Simulation Studies for a Future Balloon-Borne MeV Gamma-Ray Observatory

Occupancy and Optical Trigger Studies for the GRAMS LArTPC

REU Nevis Laboratories at Columbia University

Mentors: Svanik Tandon, Georgia Karagiorgi, Reshmi Mukherjee, William Seligman, Yinrui Lui

By: Nerea Real Nsi

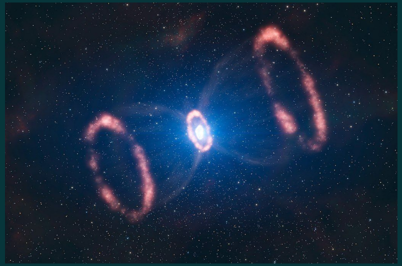
NSF NASA UNIVERSITY OF CALIFORNIA SANTA CRUZ

NEVIS LABORATORIES COLUMBIA UNIVERSITY

Outline

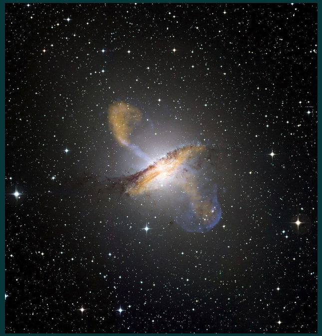
Why MeV Gamma Rays?

- Trace the most energetic phenomena in the universe
  - Supernovae, active galactic nuclei, compact binaries, and gamma-ray bursts
- Reveal nuclear processes and element formation
  - Characteristic gamma-ray lines (e.g., 511 keV) probe nucleosynthesis and radioactive decay
- Support multi-messenger astronomy
  - Provide electromagnetic counterpart observations to gravitational wave and neutrino events
- Remains under explored

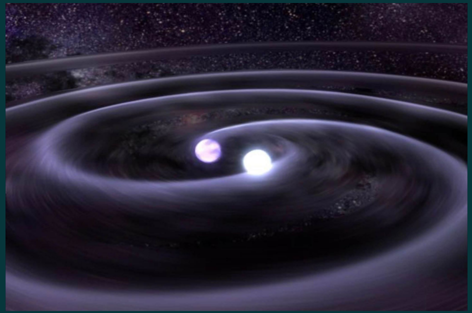


Superluminous supernovae, though rare, tend to be found in star-forming regions of our universe. Image credit - ESO/L. Calçad/ Wikimedia, licenced under CC BY 3.0

Nasa Image of the Crab Nebula 1999 The Hubble image was created from HST data from proposal 8222 (J. Hester)



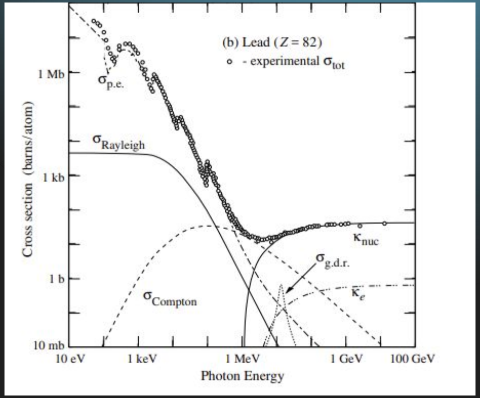
A multi-wavelength image showcasing the AGN jets of Centaurus A Credit: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss

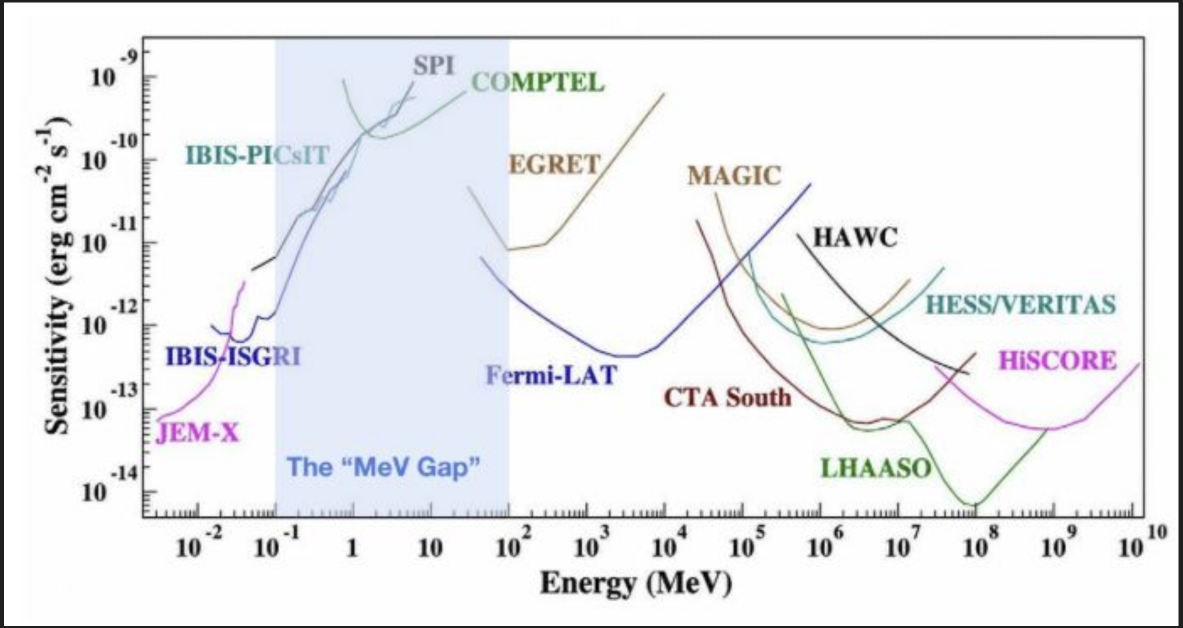


An illustration of two neutron stars merging, along with the resulting gravitational waves [NASA's Goddard Space Flight Center]

The Mev GAP

“Passage of particles through matter” - PDG





The current instrumental landscape in high energy astrophysics

- Sensitivity drop between ~0.1 and 100 MeV
- Around 1 MeV, Compton scattering becomes the dominant interaction.
- Compton events produce a scattered gamma ray and a recoil electron, making the original photon direction difficult to reconstruct.
- **GRAMS is designed to close this sensitivity gap**

The Gamma-Ray and Antimatter Survey Mission

NASA image

What my work has focused on!

What is it ?

