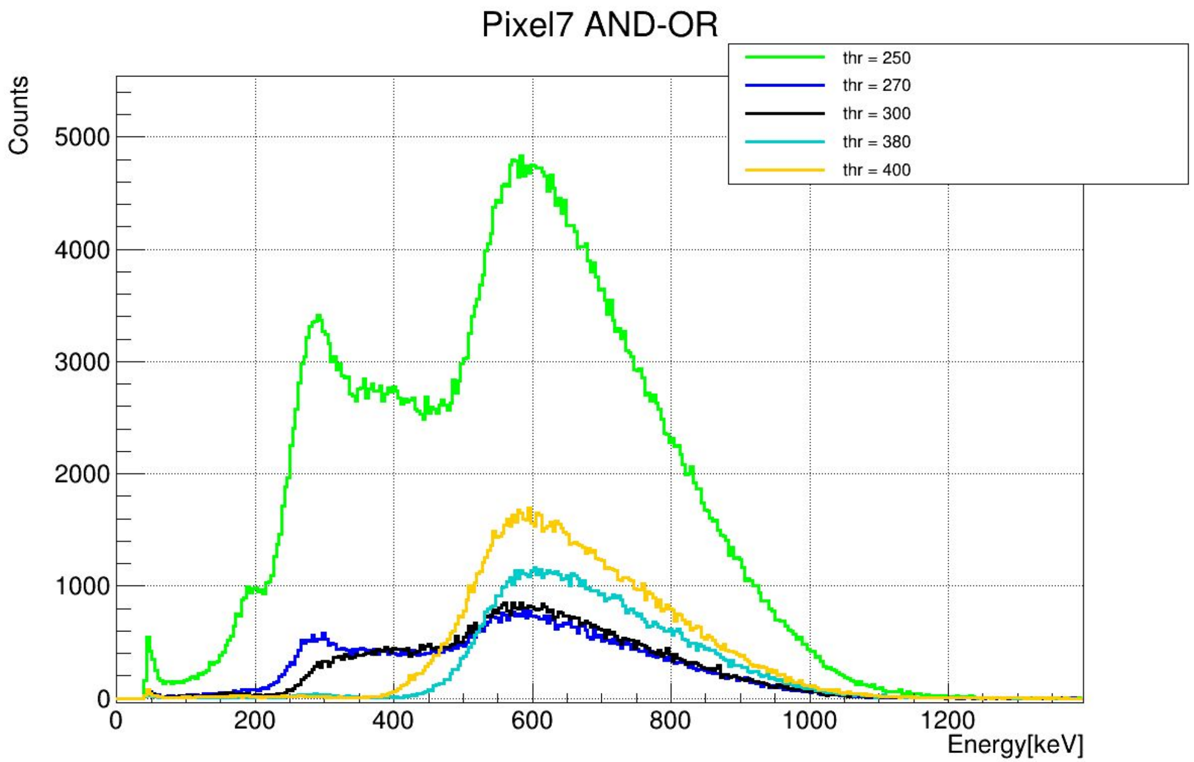
8 Writing on disk 2

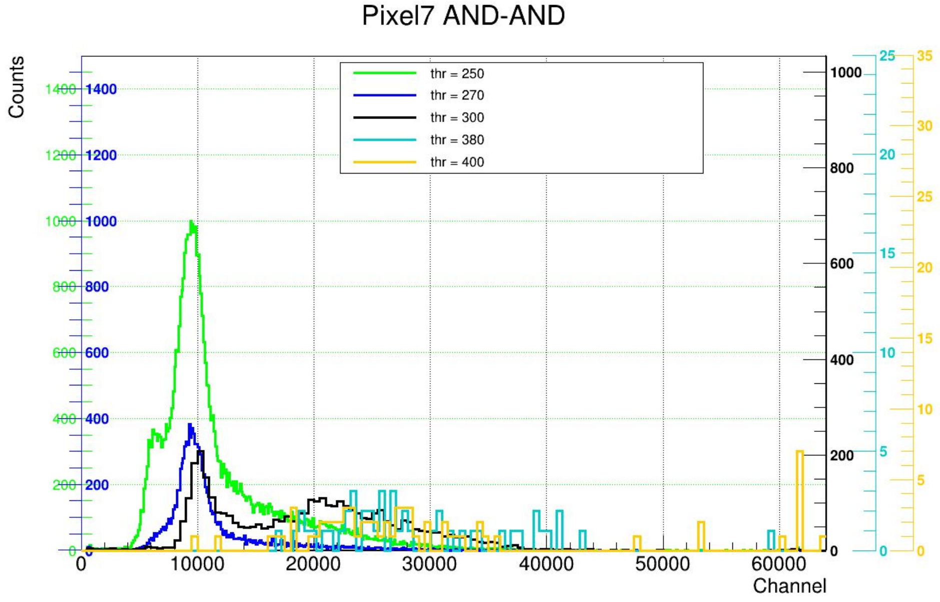
3 IDLE

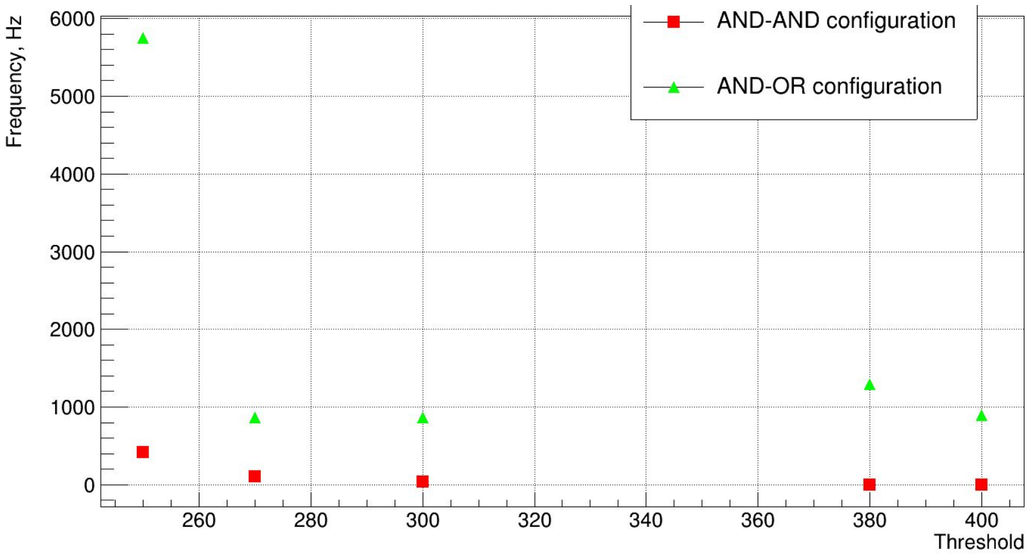
4 Disk 1 off, disk 2 off, switch off

SETTING THE TRIGGER THRESHOLD

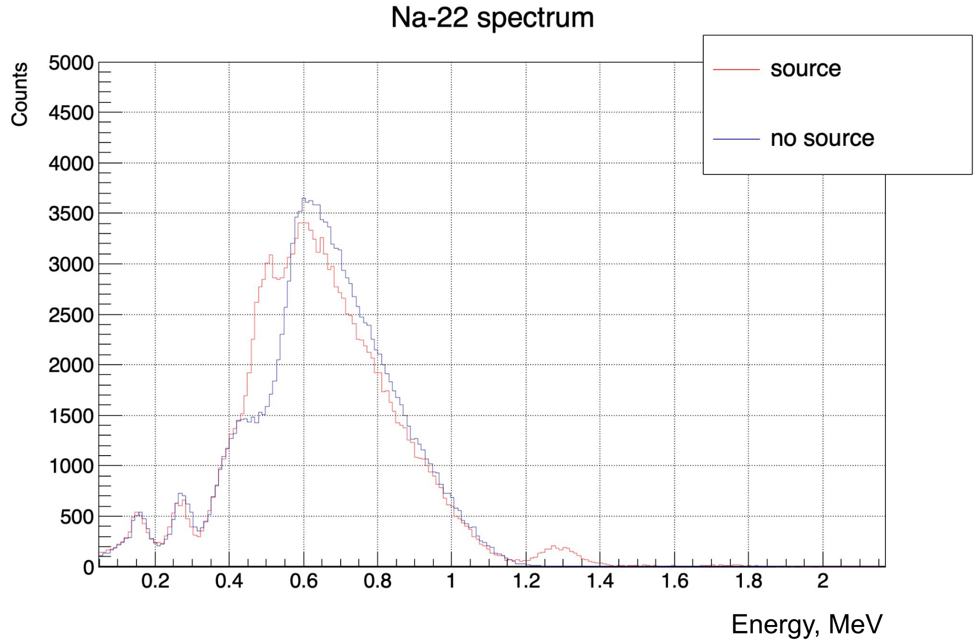


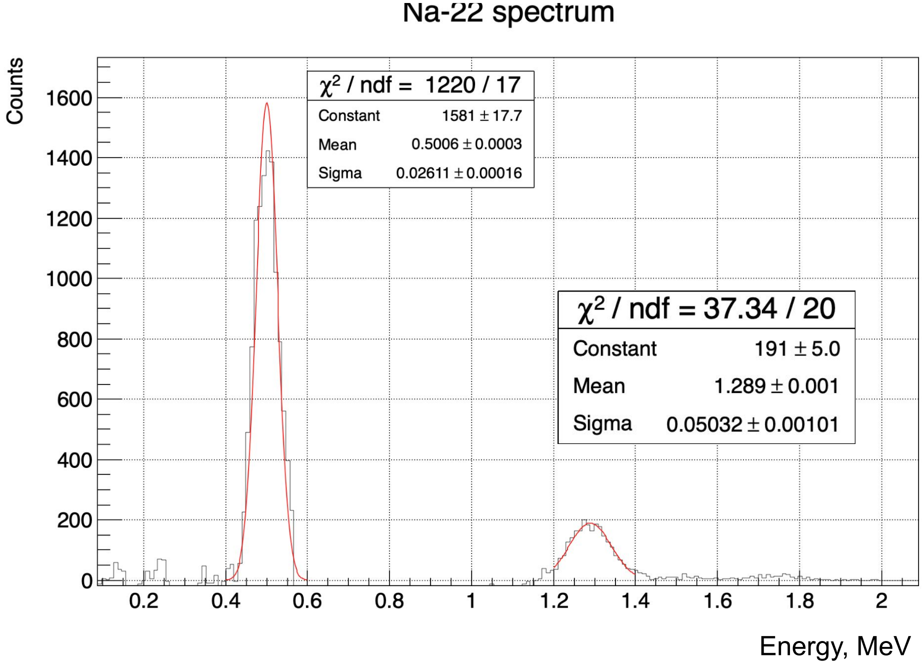




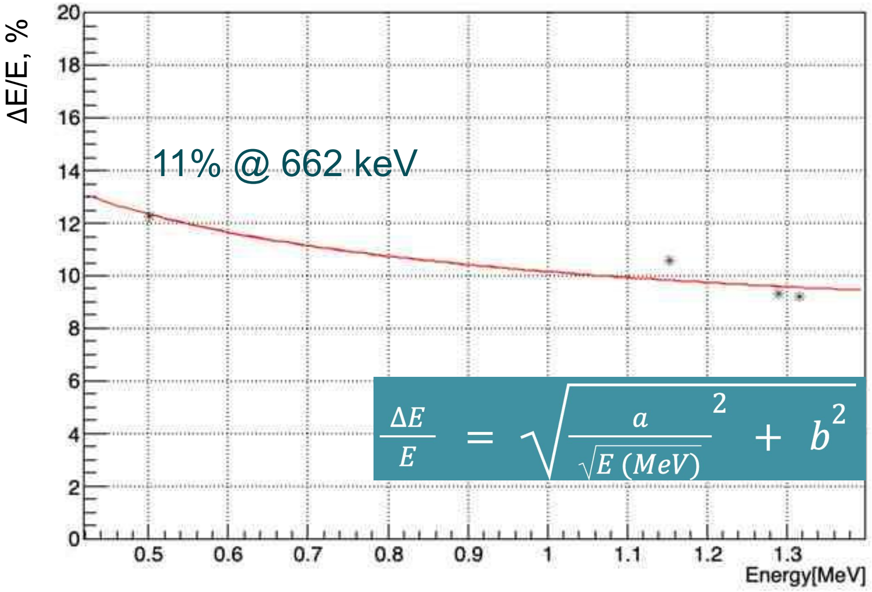


SOURCE SPECTRUM





$$F_E = \frac{FWHM}{E} = \frac{2.355\sigma}{E}$$

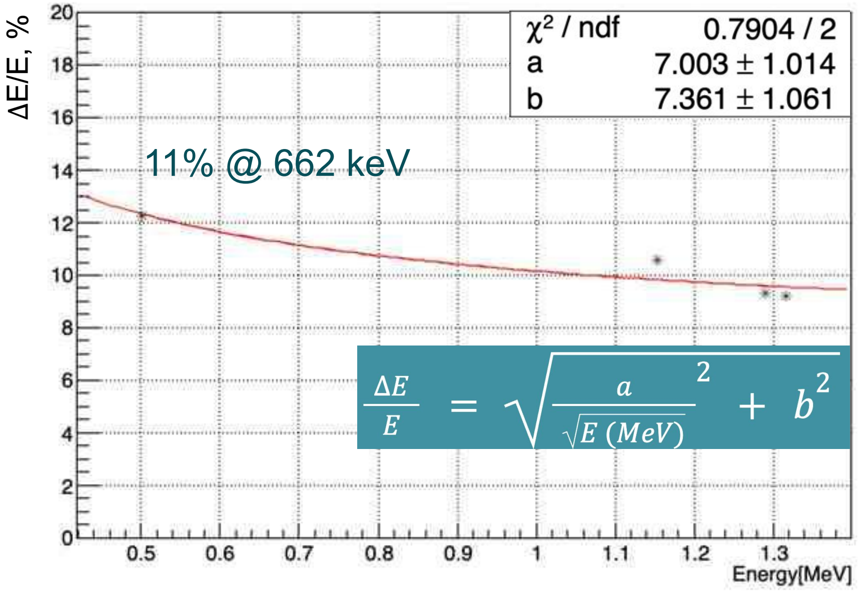


$$\frac{\Delta E}{E} = \sqrt{\frac{a}{\sqrt{E\ (MeV)}}^2 + b^2}$$

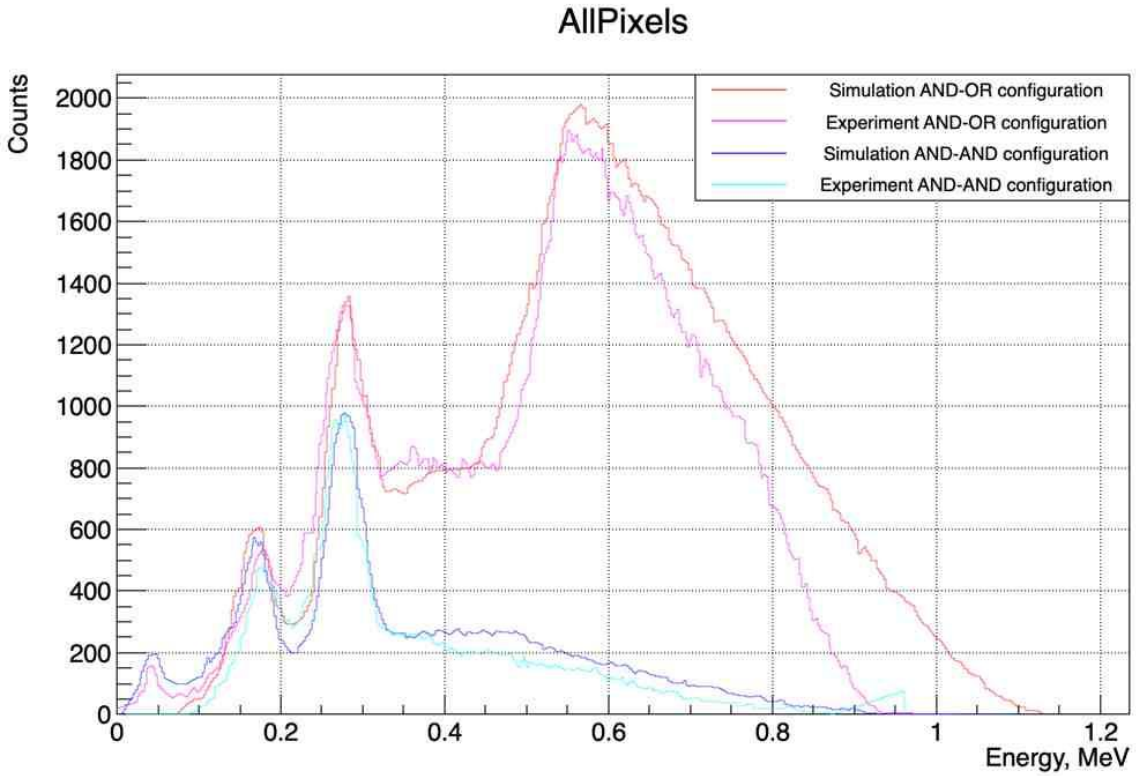
SIMULATION SPECTRA

$$F_E = \frac{FWHM}{E} = \frac{2.355\sigma}{E}$$

Resolution



$$\frac{\Delta E}{E} = \sqrt{\left(\frac{a}{\sqrt{E\ (MeV)}}\right)^2 + b^2}$$

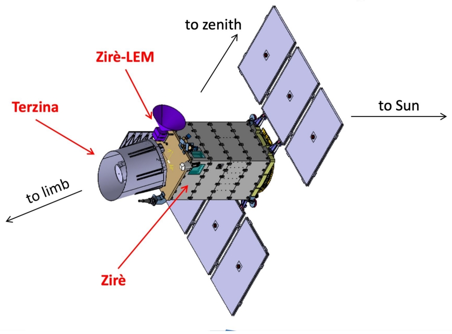


For each peak in our spectra:
511 keV and **1275 keV** peaks from **Na-22**
1.17 MeV and **1.33 MeV** peaks from **Co-60**
we calculate the resolution using this formula.

This enables us to assess the performance of our detector across **different energy levels**.

Terzina

Pathfinder for future missions devoted to **UHE cosmic rays and neutrino astronomy** throught space-based atmospheric **Cerenkov light** detection.



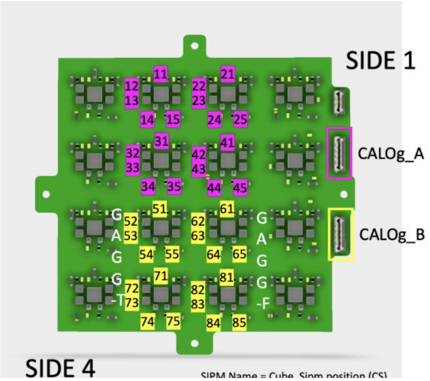
Zirè

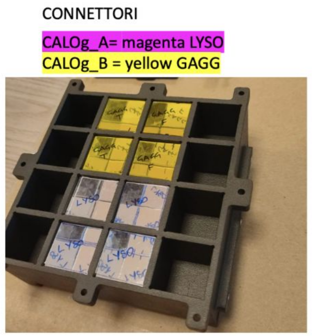
Measure the fluxes **of low energy (<250 MeV) CR**, mainly electrons and protons, to study cosmic rays, Van Allen belts**,** space weather and the magnetosphere-ionosphere-litosphere couplings (MILC) in case of seismic / volcanic activities.
Detect **0.1-10 MeV photons** for the study of transient (**GRB**, e.m. follow up of GW events, SN emission lines,…) and steady gamma sources.

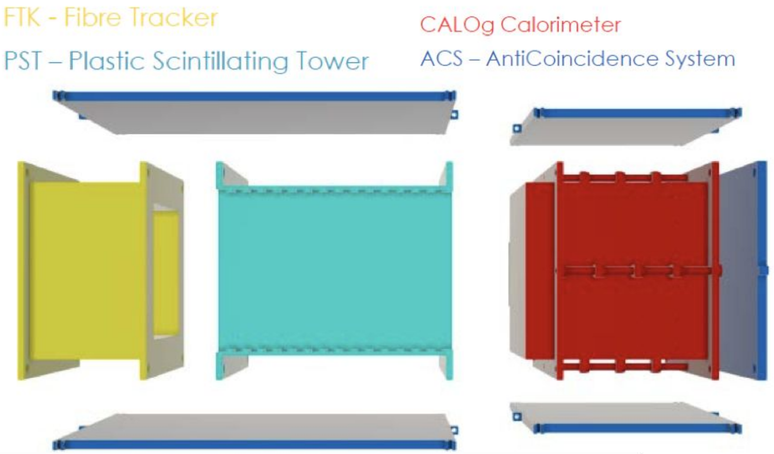
New technologies and approaches

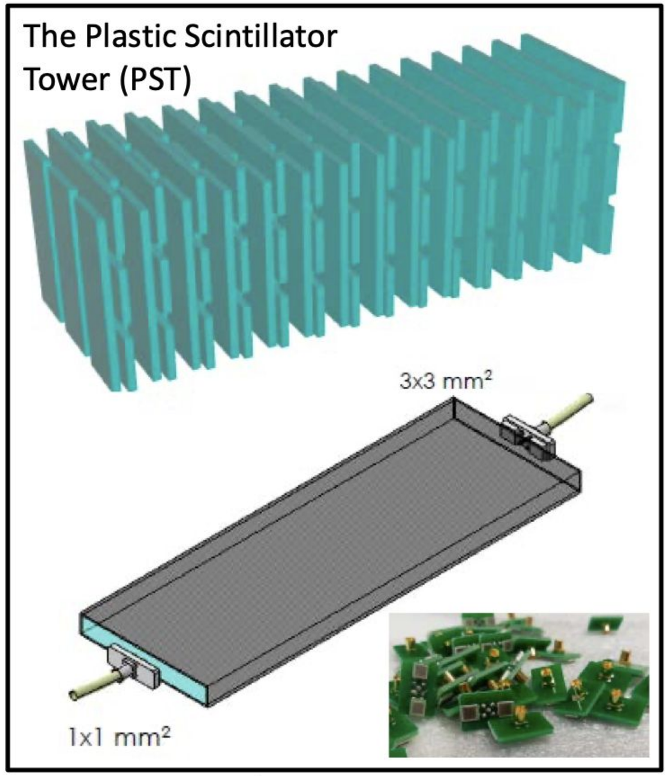
Developement of new observational techniques , testing new sensors (e.g. **SiPM**) and related electronics/DAQ for space missions. New solutions for the satellite platform.

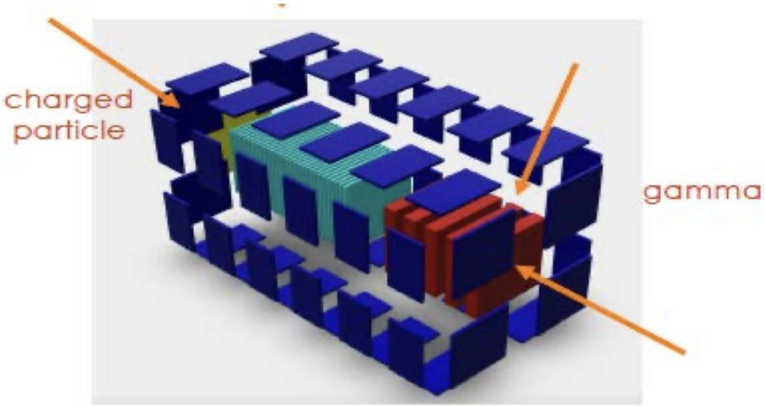
THE NUSES MISSION: TWO PAYLOADS

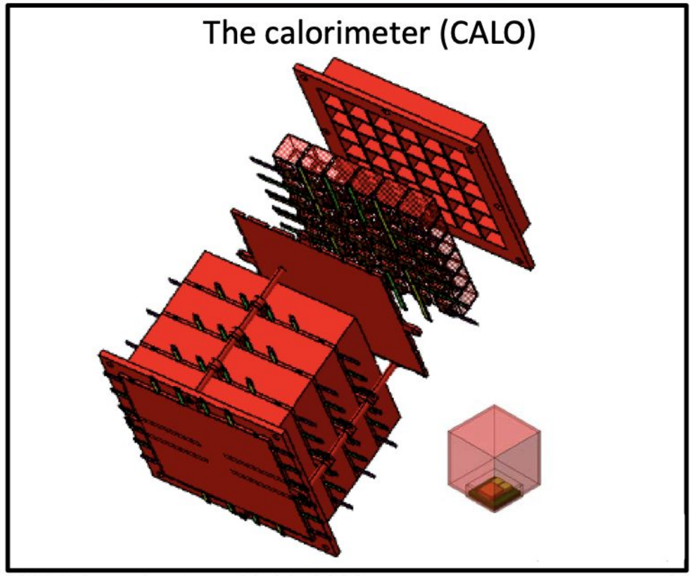


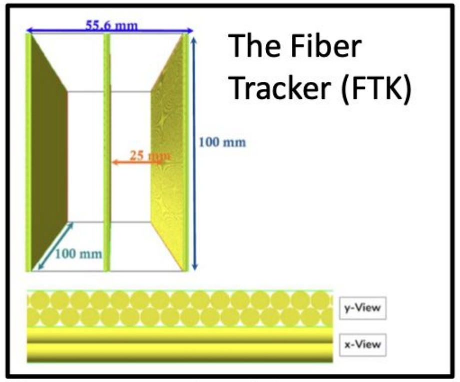


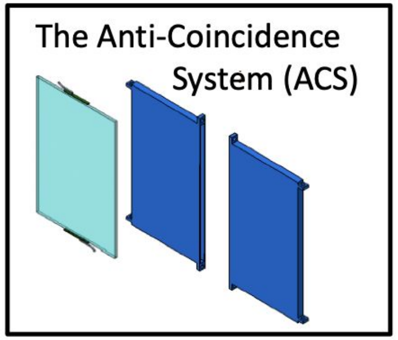






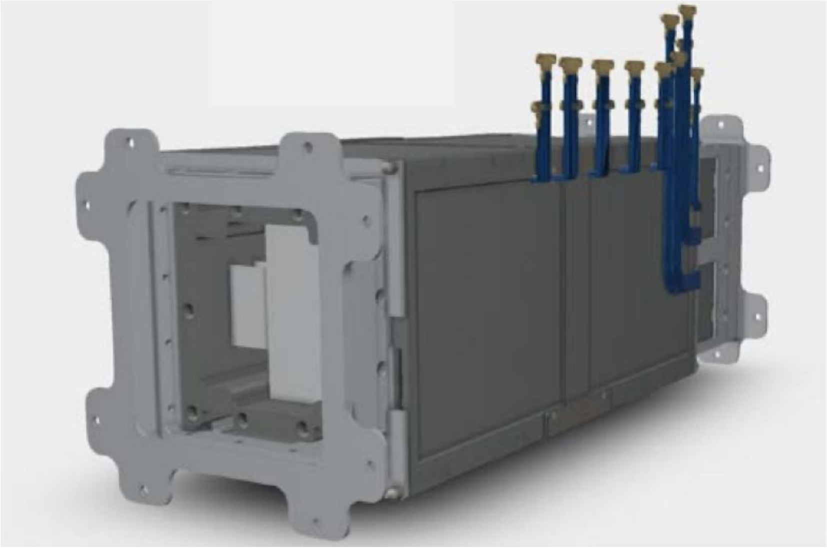




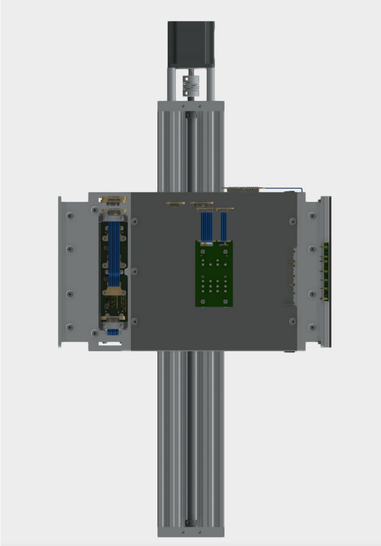


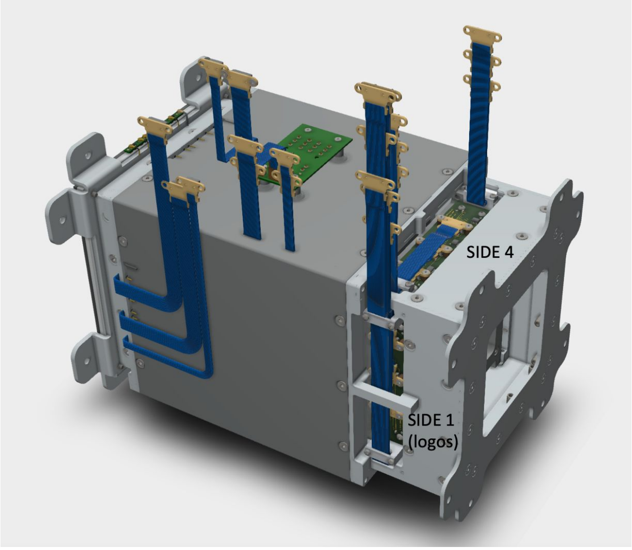
ZIRETTINO CONSTRUCTION

Zire final design



Zirettino
(for test and calibrations)



