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Special Issue
Recent Advances in Gamma Ray Astrophysics and Future Perspectives

Edited by
Dr. Pat Romano

MDPI

https://doi.org/10.3390/universe10020057 *universe* MDPI

Review

Gamma-ray Bursts: 50 Years and Counting!

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Abstract: Gamma-ray bursts were discovered by the Vela satellites in the late 1960s, but they were announced for the first time exactly 50 years ago, in 1973. The history of our understanding of gamma-ray bursts can be subdivided into several eras. We will highlight the main discoveries about GRBs, as well as the path toward the future that each GRB era could still indicate.

Keywords: gamma-ray astrophysics; gamma-ray burst; transients; gamma-ray instrumentation

1. Introduction

Gamma-ray bursts (GRBs) are extraordinary astrophysical events characterized by brief and intense flashes of gamma-ray radiation, representing some of the most energetic phenomena known in the universe. Their enigmatic nature has intrigued the scientific community for decades, prompting extensive research to decipher their origins and the underlying physical processes involved.

The serendipitous discovery of GRBs traces back to the late 1960s when the secret Vela satellites, designed for nuclear test detection, revealed anomalous gamma-ray emissions from deep space. Following meticulous study and analysis, the first public announcement of these mysterious gamma-ray bursts was made in 1973, marking the inception of a new era in astrophysical exploration.

This review paper provides a comprehensive historical account of the progression of GRB research, encompassing seven distinctive eras of study.

2. The "Dark" Era (1973(67)–1991)

The discovery of GRBs was made by the US military Vela satellites [1] in the late 1960s. These were a satellite constellation launched in order to monitor Soviet compliance with the Partial Test Ban Treaty of 1963, which prohibited all test detonations of nuclear weapons, except for those conducted underground.

In order to look for traces of nuclear tests in space, the Vela satellites were equipped with scintillation X-ray detectors, sensitive between 3 and 12 keV, and highly sensitive CsI gamma-ray detectors, sensitive between 150 and 750 keV. The satellites were launched in pairs, in a common circular orbit at an altitude of 118,000 km, in order to be well above the Van Allen radiation belts, drastically reducing the noise in the sensors and allowing some localization of the signal through time triangulation techniques.

At 14:19 UTC on 2 July 1967, the Vela 3 and Vela 4 satellites recorded an unprecedented gamma-radiation burst distinct from any previously identified astrophysical source. Despite the limited temporal resolution of the Vela satellites, GRB670702 (as it would be called with the modern-day naming convention) exhibited fundamental characteristics typical of GRBs (such as a duration of approximately 10 s, a two-pulse light curve and a peak emission around the MeV energy band), very different from the properties (duration, spectrum, variability) expected for a nuclear test in space (a short-duration, hard, nonstructured X-ray

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Citation: Vigliano, A.A.; Longo, F. Gamma-ray Bursts: 50 Years and Counting! *Universe* **2024**, *10*, 57. https://doi.org/10.3390/universe10020057

Academic Editor: Binbin Zhang

Received: 28 December 2023
Revised: 15 January 2024
Accepted: 18 January 2024
Published: 26 January 2024

burst). Although the data were never classified (the emission was not of nuclear origin), they were only published in 1973 [1], after a total of 16 such signals had been observed. Around the same time, other instruments reported the observation of GRB signals, such as the American satellite IMP-6 [2] and the Soviet space satellite Konus/Venera [3].

The low number of signals made it impossible to estimate the spatial distribution of the events, and the lack of a method to determine the distance of their sources meant that the total energy and the location remained unknown. The poor localization capability of gamma-ray detectors made it very difficult to discover the electromagnetic counterparts of GRBs at lower frequencies. Still, a lot of information was gathered. It was clear that these signals, not thermal in origin, were not coming from Earth and not even from the Solar System plane. Spectral lines, not confirmed by subsequent missions, were reported with low significance in some GRBs detected with the Soviet Konus/Venera instruments [4] and with the Japanese Ginga satellite [5,6]. With so few constraints, theorists came up with all kinds of models based on a wide range of physics, with energy requirements varying over 20 orders of magnitude. By 1992, over 100 models existed [7], some proposed even before the official publication of the Vela results. The proposed models can be broadly divided into three categories: Earth and Solar System (for example, Terrestrial Gamma-ray Flashes, gamma rays produced by lightning at high altitudes in Earth's atmosphere), galactic, and cosmological models.

Galactic models, favored by the lower energies required in the processes, posited that the GRBs were produced either by the accretion/fall of material onto compact objects (supernova fallbacks, accretion from a binary companion onto white dwarfs or neutron stars, later observed as X-ray Novae) or through magnetic reconnection/quakes in the crusts of magnetars (neutron stars with magnetic fields reaching 10^{15} G). The first models came out even before the publication of the Vela results, and as early as 1968, Stirling Colgate proposed a model of GRBs as bremsstrahlung and inverse Compton emissions from Type II supernova shocks [8]. According to the current standard paradigm, long GRBs are indeed associated with supernovae, but only with one special type, namely, broad-line Type Ic, not Type II as envisaged by Colgate. A clear prediction of all these models was that, given the galactic nature of the phenomena, the spatial distribution of GRBs would be centered around the Galactic Equator. The hope was, therefore, that by placing more sensitive satellites with superior localization capabilities into orbit, a distribution along the plane of the Milky Way would be observed. We now note that a subclass of GRBs is definitively of galactic origin: Soft Gamma-ray Repeaters (SGRs), objects that emit repeated flashes of gamma and X-rays at irregular intervals. It is hypothesized that they could be a type of magnetar or neutron star surrounded by fossil disks [9].

Due to the large distances, extragalactic models in general had very high energy demands (with energies up to 10^{51}–10^{53} erg). This, in addition to implying a particularly low rate of events (10^{-6}–10^{-5} events per year in a galaxy with the luminosity of the Milky Way), has led to the proposal of exotic phenomena and/or objects (collapsing white dwarfs, stars accreting onto AGNs, white holes, accretion onto black holes in binary mergers or collapsing stars) among the possible origins of GRBs. The first extragalactic model of GRBs was probably the one proposed by Prilutskii and Usov [10], who proposed that GRBs are produced in the collapse of the cores of active galaxies. As early as 1975, Ruderman recognized that the electron–positron pair production condition is a limiting factor for the achievable GRB luminosity (the so-called compactness problem) [11]. He noted that this condition posed fewer challenges for galactic models compared to extragalactic ones and pointed out that relativistic motion had the potential to mitigate the compactness problem by enlarging the emission size. In 1978, using a more elaborate version of the two-photon pair production condition proposed by Ruderman to set general constraints on the luminosities of GRBs, Cavallo and Rees proposed, for the first time, a fireball model for modeling GRB emissions [12]. In 1989, Eichler and colleagues conducted an extensive examination of the neutron-star–neutron-star (NS-NS) merger model, presenting a detailed analysis of its potential relevance to gamma-ray bursts (GRBs). Their work introduced the notion that mergers of compact objects (either NS-NS, NS-black hole, or BH-BH) could serve as the progenitors for a specific subclass of observed GRBs [13]. In the paper, it was also suggested that these systems are important multi-messenger emitting sources, as, beyond gravitational waves, binary neutron star mergers are important sources of neutrino emissions, as well as fundamental heavy-element factories through the rapid neutron capture process (the r-process) of neutron-rich material ejected from the merger. Ref. [13] laid the foundation for the standard paradigm of the modern short-GRB models.

This era can be summarized as follows:

- GRBs were discovered in the 1960s by the Vela military satellites and later observed by other missions.
- The spatial distribution and total energy of GRBs remained unknown due to low instrumental capabilities and a low number of events.
- Galactic models suggested that GRBs were related to processes like supernovae, accretion onto compact objects and magnetic reconnection in magnetars.
- Galactic models predicted GRBs to be distributed on the galactic plane.
- Extragalactic models had high energy demands, and possible origins included collapsing white dwarfs, active galaxy cores, and neutron star mergers.
- The compactness problem and relativistic motion were already considered in these models.
- The relativistic fireball model was introduced to explain GRB emissions.

3. The BATSE Era (1991–1996)

On 5 April 1991, the US spacecraft Compton Gamma Ray Observatory (CGRO) was launched in low Earth orbit. On board, there were four instruments that covered a huge energy range, at the time unprecedented, of six orders of magnitude of the electromagnetic spectrum, ranging from 20 keV X-rays to 30 GeV gamma rays. Among these instruments, the Burst and Transient Source Experiment (BATSE) [14] has led to substantial improvements in our understanding of GRBs. It consisted of eight identical detector modules, each composed of a NaI (sodium iodide, i.e., crystal detector) scintillator Large Area Detector covering the energy range 20 keV–2 MeV to act as a trigger for the observations and a thick NaI Spectroscopy Detector covering the energy range 10 keV–100 MeV. Each module was placed on one of the corners of the satellite in order to obtain complete coverage of the sky, achieving a burst detection sensitivity of 3×10^{-8} erg cm^{-2} for a 1 s burst. BATSE was thus able to obtain approximate localizations of GRB signals based on the ratios of the count rates between the eight detectors.

GRB light curves have a broad range of characteristics and are quite irregular, ranging from single peak light curves to more complex multipeaked extended structures. However, in this period, enormous progress was made in their characterization. In 1996, Norris and colleagues found that the light curves of individual pulses are well fitted with a fast-rise exponential decay (FRED) profile with an average rise-to-decay ratio of 1:3 [15]:

$$I(t) = \begin{cases} A\exp(-(|t - t_{\max}|/\sigma_r)^{\nu}) & t \leq t_{\max} \\ A\exp(-(|t - t_{\max}|/\sigma_d)^{\nu}) & t > t_{\max} \end{cases}, \tag{1}$$

where $t_{\max}$ is the time of the pulse's maximum intensity; A is the peak value; σ_r and σ_d are the rise $(t \leq t_{\max})$ and decay $(t > t_{\max})$ time constants, respectively; and ν is the "peakedness", a measure of the pulse's sharpness. In the same paper, a delay between the emission at low energies and that at high energies was highlighted. Low/high energies are defined based on the low vs. high channels of BATSE: 20–50 keV, 50–100 keV, 100–300 keV, and $>$300 keV. The BATSE team also reported a width–symmetry–intensity correlation. In particular, high-intensity pulses were (statistically) more symmetric (i.e., with lower decay-to-rise ratios) and had shorter spectral delays. Furthermore, the low-energy light curves of individual pulses are generally wider than the high-energy ones, with a width of $\sim E^{-0.4}$ [16]. BATSE observed GRBs with very disparate durations, from $\sim$6 ms up to

∼2000 s. To classify the light curves, a duration measurement standard was introduced, the T90 (T50), in which 90% (50%) of the total counts of the GRB arrive. After subtracting the background counts and normalizing the cumulative counts so that the total is 1, the T90 (T50) is defined as the time interval between the arrival of 5% (25%) and 95% (75%) of the counts. With this definition, Kouveliotou and colleagues showed that a GRB can be divided into two distinct groups: long bursts with T90 $>$ 2 s and short bursts with T90 $<$ 2 s [17]. The two groups also have different spectral characteristics, with short GRBs tending to be spectrally "harder" than long GRBs, where the hardness ratio is the ratio of photons observed in two BATSE channels: channel 3 (100–300 keV) counts divided by channel 2 (50–100 keV) counts.

Spectral studies of BATSE GRBs have shown that the emission is non-thermal, with spectra generally characterized by a double power law and a smooth break. Band and colleagues proposed a phenomenological function, now known as the Band function, to fit GRB spectra [18]:

$$F_{\mathrm{Band}}(E) = \begin{cases} A\left(\frac{E}{100\,\mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E(2+\alpha)}{E_{\mathrm{peak}}}\right) & E < E_c \\ A\left[\frac{(\alpha-\beta)E_{\mathrm{peak}}}{100\,\mathrm{keV}(2+\alpha)}\right]^{\alpha-\beta} \exp(\beta-\alpha)\left(\frac{E}{100\,\mathrm{keV}}\right)^{\beta} & E \geq E_c \end{cases}, \quad (2)$$

where

$$E_c = (\alpha-\beta)\frac{E_{\mathrm{peak}}}{2+\alpha} \equiv (\alpha-\beta)E_0$$

α is the low-energy index, β is the high-energy index, E_c is the break energy, and E_{peak} is the peak energy of the νF_ν spectrum. No specific theoretical model predicts this spectral shape; however, the Band function provides an excellent fit to most observed spectra. Most GRBs show substantial spectral evolution with two typical behaviors: hard to soft throughout the whole GRB duration or hard to soft during each pulse. The value of E_{peak} generally follows the shape of the light curve. In the same year, CGRO/EGRET detected high-energy (HE) photons, from 30 MeV up to 18 GeV, for a few GRBs, with emission lasting up to thousands of seconds after the onset of the GRB. The average spectrum of the events detected by EGRET is well fitted by a single power law with an index of ∼2, consistent with the extension of the low-energy spectra.

While the exact distances of GRB sources remained a topic of discussion, the data collected by BATSE offered pivotal insights strongly indicative of the cosmological nature of GRBs. GRB signals were found to be distributed isotropically in the sky, with no clustering near the Galactic Disk (as predicted by galactic models) [19]. However, this did not completely rule out the galactic models, which were recalibrated to shift the GRB sources to the galactic halo to smooth out the inconsistency with the observed distribution. The intensity distribution of the bursts was found to deviate from homogeneity at the faint end, indicating a deficit of weak bursts compared to the predictions [20]. The intensity distribution provides information on the radial distribution of the sources and is defined as the ratio $V/V_{\mathrm{max}} = (C_{\mathrm{max}}/C_{\mathrm{min}})^{-3/2}$, where V is the volume contained by a sphere extending to the location of the burst, V_{max} is the volume of a sphere extending to the maximum distance at which the burst would still be detectable by the instrument, C_{max} is the peak count rate, C_{min} is the minimum rate required for triggering, and $-3/2$ is the power-law exponent predicted if the burst follows a homogeneous distribution in Euclidean space. For a homogeneous distribution of sources, the average ratio would be $\langle V/V_{\mathrm{max}}\rangle = 1/2$. BATSE reported an average ratio of $\langle V/V_{\mathrm{max}}\rangle = 0.348 \pm 0.024$, showing a deficit of low-fluence bursts and strongly hinting at a deviation from spatial homogeneity of the distribution of the sources. These findings imposed great constraints on current galactic models but could be easily explained if GRBs have an extragalactic origin. Despite great efforts to locate extragalactic GRBs with a certain precision, both through BATSE module counts and through temporal triangulation with other instruments

(BATSE Gamma-ray Burst Coordinates Distribution Network, BACODINE, now known as the GCN–GRB Coordinates Network), no host galaxy was identified, which is the so-called "No host problem".

During this era, the extragalactic models received a huge push in development. Peter Mészáros and Martin Rees proposed, in a series of papers, the now-standard fireball shock model, which already included the main ingredients of the current GRB theoretical framework, from the external shock of a relativistic fireball and synchrotron radiation as the main radiation mechanism to the external reverse shock and inverse Compton scattering. In 1997, two weeks before the discovery of the first X-ray and optical afterglows from BeppoSAX, they published a seminal paper in which they systematically predicted the multiwavelength afterglows of GRBs in a self-consistent manner [21]. In those years, new candidates for the sources of GRBs were also proposed. Woosley proposed that the collapse of a rapidly rotating Wolf–Rayet star (massive star whose outer hydrogen envelope is stripped away by a stellar wind), leading to a supernova, now known as the collapsar model for long GRBs, could be an appropriate progenitor of long-duration GRBs with a complex time profile [22]. The first mention of a millisecond magnetar (a newborn, rapidly spinning, highly magnetized neutron star) as a possible central engine [23] was made for the first time as an alternative to the standard hyper-accreting black hole scenario adopted by most modelers of the time.

The tension between extragalactic models, favored by the observation of the spatial distribution of GRBs but with surprisingly high energy demands (at a distance of 1 Gpc, the energy required would be $\sim 10^{51}$ erg, with a flow of $\sim 10^{-7}$ erg cm^{-2} s^{-1}), and galactic models, with decidedly more "reasonable" energy budgets ($E \sim 10^{43}$ erg at a distance of 100 kpc) but disfavored by observations, culminated in the so-called "Great Debate" of 1995, where Lamb and Paczynski showed evidence and arguments as to why a scale distance should be preferred to the other. As we will see, the solution to this debate later came thanks to precise localization measurements from the BeppoSAX satellite.

BATSE reported 2704 GRBs in its last catalog [24]. The failure of one of the three gyroscopes responsible for the maneuvering of CGRO determined the conclusion of the mission, and the satellite was de-orbited on 4 June 2000.

This era can be summarized as follows:

- BATSE observed a large number of GRBs, leading to better modeling of GRB properties.
- GRBs come in all shapes and sizes, but two subgroups exist: short hard bursts and long soft bursts.
- GRBs are distributed isotropically in the sky. This marked the beginning of the end of galactic models. Still, they were not ruled out completely, and this led to the Great Debate in 1995.

4. The BeppoSAX Era (1996–2000/2004)

As we have seen, much progress was made during the BATSE era in the investigations of GRBs. Still, regardless of the large amount of data acquired, these were not sufficient to single out a clear model for the production of these signals, and two vastly different classes, galactic and extragalactic models, were discussed in the community. The lack of multiwavelength observations limited the possibilities to understand the underlying mechanism of the production of these signals. At the same time, the poor localization capabilities, together with the impossibility of estimating the distance of the sources, meant that it was not yet possible to understand the energy scales of these phenomena and completely rule out any of the two model paradigms that were proposed. This was aggravated by the no-host problem, i.e., the impossibility of identifying the host galaxies of such signals. In order to move forward and solve these problems, it was therefore necessary to carry out a new type of observation. The key to making multiwavelength observations and estimating distances was to obtain the very precise localizations of the GRBs.

BeppoSAX was an Italian–Dutch satellite for X-ray astronomy [25]. Launched from the US space base at Cape Canaveral on 30 April 1996 and built largely by Italian companies, the satellite called SAX ("Satellite per Astronomia a raggi X", Italian for "Satellite for X-ray Astronomy"), once in orbit, was renamed BeppoSAX, from the nickname of Professor Giuseppe "Beppo" Occhialini, a pioneer of Italian high-energy astrophysics.

BeppoSAX hosted five scientific instruments:

- A Low-Energy Concentrator Spectrometer (LECS);
- A Medium-Energy Concentrator Spectrometer (MECS);
- A High-Pressure Gas-Scintillation-Proportional Counter (HPGSPC);
- A Phoswich Detector System (PDS);
- Two Wide-Field Cameras (WFCs).

