galaxies

MDPI

Review

Gamma-Ray Bursts: What Do We Know Today That We Did Not Know 10 Years Ago?

Asaf Pe'er

Department of Physics, Bar Ilan University, Ramat-Gan 52900, Israel; asaf.peer@biu.ac.il

Abstract: I discuss here the progress made in the last decade on a few of the key open problems in GRB physics. These include (1) the nature of GRB progenitors, and the outliers found to the collapsar/merger scenarios; (2) jet structures, whose existence became evident following GRB/GW170817; (3) the great progress made in understanding the GRB jet launching mechanisms, enabled by general-relativistic magnetohydrodynamic (GR-MHD) codes; (4) recent studies of magnetic reconnection as a valid energy dissipation mechanism; (5) the early afterglow, which may be highly affected by a wind bubble, as well as recent indication that in many GRBs, the Lorentz factor is only a few tens, rather than a few hundreds. I highlight some recent observational progress, including the major breakthrough in detecting TeV photons and the on-going debate about their origin, polarization measurements, as well as the pair annihilation line recently detected in GRB 221009A, and its implications for prompt emission physics. I probe into some open questions that I anticipate will be at the forefront of GRB research in the next decade.

Keywords: data analysis; gamma-ray bursts; gravitational waves; theoretical modeling

1. Introduction

Since the realization in the early 1990s that gamma-ray bursts (GRBs) are of cosmological origin, and therefore release a huge amount of energy, typically 10^{50}–10^{53} erg, in the form of gamma rays over a duration of a few seconds, they have challenged the boundaries of physics and have fascinated the imagination of many astronomers. They further show an extremely rich phenomenology, with broadband spectra that extend over the entire electromagnetic spectrum—from radio to the TeV range—and with a highly variable lightcurve (down to 0.01 s in some cases). As no two GRBs are identical, the data challenge both observational campaigns and theoretical models (see, e.g., [1–4] for recent reviews).

Although naturally the field is maturing, interestingly many fundamental questions about the underlying nature and physics of GRBs still remain unsolved. In fact, there are many open problems whose answers were unknown, or at least there was not a consensus on, 10 years ago, and still are today. Nonetheless, clearly there has been a huge volume of works (according to NASA ADS, about 18,000 papers whose titles contain "GRB" appeared since 2014), which have addressed some of the questions, while opening new ones. It is therefore useful to look at the big open questions that have occupied researchers in this field, and the progress that has been made in the past decade. This enables one to look into the future, and foresee the progress that we hope and expect to make in the coming years.

Phenomenologically, GRBs are traditionally classified into two categories: "short" (or short/hard) GRBs, with an average duration of a few tenths of a second; and "long" (or long/soft) GRBs, with an average duration of 20 s. The dividing line is typically found at $\sim$2 s [5–9]. Furthermore, there is evidence for a sub-class of "ultra-long" GRBs [10,11],

Academic Editor: Christian Corda

Received: 24 November 2024
Revised: 22 December 2024
Accepted: 24 December 2024
Published: 31 December 2024

Citation: Pe'er, A. Gamma-Ray Bursts: What Do We Know Today That We Did Not Know 10 Years Ago? *Galaxies* **2025**, *13*, 2. https://doi.org/10.3390/galaxies13010002

whose duration exceeds 10,000 s. It is unclear whether these "ultra-long" GRBs form a separate population with distinct physical properties or not. For example, the ultra-long GRB220627A did not show any different properties than long GRBs (in terms of jet break or ambient density) [12], supporting the idea that its progenitor is similar in nature to other, more standard long GRBs.

Despite this huge variation in the GRB duration, as well as the X- and gamma-ray lightcurves, with some GRBs being very "spiky" and others show a much smoother lightcurve, all GRBs share some common spectral features. These include a distinct observed spectral peak in the sub-MeV energy range, and spectra that are often modeled (even if crudely, see below) as a "broken power law" [13], with distinct low- and high-energy spectral slopes. In recent years, there has been evidence for an additional high-energy component that extends, in some cases, to the TeV range, e.g., [14,15]. Furthermore, clearly all GRBs are transients, lasting a (relatively) short duration, and no repetition has ever been found.

Interestingly enough, the basic skeleton of the theoretical understanding of GRBs had not changed: it is the famous GRB "fireball" model [16–20]; see Figure 1. According to the "fireball" model, a vast explosion, associated with the formation of a black hole, leads to the ejection of material that forms a relativistic jet. There is still a debate about the role played by the magnetic field in the jet acceleration process (see below). At a second stage, some of the jet kinetic energy is dissipated, e.g., by internal shock waves ([20–24], and many others), magnetic reconnection (e.g., [25–29], and many more), or other unspecified mechanisms, producing the observed prompt emission signal. Following the dissipation, the material in the jet continues to expand relativistically into the interstellar medium (ISM), driving a relativistic shock wave. This shock wave, in turn, heats the ISM material, generates a magnetic field, and accelerates a substantial fraction of the particles to a non-thermal distribution above the thermal peak. During the acceleration process, these non-thermal particles acquire a power-law energy distribution. They then radiate synchrotron emission, which is the main source of the afterglow emission [30,31]. This afterglow has been routinely detected since 1997 [30,32,33].

One of the open questions that is still debatable is the role of magnetic fields in this process. The original "fireball" model assumed a baryon-dominated outflow [16,17,34–36], in which the gravitational energy is converted to the jet kinetic energy via neutrino–anti-neutrino annihilation, that produces a copious number of $e^{\pm}$ pairs. The "fireball" is thus composed of photon pairs, as well as electrons and baryons (that carry the momentum), relics from the explosion that initiated the process. However, already in the 1990s it was suggested that magnetic fields may play a significant role in shaping the dynamics of the flow [25,27,37–43]. According to the "magnetized fireball" models, most of the energy is carried in the form of the Poynting flux, which is later used in accelerating and heating the gas via the magnetic reconnection process. Although many details are uncertain (see below), this model has several advantages over the classical "fireball" model, and is thus considered by many as a viable alternative. However, this is still highly debatable.

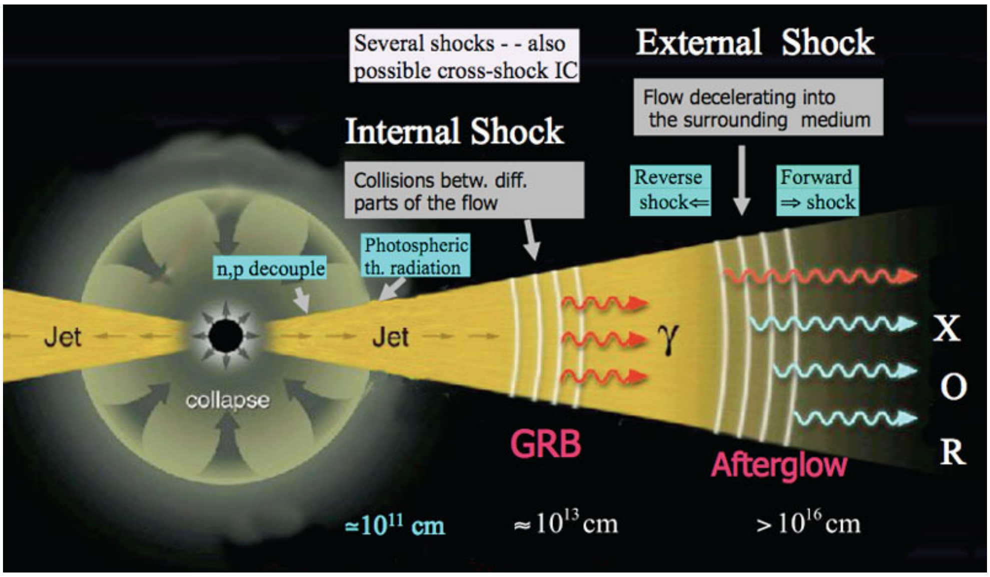

Figure 1. Illustration showing the basic ingredients of the GRB "fireball" model. (1) The source of energy is the collapse of a massive star (or binary merger, not shown here). (2) Part of this energy is used in producing the relativistic jet. This could be mediated by hot photons ("fireball"), or by a magnetic field. (3) The thermal photons decouple at the photosphere. (4) Part of the jet kinetic energy is dissipated (by internal collisions, in this picture) to produce the observed γ rays. (5) The remaining kinetic energy is deposited into the surrounding medium, heating it and producing the observed afterglow. Figure is taken from [44].

The question of the role played by the magnetic field is related to the nature of the explosion that triggers this chain of events. Indeed, the nature of the explosion itself is also somewhat uncertain. The two leading models are the collapse of a massive star (the so-called "collapsar" model; [45–47]), and the merger of binary stars [48,49], e.g., a neutron star (NS) and a black hole (BH). Evidence for the connection of massive star collapse with GRBs has existed for 20 years, since the discovery of absorption lines in the afterglow of GRB030329 [50,51]. However, as I discuss below, in recent years several outliers were found to this seemingly clear picture.

As for the origin of short GRBs, for many years only indirect evidence connected them with the merging of binaries. Such evidence included their observed occurrence location in the outskirts of their host galaxies [52–55], their existence in both star forming and elliptical galaxies, lack of association with supernovae, and their tendency to trace under-luminous locations within their host galaxies [56]; see, e.g., [57] for a review. This changed in 2017 with the discovery of gravitational waves associated with GRB170817 [58–60]. Such a gravitational wave signal, which preceded this GRB by 1.7 s, could only originate from the merging of two neutron stars. This discovery, thus, served as a smoking gun proving the merger origin of this GRB. This light-shedding event triggered an enormous amount of observations as well as theoretical modeling, significantly promoting our knowledge of both GRB progenitors and their jet properties, as is discussed below. I point out, however, that this GRB was peculiar in several ways, including being 10^2–10^4 times less luminous than typical short GRBs. This may challenge the claim of universality.

A unique observational consequence of this binary merger scenario is the rapid production of heavy nuclei. The very high temperature during the merger event, $\gtrsim 10^{13}$ °K, implies the release of a huge number of neutrons and protons. These recombine into α-particles, which merge with free neutrons to assemble heavy seed nuclei (with nuclei larger than an iron nucleus). These heavy nuclei then radioactively decay very rapidly, producing bright emission on a time scale of about a day, which became known as "kilonova". The origin of the name is that the events are approximately 1000 times brighter than regular novae [61,62]. The discovery of a kilonova was a major success of this model [63]. Nonetheless, here too several outliers were recently found, whose origin is still a mystery. I briefly discuss these below.

Although the basic picture of GRB formation and evolution, namely, the 'skeleton' of the fireball model, is well accepted by the community, many, possibly most, of the details remain open questions, even after three decades of extensive research. GRBs represent a very complicated environment, in which several independent processes of energy exchange exist: from gravitational energy release that leads to an explosion, through conversion of the explosion energy to kinetic energy in the form of a relativistic jet, and finally kinetic energy dissipation leading to the observed radiative signal. Many of the details of each of these processes are still actively debated in the literature. The main reason for this is that we only see the final outcome of this complicated chain of processes —the radiative signal (spectra and lightcurve), which varies from burst to burst, from which we try to deduce the full physics of the entire chain.

In the past decade, a plethora of continuous streams of data have been collected, due to a large number of telescopes that are active at all wavelengths. One interesting consequence is that in recent years several unique bursts have been detected which challenge what is already considered as "common knowledge" in this field. Furthermore, the continuous flow of data serves as a great platform on which new theoretical ideas flourish.

Here, I highlight some of the big open questions, and discuss the progress made in the past decade, with a view into the next decade. Clearly, any such list is subjective; nonetheless, I believe that the questions I highlight here are representatives of at least the main stream in this field today. The big problems that I would like to highlight can be summarized as follows.

1. The nature of the progenitor: What causes a GRB in the first place? As discussed above, both the "collapsar" and binary merger are considered valid scenarios. However, many of the details of the processes are still unknown, as well as the basic question of why two such different scenarios lead to similar observational outcomes. Moreover, as we have seen, in recent years several observations have challenged the simplified, binary picture.
2. The jet composition and the origin of the magnetic field. While in the classical GRB "fireball" model [18] the jet is accelerated by the radiative pressure, today there are indications that the jet may be highly magnetized [64,65], in which case the Blandford–Znajek process [66] may play a key role in the jet formation as well as its properties.
3. The geometrical jet structure, namely, its velocity profile, its dynamics, and evolution. While early works mainly considered a 'top-hat' jet, neglecting a lateral jet profile, in recent years it has become evident that GRB jets have a lateral structure, namely, $\Gamma = \Gamma(\theta)$ [67,68]. This affects the observed signal, which is different for observers located at different angles to the jet axis. Furthermore, as of today there is still no clear understanding of why GRB jets reach extremely high Lorentz factors, with Γ of several hundreds in some cases, while other astronomical transients are "only" mildly relativistic at most.
4. The nature of the energy dissipation mechanism that leads to the observed prompt emission signal (flux, spectrum, and lightcurve) is unclear. Many early works considered internal shocks as the key mechanism for kinetic energy dissipation [20,22,23]. However, it was quickly realized that this process suffers from low energy conversion efficiency. Therefore, alternative models were suggested, such as magnetic reconnection [28,69] or dominant contributions from the photosphere [70].
5. The radiative processes that lead to the resulting radiative signal, as well as other counterparts, such as cosmic rays, neutrinos, or gravitational waves are still debatable.

Production of the observed signal is the final outcome of a chain of events, from the dynamics through energy conversion, that accelerates particles in the radiative process. Many details of these events are uncertain, and therefore there is a high theoretical uncertainty in the expected signals.

6. The ambient medium density profile. The vast majority of early models considered the relativistic jet to expand into either a "constant-density" environmental profile ($n(r) \propto r^0$) or, alternatively, a "wind" profile of the form $n(r) \propto r^{-2}$, resulting from a stellar wind at constant velocity (e.g., [71,72]). However, in recent years there has been increasing evidence that these approximations are too simplified. One naturally expects a 'wind bubble' structure around GRB progenitor stars [73–75]. Such 'wind bubbles' result from stellar mass ejection prior to its terminal explosion that leads to a GRB, and can clearly affect the observed signal during the early afterglow phase [76–78].
7. Finally, I will mention as open questions the connection of GRBs with other objects of interest, such as stellar evolution, star formation, host galaxies, supernovae, binary stars, etc., which are not yet fully understood. Similarly, the connection between GRBs and fundamental physics, such as the use of GRBs as cosmological probes [79,80], Lorentz violation [81], etc., is a field that is still being explored.

Clearly, all these questions are related to each other, and answering one can provide important clues to the nature of the others. However, interestingly enough, as of today there is no firm answer to any of these questions. Here, I highlight some of the recent developments that occurred in the past decade on addressing some of these questions, and try to predict where the next steps will head.

2. The Nature of the GRB Progenitor

Already, in the mid-1990s, it was evident that GRBs are composed of two separate populations: "short" (or short/hard) GRBs, with an average duration of a few tenths of a second; and "long" (or long/soft) GRBs, with an average duration of 20 s. The dividing line is typically found at $\sim$2 s [5,6]. While initially, many theoretical ideas were proposed to explain these results, they quickly converged to two theoretical models: collapse of a massive star [45–47], and a merger of binary stars [48,49].

2.1. Long-GRB Progenitors: Outliers to the "Collapsar" Model

In the early 2000s, direct evidence for the connection of massive star collapse with GRBs emerged, with the discovery of absorption lines in the afterglow of GRB030329 [50,51]. Such absorption lines are typical for core collapse supernova (known as SN type Ib/c [1]), and their existence is a clear indication that the generation of long GRBs is associated with a core collapse of a massive star. Following these discoveries, this became 'common knowledge' [82,83].

However, in recent years, evidence has been accumulating that the picture is more complicated. Some GRBs that are clearly categorized as "long" GRBs, such as GRB211211A at a redshift of $z = 0.08$ ($T_{90}\sim$40 s) [84–86] or GRB230307A at $z = 0.065$ with $T_{90}\approx$45 s [87,88] (which is the second brightest GRB ever detected), are bright enough and close enough to show evidence for a supernova. However, instead of detecting a supernova as expected, both these GRBs show evidence for a kilonova, as expected from a binary merger.

For example, clear evidence for a kilonova emission was observed in GRB230307A, starting 2.4 days after the burst and lasting for more than two months [89]. Such a signal is a clear indication for a binary neutron star (BNS) merger origin, and is not expected when the collapse of a massive star generates a GRB. Thus, this GRB challenges the accepted division between the long and short-GRB populations, as well as the common belief that long GRBs originate from the collapse of a single, massive star. Moreover, evidence for heavy elements, such as tellurium, generated by the r-process was reported in the JWST lightcurve of this burst at late times, after 29 and 61 days [90]. These results therefore provide a strong indication in favor of a BNS merger progenitor for this GRB.

Similar considerations led to the suggestion [91] that GRB211211A originated from a binary merger. The evidence for a neutron star merger origin in GRB211211A was the excess of optical and near-infrared emission, both consistent with the kilonova observed after the gravitational wave detected, GW170817. However, it was argued [92] that an unusual collapsar could explain both the duration of GRB 211211A and the r-process-powered excess in its afterglow. These GRBs therefore are either outliers to the long-GRB population, or possibly hint towards a new type of GRB progenitor.

2.2. Binary Merger as Short-GRB Progenitor: Final Word?

As opposed to the question of long-GRB progenitors, prior to 2017, evidence for the association of short GRBs with binary mergers was only indirect. This included (1) the association of short GRBs with elliptical galaxies [55], as opposed to long GRBs, which are associated with star-forming galaxies; (2) the location of short GRBs within their host galaxies are observed to be at an offset from the galactic center [52,54]; (3) the lack of evidence for a supernova association; and (4) their location relative to the light—long GRBs are far more concentrated in the very brightest regions of their host galaxies [93] than short ones [94].

