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New space-based tools for GRB detection in the MeV energy range

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Introduction

Gamma-ray bursts (GRBs) are among the most energetic transient phenomena in the universe, releasing energies of the order of 10^{51} – 10^{54} erg on timescales ranging from milliseconds to tens of minutes. Despite decades of observation, the MeV energy domain, spanning roughly 0.1 to 100 MeV, where **GRB** prompt emission peaks, remains the least explored region of the electromagnetic spectrum accessible from space. Existing instruments suffer from large localization uncertainties, limited sensitivity in the sub-MeV band, and significant background contamination in low-Earth orbit, leaving fundamental questions about **GRB** emission mechanisms unresolved.

This thesis contributes to the design of instruments intended to address these challenges through a pre-launch simulation-based performance evaluation of two novel compact space-based detectors designed for **GRB** detection in the MeV energy range, namely the calorimeter of the **NeUtrino and Seismic Electromagnetic Signals (NUSES)/Zirè** instrument and the Crystal Eye all-sky gamma-ray monitor. Both instruments exploit advanced inorganic scintillating crystals, specifically cerium-doped **Lutetium Yttrium Oxyorthosilicate (LYSO:Ce)** and **Cerium-doped Gadolinium Aluminium Gallium Garnet (GAGG:Ce)**, read out by **Silicon Photomultipliers (SiPMs)**.

The thesis is organized as follows.

Chapter 1 reviews the astrophysical context of **GRBs**, covering their classification, physical interpretation within the fireball model, prompt emission mechanisms, and the observational limitations of current MeV-band instrumentation.

Chapter 2 describes the scintillating materials central to both instruments, including the characterization of the intrinsic radioactive background of **LYSO:Ce** that arises from the natural decay of ^{176}Lu , and presents laboratory measurements I performed using a **High Purity Germanium (HPGe)** spectrometer and a **SiPM**-based detector assembly with ^{60}Co calibration.

Chapter 3 introduces the **NUSES** mission and its Zirè payload together with the Crystal Eye detector concept and its hemispherical pixel geometry.

Chapter 4 presents the characterization of the CALOG sub-detector performed through detailed GEANT4 Monte Carlo simulations. The effective area is evaluated for both **LYSO:Ce** and **GAGG:Ce** scintillator configurations, demonstrating comparable detection performance. Orbital background spectra are modeled under a conservative 98° inclination scenario. Transient sensitivity is assessed through an **Minimum Detection Flux (MDF)** analysis and a **Signal-to-Noise Ratio (SNR)** study applied to a population of ~ 2300 Fermi **GRBs**. A sliding-window trigger algorithm shows a detection latency of approximately 0.5 s. A boosted decision tree classifier is also implemented to investigate the feasibility of separating astrophysical gamma-ray events from intrinsic **LYSO:Ce** background, establishing the limitations of machine learning-based background rejection, and motivating the selection of **GAGG:Ce** as the baseline scintillator material.

Chapter 5 presents the performance evaluation of the Crystal Eye detector across four geometrical configurations and three scintillator material compositions. The hybrid **GAGG:Ce+LYSO:Ce** configuration, with **GAGG:Ce** in the upper layer and **LYSO:Ce** in the

lower layer, is identified as optimal, reducing the intrinsic radioactive background by nearly two orders of magnitude relative to the **LYSO:Ce** only case while preserving detection efficiency. The optimized geometry achieves a minimum detectable flux of approximately $3 \times 10^{-4} \text{ ph s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$ in the 400–600 keV energy range. A template-based Kolmogorov–Smirnov source localization pipeline is developed and validated, yielding a 95% containment radius of $r_{95} \approx 2.75^\circ$, suitable for rapid multi-messenger follow-up.

Chapter 1

Gamma-Ray Bursts: Observations, Models, and Challenges

GRBs are brief flashes of high-energy radiation produced by ultra-relativistic outflows and observable across cosmological distances. Their prompt emission typically peaks in the hard X-ray to MeV energy range, placing **GRBs** among the most prominent transient sources of cosmic gamma-ray photons. Therefore, the MeV regime might be central in understanding the physical processes responsible for energy dissipation and radiation in relativistic jets [1, 2, 3]. Despite this importance, the MeV domain has historically remained the least explored region of the electromagnetic spectrum, primarily due to the difficulty of achieving high sensitivity and precise source localization at these energies.

Instruments designed for all-sky monitoring face fundamental challenges arising from Compton scattering in this energy range, restricting the detection of weak spectral components and accurate source positioning. This challenge has driven the adoption of advanced detector technologies, including high-yield scintillators, solid-state photosensors, and improved readout and background-rejection schemes, aimed at significantly enhancing sensitivity and localization performance in the MeV energy range.

This chapter brings together the observational, physical, and instrumental aspects that underpin current studies of gamma-ray bursts and their detection in the MeV energy range. The aim is to establish a coherent framework that links **GRB** phenomenology and emission models with the capabilities and limitations of space-based gamma-ray detectors.

Section 1.1 reviews the discovery of **GRBs** and the sequence of space missions that established their basic observational properties, including burst classification, timing diagnostics, and sky distribution.

Section 1.2 introduces the fireball model as the standard framework for interpreting **GRB** emission, describing the role of the central engine, relativistic jet dynamics, and the transition from prompt emission to afterglow formation.

In section 1.3, the empirical spectral models commonly used to describe **GRB** prompt emission are presented, together with the motivation for joint spectral analyses across a broad energy range.

Section 1.4 discusses the main energy dissipation channels and radiation mechanisms proposed for **GRBs**, with emphasis on synchrotron and inverse Compton processes.

Finally, section 1.5 addresses the observational challenges associated with the MeV energy range, highlighting the long-standing sensitivity and localization gap and its implications for **GRB** physics and detector development.

1.1 Gamma-ray bursts and their discovery

GRBs are among the most energetic transient phenomena in the universe, with durations ranging from a few milliseconds to several hours. Observed almost uniformly across the sky, the bursts can reach $10^{51} - 10^{52}$ erg/cm², making them the brightest known cosmic explosions [3].

The initial detection came from Vela satellites in the 1960s [4]. However, due to limited technology and little understanding, the field remained primarily dormant. Early models included neutron star accretion [5], subsurface stellar explosions in neutron stars [6], and star cluster collapse [7]. Despite these efforts, the true nature of GRBs remained elusive. A more accurate observation of the high-energy emission came from the Compton Gamma-Ray Observatory (CGRO) [8] and the high-energy emissions were explored properly. The CGRO operated between the energy range of 0.02 – 30 MeV. The Burst And Transient Space Experiment (BATSE) observed ~ 2700 GRBs, and the primary classification was derived from the data's T_{90} duration [9]. BATSE also confirmed GRBs cosmological origins and isotropic distribution; see figure 1.2.

The temporal classification categorized the GRBs in small ($T_{90} < 2$ s) and long ($T_{90} > 2$ s) bursts [9], see figure 1.1. The T_{90} is the detector-based duration during which the burst deposits 90% of its total energy. A related quantity, T_{50} encloses the central 50% of the counts. Apart from the length of the emission, GRBs also exhibits diverse temporal structures. These are often composed of one or more pulses with rise times ranging from milliseconds to seconds and decay times that can be longer. Rapid substructure in individual pulses places tight constraints on the size of the emitting region and the bulk Lorentz factor. Another important diagnostic is the spectral lag, defined as the relative delay between high- and low-energy photons. This lag is typically small or negligible in short GRBs, while it is significantly larger in long GRBs [10, 11, 12].

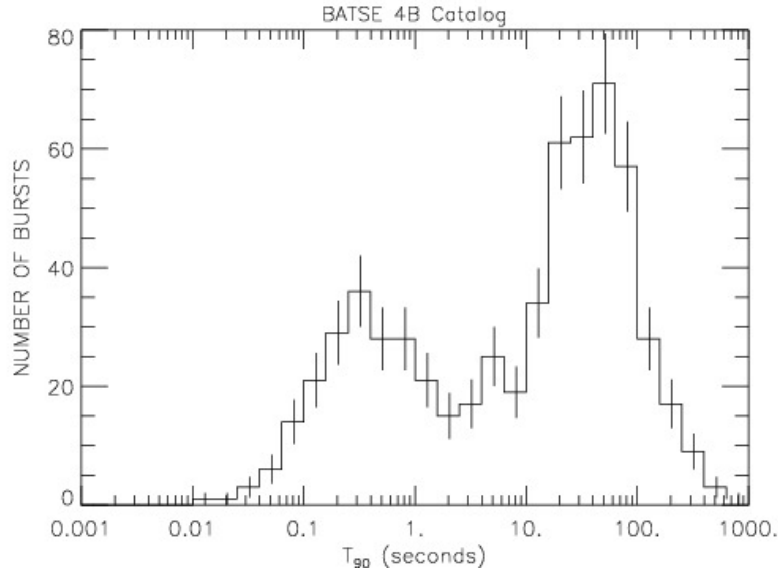


Figure 1.1: Bimodal distribution of GRB durations (T_{90}) in the BATSE 4B catalog, separating short and long bursts [13].

The BeppoSAX experiment [14] discovered the fading afterglow of these bursts [15, 16, 17, 18, 19] solidifying the extragalactic origins of GRBs. Due to the long duration and multiple observation sources for afterglow emission, their detection allows unambiguous host-galaxy identification, enabled redshift measurements [3], and established a link between long GRBs and core-collapse supernovae [20, 21, 22, 23]. Observations place GRBs over a

wide redshift range, from nearby events ($z \approx 0.008$) to the most distant known ($z \approx 7.5$) [24].

The **IN**TERNational **G**amma-Ray **A**strophysics **L**aboratory (**INTEGRAL**), launched in 2002, was one of the most sensitive instruments for gamma-ray observations [25]. The two primary instruments, namely (a) **I**mager **o**n-**B**oard the **INTEGRAL** **S**atellite (**IBIS**) [26], and (b) the **S**Pectrometer of **INTEGRAL** (**SPI**) [27] used active **B**ismuth **G**ermanate **O**xide (**BGO**) detectors working to detect particles and photons above ~ 75 keV.

The *Swift* mission, launched in 2004, remains operational. The **B**urst **A**lert **T**elescope (**BAT**) instrument provides rapid localizations with arc-minute accuracy and enables prompt follow-up. The **X**-**R**ay **T**elescope (**XRT**) refines the positions up to a few arcseconds and performs afterglow spectroscopy in the 0.2–10 keV range. The **U**ltra-**v**iolet/**O**ptical **T**elescope (**UVOT**) captures afterglows from 172 to 650 nm [28]. The *Swift* telescope has been central to multi-wavelength **GRB** studies.

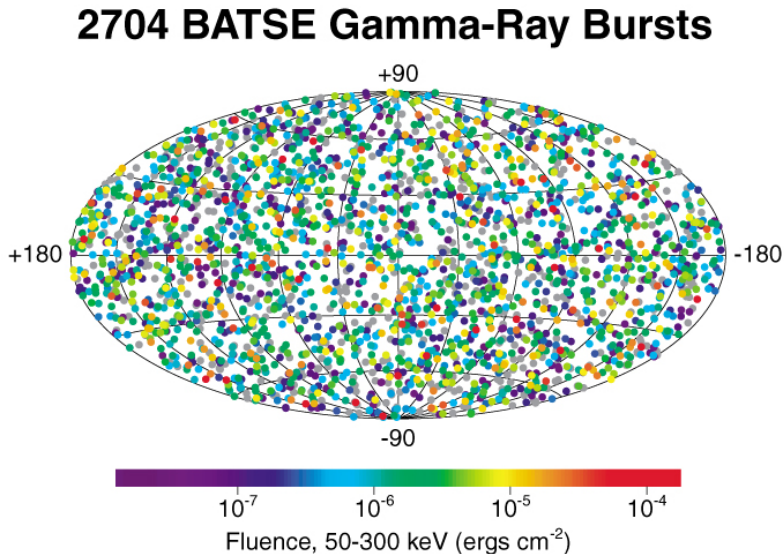


Figure 1.2: Isotropic sky distribution of GRBs detected by BATSE (50–300 keV fluence). The lack of concentration toward the galactic plane supports a cosmological origin [29].

In 2008, the **F**ermi **G**amma-ray **S**pace **T**elescope (**FGST**) was launched into low Earth orbit. It observes from 8 keV to beyond 300 GeV and carries two instruments: the **G**amma-ray **B**urst **M**onitor (**GBM**) and the **L**arge **A**rea **T**elescope (**LAT**). The **GBM** employs 12 **S**odium **I**odide (**NaI**) detectors (5–1000 keV) and 2 **BGO** detectors (200 keV–40 MeV) [30] for near all-sky **GRB** detection. The **LAT** detects high-energy photons from 20 MeV to over 300 GeV [31]. Fermi observations have revealed extended high-energy emission and placed strong constraints on **GRB** emission mechanisms.

1.2 The fireball model

To explain the emission mechanisms of the **GRBs**, the fireball model was proposed by Goodman [32] and Paczyński [33]. In the fireball model, photons, electrons, positrons, and baryons remain in thermal equilibrium at very high temperatures until the flow becomes transparent at the photosphere. This models **GRBs** as the outcome of an initially *optically thick*, ultra-relativistic radiation-pair plasma created when a large energy release occurs in a compact region $R \lesssim 10^7$ cm.

A massive star’s core collapse or compact object merger can also trigger **GRB** events. The event either produces a single black hole or a highly magnetized neutron star. This remnant

object is called the “central engine” and it can coerce the material around into forming an accretion disk. The material in the accretion disk then gets ejected by the central engine using highly collimated jets. As the plasma expands, the radiation pressure accelerates the outflow. When the Thomson optical depth drops to order unity at the *photosphere*, the trapped energy escapes as gamma rays [32, 33, 34, 35]. Typical total (isotropic-equivalent) energies are $E \sim 10^{51} - 10^{53}$ erg, and in some cases reach $\sim 10^{54}$ erg [34]. The prompt “burst” corresponds to the segment labeled *Burst* in figure 1.3. Variability in the central engine ejects shells with different Lorentz factors. Collisions at $R \sim 10^{13} - 10^{15}$ cm generate *internal shocks* (or magnetic dissipation), which accelerate particles and produce non-thermal γ -rays.

The “burst” or prompt duration is also what is reported as T_{90} in the detectors. It is the initial, intense flash of gamma rays that defines a **GRB**. It dominates the energy output over a short period, ranging from a few milliseconds to several minutes, and is most prominent in the ~ 10 keV to few MeV energy range [36, 2, 37]. In some bursts, much higher-energy photons, above 100 MeV, have also been detected by the Fermi-LAT instrument, revealing an additional spectral component [38].

A key control parameter in the **GRB** dynamics is the *dimensionless entropy*,

$$\eta \equiv \frac{E}{Mc^2},$$

where, E is the initial radiation energy of the fireball and M is the baryonic mass entrained in the flow. For a low baryon load ($\eta \gg 1$), nearly all of this radiation energy converts into bulk kinetic energy. The terminal Lorentz factor is then

$$\Gamma \simeq \eta = \frac{E}{Mc^2}.$$

For a large baryon load ($\eta \ll 1$), the expansion is essentially Newtonian; the same injected energy is shared by a larger mass, and the outflow is slower [39, 40, 34]. Consequently the characteristic velocity scales as,

$$v \simeq \sqrt{\frac{2E}{M}},$$

Without relativistic expansion, the source would be opaque to high-energy photons because of $\gamma\gamma \rightarrow e^+e^-$. The observed short variability times and high photon energies therefore require a large bulk Lorentz factor. Typical values are $\Gamma \gtrsim 10^2$ [34]. This both lowers the pair-production opacity and reconciles the source size with the variability.

The prompt emission is widely interpreted as radiation from within the relativistic jet before it interacts with the external medium. Two main energy dissipation channels are considered for producing the prompt emission. In a baryon-dominated flow, internal shocks occur when faster shells within the relativistic jet collide with slower ones. These collisions accelerate electrons and can naturally explain the rapid variability observed in **GRB** light curves [41]. The acceleration and collision of the “shells” is what creates the so-called shock mechanisms. On the other hand, in a magnetically dominated flow, magnetic reconnection plays the key role, where magnetic field lines break and reconnect, efficiently converting magnetic energy into the acceleration of particles.

1.2.1 Afterglow formation

The transition from the internal dissipation phase to the afterglow emission is governed by the interaction of relativistic ejecta with the surrounding **Interstellar Medium (ISM)**. This generates a long-lived forward shock and a transient reverse shock. Once the central engine ejects the material, the leading shell propagates into the surrounding **ISM**. A relativistic

forward shock forms at the contact point where the shock meets the **ISM**. From the shock frame, incoming **ISM** particles are heated to relativistic temperatures and compressed, creating a region of high magnetic field energy density. This forward shock converts the outflow's bulk kinetic energy into radiation, marking the onset of the broadband afterglow.

With the formation of the forward shock, sometimes a reverse shock is driven back into the fast-approaching shell as well. This is primarily due to the decelerated signal propagating backwards from the points where the shock meets the **ISM**. In the “thick shell” regime, for many long **GRBs**, where $\Delta > R/\Gamma^2$, the reverse shock is relativistic. Here, Δ is the co-moving shell width. Due to high velocity, the shock crosses the ejecta on a timescale comparable to or longer than the prompt emission duration. This shock decelerates the ejecta, which can be either baryonic-rich or Poynting-flux-dominated. The reverse shock's strength also depends on the magnetization parameter σ (the ratio of magnetic to kinetic energy flux) of the unshocked ejecta. A high σ suppresses shock formation, thus generating a faint optical flash.

However, despite the success of internal-shock mechanisms, there are some **GRBs** that are compatible with magnetic reconnection models, explained by Poynting-flux-dominated flow. In the Poynting-flux flow, the particles move near the electric field to gain energy.

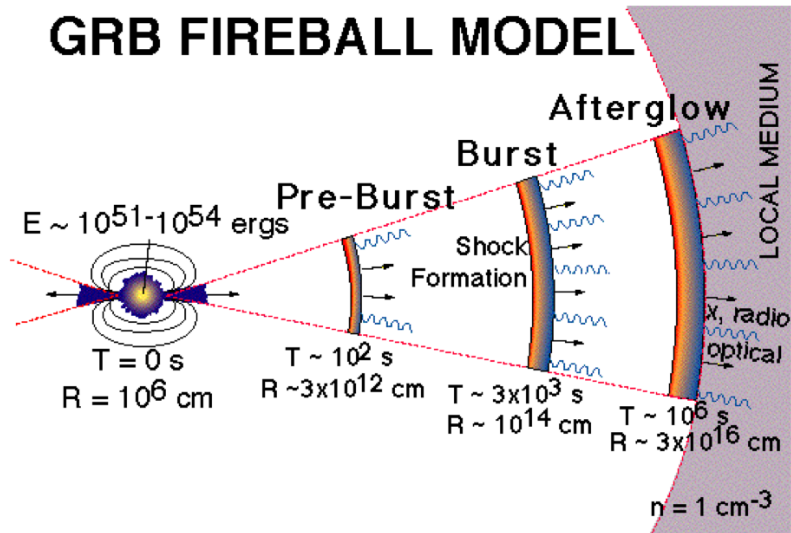


Figure 1.3: Schematic diagram of the fireball and the internal/external shocks (left to right: pre-burst acceleration, prompt burst, and afterglow) [42].

Figure 1.3 summarizes the canonical sequence. In the *pre-burst* phase, the newly launched outflow is still optically thick and accelerating; $e^\pm$ pairs annihilate as the rest-frame temperature falls, and most of the energy becomes bulk motion (illustrative schematic values $T \sim 10^2$ s, $R \sim 3 \times 10^{12}$ cm). During the *burst*, variability in the central engine drives collisions and other internal dissipation at larger radii, producing the prompt γ -rays ($T \sim 3 \times 10^3$ s, $R \sim 10^{14}$ cm). The *afterglow* then arises as the ejecta decelerate in the external medium. This interaction produces long-lived synchrotron emission from X-ray to radio ($T \sim 10^6$ s, $R \sim 3 \times 10^{16}$ cm for $n \sim 1 \text{ cm}^{-3}$). For further discussion on how the energy is dissipated in the gamma-ray burst, see section 1.4

1.3 Spectral models for GRBs

The prompt emission spectra of **GRBs** exhibit complex shapes. As a consequence, empirical functions are widely employed to characterize their spectral properties. Several models are

commonly adopted, including the **Power Law (PL)**, the **Comptonized Power Law (CPL)**, the Band model [43] (Band model hereafter), and the **Smoothly Broken Power Law (SBPL)**. Among these, the Band model is the most widely used. These empirical models can be organized according to their level of complexity and the spectral features they are able to reproduce.

Power law model: The simplest description is provided by the **PL** model.

$$f_{\text{PL}}(E) = A \left(\frac{E}{E_0} \right)^\alpha \quad (1.1)$$

which is typically employed when the observed spectrum does not exhibit a clean spectral break or when the available energy range is limited.

Comptonized power law: The **PL** model can be extended by including an exponential cutoff:

$$f_{\text{CPL}}(E) = A \left(\frac{E}{E_0} \right)^\alpha \exp \left[-\frac{(\alpha + 2) E}{E_{\text{peak}}} \right], \quad (1.2)$$

Band model: This empirical model was discovered using the **BATSE** catalog and is defined as:

$$f_{\text{BAND}}(E) = A \begin{cases} \left(\frac{E}{E_0} \right)^\alpha \exp \left[-\frac{(\alpha + 2) E}{E_{\text{peak}}} \right], & E < \frac{(\alpha - \beta) E_{\text{peak}}}{\alpha + 2}, \\ \left(\frac{(\alpha - \beta) E_{\text{peak}}}{(\alpha + 2) E_0} \right)^{\alpha - \beta} \left(\frac{E}{E_0} \right)^\beta \exp(\beta - \alpha), & E \geq \frac{(\alpha - \beta) E_{\text{peak}}}{\alpha + 2}, \end{cases} \quad (1.3)$$

Smoothly Broken Power Law (SBPL): This model was introduced by Ryde [44] and then later refined by Kaneko et al. (2006) [45] with a fixed $\Delta = 0.3$ for transitioning between the two power laws:

$$f_{\text{SBPL}}(E) = A \left(\frac{E}{E_0} \right)^b 10^{(\beta - \beta_{\text{piv}})}, \quad (1.4)$$

with

$$\beta = m \Delta \ln \left(\frac{\exp(\alpha) + \exp(-\alpha)}{2} \right), \quad \beta_{\text{piv}} = m \Delta \ln \left(\frac{\exp(\alpha_{\text{piv}}) + \exp(-\alpha_{\text{piv}})}{2} \right),$$

$$m = \frac{\lambda_2 - \lambda_1}{2}, \quad b = \frac{\lambda_2 + \lambda_1}{2}, \quad \alpha = \frac{\log(E/E_b)}{\Delta}, \quad \alpha_{\text{piv}} = \frac{\log(E_0/E_b)}{\Delta}.$$

As can be observed from Eq. (1.3) and Eq. (1.4), the actual difference between these two descriptions is the smoothness around the peak energy; in the Band model it is fixed to an exponential shape, while in the **SBPL** model, the smoothness is a free parameter (fixed later by Kaneko).

For the models discussed in this section, unless noted otherwise, the normalization factor A has units of $\text{ph cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$ for all models. Additionally, the pivot energy E_0 is fixed at 100 keV. Although the non-thermal models dominate the **GRB** spectrum, scientists have also applied physically motivated thermal emission models.

The results obtained from the first four years of **FGST** observations are reported in the figure 1.4. The dataset contains 943 **GRBs**, with spectra modeled in the 8 keV–40 MeV energy range. The figures show a low-energy index $\langle\alpha\rangle = -1.08^{+0.43}_{-0.44}$ and a mean high-energy index $\langle\beta\rangle = -2.14^{+0.27}_{-0.37}$ [38].

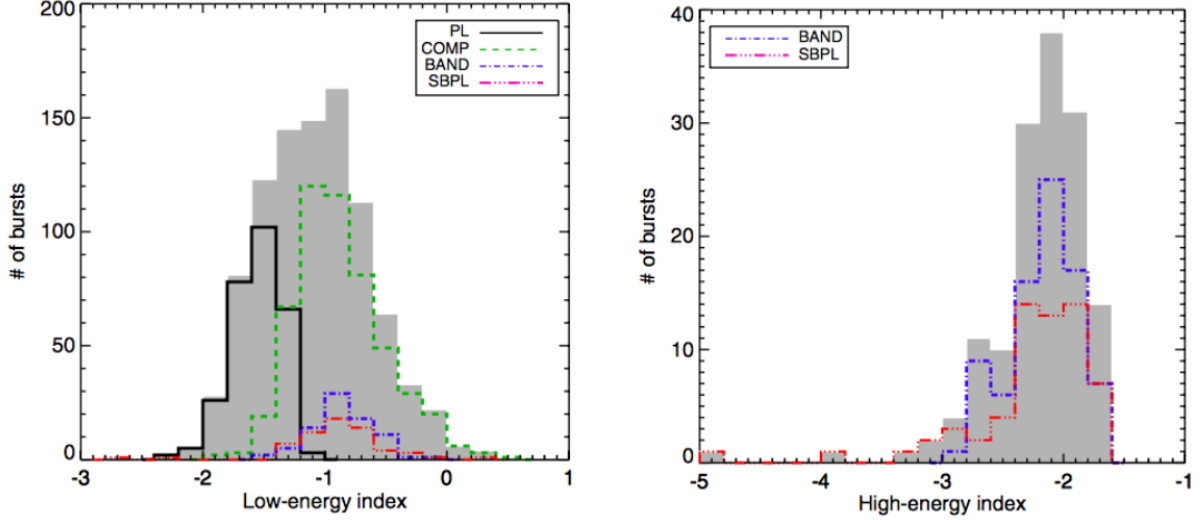


Figure 1.4: Distributions of the low-energy photon index α (left) and high-energy photon index β (right) for the Fermi-GBM four-year catalog BEST sample [38].

The left panel of figure 1.5 shows the distribution of the peak energy E_{peak} of different **GRB** spectra, with a median value of $E_{\text{peak}} = 196^{+336}_{-100}$ keV. The right panel shows the observed flux in the 10 keV–1 MeV range of $(3.03^{+7.41}_{-1.40}) \times 10^{-7}$ erg cm $^{-2}$ s $^{-1}$ [38].

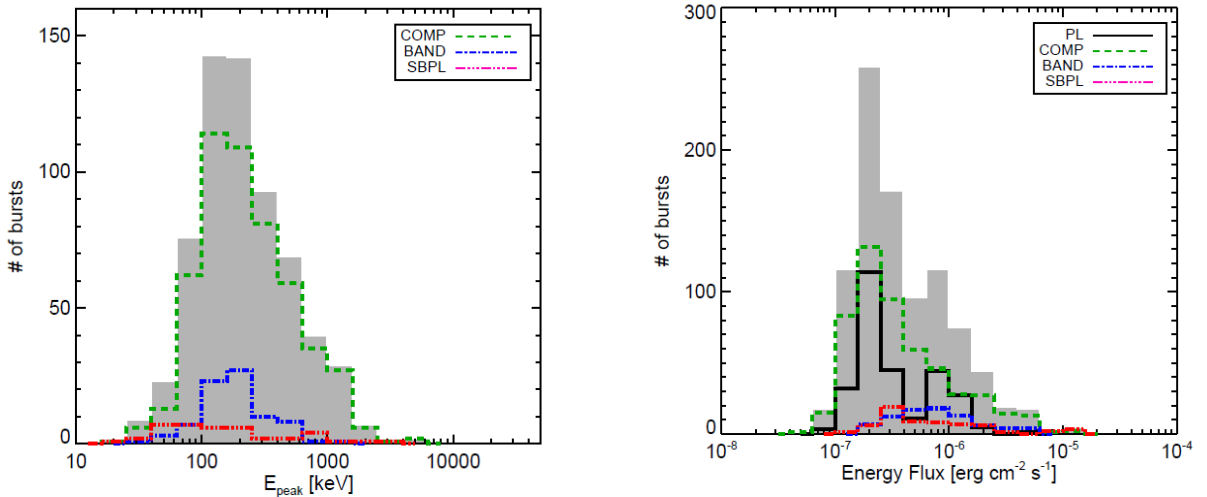


Figure 1.5: Distributions of the peak energy E_{peak} (left) and energy flux ϕ in the 10 keV–1 MeV range (right) for the Fermi-GBM four-year catalog BEST sample [38].

In some bursts, **LAT** detects photons above 100 MeV in addition to the **GBM** measured keV–MeV peak. Joint fitting of **GBM** and **LAT** data typically requires two components: a Band model for the keV–MeV range and a separate **PL** or **CPL** for the high-energy spectral extension [36, 46, 47]. This extension helps fit the extended high-energy emission where the curve of the Band or **SBPL** model cannot reach. Figure 1.6 shows GRB090926A [48], where the high-energy tail has a cutoff at ~ 1.4 GeV.

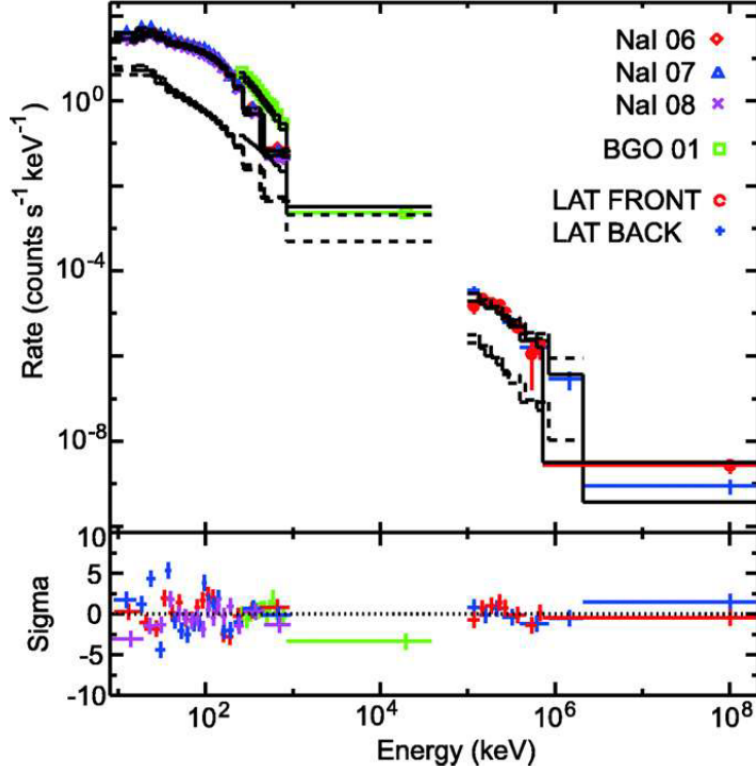


Figure 1.6: Joint GBM (NaI, BGO) and LAT (Front/Back) spectrum of GRB090926A [48]. The Band model covers the keV-MeV peak, while an extra high-energy component fits the LAT data. A cutoff at ~ 1.4 GeV is consistent with $\gamma\gamma$ pair-production attenuation.

1.4 Prompt emission models

While the fireball model describes the global dynamical behavior of GRB outflows, it does not describe how the observed radiation is produced. In the following, the main radiation mechanisms proposed to explain GRB spectra are reviewed with particular emphasis on synchrotron and inverse Compton processes.

1.4.1 Synchrotron radiation

Non-thermal synchrotron radiation has long been regarded as the leading explanation for GRB prompt emission. Synchrotron radiation occurs when relativistic electrons spiral around magnetic field lines, generating broad non-thermal spectra. This mechanism has long been considered a natural explanation for GRB prompt emission, as it can account for the observed high luminosities and rapid variability.

As shown in figure 1.7, early analyses of BATSE data revealed a tension between data and expectation. In the standard synchrotron model, the low-energy photon index α of the Band model should fall between -1.5 (fast cooling) and $-2/3$ (slow cooling) [50, 49, 51]. Yet a large fraction of observed bursts exhibited values harder than $-2/3$, sometimes even approaching 0. This lower bound of $-2/3$ is known as the synchrotron line of death because any spectrum harder than this cannot be explained by the simplest synchrotron theory. The frequent violation of this limit [49] challenged synchrotron radiation as the dominant emission mechanism in GRBs and motivated the exploration of alternative processes such as photospheric emission or jitter radiation.

More recent theoretical work has suggested ways to reconcile synchrotron emission with the data, like the magnetic field decay model [52]. These models can produce much flatter

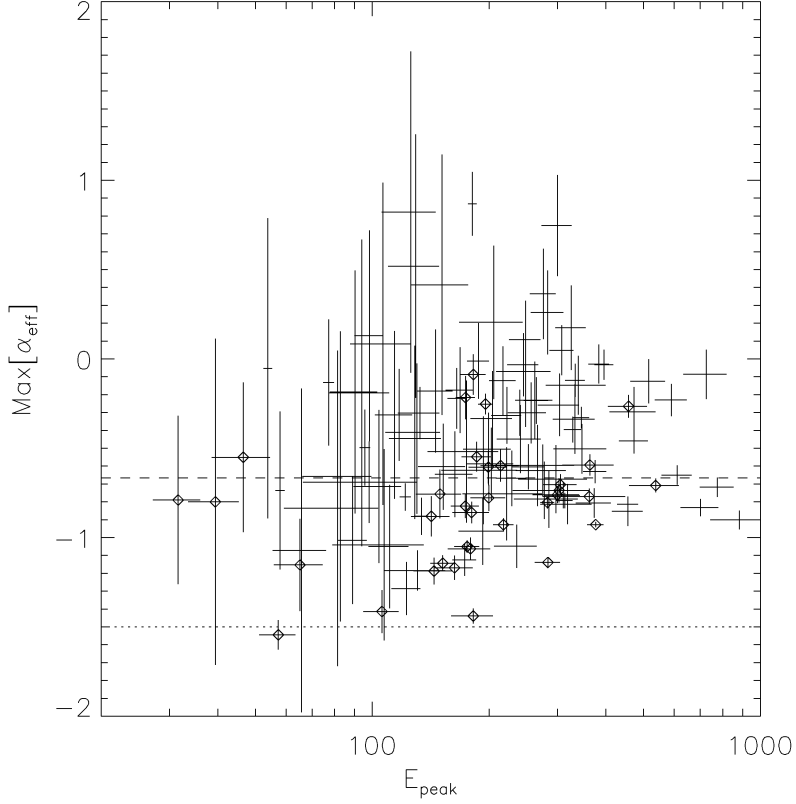


Figure 1.7: Fitted low-energy photon index α_{eff} versus spectral peak energy E_{peak} for BATSE bursts, adapted from Preece et al. [49]. The dashed and dotted lines mark the synchrotron “line-of-death” and the fast-cooling limits respectively.

spectra, as illustrated in figure 1.8. This framework naturally reproduces the observed distribution of α values in both **BATSE** and **FGST** bursts. At the same time, it preserves synchrotron radiation as the primary emission mechanism.

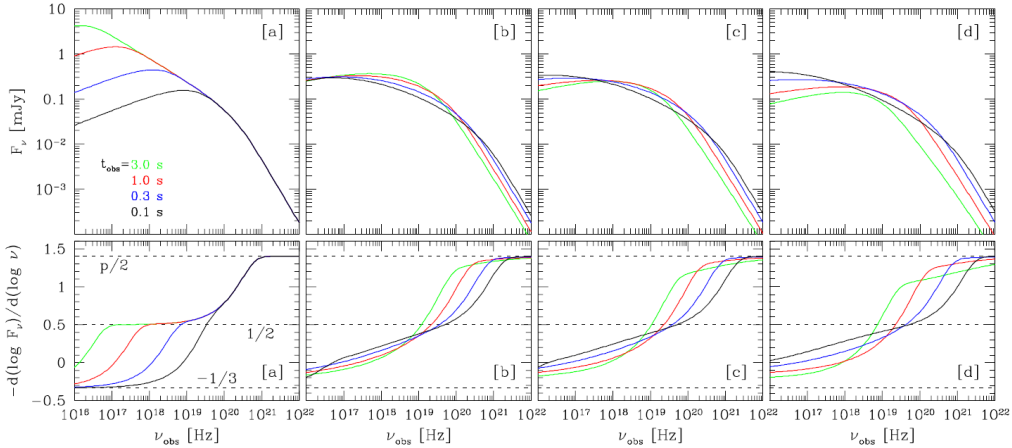


Figure 1.8: Synchrotron emission spectra for different magnetic field decay scenarios, adapted from Uhm and Zhang [52]. The top panels show flux density F_ν for several epochs, while the lower panels present the corresponding spectral slopes. Compared to the constant-field case (panel a), decaying magnetic fields (panels b–d) yield much harder low-energy spectra, consistent with the photon indices observed in GRBs.

Thus, synchrotron radiation is still considered one of the leading emission processes for the prompt emission. Nevertheless, it relies on physical conditions more intricate than a

simple, uniform magnetic field. Current research is actively exploring how evolving magnetic fields, particle acceleration, and additional radiative processes combine to produce the complex spectra we observe in **GRBs**.

1.4.2 Inverse Compton scattering

The **Inverse Compton (IC)** scattering occurs when relativistic electrons transfer part of their energy to lower-energy photons, boosting them to much higher frequencies. In **GRBs**, the seed photons can originate from synchrotron radiation produced by the same population of electrons. This case is referred to as **Synchrotron Self-Compton (SSC)**. Alternatively, seed photons may come from other sources, such as photospheric thermal emission.

A central question is whether the observed MeV peak could arise from **IC** scattering rather than synchrotron emission. As argued by Piran, Sari, and Zou [53], if this were the case, then the same electrons should up-scatter photons a *second* time, producing a GeV–TeV component even more luminous than the MeV energy range. This expectation creates an “energy crisis,” since such an overwhelming TeV bump is not observed in real **GRB** spectra.

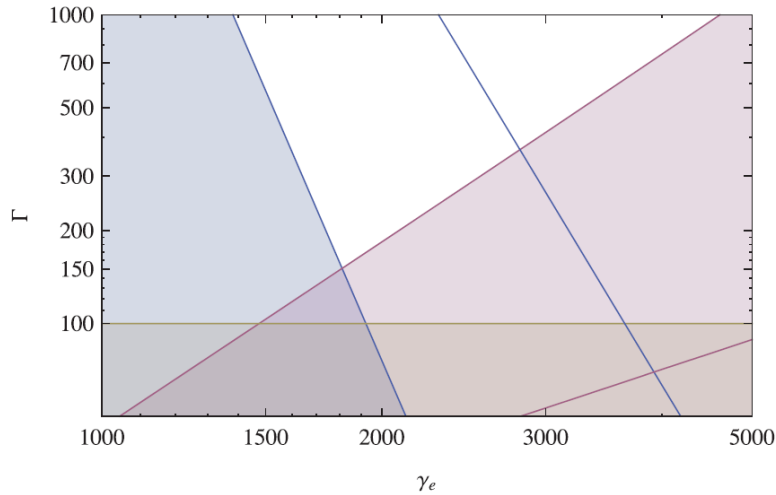


Figure 1.9: Constraints on the IC scenario in the infrared regime, showing the allowed parameter space in terms of bulk Lorentz factor Γ and electron Lorentz factor γ_e . The TeV overproduction limit and the self-absorption cap together shrink the viable region to a tiny island near $\Gamma \sim 120$ and $\gamma_e \sim 1.8 \times 10^3$ [53].

Two narrow regimes can, in principle, ease this tension. In the *UV solution*, the seed photons lie above the optical energy range, and the electron Lorentz factor is modest ($\gamma_e \lesssim 100$). Here, Klein-Nishina effects are weak, but the required seed photon energies are so high that they rival or exceed the MeV flux, contradicting observed X-ray spectra. In the *IR solution*, the seed photons are in the far-infrared, and the electrons are very energetic ($\gamma_e \gtrsim 10^3$) with bulk Lorentz factors $\Gamma < 300$. This case relies on Klein-Nishina suppression of the second **IC** bump. However, it is strongly constrained by self-absorption: the seed photon flux cannot exceed the synchrotron self-absorption limit, which eliminates almost all of the viable parameter space [53]. Figure 1.9 shows the constraints on the **IC** scenario in the infrared regime, illustrating how the TeV overproduction limit and the self-absorption cap together shrink the viable parameter space to a narrow region.

Observations with Fermi-**LAT** have provided important tests of these theoretical predictions. For example, Ackermann et al. [46] analysed GRB090510, which displayed a distinct GeV component delayed relative to the MeV emission. While such a component could in

principle arise from **SSC**, its temporal offset and hard spectrum are not well explained by a simple one-zone **SSC** model. Instead, these data suggest that if **IC** processes are at work, they likely operate in a more complex, multi-zone, or time-dependent environment.

1.5 MeV range challenges in GRB observations

The spectral peak of most **GRB** prompt emission lies in the MeV range, making this energy domain central to testing theoretical models. Processes such as thermal photospheric emission, synchrotron radiation from relativistic electrons, and inverse Compton scattering predict characteristic signatures in the hundreds of keV to a few MeV range.

Yet, despite this importance, the MeV range has historically been the least explored region of the electromagnetic spectrum. This deficiency is often referred to as the “*MeV gap*” (see Figure 1.10). It corresponds to a valley in sensitivity between the soft X-ray regime (<100 keV), where focusing telescopes achieve excellent angular resolution, and the high-energy gamma-ray regime (>50 MeV), where pair-conversion telescopes such as Fermi-**LAT** operate efficiently.

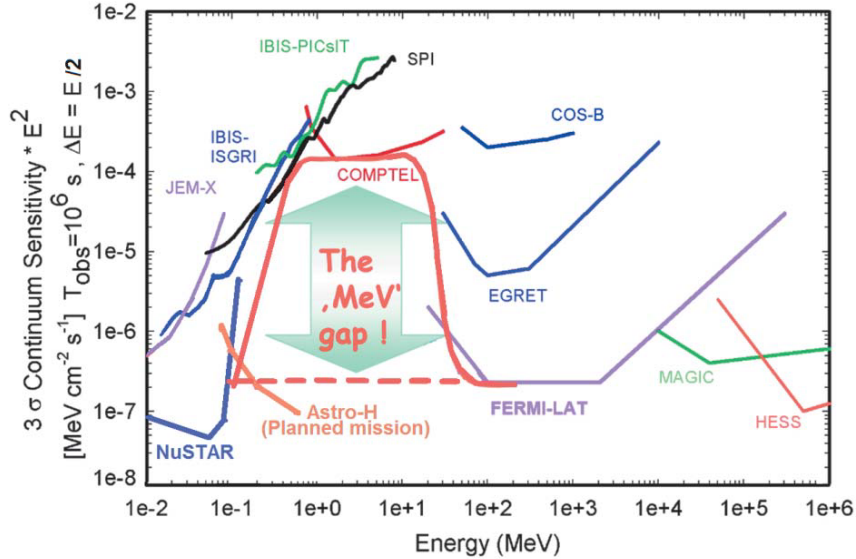


Figure 1.10: Representative 3σ continuum sensitivities of past, current, and planned high-energy missions versus photon energy, highlighting the *MeV gap* between ~ 0.1 and ~ 100 MeV. Focusing X-ray instruments perform best below ~ 100 keV, while pair-conversion telescopes (e.g., Fermi-**LAT**) dominate above ~ 50 MeV; sensitivities degrade in between where Compton techniques are required [54].

Historically, **Imaging Compton Telescope (COMPTEL)** on **CGRO** demonstrated the feasibility of Compton imaging in space. It achieved continuum sensitivities in the 10^{-5} photons $\text{cm}^{-2} \text{s}^{-1}$ range and line sensitivities down to a few 10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ [55]. Subsequent missions, including *Swift*, **INTEGRAL**, and the Fermi-**GBM**, dramatically increased the number of detected **GRBs**. However, they were fundamentally constrained by high instrumental backgrounds, modest energy resolution, and limited capability to isolate weak spectral components in the MeV range [56, 30]. Consequently, the MeV range remains the weakest observational link in **GRB** studies.

