pGRAMS Design Calculations

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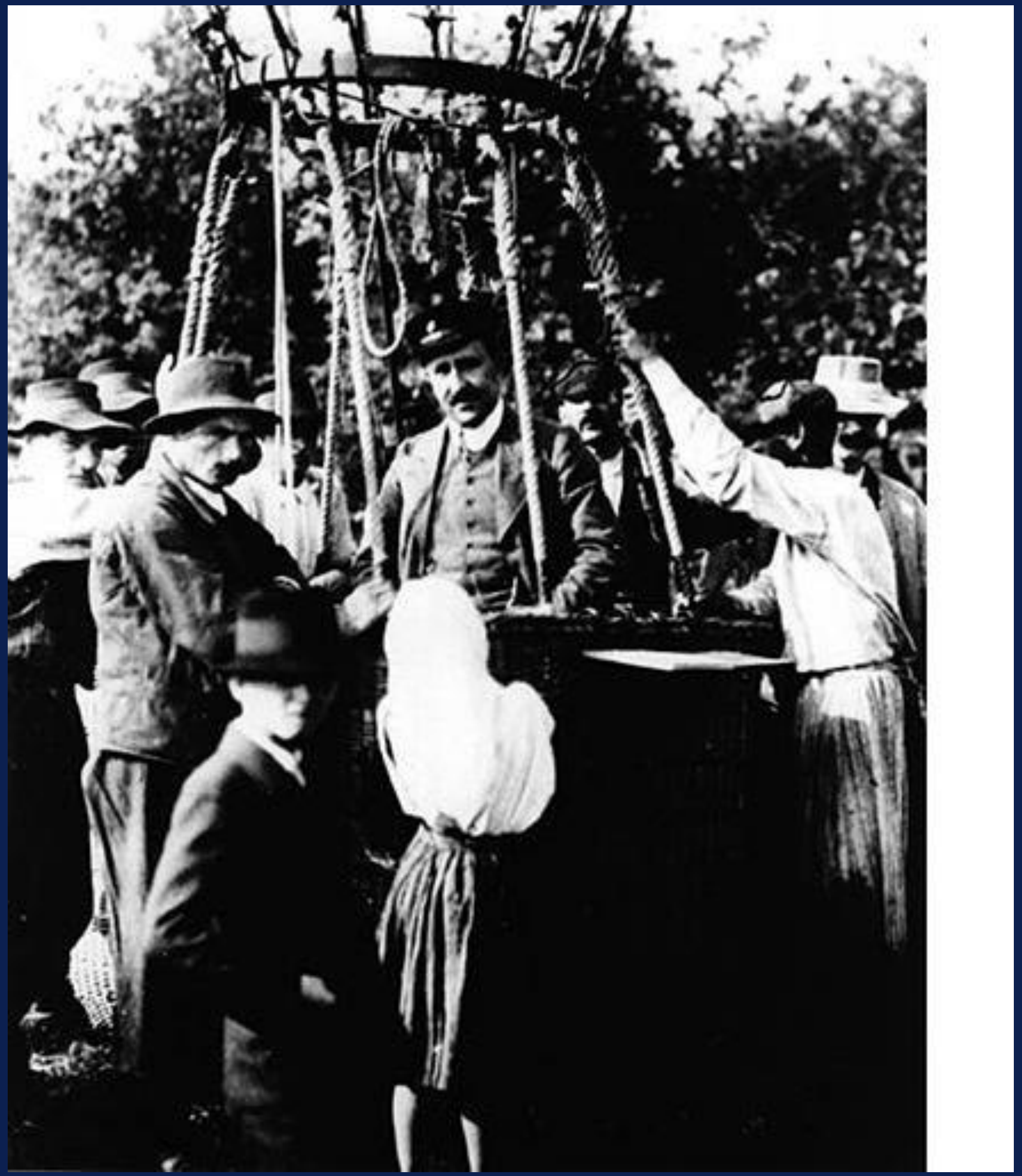
What is GRAMS?

GRAMS which stands for Gamma-Ray and Anti-Matter Survey is an experiment that will search for both gamma-rays directly dark matter indirectly through the detection of antimatter.
It will be a ballon/satellite mission, the prototype ballon is projected to fly by the end of 2025.
The detector will be the same as modern accelerator neutrino experiments, a LArTPC (Liquid Argon Time Projection Chamber).

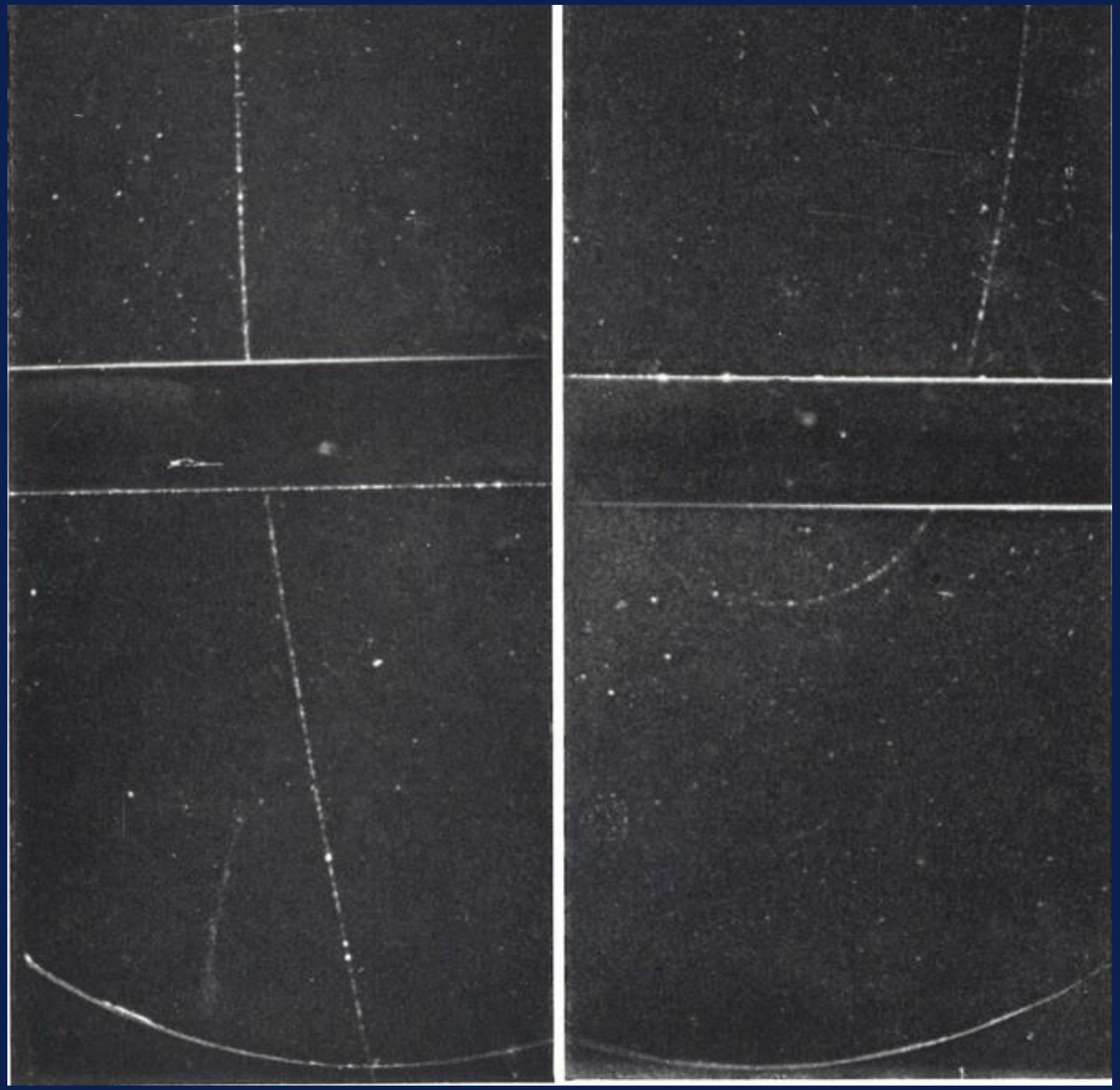
Cosmic Rays



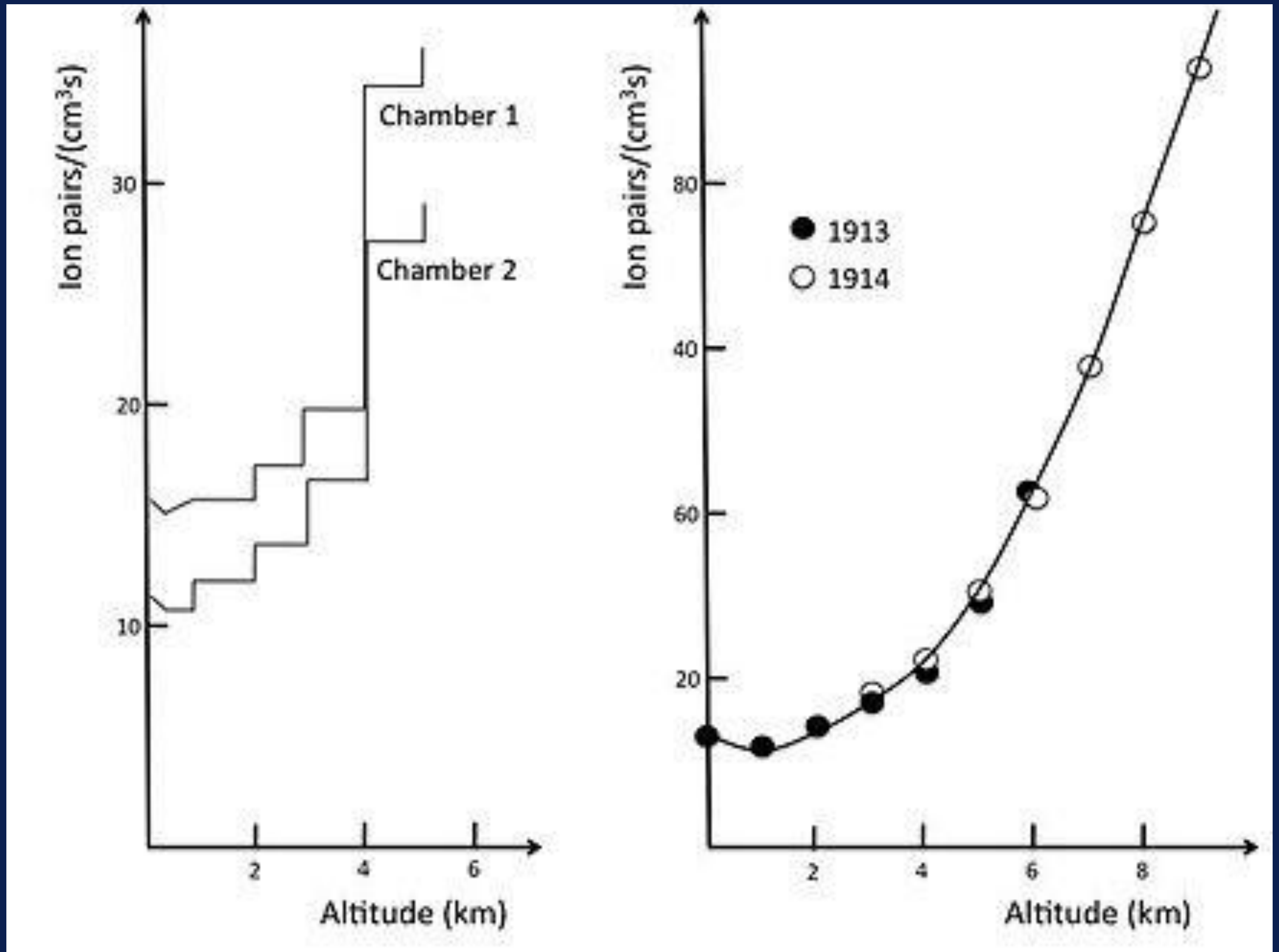
In 1909 Theodore Wulf developed a device to measure the radiation at the base of the Eiffel Tower and at the top. The results were inconclusive even though the radiaon at the top was higher.

Cosmic Rays were discovered by Victor Hess in 1912 during a ballon flight. During the ballon flight it was seen that the higher the altitude the more radiation there was, in order to validate the results Hess did the same experiment during a solar eclipse.

