SHORT GAMMA-RAY BURSTS AND DARK MATTER SEEDING IN NEUTRON STARS

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ABSTRACT

We present a mechanism based on internal self-annihilation of dark matter accreted from the galactic halo in the inner regions of neutron stars that may trigger full or partial conversion into a quark star. We explain how this effect may induce a gamma-ray burst (GRB) that could be classified as short, according to the usual definition based on time duration of the prompt gamma-ray emission. This mechanism differs in many aspects from the most discussed scenario associating short GRBs with compact object binary mergers. We list possible observational signatures that should help distinguish between these two possible classes of progenitors.

Key words: dark matter – dense matter – gamma-ray burst: general – relativistic processes – stars: neutron

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1. INTRODUCTION

Gamma-ray bursts (GRBs) are interesting highly energetic phenomena for which there is still no definitive explanation for the originating mechanism (see, e.g., Piran 2004; Gehrels et al. 2009). Regarding the initial event that triggers a GRB, the combination of the observed short variability timescales and huge radiated energies points toward cataclysmic events leading to the formation of a stellar compact object with mass M and radius R releasing a gravitational energy AE \approx GM^2/R \approx 10^{53} – 10^{55} \text{ erg}. Specifically, according to their time duration, GRBs can be classified as long GRBs (LGRBs) if the duration of the gamma-ray signal is longer than 2 s and short GRBs (SGRBs) in other cases (Kouveliotou et al. 1993), although the boundary is not sharply delimited (see, e.g., Zhang et al. 2009; Bromberg et al. 2012). There are several pieces of evidence in favor of an association of LGRBs with massive stars, especially the facts that they occur in star-forming regions (Bloom et al. 2002) and that supernovae have been found in association with a few of them (see, e.g., Stanek et al. 2003). This leads to the collapsar model (Woosley 1993) where an LGRB is associated with the gravitational collapse of a massive, Wolf-Rayet star leading to the formation of an accreting stellar-mass black hole (BH). An alternative scenario where the central engine formed after the gravitational collapse is a young, rapidly rotating (ms period) neutron star (NS) has also been considered by Usov (1992), Thompson (1994), and Metzger et al. (2011). On the other hand, the identification of the progenitors of SGRBs is more uncertain (Nakar 2007). This is partially due to the fact that the detection of SGRB afterglows is technically more difficult, and therefore rarer, than for LGRBs. So far there is only a handful of detected afterglows, since the first detection in 2005 (Gehrels et al. 2005; Villasenor et al. 2005). SGRBs can occur in all types of galaxies, either of a star-forming type or not (Berger 2011). This is consistent with the most popular scenario, that is, the merger of a NS+NS or NS+BH binary system.

As a main motivation for the present contribution and due to the current uncertainties on the origin of (especially short) GRBs, it is worth investigating other possible classes of cataclysmic events where astrophysical stellar compact objects are involved. We will focus on NSs. A NS can be partially characterized by a set of static observables, namely, mass, M_{NS}, and radius, R_{NS}. The structure of a NS has been discussed thoroughly in the past (for a review see, e.g., Glendenning 2000). It can be briefly described by a dense core, where matter is in the form of a liquid of nucleons (or additional particles including strangeness), and a crust where matter undergoes a liquid-solid transition into a clustered myriad of nuclei (Horowitz et al. 2005). In more detail, the so-called neutron drip (ND) line signals the boundary between the outer and inner crust where neutrons start to leak out from nuclei. The mass in the crust is small (up to a few percent) as compared to the whole NS and therefore it could be accelerated, if ejected by large energies, to large velocities or even high Lorentz factors.

The equation of state (EoS) that governs the description of matter in the inside of NSs is currently poorly known. Whether matter remains in the form of baryons or deconfined quarks is a matter of debate. The problem of the internal constituents in a NS has been thoroughly and periodically revisited from the early 1930s when Landau predicted the existence of such objects (Landau 1932) from the basis of the existence of neutral hadronic particles. From the discovery of the neutron by Chadwick in 1932 to 1984 when it was hypothesized (Witten 1984) that a more stable type of matter could be possible (formed by roughly equal quantities of uuds quarks, arising from weak decay of regular ud matter present in nucleonic matter made of protons and neutrons), a wide variety of possible nuclear configurations has been proposed. In this latter quark system case, for example, recent attention has been devoted to lattice calculations showing the possibility of the existence of the H-dibaryon, with uuddss quark content (Beane et al. 2011) and experimental input from the Large Hadron Collider is expected on the formation of a quark–gluon plasma.

A stable type of extended strange matter would allow the existence of stars even more compact than NSs, i.e., hybrid or pure quark stars (QSs; Itoh 1970; Alcock et al. 1986). The transition from a nucleonic type of matter to a quark phase is presently not well understood. From the theoretical point of view, some work has been done (Berezhiani et al. 2003; Horváth et al. 1992) on the possibility of quark bubble nucleation in a...
cold system, where the temperature is well approximated by $T \approx 0$. As this mechanism is not efficient enough, this process may seem unlikely to occur. Another series of works have been developed by Ouyed and collaborators who propose the Quark–Nova model in which a massive NS converts explosively to a QS (Ouyed et al. 2002). The transition is obtained mostly via a central density increase due to spin-down or accretion forming a conversion front that propagates toward the surface. The outcome is ejection of the NSs’ outermost layers at relativistic speeds. Alternatively, as we explain in this work, additional external agents may be able to produce thermal excitations in these dense degenerate matter systems.

From indications concerning astrophysical and cosmological backgrounds we know that dark matter (DM) is distributed inhomogeneously in the universe and, additionally, could be gravitationally accreted onto individual massive astrophysical objects. One of the most popular DM candidates is considered to be a Majorana-type weakly interacting particle (WIMP), although other asymmetric DM candidates could exist as well (Kaplan et al. 2009). From the experimental point of view, current direct and indirect detection experiments try to constrain its properties. For example, direct detection Earth-based experiments DAMA (DAMA Collaboration: Bernabei et al. 2010), CoGeNT (CoGeNT Collaboration: Aalseth et al. 2011), CRESST, and lately COUPP (Behnke et al. 2012) seem to point toward a light particle in the $\sim 10$–20 GeV/$c^2$ mass range (although this is in tension with other null searches) while there has been a lot of interest in indirect detection of new excesses of extra photon components from the Galactic center that could be due to annihilation of a $\sim 130$ GeV/$c^2$ particle (Bringmann et al. 2012; Weniger 2012), albeit so far at only the $2\sigma$–$3\sigma$ level of significance.

DM passing through massive astrophysical objects is expected to scatter off their constituent nuclei, lose energy, and become trapped by their gravitational field. Multiple scatterings cause DM to sink toward the center and afterward, assuming that it may self-annihilate, a series of end products are available. Based on the previous arguments, a set of current experiments try to find evidence for this process in the Sun, Earth (Avrorin et al. 2011; Baer et al. 2004), or even more compact-sized objects such as NSs (Kouvaris & Tinyakov 2010).

Recently, new ideas on the possibility that quark bubbles may be formed by spark seeding in the inner cores of dense NSs have been proposed by Perez-Garcia et al. (2010). Sparks would be generated in a sort of Trojan horse mechanism by self-annihilation of DM particles gravitationally accreted by NSs gathering in their internal cores. As estimated, this would allow the release of energies of up to about one order of magnitude higher than the quark binding energies in the present baryons (Perez-Garcia 2012). This mechanism then could lead to the conversion of NSs into QSs if the transition to quark matter phase is macroscopic. In this way the matter component in the form of DM would not only influence cosmological observables, but even NS dynamics (Perez-Garcia & Silk 2012). Similar arguments have been claimed in the solar seismology observables (Lopes & Silk 2010).

