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Review Article

Isotropic Long Gamma-Ray Bursts From Unbinding Neutron Stars: The Teranova Model

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Abstract

Long gamma-ray bursts (GRBs), the most luminous explosions in the Universe, are generally explained with the highly anisotropic “jetted-collapsar-seen-head-on” model (collapsar model). We argue that this model has suffered critical experimental setbacks, in particular: non-periodical light curves, quasi-absence of off-axis collapsars, frequent absence of associated supernovae (SNe), weird exclusivity of type 1c/1b SNe, unexplainable ultra-long GRBs, not to mention severe internal inconsistencies.

To overcome these issues, we call for a paradigm change. We suggest modelling long GRBs as *isotropic* explosions powered by unbinding neutron stars (NSts). Indeed, neutron stars possess binding energies that are in line with isotropic energy levels of bursts.

We argue that such tremendous NSt explosions (“teranovae”) may occur during collisions between high-velocity (HV) magnetars and blue supergiant stars. Such collisions have a much more chances to occur in high-density blue galaxies, where indeed most bursts are observed.

A HV magnetar punching into a supergiant star enters extreme super-Eddington mode, attracting 5-10 $M_{\odot}$ or more into its accretion torus in a short time. The disk heats the central NSt, which reaches unbinding temperature and explodes within the host star. The detonation blows away the supergiant’s external layers, creating the H&He stripped core necessary for the ensuing 1c-SN. When the core is smashed into pieces or left behind the optically thick ejecta, we witness a SN-lacking long GRB.

We show that this model fits nicely with most observational data. In particular, we seamlessly integrate the ultra-long GRBs into the framework, we interpret the relativistically-expanding spherical afterglow bubbles naturally, we explain the supernovae blueshifts, we find the creation mechanism for the SN-1c progenitors, and we reconcile kilonova-having long bursts and SN-having short bursts in a unified theory.

Section 1

Introduction

Long Gamma-Ray Bursts

Long Gamma Ray Bursts (GRBs) are the most powerful electromagnetic explosions known in the Universe. They consist of intense emissions of gamma and hard X-rays, typically lasting from 2 s up to several 10³ seconds (the

“prompt emission”) followed by a longer decay phase (the “afterglow”) that usually is observable in X, optical, IR, and radio, lasting for weeks or months.

Gamma-Ray Bursts (GRBs) are usually divided into “short” GRBs, lasting <2 s in the observer frame, arising from binary NSt mergers and from giant magnetar flares, and “long” GRBs (>2 s), supposed to be produced by narrowly collimated-jet-emitting collapsing Wolf-Rayet stars (collapsars) seen head-on. This categorization was

first proposed by Kouveliotou et al. [1]. Recently, new observations have somehow blurred this pure duration-based categorization: some short GRBs showed features of “collapsars” (SNe), and long GRBs have shown features of compact binary mergers (kilonovae).

This justifies the use of the Type-I and Type-II terminology. A burst proceeding from a compact binary merger or from a giant magnetic flare is said to belong to type I (whatever its duration, but normally it will be a short one), and a burst produced by the full unbinding of an NS (normally a long GRB) will be associated with type II.

We shall henceforth quote energy levels in units of foe (fifty-one-erg), with 1 foe=1051 erg, equivalent to the canonical SN-1a total energy budget. Long GRBs typically release isotropic-equivalent electromagnetic energy budgets of 1 to 104 foe (1051 to 1055 erg) in the progenitor rest frame.

In Section 2, we shall argue that the most widely accepted model for explaining long GRBs, namely the “collapsar model”, has failed many critical experimental tests and even theoretical criteria, and that it should therefore be entirely discarded.

We argue that most available evidence hints at long GRBs being isotropic explosions. We shall then engage in the not-so-straightforward task of figuring out a realistic physical process capable of releasing such tremendous amounts of energy (1 to 104 foe) in such short times (101 to 103 seconds).

In Section 3, we introduce our new model for isotropic long GRBs, the “teranova model” – named according to peak luminosity nova-kilonova, etc, convention. According to this new theory, long GRBs are tremendously energetic (roughly isotropic) detonations (teranovae) powered by unbinding neutron stars. We cautiously develop a possible, albeit very rare, scenario leading to an NSt unbinding, namely a collision between a high-speed magnetar and a supergiant star.

To introduce the teranova model, we present mainly ideas, with energy level estimates. Indeed, at this stage, ideas are what are needed, since the community is stuck in the collapsar model dead end. We need to understand what is really going on in long GRBs. Only then will we be able to develop any meaningful new simulations. Furthermore, precise simulations will take a lot of time to elaborate, since the involved ultra-high-energy physics is mostly unknown. In the field of supernovae, similarly, the main ideas were discovered first, and the community had to live for decades before the first successful digital simulations were achieved.

In Section 4, we confront the teranova theory with observational data. We show that the new model elegantly

solves most of the open issues currently plaguing the jetted collapsar model. It could thus solve two long-standing mysteries of astrophysics: the real nature of long gamma-ray bursts and the formation process of 1c-SN progenitors.

Section 2

Difficulties of the collapsar model

The failures of the predominant collapsar model

In this section, we detail the main (experimental and theoretical) failures of the collapsar model of long GRBs/bursts of Type II, namely:

- The clearly non-periodic pattern of the light curves (suggesting that they do not arise from highly anisotropic, fast-rotating sources).
- The absence of any clear-cut observation of jetted collapsars from the side, even after several years of intense monitoring.
- The lack of any mechanism for creating the SN-1c progenitors.
- The lack of good physical reasons why only supernovae of type 1c should be associated with bursts.
- The absence of any associated SNe in cases when they should have been detectable.
- The (radio-imaged) spherical afterglows expanding at relativistic speeds.
- The absence of neutrino detection.
- The unexplainable duration of the longest bursts, the ultra-long GRBs (ULGRBs).
- The too numerous or too early precursors.
- The large observed blueshifts of many associated SNe.
- The significant proton contribution to the observed synchrotron radiation. And, last but not least,
- The internal collapsar model theoretical inconsistencies.

Some of the collapsar model experimental failures (the *TeV photon showers experienced in some very powerful long bursts and the kilonova emissions detected in some nearby long bursts*) shall be dealt with in the following paper.

Non-periodical light curves

The most serious and obvious problem of the collapsar model is the absence of any periodicity in the time-

resolved (bolometric or energy-specific) light curves. This is especially disturbing since long GRB prompt emissions typically last 10(1 to 3) sec or more, looking only at their t_{90} (the time interval during which 90% of the energy is received), while their emitting sources are supposed to rotate tens or hundreds of times per second.

That is, the prompt phase light curves extend over many progenitor periods, as newly born neutron stars or black holes left over from supernovae explosions are known to rotate with spin rates of 10 to 100 Hz [2]. During the collapse, the collapsar should reach spinning rates that would translate into detectable light curve periodicity. In essence, a jetted collapsar is a (very powerful) short-lived pulsar. It should display a signal that is similarly oscillating.

Some authors have, in fact, found oscillatory features in some burst light curves, but only of small amplitudes, hinting at ancillary pulsations or eclipsing phenomena, rather than entire source rotation [3]. A recent study has found quasi-periodical oscillations (in some cases with up- or down-chirping) in 34 long GRBs [4], but they were of small amplitudes (no full periodicity of the signal, and all of them had main periods between 1 and 30 sec, i.e. much longer the typical spin periods of expected progenitors, hinting at other causes [4].

This non-periodicity does not proceed from a limitation of the detectors since, for example, the Fermi observatory tags individual arriving photons with 2 microseconds precision in its full 128 spectral channels [5].

Blazars offer perhaps the best counter-example. In the cosmic zoo, blazars are the closest thing that can be found to a jetted collapsar pointing at us. As should be expected, blazars have been found to display true light curve periodicity, obviously with much longer periods, expressed in hundreds of days, since their sources are much more massive [6,7].

By visual inspection, long GRB light curves really do not suggest highly anisotropic, fast-rotating sources, but rather a roughly isotropic (and chaotic) phenomenon, closer in nature to a SN explosion than to a highly-focused, fast-rotating jet.

Quasi-absence of off-axis collapsars

Even after trying for dozens of years, astronomers have never detected with a satisfactory level of confidence any jet-emitting collapsar seen from the side. Not a single direct visual case and only a handful of indirect, tentatively deducted but unconfirmed cases.

Whereas the collapsar model predicts that hundreds of off-axis collapsars should occur every day, since those should be a thousand times more frequent than head-

on collapsars (i.e., the detected long GRBs). Heuristic arguments suggest that, even if considering only distances $z < 0.1$ ($d < 400$ Mpc), we should observe 1 off-axis collapsar every 10 to 30 days.

Many teams have expressed hopes of having serendipitously identified one off-axis long GRB, based on different indirect indices, like similarities with X-ray light curves of LGRBs or with typical associated SN light curves [8-14]. However, in all cases, the evidence has remained piecemeal and inconclusive.

Systematic searches for off-axis jetted collapsars were undertaken as well, relying on indirect evidence, but mostly without success [15,16]. Recently, a sample of 14 GRB-lacking SNe of type 1c-BL, found in galaxies typical for long GRBs, was investigated with the VLA radio telescopes, with just one possible positive result – that was, however, compatible with other explanations [17].

The most ambitious systematic search program was the afterglow-based survey conducted at the Zwicky Transient Facility (ZTF) at the Palomar observatory, aiming at finding LGRB-like optical afterglows with no simultaneous burst as seen from the Earth. Ho et al. and Ho et al. [18,19] reported that over four years, from June 2018 to August 2022, the ZTF scoring the sky every night, has discovered exactly 3 suitable transients, with redshifts spectroscopically measured between $z=0.876$ and $z=2.9$. A total of 3 off-axis afterglow candidates over the whole Universe up to $z=2.9$ during a 4 yr interval is a far cry from the 100,000 to 200,000 cases per year that would be absolutely needed if the collapsar model were true. The authors could not exclude that their paltry sample of 3 cases was linked to technical errors, like brief shutdown of the observatories, that would have led us to miss detectable associated gamma bursts.

Clearly, something is deeply wrong with our picture of the central engines powering long GRBs.

If we cannot find any off-axis long GRB, however hard we try, the most straightforward explanation for this is that there is no such thing as an off-axis jetted collapsar, i.e., that there is no jetted collapsar at all.

No credible mechanism for creating the SN-progenitors

All SNe associated with long GRBs belong to type 1c (or sometimes 1b). From the complete absence of any H and He lines in their spectra, it is inferred that the progenitors of SN 1c were stripped of their hydrogen and helium layers before going supernova. The counter-hypothesis that He was still present in the progenitor and that the He lines were just smeared out in the spectra has been eliminated after detailed analysis by Modjaz et al. [20].

This stripping of the core is supposed to have occurred either from the star's own stellar wind or from the action of a companion star in a binary system. However, as Modjaz et al. [20] emphasized, neither of these models does succeed in removing the whole He-layer (so that less than $0.2 M_{\odot}$ remains).

The generation process of the SN-1c remains an open issue.

Weird exclusivity of type 1c/1b SNe

Furthermore, the collapsar model fails to explain why the associated SN should systematically belong to the 1c-BL class (or 1b) and never to the more usual hydrogen & helium-showing Type II core collapse SNe.

The usual collapsar modelling assumes a stripped core (and hence relies on hydrogen-free Wolf-Rayet stars), since this is needed to be in line with empirical observations, but this feature looks artificial and does not really come out as a logical feature within the collapsar model.

Whereas there is a big physical difference between a stripped and a usual progenitor. Hence, there should exist a solid physical reason why only SNe of type 1c (or 1b) may appear alongside long gamma-ray bursts.

Frequent absence of associated SNe

The collapsar model in its second version, the 1999 "Collapsar with Hypernova" model [21], has become the generally accepted theory after it triumphed with the observation of GRB 030329A, the second closest long GRB observed at the time, at $z=0.1685$ ($d=590$ Mpc roughly), that belonged to the typical cosmological long GRB class.

Observationally, however, most long GRBs come out without any associated SN. Among the 1,000 long GRBs that have been localized with high angular precision after SN1998bw, only ~50 have been found to display an associated SN [22].

Far-away SNe are clearly most difficult to observe, due to intrinsic faintness and galaxy extinction. However, even in the relatively local Universe, up to $z<0.15$, Dado & Dar [23] have found that just 50% of long GRBs displayed an associated SN, i.e., 5 in a sample of 10 GRBs with a known redshift $z<0.15$. Some nearby bursts have conspicuously lacked any SN, as emphasized by Tanga et al. [24], who gave three examples of long bursts, namely GRB 060505, GRB 060614, and GRB 111005A (the latter at $z=0.01326$, at this time the second closest long GRB ever detected), showing no coincident SN even after intense search trial by MUSE and even as a radio afterglow was found.

One way to iron out this issue of the missing associated supernovae would be to reactivate the original, 1993-Failed

Supernova Collapsar model [25]. However, this solution would transform the other half of the burst sample, namely, the 50% of SN-having long GRBs, into a problem.

The collapsar model entirely fails to explain that "supernova optionality" in long GRBs.

Relativistically-expanding spherical afterglows

In two lucky cases (bursts that were both nearby and powerful), namely for GRB 030329A, the historical first SN-having cosmological long burst at $z=0.1685$, and for GR 221009A, the "Brightest Of All Times" (BOAT), at $z=0.1505$, the afterglow scenery could be imaged directly via radio VLBI. The size and expansion speed of the emission region could be estimated, and the results tended again to be very difficult to reconcile with the collapsar model [26,27].

The best fit was a spherical emission zone expanding with a Lorentz factor $\Gamma=3$ to 5 for 030329A [26], i.e., $\beta=0.94-0.98$, and even faster for 221009A, after correcting for relativistic geometric effects as per Rees (1966). The kinetic energy budget required for such a relativistically-expanding bubble was estimated at 300 foe... That is, much more than any supernova can release. This result ruined decade-long efforts to bring down long GRB energy budgets to "reasonable" levels (i.e., not exceeding 1 foe, the canonical SN e-m budget) via the collapsar model. Moreover, these afterglow emission zone imaging clearly hint at long GRBs being isotropic explosions.

Absence of neutrino detection

No clear-cut detection of GRB-emitted neutrinos was reported so far. Ai & Gao [28,29] showed that, in the case of the BOAT GRB 221009A, the absence of any VHE neutrino detection leads to discard two collapsar sub-models, namely the dissipative photosphere model and the internal shock model (except if the different sub-jets had extreme bulk Lorentz factors of respectively $\Gamma>\sim 400\Gamma$ and $\Gamma>\sim 200$). Only the "Internal-collision-induced Magnetic Reconnection and Turbulence" (ICMART) collapsar submodel remained unscathed by the neutrino non-detection.

Unexplainable ultra-long GRBs

Ultra-long GRBs (ULGRBs) are generally defined as bursts exceeding 1,000 sec, though this duration sometimes includes the X-ray phase following the pure gamma-ray phase. Most authors agree that ultra-long bursts cannot be generated by fast-collapsing Wolf-Rayet stars. As pointed out by Boër, Gendre & Stratta [30], during such ultra-long bursts, we see a continuous emission of the source for up to 6,000 sec in gamma-rays, and 20,000 sec in X-rays, both emissions showing a strong correlation. Furthermore, ULGBs display much stronger thermal emissions than usual long GRBs.

All of this seems all but impossible to reconcile with the scenario of a star emitting focused jets (seen head-on) while undergoing a very brief, millisecond-long, collapse.