Cosmic Rays



Cosmic Muon Track



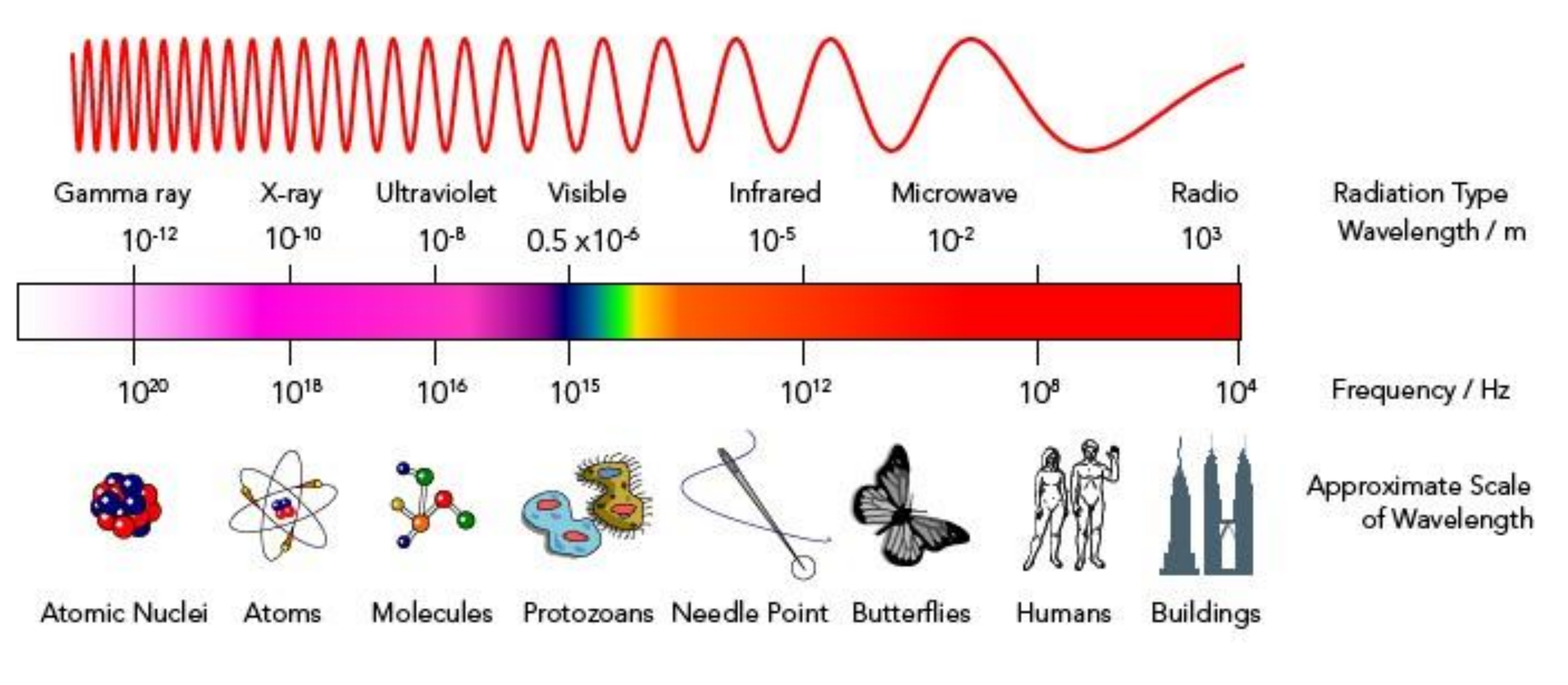
Victor Hess Results

What are Gamma-Rays?

Gamma-Rays have the shortest wavelengths, they are also the most energetic in the electromagnetic spectrum.

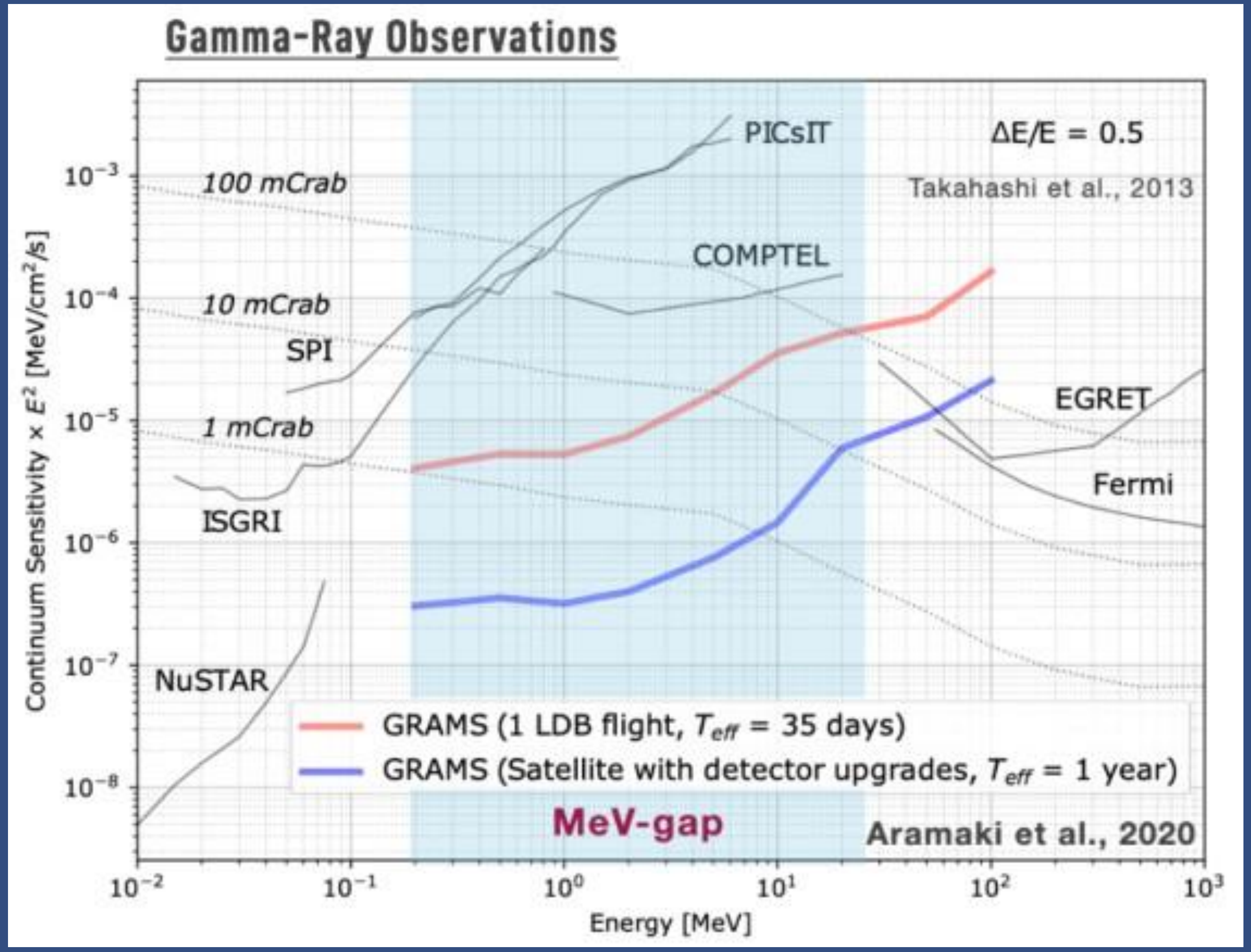
They are produced by Active Galactic Nuclei (AGN), supernovae explosions, pulsars, black holes, etc.

Cosmic Rays sources can't be detected directly, instead we look at gamma-rays or neutrinos in order to identify these sources.



Why Gamma-Rays?

There is lack of observation in the MeV range of gamma-ray energies.

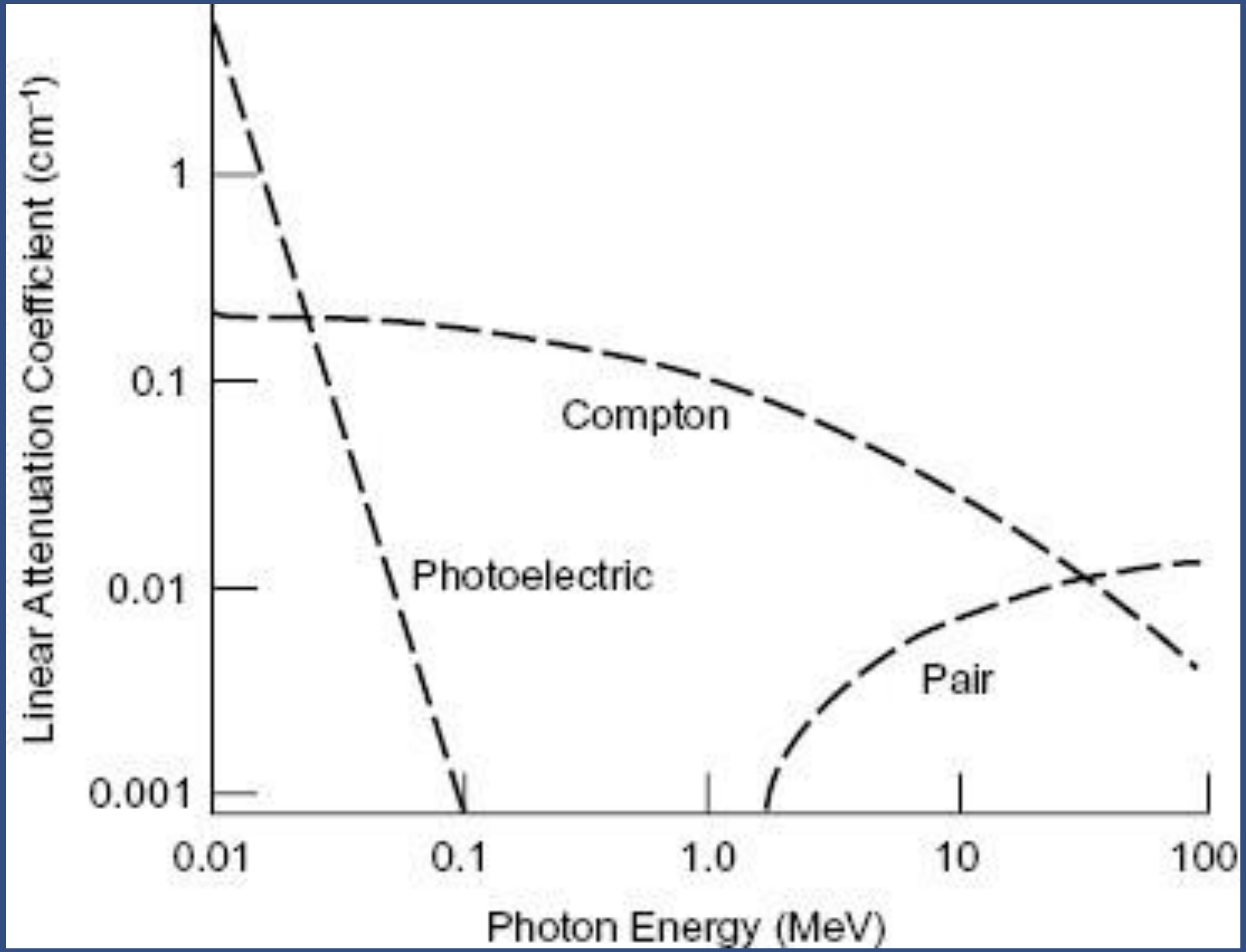


Additionally Compton scattering occurs in the MeV energy range. By looking at the MeV range GRAMS is expected to improve sensitivity of MeV gammas by an order of magnitude over previous experiments.

It allows us to study some physics process like nucleosynthesis, annihilating/decaying DM.

A crucial component to detect cosmic ray sources.

How do we see gamma-ray?

