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# Gamma Rays from Space

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## Abstract

An overview of gamma rays from space is presented. We highlight the most powerful astrophysical explosions, known as gamma-ray bursts. The main features observed in detectors onboard satellites are indicated. In addition, we also highlight a chronological description of the efforts made to observe their high energy counterpart at ground level. Some candidates of the GeV counterpart of gamma-ray bursts, observed by Tupi telescopes, are also presented.

**Keywords:** gamma-ray astrophysics, cosmic rays, particle detectors

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## 1. Introduction

Gamma rays are the most energetic form of electromagnetic radiation, with a very short wavelength of less than 0.1 nm. Gamma radiation is one of the three types of natural radioactivity discovered by Becquerel in 1896. Gamma rays were first observed in 1900 by the French chemist Paul Villard when he was investigating radiation from radium [1].

They are emitted by a nucleus in an excited state. The emission of gamma rays does not alter the number of protons or neutrons in the nucleus. Gamma emission frequently follows beta decay, alpha decay, and other nuclear decay processes.

On the other hand, cosmic-ray particles (mostly protons) that arrive at the top of the Earth's atmosphere are termed primaries; their collisions with atmospheric nuclei give rise to secondaries. These secondary particles are constituted by pions (subatomic particles); the dominant decay of a neutral pion is the electromagnetic decay in two photons (two gamma rays). This process is the origin of the highest energy gamma rays.

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Nowadays, the artificial production of pions (and consequently gamma rays) in N-N collisions is produced copiously. The artificial production of pions started in 1948, with Lattes and Gadner using the 184-inch synchrocyclotron at Lawrence Berkeley National Laboratory (California) which accelerated protons to 350 MeV [2, 3].

As gamma rays coming from space are absorbed by the Earth's atmosphere, the first detection of gamma rays coming from space was through satellites. Indeed, the Explorer satellite in 1961 confirmed the existence of gamma rays in space [4]. Gamma rays coming from space have frequencies greater than about  $10^{18}$  Hz; they occupy the same region of the electromagnetic spectrum as hard X-rays or above them. The only difference between them is their source: X-rays are produced by accelerating electrons, whereas gamma rays are produced by atomic nuclei decays and/or nuclear collisions.

There is a large variety of gamma-ray sources from space: the most important is the Sun's transient activity, such as solar flares and coronal mass ejection (CME). This means that there is also a "gamma-ray background" due to other stars in our galaxy and from the stars of other galaxies, as well as that expected from the interaction of cosmic rays (very energetically charged particles in space) with interstellar gas. There are also sources of gamma rays with continuous emission, or long-lived gamma-ray emission from compact sources. This emission is in the high-energy region from GeV to TeV. The Fermi Large Area Telescope (LAT) produced an inventory of 1873 objects shining in gamma-ray light [5].

The most intense are the galactic objects, such as the Crab nebula (Taurus constellation) and the W44 nebula (Aquila constellation), both two supernova remnants. There are also bright extragalactic objects, such as the objects called active galactic nuclei (AGN); the most bright are the so-called Markarian 501 and 421 AGNs. These extragalactic objects were discovered by a ground-based gamma-ray telescope, the "air Cherenkov" Whipple telescope [6], confirmed by telescopes mounted on satellites.

Gamma-ray bursts (GRBs) are the most energetic explosions in the Universe: they are bright flashes of gamma rays for a short period of time, in most cases less than 100 s, with a photon's flux of around  $0.1\text{--}100$  ph/cm<sup>2</sup>/s/keV at Earth. There is some evidence that indicates that a GRB of long duration (i.e., above 2 s). They are associated with exploding massive stars called as Hypernovas. The signature of these explosions is two opposing beams of gamma rays and if any one of these beams is in the Earth's direction, we will see the gamma-ray burst.

In addition, sometimes, several narrow lines are detected; this radiation comes from the material around the explosion that was excited by the blast and that permits the detection of its host galaxy. However, sometimes, no narrow gamma-ray lines are detected, especially in GRBs of short duration (less than 2 s), meaning that some of these bursts come from different progenitors, such as merging compact objects such as black holes or neutron stars, or perhaps from a massive star explosion, but without the formation of a supernova.

In most cases, the gamma rays from GRBs, observed by space crafts, have energies in the keV region; a fraction has photons in the MeV region, called a high-energy counterpart. In some cases, photons can reach energies up to several dozen of GeV. In this case, the photons have sufficient energy to produce other particles when they reach the upper atmosphere, i.e., particles in the air, forming showers via cascading processes. This suggests the possibility of detecting gammas from the ground level, at least those that are more energetic and relatively long-term.

Despite great efforts for the systematic observation of GRBs at ground level, the results have been negative. However, a few events have been detected with a high significance, by the Tupi experiment in Brazil. They are considered as good candidates. Here, in addition to giving an overview of the GRBs, we will highlight these remarks (i.e., the Tupi events) and their implications on GRB physics.

## 2. General features of GRBs

The first scientific paper on GRBs was published in 1973 [7]. This paper reported the observation of 73 GRBs, starting on 2 July 1967, based on data from US satellites (Vela project) designed to monitor Russian nuclear weapon tests in space.

However, this first work did not answer several fundamental questions on the origin and nature of GRBs; for instance, are they from the solar system, Galactic halo, or are they extragalactic objects?

The mystery persisted until 1998, when the first spatial distribution of GRBs came from BATSE gamma detector and the more energetic (MeV to GeV) by EGRET, both onboard the Compton Gamma-Ray Observatory (CGRO). It was one of the best space observatories for detecting gamma rays from 20 keV to 30 GeV in Earth's orbit from 1991–2000. The BATSE instrument detected gamma-ray burst, at a rate of one per day, with a total of approximately 2700 detections. An isotropic sky distribution of GRBs was reported by BATSE. This means an extragalactic origin for the GRBs.