Detectors working in the MeV regime usually rely on scintillator technology or Compton scattering techniques, and both approaches come with intrinsic limitations. **BATSE** reached a sensitivity of about ~ 0.2 to 0.3 photons $\text{cm}^{-2} \text{s}^{-1}$ in the 50–300 keV range, with a

one-second peak flux definition [56]. For Fermi-GBM, the onboard trigger threshold is around ~ 0.74 photons $\text{cm}^{-2} \text{s}^{-1}$ in the same energy band and time scale, corresponding to a significance of 4.5σ above background [30]. However, the sensitivity is not constant across the full energy range, as it depends on the effect area of the instrument and the energy and angle of incident particles. The effective area declines, and the cosmic-ray-induced background becomes dominant (see, figure 1.11). As a result, only the most luminous bursts provide spectra that are precise enough for detailed emission modeling.

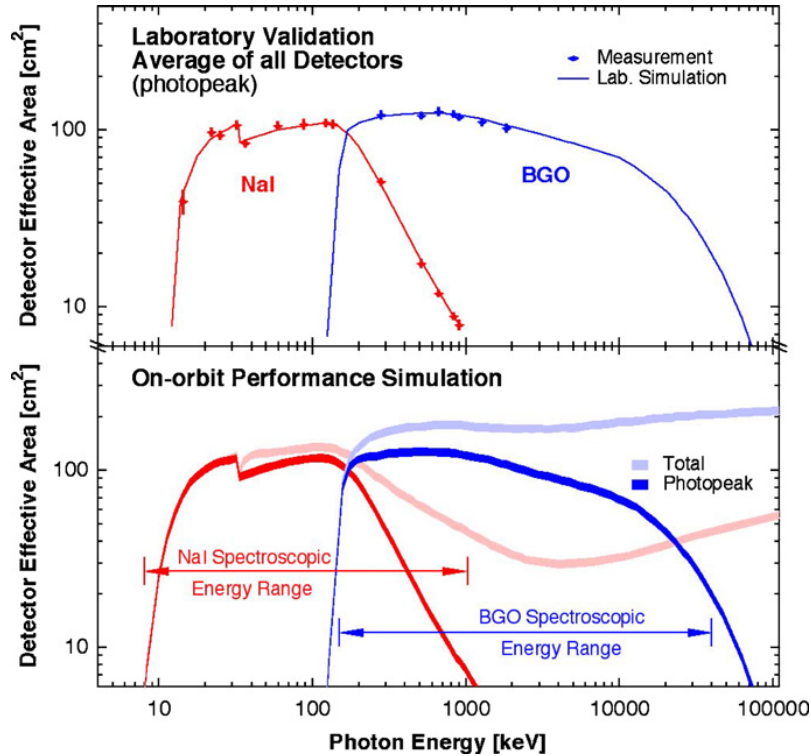


Figure 1.11: Energy dependence of the effective area of the Fermi-GBM detectors at normal incidence. The upper panel shows laboratory measurements compared with simulations. The lower panel illustrates the on-orbit performance, which includes the effects of spacecraft scattering. The NaI detectors cover photon energies from about 8 keV to 1 MeV, while the BGO detectors extend the range up to nearly 40 MeV. At high energies, however, the effective area decreases sharply, reducing sensitivity [30].

Upcoming missions such as NUSES and Crystal Eye are being developed specifically to address these gaps. They aim to combine wide-field-of-view monitoring with improved sensitivity and background suppression, thereby opening a new observational window in the poorly charted MeV regime. Detailed discussions of their design and expected performance are presented in Chapters 4 and 5.

A long-standing limitation of detectors in the MeV range is their lack of true imaging capability. Unlike X-ray telescopes, which can use grazing-incidence optics to focus photons with arcsecond precision, MeV instruments cannot focus radiation with mirrors. Instead, they rely on indirect methods such as relative count rate comparisons among detectors or Compton scattering reconstruction. This results in localization accuracies that are generally orders of magnitude poorer than those of instruments operating at lower energies.

BATSE on CGRO localized bursts using the relative count rates from its eight detector modules. Typical uncertainties were several degrees, sufficient to demonstrate the isotropic sky distribution of GRBs but far too coarse to identify host galaxies or measure redshifts directly [56]. The Fermi-GBM employs a similar technique, comparing observed count rates in its twelve NaI detectors to a pre-calculated response table of 1634 sky directions.

Onboard locations are determined within $\sim 15^\circ$ for strong bursts, with an average error of $\sim 9^\circ$ for events with independently known positions [30]. As a result, Fermi-GBM alone cannot provide the precise localizations required for host identification and must rely on complementary instruments such as the *Swift* XRT or Fermi-LAT for arcminute to arcsecond scale accuracy.

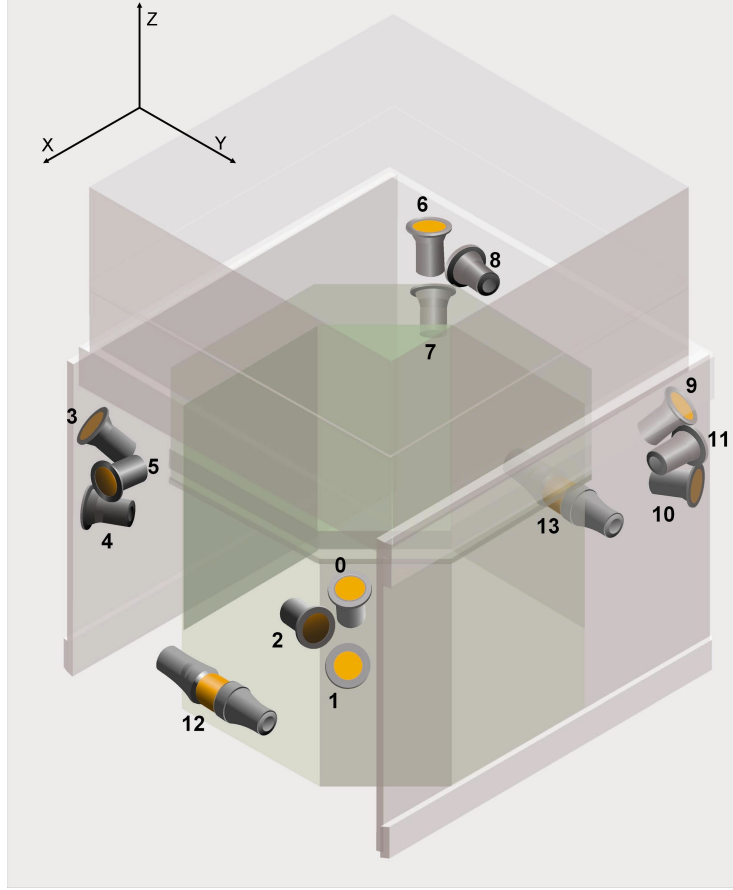


Figure 1.12: Locations and orientations of the twelve NaI and two BGO detectors of the Fermi-GBM on the spacecraft [30]. The NaI detectors, distributed around the spacecraft and pointing in different directions, allow burst localization by comparing relative count rates. This geometry enables all-sky coverage but limits localization accuracy to degree scales, with typical errors of $\sim 9^\circ$ for strong bursts and up to $\sim 15^\circ$ in onboard estimates. Ground-based refinements reduce these values somewhat, but the positions remain much coarser than the arcminute-to-arcsecond localizations achievable at lower energies.

The difficulty stems from fundamental physics in the 0.1–50 MeV range. Here photons are too energetic to be focused by grazing-incidence optics, yet too soft to leave a clear e^+e^- pair signature. Compton telescopes, such as COMPTEL onboard CGRO, demonstrated that directional information can be reconstructed from scattering kinematics, but the resulting event rings or arcs limited angular resolution to several degrees. Even modern proposals such as the Chinese-French satellite Space Variable Object Monitor (SVOM), the Chinese Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor (GECAM), the European Space Agency (ESA) *e-ASTROGAM*, and *ASTROME*V aim for angular resolutions of only $\lesssim 1.5^\circ$ at 1 MeV [1], which is a major improvement over BATSE and GBM but still far from the arcsecond localizations achievable at X-ray energies. The upcoming Crystal Eye all-sky monitor uses the same scintillation crystals but with 126 modularized pixels and dome like configuration [57]. The configuration has been tested to provide better localization than the GBM instrument aboard the Fermi telescope [58].

The **Gamma-Ray Monitor (GRM)** onboard **SVOM** follows a well-established design with **NaI** crystals coupled with **Photomultiplier Tubes (PMTs)** [59, 60]. On the other hand, **GECAM** makes use of **Cerium-doped Lanthanum Bromide (LaBr₃:Ce)** scintillators for their high-energy resolution along with high radiation tolerance and stability against temperature fluctuations. Another critical difference of **GECAM** from **SVOM** is the usage of **SiPMs** for readout instead of **PMTs** [61, 62, 63].

Both **SVOM** and **GECAM** work in a few keVs to ~ 5 MeV energy range, with Crystal Eye working between 10 keV to 30 MeV [57, 64, 63, 60]. The extended high energy emission of Crystal Eye can be attributed to its dual layered colorimetric design granting significant stopping power to the detector. This configuration also allows the Crystal Eye detector to have an effective area several times larger than that of Fermi-**GBM**, **SVOM**¹, and **GECAM**². Additionally, where **SVOM-GRM** and **GECAM** provide localization of approximately a few degrees, between sub-degree and a few degree respectively, simulations have shown that Crystal Eye can achieve sub-degree localization accuracy reliably [67, 68, 64]. Despite the similarities, **SVOM** is not intended for an all-sky monitor satellite system. However, both Crystal Eye and **GECAM** support all-sky coverage with three and two satellite modules covering the entire sky.

1.5.1 Future prospects of the MeV gap

The observational limits of the MeV range have wide-reaching consequences for **GRB** theory and for multi-messenger astrophysics. Low sensitivity makes it difficult to detect faint components such as weak thermal emission components, inverse Compton features, or high-energy cutoffs. Yet these subtle signals may be essential for telling apart synchrotron and photospheric models or for constraining jet Lorentz factors through pair-opacity arguments. Because most spectra lack this information, fundamental questions about the nature of the prompt emission remain unresolved.

Likewise, a number of **GRBs** detected in the MeV energy range do not have accurate positions, which means redshift measurements are often missing. This reduces their value for population studies, making it harder to test luminosity energy correlations such as the Amati relation [69] (linking E_{iso} to E_{peak}) and the Yonetoku relation [70] (linking E_{peak} to L_{peak}), or to trace the cosmic evolution of **GRB** progenitors. Large error regions, of the order of several degrees, as in **BATSE** and **GBM** also limit multi-messenger science. With such uncertainties, it becomes challenging to connect MeV bursts with gravitational-wave events, high-energy neutrinos, or TeV afterglows observed by ground-based Cherenkov arrays. These challenges strongly motivate the development of next-generation missions.

e-ASTROGAM has been proposed as a breakthrough gamma-ray observatory covering 0.3 MeV to 3 GeV. It would improve continuum sensitivity in the 0.3–100 MeV range by one to two orders of magnitude compared to **COMPTEL** and **INTEGRAL**, detect about 600 **GRBs** in three years, and localize them to sub-degree precision. Its polarimetric capability would allow the measurement of **GRB** polarization at the 20% level for dozens of events per year, providing direct insight into jet magnetization and emission mechanisms [71].

The **Compton Spectrometer and Imager (COSI)** offers a complementary approach in the 0.2–5 MeV range. It combines wide field-of-view monitoring with Compton event reconstruction, achieving angular resolutions of about 1.5° at 1.8 MeV and sub-degree localizations for bright bursts. **COSI** also functions as a sensitive Compton polarimeter, able to detect high-polarization fractions in **GRBs**. Its wide sky coverage (25% at any

¹ $\sim 500 \text{ cm}^2$ for three Gamma-Ray Detectors (GRDs) combined [65].

² $\sim 440 \text{ cm}^2$ for all 25 GRDs combined [66].

instant, 100% per day) makes it well-suited to capturing short **GRBs** as gravitational-wave counterparts, addressing one of the key limitations of current MeV-band instruments [72].

NUSES and Crystal Eye are designed to operate in the 30 keV–50 MeV energy range, especially for **GRB** localization. With its use of advanced electronics like **SiPM** and high-yield **LYSO:Ce** and **GAGG:Ce** crystals promise unprecedented detection as well [57, 58]. In this sense, the MeV energy range remains both the weakest link in current **GRB** observations and the most promising frontier for the next generation of space missions. By combining large effective area, sub-degree imaging, and polarization sensitivity, future instruments like e-ASTROGAM, **COSI**, **NUSES**, and Crystal Eye will not only close the long-standing MeV gap but also enable decisive progress in understanding the physics of relativistic jets and their connection to the multi-messenger universe.

Chapter 2

Scintillating materials for modern space detectors

Scintillating crystals play a central role in space-based gamma-ray detection, where they convert the energy deposited by ionizing radiation into optical photons that can be read out by photodetectors. Their properties directly affect stopping power, energy resolution, timing response, intrinsic background, mechanical robustness, and compatibility with compact readout systems. These requirements are particularly stringent for instruments devoted to gamma-ray bursts, transient phenomena, and multimessenger observations, where weak and rapidly varying signals must be detected under severe constraints on mass, volume, power consumption, and long-term reliability.

The selection of the scintillation material is therefore a key design choice, and must be supported not only by literature values of material properties but also by laboratory measurements performed under controlled conditions. For this reason, this chapter combines a comparative discussion of scintillating crystals relevant to space detectors with two experimental characterizations focused on **LYSO:Ce** and **HPGe** measurement of its intrinsic radioactive background and a **SiPM**-based measurement of its response to MeV gamma rays.

Traditional space instruments have relied on well-established materials such as **NaI**, **Cesium Iodide (CsI)**, and **BGO**, which have enabled several successful gamma-ray missions. However, their limitations, including hygroscopicity for alkali-halide crystals and relatively modest light yield or slow components for **BGO**, motivate the use of modern oxide scintillators with improved environmental stability and readout compatibility.

Among these materials, cerium-doped **LYSO:Ce** and **GAGG:Ce** are especially relevant for compact space detectors. **LYSO:Ce** offers high density, fast scintillation response, and strong stopping power, but its intrinsic ^{176}Lu radioactivity introduces an unavoidable internal background that must be quantified experimentally. **GAGG:Ce**, in contrast, combines high light output, non-hygroscopic behavior, and intrinsic radiopurity, although scintillation afterglow remains an important limitation for high-rate and transient detection environments.

This chapter reviews the scintillation properties of advanced inorganic crystals relevant to modern space-based radiation detectors, with emphasis on **LYSO:Ce** and **GAGG:Ce**. Section 2.2 summarizes the scintillation mechanism in inorganic crystals and the material parameters that influence detector performance. Sections 2.3 and 2.4 discuss the properties, advantages, and limitations of **LYSO:Ce** and **GAGG:Ce**, including the role of afterglow in **GAGG:Ce**. Section 2.5 compares the two materials in the context of space detector design. The chapter then presents two experimental studies: an **HPGe** measurement of the intrinsic ^{176}Lu background in **LYSO:Ce**, described in Section 2.6, and a **SiPM**-based characterization

of **LYSO:Ce** using ^{60}Co gamma-ray lines, presented in Section 2.7.

2.1 Scintillating materials in space gamma-ray instruments

Historically, space instrumentation has relied predominantly on alkali-halide scintillators, most notably sodium iodide doped with thallium, **NaI**, and cesium iodide doped with thallium, **CsI**. These materials were adopted because of their relatively high light yield, mature crystal-growth technology, and availability in large detector volumes. Alongside them, dense oxide scintillators such as **BGO** have also been employed in space and high-energy detectors, especially where stopping power and mechanical robustness were prioritized over spectroscopic performance [73].

NaI scintillators have been extensively used in gamma-ray astronomy. A prominent example is the **BATSE** aboard the **CGRO**, where large-area **NaI** detectors enabled all-sky monitoring of gamma-ray bursts [13]. More recently, **NaI** detectors have continued to play a key role in the **GBM** on board the **FGST** satellite, where multiple **NaI** detectors provide broadband transient detection [30].

CsI scintillators have also been employed in space-based gamma-ray instruments, particularly in configurations requiring mechanical robustness and efficient detection at higher energies. In the **INTEGRAL** mission, **CsI** crystals form the active detection material of the **PICsIT** detector plane in the **IBIS** instrument, acting as the lower detector layer for higher-energy gamma rays while contributing to the imaging capability of the telescope [74]. A further large-scale use of **CsI** is found in the calorimeter subsystem of the **Fermi-LAT**, where segmented crystals measure the energy of electromagnetic showers induced by high-energy gamma rays [31].

BGO represents another important reference material. Its high density and large effective atomic number provide strong gamma-ray stopping power, while its oxide composition makes it non-hygroscopic and mechanically robust. However, its relatively low light yield and slow scintillation components limit its spectroscopic and timing performance compared with more recent materials [73]. In the **Fermi-GBM**, two **BGO** detectors extend the energy coverage from a few hundred keV to several tens of MeV, complementing the **NaI** detector array and supporting cross-calibration over a broad energy range [30].

Despite their successful deployment, traditional scintillators present important limitations for modern compact space detectors. Alkali-halide crystals such as **NaI** and **CsI** are strongly hygroscopic, so exposure to moisture can degrade optical transparency and crystal integrity. They therefore require hermetic sealing and mechanical encapsulation, increasing mass, complexity, and potential reliability risks [73]. **BGO** avoids this problem but offers lower light output and slower timing response.

These limitations have motivated increasing interest in non-hygroscopic oxide scintillators such as **LYSO:Ce** and **GAGG:Ce**. Both materials offer high density, good mechanical stability, and compatibility with compact solid-state photodetectors. **LYSO:Ce** provides fast timing and strong stopping power, while **GAGG:Ce** offers high light yield and the advantage of negligible intrinsic radioactivity. Their main material properties, together with those of traditional scintillators, are summarized in Table 2.1.

2.2 Scintillation mechanism in inorganic crystals

Scintillators are materials that emit visible or near-visible light upon interaction with ionizing radiation, a principle widely used in radiation detection. These materials are

Table 2.1: Comparison of selected properties of scintillating crystals commonly used in space-based detectors. The values for LYSO:Ce and GAGG:Ce correspond to the crystals used in this work, both procured from **EPIC Crystal**; the GAGG:Ce values correspond to the high-light-output (GAGG:Ce-HL) formulation. Values for NaI, CsI, and BGO are representative literature values [73].

Property	NaI	CsI	BGO	LYSO:Ce	GAGG:Ce (HL)
Density (g/cm ³)	3.67	4.51	7.13	7.25	6.6
Peak emission (nm)	415	540	480	420	530
Refractive index	1.85	1.80	2.15	~1.82	~1.91
Decay time	230 ns	0.68 / 3.34 μ s	~300 ns	~40 ns	~150 ns
Light yield (photons/MeV)	38 000	65 000	8 200	30 000	54 000
Hygroscopic	Yes	Yes	No	No	No
Intrinsic radioactivity	No	No	No	Yes (¹⁷⁶ Lu)	No

broadly classified into two categories: inorganic scintillators, such as **NaI** or **LYSO:Ce**, and organic scintillators, such as plastic scintillating fibers.

Organic scintillators are based on carbon-rich molecular compounds and typically offer fast timing and mechanical flexibility, but have lower density and atomic number. They are commonly used in tracking systems or veto layers [75]. Among organic scintillators, plastic scintillators are the most widely used in particle physics. They consist of organic fluorescent compounds dissolved in a polymerized solid base, typically polyvinyltoluene (PVT) or polystyrene [73]. Several commercial grades are available, differing mainly in light output, decay time, and emission wavelength. Common examples include the general-purpose **Eljen**’s EJ-200 and its Saint-Gobain equivalent BC-408, as well as the higher-light-yield EJ-204. Unlike inorganic crystals, their scintillation originates from molecular π -electronic transitions rather than from a crystalline lattice, giving a fast prompt fluorescence of only a few nanoseconds and, owing to a large Stokes shift, high transparency to their own emitted light. Being composed mainly of low-atomic-number elements (hydrogen and carbon), they have a small photoelectric cross-section and interact predominantly with charged particles while remaining largely insensitive to gamma rays. This combination of fast response, low Z , and easy fabrication makes them well suited to the anti-coincidence and veto systems employed in both the Zirè and Crystal Eye instruments (Chapter 3).

In inorganic scintillators, ionizing radiation interacts with the crystal lattice and excites electrons from the valence band to the conduction band, generating electron-hole pairs. To enhance light emission efficiency, activator impurities such as cerium are introduced into the crystal structure. These activators create energy levels within the forbidden band gap, enabling radiative de-excitation through visible photon emission at luminescence centers. Figure 2.1 summarizes the scintillation sequence in an inorganic crystal, from energy deposition and carrier generation to activator-mediated photon emission and optical readout.

For Ce-doped inorganic scintillators such as **LYSO:Ce** and **GAGG:Ce**, the emitted scintillation light typically lies in the blue region of the spectrum and is well matched to the spectral sensitivity of standard photodetectors, including **PMTs** and **SiPMs**.

The efficiency of the scintillation process depends on how effectively the deposited energy is channeled into radiative decay paths. Material properties such as the crystal band structure, activator concentration, and crystal purity play an important role. Non-radiative processes, including thermal quenching and delayed phosphorescence, can reduce the total photon yield [73].

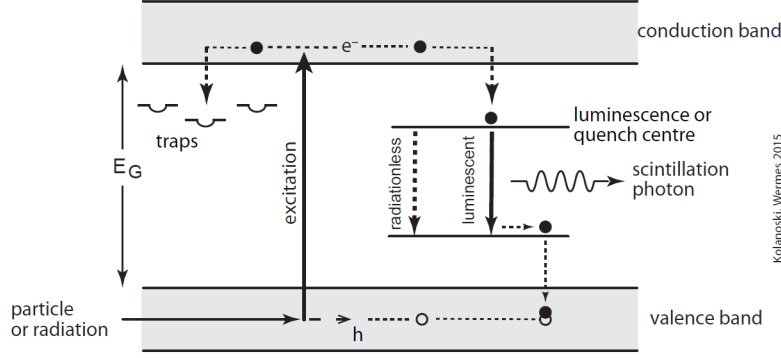


Figure 2.1: Simplified diagram of scintillation light production in inorganic crystals. The scheme follows the descriptions by Birks (1964) and Kolanoski & Wermes (2020), as cited in [75].

Key parameters in selecting a scintillator include the light yield and the scintillation decay time. The light yield refers to the number of photons emitted per unit energy deposited, while the decay time characterizes how quickly the scintillation signal returns to its ground state following excitation. For many practical applications, the light yield can be approximated as proportional to the energy loss of the incident particle,

$$\frac{dL}{dx} = S_e \frac{dE}{dx},$$

where S_e is the scintillation efficiency, commonly referred to as Birks' constant. This linear approximation is valid for minimum ionizing particles.

Scintillators with high light yield are preferred in spectroscopy applications requiring good energy resolution, whereas short decay times are essential for fast timing or triggering applications, such as **GRB** detection. In practical detector systems, scintillators are coupled to photodetectors such as **PMT** or **SiPM**, which convert the scintillation light into electronic signals via the photoelectric effect [75].

2.3 LYSO:Ce Scintillator

Cerium-doped oxyorthosilicate scintillators, such as $\text{Lu}_2\text{SiO}_5:\text{Ce}$ (LSO) and its yttrium-substituted variant $\text{Lu}_{2(1-x)}\text{Y}_{2x}\text{SiO}_5:\text{Ce}$, are widely used in high-resolution radiation detection. Initially developed by Melcher and Schweitzer [76], these materials have found broad application in conjunction with position-sensitive photodetectors, including **PMTs** and **SiPMs**.

The suitability of **LYSO:Ce** for space-based gamma-ray instrumentation arises from a combination of favorable material properties, including high density, high effective atomic number, high scintillation light yield, and fast decay time, which together enable efficient photoelectric absorption and compact detector geometries in the sub-MeV energy range [77]. With a typical density of about 7.1 g/cm^3 and an attenuation length of approximately 1.2 cm at 511 keV, **LYSO:Ce** provides strong stopping power while maintaining a relatively small detector volume.

LYSO:Ce exhibits a fast scintillation decay time of the order of 36 ns and a light output of approximately 33 photons/keV, corresponding to a light yield comparable to that of **NaI** while offering significantly improved mechanical and environmental stability. In contrast to alkali-halide scintillators, **LYSO:Ce** is non-hygroscopic and does not require hermetic encapsulation, an important advantage for space-based detector systems.

The scintillation emission of **LYSO:Ce** peaks in the blue region around 420 nm, providing good spectral matching to both photomultiplier tubes and modern **SiPM**. This compatibility enables efficient optical coupling and high photon collection efficiency, supporting compact, low-power, and fully solid-state detector designs. Such characteristics are particularly advantageous for space instrumentation, where constraints on mass, volume, power consumption, and long-term reliability strongly favor **SiPM**-based readout systems [78].

While **LYSO:Ce** offers many advantages, its application in low-background astrophysical measurements is limited by its intrinsic radioactivity, originating from the naturally occurring isotope ^{176}Lu . This isotope constitutes approximately 2.6% of natural lutetium and undergoes β decay with a half-life of 3.76×10^{10} years.

The decay emits β -particles with a mean energy of 182 keV and a maximum energy of 593 keV, populating excited states of ^{176}Hf , which subsequently de-excite through the emission of characteristic γ rays. The dominant decay pathway (β_1 , 99.66%) is accompanied by γ -ray emissions at 88 keV, 202 keV, and 307 keV, while the less probable β_2 branch (0.34%) leads to a higher endpoint energy and is typically neglected in spectral modeling. A simplified schematic of the ^{176}Lu decay scheme together with the corresponding β -particle energy spectrum for the dominant transition is shown in Fig. 2.2.

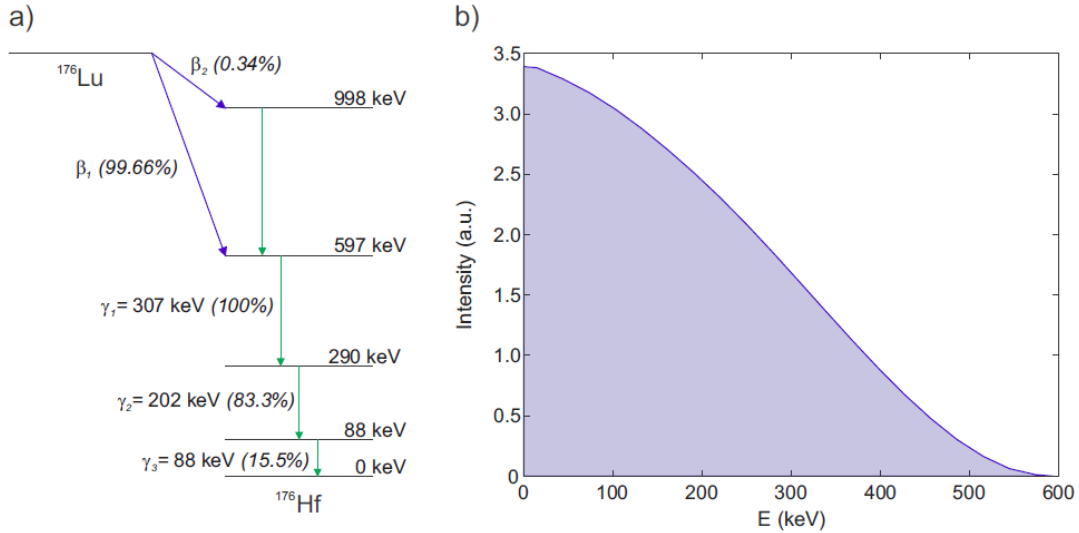


Figure 2.2: (a) Simplified ^{176}Lu decay scheme and (b) β -particle energy spectrum corresponding to the dominant β_1 transition. Adapted from [79].

Experimental studies have shown that the intrinsic background spectrum of **LYSO:Ce** is significantly broadened due to the coincident detection of β -particles and associated γ rays emitted during the de-excitation of ^{176}Hf [80]. The resulting spectral shape arises from a combination of energy deposition by primary β -particles, secondary electrons produced by γ -ray interactions, and internal conversion electrons from the excited states of ^{176}Hf [79]. Representative energy spectra illustrating the different $\beta + \gamma$ and internal conversion combinations for two **LYSO:Ce** geometries are shown in Fig. 2.3.

The upper panels display the dominant coincidence combinations, corresponding to the 88 keV, 88+202 keV, 88+307 keV, and 88+202+307 keV contributions. Their relative intensities shift with crystal size. In larger crystals, the probability of all three γ -rays being detected within the volume increases, causing the high-energy peak near 597 keV to grow in relative intensity compared to the lower-energy combinations. The lower panels show the resulting summed energy spectra, obtained by combining all individual $\beta + \gamma$ and internal conversion contributions. The characteristic multi-peak structure reflects the discrete energy combinations associated with each γ -ray transition of ^{176}Hf , and its shape

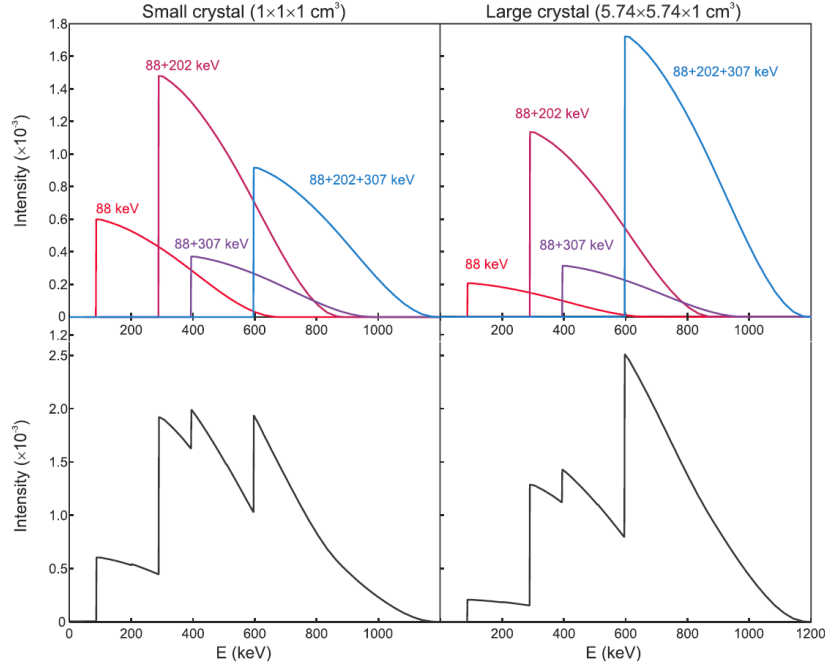


Figure 2.3: Energy spectra of the different $\beta + \gamma$ -ray and internal conversion combinations for two LYSO:Ce geometries. Adapted from [79].

evolves with crystal size, with the high-energy peak becoming increasingly dominant in larger crystals. This geometry-dependent behavior has direct implications for detector design, as the intrinsic background spectral shape of a **LYSO:Ce** crystal is not fixed but evolves with the crystal dimensions used in the instrument.

Low-energy X-rays generated by crystal ionization and atomic vacancies are typically assumed to deposit their full energy within the scintillator volume through photoelectric absorption [81]. As a result, the intrinsic radioactivity of **LYSO:Ce** constitutes a non-negligible internal background component that must be considered in detector sensitivity estimates and background modeling studies for space-based applications.

Despite its excellent scintillation performance and its widespread use in compact gamma-ray instrumentation, **LYSO:Ce** presents a critical limitation for low-background measurements in the 100 keV to 1 MeV energy range. The intrinsic activity of ^{176}Lu introduces an irreducible internal count rate and produces spectral structures that can overlap with low-energy astrophysical signals. For space-borne detectors operating in low Earth orbit, where the detection of faint transients relies on stringent background control, this self-activity can degrade sensitivity, particularly below ~ 1 MeV where the internal $\beta + \gamma$ cascade contributes significantly.

For these reasons, **LYSO:Ce** is not always treated as a favorable baseline material for the detector configurations considered in this work, and alternative scintillators with negligible intrinsic activity become attractive for flight designs. Nevertheless, a quantitative characterization of the intrinsic **LYSO:Ce** background is essential, both to assess its impact on detector performance and to provide reference line identifications for calibration and validation studies. This characterization is presented in Section 2.6, where the intrinsic activity of **LYSO:Ce** is measured using a **HPGe** detector whose superior energy resolution enables the identification and precise parameterization of the characteristic ^{176}Lu γ -ray lines.

2.4 GAGG:Ce Scintillator

GAGG:Ce is a high-performance inorganic scintillator that has gained increasing attention in recent years for space-based radiation detection applications. It combines high scintillation light yield, good spectroscopic performance, and mechanical robustness, making it well suited for compact detector geometries and solid-state readout systems. In the context of space-based detectors, performance is primarily defined by scintillation light yield, energy resolution, intrinsic background, timing characteristics, and radiation tolerance.

A key advantage of **GAGG:Ce** compared to **LYSO:Ce**-based scintillators is the absence of intrinsic radioactivity associated with naturally occurring isotopes such as ^{176}Lu . This intrinsic radiopurity makes **GAGG:Ce** particularly attractive for low-background detection. Experimental investigations performed on multiple **GAGG:Ce** samples have demonstrated mutually consistent scintillation performance, indicating good reproducibility despite variations in crystal growth and formulation [82].

At the material level, **GAGG:Ce** exhibits a high density of approximately 6.6 g/cm^3 and a refractive index close to 1.91. Its scintillation emission lies in the blue-green region, peaking between 520 and 530 nm, which provides good spectral matching to **SiPMs** and enables efficient optical coupling in compact, low-power detector designs.

GAGG:Ce scintillators are available in multiple formulations optimized for different detector requirements, commonly referred to as **GAGG:Ce-F** (fast), **GAGG:Ce-T** (typical), and **GAGG:Ce-HL** (high-light-output) variants. While the crystal composition remains broadly similar across these formulations, they differ in scintillation timing characteristics, light yield, and energy resolution as a result of optimized growth conditions and activator concentrations. A comparison of the principal properties of these **GAGG:Ce** variants is provided in Table 2.2. The selection of a specific **GAGG:Ce** formulation therefore represents a trade-off between timing performance, light yield, and energy resolution, depending on the intended detector application and count-rate environment.

Table 2.2: Representative properties of GAGG:Ce scintillator formulations optimized for different detector requirements¹.

Parameter	GAGG:Ce-F	GAGG:Ce-T	GAGG:Ce-HL
Density (g/cm^3)	6.6	6.6	6.6
Hardness (Mohs)	8	8	8
Refractive index	1.91	1.91	1.91
Light output (photons/MeV)	30 000	42 000	54 000
Energy resolution @ 662 keV (%)	7	6	5
Decay constant (ns)	50	90	150
Emission peak wavelength (nm)	520	530	530
Radiation resistance (rad)	10^7	10^7	10^7
Hygroscopic	no	no	no

The scintillation decay behavior of **GAGG:Ce** is therefore strongly formulation dependent. Fast variants (**GAGG:Ce-F**) exhibit short decay times of order 40–50 ns, making them well suited for applications involving high count rates and short-duration events. Standard formulations provide a balance between timing performance and light yield, while high-light-output variants (**GAGG:Ce-HL**) achieve improved spectroscopic performance at the expense of longer decay components. This tunability allows **GAGG:Ce** to be optimized for a wide range of space-based detection scenarios.

¹<https://www.epic-crystal.com/data/upload/20240409/6614a154ea168.pdf>

Environmental qualification studies further indicate that **GAGG:Ce** maintains stable scintillation performance under conditions relevant to low-Earth orbit, including vacuum operation, temperature cycling, and proton irradiation.

2.4.1 Afterglow effects in GAGG:Ce

Despite these advantages, scintillation afterglow has emerged as a critical material limitation of **GAGG:Ce** in certain high-rate and space-based detector applications. The afterglow behavior observed in **GAGG:Ce** scintillators is attributed to the presence of shallow and deep electron traps within the garnet crystal lattice. These traps are commonly associated with antisite defects, such as Gd_{Al} and Ga_{Al} , as well as with vacancies introduced during high-temperature crystal growth. The incorporation of gallium further influences the electronic structure of the host material, reducing the energy separation between the Ce^{3+} excited states and the conduction band. As a result, a fraction of charge carriers becomes temporarily trapped and is released on longer timescales, leading to delayed radiative recombination and a measurable afterglow component in the scintillation signal [83].

From a detector performance perspective, this afterglow has been identified as a significant limiting factor for the application of **GAGG:Ce** in demanding radiation detection environments. Dedicated studies explicitly report that afterglow constitutes the main performance bottleneck of **Ce:GAGG:Ce** scintillators, particularly in fast imaging systems such as X-ray computed tomography, in dynamic radiation fields, and in space-based detector applications [84].

Afterglow also results in a degradation of the detector energy resolution, thereby hindering the reliable monitoring of high-energy ion irradiation and transient radiation processes in space-based applications [85]. Although several mitigation strategies have been proposed, including suppression of antisite defects through alternative growth techniques or compositional modification of the garnet host [86], a fully consistent and comprehensive understanding of the afterglow behavior in garnet scintillation ceramics of different compositions is still lacking. As a result, afterglow remains a critical material characteristic that must be carefully quantified and controlled when considering **GAGG:Ce** for high-rate or space-based detector systems.

2.5 Comparative perspective: LYSO:Ce versus GAGG:Ce

LYSO:Ce is characterized by a high density, large effective atomic number, and fast scintillation response, which together provide strong gamma-ray stopping power and excellent timing performance in compact detector volumes. These characteristics make **LYSO:Ce** particularly attractive for applications requiring efficient detection and fast timing performance in the sub-MeV energy range (up to ~ 1 MeV), while still enabling sensitivity to higher-energy gamma rays extending into the multi-MeV regime (see Table 2.1). Furthermore, its non-hygroscopic nature and mechanical robustness simplify detector integration and long-term operation in the space environment. However, the presence of intrinsic radioactivity arising from the natural abundance of ^{176}Lu introduces an unavoidable internal background component. This self-activity can limit sensitivity in low-count-rate or low-background measurements, particularly in energy ranges overlapping the intrinsic decay spectrum, and necessitates careful background modeling and mitigation strategies at the system level.

GAGG:Ce, in contrast, offers an intrinsically non-radioactive scintillator with high and reproducible light output, making it well suited for low-background detection scenarios

and long-duration observations (see Table 2.1). Its emission spectrum is well matched to silicon photomultipliers, enabling efficient optical readout in compact, low-power detector architectures. In addition, the availability of multiple **GAGG:Ce** formulations allows partial optimization of scintillation timing characteristics and energy resolution to suit different detector environments. These advantages are complemented by good mechanical stability and demonstrated resistance to radiation and thermal cycling under space-relevant conditions. Nevertheless, **GAGG:Ce** is affected by scintillation afterglow associated with charge trapping in the garnet lattice, which can degrade energy resolution and limit performance in high-rate or rapidly varying radiation fields. This afterglow represents a key material limitation that must be carefully quantified and controlled in demanding space-based applications.

From a comparative standpoint, **LYSO:Ce** and **GAGG:Ce** can therefore be regarded as complementary rather than competing scintillator materials. **LYSO:Ce** excels in applications where fast timing, high stopping power, and compact detector geometries are prioritized, while **GAGG:Ce** provides clear advantages in situations where intrinsic radiopurity and low internal background are critical to instrument sensitivity. The optimal choice between the two materials depends on the scientific objectives of the mission, the expected radiation environment, and the acceptable trade-offs between timing performance, background levels, and spectroscopic resolution.

These considerations are directly reflected in the design choices adopted for contemporary space missions. In the final configuration of the **NUSES** mission, **GAGG:Ce** has been selected as the primary scintillation material, driven by its intrinsic radiopurity, mechanical robustness, and suitability for long-term, low-background operation. In contrast, the Crystal Eye detector concept employs a hybrid approach, incorporating both **GAGG:Ce** and **LYSO:Ce** scintillators within its detection architecture. This combined strategy leverages the low-background advantages of **GAGG:Ce** alongside the fast timing and high stopping power of **LYSO:Ce**, enabling a flexible and optimized response across a broad range of energies and event types.

Overall, the deployment of **LYSO:Ce** and **GAGG:Ce** in modern space-based detector systems illustrates how material-specific strengths can be exploited, and inherent limitations accommodated, through informed detector design. Rather than relying on a single universally optimal scintillator, contemporary missions increasingly adopt material choices that reflect a balanced assessment of performance, environmental constraints, and scientific goals.

2.6 HPGe detector for intrinsic background measurements in **LYSO:Ce**

High-purity germanium (**HPGe**) detectors are widely used in gamma-ray spectroscopy due to their fine energy resolution. They are commonly employed as reference detectors in laboratory measurements for accurate peak identification and energy calibration. As discussed in Section 2.3, the natural abundance of ^{176}Lu in **LYSO:Ce** crystals gives rise to an irreducible internal radioactive background through its β decay, which produces a continuous spectral component accompanied by characteristic γ -ray lines at 88 keV, 202 keV, and 307 keV. This intrinsic activity is particularly problematic for space-based detectors operating in the sub-MeV energy range, since these spectral features fall directly within the scientifically important MeV gap region where astrophysical signals from gamma-ray bursts and other transient phenomena are expected. A precise characterization of these background lines is therefore essential, as it allows accurate background modeling in detector simulations,

supports the development of mitigation strategies, and provides reliable reference energies for calibration and validation of **LYSO:Ce**-based instruments.

The theoretical description presented in this section is largely based on the treatment of germanium gamma-ray detectors given in Knoll, *Radiation Detection and Measurement* [73]. In this work, an **HPGe** detector is used to investigate the intrinsic radioactive background of **LYSO:Ce**, exploiting its superior energy resolution to cleanly resolve and precisely parameterize the characteristic ^{176}Lu γ -ray lines that would otherwise be smeared and difficult to disentangle in a scintillator-based measurement. A typical **HPGe** detector assembly used in laboratory spectroscopy is shown in Fig. 2.4, illustrating the cylindrical detector housing connected to the liquid-nitrogen cryostat system that maintains the germanium crystal at cryogenic operating temperature.

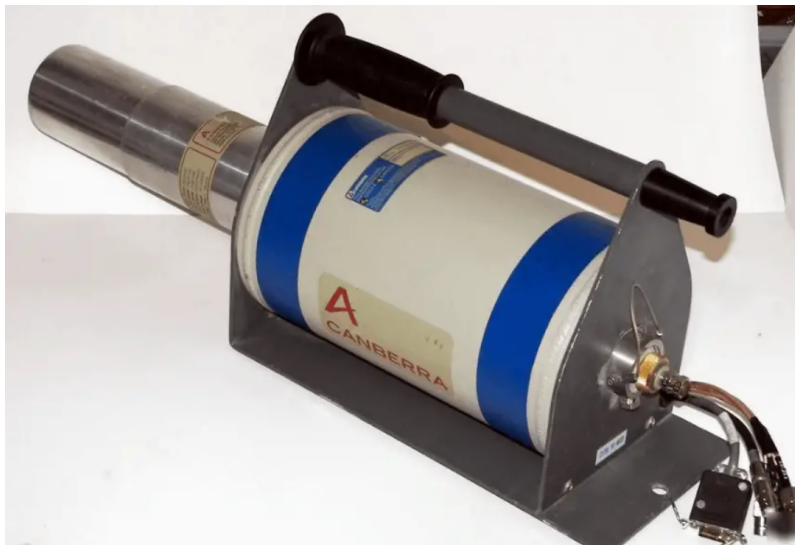


Figure 2.4: HPGe detector with the cryostat system connected to the liquid-nitrogen cooling system. image taken from [nuclear power website](#)

Unlike scintillation detectors, which rely on light production and optical readout, germanium detectors measure deposited energy through direct charge generation in a semiconductor crystal. When ionizing radiation interacts with the germanium lattice, it creates electron-hole pairs in proportion to the deposited energy. An externally applied electric field causes these charge carriers to drift toward the electrodes, producing a measurable current pulse. The pulse amplitude is directly proportional to the incident gamma-ray energy, enabling precise spectroscopic measurements.

