A lesson from GW170817: most neutron star mergers result in tightly collimated successful GRB jets

Paz Beniamini\textsuperscript{1,2}, Maria Petropoulou\textsuperscript{3}, Rodolfo Barniol Duran\textsuperscript{4} & Dimitrios Giannios\textsuperscript{5}

\textsuperscript{1}Department of Physics, The George Washington University, Washington, DC 20052, USA
\textsuperscript{2}Astronomy, Physics and Statistics Institute of Sciences (APSIS)
\textsuperscript{3}Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton, NJ 08544, USA
\textsuperscript{4}Department of Physics and Astronomy, California State University, Sacramento, 6000 J Street, Sacramento, CA 95819, USA
\textsuperscript{5}Department of Physics and Astronomy, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907, USA

Accepted; Received; in original form ...

ABSTRACT

The joint detection of gravitational waves (GWs) and $\gamma$-rays from a binary neutron-star (NS) merger provided a unique view of off-axis GRBs and an independent measurement of the NS merger rate. Comparing the observations of GRB170817 with those of the regular population of short GRBs (sGRBs), we show that an order unity fraction of NS mergers result in sGRB jets that breakout of the surrounding ejecta. We argue that the luminosity function of sGRBs, peaking at $\approx 2 \times 10^{52}$ erg s$^{-1}$, must be an intrinsic property of sGRB jets and that sGRB jets are typically narrow with opening angles $\theta_0 \approx 0.1$. We perform Monte Carlo simulations to examine models for the structure and efficiency of the prompt emission in off-axis sGRBs. We find that only a small fraction ($\sim 0.01 \sim 0.1$) of NS mergers detectable by LIGO/VIRGO in GWs is expected to be also detected in prompt $\gamma$-rays, and GW170817-like events are very rare. For a NS merger rate of $\sim 1500$ Gpc$^{-3}$ yr$^{-1}$, as inferred from GW170817, we expect within the next decade up to $\sim 12$ joint detections with off-axis GRBs for structured jet models and just $\sim 1$ for quasi-spherical cocoon models where $\gamma$-rays are the result of shock breakout. Given several joint detections and the rates of their discoveries, the different structure models can be distinguished. In addition the existence of a cocoon with a reservoir of thermal energy may be observed directly in the UV, given a sufficiently rapid localisation of the GW source.

Key words: gamma-ray burst: general – gravitational waves – stars: jets – stars: neutron

1 INTRODUCTION

The connection between neutron star-neutron star (NS-NS) or neutron star-black hole (NS-BH) mergers with short-duration Gamma Ray Bursts (sGRBs) and the nucleosynthesis of $r$-process elements dates back to a few seminal works from the nineteen eighties (Blinnikov et al. 1984; Paczynski 1986; Goodman 1986; Eichler et al. 1989). In recent years, the rate of $r$-process formation has been constrained using various observational lines of argument (Hotokezaka, Piran & Paul 2015; Ji et al. 2016; Beniamini, Hotokezaka & Piran 2016; Macias & Ramirez-Ruiz 2016; Hotokezaka, Beniamini & Piran 2018; Beniamini, Dvorkin & Silk 2018). It was shown to be broadly consistent with the rate of sGRBs (Guetta & Piran 2006; Guetta & Stella 2009; Coward et al. 2012; Wanderman & Piran 2015; Ghirlanda et al. 2016) and with the rate of NS mergers as inferred from observations of Galactic double neutron stars (Kochanek & Piran 1993; Kim, Perera & McLaughlin 2015). However, a clear determination of NS-NS mergers being the progenitors of sGRBs and the main source of $r$-process elements remained somewhat uncertain until the recent discovery of the kilonova AT2017gfo (Tanvir et al. 2017) and GRB170817 (Goldstein et al. 2017), accompanying the NS-NS merger event GW170817 (Abbott et al. 2017). This recent discovery also leads to a new and independent estimate of the rate of NS-NS mergers. Furthermore, the observations of a very weak GRB accompanying the event, and detailed modelling of the peculiar and long-lived afterglow that followed the event, provides us with information regarding the opening angle, viewing angle, and core luminosity of GRB170817.

The GW170817/GRB170817 event provides an unprecedented opportunity to explore sGRB jets in a broader context: How frequently do sGRB jets manage to break through the ejecta material surrounding the NS-NS mergers? What are the typical opening angles of sGRB jets? What determines the shape of the sGRB luminosity function? These topics have been partially explored in the past, either from an observational point of view, using the data from electromagnetically-detected sGRBs (i.e., not accompanied by a GW event) (Wanderman & Piran 2015; Ghirlanda et al. 2016; Moharana & Piran 2017), or from hydrodynamical studies of...
the GRB jet propagation through the NS-NS merger ejecta (Aloy, Janka & Müller 2005; Hotokezaka et al. 2013; Nagakura et al. 2014; Murguia-Bethier et al. 2014; Lazzati et al. 2017b; Bromberg et al. 2018; Duffell et al. 2018). Here, we show that by combining this knowledge with the unique constraint from GW170817 we can probe these questions in greater detail, thus significantly improving our understanding of these issues.