Of these, the two X-ray focusing telescopes (LECS and MECS), the HPGSPC and the PDS (collectively called Narrow-Field Instruments, NFIs) pointed in the same direction, thus allowing observations in a large energy range, from 0.1 to 300 keV, while the two WFCs pointed orthogonally to the other instruments' axis, covering a large area of the sky. The LECS, MECS, and HPGSPC detectors were all based on gas-scintillation-proportional counters operating in a total energy window from 0.1 keV (LECS) to 120 keV (HPGSPC) with high sensitivity. The PDS detector was a crystal (sodium iodide/cesium iodide) scintillator detector capable of collecting photons from 15 to 300 keV. The PDS detector was covered on its sides by four CsI scintillators that acted as anticoincidence shields for background rejection. With sensitivities from 40 to 700 keV, these panels had large fields of view that were aligned with the two WFCs. It was thus possible to use them to trigger GRB observations, obtaining the first localization with the WFCs in order to then slew the satellite and observe with the NFIs. For this reason, they were referred to as the Gamma-Ray Burst Monitor (GRBM). The WFCs were two units each composed of a proportional counter and a coded mask to obtain excellent angular resolutions covering extended fields of view of $20^\circ \times 20^\circ$ in the energy range 2–28 keV. The simultaneous detection of GRBs by the GRBM and WFCs therefore made it possible to obtain the localizations of these signals with excellent precision, reaching accuracies of a few arcminutes. The estimated coordinates were quickly sent to the International Astronomical Union (IAU) and the Gamma-ray burst Coordinate Network Circular. Subsequently, immediate follow-up observations with the onboard NFIs and ground-based optical observatories allowed the accurate localization and detailed observations of GRBs.

The BeppoSAX mission achieved a breakthrough in February 1997, within a year of its launch. The gamma-ray burst GRB 970228 was initially detected by BeppoSAX's WFCs, and subsequently, when the X-ray NFIs aboard BeppoSAX were directed toward the source of the burst, they captured a diminishing X-ray emission [26]. Ground-based telescopes corroborated the findings by identifying a fading optical counterpart [27]. These later, fading emissions were called the afterglow of the GRB, to distinguish them from the initial prompt emission, which was the only signal observed up to that moment. Once the event's localization was pinpointed, subsequent deep imaging revealed a faint, very distant host galaxy in the GRB's location. This discovery had far-reaching implications. It swiftly resolved the longstanding debate about the distance scale of GRBs, confirming them as extragalactic events originating within faint galaxies situated at staggering distances. The establishment of this distance scale not only concluded a significant debate but also provided crucial insights into the environments in which GRBs unfold. A few months later, the observation of GRB970508 led to two further breakthroughs. In less than 4 h after its discovery, it was possible to obtain the accurate localization of this event, allowing follow-up observations to begin much earlier than with any previous burst, detecting the optical transient while still on the rise. In addition to the optical component, a radio component of the afterglow emission was observed for the first time [28]. Thanks to the analysis of the absorption lines in the optical spectrum, it was also possible to estimate, for the first time, the distance of the GRB, with a redshift of $z = 0.835$ [29], proving the extragalactic origin of these phenomena.

The possibility of measuring the distances of the origins of these signals allowed the discovery of the empirical correlation today known as the Amati relation [30] between the GRB isotropic bolometric emission energy ($E_{\gamma,\mathrm{iso}}$) and the rest-frame peak energy ($E_{p,z} = (1+z)E_p$):

$$\frac{E_{p,z}}{100\,\mathrm{keV}} = C\left(\frac{E_{\gamma,\mathrm{iso}}}{10^{52}\,\mathrm{erg}}\right)^m \tag{3}$$

with $C \sim 0.8$–1 and $m \sim 0.4$–0.6 [31]. This correlation holds for long GRBs with known redshifts, and its discovery hinted at the possibility of using GRBs as cosmological probes. In 2004, a correlation (now known as the Yonetoku relation) similar to the Amati relation was highlighted between the isotropic, bolometric peak luminosity $L_{\gamma,p,\mathrm{iso}}$ and the rest-frame peak energy $E_{p,z} = (1+z)E_p$ [32]:

$$\frac{E_{p,z}}{100\,\mathrm{keV}} \approx 1.8\left(\frac{L_{\gamma,p,\mathrm{iso}}}{10^{52}\,\mathrm{erg\,s^{-1}}}\right)^{0.52} \tag{4}$$

Although it has been suggested by several groups that the Amati and Yonetoku relations may be due to observational selection effects (e.g., [33]), this conclusion is not widely accepted, with other groups stating that the presence of such selection effects, despite lowering the correlation, are not enough to destroy it completely (e.g., [34]). Another piece of evidence supporting the existence of such correlations could be the existence of a similar correlation between L and E_p within some bursts themselves [35]. It is interesting to note that short and long GRBs do not share the same Amati relation, with short GRBs having a parallel and higher relation compared to that for the long GRBs, suggesting that they are systematically less energetic than the long GRBs given the same $E_{p,z}$. This could be attributed to the shorter durations, which would tighten the relationship between luminosity and $E_{p,z}$ for such phenomena. On the other hand, short and long GRBs are no longer well distinguishable in the $E_{p,z} - L_{\gamma,p,iso}$ plane, suggesting that the radiative processes responsible for the emissions are the same [36,37].

The abundant multiwavelength afterglow data allowed an in-depth understanding of the physics of GRBs. The spectral data were found to be generally in agreement with the power-law decay behavior predicted by the fireball forward shock model [38,39], while early optical flashes were interpreted as reverse shock emission [21,40]. The possibility of analyzing the evolution of the afterglow spectrum over time led to the proposal that GRB emission occurs in highly collimated jets: the discovery of an achromatic break (optical and radio bands) in the afterglow of GRB990510 (later observed in other GRBs) of around $t \sim 1$ day led, for the first time, to the hypothesis that the emission could occur in the jet rather than isotropically [41]. Analyzing the relatively small sample of afterglows observed until then, it was discovered that, surprisingly, the total jet-corrected energy of the GRB sample is essentially constant, narrowly clustered around 5×10^{50} erg [42]. This finding was at first interpreted as a hypothesis that different GRBs can collimate a standard energy reservoir into different jet angles. A different explanation was proposed in parallel in [43,44]: all GRBs have an (almost) universal, structured jet. The differences between the various GRBs may correspond to the different viewing angles of this universal jet such that the measured "jet angle" is not the opening angle of a uniform jet, but rather the observer's viewing angle from the jet axis.

Thanks to multiwavelength data and the ability to measure the jet angle, it was possible to discover another tight correlation between $E_{p,z}$ and the beaming-corrected bolometric emission energy E_γ (Ghirlanda's relation [45]):

$$\frac{E_{p,z}}{100\,\mathrm{keV}} \approx 4.8\left(\frac{E_\gamma}{10^{51}\,\mathrm{erg\,s^{-1}}}\right)^{0.7} \tag{5}$$

The discovery of these robust correlations led to the proposal to use GRBs as standard rulers for cosmological measurements (e.g., [46]).

Thanks to the possibility of carrying out multiband observations of these signals, particularly in the optical range, with excellent localization, it became possible to look for further clues about the nature of the progenitors. The detection of the long-lasting, fading, multiwavelength afterglow emissions allowed the identification of the host galaxies, solving the "no host problem" and firmly establishing the origin of GRBs as extragalactic. The ability to obtain accurate localizations showed that the GRBs are located toward the edges of the host galaxies [47,48], i.e., in the star formation zones [49], and not toward the center. This fitted well with one of the most investigated scenarios, i.e., the supernova–GRB association. The first hint of such an association was the discovery of SN 1998bw, a type Ic supernova in a galaxy near $z = 0.0085$, in the error box of the BeppoSAX burst GRB980425 [50,51]. Furthermore, a supernova red bump was discovered in the optical light curves of several other GRBs [52]. These findings led to the development of various models for the progenitors. Refinements of the collapsar model, first proposed by Woosley in 1993 [22], have been proposed by various groups. Woosley's group performed the first detailed numerical simulations of a jet launched from a collapsing Wolf–Rayet star, giving robustness to the collapsar model [53]. Many observational features were elegantly explained with this model, such as the presence of a less energetic "cocoon" surrounding the jet, as shown in [54]. In 1998, in the same article where he located GRBs within the star-forming regions of their host galaxies, Paczynski proposed a variant of Woosley's collapsar model, the so-called hypernova model: a rapidly rotating star collapses into a black hole surrounded by a thick accretion disk (or "torus"), which magnetically launches a relativistic jet, which, in turn, powers the observed GRB [49]. Another variation of this scenario was proposed in the Black-Hole Accretion Disk (BHAD) Models, where the binary merger of two compact objects or the collapse of a rotating star produces a rapidly accreting disk ($>$0.1 solar masses per second) around a "hyperaccreating" black hole [55]. Other models went in different directions. In particular, the supranova model posited that GRBs are emitted when a supramassive neutron star (a neutron star with a mass greater than the Tolman–Oppenheimer–Volkoff limit, supported by fast rotation) loses so much angular momentum that centrifugal support against self-gravity becomes impossible, and the star implodes into a black hole [56,57]. The interaction of the material ejected from the collapse with an almost baryon-clean environment would produce the GRB signals. A more radical proposal was put forward by Dar and De Rujula with the Cannonball model, an alternative to the paradigm of the forward-and-backward-shocks model, where each GRB pulse is given by the expulsion of "cannonballs" of relativistic plasmas from the supernova shell rather than by the interactions of the fronts in a collimated jet [58].

This era can be summarized as follows:

- In 1996, the BeppoSAX mission was launched with large-FoV gamma-ray instruments and X-ray instruments with great sensitivity, which allowed GRB signals to be localized with unprecedented precision.
- The discovery of afterglows led to the first multiwavelength observations, the measurement of redshifts (and therefore distances and energies), and the identification of host galaxies.
- The Amati, Yonetoku, and Ghirlanda correlations for long GRBs were discovered.
- In this era were the first indications of the GRB–supernova association.
- Since the X-ray telescopes and WFCs were not aligned, BeppoSAX had to be slewed after locating each GRB. The procedure had to be carried out from the ground, leading to slow replacements. For this reason, in this era were predominantly (almost exclusively) observed long GRBs.

5. The HETE-2 Era (2000–2004)

After the first High Energy Transient Explorer 1 (HETE-1) satellite was lost during its launch on 4 November 1996, a second mission was designed, and HETE-2 was then successfully launched on 9 October 2000. HETE-2 was a NASA science mission with international collaboration (mainly with Japan and France), with the main objective of making multiwavelength observations of GRB counterparts for the first time [59]. The satellite carried on board three main instruments: the French Gamma Telescope (FREGATE), the Wide-Field X-Ray Monitor (WXM), and the Soft X-ray Camera (SXC). FREGATE was composed of wide-field ($\sim\pi$ FoV) gamma-ray spectrometers sensitive between 6 and 400 keV, designed to conduct spectroscopy of GRBs thanks to its high spectral and timing resolutions. The WXM consisted of a pair of orthogonal, one-dimensional X-ray detectors sensitive in an energy range of 2 to 25 keV, allowing excellent localizations of $\sim$10 arcminutes. The SXC consisted of two orthogonal sets of one-dimensional coded-aperture X-ray imagers sensitive in the 0.5–14 keV energy range. These instruments had an identical field of view of 1.5 steradians and were able to communicate with each other in order to coordinate observations.

On 29 March 2003, HETE observed three different GRBs. The first of them, GRB030329, was fundamental to our understanding of GRBs by definitively confirming the association between long GRBs and supernovae [60,61]. GRB030329's distance from Earth allowed its afterglow to be studied extensively. On 6 April 2003, a spectroscopic analysis of the burst's optical afterglow revealed discernible peaks at approximately 570 nm and 470 nm. This spectral profile was effectively reproduced through a composite model, integrating a power-law distribution with the spectral characteristics derived from SN1998bw. Noteworthy was the sustained evolution of supernova-like features during the subsequent weeks following the initial burst. Optical observations conducted at the Kitt Peak National Observatory indicated a luminosity in the burst's optical afterglow that surpassed predictions based on a power-law decay. This observed departure from the expected decay pattern could be rationalized by postulating the influence of additional luminosity originating from a concurrent supernova event (later named SN2003dh) [62].

A further fundamental contribution of HETE was the discovery of X-ray Flashes (XRFs). XRFs are intense and transient cosmic events characterized by a rapid release of X-ray radiation. Although very similar to GRBs, the distinction between them lies in the energy distribution of the emitted radiation. Originally defined operationally as those X-ray signals detected by BeppoSAX's WFCs (energies between 2 and 25 keV), which were not triggered and not detected by the GRBM (in the energy range 40–700 keV) [63], they are now considered a subclass of gamma-ray bursts (GRBs), sharing similarities with traditional GRBs but with a spectral peak in the X-ray range. Even though the nature of XRFs is largely unknown, the most credited model posits that XRFs could be given by off-axis GRB emission: it is thus postulated that gamma rays are indeed emitted, but their trajectories are directed away from our instruments [64]. Consequently, the initially observable phenomenon is confined to lower-energy X-rays emitted in a divergent beam, exhibiting greater dispersion compared to the more narrowly focused gamma-ray beam.

This era can be summarized as follows:

- The common spectral properties of SN1998bw and SN2003dh provided a "smoking gun" for their common origin, proving once and for all the association between long-duration GRBs and supernovae.
- Discovery of X-ray Flashes (XRFs), a subpopulation of GRBs.
- Together with BeppoSAX, HETE-2 enabled accurate localization (of the order of arcminutes) that kick-started the era of multiwavelength observations of GRBs before the advent of *Swift*.

6. The Swift Era (2004–Ongoing)

In the early 2000s, the GRB phenomenon seemed almost completely decoded. BATSE observations had led to excellent modeling of gamma emissions, identifying two subpopulations of GRBs depending on their duration. Subsequent observations by BeppoSAX and HETE-2 led to the identification of multiwavelength afterglows and, through accurate localization, allowed long GRBs to be correlated with supernova emissions. These discoveries were accompanied by impressive and rapid theoretical advances that led to the development of, among others, the internal/external shock fireball model and the possible central engines of GRBs. Still, there were some "details" of these phenomena that were not yet well understood. First of all, even though BeppoSAX had been able to observe a large number of GRB afterglows, these were just from long-duration bursts due to the requirement to slew the telescopes to observe the signals with the main cameras once the wide-field cameras were triggered. This operation, carried out from the ground, was very slow and therefore limited the observation possibilities only to long-duration GRBs and meant that there was a gap in the data acquired between the prompt-emission signals that triggered the wide-field cameras and afterglow observations after slewing. To fill these observational gaps, the Neil Gehrels Swift Observatory mission [65] was launched on 20 November 2004.

Swift is an international space observatory with five main objectives: to quickly (automatically, in ∼1–2 min) repoint its NFIs in order to study the early afterglow emissions (and better understand both the afterglow onset and the connection with the prompt-emission phase), to observe GRBs across a large spectral band, to collect a large sample of GRBs and afterglows, and to study short GRBs and to trigger ground-based follow-up observations in order to perform accurate spectroscopy measurements.

To achieve these objectives, *Swift* hosts three instruments on board. The Burst Alert Telescope (BAT) [66] is a coded-aperture-mask telescope sensitive between 15 and 150 keV capable of localizing the position of the signals with an accuracy of 1 to 4 arcminutes within 15 s over a 1.4-steradian field of view. This instrument is used to quickly localize the positions of the GRBs to slew the telescope in order to point the NFIs and simultaneously send the localization to the ground through the GCN system to trigger follow-up observations. The X-ray Telescope (XRT) [67] is an X-ray focusing telescope sensitive between 0.3 and 10 keV capable of taking images and light curves and performing a spectral analysis of the GRB afterglows. This instrument also allows the refinement of the BAT localizations of GRBs, with a typical error radius of approximately 2 arcseconds. The Ultraviolet/Optical Telescope (UVOT) [68] is a 30 cm Ritchie–Chretien UV/optical telescope used to detect GRBs' optical afterglows, providing localization with <arcsecond precision and performing optical and ultraviolet photometry through the use of lenticular filters and low-resolution spectra (170–650 nm) thanks to optical and UV prisms. UVOT can also provide long-term follow-up of the afterglow light curves of GRBs. The combination of these instruments allowed a progressive refinement of the localizations of the signals. First, BAT is triggered by the GRB signal and calculates the position to <4 arcmin. Then, while the first localization is sent to the ground through the GCN network, the spacecraft autonomously slews to the GRB position in 20–70 s. XRT and UVOT then start their observations, determining the position to <5 arcseconds, and then transmit their data to the ground. In this way, *Swift* manages to identify on average 100 new GRBs every year, of which the vast majority are long GRBs. *Swift* has obtained (and continues to obtain) exceptional results in this way, which have revolutionized our understanding of GRBs in several ways thanks to some fundamental discoveries.

Thanks to the fast automatic slewing, *Swift* is able to detect the faint X-ray afterglow of short-duration GRBs. This was impossible before *Swift*. One year after the launch, in 2005, it was already possible to identify the host galaxies of some of these short GRBs (e.g., GRB050509B and GRB050709 detected with HETE-2 and GRB050724) and obtain their precise positions within them. The observations turned out to be rather different than expected: while long GRBs are generally found in blue, regular, and highly star-forming host galaxies and are located precisely in the star-forming regions of these galaxies, short GRBs, on the other hand, are hosted mainly by elliptical or irregular galaxies, far from star-forming regions [69–71]. This led to the suggestion that short GRBs may have different progenitors than long GRBs, not being associated with the death of massive stars but with the coalescence of compact objects (such as neutron stars or black holes).

The ability to quickly repoint the telescope and observe the initial stages of the afterglows has led to a true revolution in our understanding of these emissions thanks to the abundant available data [72,73]. Before *Swift*, GRB afterglows were simply modeled with two power laws, one for the "initial" phase and one for the "post jet-break" phase. It was therefore expected that by observing the initial phases of the afterglow, the same simple power-law trend would be found to connect up to the peak given by the prompt emission. In addition to the two phases already known, it was found that most GRBs have a complex light curve, with two additional phases connecting the prompt-emission phase with that of the afterglow. The early afterglows show, in addition to the two already-known decay phases, an "early steep decay" phase directly connected to the prompt emission [74,75] and a "plateau" phase (or "shallow decay") before the onset of the normal decay phase [76,77]. In nearly half of the GRBs, additional X-ray flares, following the prompt gamma-ray emission, were also discovered [78–80]. The abundance of data has allowed the development of a phenomenological model for all afterglow light curves, the "canonical X-ray afterglow lightcurve" [81,82]. In addition to these more widespread characteristics, some afterglows present even more particular behaviors, such as the presence in some GRBs of a "chromatic afterglow" behavior, where the optical light curve has no break coinciding with the X-ray break time (or vice versa), and in particular, there is no association between the temporal variations in the light curve in the optical and in the X-rays [83]. This evidence, which challenged the standard external shock fireball model, led to the proposal that the afterglow emission could be generated by the superposition of different physical processes. The initial steep-decay phase is the continuation of the prompt emission after it has ended due to emission from high latitudes relative to the observer's line of sight. The plateau phase could be given by an external shock emission with continuous energy injection, which requires either a long-duration central engine or a jet with stratified Lorentz factors. In particular, to justify this plateau phase, the models seem to favor the notion that the central engine could be a (supramassive) millisecond magnetar that, thanks to the rotation, manages to survive the collapse long enough to emit the signal in the early afterglow and then collapses into a black hole (with an extremely rapid decay of the light curve) [84]. And finally, X-ray flares may be internal emissions due to the tail end of central engine activity, similar to how prompt gamma-ray emission is produced. Various models have been proposed to explain such emissions as intermittent activity (or re-ignition) of the GRB's central engine. Among the proposed models, we mention the fragmentation of the star during the collapse [85] and/or the fragmentation of the accretion disk due to gravitational instability [86] in the black hole–torus/accretion disk model. Alternatively, these spikes could be produced by the magnetic activity of a rapidly spinning neutron star (magnetars) [87,88].