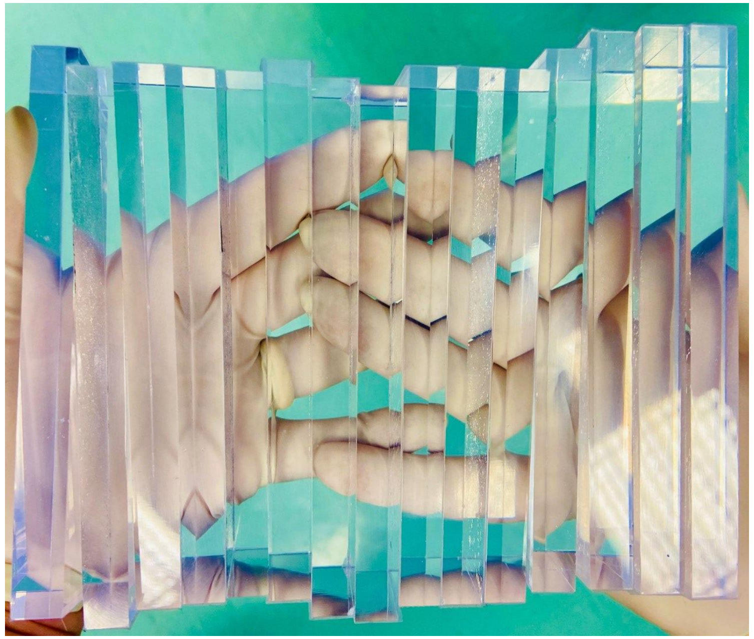


- 3 planes x-y view FTK
- 32 layers PST
- 2 layers 4x4 CALOg
- 9 ACS

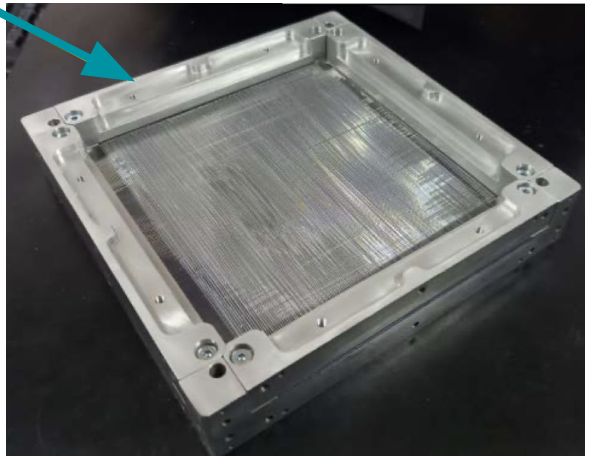
- 1 plane x-y view FTK
- 8 layers PST
- 1 layers 2x4 CALOg
- 5 ACS

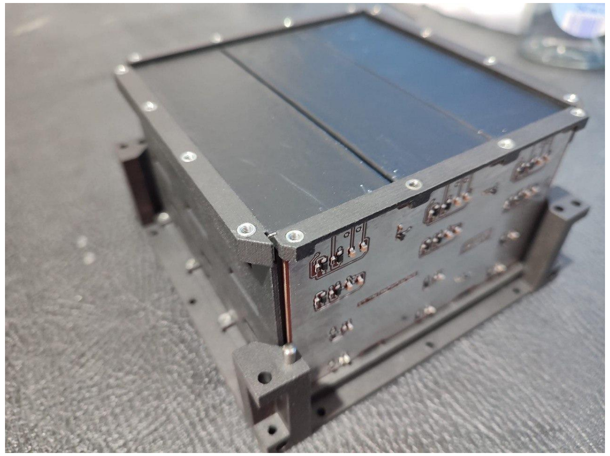
ZIRETTINO CONSTRUCTION

Plastic Scintillator Tower (PST) bars



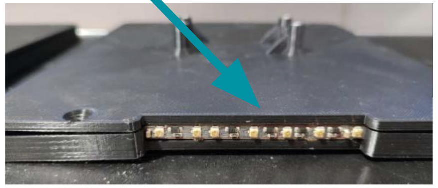
The fiber tracker (FTK)



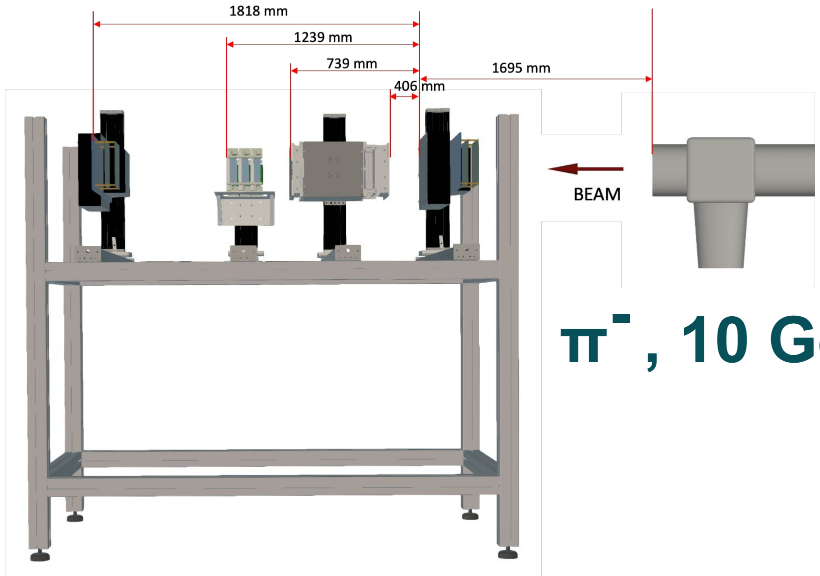


PST layout

Anticoincidence and SiPM readout

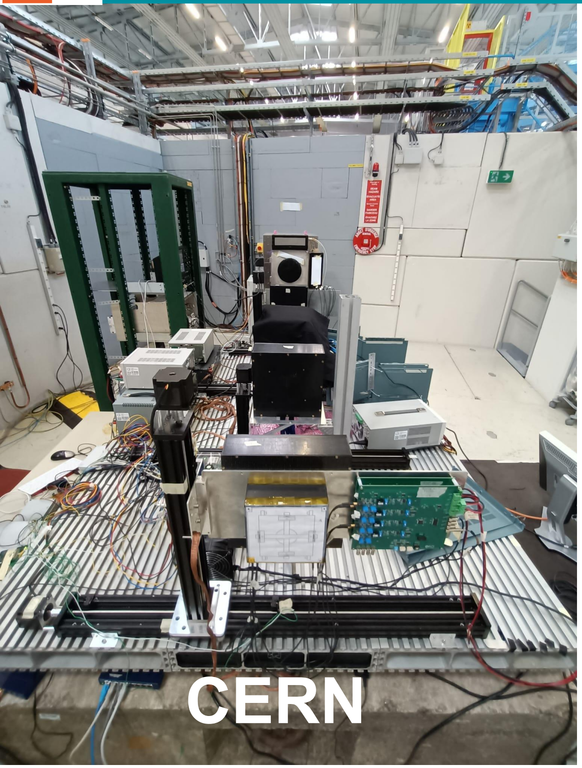


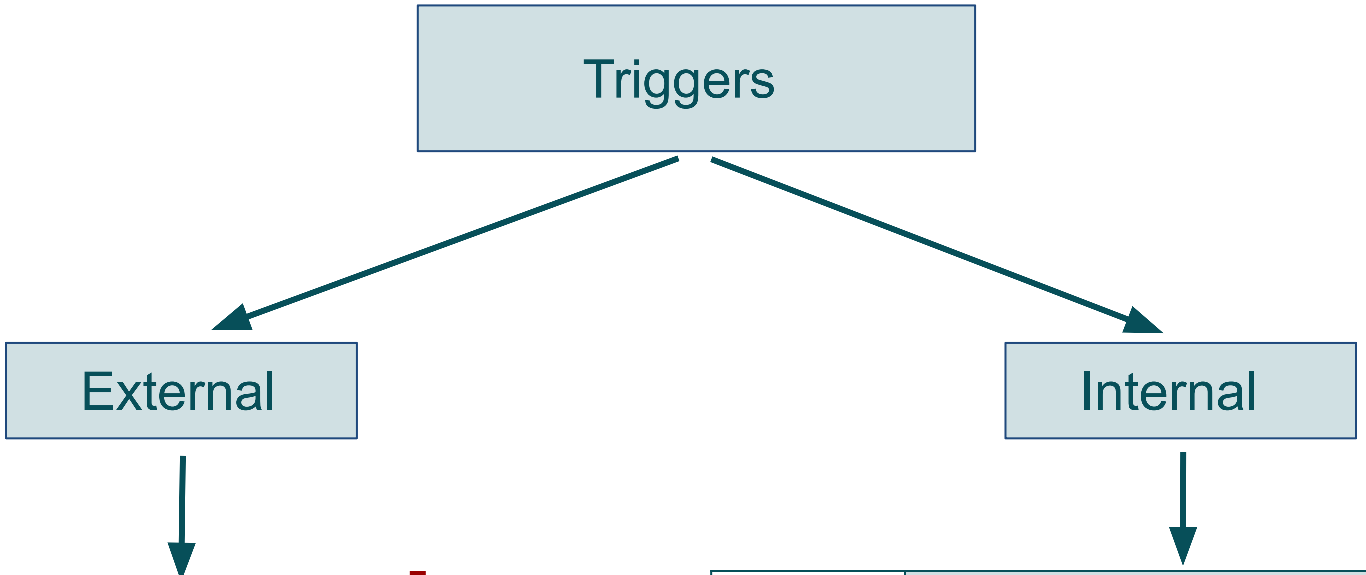
CERN

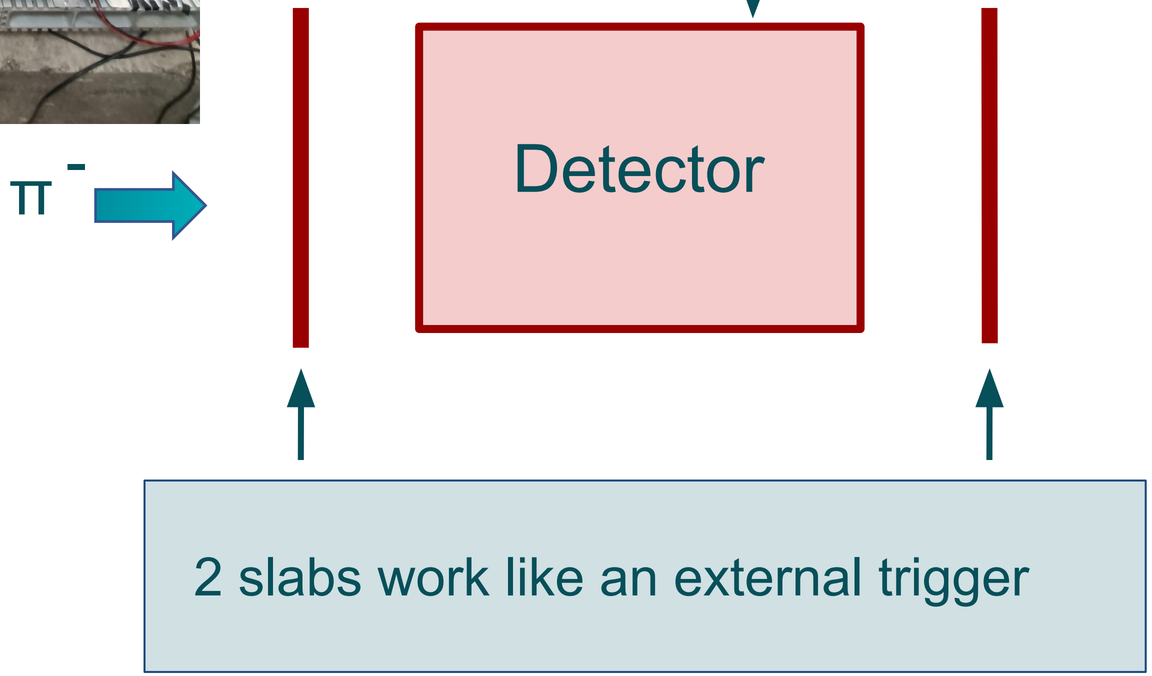


π^-, 10 GeV

ZIRETTINO TRIGGERS

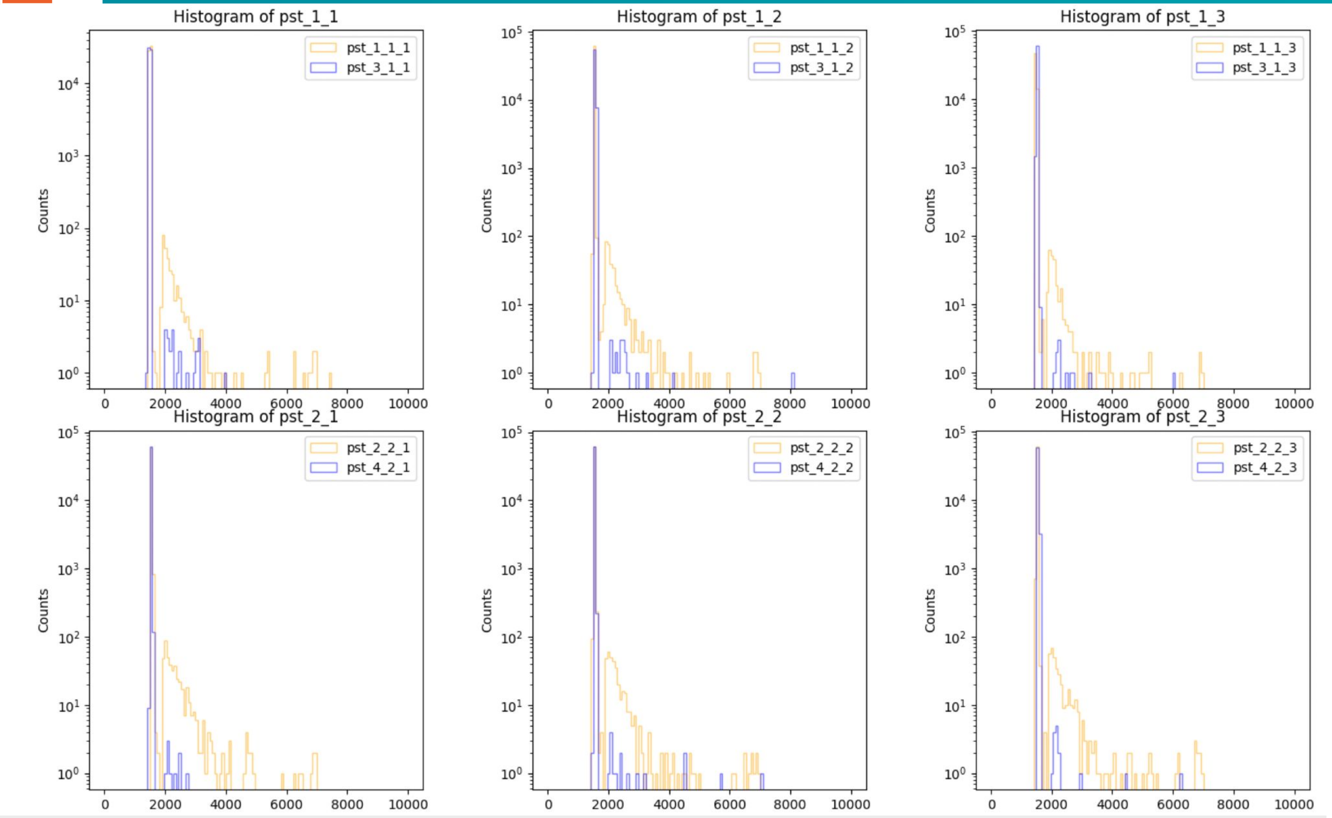


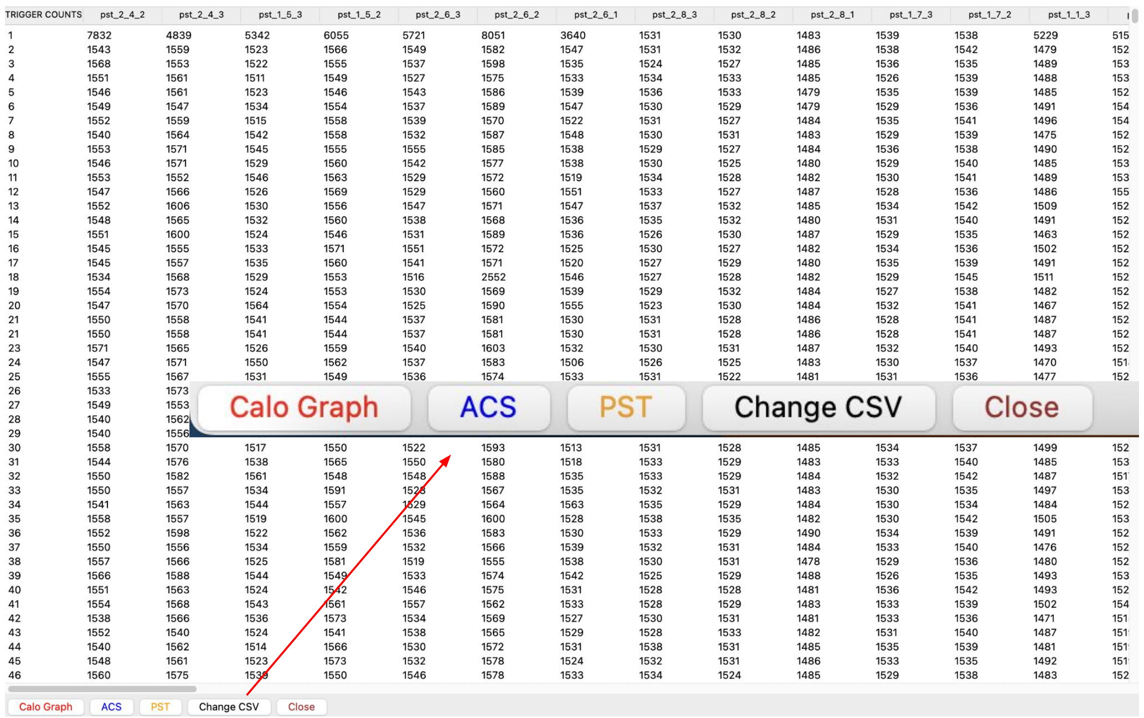


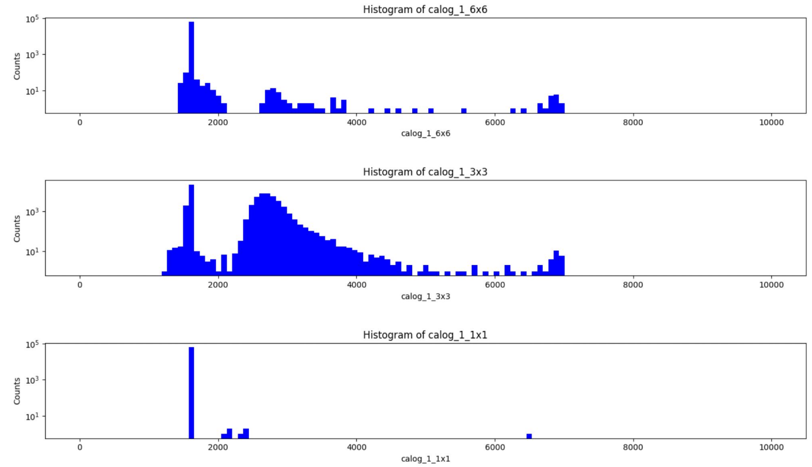


Muon vertical	Pst_cross & central_calog (3,4,5,6)
Pst cross	pst_1_1_2 & pst_2_2_2 & pst_1_3_2
Calog on	calog_on(1) or calog_on(2) or calog_on(3) or calog_on(4) or calog_on(5) or calog_on(6) or calog_on(7) or calog_on(8)
Mip pass no acs	Any pst on & calog_on

ZIRETTINO GUI







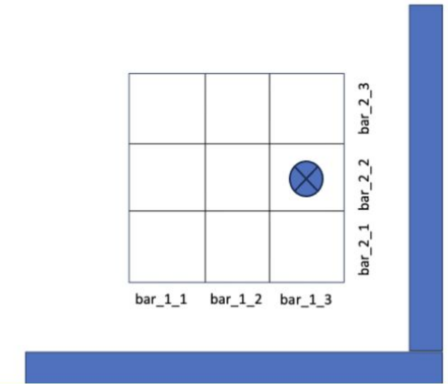
Tkinter

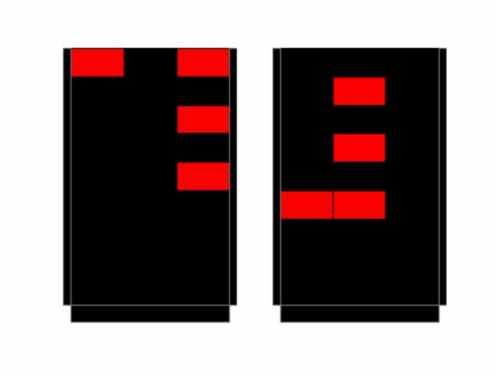
BEAM SPOT POSITION

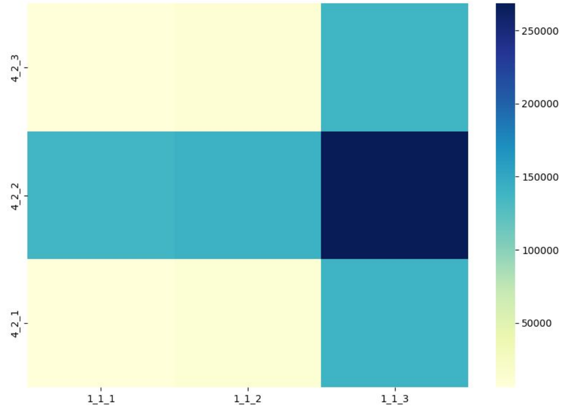
POSITION

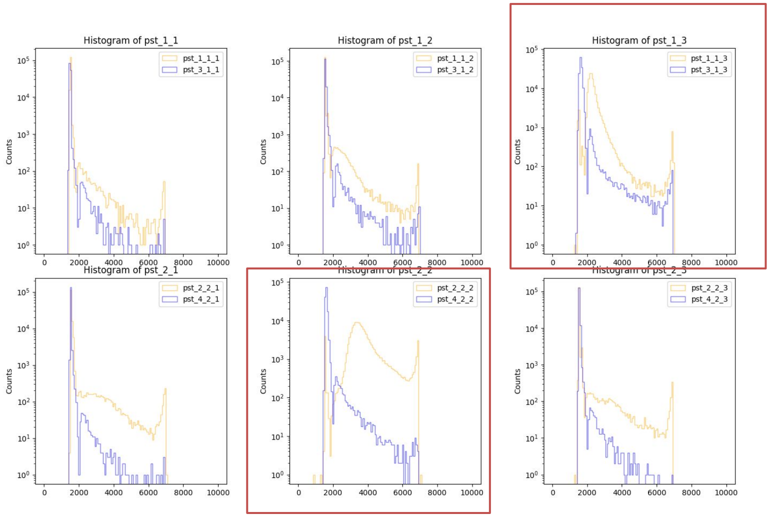
VISUALIZATION

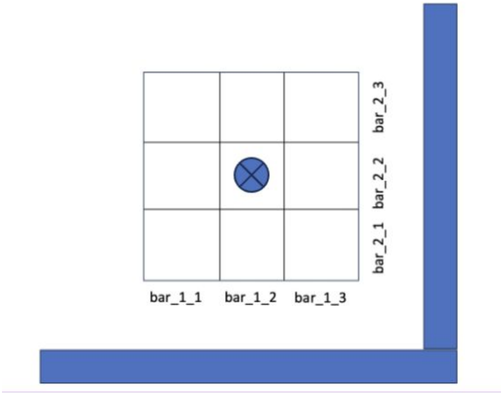
HIT MAP

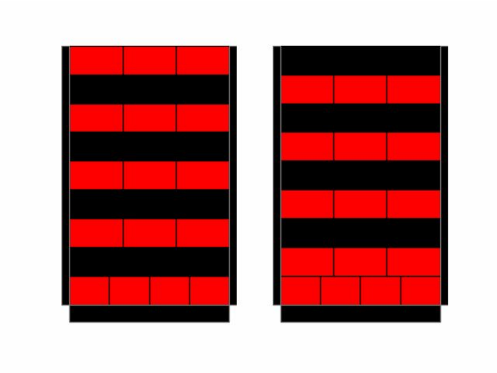


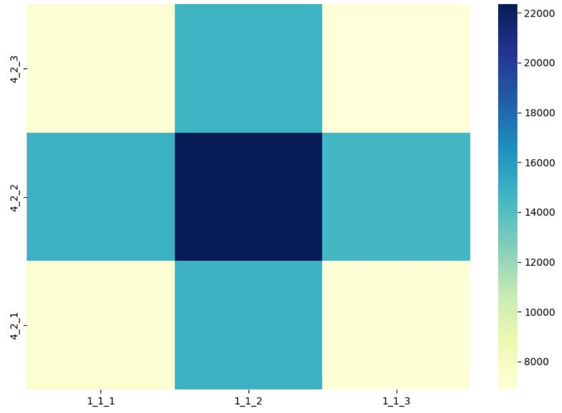


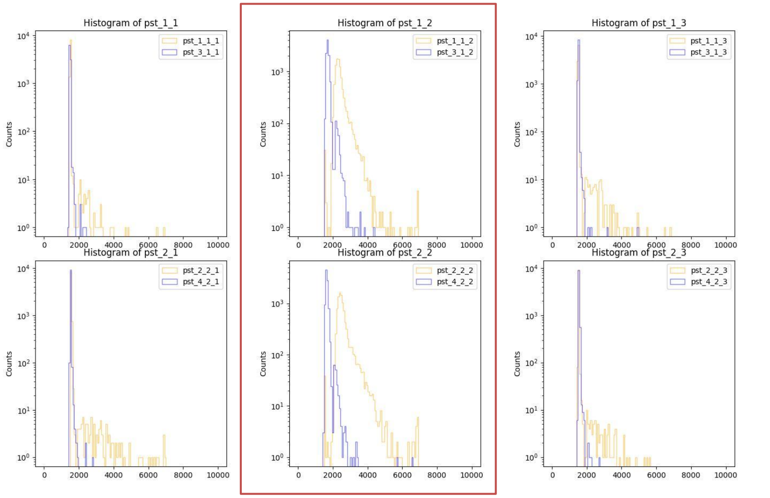












CONCLUSION

CONFERENCES

- SIF conference, Crystal Eye report, A.Smirnov, https://2023.congresso.sif.it/talk/508
- Crystal Eye: a wide sight on the Universe for X and gamma-ray detection, R.Colalillo et al,38th International Cosmic Ray Conference (ICRC2023), Proceedings of Science

FUTURE PERSPECTIVES

- Realization of a “slice”-prototype in 2024
- Space Rider mission in 2025
- Undergo test beams
- New geometry for the full detector and prototype