We investigate in the present paper whether this type of non-repeating cataclysmic event could produce SGRBs and what could be a possible specific signature. After a short summary of the scenario in Section 2, in Section 3 we compare the energy released by SGRBs with the energetics of the progenitor model that we propose, and in Section 4 we discuss the SGRB event rate in light of this scenario as compared to observed rates, as well as the natural delay time between the regular NS phase and QS formation and how this mechanism may affect the properties of the host galaxies of SGRBs. In Section 5 we present and analyze the ejecta and crust masses that could be expelled due to the NS $\rightarrow$ QS conversion and we present the details of the resulting central engine model. In Section 6 we attempt to discuss the expected temporal (Section 6.1) and spectral (Section 6.2) properties of the prompt gamma-ray emission and the afterglow. In Section 6.3 we discuss our results and possible genuine additional signals and gravitational wave emission that could finally lead to a clear identification as compared with the SGRB scenario involving binary mergers. Finally in Section 7 we give a brief summary of our conclusions and suggestions on how to proceed in further work.

2. SUMMARY OF THE SCENARIO

There has been some previous work where DM accretion in astrophysical objects has been considered (Goldman & Nussinov 1989; Kouvaris & Tinyakov 2010; Lionel & Tinyakov 2012). As a summary, we start in this section by motivating the scenario where the emission of a SGRB may occur.

In our previous work (Perez-Garcia et al. 2010) the possibility of spark seeding in NS as a result of DM accretion was proposed. We found a relationship between the mass of the DM particle, $m_\chi$, and the binding energy of the lump of quark matter or strangelet formed, $E_{\text{th}}^\delta(\mu_i, n_A, m_\chi, B)$, as calculated from the MIT bag model (Chodos et al. 1974),

$$2m_\chi c^2 \geq E_{\text{th}}^\delta(\mu_i, n_A, m_\chi, B),$$

(1)

where $n_A$ is the baryonic number density and $\mu_i$ and $m_i$ are the chemical potential and mass of the quark of $i$th type in the light sector, $i = u, d, s, B$ is the bag constant. The channels available to $\chi$ annihilation are, so far, not known and this uncertainty is phenomenologically parameterized into the fraction $f$. Inside the NS, it is believed that DM scatters one or more times and thermalizes according to a Boltzmann distribution. The thermal radius is given by

$$r_{\text{th}}(f) = \left( \frac{3k_\text{B} T_c(t)}{2\pi G \rho_{\text{c}}(t) m_\chi} \right)^{1/2}. $$

(2)

This radius is, in general, time-dependent since evolution proceeds for central temperatures $T_c$ and baryonic mass densities $\rho_{\text{c}}$. DM at high density may self-annihilate to channels involving photons, leptons, and light $q\bar{q}$ pairs (Kuhlen 2010). Due to the fact that either a light or heavy self-annihilating particle in the $\sim 1$–100 GeV/$c^2$ mass range may release a spark of energy able to liberate the constituent quark content of the baryons forming the very dense matter in the core of these objects, a pure nucleonic NS could then be considered a metastable state of compact stars. Note that a self-annihilating $\sim 20$ GeV/$c^2$ particle as recently suggested in the context of direct detection experiments would, in particular, fit into this scenario. The annihilation power is then given as

$$\mathcal{L}(r) = \frac{\langle \sigma_a\nu \rangle c^2}{m_\chi} \int_0^r \rho_\chi^2(r') d^3r',$$

(3)

where $\rho_\chi$ is the DM mass density and $\langle \sigma_a\nu \rangle \simeq 3 \times 10^{-26}$ cm$^3$ s$^{-1}$ is the thermally averaged annihilation cross section.

If the spark seeding is able to form quark lumps or strangelets, most likely off-center, inside a volume $\sim r_{\text{th}}^3$, they could
individually grow or coalesce from a stable minimum mass number, so far poorly known, $A_{\text{min}} \sim 10–100$, according to previous estimates (Madsen 2001). In this way a burning front may proceed if particular thermodynamical conditions are fulfilled. If the burning is partial, the final configuration object would be a hybrid, constituted by an inner quark matter phase and an outer nucleonic phase. However, if the burning is complete the resultant object would be formed by a pure quark phase. In both cases the final configuration in the mass–radius phase space $(M_F, R_F)$, as computed from different EoSs using a variety of many-body effective theories (Haensel et al. 2007), is a smaller, slightly lighter, more compact object than the initial one characterized by $(M_i, R_i)$.

In Figure 1 we show a qualitative scheme, inspired from the work by Bombaci et al. (2004), of how the transition would produce a more compact object. The transition point, and therefore the initial configuration mass, would be influenced by the presence of spark seeding by self-annihilating DM in this model.

In such a $\text{NS} \rightarrow \text{QS}$ transition, part of the outer crust of the initial NS can be expelled, and possibly accelerated to relativistic speed, which may lead to a transient episode of high-energy emission. In the following, we discuss a possible association of some GRBs with such events. We focus on SGRBs for several reasons:

1. the energetics of bright LGRBs may be a challenge for this scenario, whereas typical energies of SGRBs are in much better agreement (see Section 3);
2. a delay of at least $\Delta \sim 10^3$ yr is expected between the formation of a NS and the transition to a QS, which is too long for LGRBs as supernovae within a few days have been found in association with some of these events. On the other hand, the scenario naturally leads to a broad distribution of the delay $\Delta t$, allowing long delays that are necessary to explain the properties of the afterglows and host galaxies of SGRBs (see Section 4);
3. the scenario naturally leads to short (or very short) timescales for the gamma-ray emission, pointing toward SGRBs or ultra-SGRBs (see Section 6.1).

3. ENERGETICS

Since 2005 and the first accurate localization of a SGRB (Gehrels et al. 2005) the redshift of an increasing number of SGRBs has been measured, confirming their cosmological origin and leading to a large dispersion in the isotropic equivalent energy released in gamma-rays, $E_{\gamma, \text{iso}} \sim 10^{48}–10^{52}$ erg (Nakar 2007; Berger 2007). This energy is emitted by a relativistic outflow which is probably beamed within an opening angle $\theta_j$ so that the true energy release is $E_{\gamma} = f_b^{-1} E_{\gamma, \text{iso}}$, where the beaming factor is defined as

$$f_b = (\frac{\Omega}{4\pi})^{-1} = (1 - \cos \theta_j)^{-1} \approx \frac{2}{\theta^2}$$ if $\theta_j \ll 1$.  (4)

Unfortunately, the opening angle $\theta_j$ cannot be easily measured in GRBs. It can be estimated if a jet break is identified in the late afterglow (Rhoads 1997). It is only in very rare cases that a precise constraint on $\theta_j$ is obtained, such as $\theta_j \sim 7^\circ$ in GRB 051221A (Soderberg et al. 2006), and even in such cases, it remains partially model-dependent. The distribution of $f_b$ for SGRBs is therefore unknown (Nakar 2007). Highly beamed SGRBs with $\theta_j \sim 1^\circ$ would lead to $f_b = 6.5 \times 10^3$ whereas larger opening angles of about $\theta_j \sim 30^\circ$ give $f_b = 7.5$. This will remain as a major source of uncertainty in what follows.