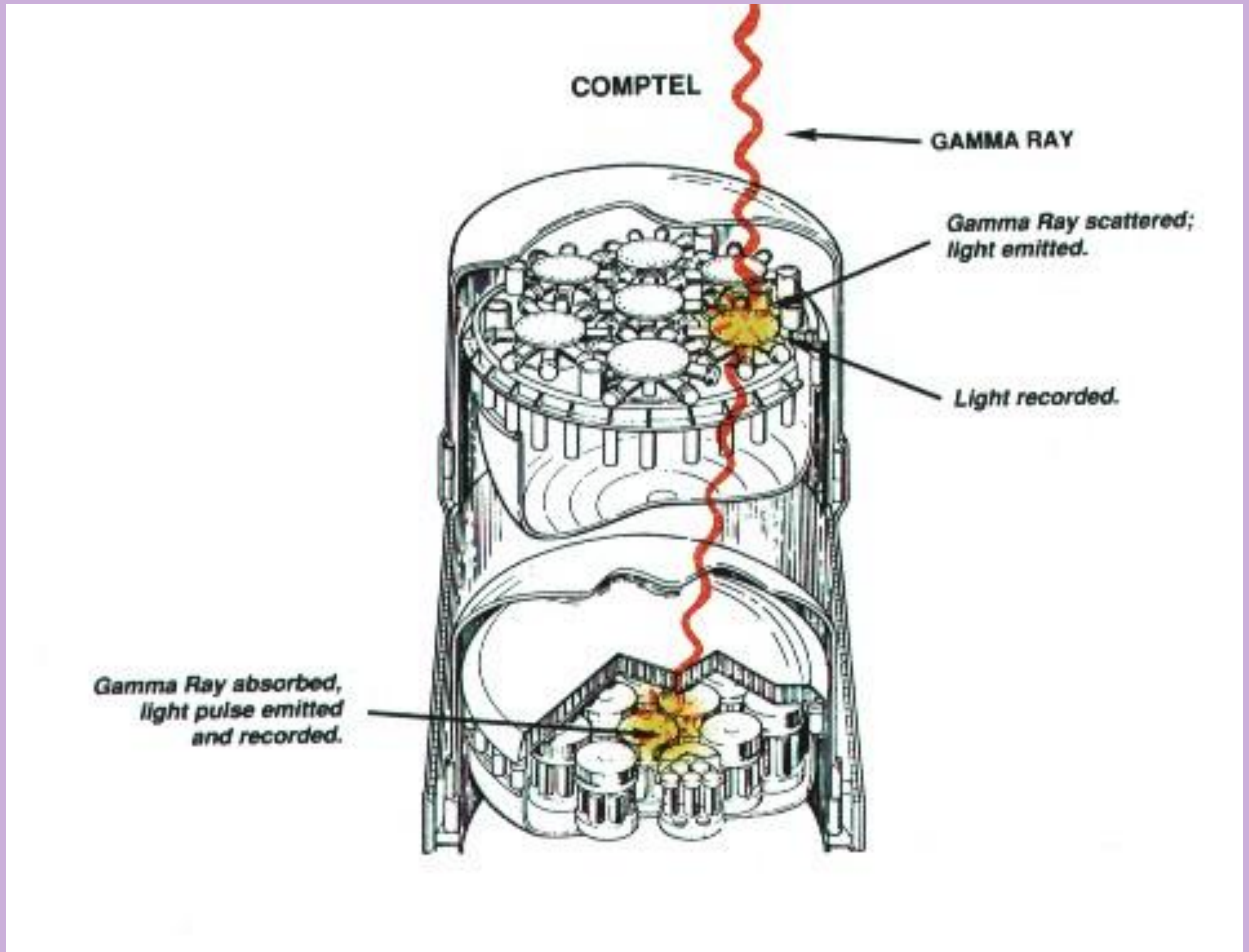


Previous Compton Telescopes

Previous experiments that searched for MeV gammas used scintillation light or semiconductors.

COMPTEL is a Compton Telescope that used liquid scintillator in the upper detector and a NaI crystals in the lower one.

The incoming gamma will scatter in the first detector, then it will be absorbed by the second detector.



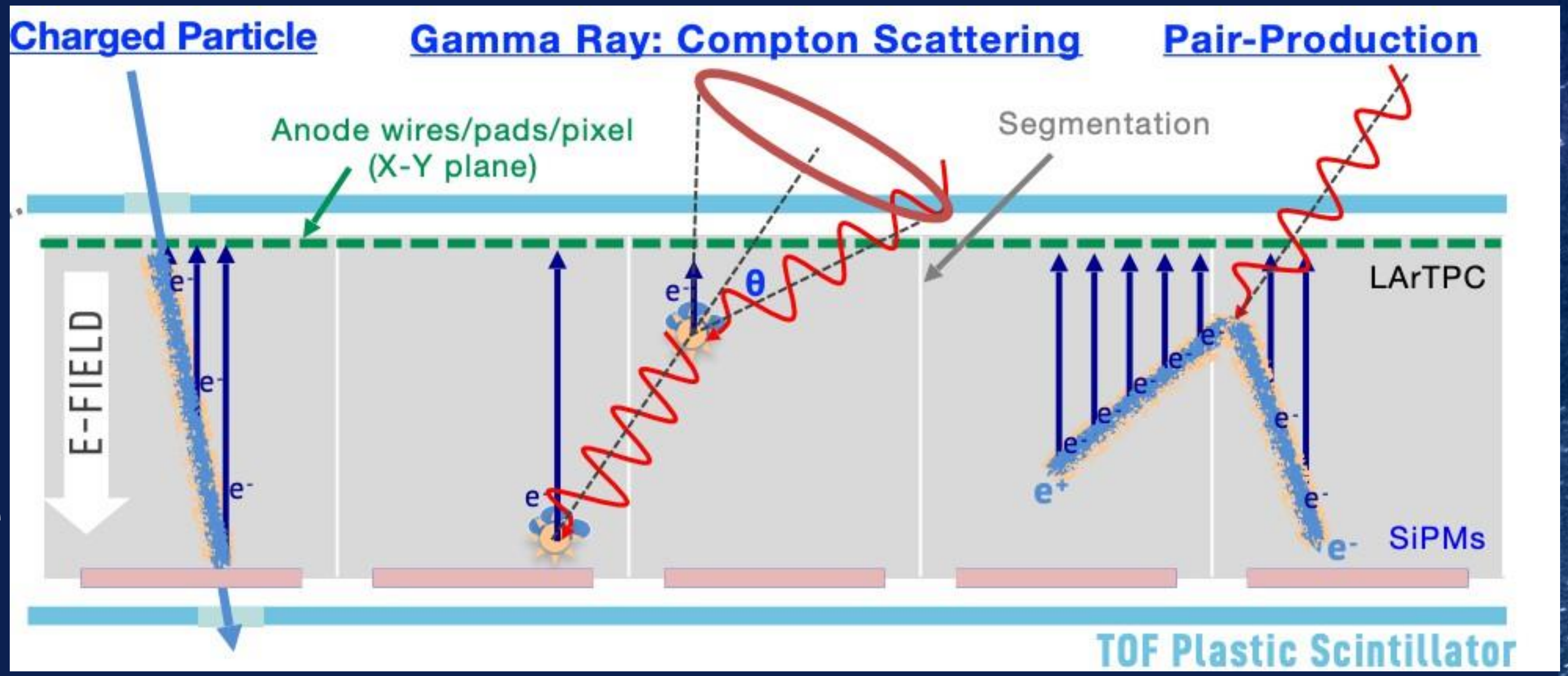
LArTPC

A LArTPC detects charged particles that are in the detector.

For GRAMS the incoming photon will interact with the Argon nucleus and the charged particles from this interaction are the ones that we will see.

The charged particles will drift towards the anode plane because of the electric field that is applied to the detector.

Once they make it to the wires this will give the position of the particles allowing for an event reconstruction.



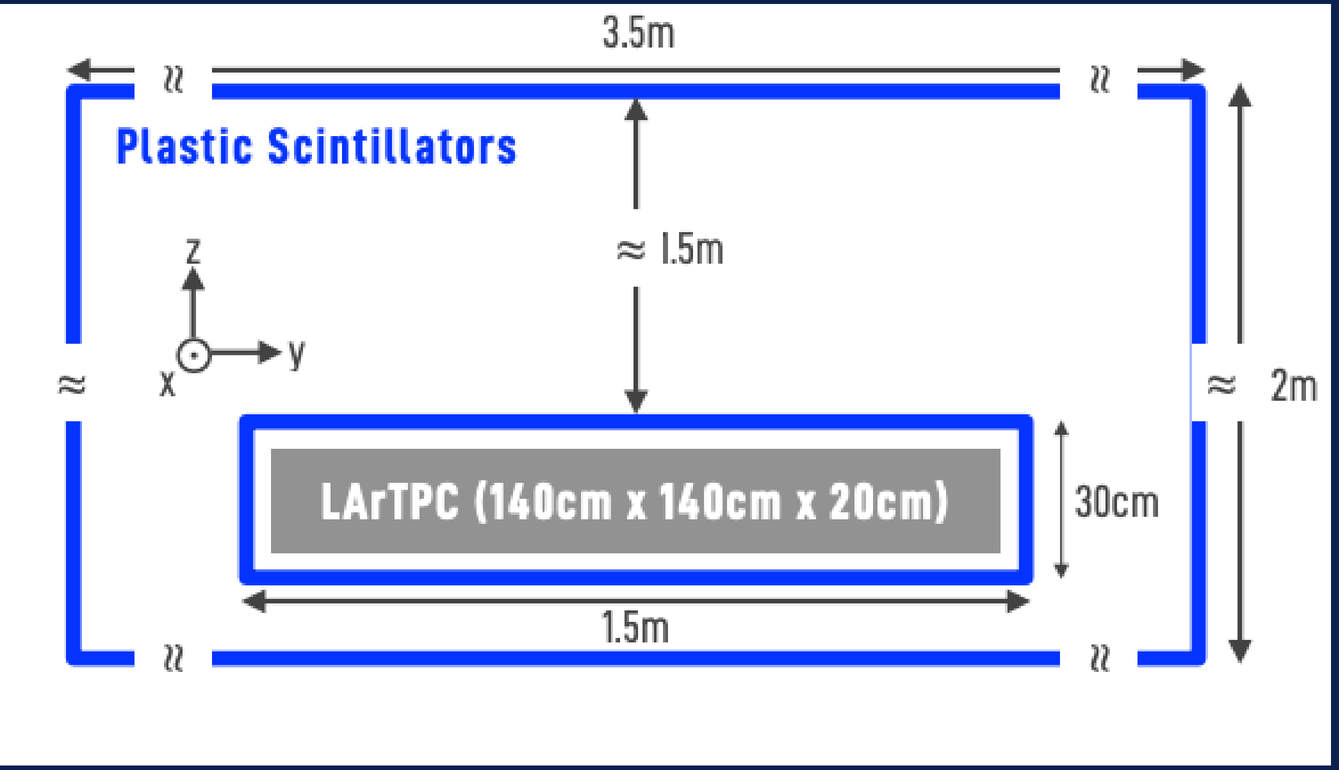
GRAMS Detector

LArTPC have been used for neutrino and dark matter experiments making them reliable while obtaining valuebale information. They also allow 3D reconstruction of events throughout the detector, this allows us to study the incoming gamma-rays.

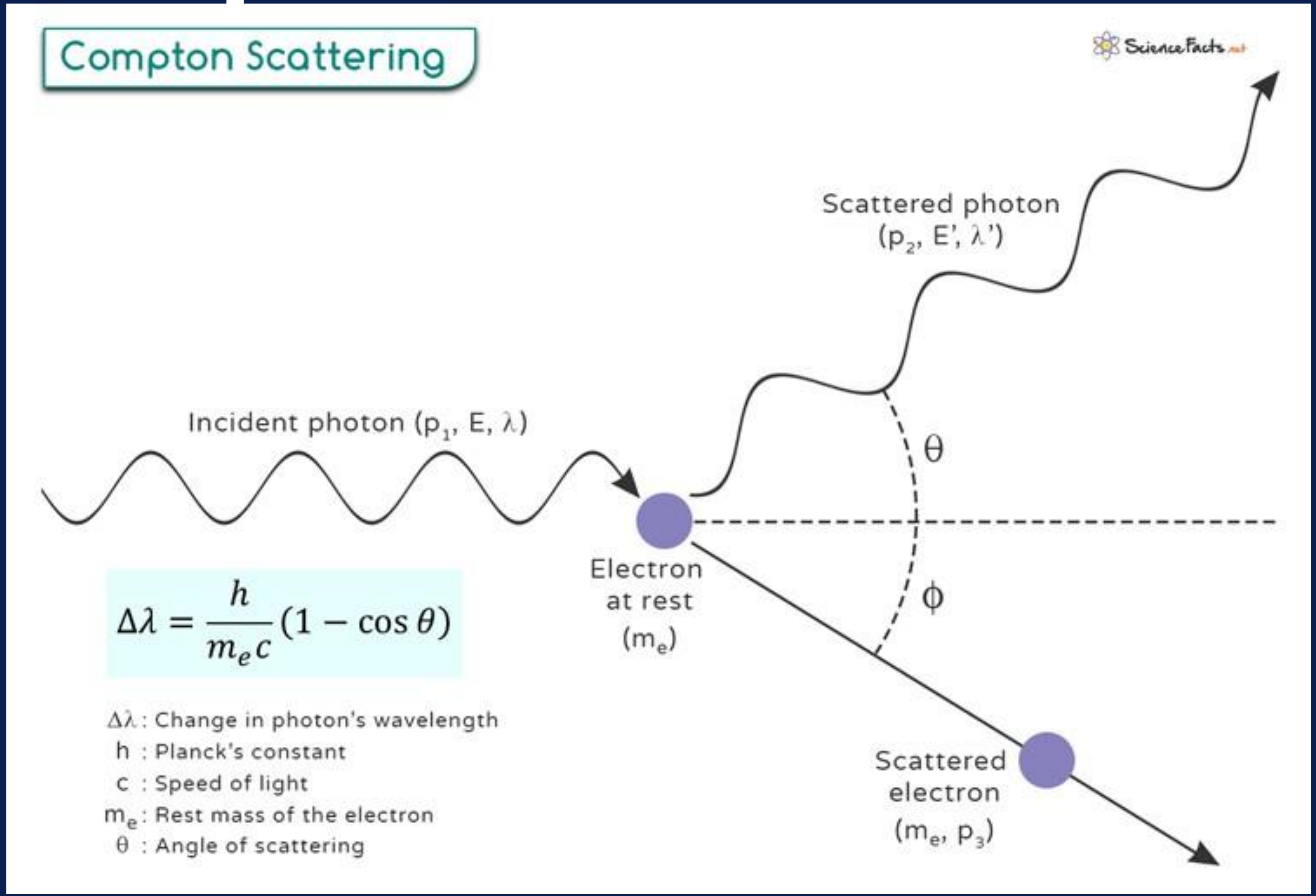
The Time of Flight Plastic Scintillators (TOF) measure the velocity and angle of the incoming charged particle.