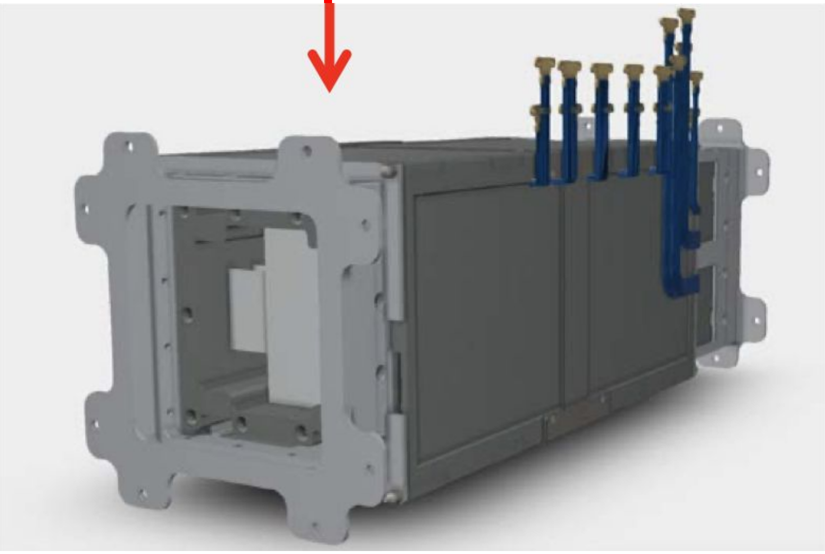
BACK UP

CONCLUSION

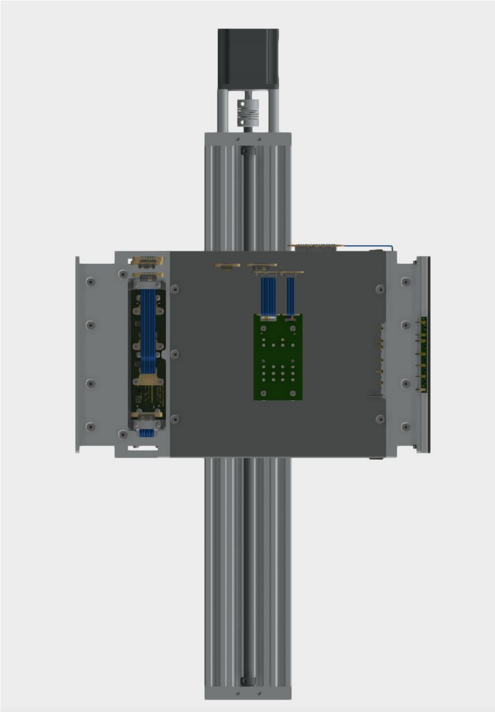
CRYSTAL EYE PERFOMANCE

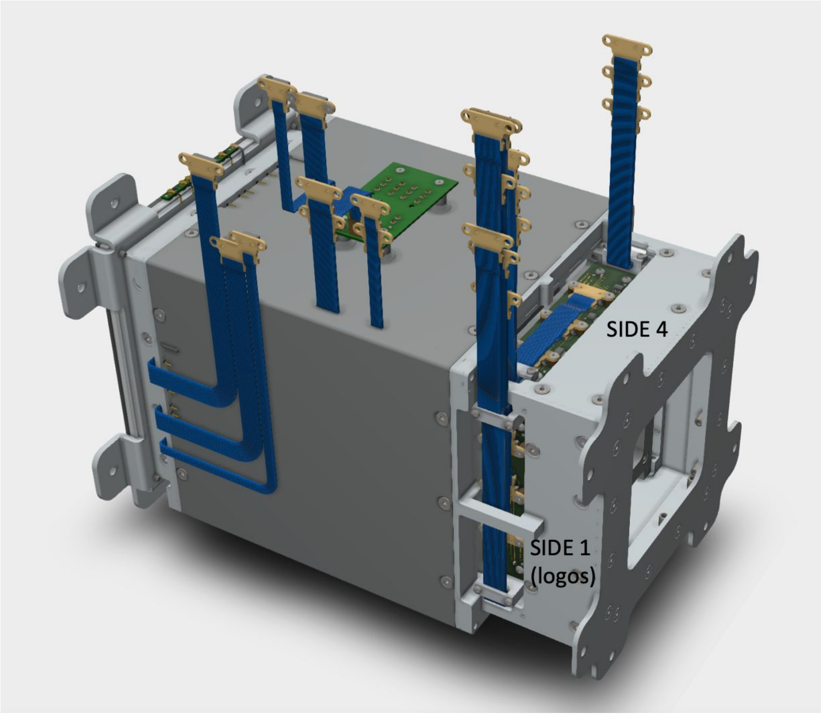
ZIRETTINO CONSTRUCTION

Zire final design



Zirettino
(for test and calibrations)

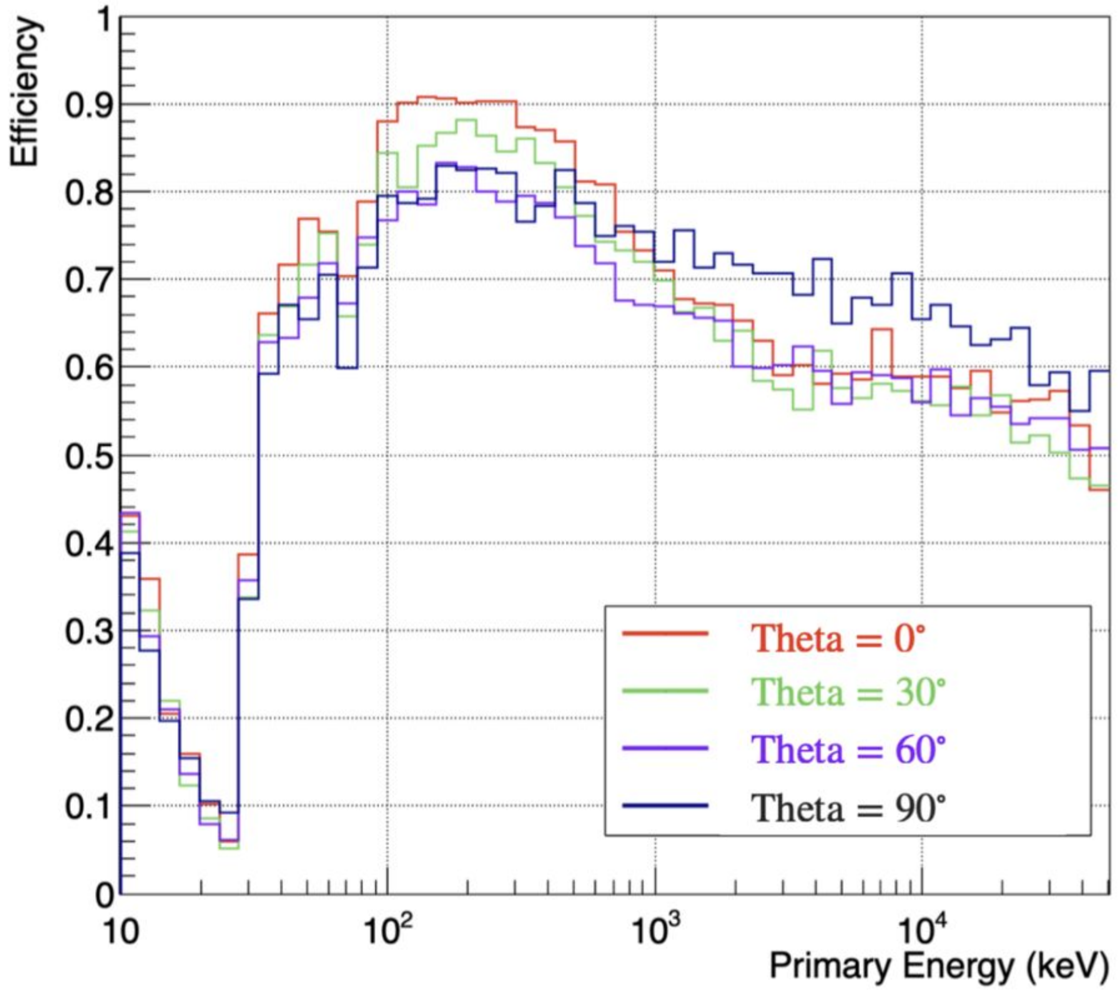




EFFICIENCY

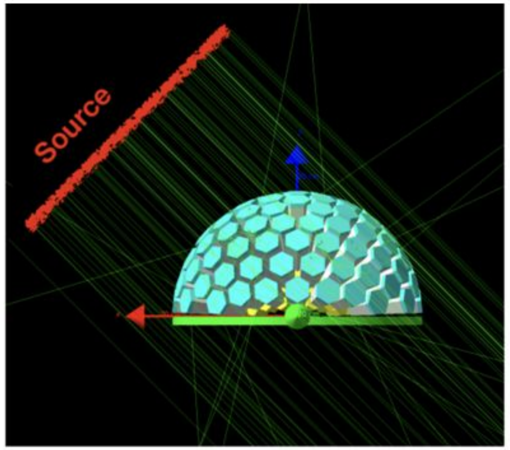
Efficiency in th i-th bin is defined as follows:

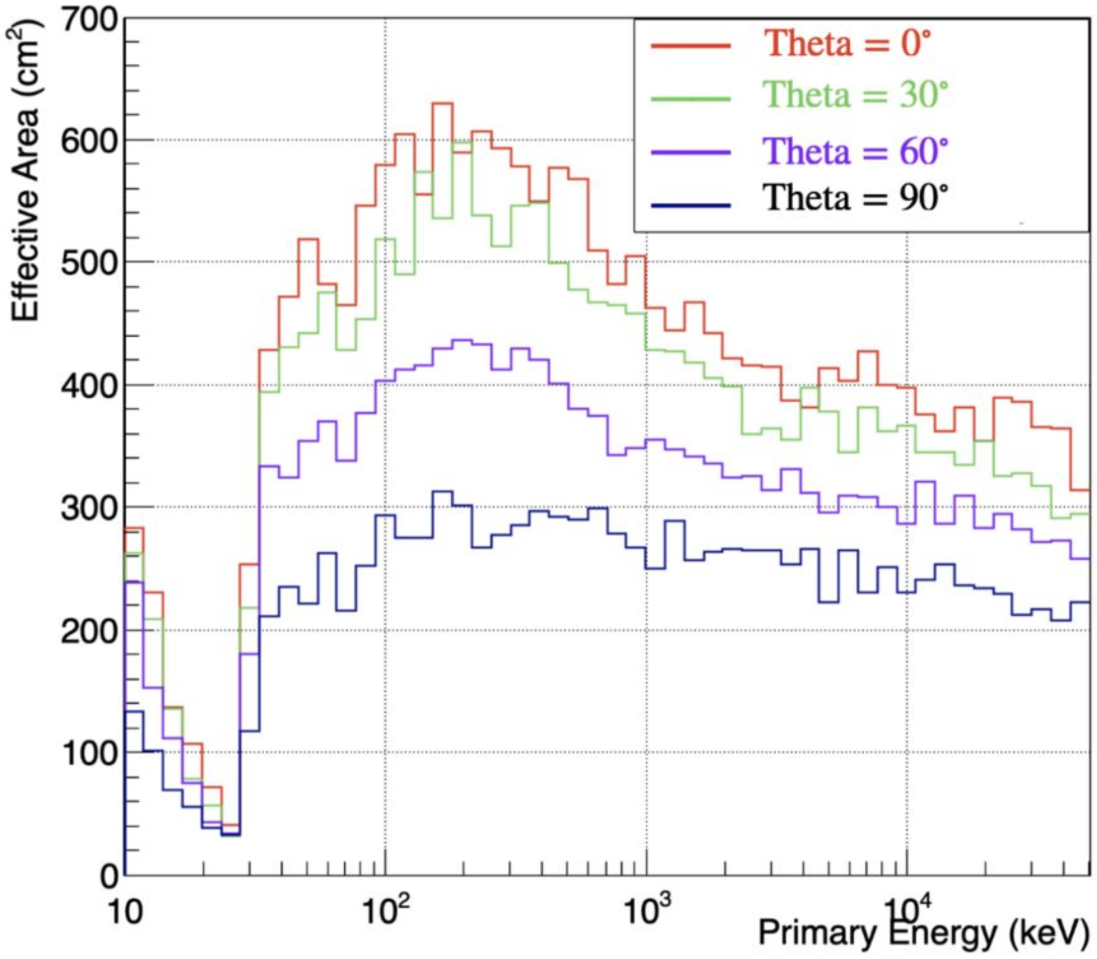
$\epsilon_i = \frac{n_i}{N_i}$, with n the number of events after the selection cuts and N are the simulated number of events in the field of view hitting the detector.



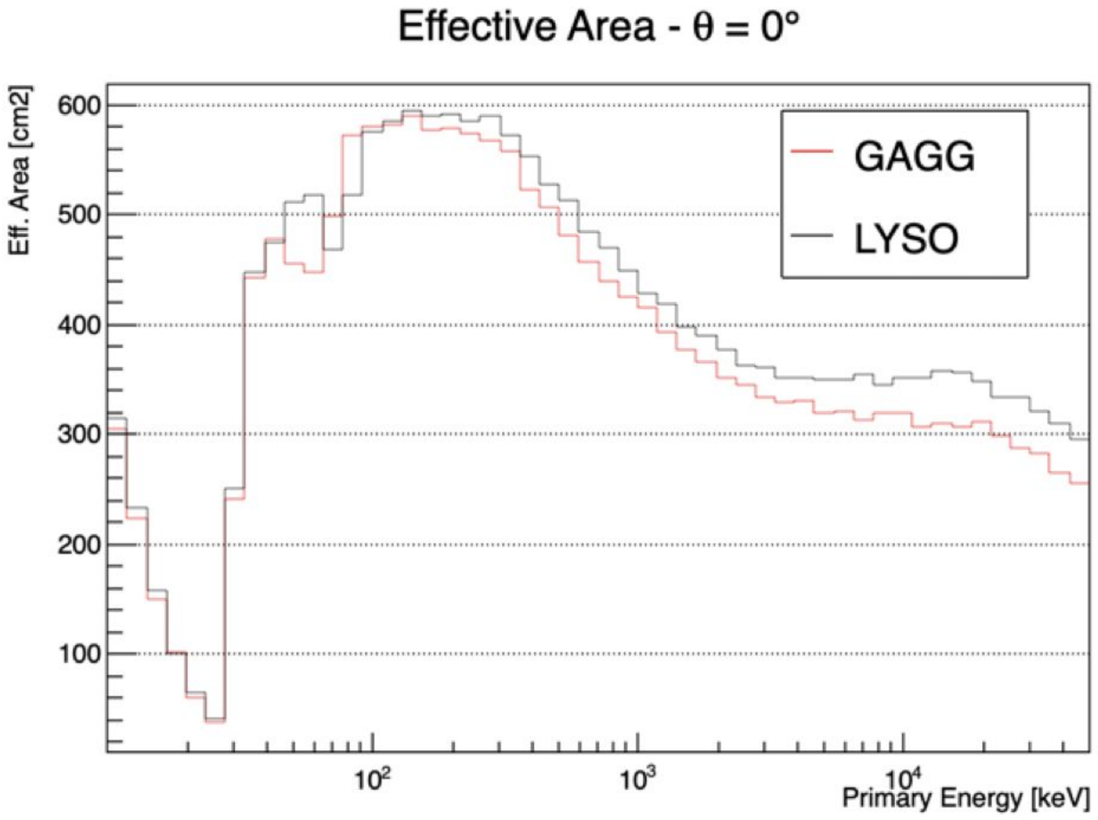
The effective area in the i-th bin is defined as follows:

$A_{eff_i} = \frac{n_i}{N_i} \times A_{source}$, with *n* the number of events after the selection cuts, *N* the total number of simulated events and A_{source} the surface area of the source where gamma rays are generated.





Effective area was calculated considering LYSO and GAGG scintillating crystals for the pixel material.



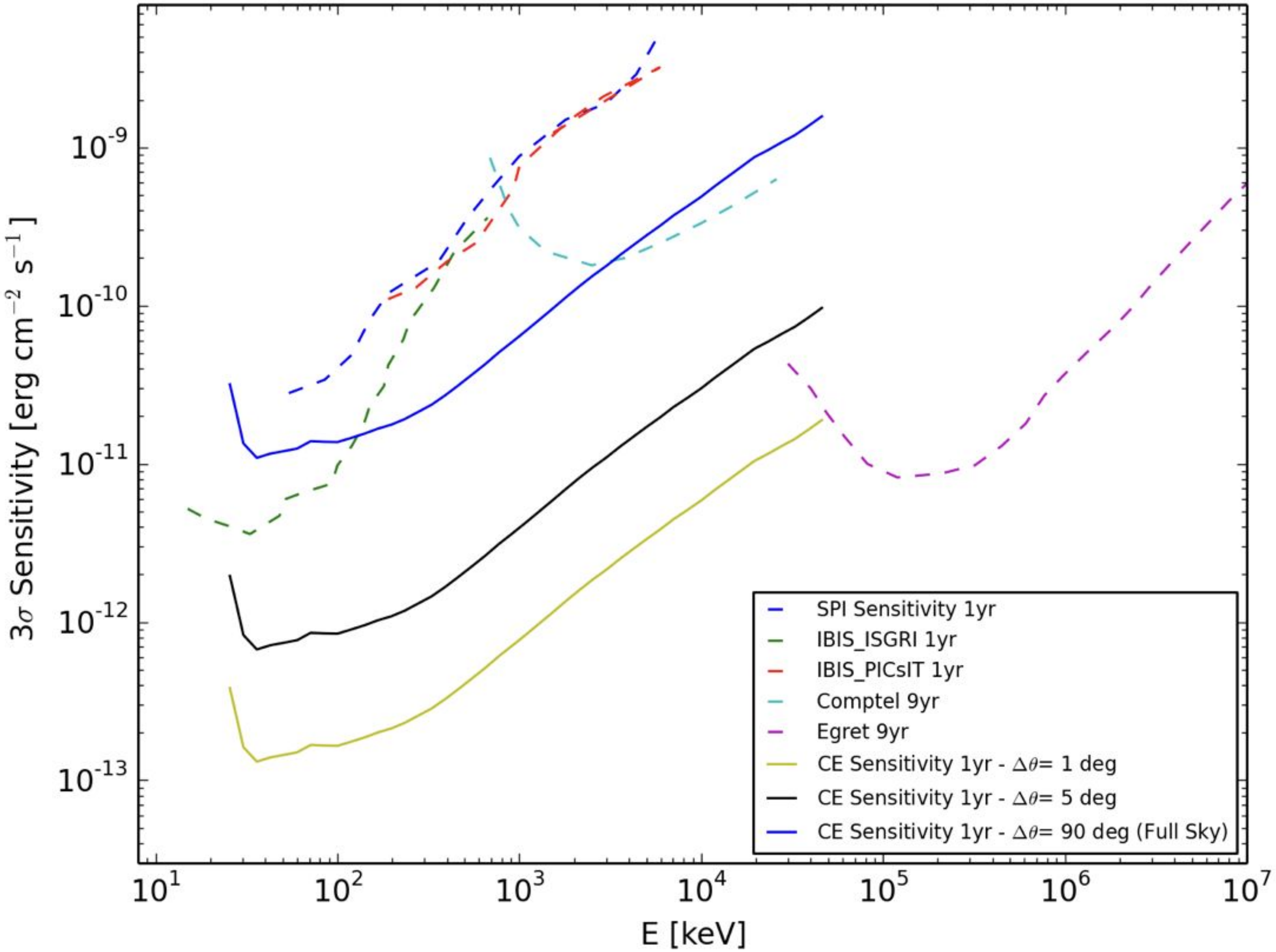
CONTINUUM SENSITIVITY

Continuum sensitivity at the N_σ significance level for a Tobs observation time is defined as follows:

$$S = \frac{N_\sigma}{0.68}\sqrt{\frac{B\,\Delta\Omega_{68}}{A_{eff}\,T_{obs}\,\Delta E}}$$

Where B is the background level, A_{eff} the effective area within a energy bin ΔE.

This sensitivity depends on the angular resolution of the instrument. Here on the left are the 1 year sensitivity curves for different assumed theta resolutions (analogous to PSF 68% containment).



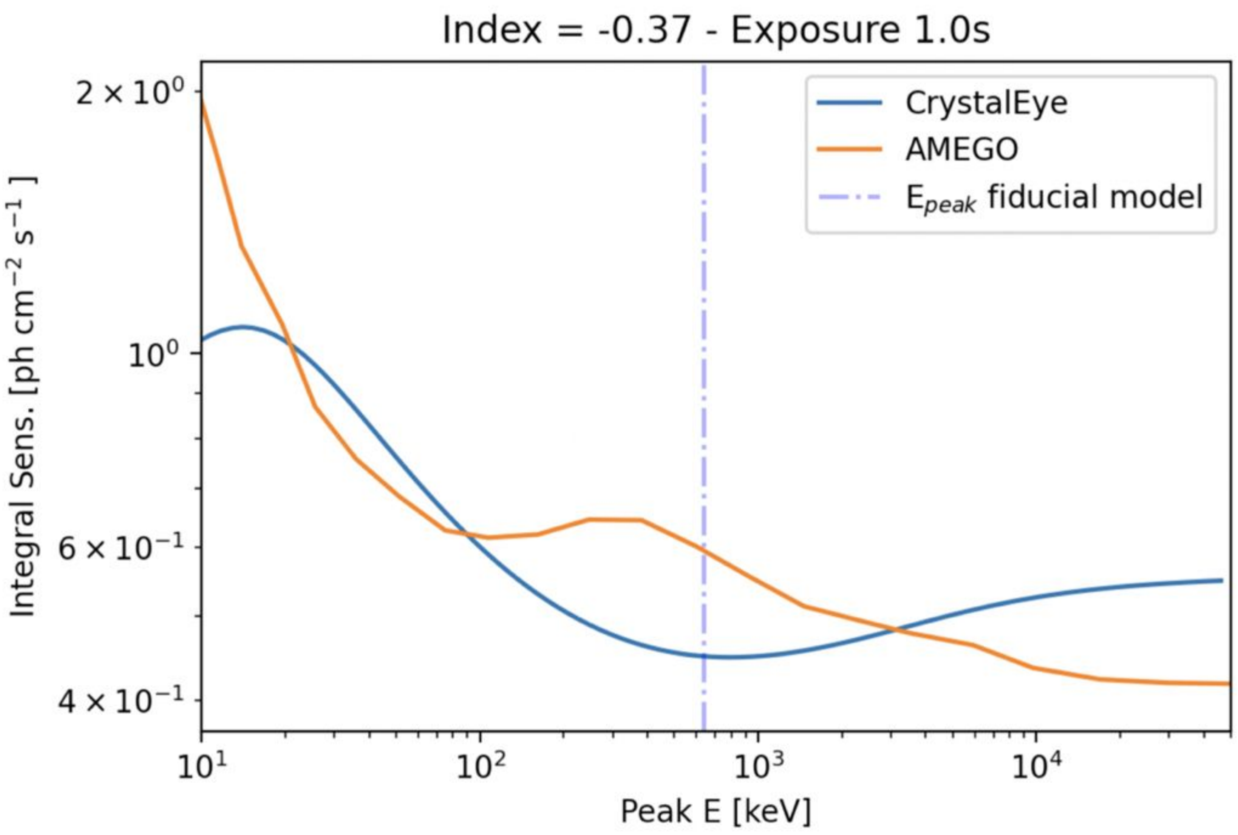
This sensitivity is computed from the following signal/noise ratio:

$$\frac{S}{N} = \frac{N}{\sqrt{N+B}}$$

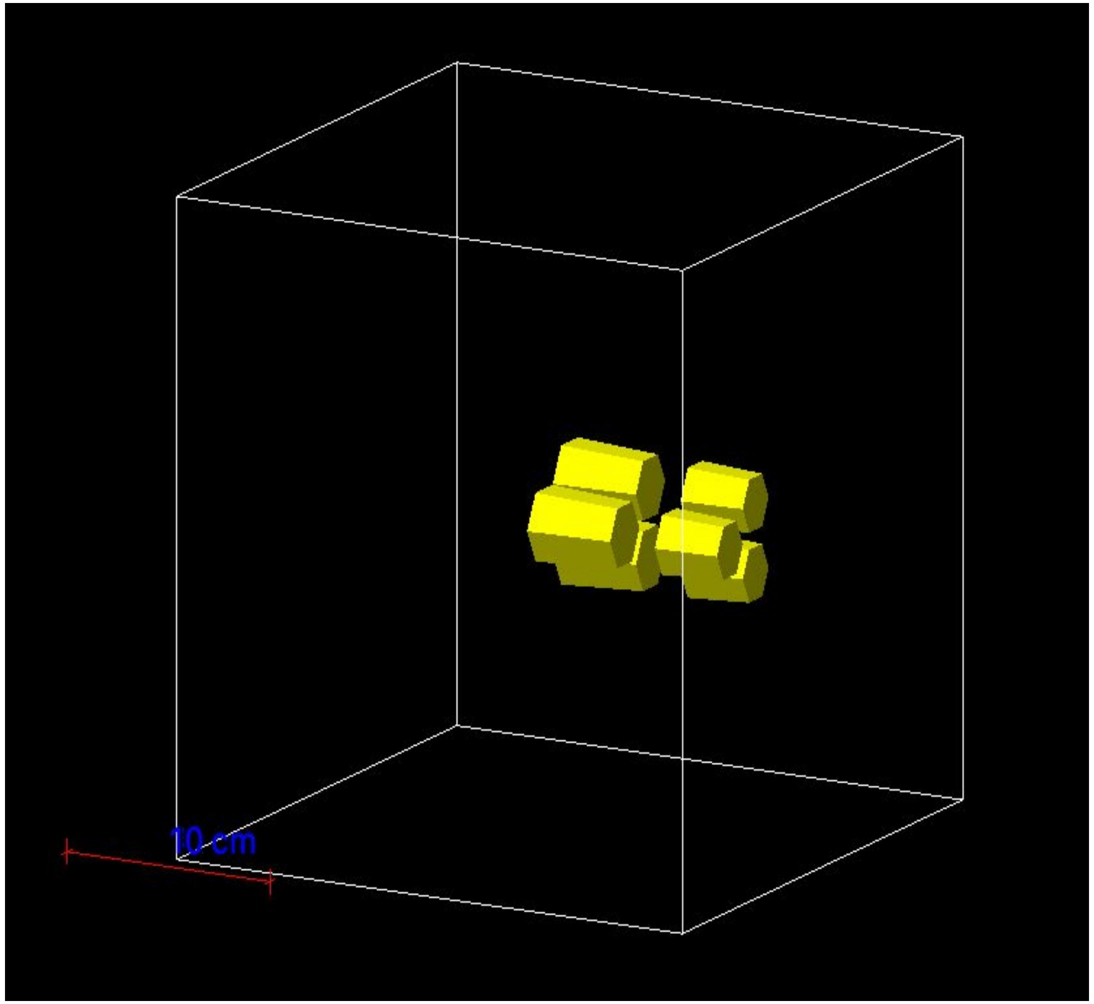
Where N is the number of counts from an assumed source spectral model and B the background count level.

The plot shows the integrated sensitivity (1s exposure time) for an assumed GRB comptonized model, as a function of the peak energy of the model.