- NASA balloon mission using a Liquid Argon Time Projection Chamber (LArTPC) as a Compton telescope
- Designed to study MeV gamma rays and cosmic antimatter

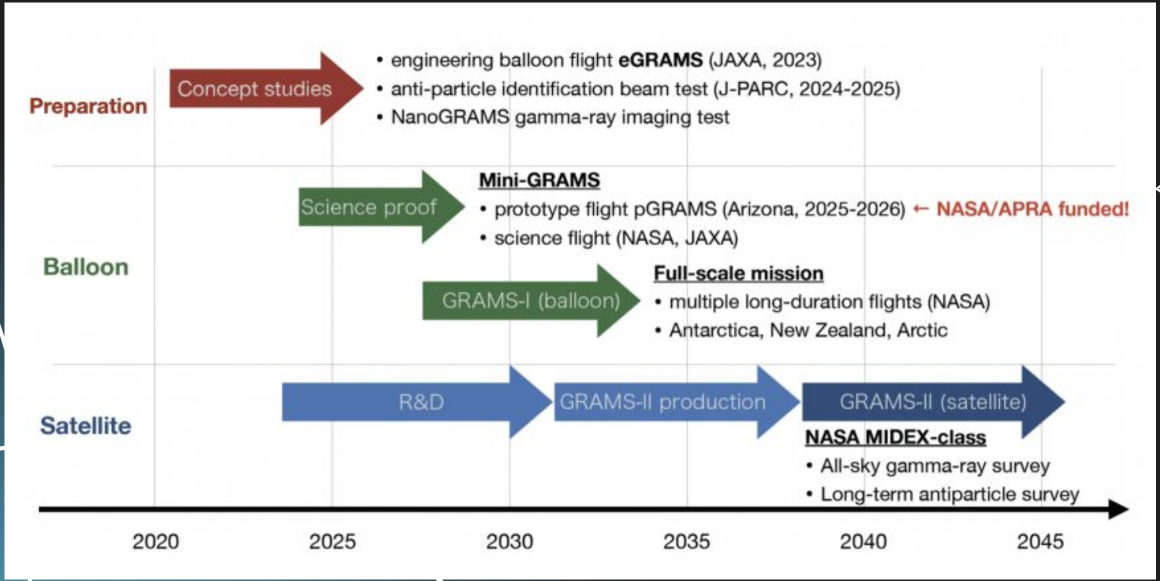
Objective 1: Bridge MeV Gap

- Improve MeV gamma-ray sensitivity by more than an order of magnitude
- Study astrophysical sources in the 0.1–100 MeV energy range

Objective 2: Indirect Dark Matter Search

- Search for low-energy cosmic antideuterons
- Probe indirect signatures of dark matter

Launch Timeline



NASA image from a balloon science flight (not GRAMS)

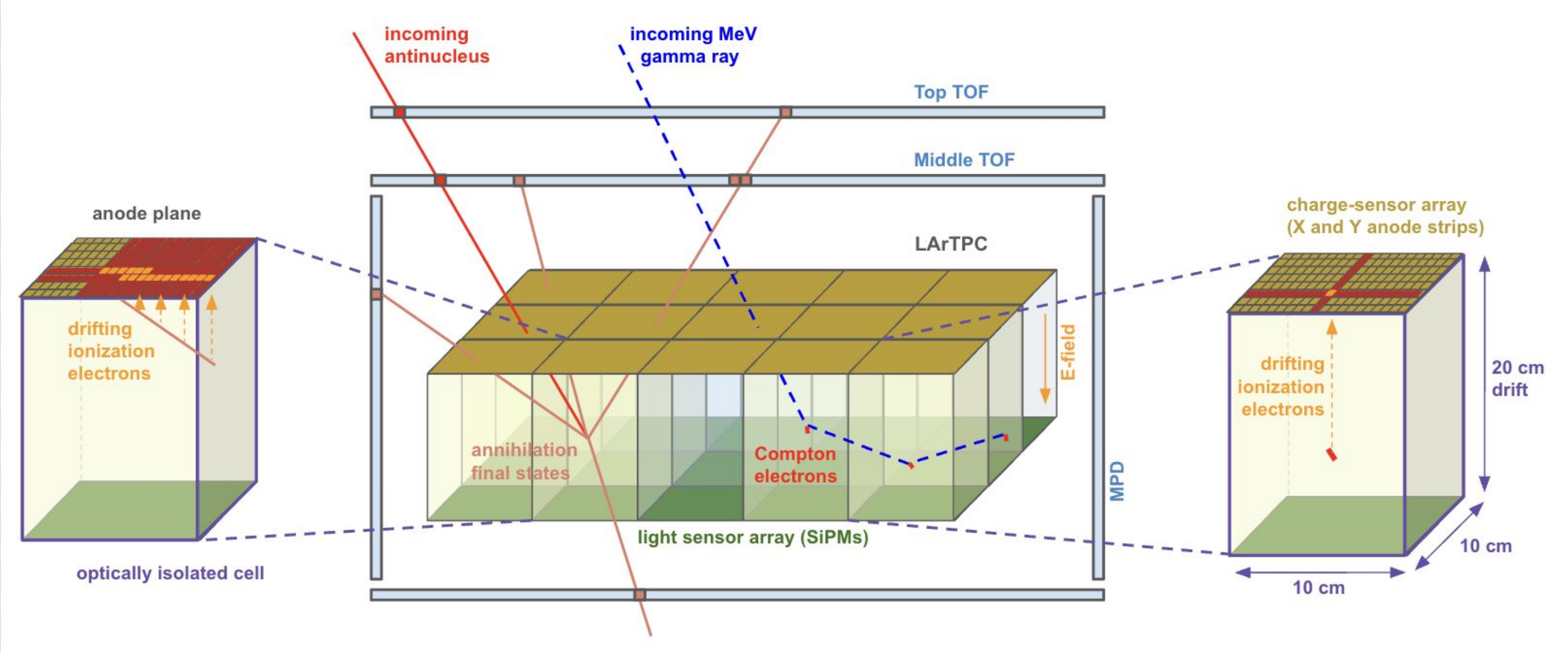
Current Phase: pGRAMS

- Prototype Liquid Argon Time Projection Chamber (LArTPC) detector
- First prototype balloon flight planned for 2026 goals:
  - Demonstrate LArTPC performance in flight, reconstruct Compton scatters, validate detector and readout systems
- Critical step toward the full-scale GRAMS science mission

- My work will contribute through validating the readout design for the first science flight by better understanding data rates and trigger rates from the optical detector