Silicon Photo-Multipliers (SiPMs) are used to measure the time of events in the detector.

Once the particle makes it to the detector the ionization electrons will drift due to the electric field towards the anode plane where it will be readout.



Compton Scattering

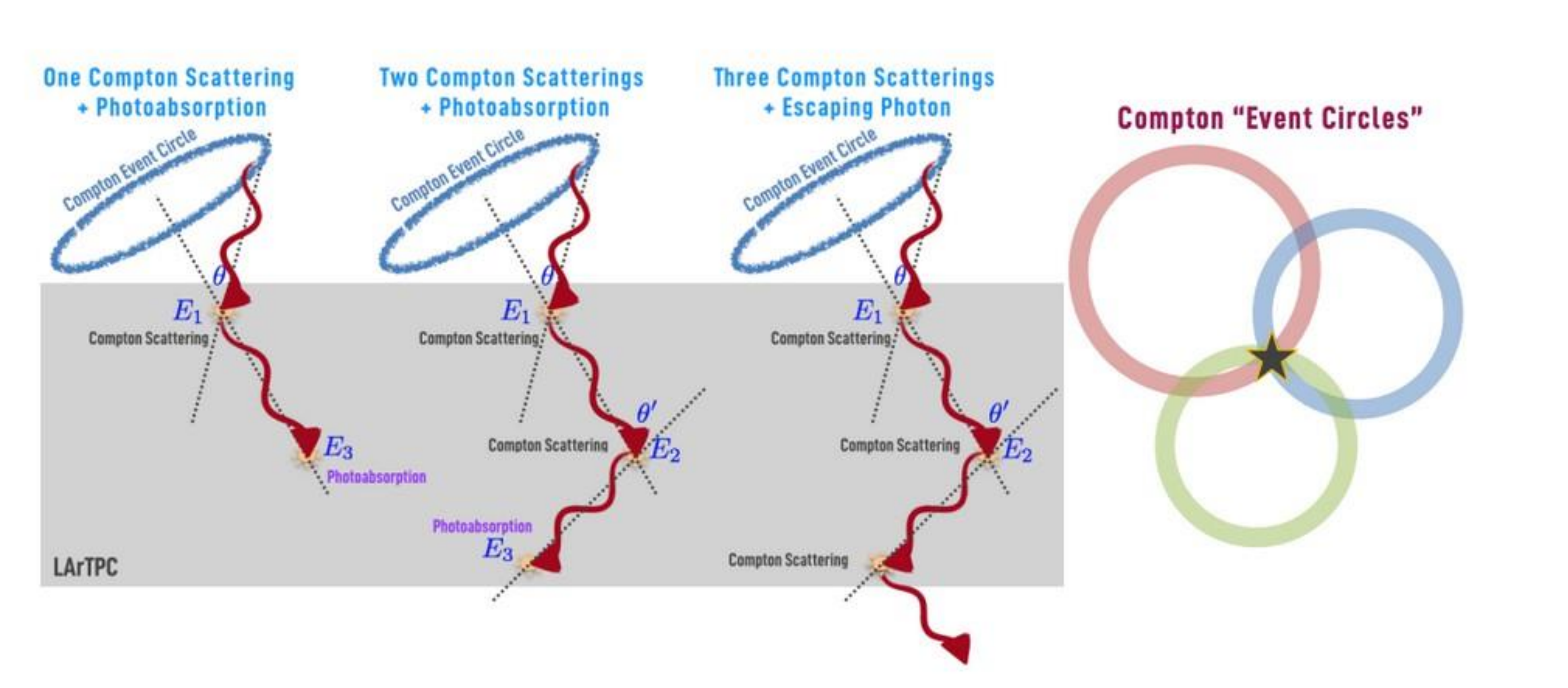


Detecting Gamma-Rays

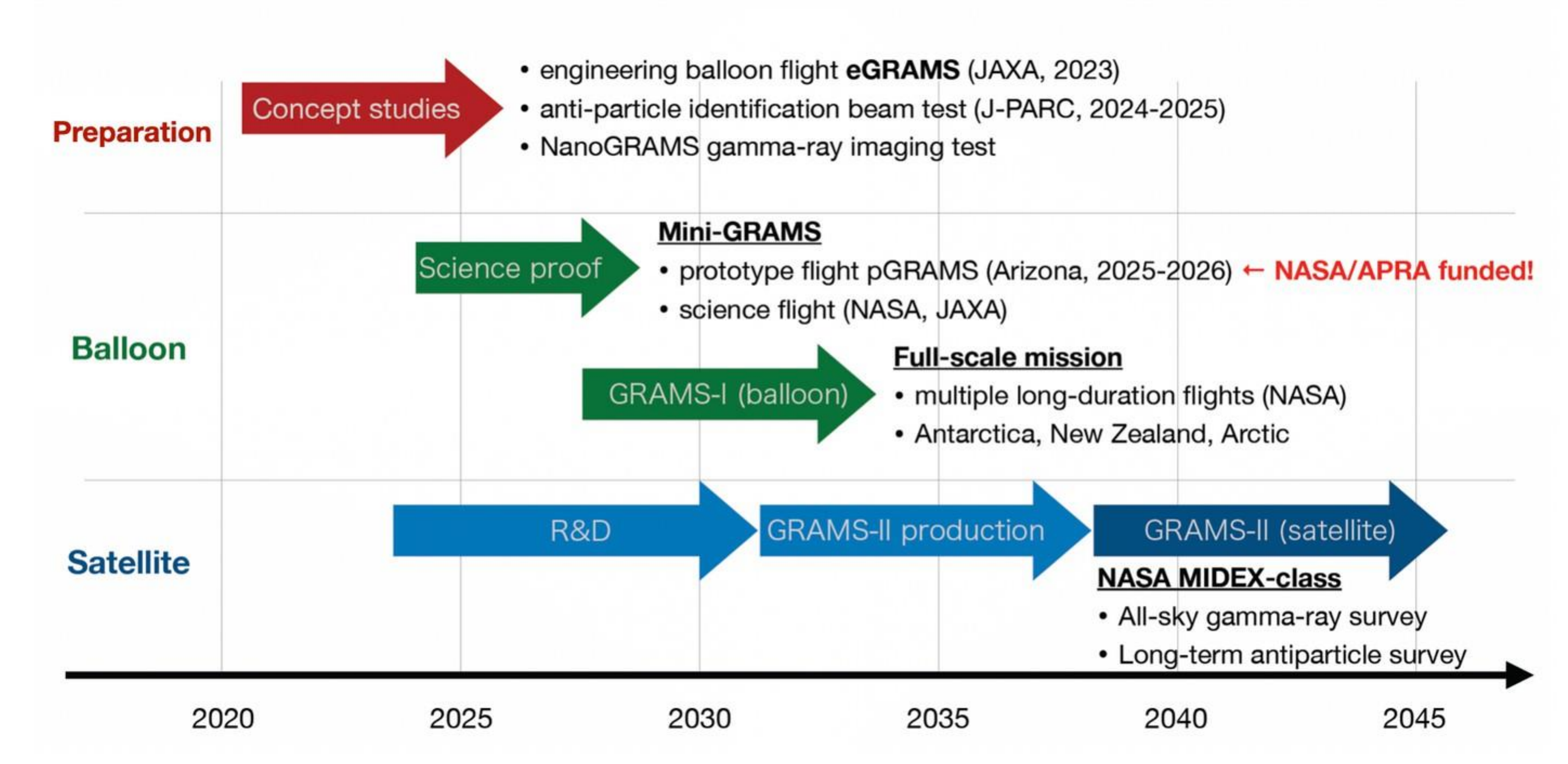
Compton scatters happen in the MeV range, which gives us the advantage of being able to know the direction of the incoming gamma-ray.

The incoming gamma-ray source direction can be reconstructed when two or more Compton scatters occur.

It is possible to add a calorimeter to the detector in order to measure the gamma-rays that escaped.



Experiment Timeline

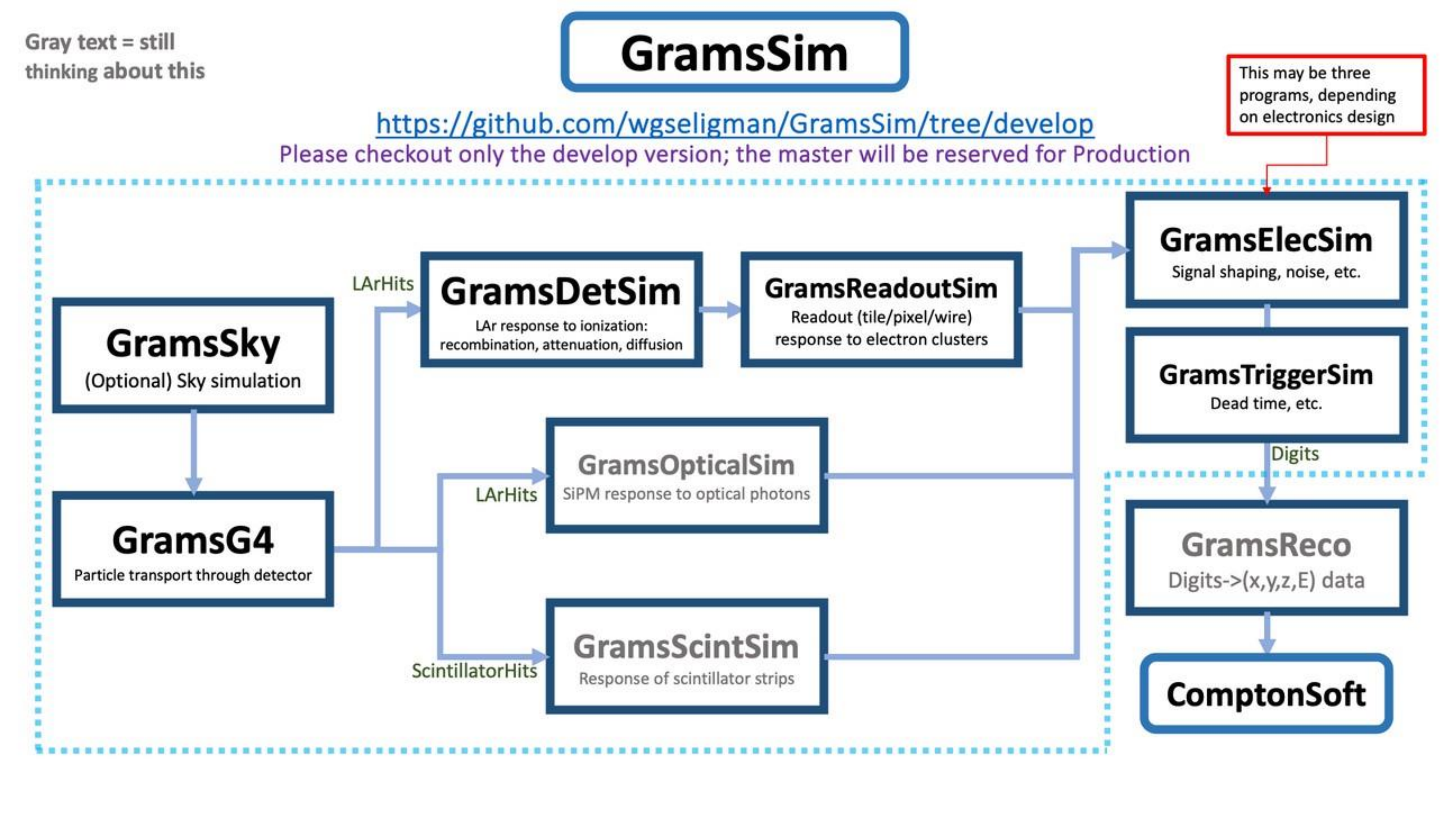


My Project Motivation

- Using simulation software will help design and tune the electronics components of the data acquisition system (DAQ).
  - Tuning of signal shaping, readout configuration, triggering.
  - From this simulation the occupancy and hit rates can be calculated.
  - The occupancy and hit rates are necessary in order to determine how much disk space is needed.
- The simulation software will also allow to study the feasibility of the physics goals for the experiment.
- Additionally there are going to be many particles going through the detector and it is important to know how much to account for.