This situation dramatically changed in August 2017 with the association of the short GRB170817A to the gravitational wave source GW170817 [58–60,95,96]. Since gravitational waves at the observed magnitude can only originate from binary neutron star mergers, this discovery served as a smoking gun for the association of short GRBs with the merger scenario. Furthermore, several hours later, an optical counterpart was discovered with a luminosity, thermal spectrum, and rapid temporal decay consistent with those predicted for "kilonova" (KN) emission [97–101]. This emission is powered by the radioactive decay of heavy elements synthesized in the merger ejecta [61,62,102]. This discovery not only confirmed the NS merger origin of this burst, but was also used to prove that the origin of heavy elements is indeed in the mergers of binaries, as long thought.

Interestingly enough, signs of a kilonova were observed earlier, associated with the short GRB 130603B [103,104], although no gravitational wave signal was detected from this event as LIGO was not sensitive enough to detect a potential signal at that time. These results clearly indicate the merger origin of at least some of the short GRBs.

The picture, though, at least to me, is not complete yet. First, GRB170817, though clearly a light-shedding event, was a very peculiar GRB. In particular, its luminosity was two-to-four orders of magnitude lower than typical for short GRBs [105]. Furthermore, as of today, this is still only a single, unique event. No other events were detected, although the prospects for additional detection in the LIGO O3 run were good [106]. It was argued, though, that this lack of additional detections can be used to constrain GRB jet opening angles, which are typically a few degrees [107].

Thus, at least to my view, there is still a way to go before claiming that all short GRBs originate from binary mergers. In fact, there is at least one reported case, namely, GRB 200826A, with a duration (T90) of 1.14 ± 0.13 s, in the 50–300 keV energy range, which shows clear indication for a collapsar progenitor [108]. This may very well be at the edge of the Gaussian distribution of long-GRB duration, though its existence indicates that the categorization of GRBs needs to be looked at on a case-by-case basis.

Lessons from GW/GRB170817A

Despite the fact that, at least to my view, the final word on the origin of short GRBs had not been reached yet, there is no doubt that GW/GRB170817A was a light-shedding event. It is therefore useful to briefly summarize the key lessons learned from this event.

1. There is a clear association of (at least some) short GRBs with binary neutron star mergers.
2. The detection of kilonovae: Theoretical modeling shows that the matter that is expelled in the violent merger of two neutron stars can assemble into heavy elements such as gold and platinum in a process known as rapid neutron capture (r-process) nucleosynthesis. The radioactive decay of isotopes of the heavy elements is predicted to power a distinctive thermal glow (a 'kilonova'; [61,62]). The data confirm these predictions [63].
3. Furthermore, the data constrain the maximum neutron star mass to be $2.17 M_{\odot}$ [109,110].
4. There is clear evidence that the merger produces a relativistic jet [111], which is detected at late times [112].
5. Late-time observations revealed that the jet associated with GRB170817A was (i) structured, and (ii) viewed off-axis (see Section 3 below).

Thus, there is no doubt that this was the single most important event in the history of GRBs, in terms of the information and insight it provided the community with.

2.3. Magnetar Giant Flare: A Distinct GRB Population?

While the vast majority of GRBs are associated with a one-time terminal event, it has been suggested that some fraction may be associated with a repeated event.

Soft gamma repeaters (SGRs) are galactic X-ray stars that emit numerous short-duration (about 0.1 s) bursts of hard X-rays during sporadic active periods. They are thought to originate from magnetars, which are strongly magnetized neutron stars with emission powered by the dissipation of magnetic energy. Several SGRs have been detected in our galaxy [113–115]. Most importantly, several giant flares have been detected from these magnetars [116–118], with isotropic energy exceeding 10^{46} erg [118]. If such a magnetar is extra-galactic, the giant flare would be visible as a single flare, as lower energy flares are below current detector limits. It was therefore proposed that some observed single-pulse short GRBs may be associated with these extragalactic magnetar giant flares (MGFs) [119–121].

Analysis showed that these MGFs can account for a small fraction, a few %, of the short-GRB population [122,123]. Nonetheless, as they represent an alternative channel for producing GRBs, and the only one that can lead to a repeater, they have gained interest in recent years. Indeed, a recent analysis identified several nearby short GRBs that are unambiguously associated with MGFs [124]. Furthermore, this fraction depends on the detector's sensitivity: as MGFs are weaker than binary merger signals, yet they are more abundant than the merger rate, this fraction is expected to grow in the future, when more sensitive instruments become available [125].

3. Jet Structure

The fact that GRB explosions lead to the formation of jets (rather than spherical explosions) has been well known for over 20 years, following observations of jet breaks [126–128]. Indeed, such jet breaks are useful for GRB calorimetry [72,126,128,129], from which constraints on progenitor models can be derived, as well as the true GRB occurrence rates. For example, measuring the jet opening angle of 29 short GRBs [130] enabled the calculation of the true event rates. The inferred rates ($\sim$1000 Gpc^{-3} yr^{-1}) are consistent with the rate of NS–NS mergers, but are higher than the BH–NS merger rate [131,132] by a factor of 2–13. This result therefore implies that at most a small fraction of short-GRB progenitors are

BH–NS mergers. Similarly, when calibrating the true released energy, an average value of 10^{49}–10^{50} erg is found, which constrains possible jet launching mechanisms (see below).

For a long time, GRB jets were treated by most of the theoretical models as being 'top-hat', namely, $\Gamma(\theta) = \Gamma_0$ for $\theta < \theta_j$, and $\Gamma(\theta) = 0$ for larger angles. This is despite the fact that numerical simulations of jets propagating through a collapsing star clearly show a more complicated internal structure [46,67]. A possible reason for the consideration of top-hat jets is the ease of the dynamical calculations, which, in this case, can mostly be performed analytically. Furthermore, when considering structured jets, there is a high degree of uncertainty in the exact jet structure.

Prior to 2017, only a handful of works considered the possible effect of a structured jet on the observed signal [133–136]. This situation dramatically changed following the observations of GW/GRB170817. As this GRB attracted a lot of attention, high-quality data exist at late times (up to months, even years). Fitting late-time radio and X-ray data clearly revealed a structured jet of the form $\Gamma(\theta) \propto \Gamma_0/\sqrt{1+(\theta/\theta_j)^{2p}}$, namely, an inner ("core") region, $\theta < \theta_j$, in which the Lorentz factor was roughly constant, and an outer, "shear" region ($\theta > \theta_j$) in which the Lorentz factor decayed roughly as $\Gamma(\theta) \propto \theta^{-p}$ [137–139]; see Figure 2. Analyzing broadband afterglow data, from radio through optical (HST) to X-rays, on a time scale of months, led to the conclusion that this jet must have been structured [140,141] and viewed off-axis, at an offset of 22° from the jet axis [142–146].

Indeed, additional late-time afterglow measurements of other GRBs, for example, GRB221009A, also suggest a similar structured jet [147–149]. This realization of a jet structure is thus now becoming standard when analyzing GRB signals [150]. Fitting data is now used to estimate the exact jet shape.

The jet structure does not only affect the late-time signal but also the very early times, namely, the prompt phase. Despite the beaming, structured jets implies that the prompt is expected to be detected even for off-axis observers [151].

Of particular interest is the jet structure's effect on the signal observed from the photosphere, which is the earliest signal that can be detected. A jet structure has a major effect on the photospheric signal [135] by modifying the observed spectra, both at low and high energies [152–154]. Various non-trivial effects, such as photon energy gain by scattering back and forth in the shear layer, were discovered [135,155]. The resulting spectrum is far from having a "black body" shape, and rather resembles the observed "Band" function. Furthermore, it also produces a unique polarization signal (for an observer located off-axis [136,156]). A very important result is that a high polarization degree is achieved from the photosphere of a structured jet, without assuming any synchrotron radiation.

To summarize, the jet structure has been realized, in recent years, to play an important role in both the prompt and afterglow emission phases of GRBs. Studying the jet structure therefore provides a new set of constraints in studying the jet launching mechanism as well as its composition. While I focus here on the lateral jet structure, as there has been major progress in recent years, there is also a radial jet evolution that is non-trivial. For example, radio data of GRB221009A at a time scale of a few days show inconsistency with the expectation of the forward shock [157]. This suggests an additional emission component, whose origin is uncertain, as this time scale is much later than that expected for a reverse shock.

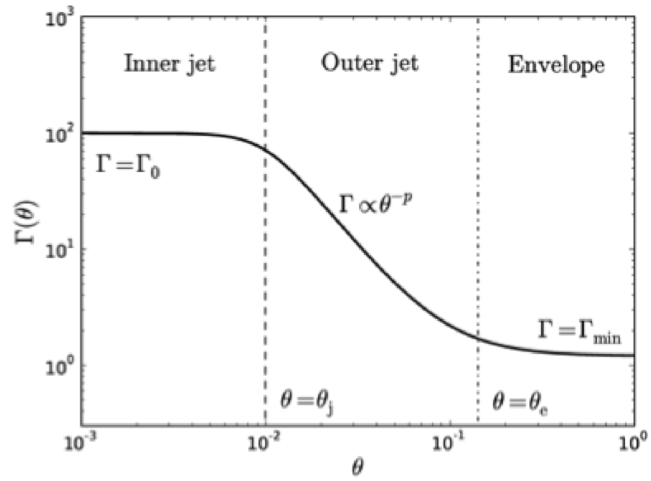

Figure 2. Illustration demonstrating a lateral jet structure. The Lorentz factor is maximal in the inner jet region ($\theta < \theta_j$) and drops as a power law in angle in outer jet regions, $\theta > \theta_j$. This jet profile emerges due to shear that develops as the jet drills its way through a collapsing star [67]. Figure is taken from [135].

4. Jet Launching Mechanism

The initial source of energy that fuels the GRB engine is the gravitational energy of a massive star collapse, or alternatively, the merger of binary stars. The fundamental question is how this gravitational energy is converted into the form of kinetic energy, namely, to a relativistically expanding jet. Clearly, the details of the answer to this question also provide insight into the jet structure.

In the traditional "collapsar" model, the collapse of the stellar core leads to the formation of an accretion disk rotating around the newly formed BH [47,158]. Alternatively, a millisecond pulsar (magnetar) may be formed with enough rotational energy to prevent gravitational collapse [37,159]. In this 'proto-magnetar' model [64,65,160,161], the rotational energy is released as gravitational waves and electromagnetic radiation, causing the magnetar to spin down. If the magnetar is sufficiently massive it may reach a critical point at which differential rotation is no longer able to support it, resulting in collapse to a BH.

Within the original "collapsar" model, i.e., neglecting BH rotation, energy conversion is mediated by a strong flux of neutrinos, that are produced in the inner regions close to the newly formed BH [158,162,163]. The neutrinos and anti-neutrinos annihilate into $e^{\pm}$ pairs, thereby triggering the formation of the "fireball".

An alternative scenario for jet launching is the Blandford–Znajek process [66]. In this model, the source of energy is the rotational energy of the newly formed BH. This energy is extracted by magnetic field lines that are brought to the horizon as they are attached to the accreting disk. They then act as 'springs', expanding by their self-pressure, and convert the rotational energy into Poynting flux-dominated outflow. Particles are introduced into the jet at a later stage, e.g., by instabilities that develop at the jet boundaries [164]. These particles are accelerated, thereby converting the Poynting energy to kinetic energy, although the details of this last conversion are still uncertain. While this mechanism is in wide use in the study of AGNs and XRBs, it was only recently claimed to be highly efficient in the context of GRBs as well [165].

In the past two decades, there has been a rapid development in parallel computation facilities. This has enabled the development of various codes that explores the core collapse during the stellar explosion (e.g., [166–168]) as well as general relativistic, magnetohydrodynamic (GR-MHD) codes aimed at exploring the evolution of the disks and emerging jets; as an example, see Figure 3. Over the years, several GR-MHD codes have been developed (e.g., [169–177], and more). These codes are most frequently used in studying the properties of accretion disks around rotating BHs. Given initial conditions, the codes trace the evolution of the gas as it accretes into the BH. The numerical calculations enable the various instabilities that develop to be traced, such as magneto-rotational instability (MRI; [178,179]), which strongly affects the magnitude and global magnetic field configuration evolution. A major finding was that the accretion disks evolve into two distinct quasi-steady state structures. The fate of the disk evolution largely depends on the initial magnetic field configuration.

The two quasi-steady-state disk configurations are the "standard and normal evolution" (SANE; [180]) and "magnetically arrested disks" (MAD; [181,182]). These separate configurations are important, as it was found that in addition to the different disk structures, the emerging jets are much more powerful when the disks are in the MAD states [183,184]. Furthermore, these codes enabled detailed numerical study of the Blandford–Znajek process [185], confirming its validity.

In recent years, several authors applied some of these codes to study the properties of the jets emerging from GRBs [186–190]. These GR-MHD codes do not simulate the entire collapse or merger, but rather it is assumed that the merger or collapse leads to the formation of an accretion disk surrounding a newly formed rotating BH. The simulations are then run to explore the emerging jet's properties under various assumptions on the initial disk structure, magnetic field configuration, etc. These properties include, among others, jet velocity profile, fluctuations, location of internal shocks, and magnetic field configuration. When radiation is added, which is currently performed in post-processing (i.e., separated from the dynamical calculations), one also obtains the expected photospheric signal [186]. It should be pointed out that deep in the flow, in regions of very high optical depth, where radiation is fully coupled to the plasma, the effect of radiation can be directly incorporated by simply considering the relativistic equation of state (adiabatic index $\hat{\gamma} = 4/3$). Some authors used this to calculate the photospheric signal resulting from fluctuations deep in the flow [190,191]. Such calculations, though, are very limited, as the photons start to decouple from the gas close to, but below, the photosphere [192], and therefore the approximations used fail.

Crudely, currently existing simulations provide the following:

1. A realistic structure of both the collapsing star and the newly formed disk, of course for a given set of initial conditions. There is still a high degree of uncertainty as to whether the initial conditions chosen represent those that occur in nature.
2. An insight into the role of magnetic fields in the jet launching process, as well as connection between the jet properties and the inner disk properties, including the magnetic field configuration.
3. A realistic calculation of the internal jet structure, its temporal evolution and the role of various instabilities (in particular, the Rayleigh–Taylor instability), again, for a given set of initial conditions.
4. An insight into some of the jet properties, such as its terminal Lorentz factor.

These results cannot be achieved analytically, and necessitate the use of very considerable numerical calculations. Therefore, existing GR-MHD codes enable substantial progress in understanding the GRB physics.

While this direction is obviously very promising, there are still very serious gaps that need to be filled before these simulations can provide realistic predictions to understand the nature of GRBs. The key gaps that still exist today include the following:

- Missing physics. Despite the great progress made, still there are important physical ingredients that are not considered in the currently existing models. These include the following: (a) the full effects of radiation, namely, radiation back reaction (i.e., its effect on the dynamics) as well as independent treatment of radiation close to the photosphere; (b) the effects of neutrinos that transfer energy, momentum, and angular momentum. These transfers can be substantial under the appropriate conditions [163]. (c) Exact cross-sections for various nuclear processes.

- The results of the models are sensitive to the uncertain initial conditions. This is an inherent problem that could not easily be resolved.
- Key ingredients, such as the initial configuration of the magnetic field, are unknown, and are therefore 'put by hand'.
- The dynamical range of the calculations is limited by computational power. Therefore, some calculations are interpolated to larger radii. As explained, when approaching the photosphere this interpolation becomes less valid.
- There are various numerical limitations, such as numerical treatments of the polar regions, the need for 'flooring' (adding material 'by hand' into empty regions, in order to achieve computational stability), etc.

Nonetheless, many of these are technical problems that are expected to be solved in the coming years with the continuous developments of algorithms as well as the continuous increase in computational power. I therefore anticipate that the role of GR-MHD simulations in the study of GRBs will increase in the coming years, and they will enable new insights to be provided into some of the yet unsolved problems.

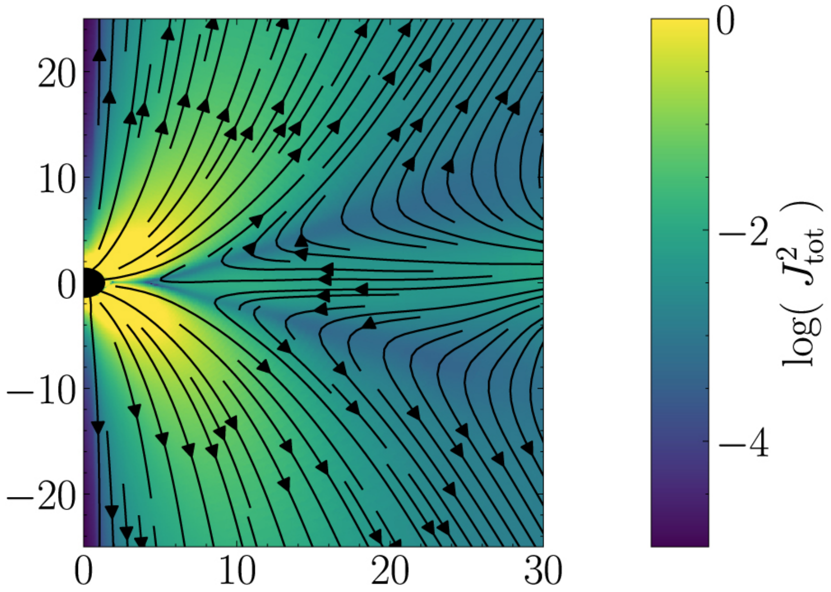

Figure 3. Demonstration of a result obtained by 3D GR-MHD simulation. This shows the flux of the ϕ component of the angular momentum between the disk and the jet. Here, the BH assumes a positive spin, $a = 0.94$, and the angular momentum is the sum of angular momentum in the magnetic field and the gas. The scale is normalized to the gravitational radius of the BH. These results show the formation of the jet, its structure, and that it transforms a significant amount of angular momentum to infinity. The result is taken from [193].