In SGRBs, the isotropic equivalent energy $E_{\gamma, \text{iso}}$ is released in gamma-rays on a very short timescale ($\lesssim 2$ s) and observed well above 1 MeV (see, e.g., Guiriec et al. 2010). Then, the gamma-ray emission must be produced from relativistic ejecta to avoid the compactness problem: this provides a constraint on the minimum value of the Lorentz factor for the emission region to be optically thin for $\gamma \gamma$ annihilation (Rees 1966; Baring & Harding 1997; Lithwick & Sari 2001). The analysis of a few pre-Fermi short bursts (Ghirlanda et al. 2004) leads to $\Gamma > \Gamma_{\text{min}} \simeq 15$ from this $\gamma \gamma$ opacity constraint (Nakar 2007). When a SGRB is detected up to the GeV range by Fermi-LAT, stricter constraints are obtained, such as $\Gamma \gtrsim 300–1000$ in GRB 090510 (Ackermann et al. 2010; Hascoët et al. 2012).

Let us compare these constraints on the energetics and the relativistic nature of the emitting material in SGRBs with the predictions of the scenario described in the previous section. If there is a transition triggered from the inside (Perez-Garcia et al. 2010), namely, due to DM self-annihilation in the central core of a NS ($M_{\text{NS}}, R_{\text{NS}}$) then the final configuration may lead to a more compact object with partially deconfined quark content. The energy gap to this new configuration ($M_{\text{QS}}, R_{\text{QS}}$) will release approximately (here we assume $M_{\text{NS}} \approx M_{\text{QS}}$ for the sake of comparison)

$$\Delta E_{\text{grav}} \simeq GM_{\text{NS}} \left( \frac{1}{R_{\text{QS}}} - \frac{1}{R_{\text{NS}}} \right).$$  (5)

Note that the internal energy due to the matter EoS has been estimated to be of the order of $E_{\text{grav}}$ (Bombaci & Datta 2000), and therefore this estimate is correct up to a numerical factor that somewhat depends on the EoS. The energy $\Delta E_{\text{grav}}$ liberated in a NS $\rightarrow$ QS transition can be compared with the energy $\Delta E_{\text{grav,prog}} \rightarrow \text{QS} \simeq GM_{\text{NS}}^2 / R_{\text{NS}}$ released in the gravitational collapse leading to the formation of a NS (standard core-collapse supernova). We define this ratio (in the approximation $M_{\text{NS}} \approx M_{\text{QS}}$ as $f_{\text{QS,NS}} \approx |\Delta E_{\text{grav,prog}} \rightarrow \text{QS} / \Delta E_{\text{grav,prog}} \rightarrow \text{NS}| \approx |(R_{\text{NS}} / R_{\text{QS}}) - 1|$. The calculation is made assuming a
transition of a hadronic type star with a combined EoS model including additional hyperons (Bombaci & Datta 2000) to a hybrid star with a quark content described by the MIT bag model. Two relativistic nonlinear Walecka-type EoS models of Glendenning and Moszkowski (Glendenning & Moszkowski 1991) are tested, namely, GM1 (blue curve) and GM3 (red curve) usually used to describe the hadronic phase. The typical compressibility values \( K \) for the GM1 model are stiffer than for the GM3 model. Note that in this scenario of hybrid stars the maximum mass for the hybrid object must be somewhat lower than in the case of the pure hadronic star. Although both of them predict maximum hadronic star masses somewhat on the low side with \( M_{\text{max}} \leq 1.9 \times 10^{-3} M_{\odot} \) (as compared to recent measurements reporting masses of about \( 2 M_{\odot} \); Demorest et al. 2010), they can be considered illustrative of a general trend of the typical original configurations before transitioning to hybrid or pure QSs. In this figure the value of some nuclear parameters such as the \( s \)-quark mass has been taken to be \( m_s = 150 \text{MeV}/c^2 \) and the strong coupling constant \( \alpha_s = 0 \). Surface tension is \( \sigma = 30 \text{ MeV fm}^{-2} \). No curvature energy has been considered.

In this situation the initial configuration masses and radii are not the same, since they depend on the value of the \( B \) bag constant in the MIT model. Following Bombaci & Datta (2000) we consider that the transition takes place between a configuration in the initial hadronic star with gravitational mass \( M_i^G = \int_0^{R_i^G} \rho_i(r) d^3r \) and with some baryonic mass \( M_i^B = \int_0^{R_i^B} n_i(r) d^3r \) and that of a final hybrid object (computed with the hybrid EoS) with the same baryonic mass, \( M_f^B = M_i^B \), since that charge is conserved, \( \rho_f(r) \) and \( n_f(r) \) are the energy density and baryonic mass density for the baryonic object. Physically, the transition occurs due to the fact that as the density or central pressure exceeds a threshold value, it is energetically allowed that, at the transition point, bubbles of quark matter form. This is due to the lowering of the chemical potential in the system as more degrees of freedom are available. These lumps of quark matter can grow very rapidly, driving a burning front and the original hadronic star will be converted into a hybrid star or QS. In the mechanism involving self-annihilating DM this energy released could be considered as sparks that would coalescence or ignite the medium and allow quark deconfinement out of the baryons present (this is \( B \)-dependent and therefore, EoS-dependent in our model). If we further include corrections due to slightly different masses for the initial and final configurations we have \( f_{QS/NS} \approx |\Delta E_{\text{grav},NS/QS}/E_{\text{grav,prog}-NS}| \approx |(M_{QS}/M_{NS})^2(R_{NS}/R_{QS}) - 1| \). We typically find \( f_{QS/NS} \approx 0.1 \text{–} 0.3 \), which illustrates that the transition mechanism discussed here indeed belongs to the class of the most energetic phenomena in the universe. The efficiency \( f_{QS/NS} \) is plotted in Figure 2 as a function of the bag constant \( B^{1/4} \). It shows that the efficiency \( f_{QS/NS} \) is higher as the bag constant \( B \) grows, pointing to heavier DM particles in order to ignite the nucleation of quark matter lumps but well in the conservative range shown in Figure 2 in Perez-Garcia et al. (2010). Further work is needed to clarify the role of the EoS in the efficiency of the transition since the possible existence of a burning front able to fully convert the NS into a QS and proceed toward higher radii is a crucial point.

Numerically, using typical values \( M_{NS} = 1.5 M_{\odot}, R_{NS} = 12 \text{ km}, \text{ and } R_{QS} \approx 7 \text{ km results in } \Delta E_{\text{grav}} \approx 3.5 \times 10^{33} \text{ erg.} \) In the \( \text{NS} \rightarrow \text{QS} \) transition most of the energy \( \Delta E_{\text{grav}} \) will be radiated as neutrinos and photons, as shown by detailed calculations (Jaikumar et al. 2002; Vogt et al. 2004). Additionally, gravitational radiation should also be emitted (see Section 6.3).

We assume now that a small fraction, \( f_{ej} \), of this energy may be injected into the outer crust which is then ejected and becomes relativistic. The kinetic energy of the expelled crust is \( E_{\text{kin}} \approx f_{ej} \Delta E_{\text{grav}} \) if acceleration is complete. The isotropic equivalent energy that could be radiated as gamma-rays by such an ejecta can be estimated by

\[
E_{\gamma,\text{iso}} \approx 3.5 \times 10^{51} \left( \frac{f_b}{100} \right) \left( \frac{f_y}{0.1} \right) \left( \frac{f_{ej}}{10^{-3}} \right) \left( R_{NS}/12 \text{ km} \right)^{-1} \left( \frac{M}{1.5 M_{\odot}} \right)^2 \text{ erg},
\]

where \( f_b \) is the efficiency of gamma-ray energy extraction from the ejecta and could range from \( 0.01 \text{–} 0.1 \) for the extraction of kinetic energy by internal shocks (Rees & Mészaros 1994; Kobayashi et al. 1997; Daigne & Mochkovitch 1998) to \( 0.5 \) for photospheric emission (see, e.g., Rees & Mészáros 2005) or magnetic reconnection (Thompson 1994; Zhang & Yan 2011).