GramsSim

GramsSim is a simulation software the allows you to run simulations of the detector throughout different stages of an event



Geant4 Stage

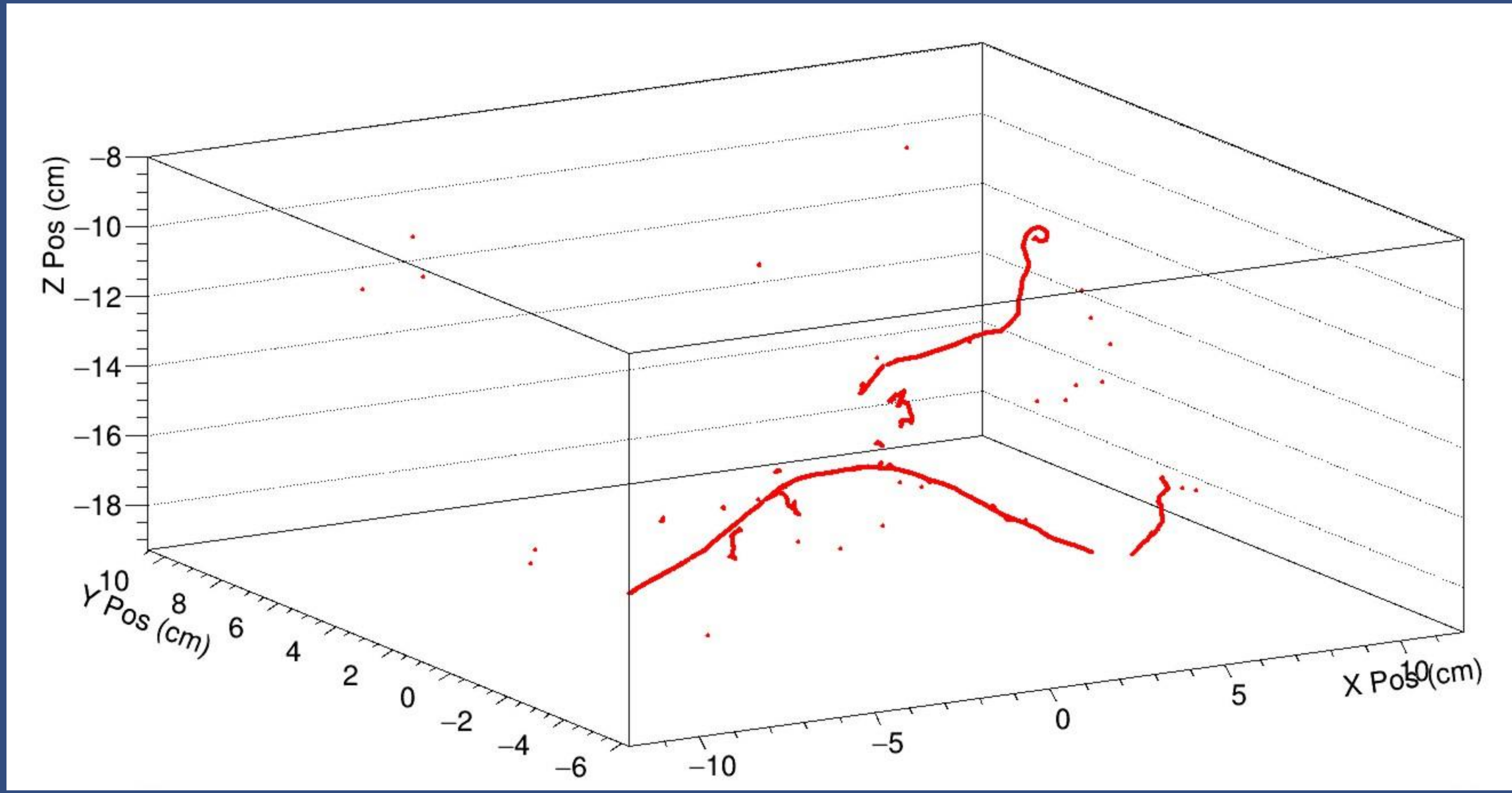
The Geant4 (G4) simulation models the particle transport in the detector.

The redline is a “Compton” electron and the green line is the photons trajectory. Each red line represents a track and the yellow dots are the steps.

This is a zoomed in image of a track, the maximum step size is 0.2mm.

G4 Event Visualization

Truth level information from the G4 stage was plotted to be visualized.



Detector Models

As the ionization electrons are drifted to the anode there are three models that are applied during this stage of the simulation. The first model that is applied is the recombination model, then the absorption model is applied, and the last model is the diffusion model.

For recombination the modified box modeled was used, this models the effect of electrons being absorbed by an Argon atom.

Absorption models electrons being absorbed by the liquid argon impurities.

Diffusion models how much the ionization electrons spread as they drift towards the anode

Detector Models

Recombination

- β', α, A_B, and k_B are material- and detector-based parameters that must be measured empirically;
- ε is the electric field;
- ξ is the effective electric field;
- ρ is the density of the liquid argon;
- dE/dx is the ionization energy per unit length.

$$\xi = \frac{\beta'}{\rho \mathcal{E}} \frac{dE}{dx}$$

$$\mathcal{R}_{Box} = \frac{1}{\xi} \ln(\alpha + \xi)$$

Absorption

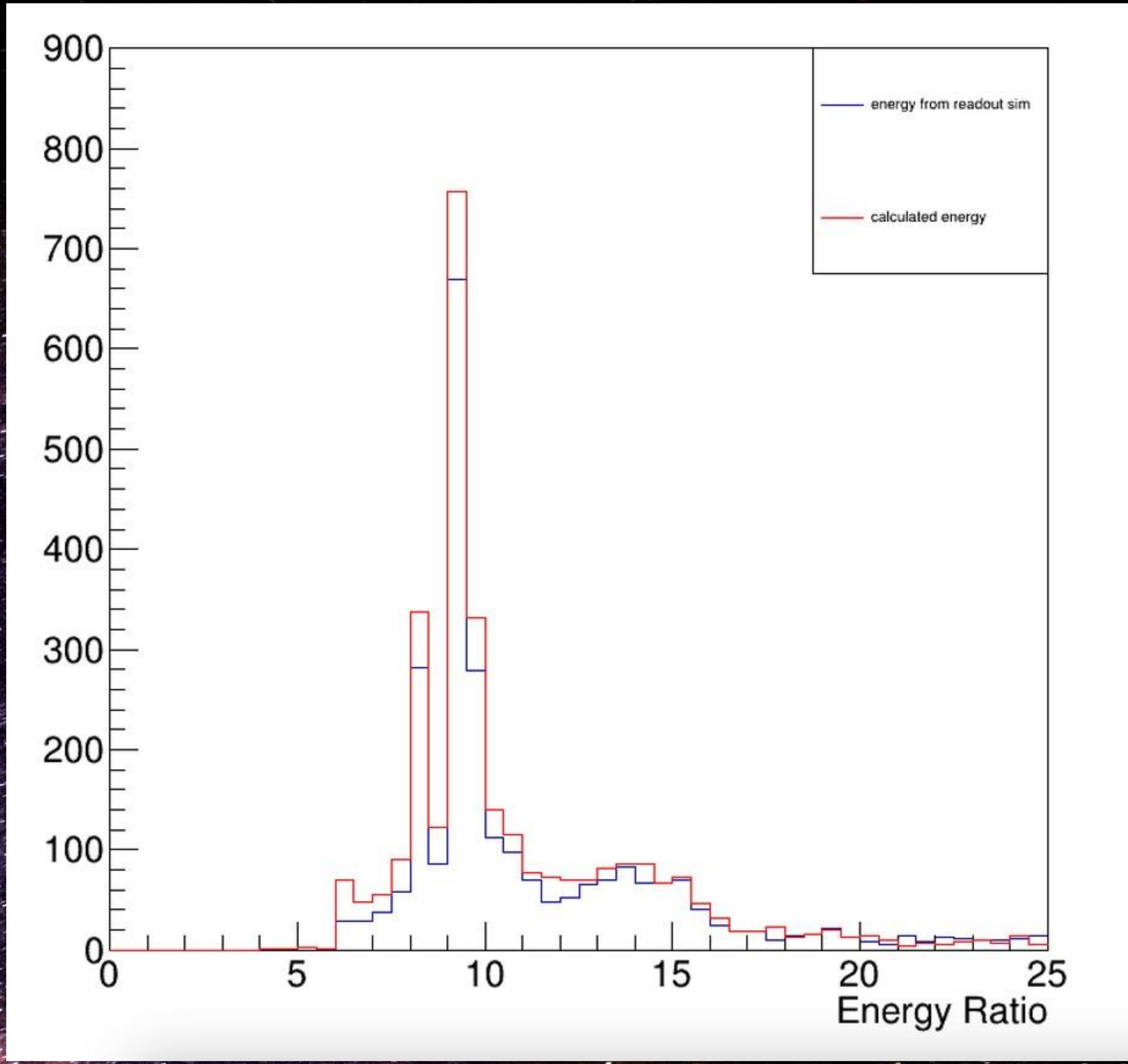
- s_{drift} = the drift distance between the ionization hit in the TPC to the anode;
- v_{drift} = the drift velocity;
- t_{elec} = the electron lifetime in the liquid argon.

$$t_{drift} = \frac{s_{drift}}{v_{drift}}$$

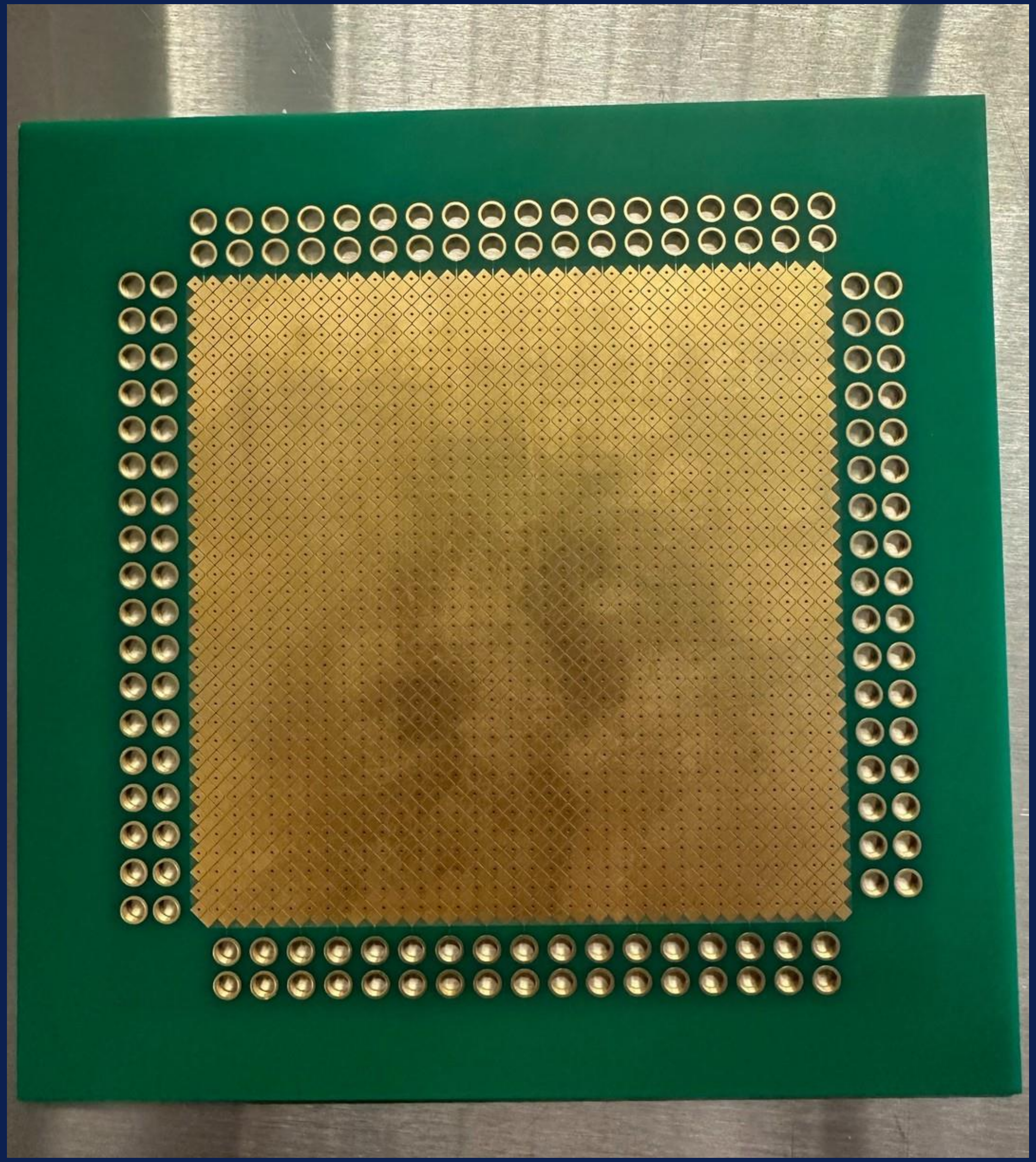
$$\mathcal{R}_{abs} = e^{-t_{drift}/t_{elec}}$$

Energies at G4 Stage

To check that the models are being applied correctly we can use the deposited ionization energy from the G4 stage and calculate the models ourselves to verify the energy recorded by the detector matches.