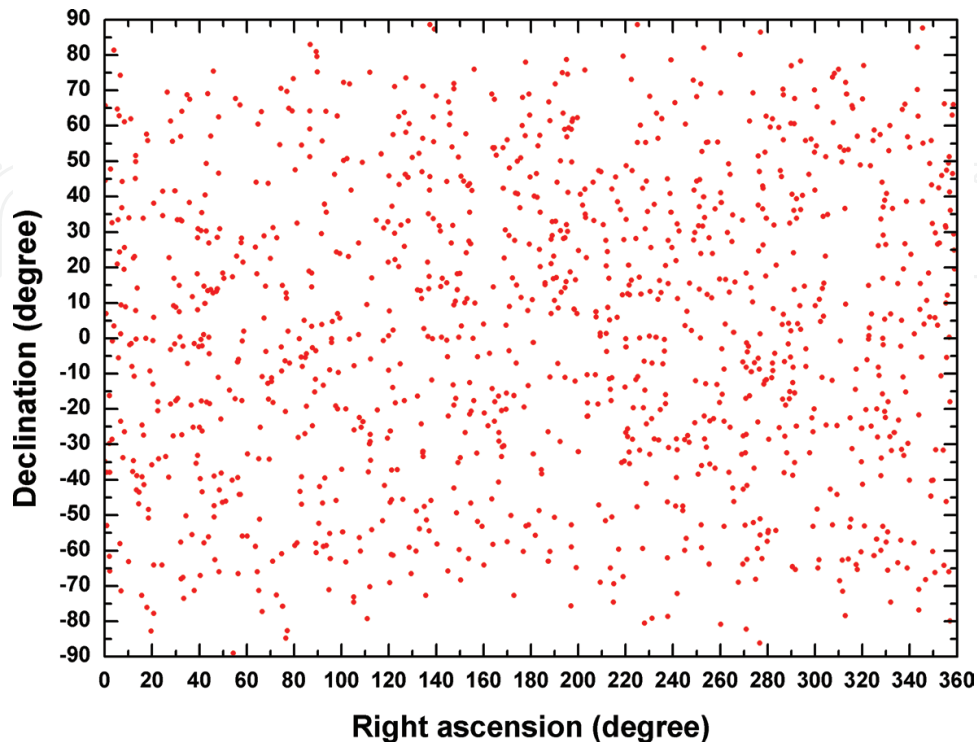
These observations were confirmed by new observations made by the new generations of GRBs detectors onboard satellites, such as the Swift, which is a multiwavelength GRB detector [8] with a wide field of view being able detect more than 100 GRBs per year. Swift has the Burst Alert Telescope (BAT) which covers the 15–150 keV energy band, the X-ray telescope (XRT), and an ultraviolet and optical telescope (UVOT) to detect X-ray and UV optical afterglows.

Swift has several online (free access) catalogs of GRBs. **Figure 1** shows the location in the sky (equatorial coordinate system) of 1188 Swift GRBs, detected from 17 December 2004 to 25 May 2016.

Thus, Swift confirmed the isotropic distribution of GRBs.

However, only the discovery of the first X-ray afterglows in 1998 by the BeppoSax satellite [9] allowed the accurate positions and the identification of the  $\gamma$ -ray afterglow with 'normal'

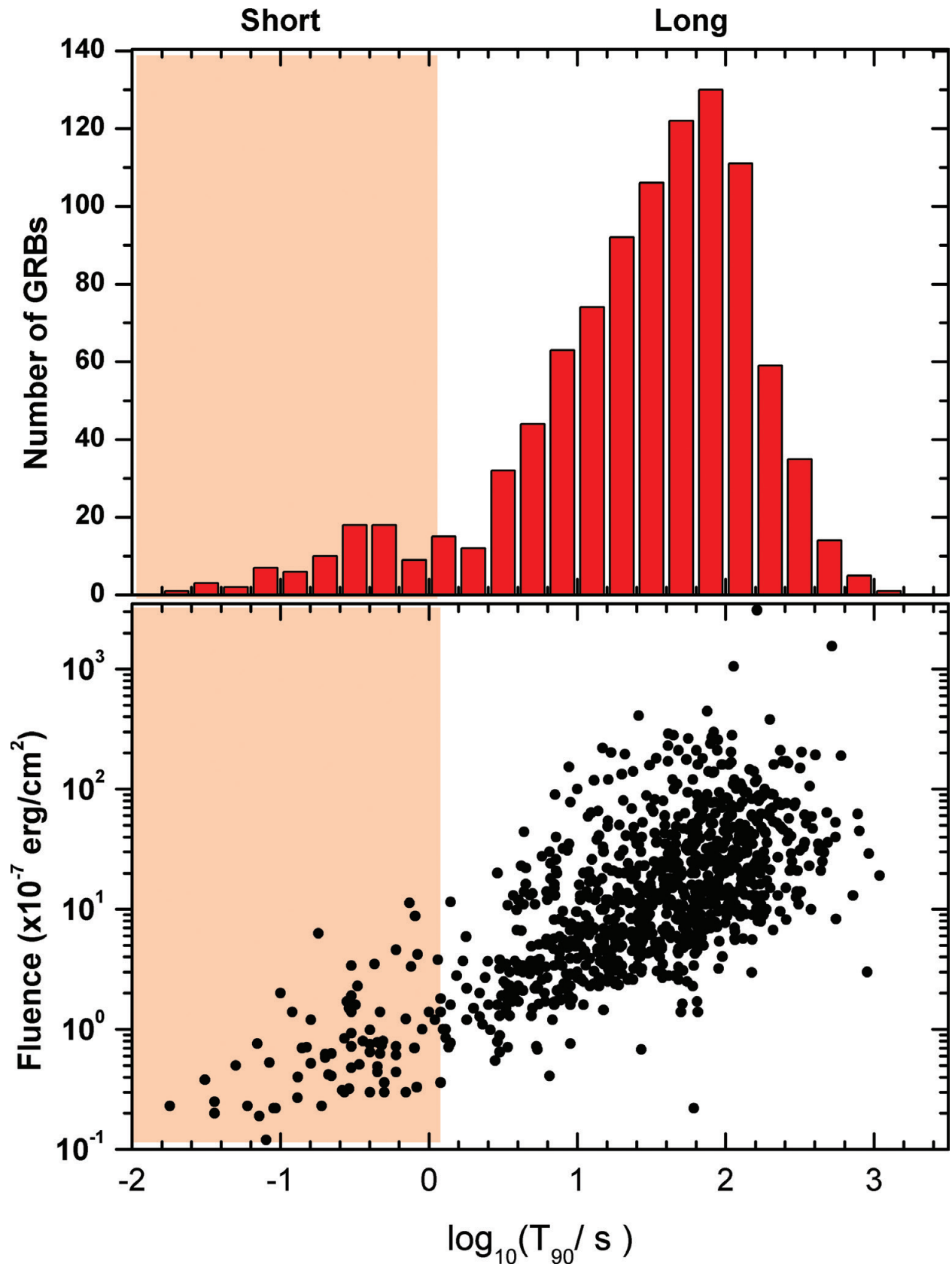
galaxies to be obtained. It was also possible to obtain the redshifts and consequently their distances, confirming that GRBs have a cosmological origin.



**Figure 1.** Location in the sky (equatorial coordinate system) of 1188 Swift GRBs, detected from 17 December 2004 to 25 May 2016.

It was also the BATSE gamma detector onboard the CGRO that showed that there are two different types of GRBs; that is, GRBs are separated into two classes: long-duration bursts, normally from 2 to 500 s, with an average duration of about 30 s; and short-duration bursts, ranging from a few ms to 2 s, with an average duration of only 0.3 s, following a bimodal distribution. They are not small and large versions of the same phenomenon; the two types of bursts have completely different sources. The origin of long-duration bursts is linked to supernovae explosions of massive stars (with masses 100 times greater than the solar mass), called hypernovae. Short-duration bursts are linked to the merging of two objects, such as two neutron stars, or a neutron star and a black hole, or two black holes.