As discussed below, relativistic motion of the ejecta is favored by a small ejected mass, \( M_{ej} \approx 10^{-3} M_{\odot} \), which corresponds typically to the outer crust. The crust is defined as the region where the density drops below nuclear saturation density (NSD) at \( \sim 2 \times 10^{14} \text{ g cm}^{-3} \), and the outer crust is limited by the ND at \( \sim 4 \times 10^{11} \text{ g cm}^{-3} \) (see Section 5). Then, the value \( f_{ej} \approx 10^{-3} \) used in Equation (6) would correspond for instance to a situation where 1% of \( \Delta E_{\text{grav}} \) is injected in the crust and 10% of this energy is injected preferentially in the outer crust, so that \( f_{ej} \approx 0.01 \times 0.1 \). As there is large uncertainty in this estimate we use a safe approximation below the \( f_{ej} \approx 0.1 \) quoted in other detailed calculations (Ouyed et al. 2005a).

This estimate of \( E_{\gamma,\text{iso}} \) is in reasonable agreement with observations of SGRBs: the \( \text{NS} \rightarrow \text{QS} \) conversion scenario investigated here can reproduce measured energies in SGRBs for \( f_b f_y f_{ej} \approx 3 \times 10^{-4} \text{–} 0.3 \).

Regarding the relativistic nature of the ejecta, the maximum Lorentz factor, \( \Gamma_{\text{max}} \), that can be reached depends on the expelled fraction or ejected mass, \( M_{ej} \), of the crust. The maximum Lorentz factor can be deduced from the estimate of \( E_{\text{kin}} \) above, and from the ejected mass \( M_{ej} \) as:

\[
\Gamma_{\text{max}} = \frac{E_{\text{kin}}}{M_{ej} c^2} \approx 19 \left( \frac{f_{ej}}{10^{-3}} \right) \left( \frac{R_{NS}}{12 \text{ km}} \right)^{-1} \left( \frac{M_{ej}}{1.5 M_{\odot}} \right)^2 \left( \frac{M_{ej}}{10^{-5} M_{\odot}} \right)^{-1}.
\]
Again, it seems that Lorentz factors above 15, in agreement with the observational constraints described above, can be reached as long as the ejected mass remains low \((M_{\text{ej}} \lesssim 10^{-4} M_\odot)\) and the fraction of the energy injected in the outer crust is not too small \((f_{\text{ej}} \gtrsim 10^{-3})\). This is in agreement with some numerical estimations (Bauswein et al. 2009). Even ultra-high relativistic ejecta with \(\Gamma > 100\) could in principle be produced, if the ejected mass is really small. This could be the scenario where the outer crust is expelled.

We conclude that the DM self-annihilation triggered NS\(\rightarrow\)QS scenario can, in principle, release enough energy to power a SGRB, and that the ejected crust can reach high Lorentz factors, which is necessary to emit gamma-rays. This is however strongly dependent on the two parameters \(f_{\text{ej}}\) and \(M_{\text{ej}}\) which are very difficult to predict accurately at this stage. This will be briefly discussed in Section 5.

4. EVENT RATE AND DELAY BETWEEN THE NS FORMATION AND THE TRANSITION TO A QS

Assuming that the transition of a NS to a QS triggered by the self annihilation of accreted DM in the core can inject enough energy into relativistic ejecta to produce a SGRB, it is worth comparing the observed rate of these phenomena with the predicted rate of NS\(\rightarrow\)QS conversions. The local rate per unit volume of SGRBs, \(R_{\text{SGRB}}\), can be estimated from their observed rate and distribution of flux using a population model (luminosity function, comoving rate, etc.), as has been done by Guetta & Piran (2006) and Nakar et al. (2006), who obtain

\[
R_{\text{SGRB}} \simeq \left( \frac{f_{\text{ej}}}{50} \right) \text{Gpc}^{-3} \text{yr}^{-1}.
\]

The lower limit corresponds to a comoving SGRB rate that follows the cosmic star formation rate with a long delay, and the upper limit to a constant comoving rate. Unfortunately, the unknown distribution of the beaming factor and its average \(\langle f_b \rangle\) is again a major source of uncertainty in this estimate.

In the scenario presented in this work, the local rate of NS formation, estimated as the local rate of Type II supernovae, gives an upper limit for the rate of NS\(\rightarrow\)QS conversions. It is of the order of (Dahlen et al. 2004)

\[
R_{\text{NS\rightarrow QS max}}^{(\text{SNI})} \simeq 5 \times 10^5 \text{Gpc}^{-3} \text{yr}^{-1}.
\]

Then the ratio of the former two rates is

\[
R_{\text{SGRB}} / R_{\text{NS\rightarrow QS max}}^{(\text{SNI})} \simeq (8 \times 10^{-4} \rightarrow 3 \times 10^{-3}) \left( \frac{f_{\text{ej}}}{50} \right).
\]

From these estimates only, one can conclude that the NS\(\rightarrow\)QS transition can be much more frequent than SGRBs, depending on the fraction of NS that will experience such a transition. If all SGRBs are due to NS\(\rightarrow\)QS conversions, the low ratio obtained in Equation (10) could be (1) either due to the fact that only a fraction of NS\(\rightarrow\)QS transitions lead to SGRBs; or (2) be related to the fact that only a small fraction of NS are converted into QS.

Having only a small fraction of NS converting to a QS is expected if the delay \(\Delta t\) between the formation of a NS and its conversion to a QS is usually long, e.g., \(\Delta t \sim\) several Gyr. For a broad probability distribution \(p(\Delta t)\) of the delay \(\Delta t\), with a high mean value \(\langle \Delta t \rangle\) of the order of the Hubble time, most conversions would not have occurred yet, resulting in a low ratio \(R_{\text{SGRB}} / R_{\text{NS\rightarrow QS max}}\), the observed SGRBs being produced by the conversions with the shortest delays. In addition, such a distribution of \(p(\Delta t)\) would make the scenario in good agreement with the properties of SGRB afterglows and host galaxies: contrary to the case of LGRBs which are always observed in central regions of star forming galaxies (Bloom et al. 2002), SGRBs can occur at any place (sometimes at the periphery or outside) in any type of galaxy (Berger 2011). This indicates a delay between the end of the life of the massive progenitor star and the production of the SGRB. It is already a well-known fact that most NSs are born with a natal velocity kick \(v\) that can be as large at \(\sim 10^3\) km s\(^{-1}\) (Arzoumanian et al. 2002). Therefore, with high values of \(\Delta t\), not only can any correlation with star formation be lost, but the NS can travel a distance

\[
D \approx v\Delta t \approx 10 \text{kpc} \left( \frac{v}{1000 \text{km s}^{-1}} \right) \left( \frac{\Delta t}{10 \text{Myr}} \right),
\]

and most likely experience the conversion to a QS far from the galactic central regions, or even outside the galaxy.