Thanks to its high performance, *Swift* was able to greatly expand the redshift range in which GRBs were observed: at low redshifts, several "low-luminosity" GRBs were observed, leading to the hypothesis that they may form a distinct population compared to "high-luminosity" GRBs [89], while at high redshifts, *Swift* broke the record several times over the years with different observations. The first record-breaking GRB observed was GRB050904 at a redshift $z = 6.29$ [90,91], discovered about a year after the mission's launch. Other notable GRBs were GRB080913 at $z = 6.7$ [92] and GRB090423 at $z = 8.2$ [93,94] (still the most distant GRB with strictly spectroscopic redshift estimation) and GRB090429B, which, at $z = 9.4$, remains the most distant GRB ever observed (with photometric redshift estimate) [95]. The increasing number of GRBs with known redshifts allowed the parameters of the Amati relation to be finely calibrated [31] and led to the discovery of two new empirical correlations between the observational parameters.

Some "anomalous" signals observed by *Swift* led, for the first time, to the question of whether the distinction between long and short GRBs is intrinsically linked to different progenitor populations. In 2006, *Swift* had already detected two long-duration GRBs (GRB060614 and GRB060505, [96]) that had temporal lags and peak luminosities that did not fit with those expected for long GRBs but were perfectly reasonable for short GRBs. Moreover, deep optical observations never found any supernovae associated with these emissions, putting very strong constraints on the possibility of an association. These events challenged both the collapsar and the merging neutron star theoretical models for long and short GRBs, suggesting that these long-duration events could be part of a subgroup of the category of short GRBs [96,97]. This first suggestion of the blurring of the two classes of GRBs was reinforced in the following years by the detection of several short-duration (or “rest-frame” short) bursts found to be more consistent with the long-duration population (e.g., GRB080913, GRB090423, GRB090426) [92,98]. All these findings led to the now-accepted conclusion that the duration criterion alone is insufficient to determine the physical category of a particular GRB, and other criteria must be taken into consideration [36].

Other exceptional events have, in time, appeared, challenging our models and understanding with unexpected characteristics. Some notable examples follow. GRB060218 (and SN2006aj) was a GRB with unusual characteristics never seen before: in fact, it had a duration of almost 2000 s, much longer than the typical gamma-ray bursts seen previously, and its host galaxy was identified at a distance of only 440 million light years, much closer than all the bursts previously observed. Furthermore, despite its proximity, the burst was much dimmer than the usual high-luminosity GRBs. Moreover, a smooth light curve, a thermal X-ray component in the time-resolved spectra, and a puzzling UV emission posed strong challenges to the theoretical models [99]. The aforementioned GRBs 060505, 060614, 080913, 090423, and 090426 have led to the understanding that the simple long–short classification scheme is not enough to completely describe the physical origin of GRBs. GRB080319B, also known as the “Naked eye Burst”, was the first GRB to have a prompt optical emission visible to the naked eye: with a peak visibility at an apparent magnitude of 5.3, it remained visible to the human eye for about 30 s, breaking the record for being the object observable with the naked eye coming from the largest distance [100]. Some bursts, such as GRB101225 (the “Christmas Burst”) or GRB111209A, were extremely long (with GRB111209A still holding the record as the longest GRB observed, with a duration of more than 7 h) with observational properties difficult to interpret with the models of the time; these represented a prototype of a separate class of ultralong GRBs with a possible progenitor different from the others [101]. GRB110328, now called “Sw J1644+57”, was a totally anomalous event, later recognized as the gamma-ray emission from a tidal disruption event (TDE), the destruction of a star by a supermassive black hole [102–105]. This remarkable GRB marked the first time such type of events was ever observed.

This era can be summarized as follows:

- *Swift* was able to detect the X-ray afterglow of short-duration GRBs, and thanks to multiwavelength follow-up campaigns, it was possible to identify their host galaxies: short GRBs are hosted in different galaxies (and outside of star formation regions) with respect to long GRBs. This was the first strong hint that the two categories might come from different precursors.
- The observation of the early GRB afterglows allowed the discovery of a complex multiphase structure given by a superposition of processes, at odds with the theoretical models of the time.
- The detection of some “anomalous” signals challenged the use of the temporal criterion (short vs. long) alone for the classification of GRBs.
- *Swift* is able to detect the highest-redshift GRBs, which led to their use to study the Early Universe.

7. The High-Energy (AGILE and Fermi) Era (2007–Ongoing)

Until the early 2000s, most GRB observations had been carried out exclusively in the hard-X-ray, dim-gamma-ray regimes in order to exploit the technological advances then available to optimize the capabilities (localization, spectral and temporal) of the detectors. In fact, until that time, only one mission had an instrument on board that was sensitive beyond a few MeV: CGRO. As seen in Section 3, CGRO had four instruments on board that covered an unprecedented energy range of 6 orders of magnitude, from 20 keV to 30 GeV. The Energetic Gamma Ray Experiment Telescope (EGRET) [106] was an instrument covering the higher-energy bands, sensitive between 30 MeV and 30 GeV. To achieve such high-energy detections, EGRET used the pair-conversion technique. The detector consisted of three components: a tracker, a calorimeter, and an anticoincidence detector. The tracker, a multilayer thin-plate spark chamber, was used to convert gamma-ray photons into electron–positron pairs, whose trajectories, reconstructed through the multiple interactions and the crossing of the different layers of the detector, were used to estimate the direction of arrival of the photon, reaching high angular resolutions. The NaI(Tl) calorimeter was used to collect the electron–positron shower and measure its energy. Finally, in order to reject unwanted signals from charged particles (cosmic rays), the telescope was covered by a plastic anticoincidence scintillation dome with a high-enough efficiency to reject charged particles but not to veto gamma rays. During its active life, EGRET allowed the observation of high-energy emission from some GRBs [107–109], not all of which could be explained by a simple extension of the models of the time [110], thus showing the need for optimal timing and fast broadband detectors to extend the studies of such phenomena to higher energies. In 2007 and 2008, two new missions for the observation of the gamma-ray sky were launched that substantially changed our way of understanding GRBs, starting a new high-energy era of observation characterized by the possibility of observing energies that, up to that moment, had been inaccessible ($>GeV$).

7.1. AGILE (2007–Ongoing)

AGILE ("Astro rivelatore Gamma a Immagini LEggero", Italian for "Lightweight imaging gamma astro detector") [111] is an Italian high-energy astrophysics mission launched on 23 April 2007 dedicated to the observation of the high-energy gamma-ray sky. With a weight of just ∼100 kg and the dimensions of a cube with sides of about 60 cm, AGILE is the lightest and most compact instrument for high-energy astrophysics flying today. AGILE combines, for the first time, a silicon–tungsten tracker gamma-ray imager ("GRID", sensitive in the 30 MeV–30 GeV range) [112] with a hard X-ray imager ("SuperAGILE", sensitive in the 18–60 keV energy range) [113] with a large FoV (∼1–2.5 steradians) and optimal angular resolution. AGILE is also equipped with a non-imaging gamma-ray scintillation mini-calorimeter (MCAL) sensitive between 350 keV and 100 MeV and a plastic scintillator anticoincidence system. AGILE operated in "pointing" mode until April 2009 when, following the failure of the inertial pointing system, the satellite was placed in "Sun Pointing Spinning" (scanning) mode to continue operations despite the failure. Since then, AGILE has operated in this scanning mode, rotating at a speed of $\sim 1^{\circ}\ s^{-1}$ and thus sweeping approximately 70% of the sky every day. This operating mode was found to be optimal for studying the variability of celestial sources. Central to AGILE's success is its world's fastest gamma-ray alarm monitoring system. AGILE is, in fact, equipped with two independent pipelines for monitoring gamma-ray alarms that process data with different data-quality results in order to optimize the response time [114].

Using data from the AGILE mini-calorimeter (MCAL), it was possible to publish two GRB catalogs, the first in 2013 [115] and the second, more recently, in 2022 [116]. The amount of data obtained made it possible to calculate the counts and flux upper limits pertaining to GRB high-energy emissions between 30 MeV and 3 GeV (the AGILE-GRID energy range), thereby imposing strong constraints on high-energy radiation originating from both the afterglow emission and synchrotron self-Compton emission within internal shocks [117].

Two exemplary GRBs seen by AGILE were GRB080514B and GRB090510. The first, GRB080514B [118], was the first GeV-bright GRB observed after EGRET. This event also had an afterglow phase, the observation of which allowed a photometric redshift measurement (z∼1.8). Remarkably, the high-energy tail of the spectrum of this GRB fell right on the continuation of the Band spectrum used at lower energies, extending it from 20 keV up to ∼50 MeV. GRB090510 was first localized by *Swift* and then detected both by AGILE [119] and by *Fermi*/LAT [120]. This nearby burst (estimated redshift z∼0.903) was unprecedented, as it was the first time that a short GRB was observed simultaneously by three different instruments, managing to extend its spectrum up to more than 300 GeV. The light curve was also anomalous compared to those observed up to that point for short GRBs, as it presented a delayed emission at high energies compared to the prompt phase and a substantial spectral evolution. This temporal behavior and the evolution of the power-law spectrum challenged the models based on synchrotron emission/synchrotron self-Compton in external shocks and on the hadronic models [121].

More recently, AGILE has had huge success in the application of modern machine-learning techniques for the identification of GRB signals in data from both the gamma-ray imaging detector (GRID) [122] and the anticoincidence system (ACS) [123], leading to the identification of 72 GRB signals with significance $\geq 3\sigma$, 15 of which are not present in the second MCAL GRB catalog, as they were not identified before when using traditional methods for the data analysis.

7.2. Fermi (2008–Ongoing)

In those same years, another NASA gamma-ray mission, the Gamma-ray Large Area Space Telescope (GLAST), later renamed the *Fermi* Gamma-Ray Space Telescope (FGST), was launched on 11 June 2008. *Fermi* carries two scientific instruments on board, the Large Area Telescope (LAT) [124] and the Gamma-ray Burst Monitor (GBM) [125]. The LAT is a gamma-ray imaging detector that detects photons with energies from about 20 MeV to about 300 GeV, with a field of view of about 20% of the sky, capable of exposing all parts of the sky for about 30 min every 3 h in sky survey mode. The GBM consists of 14 scintillation detectors, namely, 12 NaI crystals for the range from 8 keV to 1 MeV, primarily used for onboard triggering, onboard and ground localization, and spectroscopy, and two bismuth germanate (BGO) crystals with sensitivity from 150 keV to 30 MeV. The GBM is used for spectroscopy and is capable of detecting GRBs in this energy range throughout the entire sky not occluded by the Earth. Thanks to these instruments, *Fermi* offers numerous advantages compared to all previous instruments and, in particular, an enormous range of energies, spanning more than 7 orders of magnitude, including the largely unexplored 10 GeV–100 GeV band and a huge field of view. These allow *Fermi* to observe $\sim$200 GRB/year with observations from 8 keV to 40 MeV and $\sim$15 GRB/year with observations from 8 keV to 300 GeV with excellent spectral and timing capabilities, setting *Fermi* as one of the leading instruments in the current study of the gamma-ray sky. These two instruments have, in many ways, revolutionized our understanding of GRBs.

In its years of operation, *Fermi* observed a lot of GRBs, both with the GBM and with the LAT, and produced various catalogs. The latest ones are dated 2018 (though regularly updated) for both instruments, boasting as many as 2356 GRBs detected by the GBM [126] and 186 (approximately 7–8% of those seen by the GBM) above 100 MeV seen by the LAT [127]. For those detected by both instruments, the LAT band emission usually lasts much longer than the GBM band emission, and it decays as a power law [128,129]. This has been interpreted as an external-shock origin of the observed > 100 MeV emission of the GRB, after the prompt-emission phase has ended [128–131]. Another, yet unexplained, feature that was found confronting the observations of the GBM and LAT is that, in some GRBs, the LAT GeV emission has a delayed onset with respect to the MeV emission. This was not predicted by theoretical models, and there is still no agreement on the origin of such emission, even though many mechanisms have been proposed. Still, the presence (or lack) of delays between the emissions at different energies has been used to put strong constraints on Lorentz Invariance Violations (LIVs), a feature allowed by many models of Quantum Gravity (e.g., GRB090510 [132]). The LAT was able to detect the presence of photons with rest-frame energies exceeding 100 GeV in several bright GRBs. Some examples are GRB080916C [133], i.e., the very first bright LAT burst; GRB090510 [132]; and GRB130427A [134], which, at the time, was a record-setting bright GRB detected both by *Fermi* and by *Swift*. The existence of these photons was not consistent with the predictions of the standard fireball synchrotron internal-shock model of the time and placed strong constraints on GRB physics, including the minimum bulk Lorentz factor (from opacity arguments) [135], particle acceleration mechanisms in relativistic shocks, and relativistic particle radiation mechanisms. These photons can also be used to study the extragalactic background light (EBL) via the expected attenuation of high-energy photons due to two-photon pair production (e.g., [136]).

The ability to carry out highly accurate spectral analysis over such a wide range of energies (7 orders of magnitude, including the hitherto unexplored range > 10 GeV) has provided fundamental information for understanding the composition of the GRB jet and the emission mechanisms of the prompt emission, triggering a real theoretical renaissance in trying to understand the large number of unexplained observational effects. The observation of the LAT's first bright GRB, GRB080916C, already showed almost-featureless, time-resolved spectra and spectral features divergent from the predictions put forward by the conventional fireball internal-shock model, thus necessitating a reevaluation of the fundamentals of the theoretical framework [137]. Subsequent observations of other GRBs (e.g., GRB090510, 090902B, and 090926A) have introduced a layer of complexity into the observed GRB spectra: these analyses have shown that the spectra of the observed GRBs are composed of the superposition of at least three distinct spectral components [138,139]. In addition to the conventional non-thermal component of the Band function, in some GRBs, a further quasi-thermal component is present, assuming a dominant [140] or sub-dominant role [141]. The observation of other signals (e.g., GRB090902B, 090510, and 090926A), moreover, suggested the existence of a third component of the power-law spectrum, which extends to both high and low (GBM) energies [142]. The origins of this additional spectral component remain elusive. Recently, more in-depth analyses of low- energy spectra have been carried out, going down to the optical, highlighting the existence of a spectral break in the low-energy part of prompt spectra. This is consistent with emission from synchrotron radiation in the moderately rapid cooling regime, identifying the spectral break with the cooling frequency [143,144].The Band spectrum thus modified is in better agreement with the data compared to the addition of ad hoc thermal and non-thermal components to the total spectrum.

This era can be summarized as follows:

- By fully exploiting the production of electron–positron pairs in the detectors, it was possible to extend the energy range to hundreds of GeV.
- Comparing GRBs observed by both the GBM and LAT, it was found that the LAT band emission usually lasts much longer than the GBM band emission.
- Comparing the GBM and LAT data also shows that the GeV emission has a delayed start compared to the MeV emission.
- The possibility of performing unprecedentedly detailed spectral analysis in a wide spectral window, including HE, has provided very important information for understanding the composition of GRB jets and the prompt-emission mechanisms.
- The use of modern machine-learning techniques applied to AGILE detectors led to the identification of previously unidentified GRB signals.

8. The Birth of the Multi-Messenger Era (2017–Ongoing)

GRBs have been believed to be multi-messenger emitters since 1989.

In 1995, three independent groups proposed that GRBs could be a dominant source of Ultra-High-Energy Cosmic Rays (UHECRs) through different mechanisms. Two groups proposed that the origin of UHECRs is in the internal shocks [145] or external shocks [146] of a GRB fireball. The latter group suggested a GRB-UHECR association after noticing that each of the error boxes of the two highest-energy cosmic-ray-shower events known at the time overlapped very well with that of a strong GRB [147]. GRB-accelerated cosmic rays can interact with background photons or other baryons through hadronic processes ($p\gamma$) to produce high-energy neutrinos, and as early as 1997, it was suggested that these neutrinos could reach PeV energies [148]. Predictions of the neutrino fluxes from GRBs are still a matter of debate, as they depend on many unknown parameters and are highly model-dependent [149,150]. Even though the theoretical evidence is particularly convincing, to date, no detection of neutrinos in conjunction with GRB signals has been observed, and progressively more stringent constraints on the neutrino flux from GRBs have been reported from both the IceCube neutrino observatory in the South Pole [151] and the ANTARES neutrino observatory in the Mediterranean Sea [152,153].

Ever since it was suggested that the merger of compact objects, such as two neutron stars, could be the progenitors of some GRBs [13], it was clear that this would make them ideal candidates for emitting gravitational waves together with gamma rays. In fact, these systems were already known sources of gravitational waves (GWs) [154]. Over the years, the possible association between short GRBs and GWs was revisited several times and consolidated. On 17 August 2017, GW170817 was detected by the gravitational wave observatories Advanced LIGO in the USA and Advanced Virgo in Italy, identifying it as an NS-NS merger event and obtaining an accurate localization [155]. Then, 1.7 s later, the low-luminosity short GRB GRB170817A was observed by *Fermi*/GBM and INTEGRAL, with a localization compatible with that obtained by LIGO-Virgo [156,157]. The joint detection thus confirmed the association between short GRBs and mergers of compact objects (NS-NS) [158]. At the same time, this detection triggered a massive observational follow-up campaign, which led to the observation of the signal in the optical, radio, and X-ray bands and allowed the localization of the signal in a nearby galaxy, NGC4993, at $\sim$40 Mpc [159–165]. Particularly remarkable is the observation of the simultaneous emission of a "kilonova", a short-lived (days) IR-UV signal powered by the radioactive decay of heavy elements synthesized in the ejected outflow, predicted by many models [88,166–168]. Other than these, various electromagnetic counterparts originating from gravitational wave (GW) sources have been linked to compact binary mergers, such as a faint radio afterglow ("radio flare"), arising from the interaction between the ejected material and the ambient medium [168], and an X-ray counterpart due to magnetic dissipation if the neutron-star–neutron-star (NS–NS) merger product takes the form of a millisecond magnetar or a black hole. It is speculated that collapsars might exhibit strong GW burst emissions, presenting the intriguing prospect of long GRBs and core-collapse hypernovae as potential multi-messenger targets [169].

The joint detection of GRB-GW170817 had enormous importance for fundamental physics, as it allowed a constraint to be imposed on the difference between the speed of gravity and the speed of light:

$$-3 \times 10^{-15} \leq \frac{\Delta \nu}{\nu_{EM}} \leq 7 \times 10^{-16} \tag{6}$$

This allowed new bounds to placed on Lorentz Invariance Violations and allowed a new test of the equivalence principle by constraining the Shapiro delay between gravitational and electromagnetic radiation [157]. These unprecedented results had huge repercussions for some dark matter (DM) and dark energy (DE) models, completely ruling out some classes of modified gravity theories that had been perfectly viable up to that detection [170].

This detection has renewed momentum in the development of strategies and synergies between different observatories to try to obtain repeat observations of this impact. To date, no other joint detections have been carried out, underscoring that the field of multi-messenger astronomy is still in its infancy.

This era can be summarized as follows:

- GRBs have been believed to be multi-messenger emitters since 1989.
- To date, no neutrino detections have been observed in conjunction with GRB signals, placing progressively more stringent constraints on the flux of neutrinos from GRBs.
- GRB-GW170717A was the first-ever multi-messenger observation of a GRB, allowing for some unprecedented results in GRB and fundamental physics.