The discovery of GRB170817 raised perhaps as many new questions as answers. In particular, the extremely dim prompt GRB raises questions as answers. In particular, the extremely dim prompt GRB

$\gamma$

to which the observed

questions as answers. In particular, the extremely dim prompt GRB...

...in long (collapsar) GRBs (Petropoulou, Barniol Duran & Giannios 2017). This huge difference in the expected rates of failed short and long GRBs may be related to the nature of the ejecta that the jet has to propagate through. For example, the expansion of the dynamical ejecta in the case of a NS merger may facilitate the jet breakout (Duffell et al. 2018) in contrast to the jet propagation through the quasi-static outer layers of the collapsing star expected in the case of long GRBs (Bromberg et al. 2011).

2.2 Interpretation of the sGRB luminosity function

The (isotropic equivalent) luminosity function of both short and long GRBs (after de-convolving with the rate function) is described by a broken power law:

$$\phi(L) \propto \frac{dN_{\text{GRB}}}{d\log L} = \begin{cases} \left( \frac{L}{L_{\text{min}}} \right)^{-\alpha_L} & L_{\text{min}} \leq L \leq L_*, \\ \left( \frac{L}{L_*} \right)^{-\beta_L} & L > L_* \end{cases}$$

For sGRBs $\alpha_L \approx 0.95$, $\beta_L \approx 2.0$ and $L_* \approx 2 \times 10^{49}$ erg s$^{-1}$ (Wanderman & Piran 2015). Henceforth, we adopt the luminosity function reported by Wanderman & Piran (2015), while noting that none of our main conclusions would change, if we were to adopt other values for the power-law slopes and/or break luminosity reported in the literature (Guetta & Piran 2006; Salvadori et al. 2008; Ghirlanda et al. 2016). We next explore three different interpretations to the broken power-law nature of $\phi(L)$: (i) arising due to the increasing fraction of failed GRB jets for $L < L_*$, (ii) being the result of the angular structure of sGRBs, or finally (iii), being an intrinsic property of the sGRB central engine.

2.2.1 Failed jets

Petropoulou, Barniol Duran & Giannios (2017) have argued that the broken power-law nature of $\phi(L)$ in long GRBs could result from an underlying single power-law distribution of luminosities, that is then modified at lower luminosities due to an ever increasing fraction of failed GRB jets. This provides a natural explanation for the apparent more complicated luminosity function whereby the interpretation for $L_*$ is the maximum luminosity for which not all long GRB jets manage to break out of the stellar envelope.

Interestingly, the same interpretation cannot hold for sGRBs. This is clear from the fact that within the Petropoulou, Barniol Duran & Giannios (2017) framework, the slope of $\phi(L)$ above $L_*$ is that of the true underlying distribution. In this context, the ratio of failed sGRB to successful sGRB engines at $L < L_*$ can be then extrapolated to lower luminosities as:

$$r_{\text{fail}} = \frac{R_{\text{merg}}}{R_{\text{GRB}}} - 1 \approx \left( \frac{L_{\text{min}}}{L_*} \right)^{-\beta_L + \alpha_L} \approx 540 \frac{L_{\text{min}}^{-1}}{L_{49.7}^{-1}}.$$
which is clearly in contradiction with equation (2) by more than two orders of magnitude.

2.2.2 Angular structure

Another potential way to explain the broken power-law nature of the luminosity function is to consider that GRBs have a wide structure beyond the jet core, i.e., the jet luminosity is constant up to some $\theta_0$ and then decreases for larger angles (Lipunov, Postnov & Prokhorov 2001; Frail et al., 2001; Rossi, Lazzati & Rees 2002; Zhang & Mészáros 2002; Eicher & Levinson 2004; Van Eerten & MacFadyen 2012; Pescalli et al., 2015). In this context, the distribution $\Phi (L)$ below $L_*$ may become dominated by GRBs that are marginally above the critical core luminosity $L_*$, but are seen progressively more off axis (as $L \ll L_*$). This particular scenario would imply an increased intrinsic minimal core luminosity, $L_{\text{min}} \approx L_*$, and hence would increase the ratio of failed to successful jets given by equation (2), which could help to reduce (and potentially resolve) the inconsistency with the estimate given by equation (4). As an illustration, let us consider that the jet (isotropic equivalent) luminosity is constant up to a latitude $\theta_0$ and then declines as $\theta^{-4}$ for $\theta > \theta_0$. Assuming an isotropic distribution of solid angles and the same structure for all sGRB jets, this will lead to $\Phi (L) \propto L^{dN/dL} / dL \propto L^{-2/\gamma}$. This matches the observed $\Phi (L) \propto L^{-\gamma_e}$, only if the typical value of the jet structure slope is $\gamma \approx 2$. Such a shallow profile however (close to the so-called “universal jet” structure; see Rossi, Lazzati & Rees 2002; Zhang & Mészáros 2002) is in contradiction with observations of the X-ray afterglow luminosity to $\gamma$-ray energy ratio (Beniamini & Nakar, in prep.) and with the observation of jet breaks in GRB light curves (Harrison et al., 1999; Pong et al., 2012; Wang et al., 2018). Therefore, the interpretation that the luminosity below $L_*$ being dominated by off-axis events is also ruled out under the assumption of a common jet structure among all sGRBs.