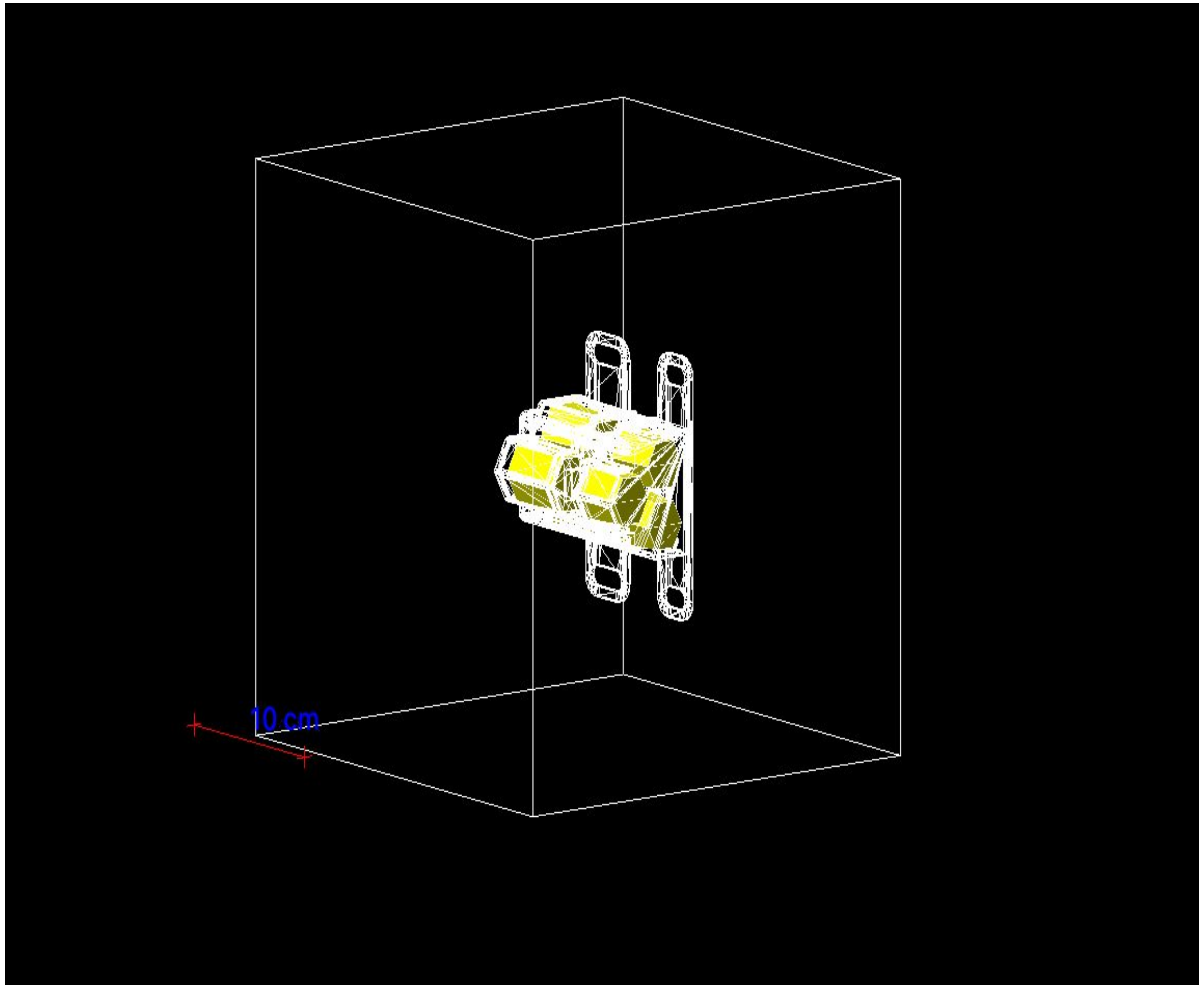
$$\frac{dN}{dE} = A_{norm} \left(\frac{E}{E_0}\right)^{\gamma} exp\left(-\frac{E(\gamma+2)}{E_{peak}}\right)$$



SIMULATION DESIGN



Without structure

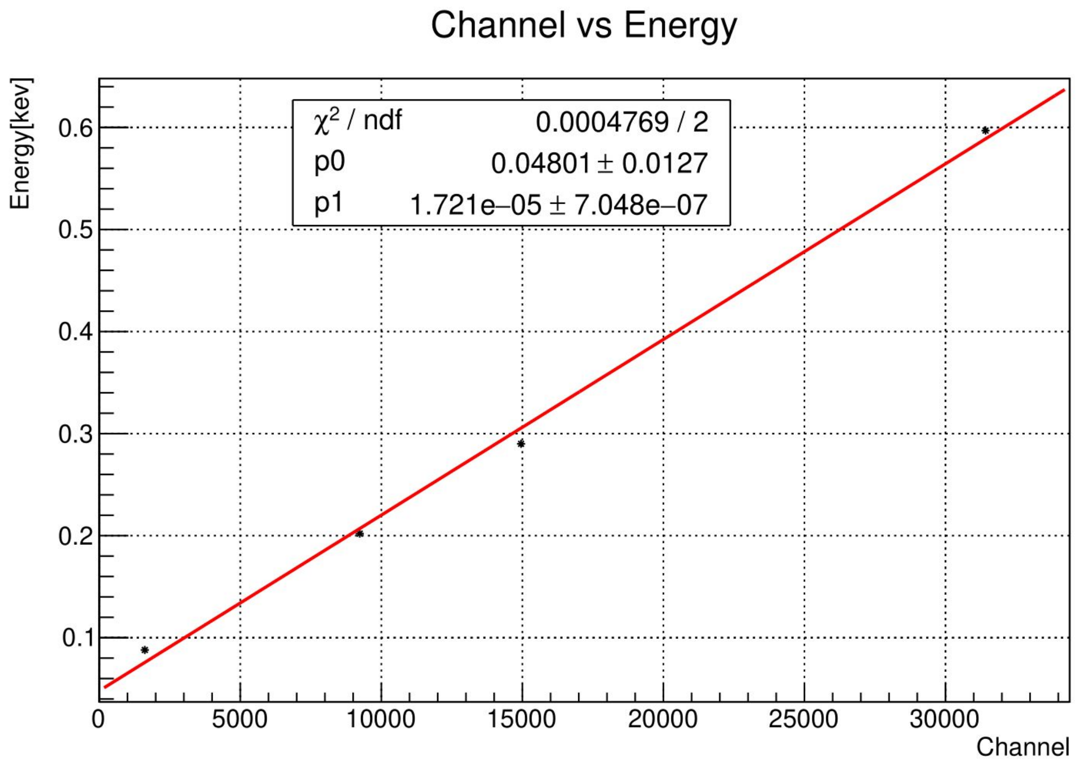


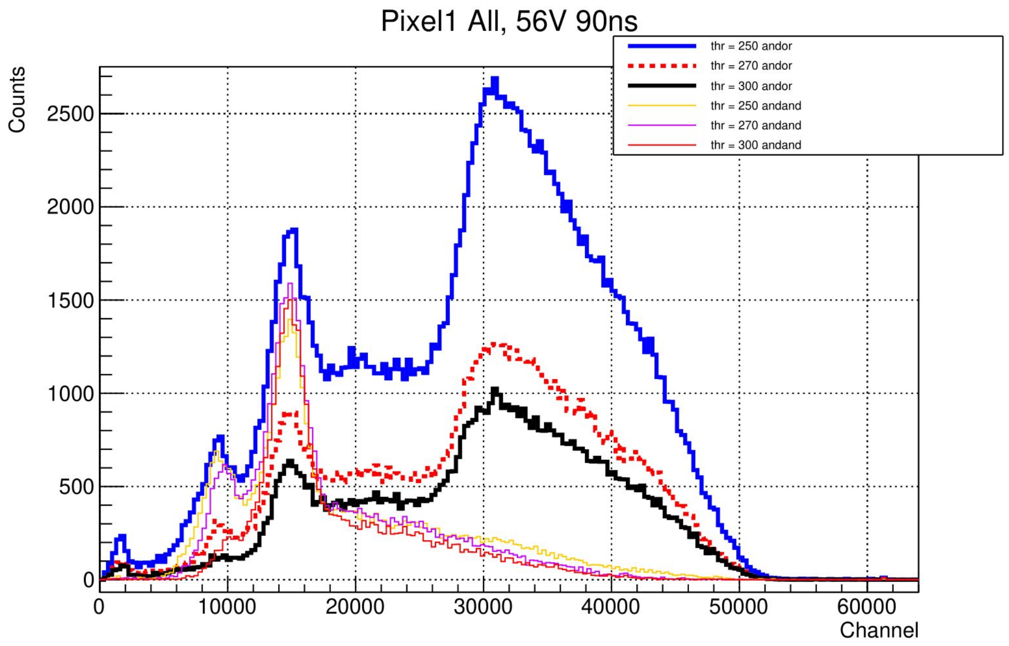
With structure

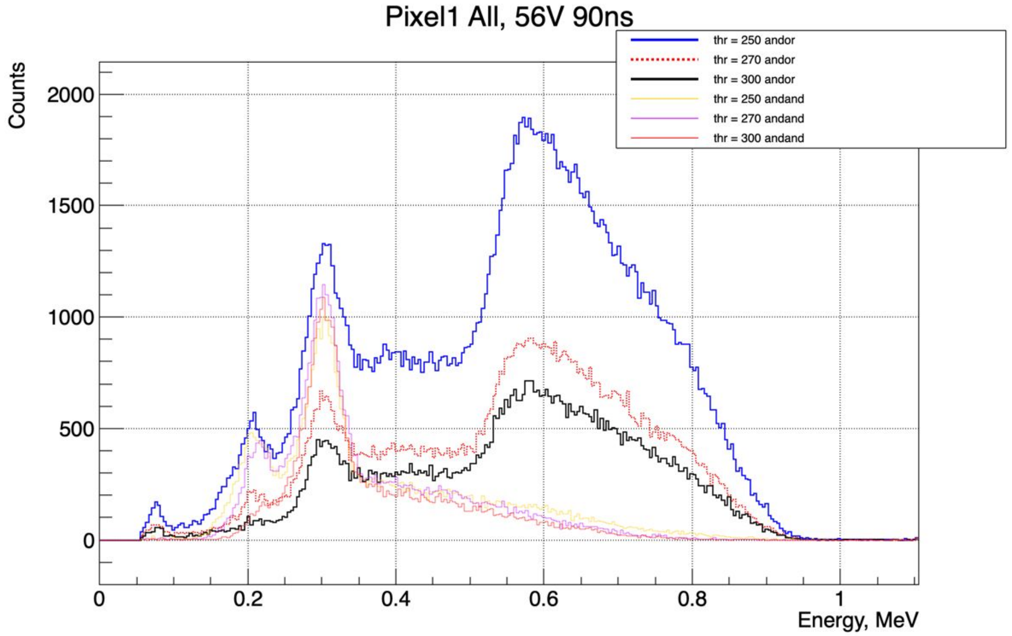
MEASUREMENT SPECTRA

CONFIGURATION

- Shaping time 87.5 ns
- Gate coincidence 90 ns
- High voltage 56 V
- High gain - 5 units







SIMULATION SPECTRUM

1. Calculate the expected number of decay events that would occur within the 100-second time window, based on the source activity and the half-life.

2. Generate a simulation of this number of decay events, using a Monte Carlo method.

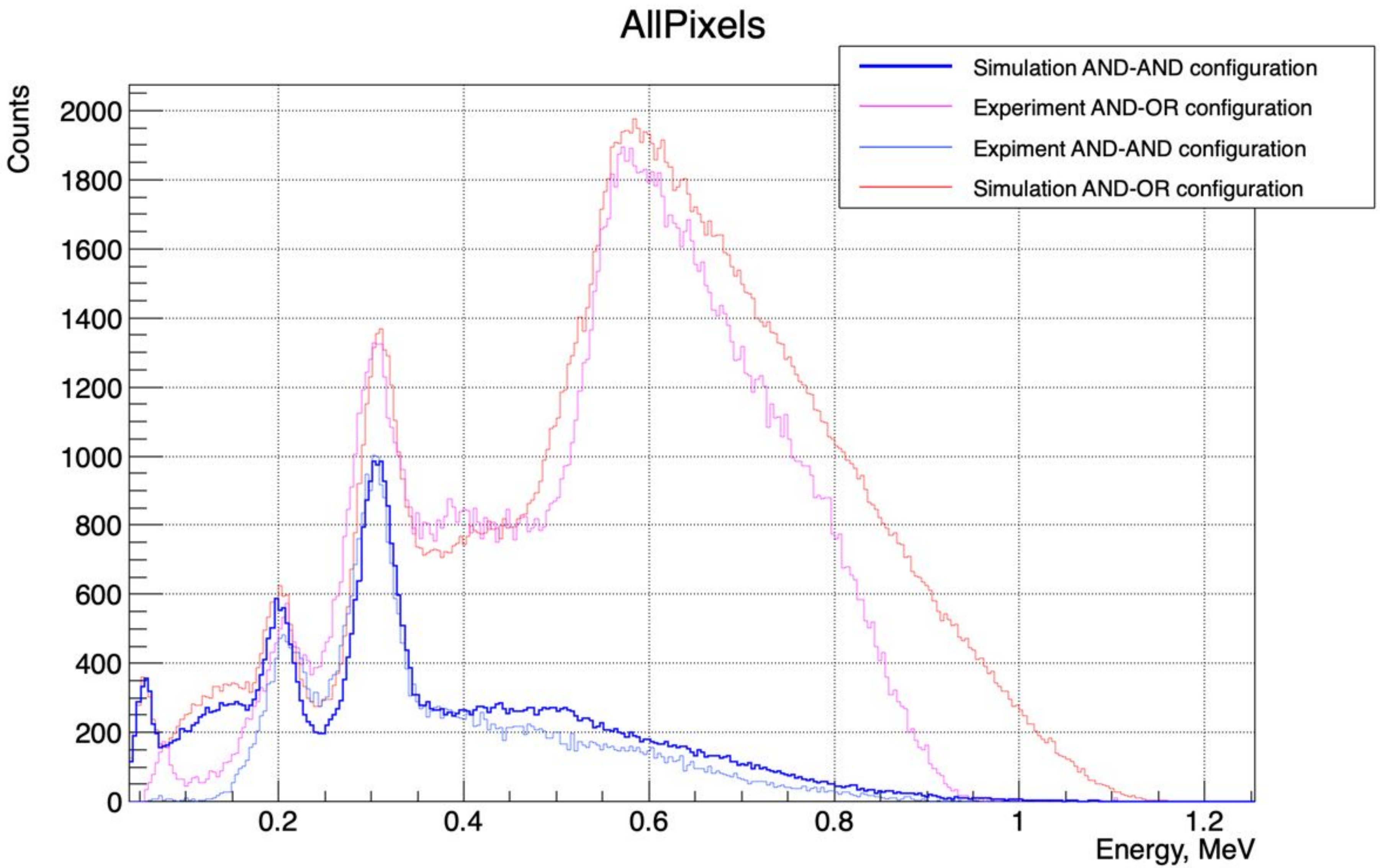
3. For each decay event, calculate the energy deposited in the detector by the decay products, using a detector response simulation.

4. Assign a random time value to each decay event, sampled from a distribution that reflects the decay time distribution of the source. This can be a uniform distribution, assuming a constant rate of decay.

5. Sort the events by time and use a Poisson distribution to determine the number of events that occur in each time bin. This generates a simulated energy spectrum for the given time window.

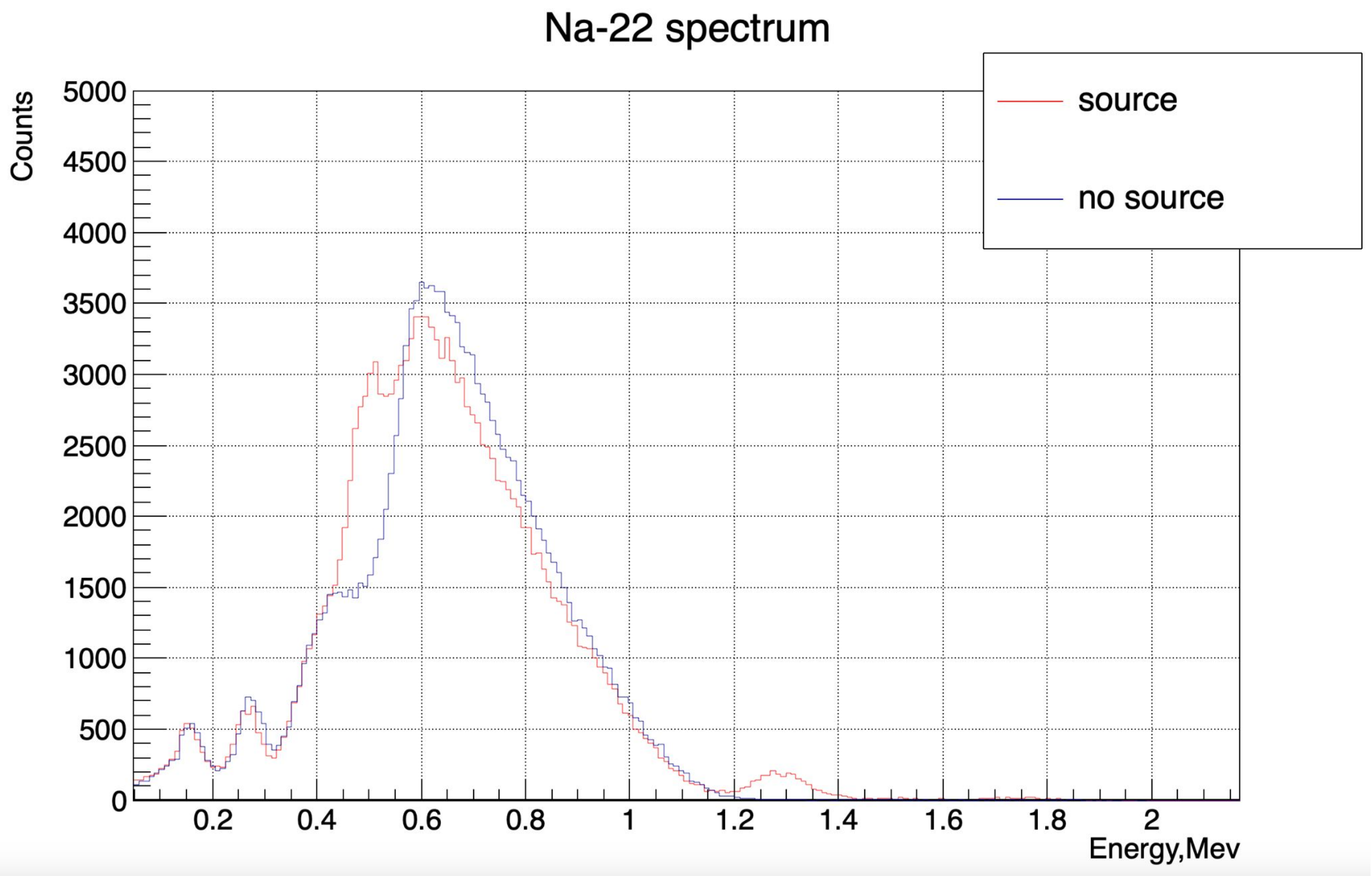
6. Apply Calibration Curve to smear simulation result

SIMULATION SPECTRUM



LYSO (Lutetium Yttrium Orthosilicate) is a popular scintillating material used for radiation detection due to its high light output, good energy resolution, and fast decay time.

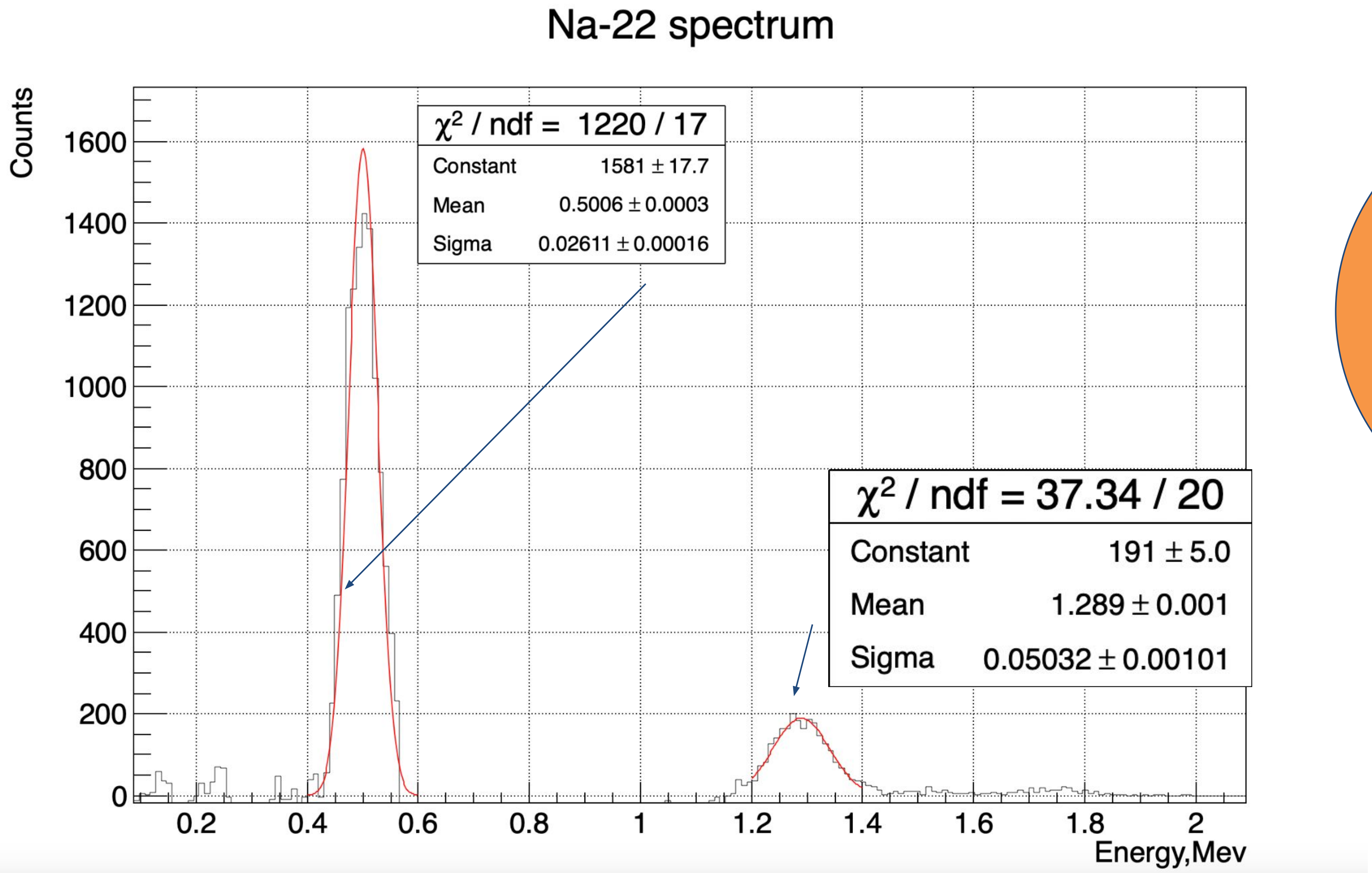
We have a spectrum generated from a LYSO scintillator with Na-22. Na-22 decays through beta-plus decay and results in two gamma photons with energies of 511 keV, which are used for energy calibration. In addition to the primary 511 keV gamma radiation emitted as a result of positron annihilation, Na-22 decay also leads to a characteristic secondary peak. This is due to a subsequent nuclear de-excitation process.



Comparing these two spectra, we can observe the impact of Na-22 on the energy spectrum. The prominent peak at 511 keV is due to the gamma radiation from Na-22 decay. This peak is used to calibrate and test our detection system, ensuring accurate energy measurements.

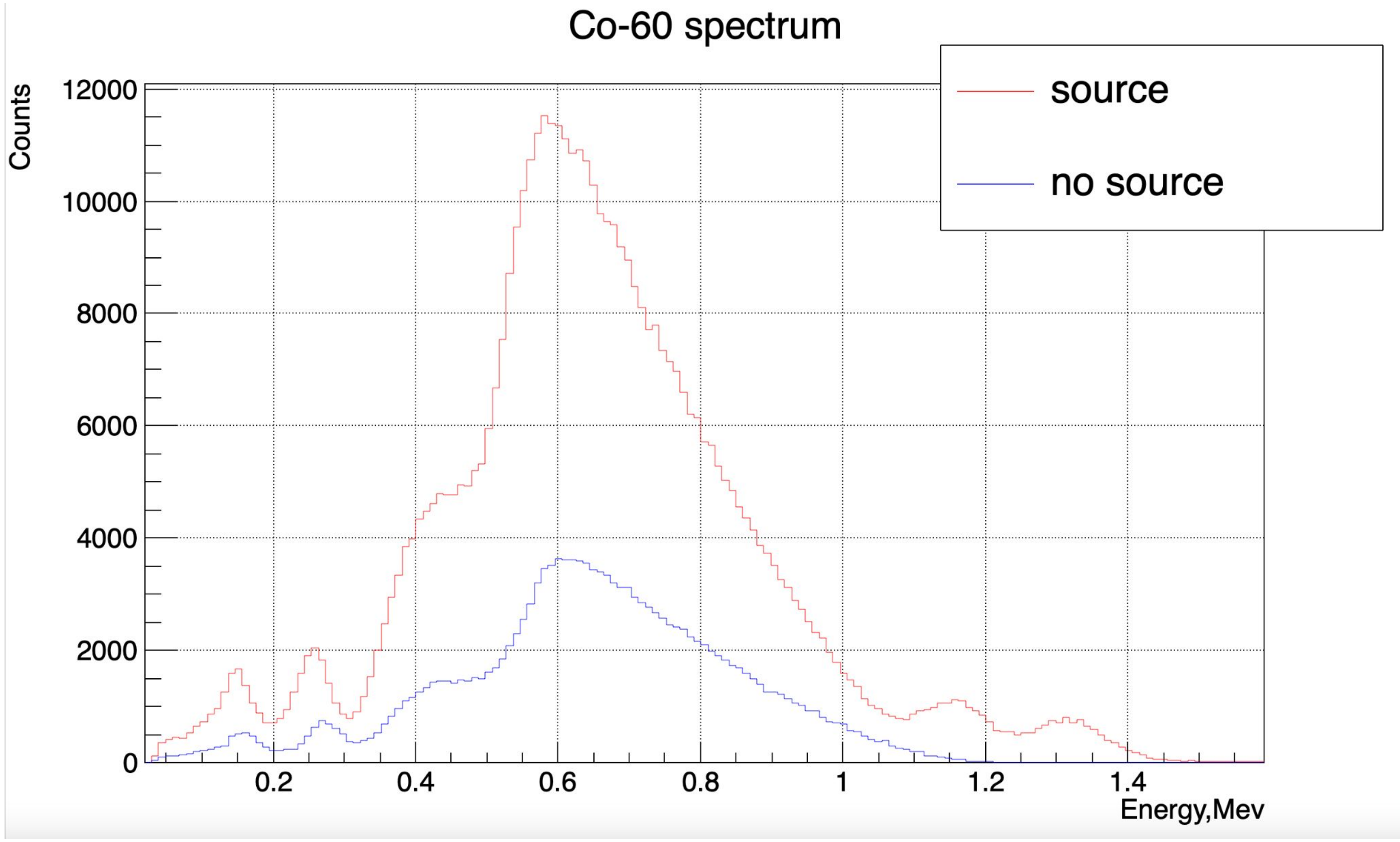
The histogram subtraction method is a technique commonly used in data analysis, especially in radiation spectroscopy. In this process, we subtract the spectrum of the LYSO scintillator alone from the combined LYSO + Na-22 spectrum. See the next slide.

Subtraction Spectrum

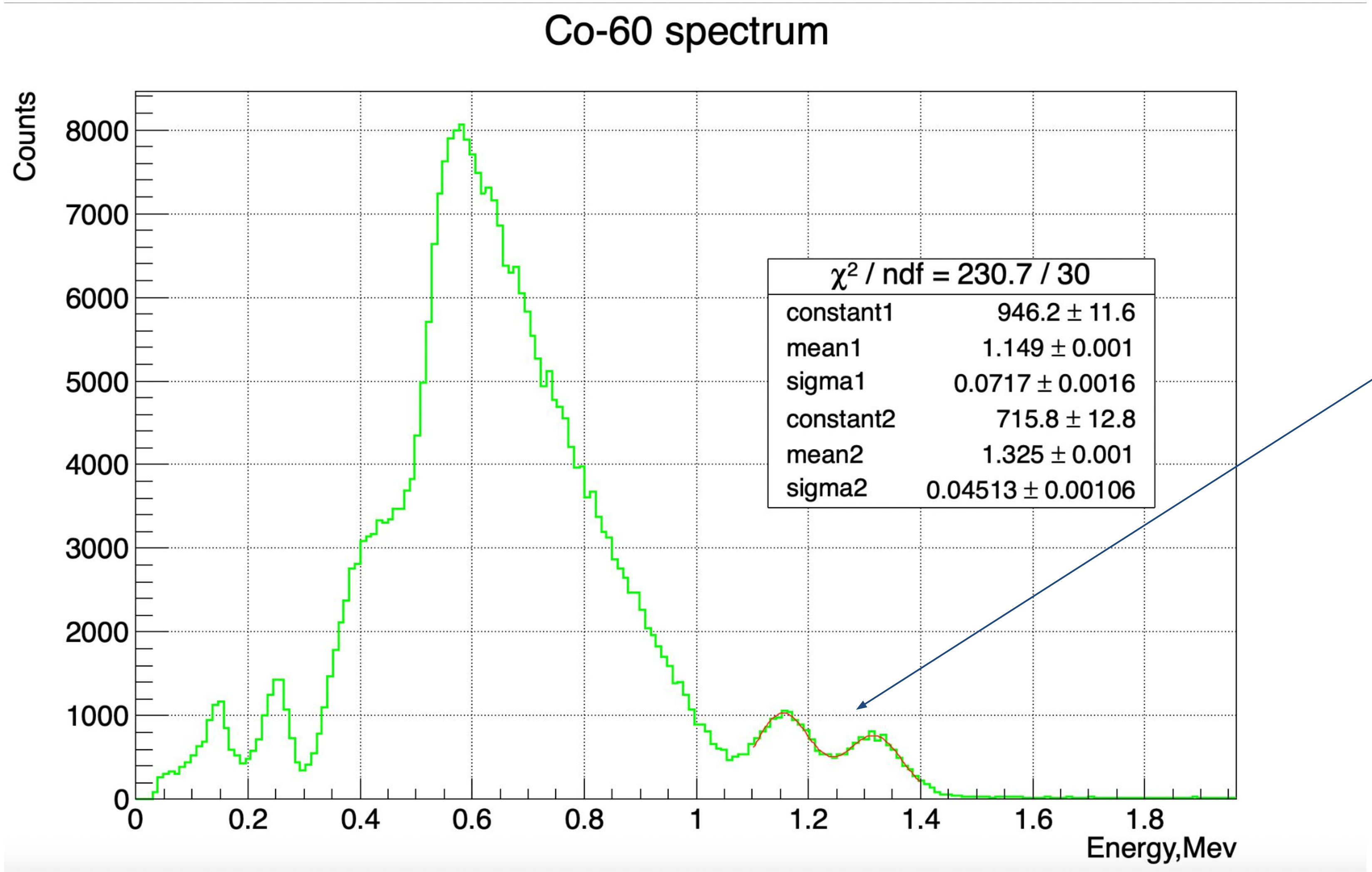


We used Gaussian fits to determine the precise energy levels corresponding to the 511 keV and 1275 keV peaks

Cobalt-60 decays by beta decay into Nickel-60, a process during which it emits two gamma rays with energies of 1.17 and 1.33 MeV, respectively. These two gamma rays provide distinct peaks in the energy spectrum.