Even as they represent a small minority (less than one percent) of long GRBs, these ultra-long bursts are only adding to the collapsar model woes.

Unexplainable precursor patterns

Some long GRBs are preceded by one or two weaker energy releases, in gamma and X-rays, coming several seconds to hundreds of seconds before the main gamma-ray pulse. 10% to 20% of long GRBs seem to display such precursors. We may, however, expect the real proportion to be higher, since it is very likely that not all precursors are captured, due to detector availability, energy thresholds, and other practical limitations. Some bursts even showed two precursors, like GRB 210204A [31].

In the collapsar model, precursors are interpreted as either (1) the first emergence of the jet outside of the stellar envelope. This first jet would be later dimmed by a “rarefaction wave” propagating backwards. Reinforced by this wave, a final, stronger relativistic jet would finally arrive. This scenario works only for single precursors preceding the main pulse by no more than 10 sec, whereas many precursors show up much earlier. (2) Alternatively, the precursor may be interpreted as a tinier jet taking place during an intermediary collapse of the Wolf-Rayet Star into a neutron star, before entering into main-jet-emitting black-hole forming collapse [32]. The latter explanation runs into intrinsic difficulties for the bursts displaying two or more precursors.

In short, the collapsar model falls short of any explanation for a sizeable subsample of observed precursors in long GRBs.

Blueshifted supernovae

Modjaz et al [20] have identified in the spectra of GRB-associated SNe an increased photospheric expansion velocity of 5,000-10,000 km/s on average. That could be interpreted as very bright SNe, or as blueshifted SNe. The latter case, the most likely as we shall argue in Section 4, may not be accounted for by the collapsar model.

Overwhelming proton contribution to observed synchrotron radiation

Ghisellini et al. [33] have shown that the (time-integrated) spectral energy distribution (SED) of most long GRBs can be best fitted with three patched power law functions instead of two, i.e., with a Band function [34] containing two junctions (or “breaks”).

However, this improved Band-Ghisellini function implies a slow cooling down (>1 s) for the particles emitting

the cool component of the synchrotron radiation. The only way to explain that (while keeping the other parameters, like the magnetic field strength, at reasonable levels) is to assume a synchrotron radiation predominantly emitted by protons. Such a proton-dominated synchrotron radiation cannot be accounted for by the jetted collapsar model.

Weaknesses and internal inconsistencies of the collapsar model

Finally, the collapsar model is plagued by internal inconsistencies and mathematical weaknesses.

No suitable modelling for the prompt emission light curve could be developed so far. The light curves are chaotic, very different from burst to burst, and they have resisted any standardization and any classification attempt, other than very superficial [35].

The precise physical mechanism powering the prompt phase gamma emission has remained a mystery [36,37]. It could be a baryonic fireball or a Poynting flux-dominated jet. The radiation mechanism could be synchrotron, synchrotron self-Compton, or Comptonization of quasi-thermal emission from the photosphere, none of these models fitting the data convincingly [38-40]. The energy dissipation and particle acceleration mechanisms vary from shocks to magnetic reconnections.

The required extreme jet collimation is another modelling challenge. Most models of jet formation rely on neutrino-induced heating or magnetic collimation, but they are unable to cope with observational data.

Worse, some recent works have led to the conclusion that the collapsar model was impossible altogether. The first 3D-GRMHD simulations of a collapsar demonstrated that any associated supernova was in fact entirely excluded: the collapsar’s nascent jets actually sweep away the external star layers, while the core swiftly collapses into a black hole, preventing any supernova-like explosion from happening [41].

Similarly, the jets generated by the collapsing core are supposed to explode the star’s external layers, but it is doubtful that the jet energy budget suffices to impart the kinetic energy released by the (effectively observed) associated SN 1c-BL. Moreover, in order to transfer the required kinetic energy to the external layers, the jets should be less collimated than required by observed GRBs, or alternatively start with unreasonable energy levels [42].

Conclusion

By assuming highly anisotropic explosions, the collapsar model has helped us keep long GRBs apparently “decent”, by seemingly reducing their total energy budgets down

to SN-levels or below. However, this craving for decency has led us to a dead end, with a model that does not work mathematically and has been disproven by observations. Worse, it has made us blind to very interesting new physics.

The collapsar model has failed and should be replaced by a new, more performing model – a model that should be coherent and more in line with observational data.

Section 3

The Teranova Model

1---Binding energies of NSt vs long GRB energy releases

Long GRBs are measured to release total (isotropic equivalent) energies in their rest frame that are comparable in magnitude to the binding energy of neutron stars (NSts).

The total binding energy ϵ of a star can be expressed as $M_{\text{grav}} = N_B \cdot m_B - \epsilon/c^2$, where N_B is the number of baryons, m_B is the mass of the baryon, and the gravitational mass M_{grav} is the final mass of the star once formed. Most of ϵ is supposed to come from gravitational binding energy (GBE), the remaining parts consisting of other potential energies, notably stemming from the strong interaction and from the Pauli exclusion principle.

For calculating the gravitational binding energies (GBE) of an NSt, the Newtonian formula gives a first approximation:

$$E_{\text{grav}} = \frac{3}{5} G \frac{M^2}{R} = \frac{3c^4}{20G} \frac{R_g^2}{R} \quad (1)$$

This formula supplies the Newtonian gravitational binding energy E_{grav} of a sphere of final (after star formation) mass M and radius R Where $R_g = 2GM/c^2$ is the Schwarzschild radius or gravitational radius.

The possible ranges for NSt gravitational masses and radii, the main parameters in the Newtonian formula, are not known accurately. According to theory, neutron stars may exist with gravitational masses between 1.44 and 2.16 $M_\odot$. However, observational results suggest that neutron stars may exist from $M=1.20$ -1.30 $M_\odot$ up to $M=2.50$ -2.90 $M_\odot$. The most massive NSt masses measured so far are PSR B1516+02B, a 7.95 ms pulsar member of a binary system, with an individual mass $M=1.94$ (+0.17 -0.19) $M_\odot$, and PSR J1748-2021B, a 59.665Hz (16.76 ms) pulsar with a mass $M=2.74$ +/-0.21 $M_\odot$ belonging to another binary system [43,44].

As for NSt radii, the NICER experiment has obtained the first precise estimations in the case of the 205.53 Hz millisecond pulsar J0030+0451. Two separate sub-projects have obtained for this object either a mass of 1.44 $M_\odot$ (+0.15/-0.14) and a radius of 13.02 km (+1.24/-1.06 km)

[45] or a mass of 1.34 $M_\odot$ (+0.15/-0.16 $M_\odot$) and for the equatorial radius 12.71 km (+1.14/-1.19 km) [46].

For such cases of measured NSts, the Newtonian formula gives binding energies between 9% of the gravitational mass for the smaller NSt (J0030+0451) and 15-17% for the larger one (PSR J1748-2021B) – by assuming for the latter a radius of 14,7-15,5 km after conservatively assuming a density close to the highest end of the densities measured in the other, smaller and better known NICER NSt (to compare to 7,5-8,7 grav radius for the same mass).

Recently, the most precise estimate for a 1.4 $M_\odot$ -NSt radius was obtained by Guedes et al. (2025), at 12.48 km (+0.41/-0.40 km), by interpreting quasi-periodic oscillations detected in the light curves of two (thirty-year-old) short GRBs (namely GRB 910711A and 931101B), as quasiradial and quadrupolar oscillations of binary neutron star merger remnants.

To refine GBE estimations, relativistic effects are taken into account with numerical simulations. Lattimer [47] provided values from different models. With $R_g/R=0.15$, the GBE should remain round 10% of the gravitational (final) mass of the NSt. With a ratio $R_g/R = 0.33$, NSt should typically possess a binding energy from 17 to 35% of the gravitational mass, depending on the models.

Jiang, Wen & Chen [48] estimated that NSt binding energies may, depending on the equation of state and compactness, take values from 5% to 50% of the gravitational mass for a non-rotating NSt from 1.40 $M_\odot$ up to 2.47 $M_\odot$.

We shall keep in this paper the broadest interval (5 to 50%), to remain on the safe side. This implies that (non-rotating) NSts may be considered to be endowed with binding energies of between 90 and 2,700 foe – admitting an interval for possible NSt mass values ranging between 1 and 3 $M_\odot$.

Long GRBs have been observed to release between 10 and 4,000 foe in isotropic equivalent electromagnetic energy, with a few exceptions below and above [49-52]. That is, there is a good match between both energy distributions, at least between the NSt binding energy distribution and the central part of the long GRB energies. We shall discuss the mismatch in the lower and higher segments of the spectrum at the end of Section 4.

2---Could unbinding NSt provide the central engines for long GRBs?

This comparison suggests the idea that exploding neutron stars could indeed be the central engines of long GRBs. However, neutron stars are usually thought of as dead ends of stellar evolution, not able to lose mass or explode.

Due to their extremely strong gravity, they are supposed to have no other option than to grow further by aggregating more mass, or at some point, to become a black hole.

NSt mergers during a binary coalescence and giant magnetic flares may provide rare minor deviations to this rule, as it is widely accepted that such events may allow NSts to liberate some of their mass. It is believed that NSts may expel $3\text{--}5 \times 10^{-2} M_{\odot}$ of NSt matter during binary mergers [53], or $\sim 10\text{--}6 M_{\odot}$ of crustal matter during magnetic flares [54].

However, losing a minor amount of mass is a far cry from unbinding entirely. Everybody shall agree, however, that an NSt can unbind in principle, provided it is given enough energy for its component particles to reach escape velocity – that means, a tremendous amount of energy. In that paper, we argue that such scenarios do indeed occur in Nature, albeit in exceptional cases.

3---The Fast-Accreting Shooting NSt Scenario

The main scenario that we suggest in that paper is a collision between a hypervelocity NSt and a supergiant star, for instance, a blue supergiant star.

Such collisions between hypervelocity NSts and blue supergiants have barely been investigated so far, perhaps because they seem so weirdly asymmetrical (they pit an object of 20-30 km against one of 10(7 to 9) km) and because they have a vanishingly low probability of occurring.

However, when it comes to explaining extremely rare events, very low frequency turns out to be an advantage. Long GRBs have occurrence rates of barely 2×10^{-9} to $2 \times 10^{-10} \text{ Gyr}^{-1}$ in any given galaxy, assuming 400 events Universe-wide per year for a total number of 2×10^{11} to 2×10^{12} galaxies. Hence, a very low probability phenomenon is what is needed to explain long GRBs.

We call this scenario the “Fast-Accreting Shooting NSt scenario”. We shall restrict the discussion to the main ideas and energy levels, since the extreme physics at play is mostly unknown. We begin with an NS endowed with a very strong magnetic field – a magnetar or a highly magnetized pulsar.

This object has a very high speed – typically in the range of 0.1%-1% of the speed of light. This compact star was initially (“rectilinear collision”, or unbound collision) accelerated either by the central galactic supermassive black hole (SMBH) or by an asymmetric SN explosion, or by a binary system companion gone supernova. Alternatively, the shooting NSt was a member of a multiple system (“loop collision”, or bound collision) comprising at least one NSt and one supergiant star. The NSt was deflected onto the supergiant companion after some external perturbation. Or the NSt dived into the supergiant after a coalescence process. We shall detail these different cases below.

When the collision between the blue supergiant star and the hypervelocity magnetar takes place, several outcomes are possible, depending on the striking angle, NSt speed and spin, and on the supergiant star mass, density function, and spin.

The shooting NSt might just superficially dive into some exterior layers and escape, thanks again to its very high speed, or it may punch deeply into the supergiant hydrogen layers. It may possess sufficient speed to come out again at the other side of the supergiant (provided it is still there), as suggested by Hirai & Podsiadlowski [55], or it may slow down sufficiently and inspiral around the supergiant core.

Fast Accretion and Heating from the Accretion Torus

In the case of a deep dive into the supergiant, the shooting magnetar will aggregate sizeable amounts of gas from the target supergiant star envelope.

A hypervelocity NSt punching at 0.1%-1% of the speed of light into a $30 R_{\odot}$ -star (diameter 150 light-seconds) shall spend several hours or more diving across the host before escaping on the other end – and even longer if it slows down significantly.

We argue that, due to its high speed, the shooting NSt will enter an extreme Super-Eddington mode and build an accretion torus of $\sim 1\text{--}10 M_{\odot}$ or more, within a time shorter than its host-star-crossing time.

Friction forces in the accretion torus will convert 10-20% of this accreted mass into thermal energy. This tremendous release of radiation shall be absorbed in part (perhaps as much as 50%) by the NSt at the center of the accretion torus, implying that ~ 0.1 to $1 M_{\odot}$ (or 180 to 1,800 foe) or more of thermal energy shall be absorbed by the NSt in a very short time if $1\text{--}10 M_{\odot}$ was accreted in the first place. This brings us to the energy release range of most long GRBs.

We argue that during this whole fast-accretion process, the shooting NSt shall be mostly shielded at lower altitudes above its surface against infalling matter absorption by its extremely strong magnetic field, thermal radiation pressure, and neutrino emission pressure, with the radiative pressure playing a heavier role due to the even more extreme temperatures encountered there, as summarized, e.g., by Mushtukov et al. [56]. Therefore, the magnetar has a good chance of not becoming a black hole before reaching the critical unbinding temperature.

Central star heating with an accretion disk

The accretion disk produces energy by shocks and friction between the particles that are aspired into it. It is a highly efficient way of converting matter into energy, more

efficient than thermonuclear reactions. As much as 40% of the initial matter mass entering the disk may finally be converted into pure radiation energy.

The overheating accretion disk emits some share of its luminosity L_{acc} towards the central star. Popham [57] has shown that the emission by the internal disk layer may reach 40% of the total accretion luminosity L_{acc} , and that the central star may absorb up to 50%-75% of that energy, i.e. $0.4 \cdot (0.5 \text{ to } 0.75) \cdot L_{\text{acc}} = 0.2 \text{ to } 0.3 L_{\text{acc}}$. This means that 8% to 12% of the total initial mass accreted by the disk may typically end up heating the central star.

Averting neutrino cooling

It may be objected that fast neutrino cooling should impede the central NSt from reaching the unbinding temperature. Neutrino cooling is assumed to be the main cooling channel for NSt in high temperature ranges. A very hot NSt should indeed emit large quantities of neutrinos via Urca processes (beta disintegrations and integrations, mainly: $n \rightarrow p + e^- + \bar{\nu}_e$ and $p + e^- \rightarrow n + \nu_e$) or above a certain temperature by neutrino-antineutrino pair creations. This could allow the shooting NSt to evacuate the excess energy and cool down, and thus avoid reaching critical temperature.

However, we shall argue that very strong neutrino emissions coming from the ultra-hot accretion torus plasma (via thermonuclear reactions and pair creations) may match at least partially the NSt- emitted neutrino radiation and bring the system into a neutrino thermal equilibrium, allowing the central magnetar to further increase its temperature.

This assumption is confirmed by the fact that in some simulations, the neutrino pressure could even explode the whole accretion torus [58]. The authors have applied much lower infalling rates in the range Eddington rate $dM/dT \sim 10^{-8} \text{ M/yr}$. We assume that with a 10^9 times stronger infalling rate, the accretion torus thickness and weight may reduce its probability to be carried away by the central NSt neutrino pressure, while the neutrino luminosity stemming from the NSt should still efficiently impede too much infalling matter from reaching the NSt surface. This remains to be modeled.