This bimodal distribution was also confirmed by Swift as shown in **Figure 2** (top panel). The figure includes also a scatter plot (bottom panel), a correlation between the T90 duration of the GRB and the integrated time fluence. T90 is defined as the time interval over which 90% of the total background-subtracted counts are observed, with the interval starting when 5% of the total counts have been observed. In addition, the integrated time fluence is the energy deposited on the detector per unit area, during the T90 duration of the GRBs. If the distance of the source of the GRB is determined, this last quantity allows estimate the energy released during the explosion. The energy output of GRBs on some cases, if spherically radiated is above  $10^{54}$  erg. This exceeds any reasonable source during such a short timescale, so the radiation is likely highly beamed.



**Figure 2.** Top panel: bimodal classification of Swift GRBs, as short and long. Bottom panel: correlation between the  $T_{90}$  duration of the GRBs and the integrated time fluence, on the basis of 1188 Swift GRBs, detected from 17 December 2004 to 25 May 2016.

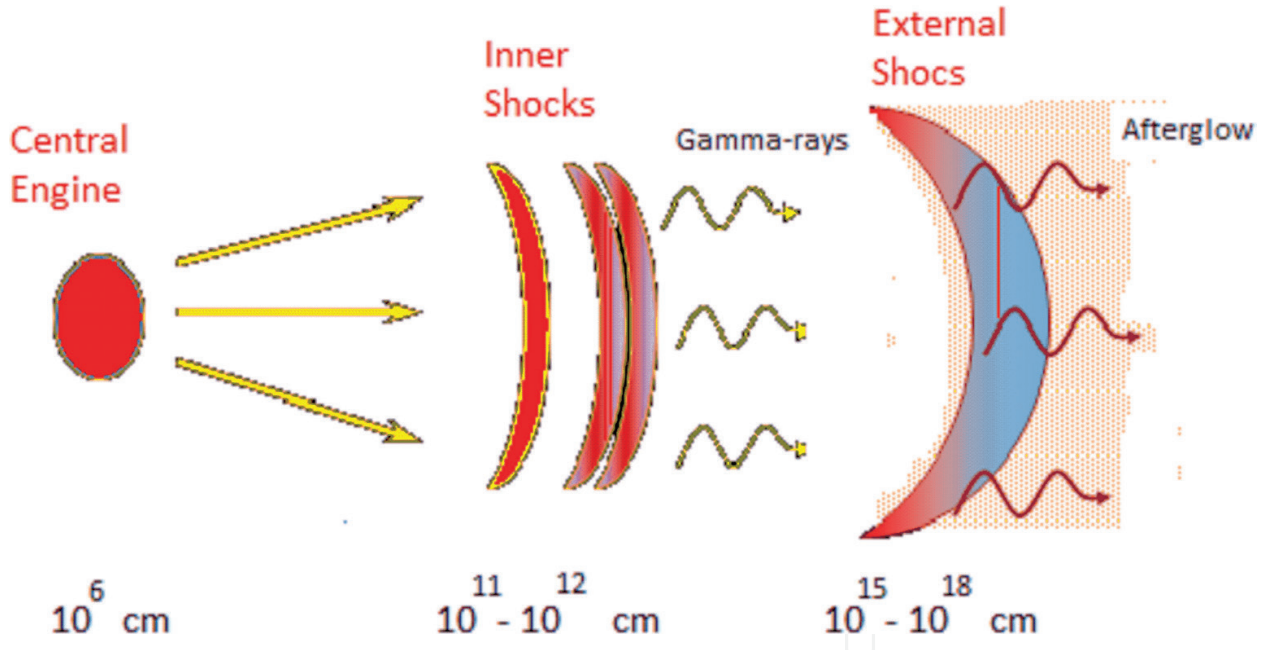


### 3. Emission mechanisms

Despite remarkable progress in the past few years by theory and breakthroughs of observations, our understanding of these fascinating cosmic events is still very incomplete. Many aspects remain uncertain and demand further exploration. For instance, the detailed physics of the central engine is poorly understood. Even so, some GRB models can reproduce the main features of the observed bursts, irrespective of the detailed physics of the central engine.

The relativistic fireball GRB model was introduced in the 1990s [10, 11] on the basis of earlier works [12–14]. Although the model does not explain the central engine of a GRB, it has been successful in explaining the various features of GRBs, such as the origin of their afterglows.

According to this model, GRBs are produced far from the source ( $10^{11}$ – $10^{12}$  m), through the interactions between the outflow (fireball) and the surrounding medium (internal shocks). Following **Figure 3** that illustrates the generation mechanism of the GRBs, we can see that the X-rays afterglow result from the subsequent interaction of the outflow (fireball) with the surrounding medium (external shocks). The outflow fireball ends up losing its kinetic energy through successive interactions with the external medium, resulting in UV, visible, and radio afterglows.



**Figure 3.** Fireball model scheme of the generation mechanism of the GRBs. The GRBs are generated far from the source, through the interactions between the outflow (fireball) and the surrounding medium (internal shocks). The X-ray, UV, visible, and radio afterglow result from the subsequent interaction of the outflow (fireball) with the surrounding medium (external shocks).

The time variability of the gamma rays is  $10^{-3}$  s, meaning a size of the emitting region of around  $10^5$  m; that is, a relativistic fireball, with a Lorentz factor above 1000 ( $\Gamma > 1000$ ). The typical energy emitted in a collimated beaming flux is around  $10^{45}$  J. A high Lorentz factor  $\Gamma$  also allows a relativistic collimated jet, with an aperture of  $\theta \sim 1/\Gamma$ . As a consequence of this

behavior, the relative angle at which photons collide decreases and leads to an increase in the pair production threshold.

However, the simple relativistic fireball model produces a modified blackbody spectrum. This mechanism converts energy into thermal energy efficiently, thus it is necessary to reconvert kinetic energy into nonthermal emission, which happens when the fireball becomes optically thin. Thus, the reconverted kinetic energy into random energy must be via shocks, after the flow becomes optically thin (mainly synchrotron radiation).

In short, the fireball model can reproduce the main features of the observed bursts, irrespective of the detailed physics of the central engine.

Many GRB afterglow models [15–17] predict the production of photons in the GeV to TeV energy range, and GeV emission has indeed been detected by previous [18] and current-generation (Fermi LAT) space-based ray detectors [19].

The several GRBs observed by EGRET and Fermi LAT in the GeV energy region, as well as the ground-based observations of GRB candidates by Tupi suggest that the energy spectrum extend beyond GeV energies. In addition, there are some mechanism to explain this extension to very high energies, such as the synchrotron selfCompton model [20, 21], which provides a natural explanation for the optical and gamma-ray correlation seen in some GRBs. It has also been shown that a relatively strong second-order inverse Compton (IC) component of the GRB spectrum should peak in the 10s GeV energy region [22].