Readout Anode



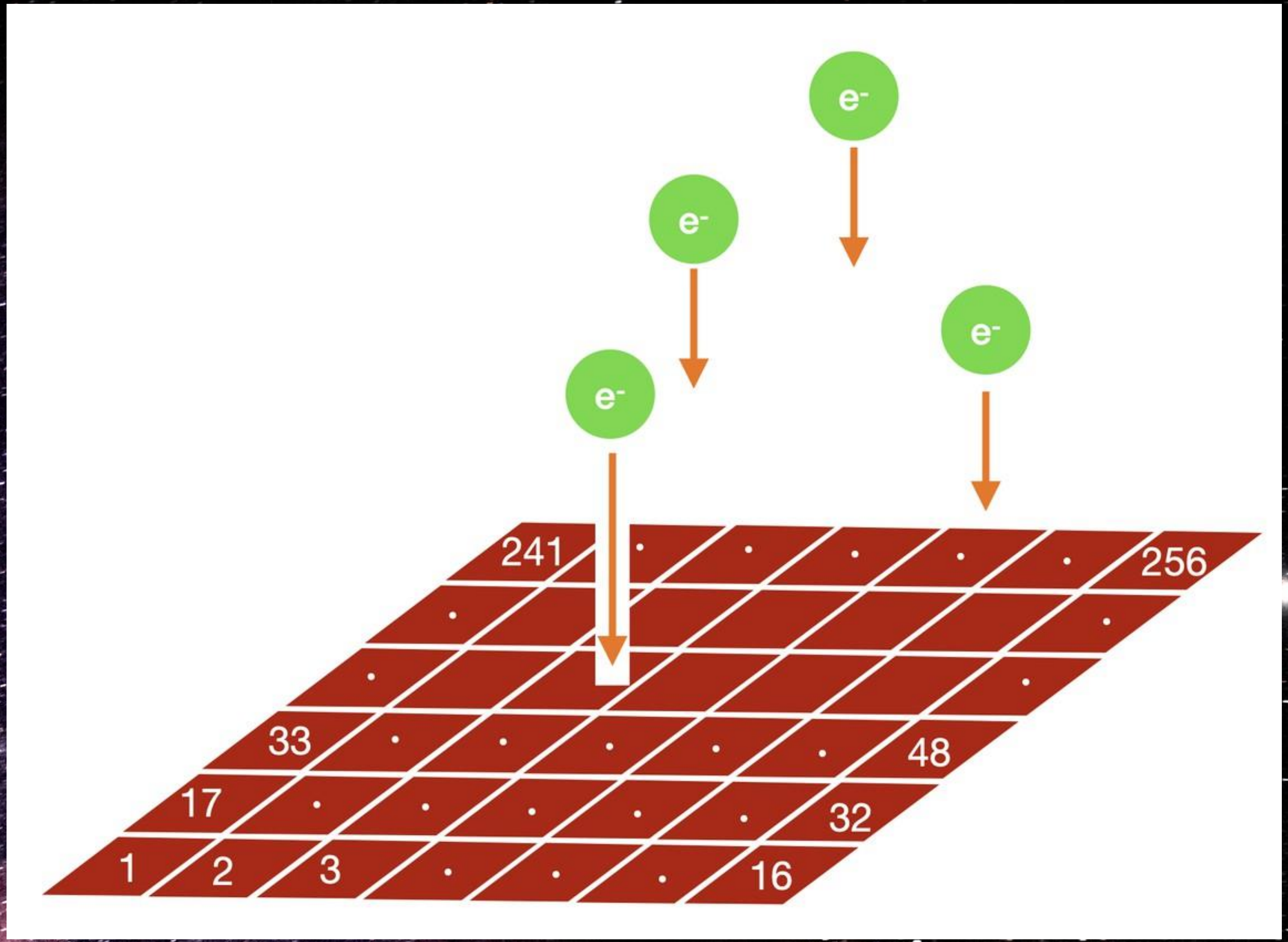
For pGRAMS the readout anode will consist of wire strips. When an electron reaches the anode the whole strip will light up.

For future GRAMS the readout anode will consist of pixels instead of wires

Readout Simulation

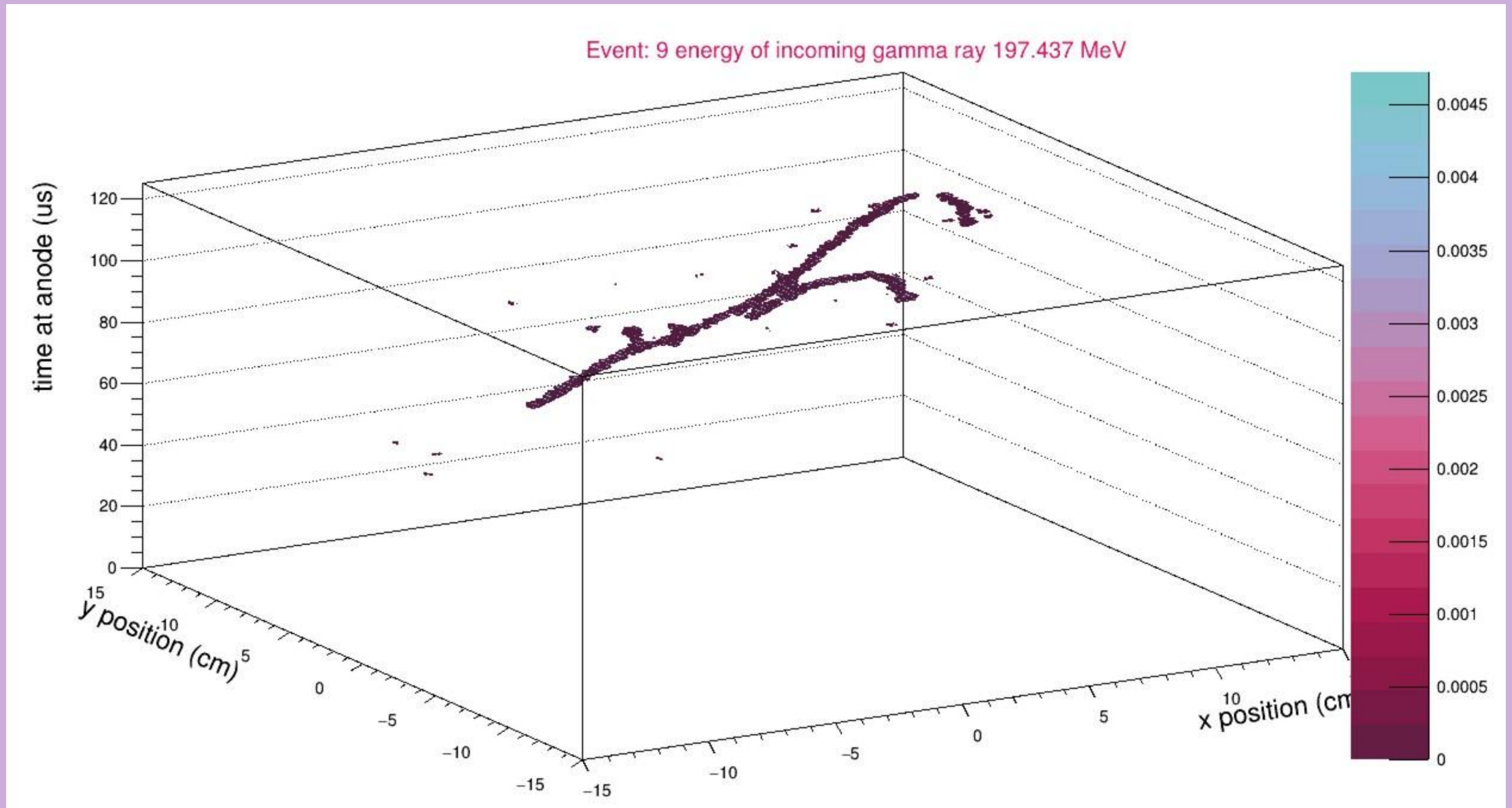
The detector simulation takes the ionization electrons left by the charged particles and groups them into cluster.

The readout simulation assigns a pixel ID for the x and y position to represent the readout anode.



Event Reconstruction

Using the data from the readout simulation the position, time, and energy at anode can be extracted to have a 3D visualization of an event.
Reconstructing an event from the simulation was one of the first steps to make sure the simulation works.

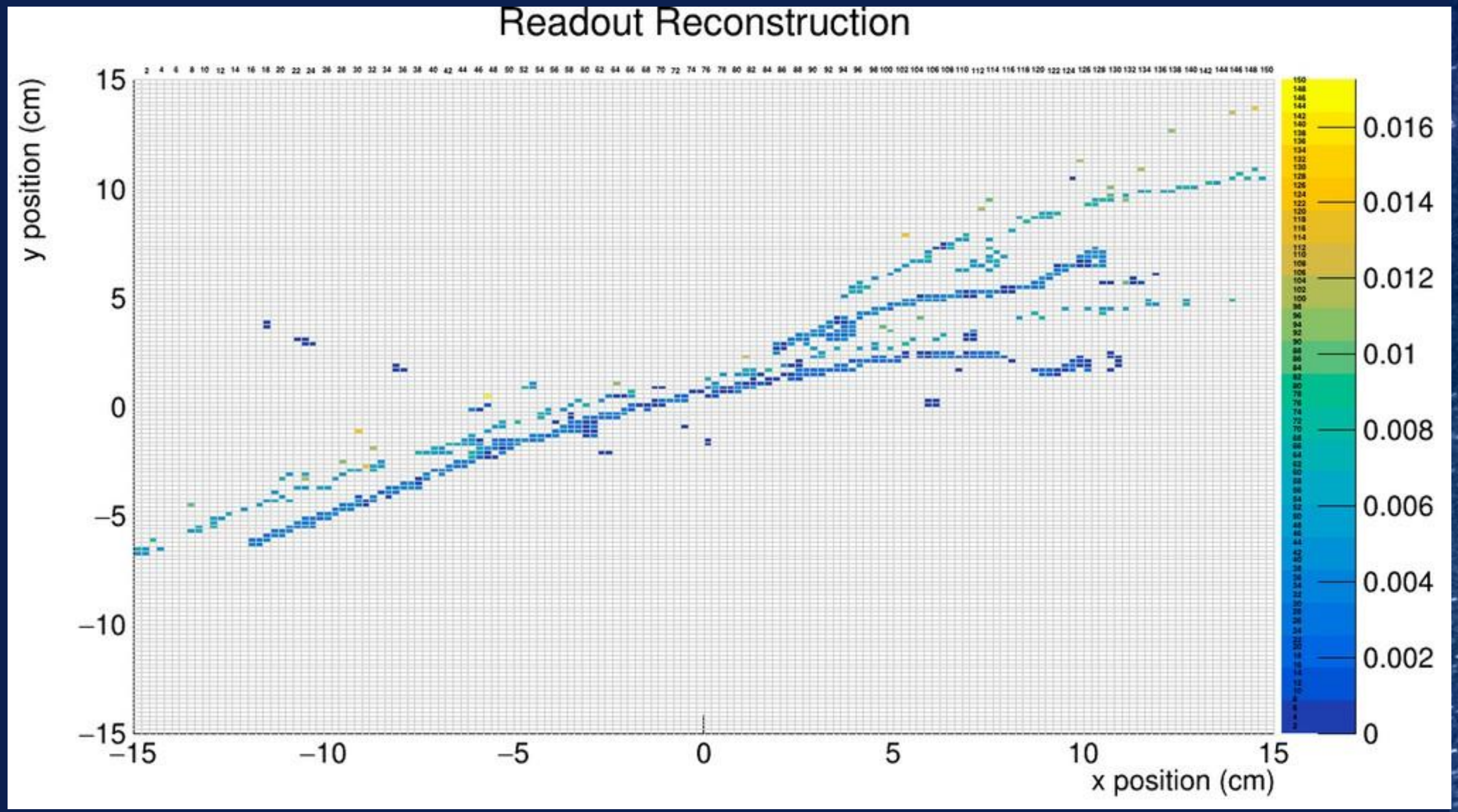


Readout Anode Reconstruction

The readout anode will have the x and y position of the ionization electrons clusters.