In the scenario presented here a lower limit on \(\Delta t\) can be obtained from the physics of the transition, which is triggered by self-annihilation of accreted DM from the galactic halo. In our Galaxy the DM density distribution can be taken to be of type (Navarro et al. 2004)

\[
\rho_x(r) = \rho_{x,0} e^{-r/r_s} / \left[ (r_s^2 + r^2)^{1/2} \right],
\]

with parameters \(\rho_{x,0} = 0.22 \text{ GeV cm}^{-3}\), \(\sigma = 0.19\), and \(r_s = 16 \text{ kpc}\) so that at the solar neighborhood the Keplerian velocity is \(v \sim 220\) km s\(^{-1}\) and the local DM density is \(\rho_{x,0} \sim 0.3 \text{ GeV cm}^{-3}\). DM from this halo can be accreted by gravitational capture (Gould 1987) at the peak of NS distribution (Lorimer 2004) at a rate of

\[
C \approx \frac{2.7 \times 10^{29}}{m_x(\text{GeV})} \frac{\rho_x}{\rho_{x,0}} \text{ particles s}^{-1},
\]

but off-peak, at about solar circle it may be reduced somewhat. In this estimate, we assume a WIMP–nucleon (spin independent) cross section \(\sigma = \sigma_{NN} = 7 \times 10^{-41} \text{ cm}^2\) (Bertone 2010). Once the steady state, resulting from competing processes of annihilation and accretion, has been reached, the elapsed time is \(t_{DM} \simeq 1/\sqrt{C(\sigma_h v)/V}\), where \(V\) is the volume of the star. Typically, if we assume a light \(\sim 20 \text{ GeV/c}^2\) DM particle, as direct detections experiments seem to preliminary suggest, we obtain \(t_{DM} \sim 3.5 \times 10^3\) yr. For a velocity (temperature) dependent cross section and heavier DM particles \(\sim 100 \text{ GeV/c}^2\), this delay can be longer, \(t_{DM} \geq 6 \times 10^5\) yr (Kouvaris 2008). From the condition that the transition should likely occur after reaching the steady state, we get a lower limit on the delay \(\Delta t\),

\[
\Delta t_{\text{min}} \simeq t_{DM} \simeq 10^3–10^5 \text{ yr}.
\]

Notice that this delay is already much too large to allow us to consider producing LGRBs with NS\(\rightarrow\)QS conversions, as an associated SN is sometimes found in association with such events within a few days (Stanek et al. 2003). On the other hand, it is too small to have SGRBs uncorrelated with star formation, which is required by the observed diversity of SGRB host galaxies and afterglow locations (Berger 2011).
We conclude that $\Delta t$ is related to the microphysical processes happening in the burning of the NS. This, in turn, depends on the ability of the compact object (mainly related to the EoS) and environment conditions to accrete DM and, therefore, cannot be simply predicted and should present some spread and extend up to a large value $\Delta t_{\text{max}}$ that can be constrained by observations.

In our Galaxy, there are hundreds of confirmed NSs, with measured radii and masses (Lattimer & Prakash 2005). On the other hand, the subsample of confirmed NSs with an estimate of the age is very small, due to the difficulty of age determination, based on cooling theory (Page et al. 2009). It seems that NSs with an age of at least $\sim 1\text{–}10 \text{ Myr}$ are identified (Yakovlev & Pethick 2004) which would put a lower limit on the maximum value of the delay $\Delta t$,

$$\Delta t_{\text{max}} > 10 \text{ Myr}. \quad (15)$$

Such delays, as shown by Equation (11), lead to travelled distances of the order of 10 kpc or more, reaching the outskirts of a galaxy but are still too small to de-correlate from the star formation activity. One cannot of course exclude that much older NSs are present in the sample of confirmed NSs, which would increase $\Delta t_{\text{max}}$ up to 100 Myr or more. Nevertheless, a detailed comparison with the properties of the SGRB host would require the knowledge of the distribution $p(\Delta t)$, which seems yet out of reach.

Another possible approach to constrain the rate of NS $\rightarrow$ QS transitions in the scenario proposed here is to focus on the kinematics of observed pulsars. The pulsar tangential velocity data can be fitted with a bimodal distribution peaked around $v_1 = 300 \text{ km s}^{-1}$ and an upper $v_2 = 700 \text{ km s}^{-1}$ (Arzoumanian et al. 2002). The high velocity pulsars with $v > v_2$ roughly account for 10% of the pulsar population. The first peak in the distribution is believed to be due to the kick velocity given to the NS when it is formed in a core collapse supernova. It has been suggested by Bambaci & Popov (2004) that the second higher velocity peak could be due to a second kick when the NS $\rightarrow$ QS conversion takes place. In previous works (Perez-Garcia et al. 2010; Perez-Garcia & Silk 2012), it was shown that DM seeding in NSs may form a stable and long-lived strange quark matter (SQM) lump that could induce a partial transition in the scenario proposed here is to focus on the microphysical processes happening in the burning of the NS.

This additional factor $f_{\text{SGRB}}$ can be related to internal processes, such as the capacity of the burning front to proceed to the crust (see Section 5).

Note that the value of the efficiency $f_{\text{SGRB}} \sim 1\%-10\%$ has been obtained here assuming that all SGRBs are produced by NS $\rightarrow$ QS transitions. However, we will show below (Section 6.1) that this scenario naturally leads to SGRB durations $t_{\text{GRB}} < 0.1 \text{ s}$, so that only very short GRBs are good candidates for counterparts of these NS $\rightarrow$ QS transitions. Then, it reduces in principle even more the value of $f_{\text{SGRB}}$.

On the other hand, observations of afterglows of ultra-SGRBs, identifications of their host galaxy and measurements of their distance are extremely rare so that their intrinsic rate is unknown. The distribution of the duration of BATSE bursts show that $\sim 8\%$ of the short bursts have a duration below 100 ms (Horváth 2002). This factor cannot however be directly applied to the estimate of the intrinsic rate given by Equation (8). Indeed, this population of very short bursts may very well be a separate group with different properties: they are usually made of a single short and hard spike with possible substructure on a timescale of a few $10 \mu s$ (Cline et al. 1999). The analysis ($\langle V/V_{\text{max}}\rangle$ and $\log N – \log S$ diagram) of the distribution of very short bursts observed by BATSE and Konus gives some evidence for a local origin (Cline et al. 1999, 2005). This is however a bit contradictory with more recent results obtained by Swift: 10 very short bursts with a duration of less 100 ms have been detected by Swift until 2012 June.5 All of these show indeed a single short duration hard spike in the Burst Alert Telescope. In many cases, the afterglow has not been identified or is very weak at the limit of the detection (GRB 050925, GRB 051105A, GRB 070209, GRB 070810B, GRB 070923, GRB 090417A, GRB 100628A, and GRB 120305A). There are however two very short bursts where the afterglow has been well detected and localized and where there is a good candidate for the host galaxy. In both cases, the host candidate is an early type galaxy and the afterglow shows a large offset of a few 10 kpc: GRB 050509B seems to be associated to an elliptical galaxy at $z = 0.225$ with an offset of 35–55 kpc (Gehrels et al. 2005; Berger 2011); GRB 090515 is probably associated to an early type galaxy at $z = 0.403$ with a large offset of 75 kpc (Berger 2011). These two examples indicate a population at cosmological distance which is uncorrelated to star formation, in agreement with the discussion above. The sample is however much too small to allow for a determination of the intrinsic rate of very short GRBs and an estimate of $f_{\text{SGRB}}$.