9. The Very High Energy Era (2019–Ongoing)

The use of the photon-pair-conversion technique for the detection of gamma photons in space is severely limited by the volumes of the detectors. In order to observe photons with $\geq$TeV energies (VHE), the dimensions of the detectors are such that they make it impossible to observe this radiation from space. In order to observe photons of such energies, it is therefore necessary to use different techniques, exploiting the Earth's atmosphere as the "medium" of the telescope and observing the effect of the interaction of such photons with it. Gamma rays (as well as primary cosmic rays) crossing the atmosphere collide with atmospheric nuclei, producing secondary particles that, in turn, generate a cascade of particles as they traverse the atmosphere. The intricate interplay of these particles cascading down through the atmosphere creates an extensive spread of ionization and fluorescence, offering a unique signature for detection called an "Air Shower". There exist two types of ground observatory for VHE: Imaging Air Cherenkov Telescopes (IACTs) and Extensive Air Shower (EAS) experiments. Cherenkov experiments consist of almost-optical telescopes devoted to detecting the Cherenkov light emitted by particles produced in air showers and moving superluminally in the atmosphere. EAS experiments are huge arrays or carpets of particle detectors that directly collect the particles in air showers. Cherenkov experiments have lower energy thresholds but also a lower duty cycle, as well as a smaller field of view, when compared to EAS experiments.

Since as early as 1994, various theoretical models have predicted the possibility of the existence of a very high TeV energy component of the GRB emission [171–175]. This stimulated a search for this component of GRB emission with various instruments, however, with poor results. Some first tentative hints of TeV emissions from GRBs came with the claims of the detection of GRB920925C by the AIRshower Observation By angle Integrating Cherenkov Counters (AIROBICC) [176] and GRB970417A by Milagrito [177,178]. The HEGRA AIROBICC array was an array of 7×7 40 cm diameter PMT-based air Cherenkov integrating telescopes located in La Palma (Canary Islands) and was sensitive up to a few tens of TeV. After searching for GRBs above 20 TeV within AIROBIC's field of view, using data gathered between March 1992 and March 1993, evidence of a $\sim$2.7 σ detection from GRB920925c was reported. However, since the "signal" preceded the activation of WATCH (an all-sky X-ray monitor on board the GRANAT satellite [179,180]) by $<$1 min and was located approximately 9° away from the position identified by this instrument, no evidence was claimed. Milagrito, a prototype of the Milagro EAS experiment, consisted of a flat array of 228 photomultiplier tubes (PMTs) submerged in a light-proof water pool with a size of $\sim 42 \times 42$ m^2. In 2000, Milagrito reported evidence for an emission above 650 GeV from GRB970417A, with a (post-trial) probability of 1.5×10^{-3} of being a background fluctuation. GRB970417A was a weak, soft GRB first observed by BATSE. Still, this was not enough to claim evidence of VHE emission from GRBs with full certainty.

Despite enormous and growing efforts, no evidence was found, and only upper limits from various collaborations were set [181–185] until 2019, with the observation of GRB190114C by the Major Atmospheric Gamma-ray Imaging Florian Goebel Cherenkov Telescopes (MAGIC) [186,187]. On 15 January 2019, MAGIC, a system of two IACTs located on the island of La Palma, reported the first observation of 0.2–1 TeV photons from GRB190114C. Triggered by the *Swift*-BAT alert, the MAGIC telescopes, thanks to their fast repointing capabilities, were able to start the observations of the GRB after just 57 s, "revealing a distinct emission component of the afterglow with power comparable to that of the synchrotron component" [187]. The observed emission, associated with the afterglow, has been explained as an emission from the inverse Compton scattering of synchrotron photons from high-energy electrons. The announcement of this unprecedented event triggered a renewed push in the theoretical research to understand VHE GRB emission. Moreover, the same year, 5 months later, the observation of the TeV afterglow of GRB180720B by the High Energy Stereoscopic System (H.E.S.S.) telescopes was announced [188]. Located in Namibia, H.E.S.S. is a system of five IACTs that are sensitive in the energy range of 0.03 to 100 TeV. It is currently the only VHE photon observatory in the Southern Hemisphere. The emission was also interpreted in this case as synchrotron photons accelerated by inverse Compton scattering with electrons (synchrotron self-Compton radiation, SSC). That same year, H.E.S.S. observed another TeV GRB, GRB190829A [189], bringing the total of such signals ever observed to three. The following year, the observations of GRB201015A [190], with a signal at the $>3\sigma$ level, and GRB201216C [191,192], with a $>5\sigma$ level, were announced by the MAGIC collaboration. After an in-depth analysis of the data taken for GRB160821B, an extremely close short GRB with a redshift of $z = 0.162$, MAGIC unveiled $\sim 3\sigma$ evidence pointing toward a gamma-ray signal exceeding approximately 0.5 TeV. The observations lasted approximately 4 h after the initial burst [193]. The presence of this signal poses a challenge to the most straightforward interpretation provided by one-zone models of the synchrotron self-Compton emission originating from the external direct shock. These models face difficulties in adequately explaining the reconstructed TeV flux associated with the observed gamma-ray signal.

On 9 October 2022, the last (to date) GRB with a TeV emission was observed. The Large High Altitude Air Shower Observatory (LHAASO) [194,195], the largest High Altitude Water Cherenkov Experiment in the world, located in China, reported the detection of the early onset of the afterglow of GRB221009A, with 64,000 photons (above $\sim$0.2 TeV) detected within the first 3000 s [196]. GRB221009A broke every record and remains to this day the Brightest (GRB) Of All Time (B.O.A.T.).

This era can be summarized as follows:

- Ground-based observations are needed to observe photons at TeV. There are two types of instruments, IACTs and EASs, with different performance and merits.
- Despite some claims (AIROBICC and Milagrito), no detection of GRB at TeV energies occurred until GRB190114C.
- To date, only five GRBs have been observed to have TeV emission with significance $> 5\sigma$, and two more have been observed with significance $> 3\sigma$. Despite enormous efforts, the detection of GRB emissions at TeV remains extremely difficult.

10. The Record Breaker: GRB221009A, the B.O.A.T.

On 19 October 2022, an unprecedented GRB event was observed by several instruments: GRB221009A. This event was so extreme that it broke the record as the brightest and most energetic GRB ever observed [197–199]. First detected by both the *Fermi* [200] and *Swift* [201] satellites, the GRB lasted around seven minutes, but the multiwavelength afterglow remained detectable for more than a month. This led to one of the biggest and most successful follow-up campaigns ever conducted, which led to the observation of the emission on an unprecedented 15 orders of magnitude on the electromagnetic spectrum, from radio emissions to VHE gamma rays. The burst completely saturated the detectors aboard *Fermi*, which captured gamma-ray photons with energies above 100 GeV [200]. GRB221009A produced the largest number of very high energy (VHE) photons ever observed by scientific instrumentation: before GRB221009A, the number of VHE photons detected in the entire history of GRB astronomy amounted to only a few hundred. For GRB221009A, however, the LHAASO alone saw more than 5000 VHE photons, some of these having a record energy of 18 TeV [196]. This claim is still debated, though. Still, photons of these energies are difficult to explain within the modern standard paradigms and prompted a new impulse in the development of theoretical models.

At the moment, there is still no consensus about the mechanism for generating these highly energetic gamma photons, which are difficult to explain with the standard synchrotron- and synchrotron-self-Compton-based leptonic models for the afterglow, and many different mechanisms and jet geometries are continuously being proposed to explain them (e.g., [202–205]). Some proposals have been put forward in which GRB221009A would be a huge accelerator of UHECRs, whose propagation would induce an electromagnetic cascade in the extragalactic medium. The line-of-sight component of this flow could explain the detected > 10 TeV emission [206,207].

The presence of photons of such energies, coming from an estimated distance of about $z = 0.151$ [208], is at odds with theoretical models because of the expected attenuation due to the extragalactic background light (EBL). This has led to much speculation on the presence or absence of exotic effects to explain the detection, with different groups proposing different mechanisms, such as the presence of LIV effects [209,210] or of axion-like particles (ALPs) [211,212]. Other groups have, however, highlighted how these observations, although exceptional, can still fit into standard paradigms.

Despite the extensive follow-up campaign, no multi-messenger detection occurred, managing to place stringent constraints on the emission mechanisms thanks to the non-observation of neutrino emission [213–215].

An important claim was made following an analysis of the spectral evolution of GRB221009A, as seen by *Fermi*/GBM, reporting the discovery of a narrow emission feature at around 10 MeV with very high significance ($>6\sigma$), interpreted in the paper as a blue-shifted annihilation line of relatively cold electron–positron pairs ($k_B T \ll m_e c^2$) [216]. This feature has never been observed in any other GRB, and its detection would be made possible by the exceptional brightness of the event, which dwarfs even the next-brightest bursts (such as GRB130427A). The presence of an excess around 10 MeV was also reported in the spectral analysis by the *Fermi* team [200].

In [197], it is argued that, while GRB2201009A might not be the intrinsically brightest GRB ever, its proximity to Earth makes it so that it is the brightest ever observed. In the same paper, they report an estimated timescale of approximately 10,000 years for any such event to happen again. These estimates underline the exceptional nature of this event, so much so that the authors themselves write in the acknowledgments at the end of the article:

> We acknowledge the universe for timing this burst to arrive at Earth after the invention of GRB monitors but during our active research careers. Our token optical astronomer would like to complain about the alignment with the Galactic plane and requests that the next one avoid this issue.

To this, we would also add the following:

> Our VHE colleagues would also request the next one not to arrive on a full moon night.

This exceptional event continues to surprise us by challenging our understanding of such phenomena, and there is no doubt that it will be a matter of study and debate for many years.

This era can be summarized as follows:

- GRB221009A was by far the brightest and most energetic burst ever observed by humans.
- The observation of photons at energies > 10 TeV challenges current theoretical models. Many mechanisms to explain such an emission have been proposed, but there is no consensus, yet.
- The observation of photons at energies > 10 TeV from a distance of $z = 0.151$ is at odds with predictions about attenuation by the EBL. Among the possible explanations, exotic/fundamental physics effects (LIV vs. ALPs) have been proposed.
- There is evidence of a highly significant narrow emission feature at around 10 MeV. However, this feature has never been observed in other GRBs and was observed in GRB221009A only due to its extreme brightness.

11. Future Prospects

As we have seen, the evolution of our understanding of the GRB phenomenon is intimately linked to the technological–scientific advances that have allowed us to carry out new measurements, thus revealing new pieces of this complex puzzle from time to time. Since a complete review of all the very interesting proposals for new instruments that could lead to a better understanding of these phenomena is an enormous undertaking, well beyond the scope of the present article, we mention here just four examples of instruments designed specifically for the observation of GRBs (among other things) that are guaranteed to be able to make a very important contribution to this field in the near future.

The High Energy Modular Ensemble of Satellites (HERMES) is a project for a constellation of nanosatellites (CubeSats) sensitive in the 50–300 keV range, with full-sky coverage, that will exploit the "temporal triangulation" technique to obtain the accurate localizations of GRB signals (and transient signals in general). In particular, the complete HERMES constellation should be able to obtain a localization accuracy better than 15′ (approx. an error area < 0.2 deg^2) for long GRBs and a localization better than 1° (error area ~ 3 deg^2) for short GRBs [217]. This is thanks to the very high precision of the timing (better than a few hundred nanoseconds), which allows the measurement of the delays between the arrival times of the signal at the different satellites at less than a few dozen μs, thus managing to accurately estimate the direction of arrival of the signal relative to the constellation. As we have seen, the ability to obtain the accurate and timely localizations of GRBs is essential to organizing a proper observational follow-up strategy. HERMES will therefore be extremely important in the future for the study of GRBs (and, in general, of gamma-ray transient events) thanks to its unprecedented localization capabilities. It should also be noted that a major advantage of CubeSats over typical larger gamma-ray space missions is that it is relatively cheap, greatly limiting construction and launch costs. A great milestone for this project was achieved on 1 December 2023 with the launch of the Space Industry Responsive Intelligent Thermal nanosatellite (SpIRIT). SpIRIT, an Australian–Italian collaborative project, will be the first satellite of the HERMES Scientific Pathfinder Constellation.

The Space Variable Objects Monitor (SVOM) [218,219] is a Chinese–French-approved mission, with a launch scheduled for spring 2024. SVOM will host four instruments on board and will be complemented by a ground segment composed of three other instruments. SVOM's payload is composed of the following four main instruments: a wide-field coded-mask camera sensitive between 4 and 120 keV to quickly localize GRBs with an accuracy of a few arcmin called ECLAIRs; a gamma-ray non-imaging spectrophotometer (GRM) sensitive in the 50 keV to 5 MeV energy range for monitoring the FoV of ECLAIRs; and two narrow-FoV telescopes for the study of GRB afterglows, one operating in the soft X-rays (MXT) and one in the optical band (VT). The ground segment includes three dedicated instruments: a set of cameras for follow-up observation of the ECLAIR FoV in the visible (GWAC) and two robotic telescopes (GFT), sensitive in the visible and NIR, for studying the GRB afterglow [218]. The ground segment will be fundamental for coordinated and automated follow-up observations of satellite alerts. This design was developed in order to better study two categories of GRBs specifically: very distant GRBs with redshifts $z > 5$ (in order to be able to use them as cosmological probes) and faint/soft nearby GRBs, effectively expanding on the scientific goals borrowed from *Swift* [219].

The Transient High-Energy Sky and Early Universe Surveyor (THESEUS) is a mission proposal to the European Space Agency for a satellite telescope with the main objective of using GRBs to study the Early Universe and will be invaluable for multi-messenger and time-domain astrophysics in general [220,221]. To achieve these goals, THESEUS will host three instruments on board whose combination will allow GRB and X-ray transient detection over an extensive field of view with accurate localization ($\sim$0.5–1 arcmin) over a wide energy range. These instruments will be a Soft X-ray Imager (SXI) sensitive between 0.3 and 6 keV with a wide FoV ($\sim$1 sr) and a great angular resolution ($\sim$1–2 arcmin), an InfraRed Telescope (IRT) operating in 0.7–1.8 μm with both imaging and (some) spectroscopic capabilities, and an X/Gamma-ray Imaging Spectrometer (XGIS), a set of coded-mask cameras sensitive in an unprecedented 2 keV–20 MeV energy range. With this instrumentation, THESEUS will be perfect for studying the most distant high-redshift GRBs, offering a unique opportunity to delve into pivotal unresolved questions within modern cosmology. These inquiries encompass understanding the population of low-mass and low-luminosity primordial galaxies and exploring the origins and the evolution of cosmic re-ionization, and the results will contribute to our comprehension of the evolution of the Star Formation Rate (SFR) and metallicity up to the "cosmic dawn" and through Pop-III stars [222]. Furthermore, THESEUS, by enabling the precise localization, identification, and in-depth study of the electromagnetic counterparts of GW and neutrino sources, will bring fundamental advances in multi-messenger and time-domain astrophysics.

We also mention the GAmma-ray burst Localizing Instrument (GALI) proposal [223]. GALI is a new concept for identifying the positions of GRBs by using numerous small scintillators in a 3D array using their mutual shielding. GALI can be thought of as an omnidirectional coded-mask detector, where the mask itself, rather than being applied externally to the detector, is made up of the grid of the sensor elements themselves. Furthermore, the detector (and therefore the mask) does not have a preferred direction and therefore provides coverage of the entire sky, unlike traditional coded-mask instruments. The GALI concept of using mutual masking of modular detector elements can be scaled to any size, thus adapting to a multitude of different missions. In particular, larger versions of the detector, with more elements, in addition to having greater sensitivity, will obtain a great improvement in angular resolution compared to smaller versions. However, simulations show how even a small detector, with a total volume of just $\sim$1 L, could identify the direction of a burst down to approximately $\pm$2 for a 1 s GRB in the 10 keV–1 MeV range and a flux of $\sim$10 ph $cm^{-2}s^{-1}$. While GALI is capable of functioning as a standalone instrument aboard a single satellite, its versatility extends to its integration within a distributed satellite architecture. This incorporation enhances both the sky coverage and the localization capabilities of the entire satellite constellation.

On 9 January 2024, the Einstein Probe (EP), a joint mission of the Chinese Academy of Sciences, the European Space Agency, and the Max Planck Institute for Extraterrestrial Physics [224], was successfully launched. The EP is a space satellite for the observation and monitoring of transient X-ray phenomena, which will exploit the combination of two instruments: a Wide-field X-ray Telescope (WXT) [225], which uses lobster-eye optics to obtain an FoV of approximately 3600 square degrees in the range 0.5 $\sim$ 4.0 keV, and the Follow-up X-ray Telescope (FXT) [226], a Wolter-I type of X-ray telescope highly sensitive between 0.3 and 10 keV, for observations of transients identified by WXT.

Finally, we mention some NASA mission proposals at various stages of development and financing.

BurstCube is a mission under development by NASA with a launch scheduled for March 2024, with the main objective of studying short GRBs and their gravitational wave counterparts [227]. BurstCube will be a cubesat equipped with four cesium iodide (CsI) detectors, each coupled to an array of silicon photomultipliers (SiPMs) sensitive in the 50 keV to 1 MeV energy range, thus expanding the coverage of the sky in this energy window.

Another smallsat project under development by NASA is the StarBurst Multimessenger Pioneer [228], also developed for the observation of the prompt-emission phase of short GRBs and the electromagnetic counterparts of gravitational waves, which will exploit the combination of scintillator arrays (12 NaI(TI) detectors) with SiPMs to achieve high sensitivities in the energy band between 30 keV and 1 MeV.

The Moon Burst Energetics All-sky Monitor (MoonBEAM) [229,230] proposal expands the concept of using the difference in light travel time between different spacecraft to precisely estimate the position of GRBs (time triangulation) by proposing to place two cubesats in Earth and cislunar orbit, thus maximizing the flight time (>1 s) of light between the two satellites and achieving a great improvement in localization capabilities.

Last but not least is the proposal of the LEAP GRB polarimeter [231,232]: a single wide-FoV Compton polarimeter ($\sim$1.5π steradians) capable of precisely measuring the polarization of GRBs between 50 and 500 keV and, at the same time, carrying out spectroscopy measurements between 20 keV and 5 MeV, to be mounted on board the International Space Station (ISS). The possibility of reliably measuring the polarization of GRB signals will allow an enormous advance in our understanding of these events, thanks to the possibility of clearly distinguishing the different emission mechanisms (synchrotron, inverse Compton, etc.) as well as directly probing the geometries of the magnetic fields in GRB jets, opening a completely new window for the study of these phenomena.

The proposals for new missions for the observation of GRBs are many and very varied, pushing in various directions (depth, rapid repointing, localization capability, polarimetry). It is interesting to note how, for the first time, a substantial methodological difference is emerging between large-single-satellite missions, with very high capabilities and costs, and distributed architectures, where constellations of smaller and cheaper instruments are used to obtain exceptional results. What the future of the sector will be remains to be seen:

"Ai posteri l'ardua sentenza!" (Il Cinque Maggio, Manzoni).

12. Conclusions and Open Questions

GRBs are extreme phenomena, pushing the limits of our physical theories. Even 50 years after the first publication about their discovery, they continue to surprise us and elude our complete understanding. Given their extreme nature, GRBs are (almost) unique in astrophysics in their multi-disciplinary nature. As discussed in [233], the study of GRBs has connections with many other major branches of astrophysics, with important consequences for stellar astronomy, the study of the interstellar medium, galactic astronomy, and cosmology. The connections do not end here, and indeed, the study of the GRB phenomenon has connections with various branches of physics (and not only). These connections go far beyond just physics; e.g., some groups have studied the possible links between GRBs and mass-extinction phenomena. Focusing more precisely on the study of the basic mechanisms of these phenomena, it is evident that every step forward in our understanding has been intimately linked to a technical–scientific advancement, which, through the conception and implementation of increasingly targeted measures, has allowed, from time to time, the discovery of more and more details of these fascinating and varied phenomena.