Subtraction Spectrum



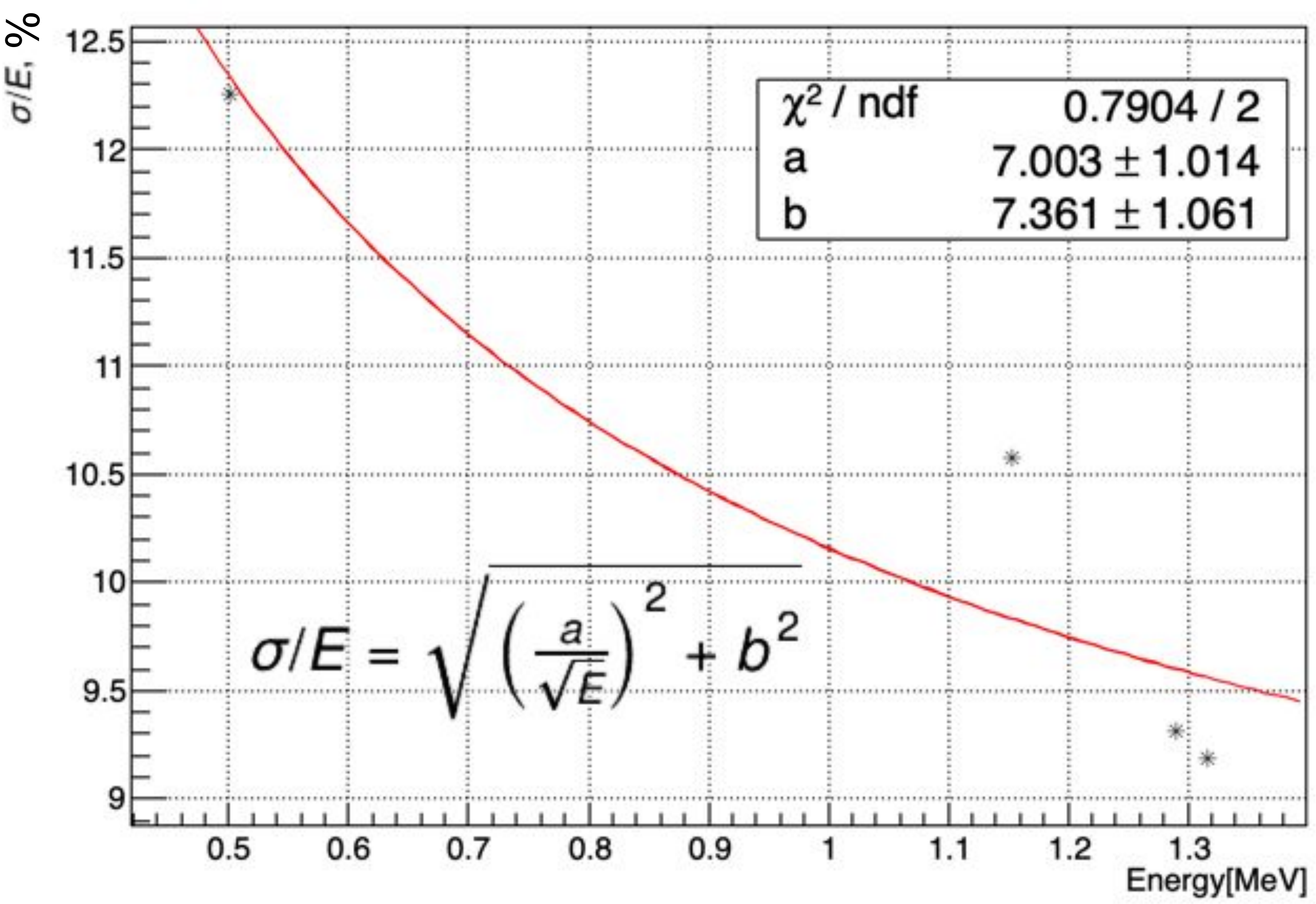
We used double Gaussian fit to determine the precise energy levels

Resolution

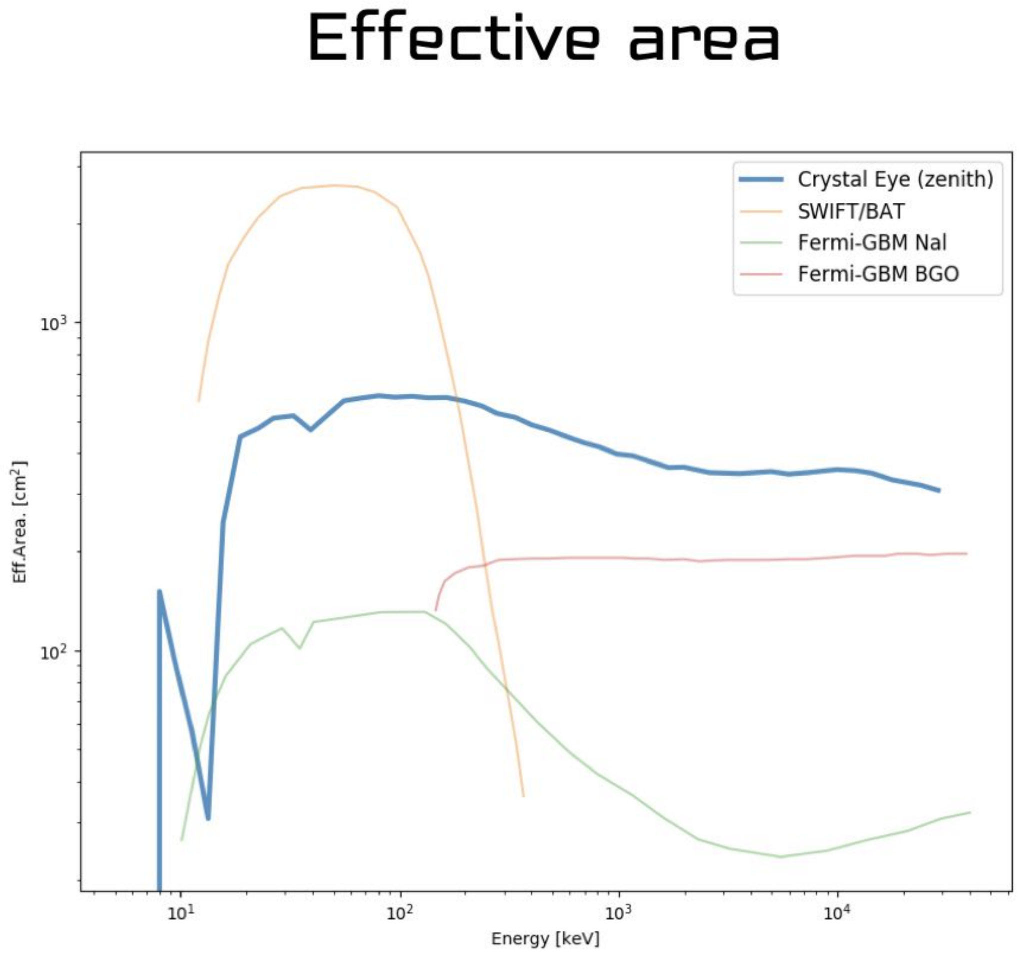
$$R_E = \frac{\text{FWHM}}{E} = \frac{2.355\sigma}{E}$$

The formula for calculating resolution is given by R , where σ represents the width of the peak (standard deviation) and E represents the center of the peak (mean). Essentially, this formula gives us the full width at half maximum (FWHM) as a percentage of the mean energy, providing a measure of how well our detector can resolve distinct energy levels.

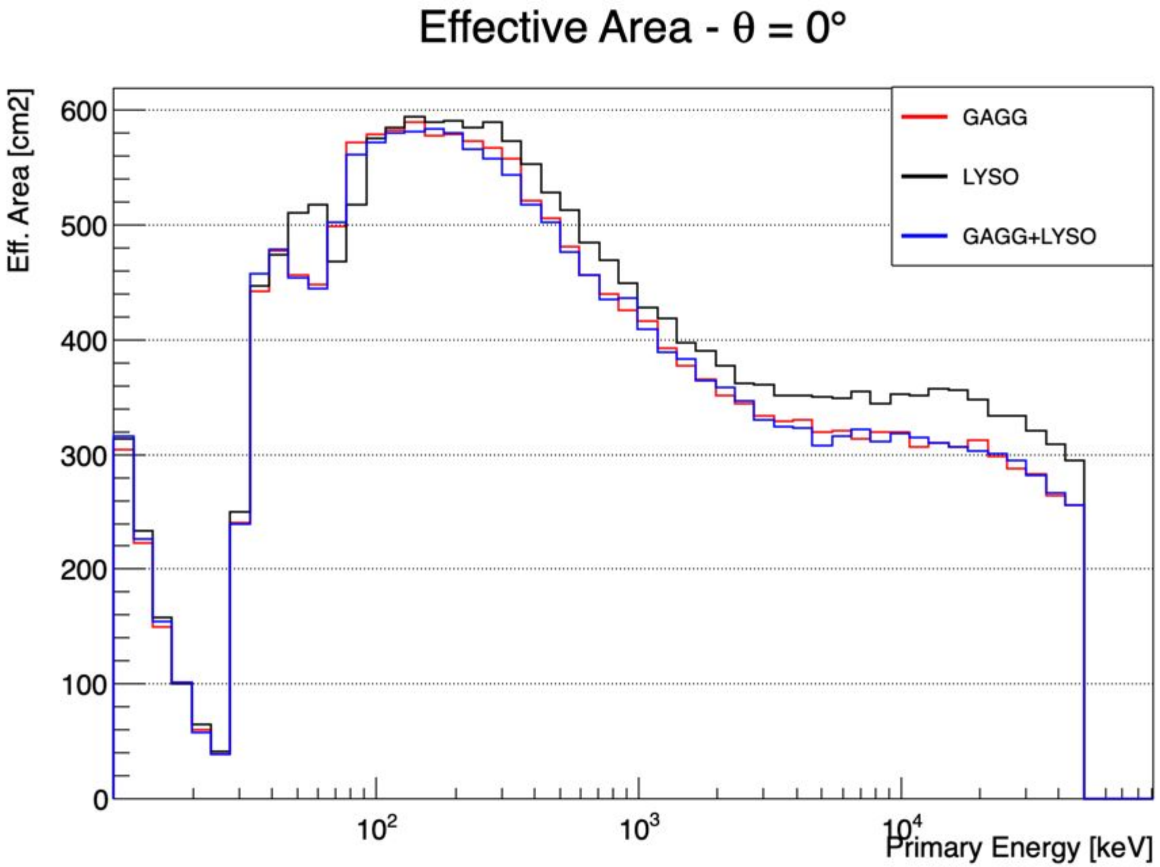
For each peak in our spectra – whether it's the 511 keV and 1275 keV peaks from the Na-22 source, or the 1.17 MeV and 1.33 MeV peaks from the Cobalt-60 source – we calculate the resolution using the aforementioned formula. This enables us to assess the performance of our detector across different energy levels



CRYSTAL EYE PERFOMANCE

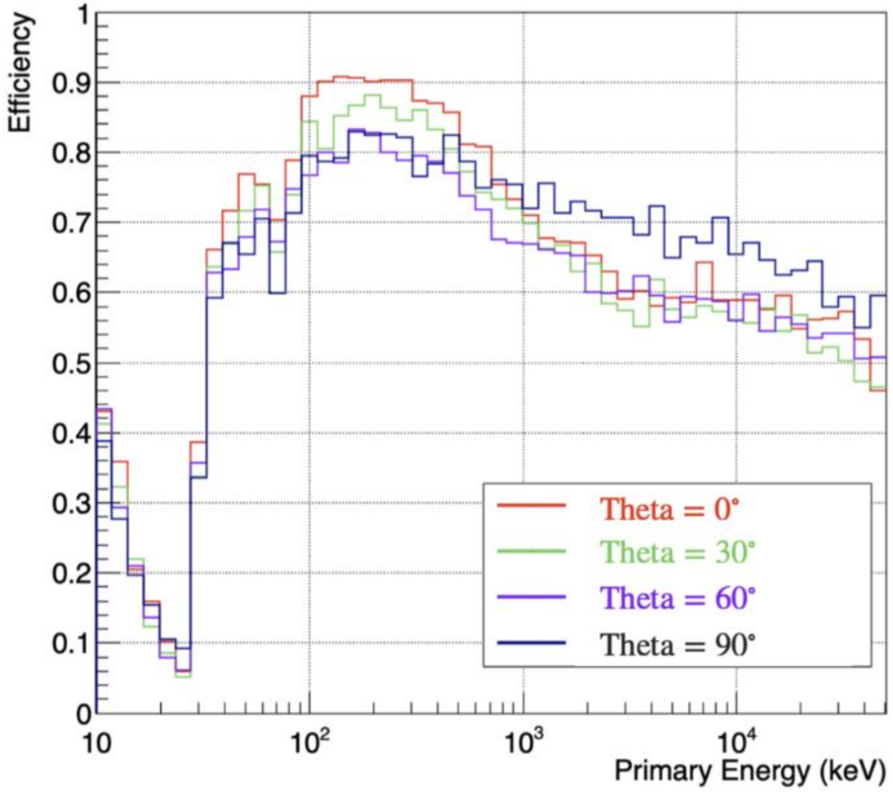


Comparing Detector Effective Areas



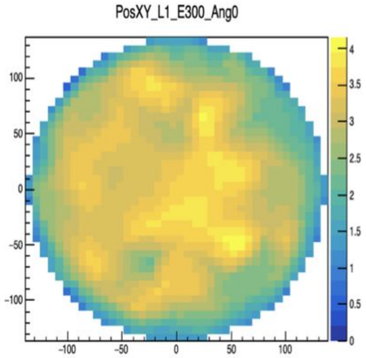
Effective area was calculated considering LYSO and GAGG scintillating crystals for the pixel material

CRYSTAL EYE PERFOMANCE



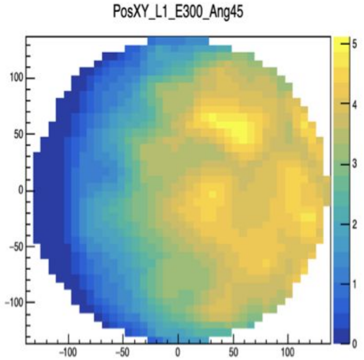
Efficiency in th i-th bin is defined as follows:

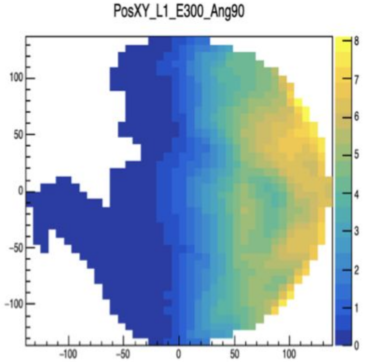
$\epsilon_i = \frac{n_i}{N_i}$, with n the number of events after the selection cuts and N are the simulated number of events in the field of view hitting the detector.



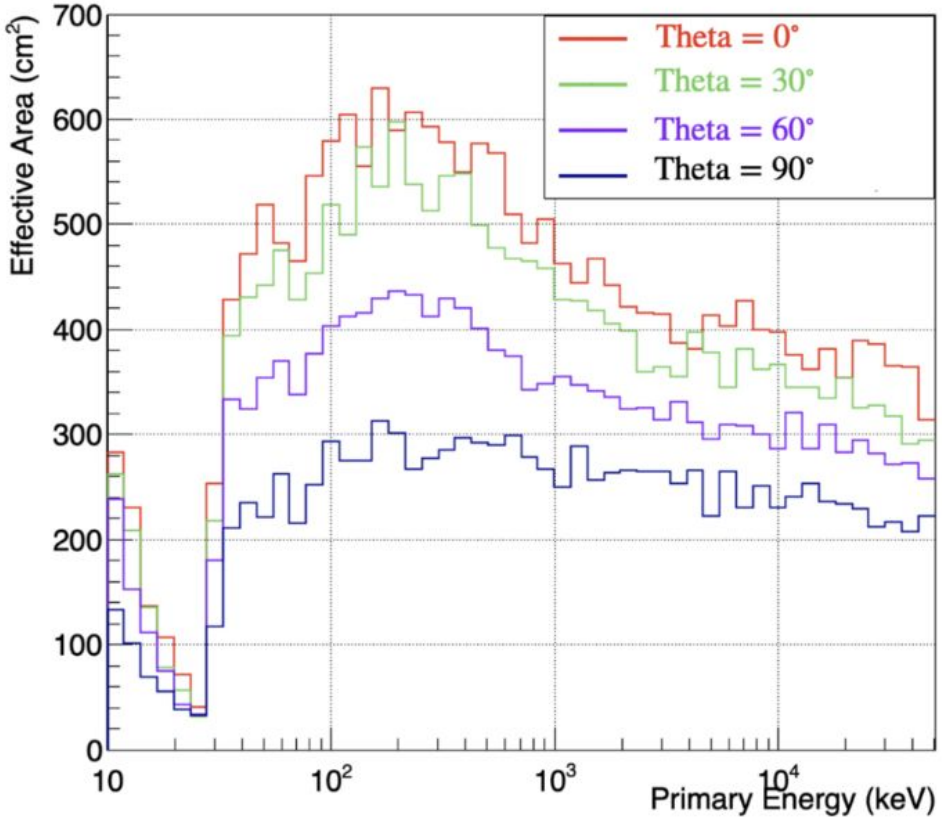
0°

45°



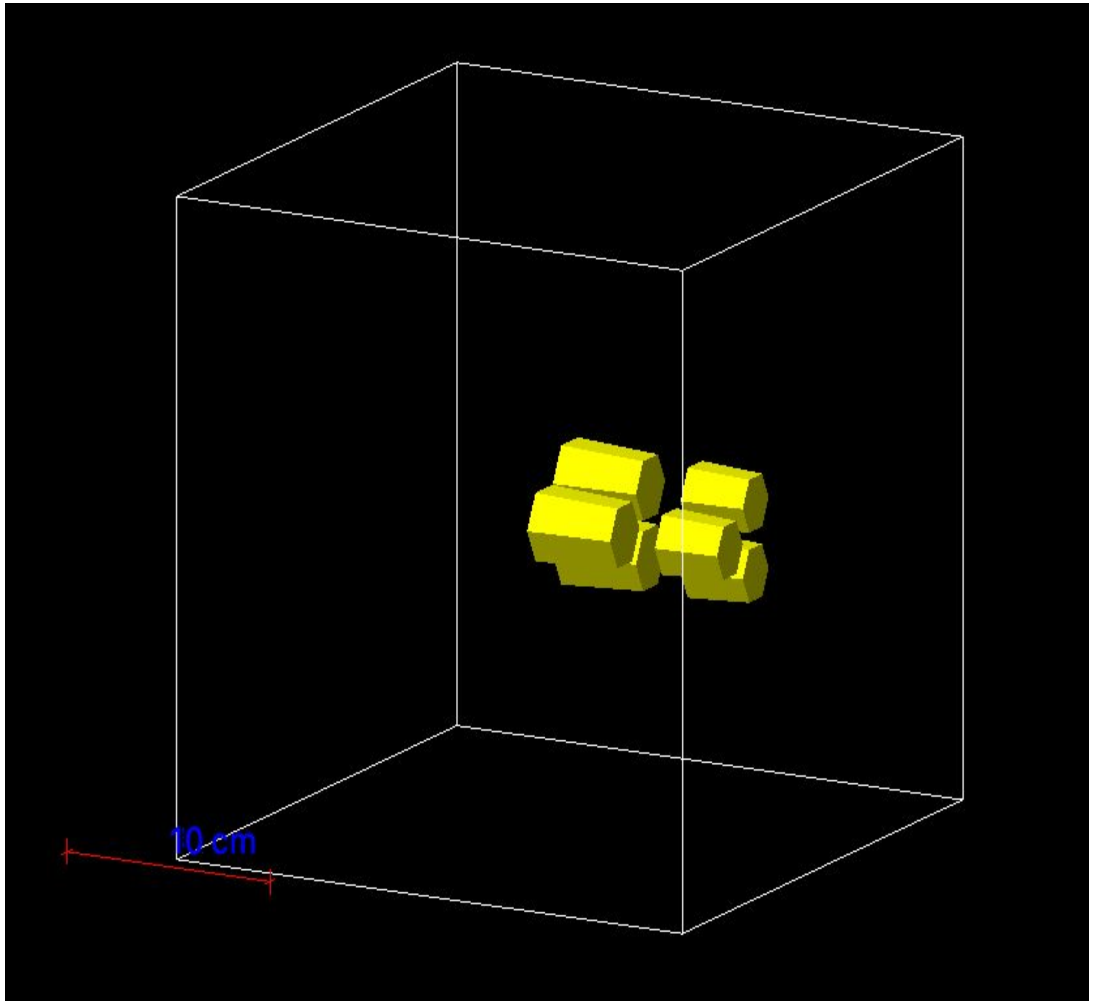


90°

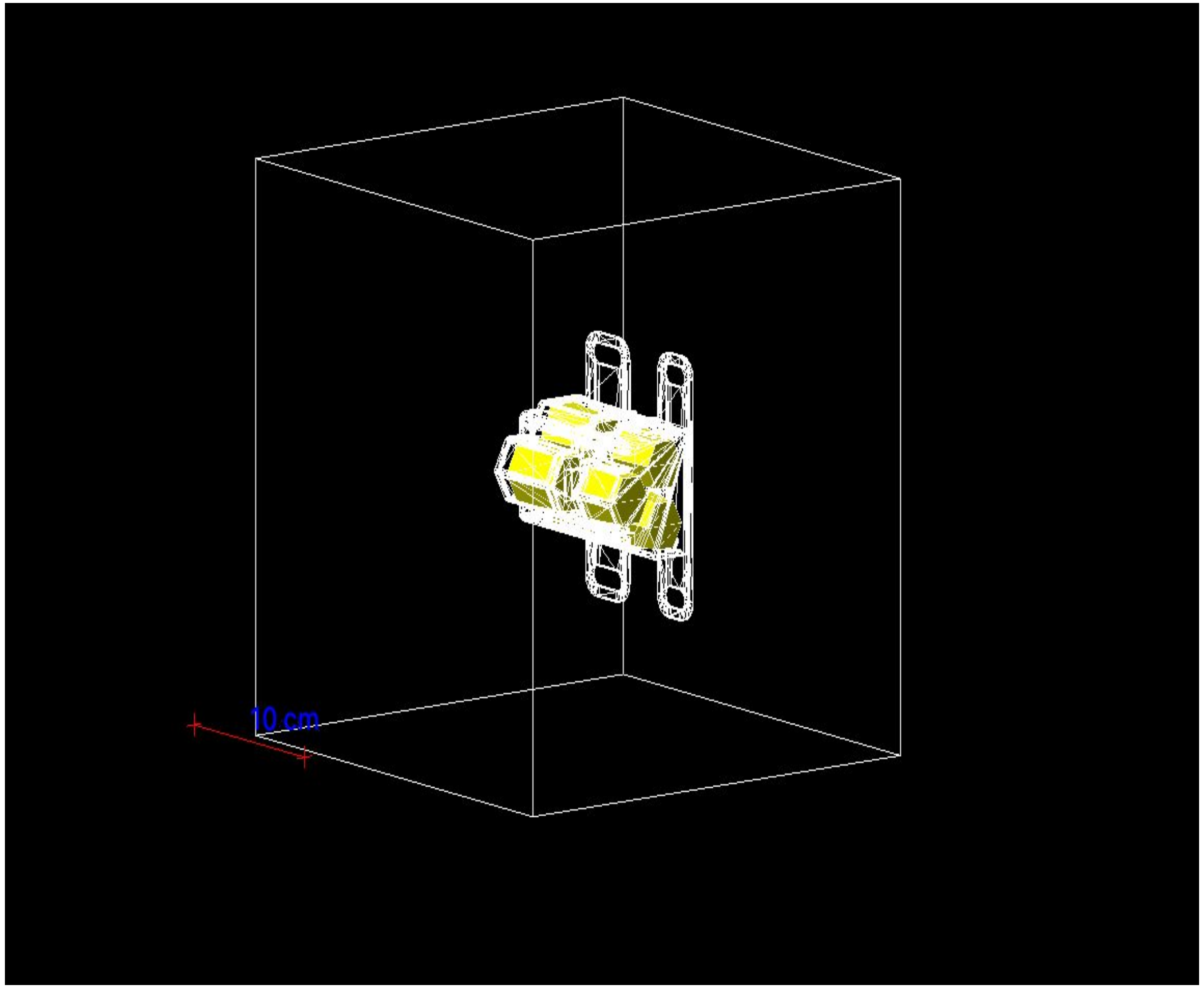


The effective area in the i-th bin is defined as follows: $A_{eff_i} = \frac{n_i}{N_i} \times A_{source}$, with n the number of events after the selection cuts, N the total number of simulated events and A_{source} the surface area of the source where gamma rays are generated.