Another proposed model is the cannonball (CB). The cannonball model is inspired by observations of quasars and microquasars [23–25] and assumes that a supermassive star, when entering the final phase of its life, undergoes gravitational collapse, becoming a supernova (SN). In this internship, an accretion toroidal disk is developed around a compact object that is newly formed. The matter is then ejected as a CB in bipolar jets of plasma droplets (plasmoids) that are highly relativistic.

These jets collide with the photons inside the star through an inverse Compton scattering process, producing gamma rays. In this model, each pulse of GRB produced during the collapsing star corresponds to a CB.

The range of emission of these gamma rays is related to the layers (shields) of the star's interior, where these missiles collide. The CBs are individually ejected and the light curve observed in GRB depends on the local emission properties. As with the fireball model, the CB model can also describe the afterglows, such as X-ray, UV, and radio flares. The CB model also includes a description of other phenomena, such as the acceleration of cosmic rays (CRs) in a successful way [26].

The observed energy spectra of gamma-ray bursts reveal a diverse phenomenology. The spacecraft observed gamma-rays up to 33 GeV [27]. While some energy spectra have been fitted by a simple expression over many decades [28], others require a few separate components to explain high-energy emission [27]. In most cases (at low energies), the GRB spectrum is well described by a phenomenological “band function” in a “Comptonized model” using a power law with an exponential cutoff:



$$N(E) = K E^{-\alpha} e^{-E/E_0} \quad (1)$$

where  $\alpha$  is the power-law exponent and  $E_0$  is the cutoff energy. At high energies, the spectrum is described well by a power-law function with a steeper slope:

$$N(E) = A_\gamma E^{-\beta} \quad (2)$$

where  $\alpha > \beta$ , and the spectral parameters  $\alpha$ ,  $\beta$ , and  $E_0$  vary from burst to burst. For instance, a “blast wave model,” usually considered for GRB sources, is quite sensitive to the relationship between these two power-law indices.

## 4. Ground level observations

We present in this section a brief description of the various efforts for detecting at ground level, the GeV to TeV counterpart of the GRBs.

### 4.1. Milagrito

Milagrito was a detector (air shower detector, the predecessor of the Milagro detector) sensitive to very high-energy gamma rays, which monitored the northern sky with a large field of view and a high duty cycle, located near the Los Alamos Laboratory (New Mexico, USA). This instrument was well suited to perform a search for TeV gamma-ray bursts (GRBs). From February 1997 through May 1998, BATSE (Transient Satellite experiment) aboard the Compton Gamma-Ray Observatory detected 54 GRBs within the field of view of Milagrito.

The Milagrito results were negative; that is, no significant correlations were detected from the other bursts, with the exception of a single event, which was reported as evidence of a marginal emission at TeV energies from GRB 970417a. The event had a chance probability of  $2.8 \times 10^{-5}$  of being background fluctuation. The probability of observing an excess at least this large from any of the 54 bursts is  $1.5 \times 10^{-3}$  [29].

### 4.2. Milagro

Milagro was a wide-field (2 sr) high-duty cycle (>90%) ground-based water Cherenkov detector (60 m wide  $\times$  80 m long  $\times$  8 m deep) located at 2630 m above sea level in the Jemez mountains, New Mexico. Milagro had 723 PMTs divided into two layers under water. It triggers mainly on extensive air showers (EAS) in the energy range of 100 GeV to 100 TeV.

Milagro operated from January 2000 to May 2008. The gamma-ray coordinates network (GCN) system incorporated the distribution of positions of GRBs and transients detected by the MILAGRO instrument. However, none of these events was confirmed as true GRBs. Even so, Milagro succeeded in the detection of gamma rays in the TeV energy region, such as TeV gamma rays from the galactic plane [30], and the discovery of TeV gamma ray emission from the Cygnus region of the Galaxy [31]. Perhaps, its high energy threshold (above 100 GeV) set for gamma rays did not allow the detection of GRBs; thus only the upper limits were reported [32].

### 4.3. ARGO

The Astrophysical Radiation with Ground-based Observatory at Yangbajing, China (Tibet—4300 m a.s.l.), under the auspices of the ARGO-YBJ experiment, is through an air shower detector. The ARGO-YBJ detector has a large active surface of around 6700 m<sup>2</sup> of Resistive Plate Chambers, a wide field of view ~2 sr, and a high duty cycle (>86%). The ARGO-YBJ experiment is a collaboration of Italian and Chinese institutions [33].

The ARGO-YBJ performed a search for gamma-ray bursts (GRB) emission in the energy range 1–100 GeV in coincidence with satellite detection. From 17 December 2004 to 7 February 2013, a total of 206 GRBs occurring within the ARGO-YBJ field of view (zenith angle  $\theta = 45^\circ$ ) were analyzed, no significant excess was found, and only the corresponding fluence upper limits in the 1–100 GeV energy region were derived, with values as low as 10<sup>-5</sup> erg/cm<sup>2</sup>.

### 4.4. HAWC

The HAWC gamma-ray observatory is a wide field of view, continuously operating, TeV gamma-ray telescope that explores the origin and solar modulation of cosmic rays and searches for new TeV physics. HAWC is located at a high altitude of 4100 m above sea level in Mexico (Sierra Negra) and is a collaboration of 15 US and 12 Mexican institutions.

HAWC consists of an array of 300 water Cherenkov detectors and is expected to be more than one order of magnitude, which is more sensitive than its predecessor, Milagro. HAWC monitors the northern sky and makes coincident observations with other wide field of view observatories. The HAWC experiment is particularly suitable to detect short and unexpected events like GRBs. However, thus far, no excess candidate events, nor GRB counterparts, have been reported.

Many other experiments have searched for the GeV-TeV counterpart of GRBs. No conclusive detection such as INCA [34], Tibet AS [35], HEGRA AIROBICC [36], GRAND [37], LAGO [38], and the Cherenkov detector MAGIC have given a very low upper limit between 85 and 1000 GeV [39]. In short, no significant correlations among events of these experiments and Satellite GRBs observations have been related.

## 5. Ground level observation of gamma-ray bursts from space

The Earth's magnetic field effects on the development of a particle shower in the atmosphere spread the collecting particles and therefore decrease the sensitivity of the detector. This deflection is caused by the component of the Earth's magnetic field perpendicular to the particle trajectory. Thus, if the source of gamma rays is close to the vertical direction, the places with the smaller horizontal magnetic component will be the best places, to ground level detection of GRBs.

We point out that the location of the Tupi detector is within the South Atlantic Anomaly (SAA). It is the region characterized by anomalously weak geomagnetic field strength. It is the lowest magnetic field of the world. The SAA central region is located on 26° S, 53° W, over the South Atlantic Ocean on Brazil, close to the Tupi detector location. The horizontal geomagnetic

field component is only 18.13 mT, that is, almost half than the horizontal geomagnetic field component of other locations, where a search for the detection of GRBs at ground level was performed. For details, please see Section 7 of the reference [40].