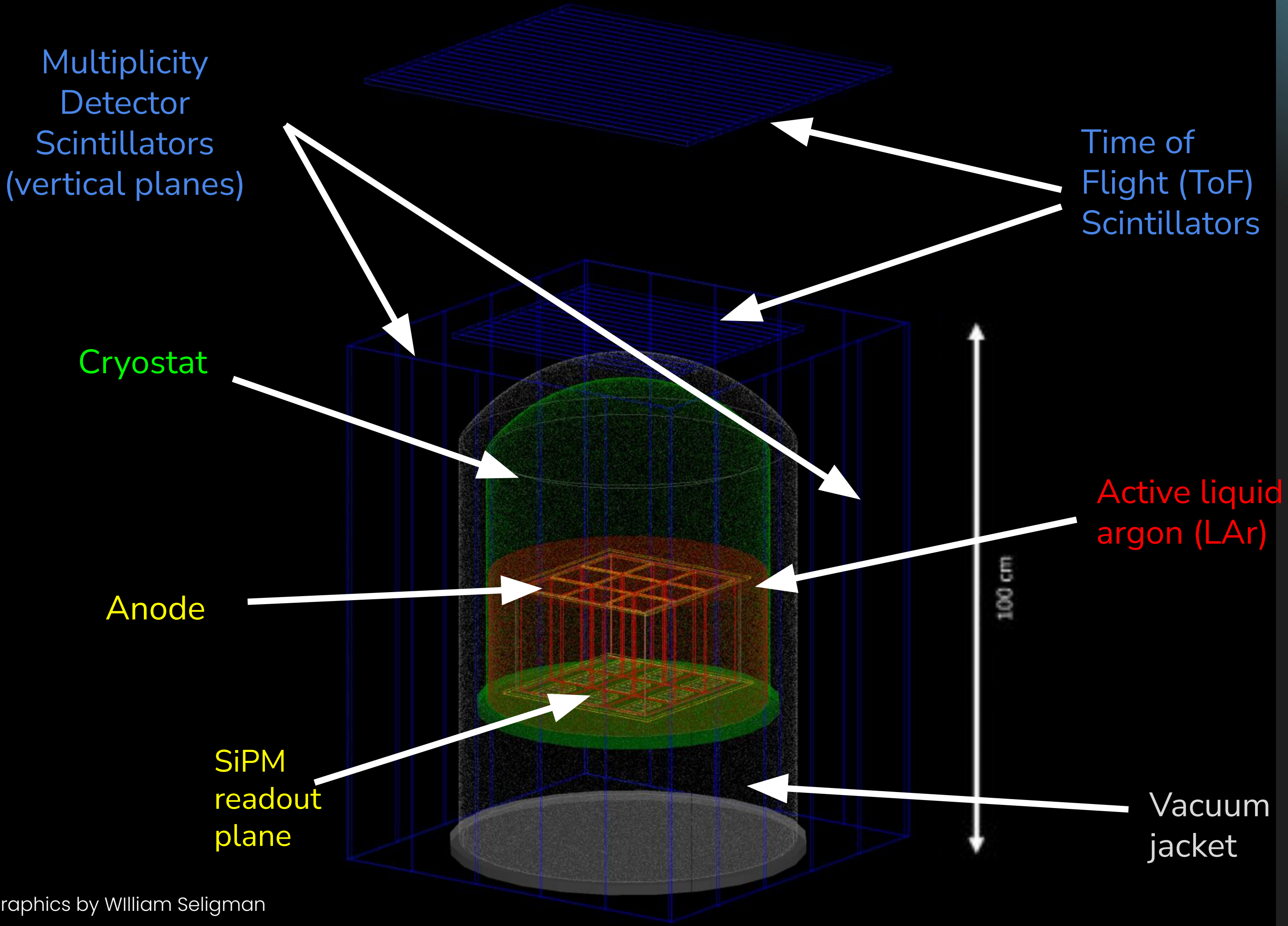
How Does The LArTPC Work?

- Gamma-ray interactions produce scintillation light and ionization electrons.
- Scintillation light is detected by SiPMs and provides the fast trigger signal.
- Charge readout + drift time reconstruct the 3D interaction position