5. The Nature of the Energy Dissipation Mechanism

Perhaps the easiest way to understand the complex chain of events that lead to a GRB is to follow the energy conversion episodes. The GRB "fireball" model (which is referred to here in a very broad context) provides the basic skeleton. The source of energy is the gravitational energy of either a collapsing star or a merger of binaries. During the formation of the BH, (part of) this energy is then converted to kinetic energy, in the form of a jet. This conversion can be mediated by neutrinos and photons (the so-called "fireball"), or alternatively by a magnetic field, in which case there is another energy conversion of Poynting energy to gas kinetic energy.

Since an observer does not directly see kinetic energy, the next stage must be a mechanism that converts part of this kinetic or magnetic energy into photons. A plausible intermediate step is the use of this energy to accelerate particles to high energies. These energetic particles then radiate the photons observed. Within this framework, a photospheric model provides an alternative to this part of energy conversion, as it does not require energetic particles, but rather assumes that one directly observes photons that decouple the plasma at the photosphere.

In the early days (mid-1990s), internal energy dissipation in the form of 'internal shocks', resulting from velocity differences within the jet, was suggested as a way of converting the kinetic energy to energetic particles [20,21,194]. This seemed a natural outcome, as the flow is relativistic and shock waves are common. Furthermore, a propagating shock wave is required to explain the afterglow. However, it was quickly realized that the internal shock idea suffers a severe efficiency problem, with a typical efficiency of no more than a few percent [23,24,195–197]. This is due to the fact that only the differential kinetic energy is available for extraction.

This severe drawback motivated the search for alternatives. A leading alternative that has also been discussed since the 1990s is that of a magnetized jet. In a magnetically dominated flow, magnetic field lines of different orientations reconnect, thereby releasing a magnetic energy that is used in heating and accelerating particles. While the basic theory of magnetic reconnection was studied already in the 1950s and 1960s [198–200], the original theoretical models showed that this process may be too slow to be relevant to GRBs, making this idea less appealing until the last decade.

The rapid development in parallel computational facilities enabled rapid progress in this field as well. Studying magnetic reconnection is achieved using particle-in-cell (PIC) simulations [69,201,202]. These simulations trace the evolution of individual charged particles along a grid, by solving for the electromagnetic forces they exert on each other. Inside each grid cell, the currents resulting from particle motion are calculated. Using these currents, electromagnetic (EM) fields on the grid are computed by summing over all the particles in a cell. These EM fields are then interpolated back to the particles in each cell, from which the Lorentz force acting on individual particles is deduced. The particles' motions are then calculated from the Lorentz force.

These simulations have matured in the past decade, and provide an insight into the mechanism of magnetic reconnection. It was found that the reconnecting lines lead to the formation of plasmoids, which are regions in space filled with energetic particles and magnetic fields [203]; see Figure 4. Particles are accelerated by the generated electromagnetic potential, and can reach substantial energies as they enter the 'reconnection island', and are then accelerated by strong electric fields that are formed between the islands [203,204]. The limit occurs when the particle's Larmor radius becomes comparable to the plasmoid size. The accelerated particles leave the plasmoid due to the developed turbulence, and their emerging distribution follows a power law [205,206]. The plasmoids themselves grow with time, and can reach a substantial fraction of the system size. Furthermore, due to turbulence in the flow, the rate of reconnection can be much higher than initially thought [207–209].

Thus, overall, the rapid progress in this field in the past 10 years puts reconnection as a very viable method for explaining particle acceleration. I anticipate here too rapid progress in the coming years.

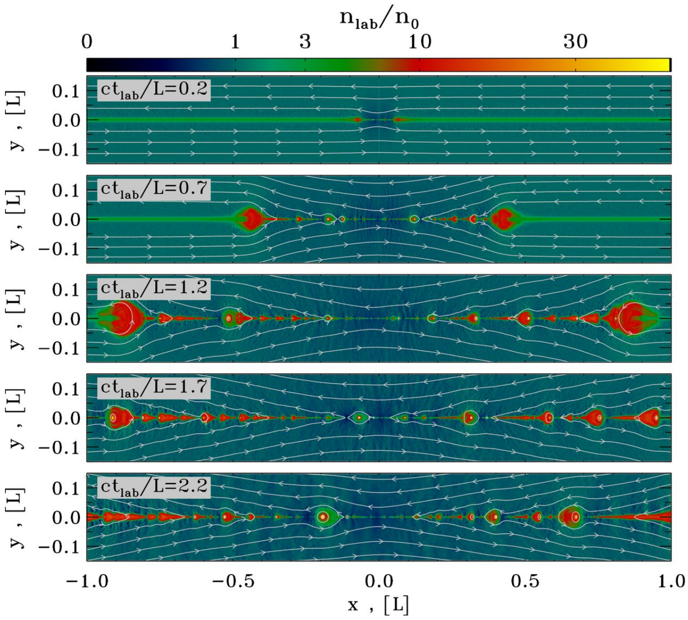

Figure 4. Results of 2D simulation shows the particle number density along the magnetic reconnection layer. Time evolves from top to bottom, as marked. After triggering reconnection in the center of the current sheet (x = 0 in the top panel), two 'reconnection fronts' propagate: to the right and to the left. The result is taken from [203].

6. The Ambient Medium: Deviation from Self-Similar Motion

It is surprising how little is known about the surrounding medium into which GRBs explode. This is mainly due to two reasons: (1) GRBs reside in distant galaxies, which cannot be resolved directly; and (2) theoretically, little is known about the final stages of massive stellar evolution, prior to a star's terminal collapse. This is the stage in which they may emit strong stellar winds, which would affect the GRB environment. It is therefore difficult to theoretically predict the stellar environment, which is affected by the stellar wind.

Early models of GRB afterglows [30,210] show a broadband spectral distribution and late-time (hours onward) temporal evolution that are well fitted with the basic theoretical model of self-similar motion [211]. The basic idea is that following an initial acceleration and coasting phases, the relativistic GRB blast wave propagates into the ambient medium in a self-similar way; namely, its Lorentz factor is a power law in radius, $\Gamma(r) \propto r^{-\alpha}$, where the index α depends on the ambient density profile ($\alpha = 3/2$ for constant density ISM, and $\alpha = 1/2$ for a decaying density, $n(r) \propto r^{-2}$, as is expected for a constant-velocity stellar wind).

Electrons are accelerated based on a power law in this propagating shock wave. The spectra are fitted with synchrotron emission from power-law-accelerated particles [31,212], while the lightcurve evolves according to the expectation from a relativistic blast wave explosion into a constant-density environment [211]. While initially only explosions into constant-density ISM were considered, extensions were quickly made to a power-law density environment; namely, $n(r) \propto r^{-2}$, as is expected if the star emits a constant-velocity wind for a substantial duration prior to its terminal explosion [213].

Thus, this model predicts early-time light curve fluctuations, expected either before or during the transition to the self-similar phase, while it predicts a smooth late-time afterglow. During the transition, a reverse shock is expected that propagates into the plasma and wipes out the memory of the initial explosion [18,214]. The time scale of the existence of the reverse shock is expected to be of the order of tens of seconds to minutes, i.e., close to the end of the prompt phase. This was used to explain some rebrightening seen, e.g., in GRB180720B [215].

In recent years, analysis of late-time afterglow data has revealed that the expectation for self-similar motion is not always fulfilled. Various wiggles and fluctuations are detected, that are not expected. For example, it was argued that a reverse shock may exist in the lightcurve of GRB181201A, 3.9 days after the explosion, i.e., 3–4 orders of magnitude later than expected [216]. A second example is GRB201216C, in which radio data after $\sim$a month require a different emission component than the forward shock [217,218]. Another peculiar event was the short GRB210726A. No radio signal was detected during the first 11 days, but then the radio flux showed a rebrightening by a factor of 3 over a duration of a week [219]. Such a result cannot be explained as being due to the forward shock, and explaining it requires either a very late reverse shock, or late-time energy injection. These results, therefore, challenge the basic self-similar motion picture.

The environment profile in the stellar vicinity is expected to be much more complicated than the power-law description often assumed. As the stellar wind from a GRB progenitor star is emitted over a finite, uncertain duration of thousands to millions of years, it cannot cover the entire relevant space. Instead, the massive star that emits the wind is surrounded by a "wind bubble" structure [220].

This structure is characterized by four distinct regimes (see Figure 5). The inner-most regime ("region *a*") contains the freely expanding stellar wind. The outer-most regime ("region *d*") contains the interstellar medium (ISM). Two more regions are the shocked stellar wind ("region *b*"), consisting of stellar wind shocked by the wind termination shock (reverse shock); and the shocked ISM ("region *c*"), shocked by the forward-propagating shock, which also marks the edge of the bubble. The shocked wind and shocked ISM (regions (*b*) and (*c*)) are separated by a contact discontinuity; see Figure 5.

The size of this cavity is $\sim$ 1 pc, and it clearly depends on uncertain model parameters, such as the wind velocity, the mass ejection rate, and the time the star emits the wind [221]. While in the basic picture the relevant radii can be calculated analytically, clearly additional physical ingredients such as stellar rotation will further complicate the structure [75,222]. Indeed, such ring nebulae are observed around one-third of the massive stars in our galaxy in their Wolf–Rayet phase [223–225].

When the star explodes to produce a GRB, the GRB jet must cross the surrounding bubble [76]. During its crossing, it encounters the reverse and forward shock waves as well as the contact discontinuity. These encounters lead to observable signals [226]. For plausible wind bubble parameters, interaction of the GRB blast wave with the wind termination (reverse) shock is observed on a time scale of a few seconds, and may therefore be associated with an observed precursor. The main interaction may take place with the contact discontinuity at an observed time of the order of $\sim$100 s. This could lead to a significant observed signal, which would be detected as a strong rebrightening at this time frame. Energy dissipation at this stage is much more efficient than internal shocks, as the contact discontinuity is nearly static.

This model can explain about 5–10% of GRB lightcurves, that show a weak precursor followed by a quiescent period and a main emission after 100–200 s [227,228]. As a concrete example, the bright GRB160821A [229–231] showed a giant flare at $\sim$100 s, which was not directly connected to the following "afterglow" emission. This could very well be due to the blast wave–bubble interaction. One can conclude therefore that observations on the time scale of minutes may provide new insights on the wind structure in the vicinity of GRB progenitors, hence may be used as an independent probe of the last stages in the life of massive stars that end their lives as GRBs.

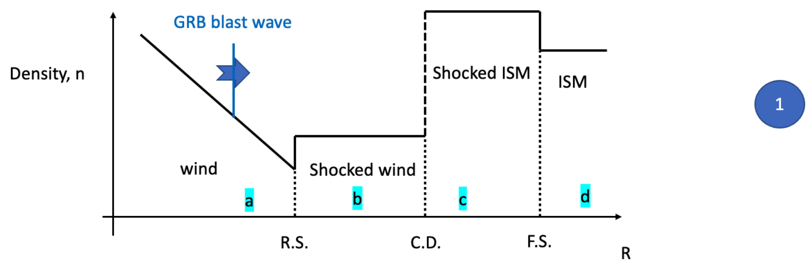

Figure 5. An illustration demonstrating the four regimes in the wind bubble. The star is to the left, emitting a wind prior to its explosion. Region *a* is the unshocked wind. Region *d* is the (constant-density) ISM. Region *b* is the shocked wind, and region *c* is the shocked ISM. When the star explodes into a GRB, the GRB blast wave propagates into this environment, interacting with the shock waves and contact discontinuity in it. Figure is taken from [226].

7. The X-Ray Plateau: Potential Revolution

Associated with the question of the environment, is the open question of the origin of the X-ray plateau. The plateau in GRB X-ray lightcurves was identified shortly after the launch of the *Swift* mission [232,233]. Prior to *Swift*, data existed only during the prompt phase, and then during the later afterglow (after a time of $\sim$ hours). *Swift* bridged this gap by enabling a near-continuous probe of the X-ray afterglow from the prompt phase onward. The surprising result is that immediately after the prompt phase, the flow does not transform into a similar motion as is expected [211]. Rather, the X-ray lightcurve in a significant fraction, of about 60%, of GRBs [234] is flat for a long duration of several hundreds to several thousands of seconds—tens of minutes, sometimes even a few hours.

Over the years, a plethora of ideas have been suggested to explain this result. Notable suggestions include the following. (1) A continuous energy injection that slows the acceleration [232,233,235–237]. This requires the GRB progenitor to operate for a much longer period than a few seconds. (2) Emission in inhomogeneous media [238,239] that causes rebrightening of the lightcurve. (3) Dominant emission from a long-lasting reverse shock [240–242]. This idea requires that the (microphysical) properties of the plasma shocked by the reverse shock are significantly different than at the plasma shocked by the forward shock. (4) Jets viewed off-axis, namely, a viewing angle effect [243,244]. This is particularly appealing for structured jets viewed off-axis, when gradually inner, brighter regions become accessible [245,246]. Finally, (5) emission during the coasting phase [247,248]. As was found, if emission occurs into a low-density “wind” environment ($n(r) \propto r^{-2}$) during the coasting phase, the resulting lightcurve can be flat [248]. The fact that no consensus has been reached nearly 20 years since its discovery implies that this is still considered an open question which is debated in the literature.

The last idea—emission during the coasting phase—may hold the key to revolutionizing our understanding of GRB jet physics. The reason is that it was proven that a plateau emission is a natural outcome of a model in which the Lorentz factor of the flow is only a few tens, rather than a few hundreds as is often assumed [248]. The average Lorentz factor of GRBs in the analyzed sample in that work is $\langle\Gamma\rangle \simeq 50$, with variations between a few and a couple of hundred (see Figure 6).

The reasoning behind the claim that GRB Lorentz factors reach terminal values of several hundred are as follows. (i) The opacity argument: photons with energies that exceed the threshold energy (0.5 MeV) will produce $e^{\pm}$ pairs [249–251], unless the observed signal is highly blue-shifted. (ii) Identifying the onset of the self-similar motion by identifying emission from the reverse shock [252,253]. The observed time is related to the terminal value of the Lorentz factor. (iii) Deducing the value of the Lorentz factor directly from measuring the properties of the thermal emission component [254–256].

A close analysis reveals that none of these observational constraints apply to GRBs with X-ray plateaus. Only 3/186 GRBs in the Fermi LAT catalog [257] show any evidence for a plateau, implying an anti-correlation between the existence of a plateau and high energy emission. Furthermore, no evidence for a substantial thermal emission component, and no clear identification of reverse shock emission were observed in GRBs with plateaus. These results therefore suggest that the distribution of terminal Lorentz factors within the GRB population may be much broader than previously assumed, ranging between a few (say, $\Gamma \sim 10$) to several hundred.

In the past year, several pieces of supporting evidence for this idea were found. These result from analyzing prompt emission pulses [258], from analyzing GRB spectral lags [153], and, most importantly, from analyzing the properties of the observed late-time X-ray flares [259]. This last analysis is of particular importance, since different explanations for the origin of the plateau give different, testable theoretical predictions. For example, if the plateau originates from observers located off the jet axis, then the observed time of the X-ray flares are expected to be later than for GRBs without a plateau due to the different Doppler boost. The results of the analysis show that there is no difference between the average flare times for GRBs with and without plateaus, which seems to contradict this prediction. This, though, is expected if the Lorentz factor of GRBs with plateaus is lower, since in this case the flare emission radius is smaller, and the dependence on the Lorentz factor cancels.

This idea of low-Lorentz-factor GRBs, if proven correct, obviously marks a paradigm shift in the study of GRBs, by proving that the majority of GRBs in fact have Lorentz factors of tens rather than hundreds. One can conclude that this epoch of early afterglow provides several open questions that are still unanswered, and I anticipate that it will continue to be explored in the coming decade. It has already shown the potential to revolutionize our understanding of GRB physics, if indeed proven that the Lorentz factor of many GRBs is "only" a few tens, as recently suggested.

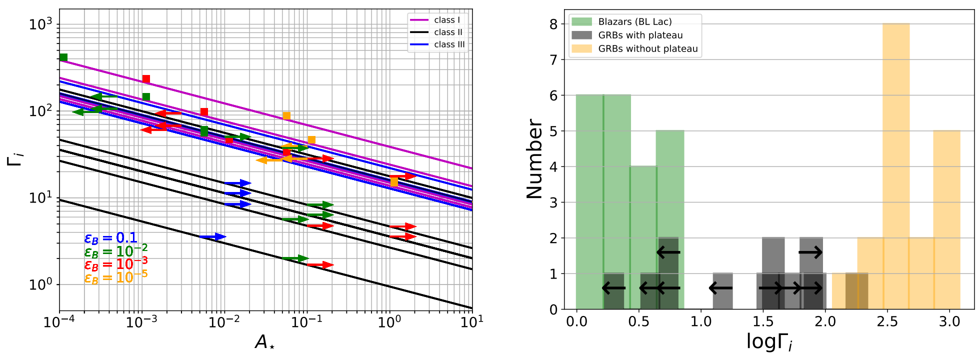

Figure 6. The results of an analysis shows that the plateau can naturally be explained as due to emission during the coasting phase of jets with mild Lorentz factors, propagating into low-density stellar wind. The left panel shows the constraints set on the Lorentz factor and the wind density (marked as $A_\star$, where $A_\star = 1$ is expected for a Wolf–Rayet star). The right panel compares the results obtained (black) to measured Lorentz factors in AGNs (a few, marked in green) and high GRBs without plateaus (several hundreds, yellow). The region of a Lorentz factor, in GRBs that show a plateau, of several tens, therefore, fills the observational gap. The figure is taken from [248].