A key advantage of germanium detectors is the low average energy required to create an electron-hole pair, approximately 2.9 eV, resulting in a larger number of charge carriers and improved energy resolution. This value is significantly smaller than the effective energy required to generate a scintillation photon in inorganic scintillators. As a consequence, the number of charge carriers produced per unit energy is large, reducing statistical fluctuations in signal formation. This fundamental property results in the excellent intrinsic energy resolution observed in germanium-based detectors.

Moreover, **HPGe** detectors are characterized by extremely low impurity concentrations. High material purity minimizes charge trapping and recombination losses, ensuring efficient charge collection. To suppress thermally generated charge carriers and reduce electronic noise, **HPGe** detectors are operated at cryogenic temperatures. Cooling is typically achieved using liquid nitrogen at approximately -196°C . This requirement presents a practical limitation compared to room-temperature scintillation detectors.

High-purity germanium detectors provide excellent energy resolution for gamma-ray

spectroscopy. At MeV gamma-ray energies, typical full widths at half maximum are of the order of a few keV. For example, at the 1332 keV gamma-ray line of ^{60}Co , an **HPGe** detector commonly exhibits a full width at half maximum of approximately 2-3 keV. This high resolution enables precise peak separation and accurate identification of closely spaced gamma-ray lines. Such performance makes **HPGe** detectors particularly suitable for detailed spectral analysis, despite the additional requirements associated with cryogenic operation and specialized readout electronics.

2.6.1 Experimental setup

Gamma-ray spectroscopy measurements have been performed using a high-purity Broad Energy Germanium (BEGe) detector (Mirion Technologies, model BE6530) to characterize the intrinsic radioactive background of a **LYSO:Ce** crystal [87]. The specimen under investigation was a cerium-doped lutetium-yttrium oxyorthosilicate (**LYSO:Ce**) crystal with dimensions $2 \times 2 \times 3 \text{ cm}^3$. The **LYSO:Ce** crystal was treated as an external radioactive sample and measured under fixed and reproducible experimental conditions.

This detector operates effectively over a broad energy range from 3 keV to 3 MeV [87]. Thanks to its wider and flat crystal design, it is highly efficient for analyzing samples placed directly next to the detector [87]. This makes it particularly well-suited for our measurements, as it performs best in the 3 keV to 662 keV region where the main ^{176}Lu γ -ray signals are found [87].

The **HPGe** detector used in this work was operated as a cryogenically cooled system housed inside a vacuum cryostat under vacuum conditions and cooled to liquid-nitrogen temperature. The liquid nitrogen was stored in an integrated dewar located beneath the detector assembly, with thermal contact between the dewar and the germanium crystal ensured by a cold finger. The germanium crystal itself remains physically isolated from the liquid nitrogen and is positioned directly behind a thin entrance window at the detector's end, as schematically illustrated in Fig. 2.5a.

For gamma-ray spectroscopy measurements, the **HPGe** detector was housed inside a cylindrical lead shielding structure with an internal copper lining, as shown in Fig. 2.5b. The lead shield is used to suppress ambient laboratory background radiation, while the copper liner reduces characteristic X-rays produced in the lead. The shielding assembly includes an upper sample chamber aligned with the detector's end, providing a reproducible measurement geometry.

During measurements, the **LYSO:Ce** crystal was placed inside the shielding chamber directly in front of the detector endcap, without any physical contact with the germanium crystal. Gamma rays emitted from the **LYSO:Ce** crystal traverse the shielding cavity and detector endcap before interacting with the germanium crystal.

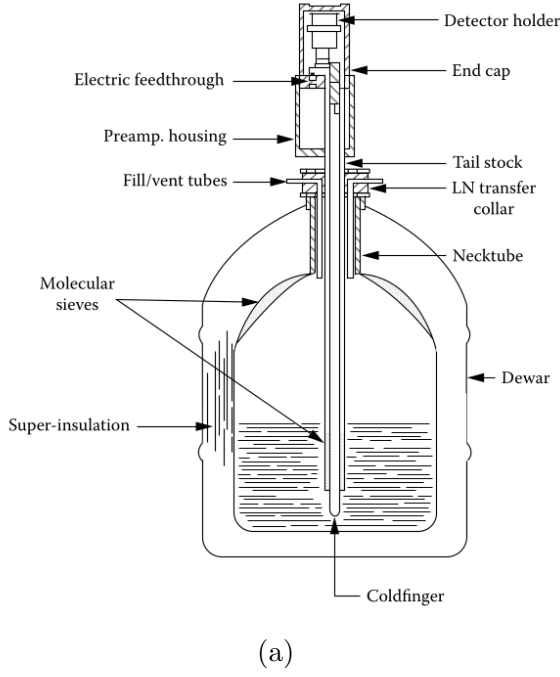


Figure 2.5: (a) Schematic cross section of a typical HPGe detector cryostat, illustrating the liquid-nitrogen dewar, cold finger, and the vacuum-sealed germanium crystal mounted behind the detector endcap. Adapted from Khater [88], (b) The HPGe detector and internal copper lining installed inside a lead shielding assembly. The upper shielding chamber accommodates the sample placement region in front of the detector end, while the cryostat and liquid-nitrogen dewar are located below the shielding structure.²

2.6.2 Data acquisition

Two independent data sets were acquired under identical detector and environmental conditions. A background spectrum was recorded in the absence of the **LYSO:Ce** crystal over a duration of 24 hours, while a second spectrum was acquired with the **LYSO:Ce** crystal in place over a duration of 18 hours. Data acquisition was performed using the built-in Genie™ Spectroscopy Software Suite (Canberra), which interfaces directly with the **HPGe** detector electronics and multichannel analyzer. Both measurements represent time-integrated spectra accumulated by the detector over the respective acquisition durations.

The detector output was processed using a multichannel analyzer (MCA), which sorted the detected events into discrete energy channels over the full acquisition time. The resulting spectra were stored as histogram, with each channel associated with a calibrated energy value (in keV) and the corresponding total number of recorded counts.

To isolate the intrinsic radioactive contribution of the **LYSO:Ce** crystal, the background spectrum was subtracted from the **LYSO:Ce** measurement. Prior to subtraction, both spectra were normalized to their respective acquisition times to get proper count rate per second per channel. The source spectrum, background spectrum, and the resulting **LYSO:Ce** spectrum after normalization are shown in Fig. 2.6. The resulting background-subtracted spectrum represents the intrinsic activity associated with the **LYSO:Ce** crystal.

²<http://www.nuclearphysicslab.com/npl/npl-home/spectroscopy/gamma-ray-spectroscopy/gamma-ray-spectroscopy-education/>.

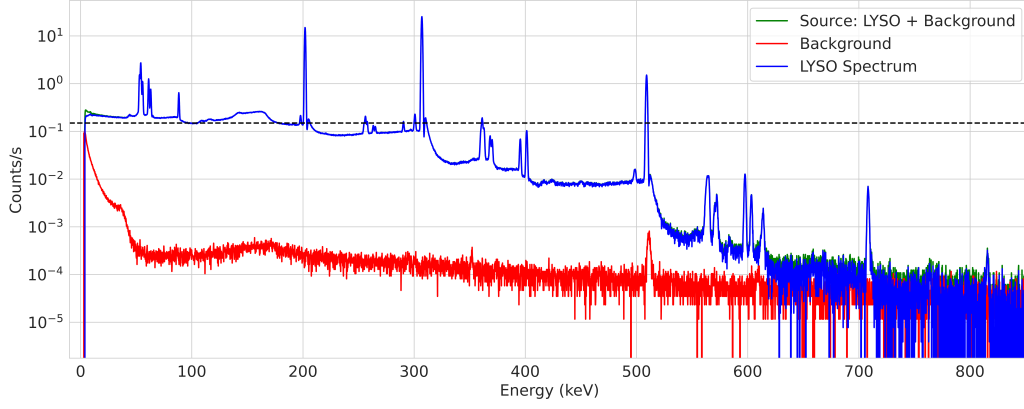


Figure 2.6: Energy spectra recorded for the intrinsic background measurement of the LYSO:Ce crystal. The background spectrum (red), the source spectrum with LYSO:Ce (green), and the resulting LYSO:Ce spectrum after normalization and background subtraction (blue) are shown in units of counts per second. The dashed black line marks the 0.15 counts/s threshold above which spectral features were considered in the quantitative analysis.

2.6.3 Spectral analysis of the data

The processed spectra were analyzed using a custom Python-based data analysis framework. For selected energy intervals, the data were modeled using analytical functions describing discrete γ -ray photopeaks superimposed on a continuous background. The spectrum measured from the **LYSO:Ce** crystal exhibits distinct photopeaks at characteristic energies, including prominent lines around 88 keV, 202 keV, 307 keV, and 509 keV, as well as two closely spaced structures in the 290–301 keV energy region.

The observed photopeaks in the **LYSO:Ce** spectrum can be attributed to specific γ -ray transitions and coincidence-sum contributions arising from the ^{176}Lu decay cascade. The single-transition peaks at 88 keV, 202 keV, and 307 keV correspond directly to the three characteristic γ -ray emissions of ^{176}Hf following the β_1 decay of ^{176}Lu [79]. In contrast, the features observed at 290 keV and 509 keV are coincidence-sum peaks, arising when two γ -rays from the same decay cascade are detected within the resolving time of the acquisition system and their energies are summed into a single event. Specifically, the 290 keV feature corresponds to the sum of the 88 keV and 202 keV transitions, while the 509 keV feature arises from the coincident detection of the 202 keV and 307 keV lines.

The 290–301 keV energy region contains two closely spaced peaks: the 290 keV coincidence-sum peak and a distinct feature at approximately 301 keV. This feature cannot be attributed to a known $^{176}\text{Lu}/^{176}\text{Hf}$ transition: dedicated high-statistics **HPGe** measurements of natural lutetium report only the 88, 202, 307, and 401 keV γ -ray lines [81], with no transition near 301 keV. Comparison with common environmental background lines is similarly inconclusive: although the peak energy is close to the 300.087 keV transition of ^{212}Pb , the absence of its dominant 238.6 keV companion line ($I_\gamma = 43.3\%$, more than 13 times stronger) [89] argues against this assignment, while a ^{214}Pb (radon-222 progeny) [90] origin is disfavoured by the fact that the feature persists after subtraction of the independently measured background spectrum, whereas ambient radon-related lines would be expected to cancel in this procedure. Consequently, although the origin of this feature remains unidentified and is noted here as an open point for future investigation, it was retained in the overall spectral analysis but excluded from the polynomial fit used to parametrize the FWHM and energy resolution as a function of energy.

Accordingly, a region-of-interest (ROI)-based approach was adopted, in which restricted

energy intervals centered around the intrinsic photopeaks were selected to isolate each feature from the surrounding continuum and neighboring spectral lines. The ROI selected in this analysis correspond to characteristic γ -ray photopeaks originating from the intrinsic radioactivity of the **LYSO:Ce** crystal, which is dominated by the natural decay of ^{176}Lu . To ensure statistical robustness, only spectral features associated with more than a rate of 0.15 counts/s were considered in the quantitative analysis (see figure 2.6).

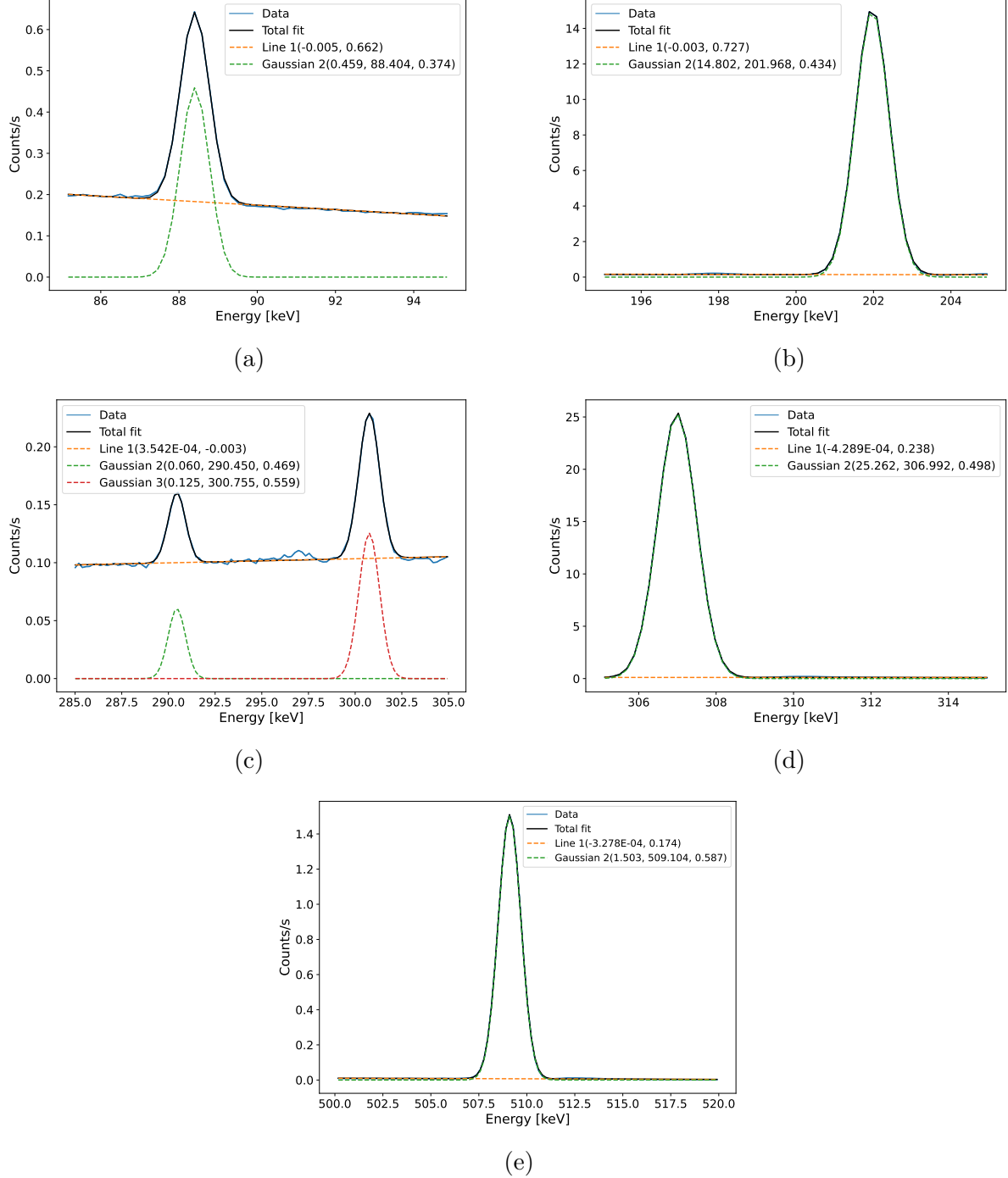


Figure 2.7: Gaussian fits applied to selected ROIs in the spectrum of the LYSO:Ce crystal, (a) 88 keV, (b) 202 keV, (c) 290 – 301 keV, (d) 307 keV, and (e) 509 keV. Each panel shows the measured data and the Gaussian peak components used to extract the centroid and width of the corresponding photopeak.

Within each ROI, the measured spectrum was fitted using a Gaussian function superim-

posed on a linear background component. All model components within a given ROI were fitted simultaneously to the measured spectrum using the `MixedDataFitter` class from the `pyMultiFit` library [91]. Initial parameter values were chosen based on the expected peak positions. Representative ROI fits are shown in Fig. 2.7. From the Gaussian fits, the peak centroid μ and standard deviation σ were extracted for each photopeak, enabling a reliable determination of peak parameters by exploiting the excellent intrinsic energy resolution of the **HPGe** detector.

Additionally, the low-energy spectral features observed in the 50–65 keV region, although exceeding the count rate threshold, were excluded from the Gaussian fitting analysis. These features correspond to overlapping ^{176}Lu characteristic X-ray lines and closely spaced doublet structures whose individual contributions cannot be reliably decomposed by independent Gaussian fits without introducing significant systematic uncertainties in the extracted peak parameters.

Energy resolution of the **HPGe** detector

The peak width extracted from the Gaussian fits provides a direct measure of the energy resolution of the **HPGe** detector. For each intrinsic γ -ray photopeak, the full width at half maximum (FWHM) was calculated from the fitted standard deviation σ assuming a Gaussian peak shape, according to

$$\text{FWHM} = 2\sqrt{2\ln 2} \sigma \simeq 2.355 \sigma. \quad (2.1)$$

The energy resolution R of the detector was then determined as the ratio of the FWHM to the centroid energy E of the corresponding photopeak in the calibrated energy spectrum:

$$R = \frac{\text{FWHM}}{E} \times 100 \%. \quad (2.2)$$

The uncertainties on the FWHM and energy resolution were determined by propagating the errors on the Gaussian fit parameters σ and μ . The uncertainty on the FWHM follows directly from the fitted standard deviation uncertainty $\delta\sigma$ as

$$\delta(\text{FWHM}) = 2.355 \delta\sigma, \quad (2.3)$$

while the uncertainty on the resolution was obtained by propagating both $\delta\sigma$ and $\delta\mu$ through Eq. (2.2):

$$\delta R = R \sqrt{\left(\frac{\delta\sigma}{\sigma}\right)^2 + \left(\frac{\delta\mu}{\mu}\right)^2}. \quad (2.4)$$

The resulting FWHM values, energy resolutions, and their propagated uncertainties for the selected intrinsic γ -ray lines of the **LYSO:Ce** crystal are summarized in Table 2.3. The measured energy resolution improves with increasing energy, ranging from approximately 1.0% at 88 keV to below 0.3% at 509 keV. These values are consistent with the expected performance of high-purity germanium detectors and confirm their suitability as reference instruments for precise γ -ray spectroscopy.

Figure 2.8 illustrate the measured FWHM and energy resolution as a function of energy. As established in Section 2.6.3, the 300.75 keV data point is excluded from the polynomial fit, as it does not correspond to a transition of the intrinsic ^{176}Lu decay cascade and its physical origin could not be conclusively identified. To make this distinction visually clear, it is plotted separately in Fig. 2.8 as a cross marker, separating it from the intrinsic ^{176}Lu peaks used in our parametrization. The observed decrease in energy resolution with increasing energy is in agreement with results reported in the literature [92, 93]. Previous

Table 2.3: Measured full width at half maximum (FWHM) and corresponding energy resolution of the HPGe detector for selected intrinsic γ -ray lines of the LYSO:Ce crystal. Uncertainties represent propagated errors from the Gaussian fit parameters.

Energy (keV)	FWHM (keV)	δ FWHM (keV)	Resolution (%)	δR (%)
88.40	0.880	0.005	0.995	0.005
201.97	1.023	0.001	0.506	0.001
290.45	1.104	0.028	0.380	0.010
300.75	1.316	0.015	0.438	0.005
306.99	1.174	0.002	0.382	0.001
509.10	1.382	0.001	0.271	<0.001

studies have shown that the energy resolution of **HPGe** detectors varies more strongly at low energies, particularly below approximately 300 keV, while it tends to become more stable at higher energies. This behavior is attributed to the intrinsic physical characteristics of the detector, including electronic noise contributions and charge collection statistics.

In the literature, the energy dependence of the peak width is commonly described using a second-order polynomial function [92]:

$$\text{FWHM}(E) = a_0 + a_1 E + a_2 E^2, \quad (2.5)$$

where E is the γ -ray energy, and a_0 , a_1 , and a_2 are empirical fitting coefficients.

In the present analysis, the measured FWHM values were fitted using the same second-order polynomial parametrization. The fitted coefficients were found to be $a_0 = 0.695$ keV, $a_1 = 2.07 \times 10^{-3}$, and $a_2 = -1.39 \times 10^{-6}$ keV $^{-1}$. The residuals shown in the lower panels of Fig. 2.8 were computed as the difference between the measured values and the fitted polynomial:

$$\Delta\text{FWHM} = \text{FWHM}_{\text{measured}} - \text{FWHM}_{\text{fit}}, \quad \Delta R = R_{\text{measured}} - R_{\text{fit}}. \quad (2.6)$$

Owing to the excellent intrinsic energy resolution of the **HPGe** detector, closely spaced

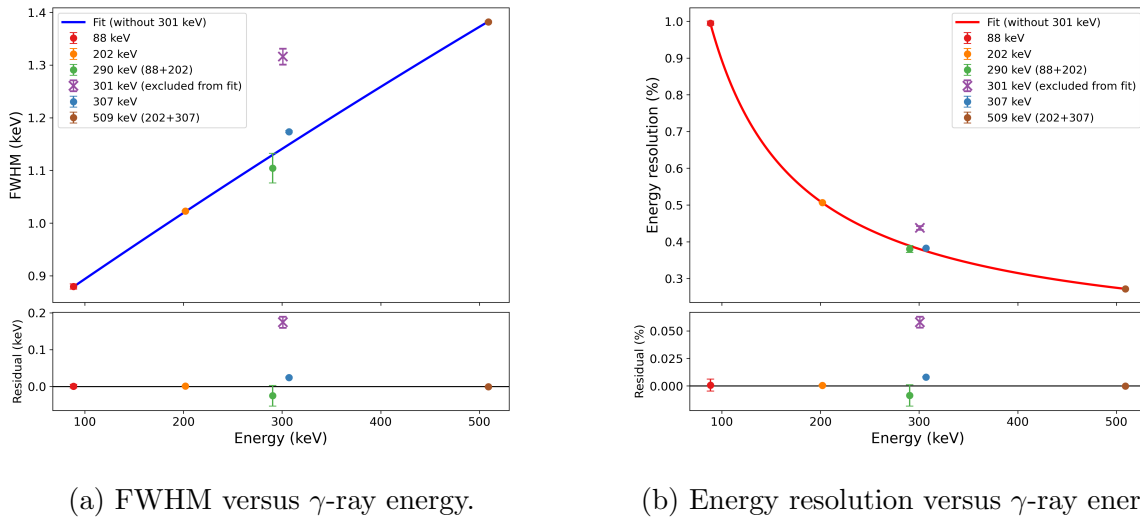


Figure 2.8: Energy-dependent performance of the HPGe detector for intrinsic γ -ray lines of the LYSO:Ce crystal. The markers represent the measured values obtained from Gaussian fits, while the solid curves represent the second-order polynomial fit to the data. The cross marker at 301 keV is excluded from the fit; see text for details.

γ -ray lines can be clearly resolved, providing reliable reference information for peak identification and supporting the interpretation of intrinsic background features observed in **LYSO:Ce** scintillation measurements.

Efficiency of the HPGe detector

Detector efficiency describes the ability of a detector to accurately and reliably detect and measure gamma radiation emitted by a radioactive source. In gamma-ray spectrometry, this capability is characterized by different efficiency definitions, including intrinsic, photopeak, relative, and absolute efficiencies [94]. The accuracy of gamma-ray spectrometric measurements depends directly on the detector efficiency under the given measurement conditions, and the energy resolution is likewise an important performance parameter [95, 96].

Detector efficiency depends on several factors, such as the gamma-ray energy, detector dimensions, source dimensions, and the detector-source geometry. Therefore, an efficiency calibration obtained for one detector configuration may not be applicable to another system [97]. The most reliable approach is experimental efficiency calibration performed under the relevant measurement geometry, since efficiency depends on the gamma-ray energy, detector properties, and measurement setup [98].

The photopeak efficiency of the **HPGe** detector was determined from the measured gamma-ray spectra by relating the net number of counts recorded in a given photopeak to the known activity of the radionuclide and the corresponding gamma-ray emission probability. For each photopeak, the net counts were obtained by subtracting the contribution of the underlying continuum from the total recorded counts. The photopeak efficiency at energy E is defined as

$$\varepsilon(E) = \frac{N}{A I_{\gamma} t}, \quad (2.7)$$

where N is the net number of counts under the photopeak at energy E , A is the activity of the radionuclide, I_{γ} is the gamma-ray emission intensity (branching ratio) of the corresponding transition, which in the case of intrinsic **LYSO:Ce** activity refers to the ^{176}Lu γ -ray decay, and t is the live time of the measurement.

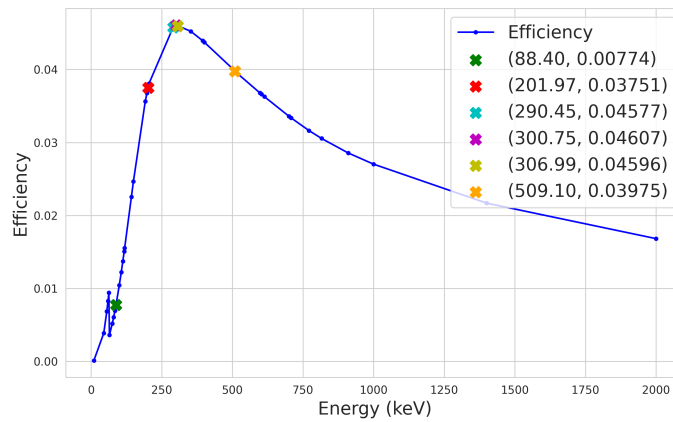


Figure 2.9: Photopeak efficiency of the HPGe detector as a function of gamma-ray energy.

Figure 2.9 shows the photopeak efficiency of the **HPGe** detector as a function of gamma-ray energy, as provided by the detector acquisition and analysis software. The efficiency exhibits the characteristic behavior of **HPGe** detectors, increasing rapidly at low

energies due to the rising photoelectric absorption probability, reaching a maximum in the intermediate energy range, and gradually decreasing at higher energies where Compton scattering and incomplete energy deposition become dominant. The highlighted efficiency points correspond to the intrinsic γ -ray lines of the **LYSO:Ce** crystal used in this study.

2.7 SiPM-based Characterization of LYSO:Ce with ^{60}Co

A measurement of the **LYSO:Ce** scintillator response was performed using a silicon photomultiplier (**SiPM**) as the photodetector, representing a configuration directly relevant to compact, low-power space-based instruments such as the crystals employed by the Zirè and the Crystal Eye detectors presented in Chapter 3. The **SiPM** used was an Onsemi MicroFC-60035 device, a 6 mm $\times$ 6 mm sensor with 35 μm microcells, operated at room temperature and biased at 27 V.

2.7.1 Experimental Setup and Data Acquisition

The overall signal acquisition chain is shown in Fig. 2.10. The **LYSO:Ce** crystal ($3.0 \times 2.1 \times 2.1 \text{ cm}^3$) was optically coupled to the Onsemi **SiPM** using optical grease, and the assembly was wrapped in Teflon tape to maximize light collection and minimize internal reflections. The detector was housed inside a light-tight dark box to prevent ambient light from reaching the **SiPM** surface; the enclosure was further covered with black cloth to suppress any residual stray light. The ^{60}Co source was mounted in a fixed holder on top of the enclosure at a distance of approximately 1–2 cm from the scintillator crystal.

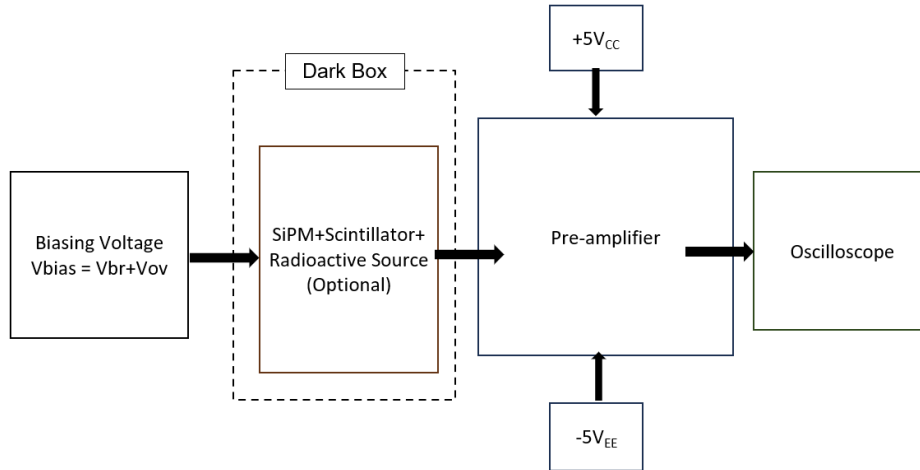


Figure 2.10: Block diagram of the signal acquisition chain, showing the bias supply ($V_{\text{bias}} = V_{\text{BR}} + V_{\text{OV}}$), the SiPM–scintillator assembly inside the dark box, the preamplifier powered by $\pm 5 \text{ V}$ supplies, and the oscilloscope used for pulse-area histogram acquisition.

Signals from the **SiPM** were amplified by a low-noise preamplifier (AGE Scientific) and fed into a Teledyne LeCroy HDO-series digital oscilloscope (12-bit vertical resolution) operating with a 50 Ω input termination, DC coupling, a sampling rate of 10 GS/s (corresponding to 100 ps per sample point), and a bandwidth limit of 200 MHz to suppress high-frequency noise. The same instrument and the key acquisition parameters relevant to the pulse-area measurement (sampling rate, bandwidth, coupling, and trigger threshold) were held constant

between the **LYSO:Ce**-only and the ^{60}Co +**LYSO:Ce** measurements. The recommended biasing and readout circuit for the Onsemi MicroFC-60035 is shown in Fig. 2.11a: the standard output (Sout) across the $50\ \Omega$ load was used for pulse area integration, while the fast output (Fout) was available for timing applications. The oscilloscope was operated in pulse-area histogram mode: the instrument’s built-in “Area” measurement parameter was computed for each triggered waveform in real time, and the resulting values were accumulated into a live histogram using the oscilloscope’s native histogram function, without requiring offline waveform processing. Each histogram accumulated approximately 8×10^6 waveforms over the acquisition period. The trigger threshold was set to 15 mV for both acquisition runs. All measurements were performed at room temperature, maintained at $25 \pm 2^\circ\text{C}$ throughout the acquisition.

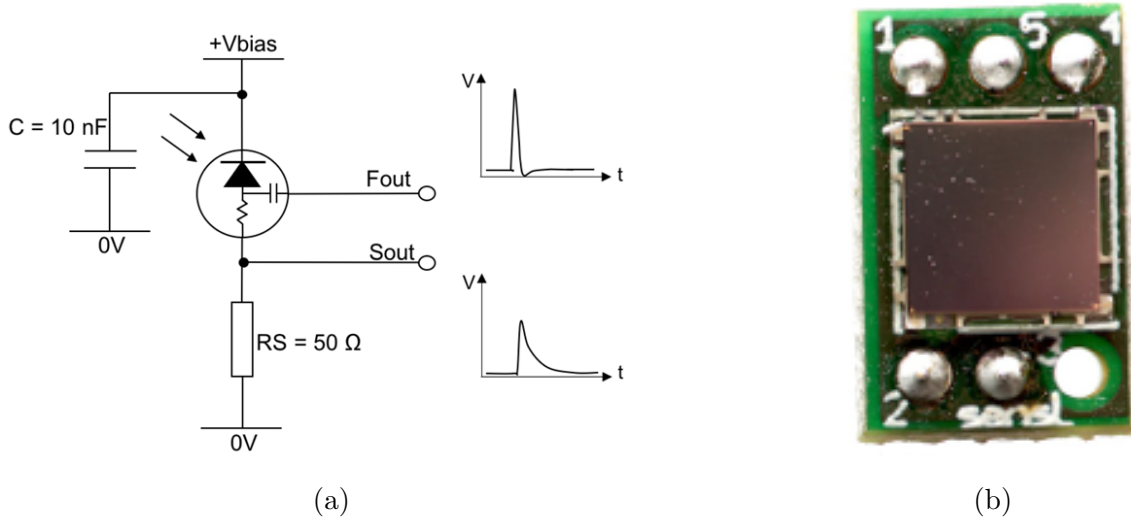


Figure 2.11: (a) Recommended biasing and readout circuit for the Onsemi MicroFC-60035. The fast output (Fout) provides sub-nanosecond timing pulses; the standard output (Sout) across the $50\ \Omega$ load is used for pulse area integration. (b) Photograph of the 6 mm $\times$ 6 mm SMT package showing the pad layout (pads 1–5 visible along the bottom edge).

Two independent 24-hour acquisitions were performed. The first used the **LYSO:Ce** crystal alone to record the intrinsic background spectrum. The second included a ^{60}Co source placed in front of the crystal to record the combined signal. Each histogram was normalized to the live acquisition time to obtain event rates in counts per second. The ^{60}Co source was chosen as an external energy reference, as its well-known γ -ray lines at 1173.2 keV and 1332.5 keV provide a reliable calibration anchor in the high-energy region of the spectrum.

Figure 2.12 shows the pulse area spectra recorded for the **LYSO:Ce**-only (background) and the combined ^{60}Co +**LYSO:Ce** (total signal) configurations. The two spectra overlap well in the low-area region, confirming that the live-time normalization successfully aligned the count rates of the two datasets. The **LYSO:Ce** intrinsic spectrum is dominated by the ^{176}Lu $\beta + \gamma$ cascade, which produces a broad continuum extending up to approximately 200 nV·s in pulse area. The inclusion of the ^{60}Co source produces a visible excess in the total signal spectrum relative to the background, reflecting the additional energy deposits associated with the 1173.2 keV and 1332.5 keV γ -ray lines of ^{60}Co .

The **LYSO:Ce** background spectrum falls steeply beyond 200 nV·s, becoming negligible above 400 nV·s, which confirms that the high-energy region of the total spectrum is dominated by the ^{60}Co signal as shown in Fig. 2.12. The ^{60}Co contribution was isolated by subtracting the **LYSO:Ce**-only (intrinsic ^{176}Lu background) spectrum from the total

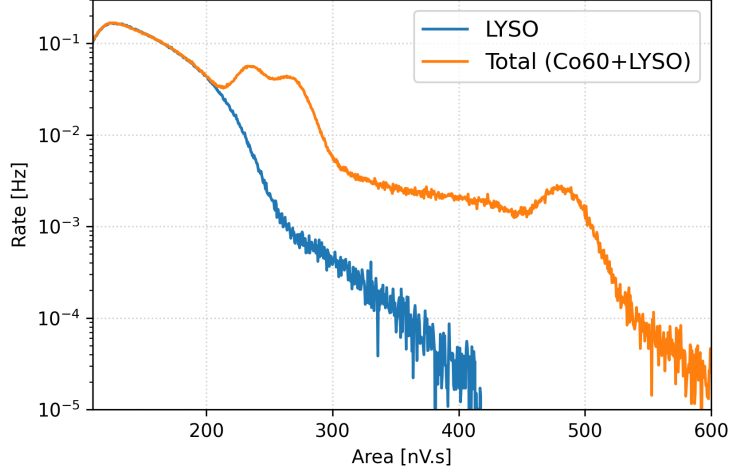


Figure 2.12: Pulse area spectra for the LYSO:Ce-only background run (blue) and the combined ^{60}Co +LYSO:Ce signal run (orange), shown on a logarithmic scale.

^{60}Co +LYSO:Ce measurement. Prior to subtraction, both spectra were interpolated onto a common uniform grid of 2001 points using linear interpolation, with zero fill-value outside the measured range. The resulting ^{60}Co spectrum is shown in the left panel of Fig. 2.13. Each of the two ^{60}Co γ -ray peaks was fitted with a Gaussian function plus a constant background term $f(x) = A \exp\left[-\frac{1}{2} \left(\frac{x-\mu}{\sigma}\right)^2\right] + c$ using the `iminuit` minimization package with a least-squares cost function.

The uncertainty on each bin was estimated by propagating the Poisson counting uncertainty. For a bin with N raw counts scaled by a factor s , the uncertainty is $\sigma = \sqrt{N} \cdot s$, where s accounts for live-time and efficiency corrections. The fit was performed over restricted area windows selected to isolate each peak: 221–244 nV·s for the 1173.2 keV line and 260–300 nV·s for the 1332.5 keV line. A third window (460–510 nV·s) was also tested for the 2614.0 keV ^{208}Tl line. Two prominent peak structures are visible in the 200–300 nV·s range, corresponding to the 1173.2 keV and 1332.5 keV γ -ray lines of ^{60}Co . A weaker feature is also observed near 480 nV·s, consistent with the 2614.0 keV line of ^{208}Tl arising from natural thorium-series background. Negative values in the subtracted spectrum arise from statistical fluctuations in the interpolation procedure and carry no physical significance. The fitted peak positions and their uncertainties are summarized in Table 2.4, and were used as input to the linear energy calibration.

Energy [keV]	Peak Position [nV.s]	Uncertainty [nV.s]
1173.2	237.2	0.10
1332.5	264.6	0.16
2614.0	479.3	0.21

Table 2.4: Fitted peak positions and their uncertainties.

To establish a correspondence between the measured pulse area and the incident photon energy, a linear energy calibration was performed using the fitted peak positions of the three ^{60}Co γ -ray lines described above as calibration points. The calibration assumes a linear relation between pulse area A and energy E as $A = m \cdot E + q$, where m is the gain factor in nV·s/keV and q is the offset. The best-fit parameters obtained are $m = (0.1679 \pm 0.0002)$ nV·s/keV and $q = (40.37 \pm 0.24)$ nV·s. The right panel of Fig. 2.13 shows the calibration curve together with the residuals. The three ^{60}Co points are consistent with a linear

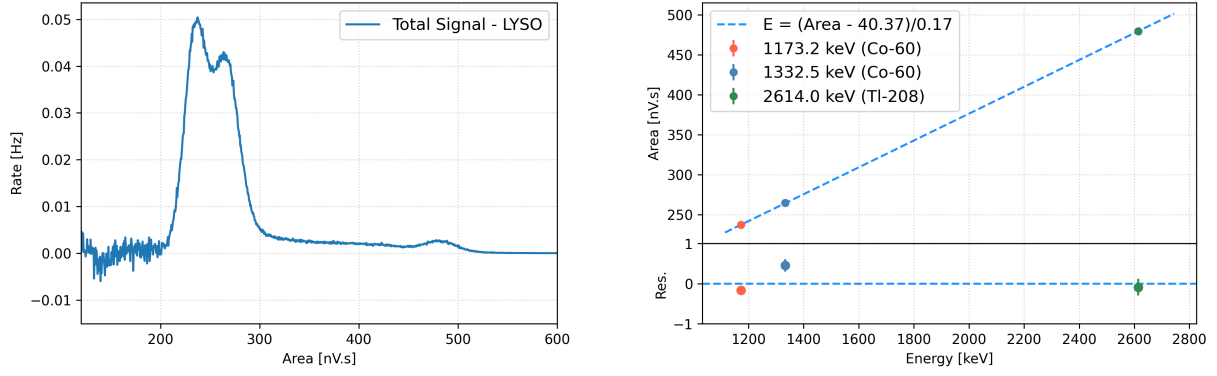


Figure 2.13: Left: extracted ^{60}Co spectrum after LYSO:Ce background subtraction. Right: linear energy calibration using the two ^{60}Co γ -ray lines, with fit residuals shown in the lower panel.

response within their uncertainties, confirming that the SiPM+LYSO:Ce system exhibits a linear area-to-energy conversion in this energy range.

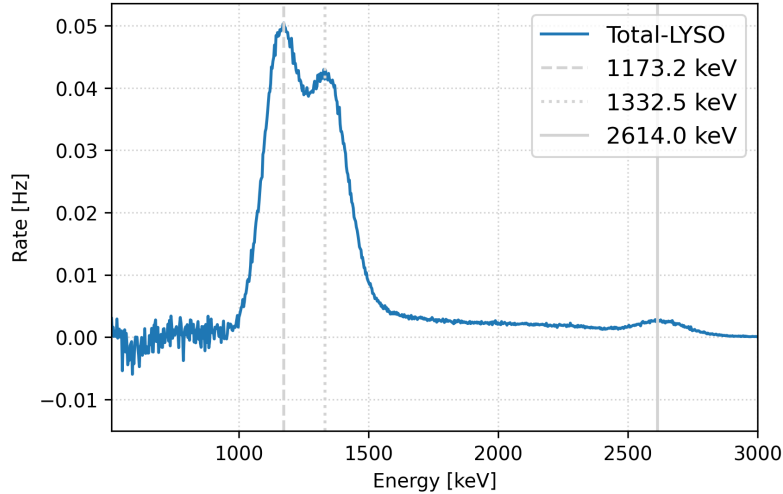


Figure 2.14: Calibrated ^{60}Co spectrum in energy units [keV], obtained by applying linear regression to the subtracted spectrum. Vertical lines indicate the expected positions of the 1173.2 keV and 1332.5 keV ^{60}Co lines and the 2614.0 keV ^{208}Tl line.

The calibration relation $E = (A - q)/m$ was applied to convert the subtracted ^{60}Co pulse area spectrum to an energy scale. The resulting calibrated spectrum is shown in Fig. 2.14, confirming the correspondence between the observed spectral features and the known ^{60}Co γ -ray energies.

The results presented in this section demonstrate that the SiPM+LYSO:Ce detector configuration is capable of resolving the characteristic γ -ray lines of ^{60}Co at 1173.2 keV, 1332.5 keV, and 2614 keV and of establishing a linear energy calibration in the MeV range. The background subtraction procedure isolated the ^{60}Co signal from the intrinsic ^{176}Lu activity of the LYSO:Ce crystal. These findings confirm the suitability of compact SiPM-based scintillator assemblies for gamma-ray spectroscopy in the energy range relevant to space-based instruments, and provide a basis for more refined measurements with improved acquisition conditions in future campaigns.

While the conclusions drawn in this section remain valid above 1 MeV, where the ^{60}Co photopeaks are located, and for the source intensity tested here, Fig. 2.12 shows that

intrinsic background contributions from the **LYSO:Ce** crystal become increasingly significant at lower energies, consistent with the dominance of the intrinsic ^{176}Lu background below 1 MeV reported in the full Crystal Eye detector simulations discussed in later chapters.

The measurements presented in this and section 2.6 were not used to validate the Geant4 simulation chain developed in Chapters 4 and 5. In particular, no quantitative comparison between the measured ^{176}Lu γ -ray spectrum and the simulated intrinsic **LYSO:Ce** background has been performed. This validation is left to future work and represents a limitation of the present study.

Chapter 3

New compact space based detectors

Advances in detector miniaturization, onboard data processing, and modular spacecraft architectures now enable sophisticated scientific instruments to be deployed within compact payloads. A key enabling technology is **SiPM**, a relatively recent solid-state photodetector consisting of an array of Geiger-mode avalanche photodiodes (APDs), each coupled with a quenching resistor [99]. **SiPMs** offer high gain (10^5 – 10^6), fast timing response, high photon detection efficiency, and excellent photon-counting resolution, while operating at low bias voltages of a few tens of volts. Compared to traditional **PMTs**, **SiPMs** are significantly more compact in size, consuming less space and power, while remaining mechanically robust and insensitive to magnetic fields, making them particularly well suited for space-based detector systems where constraints on mass, volume, and power are stringent. As a cutting-edge technology, **SiPMs** are now being deployed and tested in space-based detectors, with strong expectations that their unique combination of compactness, efficiency, and low power consumption will yield improved detector performance in the space environment. This approach supports rapid development cycles, in-orbit technology validation, and focused scientific investigations, while significantly reducing cost and complexity.