Travel time inside the supergiant and accreted mass

We argue that in favorable cases, all of this can take place during no more than $(10 \text{ to } 100) \cdot 10^3$ seconds, so that the travel time within the supergiant star should be long enough to pursue this whole process until it brings the NSt to critical unbinding temperature. Some shooting NSt might become gravitationally bound to their host and cross it several times, diving back after escaping.

When the NSt unbinds and explodes, it sequentially frees the accretion torus that had formed around it, since the central gravitationally attractive body is gone.

During that liberation, the inner tore of the torus will escape first (its particles changing their trajectories from small circles to larger circles and finally straight lines). Then the median torus will deviate similarly, and then the external part of the torus. This immediately suggests a first explanation for why long GRB explosions may, in some cases, release more energy than the pure binding energy of an NS.

4---The prompt phase interpreted as the front-wave emergence into the photosphere

When the NSt explodes, the blast wave carrying the expelled particles (neutrons, protons, atomic nuclei...) propagating at close to the speed of light will create inside the supergiant host a violent shock along its path. This shockwave will imprint a tremendous momentum into the supergiant star envelope, basically blowing it away into the interstellar medium (ISM).

We argue that the most energetic radiation of this whole process will be generated along the first, outermost shock wave. Similarly, the shells expelled by supernovae have been measured to emit their hardest X-rays along the front bubble rushing across the ISM.

Since the supergiant star is optically thick, in particular for the X and gamma photons, the prompt phase that we see from the Earth should essentially consist of that first shock wave as seen when it emerges into the host photosphere. This should be followed by the thermal radiation induced by the violent heating up of the supergiant envelope, and finally by the scenery (if we could resolve it) of the supergiant envelope expanding away in all directions at relativistic speeds.

Since the front wave should reach the photosphere at different times along different directions (depending on the initial position of the NSt within the host star, relative to the supergiant center and relative to the Earth), and since the light needs different times to reach us from these different photosphere point locations, the gamma-ray emissions (the prompt phase) should extend over some period of time and should mix at any given time the emissions from several places on the host photosphere.

If we could resolve the supergiant apparent disk, we would see first a gamma-ray-shining dot along the line of sight between the detonating NSt and us. That would be the first sighting of the blast wave reaching the photosphere. This event would be followed by a growing, gamma-ray emitting ring centered on the previously spotted. The gamma-ray ring would increase in radius until it reaches the

edges of the visible disk, the nearest edge first as seen from the Earth, and the farthest edge last, and then disappear altogether. At each spot of the photosphere, immediately following the gamma-ray enlightenment, would come the view of the expelled supergiant layers expanding into space.

Early Afterglow: the accretion torus liberation

In most long GRBs, the (gamma-ray) prompt phase is followed by an X-ray phase divided into two parts. The first part shows a steep decay where the X-ray flux follows a power law with a coefficient $\alpha > 2$ and significant spectral changes. The second part is a plateau that typically lasts 103–104 s, with a slower X-ray flux decay ($0 < \alpha < 0.80$) [59]. Later on, the classical afterglow sets in.

In the Teranova theory, the early steep X-ray decay phase may correspond to the ending of the NSt blast wave escaping through the photosphere. The X-ray plateau may be generated by the accretion torus ejecta crossing the (blown-away and fast-expanding) supergiant photosphere. First, the very-high energy inner rings of the accretion torus, second, the lower energy medium, and finally, the external rings. (It should be remembered that, in the collapsar model, this plateau phase is quite challenging to account for.)

The reason why the X-ray plateau lasts longer than the gamma prompt phase is that the supergiant envelope has inflated in the meantime, and that the accretion torus particles are liberated gradually, in a process that is slightly longer (lasting $t = r/c$ with r the torus radius) than the practically instantaneous NSt explosion.

Later Afterglow: continuation of the expansion

In the Teranova model, the later X, UV, and optical afterglow phase, after the “jet break”, should stem from the further expansion of the NSt ejecta, accretion torus ejecta, and supergiant blown-away external layers across the ISM, shocking the low-density matter found there, all of them moving chaotically in all directions at high temperatures while cooling down.

All of these fast-expanding materials have been heated to billions of degrees by the NSt explosion shockwave rushing across, not to mention the intense synchrotron and inverse Compton scattering radiations produced by the same ejecta.

Long GRBs akin to SNe-Ia: both are powered by compact star explosions

The Teranova model implies, if correct, that long GRBs bear a deep similarity with SNe of type Ia, insofar as the central engine of both cases is an exploding compact star.

1a-SNe are powered by white dwarves, long GRBs by NSts. The 1a-SNe generate 1-2 foe of energy (out of which most is kinetic energy and 1% in e-m energy), the long GRBs generate thousands of times more energy, since the binding energies of NSts are typically thousands of times larger. Hence, long GRBs are a kind of “type III supernovae”.

There is also obviously a big difference: 1a-SNe are powered by the thermonuclear reactions fed by their own fuel (carbon and oxygen) contained in the white dwarf interior, whereas in long GRBs, there is no nuclear fuel available inside the compact star. The fuel is provided by the accretion torus, transforming gravitational energy into thermal energy.

6---Associated SN of type Ic-BL

The teranova theory provides the so bitterly sought-after mechanism for generating the H&He stripped progenitor of the ensuing type-1c supernova.

When the magnetar explodes deep in the interior of the blue supergiant star, and the accretion torus is liberated, a huge tsunami of high-Lorentz factor ejecta (with an initial kinetic energy of typically up to a few thousand foe), much larger than those of classical supernovae (1 foe for 1a-SNe), is released.

Such a detonation may easily blow away all the supergiant star’s remaining H and He layers. This is easy to assume, since the core-collapse supernova kinetic energy budgets (that can blow away a supergiant envelope) are much lower.

If the NSt blows up far enough from the blue supergiant star core, then we may expect this core to overcome the explosion relatively intact (albeit with some imprinted momentum), because it is more strongly gravitationally bound than the rest of the supergiant star. This creates the stripped core.

That stripped core later evolves into the associated SN 1c-BL a few hours or days later, depending on its size and fuel quantity. Thus, we have found a natural, straightforward process for creating stripped cores, the progenitors of 1c-SNe.

Section 4

The broad line (BL) type of supernova, i.e., the very high photosphere expansion velocities, may be explained by the abrupt heating up of the core induced before the explosion by the interaction with the spinning NSt’s magnetic field. That very strong and rotating magnetic field of the shooting magnetar triggers electrical currents in the supergiant core, transferring tremendous amounts of energy to it while slowing down its spin rate.

Indeed, as hinted at by Mazzali et al. [42], the measured kinetic energy level of the SNe 1c-BL associated with long GRBs reaches at most the maximum rotation energy of an NS, that is, roughly, 20 foe – a budget which exceeds by 20 to 2,000 times the kinetic energy of a typical core-collapse supernova [42].

7---Associated SN... or not

To explain why some long GRBs appear to be associated with a supernova, and some not, the Teranova model offers two different explanations, which both apply, albeit in different cases.

In the first case, the explosion takes place close enough to the blue supergiant center to smash the core into pieces, leaving no progenitor behind for an associated SN. The burst ends up lacking any associated SN.

In the second case, the shooting NSt is situated in front of the supergiant core, as seen from the Earth. The high-energy hotchpotch produced by the NSt unbinding & accretion torus liberation, and the overheated expelled supergiant star external layers, form an optically thick curtain that keeps the ensuing associated SN, on the other side of the hotchpotch, undetectable.

For comparison, Ryu et al. [60] found that the cloud expelled by two red giant stars colliding at 1,000 km/s (a cloud very similar in content and temperature to our ejecta) would remain optically thick for typically 7-8 months. Moreover, usual core-collapse SN ejecta are known to be optically thick.

This second explanation (SN hidden from view) matches well with the empirical fact that, in the case of relatively nearby bursts, half of them appear not to show any associated SN (as obtained by Dado & Dar 2018 A) [23]. Indeed, if randomly distributed, the shooting NSt should detonate about half of the time within the near hemisphere of the host supergiant star (veiling the associated SN), and about half of the time in the far hemisphere (leaving the SN detectable).

This explanation also harmonizes well with the fact that only blueshifted (and no redshifted) GRB-SNe have been discovered [20], since the redshifted SNe are those that remain hidden from our view.

In summary, the shooting NSt model offers a natural explanation to four open issues: (1) why all associated SNe belong to type 1c or 1b (2) how their progenitors are created, (3) why an associated SN is detected only about half of the time (when near to us), and (4) why all GRB-SNe seem blueshifted, to different degrees, but never redshifted.

8---Collisions between compact and massive stars: existing studies

Collisions involving massive stars or hypervelocity compact stars have been studied in very rare cases.

Balberg, Sari & Loeb and Balberg & Yassur [61,62] have theoretically investigated collisions between massive stars within dense stellar clusters orbiting around the central galactic black hole. Kremer et al. [63] have simulated stellar collisions leading to intermediate-mass black holes of above $50 M_{\odot}$. Balberg, Sari & Loeb, Balberg & Yassur, Dessart et al., and Ryu et al. [60-64] focused on collisions between same-size $1 M_{\odot}$ red giants in dense stellar clusters of galactic centers at relatively modest speeds $v > 100 \text{ km/s}$. They found that even at such non-hyper-velocities, 10% of the kinetic energy of the incoming red giants was converted into thermal energy, producing a supernova-like transient.

Kremer et al. [65] have investigated collisions of NSts with main-sequence stars between 0.5 and $1.5 M_{\odot}$ in globular clusters to investigate the formation of millisecond pulsars.

However, collisions between hypervelocity neutron stars and supergiant stars have been studied remarkably little. On top of the already mentioned 2-dimensional studies by Fryer, Benz & Herant or Shapiro & Teukolsky [58], the recent 3D research coming closest to our GRB-producing scenario was conducted by Hirai & Podsiadlowski [55], who have numerically simulated a shooting $1.4 M_{\odot}$ NSt punching at 1,000 km/s into different stars from 1 up to $10 M_{\odot}$. In their scenario, the shooting NSt was born out of an asymmetric SN explosion in a tight binary system, and it rushed right into its companion by chance.

The authors tested target companion stars with masses $M=1, 5, 10 M_{\odot}$ and radii $R=0.94, 2.53, 4.82 R_{\odot}$. The latter case is of interest to us as it belongs to the (inferior segment of) the supergiant star class.

The authors have studied how the supergiant star's external layers evolve during this disruptive event – swept away or rearranged – as well as the incoming NSt trajectory during and after its diving into the target star. They demonstrated that in some cases the shooting NSt may entirely cross the target star, and may even come back and delve again into the target supergiant.

The authors did not, however, focus on the processes that are of interest to us here, namely the accretion process around the NSt during its deep dive into the supergiant, potentially leading it to overheat. They were mostly interested in the binary system dynamics at large. They have restricted themselves to hydrodynamical simulations with gravity as the only acting force (enforcing linear &

angular momentum as well as kinetic & potential energy conservation). They did not include magnetic fields, nor friction forces, nor thermal energy, as this was not in their focus. Neither did they attempt to develop realistic gas accretion processes around the shooting NSts, since the applied simulation grid within the 3 tested stars consisted of 600 steps in the radial direction, i.e., about 6,000 km between grid points on average in the case of the larger star. Such spacing was not meant to simulate a gas flow accreting onto a torus around a 25 km-wide NSt. The implemented simulation would basically remain the same, with a compact object of the same mass and 1,000 km in diameter. Moreover, the authors used a cubic-spline kernel to soften the gravitational potential of the point-like NSt. The adaptive adjustment led to softening lengths of up to 3 grid points, i.e., much larger than the physical size of the NS, and therefore their calculations, per construction, did not model the accretion flux. Also, they did not touch the part of the star family that is of most interest to long GRBs, namely the supergiant stars with masses over $10 M_{\odot}$.

Neights et al [66] have discussed the triple burst GRB 250702 BDE, the scenario of an NS falling into a star. But they have assumed that the NSt would shoot into an already stripped star and that the shooting NSt would quickly evolve into a black hole and then emit a collapsar-like collimated jet while disrupting the target star. They called this model a “helium star merger”, referring to the merger of a compact object (already a BH or to quickly become a BH) with a stripped star. That model clearly remains within the highly anisotropic jetted collapsar paradigm.

9---Fast Accreting Shooting NSt Energetics

Obstacle Supergiant Star

To be able to foster a classical, cosmological long GRB, the supergiant star encountered by the shooting NSt along its way should contain a mass of ideally $M \approx 50\text{--}100 M_{\odot}$, with a radius $R \approx 20\text{--}200 R_{\odot}$. It should belong to the category of the (blue, yellow and red) supergiants of the kind of Zeta Puppis ($56 M_{\odot}$, $20 R_{\odot}$ or 50 light-seconds), Epsilon Orionis/Alnilam ($64 M_{\odot}$, $42 R_{\odot}$ or 100 light-seconds), Eta Carina A ($100 M_{\odot}$, $240 R_{\odot}$ or 600 light-seconds), Rho Cassiopeiae ($40 M_{\odot}$, $700\text{--}900 R_{\odot}$ or max 1,750–2,250 light-seconds) or R136a1 ($200 M_{\odot}$, $43 R_{\odot}$ or 120 light-seconds).

In some cases, for magnetars having masses in the lower range, even a star like Alpha Cygni ($20 M_{\odot}$, $190\text{--}220 R_{\odot}$ or 500 light-sec radius) or Beta Orionis (Rigel), $18\text{--}24 M_{\odot}$, $67\text{--}80 R_{\odot}$) might be big enough to provide enough fuel reserves. We shall say “blue” supergiant to simplify, because blue supergiant stars are the most common case, but our supergiant host could basically be either blue, yellow, or red.

A diameter of 20 to $200 R_{\odot}$ (50 to 5,000 light-seconds) implies that the shooting NSt, even at one percent of the speed of light, shall need, before escaping at the other end of the supergiant, even if not slowing down, at least 5,000 to 500,000 sec (1.5 to 15 hrs), likely giving if sufficient time to accrete enough material to overheat, even if numerical simulations will need to confirm this.

Speed at collision time

A shooting magnetar diving into a supergiant star will need a minimum speed to continue zipping through its host, to accrete further onto its torus until overheating. Otherwise, the shooting NSt would grind to a halt before reaching critical temperature and plunge to the core, where it could build a static Thorne-Żytkow object (a supergiant containing an NSt in its core).

A speed of $1,000 \text{ km/s}$ should be sufficient, since, like Hirai & Podsiadlowski [55] have shown, a shooting NSt endowed with that speed can cross a whole $10 M_{\odot}$ -star and re-emerge on the other side. And indeed, such hypervelocity NSts do exist in Nature. In the Milky Way (MW), young (independent) NSts have been discovered that are darting at velocities of several hundreds of $\text{km}\cdot\text{s}^{-1}$ (i.e., of the same order as the galactic escape velocity). Some pulsars have been found to exhibit speeds exceeding $1,000 \text{ km}\cdot\text{s}^{-1}$, like the central compact object RX J0822-4300 with $1,100 \text{ km/s}$ or like PSR B1508+55 with a transverse speed of $1,083 \text{ km/s}$ [67].

Lower speeds like 500 km/s may suffice as well, since an NS belonging to a binary system with a supergiant (probably the most common source systems for long GRBs) will touch upon that supergiant (after coalescence or after some external perturbation) at typically between 500 and $1,000 \text{ km/s}$. Numerical simulations will yet need to settle this minimum entry speed issue.