8. Radiative Processes and Radiative Counterparts

Since nearly the entire signal detected from GRBs is electromagnetic, the basic question of its origin is a fundamental one. The nature of the observed spectrum strongly depends on the radius in which it originates. Emission from small radii, i.e., below or close to the photosphere, is expected to behave as a modified black body, with a leading radiative process of inverse Compton (IC) scattering [70,260,261]. On the other hand, emission at larger radii —above the photosphere—is expected to be mainly of synchrotron origin, with IC scattering contributing to the high-energy part.

Already, in the early 1990s, when it was realized that the observed GRB spectra did not resemble a "Planck" function, synchrotron emission was suggested as a leading radiative mechanism [20,262,263]. However, inconsistency with the synchrotron model prediction [264] (but see [265] for a reanalysis) prompted interest in alternative models. One example was a revived interest in a proton–synchrotron model that was found to better fit the observed spectral slopes [266]; see further discussion below. Alternatively, a photospheric (thermal) model contribution also became the subject of increasing interest ([70,267–271], and many more).

It should be noted that since the photospheric radius strongly depends on the Lorentz factor, $r_{ph} \propto \Gamma^{-3}$ (e.g., [272,273]), a low Lorentz factor implies a larger photospheric radius, resulting in a likely more pronounced contribution from the photosphere. This, though, will necessitate sub-photospheric energy dissipation, or alternatively, lateral jet confinement, to reduce adiabatic losses that will lower the peak energy below the sub-MeV range in which it is observed.

Although initially, emission from the photosphere was expected to resemble a "Planck" function [17], it was realized that this approach was too simplified. There are several effects that act to broaden the naively expected black-body signal from the photosphere. First, sub-photospheric energy dissipation that occurs due to any cause, such as shocks, magnetic reconnection, neutrino annihilation, or any unspecified dissipation process, will modify the emitted spectra. If the dissipation does not occur too far below the photosphere, the photons will not have sufficient time to re-thermalize, and the resulting spectra will be broadened [70,269,274–277]. Second, due to the relativistic motion of the jet, light aberration effects will further modify the observed signal [260,261,278]. This will become very pronounced for any non-spherical expansion, such as a structured jet [135,136,152,153], a jet with an angle-dependent Lorentz factor, $\Gamma = \Gamma(\theta)$, which is expected in a realistic scenario, as discussed above. Third, the photospheric signal, like any signal in a transient event, is time dependent. Therefore, integrating over a finite time automatically smears the signal. And fourth, there are instrumental effects—due to the limited bandwidth of the detectors, as well as the "curvature" of the spectrum near the energy peak, it is found that the expected observed values of the low energy spectral slope are much shallower than the Rayleigh–Jeans slope [279].

After considering these effects, a recent analysis shows that in fact more than a quarter of long GRBs, and a third of short GRBs are consistent with having a pure thermal origin [280,281]. When adding a possible sub-photospheric energy dissipation that could potentially broaden the spectra, these fractions become much larger, close to 100%.

On the other hand, a recent analysis of time-resolved GRB spectra of single-pulse GRBs, showed that synchrotron emission can account for about 95% of the spectra [265]. Thus, overall, the debate on the radiative origin of the observed signal is still on-going, and may potentially be resolved in the next decade with a more refined time-resolved analysis.

8.1. The Pair Annihilation Line in BOAT GRB 221009A: Further Constraints on the Physical Parameters

The existence of energetic photons implies that a large number of $e^{\pm}$ pairs are expected to be produced within a GRB outflow. Indeed, as discussed above, within the framework of the GRB "fireball" model, the existence of these pairs is a natural outcome. These pairs, in turn, are expected to annihilate, producing a distinct line at the observed energy $\Gamma m_e c^2$, where Γ is the outflow Lorentz factor. Detection of such a line has long been predicted [282]. It is therefore a surprise that such a line has never been detected. A possible reason for this is the lower sensitivity of existing detectors in the $>$MeV band.

This situation has changed recently, with the observation of GRB221009A—the "brightest of all time" (BOAT) GRB [283]. This burst was so bright that its observed fluence, 0.21 ± 0.02 erg cm^{-2} (as seen by Konus-Wind; [284]), was more than 50 times larger than that of the second brightest GRB observed to date, GRB230307A.

In addition to being so extremely bright, this GRB showed clear evidence of an emission line, starting approximately 80 s after the onset of the afterglow (at 226 s after the explosion [285]). This line was detected at $\sim$10 MeV, and its peak energy showed a clear decay in time, as $\epsilon_{peak}(t) \propto t^{-1}$. Such a discriminated line can result from the annihilation of pairs. However, a direct calculation results in a Lorentz factor of $\sim$20 (the Doppler boost needed to reach this energy), which seem too low given the extreme brightness of this GRB.

A more comprehensive calculation carried out recently [286] examined the conditions for producing such a line. The temporal decay of the peak is a strong hint towards a high-latitude emission, i.e., that the emission at different times originates from off the line of sight, therefore the Doppler boost varies with observed time, as an observer sees the emission from different angles [287]. Taking this into account, it was shown that this GRB jet had a more realistic Lorentz factor, of $\Gamma \approx 600$. Most importantly, a detailed analysis revealed that only a relatively narrow range of physical conditions, very high luminosity and Lorentz factor that is in a relatively narrow range of few hundreds, is needed in order to produce the observed pair annihilation line signal. The conditions found, in a range that is much narrower than previously thought, explain the rareness of this line (see [286] for further details). These results therefore demonstrate that further identification of such annihilation lines could be a very useful tool in constraining the physical properties of GRB jet outflows.

8.2. TeV Emission and Its Origin

Another field which matured in the past decade is that of very high energy detectors. In the past decade, we witnessed the matureness of high-energy (GeV-TeV range) detectors, such as MAGIC [288,289], H.E.S.S [290,291] and recently LHAASO [292–294]. For example, the MAGIC collaboration recently published lightcurves and spectra of GRB190114C [14,289,295], starting about a minute after the onset of this burst, and lasting for about 40 min. The MAGIC data show a comparable flux at the TeV band to that of longer wavelengths, in particular the GeV (Fermi-LAT band) and X-rays (XRT and Fermi-GBM bands). Similarly, LHAASO reported 7/13 TeV photons in GRB221009A [293,294].

These new data naturally called for a theoretical interpretation. A basic model that was suggested as a way of explaining the TeV data was IC scattering (e.g., [14,296]). Indeed, this process is naturally expected: as energetic electrons are needed to explain the lower-energy (optical, X- and gamma-rays) signal observed by synchrotron emission, they must be accelerated to high energies inside the plasma. These energetic electrons up-scatter the synchrotron photons to higher energies, and may therefore contribute to the TeV signal. Additional advantages of this model is that the energy budget needed is relatively not very high, and the required magnetic field energy is relatively low.

However, a close look reveals that this model requires some additional assumptions in order to provide good fits to the TeV data. Both the flux and the observed spectral and temporal slopes predicted do not match those observed very well. In order to overcome these problems, additional 'freedom factors' were suggested [296], which enable some fine-tuning of the model parameters. Such freedom parameters include a certain freedom factor in connecting the emission radius and the observed time, the emitted and observed frequency, or the dependence of the observed luminosity on the jet kinetic energy; it turned out that the use of the classical, basic theoretical relations did not provide sufficient fits.

An alternative model that was proposed was synchrotron emission from accelerated protons [297,298]. This idea is not new, as similar ideas were already proposed in the 1990s (e.g., [299–301]). These were less appealing due to the fact that protons are much less efficient radiators than electrons. As a result, a high total energy budget is required to be provided to the energetic protons to reproduce the observed flux.

However, as pointed out recently [297], the problem can be easily overcome by noting that it is sufficient to assume that only a small fraction, ≈10%, of the protons are accelerated. This aligns both with the results of particle-in-cell simulations, that show that only a few % of the particles are accelerated in shock waves [302], and lead to a dramatic decrease in the required overall explosion energy budget, which is $\sim 10^{54.5}$ erg—high, but not unreasonable.

According to this model, both electrons and protons are accelerated by the propagating shock. The electrons though have a lower energy, and therefore are in the slow-cooling regime, while the more energetic protons are in the fast-cooling regime [31]. Radiation in the X-ray and gamma-ray bands is explained by synchrotron emission from the electrons, while the TeV emission is due to synchrotron emission from the accelerated protons. The condition for proton–synchrotron to dominate over IC scattering is that the fraction of post-shock thermal energy converted to the magnetic field is much higher than the fraction of energy given to the electrons, namely, $\epsilon_B \gg \epsilon_e$. Here, ϵ_B is the fraction of post-shock thermal energy that is converted to the magnetic field, and ϵ_e is that fraction used in accelerating electrons above the thermal distribution. Indeed values that are found to fit the broadband data of GRB190114C are $\epsilon_B = 0.13$ and $\epsilon_e = 0.003$. Both values are consistent with the results of PIC simulations, as well as with fits of late-time afterglow data of various GRBs. In the opposite regime, $\epsilon_e \gg \epsilon_B$, IC emission from the electrons is found to dominate the proton–synchrotron contribution. These results seem to be universal: similar fitting holds also for the spectra and lightcurve of GRB221009A [298]. Similarly, protons accelerated at the reverse shock may also contribute to the TeV flux [303,304].

Thus, a continuous stream of TeV data, as is expected with the matureness of current TeV detectors, and the coming CTA observatory [305], may revolutionize our understanding of the radiative processes, and of the protons' role in the observed signal. This will clearly have a direct impact on the physics of cosmic rays and expected high-energy neutrinos.

8.3. Polarization: Introducing a New Dimension

The final signal that I would like to mention is that of X- and γ-ray polarization. These represent another observational field that has matured in recent years. While claims of a high degree of polarization from GRBs have existed for over 20 years [306,307], these were by and large sparse and not always reliable. Polarization measures were expected, though, as both the leading radiative models in GRBs, namely, synchrotron emission and Compton scattering, were predicted to produce a high degree of polarization [134,136,308,309].

Following the launch of AstroSat, a plethora of polarization information became available [310]. This is due to the Cadmium–Zinc–Telluride Imager (CZTI) on board this satellite, which is sensitive to both soft and hard X-rays (0.3–100 keV). A unique example is GRB160821A. This was a very energetic burst ($E \gtrsim 10^{53}$ erg) which showed high degree of polarization—more than 30% in the gamma-ray lightcurve. The most interesting observation was a polarization angle change, which was detected twice: once during the rise phase and once during the decay phase of a bright pulse that was seen after ~ 120 s. Each of these polarization angle changes was consistent with 90 degrees [229].

Such a polarization angle change challenges existing models. While current models can explain a 90-degree change for an observer located close to the jet edge (e.g., [311]), this is accompanied by a sharp decrease in the flux. The reason for this flux decay is that in order to obtain such a 90-degree change, the observer needs to be located close to the jet edge. Initially, the detected photons originate from a small, magnetized region, which produces a polarized signal. As time elapses, the region from which photons reach the observer grows, and part of it is outside of the jet. Thus, while the observed parts that remain within the jet can produce a signal polarized by 90 degrees to the initial polarized signal, most of the viewing region is outside of the jet opening angle, and therefore the flux is expected to sharply drop.

As of today, a convincing explanation to this observational result is still lacking, and it requires some 'out-of-the-box' ideas, such as unconventional jet geometry. Indeed, most existing theories for polarization assume simple 'top-hat' jets. However, recently, more advanced models, that consider the possibility of jet structure have emerged [312]. I anticipate that many more such models will emerge in the coming years, with the realization that GRB jets are structured.

9. Summary

Extensive study of GRBs began in the early 1990s, about 30 years ago. Despite the matureness of the field, basic open questions still remain. In this short review, I tried to highlight the key advances that took place in the past decade, while looking forward to the next decade and trying to predict the next challenges that are expected to be addressed in the coming years.

Looking at the different subjects, one can summarize as follows.

1. **The nature of the progenitor.** Ten years ago there was already firm evidence supporting the idea that long GRBs originate from the collapse of a massive star (the "collapsar"), and there was plenty of indirect evidence supporting the idea that short GRBs originate from a binary merger. Today, while there is a consensus that long GRBs indeed originate from a collapsar, there are several outliers known, whose origin is not clear. There is one firm detection of the association of a short GRB with a merger—the GW/GRB170817 event—but it is not fully clear whether this event is representative of the entire short-GRB population.
2. **Jet launching mechanism and GRB jet composition.** Ten years ago, the basic theories—namely, the Blandford–Znajek [66], collapsar, and merger—already existed, but most of the details were uncertain. In the past decade, major progress in computational facilities took place, which enabled the study these mechanisms in much more detail. These mechanisms include many relevant physical processes that cannot be studied analytically, such as instabilities, the effect of radiation on the dynamics, and magnetic field configurations. I anticipate that this field will continue to flourish in the next decade.
3. **Jet structure, dynamics and evolution.** Ten years ago, most works considered a simple 'top hat' jet, i.e., a jet with a sharp cutoff, as well as 'standard' (self-similar) jet dynamics. In the past decade, and especially after GW/GRB170817, it was realized that GRB jets have a spatial structure, which has now been taken into consideration by several authors. Furthermore, the idea that many GRB jets have a Lorentz factor of tens rather than 100 s, although suggested relatively recently, has a strong potential to revolutionize the field.
4. **Properties of the ambient medium.** Ten years ago, the vast majority of works assumed a very simple ambient density profile, either constant or decaying as a power law with radius from the progenitor, as is expected from a steady stellar wind. Only recently did the realization that massive stars are surrounded by wind nebulae, or wind bubbles, which may have a significant effect on the early afterglow in (long) GRBs, start to be explored more in depth. Here too, I anticipate a potential for further breakthroughs in the next decade.

5. **Energy dissipation mechanism.** While early models suggested shock waves, whose physics is well understood, as a leading kinetic energy dissipation mechanism, already ten years ago it was realized that this mechanism is not able to provide efficient enough dissipation. The matureness of computational facilities and PIC simulations in the past decade has enabled a detailed study and several breakthroughs in understanding the alternative mechanism of magnetic reconnection. Here too, additional progress is anticipated in the next decade.
6. **Radiative process.** The basic radiative processes—synchrotron, inverse Compton, and photosphere—have been known for decades, and have been used since the 1990s to the present day to fit most GRB spectra. However, in the past few years, with the increase in the data quality (and quantity) it was realized that many of these models are too simplified, and do not provide good enough fits to the data. This led to a renewed interest in alternative models, such as proton–synchrotron.
   Major efforts are being devoted to obtaining new signals, such as TeV and polarization, which are expected to flourish in the next decade, promising a wealth of new data. Furthermore, the need for a time-dependent spectral analysis, as well as abandoning the "Band" function, have become more evident in the past few years. New detections, such as the pair annihilation line in GRB221009A, challenge existing theories, and call for renewed modeling. Thus, overall, the continuous streams of new data promise to stimulate new ideas in the next decade and beyond.

Funding: This work is supported by the EU via ERC consolidating grant #773062 (O.M.J.) and by the Israel Space Agency via grant #6766.

Conflicts of Interest: The author declares no conflicts of interest.

Notes

[1] Supernova type Ib/c are core collapse supernovae with stripped hydrogen envelopes.

References

1. Pe'er, A. Physics of Gamma-Ray Bursts Prompt Emission. *Adv. Astron.* **2015**, *2015*, 907321. [CrossRef]
2. Kumar, P.; Zhang, B. The physics of gamma-ray bursts & relativistic jets. *Phys. Rep.* **2015**, *561*, 1–109. [CrossRef]
3. Zhang, B. *The Physics of Gamma-Ray Bursts*; Cambridge University Press: Cambridge, UK, 2018. [CrossRef]
4. Bošnjak, Ž.; Barniol Duran, R.; Pe'er, A. The GRB Prompt Emission: An Unsolved Puzzle. *Galaxies* **2022**, *10*, 38. [CrossRef]
5. 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–L104. [CrossRef]
6. 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). *Astrophys. J.* **1999**, *122*, 465–495. [CrossRef]
7. Gruber, D.; Goldstein, A.; Weller von Ahlefeld, V.; Narayana Bhat, P.; Bissaldi, E.; Briggs, M.S.; Byrne, D.; Cleveland, W.H.; Connaughton, V.; Diehl, R.; et al. The Fermi GBM Gamma-Ray Burst Spectral Catalog: Four Years of Data. *Astrophys. J.* **2014**, *211*, 12. [CrossRef]
8. Von Kienlin, A.; Meegan, C.A.; Paciesas, W.S.; Bhat, P.N.; Bissaldi, E.; Briggs, M.S.; Burgess, J.M.; Byrne, D.; Chaplin, V.; Cleveland, W.; et al. The Second Fermi GBM Gamma-Ray Burst Catalog: The First Four Years. *Astrophys. J.* **2014**, *211*, 13. [CrossRef]
9. Lien, A.; Sakamoto, T.; Barthelmy, S.D.; Baumgartner, W.H.; Cannizzo, J.K.; Chen, K.; Collins, N.R.; Cummings, J.R.; Gehrels, N.; Krimm, H.A.; et al. The Third Swift Burst Alert Telescope Gamma-Ray Burst Catalog. *Astrophys. J.* **2016**, *829*, 7. [CrossRef]
10. Gendre, B.; Stratta, G.; Atteia, J.L.; Basa, S.; Boër, M.; Coward, D.M.; Cutini, S.; D'Elia, V.; Howell, E.J.; Klotz, A.; et al. The Ultra-long Gamma-Ray Burst 111209A: The Collapse of a Blue Supergiant? *Astrophys. J.* **2013**, *766*, 30. [CrossRef]
11. 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]
12. De Wet, S.; Izzo, L.; Groot, P.J.; Bisero, S.; D'Elia, V.; De Pasquale, M.; Hartmann, D.H.; Heintz, K.E.; Jakobsson, P.; Laskar, T.; et al. The ultra-long GRB 220627A at z = 3.08. *Astron. Astrophys.* **2023**, *677*, A32. [CrossRef]