Without any pretense of completeness, we can summarize the open questions and the lines of research to follow as follows:

- The Standard Model:
  - The standard fireball (plus internal/external shocks) model can explain many features observed in prompt GRBs and afterglows ... before the *Swift*, HE, and VHE eras. More realistic assumptions are needed (ejecta, environment).
  - What is the nature of GRB jets?
- Long GRBs:
  - Collapsar vs. magnetar: which is dominant?
  - Where are the GRB remnants?
  - The nature of subluminous vs. ultraluminous GRBs: what determines the difference?
- Short GRBs:
  - Are all short-hard GRBs compact binary mergers? NS-NS or NS-BH mergers?
  - How can hard long GRB "spikes" be distinguished from short GRBs?
- GRBs as probes of the Early Universe:
  - What is reionizing the IGM?
  - Did the reionization begin at $z \sim 12$?
  - Do Pop III stars make luminous GRBs?
- GRB221009A and other extreme events:
  - How are $\geq$10 TeV photons produced?
  - Are UHECRs accelerated in high numbers in GRBs? Why are there still no associated detections of GRBs and neutrinos (only upper limits)?
  - How is it possible that $\geq$10 TeV photons arrived from $z \sim 0.151$ despite the theoretically predicted EBL absorption? Is the signal of exotic or fundamental physics effects (LIV, ALPs, other)?
  - Does the narrow $\sim$10 MeV emission component seen in GRB221009A really exist? Is this a characteristic of this burst only or of all GRBs?
- Experimental development: how can we develop new instruments to make new and better observations?
  - Large sky coverage with high localization capabilities/better angular resolutions to observe more signals (better statistics). Large-single-satellite missions vs. distributed geometries?

– Better spectroscopic capabilities over wider energy ranges.
– Better timing capabilities to characterize the light curves.
– Ability to measure gamma-ray polarization to distinguish emission mechanisms.
– Better follow-up strategies (and collaborations) for reliable multi-messenger observations.

After 50 years of research on GRBs, enormous progress has been made in the study of these phenomena. However, we are still far from a complete understanding of them. There is no doubt that this research area is one of the liveliest at the moment and that, thanks to the enormous effort of experimental improvement and theoretical understanding of the scientific community, it will still yield great surprises and lessons in the future.

Author Contributions: Writing, A.A.V.; review and editing, F.L. and A.A.V.; supervision, F.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We acknowledge Lorenzo Amati for the original idea of dividing the history of GRBs into eras based both on the development of innovative instruments and the main discoveries of physical properties of GRBs they made.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AGNs	Active Galactic Nuclei
ALP	Axion-Like Particle
BH	Black Hole
EAS	Extensive Air Shower experiment
EBL	Extragalactic Background Light
FOV	Field Of View
GCN	GRB Coordinate Network
GRB	Gamma-Ray Burst
GW	Gravitational Wave
IACT	Imaging Atmospheric Cherenkov Telescope
LIV	Lorentz Invariance Violation
NFI	Near-Field Instrument
NS	Neutron Star
SGR	Soft Gamma Repeater
SN	Supernovae
UHECR	Ultra-High-Energy Cosmic Ray

References

1. Klebesadel, R.W.; Strong, I.B.; Olson, R.A. Observations of Gamma-Ray Bursts of Cosmic Origin. *Astrophys. J.* **1973**, *182*, L85. [CrossRef]
2. Cline, T.L.; Desai, U.D.; Klebesadel, R.W.; Strong, I.B. Energy Spectra of Cosmic Gamma-Ray Bursts. *Astrophys. J.* **1973**, *185*, L1. [CrossRef]
3. Mazets, E.P.; Golenetskii, S.V.; Il'Inskii, V.N. Flare of cosmic gamma radiation as observed with "Cosmos-461" satellite. *Sov. J. Exp. Theor. Phys. Lett.* **1974**, *19*, 77.
4. Mazets, E.P.; Golenetskii, S.V.; Ilinskii, V.N.; Panov, V.N.; Aptekar, R.L.; Gurian, I.A.; Proskura, M.P.; Sokolov, I.A.; Sokolova, Z.I.; Kharitonova, T.V. Catalog of cosmic gamma-ray bursts from the KONUS experiment data. *Astrophys. Space Sci.* **1981**, *80*, 3–83. [CrossRef]
5. Murakami, T.; Fujii, M.; Hayashida, K.; Itoh, M.; Nishimura, J. Evidence for cyclotron absorption from spectral features in gamma-ray bursts seen with Ginga. *Nature* **1988**, *335*, 234–235. [CrossRef]
6. Fenimore, E.E.; Conner, J.P.; Epstein, R.I.; Klebesadel, R.W.; Laros, J.G.; Yoshida, A.; Fujii, M.; Hayashida, K.; Itoh, M.; Murakami, T.; et al. Interpretation of Multiple Absorption Features in a Gamma-Ray Burst Spectrum. *Astrophys. J.* **1988**, *335*, L71. [CrossRef]

7. Nemiroff, R.J. A Century of Gamma Ray Burst Models. *Comments Astrophys.* **1994**, *17*, 189. [CrossRef]
8. Colgate, S.A. Prompt gamma rays and X-rays from supernovae. *Can. J. Phys. Suppl.* **1968**, *46*, 476. [CrossRef]
9. Zhang, B.; Xu, R.X.; Qiao, G.J. Nature and Nurture: A Model for Soft Gamma-Ray Repeaters. *Astrophys. J.* **2000**, *545*, L127–L130. [CrossRef]
10. Prilutskii, O.F.; Usov, V.V. On the Nature of γ-ray Bursts. *Astrophys. Space Sci.* **1975**, *34*, 395–401. [CrossRef]
11. Ruderman, M. Theories of gamma γ-ray bursts. *Seventh Tex. Symp. Relativ. Astrophys.* **1975**, *262*, 164–180. [CrossRef]
12. Cavallo, G.; Rees, M.J. A qualitative study of cosmic fireballs and γ-ray bursts. *Mon. Not. R. Astron. Soc.* **1978**, *183*, 359–365. [CrossRef]
13. Eichler, D.; Livio, M.; Piran, T.; Schramm, D.N. Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars. *Nature* **1989**, *340*, 126–128. [CrossRef]
14. Fishman, G.J.; Meegan, C.A.; Wilson, R.B.; Paciesas, W.S.; Pendleton, G.N. The BATSE experiment on the Compton Gamma Ray Observatory: Status and some early results. *Nasa Conf. Publ.* **1992**, *3137*, 26–34.
15. Norris, J.P.; Nemiroff, R.J.; Bonnell, J.T.; Scargle, J.D.; Kouveliotou, C.; Paciesas, W.S.; Meegan, C.A.; Fishman, G.J. Attributes of Pulses in Long Bright Gamma-Ray Bursts. *Astrophys. J.* **1996**, *459*, 393. [CrossRef]
16. Fenimore, E.E.; in 't Zand, J.J.M.; Norris, J.P.; Bonnell, J.T.; Nemiroff, R.J. Gamma-Ray Burst Peak Duration as a Function of Energy. *Astrophys. J.* **1995**, *448*, L101. [CrossRef]
17. Kouveliotou, C.; Meegan, C.A.; Fishman, G.J.; Bhat, N.P.; Briggs, M.S.; Koshut, T.M.; Paciesas, W.S.; Pendleton, G.N. Identification of Two Classes of Gamma-Ray Bursts. *Astrophys. J.* **1993**, *413*, L101. [CrossRef]
18. Band, D.; Matteson, J.; Ford, L.; Schaefer, B.; Palmer, D.; Teegarden, B.; Cline, T.; Briggs, M.; Paciesas, W.; Pendleton, G.; et al. BATSE Observations of Gamma-Ray Burst Spectra. I. Spectral Diversity. *Astrophys. J.* **1993**, *413*, 281. [CrossRef]
19. Briggs, M.S.; Paciesas, W.S.; Pendleton, G.N.; Meegan, C.A.; Fishman, G.J.; Horack, J.M.; Brock, M.N.; Kouveliotou, C.; Hartmann, D.H.; Hakkila, J. BATSE Observations of the Large-Scale Isotropy of Gamma-Ray Bursts. *Astrophys. J.* **1996**, *459*, 40. [CrossRef]
20. Meegan, C.A.; Fishman, G.J.; Wilson, R.B.; Paciesas, W.S.; Pendleton, G.N.; Horack, J.M.; Brock, M.N.; Kouveliotou, C. Spatial distribution of γ-ray bursts observed by BATSE. *Nature* **1992**, *355*, 143–145. [CrossRef]
21. Mészáros, P.; Rees, M.J. Optical and Long-Wavelength Afterglow from Gamma-Ray Bursts. *Astrophys. J.* **1997**, *476*, 232–237. [CrossRef]
22. Woosley, S.E. Gamma-Ray Bursts from Stellar Mass Accretion Disks around Black Holes. *Astrophys. J.* **1993**, *405*, 273. [CrossRef]
23. Usov, V.V. Millisecond pulsars with extremely strong magnetic fields as a cosmological source of γ-ray bursts. *Nature* **1992**, *357*, 472–474. [CrossRef]
24. Paciesas, W.S.; Meegan, C.A.; Pendleton, G.N.; Briggs, M.S.; Kouveliotou, C.; Koshut, T.M.; Lestrade, J.P.; McCollough, M.L.; Brainerd, J.J.; Hakkila, J.; et al. The Fourth BATSE Gamma-Ray Burst Catalog (Revised). *ApJS* **1999**, *122*, 465–495. [CrossRef]
25. Piro, L.; Scarsi, L.; Butler, R.C. SAX: The wideband mission for x-ray astronomy. In Proceedings of the X-ray and EUV/FUV Spectroscopy and Polarimetry, San Diego, CA, USA, 11–12 July 1995; Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series; Fineschi, S., Ed.; Volume 2517, pp. 169–181. [CrossRef]
26. Costa, E.; Frontera, F.; Heise, J.; Feroci, M.; in't Zand, J.; Fiore, F.; Cinti, M.N.; Dal Fiume, D.; Nicastro, L.; Orlandini, M.; et al. Discovery of an X-ray afterglow associated with the γ-ray burst of 28 February 1997. *Nature* **1997**, *387*, 783–785. [CrossRef]
27. van Paradijs, J.; Groot, P.J.; Galama, T.; Kouveliotou, C.; Strom, R.G.; Telting, J.; Rutten, R.G.M.; Fishman, G.J.; Meegan, C.A.; Pettini, M.; et al. Transient optical emission from the error box of the γ-ray burst of 28 February 1997. *Nature* **1997**, *386*, 686–689. [CrossRef]
28. Frail, D.A.; Kulkarni, S.R.; Nicastro, L.; Feroci, M.; Taylor, G.B. The radio afterglow from the γ-ray burst of 8 May 1997. *Nature* **1997**, *389*, 261–263. [CrossRef]
29. Metzger, M.R.; Djorgovski, S.G.; Kulkarni, S.R.; Steidel, C.C.; Adelberger, K.L.; Frail, D.A.; Costa, E.; Frontera, F. Spectral constraints on the redshift of the optical counterpart to the γ-ray burst of 8 May 1997. *Nature* **1997**, *387*, 878–880. [CrossRef]
30. Amati, L.; Frontera, F.; Tavani, M.; in't Zand, J.J.M.; Antonelli, A.; Costa, E.; Feroci, M.; Guidorzi, C.; Heise, J.; Masetti, N.; et al. Intrinsic spectra and energetics of BeppoSAX Gamma-Ray Bursts with known redshifts. *Astron. Astrophys.* **2002**, *390*, 81–89. [CrossRef]
31. Amati, L. The $E_{p,i}$-E_{iso} correlation in gamma-ray bursts: Updated observational status, re-analysis and main implications. *Mon. Not. R. Astron. Soc.* **2006**, *372*, 233–245. [CrossRef]
32. Yonetoku, D.; Murakami, T.; Nakamura, T.; Yamazaki, R.; Inoue, A.K.; Ioka, K. Gamma-Ray Burst Formation Rate Inferred from the Spectral Peak Energy-Peak Luminosity Relation. *Astrophys. J.* **2004**, *609*, 935–951. [CrossRef]
33. Nakar, E.; Piran, T. Outliers to the peak energy-isotropic energy relation in gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **2005**, *360*, L73–L76. [CrossRef]
34. Ghirlanda, G.; Nava, L.; Ghisellini, G.; Firmani, C.; Cabrera, J.I. The E_{peak}-E_{iso} plane of long gamma-ray bursts and selection effects. *Mon. Not. R. Astron. Soc.* **2008**, *387*, 319–330. [CrossRef]
35. Liang, E.W.; Dai, Z.G.; Wu, X.F. The Luminosity-E_p Relation within Gamma-Ray Bursts and the Implications for Fireball Models. *Astrophys. J.* **2004**, *606*, L29–L32. [CrossRef]
36. Zhang, B.; Zhang, B.B.; Virgili, F.J.; Liang, E.W.; Kann, D.A.; Wu, X.F.; Proga, D.; Lv, H.J.; Toma, K.; Mészáros, P.; et al. Discerning the Physical Origins of Cosmological Gamma-ray Bursts Based on Multiple Observational Criteria: The Cases of z = 6.7 GRB 080913, z = 8.2 GRB 090423, and Some Short/Hard GRBs. *Astrophys. J.* **2009**, *703*, 1696–1724. [CrossRef]

37. Ghirlanda, G.; Nava, L.; Ghisellini, G.; Celotti, A.; Firmani, C. Short versus long gamma-ray bursts: Spectra, energetics, and luminosities. *Astron. Astrophys.* **2009**, *496*, 585–595. [CrossRef]
38. Rees, M.J.; Meszaros, P. Relativistic fireballs—Energy conversion and time-scales. *Mon. Not. R. Astron. Soc.* **1992**, *258*, 41. [CrossRef]
39. Sari, R.; Piran, T.; Narayan, R. Spectra and Light Curves of Gamma-Ray Burst Afterglows. *Astrophys. J.* **1998**, *497*, L17–L20. [CrossRef]
40. Sari, R.; Piran, T. Predictions for the Very Early Afterglow and the Optical Flash. *Astrophys. J.* **1999**, *520*, 641–649. [CrossRef]
41. Harrison, F.A.; Bloom, J.S.; Frail, D.A.; Sari, R.; Kulkarni, S.R.; Djorgovski, S.G.; Axelrod, T.; Mould, J.; Schmidt, B.P.; Wieringa, M.H.; et al. Optical and Radio Observations of the Afterglow from GRB 990510: Evidence for a Jet. *Astrophys. J.* **1999**, *523*, L121–L124. [CrossRef]
42. Frail, D.A.; Kulkarni, S.R.; Sari, R.; Djorgovski, S.G.; Bloom, J.S.; Galama, T.J.; Reichart, D.E.; Berger, E.; Harrison, F.A.; Price, P.A.; et al. Beaming in Gamma-Ray Bursts: Evidence for a Standard Energy Reservoir. *Astrophys. J.* **2001**, *562*, L55–L58. [CrossRef]
43. Zhang, B.; Mészáros, P. Gamma-Ray Burst Beaming: A Universal Configuration with a Standard Energy Reservoir? *Astrophys. J.* **2002**, *571*, 876–879. [CrossRef]
44. Rossi, E.; Lazzati, D.; Rees, M.J. Afterglow light curves, viewing angle and the jet structure of γ-ray bursts. *Mon. Not. R. Astron. Soc.* **2002**, *332*, 945–950. [CrossRef]
45. Ghirlanda, G.; Ghisellini, G.; Lazzati, D. The Collimation-corrected Gamma-Ray Burst Energies Correlate with the Peak Energy of Their νF_ν Spectrum. *Astrophys. J.* **2004**, *616*, 331–338. [CrossRef]
46. Ghirlanda, G.; Ghisellini, G.; Lazzati, D.; Firmani, C. Gamma-Ray Bursts: New Rulers to Measure the Universe. *Astrophys. J.* **2004**, *613*, L13–L16. [CrossRef]
47. Fruchter, A.S.; Thorsett, S.E.; Metzger, M.R.; Sahu, K.C.; Petro, L.; Livio, M.; Ferguson, H.; Pian, E.; Hogg, D.W.; Galama, T.; et al. Hubble Space Telescope and Palomar Imaging of GRB 990123: Implications for the Nature of Gamma-Ray Bursts and Their Hosts. *Astrophys. J.* **1999**, *519*, L13–L16. [CrossRef]
48. Fryer, C.L.; Woosley, S.E.; Hartmann, D.H. Formation Rates of Black Hole Accretion Disk Gamma-Ray Bursts. *Astrophys. J.* **1999**, *526*, 152–177. [CrossRef]
49. Paczyński, B. Are Gamma-Ray Bursts in Star-Forming Regions? *Astrophys. J.* **1998**, *494*, L45–L48. [CrossRef]
50. Galama, T.J.; Vreeswijk, P.M.; van Paradijs, J.; Kouveliotou, C.; Augusteijn, T.; Böhnhardt, H.; Brewer, J.P.; Doublier, V.; Gonzalez, J.F.; Leibundgut, B.; et al. An unusual supernova in the error box of the γ-ray burst of 25 April 1998. *Nature* **1998**, *395*, 670–672. [CrossRef]
51. Kulkarni, S.R.; Frail, D.A.; Wieringa, M.H.; Ekers, R.D.; Sadler, E.M.; Wark, R.M.; Higdon, J.L.; Phinney, E.S.; Bloom, J.S. Radio emission from the unusual supernova 1998bw and its association with the γ-ray burst of 25 April 1998. *Nature* **1998**, *395*, 663–669. [CrossRef]
52. Bloom, J.S.; Kulkarni, S.R.; Djorgovski, S.G.; Eichelberger, A.C.; Côté, P.; Blakeslee, J.P.; Odewahn, S.C.; Harrison, F.A.; Frail, D.A.; Filippenko, A.V.; et al. The unusual afterglow of the γ-ray burst of 26 March 1998 as evidence for a supernova connection. *Nature* **1999**, *401*, 453–456. [CrossRef]
53. MacFadyen, A.I.; Woosley, S.E.; Heger, A. Supernovae, Jets, and Collapsars. *Astrophys. J.* **2001**, *550*, 410–425. [CrossRef]
54. Ramirez-Ruiz, E.; Celotti, A.; Rees, M.J. Events in the life of a cocoon surrounding a light, collapsar jet. *Mon. Not. R. Astron. Soc.* **2002**, *337*, 1349–1356. [CrossRef]
55. Fryer, C.L.; Woosley, S.E.; Herant, M.; Davies, M.B. Merging White Dwarf/Black Hole Binaries and Gamma-Ray Bursts. *Astrophys. J.* **1999**, *520*, 650–660. [CrossRef]
56. Salgado, M.; Bonazzola, S.; Gourgoulhon, E.; Haensel, P. High precision rotating neutron star models. I. Analysis of neutron star properties. *Astron. Astrophys.* **1994**, *291*, 155–170.
57. Vietri, M.; Stella, L. A Gamma-Ray Burst Model with Small Baryon Contamination. *Astrophys. J.* **1998**, *507*, L45–L48. [CrossRef]
58. Dar, A.; De Rújula, A. The Cannonball Model of Gamma Ray Bursts: Spectral and Temporal Properties of the Gamma Rays. *arXiv* **2000**, arXiv:astro-ph/0012227. [CrossRef]
59. Ricker, G.R.; Atteia, J.L.; Crew, G.B.; Doty, J.P.; Fenimore, E.E.; Galassi, M.; Graziani, C.; Hurley, K.; Jernigan, J.G.; Kawai, N.; et al. The High Energy Transient Explorer (HETE): Mission and Science Overview. In Proceedings of the Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission, Woods Hole, MA, USA, 5–9 November 2001; American Institute of Physics Conference Series; Ricker, G.R., Vanderspek, R.K., Eds.; Volume 662, pp. 3–16. [CrossRef]
60. Hjorth, J.; Sollerman, J.; Møller, P.; Fynbo, J.P.U.; Woosley, S.E.; Kouveliotou, C.; Tanvir, N.R.; Greiner, J.; Andersen, M.I.; Castro-Tirado, A.J.; et al. A very energetic supernova associated with the γ-ray burst of 29 March 2003. *Nature* **2003**, *423*, 847–850. [CrossRef] [PubMed]
61. Matheson, T.; Garnavich, P.M.; Stanek, K.Z.; Bersier, D.; Holland, S.T.; Krisciunas, K.; Caldwell, N.; Berlind, P.; Bloom, J.S.; Bolte, M.; et al. Photometry and Spectroscopy of GRB 030329 and Its Associated Supernova 2003dh: The First Two Months. *Astrophys. J.* **2003**, *599*, 394–407. [CrossRef]
62. Stanek, K.Z.; Matheson, T.; Garnavich, P.M.; Martini, P.; Berlind, P.; Caldwell, N.; Challis, P.; Brown, W.R.; Schild, R.; Krisciunas, K.; et al. Spectroscopic Discovery of the Supernova 2003dh Associated with GRB 030329. *Astrophys. J.* **2003**, *591*, L17–L20. [CrossRef]