Graphics by Georgia Karagiorgi

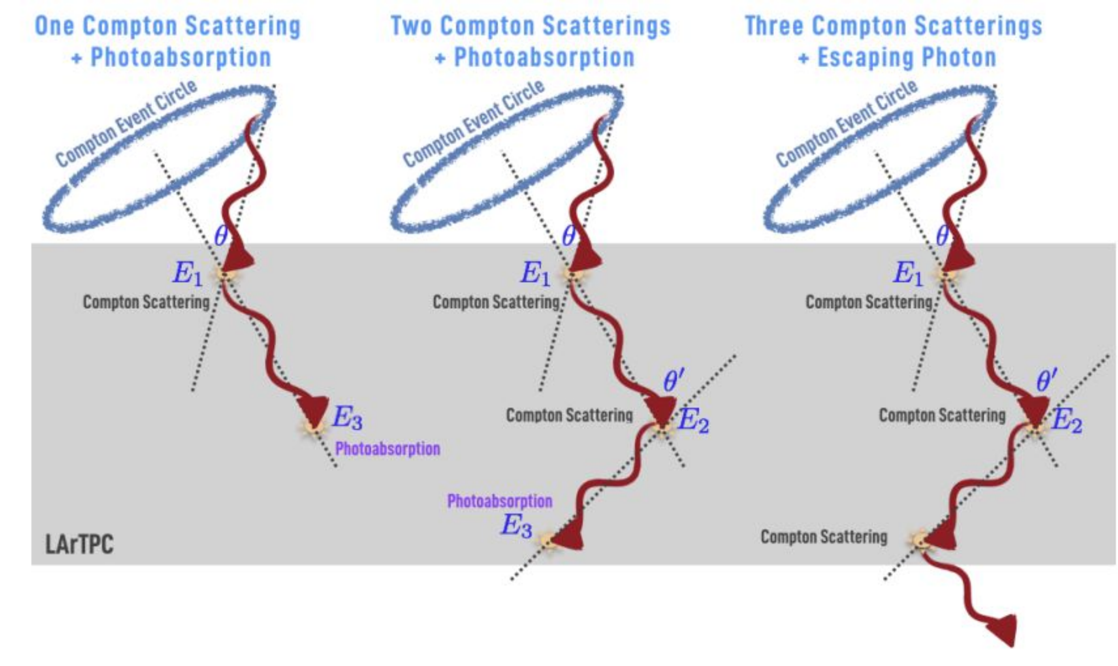
The GRAMS Detector



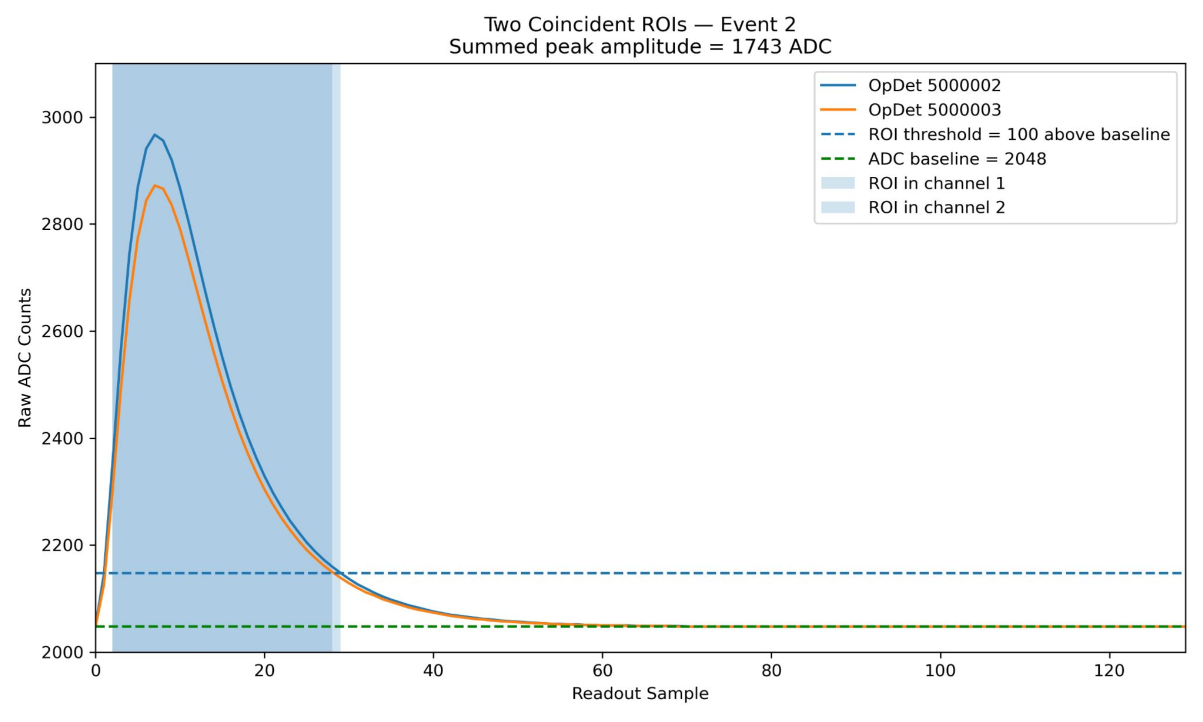
Graphics by WIlliam Seligman

Event Reconstruction: Compton Scattering

- A gamma ray undergoes one or more Compton scatters before being absorbed or escaping the detector
- One scatter: deposited energy can be measured, but the source direction and energy is underconstrained
- Two or more scatters: reconstruct a Compton cone to localize the source
- Reliable reconstruction requires detecting multiple interaction points



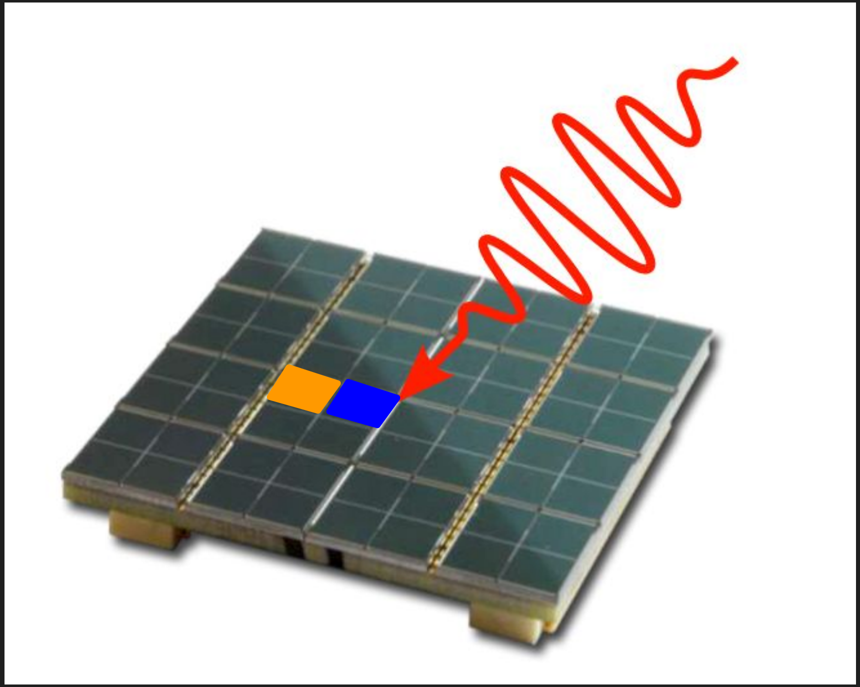
From Scintillation Light Waveforms to a Trigger



Example trigger candidate: Two coincident ROIs (ROI threshold = 100 ADC above baseline). Their baseline-subtracted peak amplitudes (919 and 824 ADC) sum to 1743 ADC, exceeding the 1024 ADC trigger threshold

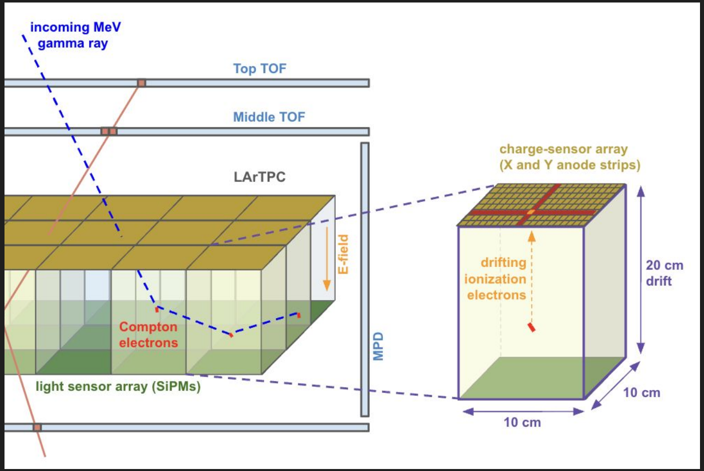
- A gamma-ray interaction produces scintillation light.
- SiPMs continuously record light as ADC waveforms.
- A Region of Interest (ROI) isolates a potential scintillation pulse and is buffered.
- **Trigger Decision:** If the summed amplitude of two coincident ROIs exceeds an ADC threshold → the trigger occurs → buffered ROIs are recorded and used for reconstruction

Why Does Triggering Matter?



Electronics/readout board

- Atmospheric backgrounds produce continuous optical activity.
- The readout electronics have limited storage and data bandwidth.
- Triggering reduces the event rate sent to storage.
- The trigger threshold must balance background rejection with signal retention.



Research Project Motivation:

1. What is the detector's particle environment at balloon altitude?
2. At what ADC threshold can GRAMS trigger reject the most atmospheric background while preserving the most actual MeV gamma-ray events?
3. Does a Crab-like gamma-ray signal survive that threshold?