13. 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*, 281–292. [CrossRef]
14. MAGIC Collaboration; Acciari, V.A.; Ansoldi, S.; Antonelli, L.A.; Arbet Engels, A.; Baack, D.; Babić, A.; Banerjee, B.; Barres de Almeida, U.; Barrio, J.A.; et al. Teraelectronvolt emission from the γ-ray burst GRB 190114C. *Nature* **2019**, *575*, 455–458. [CrossRef]
15. 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] [PubMed]
16. Paczynski, B. Gamma-ray bursters at cosmological distances. *Astrophys. J.* **1986**, *308*, L43–L46. [CrossRef]
17. Goodman, J. Are gamma-ray bursts optically thick? *Astrophys. J.* **1986**, *308*, L47–L50. [CrossRef]
18. Rees, M.J.; Meszaros, P. Relativistic fireballs—Energy conversion and time-scales. *Mon. Not. R. Astron. Soc.* **1992**, *258*, 41P–43P. [CrossRef]
19. Meszaros, P.; Laguna, P.; Rees, M.J. Gasdynamics of relativistically expanding gamma-ray burst sources—Kinematics, energetics, magnetic fields, and efficiency. *Astrophys. J.* **1993**, *415*, 181–190. [CrossRef]
20. Rees, M.J.; Meszaros, P. Unsteady outflow models for cosmological gamma-ray bursts. *Astrophys. J.* **1994**, *430*, L93–L96. [CrossRef]
21. Paczynski, B.; Xu, G. Neutrino bursts from gamma-ray bursts. *Astrophys. J.* **1994**, *427*, 708–713. [CrossRef]
22. Sari, R.; Piran, T. Variability in Gamma-Ray Bursts: A Clue. *Astrophys. J.* **1997**, *485*, 270–273. [CrossRef]
23. Kobayashi, S.; Piran, T.; Sari, R. Can Internal Shocks Produce the Variability in Gamma-Ray Bursts? *Astrophys. J.* **1997**, *490*, 92. [CrossRef]
24. Daigne, F.; Mochkovitch, R. Gamma-ray bursts from internal shocks in a relativistic wind: Temporal and spectral properties. *Mon. Not. R. Astron. Soc.* **1998**, *296*, 275–286. [CrossRef]
25. Thompson, C. A Model of Gamma-Ray Bursts. *Mon. Not. R. Astron. Soc.* **1994**, *270*, 480. [CrossRef]
26. Katz, J.I. Yet Another Model of Gamma-Ray Bursts. *Astrophys. J.* **1997**, *490*, 633–641. [CrossRef]
27. Mészáros, P.; Rees, M.J. Poynting Jets from Black Holes and Cosmological Gamma-Ray Bursts. *Astrophys. J.* **1997**, *482*, L29–L32. [CrossRef]
28. McKinney, J.C.; Uzdensky, D.A. A reconnection switch to trigger gamma-ray burst jet dissipation. *Mon. Not. R. Astron. Soc.* **2012**, *419*, 573–607. [CrossRef]
29. Cerutti, B.; Werner, G.R.; Uzdensky, D.A.; Begelman, M.C. Simulations of Particle Acceleration beyond the Classical Synchrotron Burnoff Limit in Magnetic Reconnection: An Explanation of the Crab Flares. *Astrophys. J.* **2013**, *770*, 147. [CrossRef]
30. Wijers, R.A.M.J.; Rees, M.J.; Meszaros, P. Shocked by GRB 970228: The afterglow of a cosmological fireball. *Mon. Not. R. Astron. Soc.* **1997**, *288*, L51–L56. [CrossRef]
31. Sari, R.; Piran, T.; Narayan, R. Spectra and Light Curves of Gamma-Ray Burst Afterglows. *Astrophys. J.* **1998**, *497*, L17. [CrossRef]
32. 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]
33. 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]
34. Cavallo, G.; Rees, M.J. A qualitative study of cosmic fireballs and gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **1978**, *183*, 359–365. [CrossRef]
35. Shemi, A.; Piran, T. The appearance of cosmic fireballs. *Astrophys. J.* **1990**, *365*, L55–L58. [CrossRef]
36. Paczynski, B. Super-Eddington winds from neutron stars. *Astrophys. J.* **1990**, *363*, 218–226. [CrossRef]
37. Usov, V.V. Millisecond pulsars with extremely strong magnetic fields as a cosmological source of gamma-ray bursts. *Nature* **1992**, *357*, 472–474. [CrossRef]
38. Spruit, H.C.; Daigne, F.; Drenkhahn, G. Large scale magnetic fields and their dissipation in GRB fireballs. *Astron. Astrophys.* **2001**, *369*, 694–705. [CrossRef]
39. Drenkhahn, G. Acceleration of GRB outflows by Poynting flux dissipation. *Astron. Astrophys.* **2002**, *387*, 714–724. [CrossRef]
40. Drenkhahn, G.; Spruit, H.C. Efficient acceleration and radiation in Poynting flux powered GRB outflows. *Astron. Astrophys.* **2002**, *391*, 1141–1153. [CrossRef]
41. Spruit, H.C.; Drenkhahn, G.D. Magnetically powered prompt radiation and flow acceleration in GRB. *Gamma-Ray Bursts Afterglow Era* **2004**, *312*, 357.
42. Lyutikov, M.; Blandford, R. Gamma Ray Bursts as Electromagnetic Outflows. *arXiv* **2003**, arXiv:astro-ph/0312347.
43. Komissarov, S.S.; Vlahakis, N.; Königl, A.; Barkov, M.V. Magnetic acceleration of ultrarelativistic jets in gamma-ray burst sources. *Mon. Not. R. Astron. Soc.* **2009**, *394*, 1182–1212. [CrossRef]
44. Meszaros, P.; Rees, M.J. Gamma-Ray Bursts. *arXiv* **2014**, arXiv:1401.3012.
45. Woosley, S.E. Gamma-ray bursts from stellar mass accretion disks around black holes. *Astrophys. J.* **1993**, *405*, 273–277. [CrossRef]

46. MacFadyen, A.I.; Woosley, S.E. Collapsars: Gamma-Ray Bursts and Explosions in "Failed Supernovae". *Astrophys. J.* **1999**, *524*, 262–289. [CrossRef]
47. MacFadyen, A.I.; Woosley, S.E.; Heger, A. Supernovae, Jets, and Collapsars. *Astrophys. J.* **2001**, *550*, 410–425. [CrossRef]
48. Eichler, D.; Livio, M.; Piran, T.; Schramm, D.N. Nucleosynthesis, neutrino bursts and gamma-rays from coalescing neutron stars. *Nature* **1989**, *340*, 126–128. [CrossRef]
49. Narayan, R.; Paczynski, B.; Piran, T. Gamma-ray bursts as the death throes of massive binary stars. *Astrophys. J.* **1992**, *395*, L83–L86. [CrossRef]
50. 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]
51. 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]
52. Bloom, J.S.; Kulkarni, S.R.; Djorgovski, S.G. The Observed Offset Distribution of Gamma-Ray Bursts from Their Host Galaxies: A Robust Clue to the Nature of the Progenitors. *Astronomical J.* **2002**, *123*, 1111–1148. [CrossRef]
53. 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]
54. Fong, W.; Berger, E. The Locations of Short Gamma-Ray Bursts as Evidence for Compact Object Binary Progenitors. *Astrophys. J.* **2013**, *776*, 18. [CrossRef]
55. Berger, E. Short-Duration Gamma-Ray Bursts. *Annu. Rev. Astron. Astrophys.* **2014**, *52*, 43–105. [CrossRef]
56. Fong, W.; Berger, E.; Fox, D.B. Hubble Space Telescope Observations of Short Gamma-Ray Burst Host Galaxies: Morphologies, Offsets, and Local Environments. *Astrophys. J.* **2010**, *708*, 9–25. [CrossRef]
57. Berger, E. The environments of short-duration gamma-ray bursts and implications for their progenitors. *New Astronomy Rev.* **2011**, *55*, 1–22. [CrossRef]
58. Kasliwal, M.M.; Nakar, E.; Singer, L.P.; Kaplan, D.L.; Cook, D.O.; Van Sistine, A.; Lau, R.M.; Fremling, C.; Gottlieb, O.; Jencson, J.E.; et al. Illuminating gravitational waves: A concordant picture of photons from a neutron star merger. *Science* **2017**, *358*, 1559–1565. [CrossRef]
59. 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]
60. 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]
61. Metzger, B.D.; Martínez-Pinedo, G.; Darbha, S.; Quataert, E.; Arcones, A.; Kasen, D.; Thomas, R.; Nugent, P.; Panov, I.V.; Zinner, N.T. Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei. *Mon. Not. R. Astron. Soc.* **2010**, *406*, 2650–2662. [CrossRef]
62. Metzger, B.D.; Berger, E. What is the Most Promising Electromagnetic Counterpart of a Neutron Star Binary Merger? *Astrophys. J.* **2012**, *746*, 48. [CrossRef]
63. Kasen, D.; Metzger, B.; Barnes, J.; Quataert, E.; Ramirez-Ruiz, E. Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event. *Nature* **2017**, *551*, 80–84. [CrossRef]
64. Metzger, B.D.; Giannios, D.; Thompson, T.A.; Bucciantini, N.; Quataert, E. The protomagnetar model for gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **2011**, *413*, 2031–2056. [CrossRef]
65. Bucciantini, N.; Metzger, B.D.; Thompson, T.A.; Quataert, E. Short gamma-ray bursts with extended emission from magnetar birth: jet formation and collimation. *Mon. Not. R. Astron. Soc.* **2012**, *419*, 1537–1545. [CrossRef]
66. Blandford, R.D.; Znajek, R.L. Electromagnetic extraction of energy from Kerr black holes. *Mon. Not. R. Astron. Soc.* **1977**, *179*, 433–456. [CrossRef]
67. Zhang, W.; Woosley, S.E.; MacFadyen, A.I. Relativistic Jets in Collapsars. *Astrophys. J.* **2003**, *586*, 356–371. [CrossRef]
68. Parsotan, T.M.; Lazzati, D. Monte Carlo simulations of photospheric emission in Gamma Ray Bursts. In Proceedings of the Sixteenth Marcel Grossmann Meeting, Online, 5–10 July 2021; On Recent Developments in Theoretical and Experimental General Relativity, Astrophysics, and Relativistic Field Theories; Ruffino, R., Vereshchagin, G., Eds.; pp. 2972–2981.
69. Werner, G.R.; Uzdensky, D.A. Nonthermal Particle Acceleration in 3D Relativistic Magnetic Reconnection in Pair Plasma. *Astrophys. J.* **2017**, *843*, L27. [CrossRef]
70. Pe'er, A.; Mészáros, P.; Rees, M.J. The Observable Effects of a Photospheric Component on GRB and XRF Prompt Emission Spectrum. *Astrophys. J.* **2006**, *642*, 995–1003. [CrossRef]

71. Chevalier, R.A.; Li, Z.Y. Gamma-Ray Burst Environments and Progenitors. *Astrophys. J.* **1999**, *520*, L29–L32. [CrossRef]
72. Panaitescu, A.; Kumar, P. Properties of Relativistic Jets in Gamma-Ray Burst Afterglows. *Astrophys. J.* **2002**, *571*, 779–789. [CrossRef]
73. Weaver, R.; McCray, R.; Castor, J.; Shapiro, P.; Moore, R. Interstellar bubbles. II - Structure and evolution. *Astrophys. J.* **1977**, *218*, 377–395. [CrossRef]
74. Dai, Z.G. Relativistic Wind Bubbles and Afterglow Signatures. *Astrophys. J.* **2004**, *606*, 1000–1005. [CrossRef]
75. Van Marle, A.J.; Langer, N.; Yoon, S.C.; García-Segura, G. The circumstellar medium around a rapidly rotating, chemically homogeneously evolving, possible gamma-ray burst progenitor. *Astron. Astrophys.* **2008**, *478*, 769–778. :20078802 [CrossRef]
76. Pe'er, A.; Wijers, R.A.M.J. The Signature of a Wind Reverse Shock in Gamma-Ray Burst Afterglows. *Astrophys. J.* **2006**, *643*, 1036–1046. [CrossRef]
77. Bucciantini, N.; Quataert, E.; Arons, J.; Metzger, B.D.; Thompson, T.A. Magnetar-driven bubbles and the origin of collimated outflows in gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **2007**, *380*, 1541–1553. [CrossRef]
78. Yu, Y.W.; Dai, Z.G. Shallow decay phase of GRB X-ray afterglows from relativistic wind bubbles. *Astron. Astrophys.* **2007**, *470*, 119–122. [CrossRef]
79. 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]
80. 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]
81. 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]
82. Woosley, S.E.; Bloom, J.S. The Supernova Gamma-Ray Burst Connection. *Annu. Rev. Astron. Astrophys.* **2006**, *44*, 507–556. [CrossRef]
83. 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]
84. Rastinejad, J.C.; Gompertz, B.P.; Levan, A.J.; Fong, W.f.; Nicholl, M.; Lamb, G.P.; Malesani, D.B.; Nugent, A.E.; Oates, S.R.; Tanvir, N.R.; et al. A kilonova following a long-duration gamma-ray burst at 350 Mpc. *Nature* **2022**, *612*, 223–227. [CrossRef]
85. Troja, E.; Fryer, C.L.; O'Connor, B.; Ryan, G.; Dichiara, S.; Kumar, A.; Ito, N.; Gupta, R.; Wollaeger, R.T.; Norris, J.P.; et al. A nearby long gamma-ray burst from a merger of compact objects. *Nature* **2022**, *612*, 228–231. [CrossRef] [PubMed]
86. Yang, J.; Ai, S.; Zhang, B.B.; Zhang, B.; Liu, Z.K.; Wang, X.I.; Yang, Y.H.; Yin, Y.H.; Li, Y.; Lü, H.J. A long-duration gamma-ray burst with a peculiar origin. *Nature* **2022**, *612*, 232–235. [CrossRef] [PubMed]
87. Sun, H.; Wang, C.W.; Yang, J.; Zhang, B.B.; Xiong, S.L.; Yin, Y.H.I.; Liu, Y.; Li, Y.; Xue, W.C.; Yan, Z.; et al. Magnetar emergence in a peculiar gamma-ray burst from a compact star merger. *arXiv* **2023**, arXiv:2307.05689. [CrossRef]
88. Dichiara, S.; Tsang, D.; Troja, E.; Neill, D.; Norris, J.P.; Yang, Y.H. A Luminous Precursor in the Extremely Bright GRB 230307A. *Astrophys. J.* **2023**, *954*, L29. [CrossRef]
89. Yang, Y.H.; Troja, E.; O'Connor, B.; Fryer, C.L.; Im, M.; Durbak, J.; Paek, G.S.H.; Ricci, R.; Bom, C.R.; Gillanders, J.H.; et al. A lanthanide-rich kilonova in the aftermath of a long gamma-ray burst. *Nature* **2024**, *626*, 742–745. [CrossRef]
90. Levan, A.J.; Gompertz, B.P.; Salafia, O.S.; Bulla, M.; Burns, E.; Hotokezaka, K.; Izzo, L.; Lamb, G.P.; Malesani, D.B.; Oates, S.R.; et al. Heavy-element production in a compact object merger observed by JWST. *Nature* **2024**, *626*, 737–741. [CrossRef]
91. Zhong, S.Q.; Li, L.; Dai, Z.G. GRB 211211A: A Neutron Star-White Dwarf Merger? *Astrophys. J.* **2023**, *947*, L21. [CrossRef]
92. Barnes, J.; Metzger, B.D. A Collapsar Origin for GRB 211211A Is (Just Barely) Possible. *Astrophys. J.* **2023**, *947*, 55. [CrossRef]
93. Fruchter, A.S.; Levan, A.J.; Strolger, L.; Vreeswijk, P.M.; Thorsett, S.E.; Bersier, D.; Burud, I.; Castro Cerón, J.M.; Castro-Tirado, A.J.; Conselice, C.; et al. Long γ-ray bursts and core-collapse supernovae have different environments. *Nature* **2006**, *441*, 463–468. [CrossRef]
94. Fong, W.; Berger, E.; Chornock, R.; Margutti, R.; Levan, A.J.; Tanvir, N.R.; Tunnicliffe, R.L.; Czekala, I.; Fox, D.B.; Perley, D.A.; et al. Demographics of the Galaxies Hosting Short-duration Gamma-Ray Bursts. *Astrophys. J.* **2013**, *769*, 56. [CrossRef]
95. 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]
96. 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]
97. Tanvir, N.R.; Levan, A.J.; González-Fernández, C.; Korobkin, O.; Mandel, I.; Rosswog, S.; Hjorth, J.; D'Avanzo, P.; Fruchter, A.S.; Fryer, C.L.; et al. The Emergence of a Lanthanide-rich Kilonova Following the Merger of Two Neutron Stars. *Astrophys. J.* **2017**, *848*, L27. [CrossRef]