63. Heise, J.; Zand, J.I.; Kippen, R.M.; Woods, P.M. X-ray Flashes and X-ray Rich Gamma Ray Bursts. In Proceedings of the Gamma-Ray Bursts in the Afterglow Era, Rome, Italy, 17–20 October 2000; Costa, E.; Frontera, F.; Hjorth, J., Eds.; p. 16. [CrossRef]
64. Yamazaki, R.; Ioka, K.; Nakamura, T. X-ray Flashes from Off-Axis Gamma-ray Bursts. *Astrophys. J.* **2002**, *571*, L31–L35. [CrossRef]
65. Gehrels, N.; Chincarini, G.; Giommi, P.; Mason, K.O.; Nousek, J.A.; Wells, A.A.; White, N.E.; Barthelmy, S.D.; Burrows, D.N.; Cominsky, L.R.; et al. The Swift Gamma-Ray Burst Mission. *Astrophys. J.* **2004**, *611*, 1005–1020. [CrossRef]
66. Barthelmy, S.D.; Barbier, L.M.; Cummings, J.R.; Fenimore, E.E.; Gehrels, N.; Hullinger, D.; Krimm, H.A.; Markwardt, C.B.; Palmer, D.M.; Parsons, A.; et al. The Burst Alert Telescope (BAT) on the SWIFT Midex Mission. *Space Sci. Rev.* **2005**, *120*, 143–164. [CrossRef]
67. Burrows, D.N.; Hill, J.E.; Nousek, J.A.; Kennea, J.A.; Wells, A.; Osborne, J.P.; Abbey, A.F.; Beardmore, A.; Mukerjee, K.; Short, A.D.T.; et al. The Swift X-Ray Telescope. *Space Sci. Rev.* **2005**, *120*, 165–195. [CrossRef]
68. Roming, P.W.A.; Kennedy, T.E.; Mason, K.O.; Nousek, J.A.; Ahr, L.; Bingham, R.E.; Broos, P.S.; Carter, M.J.; Hancock, B.K.; Huckle, H.E.; et al. The Swift Ultra-Violet/Optical Telescope. *Space Sci. Rev.* **2005**, *120*, 95–142. [CrossRef]
69. Gehrels, N.; Sarazin, C.L.; O'Brien, P.T.; Zhang, B.; Barbier, L.; Barthelmy, S.D.; Blustin, A.; Burrows, D.N.; Cannizzo, J.; Cummings, J.R.; et al. A short γ-ray burst apparently associated with an elliptical galaxy at redshift z = 0.225. *Nature* **2005**, *437*, 851–854. [CrossRef] [PubMed]
70. Bloom, J.S.; Prochaska, J.X.; Pooley, D.; Blake, C.H.; Foley, R.J.; Jha, S.; Ramirez-Ruiz, E.; Granot, J.; Filippenko, A.V.; Sigurdsson, S.; et al. Closing in on a Short-Hard Burst Progenitor: Constraints from Early-Time Optical Imaging and Spectroscopy of a Possible Host Galaxy of GRB 050509b. *Astrophys. J.* **2006**, *638*, 354–368. [CrossRef]
71. Barthelmy, S.D.; Chincarini, G.; Burrows, D.N.; Gehrels, N.; Covino, S.; Moretti, A.; Romano, P.; O'Brien, P.T.; Sarazin, C.L.; Kouveliotou, C.; et al. An origin for short γ-ray bursts unassociated with current star formation. *Nature* **2005**, *438*, 994–996. [CrossRef]
72. Evans, P.A.; Beardmore, A.P.; Page, K.L.; Osborne, J.P.; O'Brien, P.T.; Willingale, R.; Starling, R.L.C.; Burrows, D.N.; Godet, O.; Vetere, L.; et al. Methods and results of an automatic analysis of a complete sample of Swift-XRT observations of GRBs. *Mon. Not. R. Astron. Soc.* **2009**, *397*, 1177–1201. [CrossRef]
73. O'Brien, P.T.; Willingale, R.; Osborne, J.; Goad, M.R.; Page, K.L.; Vaughan, S.; Rol, E.; Beardmore, A.; Godet, O.; Hurkett, C.P.; et al. The Early X-Ray Emission from GRBs. *Astrophys. J.* **2006**, *647*, 1213–1237. [CrossRef]
74. Tagliaferri, G.; Goad, M.; Chincarini, G.; Moretti, A.; Campana, S.; Burrows, D.N.; Perri, M.; Barthelmy, S.D.; Gehrels, N.; Krimm, H.; et al. An unexpectedly rapid decline in the X-ray afterglow emission of long γ-ray bursts. *Nature* **2005**, *436*, 985–988. [CrossRef]
75. Barthelmy, S.D.; Cannizzo, J.K.; Gehrels, N.; Cusumano, G.; Mangano, V.; O'Brien, P.T.; Vaughan, S.; Zhang, B.; Burrows, D.N.; Campana, S.; et al. Discovery of an Afterglow Extension of the Prompt Phase of Two Gamma-Ray Bursts Observed by Swift. *Astrophys. J.* **2005**, *635*, L133–L136. [CrossRef]
76. Campana, S.; Antonelli, L.A.; Chincarini, G.; Covino, S.; Cusumano, G.; Malesani, D.; Mangano, V.; Moretti, A.; Pagani, C.; Romano, P.; et al. Swift Observations of GRB 050128: The Early X-ray Afterglow. *Astrophys. J.* **2005**, *625*, L23–L26. [CrossRef]
77. Vaughan, S.; Goad, M.R.; Beardmore, A.P.; O'Brien, P.T.; Osborne, J.P.; Page, K.L.; Barthelmy, S.D.; Burrows, D.N.; Campana, S.; Cannizzo, J.K.; et al. Swift Observations of the X-ray-Bright GRB 050315. *Astrophys. J.* **2006**, *638*, 920–929. [CrossRef]
78. Burrows, D.N.; Romano, P.; Falcone, A.; Kobayashi, S.; Zhang, B.; Moretti, A.; O'Brien, P.T.; Goad, M.R.; Campana, S.; Page, K.L.; et al. Bright X-ray Flares in Gamma-Ray Burst Afterglows. *Science* **2005**, *309*, 1833–1835. [CrossRef] [PubMed]
79. Romano, P.; Campana, S.; Chincarini, G.; Cummings, J.; Cusumano, G.; Holland, S.T.; Mangano, V.; Mineo, T.; Page, K.L.; Pal'Shin, V.; et al. Panchromatic study of GRB 060124: From precursor to afterglow. *Astron. Astrophys.* **2006**, *456*, 917–927. [CrossRef]
80. Falcone, A.D.; Burrows, D.N.; Lazzati, D.; Campana, S.; Kobayashi, S.; Zhang, B.; Mészáros, P.; Page, K.L.; Kennea, J.A.; Romano, P.; et al. The Giant X-ray Flare of GRB 050502B: Evidence for Late-Time Internal Engine Activity. *Astrophys. J.* **2006**, *641*, 1010–1017. [CrossRef]
81. Zhang, B.; Fan, Y.Z.; Dyks, J.; Kobayashi, S.; Mészáros, P.; Burrows, D.N.; Nousek, J.A.; Gehrels, N. Physical Processes Shaping Gamma-Ray Burst X-ray Afterglow Light Curves: Theoretical Implications from the Swift X-ray Telescope Observations. *Astrophys. J.* **2006**, *642*, 354–370. [CrossRef]
82. Nousek, J.A.; Kouveliotou, C.; Grupe, D.; Page, K.L.; Granot, J.; Ramirez-Ruiz, E.; Patel, S.K.; Burrows, D.N.; Mangano, V.; Barthelmy, S.; et al. Evidence for a Canonical Gamma-Ray Burst Afterglow Light Curve in the Swift XRT Data. *Astrophys. J.* **2006**, *642*, 389–400. [CrossRef]
83. Panaitescu, A.; Mészáros, P.; Burrows, D.; Nousek, J.; Gehrels, N.; O'Brien, P.; Willingale, R. Evidence for chromatic X-ray light-curve breaks in Swift gamma-ray burst afterglows and their theoretical implications. *Mon. Not. R. Astron. Soc.* **2006**, *369*, 2059–2064. [CrossRef]
84. Zhang, B.; Mészáros, P. Gamma-Ray Burst Afterglow with Continuous Energy Injection: Signature of a Highly Magnetized Millisecond Pulsar. *Astrophys. J.* **2001**, *552*, L35–L38. [CrossRef]
85. King, A.; O'Brien, P.T.; Goad, M.R.; Osborne, J.; Olsson, E.; Page, K. Gamma-Ray Bursts: Restarting the Engine. *Astrophys. J.* **2005**, *630*, L113–L115. [CrossRef]
86. Perna, R.; Armitage, P.J.; Zhang, B. Flares in Long and Short Gamma-Ray Bursts: A Common Origin in a Hyperaccreting Accretion Disk. *Astrophys. J.* **2006**, *636*, L29–L32. [CrossRef]

87. Dai, Z.G.; Wang, X.Y.; Wu, X.F.; Zhang, B. X-ray Flares from Postmerger Millisecond Pulsars. *Science* **2006**, *311*, 1127–1129. [CrossRef] [PubMed]
88. Metzger, B.D.; Quataert, E.; Thompson, T.A. Short-duration gamma-ray bursts with extended emission from protomagnetar spin-down. *Mon. Not. R. Astron. Soc.* **2008**, *385*, 1455–1460. [CrossRef]
89. Liang, E.; Zhang, B.; Virgili, F.; Dai, Z.G. Low-Luminosity Gamma-Ray Bursts as a Unique Population: Luminosity Function, Local Rate, and Beaming Factor. *Astrophys. J.* **2007**, *662*, 1111–1118. [CrossRef]
90. Totani, T.; Kawai, N.; Kosugi, G.; Aoki, K.; Yamada, T.; Iye, M.; Ohta, K.; Hattori, T. Implications for Cosmic Reionization from the Optical Afterglow Spectrum of the Gamma-Ray Burst 050904 at z = 6.3*. *Publ. Astron. Soc. Jpn.* **2006**, *58*, 485–498. [CrossRef]
91. Cusumano, G.; Mangano, V.; Chincarini, G.; Panaitescu, A.; Burrows, D.N.; La Parola, V.; Sakamoto, T.; Campana, S.; Mineo, T.; Tagliaferri, G.; et al. GRB 050904: The oldest cosmic explosion ever observed in the Universe. In Proceedings of the Gamma-Ray Bursts in the Swift Era: Sixteenth Maryland Astrophysics Conference, Washington, DC, USA, 29 November–2 December 2005; American Institute of Physics Conference Series; Holt, S.S., Gehrels, N., Nousek, J.A., Eds.; Volume 836, pp. 564–569. [CrossRef]
92. Greiner, J.; Krühler, T.; Fynbo, J.P.U.; Rossi, A.; Schwarz, R.; Klose, S.; Savaglio, S.; Tanvir, N.R.; McBreen, S.; Totani, T.; et al. GRB 080913 at Redshift 6.7. *Astrophys. J.* **2009**, *693*, 1610–1620. [CrossRef]
93. Tanvir, N.R.; Fox, D.B.; Levan, A.J.; Berger, E.; Wiersema, K.; Fynbo, J.P.U.; Cucchiara, A.; Krühler, T.; Gehrels, N.; Bloom, J.S.; et al. A γ-ray burst at a redshift of z$\sim$8.2. *Nature* **2009**, *461*, 1254–1257. [CrossRef]
94. Salvaterra, R.; Della Valle, M.; Campana, S.; Chincarini, G.; Covino, S.; D'Avanzo, P.; Fernández-Soto, A.; Guidorzi, C.; Mannucci, F.; Margutti, R.; et al. GRB090423 at a redshift of z$\sim$8.1. *Nature* **2009**, *461*, 1258–1260. [CrossRef]
95. Cucchiara, A.; Levan, A.J.; Fox, D.B.; Tanvir, N.R.; Ukwatta, T.N.; Berger, E.; Krühler, T.; Küpcü Yoldaş, A.; Wu, X.F.; Toma, K.; et al. A Photometric Redshift of z$\sim$9.4 for GRB 090429B. *Astrophys. J.* **2011**, *736*, 7. [CrossRef]
96. Gehrels, N.; Norris, J.P.; Barthelmy, S.D.; Granot, J.; Kaneko, Y.; Kouveliotou, C.; Markwardt, C.B.; Mészáros, P.; Nakar, E.; Nousek, J.A.; et al. A new γ-ray burst classification scheme from GRB060614. *Nature* **2006**, *444*, 1044–1046. [CrossRef]
97. Zhang, B.; Zhang, B.B.; Liang, E.W.; Gehrels, N.; Burrows, D.N.; Mészáros, P. Making a Short Gamma-Ray Burst from a Long One: Implications for the Nature of GRB 060614. *Astrophys. J.* **2007**, *655*, L25–L28. [CrossRef]
98. Levesque, E.M.; Kewley, L.J.; Berger, E.; Zahid, H.J. The Host Galaxies of Gamma-ray Bursts. II. A Mass-metallicity Relation for Long-duration Gamma-ray Burst Host Galaxies. *Astron. J.* **2010**, *140*, 1557–1566. [CrossRef]
99. Campana, S.; Mangano, V.; Blustin, A.J.; Brown, P.; Burrows, D.N.; Chincarini, G.; Cummings, J.R.; Cusumano, G.; Della Valle, M.; Malesani, D.; et al. The association of GRB 060218 with a supernova and the evolution of the shock wave. *Nature* **2006**, *442*, 1008–1010. [CrossRef] [PubMed]
100. Racusin, J.L.; Karpov, S.V.; Sokolowski, M.; Granot, J.; Wu, X.F.; Pal'Shin, V.; Covino, S.; van der Horst, A.J.; Oates, S.R.; Schady, P.; et al. Broadband observations of the naked-eye γ-ray burst GRB080319B. *Nature* **2008**, *455*, 183–188. [CrossRef] [PubMed]
101. Levan, A.J.; Tanvir, N.R.; Starling, R.L.C.; Wiersema, K.; Page, K.L.; Perley, D.A.; Schulze, S.; Wynn, G.A.; Chornock, R.; Hjorth, J.; et al. A New Population of Ultra-long Duration Gamma-Ray Bursts. *Astrophys. J.* **2014**, *781*, 13. [CrossRef]
102. Bloom, J.S.; Giannios, D.; Metzger, B.D.; Cenko, S.B.; Perley, D.A.; Butler, N.R.; Tanvir, N.R.; Levan, A.J.; O'Brien, P.T.; Strubbe, L.E.; et al. A Possible Relativistic Jetted Outburst from a Massive Black Hole Fed by a Tidally Disrupted Star. *Science* **2011**, *333*, 203. [CrossRef] [PubMed]
103. Burrows, D.N.; Kennea, J.A.; Ghisellini, G.; Mangano, V.; Zhang, B.; Page, K.L.; Eracleous, M.; Romano, P.; Sakamoto, T.; Falcone, A.D.; et al. Relativistic jet activity from the tidal disruption of a star by a massive black hole. *Nature* **2011**, *476*, 421–424. [CrossRef] [PubMed]
104. Levan, A.J.; Butler, N.; Bloom, J.; Tanvir, N.R.; Fruchter, A.S. GRB 110328/Swift J164449.3+573451: Chandra observations. *GRB Coord. Netw.* **2011**, *11886*, 1.
105. Zauderer, B.A.; Berger, E.; Soderberg, A.M.; Loeb, A.; Narayan, R.; Frail, D.A.; Petitpas, G.R.; Brunthaler, A.; Chornock, R.; Carpenter, J.M.; et al. Birth of a relativistic outflow in the unusual γ-ray transient Swift J164449.3+573451. *Nature* **2011**, *476*, 425–428. [CrossRef]
106. Kanbach, G.; Bertsch, D.L.; Fichtel, C.E.; Hartman, R.C.; Hunter, S.D.; Kniffen, D.A.; Hughlock, B.W.; Favale, A.; Hofstadter, R.; Hughes, E.B. The project EGRET (energetic gamma-ray experiment telescope) on NASA's Gamma-Ray Observatory GRO. *Space Sci. Rev.* **1989**, *49*, 69–84. [CrossRef]
107. Hurley, K.; Dingus, B.L.; Mukherjee, R.; Sreekumar, P.; Kouveliotou, C.; Meegan, C.; Fishman, G.J.; Band, D.; Ford, L.; Bertsch, D.; et al. Detection of a γ-ray burst of very long duration and very high energy. *Nature* **1994**, *372*, 652–654. [CrossRef]
108. Kouveliotou, C.; Preece, R.; Bhat, N.; Fishman, G.J.; Meegan, C.A.; Horack, J.M.; Briggs, M.S.; Paciesas, W.S.; Pendleton, G.N.; Band, D.; et al. BATSE Observations of the Very Intense Gamma-Ray Burst GRB 930131. *Astrophys. J.* **1994**, *422*, L59. [CrossRef]
109. Sommer, M.; Bertsch, D.L.; Dingus, B.L.; Fichtel, C.E.; Fishman, G.J.; Harding, A.K.; Hartman, R.C.; Hunter, S.D.; Hurley, K.; Kanbach, G.; et al. High-Energy Gamma Rays from the Intense 1993 January 31 Gamma-Ray Burst. *Astrophys. J.* **1994**, *422*, L63. [CrossRef]
110. González, M.M.; Dingus, B.L.; Kaneko, Y.; Preece, R.D.; Dermer, C.D.; Briggs, M.S. A γ-ray burst with a high-energy spectral component inconsistent with the synchrotron shock model. *Nature* **2003**, *424*, 749–751. [CrossRef]
111. Tavani, M.; Barbiellini, G.; Argan, A.; Boffelli, F.; Bulgarelli, A.; Caraveo, P.; Cattaneo, P.W.; Chen, A.W.; Cocco, V.; Costa, E.; et al. The AGILE Mission. *Astron. Astrophys.* **2009**, *502*, 995–1013. [CrossRef]