Within this framework, the **NUSES** and Crystal Eye projects represent two complementary implementations of compact satellite experiments addressing key challenges in high-energy astrophysics. The **NUSES** mission provides a multi-instrument platform aimed at validating detector technologies, trigger strategies, and background-rejection techniques in low Earth orbit. Crystal Eye is conceived as a wide-field, all-sky gamma-ray monitor optimized for the detection and localization of transient events in the MeV energy range. Together, these experiments illustrate how compact missions can effectively combine technological development with targeted scientific objectives, establishing a foundation for future scalable and cooperative space-based observatories.

This chapter presents an overview of the **NUSES** mission and the Crystal Eye detector, highlighting their scientific motivations, detector concepts, and the shared technological framework underpinning their development.

The first part of the chapter is devoted to the **NUSES** mission. Section 3.1 introduces the mission and its NIMBUS satellite platform, together with a brief description of the Terzina telescope. Section 3.2 then presents the Zirè detector and its sub-detectors, **Fiber Tracker (FTK)**, **Plastic Scintillator Tower (PST)**, the CALOg gamma-ray calorimeter central to this thesis, and **Anti-Coincidence System (ACS)**. Its charged-particle simulation performance is summarized in Section 3.2.1, and its **SiPM**-based readout and radiation tolerance in Section 3.2.2.

The second part of the chapter is dedicated to the Crystal Eye detector, introduced in Section 3.3. Its overall concept is described in Section 3.3.1, the pixel structure and scintillator materials in Section 3.3.2, and the **Anti-Coincidence Detector (ACD)** in Section 3.3.3,

while the simulation, trigger logic, and readout electronics are presented in Section 3.3.4. The detailed performance and optimization studies are presented in Chapter 5. Finally, Section 3.4 discusses the synergy between the **NUSES** and Crystal Eye projects.

3.1 The NUSES Mission

The **NUSES** space mission, consists of two detectors, Terzina and Zirè (see Fig. 3.1). The mission is aimed at exploring new technological methods to help in the facilitation of future space-based detectors [100]. The satellite will move in low-Earth orbit (LEO) at the height of 550 km with an inclination angle of 97.8° and follow a sun-synchronous path [101]. **SiPMs** have been adopted across all **NUSES** payloads in place of traditional **PMTs**. This mission-wide choice leverages **SiPM**'s compact form factor, low power draw, and high photon-detection efficiency to meet the stringent size, weight, and power constraints of space-based astroparticle instruments.

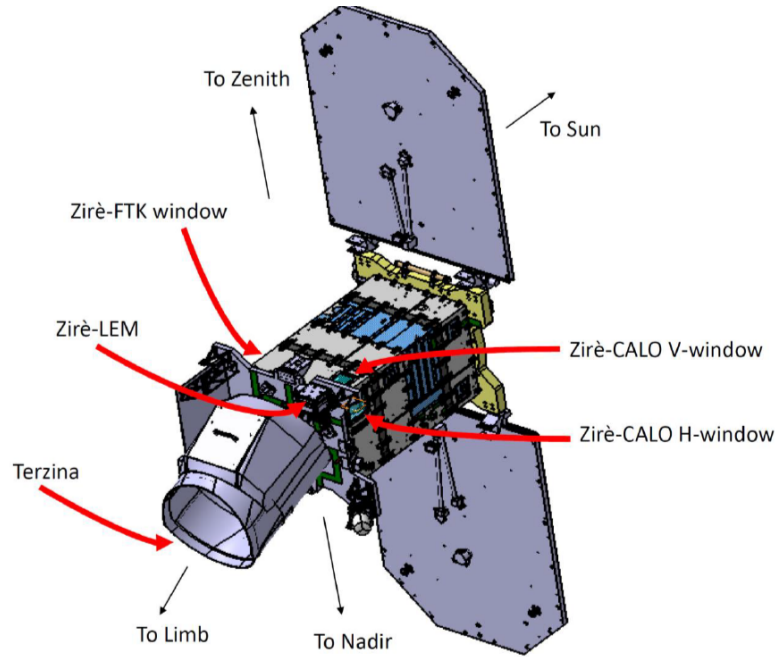


Figure 3.1: Illustration of the NUSES satellite in its fully deployed configuration, with solar panels extended. The Terzina instrument is installed atop the main structure, and Zirè resides in the first payload tray. (Image courtesy of Thales Alenia Space Italy.)

The **NUSES** payloads are hosted on the *New Italian Micro BUS* (NIMBUS), a compact satellite platform designed for scientific missions in Low Earth Orbit and optimized for small-satellite constraints in mass, volume, power, and thermal control. The NIMBUS platform is based on a modular concept in which the main subsystems are distributed across stacked functional layers from top to bottom: the Payload Tray (PL), the Electrical Power System tray (EPS), the Data Handling and Control tray (DHC), the Attitude and Orbit Control tray (AOC), and the Bottom Panel housing the propulsion system (see Fig. 3.2). Within this framework, Terzina and Zirè are accommodated in the payload tray, while the lower trays provide power distribution, onboard data handling, and attitude control, enabling straightforward integration and system-level verification.

The first detector, Terzina, is a compact Schmidt–Cassegrain Cherenkov telescope designed to study ultra-high-energy cosmic rays (UHECRs) and neutrinos by detecting the optical Cherenkov flashes produced by extensive air showers above the Earth's limb [102].

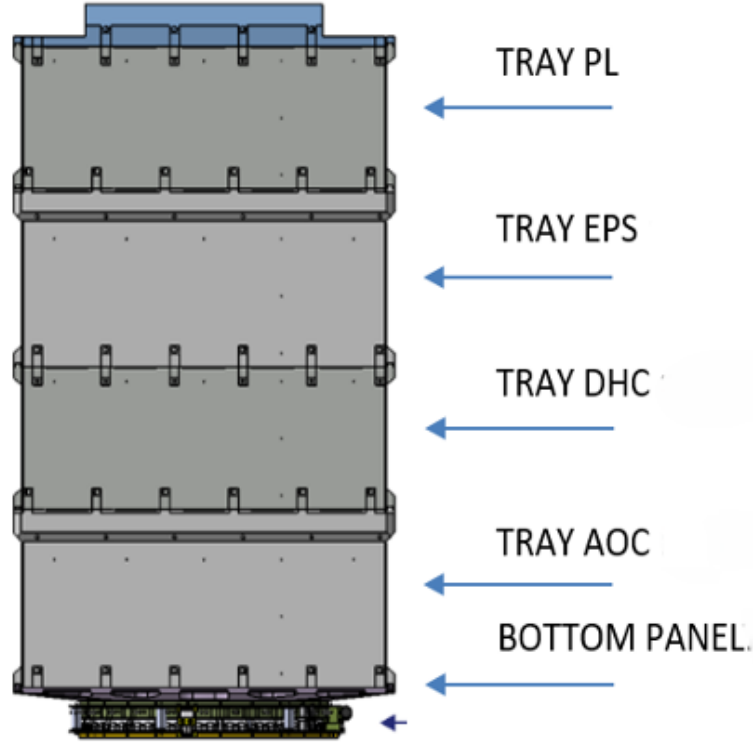


Figure 3.2: Concept of the NIMBUS modular satellite platform showing the stacked tray architecture from top to bottom: Payload Tray (PL), EPS Tray, DHC Tray, AOC Tray, and Bottom Panel (Image courtesy of Thales Alenia Space Italy).

It serves as a technological precursor for future space-based observatories such as PO-EMMA [103]. The second detector, Zirè, which carries the CALOg calorimeter central to this thesis, is described in detail in the following section.

3.2 The Zirè Detector

The Zirè's detector is designed to measure electrons, protons, and light nuclei in an energy range between few MeV upto hundreds of MeVs [104]. Additionally this experiment can investigate space weather and magnetosphere-lithosphere-ionosphere coupling through correlations between particle flux variations and seismic or magnetospheric-ionospheric disturbances. Moreover, it is designed to detect gamma rays in the 0.1-50 MeV energy range to validate photon detection technologies for both transient events (e.g., GRBs and gravitational-wave counterparts) and steady astrophysical sources [105].

Zirè is a full-fledged calorimeter system divided into specialized sub-detectors for measuring cosmic electrons, protons, and light nuclei. The instrument is composed of four specialized sub-detectors, FTK, PST, gamma-ray calorimeter (CALOg), and ACS, which operate to provide charged-particle tracking, energy measurement, particle identification, and background suppression.

A three-dimensional CAD rendering of the complete Zirè detector is shown in Figure 3.3. Charged particles can reach the detector from any direction; valid events correspond to trajectories that traverse the FTK, PST, and CALOg modules in sequence, consistent with entry through the FTK side, while the ACS surrounds the detector volume to veto particles entering from outside the nominal field of view.

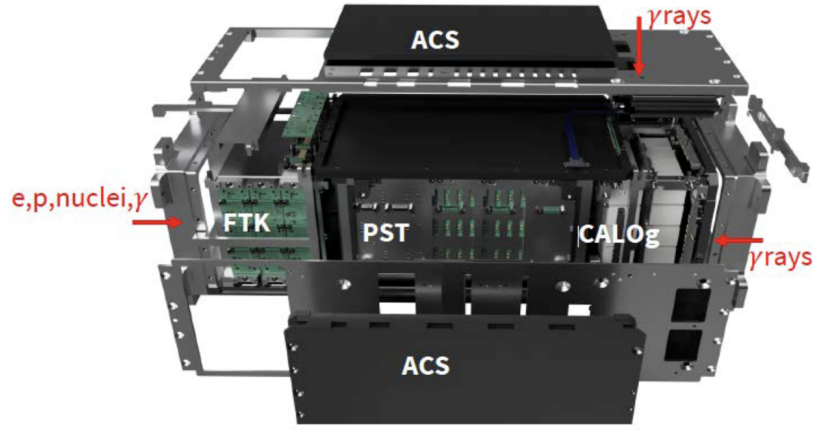


Figure 3.3: CAD rendering of the Zirè detector. Valid events correspond to particle trajectories that traverse the FTK, PST, and CALOg modules in sequence, consistent with entry through the FTK side; particles entering from other directions are vetoed by the ACS [106].

Fiber Tracker (FTK)

FTK is responsible for identifying the passage of charged particles and reconstructing their trajectories. It provides the initial spatial information required for event triggering and for guiding the interpretation of energy deposition in the downstream sub-detectors.

Figure 3.4 shows the CAD view of **FTK**. The **FTK** is composed of three orthogonal X-Y modules, each covering a sensitive area of $9.6 \times 9.6 \text{ cm}^2$, with a spacing of 2.5 cm between consecutive modules. This modular configuration allows accurate track reconstruction while maintaining a limited material budget, which is essential for minimizing multiple scattering effects at low energies.

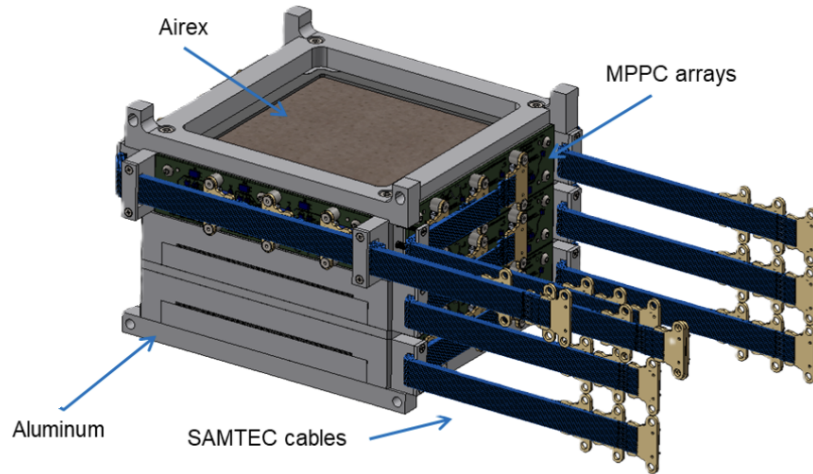


Figure 3.4: CAD view of an FTK X-Y module, showing the mechanical support structure, scintillating fiber planes, and readout routing. The module is constructed with an aluminum frame and integrates lightweight structural materials [107].

Each **FTK** module consists of two orthogonal planes, and each plane is formed by two layers of round plastic scintillating fibers arranged in a staggered double-layer geometry. The fibers adopted for the flight configuration are Kuraray SCSF-78, featuring a polystyrene

core surrounded by a double cladding structure. The inner cladding is made of polymethylmethacrylate (PMMA), while the outer cladding consists of a fluorinated polymer, a configuration chosen to enhance light trapping efficiency within the fiber. This double-clad structure provides a trapping efficiency of approximately 5.4% and a light yield of about 8000 photons/MeV.

The fibers have a diameter of $750\ \mu\text{m}$, representing a compromise between light yield, spatial resolution, and mechanical robustness. During the prototyping phase, fibers with different diameters were investigated; however, the $750\ \mu\text{m}$ configuration was selected as flight-representative for Zirè. The total on-axis thickness of each FTK module is approximately 1.4 mm, a design choice aimed at reducing multiple Coulomb scattering within the tracker and minimizing charged-particle energy loss before entering the PST and the calorimeter [107]. A photograph of an X-Y FTK module prototype is shown in figure 3.5. The image illustrates the mechanical support structure and the arrangement of the scintillating fiber planes within the tracker module.

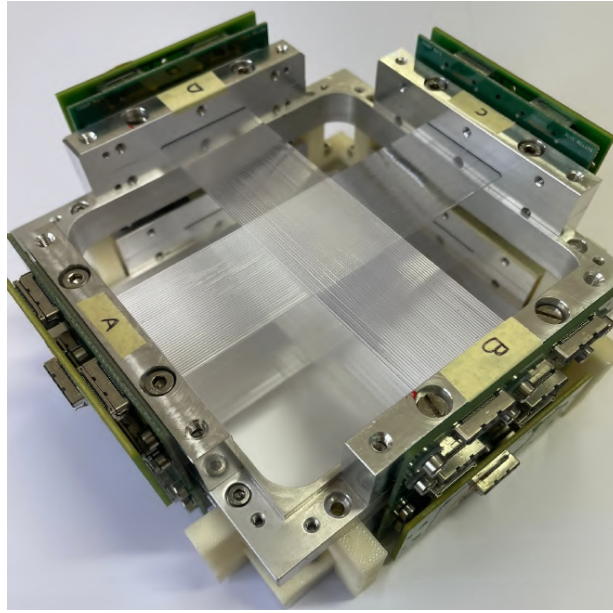


Figure 3.5: Photograph of a Fiber Tracker X-Y module prototype [107].

Plastic Scintillator Tower (PST)

Downstream of the FTK, the PST provides energy-loss measurements and contributes to particle identification and trigger formation within the Zirè payload. Its layered scintillator geometry enables both tracking and calorimetric measurements over a broad energy range.

Figure 3.6 shows the CAD view of the PST. The detector consists of 32 layers of plastic scintillator arranged in a hodoscopic configuration, with alternating X and Y orientations to allow two-dimensional track reconstruction. Each layer comprises three scintillator bars with a cross section of $4 \times 12\ \text{cm}^2$.

The first six layers are “thick” scintillators with dimensions $12 \times 12 \times 1\ \text{cm}^3$, while the remaining 26 “thin” layers ($12 \times 12 \times 0.5\ \text{cm}^3$) primarily provide calorimetric energy measurements. The individual layers are labeled PS0–PS31, with PS0 denoting the first (uppermost) PST layer, adjacent to the FTK.

The mechanical structure of the PST is realized using Windform XT 2.0, a carbon-fiber-reinforced composite material chosen for its mechanical strength and thermal stability. The total mass of the PST module is approximately 5.3 kg.

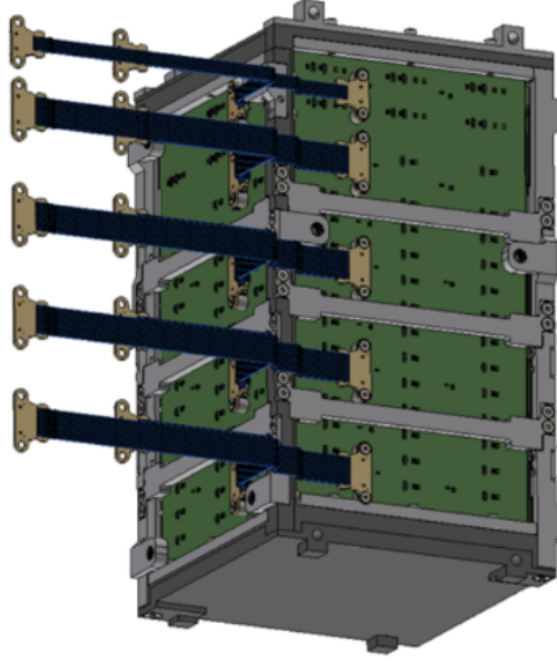


Figure 3.6: CAD view of the PST, illustrating the stacked scintillator layers and mechanical support structure (Image courtesy of the NUSES Collaboration).

A photograph of the **PST** structural model realized during the integration phase is shown in Figure 3.7, highlighting the wrapped scintillator bars and the mechanical housing.



Figure 3.7: Photograph of PST structural model realized during the integration phase. In the flight model, aluminum foil replaces the black vinyl tape used during prototyping (Image courtesy of the NUSES Collaboration).

Gamma-ray Calorimeter (CALOG)

The gamma-ray calorimeter (CALOG) is positioned downstream of the **PST** and serves as the precision energy-measurement subsystem of the Zirè payload. Unlike the **PST**, CALOG is based on high-density scintillating crystals optimized for accurate calorimetric measurements in space.

Figure 3.8 shows the CAD view of the CALOG mechanical assembly. The calorimeter is composed of a $4 \times 4 \times 2$ array of scintillating crystal elements, for a total of 32 optically

independent units. Each crystal has dimensions of $2.5 \times 2.5 \times 3.0 \text{ cm}^3$ and in its final design, is made of **GAGG:Ce**, selected for its high light yield, fast decay time, excellent energy resolution, and radiation hardness. Using the radiation length of **GAGG:Ce** ($X_0 \approx 1.6 \text{ cm}$ [108]), the total active depth of CALOg, corresponding to the two stacked crystal layers (3.0 cm each along the depth direction), amounts to approximately $3.75 X_0$.

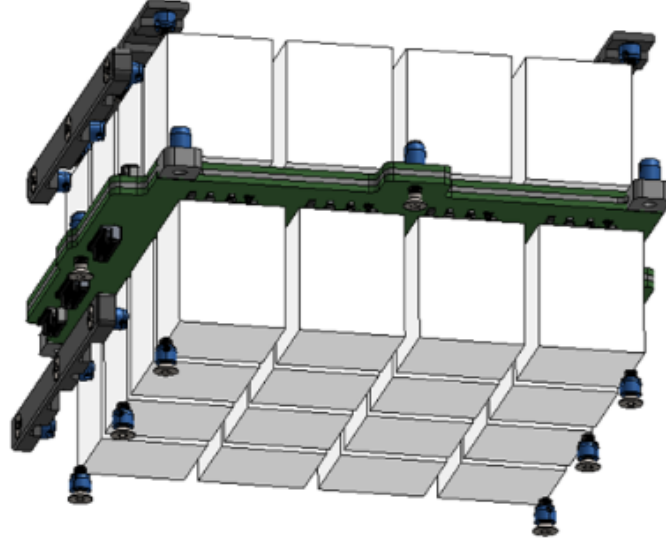


Figure 3.8: CAD view of the CALOg mechanical assembly (Image courtesy of the NUSES Collaboration).

CALOg is designed to measure the energy of incoming charged particles and to detect gamma rays in the energy range from 0.1 to 50 MeV. The uniform use of **GAGG:Ce** crystals ensures a homogeneous detector response. The total estimated mass of the CALOg module is approximately 6 kg, including the crystal matrix and mechanical support structure.

Each crystal is optically treated to enhance light collection and suppress optical cross-talk, using reflective coatings and external wrapping. The mechanical structure of the calorimeter is manufactured from Windform XT 2.0, a carbon-filled polyamide composite material chosen for its mechanical strength and thermal stability. The calorimeter modules are securely mounted to the Zirè payload chassis using precision aluminum fixtures.

CALOg incorporates two independent gamma-ray entrance windows on the calorimeter side of the detector. One window is oriented toward the zenith (V), while the second faces the horizon (H), enabling gamma-ray detection from complementary viewing geometries (see Figure 3.1).

A detailed view of the calorimeter components is shown in Figure 3.9, illustrating the mechanical housing used to accommodate the 4×4 crystal matrix and a single **GAGG:Ce** scintillating crystal.

Anti-Coincidence System (ACS)

The **ACS** is designed to suppress background events caused by charged particles entering the detector from outside the nominal field of view. It surrounds the Zirè payload on all sides except the **FTK** entrance window and provides a veto capability for side-entering or non-contained particles.

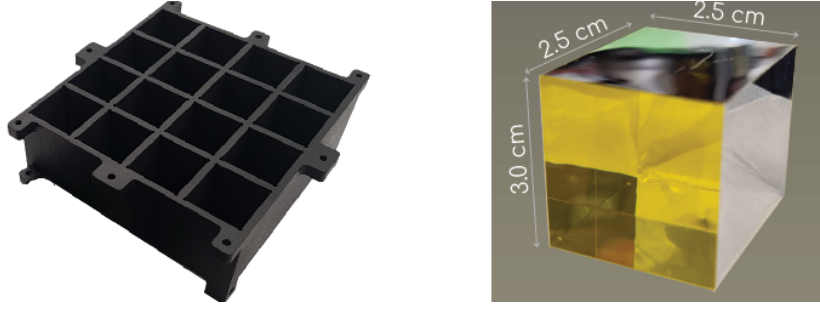


Figure 3.9: Mechanical housing used to accommodate the 4×4 crystal matrix of a single CALOG layer, together with a single GAGG:Ce scintillating crystal of dimensions $2.5 \times 2.5 \times 3.0 \text{ cm}^3$ [104].

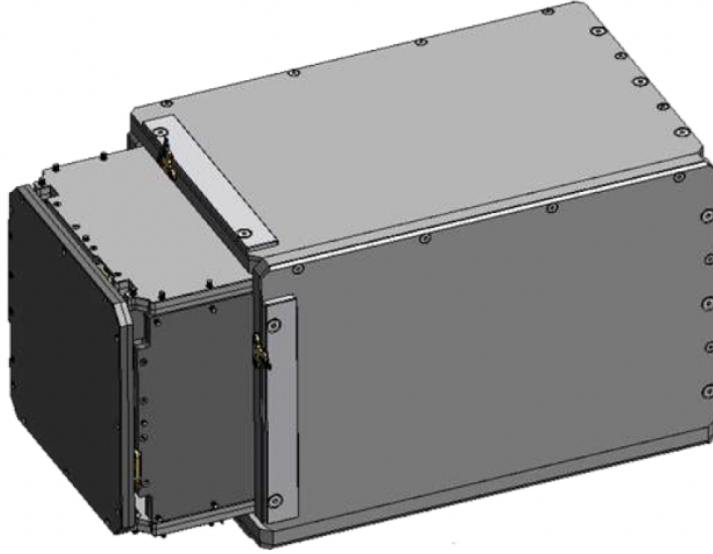


Figure 3.10: Complete detector scheme including a larger ACS surrounding the PST and FTK and a smaller ACS enclosing the CALOG (Image courtesy of the NUSES Collaboration).

As illustrated in Figure 3.10, the ACS is composed of nine plastic scintillator tiles, each with a thickness of 0.5 cm. The tiles are arranged to cover the PST on all four lateral sides and the CALOG on four sides and the bottom face. This geometry provides a high geometrical coverage of the sensitive detector volume while preserving the acceptance of particles entering through the nominal entrance windows.

Each scintillator tile is housed within a dedicated mechanical support structure made of Windform XT 2.0, a lightweight and mechanically robust composite material suitable for space applications. The ACS mechanical assembly is integrated into the Zirè payload using precision-machined aluminum fixtures, ensuring accurate alignment and mechanical stability during launch and in-orbit operation.

The final Zirè instrument, including the ACS, has a total length of approximately 50 cm and a square cross-section of 21.5 cm per side. The total mass of the complete instrument is approximately 22 kg, with the ACS contributing to the overall structural enclosure and charged-particle veto system.

3.2.1 Simulation and Performance

The response of the Zirè detector to charged particles has been evaluated through Geant4 (version 11.2.1) [109] Monte Carlo simulations, using a physics configuration based on

G4EmStandardPhysics for electromagnetic interactions, G4HadronPhysicsFTFP_BERT for hadronic inelastic processes, G4HadronElasticPhysics and G4IonElasticPhysics for elastic scattering, and G4Radioactivation for radioactive decay. From these simulations, shower containment and effective-area acceptance were estimated. Examples of simulated 300 MeV electron and proton events are shown in Fig. 3.11.

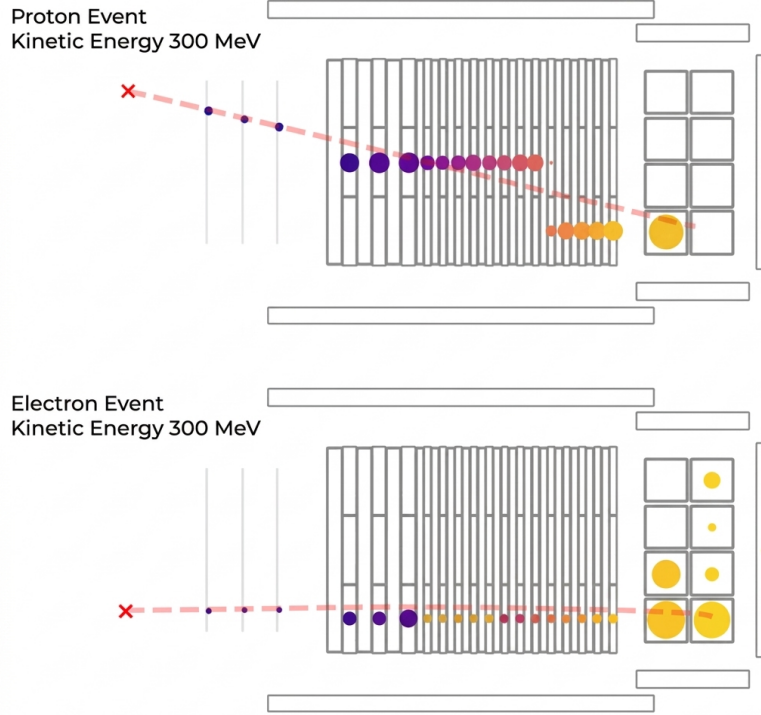


Figure 3.11: Simulated event display of a 300 MeV proton (top) and electron (bottom) interacting with the Zirè detector. Colors represent the interaction time, while marker size indicates the signal intensity [106].

Applying the event selection, effective-acceptance curves and particle-identification performance for electrons, protons, and light nuclei are obtained, as shown in Fig. 3.12. These results were obtained from simulations of 10^6 events per particle. The acceptance peaks at about $200 \text{ cm}^2 \text{ sr}$ and decreases at higher energies as shower containment degrades, while the energy-loss correlations separate the three species through their dependence on charge and velocity ($\Delta_0 \propto z^2/\beta^2$) [106, 110].

3.2.2 Silicon Photomultipliers and Readout in Zirè Payload

All four scintillator-based sub-detectors of the Zirè payload, FTK, PST, CALOg, and ACS, are read out by SiPMs instead of conventional PMTs, providing a compact, low-power, and radiation-tolerant front-end suited to a small-satellite platform [111].

Each GAGG:Ce crystal of the $4 \times 4 \times 2$ CALOg array is optically coupled to compact SiPM tiles providing a gain of order 10^6 , single-photon sensitivity down to about 30 keV, and sub-10 ns timing. The single-photon response and gain stability of the CALOg SiPMs are illustrated in Fig. 3.13: the regular spacing of the photoelectron peaks defines the gain, whose linear dependence on bias voltage confirms stable operation. The S14160-series Hamamatsu devices used in CALOg offer high photon-detection efficiency in the blue-green region, well matched to the GAGG:Ce emission spectrum [112].

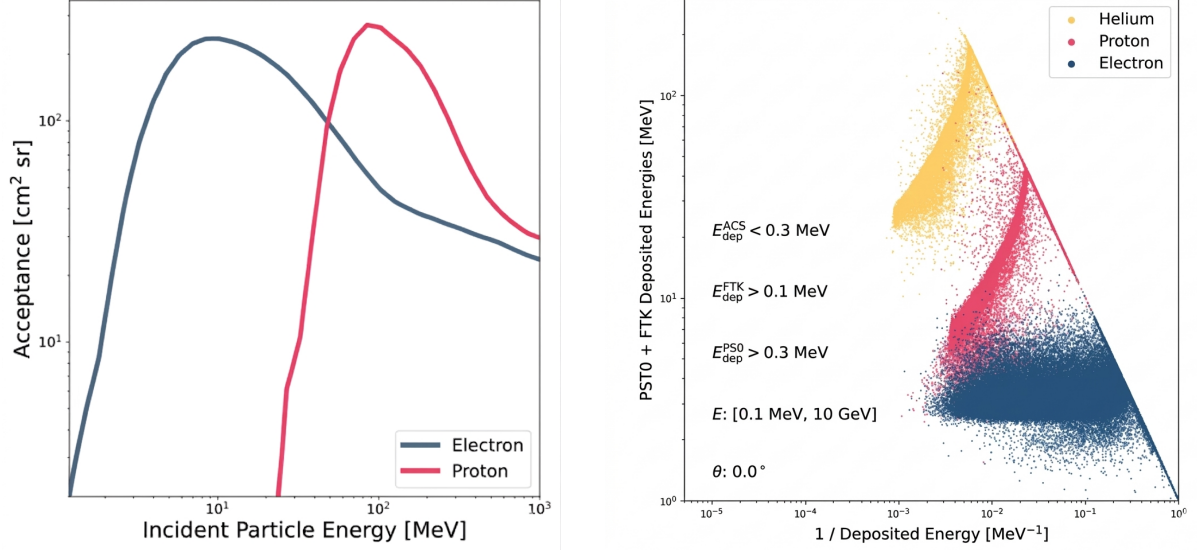


Figure 3.12: Left: preliminary effective acceptance curves for protons and electrons. Right: correlation between energy deposited in the FTK and PS0 with the inverse of total deposited energy, illustrating particle separation for electrons, protons, and helium nuclei [110].

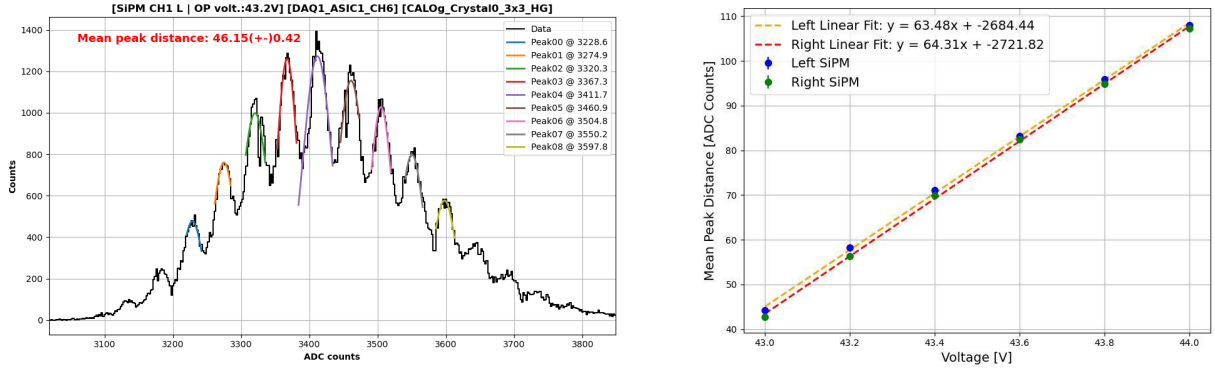


Figure 3.13: Experimental characterization of the SiPMs used in the CALog readout. Left: multi-photoelectron spectrum acquired with a Hamamatsu S14160/S14161 SiPMs coupled to a CALog crystal, showing clearly resolved photoelectron peaks with a mean peak-to-peak separation of (70.45 ± 0.32) ADC counts. Right: mean peak-to-peak separation as a function of applied bias voltage for the two SiPM channels of a representative CALog board (Image courtesy of the NUSES Collaboration.).

The CALog signal chain is based on CITIROC front-end ASICs, which provide low-noise amplification, dual high- and low-gain paths for an extended dynamic range, and trigger generation [111]. Each crystal is read out by a set of three active SiPMs of different sensitive area, serving complementary functions. These functions are energy measurement of cosmic-ray-induced events and detection of low-energy gamma rays entering through the dedicated CALog windows [113]. Figure 3.14 shows the CALog SiPM readout board. The board hosts 16 readout cells, one for each crystal of the 4×4 CALog layer. Each readout cell hosts a total of five SiPMs: one large-area SiPM mounted centrally, two smaller-area SiPMs of different sensitive area positioned together at the top of the cell, and two further SiPMs of the smaller models positioned at the bottom of the cell. The central and top SiPMs are the three active devices used in the majority-trigger logic, while the two bottom SiPMs are redundant.

The specific SiPM models and operating voltages adopted across the Zirè sub-detectors

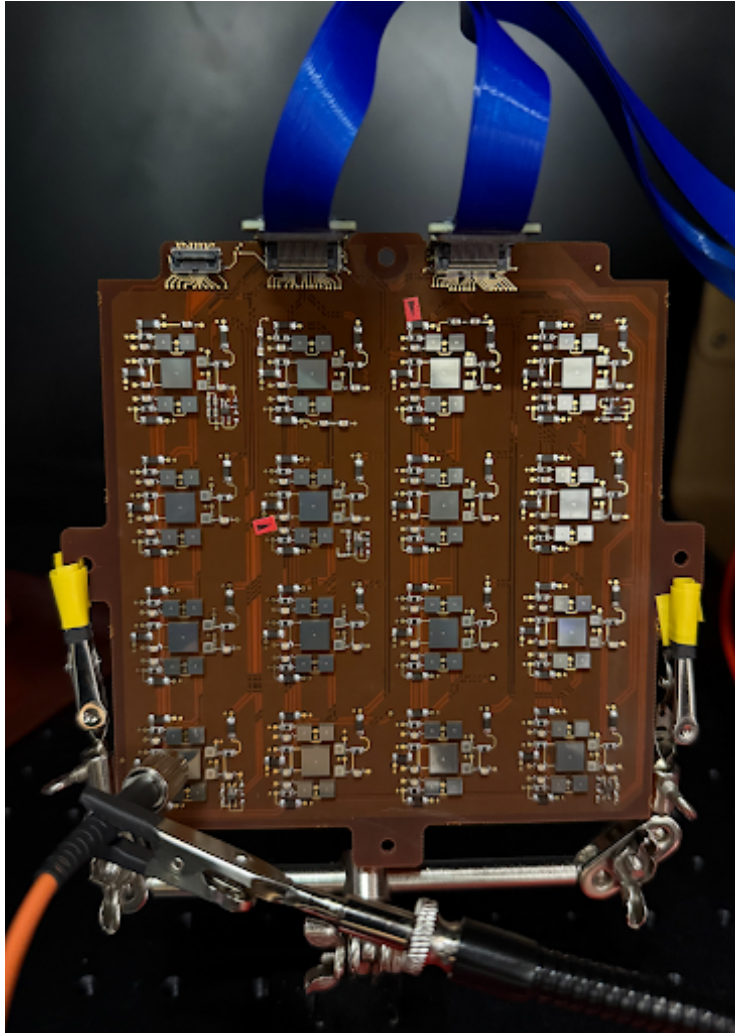


Figure 3.14: Photograph of the CALOg SiPM readout board (Image courtesy of the NUSES Collaboration).

are summarized in Table 3.1.

The radiation tolerance of the Zirè payload has also been assessed through dose and orbital-environment simulations [111]. These studies indicate that, with the passive shielding provided by the scintillator volumes and mechanical structures, the total ionizing dose accumulated over the three-year mission remains within acceptable limits for the SiPM sensors, and that an appropriate trigger and orbital-dependent prescaling strategy keeps trigger rates manageable in high-flux regions such as the South Atlantic Anomaly. Finally, in addition to the detector subsystems described above, the Zirè payload carries the Low-Energy Module (LEM), a compact particle spectrometer dedicated to electrons in the 0.1–7 MeV range and protons in the 3–50 MeV range [114]. It is based on a stack of ΔE – E silicon detectors followed by a plastic-scintillator calorimeter, and performs particle identification for studies of space weather and magnetosphere–ionosphere coupling [115].

3.3 Crystal Eye - All sky Gamma-ray Monitor

Monitoring the sky in the MeV energy range is important in the context of the study of transient events in the universe [58]. Bursts of gamma rays are produced by a wide range of sources, including supernova explosions and mergers of compact stars. Since the universe is almost transparent to MeV photons, this energy band allows the study of very distant

Table 3.1: SiPMs used in the Zirè sub-detectors [111]

Sub-detector	Hamamatsu Part No.	Operating HV
FTK	S13552	56 V
PST	S14160-3050HS S14160-1315PS	41 V
CALog	S14160-6050HS S14160-3050HS S14160-1315PS	41 V
ACS	S14160-3050HS	41 V

events such as **GRBs**.

The joint detection of the gravitational wave event GW170817 and GRB 170817A marked the beginning of the multi-messenger era [116], proving that neutron star mergers can produce both gravitational waves and short **GRBs**. In the coming years, next-generation detectors such as the Einstein Telescope [117] and the Cosmic Explorer [118] will greatly increase the sensitivity of gravitational wave observations, leading to a strong increase in the number of jointly detected events across both gravitational wave and electromagnetic channels.

The present generation of high-energy space telescopes has been highly successful: *Fermi*, **INTEGRAL**, *Swift*, and *AGILE* have each provided valuable insight into the gamma-ray sky [57]. *Swift* can localize bursts quickly in the hard X-ray range (15–350 keV) [119], while *Fermi-GBM* covers a wider range (8 keV–40 MeV) but with limited position accuracy [30, 31]. Nevertheless, the medium-energy gamma-ray range between approximately 0.1 and 50 MeV remains the least explored part of the spectrum [120, 121].

The Crystal Eye mission is designed to fill this observational gap. It will act as an all-sky gamma-ray monitor operating from 10 keV to 30 MeV with high sensitivity and improved localization. Its real-time detection and rapid localization capabilities make it particularly well suited for multi-messenger studies in the MeV range [58]. The main science goals include the detection of **GRBs**, gravitational wave counterparts, solar flares, terrestrial gamma-ray flashes, magnetar outbursts, and supernova explosions [57]. Crystal Eye will also observe persistent high-energy sources such as accreting binary systems and active galactic nuclei, helping to close the sensitivity gap between hard X-ray and GeV observatories while providing continuous monitoring of the high-energy sky in support of the growing field of multi-messenger astrophysics.

3.3.1 The Crystal Eye concept

The Crystal Eye detector is conceived as a compact, space-based instrument for wide-field monitoring of the gamma-ray sky in low Earth orbit [122, 123]. It adopts a hemispherical geometry to achieve an almost uniform angular response over a 2π field of view, a key requirement for detecting and localizing transient events at arbitrary sky positions.

In its first design, the module is a dome of approximately 32 cm diameter whose surface is tiled with 112 hexagonal pixels. Each pixel is a stacked, two-layer scintillator unit: in the mixed-material configuration, the outer (sky-facing) layer is **GAGG:Ce** and the inner layer is **LYSO:Ce**. The outer layer provides high sensitivity between about 10 keV and 3 MeV, while the combined thickness of both layers extends the gamma-ray response up to about 30 MeV [58]. The pixel structure, readout, and veto system are described in the following subsections, and the optimization of the geometry and material configuration is presented

in Chapter 5. A schematic of the module is shown in Fig. 3.15.

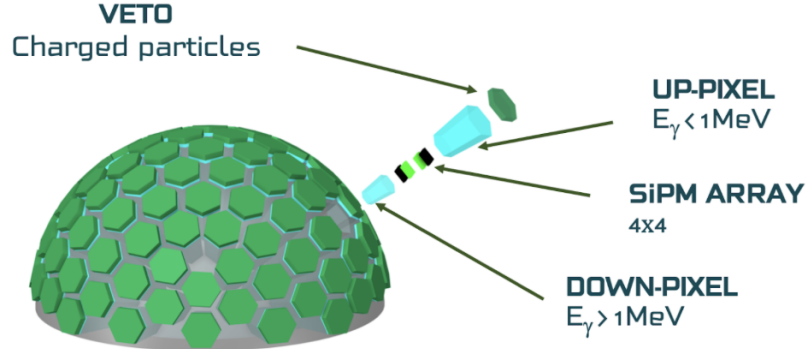


Figure 3.15: Schematic view of the Crystal Eye detector module, showing the hemispherical arrangement of hexagonal pixels with a two-layer crystal structure [58].

Crystal Eye is designed to operate in low Earth orbit at an altitude of about 550 km and an inclination of about 20° , where the dominant backgrounds arise from cosmic diffuse gamma radiation and atmospheric secondaries. Its compact geometry allows multiple modules to be deployed as a constellation for all-sky coverage with a nearly uniform zenith response, and autonomous onboard detection and localization enable rapid alerts to the General Coordinates Network (GCN) for multi-messenger follow-up.

3.3.2 The pixel

The Crystal Eye detector is based on two stacked layers of scintillating crystals arranged over a hemispherical surface (see Fig. 3.15). Each pixel consists of two optically coupled scintillating crystals separated by a compact SiPM [58], which enables independent readout of the energy deposited in the two layers (Fig. 3.16). The upper crystal has the shape of a hexagonal truncated pyramid with a height of approximately 4 cm, while the lower crystal follows a similar geometry with a height of about 3 cm. Energy depositions occurring in only one of the two layers, or in coincidence in both layers, provide indirect information on the interaction depth and on the event topology, which can be exploited for direction reconstruction and background discrimination.

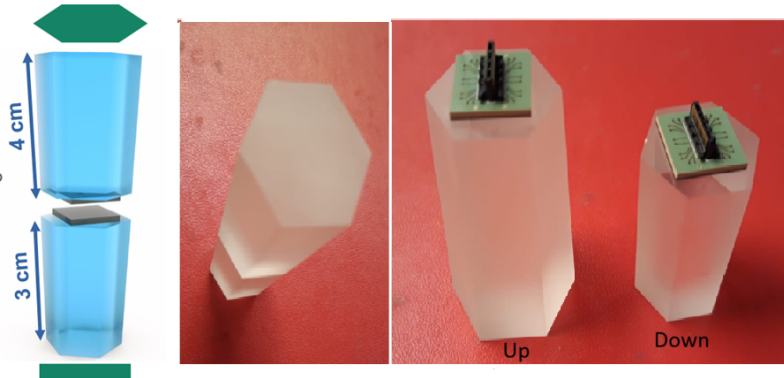


Figure 3.16: Crystal Eye pixel geometry. Left: schematic view of a pixel composed of two stacked scintillating crystals with heights of approximately 4 cm (upper) and 3 cm (lower), separated by a SiPM. Center: photograph of a hexagonal crystal. Right: assembled pixel prototypes showing the upper (Up) and lower (Down) crystals with the SiPM readout [124].

On the top of each pixel, a plastic scintillator veto layer is positioned acting as **ACD**, used to discriminate charged particles from photons, while an additional disk-shaped scintillator layer positioned beneath the detector allows the identification of upward-going particles and non-contained shower events [58]. The segmentation of the detector into pixels also enables a compact readout scheme, contributing to simplified electronics and improved thermal and radiation protection of the photosensors.