In progress…

1. Occupancy Studies

Characterize the particle environment GRAMS will see at balloon altitude.
Convert simulated MC events into physical detector rates

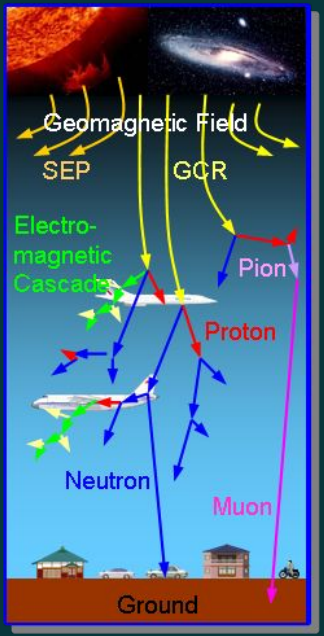
2. Trigger Studies

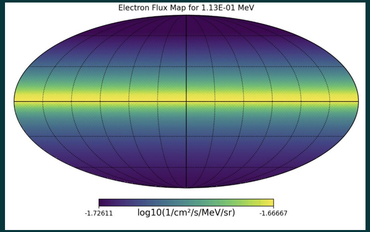
Quantify what fraction of that background actually produces a trigger, vs ADC threshold.

3. Preliminary Sensitivity Studies

Ask whether a known astrophysical source (Crab Nebula) can be observed efficiently against that background.

These studies help determine whether the current GRAMS electronics can accommodate the expected data rates and guide the selection of an appropriate trigger threshold before the balloon flight.





Simulation Workflow

GramsSim (GRAMS Collaboration-Developed)

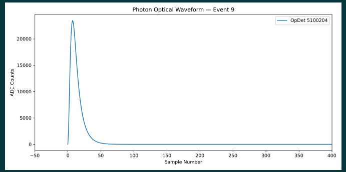
EXPACS/PARMA →
Simulates atmospheric fluxes from cosmic rays at balloon altitude and location.

HEALPIX Flux Maps →
Converts particle fluxes into sky maps of energy and direction.

GramsSky →
Samples Monte Carlo particles from the HEALPix flux maps.

Geant4 (GramsG4)→
Simulates particle interactions inside the detector.

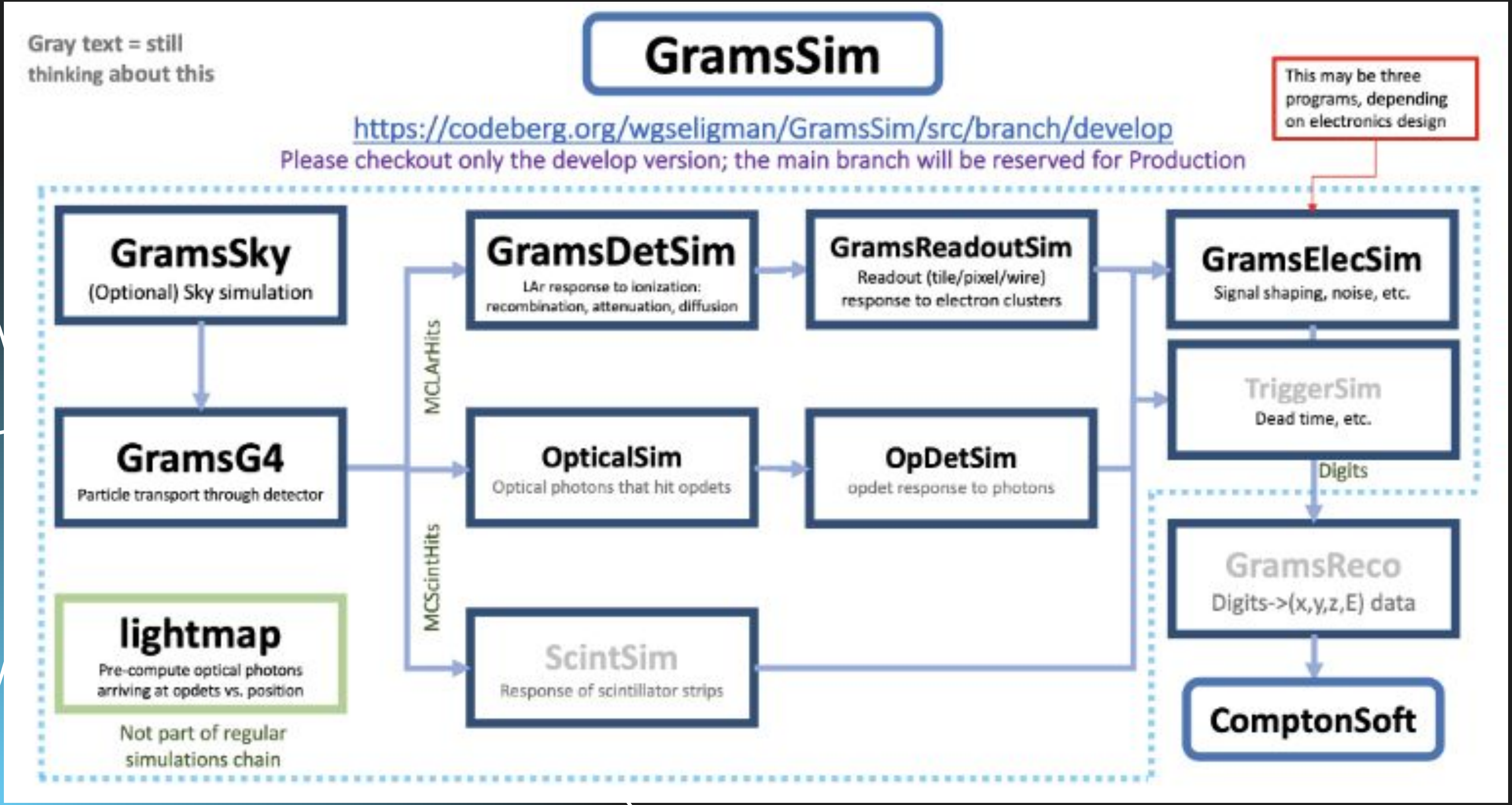
Detector Response →
Converts energy deposits into detector signals and ADC waveforms.