Simulation Design

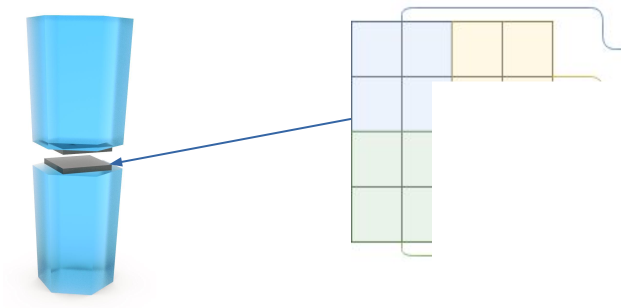


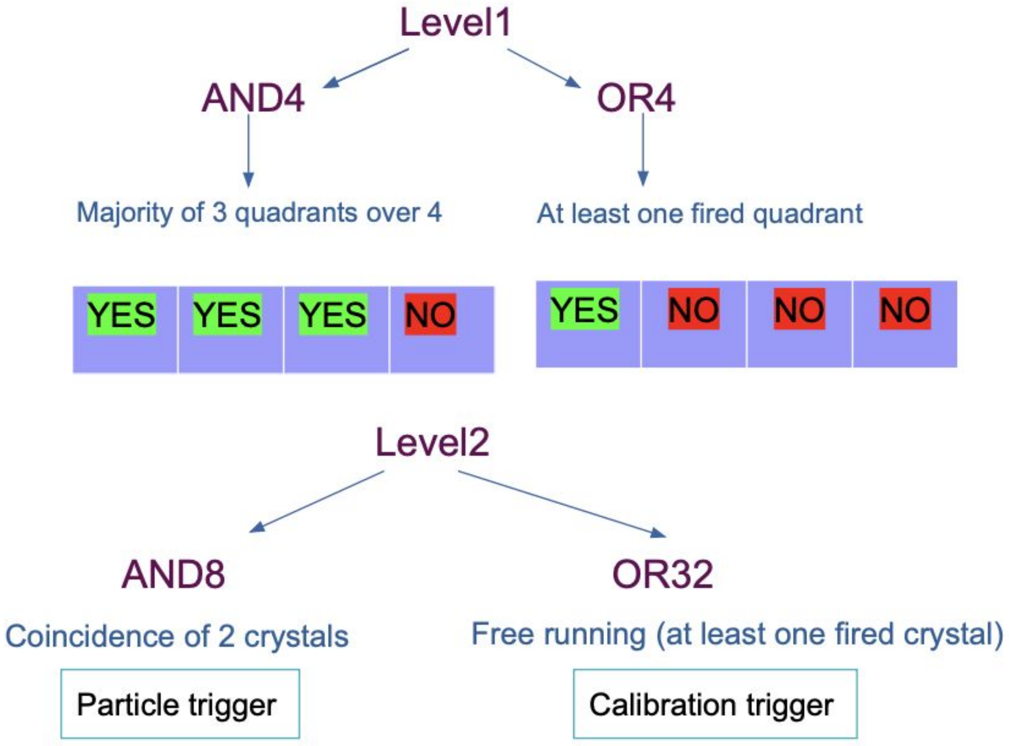
Without structure

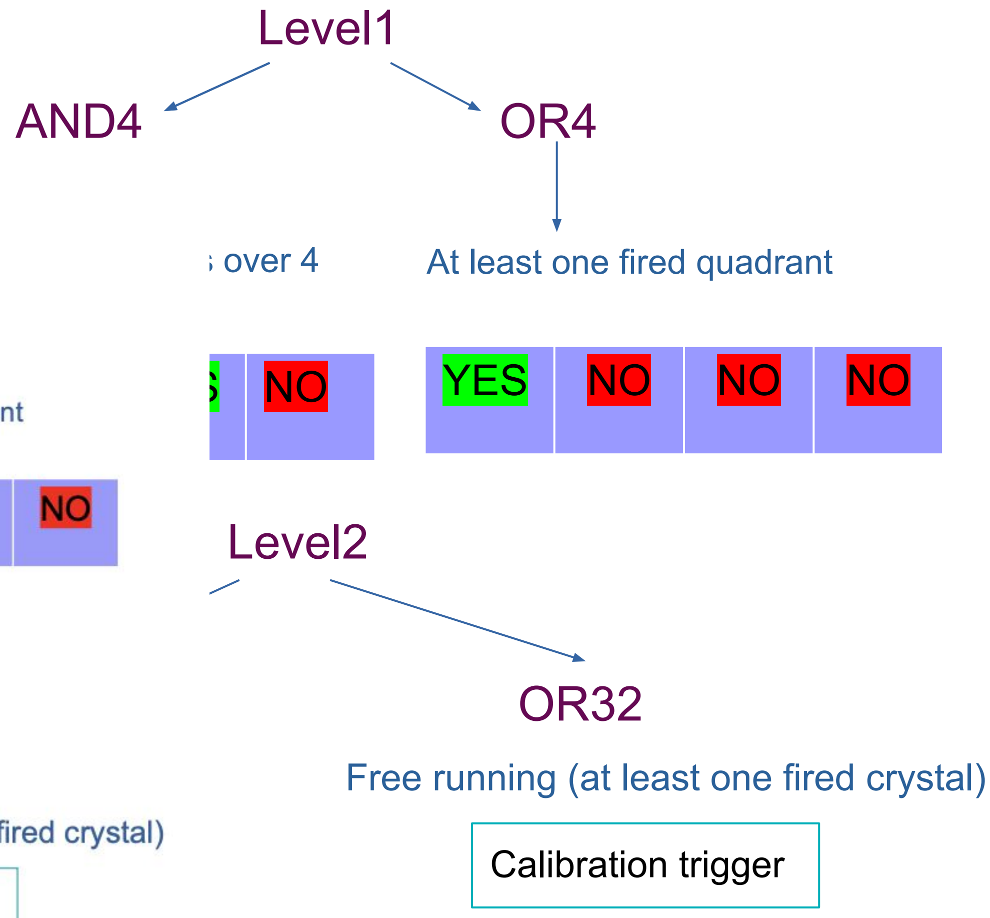


With structure

TRIGGER LOGIC







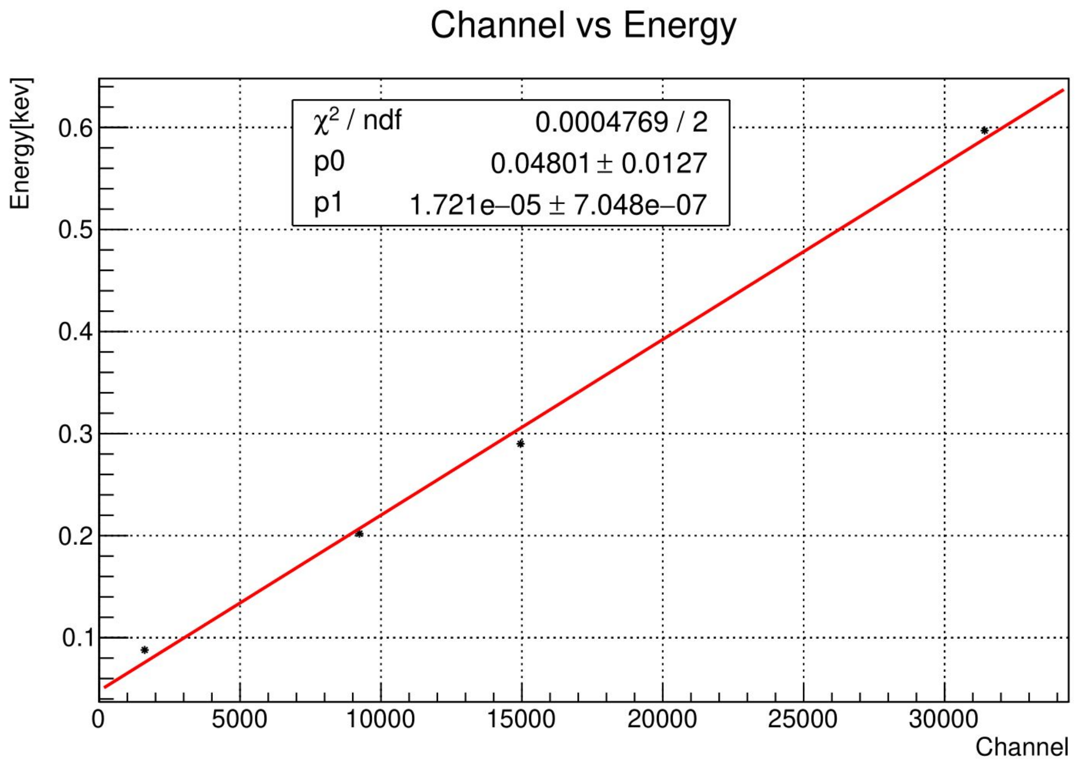
AND4 — AND8
to extract backg

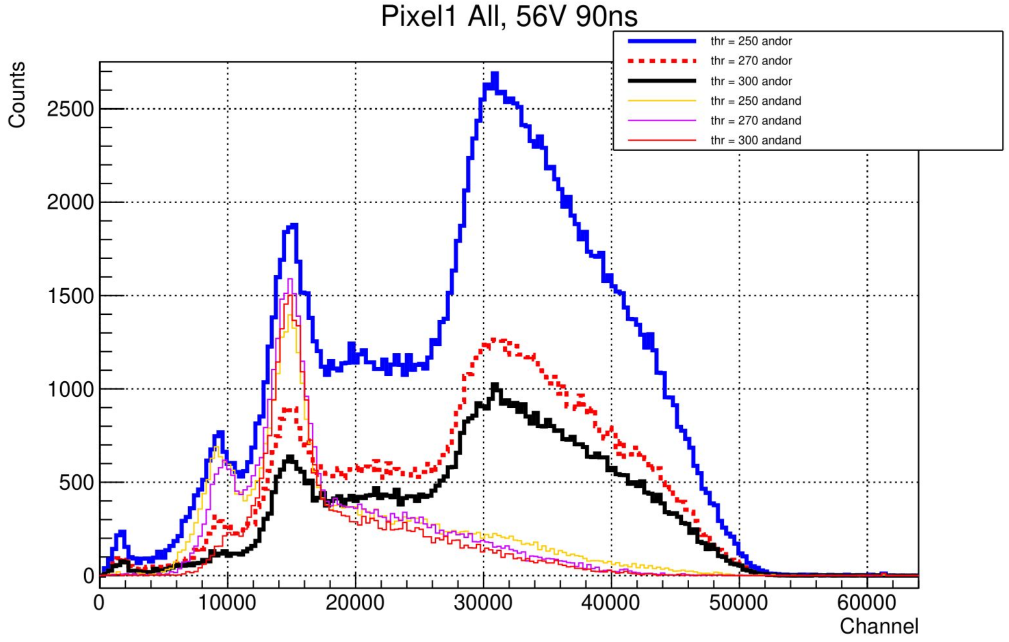
OR4 — OR32 L
do calibration

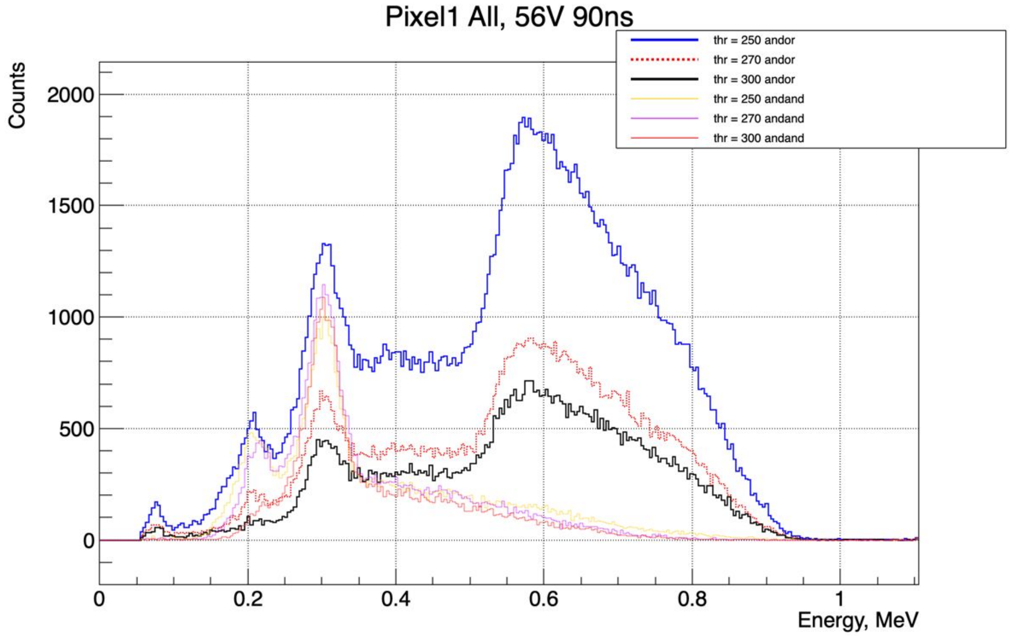
Measurement spectrum

CONFIGURATION

- Shaping time 87.5 ns
- Gate coincidence 90 ns
- High voltage 56 V
- High gain - 5 units







SIMULATION SPECTRUM

1. Calculate the expected number of decay events that would occur within the 100-second time window, based on the source activity and the half-life.

2. Generate a simulation of this number of decay events, using a Monte Carlo method.

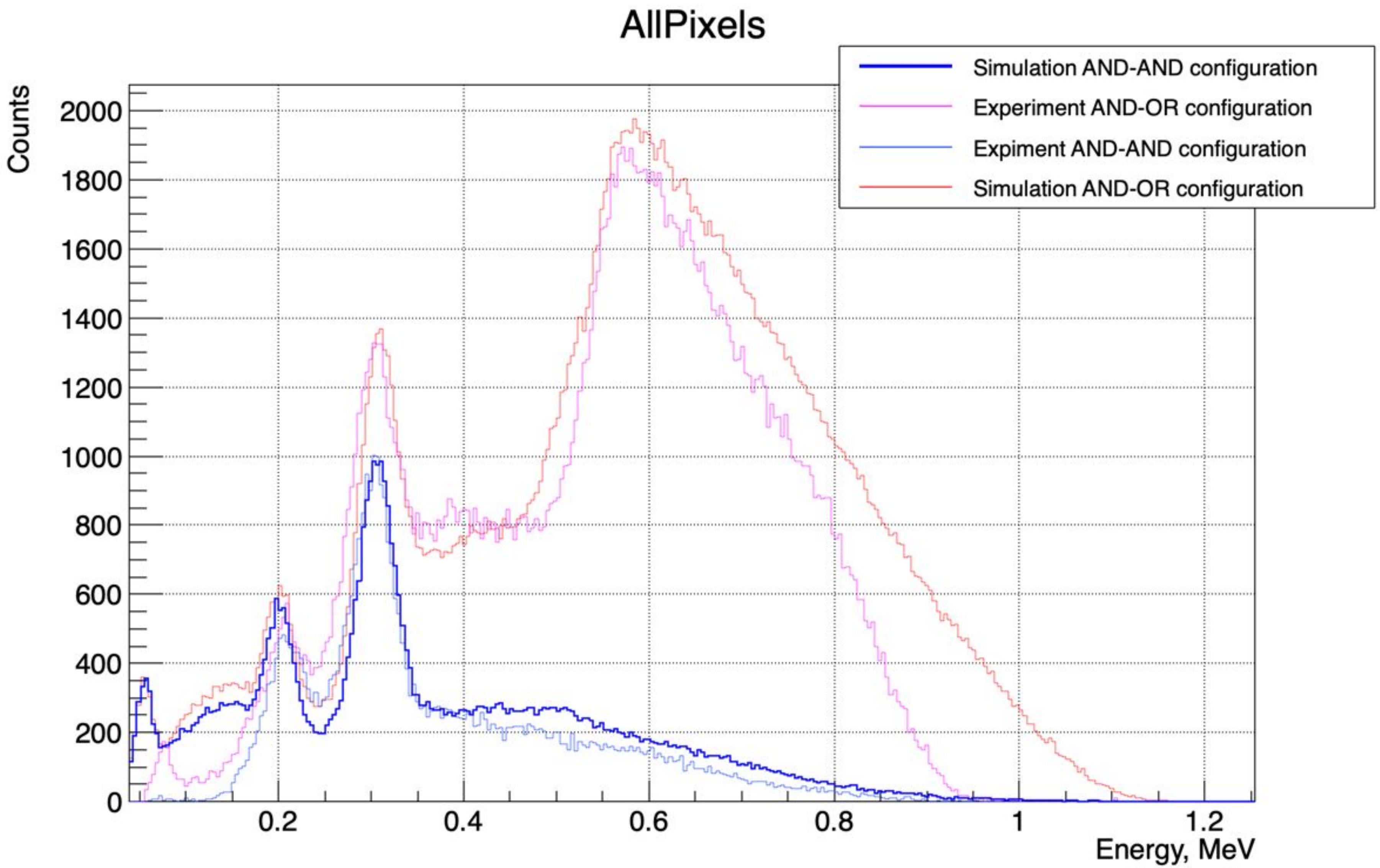
3. For each decay event, calculate the energy deposited in the detector by the decay products, using a detector response simulation.

4. Assign a random time value to each decay event, sampled from a distribution that reflects the decay time distribution of the source. This can be a uniform distribution, assuming a constant rate of decay.

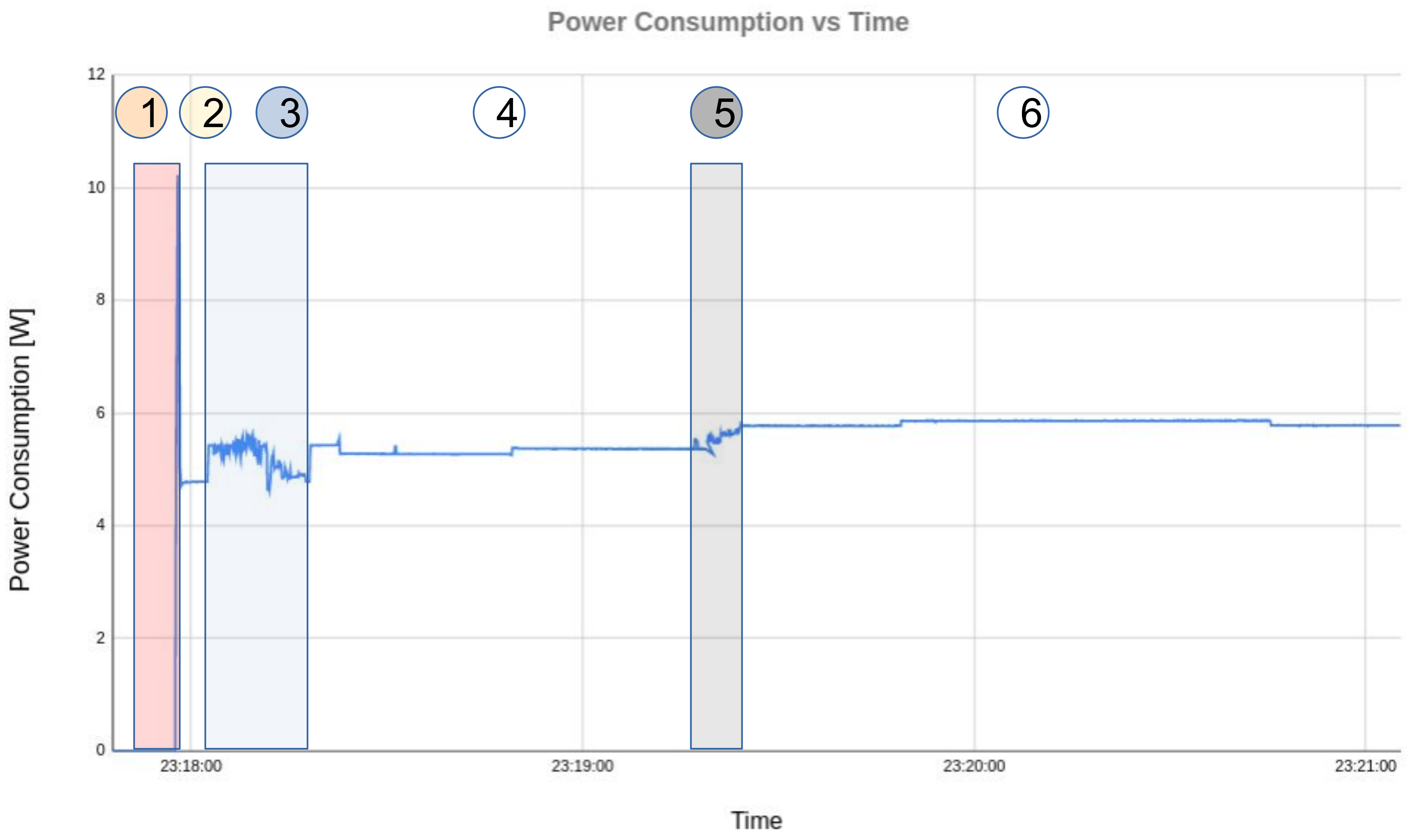
5. Sort the events by time and use a Poisson distribution to determine the number of events that occur in each time bin. This generates a simulated energy spectrum for the given time window.

6. Apply Calibration Curve to smear simulation result

SIMULATION SPECTRUM

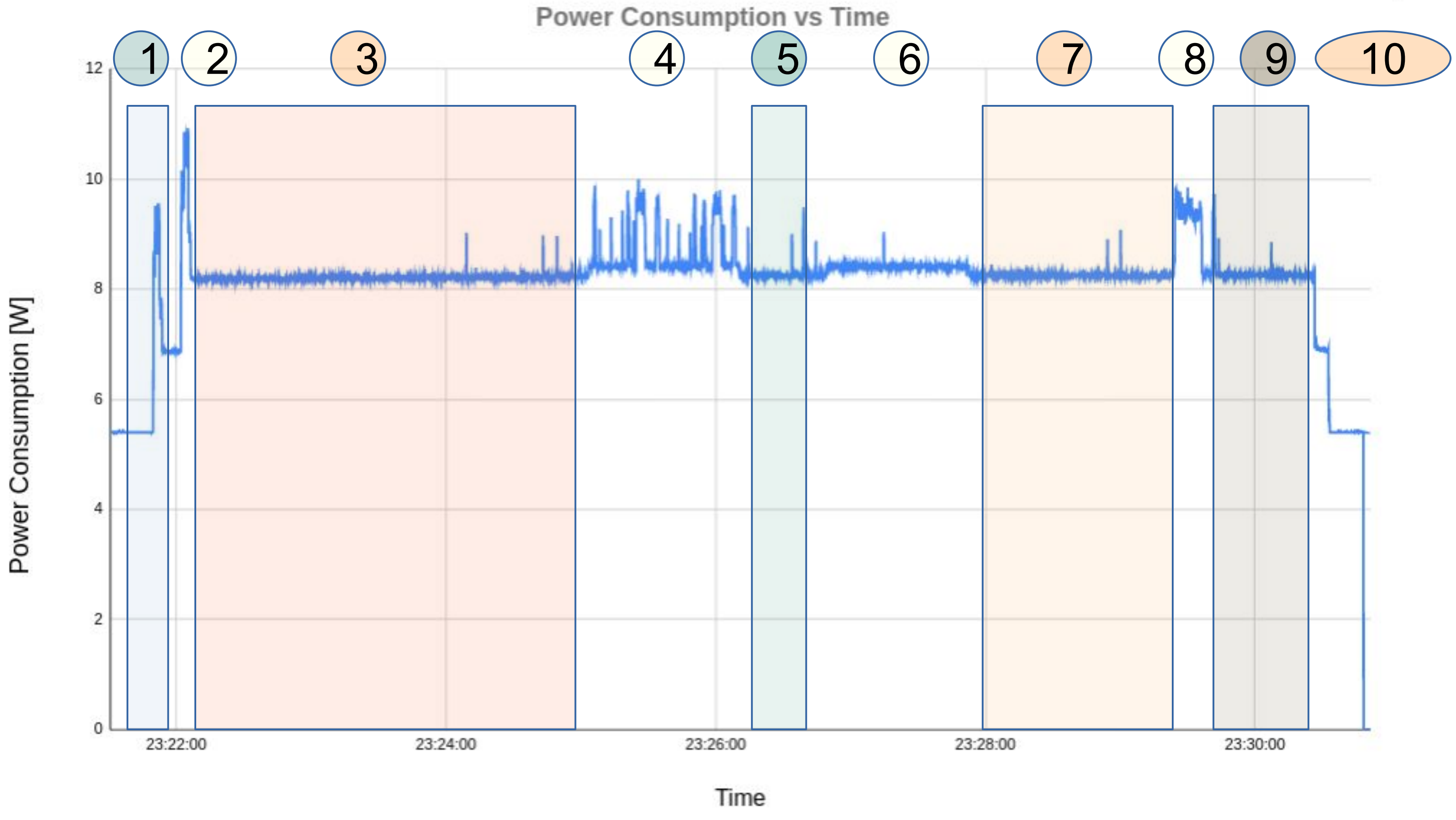


POWER CONSUMPTION



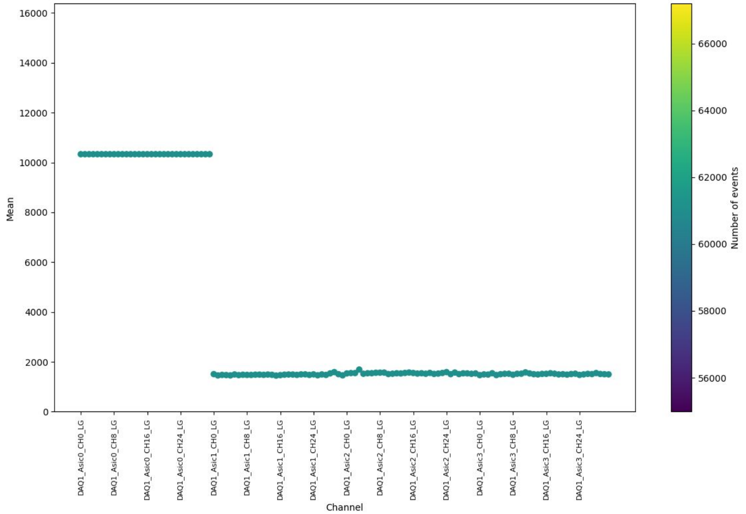
1. Switch on the board (spike)
2. IDLE mode
3. Autoboot
4. Boot
5. HV-SIPM ON
6. Data Acquisition

POWER CONSUMPTION

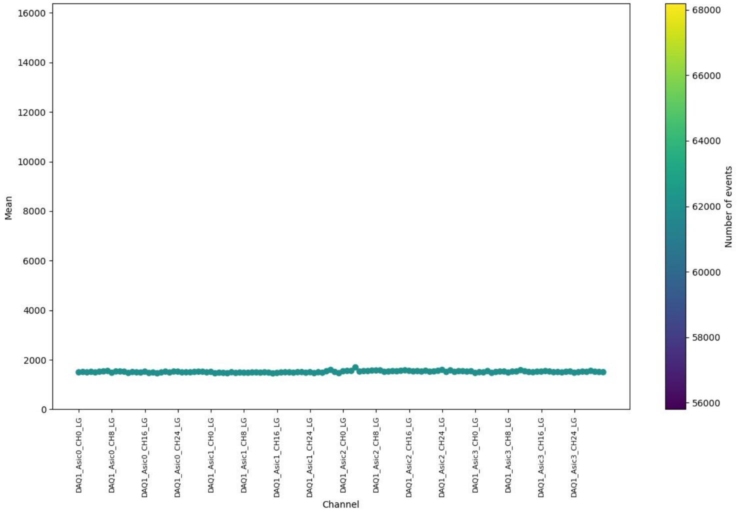


1. Disk1 ON
2. Disk2 ON
3. IDLE
4. Writing on disk 1
5. IDLE
6. Writing on ZYNQ
7. IDLE
8. Writing on disk 2
9. IDLE
10. Disk 1 off, disk 2 off, switch off

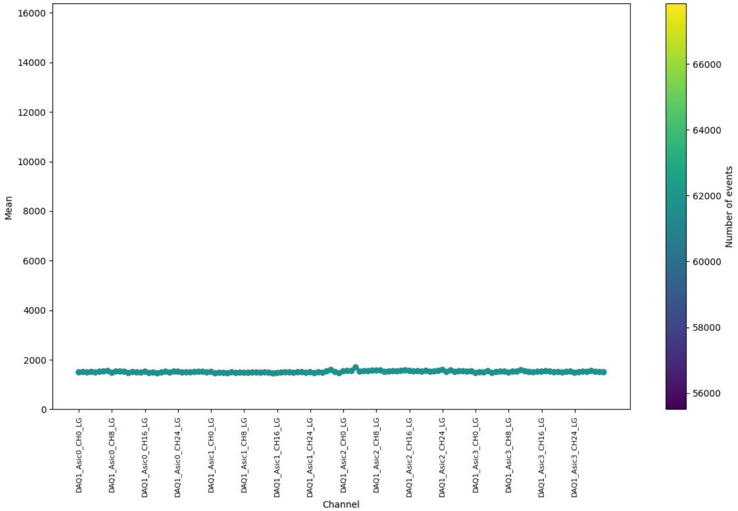
SCAN PEDESTAL PARAMETERS(LG)



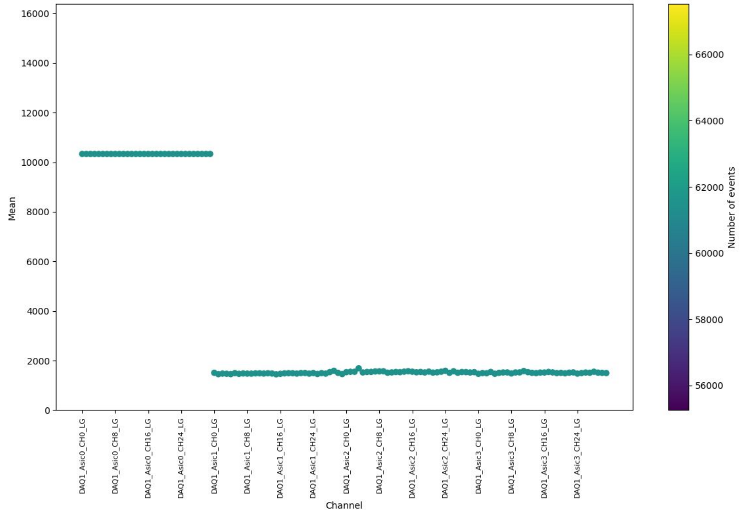
155135



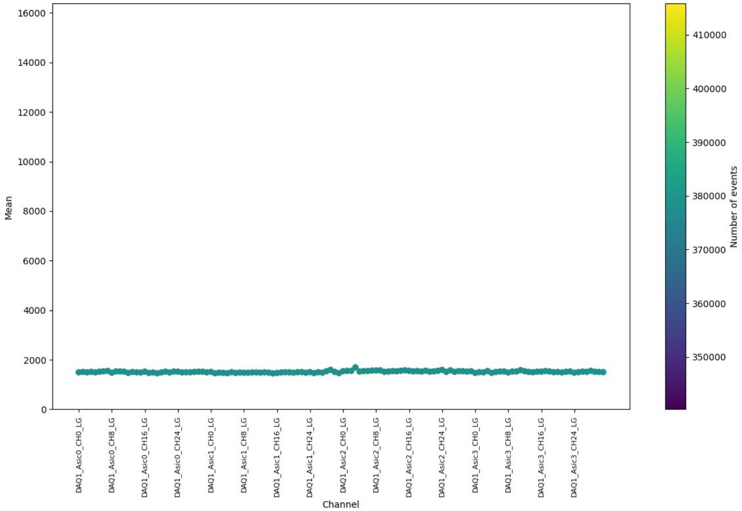
155315



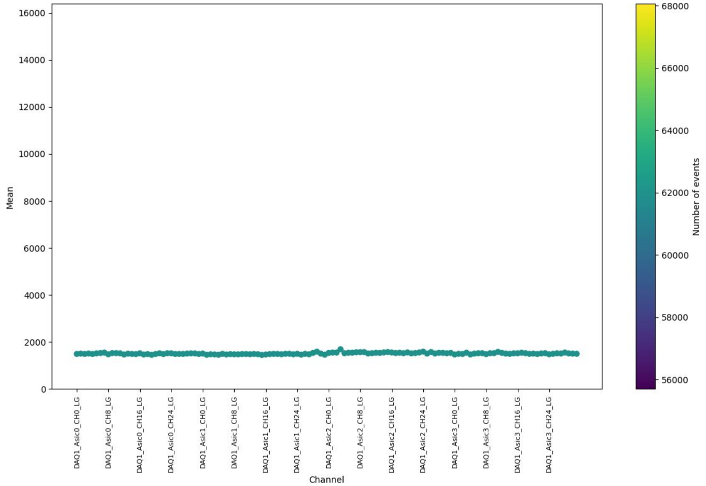
155454



155633

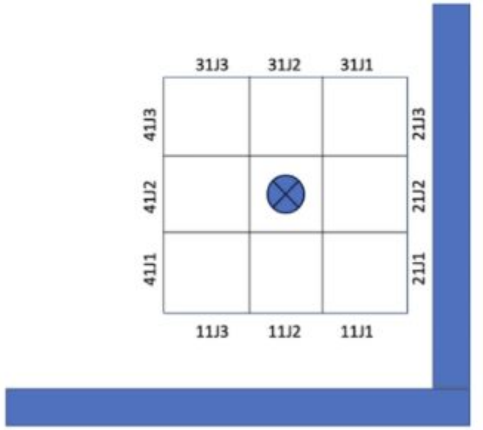


155812



155953

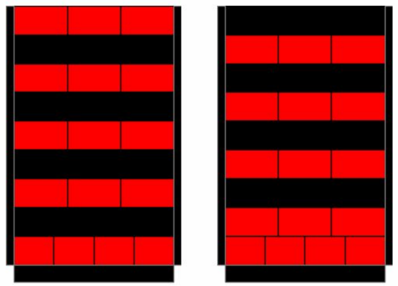
POSITION 0



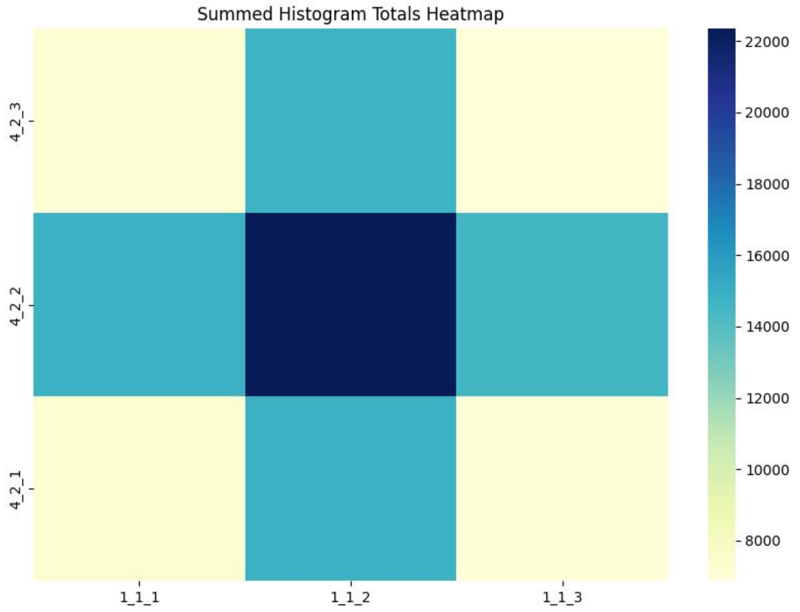
Nvalid = **Number of validation events**