Different scintillator materials have been investigated for the pixel crystals. Among the candidates considered, **LYSO:Ce** [125] and **GAGG:Ce** [83] exhibit favorable optical and mechanical properties, high light output, and fast scintillation decay due to cerium doping. **LYSO:Ce** provides higher density and stopping power, but introduces an intrinsic internal background associated with the natural radioactivity of ^{176}Lu . In contrast, **GAGG:Ce** is essentially free from intrinsic radioactive background, which is advantageous in the low- and medium-energy gamma-ray range. For this reason, a mixed configuration with **GAGG:Ce** in the top layer and **LYSO:Ce** in the bottom layer has been studied to combine low-background performance at low energies with efficient absorption at higher energies [58]. The main physical and optical properties of **LYSO:Ce** and **GAGG:Ce** (HL) used in this work are summarized in Table 2.1. At 662 keV, the measured energy resolution is 10.9% for **LYSO:Ce** and 5.0% for **GAGG:Ce** (HL).

The fractional absorption efficiency of **GAGG:Ce** and **LYSO:Ce** crystals for different thicknesses is shown in Fig. 3.17. The curves, as reported in [58], are obtained from interaction probability calculations and illustrate the absorption behavior of the two materials across the energy range relevant to Crystal Eye operations. At low energies, both **GAGG:Ce** and **LYSO:Ce** exhibit equal absorption efficiency regardless of thickness. At higher energies, however, **LYSO:Ce** demonstrates better fractional absorption efficiency compared to **GAGG:Ce**.

By combining layer-resolved crystal information with anti-coincidence signals from the plastic scintillator veto system, the detector allows efficient background rejection while maintaining a compact and power-efficient readout architecture, particularly in the energy range where Compton scattering dominates.

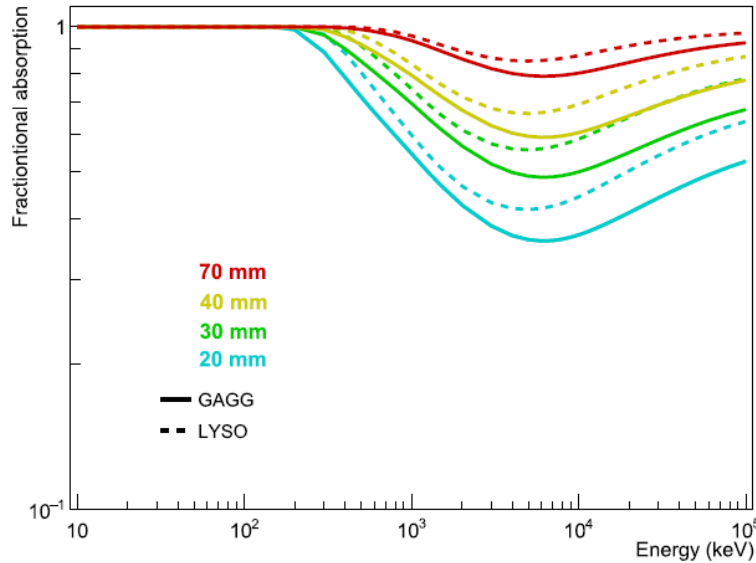


Figure 3.17: Simulated fractional absorption efficiency of **GAGG:Ce** (solid) and **LYSO:Ce** (dashed) crystals for different thicknesses [58].

3.3.3 Anti-Coincidence Detector

The Crystal Eye detector is equipped with an **ACD** based on plastic scintillator material, designed to suppress the background induced by charged cosmic rays. The **ACD** plays a crucial role in improving the signal-to-background ratio by identifying and rejecting events associated with charged particles. In low Earth orbit, the **ACD** is essential for mitigating background contributions from cosmic rays, trapped particles, and secondary radiation produced by interactions in the satellite structure.

A segmented layer of BC408 plastic scintillator tiles is placed on top of each pixel, covering the entire upper surface of the detector dome. This top **ACD** layer operates in anti-coincidence with the scintillating crystals, allowing charged particles to be efficiently vetoed. In addition to its veto function, the top plastic scintillator layer can also be used for the detection and localization of hard X-rays, providing complementary information to the main scintillator system. A second plastic scintillator layer, shaped as a continuous disk, is located at the bottom of the detector beneath the lower scintillator crystals. This bottom **ACD** layer is used to identify particles entering the detector from below and to tag non-contained shower events. The combination of the top segmented layer and the bottom continuous layer enables an effective discrimination between gamma-ray events and background contributions from charged particles [58]. The plastic scintillator tiles are read out by **SiPMs**, providing fast timing capabilities and a compact integration with the detector electronics.

Different trigger logics can be implemented by exploiting the spatial and temporal correlations between energy depositions in the scintillator crystals and the **ACD** layers. This flexibility allows the background rejection strategy to be optimized according to the observational requirements and orbital environment.

3.3.4 Simulation and Trigger Logics

The simulation and trigger logic of the Crystal Eye detector were developed following the methodology described in [57]. A detailed geometrical model of the instrument was implemented using the GEANT4 simulation toolkit (version 11.2.1), with the same physics configuration adopted for the Zirè simulation (Section 3.2.1). The model includes the scintillating calorimeter crystals and the **ACD** layers, as illustrated in Fig. 3.15.

A simplified aluminum structure was included to represent the mechanical support of the detector, while **SiPMs**, front-end electronics, and the satellite housing were not explicitly modeled at this stage.

The trigger strategy of the Crystal Eye detector is based on the spatial distribution of energy deposited in the scintillator crystals and on the response of the **ACD**, rather than on pulse shape discrimination. The characteristic event topologies, summarizing the energy deposition patterns expected for photon-induced events and background particles, are illustrated in Fig. 3.18:

- **(A)** Down-going photon with energy $E < 30$ keV: energy is fully absorbed in the upper **ACD** tile;
- **(B)** Down-going photon with energy $30 \text{ keV} < E < 1 \text{ MeV}$: energy is deposited in the upper crystal only;
- **(C)** Down-going photon with energy $E > 1 \text{ MeV}$: energy is deposited in both crystal layers with no signal in the **ACD**;

- (D) Down-going low-energy charged cosmic rays (CRs), with $E_{\text{ACD}} \sim 1$ MeV, and medium-energy gamma rays with $E_{\text{ACD}} < 20$ keV: signal is present in the upper **ACD** and upper crystal;
- (E) Intermediate-energy charged cosmic rays (CRs): energy is deposited in the upper and lower **ACD** tile and the upper and lower crystal layers as well.

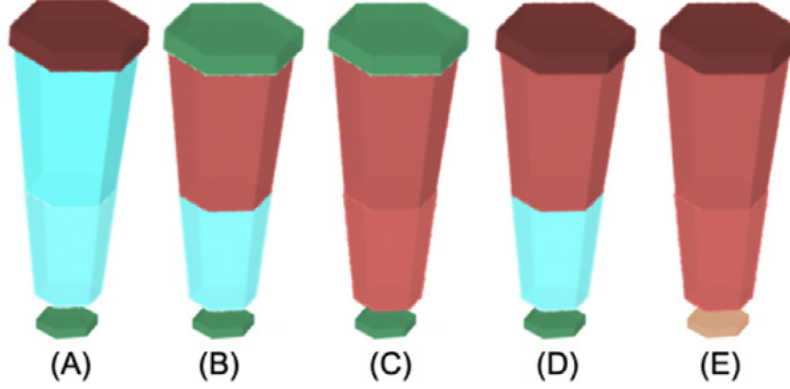


Figure 3.18: Event topologies in the Crystal Eye detector. Red regions indicate fired scintillator elements. Panels (A)-(C) correspond to photon-induced events in different energy ranges and are accepted as valid triggers. Panels (D) and (E) illustrate charged-particle and background events characterized by significant energy deposition in the anticoincidence detector and/or in the lower crystal layer, which are rejected at trigger level [57].

Configurations (A), (B), and (C) correspond to valid photon-induced events. Low- and intermediate-energy photons primarily deposit energy in the upper crystal layer, while higher-energy photons may produce multi-pixel energy depositions through Compton scattering and secondary interactions.

Figure 3.19 shows the simulated charge distribution in the Crystal Eye detector for a monochromatic diffuse gamma-ray source at 300 keV and for different incidence angles. The results are obtained from detailed GEANT4-based simulations that include the main background components affecting the detector in orbit, such as isotropic gamma radiation, cosmic-ray protons, albedo particles, electrons, and the intrinsic radioactivity of **LYSO:Ce**.

Each pixel is read out by a 4×4 Hamamatsu MPPC array (S13361-3050, with 3×3 mm² elements), whose summed output is processed by a CITIROC 1A front-end ASIC providing parallel high- and low-gain paths for an extended dynamic range [126]. Trigger decisions are handled by an FPGA that combines the multiplicity of fired pixels with the veto response; in the reference configuration, a **GRB** candidate is flagged when at least five neighbouring up-pixels exceed threshold [126].

3.4 Synergy between the NUSES and the Crystal Eye

The **NUSES** mission and the Crystal Eye detector are closely connected through a shared technological and scientific framework, developed in parallel to address the challenges of compact, high-sensitivity radiation detection in space. Although conceived as independent instruments with distinct primary objectives, the two projects adopt common design philosophies and overlapping detection technologies, enabling a strong synergy during their respective development and optimization phases.

Within the **NUSES** mission, the Zirè detector plays a key role as a technological pathfinder for the Crystal Eye concept. Zirè integrates scintillator-based detection systems read out

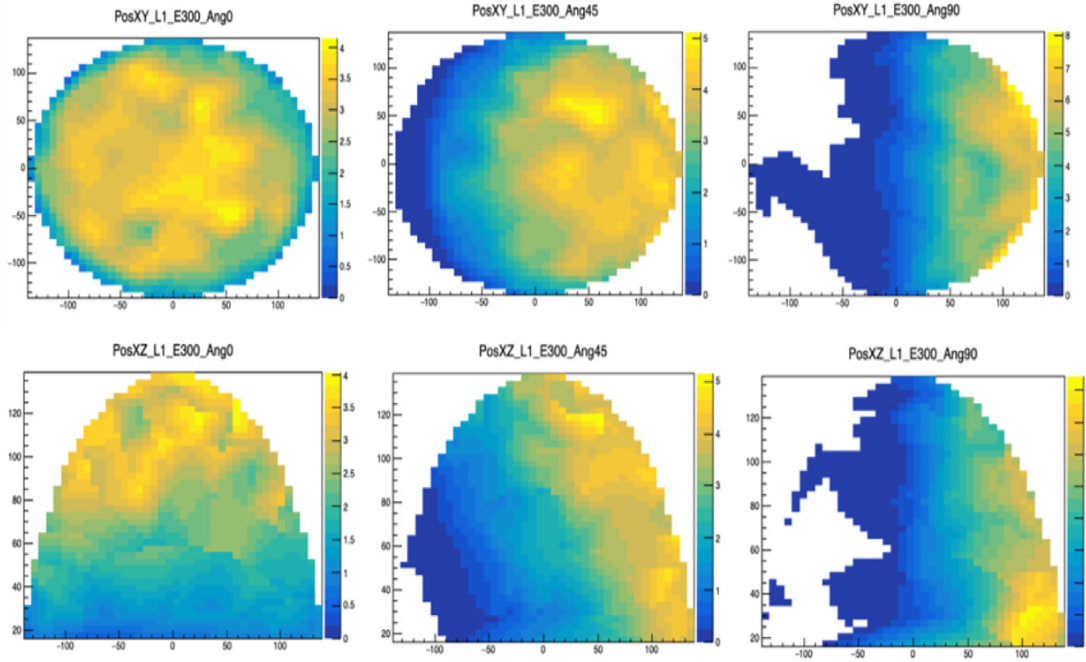


Figure 3.19: GEANT4-based simulation of the Crystal Eye charge distribution for a monochromatic diffuse gamma-ray source at 300 keV. The three columns correspond to source incidence angles of 0° , 45° , and 90° , respectively. The top row shows the detector response in the xy plane, while the bottom row shows the corresponding xz projections. The color scale represents the collected charge in the detector pixels [57].

by **SiPMs**, together with advanced trigger logic and data acquisition architectures, under realistic constraints imposed by a low-Earth-orbit environment. These same technological elements form the core of the Crystal Eye detector design, making Zirè an effective testbed for validating material choices, readout strategies, and background-rejection concepts relevant to Crystal Eye.

In particular, Zirè employs inorganic scintillators such as **GAGG:Ce** in its calorimetric subsystem, allowing a direct assessment of their performance in terms of light yield, timing characteristics, radiation tolerance under space-relevant conditions. The experience gained from integrating, simulating, and testing these materials within Zirè directly informs the optimization of the Crystal Eye detector, where similar scintillator combinations (**LYSO:Ce** and **GAGG:Ce**) are explored to balance detection efficiency and background suppression. This overlap is especially relevant in the context of intrinsic radioactive background associated with **LYSO:Ce** and the mitigation strategies enabled by hybrid material configurations.

From a scientific perspective, both instruments address gamma-ray detection in the MeV energy domain and are sensitive to transient astrophysical phenomena. Zirè targets photons in the ~ 0.1 –50 MeV range, supporting studies of space weather and transient events, while Crystal Eye is designed to extend sensitivity and localization capability for **GRBs** and other high-energy transients. This partial overlap in energy range and observational goals establishes a strong connection between the two projects. As a result, developments in triggering, event selection, and background modeling can be shared and mutually beneficial.

At the system level, the electronics and data acquisition architectures of **NUSES** and Crystal Eye follow comparable modular designs. Both instruments rely on **SiPMs** coupled to front-end ASICs and FPGA-based trigger handling, emphasizing scalability, low power consumption, and robustness. The experience gained within the **NUSES** framework, ranging from front-end optimization and trigger logic implementation to data handling and

synchronization, feeds directly into the refinement of the Crystal Eye detector concept.

Overall, the **NUSES** mission provides a valuable technological and methodological foundation for the Crystal Eye project. By acting as a pathfinder, Zirè reduces technical risk and accelerates the iterative optimization of Crystal Eye, supporting informed design choices while both instruments remain in an active simulation and development phase. This close connection between the two projects ensures a coherent development path and maximizes the scientific and technological return of the shared effort.

Chapter 4

Characterization of the CALOg

The Calorimeter (CALOg), of the Zirè instrument, is designed to measure gamma rays in the 0.1–50 MeV energy range with high efficiency and good energy containment, targeting transient high-energy phenomena such as **GRBs**, while retaining sensitivity to photons extending up to hundreds of MeV. This energy coverage enables the investigation of a broad class of astrophysical and atmospheric phenomena, including terrestrial events like earthquake, volcanic eruption and cosmic transients [110].

To maximize sky exposure, CALOg defines two geometrical acceptance windows for gamma-ray detection. The vertical window corresponds to photons incident along the detector zenith, while the horizontal window is associated with photons entering through the lateral surfaces of the detector. This dual-window configuration provides complementary observation geometries and is consistently adopted in the performance evaluations presented in this chapter [104]. This dual-view configuration is particularly advantageous for transient detection, where rapid localization and wide field-of-view coverage are essential.

The CALOg detector consists of a compact matrix of 32 scintillating crystals arranged in two layers of 16 elements each. The baseline configuration adopts **GAGG:Ce** crystals, selected for their high light yield, excellent radiation hardness, and absence of intrinsic radioactivity, making them well suited for long-term operation in low-Earth orbit and for applications where low instrumental background is critical. Each crystal is optically coupled to a **SiPM**, providing high photon detection efficiency and fast signal readout. In parallel, an alternative configuration based on **LYSO:Ce** scintillators has been investigated as part of this work. Although **LYSO:Ce** offers a high light yield and fast timing response, it exhibits intrinsic radioactivity due to the presence of ^{176}Lu , resulting in a persistent internal background that can affect low-energy performance. Both a full **LYSO:Ce**-based and a full **GAGG:Ce**-based CALOg configuration are considered, and this chapter presents the comparative evaluation of their performance.

This chapter presents a set of complementary simulation-based studies aimed at characterizing the CALOg response under different experimental conditions. Because each performance question requires a different physical configuration, several dedicated Monte Carlo samples are used throughout the chapter. Mono-directional photon simulations are adopted to evaluate the effective area for the two geometrical acceptance windows, while dedicated **LYSO:Ce** radioactive-decay simulations are used to study the intrinsic scintillator background and its possible rejection through multivariate techniques. A separate orbital-background simulation is then introduced to assess the expected in-flight count rate and to evaluate the transient trigger sensitivity under realistic low-Earth-orbit conditions.

The chapter is organized as follows. Section 4.1 describes the general Monte Carlo framework and detector geometry. Section 4.2 presents the preliminary event selection and the effective-area calculation for both acceptance windows. Section 4.3 introduces the

Boosted Decision Tree method and applies it to the discrimination of externally generated gamma-ray events from the intrinsic radioactive background of **LYSO:Ce** scintillators. Section 4.4 then describes the orbital radiation environment and the simulation setup used to reproduce the expected in-orbit background conditions. Section 4.5 presents the real-time sliding-window transient trigger algorithm and its parameter optimization. Section 4.6 discusses the transient sensitivity assessment based on the **MDF** and on a signal-to-noise analysis for a realistic **GRB** population under different representative background regimes sampled along the high-inclination orbit. Finally, Section 4.7 outlines future developments aimed at improving trigger realism, angular-response modeling, and scintillator material optimization.

4.1 Simulation Framework

To assess the CALOg response to gamma-ray bursts and to quantify its detection performance, detailed Monte Carlo simulations were carried out using the GEANT4 toolkit [109]. The simulations include the full CALOg geometry in order to realistically model photon interactions and energy deposition.

The simulated geometry reproduces the complete Zirè payload, including the CALOg crystal matrix, the **ACS** paddles, and the surrounding mechanical structures. The CALOg sensitive volume consists of 32 scintillating crystals arranged in two layers of 16 elements each. Figure 4.1 provides a visual reference for the CALOg geometry and its integration within the Zirè payload.

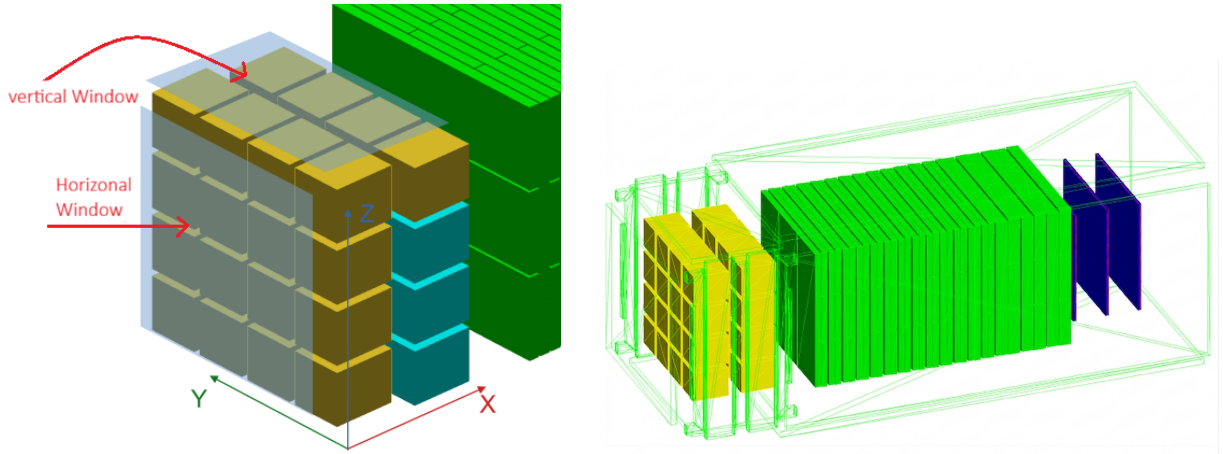


Figure 4.1: Left: CAD rendering of the CALOg crystal module showing the two stacked layers of 16 scintillating crystals. The transparent planes indicate the vertical and horizontal acceptance windows. Right: simulated view of the CALOg unit integrated within the Zirè instrument.

The simulation models all electromagnetic interactions relevant to the CALOg energy range, including photoelectric absorption, Compton scattering, and electron-positron pair production. Hadronic processes and radioactive decay are also included, and the ionizing energy deposited in the sensitive crystal volumes is recorded.

For every simulated event, the energy deposited in each individual crystal, the total energy deposited in CALOg, the number of crystals registering a signal, and the total energy deposited in the **ACS** were recorded. These quantities characterize both the spatial pattern and the overall magnitude of each energy deposition, and form the basis for the trigger selection and effective area calculation.

Representative simulated events were examined using the Zirè event display to verify that photon trajectories and energy-deposition patterns in the crystal matrix were consistent with the intended source geometry for both acceptance windows, as shown in Figure 4.2.



Figure 4.2: Representative event-display views of simulated gamma-ray interactions in CALOG for the horizontal (left) and vertical (right) acceptance windows. The dashed red line indicates the reconstructed photon trajectory; colored crystals mark energy deposition in the CALOG matrix.

4.2 Detection Performance

CALOG's ability to detect low-energy gamma rays depends on both its sensitivity and its capacity to discriminate genuine events from background. To evaluate this, simulation-based effective area calculations, and burst detection algorithms are employed. This section outlines the key criteria used to isolate valid gamma-ray events and describes the effective-area calculation used to quantify the detector response for the two geometrical acceptance windows.

4.2.1 Simulation of the electronic thresholds

A preliminary event selection is implemented using simplified conditions to approximate the detector electronics response studies. These conditions are derived from the expected behavior of the front-end electronics.

An energy threshold of 30 keV is required in at least one CALOG scintillator crystal in order to register a valid signal. In parallel, signals recorded in the ACS are required to exceed 7 keV to be considered active. These thresholds emulate the minimum detectable energy deposits expected from the front-end electronics and define the basic event-building conditions.

Following digitization, a pre-selection is applied based on the total reconstructed energy. Events are required to satisfy a minimum total energy deposit in CALOG of

$$E_{\text{CALOG}} > 30 \text{ keV},$$

while the total energy deposited in the ACS is required to remain below

$$E_{\text{ACS}} < 300 \text{ keV}.$$

This condition provides an effective veto against charged-particle-dominated events crossing the detector from outside the nominal field of view. Only events fulfilling these criteria are retained for subsequent analysis.

4.2.2 Effective Area: GAGG vs. LYSO Scintillators

The effective area quantifies the capability of a detector to measure the incident gamma rays as a function of energy, combining both geometric acceptance, trigger and selection efficiency.

CALOG defines two distinct acceptance windows for gamma-ray detection. The horizontal window corresponds to photons entering through the lateral surfaces of the detector, while the vertical window is associated with photons incident along the detector zenith. These two geometries provide complementary sky coverage and are treated separately in the effective-area evaluation. The corresponding geometric areas are $A_{\text{geom}}^{\text{Win-X}} = 10 \times 6 \text{ cm}^2$ and $A_{\text{geom}}^{\text{Win-Z}} = 10 \times 10 \text{ cm}^2$.

The effective area has been evaluated using detailed Monte Carlo simulations performed for both candidate scintillator materials under consideration for CALOG: **GAGG:Ce** and **LYSO:Ce**.

For each acceptance window, gamma-ray photons were generated from a square planar surface placed upstream of the detector and oriented perpendicular to the corresponding photon incidence direction. This configuration ensures that photons uniformly illuminate the relevant detector aperture with a well-defined beam geometry. The two windows were simulated in separate, independent runs. For the horizontal window, photons enter the detector laterally through its side face, while for the vertical window, photons are directed downward through the top face of the CALOG volume.

In both cases, the photon energy was sampled from a power-law spectrum $dN/dE \propto E^{-1}$ over the range 10 keV to 100 MeV. This relatively flat weighting in logarithmic energy space ensures adequate photon statistics across the full energy range of interest without over-representing any particular energy decade. A total of 10^7 primary photon events were simulated per acceptance window. The selection reported in Section 4.2.1 has been applied.

For a given incident photon energy E and direction $\hat{n}$ aligned with the acceptance window normal, the effective area was computed as

$$A_{\text{eff}}(E, \hat{n}) = A_{\text{geom}} \frac{N_{\text{sel}}(E)}{N_{\text{gen}}}, \quad (4.1)$$

where $N_{\text{sel}}(E)$ denotes the number of events that pass the selection at a specific energy. This definition corresponds to normal-incidence (orthogonal) photons, a convention also adopted for the reference instrument curves discussed below. Figure 4.3 shows the resulting effective area as a function of energy for both scintillator materials and both acceptance windows. The Fermi-**GBM** curves shown for comparison correspond to a single, representative **NaI** detector and a single representative **BGO** detector, including the effects of spacecraft scattering [30]. Since the 12 **NaI** and 2 **BGO** detectors of Fermi-**GBM** are mounted with different orientations around the spacecraft, their single-detector effective areas cannot be summed into an instrument-level curve; the comparison should therefore be understood at the single-detector level. The effective area is not sensitive to the intrinsic radioactivity of the scintillator material, and is therefore expected to be similar for both **GAGG:Ce** and **LYSO:Ce**. Indeed, as shown in the figure, the two materials yield nearly identical effective areas across the full energy range. The only marginal difference arises at higher energies, where the slightly higher density of **LYSO:Ce** ($\rho_{\text{LYSO}} \approx 7.25 \text{ g/cm}^3$) compared to **GAGG:Ce** ($\rho_{\text{GAGG}} \approx 6.63 \text{ g/cm}^3$) leads to a marginally higher effective area for **LYSO:Ce**, as expected from the stronger photoelectric absorption cross-section. The combined effective area exceeds 100 cm^2 over a broad energy interval for the horizontal window, from approximately 100 keV up to several MeV, demonstrating the strong detection capability of CALOG across its targeted energy range.

From an effective area standpoint, **GAGG:Ce** and **LYSO:Ce** are therefore essentially equivalent. However, **LYSO:Ce** contains naturally occurring ^{176}Lu , which gives rise to a significant intrinsic radioactive background. Since the two materials perform comparably in terms of detection efficiency, the key differentiator becomes the ability to discriminate between genuine gamma-ray signal events and **LYSO:Ce**'s intrinsic background.

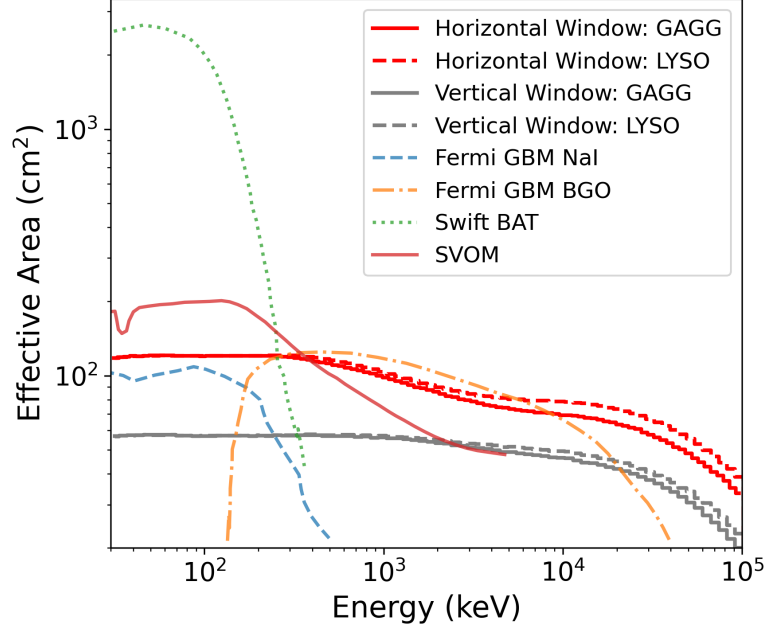


Figure 4.3: Effective area of CALOG as a function of energy for the horizontal and vertical acceptance windows, shown for both GAGG and LYSO scintillator materials. The curves are compared with the effective area of a single Fermi-GBM NaI detector and a single BGO detector [30], a single SVOM/GRM detector [65], and with Swift-BAT [127].

The energy-dependent behavior of the effective area can be understood from the event-by-event energy-deposition distributions shown in Figure 4.4. These two-dimensional histograms correlate the total energy deposited in CALOG with the incident photon energy for both acceptance windows. Events clustering along the diagonal correspond to near-complete energy absorption, while deviations below the diagonal arise from partial energy containment and shower leakage effects, which become more pronounced at higher energies. These effects directly impact the fraction of events satisfying the trigger conditions and therefore shape the effective-area curves.

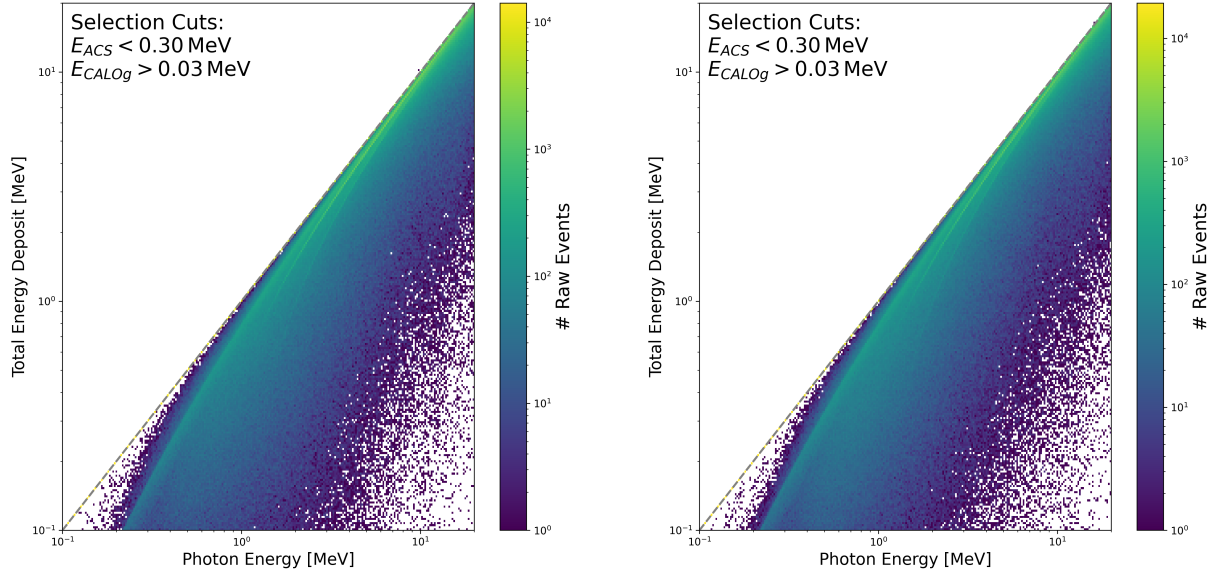


Figure 4.4: Two-dimensional distributions of the total energy deposited in CALOG as a function of the incident photon energy for the horizontal (left) and vertical (right) acceptance windows. The dashed diagonal indicates the ideal full-energy absorption condition, while deviations below the diagonal arise from partial energy containment and shower leakage at higher energies.

4.3 BDT Algorithm for the reduction of the LYSO background

In high energy astrophysics, identifying rare astrophysical signals in the presence of large and complex backgrounds is a fundamental analysis challenge. Machine learning offers tools to help separate signals from background or noise. **Boosted Decision Trees (BDTs)** are supervised multivariate classifiers widely used in physics, offering strong discriminating power.

A decision tree classifies events by recursively partitioning the feature space through a sequence of binary splits applied to the input variables. A schematic example of a simple decision tree is shown in Figure 4.5, where internal nodes represent decision points based on variable thresholds, branches correspond to the outcomes of these decisions, and terminal nodes (leaves) contain the final classification result.

At each node, all candidate splits are evaluated using an impurity measure $i(t)$, which quantifies the degree of mixture between signal and background events. A proposed split S , dividing a parent node t into two child nodes t_P (pass) and t_F (fail), is scored according to the impurity decrease

$$\Delta i(S, t) = i(t) - p_P i(t_P) - p_F i(t_F),$$

where p_P and p_F denote the fractions of events assigned to each child node. The split that maximizes Δi is selected at each node independently, without consideration of future splits. Common impurity measures include the Gini index [129], cross-entropy [130], and misclassification error. In high-energy physics applications, alternative impurity functions may also be used, for example to approximate the optimization of figures of merit such as $s/\sqrt{s+b}$, thereby guiding the tree toward regions of particular analytical interest.

Terminal nodes are assigned a signal or background label based on the relative proportions of weighted signal and background events they contain. This information can also be interpreted probabilistically and used as a continuous classifier response. For instance, a

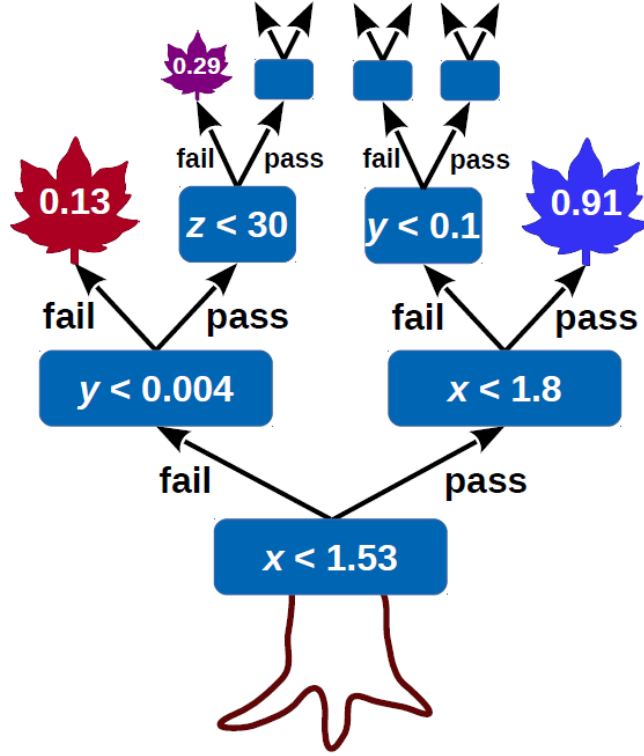


Figure 4.5: Example of a decision tree with internal nodes (blue), branches, and leaves (colored). The numbers at the leaves indicate the fraction of signal events in that node [128].

leaf containing 90% signal and 10% background events may produce an output score close to 0.9. To ensure that the model does not overfit statistical fluctuations in the training data, its performance must be evaluated on an independent dataset consisting of events not used during training. While single decision trees are intuitive and easy to interpret, they are known to be unstable. Small changes in the training dataset can lead to significantly different tree structures, and the resulting classifier output is inherently piecewise and step-like, which can limit discrimination power.

Boosting addresses these limitations by combining many weak decision trees into a single, more powerful classifier. In the AdaBoost algorithm [131], training events are reweighted after each iteration so that misclassified events receive increased emphasis in subsequent trees, while better-performing trees are assigned larger weights in the final ensemble. Gradient boosting [132] adopts a different perspective, constructing trees sequentially to model the residual errors of the current classifier, thereby improving performance in a stage-wise manner.

More generally, boosting belongs to the broader class of ensemble learning techniques, in which multiple models are combined to produce a more robust and reliable classifier [133]. By aggregating the decisions of many trees that each capture different aspects of the data, boosted ensembles typically achieve superior separation between signal and background compared to a single decision tree. These properties make BDTs particularly well-suited for the CALOG classification problem, where a clear but complex boundary between **LYSO:Ce** radioactive background and astrophysical gamma-ray signal must be learned from high-dimensional energy deposition patterns, as described in the following section.

4.3.1 Simulated dataset for BDT analysis

The dataset used for the **BDT** analysis was constructed from dedicated Monte Carlo simulations of CALOg signal and background events. The signal sample consists of externally generated gamma rays emitted from a spherical surface surrounding the detector, with energies sampled uniformly in logarithmic scale between 10 keV and 5 MeV. This simplified energy sampling was chosen to provide adequate statistics over the energy interval where the **LYSO:Ce** intrinsic activity is most relevant, and not to reproduce a specific astrophysical source population. The background sample corresponds to the intrinsic radioactive decay of the **LYSO:Ce** scintillator material. For each class, approximately 10^6 events were simulated. The samples were randomly split into training and test sets of 500,000 events each per class (a 50:50 split), using TMVA's random sampling option, with equal weighting applied to the signal and background classes.

A more realistic classification study would require the inclusion of realistic **GRB** spectra, the full orbital background composition, detector digitization effects, and the expected in-flight event selection. However, as shown below, the present exercise already reveals an important limitation of the **LYSO:Ce**-based configuration, namely the strong correlation between the classifier response and the deposited-energy range dominated by intrinsic ^{176}Lu activity. For this reason, the study was not extended to a more complex background scenario at this stage.

4.3.2 BDT Algorithm for CALOg

In the **LYSO:Ce**-based configuration considered in this study, the CALOg subdetector of Zirè utilizes **LYSO:Ce** scintillator crystals, which inherently emit internal background radiation due to their natural radioactivity. In addition to this internal component, CALOg will be continuously exposed to external space-based backgrounds, including albedo photons, neutrons, and other high-energy cosmic particles. To assess the feasibility of separating astrophysical gamma-ray signals from such background noise, a **BDT** classifier was implemented as a preliminary classification exercise.

In this setup, the signal class was defined as simulated gamma-ray events combined with an external gamma background, both consisting solely of gamma photons. The background class, on the other hand, consisted exclusively of events originating from the intrinsic radioactivity of the **LYSO:Ce** material. To keep the problem focused on photon only discrimination, non-gamma background sources such as neutrons and protons were excluded at this stage. The goal was to isolate the classifier's ability to distinguish internal **LYSO:Ce** induced events from astrophysical gamma-ray signals embedded in a similar gamma rich environment.

The simulation setup involved generating signal events by emitting gamma photons from a 30 cm spherical surface surrounding the detector. These photons followed a power-law energy distribution between 10 keV and 5 MeV. Background events were modeled using the built-in decay properties of the **LYSO:Ce** crystals. A total of one million events were simulated for each class. The resulting energy spectra for both signal and background are shown in Figure 4.6. Panel left displays the characteristic peaks associated with internal **LYSO:Ce** activity, while panel right illustrates the broad, exponentially falling distribution of the externally simulated gamma events.

A total of 34 input features were used to train the **BDT**. These included the number of hits, the total energy deposited, and the energy deposited in 32 individual **LYSO:Ce** crystals. Out of all features, the total energy deposit and the number of hits emerged as the most discriminating variables.

The output of the **BDT** classifier is represented by a continuous variable β , ranging

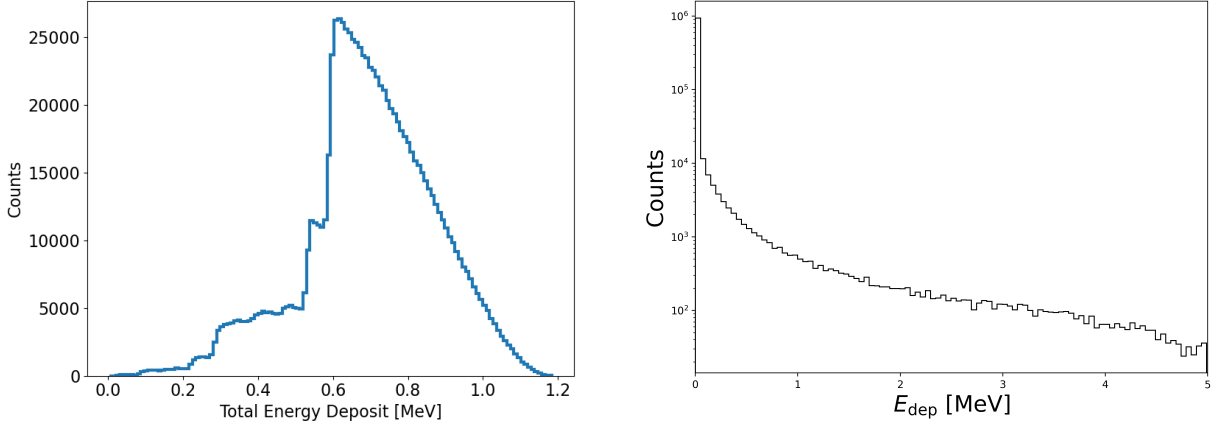


Figure 4.6: Comparison of energy deposition spectra for background and signal events. The left panel shows the characteristic spectrum arising from internal LYSO radioactivity, while the right panel illustrates the total energy deposited in CALOg by externally simulated gamma photons following a power-law distribution.

from -1 to $+1$. This score reflects the classifier’s confidence, with $\beta = +1$ corresponding to a pure signal and $\beta = -1$ to pure background. Figure 4.7 shows the β score distributions for both classes, where external events peak on the right and events originating from the radioactivity of the LYSO:Ce on the left. A vertical cut on β can be applied to adjust the balance between signal efficiency and background rejection. The dominant peaks differ by more than three orders of magnitude from the overlapping region, indicating that the contamination is below 0.1%. This result demonstrates that, within this simplified two-class scenario, the classifier is able to exploit the strong differences between internal LYSO:Ce radioactivity and externally simulated gamma-ray events. However, this performance reflects an idealized setup and does not account for additional background components or detector effects expected under realistic mission conditions.

To investigate the origin of the strong separation observed in Figure 4.7, the BDT response was studied as a function of the total energy deposited in CALOg. Figure 4.8 shows the two-dimensional distributions of the BDT output score β for signal and background events in the deposited-energy range between 30 keV and 1.5 MeV.

A clear correlation between the classifier response and the deposited energy is observed. The LYSO:Ce radioactive background is strongly concentrated around the characteristic energy region associated with the intrinsic ^{176}Lu activity, and events in this range are systematically assigned background-like scores ($\beta \approx -1$). Conversely, externally generated gamma-ray events falling outside this region are preferentially classified as signal-like.

This behavior indicates that the classifier separation is driven to a significant extent by the deposited-energy distribution itself, rather than exclusively by more subtle event-topology differences. As a consequence, genuine external gamma-ray events depositing energy in the same interval dominated by the LYSO:Ce intrinsic activity may also be rejected by the classifier.

The excellent separation observed in the one-dimensional BDT output distribution is therefore only partly representative of the real discrimination capability achievable under realistic conditions. In practice, the intrinsic radioactivity of LYSO:Ce occupies an energy range that overlaps the region of interest for transient gamma-ray detection, limiting the robustness and general applicability of the BDT-based rejection approach.

Overall, this study was conceived as a preliminary feasibility exercise to assess whether a machine-learning-based approach could effectively separate intrinsic LYSO:Ce background events from gamma-ray signals in the CALOg. While the BDT classifier demonstrates

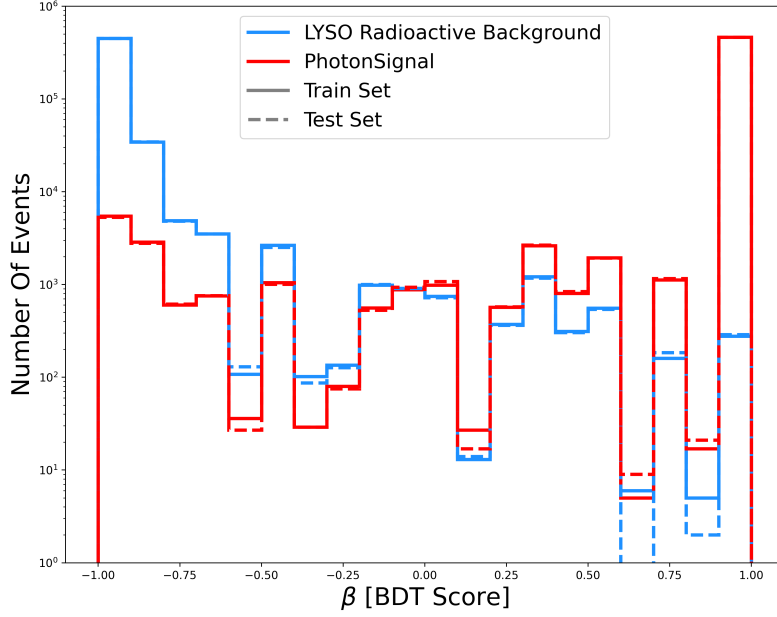


Figure 4.7: BDT output score (β) distribution for LYSO radioactive background (blue) and photon signal (red). The plot shows both training and test datasets, with solid and dashed lines respectively. A clear separation is observed: background events cluster around $\beta = -1$, while signal events peak near $\beta = +1$, enabling selection via a cut on β for efficient classification.

a strong separation capability, this behavior is largely driven by the deposited-energy distribution of the events, with the classifier strongly exploiting the energy region dominated by the intrinsic **LYSO:Ce** radioactivity rather than learning a fully general event-topology discrimination. When interpreted in the context of a realistic space environment, the strong internal radioactivity of **LYSO:Ce** introduces background features that remain challenging to disentangle from signal-like events, limiting the robustness and general applicability of the classification.