98. Cowperthwaite, P.S.; Berger, E.; Villar, V.A.; Metzger, B.D.; Nicholl, M.; Chornock, R.; Blanchard, P.K.; Fong, W.; Margutti, R.; Soares-Santos, M.; et al. The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. II. UV, Optical, and Near-infrared Light Curves and Comparison to Kilonova Models. *Astrophys. J.* **2017**, *848*, L17. [CrossRef]
99. Drout, M.R.; Piro, A.L.; Shappee, B.J.; Kilpatrick, C.D.; Simon, J.D.; Contreras, C.; Coulter, D.A.; Foley, R.J.; Siebert, M.R.; Morrell, N.; et al. Light curves of the neutron star merger GW170817/SSS17a: Implications for r-process nucleosynthesis. *Science* **2017**, *358*, 1570–1574. [CrossRef] [PubMed]
100. Arcavi, I.; Hosseinzadeh, G.; Howell, D.A.; McCully, C.; Poznanski, D.; Kasen, D.; Barnes, J.; Zaltzman, M.; Vasylyev, S.; Maoz, D.; et al. Optical emission from a kilonova following a gravitational-wave-detected neutron-star merger. *Nature* **2017**, *551*, 64–66. [CrossRef]
101. 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]
102. Li, L.X.; Paczyński, B. Transient Events from Neutron Star Mergers. *Astrophys. J.* **1998**, *507*, L59–L62. [CrossRef]
103. Tanvir, N.R.; Levan, A.J.; Fruchter, A.S.; Hjorth, J.; Hounsell, R.A.; Wiersema, K.; Tunnicliffe, R.L. A 'kilonova' associated with the short-duration γ-ray burst GRB 130603B. *Nature* **2013**, *500*, 547–549. [CrossRef]
104. Berger, E.; Fong, W.; Chornock, R. An r-process Kilonova Associated with the Short-hard GRB 130603B. *Astrophys. J.* **2013**, *774*, L23. [CrossRef]
105. Fong, W.; Berger, E.; Blanchard, P.K.; Margutti, R.; Cowperthwaite, P.S.; Chornock, R.; Alexander, K.D.; Metzger, B.D.; Villar, V.A.; Nicholl, M.; et al. The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VIII. A Comparison to Cosmological Short-duration Gamma-Ray Bursts. *Astrophys. J.* **2017**, *848*, L23. [CrossRef]
106. Howell, E.J.; Ackley, K.; Rowlinson, A.; Coward, D. Joint gravitational wave—Gamma-ray burst detection rates in the aftermath of GW170817. *Mon. Not. R. Astron. Soc.* **2019**, *485*, 1435–1447. [CrossRef]
107. Kapadia, S.J.; Dimple; Jain, D.; Misra, K.; Arun, K.G.; Lekshmi, R. Rates and Beaming Angles of Gamma-Ray Bursts Associated with Compact Binary Coalescences. *Astrophys. J.* **2024**, *976*, L10. [CrossRef]
108. Ahumada, T.; Singer, L.P.; Anand, S.; Coughlin, M.W.; Kasliwal, M.M.; Ryan, G.; Andreoni, I.; Cenko, S.B.; Fremling, C.; Kumar, H.; et al. Discovery and confirmation of the shortest gamma-ray burst from a collapsar. *Nat. Astron.* **2021**, *5*, 917–927. [CrossRef]
109. Margalit, B.; Metzger, B.D. Constraining the Maximum Mass of Neutron Stars from Multi-messenger Observations of GW170817. *Astrophys. J.* **2017**, *850*, L19. [CrossRef]
110. Rezzolla, L.; Most, E.R.; Weih, L.R. Using Gravitational-wave Observations and Quasi-universal Relations to Constrain the Maximum Mass of Neutron Stars. *Astrophys. J.* **2018**, *852*, L25. [CrossRef]
111. Rezzolla, L.; Giacomazzo, B.; Baiotti, L.; Granot, J.; Kouveliotou, C.; Aloy, M.A. The Missing Link: Merging Neutron Stars Naturally Produce Jet-like Structures and Can Power Short Gamma-ray Bursts. *Astrophys. J.* **2011**, *732*, L6. [CrossRef]
112. Piran, T.; Nakar, E.; Rosswog, S. The electromagnetic signals of compact binary mergers. *Mon. Not. R. Astron. Soc.* **2013**, *430*, 2121–2136. [CrossRef]
113. Kouveliotou, C.; Fishman, G.J.; Meegan, C.A.; Paciesas, W.S.; van Paradijs, J.; Norris, J.P.; Preece, R.D.; Briggs, M.S.; Horack, J.M.; Pendleton, G.N.; et al. The rarity of soft γ-ray repeaters deduced from reactivation of SGR1806 - 20. *Nature* **1994**, *368*, 125–127. [CrossRef]
114. Van der Horst, A.J.; Connaughton, V.; Kouveliotou, C.; Göğüş, E.; Kaneko, Y.; Wachter, S.; Briggs, M.S.; Granot, J.; Ramirez-Ruiz, E.; Woods, P.M.; et al. Discovery of a New Soft Gamma Repeater: SGR J0418 + 5729. *Astrophys. J.* **2010**, *711*, L1–L6. [CrossRef]
115. Kaneko, Y.; Göğüş, E.; Kouveliotou, C.; Granot, J.; Ramirez-Ruiz, E.; van der Horst, A.J.; Watts, A.L.; Finger, M.H.; Gehrels, N.; Pe'er, A.; et al. Magnetar Twists: Fermi/Gamma-Ray Burst Monitor Detection of SGR J1550-5418. *Astrophys. J.* **2010**, *710*, 1335–1342. [CrossRef]
116. Hurley, K.; Cline, T.; Mazets, E.; Barthelmy, S.; Butterworth, P.; Marshall, F.; Palmer, D.; Aptekar, R.; Golenetskii, S.; Il'Inskii, V.; et al. A giant periodic flare from the soft γ-ray repeater SGR1900+14. *Nature* **1999**, *397*, 41–43. [CrossRef] [PubMed]
117. Mazets, E.P.; Aptekar, R.L.; Butterworth, P.S.; Cline, T.L.; Frederiks, D.D.; Golenetskii, S.V.; Hurley, K.; Il'inskii, V.N. Unusual Burst Emission from the New Soft Gamma Repeater SGR 1627-41. *Astrophys. J.* **1999**, *519*, L151–L153. [CrossRef]
118. Palmer, D.M.; Barthelmy, S.; Gehrels, N.; Kippen, R.M.; Cayton, T.; Kouveliotou, C.; Eichler, D.; Wijers, R.A.M.J.; Woods, P.M.; Granot, J.; et al. A giant γ-ray flare from the magnetar SGR 1806-20. *Nature* **2005**, *434*, 1107–1109. [CrossRef] [PubMed]
119. Paczynski, B. GB 790305 as a Very Strongly Magnetized Neutron Star. *Acta Astronomica* **1992**, *42*, 145–153.
120. Hurley, K.; Boggs, S.E.; Smith, D.M.; Duncan, R.C.; Lin, R.; Zoglauer, A.; Krucker, S.; Hurford, G.; Hudson, H.; Wigger, C.; et al. An exceptionally bright flare from SGR 1806-20 and the origins of short-duration γ-ray bursts. *Nature* **2005**, *434*, 1098–1103. [CrossRef]
121. Svinkin, D.; Frederiks, D.; Hurley, K.; Aptekar, R.; Golenetskii, S.; Lysenko, A.; Ridnaia, A.V.; Tsvetkova, A.; Ulanov, M.; Cline, T.L.; et al. A bright γ-ray flare interpreted as a giant magnetar flare in NGC 253. *Nature* **2021**, *589*, 211–213. [CrossRef]

122. Ofek, E.O. Soft Gamma-Ray Repeaters in Nearby Galaxies: Rate, Luminosity Function, and Fraction among Short Gamma-Ray Bursts. *Astrophys. J.* **2007**, *659*, 339–346. [CrossRef]
123. Svinkin, D.S.; Hurley, K.; Aptekar, R.L.; Golenetskii, S.V.; Frederiks, D.D. A search for giant flares from soft gamma-ray repeaters in nearby galaxies in the Konus-WIND short burst sample. *Mon. Not. R. Astron. Soc.* **2015**, *447*, 1028–1032. [CrossRef]
124. Burns, E.; Svinkin, D.; Hurley, K.; Wadiasingh, Z.; Negro, M.; Younes, G.; Hamburg, R.; Ridnaia, A.; Cook, D.; Cenko, S.B.; et al. Identification of a Local Sample of Gamma-Ray Bursts Consistent with a Magnetar Giant Flare Origin. *Astrophys. J.* **2021**, *907*, L28. [CrossRef]
125. Beniamini, P.; Wadiasingh, Z.; Trigg, A.; Chirenti, C.; Burns, E.; Younes, G.; Negro, M.; Granot, J. Extragalactic Magnetar Giant Flares: Population Implications, Rates and Prospects for Gamma-Rays, Gravitational Waves and Neutrinos. *arXiv* **2024**, arXiv:2411.16846. [CrossRef]
126. 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]
127. Berger, E.; Kulkarni, S.R.; Frail, D.A. A Standard Kinetic Energy Reservoir in Gamma-Ray Burst Afterglows. *Astrophys. J.* **2003**, *590*, 379–385. [CrossRef]
128. Racusin, J.L.; Liang, E.W.; Burrows, D.N.; Falcone, A.; Sakamoto, T.; Zhang, B.B.; Zhang, B.; Evans, P.; Osborne, J. Jet Breaks and Energetics of Swift Gamma-Ray Burst X-Ray Afterglows. *Astrophys. J.* **2009**, *698*, 43–74. [CrossRef]
129. Wygoda, N.; Waxman, E.; Frail, D.A. Relativistic Jet Dynamics and Calorimetry of Gamma-ray Bursts. *Astrophys. J.* **2011**, *738*, L23. [CrossRef]
130. Rouco Escorial, A.; Fong, W.; Berger, E.; Laskar, T.; Margutti, R.; Schroeder, G.; Rastinejad, J.C.; Cornish, D.; Popp, S.; Lally, M.; et al. The Jet Opening Angle and Event Rate Distributions of Short Gamma-Ray Bursts from Late-time X-Ray Afterglows. *Astrophys. J.* **2023**, *959*, 13. [CrossRef]
131. O'Shaughnessy, R.; Kim, C. Pulsar Binary Birthrates with Spin-opening Angle Correlations. *Astrophys. J.* **2010**, *715*, 230–241. [CrossRef]
132. Grunthal, K.; Kramer, M.; Desvignes, G. Revisiting the Galactic Double Neutron Star merger and LIGO detection rates. *Mon. Not. R. Astron. Soc.* **2021**, *507*, 5658–5670. [CrossRef]
133. Zhang, B.; Mészáros, P. Gamma-Ray Burst Beaming: A Universal Configuration with a Standard Energy Reservoir? *Astrophys. J.* **2002**, *571*, 876–879. [CrossRef]
134. Granot, J.; Königl, A. Linear Polarization in Gamma-Ray Bursts: The Case for an Ordered Magnetic Field. *Astrophys. J.* **2003**, *594*, L83–L87. [CrossRef]
135. Lundman, C.; Pe'er, A.; Ryde, F. A theory of photospheric emission from relativistic, collimated outflows. *Mon. Not. R. Astron. Soc.* **2013**, *428*, 2430–2442. [CrossRef]
136. Lundman, C.; Pe'er, A.; Ryde, F. Polarization properties of photospheric emission from relativistic, collimated outflows. *Mon. Not. R. Astron. Soc.* **2014**, *440*, 3292–3308. [CrossRef]
137. D'Avanzo, P.; Campana, S.; Salafia, O.S.; Ghirlanda, G.; Ghisellini, G.; Melandri, A.; Bernardini, M.G.; Branchesi, M.; Chassande-Mottin, E.; Covino, S.; et al. The evolution of the X-ray afterglow emission of GW 170817/GRB 170817A in XMM-Newton observations. *Astron. Astrophys.* **2018**, *613*, L1. [CrossRef]
138. Mooley, K.P.; Nakar, E.; Hotokezaka, K.; Hallinan, G.; Corsi, A.; Frail, D.A.; Horesh, A.; Murphy, T.; Lenc, E.; Kaplan, D.L.; et al. A mildly relativistic wide-angle outflow in the neutron-star merger event GW170817. *Nature* **2018**, *554*, 207–210. [CrossRef] [PubMed]
139. Troja, E.; van Eerten, H.; Ryan, G.; Ricci, R.; Burgess, J.M.; Wieringa, M.H.; Piro, L.; Cenko, S.B.; Sakamoto, T. A year in the life of GW 170817: The rise and fall of a structured jet from a binary neutron star merger. *Mon. Not. R. Astron. Soc.* **2019**, *489*, 1919–1926. [CrossRef]
140. Takahashi, K.; Ioka, K. Inverse reconstruction of jet structure from off-axis gamma-ray burst afterglows. *Mon. Not. R. Astron. Soc.* **2020**, *497*, 1217–1235. [CrossRef]
141. Takahashi, K.; Ioka, K. Diverse jet structures consistent with the off-axis afterglow of GRB 170817A. *Mon. Not. R. Astron. Soc.* **2021**, *501*, 5746–5756. [CrossRef]
142. Troja, E.; Piro, L.; van Eerten, H.; Wollaeger, R.T.; Im, M.; Fox, O.D.; Butler, N.R.; Cenko, S.B.; Sakamoto, T.; Fryer, C.L.; et al. The X-ray counterpart to the gravitational-wave event GW170817. *Nature* **2017**, *551*, 71–74. [CrossRef]
143. Margutti, R.; Berger, E.; Fong, W.; Guidorzi, C.; Alexander, K.D.; Metzger, B.D.; Blanchard, P.K.; Cowperthwaite, P.S.; Chornock, R.; Eftekhari, T.; et al. The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. V. Rising X-Ray Emission from an Off-axis Jet. *Astrophys. J.* **2017**, *848*, L20. [CrossRef]
144. Alexander, K.D.; Margutti, R.; Blanchard, P.K.; Fong, W.; Berger, E.; Hajela, A.; Eftekhari, T.; Chornock, R.; Cowperthwaite, P.S.; Giannios, D.; et al. A Decline in the X-Ray through Radio Emission from GW170817 Continues to Support an Off-axis Structured Jet. *Astrophys. J.* **2018**, *863*, L18. [CrossRef]

145. Margutti, R.; Alexander, K.D.; Xie, X.; Sironi, L.; Metzger, B.D.; Kathirgamaraju, A.; Fong, W.; Blanchard, P.K.; Berger, E.; MacFadyen, A.; et al. The Binary Neutron Star Event LIGO/Virgo GW170817 160 Days after Merger: Synchrotron Emission across the Electromagnetic Spectrum. *Astrophys. J.* **2018**, *856*, L18. [CrossRef]
146. Fong, W.; Blanchard, P.K.; Alexander, K.D.; Strader, J.; Margutti, R.; Hajela, A.; Villar, V.A.; Wu, Y.; Ye, C.S.; Berger, E.; et al. The Optical Afterglow of GW170817: An Off-axis Structured Jet and Deep Constraints on a Globular Cluster Origin. *Astrophys. J.* **2019**, *883*, L1. [CrossRef]
147. 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]
148. Gill, R.; Granot, J. GRB 221009A afterglow from a shallow angular structured jet. *Mon. Not. R. Astron. Soc.* **2023**, *524*, L78–L83. [CrossRef]
149. Zheng, J.H.; Wang, X.Y.; Liu, R.Y.; Zhang, B. A Narrow Uniform Core with a Wide Structured Wing: Modeling the TeV and Multiwavelength Afterglows of GRB 221009A. *Astrophys. J.* **2024**, *966*, 141. [CrossRef]
150. Bošnjak, Ž.; Zhang, B.T.; Murase, K.; Ioka, K. Off-axis MeV and very-high-energy gamma-ray emissions from structured gamma-ray burst jets. *Mon. Not. R. Astron. Soc.* **2024**, *528*, 4307–4313. [CrossRef]
151. Kathirgamaraju, A.; Barniol Duran, R.; Giannios, D. Off-axis short GRBs from structured jets as counterparts to GW events. *Mon. Not. R. Astron. Soc.* **2018**, *473*, L121–L125. [CrossRef]
152. Vyas, M.K.; Pe'er, A. Photons' Scattering in Relativistic Plasma with Velocity Shear: Generation of High Energy Power-law Spectra. *Astrophys. J.* **2023**, *943*, L3. [CrossRef]
153. Vyas, M.K.; Pe'er, A.; Iyyani, S. Unified Theory of Negative and Positive Spectral Lags in the Gamma-Ray Burst Prompt Phase due to Shear Comptonization from a Structured Jet. *Astrophys. J.* **2024**, *975*, L29. [CrossRef]
154. Parsotan, T.; Lazzati, D. Photospheric Prompt Emission from Long Gamma Ray Burst Simulations. III. X-Ray Spectropolarimetry. *Astrophys. J.* **2024**, *974*, 158. [CrossRef]
155. Ito, H.; Nagataki, S.; Ono, M.; Lee, S.H.; Mao, J.; Yamada, S.; Pe'er, A.; Mizuta, A.; Harikae, S. Photospheric Emission from Stratified Jets. *Astrophys. J.* **2013**, *777*, 62. [CrossRef]
156. Parsotan, T.; López-Cámara, D.; Lazzati, D. Photospheric Polarization Signatures from Long Gamma-Ray Burst Simulations. *Astrophys. J.* **2020**, *896*, 139. [CrossRef]
157. Laskar, T.; Alexander, K.D.; Margutti, R.; Eftekhari, T.; Chornock, R.; Berger, E.; Cendes, Y.; Duerr, A.; Perley, D.A.; Ravasio, M.E.; et al. The Radio to GeV Afterglow of GRB 221009A. *Astrophys. J.* **2023**, *946*, L23. [CrossRef]
158. Popham, R.; Woosley, S.E.; Fryer, C. Hyperaccreting Black Holes and Gamma-Ray Bursts. *Astrophys. J.* **1999**, *518*, 356–374. [CrossRef]
159. Duncan, R.C.; Thompson, C. Formation of Very Strongly Magnetized Neutron Stars: Implications for Gamma-Ray Bursts. *Astrophys. J.* **1992**, *392*, L9. [CrossRef]
160. Bucciantini, N.; Quataert, E.; Arons, J.; Metzger, B.D.; Thompson, T.A. Relativistic jets and long-duration gamma-ray bursts from the birth of magnetars. *Mon. Not. R. Astron. Soc.* **2008**, *383*, L25–L29. [CrossRef]
161. Beniamini, P.; Giannios, D.; Metzger, B.D. Constraints on millisecond magnetars as the engines of prompt emission in gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **2017**, *472*, 3058–3073. [CrossRef]
162. 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]
163. Zalamea, I.; Beloborodov, A.M. Neutrino heating near hyper-accreting black holes. *Mon. Not. R. Astron. Soc.* **2011**, *410*, 2302–2308. [CrossRef]
164. Wong, G.N.; Du, Y.; Prather, B.S.; Gammie, C.F. The Jet-disk Boundary Layer in Black Hole Accretion. *Astrophys. J.* **2021**, *914*, 55. [CrossRef]
165. Tchekhovskoy, A.; Giannios, D. Magnetic flux of progenitor stars sets gamma-ray burst luminosity and variability. *Mon. Not. R. Astron. Soc.* **2015**, *447*, 327–344. [CrossRef]
166. Obergaulinger, M.; Aloy, M.Á. Magnetorotational core collapse of possible GRB progenitors—I. Explosion mechanisms. *Mon. Not. R. Astron. Soc.* **2020**, *492*, 4613–4634. [CrossRef]
167. Obergaulinger, M.; Aloy, M.Á. Magnetorotational core collapse of possible GRB progenitors—III. Three-dimensional models. *Mon. Not. R. Astron. Soc.* **2021**, *503*, 4942–4963. [CrossRef]
168. Obergaulinger, M.; Aloy, M.Á. Magnetorotational core collapse of possible gamma-ray burst progenitors—IV. A wider range of progenitors. *Mon. Not. R. Astron. Soc.* **2022**, *512*, 2489–2507. [CrossRef]
169. De Villiers, J.P.; Hawley, J.F.; Krolik, J.H. Magnetically Driven Accretion Flows in the Kerr Metric. I. Models and Overall Structure. *Astrophys. J.* **2003**, *599*, 1238–1253. [CrossRef]
170. Gammie, C.F.; McKinney, J.C.; Tóth, G. HARM: A Numerical Scheme for General Relativistic Magnetohydrodynamics. *Astrophys. J.* **2003**, *589*, 444–457. [CrossRef]