We may estimate the entry speed of NSt colliding into its companion in a binary system. The typical NSt orbital speed when approaching the supergiant photosphere is given from the Newtonian gravitational force by:

$$v_{\text{delving}} = \sqrt{GM_{\text{Ns}}} \sqrt{\frac{M_{\text{SupG}}}{R_{\text{SupG}}}} \quad (2)$$

For a given NSt mass (say $1.5 M_{\odot}$), the only relevant factor is the mass/radius ratio of the supergiant.

For example, for a binary system comprising one $1.5 M_{\odot}$ NSt and one $50\text{--}60 M_{\odot}$ star (like Zeta Puppis with $M=56 M_{\odot}$ and $R=20 R_{\odot}$ or Epsilon Orionis/Alnilam with $M=64 M_{\odot}$ and $R=42 R_{\odot}$), we have $v_{\text{delving}}=900 \text{ km/s}$ for Zeta Puppis and $v_{\text{delving}}=660 \text{ km/s}$ for Epsilon Orionis.

Hypervelocity NSt formation mechanisms

We may list 9 possible scenarios leading to a hypervelocity NSt colliding with a supergiant star.

The first 7 cases involve independent (unbound) HV NSt and may be described as leading to “rectilinear collisions” or “unbound collisions”. The Cases 8 and 9 involve NSts that are parts of multiple systems and may be called “loop collisions” or “bound collisions”.

Case 1 – A NSt is generated by a core-collapse SN and is accelerated by an asymmetric explosion.

Case 2 – A NSt is a member of a multiple star system (binary or higher multiplicity) and is ejected when one companion goes supernova, without intercepting its companion, as first conceptualized by Zwicky. Tauris [68,69] theoretically investigated the maximum possible velocities for such HVs (of type G/K dwarfs and late-type B stars) if they are produced from very close binaries disrupted by a core-collapse supernova explosion. They found possible speeds up to ~ 770 and $\sim 1,280$ km/s in the Galactic rest frame.

Case 3 – The NSt (resp. its progenitor) may be expelled from a dense stellar cluster, following N-body interactions [67].

The next four cases (4 to 7) involve interactions with a central galactic supermassive black hole, single or binary (SMBH/SMBHB).

Case 4 – Tidal breakup of a binary star system by a (single) central galactic SMBH. This mechanism was first put forward in a prescient paper by Hills (1988), who therein coined the name “hypervelocity star”. The author suggested that a stellar binary interacting with the Milky Way’s central black hole, if the latter existed, could eject one of the stars away from the other at a velocity of up to $4'000$ km/s. At this time, no HVSt had yet been discovered. Hills went on to suggest that the discovery of such an object would provide solid evidence for the existence of an SMBH at the center of the Milky Way.

Case 5 – Single-star encounter with a binary central galactic SMBH. Guillochon & Loeb [70] have shown that this process can accelerate stars up to 30% of the speed of light, or more.

Case 6 – Single-star encounter with a cluster of stellar mass black holes around the central SMBH.

Case 7 – Interaction between a globular cluster with a single or binary SMBH in the galactic center [71].

Cases 8 and 9 take place within binary or multiple systems. Let us call them “loop collisions” or “bound collisions”.

Case 8 – An NS orbiting around a supergiant star (typically a X-binary or a higher-multiplicity system) could rush into its companion after undergoing some external perturbation, or due to the system’s intrinsic instability. Such events should be more frequent in high-density blue galaxies.

Case 9 – An NS orbiting around a supergiant star (typically a X-binary or a higher-multiplicity system) ends up merging in a classical coalescence scenario. Such an inspiraling towards the supergiant would obviously need to produce a supernova, to be completed before the end of the supergiant’s life, i.e., within a few million years. For a very tight or very eccentric binary, one could imagine the coalescence to be accelerated by the orbiting NSt being deflected into the supergiant by rubbing (via gravitational tidal forces and magnetic field interactions) the atmosphere and photosphere of its companion at each flyby.

Possible energy sources for heating the shooting NSt

As possible energy sources for heating up our shooting NSt during its crossing of the blue supergiant star, on top of its preexisting internal (thermal) energy, we may list the initial kinetic, rotational, and magnetic energies of the incoming shooting magnetar. Those can be transformed, at best, at 100%, into heat via friction and magnetic interactions. Finally, there is the energy radiated inwards by the accretion torus that shall form at a fast pace during the NSt rushing across the supergiant.

A quick review of these energy sources reveals that the accretion process is the only source that may contribute significantly to the (gigantic) energy budget required for a shooting NSt to reach critical temperature.

For the kinetic energy to play a significant role, we would need an HV NSt exceeding half the speed of light. No such object has ever been found, and we may assume that such relativistic speed NSt comes up too rarely in Nature to be of interest here.

The rotational energy may power only low-luminosity long GRBs, up to 100 foe [42].

The magnetic energy budget even of the most extreme magnetars does not exceed 0.01 foe (see e.g. Igoshev, Popov & Hollerbach [72]).

Finally, the thermal energy at a typical collision time (with the shooting NSt age expected to reach at least 1,000 yr) will not provide a significant amount of the gravitational binding energy (at most 1%), as opposed to what was the case in the early instants after their creation.

The latter conclusion may change in one case, namely in the Hirai-Podsiadlowski process, where an asymmetric

SN in a binary system sends a freshly born NSt right into its companion star by chance. In such a (rare) case, given a distance between both companions not exceeding 1 light-week to 1 light-month and a speed of roughly 0.01 c, we might end up with a very young (1-10 yr-old) NSt at collision time. In such a rare case, the shooting magnetar may still contain a significant amount of thermal energy, i.e., it would require a much lower energy input to unbind and could thus fully explode with a less massive companion as a co-progenitor.

10-Reaching an extreme Super-Eddington mode

The hypervelocity NSt will gravitationally dominate a large sector of the supergiant when punching into it. It will build up an accretion disk by grabbing sizeable swathes of matter from the supergiant envelope.

Along its path within the supergiant, the shooting NSt will basically dig a "tunnel" of radius r_{tunnel} proportional to the Hill radius, i.e., $r_{\text{tunnel}} = a \cdot r_{\text{Hill}}$ with $0 < a < 1$.

The gas captured by the shooting NSt will accumulate into an accretion torus. The NSt itself should absorb directly only a tiny portion of this infalling matter, since it is shielded by its strong neutrino emissions, thermal radiation, magnetic field, and high spin rate and ultra-hot polar regions emitting even harder X-rays.

Depending on its initial speed and striking angle, the NSt may begin to inspiral around the supergiant core, doing several orbits before reaching critical temperature, or it may run across the supergiant along an almost straight line, just to dive back into it later on. We argue that the shooting magnetar shall be able to capture during this process a significant amount of gas, i.e., several solar masses, into its accretion torus.

Inside the supergiant star, the shooting NSt is surrounded by a sphere of gravitational influence, or Hill sphere, extending over a radius (Hill radius) of

$$r_{\text{Hill}} = d \cdot \sqrt[3]{\frac{M_{\text{NSt}}}{3 \cdot (M_{\text{SupG}} + M_{\text{NSt}})}} = d \cdot \sqrt[3]{\frac{1}{3 \cdot (\alpha + 1)}} \quad (3)$$

with d the distance between the NSt and the supergiant center and $\alpha = (M_{\text{SupG}}/M_{\text{NSt}})$.

Implying that the ratio of Hills sphere volume V_{Hill} to Supergiant volume V_{SupG} is given at the time of diving ($d=R$) by:

$$(V_{\text{Hill}} / (V_{\text{SupG}})) = \frac{1}{3 \cdot (\alpha + 1)} \quad (4)$$

If we take as an example a $2M_{\odot}$ -NSt and as a coprogenitor Zeta Puppis ($56 M_{\odot}$, $20 R_{\odot}$ or 50 light-seconds) for illustration purposes, we obtain ($\alpha=28$) a Hill radius at

$r_{\text{Hill}} = 0.23 \cdot R_{\text{SupG}} = 11$ light-sec, and the Hill sphere reaching about 1.1% of the total supergiant mass, i.e., comprising $0.64 M_{\odot}$ assuming a homogenous density. Even if staying at the same distance from the core, after diving, and running in a circular orbit around the core, the shooting NSt&torus system would need roughly to continue along 10 times the Hill diameter, i.e. $4.6 R_{\text{SupG}}$ i.e. not even one full circle inside the supergiant, to aggregate about $6 M_{\odot}$ – sufficient matter to bring the NSt into critical temperature, assuming a binding energy of 30% of the gravitational mass and assuming that 10% of the accreted matter goes into heating the NSt.

A curved path inside the supergiant reaching several radii in length can be achieved by the NSt while rushing in a straight line, in case the supergiant is rotating in the direction inverse to the transverse NSt speed vector component.

These back-of-the-envelope calculations imply that we can have sufficient fuel reserves for powering practically any long GRB scenario, depending on the parameters (supergiant size, spin rate, etc). Given that supergiant stars can reach masses of $100 M_{\odot}$ and even more, and given that 10-20% of the accreted matter can be transformed into pure energy by friction forces, and given that 20-40% of that thermal energy may be absorbed directly by the shooting NSt at the center, we deduce that it is possible to feed, via this process, at least in principle, even the heaviest isotropic energy budgets of all so-far-observed long GRBs.

Eddington obstacle

The Eddington luminosity is defined as an upper "limit" for the mass transfer rate above which the inside-out radiation pressure from the warming accretion sphere should exceed the outside-in gravitation pressure from the infalling gas, impeding further growth of the mass transfer rate.

The Eddington luminosity is generally estimated, for an NS, in the spherical hydrogen accretion case, at:

$$L_{\text{Edd}} \approx 1.3 \cdot 10^{38} \cdot \left(\frac{M_{\text{NSt}}}{M_{\text{S}}} \right) \cdot [\text{erg} / \text{s}] \quad (5) [73].$$

Empirically, it has been noticed that, in our Galaxy, all known High-Mass X-Ray Sources (HMXR) or High-Mass X-Ray Binaries (HMXB) are indeed staying below their Eddington luminosities. A study by Sidoli & Paizis [74] of 56 galactic and 2 extragalactic HMXRs monitored by ESA's INTEGRAL satellite between 2002 and 2016 has obtained peak luminosities ranging from 1035 to 1038 erg/sec, with a maximum value measured at $3 \cdot 1038$ erg/sec.

ULXs

However, some HMXRs in nearby galaxies (the so-called Ultra-Luminous X-Ray sources, ULXs) have been observed to sometimes significantly outshine their Eddington luminosities. During some periods of time, these ULXs radiate so brightly that they were initially thought to be powered by black holes.

These super-Eddington ULX objects dominate the X-ray landscape in their host galaxies, accounting for up to 80% of all X-ray emissions [75].

Since then, a dozen of these ULXs have been unambiguously identified as harboring NSts [76], thanks to the discovery of spatially coincident radio pulsars (hence the acronym PULX for pulsating ULX). Furthermore, the ULXs in nearby galaxies have been observed to exceed their Eddington "limit" by a factor of 10, 100, and even 1,000.

The first super-Eddington ULX to be discovered was M82 X-2 [77] in the M82 galaxy at a distance of 3.1-4.7 Mpc [73]. During some phases of intense activity, M82 X-2 has been recorded to exceed its Eddington luminosity ceiling or "limit" by a factor of 100; it typically reached peak luminosities of $L_{\text{Mx}} = 1.8 \times 10^{40}$ erg/sec [77].

Furthermore, to settle the iso/aniso-tropicity debate regarding ULXs, it was shown that the orbital decay of M82-X2 was compatible with an average mass transfer rate between the donor ($8 M_{\odot}$) and the pulsar ($1.4 M_{\odot}$) exceeding 150-200 times the Eddington limit, which confirms that the peak emissions (up to 100 times over Eddington "limit" during flares) could indeed have been isotropic and powered by an over-Eddington mass transfer rate. [73].

Other examples are the two ULXs in the NGC 7424 galaxy at 10.8 Mpc (i.e. 2CXO J225728.9-410211 (X-1) and 2CXO J225724.7-410343 (X-2)), that both have been observed to reach 1040 erg/sec during some intense phases [78] and the ULX of galaxy NGC 7793 with a 0.42 sec pulsar called NGC7793 P3 reaching at times 5×10^{39} erg/sec [79].

The record-holder ULX so far is the pulsar in the NGC 5907 galaxy that was found to outshine its Eddington luminosity by a factor of 1,000 with $L_{\text{Mx}} = [1.9 \text{ to } 2.5] \times 10^{41}$ erg/sec (if isotropic) during a short period, as measured by XMM-Newton on 28 Feb 2003 and 09 Jul 2014 [80,81].

The Mechanism Behind The Super-Eddington Mode

These ULX observations imply that neither the Eddington mass-transfer-rate nor the Eddington luminosity is a real "limit" in the strict sense. They should rather be considered as phase transition points, i.e., as obstacles that can be overcome with sufficient pressure from the environment, that is, given a very strong external forcing from the matter inflow rate.

In the meantime, theoretical models have been developed to describe the super-Eddington modes of ULX binaries [82-85].

The results show that, if an NSt is initially submitted to an intense, super-Eddington overflow of infalling matter, and if this strong flow proves persistent, a new phase sets in. The inner accretion disk becomes thicker vertically (i.e., along the direction of the rotation and magnetic field axes). The accretion disk evolves from a thin disk to a thick disk [86].

The thickness H increases with stronger mass inflow, such as:

$$H \approx \frac{3}{8\pi} \cdot \frac{\dot{e}}{c} \cdot \frac{dM}{dt} \quad (6) [84]$$

This accretion torus thickening makes the inner part radiatively inefficient, i.e., optically thick. Its internal temperature increases without its outward radiation pressure to follow suit, which allows the super-Eddington flow to continue unabated [85].

Besides, the central NSt's extreme magnetic field impedes most particles from falling closer onto the NSt surface than the magnetic radius, shielding inside the so-called magnetosphere our NSt against too much fattening.

The accretion disk inner limit radius R_{inner} decreases with stronger mass inflows, like

$$R_{\text{inner}} = \hat{\imath} \cdot R_A = \hat{\imath} \cdot \frac{\mu^2}{2 \cdot \frac{dM}{dt} \cdot \sqrt{2GM}}^{2/7} \quad (7) [84]$$

where R_A is the magnetosphere radius or Alfvén radius (the radius at which the magnetic energy density equals the kinetic energy density of the infalling matter), μ is the neutron star magnetic moment, and (dM/dt) is the accretion rate. The dimensionless coefficient zeta (ξ) is determined by the accretion flow structure. For instance, for spherical accretion, $\xi=1$.

Below the magnetosphere radius R_A , all particles are deviated along the field lines to the regions situated above both magnetic poles. Some of the deviated particles shell the polar caps, which consequently undergo fast heating and shine heavily in X-rays. But most of the particles accumulate in two accretion columns located above both poles.

In case the magnetosphere radius becomes smaller than the NSt radius (due to the strong inflow rate), we argue that the neutrino emissions will supply a shield to avoid too much infalling matter and hence the black hole fate.

These accretion columns were first predicted by Basko [87]. They are now a robust feature of numerical simulations. These accretion columns may feed plasma jets, alleviating the pressure inside the columns. These jets should dart into the supergiant layers (ironically, like the collapsar jets, but without necessarily escaping the host star), recycling the unused gas out of the torus back into the supergiant star.