2.2.3 Intrinsic structure

A third possibility is that the broken power-law luminosity function determined by observational studies (Guetta & Piran 2006; Guetta & Stella 2009; Wanderman & Piran 2015; Ghirlanda et al., 2016) actually reflects the intrinsic power produced by the central engine. We turn next to explore the implications of this interpretation of the luminosity function on the typical opening angles of sGRBs and on the expected distributions of luminosities and observation angles as probed by future joint detections of prompt GRBs and GWs.

2.3 Constraining the opening angles of short GRBs

We now use the connection between the rate of NS mergers and sGRBs to constrain the jet opening angle, $\theta_0$, as described above. Different arguments and constraints point to jets having a narrow range of opening angles at $\theta_0 \approx 0.1$.

First, since $R_{\text{merg}} \geq R_{\text{GRB}}$, equation (2) provides a lower limit on the allowed opening angles of sGRBs (or equivalently on the beaming factor) which is roughly:

$$\theta_0 \geq \theta_{\text{min}} \equiv 0.07 L_{\text{m,49.7}}^{-1/2} R_{\text{m,1540}}^{1/2} \tag{5}$$

At the same time, observations of sGRBs over the last 14 years with Neil Gehrels Swift satellite, provide us with an upper limit on the allowed value for sGRB opening angles. Considering the sample of observed Swift BAT bursts with $T_{90} < 2$ s, we search the online database and find that the maximum peak photon flux of sGRBs within $\Delta t_{\text{obs}} = 14$ years of observations (in the 15 – 150 keV range) is $P_{\text{max}} = 12.1 \text{ ph cm}^{-2} \text{s}^{-1}$. For a given redshift $z$ and corresponding luminosity distance $d_L (z)$, this can be translated to a peak luminosity as:

$$L(z, P_{\text{max}}) = \frac{4 \pi d_L^2 (z)}{1 + z} \int_{15 \text{ keV}}^{100 \text{ keV}} E N (E) dE \frac{10^{40} \text{ erg cm}^{-2} \text{s}^{-1}}{N(E) dE} \tag{6}$$

where $N(E)$ is the differential photon spectrum described by the so-called Band function (Band et al., 1993). In what follows we assume typical observed sGRB parameters: $\alpha = -0.5$, $\beta = -2.25$, $E_{\text{p,source}} = 500 \text{ keV}$ (Nava et al., 2011). Using equation (6) and requiring that $L(z, P_{\text{max}}) > L_{\text{min}} = 5 \times 10^{49} \text{ erg s}^{-1}$ (the same value of $L_{\text{min}}$ considered above), we find a conservative minimum distance from which current Swift BAT bursts could have originated $d_L (z) \equiv d_{\text{GRB}} \geq 250 \text{ Mpc}$. In other words, even a burst that had an intrinsic (isotropic equivalent) luminosity at the core as low as $L_{\text{min}} \approx 5 \times 10^{49} \text{ erg s}^{-1}$ would have resulted in a peak flux larger than any of the observed Swift BAT bursts, if its distance from us was less than 250 Mpc. Thus, the opening angle of sGRBs has to be small enough to be consistent with the non-detection of bursts with $L > L_{\text{min}}$ at $d_L (z) < 250 \text{ Mpc}$. For a fixed rate of NS mergers, the upper limit on $\theta_0$ is independent of the inferred local sGRB rate given by equation (1):

$$\theta_{\text{max}} = \sqrt{\frac{2 (r_{\text{final}} + 1)}{R_{\text{merg}} \Delta t_{\text{obs}} V_{\text{GRB}}} \frac{L_{\text{max}}}{L_{\text{GRB}}} \frac{P_{\text{max}}}{P_{\text{GRB}}} \frac{1}{10^{-39}}} \tag{7}$$