Every-time there is an electron that makes it to the anode a channel will be triggered.

If and x and y pixel intersect both strips will light up



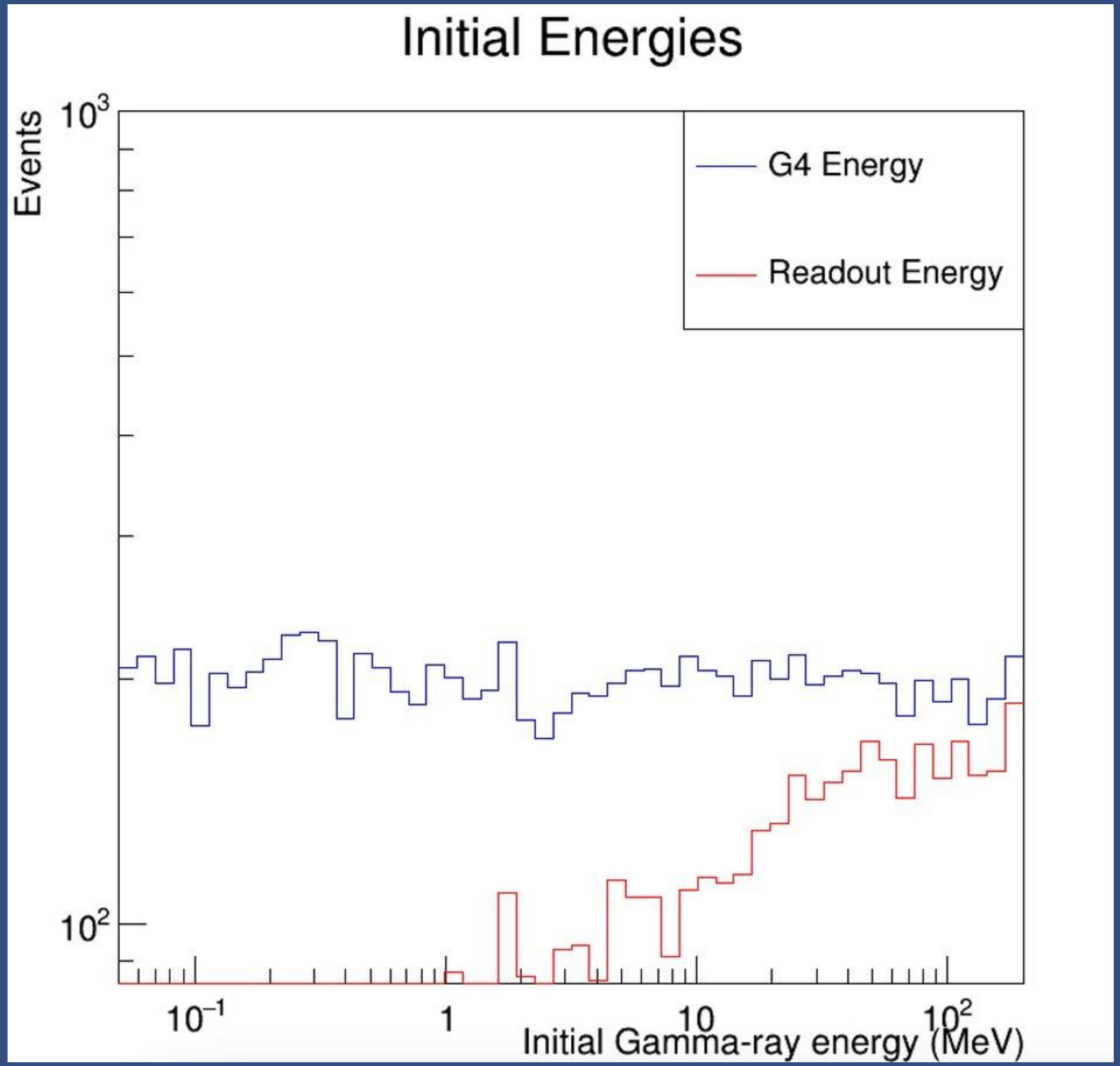
This is a reconstructed x and y position from simulated raw waveforms

Energies at the Readout Stage

During the readout stage of the simulation it is expected to see less events. Not all gammas will make it to the detector.

Lower energy gamma-rays have a smaller cross section, thus the probability of an interaction happening is unlikely.

Higher energy gammas will lose energy due to absorption in the detector.

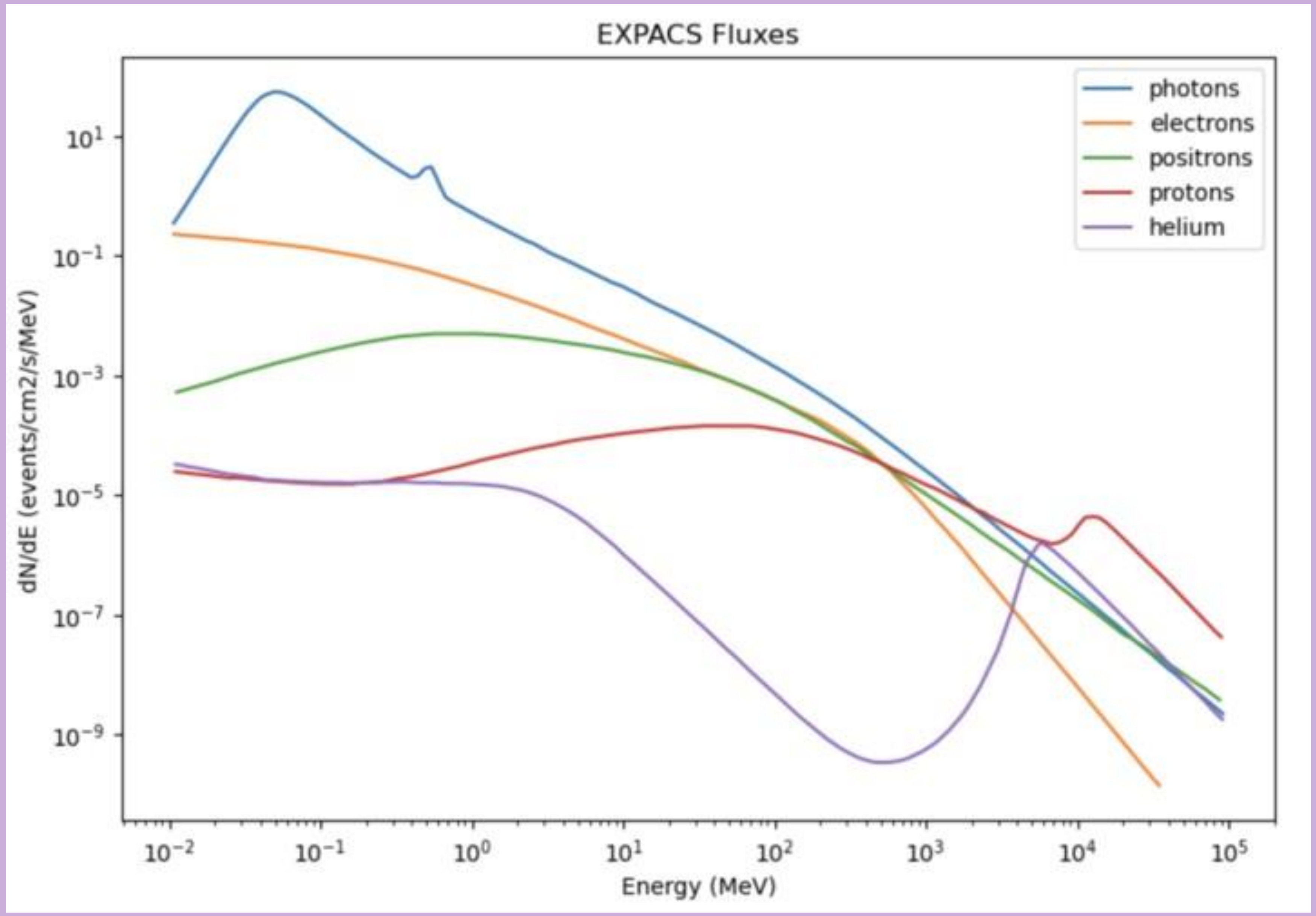


Expected Fluxes

The fluxes for electrons, positrons, muons, He, photons, and protons are known.

Comparing these fluxes to the simulation data is a good way to make sure everything is working the way it should.

These fluxes are specifically for the pGRAMS flight.