The columns are maintained at some distance from the poles by the pressure of the keV radiations emitted by the overheated polar regions. The accretion column radiates radially (in the NSt rotation axis cylindrical coordinates), as was established by magneto-hydrodynamical (MHD) simulations [88,89].

In summary, given a large enough mass transfer pressure, passing the Eddington luminosity hurdle may be considered as possible for a magnetar shooting across a blue supergiant star.

From Kilo- to Tera-Eddington

Starting from these Super-Eddington modes observed in ULXs, we argue that an even more intense mode, an extreme super Eddington mode, can set in the case of our magnetar punching with extreme speed into a blue supergiant star and building up an accretion disk at a tremendous rate. This new mode shall basically be identical to the ULX one, just with all parameters reaching much higher values.

The super-Eddington mass transfer rate estimated to take place in the binary M82-X2 amounts to $4.7 \cdot 10^{-6} M_{\odot}/\text{yr}$. As this NSt shines at about 100 times its Eddington luminosity, we could call this mode "Hecto-Eddington". In the case of the NGC 5907 ULX, we could speak of "Kilo-Eddington mode".

As for our shooting NSt diving into a blue supergiant and capturing into its accretion torus up to $10\text{-}20 M_{\odot}$ in up to 100 hours, we shall coin the expression "Tera-Eddington" mode, since it should undergo a transfer rate typically 109 to 1010 times stronger than typical ULXs.

It seems beyond doubt that a pulsar shooting with high speed into a supergiant star shall be exposed to a dramatically stronger influx of matter than a pulsar slowly nibbling at its companion's envelope, over the Roche lobe, from a farther distance.

Moreover, none of the recent research on Super-Eddington modes has fallen across any new, higher upper limit for the accretion rate above the previous Eddington "limit".

Thus, we shall suggest that a Tera-Eddington mode may occur in Nature provided the aforementioned necessary

conditions are met, even if more observations and more modelling shall obviously be necessary before we may confirm that assumption.

Exponentially increasing heating rate

Inside the accretion torus, the heating of the central shooting magnetar should become a self-reinforcing process. To begin with, the matter inflow rate increases steadily, since the accretion process will raise the torus mass, which will in turn increase the Hill radius. Second, the stronger accretion rate will make the inner part of the accretion disk thicker and thicker, thus insulating more efficiently, thereby applying a growing share of the (itself growing) thermal energy produced in the torus into heating the NSt. Third, the innermost particle orbit in the disk becomes smaller with increasing infalling matter mass and thus pressure (even as the neutrino pressure shall impede this disk from becoming too small). The accretion torus will thus convert by friction a higher proportion of the infalling mass into energy per unit mass.

As a result, the accretion torus in Tera-Eddington mode will work like an inferno oven fed with an increasing flow of fuel, while increasing its heating efficiency... It is straightforward to conclude that our shooting NSt shall undergo an exponential temperature rise with no other issue. If the game goes on long enough (i.e., if the host supergiant star is large enough and the initial shooting magnetar speed is high enough), then reaching critical unbinding temperature and is annihilated via its final explosion.

Maximum energy budget

From the size of the largest stars, we may infer that the total quantity of fuel available to feed the fast-accreting shooting star scenario is, in principle, sufficient to account for any known long GRB.

The BOAT's isotropic total e-m budget of $15'000$ foe ($8.3 M_{\odot}$) could have been produced with a total efficiency rate of 10% by a large target supergiant containing at least $100 M_{\odot}$. Such objects are known to exist. For these estimates to work, we must assume that the gamma-ray and hard X-ray energy release (i.e. the only part of the energy release that observatories have been measuring so far) represent the largest share of the total initial kinetic energy budget, at least in the most energetic bursts (say 70-80% or more), with the final kinetic energy remaining in the ejecta representing a smaller share.

11---Model Naming

Following the "nova" naming trail convention, we have coined the term "teranova" by following the peak luminosity trail.

Long GRBs typically reach peak luminosities of 1051 to 1052 erg/sec, whereas a classical nova typically reaches an absolute peak of 1039 erg/sec.

Along the same path, the term kilonova was introduced by Metzger et al. in 2010 to characterize the peak brightness of the radioactive decay glow arising from neutron star binary merger ejecta, which they showed should reach roughly 1,000 times that of a classical nova.

Section 4: Submitting The Teranova Model To Observations

In this section, we shall show that the Teranov model can account quite well for most observational data, in any case, much better than the collapsar model.

1---Host Star Radius from Burst Duration

If we get back to the hypothesis that the intense gamma-ray emission (the prompt phase) observed at the beginning of the burst is mainly emitted by the blast wave of atomic nuclei and baryons expelled by the exploding NSt when they emerge into the supergiant star's photosphere, then the apparent duration of the gamma phase as measured from the Earth can provide us with an estimation of the supergiant star initial (pre-burst) radius.

We assume that the NSt ejecta front wave propagates at practically the speed of light in all directions radially. This makes sense, given the ejecta initial temperatures of at least 1013 K, and is further confirmed by the results of direct afterglow imaging for GRB 030329 and 221009A [26,27].

We define R as the (pre-burst) supergiant star radius, assuming a spherical shape in a first approximation. We call d the distance between the Earth and the blue supergiant photosphere's nearest point to the Earth. We may then constrain the minimum and maximum possible supergiant radius by deriving the first and last arrival times of the gamma-rays in the four possible geometrically extreme spatial positions of the exploding NSt within the blue supergiant star:

First extreme position: the NSt unbinds within the blue supergiant star just below the photosphere point that is nearest to the Earth. In that case, the gamma radiation will begin to shower on the Earth at time $t=d/c$ (as counted in the supergiant rest frame with $t=0$ at the explosion start). This, of course, describes the ejecta rushing straight towards us. The latest gamma-rays to reach the Earth shall be the ones sent by the baryons first receding from us at an angle of 45 degrees to the line of sight and then reaching the farthest point of the photosphere still visible to us – on the edge of the projection disk. These gamma-rays shall reach us at the time $t=d/c+(1+\sqrt{2})*(R/c)$. That means that the total

prompt phase duration shall read (in the supergiant star rest frame), assuming the host star to be optically thick (so that we see nothing of the blast wave rushing into the far hemisphere). $\Delta t = (1 + \sqrt{2}) \cdot R / c$, that is:

$$R = c\Delta t \cdot \frac{1}{1 + \sqrt{2}} \quad (8)$$

Δt being the prompt phase duration in the supergiant star's rest frame and R the supergiant radius.

Second extreme position: the NSt unbinds in the central region of the supergiant star, close to the core. In that case, the gamma rays will last from $t=d/c+R/c$ until $t=d/c+2*(R/c)$ in the optically thick case, that is,

$$R = c\Delta t \quad (9)$$

Third extreme position: the NSt unbinds close to the edge of the supergiant disk, as seen from the Earth. In that case, the gamma rays will last from $t=d/c+R/c$ until $t=d/c+3*(R/c)$ in the optically thick case, that is

$$R = c\Delta t \cdot \frac{1}{2} \quad (10)$$

Fourth extreme position: the NSt unbinding takes place close to the farthest end of the blue supergiant, as seen from the Earth. In that case, the gamma rays will last from $t=d/c+2*(R/c)$ to $t=d/c+(1+\sqrt{2})*(R/c)$ in the optically thick case, that is

$$R = c\Delta t \cdot \frac{1}{\sqrt{2} - 1} \quad (11)$$

Hence, the destroyed supergiant star must have had, in the optically thick case, an initial radius now expressed as a function of the prompt duration Δt_{obs} as measured in the observer's time, comprised between:

$$R_{\text{SuperG_min}} = \frac{c\Delta \cdot t_{\text{obs}}}{(z + 1)} \cdot \frac{1}{(\sqrt{2} + 1)}$$

and

$$R_{\text{SuperG_max}} = \frac{c\Delta \cdot t_{\text{obs}}}{(z + 1)} \cdot \frac{1}{(\sqrt{2} - 1)} \quad (12)$$

taking account of the redshift z.

$$\text{For short: } R_{\text{SuperG}} = \frac{c\Delta \cdot t_{\text{obs}}}{(z + 1)} \cdot (0.41 \text{ to } 2.41) \quad (13)$$

We shall call this formula the Prompt-Duration-Host-Radius Formula.

For the cases with redshift $z > 0.1$ where relativistic effects need to be taken into account, we notice that all the prompt durations (in the 4 extreme geometrical cases) measured in the burst rest frame will need to be multiplied

by a factor $(1+\beta)$ where beta is the apparent recession speed of the Earth as seen from the supergiant coprogenitor (or the cosmological recession speed of the supergiant as seen from the Earth) to obtain the observed time interval. Indeed, the distance Earth-supergiant should increase by an amount of $v_{\text{cosmol}} \cdot \Delta t$ during the prompt phase duration. Which means that the light will need $v_{\text{cosmol}} \cdot \Delta t / c$ to cover that increase in distance. Hence, to recover the real rest frame duration from the observed time interval, we need to divide the observed time interval by the factor $(1+\beta)$

On the other hand, the exact parameter for measuring the time dilation between the rest frame and observer frame is the (cosmological) Lorentz factor Γ of the host galaxy, given by the formula $\gamma_{\text{cosmol}} = (1+z)/(1+\beta_{\text{cosmol}})$ where γ is the Lorentz factor of the receding host galaxy. We end up with equation (13) again:

$$\text{For short: } R_{\text{SuperG}} = \frac{c\Delta \cdot t_{\text{obs}}(1+\beta)}{(z+1)(1+\beta)} \cdot (0.41 \text{ to } 2.41) \quad (13)$$

By setting $c=1$, we obtain the radius in light-seconds. The logarithmic expectation value of the supergiant star radius is thus given in light-seconds by the prompt phase rest frame duration directly.

This formula represents of course a first approximation, since the real-life explosions may involve some degree of dirtiness, i.e. the blast wave may not be entirely spherically symmetric (particularly in case of excentric position of the shooting NSt inside the supergiant when unbinding), the supergiant star may possess huge lobes and not be exactly spherical – not to mention that the supergiant star may have been already partially destroyed (by the shooting NSt) when the detonation takes place, which will tend to reduce its spherical symmetry even more and to weaken the optical thickness hypothesis.

A further problem is that the estimation interval remains quite broad, with an uncertainty by a factor of six. Nevertheless, this represents a significant improvement, since it allows for the first time to interpret the prompt phase light curve in a straightforward way and to obtain from the prompt phase measurements meaningful physical information about the coprogenitor.

Moreover, the detection or non-detection of an associated SN shall now help us localize the exploding NSt within the host supergiant, i.e., narrowing the uncertainty interval on the supergiant radius.

2—Ultra-long GRBs linked to the largest supergiant stars

Since ultra-long GRBs (ULGRBs) have been identified as a category of their own in the 2010s, there has been some debate regarding their classification, i.e., whether

they represent the tail of the usual long burst distribution, or whether they proceed from an entirely different kind of central engine.

In the Teranova model, the ultra-long GRBs represent a critical testing ground. Indeed, the prompt duration host radius formula implies that the UGRBs must just have taken place inside larger host stars, and that's all. Apart from that, ULGBs are identical to other long GRBs, as their similar phenomenology confirms.

This brings about a critical test for the Teranova model: if the theory is correct, the supergiant host radii obtained from the Prompt Duration Radius formula should not exceed the empirically known maximum possible sizes of supergiant stars, even in the case of record ultra-long GRBs.

This plausibility check only works provided we are considering ULGRs that emit continuously, i.e., if excluding those ultra-long GRBs that show distinct emission episodes, separated by long quiescent periods – hinting at another phenomenon. That latter discontinuous ULGB category, like the double-peaked GRB 220627A or the triple-peaked GRB 250702 BDE, shall be dealt with in a following paper.

The case of the longest continuous ultra-long GRB 111209A

For our plausibility check, we thus rely on the longest continuous ULGRB ever recorded, namely GRB 111209A, using the observational data (Figure 1) provided by Gendre et al. [90].

This burst lasted in its gamma phase approx. $\sim 8,000$ s. As the burst took place at a $z=0.677$, we obtain for the prompt phase a duration of 4,770 sec in the local (rest) frame. This indicates, according to our Prompt-Duration Host Radius formula, that the host supergiant star radius reached between 780 and 4,600 $R_{\odot}$.

The upper limit for supergiant radii is believed to lie around 1,500 $R_{\odot}$. Our estimated supergiant host radius bracket is thus compatible with observational data.

Furthermore, for the lower value part of the formula to apply, we must conclude that the shooting NSt has exploded either on the near side of the host supergiant or close to the edge of the projected disk. The discovery of a very luminous supernova (SN2011kl) associated with that burst eliminates the first scenario. Hence, we must assume a detonation close to the projected disk edge, in which case we need to use $R=c\Delta t/2$. We thus obtain $R=(4770/2)/2.5=950 R_{\odot}$.

Hence, the teranova model framework passes the ULGRB plausibility test. These ultra-long bursts can now be integrated smoothly into the general burst model.

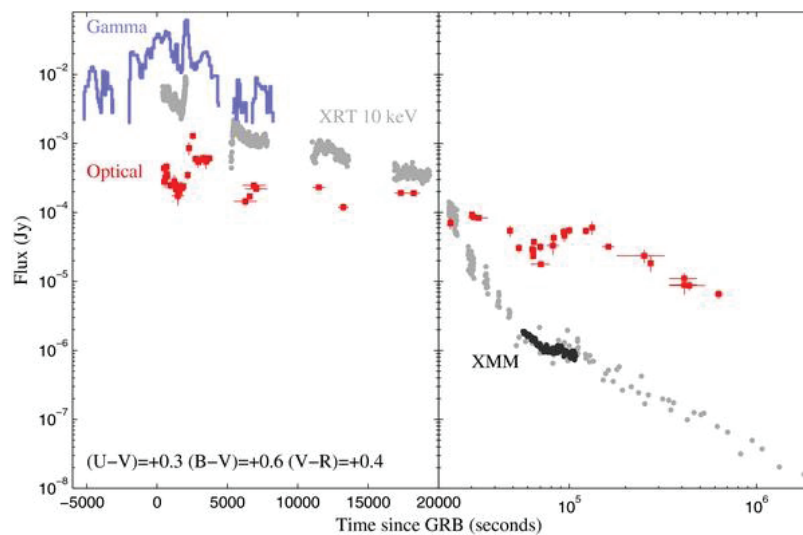


Figure 1: Light curve of GRB 111209A [90].

The host supergiant star of GRB 111209A must have been similar, for instance, to the yellow supergiant Rho Cassiopeiae ($40 M_{\odot}$, $600\text{--}1,000 R_{\odot}$) or to the red hypergiant Mu Cephei ($25 M_{\odot}$, $970\text{--}1,270 R_{\odot}$).

3---The meaning of the 2-second threshold

This analysis allows us to interpret the typical lower limit for a LGRB duration (about 2 sec in the rest frame) as implying that, from the Prompt duration host radius formula, typical long GRBs may be hosted only by stars with radii of $R=0.3$ to $2 R_{\odot}$ or more.

Keeping the higher end of this interval, we may tentatively conclude that $R=2 R_{\odot}$ should represent a lower limit for the radii of LGRB host stars.

For clarity purposes, we use the type I and type II terminology. A burst proceeding from a compact binary merger or from a giant magnetic flare is said to belong to type I (it will usually be a short GRB), and a burst produced by the full unbinding of an NS (normally a long GRB) will be classified into type II.