112. Barbiellini, G.; Bordignon, G.; Fedel, G.; Liello, F.; Longo, F.; Pontoni, C.; Prest, M.; Vallazza, E. The next generation of high-energy gamma-ray detectors for satellites: The AGILE silicon tracker. In Proceedings of the Gamma 2001: Gamma-Ray Astrophysics, Baltimore, MD, USA, 4–6 April 2001; American Institute of Physics Conference Series; Ritz, S., Gehrels, N., Shrader, C.R., Eds.; Volume 587, pp. 754–758. [CrossRef]
113. Costa, E.; Barbanera, L.; Feroci, M.; Frutti, M.; Lapshov, I.; Martino, B.; Mastropietro, M.; Morelli, E.; Rapisarda, M.; Rubini, A.; et al. Super-agile-The X-ray detector for the gamma-ray mission agile. In Proceedings of the X-ray Astronomy: Stellar Endpoints, AGN, and the Diffuse X-ray Background, Bologna, Italy, 6–10 September 1999; American Institute of Physics Conference Series; White, N.E., Malaguti, G., Palumbo, G.G.C., Eds.; Volume 599, pp. 582–585. [CrossRef]
114. Parmiggiani, N.; Bulgarelli, A.; Ursi, A.; Addis, A.; Baroncelli, L.; Fioretti, V.; Di Piano, A.; Panebianco, G.; Tavani, M.; Pittori, C.; et al. The AGILE real-time analysis software system to detect short-transient events in the multi-messenger era. *Astron. Comput.* **2023**, *44*, 100726. [CrossRef]
115. Galli, M.; Marisaldi, M.; Fuschino, F.; Labanti, C.; Argan, A.; Barbiellini, G.; Bulgarelli, A.; Cattaneo, P.W.; Colafrancesco, S.; Del Monte, E.; et al. AGILE mini-calorimeter gamma-ray burst catalog. *Astron. Astrophys.* **2013**, *553*, A33. [CrossRef]
116. Ursi, A.; Romani, M.; Verrecchia, F.; Pittori, C.; Tavani, M.; Marisaldi, M.; Galli, M.; Labanti, C.; Parmiggiani, N.; Bulgarelli, A.; et al. The Second AGILE MCAL Gamma-Ray Burst Catalog: 13 yr of Observations. *Astrophys. J.* **2022**, *925*, 152. [CrossRef]
117. Longo, F.; Moretti, E.; Nava, L.; Desiante, R.; Olivo, M.; Del Monte, E.; Rappoldi, A.; Fuschino, F.; Marisaldi, M.; Giuliani, A.; et al. Upper limits on the high-energy emission from gamma-ray bursts observed by AGILE-GRID. *Astron. Astrophys.* **2012**, *547*, A95. [CrossRef]
118. Giuliani, A.; Mereghetti, S.; Fornari, F.; Del Monte, E.; Feroci, M.; Marisaldi, M.; Esposito, P.; Perotti, F.; Tavani, M.; Argan, A.; et al. AGILE detection of delayed gamma-ray emission from GRB 080514B. *Astron. Astrophys.* **2008**, *491*, L25–L28. [CrossRef]
119. Giuliani, A.; Fuschino, F.; Vianello, G.; Marisaldi, M.; Mereghetti, S.; Tavani, M.; Cutini, S.; Barbiellini, G.; Longo, F.; Moretti, E.; et al. AGILE Detection of Delayed Gamma-ray Emission From the Short Gamma-Ray Burst GRB 090510. *Astrophys. J.* **2010**, *708*, L84–L88. [CrossRef]
120. Ackermann, M.; Asano, K.; Atwood, W.B.; Axelsson, M.; Baldini, L.; Ballet, J.; Barbiellini, G.; Baring, M.G.; Bastieri, D.; Bechtol, K.; et al. Fermi Observations of GRB 090510: A Short-Hard Gamma-ray Burst with an Additional, Hard Power-law Component from 10 keV TO GeV Energies. *Astrophys. J.* **2010**, *716*, 1178–1190. [CrossRef]
121. De Pasquale, M.; Schady, P.; Kuin, N.P.M.; Page, M.J.; Curran, P.A.; Zane, S.; Oates, S.R.; Holland, S.T.; Breeveld, A.A.; Hoversten, E.A.; et al. Swift and Fermi Observations of the Early Afterglow of the Short Gamma-Ray Burst 090510. *Astrophys. J.* **2010**, *709*, L146–L151. [CrossRef]
122. Parmiggiani, N.; Bulgarelli, A.; Fioretti, V.; Di Piano, A.; Giuliani, A.; Longo, F.; Verrecchia, F.; Tavani, M.; Beneventano, D.; Macaluso, A. A Deep Learning Method for AGILE-GRID Gamma-Ray Burst Detection. *Astrophys. J.* **2021**, *914*, 67. [CrossRef]
123. Parmiggiani, N.; Bulgarelli, A.; Ursi, A.; Macaluso, A.; Di Piano, A.; Fioretti, V.; Aboudan, A.; Baroncelli, L.; Addis, A.; Tavani, M.; et al. A Deep-learning Anomaly-detection Method to Identify Gamma-Ray Bursts in the Ratemeters of the AGILE Anticoincidence System. *Astrophys. J.* **2023**, *945*, 106. [CrossRef]
124. Atwood, W.B.; Abdo, A.A.; Ackermann, M.; Althouse, W.; Anderson, B.; Axelsson, M.; Baldini, L.; Ballet, J.; Band, D.L.; Barbiellini, G.; et al. The Large Area Telescope on the Fermi Gamma-Ray Space Telescope Mission. *Astrophys. J.* **2009**, *697*, 1071–1102. [CrossRef]
125. Meegan, C.; Lichti, G.; Bhat, P.N.; Bissaldi, E.; Briggs, M.S.; Connaughton, V.; Diehl, R.; Fishman, G.; Greiner, J.; Hoover, A.S.; et al. The Fermi Gamma-ray Burst Monitor. *Astrophys. J.* **2009**, *702*, 791–804. [CrossRef]
126. von Kienlin, A.; Meegan, C.A.; Paciesas, W.S.; Bhat, P.N.; Bissaldi, E.; Briggs, M.S.; Burns, E.; Cleveland, W.H.; Gibby, M.H.; Giles, M.M.; et al. The Fourth Fermi-GBM Gamma-Ray Burst Catalog: A Decade of Data. *Astrophys. J.* **2020**, *893*, 46. [CrossRef]
127. Ajello, M.; Arimoto, M.; Axelsson, M.; Baldini, L.; Barbiellini, G.; Bastieri, D.; Bellazzini, R.; Bhat, P.N.; Bissaldi, E.; Blandford, R.D.; et al. A Decade of Gamma-Ray Bursts Observed by Fermi-LAT: The Second GRB Catalog. *Astrophys. J.* **2019**, *878*, 52. [CrossRef]
128. Ghisellini, G.; Ghirlanda, G.; Nava, L.; Celotti, A. GeV emission from gamma-ray bursts: A radiative fireball? *Mon. Not. R. Astron. Soc.* **2010**, *403*, 926–937. [CrossRef]
129. Nava, L.; Vianello, G.; Omodei, N.; Ghisellini, G.; Ghirlanda, G.; Celotti, A.; Longo, F.; Desiante, R.; Barniol Duran, R. Clustering of LAT light curves: A clue to the origin of high-energy emission in gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **2014**, *443*, 3578–3585. [CrossRef]
130. Kumar, P.; Barniol Duran, R. On the generation of high-energy photons detected by the Fermi Satellite from gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **2009**, *400*, L75–L79. [CrossRef]
131. Kumar, P.; Barniol Duran, R. External forward shock origin of high-energy emission for three gamma-ray bursts detected by Fermi. *Mon. Not. R. Astron. Soc.* **2010**, *409*, 226–236. [CrossRef]
132. Abdo, A.A.; Ackermann, M.; Ajello, M.; Asano, K.; Atwood, W.B.; Axelsson, M.; Baldini, L.; Ballet, J.; Barbiellini, G.; Baring, M.G.; et al. A limit on the variation of the speed of light arising from quantum gravity effects. *Nature* **2009**, *462*, 331–334. [CrossRef]
133. Abdo, A.A.; Ackermann, M.; Arimoto, M.; Asano, K.; Atwood, W.B.; Axelsson, M.; Baldini, L.; Ballet, J.; Band, D.L.; Barbiellini, G.; et al. Fermi Observations of High-Energy Gamma-Ray Emission from GRB 080916C. *Science* **2009**, *323*, 1688. [CrossRef] [PubMed]

134. Ackermann, M.; Ajello, M.; Asano, K.; Atwood, W.B.; Axelsson, M.; Baldini, L.; Ballet, J.; Barbiellini, G.; Baring, M.G.; Bastieri, D.; et al. Fermi-LAT Observations of the Gamma-Ray Burst GRB 130427A. *Science* **2014**, *343*, 42–47. [CrossRef]
135. Nava, L.; Desiante, R.; Longo, F.; Celotti, A.; Omodei, N.; Vianello, G.; Bissaldi, E.; Piran, T. Constraints on the bulk Lorentz factor of gamma-ray burst jets from Fermi/LAT upper limits. *Mon. Not. R. Astron. Soc.* **2017**, *465*, 811–819. [CrossRef]
136. Razzaque, S.; Dermer, C.D.; Finke, J.D. The Stellar Contribution to the Extragalactic Background Light and Absorption of High-Energy Gamma Rays. *Astrophys. J.* **2009**, *697*, 483–492. [CrossRef]
137. Zhang, B.; Pe'er, A. Evidence of an Initially Magnetically Dominated Outflow in GRB 080916C. *Astrophys. J.* **2009**, *700*, L65–L68. [CrossRef]
138. Zhang, B.; Yan, H. The Internal-collision-induced Magnetic Reconnection and Turbulence (ICMART) Model of Gamma-ray Bursts. *Astrophys. J.* **2011**, *726*, 90. [CrossRef]
139. Guiriec, S.; Kouveliotou, C.; Daigne, F.; Zhang, B.; Hascoët, R.; Nemmen, R.S.; Thompson, D.J.; Bhat, P.N.; Gehrels, N.; Gonzalez, M.M.; et al. Toward a Better Understanding of the GRB Phenomenon: A New Model for GRB Prompt Emission and its Effects on the New L_i^{NT}- $E_{peak,i}^{rest,NT}$ Relation. *Astrophys. J.* **2015**, *807*, 148. [CrossRef]
140. Ryde, F.; Axelsson, M.; Zhang, B.B.; McGlynn, S.; Pe'er, A.; Lundman, C.; Larsson, S.; Battelino, M.; Zhang, B.; Bissaldi, E.; et al. Identification and Properties of the Photospheric Emission in GRB090902B. *Astrophys. J.* **2010**, *709*, L172–L177. [CrossRef]
141. Guiriec, S.; Connaughton, V.; Briggs, M.S.; Burgess, M.; Ryde, F.; Daigne, F.; Mészáros, P.; Goldstein, A.; McEnery, J.; Omodei, N.; et al. Detection of a Thermal Spectral Component in the Prompt Emission of GRB 100724B. *Astrophys. J.* **2011**, *727*, L33. [CrossRef]
142. Ackermann, M.; Ajello, M.; Atwood, W.B.; Baldini, L.; Ballet, J.; Barbiellini, G.; Bastieri, D.; Baughman, B.M.; Bechtol, K.; Bellardi, F.; et al. Fermi LAT observations of cosmic-ray electrons from 7 GeV to 1 TeV. *Phys. Rev. D* **2010**, *82*, 092004. [CrossRef]
143. Oganesyan, G.; Nava, L.; Ghirlanda, G.; Melandri, A.; Celotti, A. Prompt optical emission as a signature of synchrotron radiation in gamma-ray bursts. *Astron. Astrophys.* **2019**, *628*, A59. [CrossRef]
144. Oganesyan, G.; Nava, L.; Ghirlanda, G.; Celotti, A. Characterization of gamma-ray burst prompt emission spectra down to soft X-rays. *Astron. Astrophys.* **2018**, *616*, A138. [CrossRef]
145. Waxman, E. Cosmological Gamma-Ray Bursts and the Highest Energy Cosmic Rays. *Phys. Rev. Lett.* **1995**, *75*, 386–389. [CrossRef]
146. Vietri, M. The Acceleration of Ultra–High-Energy Cosmic Rays in Gamma-Ray Bursts. *Astrophys. J.* **1995**, *453*, 883. [CrossRef]
147. Milgrom, M.; Usov, V. Possible Association of Ultra–High-Energy Cosmic-Ray Events with Strong Gamma-Ray Bursts. *Astrophys. J.* **1995**, *449*, L37. [CrossRef]
148. Waxman, E.; Bahcall, J. High Energy Neutrinos from Cosmological Gamma-Ray Burst Fireballs. *Phys. Rev. Lett.* **1997**, *78*, 2292–2295. [CrossRef]
149. Murase, K.; Ioka, K.; Nagataki, S.; Nakamura, T. High-energy cosmic-ray nuclei from high- and low-luminosity gamma-ray bursts and implications for multimessenger astronomy. *Phys. Rev. D* **2008**, *78*, 023005. [CrossRef]
150. Zhang, B.; Kumar, P. Model-Dependent High-Energy Neutrino Flux from Gamma-Ray Bursts. *Phys. Rev. Lett.* **2013**, *110*, 121101. [CrossRef] [PubMed]
151. Aartsen, M.G.; Ackermann, M.; Adams, J.; Aguilar, J.A.; Ahlers, M.; Ahrens, M.; Samarai, I.A.; Altmann, D.; Andeen, K.; Anderson, T.; et al. Extending the Search for Muon Neutrinos Coincident with Gamma-Ray Bursts in IceCube Data. *Astrophys. J.* **2017**, *843*, 112. [CrossRef]
152. Albert, A.; André, M.; Anghinolfi, M.; Anton, G.; Ardid, M.; Aubert, J.J.; Avgitas, T.; Baret, B.; Barrios-Martí, J.; Basa, S.; et al. Search for high-energy neutrinos from bright GRBs with ANTARES. *Mon. Not. R. Astron. Soc.* **2017**, *469*, 906–915. [CrossRef]
153. Albert, A.; André, M.; Anghinolfi, M.; Anton, G.; Ardid, M.; Aubert, J.J.; Aublin, J.; Baret, B.; Basa, S.; Belhorma, B.; et al. Constraining the contribution of Gamma-Ray Bursts to the high-energy diffuse neutrino flux with 10 yr of ANTARES data. *Mon. Not. R. Astron. Soc.* **2021**, *500*, 5614–5628. [CrossRef]
154. Taylor, J.H.; Weisberg, J.M. Further Experimental Tests of Relativistic Gravity Using the Binary Pulsar PSR 1913+16. *Astrophys. J.* **1989**, *345*, 434. [CrossRef]
155. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.* **2017**, *119*, 161101. [CrossRef]
156. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. Multi-messenger Observations of a Binary Neutron Star Merger. *Astrophys. J.* **2017**, *848*, L12. [CrossRef]
157. Abbott, B.P.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B.; et al. Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A. *Astrophys. J.* **2017**, *848*, L13. [CrossRef]
158. Goldstein, A.; Veres, P.; Burns, E.; Briggs, M.S.; Hamburg, R.; Kocevski, D.; Wilson-Hodge, C.A.; Preece, R.D.; Poolakkil, S.; Roberts, O.J.; et al. An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: Fermi-GBM Detection of GRB 170817A. *Astrophys. J.* **2017**, *848*, L14. [CrossRef]
159. Coulter, D.A.; Foley, R.J.; Kilpatrick, C.D.; Drout, M.R.; Piro, A.L.; Shappee, B.J.; Siebert, M.R.; Simon, J.D.; Ulloa, N.; Kasen, D.; et al. Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source. *Science* **2017**, *358*, 1556–1558. [CrossRef]