where $V_{\text{GRB}} \equiv \frac{4 \pi}{3} d_{\text{GRB}}^3$ and where we have conservatively used an efficiency of $\eta_{\text{GRB}} = 0.12$ for the detectability of Swift sGRBs above the BAT threshold (Burns et al., 2016). We note also that a comparable, though somewhat larger estimate for $\theta_{\text{max}}$ can be obtained by using Fermi GBM data. In this case, the efficiency is larger $\eta_{\text{GBM}} = 0.6$ (Racusin et al., 2017) while the observation period is slightly shorter $\Delta t_{\text{obs}} = 9$ years. According to Lu et al. (2017), $P_{\text{max}} = 138 \text{ ph cm}^{-2} \text{s}^{-1}$ (between 8 keV and 40 MeV) for this period. Using the typical spectral parameters for GBM bursts, namely $\alpha = -1.5$, $E_p = 600 \text{ keV}$ (Nava et al., 2011), we find $d_{\text{GRB}} = 130 \text{ Mpc}$ and $\theta_{\text{max}} = 0.16$.

As we show next, comparing the ratio of merger rates to sGRB rates as given by equation (2) to the fraction of successful jets as probed by recent numerical analysis of the jet-merger outflow interaction (Duffell et al., 2018) provides in turn, an estimate of $\theta_0$ (instead of a lower and upper limit as presented above).

Duffell et al. (2018) find that jets are successful if the beaming corrected energy in the jet $E_j$ is larger than a critical value $E_{\text{crit}} \equiv 0.55 E_0$, where $E_0$ is the energy deposited in the NS merger ejecta. Throughout this work, we assume that the opening angle of the injected jet in the simulations by Duffell et al. (2018) is equal to the jet opening angle after breakout from the NS merger ejecta. This is an appropriate approximation for jets propagating in a non-expanding medium (Bromberg et al., 2011), but it remains to be shown whether this also holds for jets pummelling through an expanding medium. Taking $E_{\text{ej}} \approx 10^{52}$ erg as a typical value for jet energy, this is a very conservative cut-off for the population of non-collapsar GRBs seen by Swift, for which $\approx 50\%$ of these events are detected below 0.8 s, see (Bromberg et al., 2013).

\url{https://swift.gsfc.nasa.gov/archive/grb_table/}
the kinetic energy of the NS merger ejecta \cite{Hotokezaka, Beniamini & Piran 2018} and a constant time of engine activity given by the typical sGRB duration (in the central engine frame) \( t_e = 0.3 \, t_{e,3} \) s \cite{Kouveliotou et al. 1993}, the condition \( E_3 > E_{\text{c}} \) translates to:

\[
L > L_{\text{c}} \simeq 5 \times 10^{51} \frac{E_{\text{ej}}}{t_{e,3}} \left( \frac{\eta_7}{0.15} \right) \text{erg s}^{-1},
\]

where \( E_{\text{ej},51} \equiv E_{\text{ej}} / (10^{51} \text{ erg}) \). \( \eta_7 \) is the efficiency of converting the injected jet power into observed \( \gamma \)-rays in the prompt phase and is normalized to a characteristic value \( \eta_{p,0} = 0.15 \) inferred from observations \cite{Beniamini et al. 2015, Beniamini, Nava & Piran 2016}. Notice that \( L_{\text{c}} \) is very close to the canonical value for \( L_{\text{min}} \). Were \( L_{\text{c}} > L_{\text{min}} \), then a second break in the sGRB luminosity function should be present, which is not observed\(^3\). The ratio of failed to successful sGRB rates can also be estimated from the sGRB luminosity function (see equation (3)) and it may be written as \( r_{\text{fail}} \simeq (L_{\text{c}} / L_{\text{min}})^{\alpha_2} - 1 \approx 1 \). This condition is satisfied when

\[
\theta_0 = 0.07 \frac{E_{\text{ej},51}}{t_{e,3}} \left( \frac{\eta_7}{0.15} \right)^{\alpha_2} \frac{1}{L_{\text{m},49}^{\alpha_2} R_{\text{m},1540}^{-1/2}},
\]

where equation (4) was used. Interestingly, the allowed values of \( \theta_0 \) obtained from equations (3), (7), and (9) are consistent with two independent estimates of the opening angle in GRB170817: \(^{3}

(i) recent measurements of superluminal motion in GRB170817 \cite{Mooley et al. 2018a} using VLBI data demonstrated that \( \theta_0 \lesssim 0.09 \) in GRB170817; \(^{3}

(ii) the peak time of the GRB170817 afterglow in X-rays and radio suggested that \( 0.04 \lesssim \theta_0 \lesssim 0.1 \) \cite{Mooley et al. 2018b, Pooley et al. 2018}.\(^{3}

Our analysis suggests that the majority of sGRB jets (or even all) is successful in breaking out of the surrounding ejecta. In addition, assuming that the opening angle of sGRBs is independent of their luminosity, we showed that \( \theta_0 \approx 0.1 \); these are tighter constraints than existing ones for the sGRB population \cite{Janka et al. 2006, Feng et al. 2015}. Note that these results do not depend too strongly on the value of \( R_{\text{m,1540}} \), which will be better constrained in the future with more observations of GWs from NS mergers (see also \cite{Hotokezaka et al. 2018} for comparison with \( \gamma \)-process rates suggesting a comparable but possibly slightly lower rate).