Indeed, the classification along the duration only (the 2s threshold) may be misleading, as more and more short bursts have been discovered to belong to type II and the reverse.

The case of type II bursts shorter than 2 sec: the ultra-short LGRBs

Some “long bursts” by phenomenology (i.e., bursts of type II) have been found to last less than 2s. A case in point is the burst GRB 200826A at $z=0.7486$, with a duration of 0.5 s in the rest frame. It displayed a typical LGRB phenomenology – prompt phase and afterglow with typical spectral distribution, isotropic energy of 4.7 foe

(assuming a $z=0.71\pm0.14$ as per Rhodes et al. 2021) or 8 foe (assuming $z=0.759$ as per Rossi et al. 2022), not to mention an associated supernova.

Moreover, GRB 200826A took place in a low-mass blue galaxy with a relatively high metallicity and a very high star formation rate ($4.0 M_{\odot}/\text{yr}$), like usual long bursts [91].

Other examples of major bursts with durations lower than 2s were GRB 060505 ($z=0.089$) and 060614 ($z=0.125$), both without associated SN, GRB 111005A ($z=0.0133$), GRB 040924 (rest frame duration 1s, with an associated SN), and GRB 090426 with spectrum and afterglow typical of LGRBs [91]. With the growth in follow-up capacity, we can expect a larger and larger share of the short GRBs to be classified as type II bursts.

Within the Teranova model, the most straightforward explanation for such ultra-short type II bursts is that, at the time of the explosion, the shooting NSt-accretion torus system had consumed most of the supergiant host star envelope. When unbinding, the shooting NSt ejecta basically faced only the accretion torus, as well as a (largely stripped) host core, with no supergiant star worth the name around anymore. This complete takeover of the target star envelope by a shooting NSt was confirmed to be physically possible in numerical simulations [55,65].

This assumption implies that the exploding NSt blast wave produced detectable gamma-rays (the prompt phase) already when escaping the accretion torus (as the supergiant envelope was mostly gone). In such cases, the Prompt-Duration- Host-Radius formula just delivers the accretion torus radius.

Thus short type II bursts should represent a limit case, between the two more frequent situations, namely either

the shooting NSt will blow up before exhausting all its host reserves, i.e. a largely intact supergiant (if the initial supergiant star was large enough), or it will use all the reserves and not reach unbinding temperature (if the host star was too small), producing a GRB-lacking SN of type 1c.

This analysis nevertheless raises the interesting possibility that, in fact, quite many “short GRBs” could in fact be type II bursts happening within depleted supergiant hosts. This would confirm the analysis by Ghirlanda et al. [49], who emphasized the difficulty of clearly separating, phenomenologically, both kinds of bursts.

This hypothesis of short GRBs being ultra-short bursts of type II would harmonize well with the fact that the total E_{iso} released by most short GRBs does, in fact, massively exceed the E_{iso} measured in the only one short GRB identified so far with high certainty as stemming from a binary NSt merger, namely GRB 170817A. If that educated guess is correct, a significant share of the short GRBs would in fact be bursts of type II.

The fact that the total e-m energy budgets of type II bursts lasting less than 2s remains below the e-m releases of type II bursts lasting more than 2s, as a rule, does not contradict this hypothesis, since in such cases (supergiant hosts already depleted at time of detonation) a lower share of the initial kinetic energy will tend to be converted into synchrotron and thermal radiation (the observed part), since the accretion torus offers much less resistance to the blast wave than an entire supergiant star. Thus, short type II bursts are really expected to transform a lower share of their initial kinetic energy budget into e-m energy. They could be just as energetic, just less luminous.

Furthermore, the fact that many short GRBs (the would-be short type II bursts) show harder peak energies confirms that hypothesis well, since, all other things being equal, the blast wave should indeed be more energetic when emerging into the photosphere of the accretion torus rather than after crossing a full supergiant star.

GRB 200826A

Getting back to GRB 200826A, what we measure with the Prompt duration host radius formula, under the above hypotheses, is the accretion torus radius. From a duration of $\Delta t = 0.39$ to 0.57 sec in the rest frame [91], we obtain a radius of $R = 0.06$ to $0.57 R_{\odot}$.

The burst e-m energy budget (5 to 8 foe) clearly lies much below the gravitational binding energy of an NS (150-200 foe in the low-mass and low GBE model case). We must thus infer that most of the burst initial kinetic energy was not converted into gamma-rays, i.e., that it remained in the form of (not measured) final kinetic energy of the blast wave traveling across ISM.

The case of GRB 210619B

Another interesting case was GRB 210619B, at $z = 1.937$, with a strong main pulse lasting 1.33 s in the rest frame, followed by a series of weaker secondary pulses [50].

With such a short prompt phase, we can conjecture that the shooting NSt-accretion torus-system had already escaped the host at detonation time, so that the Prompt-Duration-Host-Radius relation reveals the radius of the accretion torus – if we apply the formula to the main gamma pulse. The secondary peaks must then reflect the encounters of the blast wave with the remaining pieces of the depleted supergiant co-progenitor. To deduce the supergiant radius, we would need to apply the Formula to the later, weaker secondary pulse phase.

Another exception allowing an NSt to unbind while triggering a burst shorter than 2 s is provided by the Hirai-Podsiadlowski process, during which a shooting NSt produced by an asymmetric SN within a binary system may collide by chance with its companion star. Because the latter can be very near, the shooting NSt may still be very young at collision time (1-10 yr). In such a case, the NSt would still be ultra hot (i.e., relatively near to its critical unbinding temperature) when diving into the target supergiant. It would need to extract less fuel (perhaps as little as $1 M_{\odot}$) from the supergiant's envelope to reach critical temperature and unbind. Therefore, such a major burst could take place within a relatively small star, i.e., a star with just 2-3 $M_{\odot}$. This also would permit a gamma phase duration shorter than 2 sec.

4---Direct Imaging of the Afterglow

As mentioned above, the opportunity to image the afterglow emission zones directly was offered in two strong and nearby bursts, namely GRB 030329 at $z = 0.1685$ (the historical first SN-having cosmological long burst) and GR 221009A at $z = 0.1505$ (the BOAT). It became possible with radio Very Large Base Interferometry (VLBI) to directly determine the angular size and expansion speed of the afterglow emission region for the first time [26].

The main emission zone seemed to expand at a velocity of 3c-5c for 030329 [26] and even faster for 221009A [27], cf the Figure 2 below. The authors noted that these results could be explained in a straightforward way by assuming that we were witnessing the expansion of a spherical region at relativistic speed. That is, exactly the expectation from the teranova model. We have been witnessing two isotropic explosions expanding their spherical shells much faster than supernova shells, due to their much higher energy budgets.

For 030329, Taylor et al. [26] with the help of a VLBI campaign relying on the Very Long Baseline Array of the

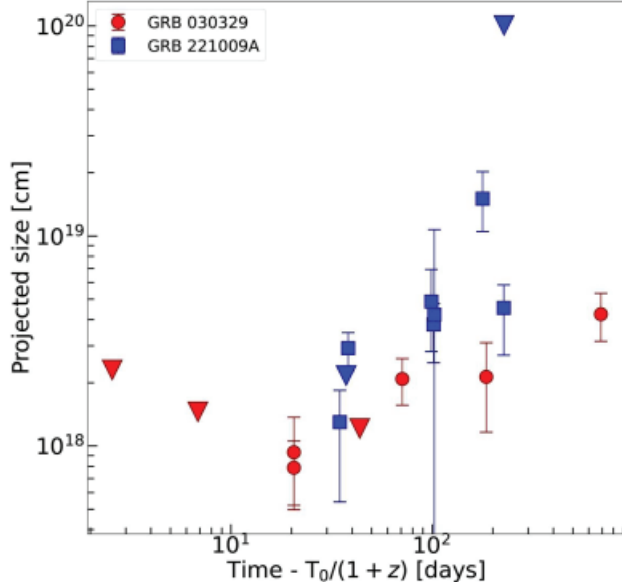


Figure 2: Measured sizes of the afterglow emission zones of GRB 030329A and 221009A at various times [27].

NRAO, Very Large Array (VLA), Green Bank, Effelsberg, Arecibo, and Westerbork telescopes, could directly measure the transverse diameter of the expanding afterglow at 0.2 pc (in the projection plane) after 25d and at 0.5 pc after 83d (as well as a not-understood component at 0.8 pc after 52 d). The apparent superluminal expansion speed (average velocity of 3c-5c for the main component, and 12-20c for the secondary component) was most likely produced by relativistic geometrical effects (more precisely, the effects produced on the apparent, measured signal speed when the signal-emitting source moves towards the observer at a speed close to the speed of the signal). The data were best fitted with a spherical fireball model with isotropic energy budget $E_{\text{iso}} = 300 \text{ foe}$ [26].

These observations were difficult to reconcile with the jetted collapsar model, as noted by the authors. They are, however, easy to reconcile with the teranova model.

As per Rees (1966) describing a spherical source expanding with a velocity close to the speed of light, the measured figures implied that the Lorentz factor of the outermost ejecta layers of the main bubble must have reached $\Gamma=3-5$ for GRB 030329A, i.e. an amazing expansion velocity $\beta=0.942-0.980$ and about twice as much for GRB 221009A, and finally $\Gamma=12-20$ or $\beta=0.9986$ (in the case of $\Gamma=19$) for the secondary bubble of GRB 030329A).

In the Teranova model, the main component ($\Gamma=3-5$, $\beta=0.94-0.98$) can most likely be ascribed to the accretion torus and/or the expelled supergiant envelope, whereas the not-understood component ($\Gamma=12-20$, or $\beta=0.9965-0.9988$) should obviously be attributed to the NSt ejecta proper.

These results would hint at temperatures of respectively $T=2.2-3.6 \times 10^{13} \text{ K}$ for the accretion torus or envelope bubble and $T=8.7-14.5 \times 10^{13} \text{ K}$ for the NSt ejecta bubble, assuming that the outermost blast wave of these emission regions consists of nucleons (by applying the formula $E_{\text{kin}}=(2/3) \cdot k_B \cdot T$) and 30-200 times higher if assuming nuclei with an average $A=30-200$.

Clearly, many model refinements are still necessary, but the important news here is that such measurements of expanding afterglow emission regions are offering us unique opportunities to directly assess the residual kinetic energies of long GRBs.

5—Reading the LGRB light curves

The teranova model offers a new approach for interpreting the burst time-resolved light curves. We can now develop a lecture grid and directly “read” light curves, obtaining insight into the involved physical processes. We showcase these points below.

GRB 990123 with 1,000 foe at 1.6004, the first known cosmological burst

For the landmark GRB 990123, the first burst identified as being located at cosmological distances, we may extract from the time-resolved light curves at different energy levels (as given by Corsi et al. 2005) [92] an apparent duration for the front wave photosphere emergence interval (the prompt phase) of 70 seconds (Figure 3). Given a redshift $z=1.60$, this leads to a rest frame duration of 27 sec, implying a supergiant radius of 4.4 to 26.0 $R_{\odot}$ (expected value $R=10.8 R_{\odot}$). These results could suggest a star similar to blue supergiant Kappa Orionis (Saiph) with a mass estimated at $M=15.5 M_{\odot}$ and a radius at $R=22.2 R_{\odot}$.

The 1,000 foe-energy budget ($0.56 M_{\odot}$) corresponds to an accreted mass of at least $6 M_{\odot}$ (for an accretion-mass-to-energy-conversion efficiency of 10%). A $15.5 M_{\odot}$ -star like Kappa Orionis matches well with these estimates, since an accretion of about $6 M_{\odot}$ would leave behind a core of 3-4 $M_{\odot}$ and a remaining envelope of about 5-6 $M_{\odot}$ left for opposing the explosion blast wave of the unbinding NSt and generating gamma synchrotron radiation.

The energy budget of 1,000 foe ($0.56 M_{\odot}$) would suggest an NSt of 1.5 to 2.5 $M_{\odot}$ (provided that the binding energy value reaches 30% to 50% of the gravitational mass, and depending on the proportion of initial kinetic energy that ended up as thermal and synchrotron e-m radiation).

Hence, GRB 990123 seems to have been a textbook teranova.

6---Explaining the exclusivity of SNe 1c-BL

As we have seen in Section 2, the Teranova model explains in a very natural way why the SNe associated with

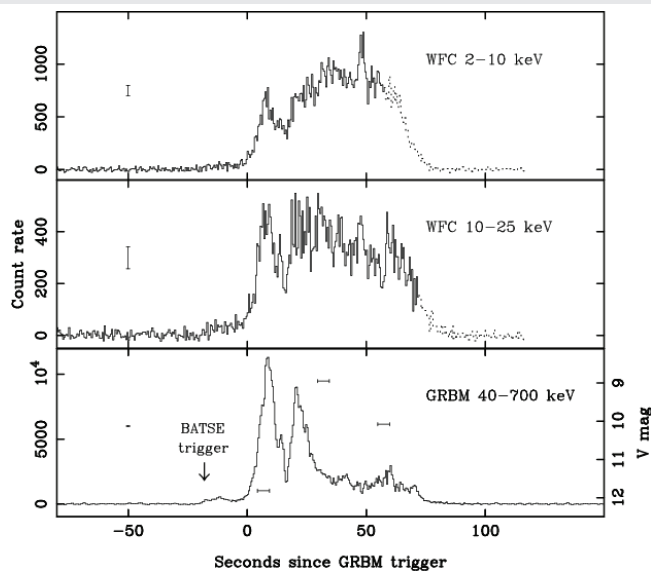


Figure 3: Time-resolved light curves at different energy levels (and with different vertical axis scales) of GRB 990123 [92].

long GRBs should have lost all or almost all their H and He layers, i.e., belong to the Type 1c (or 1b in some cases like the ultra-long GRB 111209A that was associated with the hydrogen-poor (and superluminous) supernova SN 2011kl, Fiore, Menegazzi & Stratta 2025) [59]. The explosion of an entire NSt, with its enormous binding energy freed at once, in the middle of a supergiant star host, can easily explain how the star's envelope can be blown away, thus explaining in a straightforward way how a stripped core can come into being. As is well-known, the stellar evolution necessary to create a stripped progenitor has been a challenge to model so far.

Regarding the GRB-lacking SNe of type 1c, the Teranova framework naturally suggests a possible explanation. Such SNe could be generated by shooting NSt not reaching unbinding temperature even after having depleted most of their host H and He, typically because the target star was not large enough.

The challenge of describing SN-1c progenitor genesis has thus been with us for about forty years, since the category of SN-1c was first proposed in 1986 by Wheeler and Harkness, analyzing SN1983V in NGC 1365 and confirmed by the same authors in 1990 [93].

7---Associated SNe: sometimes detectable, sometimes not

Similarly, we have seen in Section 2 that the teranova theory explains in a very natural way why some (about half of) long GRBs do exhibit a core-collapse supernova, and some do not.

8---Explaining the blueshifted GRB-Supernovae

By comparing the spectral lines of 11 SNe 1c-BL associated with a GRB and 10 SNe 1c-BL without

associated GRB, and several quieter SN 1c (with no broad lines), at redshifts from $z=0.0015$ to $z=0.0222$, Modjaz et al. [20] found that GRB-having SNe showed photospheric expansion speeds towards us that significantly exceeded the expansion speeds of GRB-lacking SNe.

The excess speed varied in amplitude from one SN to the next. The average speed excess was 5,000-10,000 km/s. Furthermore, for each SN, this velocity excess remained constant over the whole 50-day observation period. When data were available, the speed excess was also identical during the 5-10 days preceding the peak (Figure 4).