5 Source: Swift GRB table at http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table.html.

### 5. CENTRAL ENGINE AND CRUST MASSES

In this section, we model the basis of the central engine mechanism of the internal burning front that will induce a resultant outflow with several relativistically moving emitting regions. This discussion is based on a series of works (Cheng & Dai 1996; Dai & Lu 1998; Ouedry et al. 2005b; Paczynski & Haensel 2005; Xu & Liang 2009; Fischer et al. 2010). Nuclear processes involving quark deconfinement in the hadronic phase may happen if the $m_f \gtrsim 1\text{–}100 \text{ GeV/c}^2$ DM particle candidate self-annihilates, liberating $\sim \text{MeV–GeV}$ photons and other light particle pair products. The corresponding lump of SQM (uds matter) evolves toward the formation of a fireball that may cause stress and tension on the base of the inner crust of a NS. Since there are only a few preliminary simulations (Abdikamalov et al. 2009; Herzog & Ropke 2011) developed so far on...
the full process of energy transport from the inner deconfined regions to outer regions through a burning front, there is not much information where this front may stop or whether it fully proceeds to the outer crust. In these simulations the NS burning condition is dynamically analyzed, showing the possibility that a hybrid star may form if the conversion front is not able to proceed as burning. However, a full detailed treatment has not hitherto been performed.

In previous work (Perez-Garcia & Silk 2012), it was found that the seeding is most likely a non central process, and therefore, geometrically, the burning front progression may not be a radially symmetric dynamical process (see Figure 2 in Perez-Garcia 2012). The possibility of a beamed ejection of the outer crust arises then from the anisotropy in the progression of the burning front. This has been somewhat explored in the work of Lugones et al. (2002) where they discuss the possibility of preferred ejection of a fireball through the polar caps. In the present work, we discuss the constraints on the ejected mass as a result of the NS → QS conversion. Similar to what may happen in the heavy ion collision events in large colliders, a fireball may be formed and grow rapidly. Then, a pure nucleonic EoS of matter, would no longer be valid as nucleon quark content may be deconfined. Since the newer EoS is softened, later evolution may lead to the original hydrostatic structure no longer being energetically possible and re-adjustment of the object to favor lower radii and masses and then to build up tension in the crust, tending to eject it and break it up.

The crust mainly corresponds to matter where the density is below the NSD. Therefore for lower densities a myriad of nuclei with mass number A populate this phase. Since the particular distribution of nuclei depend on the competition of short-range hadronic interaction and long range Coulomb interaction a set of irregular shapes different from the spherical one can arise, forming what is known as the pasta phase. As a result, low density matter in the crust of NSs is mostly neutron-rich due to the deleptonization caused by neutrino escape in the first stages of cooling. Its isospin content is closer to that of neutron matter than to regular nuclei where proton and neutron content are balanced Z ∼ N. From the 56Fe iron content usually assumed in the lower density region in the crust, there is a series of neutron-rich nuclei going through heavier 64Ni, 82Ge, 120Sr and after this the ND transition takes place, signaling the inner crust of the NS. In the inner crust, surrounding these non-uniform pasta structures, a neutron gas is filling the system, as has been directly simulated in previous works (Horowitz et al. 2004, 2005; Perez-Garcia 2006).

Fragmented emission of ejecta is therefore possible since the stress in the base of the crust from a burning front may liberate the most abundant structures and the rest of lower A nuclei. The gradient of composition (heavy → light) should also produce some variability during the crust ejection, all regions of the crust not being necessarily ejected with the same Lorentz factor. An additional source of uncertainty is related to the fraction of the initial energy release associated with the transition in the core which will be injected into gamma-ray photons, and the associated photo-disintegration of heavy nuclei. An efficient photo-disintegration would lead to a modified chemical composition biased toward light elements, and would enrich the medium by free neutrons that can be an additional source of energy (neutron decay) and internal dissipation in the ejecta (see Section 6.1). In order to size the importance of this ejection, we plot in Figure 3 the crust mass $M_c$ as a function of the stellar radius. These data are obtained by integrating the Tolman–Oppenheimer–Volkoff (Oppenheimer & Volkoff 1939) equations for eight different representative EoSs (Datta et al. 1995) up to the core. We compute the mass of the crust by integrating above a critical density, either the neutron drip density $\rho_{\text{ND}} \approx 4 \times 10^{11} \text{ g/cm}^3$ to estimate the mass of the outer (solid) crust only, or the nuclear saturation density $\rho_{\text{NSD}} \approx 2 \times 10^{14} \text{ g/cm}^3$ (where crust–core boundary sets in) to estimate the mass of the entire crust. We find that the condition $M_{\text{ej}} \lesssim 10^{-4} M_\odot$ needed for relativistic motion (Section 3) can be fulfilled if only the outer crust is ejected ($M_c \sim 10^{-5} M_\odot$ or $10^{-3.5} M_\odot$), whereas it becomes much more difficult if the whole crust is expelled ($M_c \sim 10^{-2.5} M_\odot$ or $10^{-0.5} M_\odot$). The details of the physics of the propagation of the burning front and the associated energy deposition are required to estimate precisely the fraction of the crust that is ejected. If this fraction varies from a NS → QS transition to another, this would naturally lead to $f_{\text{GRB}} < 1$ as discussed in the previous section.

6. GRB DURATION, LIGHT CURVE, SPECTRUM

In this section we discuss some expected properties for SGRBs produced in the scenario proposed in this work. We focus on the identification of distinct features related to the specific central engine that could help in distinguishing this mechanism from others proposed in the literature.

6.1. Duration and Light Curve

Let us assume that the ejected outer crust has a mass $M_{\text{ej}} = M_{\text{ej}} - \delta \times 10^{-5} M_\odot$, an initial energy $E_{\text{ej}} = f_{\text{ej}} \times 3.5 \times 10^{50} \text{ erg}$, and a width $\Delta = c \Delta t$, where $\Delta t = \Delta t \sim 10^{-6} \text{ s}$ is the light crossing time ($\Delta = \Delta t \sim 300 \text{ m}$). The maximum final Lorentz factor that can be reached in the ejection is

$$\Gamma = \frac{E_{\text{ej}}}{M_{\text{ej}} c^2} = 20 M_{\text{ej}}^{-1} f_{\text{ej}}^{-3}.$$

(18)

Due to the large physical uncertainties regarding the energy deposition in the crust and the following ejection, we do not attempt here a detailed calculation of the relativistic ejection (see, e.g., Pan & Sari 2006 for a self-similar solution of the propagation of a strong shock wave within the NS and the following shock breakout). For a thermal acceleration, the saturation to this value of the Lorentz factor will occur at radius

$$R_{\text{sat}} \approx \frac{\Gamma R}{2} \approx 2 \times 10^7 M_{\text{ej}}^{-1} f_{\text{ej}}^{-3} \text{ cm}.$$

(19)
assuming an initial radius \( R_{\text{ej}} = R - \Delta \approx R_{\text{NS}} = 12 \text{ km} \) for the ejection. The ejecta will become transparent to its own radiation at the photospheric radius

\[
R_{\text{ph}} \approx \sqrt[3]{\frac{\kappa M_{\text{ej}}}{4\pi}} \approx 2 \times 10^{13} M_{\text{ej},-5}^{1/2} \text{ cm}, \tag{20}
\]

where we take the Thomson opacity \( \kappa \approx 0.2 \text{ cm}^2 \text{ g}^{-1} \). Here we assume \( Y_e = 0.5 \) free electrons per nucleon in the expanding gas, whereas the dynamical chemical composition discussed in the previous section may lead to lower values. This does not affect the discussion too much as the dependence goes moderately as \( R_{\text{ph}} \propto \kappa^{1.5} \).