3 PROBING GRB MODELS WITH JOINT GW & PROMPT GRB DETECTIONS

The detection of a GW signal could boost the likelihood of association of an otherwise marginal \( \gamma \)-ray signal with an underlying GRB and of the identification of the host galaxy \cite{Patricelli et al. 2016, Abbott et al. 2017, Kathirgamaraju, Barniol Duran & Giannios 2018, Beniamini et al. 2018}. NS mergers detected by GWs also select nearby events. The observed distribution of sGRB luminosities that are also detected in GWs is therefore expected to be different than that of sGRBs with no GW detection. This implies that joint GW and prompt GRB detections could provide a unique probe to the distribution of the \( \gamma \)-ray luminosity as a function of angle \( \theta \) with respect to the jet symmetry axis \( L_{\gamma,\text{iso}}(\theta) \), and therefore, to the underlying jet and/or cocoon physics.

\(^3\) This is inferred from the modelling of the kilonova emission following GW170817 \cite{Kasen et al. 2017, Tanaka et al. 2017}. \(^4\) The possibility of \( L_{\text{c}} / L_{\gamma,\text{iso}} \) is ruled out by the rate comparison in equation (2) as was demonstrated explicitly in \cite{2018}. \(^5\) This is compared to the available energy along the line of sight to the observer. \(^6\) For the distance scales relevant for GW detection, cosmological effects can, to a good approximation, be neglected, and the bursts can be assumed to be randomly distributed within a sphere of radius \( d_{\text{max}} \).
The jet core is surrounded by a radiatively inefficient quasi-isotropic (compared to the jet core) moving along their line of sight (SJ model). Bottom: The jet core is surrounded by a radiatively inefficient quasi-isotropic component with a likely radial structure in its properties (CL model).

\[ \text{d}_{\text{max}} \text{ by adopting } d_{\text{max}} = 50 \text{ Mpc for all explored models. Following our reasoning in } \text{22} \text{ we then simulate the luminosity of the jet core according to the luminosity function in } \text{13}. \text{ From the discussion in } \text{23} \text{ we expect } \theta_0 \approx 0.1. \text{ We consider this as the canonical value, but for completeness, consider also the cases of } \theta_0 = 0.05 \text{ and } \theta_0 = 0.2. \text{ For a given structure model, the emissivity is then extrapolated to larger angles. For each event, we calculate both the on line-of-sight contribution to the emission (i.e., from emitters that see the observer within their relativistic beaming cone) and the off line-of-sight contribution.} \]

\[ \Phi(\theta/\theta_0) = \frac{1}{\log(\text{L}_{\text{GRB170817}}/L_{\text{min}})\log(\theta_0/\theta_{\text{obs}})} \]

\[ \text{where } \Phi(\theta/\theta_0) \text{ is the luminosity and } \theta_{\text{obs}} \text{ is the observed angle.} \]

\[ \text{Typically, the } \theta_{\text{obs}} \text{ denotes observed ones, } q = |\theta_{\text{obs}} - \theta_0|/\Gamma \text{ and we set } \Gamma = 100 \text{ in our simulations. The duration scales as } \Delta t_{\text{obs}} = q^2 \Delta t_{\text{em}} \text{ if the burst duration is set by a 'single' emission episode that takes place at some location } r \text{ that extends over a range of radii } \Delta r \leq r \text{ or as } \Delta t_{\text{obs}} = \Delta t_{\text{em}} \text{ if the burst duration is set by the radial width of the outflow. In what follows, we assume that the duration is set by the radial width of the outflow and that } \Delta t_{\text{obs}} = \Delta t_{\text{em}} = 0.3 \text{ s. The luminosity then scales as the ratio of } E_{\gamma,\text{obs}} \text{ to } E_{\gamma,\text{em}}. \text{ This provides an upper limit on the off line-of-sight luminosity and is therefore a conservative choice for our simulations. Even in this case, we find that the off line-of-sight emission is sub-dominant to the on-line-of-sight emission, unless the angular profile is extremely steep and the observation angle is close to jet core.} \]

\[ \text{Computing the emission from structured-jet (SJ) simulated events is meaningful only if the jet has successfully broken out of the ejecta. This is in accord with results of hydrodynamical simulations of jet and NS merger interaction [Duffell et al. 2018]. Furthermore, as shown in [2] a large fraction of sGRB jets (and possibly all) are expected to successfully break out of the expanding ejecta. We therefore assume } \tau_{\text{fail}} = 1 \text{ in all SJ models. We explore three variants of the SJ models described below:} \]