Since August 2013, the Tupi experiment has operated an extended array of five muon telescopes [40], located in Niteroi, Rio de Janeiro, Brazil, (22.9° S, 43.0° W).

The first has a vertical orientation. The other four have orientations to the north, south, east, and west; each telescope is inclined 45° relative to the vertical.

Each telescope was constructed on the basis of two detectors (plastic scintillators 50 × 50 × 3 cm) separated by a distance of 3 m. The coincident signals in the upper and lower Tupi detectors are registered at a rate of 1 Hz.

There are two flagstones of concrete (150 g cm<sup>-2</sup>) above telescopes and only particles (muons) with energies above 0.1–0.2 GeV can penetrate the two flagstones. This defines the energy threshold of the telescopes. Each Tupi telescope has an effective field of view of 0.37 sr. For the vertical telescope, this corresponds to an aperture (zenith angle) of 20°.

We present ground level observations in the GeV energy range of possible counterparts associated with the gamma-ray bursts observed by spacecraft detectors [41], such as the MAXI onboard the ISS and the BAT onboard Swift [42].

In the period from 8 September 2013 to 10 August 2014, 34 GRBs observed by satellites in the keV energy region were within the field of view of the five Tupi telescopes. The majority of the events was compatible with the Tupi background fluctuations. The exceptions were the two events that are described below.

In addition, of the 34 GRBs with energies above 100 MeV observed by the Femi LAT detector up until 10 August 2014 [43], only one GRB131018B had their trigger coordinates within the field of view of one Tupi telescope. However, no signal was found. **Figure 4** shows the location in equatorial coordinates of the four Tupi telescopes and includes the trigger coordinates of the Fermi LAT GRBs until 10 August 2014.

### 5.1. Association with the MAXI gamma-ray burst

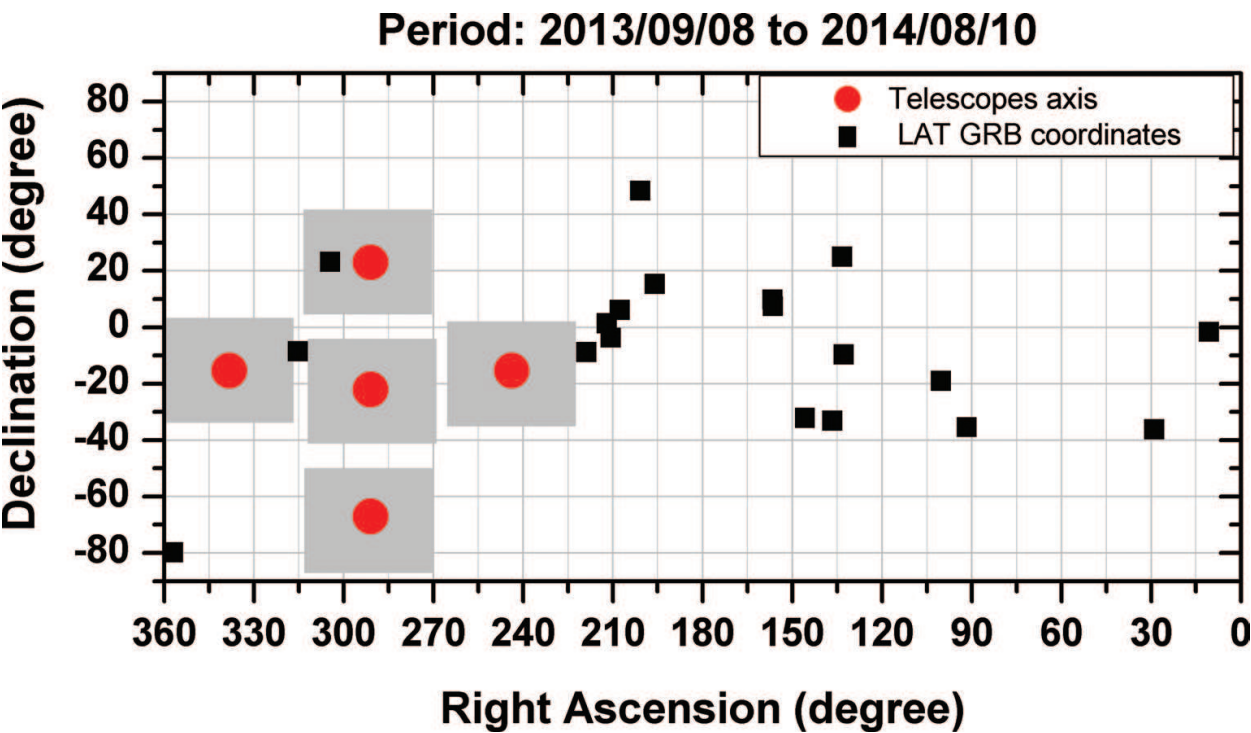
On 15 October 2013 at 21:55:44 UT, a peak (muon excess) with a significance of 5  $\sigma$  at the 68% confidence level was found in the 24 h raw data (counting rate 1 Hz) of the vertical Tupi telescope.

It was possible to recognize this peak in the time profile of the muon counting rate, just by the naked eye, as shown in **Figure 5**. The peak was found at  $T_0 + 25.7$  s, where  $T_0 = 21:55:19$  UT is the occurrence of the MAXI trigger [44]. The trigger coordinates of MAXI trigger were within the field of view of the vertical Tupi telescope.