This expression of \( R_{\text{ph}} \) is valid for \( R_{\text{ph}} \gg R_{\text{is}} \approx 2\Gamma^2 \Delta \). The radius \( R_{\text{is}} \) is defined below and is of the order of a few \( 10^7 \text{ cm} \) so that the condition is always true for the typical parameters considered here. The estimates of \( R_{\text{sat}} \) and \( R_{\text{ph}} \) are based on the standard fireball theory for GRBs (see, e.g., Piran 2004) and are only rough estimates for the scenario considered here as the physics of the ejection of the crust is much more complex. We should bear in mind that the ejecta composition (Kotera et al. 2013) and fragmentation may affect both the dynamics (\( R_{\text{sat}} \)) and the interaction with radiation (\( R_{\text{ph}} \)) (Ouyed et al. 2005b).

Therefore, if the energy is not deposited in a homogeneous way in the expelled crust, the final Lorentz factor in the ejecta may not be uniform. In addition, fragmentation of the crust during its ejection will also lead to some variability in the ejecta. If variations of \( \Gamma \) are present on length scales \( c t_{\text{rad}} < \Delta \), this will induce collisions (internal shocks) that will dissipate energy at a typical radius \( R_{\text{is}} \) given by

\[
R_{\text{is}} \lesssim 2\Gamma^2 \Delta \approx 2 \times 10^7 M_{\text{ej},-5}^{-2} f_{\text{ej},-3}^2 \Delta_{-6} \text{ cm}. \tag{21}
\]

Clearly, this possible internal dissipation will always occur well below the photosphere, and, depending on the value of the Lorentz factor, even before the acceleration is complete. Most of the dissipated energy should contribute again to the acceleration and the internal shock phase will only tend to smooth out the initial internal variability, without contributing to the emission.

The ejecta will initially expand freely, but will eventually be decelerated by the external medium. However, due to the expected delay between the formation of the NS and the NS \( \rightarrow \) QS transition, this external medium can correspond to the periphery of the host galaxy or even the surrounding intergalactic medium, i.e., have a low density. We assume a uniform medium with a number density \( n = n_{-3} \times 10^{-3} \text{ cm}^{-3} \). Then the deceleration will start at radius

\[
R_{\text{dec}} \approx \left( \frac{3M_{\text{ej}}^2 c^2}{4\pi E_{\text{iso}} m_p} \right)^{1/3} \approx 4 \times 10^{17} M_{\text{ej},-5}^{2/3} f_{\text{ej},-3}^{-1/3} n_{-3}^{-1/3} \text{ cm}. \tag{22}
\]

\( m_p \) is the proton mass. From these different estimates, we find for the proposed scenario that

\[
R_{\text{sat}} \lesssim R_{\text{is}} \ll R_{\text{ph}} \ll R_{\text{dec}}. \tag{23}
\]

This would naturally lead to two episodes of emission, a single spike emitted at the photosphere followed by an afterglow starting at late time due to the high value of \( R_{\text{dec}} \). The duration of the prompt spike should be fixed by the intrinsic curvature of the emitting region and its lateral extension, which gives

\[
\Delta_{\text{obs}} \approx \min \left( \frac{R_{\text{ph}}}{2c}, \left( \frac{\theta_{ij}^2 R_{\text{ph}}}{2c} \right) \frac{\Delta_{-6}}{\theta_{ij}^2} \right)
\]

\[
\left( \frac{M_{\text{ej},-5}^2 f_{\text{ej},-3}^{-2} \theta_{ij}^2}{3c^2} \right)^{1/2} \times 0.8 M_{\text{ej},-5}^{1/2} \text{ s}. \tag{24}
\]

Except if the ejection is highly beamed, the minimum is usually given by the first term. Nevertheless, this estimate clearly points toward short (< 1 s) and even probably very short (< 100 ms; see Figure 4) GRBs without any strong variability (one main single spike). Due to the low external density, the afterglow should rise slowly and reach a maximum around \( \tau_{\text{dec}} = R_{\text{dec}} / 2\Gamma^2 c \approx 2 \times 10^4 M_{\text{ej},-5}^{4/3} f_{\text{ej},-3}^{-1} n_{-3}^{-1/3} \text{ s} \), i.e., a few 10 ms to a few hours after the GRB, depending on the external density. In addition, the combination of a low external density and moderate energy will naturally lead to a weak afterglow. Note that if free neutrons are present in the ejecta, due to efficient photo-disintegration (see Section 5), these neutrons will decay at a typical radius \( R \approx \Gamma c t_{\text{ph}} \approx 5.4 \times 10^{10} M_{\text{ej},-5} f_{\text{ej},-3} \text{ cm} < R_{\text{dec}} \) fixed by the mean lifetime \( \tau_{\beta} \approx 900 \text{ s} \), which could lead to an early additional signature at \( \Delta_{\text{obs}} \approx 20 M_{\text{ej},-5} f_{\text{ej},-3}^{-1} \text{ s} \) (see, e.g., Beloborodov 2003).

6.2. Spectrum

If most of the gamma-rays are produced at the photosphere, one should expect a thermal (quasi-Planckian) spectrum, possibly modified at high energy by Comptonization (Rees & Mészáros 2005; Pe’er et al. 2006; Beloborodov 2011). The peak energy of the observed spectrum will then be located at \( E_p \approx 3.9 \times 10^8 T_{\text{ph}} / m_p \), where \( T_{\text{ph}} \) is the temperature of the photosphere. It can be computed assuming an adiabatic radial expansion from the ejection to the photosphere:

\[
E_p \approx 3.92 \left( \frac{3E}{16\pi a R_{\text{NS}}^2 \Delta} \right)^{1/4} \left( \frac{R_{\text{ph}}}{R_{\text{sat}}} \right)^{-2/3}
\]

\[
\approx 18 M_{\text{ej},-5}^{-1} f_{\text{ej},-3}^{11/12} \Delta_{-6}^{-1/4} \text{ keV}. \tag{25}
\]

The efficiency of the photospheric emission can also be deduced from the adiabatic evolution and equals \( f_{\gamma} \approx (R_{\text{ph}} / R_{\text{sat}})^{-2/3} \). This leads to a better estimate of the isotropic equivalent energy radiated in gamma-rays,

\[
E_{\gamma,\text{iso}} \approx 2 \times 10^{48} \left( \frac{16}{50} \right) M_{\text{ej},-5}^{1} f_{\text{ej},-3}^{5/3} \text{ erg s}^{-1}. \tag{26}
\]

that stands on the lower values for GRBs. Of course, there is still a large uncertainty due to the unknown factors \( f_b \), \( f_q \) and \( M_{\text{ej}} \). However, these two estimates confirm the capacity to produce bright and hard spikes of gamma-rays in the considered scenario, as illustrated in Figure 4 where all the constraints on the prompt gamma-ray emission expected in the NS \( \rightarrow \) QS conversion scenario are summarized.

Another possible signature of the scenario would be the presence of spectral features and lines associated with the specific chemical composition (heavy elements) of the ejected material. Following the work by Mészáros & Rees (1998) where \( \Gamma \simeq 10–100 \) were considered, the spectrum could be influenced below the MeV range.
Figure 4. In parameter space, mass of the ejected outer crust $M_{ej}$ vs. efficiency of the energy injection in the crust $f_{ej}$, the following constraints are plotted: (1) lines of constant Lorentz factor are plotted in blue for $\Gamma = 1$ (non relativistic limit), 10, 100, and 1000. The limit $\Gamma \simeq 15$ obtained from the compactness argument (see Section 3 is plotted in a thick line and the forbidden region is shaded; (2) the limit where the radius of the internal dissipation $R_i$ is equal to the radius of the photosphere is plotted in red (most of the parameter space is well below this line, i.e., $R_i \ll R_{ph}$); the limit where the observed peak energy of the photospheric emission is 100 keV is plotted in green; the limit where the observed duration of the prompt emission of photospheric origin is equal to 100 ms (1 s) is plotted in solid (dashed) magenta line; the limit where the observed peak energy of the photospheric emission is 100 keV is plotted in black. The effect of the redshift of the source on the duration and the spectrum are not included. Other parameters are $\Delta t = 1$ (i.e., the width of the outer crust is 300 m) and $f_b = 50$ (i.e., the ejecta is beamed within $\sim 10^\circ$). As can be observed, a large fraction of the parameter space (top-left region) corresponds to ultra-relativistic outflows ($\Gamma \gtrsim 100$) producing a very short ($< 100$ ms) but bright ($E_{\gamma,iso} > 10^{49}$ erg) spike of hard ($E_p > 100$ keV) photons, i.e., a very short GRB. (A color version of this figure is available in the online journal.)