171. Anninos, P.; Fragile, P.C.; Salmonson, J.D. Cosmos++: Relativistic Magnetohydrodynamics on Unstructured Grids with Local Adaptive Refinement. *Astrophys. J.* **2005**, *635*, 723–740. [CrossRef]
172. Del Zanna, L.; Zanotti, O.; Bucciantini, N.; Londrillo, P. ECHO: A Eulerian conservative high-order scheme for general relativistic magnetohydrodynamics and magnetodynamics. *Astron. Astrophys.* **2007**, *473*, 11–30. [CrossRef]
173. Stone, J.M.; Gardiner, T.A.; Teuben, P.; Hawley, J.F.; Simon, J.B. Athena: A New Code for Astrophysical MHD. *Astrophys. J.* **2008**, *178*, 137–177. [CrossRef]
174. Etienne, Z.B.; Paschalidis, V.; Haas, R.; Mösta, P.; Shapiro, S.L. IllinoisGRMHD: An open-source, user-friendly GRMHD code for dynamical spacetimes. *Class. Quantum Gravity* **2015**, *32*, 175009. [CrossRef]
175. Porth, O.; Olivares, H.; Mizuno, Y.; Younsi, Z.; Rezzolla, L.; Moscibrodzka, M.; Falcke, H.; Kramer, M. The black hole accretion code. *Comput. Astrophys. Cosmol.* **2017**, *4*, 1. [CrossRef]
176. Liska, M.T.P.; Chatterjee, K.; Issa, D.; Yoon, D.; Kaaz, N.; Tchekhovskoy, A.; van Eijnatten, D.; Musoke, G.; Hesp, C.; Rohoza, V.; et al. H-AMR: A New GPU-accelerated GRMHD Code for Exascale Computing with 3D Adaptive Mesh Refinement and Local Adaptive Time Stepping. *Astrophys. J.* **2022**, *263*, 26. [CrossRef]
177. Bégué, D.; Pe'er, A.; Zhang, G.Q.; Zhang, B.B.; Pevzner, B. cuHARM: A New GPU-accelerated GRMHD Code and Its Application to ADAF Disks. *Astrophys. J.* **2023**, *264*, 32. [CrossRef]
178. Balbus, S.A.; Hawley, J.F. A Powerful Local Shear Instability in Weakly Magnetized Disks. I. Linear Analysis. *Astrophys. J.* **1991**, *376*, 214. [CrossRef]
179. Balbus, S.A.; Hawley, J.F. Instability, turbulence, and enhanced transport in accretion disks. *Rev. Mod. Phys.* **1998**, *70*, 1–53. [CrossRef]
180. Narayan, R.; SÄ dowski, A.; Penna, R.F.; Kulkarni, A.K. GRMHD simulations of magnetized advection-dominated accretion on a non-spinning black hole: Role of outflows. *Mon. Not. R. Astron. Soc.* **2012**, *426*, 3241–3259. [CrossRef]
181. Igumenshchev, I.V.; Narayan, R.; Abramowicz, M.A. Three-dimensional Magnetohydrodynamic Simulations of Radiatively Inefficient Accretion Flows. *Astrophys. J.* **2003**, *592*, 1042–1059. [CrossRef]
182. Narayan, R.; Igumenshchev, I.V.; Abramowicz, M.A. Magnetically Arrested Disk: An Energetically Efficient Accretion Flow. *Publ. Astr. Soc. Japan* **2003**, *55*, L69–L72. [CrossRef]
183. Igumenshchev, I.V. Magnetically Arrested Disks and the Origin of Poynting Jets: A Numerical Study. *Astrophys. J.* **2008**, *677*, 317–326. [CrossRef]
184. Yuan, F.; Narayan, R. Hot Accretion Flows Around Black Holes. *Annu. Rev. Astron. Astrophys.* **2014**, *52*, 529–588. [CrossRef]
185. Tchekhovskoy, A.; Narayan, R.; McKinney, J.C. Efficient generation of jets from magnetically arrested accretion on a rapidly spinning black hole. *Mon. Not. R. Astron. Soc.* **2011**, *418*, L79–L83. [CrossRef]
186. Ito, H.; Matsumoto, J.; Nagataki, S.; Warren, D.C.; Barkov, M.V.; Yonetoku, D. The photospheric origin of the Yonetoku relation in gamma-ray bursts. *Nat. Commun.* **2019**, *10*, 1504. [CrossRef] [PubMed]
187. Gottlieb, O.; Nakar, E.; Bromberg, O. The structure of hydrodynamic γ-ray burst jets. *Mon. Not. R. Astron. Soc.* **2021**, *500*, 3511–3526. [CrossRef]
188. Gottlieb, O.; Lalakos, A.; Bromberg, O.; Liska, M.; Tchekhovskoy, A. Black hole to breakout: 3D GRMHD simulations of collapsar jets reveal a wide range of transients. *Mon. Not. R. Astron. Soc.* **2022**, *510*, 4962–4975. [CrossRef]
189. Gottlieb, O.; Issa, D.; Jacquemin-Ide, J.; Liska, M.; Foucart, F.; Tchekhovskoy, A.; Metzger, B.D.; Quataert, E.; Perna, R.; Kasen, D.; et al. Large-scale Evolution of Seconds-long Relativistic Jets from Black Hole-Neutron Star Mergers. *Astrophys. J.* **2023**, *954*, L21. [CrossRef]
190. Rudolph, A.; Tamborra, I.; Gottlieb, O. Subphotospheric Emission from Short Gamma-Ray Bursts: Protons Mold the Multimessenger Signals. *Astrophys. J.* **2024**, *961*, L7. [CrossRef]
191. Rudolph, A.; Tamborra, I.; Gottlieb, O. Subphotospheric Emission from Short Gamma-Ray Bursts. II. Signatures of Non-Thermal Dissipation in the Multi-Messenger Signals. *arXiv* **2024**, arXiv:2410.23258. [CrossRef]
192. Beloborodov, A.M. Radiative Transfer in Ultrarelativistic Outflows. *Astrophys. J.* **2011**, *737*, 68. [CrossRef]
193. Zhang, G.Q.; Bégué, D.; Pe'er, A.; Zhang, B.B. A Study of the Accretion State of Magnetically Arrested Disks across Black Hole Spins for Radiatively Inefficient Accretion Flows. *Astrophys. J.* **2024**, *962*, 135. [CrossRef]
194. Sari, R.; Piran, T. Cosmological gamma-ray bursts: Internal versus external shocks. *Mon. Not. R. Astron. Soc.* **1997**, *287*, 110–116. [CrossRef]
195. Beloborodov, A.M. On the Efficiency of Internal Shocks in Gamma-Ray Bursts. *Astrophys. J.* **2000**, *539*, L25–L28. [CrossRef]
196. Spada, M.; Panaitescu, A.; Mészáros, P. Analysis of Temporal Features of Gamma-Ray Bursts in the Internal Shock Model. *Astrophys. J.* **2000**, *537*, 824–832. [CrossRef]
197. Guetta, D.; Spada, M.; Waxman, E. Efficiency and Spectrum of Internal Gamma-Ray Burst Shocks. *Astrophys. J.* **2001**, *557*, 399–407. [CrossRef]
198. Parker, E.N. Sweet's mechanism for merging magnetic fields in conducting fluids. *JGR* **1957**, *62*, 509–520. [CrossRef]

199. Sweet, P.A. The neutral point theory of solar flares. In *Electromagnetic Phenomena in Cosmical Physics*; Lehnert, B., Ed.; Cambridge University Press: Cambridge, UK, 1958; pp. 123–134.
200. Petschek, H.E. Magnetic Field Annihilation. In *NASA Special Publication*; Hess, W.N., Ed.; NASA: Washington, DC, USA, 1964; Volume 50, p. 425.
201. Sironi, L.; Spitkovsky, A. Particle-in-cell simulations of shock-driven reconnection in relativistic striped winds. *Comput. Sci. Discov.* **2012**, *5*, 014014. [CrossRef]
202. Sironi, L.; Spitkovsky, A. Relativistic Reconnection: An Efficient Source of Non-thermal Particles. *Astrophys. J.* **2014**, *783*, L21. [CrossRef]
203. Sironi, L.; Giannios, D.; Petropoulou, M. Plasmoids in relativistic reconnection, from birth to adulthood: First they grow, then they go. *Mon. Not. R. Astron. Soc.* **2016**, *462*, 48–74. [CrossRef]
204. Sironi, L.; Comisso, L.; Golant, R. Generation of Near-Equipartition Magnetic Fields in Turbulent Collisionless Plasmas. *Phys. Rev. Lett.* **2023**, *131*, 055201. [CrossRef]
205. Zhang, H.; Sironi, L.; Giannios, D. Fast Particle Acceleration in Three-dimensional Relativistic Reconnection. *Astrophys. J.* **2021**, *922*, 261. [CrossRef]
206. Zhang, H.; Sironi, L.; Giannios, D.; Petropoulou, M. The Origin of Power-law Spectra in Relativistic Magnetic Reconnection. *Astrophys. J.* **2023**, *956*, L36. [CrossRef]
207. Comisso, L.; Sironi, L. Particle Acceleration in Relativistic Plasma Turbulence. *Phys. Rev. Lett.* **2018**, *121*, 255101. [CrossRef]
208. Comisso, L.; Sironi, L. Ion and Electron Acceleration in Fully Kinetic Plasma Turbulence. *Astrophys. J.* **2022**, *936*, L27. [CrossRef]
209. Comisso, L.; Jiang, B. Pitch-angle Anisotropy Imprinted by Relativistic Magnetic Reconnection. *Astrophys. J.* **2023**, *959*, 137. [CrossRef]
210. Wijers, R.A.M.J.; Galama, T.J. Physical Parameters of GRB 970508 and GRB 971214 from Their Afterglow Synchrotron Emission. *Astrophys. J.* **1999**, *523*, 177–186. [CrossRef]
211. Blandford, R.D.; McKee, C.F. Fluid dynamics of relativistic blast waves. *Phys. Fluids* **1976**, *19*, 1130–1138. [CrossRef]
212. Rybicki, G.B.; Lightman, A.P. *Radiative Processes in Astrophysics*; John Wiley & Sons: Hoboken, NJ, USA, 1979.
213. Granot, J.; Sari, R. The Shape of Spectral Breaks in Gamma-Ray Burst Afterglows. *Astrophys. J.* **2002**, *568*, 820–829. [CrossRef]
214. Sari, R.; Piran, T. GRB 990123: The Optical Flash and the Fireball Model. *Astrophys. J.* **1999**, *517*, L109–L112.
215. Arimoto, M.; Asano, K.; Kawabata, K.S.; Toma, K.; Gill, R.; Granot, J.; Ohno, M.; Takahashi, S.; Ogino, N.; Goto, H.; et al. Gamma rays from a reverse shock with turbulent magnetic fields in GRB 180720B. *Nat. Astron.* **2024**, *8*, 134–144. [CrossRef]
216. Laskar, T.; van Eerten, H.; Schady, P.; Mundell, C.G.; Alexander, K.D.; Barniol Duran, R.; Berger, E.; Bolmer, J.; Chornock, R.; Coppejans, D.L.; et al. A Reverse Shock in GRB 181201A. *Astrophys. J.* **2019**, *884*, 121. [CrossRef]
217. Rhodes, L.; van der Horst, A.J.; Fender, R.; Aguilera-Dena, D.R.; Bright, J.S.; Vergani, S.; Williams, D.R.A. Jet-cocoon geometry in the optically dark, very high energy gamma-ray burst 201216C. *Mon. Not. R. Astron. Soc.* **2022**, *513*, 1895–1909. [CrossRef]
218. Abe, H.; Abe, S.; Acciari, V.A.; Agudo, I.; Aniello, T.; Ansoldi, S.; Antonelli, L.A.; Arbet Engels, A.; Arcaro, C.; Artero, M.; et al. MAGIC detection of GRB 201216C at z = 1.1. *Mon. Not. R. Astron. Soc.* **2024**, *527*, 5856–5867. [CrossRef]
219. Schroeder, G.; Rhodes, L.; Laskar, T.; Nugent, A.; Rouco Escorial, A.; Rastinejad, J.C.; Fong, W.f.; van der Horst, A.J.; Veres, P.; Alexander, K.D.; et al. A Radio Flare in the Long-lived Afterglow of the Distant Short GRB 210726A: Energy Injection or a Reverse Shock from Shell Collisions? *Astrophys. J.* **2024**, *970*, 139. [CrossRef]
220. Weaver, T.A. The structure of supernova shock waves. *Astrophys. J.* **1976**, *32*, 233–282. [CrossRef]
221. Chrimes, A.A.; Gompertz, B.P.; Kann, D.A.; van Marle, A.J.; Eldridge, J.J.; Groot, P.J.; Laskar, T.; Levan, A.J.; Nicholl, M.; Stanway, E.R.; et al. Towards an understanding of long gamma-ray burst environments through circumstellar medium population synthesis predictions. *Mon. Not. R. Astron. Soc.* **2022**, *515*, 2591–2611. [CrossRef]
222. Van Marle, A.J.; Langer, N.; Achterberg, A.; García-Segura, G. Forming a constant density medium close to long gamma-ray bursts. *Astron. Astrophys.* **2006**, *460*, 105–116. [CrossRef]
223. Marston, A.P. A Survey of Nebulae around Galactic Wolf-Rayet Stars in the Southern Sky. III. Survey Completion and Conclusions. *Astrophys. J.* **1997**, *475*, 188–193. [CrossRef]
224. Crowther, P.A. Physical Properties of Wolf-Rayet Stars. *Annu. Rev. Astron. Astrophys.* **2007**, *45*, 177–219. [CrossRef]
225. Lau, R.M.; Hankins, M.J.; Han, Y.; Argyriou, I.; Corcoran, M.F.; Eldridge, J.J.; Endo, I.; Fox, O.D.; Garcia Marin, M.; Gull, T.R.; et al. Nested dust shells around the Wolf-Rayet binary WR 140 observed with JWST. *Nat. Astron.* **2022**, *6*, 1308–1316. [CrossRef]
226. Pe'er, A.; Ryde, F. Gamma-ray burst interaction with the circumburst medium: The CBM phase of GRBs. *arXiv* **2024**, arXiv:2406.03841. [CrossRef]
227. Zhu, S.; Fermi Large Area Telescope Collaboration. Precursors in gamma-ray bursts detected by the Fermi-LAT and GBM. *APS April. Meet. Abstr.* **2015**, *2015*, M2.002.
228. Coppin, P.; de Vries, K.D.; van Eijndhoven, N. Identification of gamma-ray burst precursors in Fermi-GBM bursts. *Phys. Rev.* **2020**, *102*, 103014. [CrossRef]