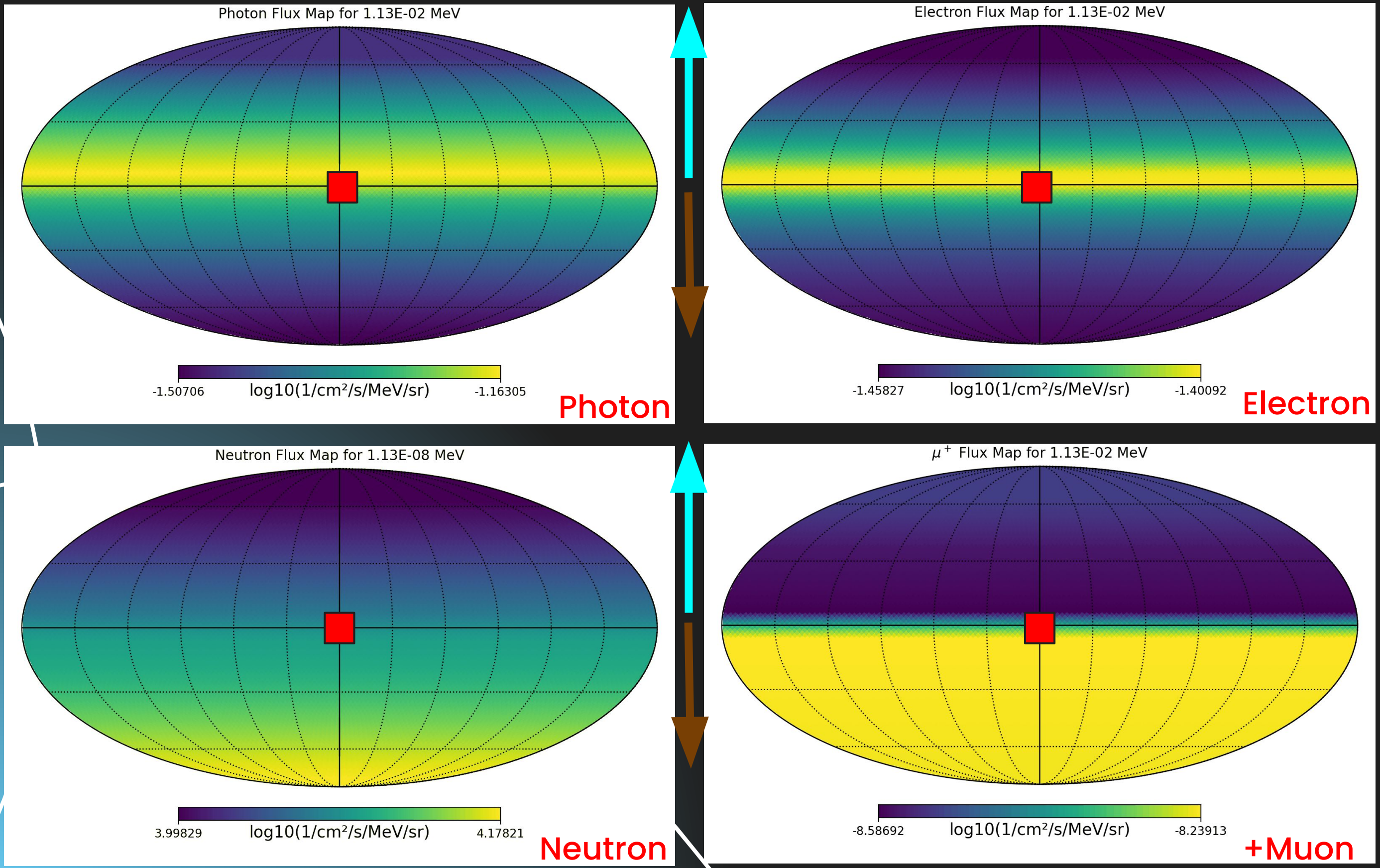
EXPACS/PARMA: EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum (public source)

GramsSim Tools: A simulation framework for the GRAMS experiment

Simulation Workflow



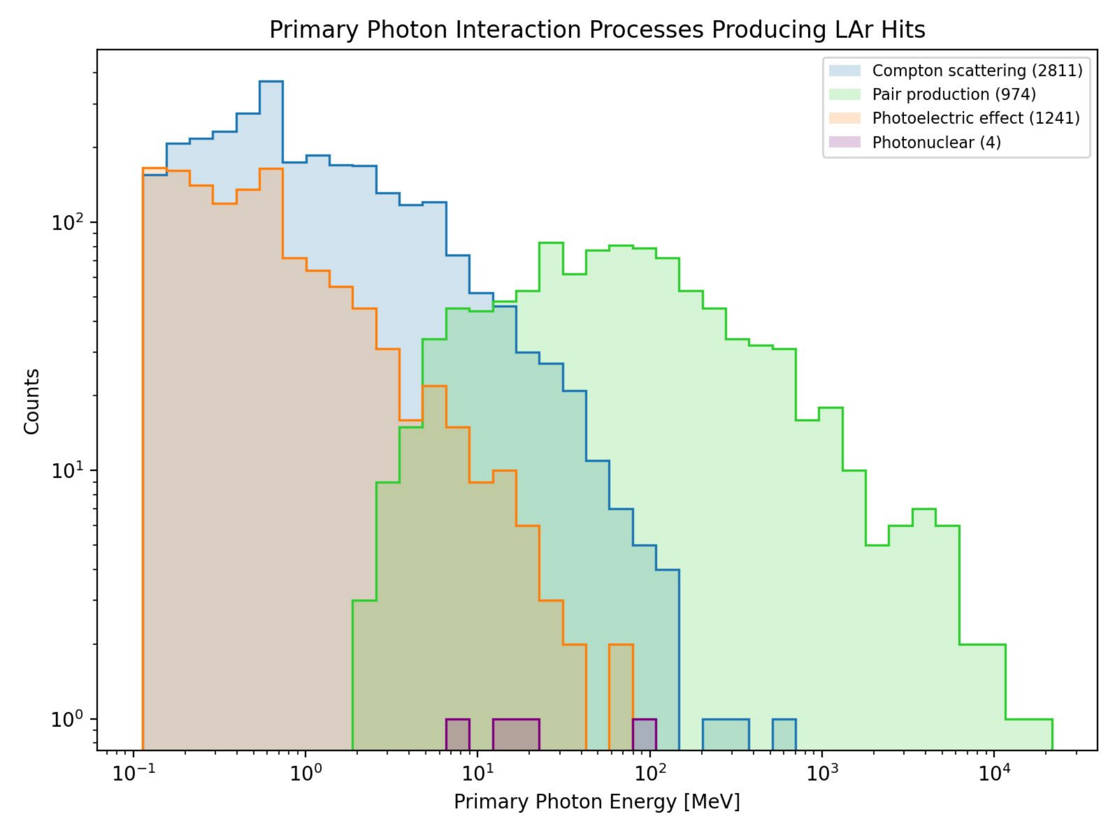
Simulating The Atmospheric Particle Environment



→ = Sky, → = Ground, Red Square = Detector

- Generated atmospheric particle fluxes calculated with EXPACS/PARMA
- Simulated particle species: γ, n, p, He, μ±, e±
- HEALPix maps encode the particle flux as a function of energy
- Energy is distributed in arrival direction
- Time lapse represents increasing energy bin

Which Primary Photon Interaction Processes Produce LAr hits?



- LAr hit = an energy deposition recorded in the liquid argon active volume
- Compton scattering dominates at MeV energies, enabling Compton imaging.
- Pair production becomes important at higher energies.
- Photoelectric and photonuclear interactions contribute at lower energy and much less frequently, respectively
- Other atmospheric particles (n, p, μ, e) interact through different processes and contribute to the detector background.