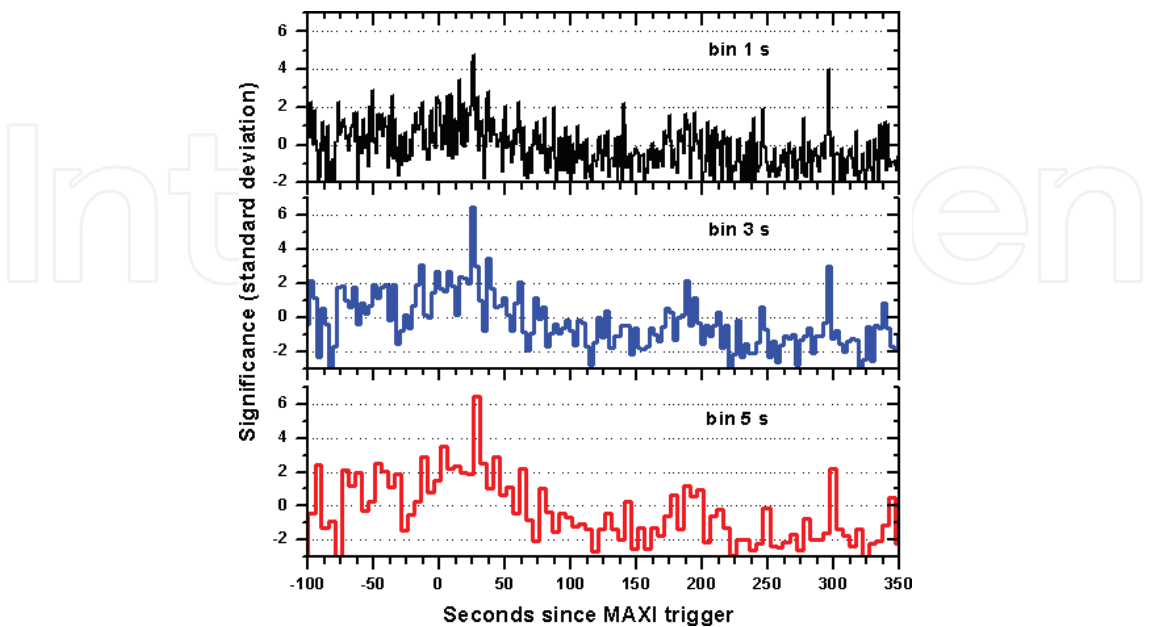
In addition, a second narrow peak with a significance of 4  $\sigma$  (1 s binning) can be observed at  $T_0 + 297.2$  s. This peak can be seen also at the 3 and 5 s binning counting rates, as shown in **Figure 5**. This behavior strongly suggests that this peak is a true signal.

In order to see the background fluctuations more accurately, we examined the time profiles up to 30 min before and after the trigger time. A confidence analysis was made for a 1 h

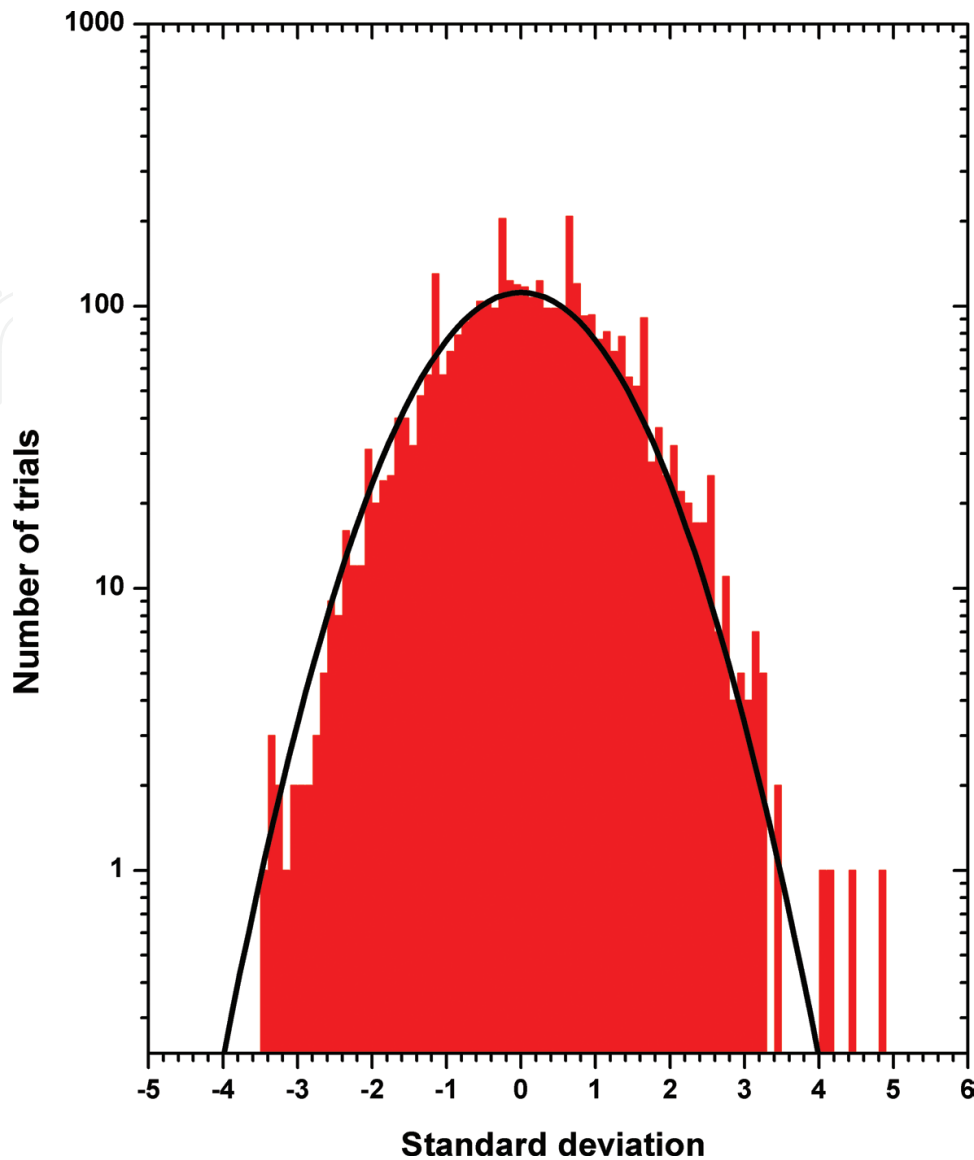
interval around the MAXI trigger time, as shown in **Figure 6**. In the absence of a signal, the background fluctuation of the counting rate follows a Gaussian distribution. Thus, the trials out of the Gaussian curve are considered as a signal's signature.



**Figure 4.** Equatorial coordinates showing the positions of the five Tupi telescope axes, as well as the Fermi LAT GRBs (>100 MeV) in the period until 10 August 2014. The squares with circles represent the FOV of the Tupi telescopes, which were within the FOV of the North Tupi telescope.



**Figure 5.** Statistical significance (i.e., number of standard deviations) of the 1, 3, and 5 s binning counting rates observed by the vertical Tupi telescope, as a function of the time elapsed since the MAXI transient 580727270 trigger time.



**Figure 6.** Distribution of the fluctuation count rate for the Tupi telescope (in units of standard deviations) within a temporal windows of 30 min around the MAXI transient event (trigger 580727270). The solid curve represents a Gaussian distribution (background fluctuation) and the signals associated with the MAXI events with significance above 4 sigma clearly are outside of the Gaussian distribution.

We estimated the Poisson probability of the counting rate excess observed in the vertical Tupi telescope, in association with the MAXI GRB events, being a background fluctuation, as  $P = (1.6 \pm 0.2) \times 10^{-9}$ , i.e., an annual rate of 2.9.