- A power-law (SJPL) model, where \( L = L_0 \Gamma^2 \) for \( \theta < \theta_0 \) and \( L = L_0/\Gamma^2 \delta^4 \) for \( \theta > \theta_0 \). The value of \( \delta \) in this model is constrained by the observations of GRB170817. For a given value of \( \theta_0, \delta \) must satisfy \( \delta \geq \log(L_{\text{GRB170817}}/L_{\text{min}})/\log(\theta_0/\theta_{\text{obs}}) \) since the lowest core luminosity is given by \( L_{\text{min}} \) and the extrapolation of this luminosity to \( \theta_{\text{obs}} \approx 0.3 \) should not overproduce \( \gamma \)-rays as compared with those observed for GRB170817. This consideration implies \( \delta \geq 3 \) for \( \theta_0 = 0.05, \delta \geq 4.5 \) for \( \theta_0 = 0.1 \) and \( \delta \geq 10 \) for \( \theta_0 = 0.2 \).

- A Gaussian (SJG) model, where \( L = L_0 \exp(-\theta/\theta_0)^2 \). As in the SJPL case, this family of models can be limited by the requirement to not overproduce \( \gamma \)-rays compared to GRB170817. Applied to this model, this consideration puts an upper limit on \( \theta_0 \) of: \( \theta_0 \leq \theta_{\text{obs}}(\log(L_{\text{min}}/L_{\text{GRB170817}}))^{-1/2} \approx 0.14 \).

- A simplified cocoon-like (CL) model, where \( L = L_0 + L_{\gamma,\text{co}} \) for \( \theta < \theta_0 \) and \( L = L_{\gamma,\text{co}} \) for \( \theta > \theta_0 \). Here, \( L_{\gamma,\text{co}} \) is the peak (isotropic equivalent) cocoon breakout luminosity and it is estimated as follows. The peak thermal energy stored in the cocoon (as a function of time) is found by Duffell et al. (2018). As mentioned above, here we assume that the that the injected opening angle is equal to the opening angle after breakout. Re-writing equations \( 10, 21 \) in Duffell et al. (2018) in a slightly different form, we obtain:

\[
E_{\text{Th}} = \left\{ \begin{array}{ll}
0.17E_j & E_{\text{ej}} < E_j < 30E_{\text{cr}} \\
1.14E_{\text{ej}} & E_j > 30E_{\text{cr}}.
\end{array} \right.
\]

(10)

where \( E_{\text{ej}} \approx 5 \times 10^{50} \theta_0^2 \) erg and \( E_j \) is the beaming corrected kinetic energy of the jet. \( E_j \approx 0.5 \theta_0^2 L_{\text{obs}}/\eta_\gamma \). The peak thermal energy in equation \( 10 \) is reached at a time

\[
t_{\text{peak}} = \left\{ \begin{array}{ll}
2t_{\text{obs}}(t < t_{\text{obs}}) & E_{\text{ej}} \leq E_j \leq 30E_{\text{cr}} \\
t_{\text{obs}} & E_j > 30E_{\text{cr}}.
\end{array} \right.
\]

(11)

where \( t_{\text{obs}} = 3t_{\text{cr}}E_{\text{cr}}/E_j \) is the time it takes the jet to breakout from the ejecta. The thermal energy stored in the cocoon provides

\[ \text{This condition is at first glance similar to the condition discussed above when considering whether it is possible to explain the broken power-law nature of the luminosity function with angular structure (in which case the minimum core luminosity is given by } L_{\gamma,\text{co}} \). However, since that possibility has been shown to be ruled out, and the luminosity function } \Phi(L) \text{ was shown to be intrinsic, we conservatively replace here } L_{\gamma} \text{ by } L_{\text{min}}. \]
a strict upper limit on its radiated energy and luminosity. This is because the cocoon is expected to be initially optically thick, in which case only a small portion of the thermal energy, can escape to the observer (see Nakar & Sari 2010 and references therein). For GRB170817, the latest modelling efforts suggest a total (beaming corrected) energy of $10^{50}$ erg (Mooley et al. 2018b) which corresponds to $E_{	ext{th}} \approx 3 \times 10^{49}$ erg. At the same time, cocoon breakout models for the prompt $\gamma$-rays radiate only $E_{\text{br}} = 4 \times 10^{46}$ erg at breakout (Gotthelf et al. 2017; Lazzati et al. 2017b), implying an efficiency of $\eta_{\gamma} \equiv E_{\text{br}}/E_{\text{th}} \sim 10^{-4}$ for this phase. In what follows we adopt $\eta_{\gamma} = 10^{-3}$ as a canonical value.