From Atmospheric Flux to Physical Event Rates

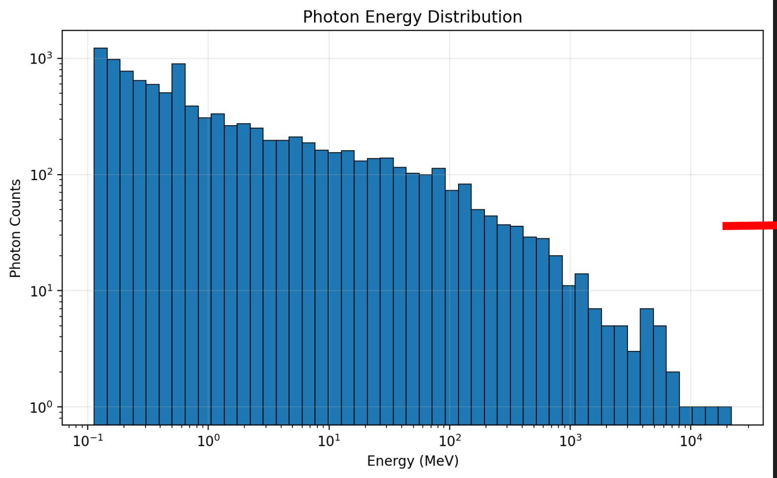
- Generate Monte Carlo events from atmospheric flux maps
- Simulate particle interactions with Geant4
- Normalize Monte Carlo events to physical rates (Hz)
- Normalization method developed by Svanik Tandon

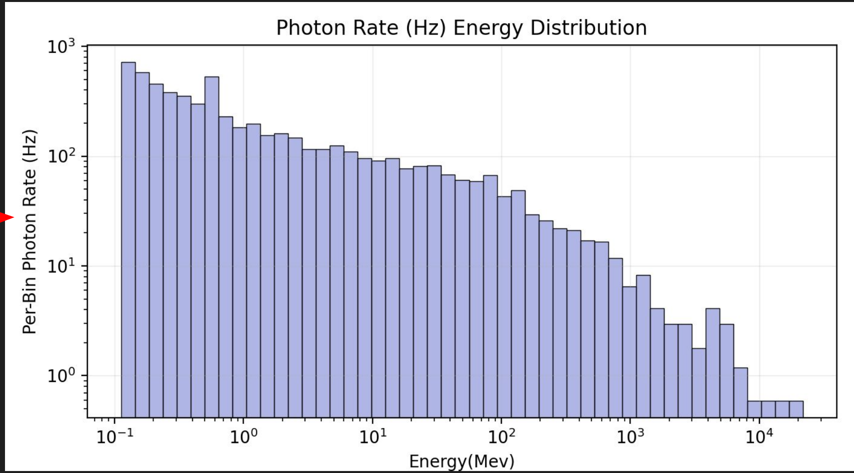
$$T = \frac{N}{S}$$

N: simulated events
S: integrated particle flux $(\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$
T: effective exposure time $(\mathrm{cm}^2\,\mathrm{s})$
A_{TPC}: average projected TPC area (cm^2)

$$S = \sum_p \int_{\Omega_p} E_p \, d\Omega = \sum_p \left(E_p * \frac{4\pi}{N_{pix}} \right) [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$

$$\mathrm{Rate} = \frac{\mathrm{MC\ Counts}}{T} \times A_{\mathrm{TPC}}$$





Expected Atmospheric Particle and Optical Response Rates

Label	Definition
Incident Rate	Expected number of particles entering the detector per second.
Interacting Rate	Expected number of particles producing at least one LAr hit per second.
Interaction Fraction	Interacting rate ÷ Incident rate.
Nonzero ADC Rate	Events with at least one nonzero SiPM optical ADC waveform*.
Nonzero ADC Fraction	Nonzero ADC rate ÷ Incident rate.
Rate ≥ 1024	Events with a summed optical ADC signal above the preliminary 1024 counts trigger threshold.
Fraction ≥ 1024	Rate ≥1024 ÷ Incident rate.

*No noise was included from electronics.

Expected Atmospheric Particle and Optical Response Rates

- These interaction rates provide the baseline background environment used for the trigger threshold studies.
- Although all particle species contribute to the background, their interaction probabilities differ significantly because they interact through different physical processes.
- Approximately 8.9 kHz of atmospheric particles are expected to enter the detector at balloon altitude.
- About 47% of incident particles interact in the liquid argon, producing measurable energy deposits.
- Photons produce the highest interaction rate (~2.5 kHz), making them the dominant contributor to detector occupancy.

Particle	Incident rate	Interacting rate	Interacting fraction	Nonzero ADC rate	Nonzero ADC fraction	Rate ≥ 1024	Fraction ≥ 1024
Neutron	1719 Hz	801 Hz	46.6%	720 Hz	41.9%	476 Hz	27.7%
Proton	501 Hz	433 Hz	86.4%	432 Hz	86.2%	430 Hz	85.8%
Helium-4	35 Hz	16 Hz	44.9%	16 Hz	44.8%	16 Hz	44.2%
μ^+	24 Hz	23 Hz	98.6%	23 Hz	98.6%	23 Hz	98.4%
μ^-	19 Hz	19 Hz	98.9%	19 Hz	98.9%	19 Hz	98.4%
Electron	419 Hz	178 Hz	42.4%	176 Hz	41.9%	164 Hz	39.1%
Positron	246 Hz	183 Hz	74.3%	181 Hz	73.4%	168 Hz	68.3%
Photon	5906 Hz	2490 Hz	42.1%	2403 Hz	40.7%	1808 Hz	30.6%
Total	**8870 Hz**	**4143 Hz**	**46.7%**	**3971 Hz**	**44.8%**	**3105 Hz**	**35.0%**