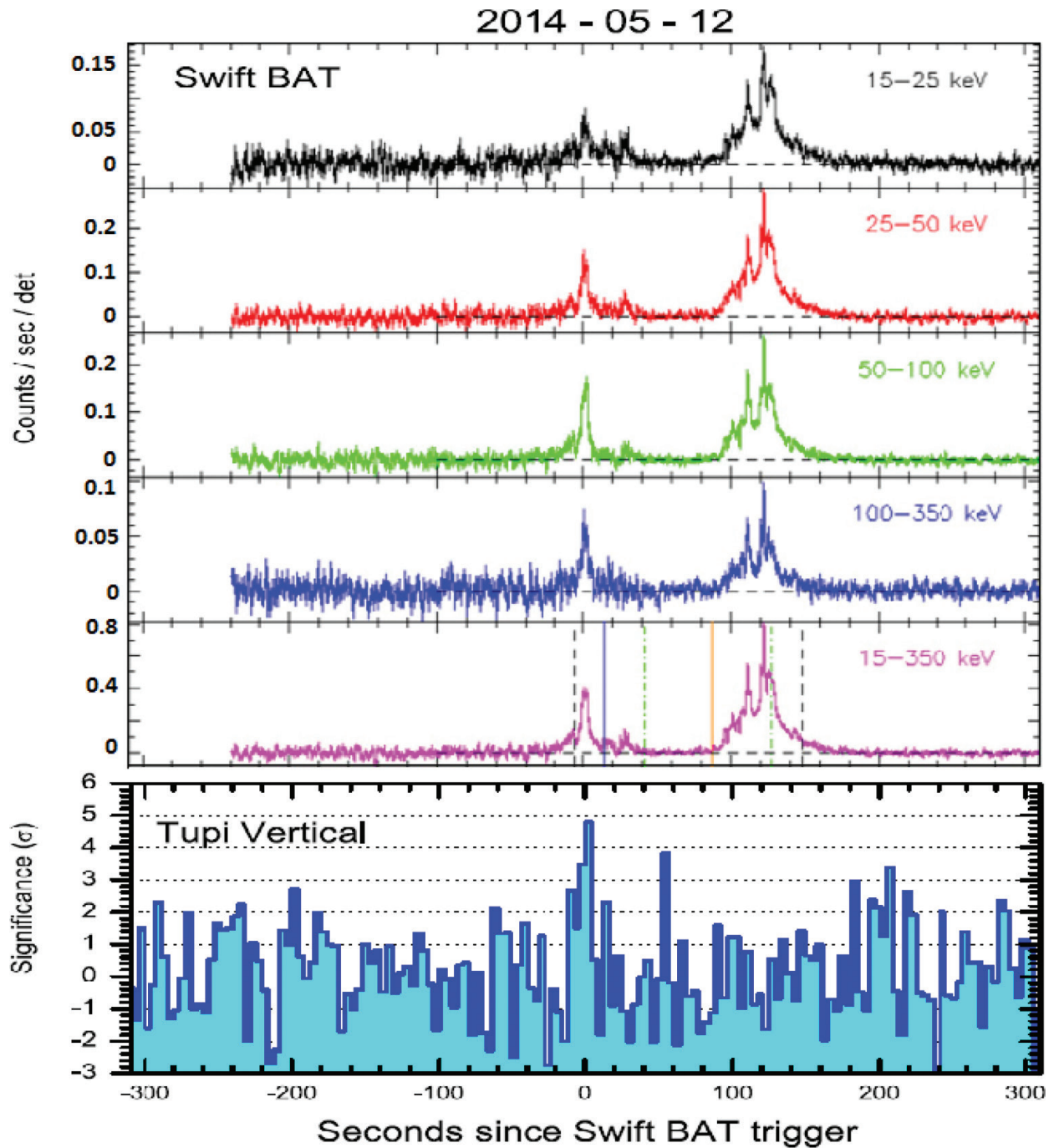
In addition, from spectral analysis, the fluence of the first peak (at  $T_0 + 25.7$  s) was estimated as  $F = (2.1 \pm 0.4) \times 10^{-7}$  erg/cm<sup>2</sup>.

## 5.2. Association with the Swift gamma-ray bursts

According to Pagani et al. (GCN 16249), on 12 May 2014 at 19:31:49 UT, the Swift BAT triggered and located a multipeak event with a total duration of about 170 s cataloged as GRB140512A



(trigger = 598819). This Swift event is also in temporal association with the Fermi gamma-ray burst monitor event (Stanbro, GCN 16262). The calculated location by Swift-BAT was (R.A., decl.) = (289.371, -15.100).

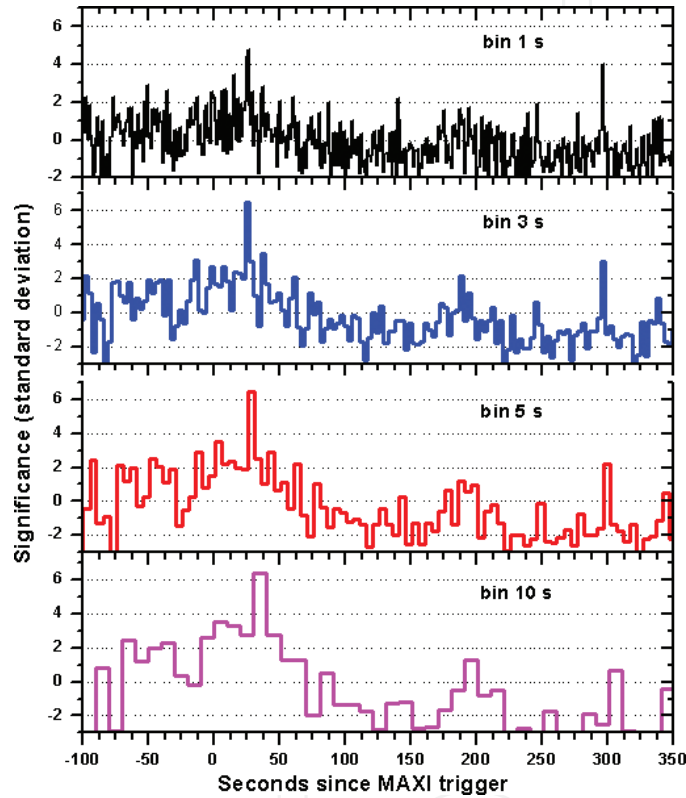


**Figure 7.** Top panels: the counting rate of gamma rays for five energy ranges for the event Swift BAT GRB140512A. Bottom panel: time profile of the counting rate 4 s binning, and expressed as the number of standard deviations, observed in the Tupi vertical telescope as a function of the time elapsed since the Swift BAT GRB140512A trigger time.

An excess in the Tupi counting rate with a significance of 4.55 sigma was found, temporally and spatially associated with the Swift BAT GRB140512A. The trigger coordinates of

this event were very close to the zenith of the Tupi location, that is, within the FOV of the vertical telescope. The signal at Tupi is within the T90 duration of the Swift GRB140512A. **Figure 7** summarizes the situation, where a comparison between the time profiles of Swift BAT and Tupi is shown, as a function of the time elapsed since the Swift BAT GRB140512A trigger time.