The entire thermal energy is eventually released on the timescale for which the medium reaches transparency $t_{\text{thin}}$. As an indicative example, let us consider a characteristic velocity $v = 0.5c$ for the cocoon ejecta of mass $M_{\text{co}}$. Assuming that the kinetic energy of the cocoon is comparable to its thermal energy (Duffell et al. 2018) ($E_{\text{Th}} = 0.5M_{\text{co}}v^2$), $t_{\text{thin}}$ is estimated as:

$$t_{\text{thin}} = \sqrt{\frac{\kappa M_{\text{co}}}{\tau_{\text{esc}}} \approx \sqrt{\frac{2E_{\text{Th}} \kappa}{\tau_{\text{esc}}}}.}$$

(12)

where $E_{\text{Th}} \equiv E_1/10^{50}$ erg, $v = c/0.5c$, $\theta_{0.1} = \theta_0/0.1$, and $\kappa$ is Thomson scattering cross section. For the adopted parameter values, we find that $t_{\text{thin}} > t_{\text{br}} > t_{\text{peak}}$ (see equation 11). This is consistent with the small efficiencies for the cocoon breakout luminosity, $\eta_{\gamma} \ll 1$ inferred for GW170817, as discussed above.

A discussion of the detectability of this component is given in §6. The peak (isotropic equivalent) cocoon breakout luminosity can be approximated by using equations (10) and (11):

$$L_{\gamma,\text{co}} \approx \eta_{\gamma} \frac{E_{\text{Th}}}{t_{\text{peak}}} \approx \frac{\theta_0^2}{2} \eta_{\gamma} kL_0,$$

(13)

where $k$ is a numerical constant that is $k \approx 0.08$ for $E_{\text{cr}} \leq E_j < 30E_{\text{cr}}$ and $k \approx 0.38$ for $E_j > 30E_{\text{cr}}$.

For each simulated event, we compute the $\gamma$-ray flux by taking all relevant contributions for the SJ and CL models, as described above. Then, a simulated GRB is assumed to be detectable, if its prompt $\gamma$-ray flux exceeds the Fermi GBM threshold $F_{\text{lim}} = 5.8 \times 10^{-7}$ erg s$^{-1}$ cm$^{-2}$ (Goldstein et al. 2017), note that for sGRBs one can neglect the duration in the definition of the limiting flux. The detectability of GWs is a complex function of the viewing angle with respect to the merger plane (Schutz 2011; Allen et al. 2012; Hilborn 2018). Using the angular dependence of the detection probability given in Schutz (2011) (see equation (27) therein) and scaling with the horizon distance for binary mergers of 218 Mpc, we define as detectable in GWs any simulated events that satisfy the condition:

$$218 \text{ Mpc} \left(1 + 6 \cos^2 \theta_{\text{obs}} + \cos^4 \theta_{\text{obs}}\right)^{1/2} > 1.$$  

(14)

The Monte Carlo process is repeated $10^5$ times, and the burst properties are recorded for events with joint $\gamma$-ray and GW detection or with just one of the two.

### 3.2 Results

The distributions of observation angles and prompt luminosities of GRBs with joint $\gamma$-ray and GW detections are presented respectively in the left and right panels of Fig. 2 (solid lines). The dot-dashed histogram (left-hand side panels) shows the probability that a GW signal is detected for a given observation angle, as given by equation (14), i.e., independent of the detectability of the prompt GRB emission. The typical observation angle is slightly larger than $\theta_0$, with the median values of $\theta_{\text{obs}}$ typically being in the range $0.1 - 0.25$ and approaching $\theta_0$ as the structure becomes steeper.

This conclusion remains true even for the cocoon models explored here, due to their intrinsically weak emission. Only very radiatively efficient cocoon models, for which the cocoon is seen much more often than the on-axis GRB, may be seen much further off-axis. For example, for $\theta_0 = 0.1$ one would require $\eta_{\gamma} \geq 0.1$ in order to obtain a median $\theta_{\text{obs}} \geq 0.4$. As a comparison, the typical observation angle of a GW detection alone is $\approx 0.65$ (see black vertical lines in the left-hand side panels of Fig. 2). The luminosity distribution is typically double-peaked, with a high-luminosity peak corresponding to jets seen on-axis and a low-luminosity peak corresponding mostly to off-axis jets; a small contribution to the low-luminosity peak comes from failed jets. This bi-modality is naturally more prominent for steeper structure models (see e.g. top right-hand side panel in Fig. 2).