6.3. Gravitational Waves and Other Non-photonic Signatures

In addition to the expected short duration burst of $\gamma$-rays and X-rays and to the afterglow, it is likely that a multi-messenger approach must be followed to spot this progenitor scenario for SGRBs. The emission of gravitational waves by the merger of NS+NS or NS+BH binary is the most promising source for detectors such as Virgo and LIGO and their advanced versions (Acernese et al. 2009; Harry & the LIGO Scientific Collaboration 2010), or the Einstein telescope (Hild et al. 2010). The predicted emission during the three main stages of the merger has been extensively studied in the literature (see Hughes 2009 for a review). In the inspiral stage, the signal is very well known up to the last stable orbit. Then, the emission during the merger is more uncertain and must be modeled using supercomputer simulations which provide information about the gravitational waveform (Duez et al. 2006; Baiotti et al. 2010) (see the recent simulations by Shibata & Taniguchi 2006; Price & Rosswog 2006; Baiotti et al. 2008; Anderson et al. 2008; Liu et al. 2008; Giacomazzo et al. 2009; Rezzolla et al. 2010; Kiuchi et al. 2010; Giacomazzo et al. 2011 which compute the evolution of the merger up to BH formation, either including or not including magnetic fields, realistic EoS, etc.). The final ringdown stage is also very well known as the inspiral. Therefore, the detection of gravitational waves in association with a SGRB would undoubtedly prove if the progenitor is a merger or not. With a horizon of $\sim 200$ Mpc for NS+NS mergers and $\sim 420$ Mpc for NS+BH mergers, there may be merger detections with advanced Virgo/LIGO (Harry & the LIGO Scientific Collaboration 2010) (0.4–400 mergers yr$^{-1}$ for NS+NS, a slightly smaller rate for NS+BH; Abadie et al. 2010b). However, the simultaneous detection with a SGRB if the merger scenario is correct is more uncertain, both for theoretical (beaming of the gamma-ray emission) and instrumental (localization of SGRBs) reasons.

The gravitational wave signature of the scenario studied here is not as well known as for compact binary mergers. It is expected that a change in the moment of inertia is caused by deformations in the NS $\rightarrow$ QS transition. Some preliminary estimates of the transient gravitational wave signal from an
The explosive quark–hadron phase transition have been done (Staff et al. 2012). It could in principle be detected out to 20 Mpc with advanced Virgo/LIGO, which unfortunately makes the probability of detection with an associated SGRB quite low, even if the intrinsic rate of very SGRBs is quite uncertain (see Section 4).

The strategy for the detection of gravitational waves associated with a GRB is to combine searches, already having identified typical patterns in temporal and directional coincidence with SGRBs that had sufficient gravitational-wave data available, although it is a very challenging task (Abadie et al. 2010a).

An additional signal that may be used to discriminate between progenitor models for SGRBs is the neutrino emission. The specific signal expected from NS+NS mergers has been studied using supercomputer simulations (see, e.g., Dessart et al. 2009). In this work and within the present scenario we do not attempt to describe such a neutrino emission since it crucially depends on the central engine details. However, it should be expected that a neutrino flux originating from hadronic reactions happens in the central engine (conversion in the nucleon burning front of quark deconfinement and strangeness production) or in the ejecta (photo-meson interactions between shock-accelerated protons and nuclei and gamma-ray photons).

In addition, if the neutrons produced do not interact they will decay accompanied by anti-neutrinos. Emission of prompt muon neutrino fluxes have been performed in some general GRB scenarios (Baerwald et al. 2011) and seem to be testable as recent preliminary estimated sensitivities for Ice Cube 86-strings quote values of $E^2 \Phi(E) \sim 5 \times 10^{-8} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. Additionally, experiments such as AMANDA-II and IceCube have the capability (Hughes et al. 2007) of detecting anisotropies from the emission (Aartsen et al. 2013) of neutrinos from gamma-ray induced air showers. Therefore, as motivated, the discovery of high energy neutrinos in correlation with a SGRB and GW signal would help in disentangling the current scenario.

7. CONCLUSIONS

In this work we discuss the possibility that a NS $\rightarrow$ QS transition may be a central engine model for short ($<1$ s) or more probably very short ($<100$ ms) GRBs. This is an alternative to the popular NS+NS or NS+BH merger scenario for SGRBs. Note that this scenario is known to be compatible with observations of SGRBs but has not been proven yet, and that in addition, there are a few observations suggesting that very short bursts could be a separate population. We suggest that these very short bursts could be produced by the ejection and acceleration to relativistic speed of the (outer) crust of the NS during the conversion to a QS. We find the following

1. The isotropic equivalent gamma-ray energy $\sim 10^{48} - 10^{52}$ erg can be accounted for, assuming that 0.1%–1% of the gravitational energy released by the transition is injected in the outer crust with, however, a large uncertainty due to the unknown beaming factor of the ejection.

2. High Lorentz factors, necessary for the emission of $\gamma$-rays on short timescales (compactness problem), can be reached, as long as the mass of the expelled crust is less than $\sim 10^{-4} M_\odot$; this is attainable for the outer crust in NS models.

3. The rate of very short GRBs can probably be reproduced, assuming that only a fraction of transitions lead to a GRB and that there is on average a large delay between the formation of the NS and the conversion into a QS. Such a delay is expected due to the fact that the transition is triggered by self-annihilation of DM, which first needs to be accreted in the core of the NS. Such delays would then naturally at least partially suppress the correlation between star formation and very short GRBs, which should be observed in any type of galaxy with a large offset (at the present time, there are only two host galaxies of very short GRBs which have been possibly identified, both being early type, and the offset is a few 10 kpc in both cases).

4. The prompt gamma-ray emission should be mainly produced at the photosphere, without a strong variability which should be washed out by internal dissipation at much smaller radii.

5. For a large fraction of the parameter space, a hard ($E_\gamma \gtrsim 100$ keV) and short (duration $<100$ ms) spike of gamma-rays is expected, in general agreement with observations of very short GRBs.

6. The afterglow should rise slowly and be rather weak, due to a low density of the external medium. A possible additional signature can be expected at early time if the ejected material initially contains free neutrons.

7. Fragmentation of the ejecta arises naturally in this model since non-uniform nuclei arranged in lattice or even pasta phases are present in the low density matter.

8. Spectral features of heavy nuclei relativistically accelerated are expected below $\sim 1$ MeV.

To summarize, possible signatures compared to the binary (NS, BH) merger scenario are the shortness of the prompt gamma-ray emission, with possibly a thermal spectrum and spectral features due to the heavy composition, the associated GW emission, and possibly the properties of the host galaxies and the distribution of the afterglow position in the host, this latter signature being however difficult to characterize due to the uncertainties on the typical delay between the NS formation and the transition to a QS. Clearly, a multi-wavelength/multi-messenger approach is needed to reach a firm conclusion.

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