This constant velocity excess of the exploding envelope, during the whole observation time, tends to support the idea that this measured difference is in essence a blueshift due to the intrinsic radial velocity of the whole SN, i.e., linked to the initial radial velocity of the stripped core before going supernova.

This hypothesis matches well with the Teranova theory assumption that the supergiant star core, just before going supernova SN 1c-BL, has been imprinted with a sizeable momentum by the powerful blast wave generated by the shooting NSt exploding in its close neighborhood (while also stripping it from all its external layers). That blast wave typically carries initially thousands of times more kinetic energy than an SN does.

The difference in blueshifts between individual SNe may be due to the different orientations of their speed vectors (on top of idiosyncratic differences in NSt and SN explosion power).

The SN with the highest blueshift in the sample of Modjaz et al. [20], namely SN2009bb at $z=0.0099$ with centroid radial speed of 37-45'000 km/s, could tentatively be interpreted as one with its imprinted speed vector almost parallel to the line of sight, whereas the SN with large spectral lines but lowest blueshift (namely PTF 10vgv at $z=0.0142$) could be interpreted a core propelled into a direction almost transverse to the line of sight.

The above results by Modjaz et al [20] suggest an average radial speed for the stripped core, before it goes supernova, of at least 5,000-10,000 km/s, thus probably 7,000 to 15,000 km/s for the average of the unprojected speed vector.

Strikingly, no GRB-having SN 1c-BL in the sample of Modjaz et al. [20] is redshifted (compared to the GRB-lacking SNe), i.e., none of those detected SNe is receding from us. Whereas the distribution of the core speeds after the NSt explosions inside the supergiant host should be basically random. There is thus a high probability, in a sample of 10 cases, of having at least 1 or 2 SNe receding from us.

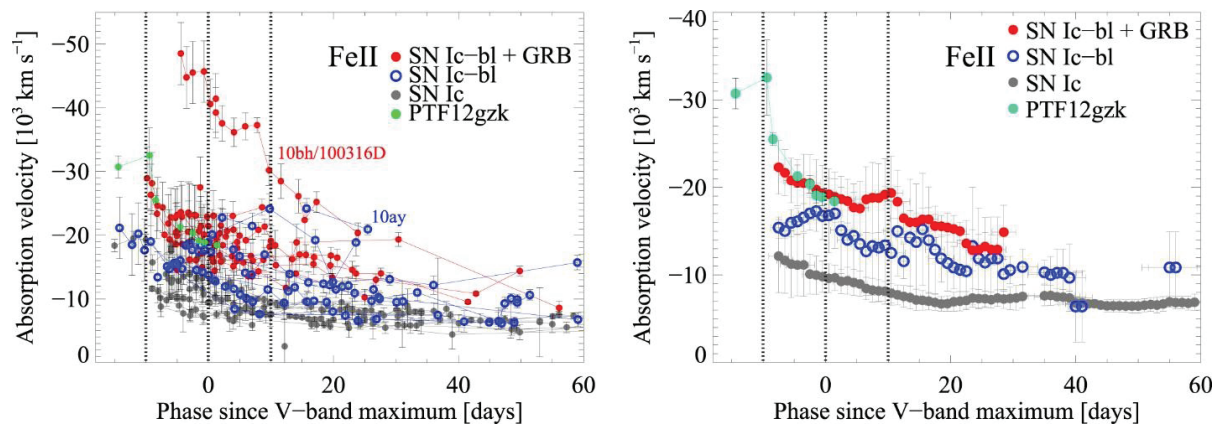


Figure 4: Left and right display Fe II $\lambda 5169$ absorption velocities of different kinds of SNe, color-coded by SN type: SNe Ic-bl with observed GRBs, are denoted by filled red circles, SNe Ic-bl (without observed GRBs) by open blue circles, SNe Ic by filled gray circles.

This absence of redshifted GRB-having SNe could be explained very naturally by assuming that these receding SNe do exist, and that they are as numerous as blueshifted SNe, but that they remain invisible to us, because they take place on the other side of the exploding NSt, as seen from the Earth, i.e., behind the optically thick burst ejecta.

The fact that, empirically, in the near Universe (where we have a good chance to detect any SN), the proportions are 50% of SN-having and 50% of SN-lacking LGRBs [23] matches quite well with that hypothesis. Half of the associated SNe go unnoticed because they take place behind the curtain of the burst optically thick ejecta.

Left: measured values for individual SNe.

Right: the rolling weighted mean of the individual SN measurements for their SN subtype, in rolling window sizes of 5 days or 10 days, in steps of 1 day. [20].

9---Multi-precursors are easier to explain

In the Teranova model, the precursors observed in many long GRBs may be attributed to giant flares preceding the main burst, i.e., phases of overheating (like NSt magnetic quakes, partial explosions, sudden larger mass inflows into the accretion torus, etc)

Perhaps, more speculatively, we could experience partial explosions of the NSt, i.e. quick matter ejections gushing through a temporary crack in the magnetar crust linked to brief, extreme electrical fields generated by violent magnetic line recombinations [54], an evolution made even more likely by the pressure and the shocks undergone by the magnetic field when the shooting NSt delves at high-velocity into the supergiant host envelope.

An example of multiple precursors is given by GRB 210204. Kumar et al. [31] provided an insightful analysis of this long burst releasing 209 foe of e-m energy at $z=0.976$, whose afterglow phase they could monitor over

30 days. The progenitor emitted two precursors (small peaks) and later a much larger peak (the main pulse), these three pulses being separated by quiescent periods.

The hypothesis of the giant flare/overheating of the shooting NSt/accretion torus harmonizes well with the fact that the precursor's spectral energy distributions are typically similar to that of the main pulse (i.e., power law distributions, sometimes, when the precursor is intense enough, a thermal component).

10--- Non-periodic light curves and absence of off-axis collapsars

Needless to say, the Teranova model explains easily why we never observe any jetted collapsar from the side.

As for the non-periodicity of light curves, on one hand, the shooting NSt is supposed to lose most or all of its rotational momentum during its deep-diving into the host supergiant, due to magnetic interactions with the host – mainly by producing very strong currents with the supergiant star envelope and core. This explains why the GRB-SN energy excess can reach typical neutron star rotational energies, as emphasized by Mazzali et al. [42].

Via this process, the shooting NSt might essentially stop spinning. However, even in the cases where the NSt does still possess a significant spin when it unbinds, the light curves, as observed from the Earth, should barely show any sign of periodicity at all, because the time interval during which the magnetar explodes should be much shorter than a typical rotation period, so that the blast wave (even within the supergiant host star) should really not be oscillatory at all.

Furthermore, the blast wave undergoes a smearing effect when crossing the host supergiant photosphere at high speed. What we see during that phase (the prompt phase) is a mixed-up collection of all the instants ($\Delta t < 1$ ms)

when the blast wave crossed the photosphere, from all the parts of the photosphere near side (the side looking at us). The signal must be blurred, since the blast wave reaches the photosphere at different times, and then the light needs different times to reach us from these different points.

The sharp fluctuations recorded in the light curve during the prompt phase should reflect the supergiant host photosphere topography and surface density much more, rather than the shooting NSt spin, since supergiant stars are not really spherical; their surface is covered with large cells produced by turbulent gas motion, in particular convection movements.

The prompt phase light curves thus deliver a kind of blurred, quasi-randomized, snapshot of this host photosphere topography, which digital simulations should help us one day to decipher, to reconstruct the exact topography of the initial supergiant host just before it undergoes full destruction – but should barely reflect any rotation of the progenitor.

11---Protons, protons everywhere.

Overwhelming proton contribution to the Band Functions

Ghisellini et al. [33] have shown that the prompt phase synchrotron radiation of long GRBs was predominantly emitted by protons.

Such a proton-dominated synchrotron radiation is hard to account for in the jetted collapsar model, where few protons are supposed to be propagated far away from the collapsing star. On the contrary, it turns out to be a very natural feature in the Teranova model – even a necessary one, since protons (besides neutrons and atomic nuclei from the NSt crust) should be expelled in large quantities during an NSt explosion, blowing away a hydrogen-burning star. The gamma rays emitted along the front shock wave (and visible for the observer when this wave reaches the host photosphere) should be produced by a proton-rich medium of NSt-expelled particles and the accelerated host envelope.

16---Host galaxy types

As Zhu S.-Y. et al. [94] summarized that long GRBs are usually observed in irregular and dwarf galaxies, at small distances from the centers, in bright and blue regions displaying high star formation rates.

Up to $z=1$, almost all well-studied long gamma-ray bursts were hosted by galaxies with high star formation rates. Using a sample of 45 host galaxies at $1 < z < 3.1$ identified by the HST, Schneider et al. (2022) have confirmed that this rule also holds for galaxies beyond $z=1$, with very good certainty at $1 < z < 2$ and with fairly good certainty for

$2 < z < 3.1$. They found that long GRB host galaxies not only have higher star formation rates but also are smaller in size, with a higher young stellar surface density, like at $z < 1$.

The fact that long GRBs occur more often in dense, star-forming, blue galaxies (“dense blue galaxies”) comes out even more as a prediction of the Teranov model than of the collapsar model. Indeed, the probability of collisions between objects distributed in space is roughly proportional to the square of their density, whereas in the collapsar.

model, the occurrence rate of collapsars should just be linearly proportional to the density.

Low metallicity is not a prerequisite for the teranova model (as opposed to the collapsar case), hence the high metallicity of some host galaxies is no issue.

17---Progenitor locations in host galaxies

Long GRB progenitors tend to be found close to their host galaxy centers, on average at 1 kpc distance from the galactic center [95]. This seems in good agreement with the teranova model, since hypervelocity NSts must have been produced either by SMBHs in the galactic center, and thus they have a higher chance to collide with another star in the central region of the host galaxy (rectilinear collisions) or they have been produced within multiple systems (loop collisions), possibly under external perturbations, which are more likely to happen in higher density regions, i.e. similarly not too far from the galactic center.

19---Neutrino (non-) detection

No clear-cut detection of neutrinos coming from long GRBs could be achieved so far [29]. The non-detection of neutrinos is an issue for many collapsar sub-models, as discussed above. In the Teranovae theory, this non-detection can be accounted for, since the expected neutrino luminosity of Teranovae is still out of reach for current detectors. They may become accessible to next-generation detectors, but only for the odd nearby bursts.

A teranova should produce large quantities of electron anti-neutrinos, as an unbinding NSt must propel into space large quantities of individual neutrons and over-neutronized nuclei. Furthermore, during the ejecta expansion, many radioactive nuclei should form by rapid neutron and proton capture (r-process and rp-process). Those should gradually disintegrate into stable nuclei, generating even more anti-neutrinos.

In principle, the total amount of emitted anti-neutrinos should be comparable to the ordinary neutrino emission volumes in NSt-forming core-collapse supernovae (depending on the share of neutrons that end up in

stable nuclei during a teranova). However, core-collapse SN luminosities are detectable with existing neutrino observatories only at relatively modest distances, not much farther away than nearby galaxies (<1-2 Mpc).

Since no long GRB has ever taken place so near to us, and since the overwhelming majority of observed redshift-identified bursts have occurred at distances >100 Mpc, it is not surprising that no GRB-emitted neutrinos have been detected so far.

Second problem, the emission of the teranova antineutrinos should be more diluted in time and space (they should arrive from a growing emission zone) than ordinary neutrinos sent by SNe during their core collapse.

Due to their mean lifetime of 14.7 min and due to Lorentz factors from 3 to 5 and 12 to 20 (in the case of GRB 030329A), the expelled neutrons should disintegrate over a longer time span (mean life of a few thousand sec for neutrons, and even longer for unstable nuclei). Whereas SNe emit most of their neutrinos over a very short timespan. In SN1987A, at 51 kpc, all 19 neutrino detections took place within an interval of 12 seconds. This time dilution will lower the luminosity and make it even more of a challenge to recognize neutrinos coming from GRBs.

A comparison with NSt binary merger (minor bursts) luminosities may provide some insight. Cusinato et al. (2021) have simulated such merger emissions and found that (ordinary and anti) neutrinos should be emitted in large quantities from the merger ejecta. Electron anti-neutrino luminosity should initially dominate over electron ordinary neutrinos by a factor of 2 to 3. The prevalence of electron antineutrino luminosity came out as a robust feature in all simulations of binary neutron star mergers.

They further found that, in equal-mass binary system mergers, the total neutrino luminosity should reach several $10^{53} \text{ erg s}^{-1}$ during several milliseconds. The neutrino luminosity should show a strong first peak at $10^{53} \text{ erg s}^{-1}$ within the first 2-3 ms after merger, followed by ample oscillations with a period comparable to the dynamical time scale of the merger remnant. After 10-15 ms, the oscillations should subside, and the luminosities enter an exponentially decreasing phase.

The total energy carried away by ordinary and anti-neutrinos should reach $\sim 10^{51} \text{ erg}$ or 1 foe. This is to be compared to $\sim 10^{53} \text{ erg}$ or $\sim 100 \text{ foe}$ in total neutrino energy for a core-collapse SN.

The authors emphasized that the detectability with current instruments remains quite low. There will be more hope with the Hyper-Kamiokande observatory, when operational: the authors expected this instrument to be

able to detect "a handful of neutrinos" from NSt mergers occurring up to a few Mpc.

From Cusinato et al. (2021), and assuming a mass of ejecta during NSt binary merger of $0.03\text{-}0.05 M_{\odot}$ [53], we may assume a typical ejecta mass during teranova explosions to be 30 to 60 times larger in the case of a $2.0\text{-}2.5 M_{\odot}$ NSt. This implies that we may multiply the binary merger neutrino luminosity figures above by the same factor to obtain the teranova anti-neutrino luminosity.

Consecutively, we may detect with Hyper-Kamiokande teranovae 7-8 times further away than NSt mergers, i.e., up to several 10 Mpc. As a reminder, the nearest (but weak) long burst ever observed, GRB 980425, took place at $z=0.0085$ (40-45 Mpc) with an associated SN. This means that we should have a reasonable chance to observe another burst at such distance scales sometime in the not-too-distant future.

In fact, with a very near burst (say, in 30 Doradus), we could even detect two neutrino emission phases: the one from the teranova (slow trickledown of anti-neutrinos) and the one from the supernova (brief shower of ordinary neutrinos).

20---Energy levels ££££

Coming back to the energy levels, we noticed that there is a good match, in the central parts of the distributions, between NSt binding energies (90 to $2 \times 10^7 \text{ foe}$) and long GRB isotropic (electromagnetic) energy releases (1 to 10^4 foe).

However, there is a mismatch at the lower and higher ends of the (GRB energy) distribution. We discuss both cases (lower and higher ends) in the following sections.

Mismatch in the energy distributions at the lower end

The distribution of long GRB energies begins at a much lower level (a minority of bursts display energy budgets of $0.1\text{-}10 \text{ foe}$) than the lowest possible NSt binding energies (around 90 foe). There are relatively many cases of long GRBs between 1 and 100 foe. According to Fermi, about 40% of long burst releases $E_{\text{iso}} < 100 \text{ foe}$.

We may find at least three good explanations for that discrepancy, which may apply separately or together, from case to case:

1-The existing measurements, limited to the electromagnetic budget, may sharply underestimate the real total burst energy release. In the overwhelming majority of bursts, we are only able to measure the e-m energy component of the total energy release. A significant amount of the released energy may, however, remain in the

form of kinetic energy carried by the ejecta from the NST and from the wiped-out supergiant.