229. Sharma, V.; Iyyani, S.; Bhattacharya, D.; Chattopadhyay, T.; Rao, A.R.; Aarthy, E.; Vadawale, S.V.; Mithun, N.P.S.; Bhalerao, V.B.; Ryde, F.; et al. Time-varying Polarized Gamma-Rays from GRB 160821A: Evidence for Ordered Magnetic Fields. *Astrophys. J.* **2019**, *882*, L10. [CrossRef]
230. Ravasio, M.E.; Ghirlanda, G.; Nava, L.; Ghisellini, G. Evidence of two spectral breaks in the prompt emission of gamma-ray bursts. *Astron. Astrophys.* **2019**, *625*, A60. [CrossRef]
231. Ryde, F.; Iyyani, S.; Ahlgren, B.; Pe'er, A.; Sharma, V.; Lundman, C.; Axelsson, M. Onset of Particle Acceleration during the Prompt Phase in Gamma-Ray Bursts as Revealed by Synchrotron Emission in GRB 160821A. *Astrophys. J.* **2022**, *932*, L15. [CrossRef]
232. 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]
233. 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]
234. Srinivasaragavan, G.P.; Dainotti, M.G.; Fraija, N.; Hernandez, X.; Nagataki, S.; Lenart, A.; Bowden, L.; Wagner, R. On the Investigation of the Closure Relations for Gamma-Ray Bursts Observed by Swift in the Post-plateau Phase and the GRB Fundamental Plane. *Astrophys. J.* **2020**, *903*, 18. [CrossRef]
235. Fan, Y.; Piran, T. Gamma-ray burst efficiency and possible physical processes shaping the early afterglow. *Mon. Not. R. Astron. Soc.* **2006**, *369*, 197–206. [CrossRef]
236. Granot, J.; Königl, A.; Piran, T. Implications of the early X-ray afterglow light curves of Swift gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **2006**, *370*, 1946–1960. [CrossRef]
237. Ghisellini, G.; Ghirlanda, G.; Nava, L.; Firmani, C. "Late Prompt" Emission in Gamma-Ray Bursts? *Astrophys. J.* **2007**, *658*, L75–L78.
238. Toma, K.; Ioka, K.; Yamazaki, R.; Nakamura, T. Shallow Decay of Early X-Ray Afterglows from Inhomogeneous Gamma-Ray Burst Jets. *Astrophys. J.* **2006**, *640*, L139–L142. [CrossRef]
239. Ioka, K.; Toma, K.; Yamazaki, R.; Nakamura, T. Efficiency crisis of swift gamma-ray bursts with shallow X-ray afterglows: Prior activity or time-dependent microphysics? *Astron. Astrophys.* **2006**, *458*, 7–12. [CrossRef]
240. Uhm, Z.L.; Beloborodov, A.M. On the Mechanism of Gamma-Ray Burst Afterglows. *Astrophys. J.* **2007**, *665*, L93–L96. [CrossRef]
241. Genet, F.; Daigne, F.; Mochkovitch, R. Can the early X-ray afterglow of gamma-ray bursts be explained by a contribution from the reverse shock? *Mon. Not. R. Astron. Soc.* **2007**, *381*, 732–740. [CrossRef]
242. Hascoët, R.; Daigne, F.; Mochkovitch, R. The prompt-early afterglow connection in gamma-ray bursts: Implications for the early afterglow physics. *Mon. Not. R. Astron. Soc.* **2014**, *442*, 20–27. [CrossRef]
243. Eichler, D.; Granot, J. The Case for Anisotropic Afterglow Efficiency within Gamma-Ray Burst Jets. *Astrophys. J.* **2006**, *641*, L5–L8. [CrossRef]
244. Oganesyan, G.; Ascenzi, S.; Branchesi, M.; Salafia, O.S.; Dall'Osso, S.; Ghirlanda, G. Structured Jets and X-Ray Plateaus in Gamma-Ray Burst Phenomena. *Astrophys. J.* **2020**, *893*, 88. [CrossRef]
245. Ascenzi, S.; Oganesyan, G.; Salafia, O.S.; Branchesi, M.; Ghirlanda, G.; Dall'Osso, S. High-latitude emission from the structured jet of γ-ray bursts observed off-axis. *Astron. Astrophys.* **2020**, *641*, A61. [CrossRef]
246. Beniamini, P.; Granot, J.; Gill, R. Afterglow light curves from misaligned structured jets. *Mon. Not. R. Astron. Soc.* **2020**, *493*, 3521–3534. [CrossRef]
247. Shen, R.; Matzner, C.D. Coasting External Shock in Wind Medium: An Origin for the X-Ray Plateau Decay Component in Swift Gamma-Ray Burst Afterglows. *Astrophys. J.* **2012**, *744*, 36. [CrossRef]
248. Dereli-Bégué, H.; Pe'er, A.; Ryde, F.; Oates, S.R.; Zhang, B.; Dainotti, M.G. A wind environment and Lorentz factors of tens explain gamma-ray bursts X-ray plateau. *Nat. Commun.* **2022**, *13*, 5611. [CrossRef]
249. Krolik, J.H.; Pier, E.A. Relativistic motion in gamma-ray bursts. *Astrophys. J.* **1991**, *373*, 277–284. [CrossRef]
250. Woods, E.; Loeb, A. Empirical Constraints on Source Properties and Host Galaxies of Cosmological Gamma-Ray Bursts. *Astrophys. J.* **1995**, *453*, 583. [CrossRef]
251. Lithwick, Y.; Sari, R. Lower Limits on Lorentz Factors in Gamma-Ray Bursts. *Astrophys. J.* **2001**, *555*, 540–545. [CrossRef]
252. Meszaros, P.; Rees, M.J. Optical and Long-Wavelength Afterglow from Gamma-Ray Bursts. *Astrophys. J.* **1997**, *476*, 232. [CrossRef]
253. Kobayashi, S.; Zhang, B. Early Optical Afterglows from Wind-Type Gamma-Ray Bursts. *Astrophys. J.* **2003**, *597*, 455–458. [CrossRef]
254. Pe'er, A.; Ryde, F.; Wijers, R.A.M.J.; Mészáros, P.; Rees, M.J. A New Method of Determining the Initial Size and Lorentz Factor of Gamma-Ray Burst Fireballs Using a Thermal Emission Component. *Astrophys. J.* **2007**, *664*, L1–L4. [CrossRef]
255. Zou, Y.C.; Piran, T. Lorentz factor constraint from the very early external shock of the gamma-ray burst ejecta. *Mon. Not. R. Astron. Soc.* **2010**, *402*, 1854–1862. [CrossRef]

256. Hascoët, R.; Daigne, F.; Mochkovitch, R. Prompt thermal emission in gamma-ray bursts. *Astron. Astrophys.* **2013**, *551*, A124. [CrossRef]
257. 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]
258. Gowri, A.; Pe'er, A.; Ryde, F.; Dereli-Bégué, H. Gamma-ray burst pulse structures and emission mechanisms. *arXiv* **2024**, arXiv:2409.17860. [CrossRef]
259. Dereli-Bégué, H.; Pe'er, A.; Bégué, D.; Ryde, F. Unraveling the Origins of GRB X-ray Plateaus through a Study of X-ray Flares. *arXiv* **2024**, arXiv:2412.11533. [CrossRef]
260. Pe'er, A. Temporal Evolution of Thermal Emission from Relativistically Expanding Plasma. *Astrophys. J.* **2008**, *682*, 463–473. [CrossRef]
261. Pe'er, A.; Ryde, F. A Theory of Multicolor Blackbody Emission from Relativistically Expanding Plasmas. *Astrophys. J.* **2011**, *732*, 49. [CrossRef]
262. Tavani, M. A Shock Emission Model for Gamma-Ray Bursts. II. Spectral Properties. *Astrophys. J.* **1996**, *466*, 768. [CrossRef]
263. Cohen, E.; Katz, J.I.; Piran, T.; Sari, R.; Preece, R.D.; Band, D.L. Possible Evidence for Relativistic Shocks in Gamma-Ray Bursts. *Astrophys. J.* **1997**, *488*, 330. [CrossRef]
264. Preece, R.D.; Briggs, M.S.; Mallozzi, R.S.; Pendleton, G.N.; Paciesas, W.S.; Band, D.L. The Synchrotron Shock Model Confronts a "Line of Death" in the BATSE Gamma-Ray Burst Data. *Astrophys. J.* **1998**, *506*, L23–L26. [CrossRef]
265. Burgess, J.M.; Bégué, D.; Greiner, J.; Giannios, D.; Bacelj, A.; Berlato, F. Gamma-ray bursts as cool synchrotron sources. *Nat. Astron.* **2020**, *4*, 174–179. [CrossRef]
266. Ghisellini, G.; Ghirlanda, G.; Oganesyan, G.; Ascenzi, S.; Nava, L.; Celotti, A.; Salafia, O.S.; Ravasio, M.E.; Ronchi, M. Proton-synchrotron as the radiation mechanism of the prompt emission of gamma-ray bursts? *Astron. Astrophys.* **2020**, *636*, A82. [CrossRef]
267. Mészáros, P.; Ramirez-Ruiz, E.; Rees, M.J.; Zhang, B. X-Ray-rich Gamma-Ray Bursts, Photospheres, and Variability. *Astrophys. J.* **2002**, *578*, 812–817. [CrossRef]
268. Ryde, F. Is Thermal Emission in Gamma-Ray Bursts Ubiquitous? *Astrophys. J.* **2005**, *625*, L95–L98. [CrossRef]
269. Giannios, D. Prompt emission spectra from the photosphere of a GRB. *Astron. Astrophys.* **2006**, *457*, 763–770. [CrossRef]
270. 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]
271. 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]
272. Rees, M.J.; Mészáros, P. Dissipative Photosphere Models of Gamma-Ray Bursts and X-Ray Flashes. *Astrophys. J.* **2005**, *628*, 847–852. [CrossRef]
273. Pe'er, A.; Zhang, B.B.; Ryde, F.; McGlynn, S.; Zhang, B.; Preece, R.D.; Kouveliotou, C. The connection between thermal and non-thermal emission in gamma-ray bursts: General considerations and GRB 090902B as a case study. *Mon. Not. R. Astron. Soc.* **2012**, *420*, 468–482. [CrossRef]
274. Pe'er, A.; Mészáros, P.; Rees, M.J. Peak Energy Clustering and Efficiency in Compact Objects. *Astrophys. J.* **2005**, *635*, 476–480. [CrossRef]
275. Vurm, I.; Lyubarsky, Y.; Piran, T. On Thermalization in Gamma-Ray Burst Jets and the Peak Energies of Photospheric Spectra. *Astrophys. J.* **2013**, *764*, 143. [CrossRef]
276. Ito, H.; Nagataki, S.; Matsumoto, J.; Lee, S.H.; Tolstov, A.; Mao, J.; Dainotti, M.; Mizuta, A. Spectral and Polarization Properties of Photospheric Emission from Stratified Jets. *Astrophys. J.* **2014**, *789*, 159. [CrossRef]
277. Gottlieb, O.; Levinson, A.; Nakar, E. High efficiency photospheric emission entailed by formation of a collimation shock in gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **2019**, *488*, 1416–1426. [CrossRef]
278. Beloborodov, A.M. Collisional mechanism for gamma-ray burst emission. *Mon. Not. R. Astron. Soc.* **2010**, *407*, 1033–1047. [CrossRef]
279. Acuner, Z.; Ryde, F.; Yu, H.F. Non-dissipative photospheres in GRBs: Spectral appearance in the Fermi/GBM catalogue. *Mon. Not. R. Astron. Soc.* **2019**, *487*, 5508–5519. [CrossRef]
280. Acuner, Z.; Ryde, F.; Pe'er, A.; Mortlock, D.; Ahlgren, B. The Fraction of Gamma-Ray Bursts with an Observed Photospheric Emission Episode. *Astrophys. J.* **2020**, *893*, 128. [CrossRef]
281. Dereli-Bégué, H.; Pe'er, A.; Ryde, F. Classification of Photospheric Emission in Short GRBs. *Astrophys. J.* **2020**, *897*, 145. [CrossRef]
282. Pe'er, A.; Waxman, E. Prompt Gamma-Ray Burst Spectra: Detailed Calculations and the Effect of Pair Production. *Astrophys. J.* **2004**, *613*, 448–459. [CrossRef]
283. 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]

284. 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]
285. 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]
286. Pe'er, A.; Zhang, B. Physical Conditions That Led to the Detection of the Pair Annihilation Line in the Brightest-of-all-time GRB 221009A. *Astrophys. J.* **2024**, *973*, L51. [CrossRef]
287. Kumar, P.; Panaitescu, A. Afterglow Emission from Naked Gamma-Ray Bursts. *Astrophys. J.* **2000**, *541*, L51–L54. [CrossRef]
288. Lorenz, E.; Martinez, M. High energy astrophysics: The MAGIC telescope. *Astron. Geophys.* **2005**, *46*, 6.21–6.25. [CrossRef]
289. Melandri, A.; Izzo, L.; Pian, E.; Malesani, D.B.; Della Valle, M.; Rossi, A.; D'Avanzo, P.; Guetta, D.; Mazzali, P.A.; Benetti, S.; et al. The supernova of the MAGIC gamma-ray burst GRB 190114C. *Astron. Astrophys.* **2022**, *659*, A39. [CrossRef]
290. H.E.S.S. Collaboration; Abramowski, A.; Aharonian, F.; Ait Benkhali, F.; Akhperjanian, A.G.; Angüner, E.; Anton, G.; Balenderan, S.; Balzer, A.; Barnacka, A.; et al. 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]
291. H.E.S.S. Collaboration; Abdalla, H.; Aharonian, F.; Ait Benkhali, F.; Angüner, E.O.; Arcaro, C.; Armand, C.; Armstrong, T.; Ashkar, H.; Backes, M.; et al. Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow. *Science* **2021**, *372*, 1081–1085. [CrossRef] [PubMed]
292. Cao, Z.; della Volpe, D.; Liu, S.; Bi, X.; Chen, Y.; Piazzoli, B.E.; 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]
293. Cao, Z.; Aharonian, F.; An, Q.; Axikegu; Bai, Y.X.; Bao, Y.W.; Bastieri, D.; Bi, X.J.; Bi, Y.J.; Cai, J.T.; et al. Very high-energy gamma-ray emission beyond 10 TeV from GRB 221009A. *Sci. Adv.* **2023**, *9*, eadj2778. [CrossRef]
294. LHAASO Collaboration.; Cao, Z.; Aharonian, F.; An, Q.; Axikegu, A.; Bai, L.X.; Bai, Y.X.; Bao, Y.W.; Bastieri, D.; Bi, X.J.; et al. A tera-electron volt afterglow from a narrow jet in an extremely bright gamma-ray burst. *Science* **2023**, *380*, 1390–1396. [CrossRef] [PubMed]
295. Ravasio, M.E.; Oganesyan, G.; Salafia, O.S.; Ghirlanda, G.; Ghisellini, G.; Branchesi, M.; Campana, S.; Covino, S.; Salvaterra, R. GRB 190114C: From prompt to afterglow? *Astron. Astrophys.* **2019**, *626*, A12. [CrossRef]
296. Derishev, E.; Piran, T. GRB Afterglow Parameters in the Era of TeV Observations: The Case of GRB 190114C. *Astrophys. J.* **2021**, *923*, 135. [CrossRef]
297. Isravel, H.; Pe'er, A.; Bégué, D. Proton Synchrotron Origin of the Very-high-energy Emission of GRB 190114C. *Astrophys. J.* **2023**, *955*, 70. [CrossRef]
298. Isravel, H.; Bégué, D.; Pe'er, A. Hybrid Emission Modeling of GRB 221009A: Shedding Light on TeV Emission Origins in Long GRBs. *Astrophys. J.* **2023**, *956*, 12. [CrossRef]
299. Böttcher, M.; Dermer, C.D. High-energy Gamma Rays from Ultra-high-energy Cosmic-Ray Protons in Gamma-Ray Bursts. *Astrophys. J.* **1998**, *499*, L131–L134. [CrossRef]
300. Totani, T. TEV Burst of Gamma-Ray Bursts and Ultra-High-Energy Cosmic Rays. *Astrophys. J.* **1998**, *509*, L81–L84. [CrossRef]
301. Razzaque, S.; Dermer, C.D.; Finke, J.D. Synchrotron Radiation from Ultra-High Energy Protons and the Fermi Observations of GRB 080916C. *Open Astron. J.* **2010**, *3*, 150–155. [CrossRef]
302. Sironi, L.; Spitkovsky, A. Particle Acceleration in Relativistic Magnetized Collisionless Electron-Ion Shocks. *Astrophys. J.* **2011**, *726*, 75. [CrossRef]
303. 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]
304. Zhang, B.T.; Murase, K.; Ioka, K.; Zhang, B. The origin of very-high-energy gamma-rays from GRB 221009A: Implications for reverse shock proton synchrotron emission. *arXiv* **2023**, arXiv:2311.13671. [CrossRef]
305. Cherenkov Telescope Array Consortium; Acharya, B.S.; Agudo, I.; Al Samarai, I.; Alfaro, R.; Alfaro, J.; Alispach, C.; Alves Batista, R.; Amans, J.P.; Amato, E.; et al. *Science with the Cherenkov Telescope Array*; World Scientific: Singapore, 2019. [CrossRef]
306. Coburn, W.; Boggs, S.E. Polarization of the prompt γ-ray emission from the γ-ray burst of 6 December 2002. *Nature* **2003**, *423*, 415–417. [CrossRef]
307. Yonetoku, D.; Murakami, T.; Gunji, S.; Mihara, T.; Toma, K.; Sakashita, T.; Morihara, Y.; Takahashi, T.; Toukairin, N.; Fujimoto, H.; et al. Detection of Gamma-Ray Polarization in Prompt Emission of GRB 100826A. *Astrophys. J.* **2011**, *743*, L30. [CrossRef]
308. Gruzinov, A.; Waxman, E. Gamma-Ray Burst Afterglow: Polarization and Analytic Light Curves. *Astrophys. J.* **1999**, *511*, 852–861. [CrossRef]
309. Lyutikov, M.; Pariev, V.I.; Blandford, R.D. Polarization of Prompt Gamma-Ray Burst Emission: Evidence for Electromagnetically Dominated Outflow. *Astrophys. J.* **2003**, *597*, 998–1009. [CrossRef]

310. Chattopadhyay, T.; Gupta, S.; Iyyani, S.; Saraogi, D.; Sharma, V.; Tsvetkova, A.; Ratheesh, A.; Gupta, R.; Mithun, N.P.S.; Vaishnava, C.S.; et al. Hard X-Ray Polarization Catalog for a Five-year Sample of Gamma-Ray Bursts Using AstroSat CZT Imager. *Astrophys. J.* **2022**, *936*, 12. [CrossRef]
311. Gill, R.; Kole, M.; Granot, J. GRB Polarization: A Unique Probe of GRB Physics. *Galaxies* **2021**, *9*, 82. [CrossRef]
312. Birenbaum, G.; Gill, R.; Bromberg, O.; Beniamini, P.; Granot, J. Afterglow Linear Polarization Signatures from Shallow GRB Jets: Implications for Energetic GRBs. *Astrophys. J.* **2024**, *974*, 308. [CrossRef]