Consequently, this preliminary investigation suggests that **LYSO:Ce** may not represent the most suitable scintillator choice for CALOG when background rejection is a primary requirement. This conclusion motivates the exploration of alternative scintillator materials and detector configurations, which are discussed in the subsequent sections of this thesis.

4.4 Orbital Background

The radiation environment encountered by gamma-ray detectors operating in low-Earth orbit (LEO) has been modeled by Cumani et al. [134]. According to this framework, a space-based detector in LEO is continuously exposed to a complex mixture of primary cosmic radiation and secondary particles produced through interactions in the Earth’s atmosphere. These background components contribute to the detector count rate and therefore directly affect the trigger threshold and detection sensitivity of gamma-ray instruments.

A significant feature of the near-Earth radiation environment is the **South Atlantic Anomaly (SAA)**, a region where the inner radiation belt approaches unusually close to the Earth’s surface due to the offset between the magnetic and rotational axes of the planet. When the satellite traverses the **SAA**, the flux of trapped protons and electrons increases substantially, leading to elevated background levels and potential activation of detector materials [135]. For this reason, data collected during **SAA** passages are typically excluded

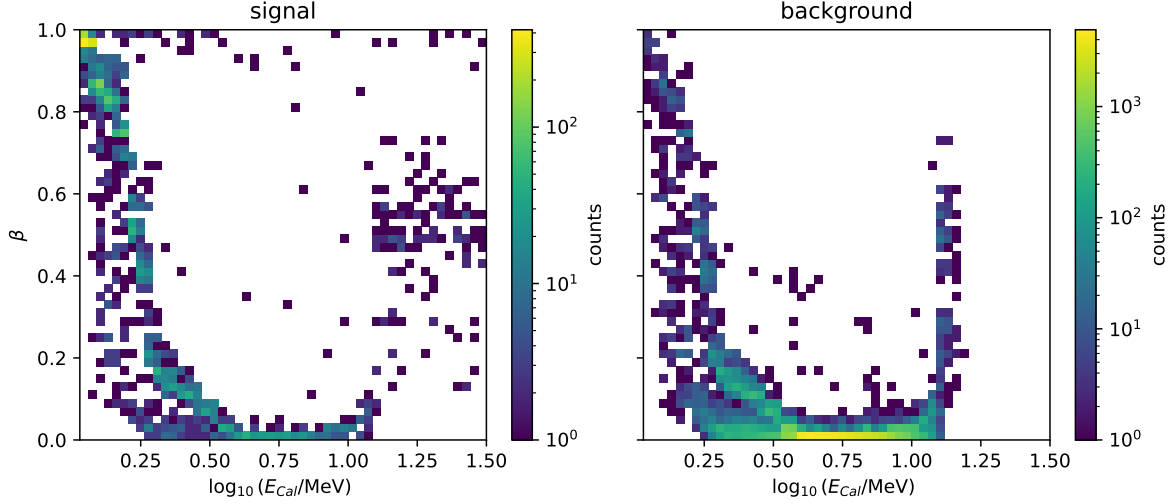


Figure 4.8: Two-dimensional distributions of the BDT output score β as a function of the total energy deposited in CALOG for signal (left) and events originating from LYSO (right) events, in the energy range 30–1500 keV. The color scale represents the event density per bin.

from scientific analysis. Nevertheless, the **SAA** remains relevant for understanding long-term background behavior and material activation effects in space-borne detectors.

Outside the **SAA**, the dominant background contributions arise from diffuse cosmic γ -rays, atmospheric albedo photons, albedo neutrons, and secondary charged particles such as protons, electrons, and positrons. Since these components originate from different physical processes, they are modeled separately in order to provide a realistic description of the orbital radiation environment. The background model combines experimental measurements from several space missions and particle detectors, including SAS-2 [136], INTEGRAL/IBIS-ISGRI [137], Fermi-LAT [31], and AMS-01 [138], to construct differential flux spectra for the main background components over a broad energy range from approximately 10 keV up to 100 GeV.

Cosmic photons

Cosmic photons constitute a diffuse high-energy background that is commonly modeled as time-stationary over the relevant observation timescales. They arise from the cumulative emission of numerous unresolved sources including active galactic nuclei and diffuse processes such as pulsars and supernova remnants [139, 140]. This component is therefore treated as a persistent background contributing to the detector count rate throughout the orbit.

Cosmic protons

Cosmic protons are high-energy particles arriving directly from outside the solar system. They dominate the galactic cosmic ray flux and constantly reach the Earth’s magnetic field and atmosphere. In low-Earth orbit, most low-energy protons are blocked by geomagnetic shielding, but high-energy ones still penetrate and interact with detector materials [134].

Albedo photons

Albedo photons are secondary γ -rays created when primary cosmic rays interact with nuclei in the Earth’s upper atmosphere. These interactions generate cascades of particles,

including mesons, muons, and electrons, with the secondary gamma rays backscattered from the atmosphere appearing as an upward-going background component for orbiting detectors. At photon energies above 50 MeV, most emission originates from meson decay, while below this energy it is mainly produced through bremsstrahlung radiation from secondary electrons [134]. Since these photons are emitted upward from the atmosphere, they dominate the background at lower energies in low-Earth orbit.

Albedo neutrons

Albedo neutrons are generated in the Earth’s atmosphere when cosmic rays collide with atomic nuclei, producing spallation reactions that release neutrons. Because neutrons carry no charge, they are unaffected by the Earth’s magnetic field and can reach satellite altitude [141]. Although their flux is lower than that of photons, neutron interactions with detector materials can create secondary γ -rays, adding to the total background.

Secondary charged particles

Secondary protons, electrons, and positrons are produced when primary cosmic rays collide with atmospheric nuclei. Secondary protons are scattered upward into space with lower energies than the primary component and remain an important contributor to the background through further nuclear interactions [134]. Secondary electrons and positrons are produced through pair production and decay of charged mesons, and a portion of these particles becomes trapped in the Earth’s magnetic field, forming part of the Van Allen radiation belts [134].

Simulation setup

The implementation of the orbital background simulation used in this work is illustrated in Fig. 4.9. Particles were generated from the upper and lower hemispheres of a spherical surface with a radius of 39 cm, centered on the CALOG detector in the simulation geometry. The particle directions were sampled within a cone spanning 0° to 20° from the surface normal, following a cosine angular distribution, which accounts for the projected area dependence of the incident flux on the spherical source surface. The cone angle was chosen to ensure adequate illumination of the CALOG sensitive volume from the spherical source surface.

Cosmic photons and cosmic protons were simulated as downward components entering the detector from the space-facing side, whereas atmospheric albedo photons and atmospheric neutrons were simulated as upward components propagating from the Earth-facing side toward the detector. Trapped electrons and trapped positrons, whose motion in the Van Allen belts is approximately isotropic due to their gyration around the geomagnetic field lines, were simulated arriving from all directions. Trapped protons, on the other hand, exhibit a predominantly directional flux and were therefore simulated only as upward and downward components, as their lateral contributions are negligible.

The incident energy ranges adopted for the different background components were selected based on their expected interaction channels in the detector and their effective contribution to energy deposits within the operational energy range of CALOG. Following the approach of [134], the limits were chosen to retain the energy intervals that produce non-negligible background contributions in the sensitive detector volume, while avoiding unnecessary simulation of energies with negligible impact. All background particle types were simulated over a common energy range from 30 keV to 1 GeV, using a power-law sampling spectrum with spectral index $\alpha = -1$.

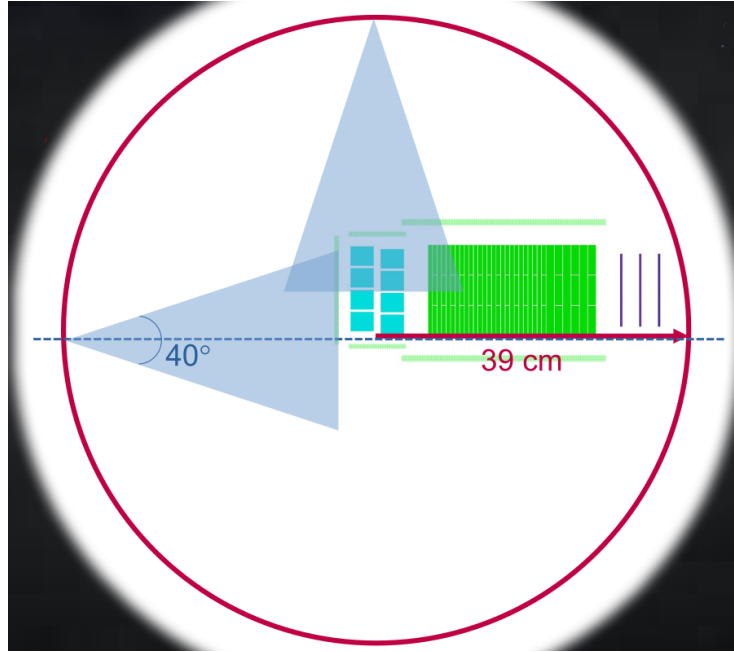


Figure 4.9: Schematic of the particle source geometry used for the orbital background simulations. Particles are generated from a spherical surface of radius 39 cm surrounding the detector, with directions sampled within a cone of 0–20° (Image courtesy of the Crystal Eye Collaboration).

The simulated events were subsequently reweighted according to the physical differential flux spectra of each particle component, following the orbital background model of [134].

Although the **NUSES** satellite follows a high-inclination orbit, the radiation environment encountered by CALOg is not constant along the trajectory. As the spacecraft moves through different geomagnetic latitudes, the local geomagnetic cutoff rigidity changes, modifying the flux of charged particles and of secondary atmospheric components reaching the detector. For this reason, the orbital background was evaluated for three representative background regimes, hereafter referred to as the *equatorial*, *intermediate*, and *polar* regimes, sampled along the high-inclination (98°) **NUSES** orbit. These cases should not be interpreted as three different satellite orbits, but rather as representative background conditions sampled along the orbit, from regions with stronger geomagnetic shielding to regions approaching the polar regime.

The *equatorial* regime corresponds to a low-latitude environment, where geomagnetic shielding is stronger and the charged-particle background is comparatively suppressed. The *intermediate* regime represents an intermediate condition, while the *polar* regime corresponds to the most severe high-latitude environment considered in this work, where the geomagnetic cutoff is strongly reduced. This last case therefore provides a conservative upper bound on the expected orbital background level for CALOg.

Figure 4.10 shows the differential flux spectra of the main orbital background components for the three representative background regimes. The comparison illustrates how the relative importance of the different components changes along the orbit. In the equatorial regime, photon components dominate over most of the relevant energy range, while charged-particle and neutron contributions become increasingly important as the geomagnetic shielding weakens.

The corresponding background spectra estimated in CALOg are shown in Fig. 4.11. These spectra include the detector response to the different orbital radiation components and therefore represent the background actually expected in the CALOg sensitive volume

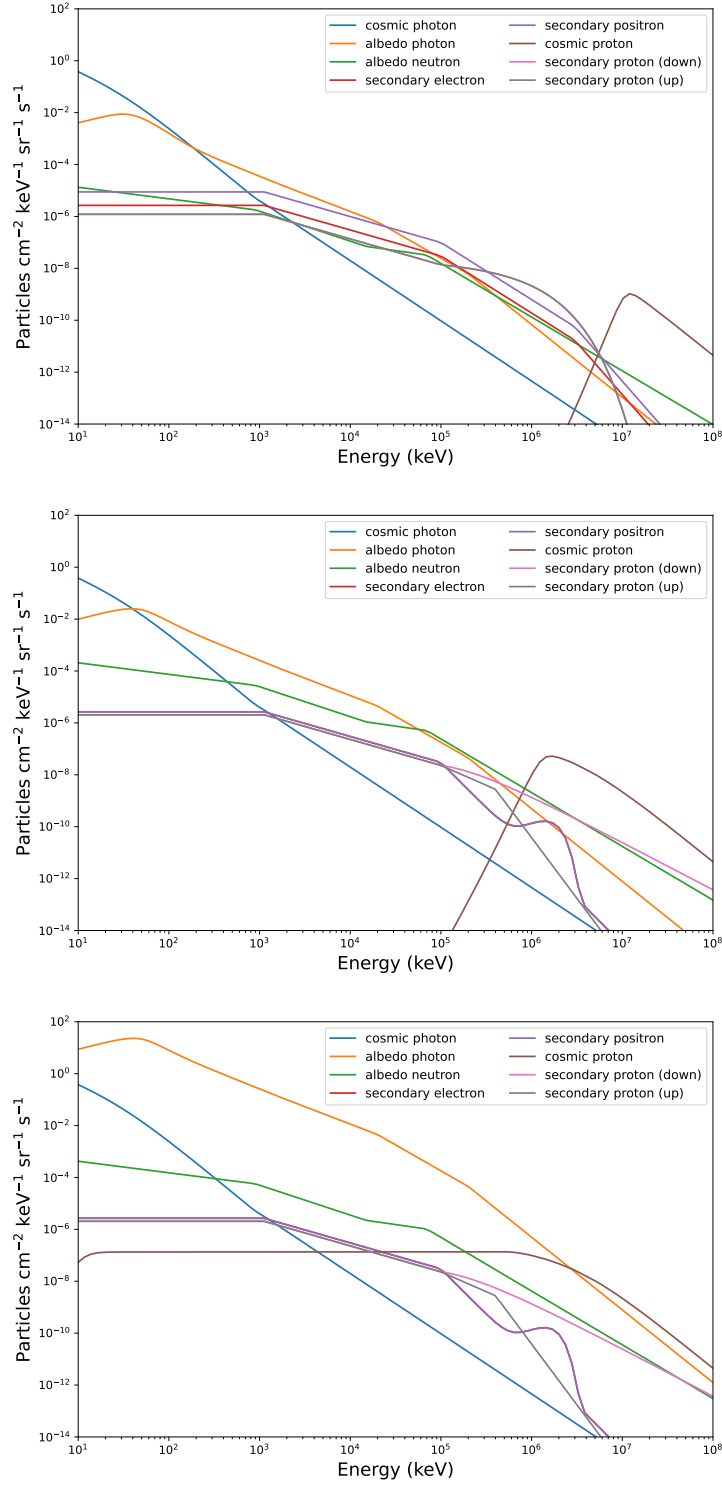


Figure 4.10: Differential flux spectra of the orbital background components for three representative background regimes sampled along the high-inclination (98°) NUSES orbit. The top, middle, and bottom panels correspond to the *equatorial*, *intermediate*, and *polar* background conditions, respectively.

for the three representative background regimes.

In all cases, the photon component dominates the total background over a broad energy range, with atmospheric albedo photons providing the largest contribution. However, the relative importance of albedo neutrons and secondary charged particles increases from the equatorial to the polar regime, reflecting the progressive reduction of geomagnetic shielding.

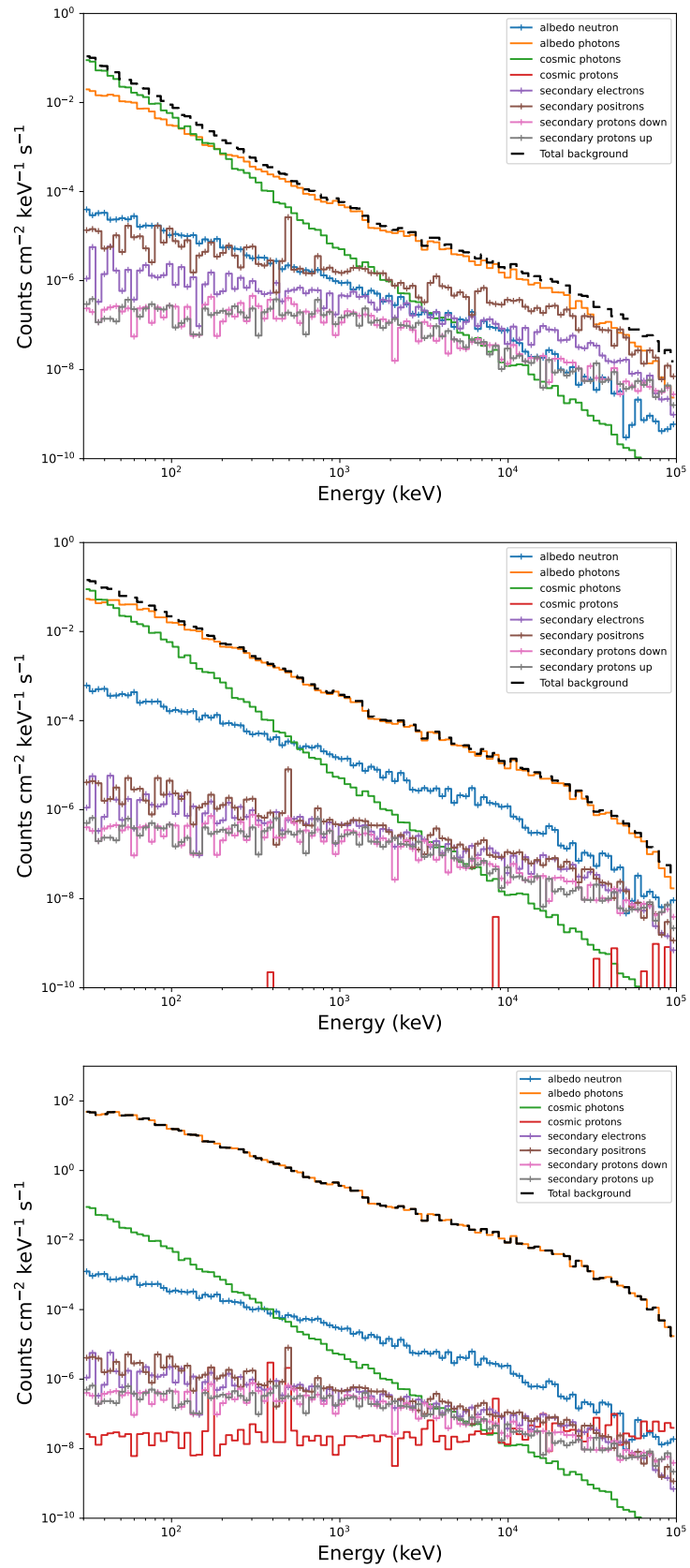


Figure 4.11: Estimated differential background spectra in CALOG for three representative background regimes sampled along the high-inclination (98°) NUSES orbit. The top, middle, and bottom panels correspond to the *equatorial*, *intermediate*, and *polar* background conditions, respectively.

In addition to the prompt background produced by incident particles, interactions between energetic particles and the detector materials can generate unstable isotopes within the spacecraft structure. The subsequent decay of these isotopes produces delayed gamma-ray emission that may mimic astrophysical signals. In particular, passages through the **SAA**, where the inner Van Allen radiation belt approaches the Earth most closely, can significantly increase the activation rate and therefore represent an important component of the orbital background.

4.5 Transient Trigger Algorithm

The sliding-window trigger logic adopted for Zirè follows an approach that has been successfully implemented in previous space-based gamma-ray instruments. The Fermi-**GBM** employs overlapping time windows across multiple energy channels to identify transient excesses with high confidence, achieving both low latency and strong background rejection [30]. The *Swift* **BAT** implements a multi-tiered trigger combining short and long integration windows with an image-based confirmation step to validate real events and suppress false triggers [142].

The detection of short-duration transient sources such as **GRBs** in real time requires a dedicated onboard trigger algorithm capable of identifying statistically significant deviations in the measured count rate above the expected orbital background level. The algorithm does not search for a spike in the signal itself, but rather monitors whether the incoming photon count rate deviates significantly from a precomputed background expectation. When the number of counts recorded within a given time window exceeds the background prediction by a statistically significant margin, a **GRB** candidate trigger is declared. The fundamental distinction is that the trigger responds to a change in the background rate, not to an absolute threshold in the signal. The trigger algorithm and its optimization study presented in this section follow the methodology described in [64].

The trigger algorithm operates on a continuous stream of detector counts. The expected background level $\langle N_B \rangle$ is derived from precomputed orbital background models, which account for the dependence of the radiation environment on the local geomagnetic conditions along the orbit, as described in Section 4.4. The total observed counts C_T in each time window are compared against this expectation, and the instantaneous **SNR** is evaluated as:

$$S/N = \frac{C_T - \langle N_B \rangle}{\sqrt{C_T}}, \quad (4.2)$$

where the denominator represents the Poisson statistical uncertainty on the total observed counts. A statistically significant excess, $S/N > N_\sigma$, above the background expectation within the accumulation window constitutes a trigger candidate.

The algorithm's implementation relies on two fundamental time parameters, comprising a fine time bin width Δt_{bin} for digitizing individual count measurements, and an accumulation time window T_{acc} for integrating counts before the S/N evaluation. The accumulation window slides forward by one time bin at each step, providing overlapping samples that allow prompt and continuous monitoring of the incoming event stream. Figure 4.12 illustrates this temporal structure.

A trigger is declared when $S/N > 3$ is satisfied in three or more consecutive accumulation windows, with at least five windows containing non-zero source contribution N_S . Requiring a significant excess in multiple consecutive windows reduces the false alarm rate while maintaining sensitivity to real **GRB** signal. The trigger time t_{trig} is recorded as the start of the first significant window, and the detection latency $\Delta t = t_{\text{trig}} - t_0$, where t_0 is the true burst onset, quantifies the real-time performance of the algorithm.

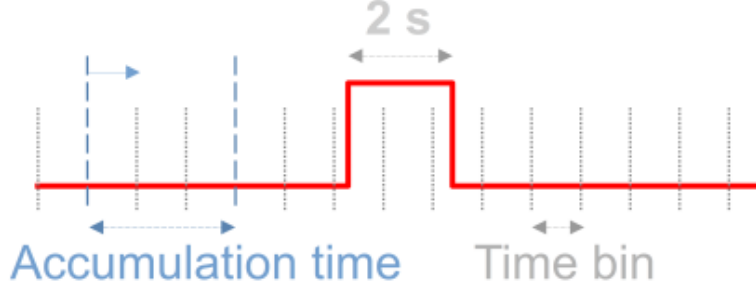


Figure 4.12: Schematic of the sliding-window transient trigger logic. Counts are digitized in time bins of width Δt_{bin} and integrated over an accumulation window of duration T_{acc} , which advances by one bin at each step [64].

The choice of Δt_{bin} and T_{acc} directly governs the sensitivity and latency of the trigger. A very fine time bin improves time resolution but increases statistical noise per bin, potentially reducing sensitivity to faint bursts. Conversely, a large accumulation window improves the S/N for weak sources but increases detection latency and reduces sensitivity to short bursts. A dedicated optimization study was therefore performed to identify the parameter combination that maximizes detection performance across a representative **GRB** population under realistic orbital background conditions.

The optimization was carried out using simulated background data corresponding to the polar regime and an average **GRB** flux described by the Comptonized spectral model, obtained by averaging the spectral parameters of 2300 **GRBs** from the Fermi-**GBM** spectral catalog [143], following the procedure adopted in [64]. This choice represents a conservative scenario, since the polar regime corresponds to the most severe background condition considered along the **NUSES** orbit. For each combination of Δt_{bin} and T_{acc} , the detection latency Δt and the maximum achieved S/N were recorded.

The study indicates that a time bin width Δt_{bin} of 0.25 s and an accumulation window T_{acc} of 4 s provide a favorable balance between detection latency and sensitivity. Under these parameters, the algorithm achieves a detection latency (Δt) of approximately 0.5s with a maximum S/N of approximately 16 for the simulated average **GRB**, as illustrated in Figure 4.13.

4.6 Transient Sensitivity

The transient sensitivity of CALoG has been assessed using two complementary metrics. The first is the **MDF**, which gives an energy-dependent estimate of the minimum differential photon flux required for detection at a specified statistical significance, accumulation time, and background level. The second is a catalog-based signal-to-noise analysis applied to a representative population of Fermi-**GBM GRBs**, providing a more direct measure of the burst detectability expected under realistic orbital conditions. Together, these approaches characterize both the intrinsic sensitivity of CALoG as a function of energy and its expected performance for transient detection.

The **MDF** was computed by requiring a detection significance of $N_\sigma = 3$, corresponding to a confidence level of 99.87%, over an integration time $\Delta T = 10$ s. For a given reconstructed-energy bin of width ΔE , the minimum detectable differential photon flux is expressed as [58]:

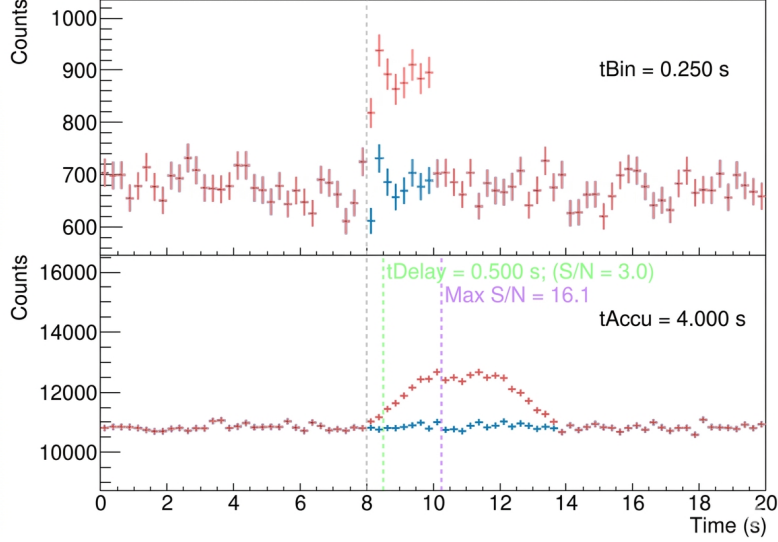


Figure 4.13: Time evolution of detector counts during a simulated GRB event. The upper panel shows the total count rate (source plus background, red) and the background-only expectation (blue) in time bins of $\Delta t_{\text{bin}} = 0.25$ s. The lower panel shows the integrated counts in the sliding accumulation window of $T_{\text{acc}} = 4$ s. The detection latency Δt and the maximum S/N are indicated. The gray dashed line marks the true burst onset t_0 [64].

$$\Phi_{\min}(E) = \frac{N_{\sigma}^2}{2 A_{\text{eff}}(E) \Delta E \Delta T} \left(1 + \sqrt{1 + \frac{4 B(E) \Delta T}{N_{\sigma}^2}} \right), \quad (4.3)$$

where $A_{\text{eff}}(E)$ is the effective area evaluated at energy E and $B(E)$ is the total background count rate in the same energy bin. In this form, the **MDF** represents a single-bin sensitivity estimator under the assumption of stationary background over the accumulation time, providing a practical and energy-resolved measure of detector performance.

The **MDF** was evaluated for the three representative background regimes introduced in Section 4.4, corresponding to the *equatorial*, *intermediate*, and *polar* cases. These cases sample different background conditions encountered along the high-inclination orbit, from regions of stronger geomagnetic shielding to the most severe polar regime. This comparison allows the dependence of the transient sensitivity on the local orbital background level to be quantified.

Figure 4.14 shows the resulting **MDF** curves for the horizontal and vertical acceptance windows for the three representative background regimes. For comparison, the figures also show the average differential photon spectra of Fermi-**GBM GRBs** described by the Comptonized, Band, and Smoothly Broken power-law spectral models, with the shaded regions representing the corresponding 1σ confidence intervals on the mean spectral shape.

The average **GRB** spectra shown for comparison were derived from a quality-selected subsample of the Fermi-**GBM** Burst Catalog [143]. Starting from the full catalog (4031 entries at the time of access, larger than the 2297-**GRB** sample reported in the original 10-year publication, since the catalog is continuously updated as new bursts are triggered), events were selected by best-fit spectral model (Comptonized, Band, or Smoothly Broken Power-Law) and further restricted to physically well-constrained parameter ranges ($-1.5 < \alpha < -0.5$, $200 < E_{\text{peak}} < 1000$ keV, and analogous cuts on β), yielding 848, 30, and 14 **GRBs** for the three models, respectively. For each model, the mean spectrum and its 1σ confidence interval were obtained via bootstrap resampling of the fitted parameters. This sample is used only for the average spectral models shown in the **MDF** figures. A

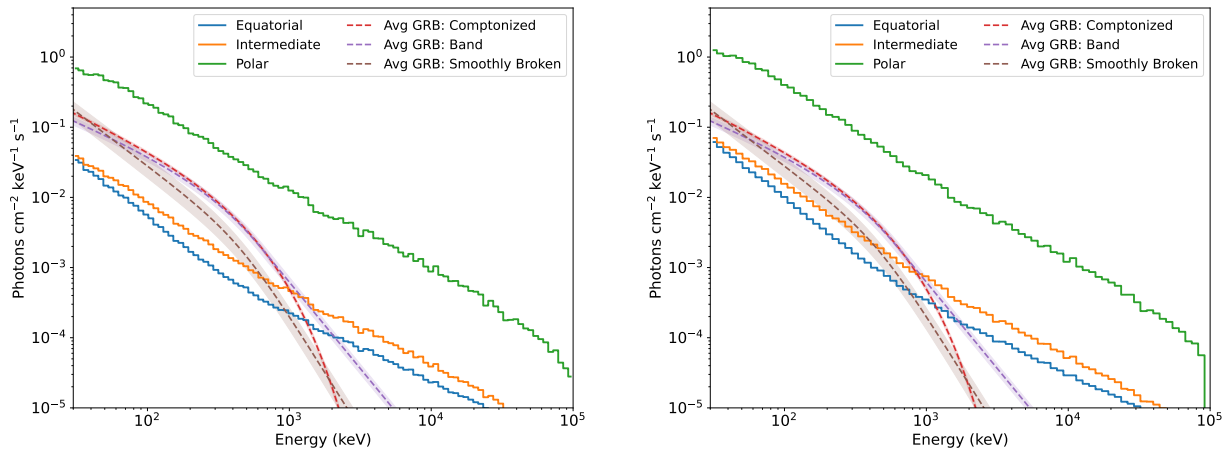


Figure 4.14: MDF of CALOG for the horizontal (left) and vertical (right) acceptance windows for three representative background regimes sampled along the high-inclination orbit.

separate and larger sample of 3588 **GRBs**, whose selection is described below, is used for the population-level signal-to-noise study following the methodology of [64, 58]; both samples are drawn from the same catalog access.

In both viewing geometries, the **MDF** increases as the background environment becomes more severe. The lowest detection threshold is obtained for the *equatorial* regime, where geomagnetic shielding is strongest, while the highest threshold is found for the *polar* regime, corresponding to the regime with the largest background level. The *intermediate* regime lies between these two limiting configurations. This behavior reflects the increase of the orbital background from the equatorial to the polar regime and confirms that the local radiation environment has a direct impact on the transient sensitivity of CALOG.

The comparison with the average **GRB** spectra shows that the most favorable sensitivity is achieved in the energy range below approximately 10^3 keV. In this interval, the **MDF** curves approach, and in the more favorable regimes can fall below, the characteristic flux levels of the Comptonized, Smoothly Broken, and Band populations. In the polar regime, the increased background raises the **MDF** threshold and therefore reduces the detectability of weaker bursts. The horizontal window configuration provides a modestly better sensitivity than the vertical one, most notably below approximately 1 MeV, consistent with its larger effective area. At higher energies, the two configurations become comparable.

While the **MDF** provides an energy-dependent threshold estimate, it does not directly show how a realistic burst population is distributed with respect to the detection boundary. For this reason, a complementary signal-to-noise study was performed using the same Fermi-**GBM** catalog access described above. Each burst is described by its fluence (time-integrated) Comptonized spectral fit; entries with missing or unphysical parameters were excluded, in particular fits with $\alpha \leq -2$, for which the model diverges at high energies, yielding a final sample of 3588 **GRBs**. For each **GRB**, the expected source counts were obtained by folding the fitted photon spectrum with the CALOG effective area for the corresponding acceptance window, assuming on-axis incidence with respect to that window. The expected background counts were derived from the orbital background model for each of the three representative background regimes, using an accumulation time fixed to $\Delta T = 10$ s. The **SNR** is evaluated as [144]:

$$S/N = \frac{N_S}{\sqrt{N_S + N_B}}, \quad (4.4)$$

where N_S and N_B are the expected source and background counts, respectively, integrated over the 30 keV–100 MeV energy range and the accumulation time ΔT .

It should be noted that, unlike detectors with a symmetric acceptance geometry, CALOg presents two geometrically distinct windows with different effective areas. The present calculation assumes that the source is located on-axis with respect to each window, which represents an optimistic scenario. For GRBs arriving from random directions, the projected effective area will in general be smaller than the on-axis value, so the source counts N_S and the resulting S/N values should be regarded as upper estimates. A more realistic assessment would require averaging the effective area over the angular response of each window, which is deferred to future work.

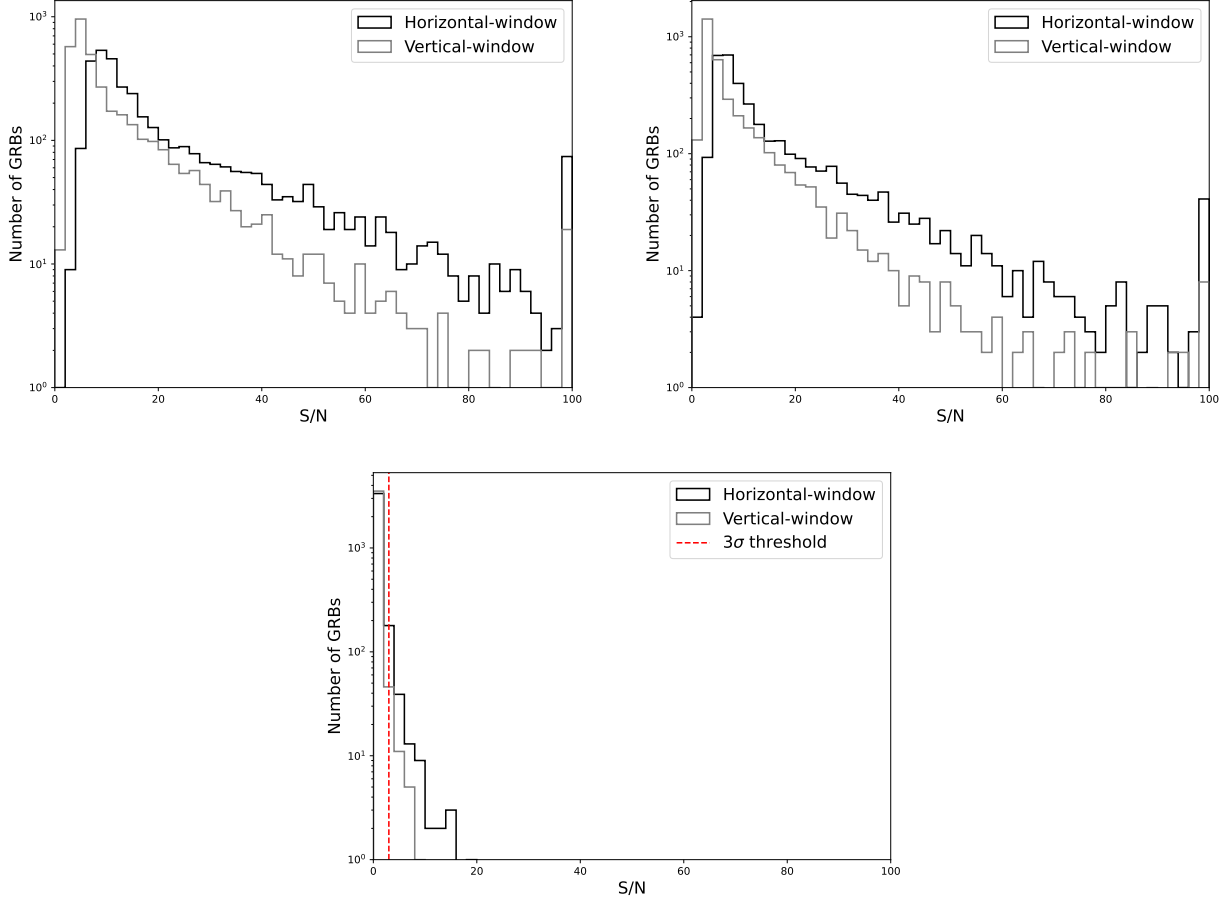


Figure 4.15: S/N distributions for 3588 Fermi-GBM GRBs in the horizontal and vertical acceptance windows for three representative background regimes. The *equatorial* and *intermediate* cases are shown in the top row, and the *polar* case in the bottom row. The calculation assumes on-axis source incidence for each window; bursts with $S/N > 100$ are accumulated in the last bin.

The resulting S/N distributions for the horizontal and vertical acceptance windows are shown in Figure 4.15 for the three representative background regimes. In all cases, the horizontal distribution is shifted toward higher significance with respect to the vertical one, consistent with the larger effective area of the horizontal acceptance window over the energy range where the GRB spectra peak, and the correspondingly larger source counts. A clear dependence on the background regime is also observed. The most favorable detectability is obtained for the *equatorial* regime, while moving from the equatorial to the polar regime progressively shifts the GRB population toward lower significance as the orbital background becomes more intense. These results show that CALOg transient detectability is governed

by the combined effect of burst intensity, detector effective area, and local background conditions along the orbit.

To further characterize the detection capability, the efficiency of **GRB** detection, defined as the fraction of the 3588-**GRB** population yielding $S/N > 3$, was evaluated as a function of the accumulation time ΔT for the representative background regimes. The result is shown in Figure 4.16. The detection efficiency is highest for the *equatorial* regime, where the background level is lowest, and decreases progressively when moving toward the polar regime. In the *polar* regime, the efficiency remains significantly suppressed across the full range of exposure times considered, reflecting the dominant impact of the elevated background. This result confirms that the choice of $\Delta T = 10$ s represents a reasonable reference timescale, while also highlighting that the detection efficiency is expected to vary along the orbit depending on the local background conditions.

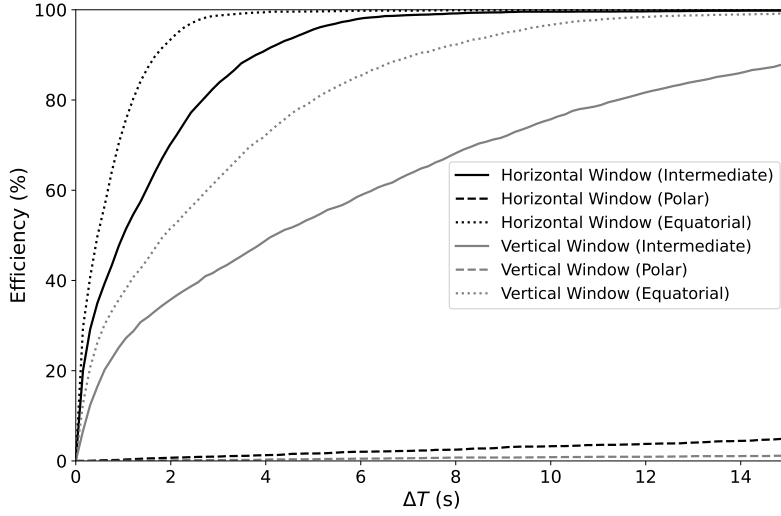


Figure 4.16: Detection efficiency, defined as the fraction of the 3588 Fermi-GBM GRBs with $S/N > 3$, as a function of the accumulation time ΔT for the three representative background regimes. Black and gray curves refer to the horizontal and vertical acceptance windows, respectively.

It should be noted that the *polar* regime represents the most conservative background condition among those considered, but it does not describe the full range of environments encountered by the satellite. As **NUSES** moves along its high-inclination orbit, CALOg samples regions with different geomagnetic cutoffs and therefore different background levels. The detector will spend part of its operational time in regions with lower geomagnetic shielding suppression, where the background conditions are more favorable and the detection efficiency is higher, as indicated by the *equatorial* and *intermediate* regimes shown in Figure 4.16. The realistic in-orbit transient sensitivity is therefore expected to vary along the orbit, with the *polar* regime providing a conservative lower bound on the instantaneous detection performance.

4.7 Future Goals

The studies presented in this chapter represent a first systematic characterization of the CALOg detection performance, and several directions for future improvement have been identified.

The trigger conditions correspond to a simplified analysis-level selection scheme designed to evaluate the detector response and effective area. Future work will extend this approach by

implementing a more detailed trigger logic at the digitization level. In particular, upcoming studies will incorporate crystal-level energy thresholds requiring a minimum energy deposit of 30 keV in individual CALOg scintillators, as well as paddle-level thresholds exceeding 7 keV in the ACS. The trigger scheme will also be extended to include a pre-selection based on the total energy deposited in the calorimeter, typically requiring a minimum total CALOg energy of 30 keV prior to the application of the global ACS veto. The inclusion of these digitization-level trigger elements will provide a more realistic representation of the onboard event-selection chain and improve the correspondence between Monte Carlo simulations and flight-representative detector behavior.

The signal-to-noise analysis presented in Section 4.6 assumed on-axis source incidence with respect to each acceptance window, which represents an optimistic scenario. A more realistic assessment requires computing a direction-averaged effective area by integrating the angular response of each window over the full sky, weighted by the angular distribution of the GRB population. This will provide a more accurate estimate of the detectable fraction of GRBs under realistic observing conditions and remove the current overestimation of the source counts.

The present sensitivity evaluation was performed for a limited set of representative background regimes, rather than by explicitly following the time evolution of the satellite position along the full orbit. As discussed in Section 4.6, these cases illustrate the dependence of the CALOg performance on the local background level, from the favorable equatorial regime to the conservative polar regime. Future work will compute a time-averaged sensitivity over the full orbit, weighting the background level by the fraction of time spent at each geomagnetic latitude, to obtain a more representative estimate of the in-flight CALOg performance.

The BDT classification study presented in this chapter was carried out exclusively for the LYSO:Ce-based CALOg configuration, using a simplified background model restricted to the intrinsic radioactive decay of the scintillator material. Since GAGG:Ce has been selected as the baseline scintillator for CALOg, a dedicated classification study using GAGG:Ce and the full orbital background model, including albedo photons, albedo neutrons, secondary protons, electrons, and positrons, should be performed. This will provide a realistic assessment of the machine-learning background rejection capability under in-flight conditions, and will allow a more robust evaluation of the signal-to-background discrimination power of the GAGG:Ce-based configuration.

The current trigger performance evaluation used a single average GRB spectral model described by the Comptonized function. A more comprehensive study should evaluate the trigger efficiency as a function of GRB fluence, spectral shape, and duration, covering the full range of spectral models present in the Fermi-GBM catalog. This will allow quantifying the fraction of the observable GRB population that CALOg can detect under realistic mission conditions and for different background regimes along the orbit.

The sliding-window trigger algorithm described in Section 4.5 provides a computationally efficient baseline for onboard transient detection. Future studies will investigate the use of more sophisticated classification algorithms, including convolutional neural networks, to improve the detection efficiency and false-alarm rejection capability beyond what is achievable with the current threshold-based approach [64].

As discussed in Section 4.4, passages through the SAA can induce activation of detector materials, producing delayed gamma-ray emission that may mimic transient signals. The quantitative impact of this activation background on the CALOg trigger rate and sensitivity has not been assessed in the present work and represents an important component to be included in future performance studies, particularly given the high orbital inclination of the NUSES mission.