Nvalid = **Number of events passing external trigger**

TIGGER	**TRIGGER EFFICIENCY FOR CENTRAL POSITION** (Nvalid/Next)
TRIG bar on	0.999
MIP PASS	0.999
TRIG FTK, MIP PASS	0.999
TRG FTK & PST Cross	0.999

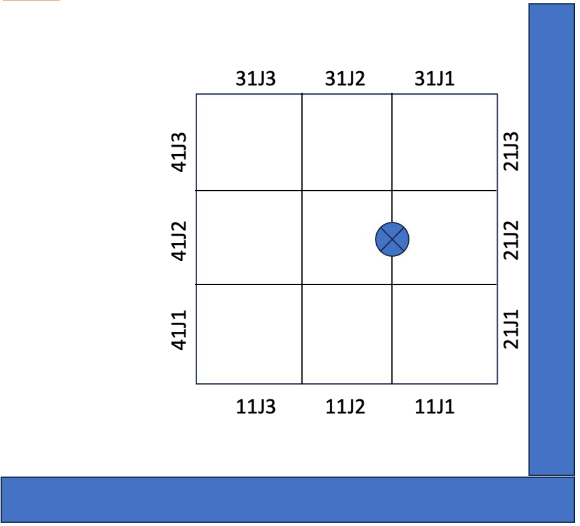


HIT MAP



it was plotted the hit map of the first 2 PST layers

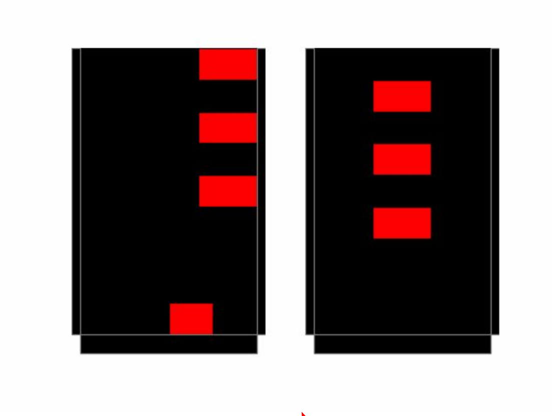
POSITION 3



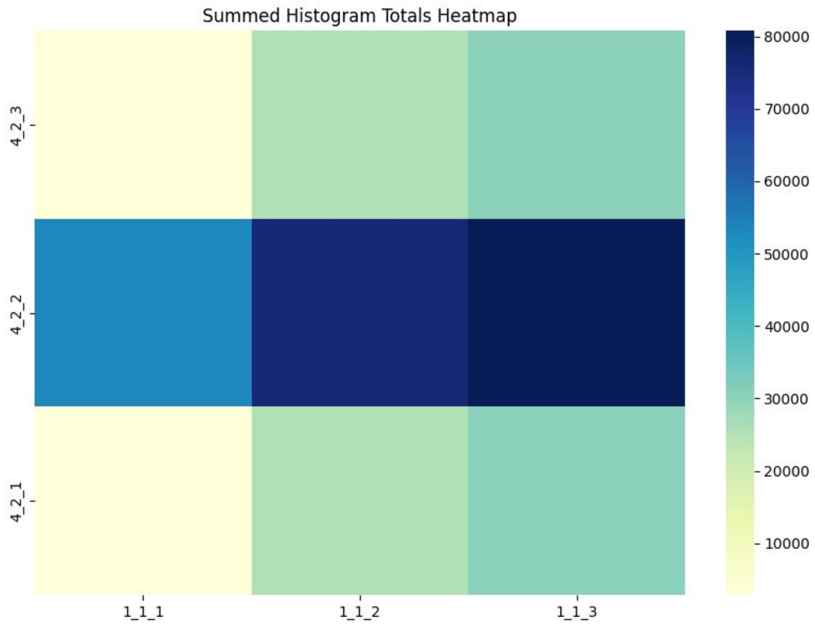
Nvalid = **Number of validation events**

Nvalid = **Number of events passing external trigger**

TRIGGER	**TRIGGER EFFICIENCY FOR CENTRAL POSITION** (Nvalid/Next)
TRIG pst bar on (any)	1

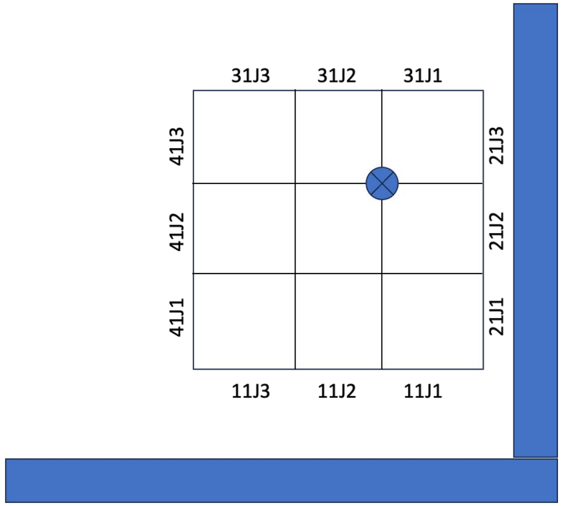


HIT MAP



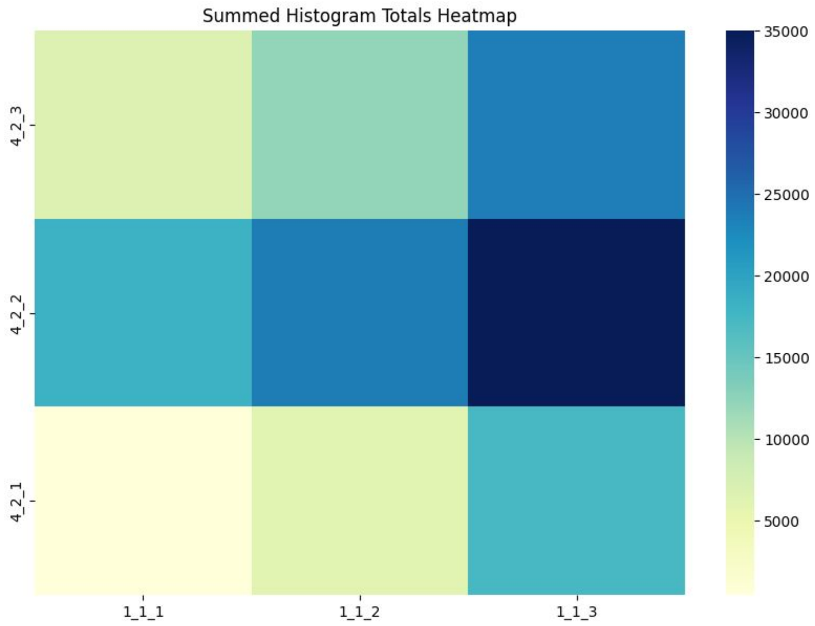
it was plotted the hit map of the first 2 PST layers

POSITION 4

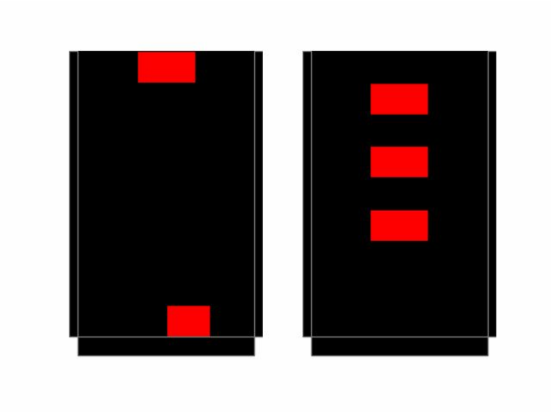


Nvalid = **Number of validation events**

Nvalid = **Number of events passing external trigger**



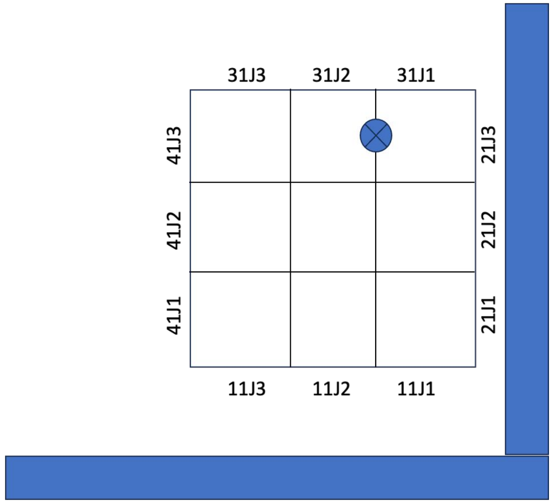
TRIGGER	**TRIGGER EFFICIENCY FOR POSITION** (Nvalid/Next)
Bar on, no fingers	1
Bar_on, fingers in	1
Trg ftk	1



HIT MAP

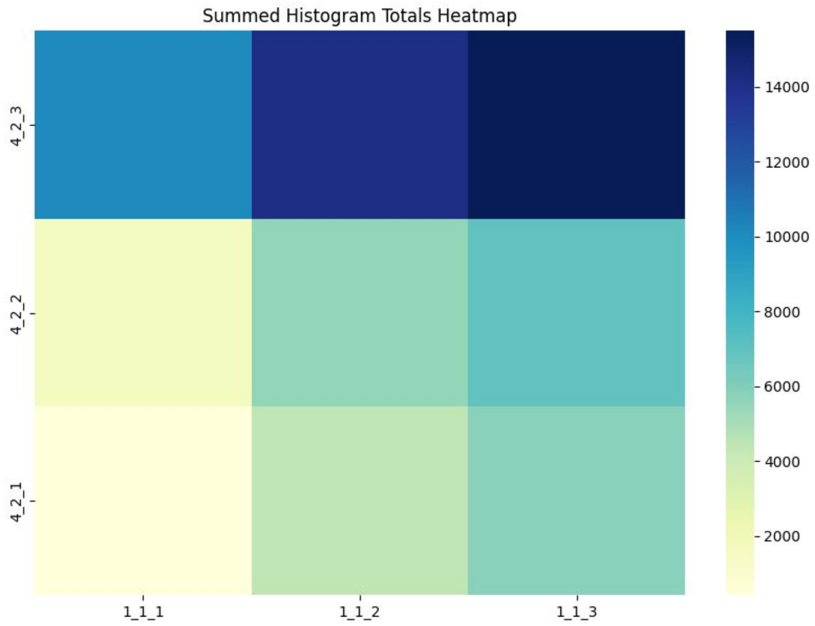
it was plotted the hit map of the first 2 PST layers

POSITION 5

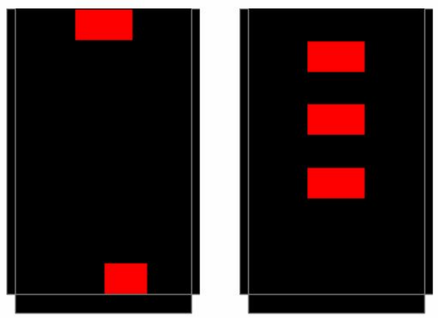


Nvalid = **Number of validation events**

Nvalid = **Number of events passing external trigger**



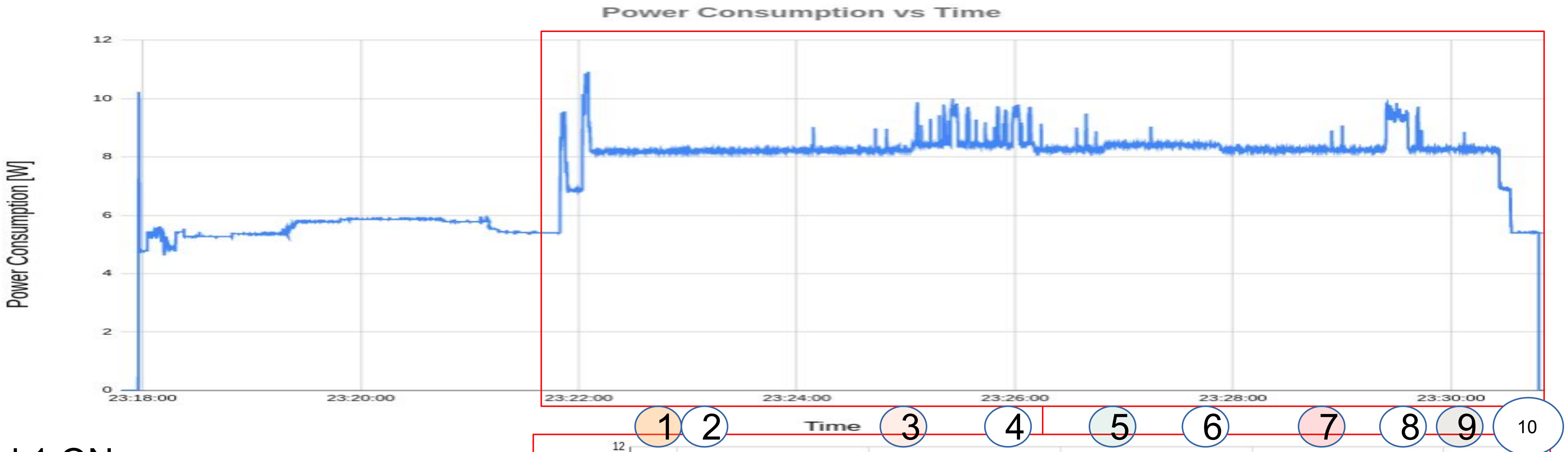
TRIGGER	**TRIGGER EFFICIENCY FOR POSITION** (Nvalid/Next)
TRIG pst bar on (any)	1



HIT MAP

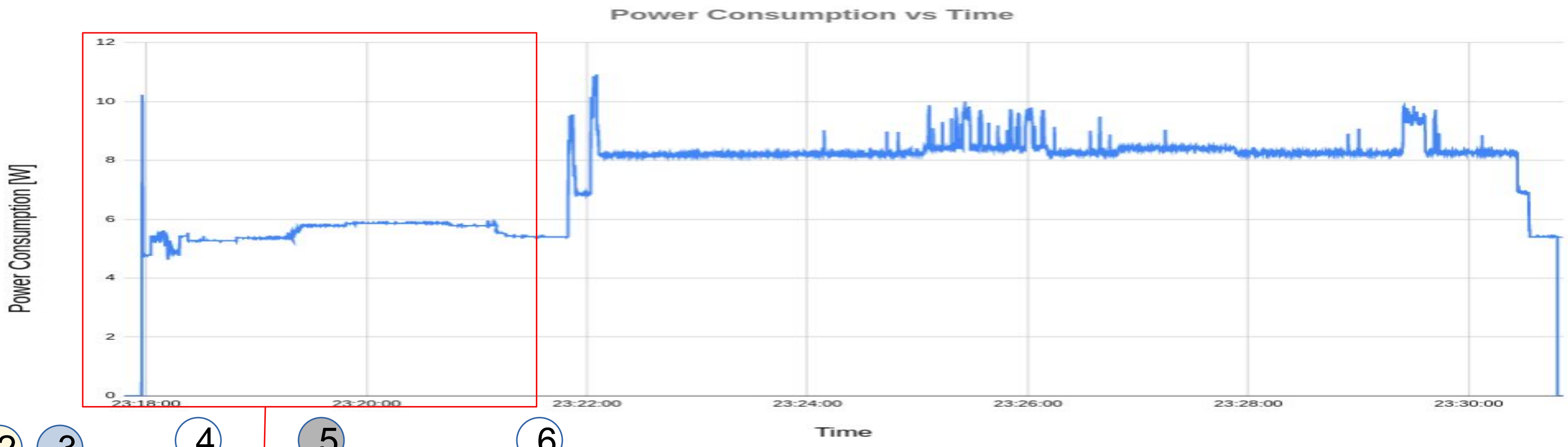
it was plotted the hit map of the first 2 PST layers

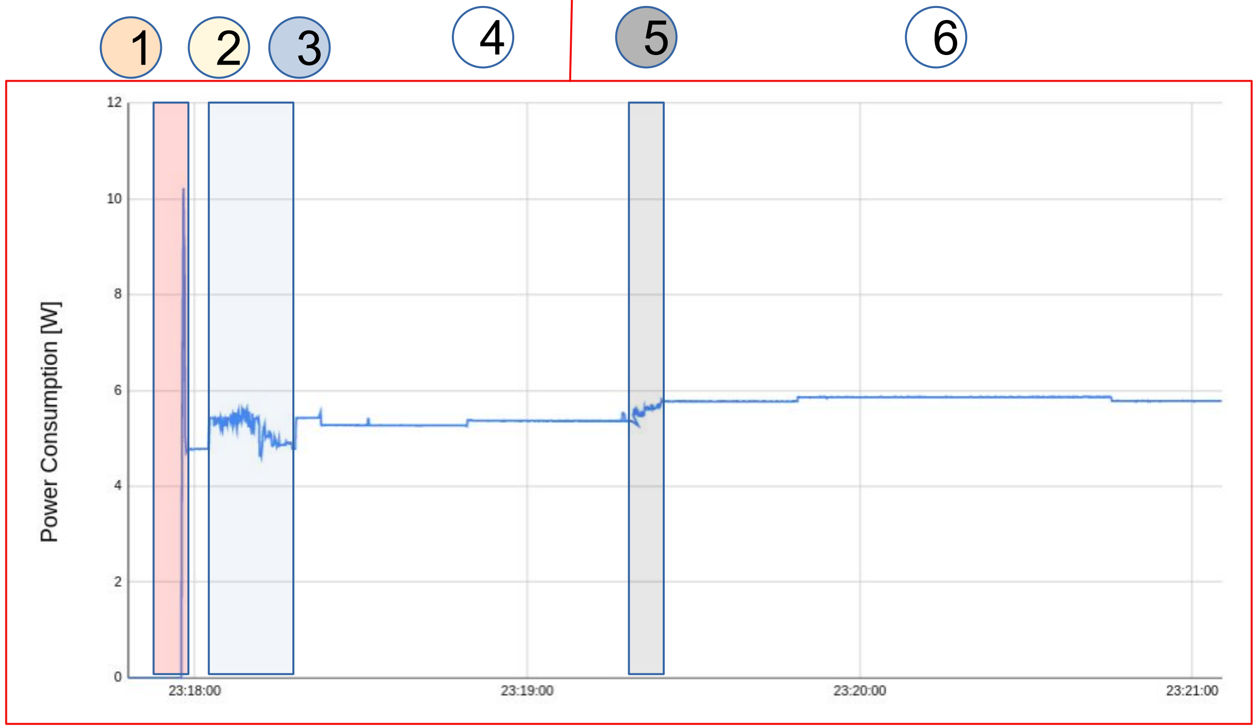
POWER CONSUMPTION



1. Disk1 ON
2. Disk2 ON
3. IDLE
4. Writing on disk 1
5. IDLE
6. Writing on ZYNQ
7. IDLE
8. Writing on disk 2
9. IDLE
10. Disk 1 off, disk 2 off, switch off

POWER CONSUMPTION



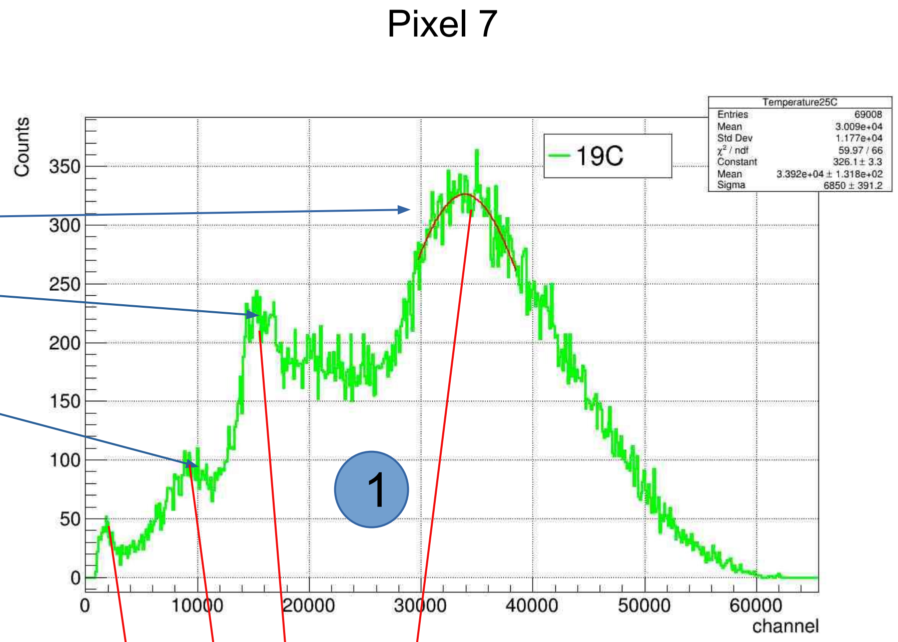


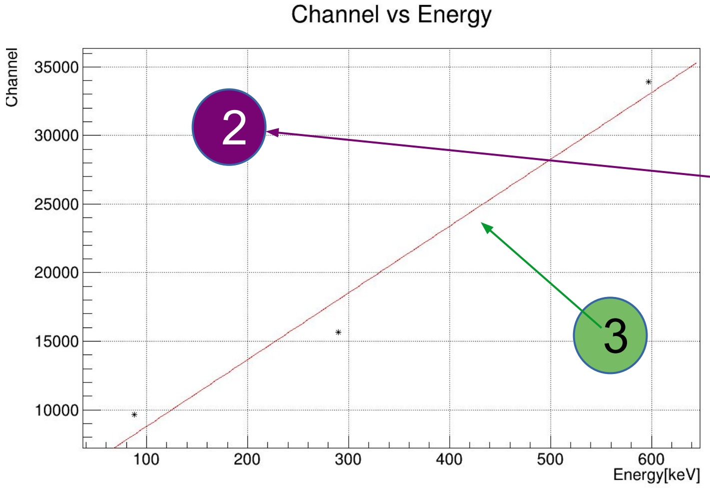
1. Switch on the board (spike)
2. IDLE mode
3. Autoboot
4. Boot
5. HV-SIPM ON
6. Data Acquisition

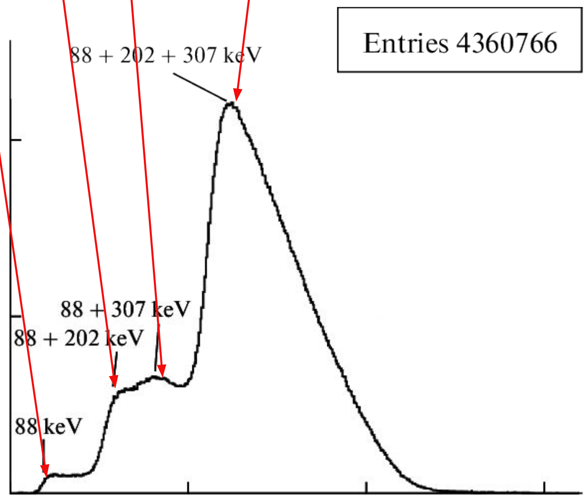
Pixel calibration with LYSO spectrum

1. **Step 1** – fit peaks and assign the corresponding energy
2. **Step 2** – make a plot ADC channel vs Energy
3. **Step 3** – linear fit
4. **Step 4** – recalculate ADC channels in energy using linear response of ADC

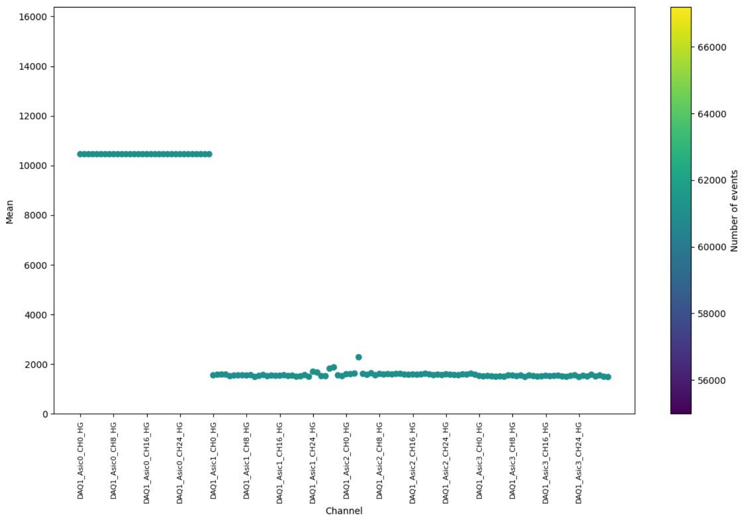
ADC_channel = k * Energy + b



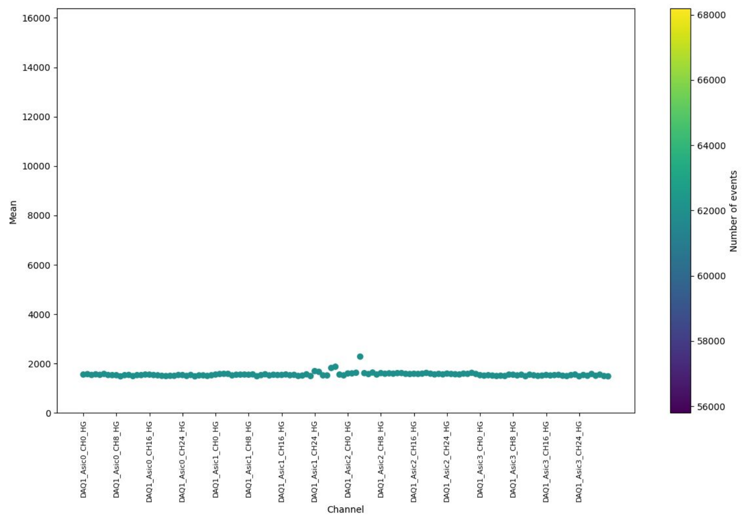




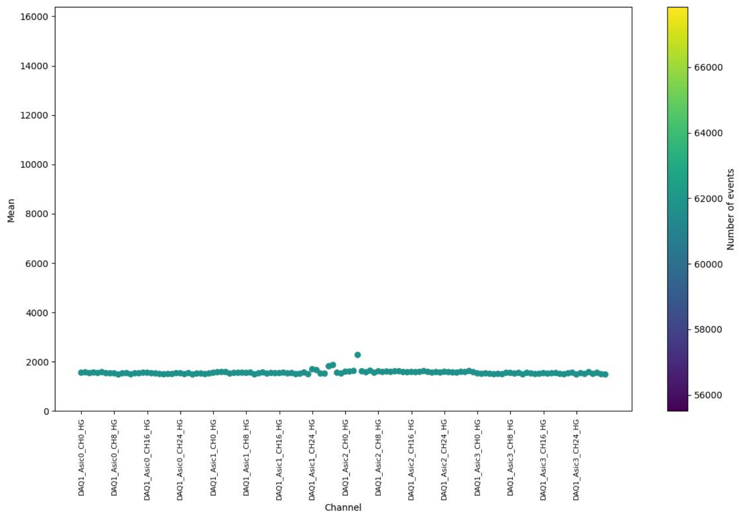
SCAN PEDESTAL PARAMETERS(HG)