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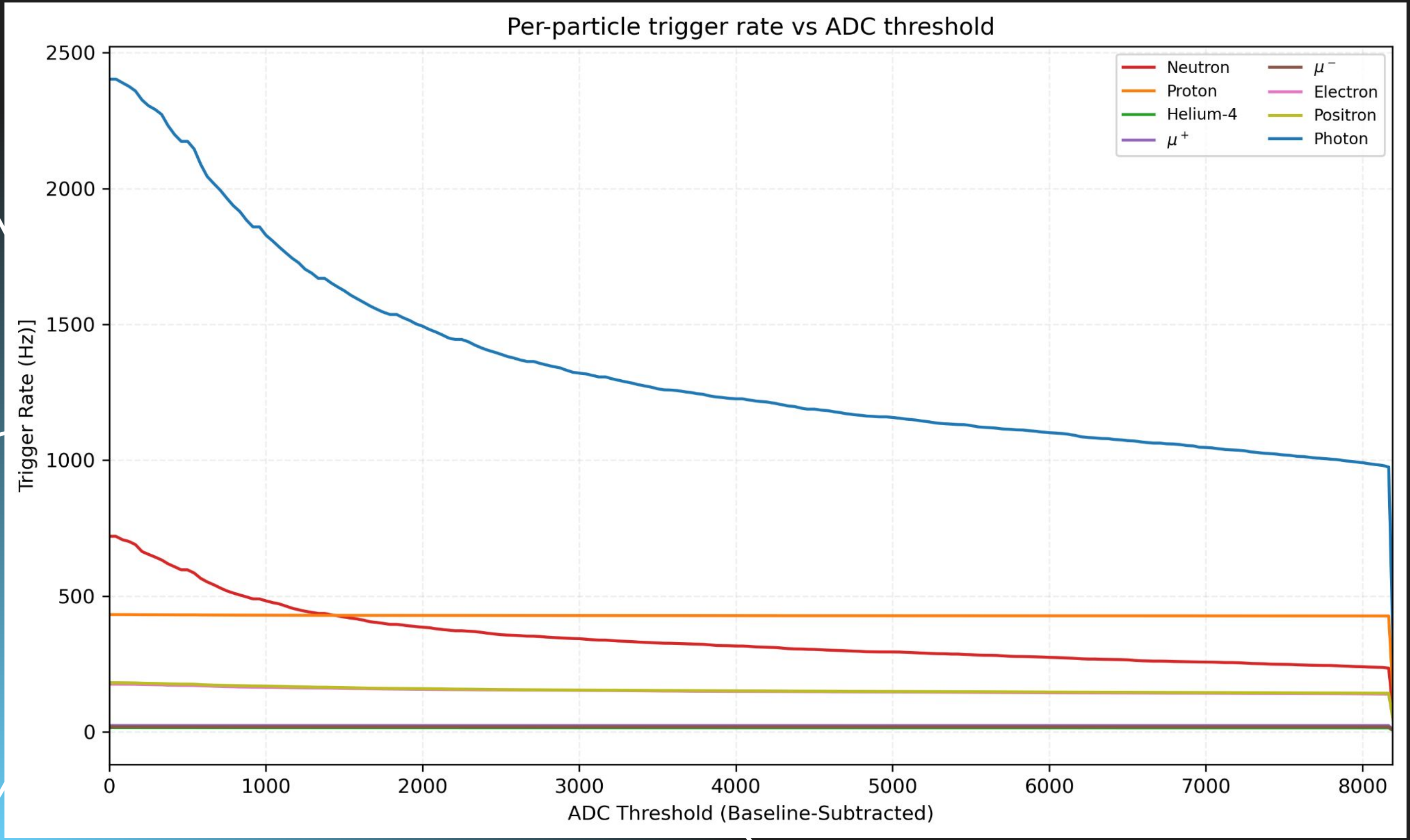
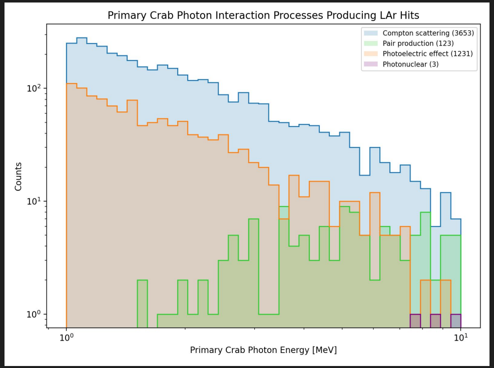
Trigger Rate vs Threshold

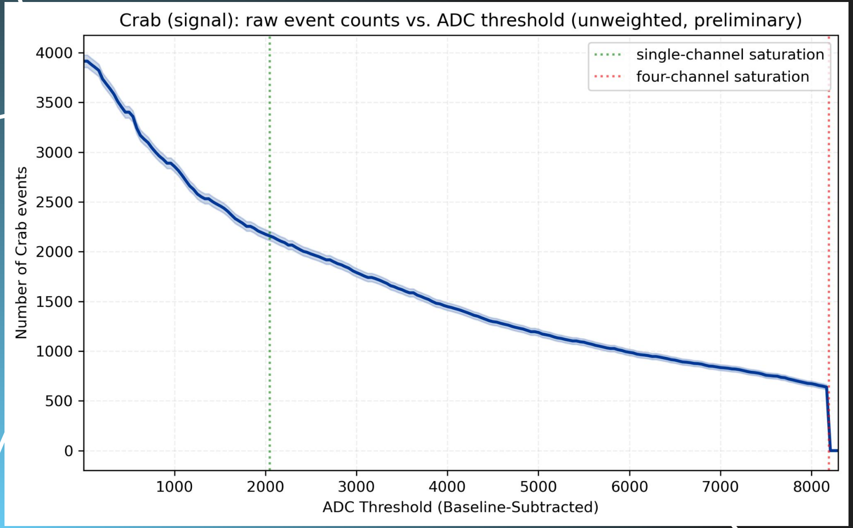
How many events per second have a summed optical waveform peak above a given a summed ADC threshold?



- Increasing the summed ADC threshold reduces the atmospheric trigger rate.
- Photons dominate the atmospheric trigger rate across all thresholds
- Higher thresholds suppress background but also risk removing low-energy signal events.



Nasa Image of the Crab Nebula 1999
The Hubble image was created from HST data from proposal 8222 (J. Hester)



Preliminary Crab nebula Study

Why the Crab Nebula?

- Bright, steady and one of the best characterized gamma-ray sources. Widely used for calibration.
- Provides a standard source for evaluating detector and trigger performance

Completed

✓ Generated a Crab-like photon source

✓ Simulated detector interactions with Geant4

Ongoing Work

- Figure out weight distribution for crab photons
- Determine trigger efficiency as a function of trigger threshold
- Compare signal and atmospheric background
- Estimate GRAMS sensitivity to Crab Nebula photons

Summary & Future Work

★ Implemented a simulation workflow to model the atmospheric particle environment expected during the GRAMS balloon flight.

★ Converted Monte Carlo event counts into physical detector rates (Hz) using a flux normalization procedure.

★ Characterized atmospheric interaction and occupancy for photons, neutrons, protons, muons, electrons, positrons, and helium nuclei.

★ Investigated the dependence of atmospheric trigger rates on the trigger threshold, establishing the trade-off between background rejection and signal retention.

Next Steps

- Complete the trigger efficiency study for a simulated Crab-like gamma-ray source.
- Compare the surviving astrophysical signal to the atmospheric background.
- Optimize the trigger threshold for the upcoming GRAMS balloon flight.
- Extend this work toward a full detector sensitivity study.

An optimal trigger threshold is essential: it must suppress atmospheric background while preserving real MeV gamma-ray events needed for Compton reconstruction.

Acknowledgements

I would like to sincerely thank my mentors, Prof. Georgia Karagiorgi, Prof. Reshmi Mukherjee, Dr. William Seligman, Dr. Yinriu Liu and Svanik Tandon for their guidance, mentorship, and support throughout this summer. I would like to thank Amy Garwood, the Nevis scientists, and the entire GRAMS Collaboration for creating such a welcoming and supportive research environment. This summer has been an incredible opportunity for both my scientific and professional growth.

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Thank you!

Questions? Ask away!