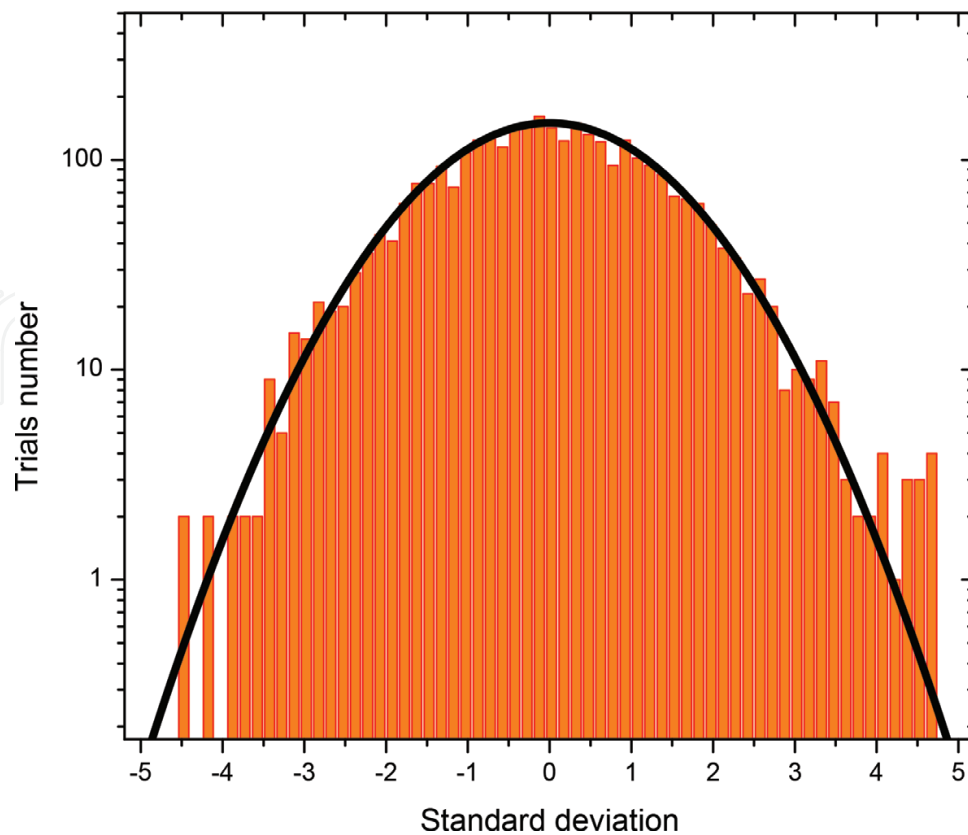
The peak in the time profiles of Tupi associated with the Swift GRB140512A persist with the same confidence in the 1, 3, 5, and 10 s binning, as shown in **Figure 8**. This means that the peak is not subjected to be the only background fluctuation.



**Figure 8.** Time profiles observed by the Tupi vertical telescope and expressed as the statistical significance (i.e., number of standard deviations) as a function of the time, since the Swift GRB140512A trigger time and for 1, 3, 5, and 10 s binning. The yellow band marks the region surrounding the Swift trigger time.

To see the expected background fluctuations, a confidence analysis was performed for a 1 h interval around the Swift BAT trigger time, as shown in **Figure 9**. The excess above the Gaussian curve (at right) is linked to the Tupi telescope's signal, associated with the Swift GRB event.

We also estimated the Poisson probability of the excess observed in the counting rate in the vertical Tupi telescope, in association with the Swift GRB event, being a background fluctuation, as  $P = (7.40 \pm 1.21) \times 10^{-6}$ , i.e., an annual rate of 73.1.



**Figure 9.** Distribution of the fluctuation count rate for the Tupi telescope (in units of standard deviations) within a temporal windows of 30 min around the Swift GRB140512A transient event. The solid curve represents a Gaussian distribution (background fluctuation) and the signals associated with the Swift events, with significance above 4 sigma clearly are outside of the Gaussian distribution.

## 6. Summary

We have carried out a systematic search for a GeV counterpart observed at ground level of GRBs triggered in gamma-ray detectors onboard of satellite. An overview on the gamma rays from space was given and the main features observed in detectors onboard satellites, since their discovery in the 1960s and their most recent observations. A brief report is also presented on the main possible mechanisms, as the fireball and the cannonballs models. Both can reproduce the main features of the observed bursts, irrespective of the detailed physics of the central engine.

In addition, several scenarios have been indicated to explain a possible high-energy component of GRBs, such as the synchrotron selfCompton model and the second-order inverse Compton component of the GRB spectrum.

We also included a chronological description of the various efforts for detecting at ground level, the high energy component, that is, the GeV to TeV counterpart of the GRBs. In most

cases, ground level detectors have an high energy detection threshold of the secondary particles detected (above 100 GeV); it has not allowed the detection at ground level.

We highlight that the location of the Tupi detector is within the South Atlantic Anomaly (SAA); it allows to achieve higher sensitivity, and some candidates to the GeV counterpart of gamma ray bursts, observed by Tupi telescopes were presented. They are in correlation with temporal and spatial GRBs detected by satellites.

Of course, that the Tupi detector has recorded excess in the counting rate, in correlation with the gamma-ray bursts. As the detector is located at sea level, it is expected that this excess is principally produced by muons. However, the assumption of photomuons as the origin of the excess requires gamma rays with energies above 10 GeV.

In addition, there is an alternative mechanism that is useful to explain high-energy electrons from terrestrial gamma-ray flashes [45] and observations of gamma-ray bursts at ground level under thunderclouds [46]. However, this mechanism requires some special conditions, such as an atmospheric high electric field.

The mechanism is known as “Relativistic runaway electron avalanche in the atmosphere”. An initial energetic electron is needed to start the process. In the atmosphere, such energetic electrons typically come from cosmic rays; for instance, gamma rays via pair production process  $\gamma \rightarrow e^+ + e^-$  in the upper atmosphere. In this case, there are several seeds for the generation of the successive avalanches; if the atmospheric electric field region is large enough, the number of second-generation avalanches (i.e., avalanches produced by avalanches) will exceed the number of first-generation avalanches, and the number of avalanches itself grows exponentially. This avalanche of avalanches can produce extremely large populations of energetic electrons [47].

Clearly, more studies are needed in order to establish whether this mechanism has the potential to explain the excesses observed in the counting rate of the Tupi detector associated with GRBs. So far, the mechanism “Relativistic runaway electron avalanche in the atmosphere” is the only promising one.

The implications of these ground level observations show that GRBs of long duration have chances of having a GeV counterpart; this characteristic can be useful to the formulations of possible mechanisms of a GeV emission. The experiment is in progress, and the aim is to obtain a large number of candidates in the next years to obtain some systemic features of this phenomenon.

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