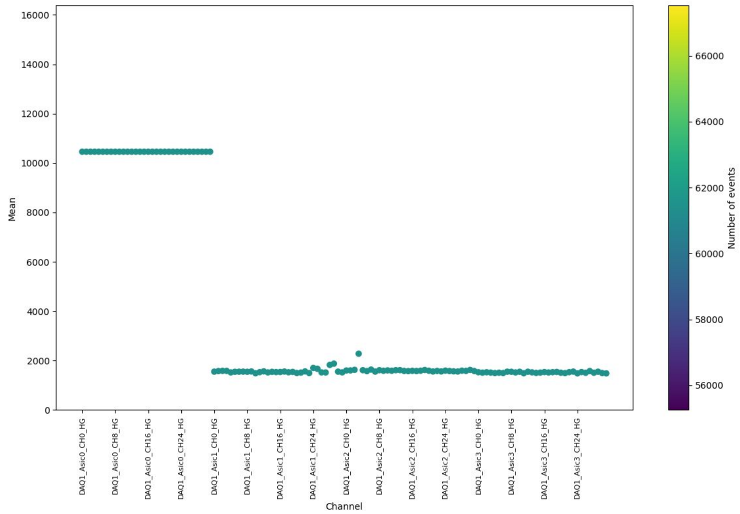
155135



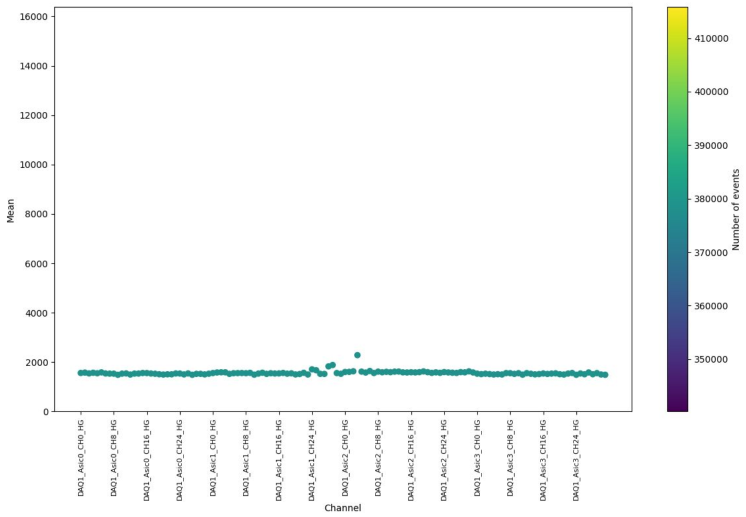
155315



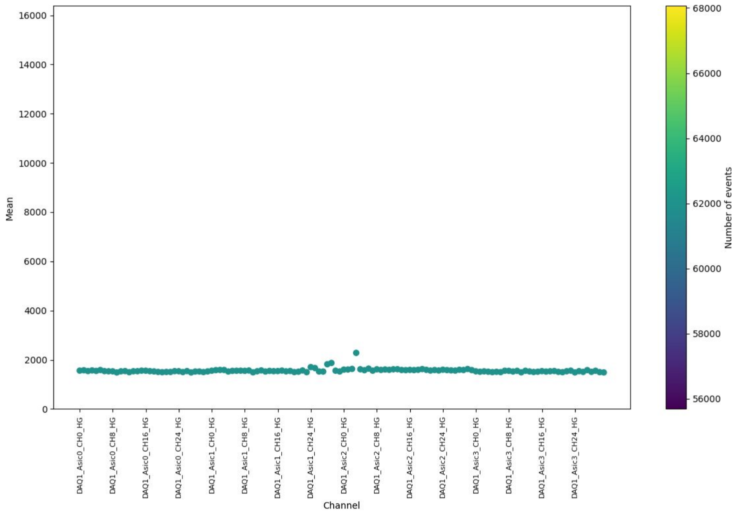
155454



155633



155812

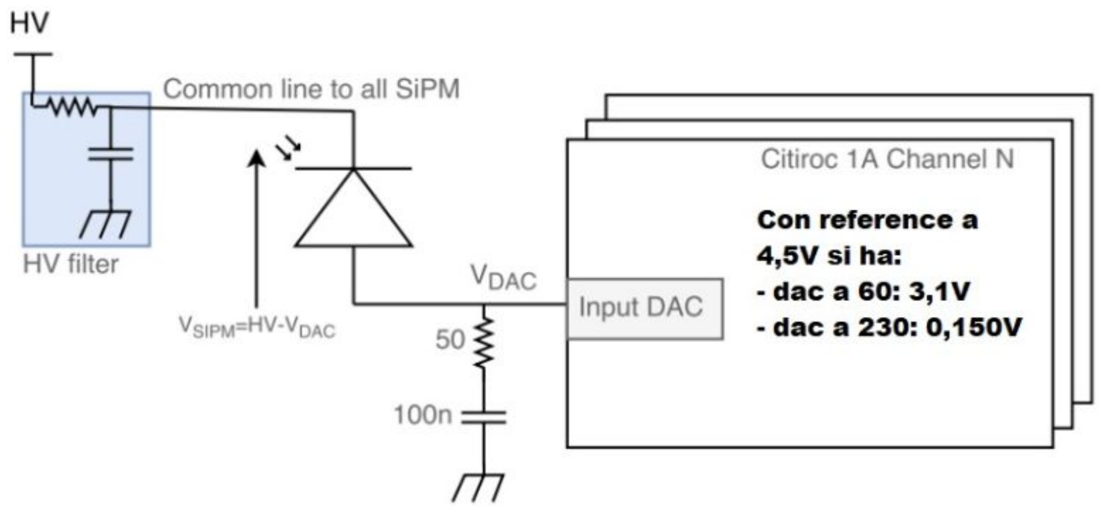


155953

SCAN PEDESTAL PARAMETERS

SCAN PARAMETERS								
FTK	PST_A		PST_B			CALOg 1x1		RUN ID
HG=LG	HG	LG	HG	LG	DAC	HG	LG	
3	10	1	57	39	140	15	1	155135
13	12	3	58	41	140	17	3	155315
20	14	5	59	43	140	19	5	155454
31	16	7	60	45	140	21	7	155633
39	18	9	61	47	130	23	9	155812
43	20	11	62	49	125	25	11	155953

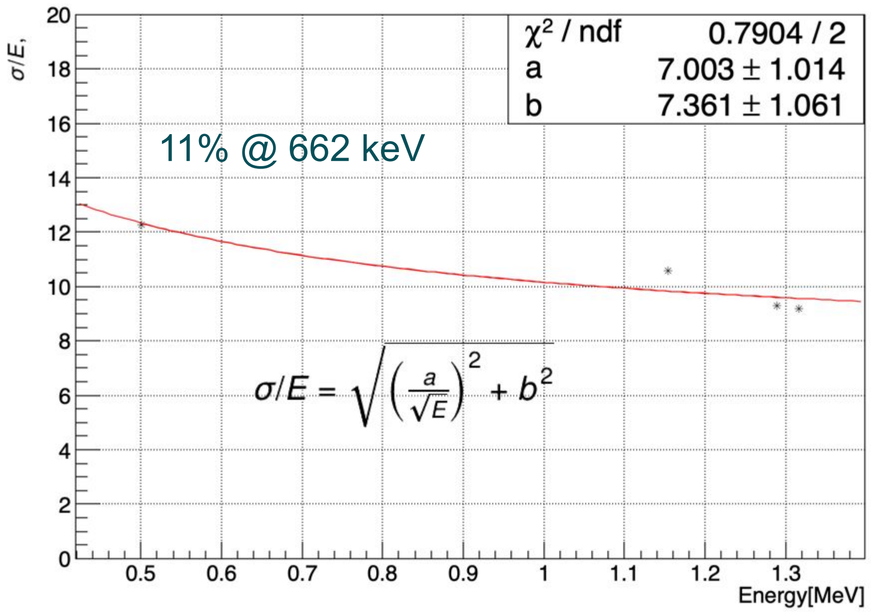
$$V_{SiPM} = V_{BD} + V_{OV} = V_{HV} - V_{DAC}$$

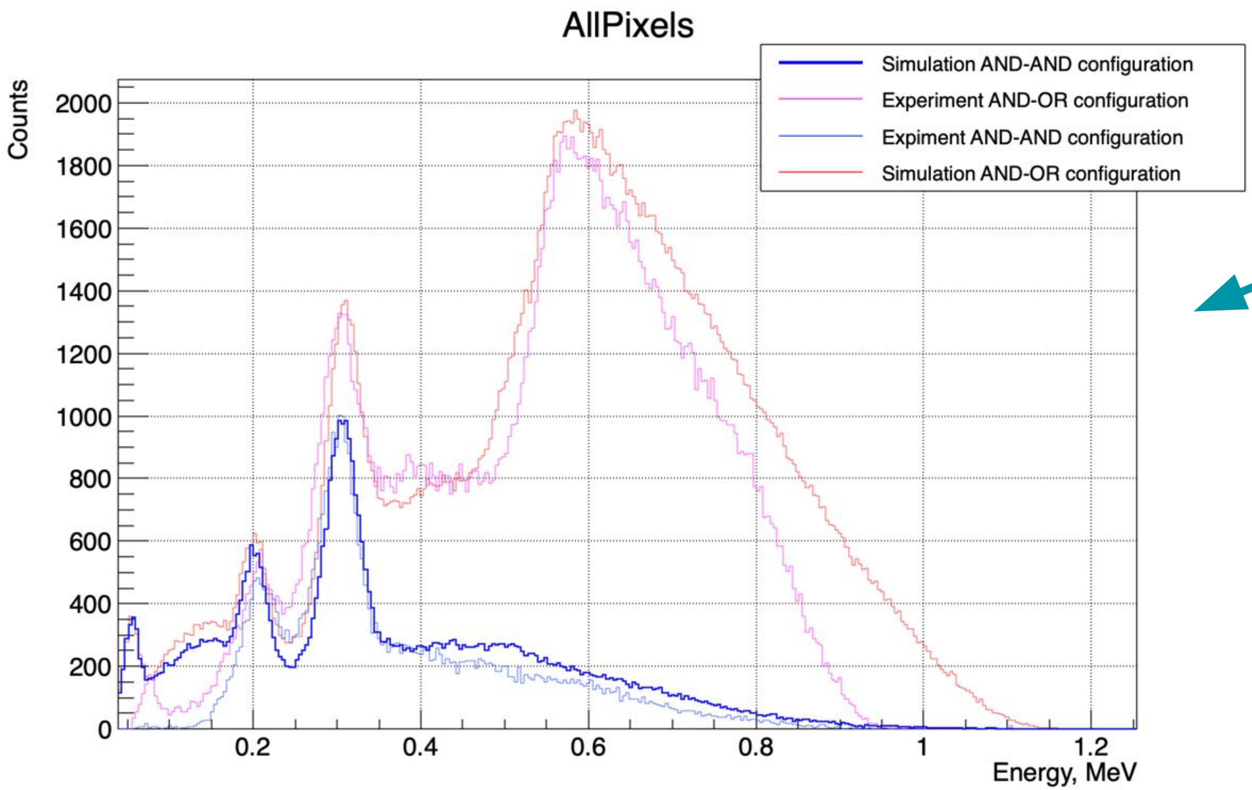


Simulation Spectra

$$F_E = \frac{FWHM}{E} = \frac{2.355\sigma}{E}$$

Resolution





For each peak in our spectra:
511 keV and **1275 keV** peaks from **Na-22**
1.17 MeV and **1.33 MeV** peaks from **Co-60**
we calculate the resolution using this formula.

This enables us to assess the performance of our detector across **different energy levels**.

Terzina

Pathfinder for future missions devoted to **UHE cosmic rays and neutrino astronomy** throught space-based atmospheric **Cerenkov light** detection.

Zirè

Measure the fluxes **of low energy (<250 MeV) CR**, mainly electrons and protons, to study cosmic rays, Van Allen belts**,** space weather and the magnetosphere-ionosphere-litosphere couplings (MILC) in case of seismic / volcanic activities.
Detect **0.1-10 MeV photons** for the study of transient (**GRB**, e.m. follow up of GW events, SN emission lines,…) and steady gamma sources.

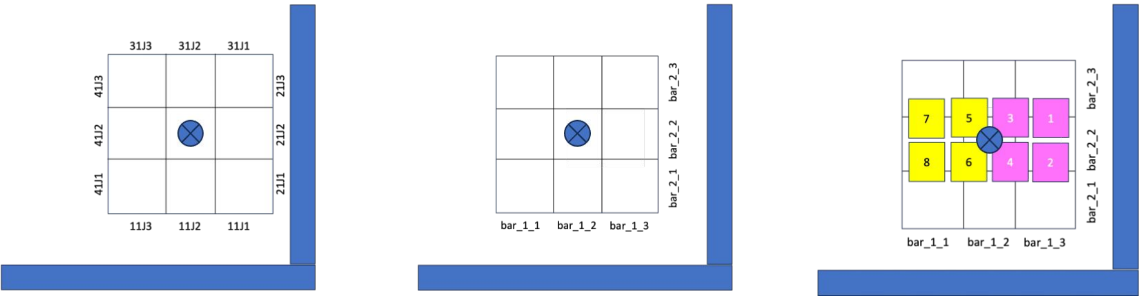
New technologies and approaches

Developement of new observational techniques , testing new sensors (e.g. **SiPM**) and related electronics/DAQ for space missions. New solutions for the satellite platform.

BEAM SPOT POSITION INVESTIGATION

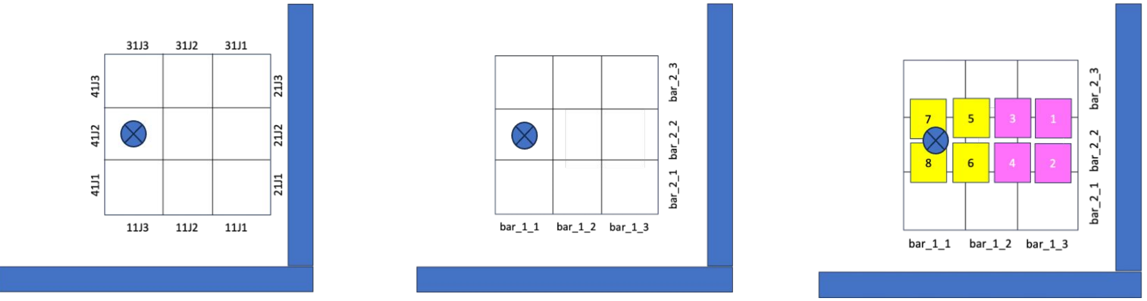
BEAM SPOT POSITION 0

FTK PST CALOg



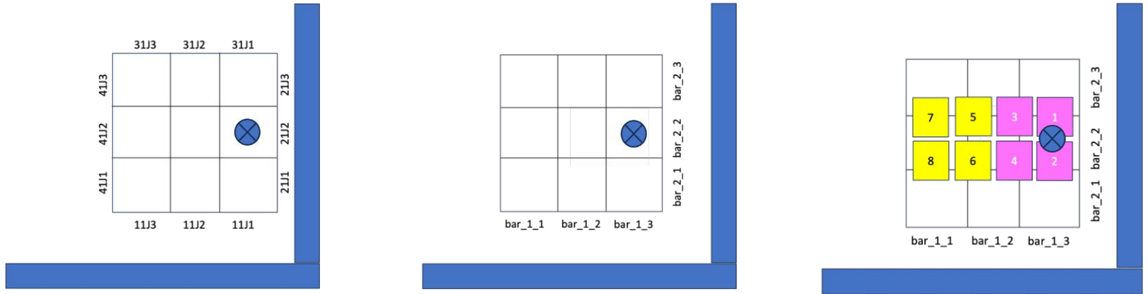
BEAM SPOT POSITION 1

FTK PST CALOg



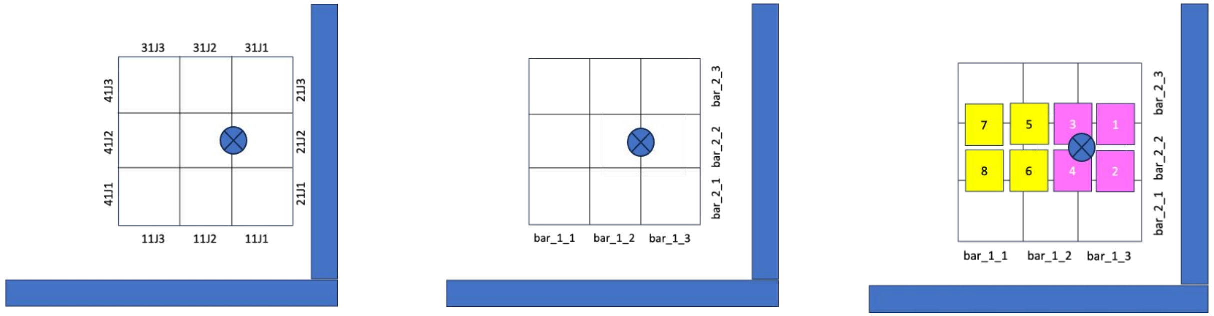
BEAM SPOT POSITION 2

FTK PST CALOg



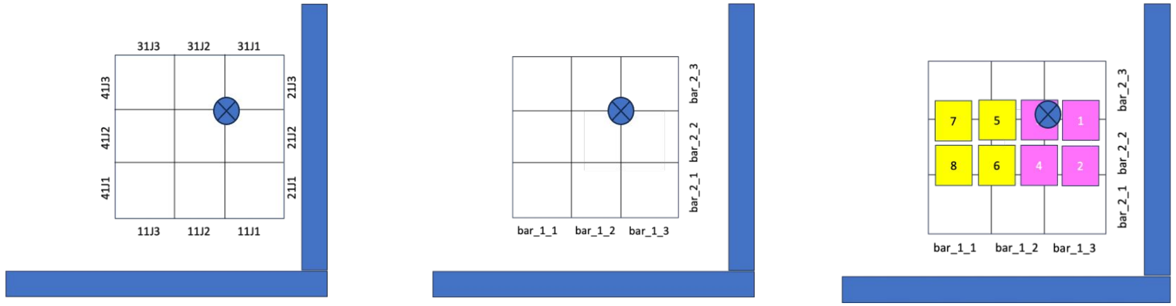
BEAM SPOT POSITION 3

FTK PST CALOg



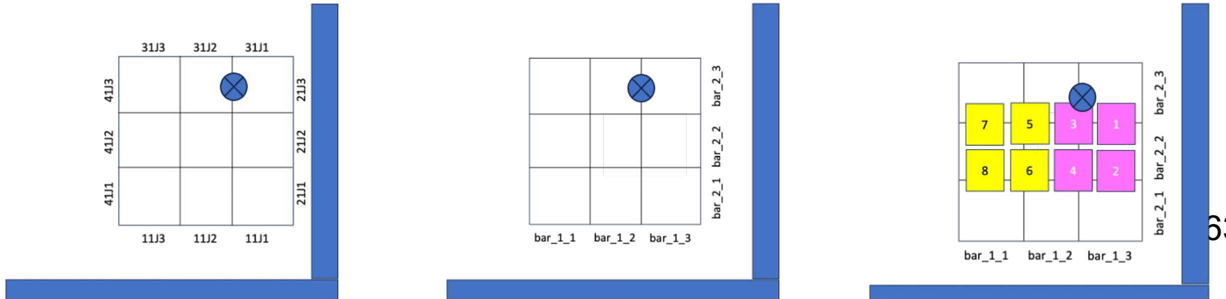
BEAM SPOT POSITION 4

FTK PST CALOg

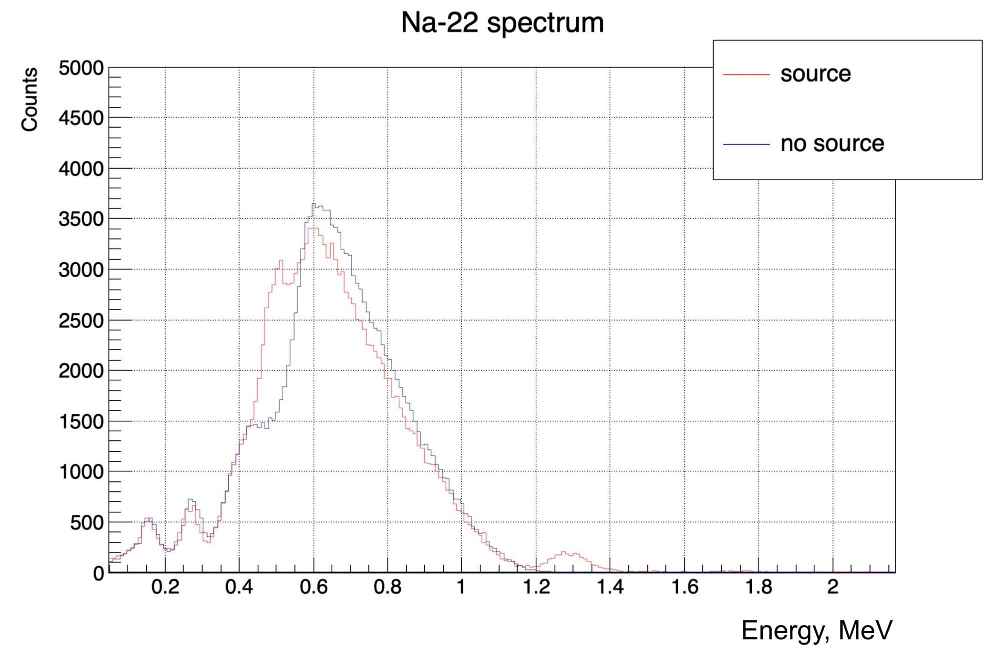


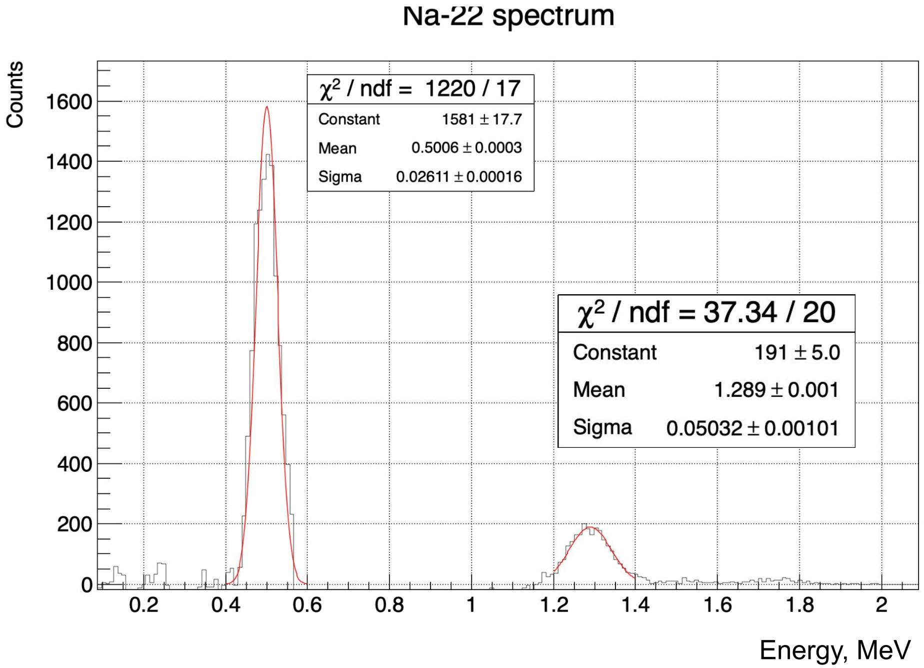
BEAM SPOT POSITION 5

FTK PST CALOg

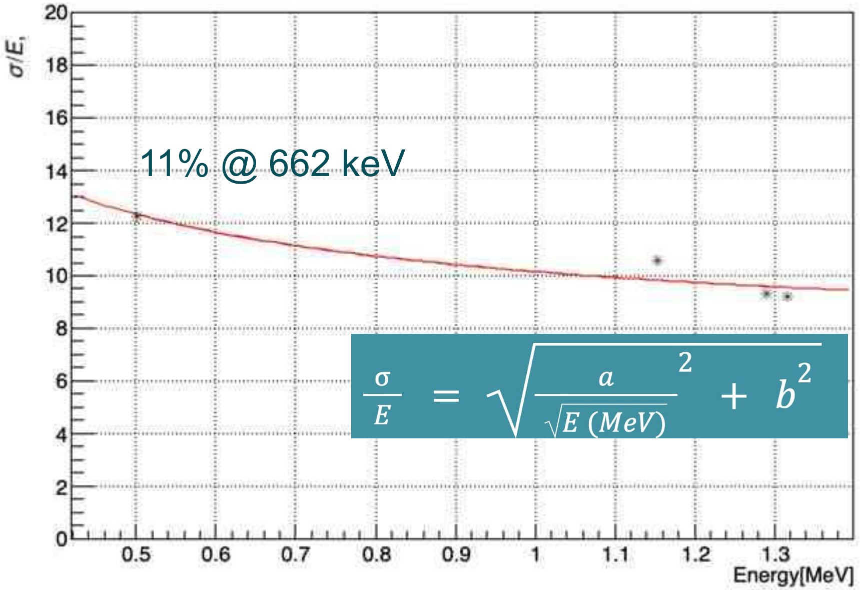


Setting the trigger threshold



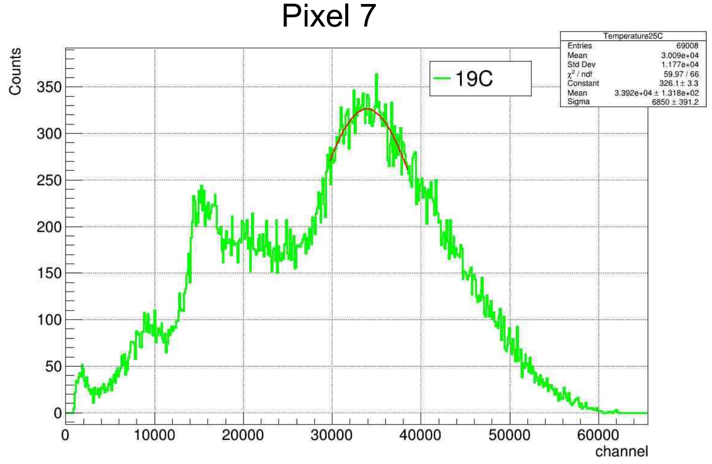


$$F_E = \frac{FWHM}{E} = \frac{2.355\sigma}{E}$$

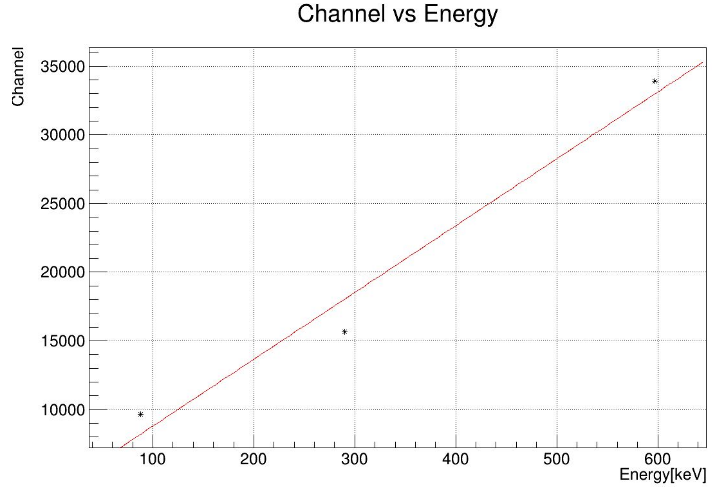


Pixel calibration with LYSO spectrum

Step 1 – Fit peaks and assign the corresponding energy



Step 2 – Make a plot ADC channel vs Energy



Step 3 – Linear fit

Step 4 – Recalculate ADC channels in energy using linear response of ADC