Chapter 5

Performance of the Crystal Eye detector on the observation of GRBs

This chapter presents a comprehensive performance evaluation of the Crystal Eye (CE) detector for the detection of GRBs in low-Earth orbit. The detector concept has been introduced and motivated in Chapter 3. Building upon that framework, the present chapter provides a simulation-based study for the optimization of GRBs detection capabilities of the instrument.

All results are obtained using a dedicated GEANT4 Monte Carlo simulation framework developed to model the detector response, the space radiation environment, and the implemented trigger logic. The simulations are used to evaluate the effective area, background levels, transient sensitivity, and source localization capability.

Section 5.1 then presents the detector performance evaluation for the baseline and optimized geometries, including the trigger logic. Within this section, the effective area is quantified in Section 5.1.1, and the orbital background modeling, normalization procedure, and the resulting background response for different geometries and scintillator compositions are detailed in Section 5.1.2. The transient sensitivity is derived in Section 5.1.3 using a minimum-detectable-flux approach, supported by a population-level signal-to-noise analysis. Section 5.2 presents the template-based localization pipeline and quantifies the expected directional reconstruction accuracy. Finally, Section 5.3 compares the optimized detector geometries balancing scientific performance against implementation constraints.

5.1 Detector performance evaluation

The performance of the CE detector for gamma-ray burst observations in low-Earth orbit is evaluated using dedicated GEANT4 Monte Carlo simulations, modeling the complete detector geometry and readout chain. Input particle fluxes and spectra were based on established models of the low-Earth-orbit radiation environment [139, 145, 141, 134], assuming a moderate solar modulation potential of 650 MV. The analysis focuses on the detector response to transient gamma-ray signals and quantifies key performance metrics, including effective area, background levels, detection sensitivity, and source localization capability.

The first complete detector design that was implemented and simulated during the development of the CE instrument is referred to as the baseline geometry and is used solely as a reference for comparison. The optimized geometries are studied for a comparison of their performance.

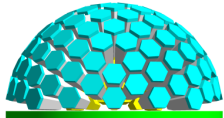
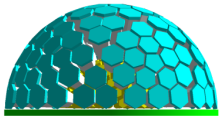
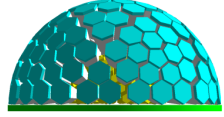
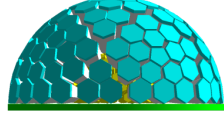
These geometries differ primarily in their total crystal mass through variations in crystal thickness. All optimized geometries include the full crystal-holding structure

made of aluminum and Windform material and represent mechanically complete detector implementations.

For each optimized geometry, three scintillator material configurations are investigated in order to disentangle the effects of detector mass and scintillator composition. These include a **LYSO:Ce**-only configuration, a hybrid configuration with **GAGG:Ce** crystals in the upper detector layer and **LYSO:Ce** crystals in the lower layer, and a **GAGG:Ce**-only configuration. All geometries are simulated under identical conditions, enabling a direct comparison of their impact on detector performance.

A summary of the detector geometries considered in this performance study is provided in Table 5.1. The table shows the baseline hemispherical geometry together with the three optimized geometries investigated in detail, along with the corresponding key geometrical parameters, including total crystal mass, dome radius, crystal heights, and number of pixels. As discussed above, the optimized geometries share an identical pixelization and dome radius, while differing primarily in total crystal mass, enabling a controlled comparison of their impact on detector performance.

Table 5.1: Baseline and optimized CE detector geometries considered in this work. The baseline hemispherical geometry is shown together with the three optimized geometries investigated in detail: the optimized low-mass, intermediate-mass, and high-mass geometries.

Configuration	Geometry	Total crystal mass (kg)	Dome radius (cm)	No. of pixels	Ext. crystal height (mm)	Int. crystal height (mm)
Baseline geometry		19.11	14.60	112	40	30
Optimized low-mass geometry		17.67	16.70	126	30	30
Optimized intermediate- mass geometry		21.08	16.70	126	30	30
Optimized high-mass geometry		24.24	16.70	126	35	30

The three optimized geometries differ primarily in their external crystal height, which directly determines the total crystal mass. Optimized low-mass geometry and Optimized intermediate-mass geometry both employ external crystals of 30 mm height, differing only in the individual crystal mass, which results in a total detector mass of 17.67 kg and 21.08 kg respectively. Optimized high-mass geometry incorporates thicker external crystals of 35 mm, yielding the highest total mass of 24.24 kg among the three designs and maximizing the active detector volume at the cost of increased structural mass. The internal crystal height is fixed at 30 mm across all three geometries, ensuring a consistent inner layer response. All three geometries include the complete crystal-holding structure made of aluminum and Windform material, and represent mechanically complete detector implementations.

5.1.1 Effective area estimation

To simulate the effect of the electronic threshold, the applied threshold values are $E_{\text{ACD,th}} > 7$ keV and $E_{\text{CAL,th}} > 30$ keV, respectively. Any energy deposition below these limits is discarded during event processing. These thresholds are derived from preliminary laboratory measurements.

Following the noise suppression thresholds, a set of “basic trigger” conditions is applied to select gamma-ray events and exclude background contamination. The total energy deposited in the top **ACD** layer is required to be less than 200 keV, thereby discriminating photons from charged-particle events such as electrons or protons. No energy deposition is allowed in the bottom **ACD** layer, ensuring the rejection of albedo backgrounds and excluding non-contained events depositing energy in the calorimeter. Finally, the deposited energy in the upper calorimeter crystal is required to exceed that in the lower crystal layer, ensuring that only photons entering from the upper, sky-facing hemisphere of the detector are retained.

In addition to the basic trigger, a “topological trigger” condition is implemented specifically for the hybrid **LYSO:Ce+GAGG:Ce** configuration. This criterion exploits the topology of the energy deposition pattern within the calorimeter to further suppress internal background from the lower **LYSO:Ce** layer while maintaining efficient detection of valid gamma-ray events. Under this condition, the maximum energy deposition in any single calorimeter crystal must occur in the top layer. At least one neighboring crystal (in either layer) is also required to register an energy deposit in the immediate vicinity of the maximum. Moreover, the combined energy deposition in this cluster of surrounding crystals must exceed 50% of the total energy deposition in the entire calorimeter. This topological requirement effectively reduces spurious events originating from the **LYSO:Ce** background and improves the discrimination of genuine gamma events from the upper hemisphere.

Table 5.2: Background rejection due to of the trigger conditions in the detector (LYSO+GAGG configuration) for different events [58].

Background type	Basic trig. [%]	Basic + topological trig. [%]
γ from upper hemisphere	25.1	29.5
γ from lower hemisphere	43.3	47.4
n from lower hemisphere	54.9	61.6
e^- from all directions	91.0	91.6
e^+ from all directions	85.7	86.5
p from all directions	91.8	91.9
p from upper hemisphere	98.7	98.9
Intrinsic radioactivity in LYSO:Ce	97.8	99.0

The results reported in Table 5.2 show that the inclusion of the topological trigger leads to a systematic improvement in background rejection across all considered particle types. All events passing these trigger and selection cuts are used in the subsequent computation of the detector’s energy-dependent effective area. In particular, a significant suppression is achieved for background events originating from the lower hemisphere and from the intrinsic radioactivity of **LYSO:Ce**. The relatively lower rejection fraction observed for photons entering from the upper hemisphere reflects the intentional design of the trigger to preserve valid astrophysical signal events. This confirms that the combined trigger strategy effectively reduces internal and charged-particle backgrounds without compromising the detector sensitivity to astrophysical gamma-ray events.

The effective area, A_{eff} , quantifies the response of the detector to incident photons as a function of energy for a given incident direction. Simulations were performed with the Monte Carlo toolkit for all geometries, with **LYSO:Ce** employed as the reference scintillator material. The intrinsic radioactivity of ^{176}Lu was not included in these runs.

The simulated photon source consisted of a plane of parallel photons injected at the zenith position. The source plane was defined large enough to fully cover the hemispherical dome of the detector. Photon energies were sampled in the range

$$30 \text{ keV} \leq E_\gamma \leq 100 \text{ MeV},$$

with a flat distribution in logarithmic energy scale (uniform in $\log E$) to ensure equal statistics per decade. The effective area was then evaluated from the ratio of detected to generated events, following the same definition introduced in Eq. (4.1), with A_{geom} replaced here by A_{src} , the geometrical area of the photon generation plane, N_{gen} replaced by N_{sim} , and N_{sel} retaining the same meaning.

To further characterize the directional response of the detector, the effective area was also evaluated as a function of both photon energy and incident angle. The polar angle θ was varied from 0° (zenith/normal incidence) to 90° (horizon) in steps of 1° , with 10^5 photons simulated at each angle using a square parallel-beam source plane positioned at 18 cm from the detector. The azimuthal angle ϕ was fixed at $\phi = 0^\circ$, exploiting the azimuthal symmetry of the hemispherical dome geometry. Figure 5.1 shows the resulting two-dimensional map, where each pixel represents the effective area obtained for photons entering at polar angle θ and energy E_γ . The map reveals that the detector response peaks for photons entering near normal incidence ($\theta \lesssim 30^\circ$) and gradually decreases toward the horizon due to geometric projection and increased self-shielding within the dome structure. At lower photon energies (below a few hundred keV), the effective area remains relatively high owing to strong photoelectric absorption, whereas at higher energies Compton scattering dominates and the efficiency decreases smoothly.

The two-dimensional effective-area map for the intermediate-mass geometry is shown in Figure 5.1(a). The low-mass and high-mass geometries yield the same qualitative angular–energy dependence, differing only in absolute normalization. To make these differences visible, panels (b) and (c) show the ratio of the low-mass and high-mass effective areas relative to the intermediate-mass case. This near-identical response is expected, since the three optimized geometries share an identical dome shape, pixelization, and scintillator layout, differing only in crystal thickness. The ratio maps show no coherent structure across the energy–angle plane, with values fluctuating randomly around unity and consistent with statistical (Monte Carlo) noise rather than a systematic geometry-dependent effect.

The resulting energy-dependent effective area for the baseline geometry is shown in figure 5.2. For comparison, the effective areas of other space-borne instruments such as *Swift*/**BAT** and Fermi/**GBM** are also overplotted. A comparison with other detectors operating in a similar energy range, shown, indicates that CE achieves an effective area several times larger than that of Fermi-**GBM** [30]. Although *Swift*/**BAT** [127] exhibits a higher effective area, its sensitivity is limited to the lower portion of the energy range covered by CE.

Following the baseline validation, the effective area was evaluated for the three optimized CE detector geometries, referred to as the low-mass, intermediate-mass, and high-mass geometries. These geometries represent successive refinements of the detector design, aimed at improving photon collection efficiency and structural stability while maintaining a common pixelization and dome radius. The resulting energy-dependent effective areas are shown in Figures 5.3a–5.3c.

When compared with the baseline configuration shown in Figure 5.2, it is observed

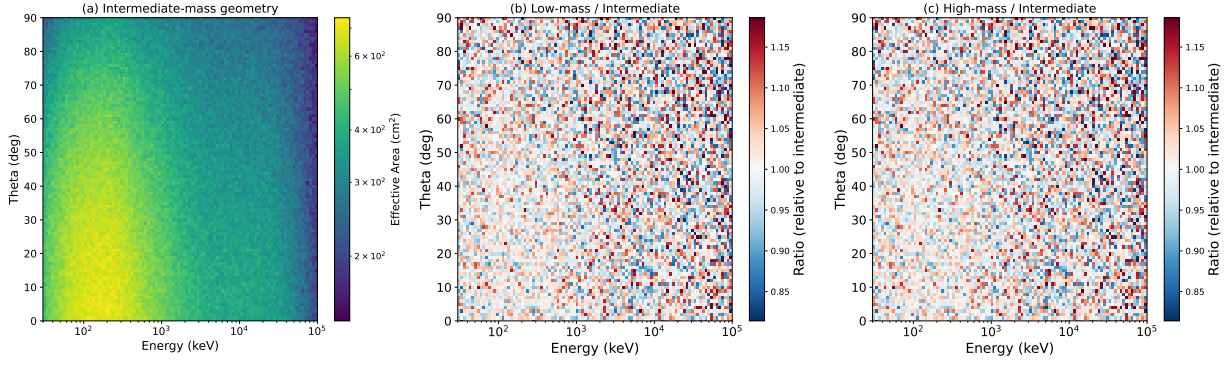


Figure 5.1: Two-dimensional effective-area maps as a function of photon energy and incidence angle for the three optimized CE detector geometries: (a) intermediate-mass geometry, (b) low-mass relative to intermediate, and (c) high-mass relative to intermediate. The ratio maps exhibit no coherent structure, consistent with statistical noise rather than a systematic geometry-dependent effect.

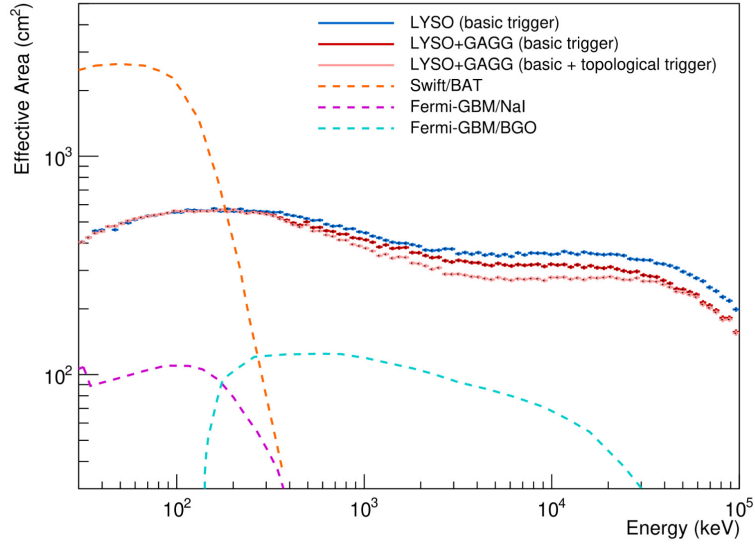


Figure 5.2: Effective area as a function of photon energy for the reference detector geometry at normal incidence ($\theta = 0^\circ$, zenith). Blue and red curves represent LYSO-only and LYSO+GAGG configurations under the basic trigger conditions, respectively. The pink line indicates the application of both basic and topological triggers. For comparison, the effective areas of *Swift*/BAT and *Fermi*/GBM NaI and BGO detectors are also shown [58].

that the application of the combined basic and topological trigger conditions in the **LYSO:Ce+GAGG:Ce** configuration results in a noticeable reduction in the effective area, particularly around 200 keV, most prominent in the mid-energy region dominated by Compton scattering [58]. This effect is evaluated in detail for the optimized intermediate-mass geometry. Given the identical pixelization and dome radius shared by all three optimized geometries (see Table 5.1), the topological trigger results obtained for the intermediate-mass configuration are expected to be representative of the low-mass and high-mass geometries as well, consistent with the approach adopted for the orbital background analysis in Section 5.1.2.

Figure 5.3 shows that the **GAGG:Ce**-only configuration performs similarly to the hybrid **GAGG:Ce+LYSO:Ce** configuration, in both effective area and background level, under basic trigger conditions. Despite this similarity, the **LYSO:Ce** layer is retained in the hybrid

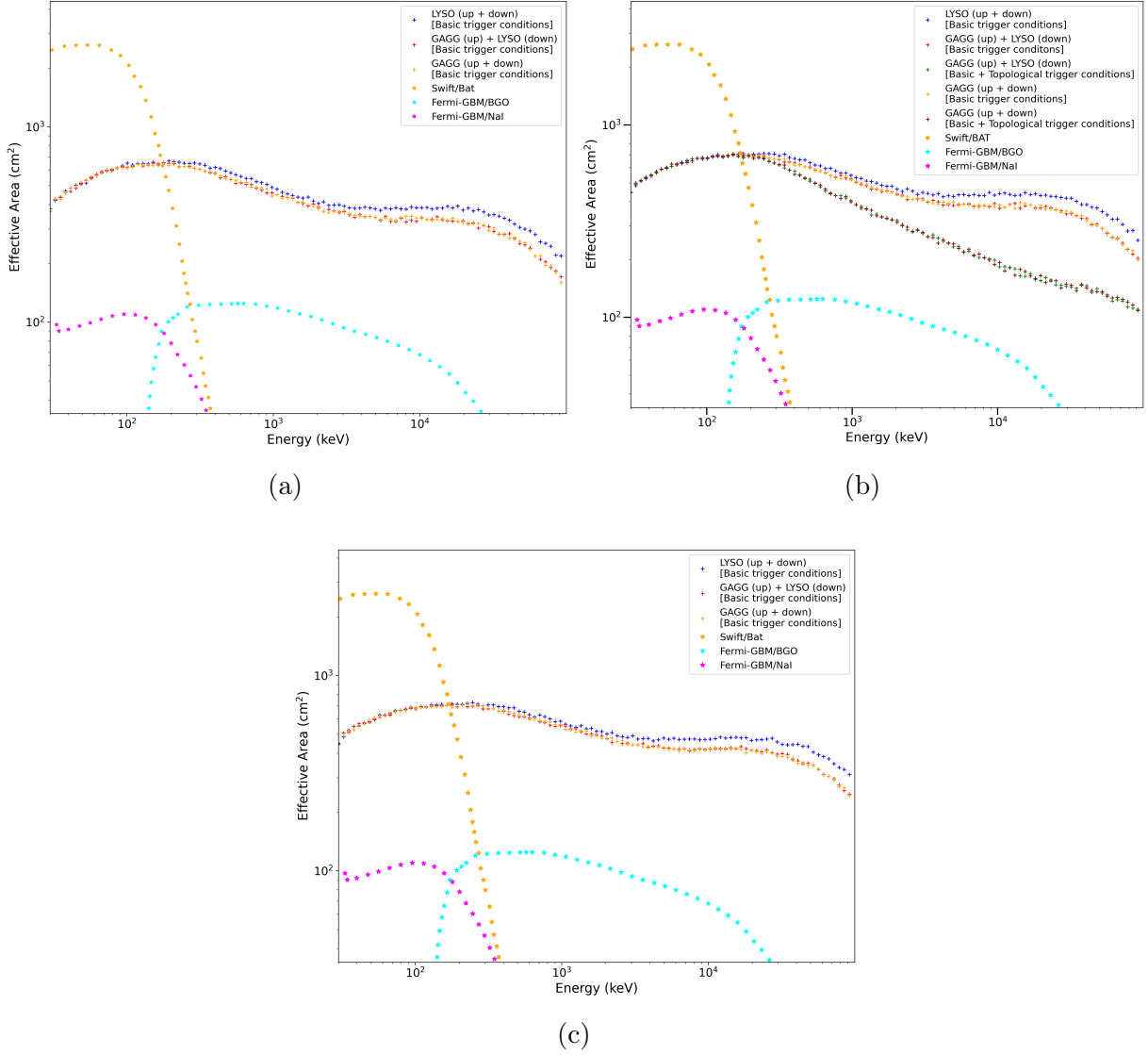


Figure 5.3: Effective area as a function of photon energy for: (a) Optimized low-mass geometry, (b) Optimized intermediate-mass geometry, and (c) Optimized high-mass geometry. Curves show basic and, where applicable, topological trigger conditions. For context, responses of *Swift*/BAT and *Fermi*/GBM (NaI, BGO) are also overplotted.

design for two reasons. First, as shown in Figure 3.17 (Section 3.3.2), **LYSO:Ce** provides a higher absorption efficiency than **GAGG:Ce** at high energies. It can therefore provide a better energy measurement for high-energy events that reach the inner layer of the detector. Second, the intrinsic radioactivity of **LYSO:Ce** can be used as an in-orbit calibration source: the ^{176}Lu decay line has a well-defined energy, so it can serve to periodically check the detector’s energy response, even though it also contributes background that must be suppressed by the topological trigger [58] (see also Section 5.1.2). For these reasons, the hybrid **GAGG:Ce+LYSO:Ce** configuration is adopted. It retains this calibration capability while still achieving an intrinsic background level and sensitivity close to those of the **GAGG:Ce**-only configuration.

5.1.2 Simulation of the orbital background

The orbital background environment encountered by the CE detector in low-Earth orbit has been modeled following the same framework described in Chapter 4, based on the

background model of Cumani et al. [134]. The dominant background contributions include diffuse cosmic γ -rays, atmospheric albedo photons, albedo neutrons, and secondary charged particles such as protons, electrons, and positrons, each arising from distinct physical processes as detailed in Section 4.4.

The CE detector operates at an orbital altitude of approximately 550 km and an inclination of about 20° . At this low inclination, the geomagnetic shielding is relatively strong, resulting in a suppressed charged-particle flux compared to higher-inclination orbits. The background simulation setup for the CE detector follows the same approach adopted for CALOg, with particles generated from a spherical surface surrounding the detector and reweighted according to the physical differential flux spectra of each component from [134].

Simulation setup

The orbital background simulations used the same framework, which reproduces the complete CE geometry, including the scintillator pixels and ACD layers. For each particle type, the deposited energy in every crystal was recorded to evaluate its contribution to the overall background count rate.

As in Section 4.4, the incident energy ranges for each background component were selected to retain only the intervals producing non-negligible contributions to the sensitive detector volume, following [134]. Specifically consistent with the modelization of different backgrounds, the following energy ranges were considered:

- 30 keV–1 GeV for photons, covering the dominant contribution of diffuse cosmic and albedo γ -rays relevant for scintillator-based detectors,
- 30 keV–10 GeV for neutrons, accounting for the broad energy distribution of atmospheric and secondary neutrons in low-Earth orbit, including the high-energy tail capable of inducing secondary interactions in detector materials,
- 10 MeV–1 GeV for secondary (albedo) protons, since lower-energy protons are largely absorbed by the spacecraft structure and anticoincidence layers, while contributions above ~ 1 GeV are dominated by primary cosmic protons,
- 4 GeV–100 GeV for primary cosmic protons, consistent with the geomagnetic cutoff at low orbital inclination and the steeply falling cosmic-ray spectrum at higher energies, and
- 30 keV–1 GeV for secondary electrons and positrons, encompassing the energy range where their contribution to the detector background is most significant.

Since the background model of [134] for secondary electrons and positrons extends only down to 1 MeV, their fluxes were extrapolated to the 30 keV lower threshold of the simulation by assuming a constant intensity equal to the value at 1 MeV, following the approach adopted in [58]. This approximation is justified by the fact that most charged particles in this low-energy range are rejected by the ACD at the trigger stage, so that any inaccuracy in the assumed flux shape below 1 MeV has a negligible impact on the final background estimate. This treatment ensures continuous energy coverage while avoiding an overestimation of the background contribution from particles that do not effectively reach the sensitive detector volume.

Figure 5.4 shows the input differential flux spectra adopted for each background component. The fluxes are expressed in $\text{cm}^{-2} \text{keV}^{-1} \text{sr}^{-1} \text{s}^{-1}$ and represent all major species expected in low-Earth orbit. Cosmic photons dominate below a few hundred keV, while

albedo photons become increasingly important at higher energies due to bremsstrahlung emission from secondary atmospheric electrons. The spectra of secondary electrons, positrons, and protons exhibit similar shapes over several energy decades, gradually decreasing toward the MeV–GeV region. Albedo neutrons contribute mainly at intermediate energies, whereas primary cosmic protons become relevant only above a few GeV. These modeled fluxes were used as input for the simulations to accurately reproduce the radiation environment encountered by the CE in orbit.

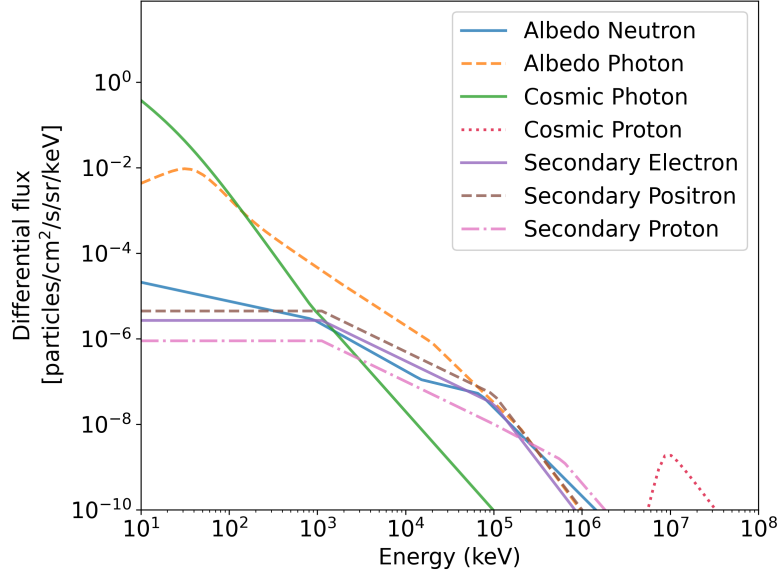


Figure 5.4: Differential flux spectra of major background components considered in the CE orbital environment. It includes contributions from cosmic and albedo photons, albedo neutrons, secondary electrons, positrons, and protons, as well as primary cosmic protons.

The resulting spatial distribution of background count rates across the detector pixels is shown in Figure 5.5. The maps reveal that cosmic and albedo photons produce a nearly uniform illumination across the detector dome, consistent with their isotropic flux distribution. In contrast, secondary charged particles such as protons, electrons, and positrons contribute at significantly lower levels, as expected from the strong geomagnetic shielding at the low orbital inclination of the CE. The total background map confirms the dominance of photon-induced components across the full detector surface.

Source geometry and particle generation

To reproduce realistic response of the detector, virtual source surfaces are positioned around the CE geometry, following the setup described by [58]. A hemispherical surface with a radius of 16 cm is placed around the detector dome to simulate incident cosmic particles and photons from space. Similarly, a circular disk of the same radius is placed below the bottom **ACD** layer to reproduce upward-going albedo components from the Earth’s atmosphere. Particles emitted from these sources follow a cosine angular distribution within 0°–90° relative to the surface normal, ensuring uniform and isotropic exposure of the detector volume.

Cosmic photons and primary protons are generated from the upper hemisphere, while albedo photons and neutrons are launched from both the upper and lower surfaces, with the latter restricted to upward directions only. Secondary electrons, positrons, and protons are simulated from both directions to account for isotropic particle populations trapped

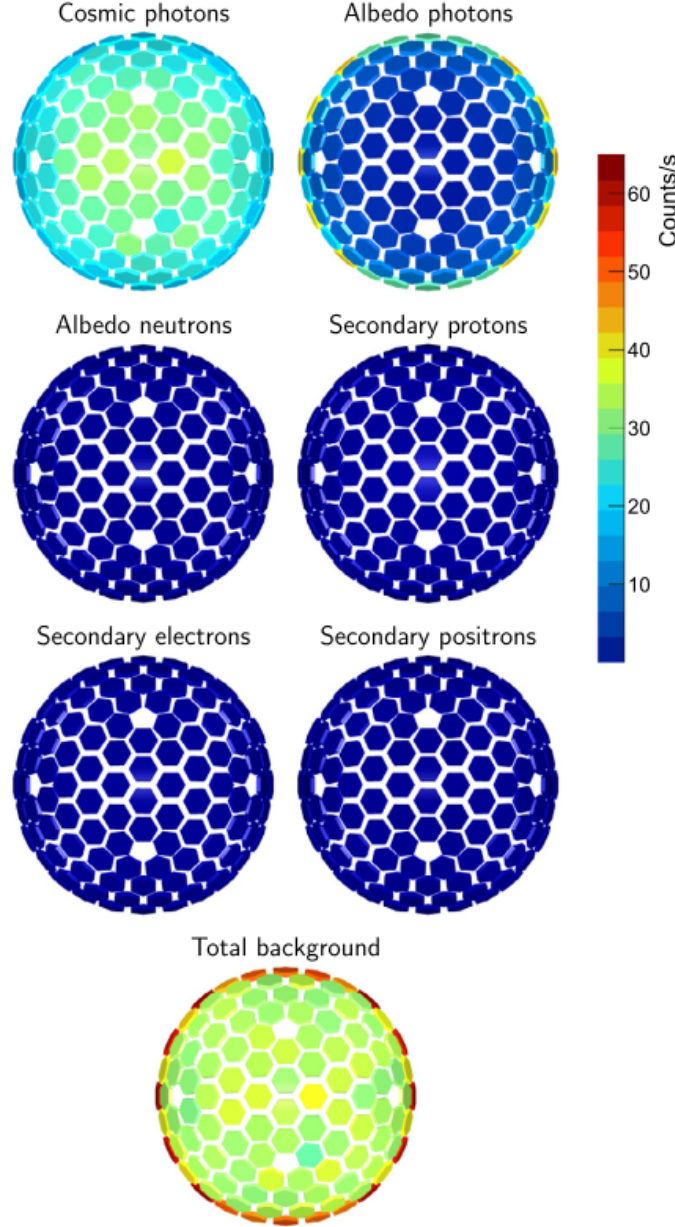


Figure 5.5: Simulated orbital background count-rate maps across the CE detector (LYSO configuration) pixels for individual background components and their total contribution [58].

in the geomagnetic field. A total of 10^6 primary particles are simulated for each species, except for primary protons, which are limited to 10^5 due to their lower flux contribution.

Flux weighting and event normalization

All simulated events are sampled from an energy distribution proportional to E^{-1} , corresponding to a flat distribution in logarithmic energy. After applying trigger and thresholds, the deposited energy spectra are weighted using the known flux models for each radiation component to reproduce realistic physical count rates. The resulting differential spectra are divided by the geometrical area of the detector and the width of the deposited energy bins, following the standard integration relation:

$$dN_j = \sum_i \int_S \int_{\Omega} \int_{E_i}^{E_{i+1}} \Phi(E_i) dE_i d\Omega dS \frac{N_{ij,\text{dep}}(E)}{N_{i,\text{gen}}(E)}, \quad (5.1)$$

where $N_{ij,\text{dep}}(E)$ is the number of events depositing energy in bin j , $N_{i,\text{gen}}(E)$ is the number of generated particles in the incident energy bin i , and $\Phi(E_i)$ represents the incident flux spectrum.

Figure 5.6 [58] shows the effective background fluxes for the different crystal configurations after the application of the trigger conditions. In particular, the effective background spectra are shown for both the *basic trigger* and the combined *basic + topological trigger* conditions, as defined in Section 5.1.1. The results indicate that photon-induced backgrounds dominate the total flux, with diffuse cosmic and atmospheric albedo photons providing the main contributions over the 30 keV–100 MeV energy range. Below approximately 200 keV, the diffuse cosmic photon component is dominant, whereas at higher energies the contribution from albedo photons becomes increasingly significant. Neutrons and secondary charged particles, such as protons, electrons, and positrons, primarily affect the detector response above several hundred keV. A sharp peak is visible at ~ 511 keV in the secondary positron spectrum, arising from positron annihilation radiation. As secondary positrons slow down within the detector material and surrounding structure, they annihilate with electrons, producing two photons of 511 keV each ($e^+ + e^- \rightarrow 2\gamma$). The contribution from primary cosmic-ray protons are negligible below a few GeV and represents a minor fraction of the total background in low-Earth orbit. Overall, the orbital background level is found to be comparable across the different scintillator configurations, with only modest variations between **LYSO:Ce-only**, **GAGG:Ce-only**, and hybrid detector layers.

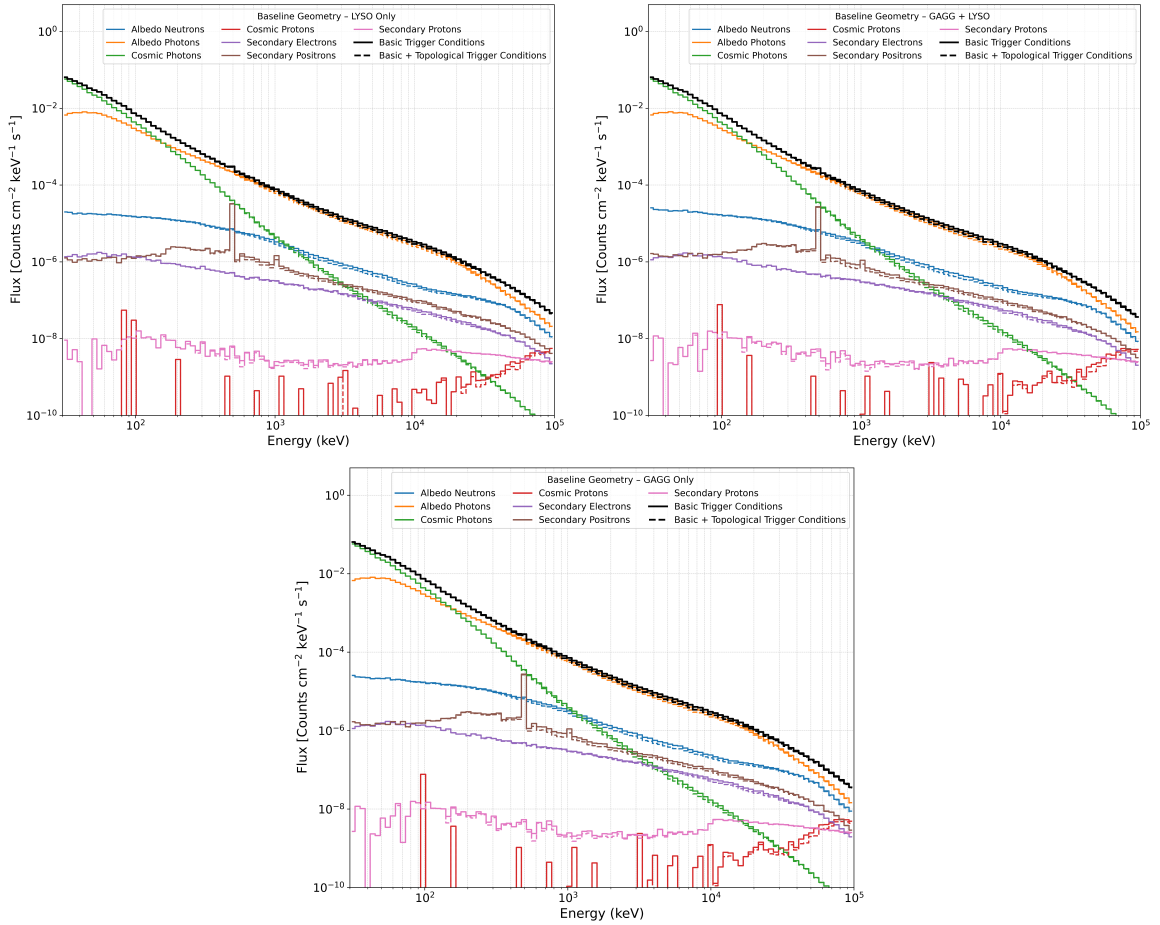


Figure 5.6: Simulated orbital background flux for the CE detector. The figure shows the results obtained for the baseline geometry, referred to as the baseline configuration, for three different material configurations: LYSO-only, hybrid GAGG+LYSO, and GAGG-only [58].

These simulations, performed for the baseline geometry, establish a reference for compar-

ison with the three optimized detector geometries — the low-mass, intermediate-mass, and high-mass geometries. The baseline results allow a direct assessment of the improvement achieved through the refined crystal dimensions, alternative scintillator compositions, and updated trigger strategies adopted in the optimized designs.

Orbital background for the optimized detector geometries

The orbital background analysis was performed for three optimized CE detector geometries, referred to as the low-mass, intermediate-mass, and high-mass geometries. The aim of this study is to investigate how these differences, together with the applied trigger conditions, affect the detector response to the orbital radiation environment.

For the low-mass and high-mass geometries, the analysis was performed using the *basic trigger conditions* only. Given the strong similarity in geometrical parameters among the three optimized designs, the topological trigger results obtained for the intermediate-mass configuration provide a representative estimate of its impact on background suppression and photon selection.

Figures 5.7–5.9 present the simulated orbital background spectra for the three optimized geometries. In all cases, photon-induced components dominate the total background. Diffuse cosmic photons prevail at energies below approximately 200 keV, while atmospheric albedo photons become increasingly significant at higher energies. Neutrons and secondary charged particles contribute mainly above a few hundred keV.

Under the basic trigger condition, all three geometries exhibit comparable overall background levels, with modest differences emerging at energies above 1 MeV, particularly in the cosmic proton component. The higher secondary particle production observed in the optimized geometries compared to the baseline can be attributed to the different structural materials employed. While the baseline geometry uses aluminum for the crystal-holding structure, the optimized geometries incorporate Windform, a hydrocarbon-based material in which proton-proton interactions are more probable, leading to an enhanced production of low-energy secondaries that contribute to the deposited energy spectrum at energies well below the primary proton threshold. The application of the topological trigger to the intermediate-mass configuration results in a clear and systematic background reduction across the full energy range, demonstrating the effectiveness of spatial event-selection criteria in suppressing residual background contributions.

The material-dependent behavior follows similar trends for all geometries. The **LYSO:Ce**-only configuration yields the highest background level, primarily due to the higher density of **LYSO:Ce** compared to **GAGG:Ce**, which results in a greater photon interaction probability and thus higher background count rates. The hybrid **GAGG:Ce+LYSO:Ce** configuration significantly reduces the background at low energies, particularly below a few hundred keV, while preserving efficient photon detection. The fully **GAGG:Ce**-based configuration provides the lowest background levels in the low-energy regime. At higher energies, differences among crystal materials diminish, indicating that the background is increasingly governed by secondary particles rather than by scintillator composition.

Intrinsic radioactive background

Figure 5.10 shows the simulated intrinsic background spectrum for the baseline geometry, comparing the **LYSO:Ce**-only and the hybrid **GAGG:Ce+LYSO:Ce** material configurations under both basic and basic+topological trigger conditions. The **LYSO:Ce**-only configuration exhibits a significantly higher intrinsic background level, while the hybrid **GAGG:Ce+LYSO:Ce** configuration shows a reduction of nearly two orders of magnitude due to the reduced amount of **LYSO:Ce** in the detector volume. For comparison, the total

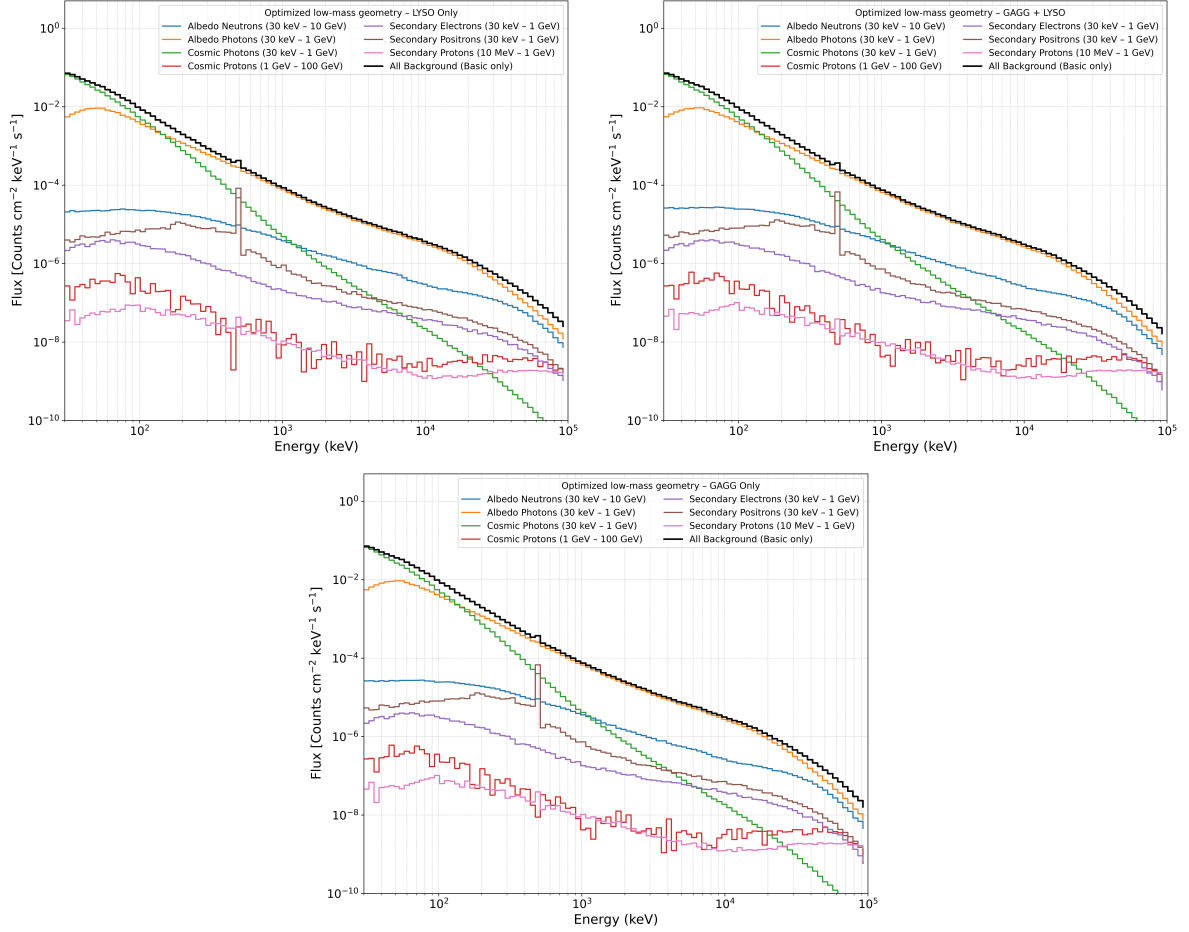


Figure 5.7: Simulated orbital background spectra for low-mass geometrical configuration using basic trigger conditions. The background spectra include contributions from the orbital background radiation components as described in the text.

orbital background is also shown for all three material configurations under both trigger conditions, demonstrating that the intrinsic background from **LYSO:Ce** dominates over the orbital background in the energy range of approximately 200–1200 keV.

The same analysis is repeated for the three optimized detector geometries — the low-mass, intermediate-mass, and high-mass geometries — in order to investigate the impact of detector geometry and total scintillator mass on the intrinsic background, as shown in Figure 5.11. All optimized geometries exhibit very similar spectral shapes, with a pronounced feature around 600 keV for configurations containing **LYSO:Ce**, while the hybrid **GAGG:Ce+LYSO:Ce** setups show substantially reduced intrinsic activity. The overall intrinsic background level scales approximately with the amount of **LYSO:Ce** present in each configuration, while differences among the optimized geometries remain modest.