160. Pian, E.; D'Avanzo, P.; Benetti, S.; Branchesi, M.; Brocato, E.; Campana, S.; Cappellaro, E.; Covino, S.; D'Elia, V.; Fynbo, J.P.U.; et al. Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger. *Nature* **2017**, *551*, 67–70. [CrossRef] [PubMed]
161. Evans, P.A.; Cenko, S.B.; Kennea, J.A.; Emery, S.W.K.; Kuin, N.P.M.; Korobkin, O.; Wollaeger, R.T.; Fryer, C.L.; Madsen, K.K.; Harrison, F.A.; et al. Swift and NuSTAR observations of GW170817: Detection of a blue kilonova. *Science* **2017**, *358*, 1565–1570. [CrossRef] [PubMed]
162. Shappee, B.J.; Simon, J.D.; Drout, M.R.; Piro, A.L.; Morrell, N.; Prieto, J.L.; Kasen, D.; Holoien, T.W.S.; Kollmeier, J.A.; Kelson, D.D.; et al. Early spectra of the gravitational wave source GW170817: Evolution of a neutron star merger. *Science* **2017**, *358*, 1574–1578. [CrossRef]
163. Smartt, S.J.; Chen, T.W.; Jerkstrand, A.; Coughlin, M.; Kankare, E.; Sim, S.A.; Fraser, M.; Inserra, C.; Maguire, K.; Chambers, K.C.; et al. A kilonova as the electromagnetic counterpart to a gravitational-wave source. *Nature* **2017**, *551*, 75–79. [CrossRef]
164. Nicholl, M.; Berger, E.; Kasen, D.; Metzger, B.D.; Elias, J.; Briceño, C.; Alexander, K.D.; Blanchard, P.K.; Chornock, R.; Cowperthwaite, P.S.; et al. The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. III. Optical and UV Spectra of a Blue Kilonova from Fast Polar Ejecta. *Astrophys. J.* **2017**, *848*, L18. [CrossRef]
165. Chornock, R.; Berger, E.; Kasen, D.; Cowperthwaite, P.S.; Nicholl, M.; Villar, V.A.; Alexander, K.D.; Blanchard, P.K.; Eftekhari, T.; Fong, W.; et al. The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. IV. Detection of Near-infrared Signatures of r-process Nucleosynthesis with Gemini-South. *Astrophys. J.* **2017**, *848*, L19. [CrossRef]
166. Kulkarni, S.R. Modeling Supernova-like Explosions Associated with Gamma-ray Bursts with Short Durations. *arXiv* **2005**, arXiv:astro-ph/0510256. [CrossRef]
167. Li, L.X.; Paczyński, B. Transient Events from Neutron Star Mergers. *Astrophys. J.* **1998**, *507*, L59–L62. [CrossRef]
168. Piran, T.; Nakar, E.; Rosswog, S. The electromagnetic signals of compact binary mergers. *Mon. Not. R. Astron. Soc.* **2013**, *430*, 2121–2136. [CrossRef]
169. Kobayashi, S.; Mészáros, P. Gravitational Radiation from Gamma-Ray Burst Progenitors. *Astrophys. J.* **2003**, *589*, 861–870. [CrossRef]
170. Ezquiaga, J.M.; Zumalacárregui, M. Dark Energy After GW170817: Dead Ends and the Road Ahead. *Phys. Rev. Lett.* **2017**, *119*, 251304. [CrossRef] [PubMed]
171. Meszaros, P.; Rees, M.J.; Papathanassiou, H. Spectral Properties of Blast-Wave Models of Gamma-Ray Burst Sources. *Astrophys. J.* **1994**, *432*, 181. [CrossRef]
172. Mészáros, P.; Razzaque, S.; Zhang, B. GeV-TeV emission from γ-ray bursts. *New A Rev.* **2004**, *48*, 445–451. [CrossRef]
173. Fan, Y.Z.; Piran, T. High-energy γ-ray emission from gamma-ray bursts—Before GLAST. *Front. Phys. China* **2008**, *3*, 306–330. [CrossRef]
174. Inoue, S.; Granot, J.; O'Brien, P.T.; Asano, K.; Bouvier, A.; Carosi, A.; Connaughton, V.; Garczarczyk, M.; Gilmore, R.; Hinton, J.; et al. Gamma-ray burst science in the era of the Cherenkov Telescope Array. *Astropart. Phys.* **2013**, *43*, 252–275. [CrossRef]
175. Nava, L. High-energy emission from gamma-ray bursts. *Int. J. Mod. Phys. D* **2018**, *27*, 1842003. [CrossRef]
176. Padilla, L.; Funk, B.; Krawczynski, H.; Contreras, J.L.; Moralejo, A.; Aharonian, F.; Akhperjanian, A.G.; Barrio, J.A.; Beteta, J.G.; Cortina, J.; et al. Search for gamma-ray bursts above 20 TeV with the HEGRA AIROBICC Cherenkov array. *Astron. Astrophys.* **1998**, *337*, 43–50.
177. Atkins, R.; Benbow, W.; Berley, D.; Chen, M.L.; Coyne, D.G.; Dingus, B.L.; Dorfan, D.E.; Ellsworth, R.W.; Evans, D.; Falcone, A.; et al. Evidence for TEV Emission from GRB 970417A. *Astrophys. J.* **2000**, *533*, L119–L122. [CrossRef]
178. Atkins, R.; Benbow, W.; Berley, D.; Blaufuss, E.; Bussons, J.; Coyne, D.G.; Delay, R.S.; De Young, T.; Dingus, B.L.; Dorfan, D.E.; et al. Observation of TeV Gamma Rays from the Crab Nebula with Milagro Using a New Background Rejection Technique. *Astrophys. J.* **2003**, *595*, 803–811. [CrossRef]
179. Lund, N. The WATCH gamma-burst detector for EURECA-1. In Proceedings of the X-ray Instrumentation in Astronomy, Cannes, France, 2–4 December 1985; p. 55.
180. Castro-Tirado, A.J.; Brandt, S.; Lund, N.; Guziy, S.S. Optical Follow-Up of Gamma-ray Bursts Observed by WATCH. In Proceedings of the Gamma-Ray Bursts, Huntsville, AL, USA, 20–22 October 1993; American Institute of Physics Conference Series; Fishman, G.J., Ed.; Volume 307, p. 404. [CrossRef]
181. Albert, J.; Aliu, E.; Anderhub, H.; Antoranz, P.; Armada, A.; Asensio, M.; Baixeras, C.; Barrio, J.A.; Bartelt, M.; Bartko, H.; et al. Flux Upper Limit on Gamma-Ray Emission by GRB 050713a from MAGIC Telescope Observations. *Astrophys. J.* **2006**, *641*, L9–L12. [CrossRef]
182. Aleksić, J.; Ansoldi, S.; Antonelli, L.A.; Antoranz, P.; Babic, A.; Barres de Almeida, U.; Barrio, J.A.; Becerra González, J.; Bednarek, W.; Berger, K.; et al. MAGIC upper limits on the GRB 090102 afterglow. *Mon. Not. R. Astron. Soc.* **2014**, *437*, 3103–3111. [CrossRef]
183. Abramowski, A. et al. [H. E. S. S. Collaboration]. Search for TeV Gamma-ray Emission from GRB 100621A, an extremely bright GRB in X-rays, with H.E.S.S. *Astron. Astrophys.* **2014**, *565*, A16. [CrossRef]
184. Aliu, E.; Aune, T.; Barnacka, A.; Beilicke, M.; Benbow, W.; Berger, K.; Biteau, J.; Buckley, J.H.; Bugaev, V.; Byrum, K.; et al. Constraints on Very High Energy Emission from GRB 130427A. *Astrophys. J.* **2014**, *795*, L3. [CrossRef]
185. Abeysekara, A.U.; Alfaro, R.; Alvarez, C.; Álvarez, J.D.; Arceo, R.; Arteaga-Velázquez, J.C.; Ayala Solares, H.A.; Barber, A.S.; Baughman, B.M.; Bautista-Elivar, N.; et al. Search for Gamma-Rays from the Unusually Bright GRB 130427A with the HAWC Gamma-Ray Observatory. *Astrophys. J.* **2015**, *800*, 78. [CrossRef]

186. Mirzoyan, R. First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C. *Astron. Telegr.* **2019**, *12390*, 1.
187. Acciari, V.A. et al. [MAGIC Collaboration]. Teraelectronvolt emission from the γ-ray burst GRB 190114C. *Nature* **2019**, *575*, 455–458. [CrossRef]
188. Abdalla, H.; Adam, R.; Aharonian, F.; Ait Benkhali, F.; Angüner, E.O.; Arakawa, M.; Arcaro, C.; Armand, C.; Ashkar, H.; Backes, M.; et al. A very-high-energy component deep in the γ-ray burst afterglow. *Nature* **2019**, *575*, 464–467. [CrossRef]
189. Abdalla, H. et al. [H. E. S. S. Collaboration]. Revealing X-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow. *Science* **2021**, *372*, 1081–1085. [CrossRef]
190. Blanch, O.; Gaug, M.; Noda, K.; Berti, A.; Moretti, E.; Miceli, D.; Gliwny, P.; Ubach, S.; Schleicher, B.; Cerruti, M.; et al. MAGIC observations of GRB 201015A: Hint of very high energy gamma-ray signal. *GRB Coord. Netw.* **2020**, *28659*, 1.
191. Blanch, O. GRB 201216C: MAGIC detection in very high energy gamma rays. *Astron. Telegr.* **2020**, *14275*, 1.
192. Blanch, O.; Longo, F.; Berti, A.; Fukami, S.; Suda, Y.; Loporchio, S.; Micanovic, S.; Green, J.G.; Pinter, V.; Takahashi, M.; et al. GRB 201216C: MAGIC detection in very high energy gamma rays. *GRB Coord. Netw.* **2020**, *29075*, 1.
193. Acciari, V.A.; Ansoldi, S.; Antonelli, L.A.; Arbet Engels, A.; Asano, K.; Baack, D.; Babić, A.; Baquero, A.; Barres de Almeida, U.; Barrio, J.A.; et al. MAGIC Observations of the Nearby Short Gamma-Ray Burst GRB 160821B. *Astrophys. J.* **2021**, *908*, 90. [CrossRef]
194. Cao, Z. A future project at tibet: The large high altitude air shower observatory (LHAASO). *Chin. Phys. C* **2010**, *34*, 249–252. [CrossRef]
195. Cao, Z.; della Volpe, D.; Liu, S.; Bi, X.; Chen, Y.; D'Ettorre Piazzoli, B.; Feng, L.; Jia, H.; Li, Z.; Ma, X.; et al. The Large High Altitude Air Shower Observatory (LHAASO) Science Book (2021 Edition). *arXiv* **2019**, arXiv:1905.02773. [CrossRef]
196. Cao, Z. et al. [LHAASO Collaboration]. A tera-electron volt afterglow from a narrow jet in an extremely bright gamma-ray burst. *Science* **2023**, *380*, 1390–1396. [CrossRef]
197. Burns, E.; Svinkin, D.; Fenimore, E.; Kann, D.A.; Agüí Fernández, J.F.; Frederiks, D.; Hamburg, R.; Lesage, S.; Temiraev, Y.; Tsvetkova, A.; et al. GRB 221009A: The Boat. *Astrophys. J.* **2023**, *946*, L31. [CrossRef]
198. An, Z.H.; Antier, S.; Bi, X.Z.; Bu, Q.C.; Cai, C.; Cao, X.L.; Camisasca, A.E.; Chang, Z.; Chen, G.; Chen, L.; et al. Insight-HXMT and GECAM-C observations of the brightest-of-all-time GRB 221009A. *arXiv* **2023**, arXiv:2303.01203. [CrossRef]
199. Frederiks, D.; Svinkin, D.; Lysenko, A.L.; Molkov, S.; Tsvetkova, A.; Ulanov, M.; Ridnaia, A.; Lutovinov, A.A.; Lapshov, I.; Tkachenko, A.; et al. Properties of the Extremely Energetic GRB 221009A from Konus-WIND and SRG/ART-XC Observations. *Astrophys. J.* **2023**, *949*, L7. [CrossRef]
200. Lesage, S.; Veres, P.; Briggs, M.S.; Goldstein, A.; Kocevski, D.; Burns, E.; Wilson-Hodge, C.A.; Bhat, P.N.; Huppenkothen, D.; Fryer, C.L.; et al. Fermi-GBM Discovery of GRB 221009A: An Extraordinarily Bright GRB from Onset to Afterglow. *Astrophys. J.* **2023**, *952*, L42. [CrossRef]
201. Williams, M.A.; Kennea, J.A.; Dichiara, S.; Kobayashi, K.; Iwakiri, W.B.; Beardmore, A.P.; Evans, P.A.; Heinz, S.; Lien, A.; Oates, S.R.; et al. GRB 221009A: Discovery of an Exceptionally Rare Nearby and Energetic Gamma-Ray Burst. *Astrophys. J.* **2023**, *946*, L24. [CrossRef]
202. Ren, J.; Wang, Y.; Zhang, L.L.; Dai, Z.G. The Possibility of Modeling the Very High Energy Afterglow of GRB 221009A in a Wind Environment. *Astrophys. J.* **2023**, *947*, 53. [CrossRef]
203. O'Connor, B.; Troja, E.; Ryan, G.; Beniamini, P.; van Eerten, H.; Granot, J.; Dichiara, S.; Ricci, R.; Lipunov, V.; Gillanders, J.H.; et al. A structured jet explains the extreme GRB 221009A. *Sci. Adv.* **2023**, *9*, eadi1405. [CrossRef] [PubMed]
204. Zhang, B.T.; Murase, K.; Ioka, K.; Song, D.; Yuan, C.; Mészáros, P. External Inverse-compton and Proton Synchrotron Emission from the Reverse Shock as the Origin of VHE Gamma Rays from the Hyper-bright GRB 221009A. *Astrophys. J.* **2023**, *947*, L14. [CrossRef]
205. Sato, Y.; Murase, K.; Ohira, Y.; Yamazaki, R. Two-component jet model for multiwavelength afterglow emission of the extremely energetic burst GRB 221009A. *Mon. Not. R. Astron. Soc.* **2023**, *522*, L56–L60. [CrossRef]
206. Das, S.; Razzaque, S. Ultrahigh-energy cosmic-ray signature in GRB 221009A. *Astron. Astrophys.* **2023**, *670*, L12. [CrossRef]
207. Alves Batista, R. GRB 221009A: A potential source of ultra-high-energy cosmic rays. *arXiv* **2022**, arXiv:2210.12855. [CrossRef]
208. de Ugarte Postigo, A.; Izzo, L.; Pugliese, G.; Xu, D.; Schneider, B.; Fynbo, J.P.U.; Tanvir, N.R.; Malesani, D.B.; Saccardi, A.; Kann, D.A.; et al. GRB 221009A: Redshift from X-shooter/VLT. *GRB Coord. Netw.* **2022**, *32648*, 1.
209. Li, H.; Ma, B.Q. Lorentz invariance violation induced threshold anomaly versus very-high energy cosmic photon emission from GRB 221009A. *Astropart. Phys.* **2023**, *148*, 102831. [CrossRef]
210. Finke, J.D.; Razzaque, S. Possible Evidence for Lorentz Invariance Violation in Gamma-Ray Burst 221009A. *Astrophys. J.* **2023**, *942*, L21. [CrossRef]
211. Galanti, G.; Nava, L.; Roncadelli, M.; Tavecchio, F.; Bonnoli, G. Observability of the very-high-energy emission from GRB 221009A. *arXiv* **2022**, arXiv:2210.05659. [CrossRef]
212. Nakagawa, S.; Takahashi, F.; Yamada, M.; Yin, W. Axion dark matter from first-order phase transition, and very high energy photons from GRB 221009A. *Phys. Lett. B* **2023**, *839*, 137824. [CrossRef]
213. Murase, K.; Mukhopadhyay, M.; Kheirandish, A.; Kimura, S.S.; Fang, K. Neutrinos from the Brightest Gamma-Ray Burst? *Astrophys. J.* **2022**, *941*, L10. [CrossRef]
214. Ai, S.; Gao, H. Model Constraints Based on the IceCube Neutrino Nondetection of GRB 221009A. *Astrophys. J.* **2023**, *944*, 115. [CrossRef]

215. Abbasi, R.; Ackermann, M.; Adams, J.; Agarwalla, S.K.; Aggarwal, N.; Aguilar, J.A.; Ahlers, M.; Alameddine, J.M.; Amin, N.M.; Andeen, K.; et al. Limits on Neutrino Emission from GRB 221009A from MeV to PeV Using the IceCube Neutrino Observatory. *Astrophys. J.* **2023**, *946*, L26. [CrossRef]
216. Edvige Ravasio, M.; Sharan Salafia, O.; Oganesyan, G.; Mei, A.; Ghirlanda, G.; Ascenzi, S.; Banerjee, B.; Macera, S.; Branchesi, M.; Jonker, P.G.; et al. A bright megaelectronvolt emission line in γ-ray burst GRB 221009A. *arXiv* **2023**, arXiv:2303.16223. [CrossRef]
217. Fiore, F.; Burderi, L.; Lavagna, M.; Bertacin, R.; Evangelista, Y.; Campana, R.; Fuschino, F.; Lunghi, P.; Monge, A.; Negri, B.; et al. The HERMES-technologic and scientific pathfinder. *arXiv* **2020**, arXiv:2101.03078. [CrossRef]
218. Paul, J.; Wei, J.; Basa, S.; Zhang, S.N. The Chinese-French SVOM mission for gamma-ray burst studies. *Comptes Rendus Phys.* **2011**, *12*, 298–308. [CrossRef]
219. Wei, J.; Cordier, B.; Antier, S.; Antilogus, P.; Atteia, J.L.; Bajat, A.; Basa, S.; Beckmann, V.; Bernardini, M.G.; Boissier, S.; et al. The Deep and Transient Universe in the SVOM Era: New Challenges and Opportunities—Scientific prospects of the SVOM mission. *arXiv* **2016**, arXiv:1610.06892. [CrossRef]
220. Amati, L.; O'Brien, P.; Götz, D.; Bozzo, E.; Tenzer, C.; Frontera, F.; Ghirlanda, G.; Labanti, C.; Osborne, J.P.; Stratta, G.; et al. The THESEUS space mission concept: Science case, design and expected performances. *Adv. Space Res.* **2018**, *62*, 191–244. [CrossRef]
221. Stratta, G.; Ciolfi, R.; Amati, L.; Bozzo, E.; Ghirlanda, G.; Maiorano, E.; Nicastro, L.; Rossi, A.; Vinciguerra, S.; Frontera, F.; et al. THESEUS: A key space mission concept for Multi-Messenger Astrophysics. *Adv. Space Res.* **2018**, *62*, 662–682. [CrossRef]
222. Amati, L.; O'Brien, P.T.; Götz, D.; Bozzo, E.; Santangelo, A.; Tanvir, N.; Frontera, F.; Mereghetti, S.; Osborne, J.P.; Blain, A.; et al. The THESEUS space mission: Science goals, requirements and mission concept. *Exp. Astron.* **2021**, *52*, 183–218. [CrossRef]
223. Rahin, R.; Salh, J.; Tarem, S.; Behar, E. GALI (Gamma-ray Burst Localizing Instrument) A New GRB Detector Concept. *AAS/High Energy Astrophys. Div.* **2022**, *54*, 111.12.
224. Yuan, W.M. Special Topic of Einstein Probe: Exploring the Dynamic X-ray Universe. *Sci. Sin. Phys. Mech. Astron.* **2018**, *48*, 039501. [CrossRef]
225. Chen, Y.; Sun, X.; Li, Z.; Wang, C.; Zhang, C.; Sun, S. Detection system of the lobster eye telescope with large field of view. *Appl. Opt.* **2022**, *61*, 8813. [CrossRef] [PubMed]
226. Chen, Y.; Cui, W.; Han, D.; Wang, J.; Yang, Y.; Wang, Y.; Li, W.; Ma, J.; Xu, Y.; Lu, F.; et al. Status of the follow-up x-ray telescope onboard the Einstein Probe satellite. *Soc. Photo-Opt. Instrum. Eng. (SPIE) Conf. Ser.* **2020**, *11444*, 114445B. [CrossRef]
227. Racusin, J.; Perkins, J.S.; Briggs, M.S.; de Nolfo, G.; Krizmanic, J.; Caputo, R.; McEnery, J.E.; Shawhan, P.; Morris, D.; Connaughton, V.; et al. BurstCube: A CubeSat for Gravitational Wave Counterparts. *arXiv* **2017**, arXiv:1708.09292. [CrossRef]
228. Kocevski, D. The StarBurst Multimessenger Pioneer. *AAS/High Energy Astrophys. Div.* **2023**, *55*, 115.23.
229. Hui, C.M.; Briggs, M.S.; Goldstein, A.; Jenke, P.; Kocevski, D.; Wilson-Hodge, C.A. MoonBEAM: A Beyond-LEO Gamma-Ray Burst Detector for Gravitational-Wave Astronomy. In Proceedings of the Deep Space Gateway Concept Science Workshop, Denver, CO, USA, 27 February–1 March 2018; LPI Contributions; LPI Editorial Board, Ed.; Volume 2063, p. 3060.
230. Fletcher, C.; Hui, C.M.; Goldstein, A.; The MoonBEAM Team. The Scientific Performance of the MoonBurst Energetics All-sky Monitor(MoonBEAM). *arXiv* **2023**, arXiv:2308.16293. [CrossRef]
231. McConnell, M.L.; Baring, M.G.; Bloser, P.F.; Briggs, M.S.; Connaughton, V.; Dwyer, J.; Gaskin, J.; Grove, J.E.; Gunji, S.; Hartmann, D.; et al. LEAP—A Large Area GRB Polarimeter for the ISS. *AAS/High Energy Astrophys. Div.* **2017**, *16*, 103.20.
232. Gaskin, J.; Baring, M.; Bloser, P.; Briggs, M.; Dwyer, J.; Ertley, C.; Fletcher, G.; Galloway, P.; Gelmis, K.; Goldstein, A.; et al. The LEAP Gamma-Ray Burst Polarimeter: An Overview. *Am. Astron. Soc. Meet. Abstr.* **2022**, *54*, 127.01.
233. Zhang, B. *The Physics of Gamma-Ray Bursts*; Cambridge University Press: Cambridge, UK, 2018. [CrossRef]