It might be the case that the conversion factor of kinetic into synchrotron energy undergoes significant differences from burst to burst. For example, in the cases when most of the supergiant external envelope has been consumed by the accretion torus at the time of the NST unbinding, we may expect the expanding NST ejecta to run across space with much less friction (and thus to keep a larger share of the initial kinetic energy) than when an essentially intact supergiant star still surrounds it and transforms much of the kinetic energy into synchrotron, inverse Compton scattering and thermal radiations.

The exact balance between e-m energy budget (that we observe) and kinetic energy budget (that we rarely see) will depend on the size and final shape of the supergiant host at explosion time.

If its envelope is mostly wiped out, i.e., aggregated into the shooting NST's accretion torus, or if the supergiant host was relatively small, it will offer less resistance to the blast wave, implying that a larger share of the explosion's initial kinetic energy will remain kinetic.

2-Measurement weaknesses may be at stake. Even if we remain within the purely e-m emission domain, some burst energies may have been underestimated due to a measurement that was not complete over all wavelengths at the right time. In the case of the BOAT, just engaging the two Chinese X-ray satellites (Insight-HXMT and GECAM-C) has led the total measured energy release to be multiplied by a factor of 10. This sometimes unmeasured component should tend to decrease in the future with the improved quality and quantity of observational resources.

3-Some bursts could proceed from partial NST unbindings. In such partial scenarios, analogous in fact to the giant magnetic flares studied by Patel et al. [54], the shooting NST may undergo magnetic line recombination, triggering violent electrical fields and magnetic quakes or overheating phases of the accretion torus – and not completely explode in the end (due to the insufficient size of the host star). Such bursts could be considered, in fact, as “precursors” not followed by a main burst. Like soft X-ray repeaters can be seen as aborted SN of type-Ia supernova.

4-Some absorption of the gamma-rays could take place for some bursts along the line of sight, depending on the ISM densities.

Mismatch in the energy distributions at the upper end

The mismatch at the upper end of the isotropic long GRB energy vs binding energy distributions is more of an issue.

The interval of theoretically possible NST binding energies reaches $2'700$ foe at the very highest, whereas observed long GRB e-m energy budgets easily reach $4,000$ foe in pure e-m energy. We even need to add an unknown additional budget to account for the (unmeasured) residual kinetic energy.

This is compounded by the fact that, over the typical distances involved, a significant share of the gamma-ray flux at or above GeV energies should be suppressed along their path by interactions with the extragalactic background light and should never reach us, as reminded by O'Connor et al. [96]. Hence, the observed E_{iso} really just represents a lower limit for the total energy budget. ££££

GRB 210619B, for instance, released $4,050$ foe in isotropic-equivalent e-m. energy (during a t_{90} of 67.38 seconds). The burst redshift was measured at $z = 1.937$. This burst was followed by the Fermi GBM in the 250-40,000 keV energy range, by the Swift BAT in the 25-100 keV range, and by the Atmosphere-Space Interactions Monitor (installed on the International Space Station) in the 0.3 to 30 MeV range with a time binning of 50 milliseconds [50].

The record holder, the Brightest Of All Times (“BOAT”), namely GRB 221009A, has reached an isotropic-equivalent Energy $E_{\text{iso}} = 1.5 \times 10^{55}$ ergs or $15,000$ foe. This measurement was obtained by the two Chinese X-ray satellites Insight-HXMT and GECAM-C. It included the most relevant period and photon energy ranges. It covered indeed from hard X-ray to soft gamma-ray band from ~ 10 keV to ~ 6 MeV. And it covered the first $\sim 1,800$ s, including precursor, main emission, flaring emission, and early afterglow [97].

To account for the upper-end energy distribution mismatch, we discuss four classes of hypotheses below. These are not mutually exclusive; they could jointly play a role, to different extents, in any given burst.

1---We might need to revise the NST binding energy estimations.

Perhaps the particle configurations in the extreme state of matter existing inside these compact objects could significantly increase their total binding energy, enough to justify the difference in LGRB energy releases.

In particular, the 500 to 800 m-thick iron-up-to-krypton crust enfolding a typical NST may form a kind of armoured sphere. This rigid crust could keep the NST interior in its grip like an ironclad hull until the pressure from inside the star has grown sufficiently to break it away. This might raise the effective NST star's binding energy above the purely gravitational energy calculation.

NSt crusts are supposed to consist of a Coulomb crystal of neutron-rich nuclei (from 56 Fe to 118 Kr) embedded in a uniform degenerate ultrarelativistic electron gas [98,99] found that the breaking strain of an NSt crust was about 20 times stronger than that of steel. Moreover, the authors found that the crust material tended to hold on up to very large strains before falling apart abruptly in a collective manner – rather than yielding continuously under low strain as observed in metals – as no dislocation forms.

As a consequence, the crust may indeed request a supplement of energy to be broken away, like a steam kettle without a safety valve, or like a fragmentation bomb. If the crust induces a total NSt binding energy (starting from the pure gravitational BE) increased by a factor up to 2, we may hope to account for LGRB energy levels up to roughly 5,000 foe.

2---We may consider the kinetic energy of the accretion torus surrounding the overheating NSt to double or triple the total burst energy output, when it is liberated from its gravitational bound to the central NSt. However, this is applicable only to the afterglow energy budget, as this energy should be emitted after the prompt phase (as mentioned, it could, however, have contributed to the BOAT's 15'000 foe budget).

When the central NSt matter is getting away and escaping the inner side of the torus, the torus itself should run in larger and larger circles, ending up shooting in all directions in straight lines. If (as assumed) only about 20-30% of the thermal energy produced by the Tera-Eddington accretion mode is absorbed by the central shooting NSt, another 20-30% may have been absorbed by the torus itself. This may very likely increase the burst energy budget beyond pure NSt GBEs.

3---We might have some degree of partial anisotropy. The teranova blast wave would still propagate in all directions, just stronger in some directions.

4---We might postulate that, in the inferno developing at the center of the Hyper-Eddington "oven" created by the thick, radiatively-inefficient accretion torus, some exotic objects, heavier than usual NSts, may form (quark stars, strange stars, etc.) that may be endowed with even more binding energy than classical NSts. Reconciling binding energies with long GRB energy releases might thus require us to explore the little-known region between NSts and BHs.

Pulled all together, these assumptions may tentatively allow us to raise the possible allowed apparent total energy budgets of long GRBs up to the highest observed levels, even if a lot of calculations and simulations will still need to be implemented.

21---Key predictions and outlook

We list below six key predictions of the teranova model, on top of the "predictions" that have been confirmed already and were discussed above. Each of these new key predictions, if verified in observation, would disprove the collapsar model and confirm the teranova theory.

1---Associated SN beginning AFTER the start of the prompt phase main pulse

In the Teranova model, the associated SN begins after the stripped core has been created by the NSt unbinding within the supergiant host. However, measuring the exact SN starting time – by detecting the neutrino flash generated by the collapsing core – to check if it takes place after, instead of before, the beginning of the main prompt phase pulse, shall be a challenge.

It would require a burst located very close to us, closer than all the redshift-measured bursts so far. A burst in the 30 Doradus region (or Tarantula Nebula) in the 50kpc-far LMC would be ideal, for example. Even bursts in the M82 or NGC5128 galaxies would offer a good hope of being detectable with the most advanced large neutrino detectors. However, the bursts observed so far have taken place much farther away.

2---More than 1 Precursor

The collapsar model is at great pains to account for 2, 3, or 4 precursors. Whereas the teranova model may live well with basically any number of precursors. Therefore, detecting major bursts with more than 1 precursor would be a good indicator in favor of the teranova model as well. This shall become easier to achieve thanks to the increasing number of observatories and their increased sensitivities.

3---Diving point-in-time signal: flares and stopping pulsars

Before their collision with the target blue supergiant star, some hypervelocity NSts should, in fact, be classical pulsars (HV-pulsars have been detected even in our Galaxy, as mentioned above). Hence, a telltale signal confirming the teranova theory would be a sudden pulsar interruption, followed a few 103 s later by a burst at the same location in the sky.

In the loop collision case, an X-binary (a HMXB or even a ULX) could abruptly stop emitting, revealing that the pulsar in the binary has dived into its supergiant companion. So far, the farthest pulsar was detected by XMM-Newton at about 17.1 Mpc. It is the most luminous ULX in the galaxy NGC 5907 [80,81]. This distance remains smaller than most long GRBs detected so far.

To increase the probability of such a pulsar binary silencing detection, it would be, in principle, beneficial in the future to map all X-binaries in our cosmic environment up to farther distances (ideally up to 300-500 Mpc), and to monitor them.

4---Both a kilonova and a supernova in the same burst

Kilonovae and supernovae come together in most type-II bursts in the teranova model, but normally either the SN overshines the kilonova and makes it invisible, or the SN takes place on the other side of the burst and remains hidden, and then the kilonova may be seen (when the burst is near enough), but no longer the associated SN.

This leads the community to believe that bursts have either a kilonova (and thus must be of type I) or they have an SN (and are of type II), whereas the teranova model infers that type II bursts produce both kilonovae and SNe at the same time.

In serendipitous cases when the associated SN-1c starts later than usual (for whatever reason, like a stripped core retaining more fuel than usual, or a core partially shattered by the NSt explosion, etc.), we may be able to see both a kilonova and, later, a supernova associated with the same GRB, which is excluded by current collapsar and compact merger models. This would be a landmark observation confirming the teranova model specifically.

5---Radio-imaging afterglows revealing more relativistic spherical bubbles

We should endeavor to image with radio interferometry the afterglow emission zones of a larger and larger number of long GRBs. Obtaining visual, geometrical information about the after-burst sceneries can only help us understand the processes leading to bursts better.

In particular, if such imagery always ends up to always reveal relativistically expanding spherical bubbles (like for GRB 030329A and GR 221009A), the burst isotropicity shall clearly be confirmed.

By measuring the expansion speed of the spherical afterglow bubble, we shall be able to directly measure the residual kinetic energy of each burst during the afterglow phase, and thus obtain a good picture of the total energy budget of major bursts.

During the afterglow phase of each burst, there should be a total of four expanding bubbles: the NSt ejecta bubble (the most relativistic), the liberated accretion torus (2nd in Lorentz factor), the expelled supergiant envelope (3rd in Lorentz factor), and the supernova bubble (last in Lorentz factor). These four layers might be distinctly observable in sufficiently close bursts.

6---Tell-tale neutrino light curves

The detection of two successive neutrino showers would be a telltale signal confirming the teranova theory. The first shower, namely the one proceeding from the associated SN, should be brief and consist of ordinary neutrinos. The second shower should be much more smeared out over time and consist mostly of antineutrinos. The latter would stem from the NSt ejecta (neutrons and unstable nuclei) during their decay process. All of this would necessitate, even with Hyper-Kamiokande, a type-II burst taking place quite nearby (<10 Mpc).

In case we detect the first shower of neutrinos, without discerning any associated SN, then we shall have the proof that the associated SN was there, just hidden by the burst's optically thick ejecta, as predicted by the Teranova model.

A very nearby burst would become a Rosetta stone.

A long GRB occurring at $d < 30$ Mpc, or $z < 0.008$ (but not closer than 10 kpc!) would be a golden opportunity for the community, given the instrumentation that is now available.

Such nearby bursts could be expected to occur more likely in active galaxies like M82 or Centaurus A, or in the star-forming region of 30 Doradus in the LMC.

We could detect the pulsar stopping a few hours before the burst, and producing a big flare, at the time of diving into the supergiant, if the diving takes place on the near side of the supergiant.

We may observe many more weaker precursors before the main burst.

We may detect the neutrino shower from the SN's collapsing core and check if it comes *after* the prompt phase, as predicted by the Teranova model. In the case of an apparently SN-lacking major burst, observing the ordinary neutrino emission shower typical of a SN without electromagnetically detecting that SN would confirm that the associated SN was there, just hidden.

We may identify, with some chance, the HV pulsar progenitor and the supergiant co-progenitor from archival data. They could form one of the neighboring ULXs, like M82 X-2 at 3.6 Mpc or NGC 7424 X-1 at 10.8 Mpc, and thus directly test the Prompt Duration Host Radius formula.

Section 5

Conclusions

In this paper, we have suggested a paradigm change for modelling long gamma-ray bursts. We have introduced a new theory, the Teranova model, describing long GRBs as *isotropic explosions* resulting from the unbinding of neutron

stars. Those explosions are supposed to mostly take place during collisions between hyper-velocity magnetars and blue supergiant stars.

We have shown that this new model may overcome most of the 12 issues that are plaguing the collapsar model, and can also explain in a more natural way 5 other elements that have remained unsolved.

These 12 issues that are now solved are: the non-periodicity of burst light curves, the absence of off-axis jetted collapsars, the lack of any mechanism for creating the SN-1c progenitors, the exclusivity of type 1c-SNe, the associated SNe optionality, the (radio-imaged) spherical afterglows expanding at relativistic speeds, the unexpected neutrino non-detections, the utterly unexplainable ultra-long GRBs, the too numerous and early precursors, the large blueshifts of associated SNe, the significant proton contribution to the synchrotron radiation, and the internal collapsar model theoretical inconsistencies.

The five further elements that find a more satisfactory explanation within the Teranova model are the X-ray plateau observed during early afterglow, the SN excess energies comparable to NSt rotational energies, the host galaxies almost always being dense blue galaxies, the high metallicity of some host galaxies, and the typical distance from the center in host galaxies.

The total isotropic energy releases can also be accounted for, whereby the higher end of the GRB energy distribution needs mechanisms that remain to be consolidated with theoretical research and simulations.

Moreover, the Teranova model allows us, at long last, to interpret the prompt phase light curves. We can now directly “read” from them the supergiant host star co-progenitor diameter and relate it to the burst total e-m energy release.

Two longstanding open issues of modern astrophysics could have found a solution if the Teranova model is confirmed: the 30-year-old mystery of the SN-1c progenitor genesis and the 60-year-old enigma of the physical mechanism producing the long gamma-ray bursts.

We have listed six key predictions that, if one day confirmed experimentally, would disprove the collapsar model even more on top of the 12 main failures and 5 elements listed above.

Many digital simulations and further observations will obviously need to be conducted in order to refine and deepen our understanding of the teranova theory. Notably, such simulations should establish the range of shooting NSt speeds and supergiant host star masses that are needed for evolving into a full-blown long GRB, the striking angles, the

time that it takes for the NSt rushing across the supergiant host to reach critical temperature, etc., not to forget the magnetar’s magnetic field evolution until and after the NSt explosion.

Within the Teranova framework, long GRBs shall become very fruitful “discovery engines”. They will offer us unique opportunities to explore the composition and equation of state of neutron stars; their binding energies, critical temperatures, and mass ranges will become accessible via direct observation.

Because the prompt phase light curves shall allow us (after some modelling) to explore the topography of host supergiant photospheres, and because long GRBs are detectable across the whole Universe, we may obtain detailed surface maps of individual Population III stars even before having imaged a single one as a single dot.

Last but not least, understanding the real physical processes underlying long gamma-ray bursts shall help us, mankind, to assess the burst risks in our immediate cosmic neighborhood.

Data availability statement

All data generated or analysed during this study are included in this published article.

The figures reproduced from other papers have received re-publication approval from the relevant entities (authors or journals).

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