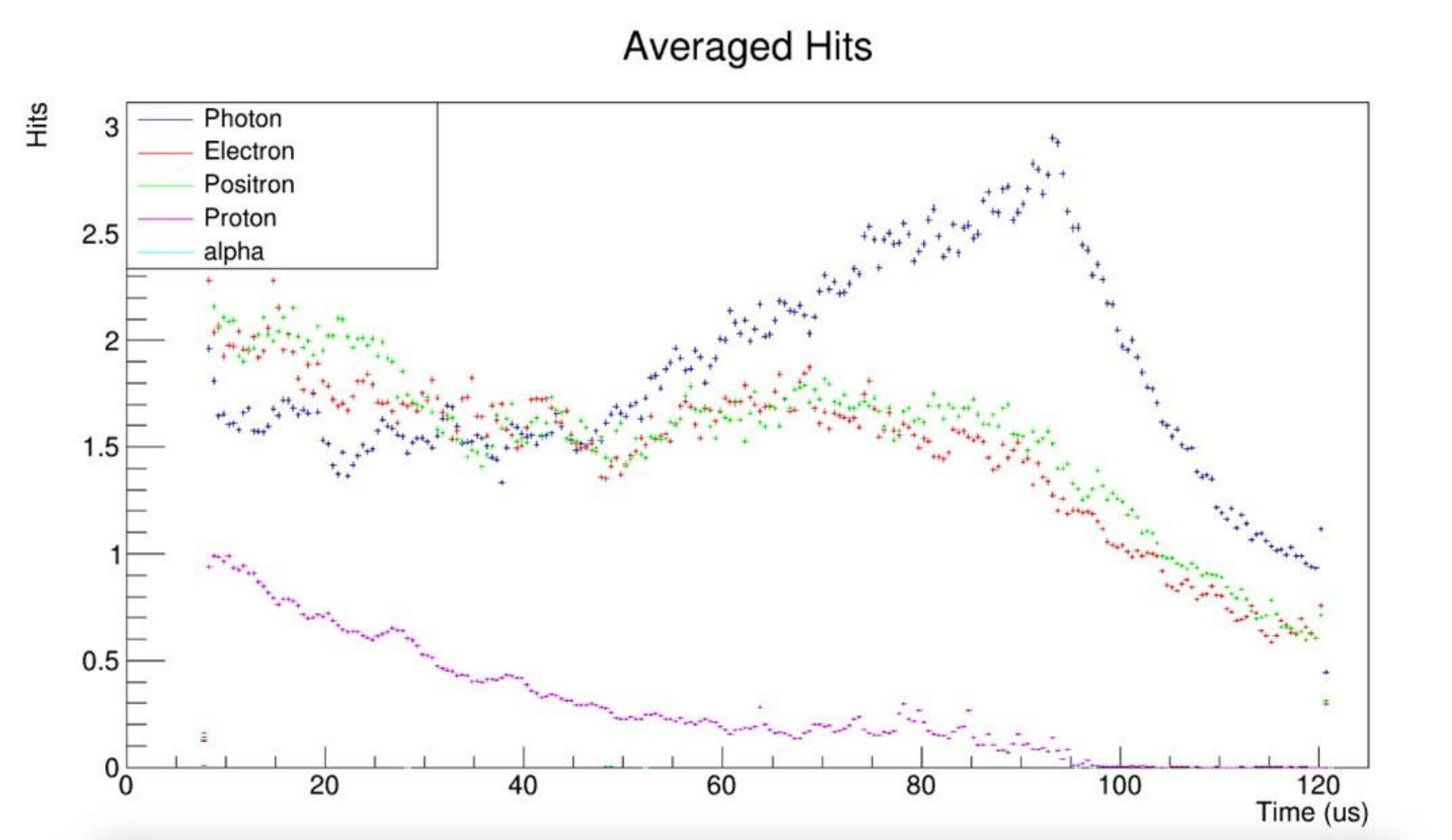


Hits for Different Particles

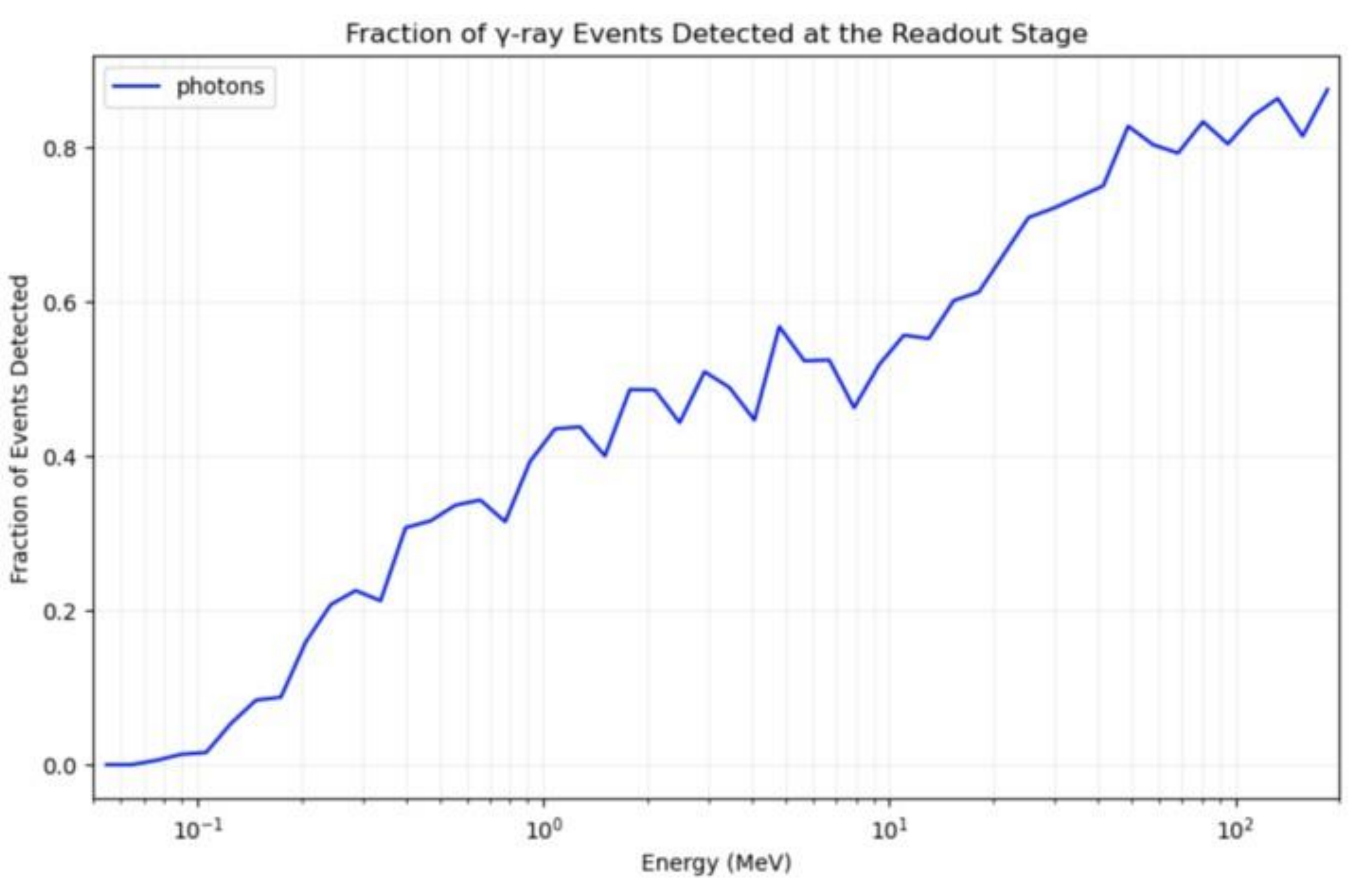
Once the code was developed, other particles were simulated to see how much cosmics the detector is going to have.

Knowing the rate of the incoming particles is crucial in order to determine accurate data rates.

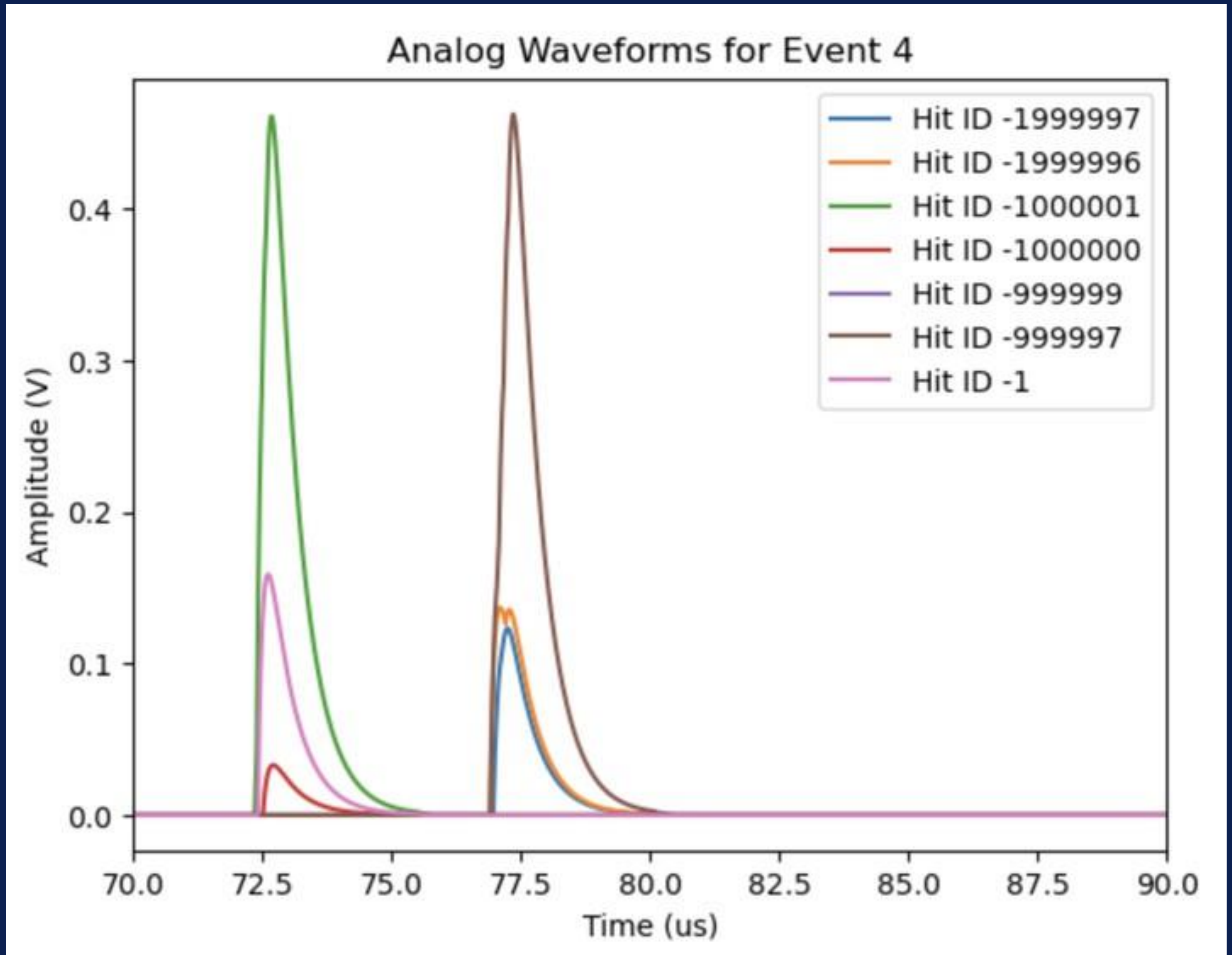
The fluxes from these particles are well known, therefore they are a good way to check the simulation data.



Fraction of Detected Events



Electronics Simulation

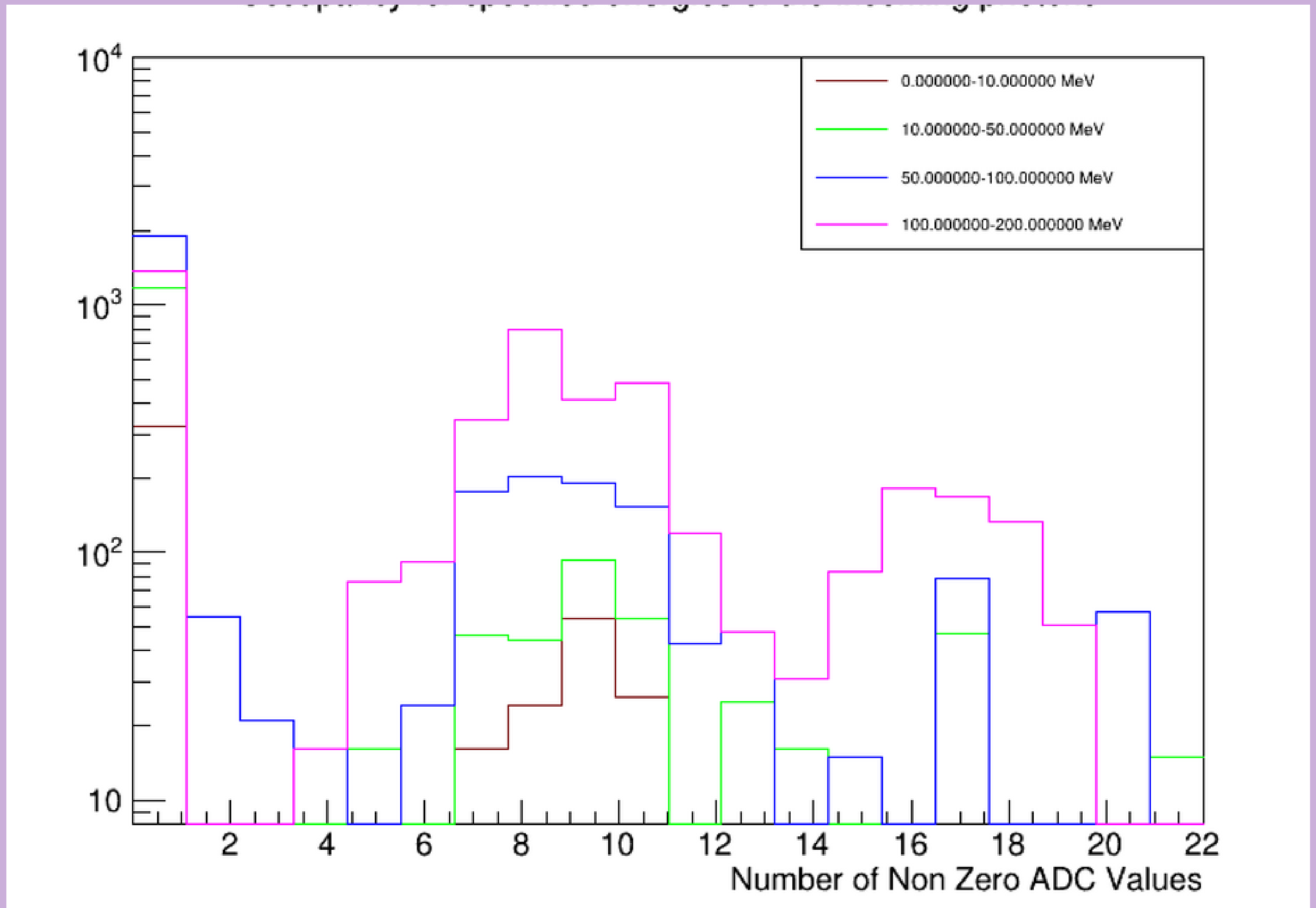


Occupancy Rates

Calculating the occupancy rates provides the information of how much activity is going on in the detector.

For this plot the occupancy rates can be calculated using the digital waveform values. If the value was greater than 0 then it would be counted.

As expected lower energy photons have lower ADC counts, thus lower occupancy rates.



Conclusion

- An end to end check for GramsSim verification was done.
- GramsSim energy calculations for the readout system are correct.
- Higher energy gammas are more likely to make it to the LArTPC and be readout.
- The tracks during the event reconstruction match the measurements of the prototype TPC.
- Developed code for event reconstruction at different stages.
- Developed a simulation chain to calculate occupancy for any incoming flux.
- Results shown here are for the prototype balloon flight.

Next Steps

- Develop a more refined version of the electronics simulation.
- Run the simulations for more event to get better statistics of the results.
- Simulate muons as the incoming particle in the detector.
- Produce waveform plots once the electronics simulation code is more developed.
- The injection of the particles during the G4 needs to be investigated more, especially for muons and alpha particles

Acknowledgements

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Thank you!
Questions?