Figure 5.12 presents a direct comparison between the baseline and an optimized detector geometry under identical trigger conditions. The optimized geometry exhibits a higher intrinsic background level than the baseline, which is consistent with its larger total crystal mass and increased number of pixels. Specifically, the baseline geometry comprises 112 pixels with a total crystal mass of 19.11 kg, whereas the optimized geometries contain 126 pixels with total masses ranging from 17.67 kg to 24.24 kg (see Table 5.1). Since the lower crystal layer consists of **LYSO:Ce** in all geometries, the greater number of pixels and larger crystal dimensions result in a higher total **LYSO:Ce** volume and consequently higher intrinsic radioactive activity. Nevertheless, when the topological trigger is applied, the intrinsic background level is substantially suppressed, with the average count rate above

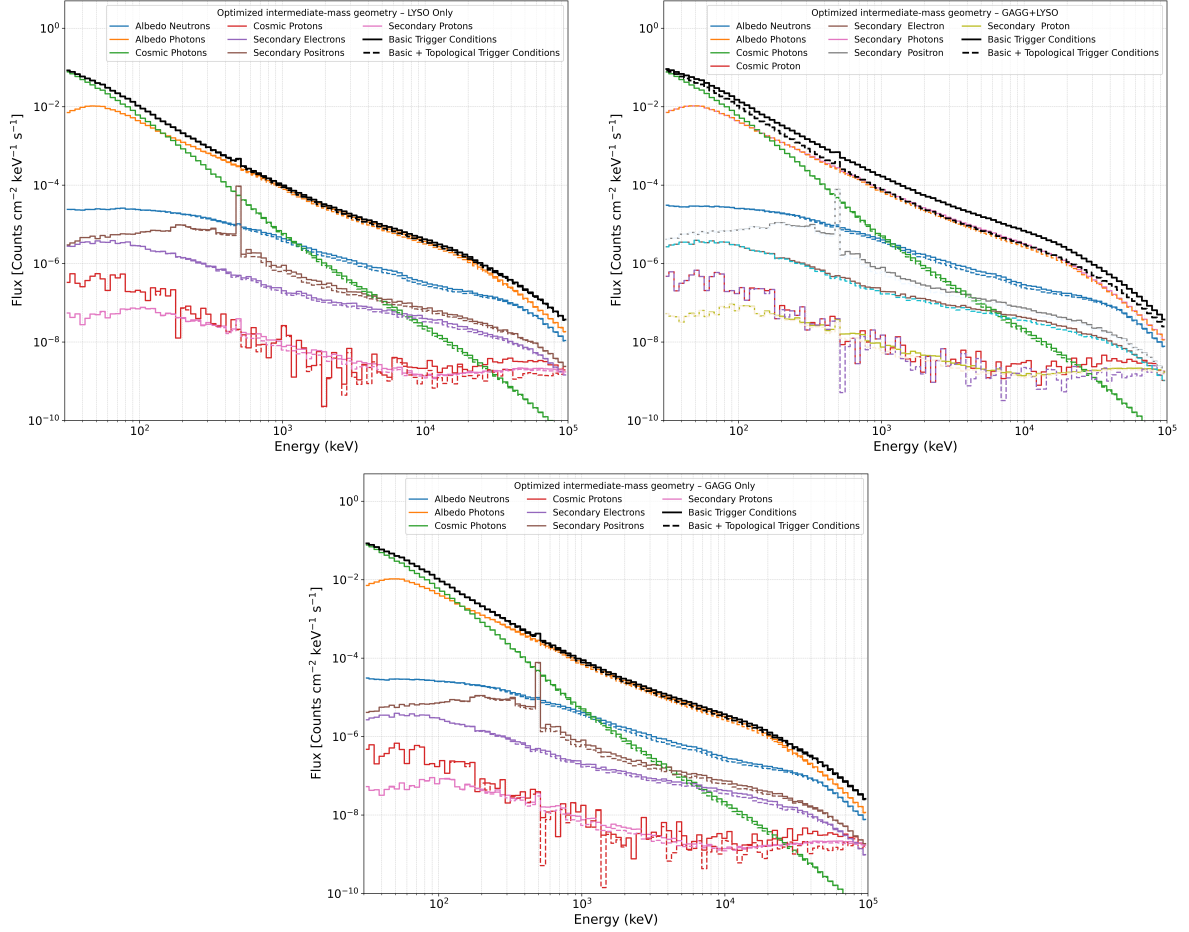


Figure 5.8: Simulated external background spectra for intermediate-mass geometrical configuration under both basic and basic + topological trigger conditions. The inclusion of the topological condition enhances background rejection over the entire energy range.

100 keV reduced by approximately one order of magnitude relative to the baseline geometry, approaching that expected for detector configurations dominated by non-radioactive scintillator material.

Overall, these results indicate that the intrinsic radioactive background is primarily governed by the scintillator material composition and the applied trigger strategy, while the effect of moderate variations in detector geometry and total scintillator mass among the optimized designs is comparatively small. The use of a hybrid **GAGG:Ce+LYSO:Ce** configuration, combined with topology-based event selection, is therefore effective in mitigating intrinsic background contributions without introducing strong geometry-dependent effects.

5.1.3 Sensitivity of the detector

This section presents the transient sensitivity analysis of the CE detector, following the methodology described in [58]. The objective is to determine the **MDF** for short high-energy transients, such as **GRBs**, under realistic orbital and intrinsic background conditions.

The transient sensitivity is evaluated using the same significance-based formalism introduced in Eq. (4.4), here denoted as ζ for consistency with the notation of [144, 58]:

$$\zeta = \frac{N_S}{\sqrt{N_S + N_B}}, \quad (5.2)$$

where N_S and N_B are the signal and background counts accumulated during an ob-

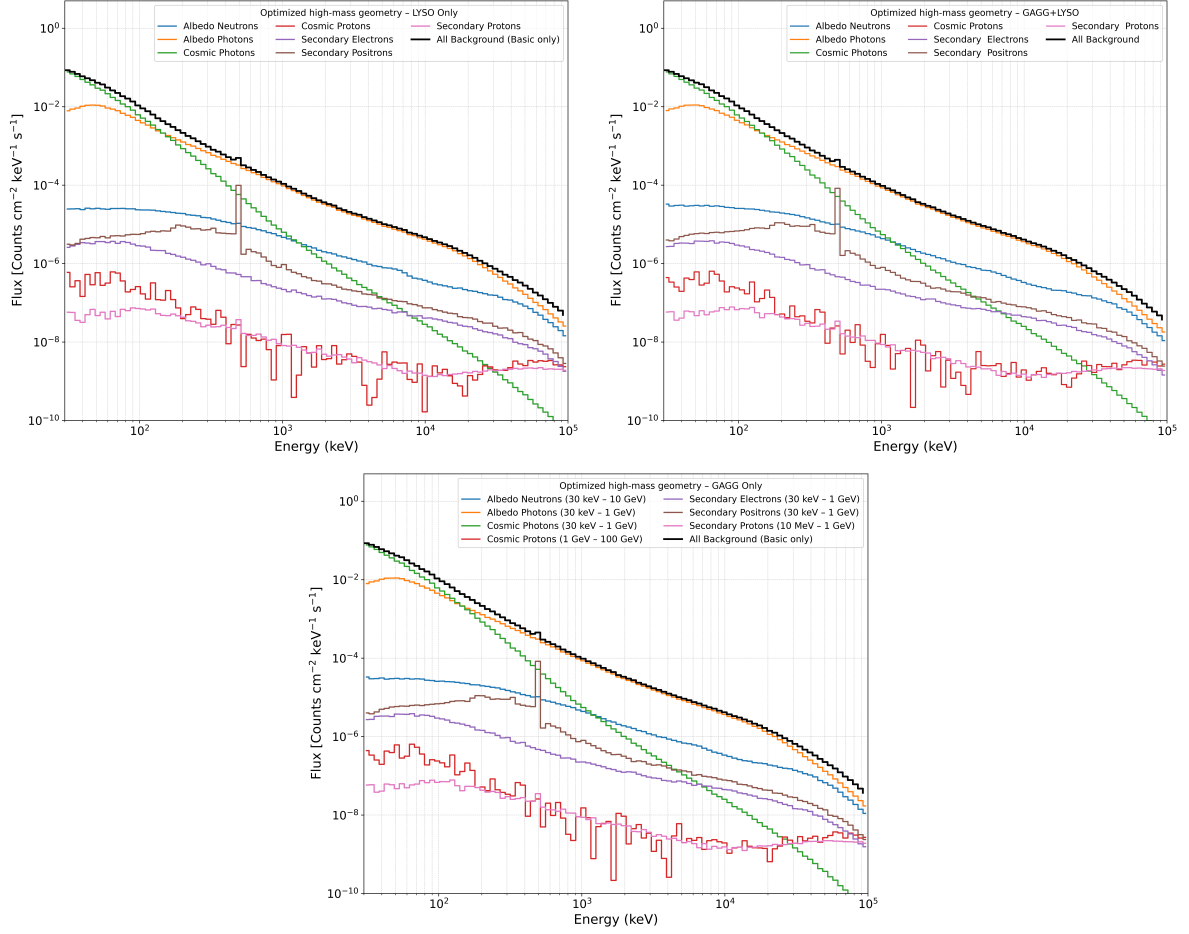


Figure 5.9: Simulated orbital background spectra for the high-mass geometry under basic trigger conditions, showing contributions from LYSO-only, hybrid GAGG+LYSO, and GAGG-only material configurations.

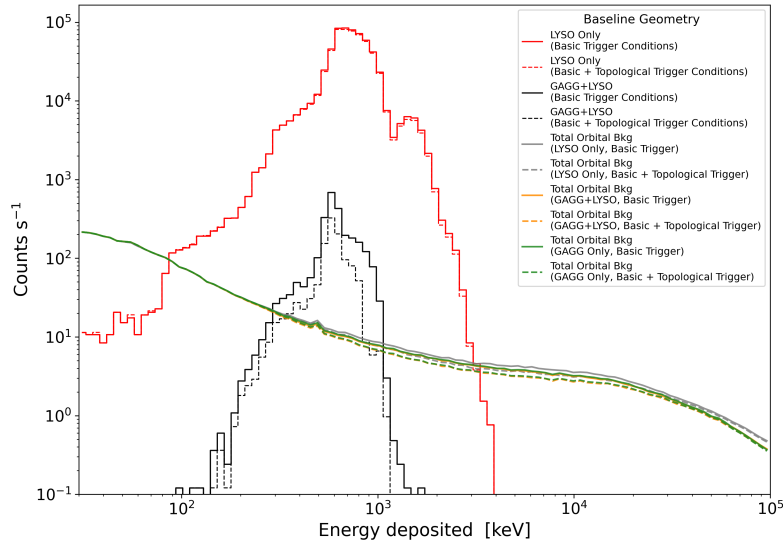


Figure 5.10: Simulated intrinsic background spectra for the baseline geometry under basic and basic+topological trigger conditions, with the total orbital background overlaid for comparison [58].

servation time ΔT . Solving Eq. 5.2 for the required signal counts in an energy bin E yields:

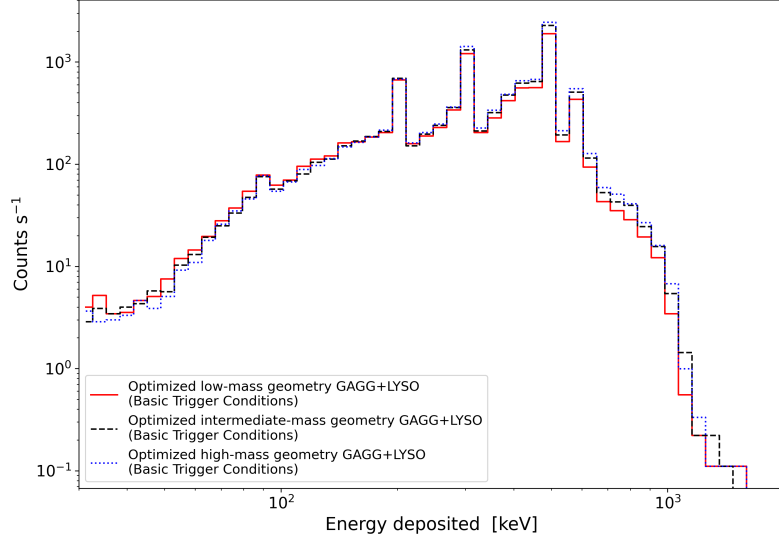


Figure 5.11: Intrinsic background spectra for the optimized low-mass, intermediate-mass, and high-mass detector geometries under identical trigger conditions.

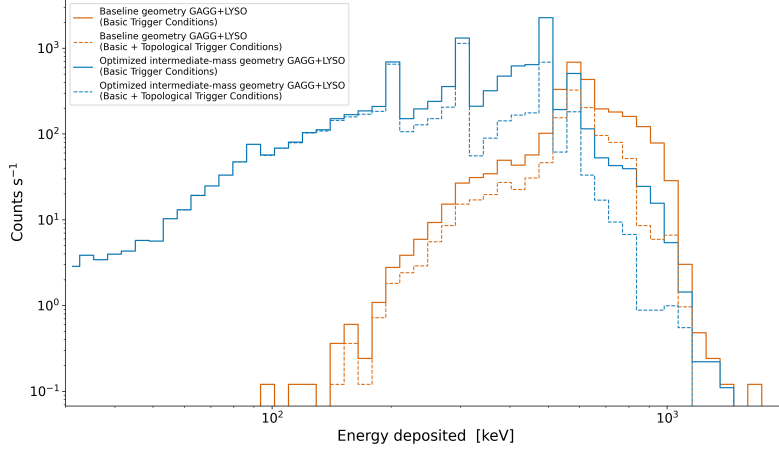


Figure 5.12: Comparison of intrinsic background spectra between the baseline geometry and an optimized detector geometry under identical trigger conditions.

$$N_S(E) = 0.5 \zeta^2 \left(1 + \sqrt{1 + \frac{4 N_B(E)}{\zeta^2}} \right), \quad (5.3)$$

and relating counts to flux gives the **MDF**, in the same form as Eq. (4.3):

$$\Phi_{\min, \text{trn}}(E) = 0.5 \frac{\zeta^2}{A_{\text{eff}}(E) \Delta E \Delta T} \left(1 + \sqrt{1 + \frac{4 B(E) \Delta T}{\zeta^2}} \right), \quad (5.4)$$

with effective area $A_{\text{eff}}(E)$, background rate $B(E)$ ($\text{counts s}^{-1} \text{keV}^{-1}$) and energy bin width ΔE .

As a reference, Figure 5.13 shows the sensitivity obtained for the reference or baseline detector geometry. The figure presents the **MDF** for both the **LYSO:Ce**-only and hybrid **GAGG:Ce+LYSO:Ce** material configurations, evaluated for integration times of $\Delta T = 2 \text{ s}$ and $\Delta T = 8 \text{ s}$, representative of short and long **GRBs**. Average **GRB** spectra derived from the Fermi-**GBM** catalog are overlaid for comparison, including the Band, Comptonized, and Comp-to-Band spectral models.

For short-duration GRBs, a comparison between the **LYSO:Ce**-only and hybrid **GAGG:Ce+LYSO:Ce** configurations shows that the two **MDF** curves are comparable at the lowest energies, indicating a similar detection threshold in the sub-100 keV range. As the energy increases, a clear divergence appears around $\sim 10^2$ keV, where the **MDF** of the **LYSO:Ce**-only configuration increases. The **LYSO:Ce**-only **MDF** exhibits a pronounced local maximum around $\sim 5 \times 10^2$ keV, reflecting the enhanced contribution of intrinsic background in this energy region. In contrast, the hybrid **GAGG:Ce+LYSO:Ce** configuration maintains a significantly lower **MDF** throughout the sub-MeV range, reducing the detection threshold by approximately one order of magnitude compared to the **LYSO:Ce**-only case. This improvement arises from replacing the upper **LYSO:Ce** layer with non-radioactive **GAGG:Ce**, which substantially suppresses intrinsic background contributions. Beyond approximately 3×10^3 keV, the **MDF** curves for the two configurations gradually converge and partially overlap, as intrinsic radioactivity becomes a sub-dominant contribution to the total background.

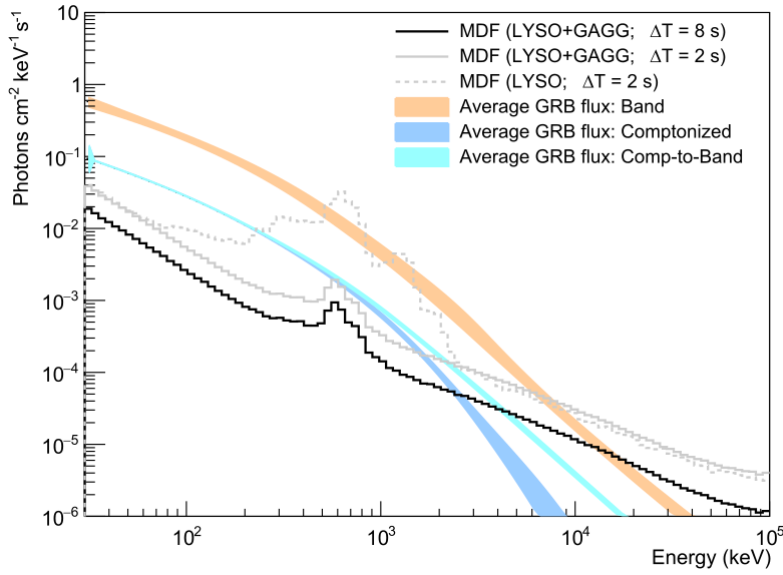


Figure 5.13: MDF for the baseline geometry, showing LYSO-only and GAGG+LYSO material configurations [58].

Building upon this reference case, the transient sensitivity was evaluated for the optimized intermediate-mass detector geometry. Simulations were performed by generating parallel photons from a flat source above the detector in the 30 keV–100 MeV energy range. Deposited energy was recorded in all active pixels using the same trigger and event-selection conditions adopted for the background studies, ensuring a consistent detector response.

The background term $N_B(E)$ was derived from simulations of the dominant orbital background components, as described in Section 5.1.2. Figure 5.5 shows the spatial distribution of background count rates from cosmic and albedo photons, neutrons, and secondary charged particles. The nearly uniform photon distributions confirm the isotropic response of the dome geometry, justifying the use of an average background rate in Eq. 5.4.

For the optimized intermediate-mass geometry, GRB spectra were modeled using the Band, Comptonized, and SBPL functions. Spectral parameters were extracted from a quality-selected subsample of the Fermi-GBM catalog, following the same selection procedure described in Section 4.6, yielding a total of 892 GRBs retained for the sensitivity analysis, comprising 848 Comptonized, 30 Band, and 14 SBPL models. Figure 5.14 shows the resulting **MDF** curves for the hybrid **GAGG:Ce+LYSO:Ce** configuration under combined

basic+topological trigger conditions, with the average spectra for each model overlaid for comparison.

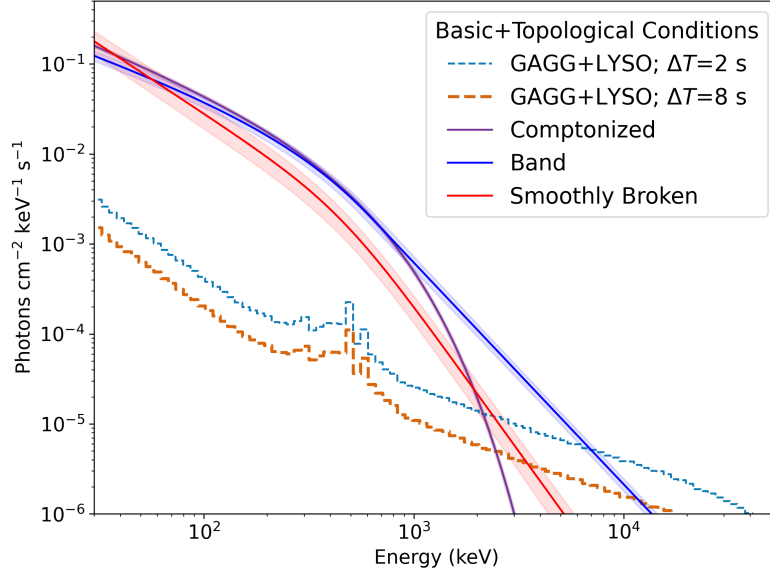


Figure 5.14: MDF for the optimized intermediate-mass detector geometry with the hybrid GAGG+LYSO material configuration, under basic and basic+topological trigger conditions.

For the hybrid **GAGG:Ce+LYSO:Ce** configuration, the transient sensitivity reaches values of approximately $\sim 3 \times 10^{-4}$ ph/s/cm²/keV in the 400–600 keV energy range for short-duration **GRBs**. A similar behavior is observed for long-duration **GRBs**, with sensitivity curves following the same trend and exhibiting a comparable overall decrease across the considered energy range.

Additional simulations were carried out for the optimized low-mass and high-mass geometries to assess the impact of geometric variations on transient sensitivity. Both geometries were evaluated under basic trigger conditions only. Figure 5.15 shows that the resulting **MDF** curves follow the same general behavior observed for the intermediate-mass configuration, confirming that the sensitivity trends are largely preserved across the optimized detector family.

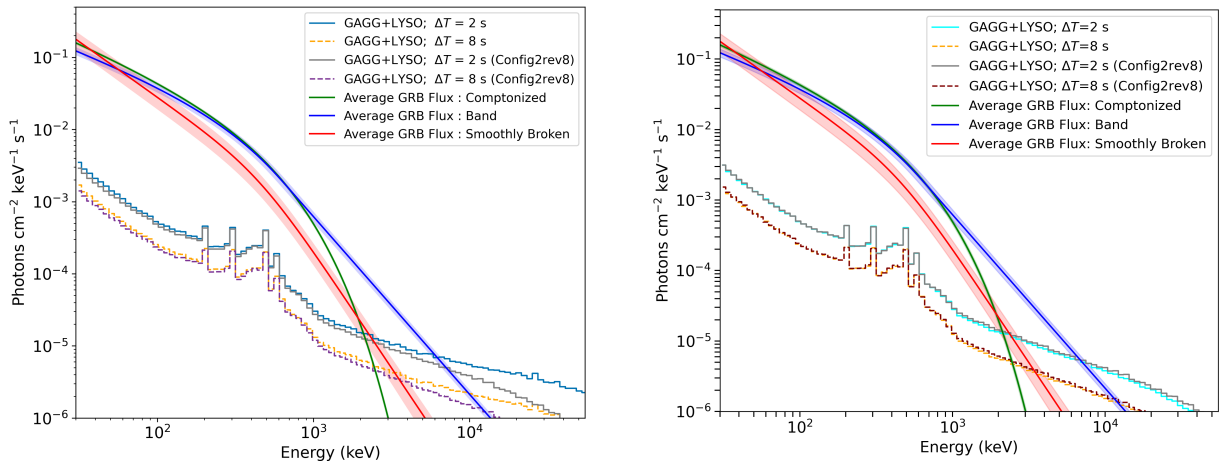


Figure 5.15: MDF for the optimized low-mass (left) and high-mass (right) detector geometries under basic trigger conditions.

Overall, the sensitivity results indicate that the hybrid **GAGG:Ce+LYSO:Ce** material

configuration substantially improves the detection threshold relative to **LYSO:Ce**-only designs, particularly below 1 MeV, where intrinsic background effects are most significant. Across the optimized detector geometries, differences in transient sensitivity remain modest, indicating that material composition and trigger strategy play a more dominant role than moderate geometric variations. Within this optimized framework, the CE detector achieves a transient sensitivity sufficient to detect a substantial fraction of Fermi-**GBM GRBs** above a 3σ significance level. As reported in [58], the CE detector achieves comparable, and in general lower, detection threshold fluxes than those reported for AMEGO-X [144] in a similar energy range for a fiducial **GRB** model.

A **SNR** analysis was performed to assess how many **GRBs** from the Fermi-**GBM** catalog would be detectable by the CE detector for the optimized geometries. Following the methodology described in [58], the S/N was computed over the 30 keV–100 MeV energy range assuming a Comptonized spectral model for a sample of 3588 **GRBs** from the Fermi-**GBM** catalog, selected as described in Section 4.6, adopting an observation time $\Delta T = 2$ s representative of short-duration **GRBs**. This choice provides a conservative estimate of the high-energy flux and ensures a uniform comparison across the **GRB** population.

Figure 5.16 shows the resulting S/N distributions for the optimized low-mass, intermediate-mass, and high-mass detector geometries, all evaluated using the hybrid **GAGG:Ce+LYSO:Ce** material configuration under basic trigger conditions. The distributions exhibit similar shapes across the three geometries, indicating a stable detector response at the population level. Only modest shifts in the peak position are observed, reflecting minor variations in effective area and background levels associated with the different geometrical designs.

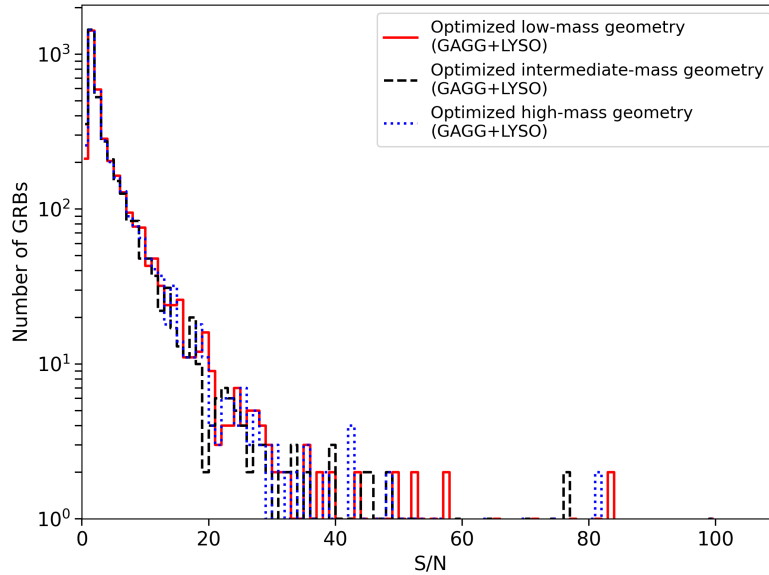


Figure 5.16: S/N distributions for 3588 Fermi-GBM GRBs for the optimized low-mass, intermediate-mass, and high-mass geometries with the hybrid GAGG+LYSO configuration ($\Delta T = 2$ s); bursts with $S/N > 100$ are accumulated in the last bin.

Overall, the similarity of the S/N distributions demonstrates that, for the hybrid **GAGG:Ce+LYSO:Ce** configuration, the optimized detector geometries provide comparable detection capabilities for **GRBs**. This confirms that moderate geometric refinements within the optimized design family do not significantly impact the performance, and that the detector sensitivity is primarily driven by material choice and trigger strategy rather than small structural variations.

5.2 Source localization

The CE detector has been designed to perform localization of transient events such as **GRBs**. The localization capability arises from the anisotropic illumination pattern produced by incoming photons across the hemispherical array of scintillator pixels. By comparing this measured count distribution with a precomputed library of simulated response maps (templates) corresponding to different sky directions, the source direction can be statistically reconstructed.

The localization algorithm implemented in [58] is fully template-based and employs the Kolmogorov–Smirnov (KS) test to quantify the similarity between the observed pixel map and each simulated template. Two nearly isotropic template grids were generated to explore the trade-off between accuracy and computational cost:

- a coarse grid with 5° angular spacing (742 templates), and
- a fine grid with 2° spacing (4980 templates).

The localization algorithm relies on a discrete set of simulated template directions that uniformly sample the detector hemisphere. Each template corresponds to the expected energy-deposition pattern in the scintillator pixels for a source located at a known sky direction. The ensemble of templates therefore defines a reference grid of possible source locations against which unknown events are compared. Figure 5.17 illustrates the hemispherical distribution of the template directions used in the reconstruction.

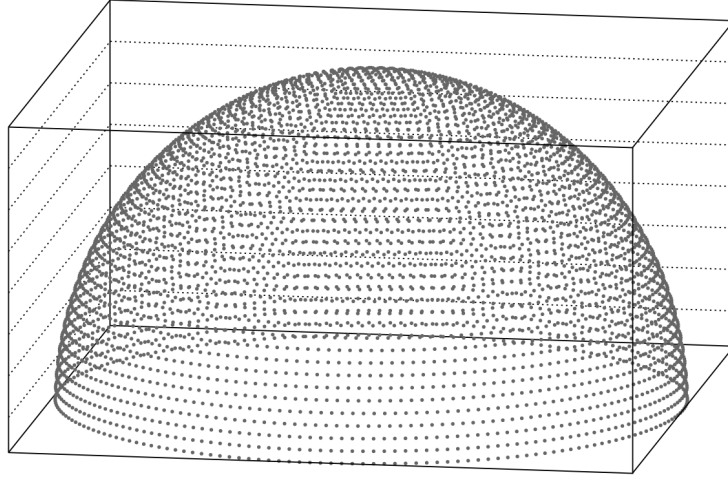


Figure 5.17: Hemispherical distribution of template source directions used in the template-based localization algorithm. Each point corresponds to a simulated source location defining the discrete sky grid against which unknown events are compared (Image courtesy of the CE Collaboration).

The finer grid provides improved directional precision by reducing the angular separation between neighboring template directions, at the cost of increased computational complexity.

Since the spatial pattern of pixel illumination depends on the source spectrum, each template was re-weighted using the incident spectrum of the simulated **GRB**, obtained approximately by dividing the detected count rates by the detector’s effective area in each energy bin. Although this approximation neglects partial energy depositions, it provides a sufficiently accurate unfolding for fully contained events. The normalized templates were then compared with the sample pixel map using the KS test, yielding a discrete probability distribution over the set of template sky directions.

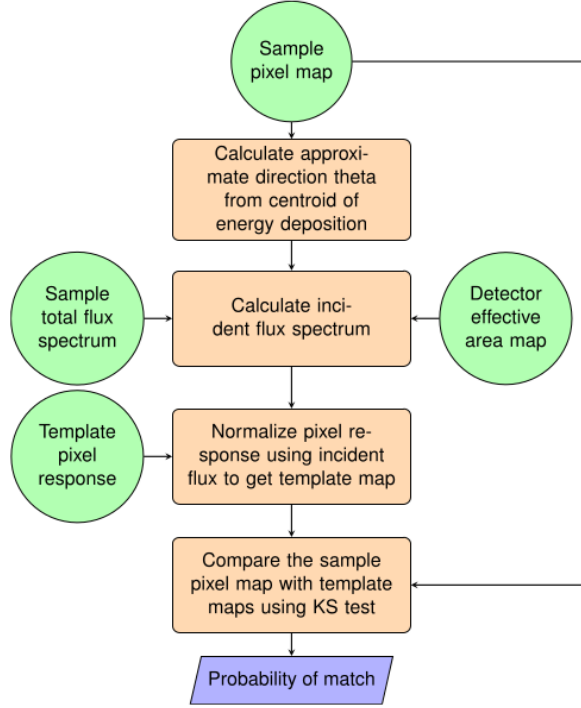


Figure 5.18: Flowchart of the direction reconstruction algorithm [58].

Figure 5.18 outlines the step-by-step direction reconstruction procedure. The algorithm begins with the construction of the sample pixel map from the detected event. An approximate source direction θ is first estimated from the centroid of the energy deposition pattern across the pixels. The sample total flux spectrum is then used to calculate the incident flux spectrum, which is obtained by dividing the detected count rates by the detector effective area map in each energy bin. This incident spectrum is subsequently used to normalize the template pixel response, producing a re-weighted template map that accounts for the spectral dependence of the pixel illumination pattern. Finally, the re-normalized template map is compared with the sample pixel map using the Kolmogorov–Smirnov (KS) test, yielding a probability of match for each template direction. The template direction with the highest matching probability, combined with a weighted average of the surrounding high-probability templates, gives the final reconstructed source direction.

For each transient event, the probability obtained from the KS test was stored as a function of the template sky coordinates. An example of this two-dimensional probability distribution is shown in the left panel of Figure 5.19, where the probability peaks cluster around the true source direction at $(\theta, \phi) = (42.83^\circ, 139.50^\circ)$. The final reconstructed position corresponds to the weighted average of the templates with the highest probabilities.

To evaluate localization accuracy, approximately 1000 independent sources were simulated from random sky directions and reconstructed using both template grids. The resulting angular deviations between true and reconstructed directions were compiled into the distributions shown in right panel of Figure 5.19. By integrating these histograms, the 68% and 95% containment radii were derived, corresponding to $r_{68} = 1.45^\circ$ and $r_{95} = 2.75^\circ$ for the 2° grid, with only marginal improvement for denser grids.

As a validation example, the well-known binary neutron star merger event of 2017, GRB170817A/GW170817, is used to demonstrate the localization capability of CE, as shown in Figure 5.20. The skymap displays the 68% (darker red) and 95% (lighter red) localization regions predicted by CE, together with the Fermi-GBM and LIGO 90% confidence contours. The Fermi-GBM onboard localization uncertainty for GRBs is typically of the order of

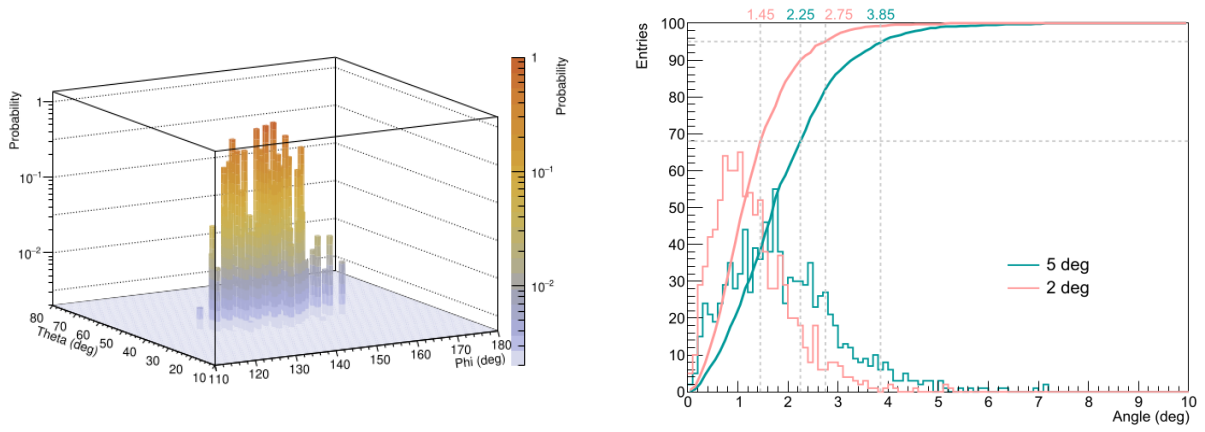


Figure 5.19: Left: probability distribution of a sample source using the 2° localization algorithm. Right: angular deviation distribution for direction reconstruction with 68%/95% confidence levels for both 2°/5° templates [58].

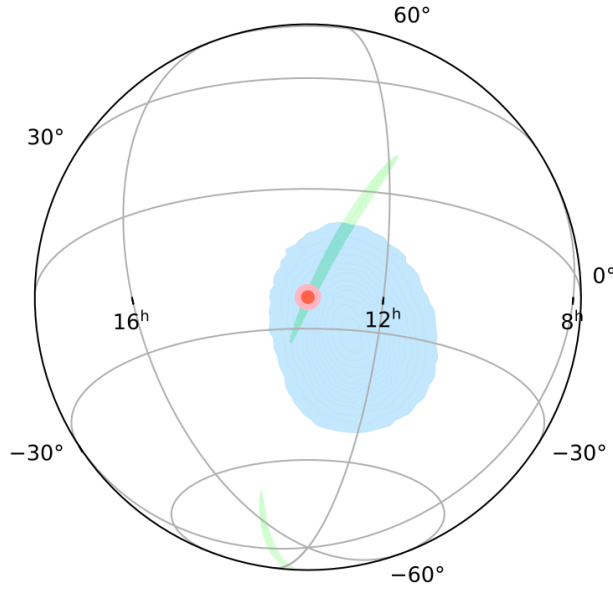


Figure 5.20: Skymap showing the Fermi-GBM 90% C.L. localization region (blue shaded region) and the LIGO 90% C.L. localization region (green strip) for GRB 170817A/GW170817 [116], along with the 68% (darker red) and 95% (lighter red) C.L. localization uncertainty regions corresponding to the CE prediction [58].

9°–15° [30], whereas the CE prediction achieves a 95% containment radius of 2.75°. This represents an improvement of nearly an order of magnitude in localization precision, and the overlap between the CE, Fermi-GBM, and LIGO regions further confirms the compatibility of the simulated CE localization with real observational data.

Overall, the results demonstrate that CE can reconstruct transient directions with better than 3° accuracy (95% confidence) within a few seconds of onboard computation. This level of performance suggests that CE could deliver rapid alerts to multi-messenger networks such as GCN, enabling prompt follow-up observations of short GRBs and other high-energy transients.

5.3 Comparative assessment and selection of the optimized detector geometry

The comparative study of the CE detector geometries focused on the baseline geometry and three optimized detector geometries, namely the low-mass, intermediate-mass, and high-mass geometries. The reference geometry serves as a baseline for performance comparison, while all optimized geometries demonstrate improved effective area and sensitivity, with background levels remaining comparable to the baseline design.

Among the optimized geometries, the high-mass configuration achieves the largest effective area and slightly enhanced sensitivity. However, these performance gains are marginal when compared to those obtained with the intermediate-mass configuration. The intermediate-mass configuration exhibits effective area, background response, sensitivity to **GRBs**, and localization performance that are comparable to those of the high-mass design. In particular, the localization accuracy of optimized intermediate-mass geometry is indistinguishable from that of optimized high-mass geometry within the systematic uncertainties of the simulation framework.

Given that detector mass and mechanical complexity are critical constraints for space-based instruments, the intermediate-mass configuration provides a more balanced solution. It preserves the performance benefits of the high-mass design while avoiding the additional material burden and structural complexity associated with the heaviest configuration.

For these reasons, intermediate-mass geometrical configuration is identified as the optimized reference geometry for the CE detector, representing a realistic and efficient compromise between scientific performance and practical implementation constraints.

Conclusion

This thesis has presented a simulation-based performance evaluation of two compact space-based instruments designed for **GRB** detection in the MeV energy range, the CALOg calorimeter of the Zirè instrument onboard the NUSES mission and the Crystal Eye all-sky monitor.

The intrinsic radioactive background of **LYSO:Ce**, arising from the natural decay of ^{176}Lu , was characterized through Geant4 Monte Carlo simulations, revealing a persistent internal background spectrum with a pronounced feature near 600 keV. A comparative effective area analysis demonstrated that **GAGG:Ce** and **LYSO:Ce** yield nearly equivalent detection performance across the full energy range of interest, with the combined effective area exceeding 100 cm^2 over a broad interval for the horizontal acceptance window. Since the two materials perform comparably in terms of detection efficiency, the key differentiator is the absence of intrinsic radioactivity in **GAGG:Ce**, which motivated its adoption as the baseline scintillator for CALOg. It should be noted that the laboratory characterization of the ^{176}Lu background presented in Chapter 2 was not used to validate the Geant4 simulation chain; this comparison is left to future work.

The transient sensitivity of CALOg was evaluated. The detector retains sensitivity in the energy range from a few hundred keV to approximately 1 MeV, overlapping the spectral region where a large fraction of **GRBs** emit most strongly. A sliding-window trigger algorithm was optimized, achieving a detection latency of approximately 0.5 s with a maximum signal-to-noise ratio of 16 for an average **GRB** flux.

The Crystal Eye detector was evaluated across four geometrical configurations and three scintillator material compositions. The hybrid **GAGG:Ce+LYSO:Ce** configuration, with **GAGG:Ce** crystals in the upper detector layer and **LYSO:Ce** in the lower layer, was adopted as the reference material choice. Although a **GAGG:Ce**-only configuration achieves a comparable effective area and background level, retaining a **LYSO:Ce** layer preserves a usable ^{176}Lu self-calibration line and provides more efficient absorption of high-energy photons (see Section 5.1.1). This configuration reduces the intrinsic radioactive background by nearly two orders of magnitude relative to the **LYSO:Ce**-only baseline, while preserving detection efficiency. The intrinsic **LYSO:Ce** background was shown to dominate over the orbital background in the 200–1200 keV energy range for all-**LYSO:Ce** configurations, confirming the importance of material selection for sub-MeV sensitivity.

The optimized geometry achieves a **MDF** of approximately $3 \times 10^{-4}\text{ ph s}^{-1}\text{ cm}^{-2}\text{ keV}^{-1}$ in the 400–600 keV energy range. The template-based Kolmogorov–Smirnov source localization pipeline yields a 95% containment radius of $r_{95} \approx 2.75^\circ$, suggesting the capability of Crystal Eye to deliver rapid sky localizations suitable for multi-messenger follow-up. It should be noted, however, that this figure is obtained from simulations of an idealized instrument and cannot be compared directly with the measured in-flight localization performance of Fermi-**GBM**; the projected value of r_{95} therefore carries a systematic margin that would need to be quantified through end-to-end validation against real data.

The results of this thesis indicate that significant advances in MeV-band **GRB** detection are achievable within the constraints of compact satellite platforms. The performance

gains realized through careful scintillator material selection, in particular the adoption of radiopure **GAGG:Ce** and the hybrid **GAGG:Ce+LYSO:Ce** layering strategy, establish a practical path toward significantly improved sensitivity and localization in the least explored region of the gamma-ray spectrum.

List of Abbreviations

- ACD** Anti-Coincidence Detector. 43, 56–58, 85, 89, 90
- ACS** Anti-Coincidence System. 43, 45, 49–51, 62, 63, 82
- BAT** Burst Alert Telescope. 8, 76, 86
- BATSE** Burst And Transient Space Experiment. 7, 11, 13, 14, 16–19, 22
- BDT** Boosted Decision Tree. 66, 68, 69, 82
- BGO** Bismuth Germanate Oxide. 8, 21–23, 64
- CGRO** Compton Gamma-Ray Observatory. 7, 16–18, 22
- COMPTEL** Imaging Compton Telescope. 16, 18, 19
- COSI** Compton Spectrometer and Imager. 19, 20
- CPL** Comptonized Power Law. 11, 12
- CsI** Cesium Iodide. 21–23
- ESA** European Space Agency. 18
- FGST** Fermi Gamma-ray Space Telescope. 8, 12, 14, 22
- FTK** Fiber Tracker. 43, 45–47, 49, 51
- GAGG:Ce** Cerium-doped Gadolinium Aluminium Gallium Garnet. 4, 20–23, 27–29, 49, 51, 54, 56, 59, 61, 64, 65, 82, 84, 85, 87, 88, 92–95, 97–100, 105, 106
- GBM** Gamma-ray Burst Monitor. 8, 12, 16–19, 22, 54, 64, 76–79, 82, 86, 97, 98, 100, 102, 103, 105
- GECAM** Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor. 18, 19
- GRB** Gamma-ray burst. 4, 6–13, 15–17, 19, 20, 24, 45, 54, 58, 59, 61, 62, 68, 76–83, 95, 97–105
- GRM** Gamma-Ray Monitor. 19
- HPGe** High Purity Germanium. 4, 21, 26, 29–33, 35–37
- IBIS** Imager on-Board the INTEGRAL Satellite. 8, 22

IC Inverse Compton. 15, 16

INTEGRAL INTErnational Gamma-Ray Astrophysics Laboratory. 8, 16, 19, 22, 54

ISM Interstellar Medium. 9, 10

LaBr₃:Ce Cerium-doped Lanthanum Bromide. 19

LAT Large Area Telescope. 8, 9, 12, 15, 16, 18, 22

LEM Low-Energy Module. 53

LYSO:Ce Lutetium Yttrium Oxyorthosilicate. 4, 5, 20–35, 37–42, 54, 56, 58, 59, 61, 62, 64, 65, 67–70, 82, 84–88, 92–95, 97–100, 105, 106

MDF Minimum Detection Flux. 4, 62, 77–79, 95, 97–99, 105

NaI Sodium Iodide. 8, 17, 19, 21–24, 64

NUSES NeUtrino and Seismic Electromagnetic Signals. 4, 17, 20, 29, 43, 44, 58–60, 73, 77, 81, 82

PL Power Law. 11, 12

PMT Photomultiplier Tube. 19, 23, 24, 43, 44, 51

PST Plastic Scintillator Tower. 43, 45, 47, 48, 50, 51

SAA South Atlantic Anomaly. 70, 71, 76, 82

SBPL Smoothly Broken Power Law. 11, 12, 98

SiPM Silicon Photomultiplier. 4, 19–21, 23–25, 27, 38, 41, 43, 44, 51–53, 55, 57, 59, 61

SNR Signal-to-Noise Ratio. 4, 76, 79, 100

SPI SPectrometer of INTEGRAL. 8

SSC Synchrotron Self-Compton. 15, 16

SVOM Space Variable Object Monitor. 18, 19

UVOT Ultra-violet/Optical Telescope. 8

XRT X-Ray Telescope. 8, 18

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