### 3.3 Joint GRB and GW Detection

It is constructive to consider the likelihood of the three following outcomes: (i) no sGRB detection given a GW detection, (ii) a joint GW and a “regular” sGRB detection ($\theta_{\text{obs}} \geq \theta_0$), and (iii) a joint GW and misaligned sGRB detection ($\theta_{\text{obs}} > \theta_0$). The probabilities for the different models considered above and the median observation angles, given a joint detection, are presented in Table 1.

Excluding the SJG model with $\theta_0 = 0.2$ that is in contention with our results in [2] and with limits from GRB170817, the probability for a detection of GW from a NS merger without an accompanying $\gamma$-ray signal is very large in all models considered here (i.e., $\approx 90 - 99\%$). In the more rare case of a joint detection, the sGRB is typically 1 to 10 times more likely to be seen off-axis.

We explored also the effect of the limiting distance $d_{\text{max}}$ on the aforementioned probabilities. In most simulations we performed, we took as a canonical value $d_{\text{max}} = 220$ Mpc, which as described above is the maximum distance to which NS mergers can be detected with current GW detectors. A smaller limiting distance ($d_{\text{max}} = 50$ Mpc) has an interesting effect on the detectability of events (see Table 1). While the fraction of events that can be detected electromagnetically increases as $d_{\text{max}}$ increases, the probability of a sGRB detection given a GW observation does not change significantly by switching $d_{\text{max}}$ from 220 Mpc to 50 Mpc. This can be understood as follows. The detectability of GWs becomes 100% for events with $d < 50$ Mpc and the typical observation angle of a GW-detected event increases as $d_{\text{max}}$ decreases. Consequently, the probability of observing an on-axis sGRB actually goes down for smaller $d_{\text{max}}$. Similar conclusions hold for any sGRB (not only on-axis), if the angular profile is very steep or its isotropic component is very dim.

GRB170817 could have been detected in $\gamma$-rays up to a distance of 50 Mpc (Goldstein et al. 2017), but instead it occurred at a distance of 40 Mpc. Moreover, the large inferred isotropic equivalent core luminosity in GRB170817 (Mooley et al. 2018b), which is roughly two orders of magnitude above those of typical sGRBs, suggests an accordingly luminous off-axis $\gamma$-ray emission. With a detection horizon of 220 Mpc, only a small fraction of future events are expected to exhibit similar properties to those of GRB170817. In models with a strong angular structure (e.g., SJPL models), bursts must be observed at small enough $\theta_{\text{obs}}$, so that there is still a significant amount of power in the material travelling to-
Successful short GRB jets

Figure 2. Probability distribution functions of observation angles \( \frac{dP}{d\theta_{\text{obs}}} \) and \( \gamma\)-ray (isotropic) luminosities \( \frac{dP}{d\log L_\gamma} \) for different structure models discussed in §3.1. Results for a joint prompt GRB and GW detection are shown with solid lines in all panels. The dot-dashed histogram (left-hand side panels) shows the probability for a GW signal detection, as given by equation (14), without considering the prompt GRB emission. Dashed lines mark the median observation angle for different models.
Table 1. Detection probabilities of NS mergers obtained from our Monte Carlo simulations for different emission models (see \[3\] for details). Values listed are calculated for \(d_{\text{max}} = 220\) Mpc and 50 Mpc (in parenthesis). Note that all the probabilities listed here are conditional probabilities assuming that there is a GW detection.

| Model   | \(\theta_0\) | \(P_1^{(a)}\) | \(P_{\text{2}}^{(b)}\) | \(P_{\text{3}}^{(c)}\) | Median \(\theta_{\text{obs}}^{(d)}\) |
|---------|---------------|----------------|------------------------|------------------------|-----------------------------|
| PL (\(\delta = 3\)) | 0.05 | 0.94 (0.9) | 0.002 (0.001) | 0.05 (0.01) | 0.21 (0.5) |
| PL (\(\delta = 4.5\)) | 0.1 | 0.93 (0.93) | 0.006 (0.002) | 0.06 (0.07) | 0.2 (0.39) |
| PL (\(\delta = 5.5\)) | 0.1 | 0.95 (0.96) | 0.006 (0.002) | 0.04 (0.04) | 0.17 (0.28) |
| PL (\(\delta = 10\)) | 0.2 | 0.92 (0.96) | 0.03 (0.01) | 0.05 (0.03) | 0.22 (0.3) |
| Gaussian | 0.05 | 0.98 (0.99) | 0.002 (0.001) | 0.02 (0.008) | 0.07 (0.19) |
| Gaussian | 0.1 | 0.93 (0.96) | 0.008 (0.002) | 0.06 (0.03) | 0.15 (0.19) |
| Gaussian | 0.2 | 0.76 (0.86) | 0.03 (0.01) | 0.2 (0.13) | 0.29 (0.38) |
| CL (\(\eta_{\text{br}} = 10^{-3}\)) | 0.05 | 0.99 (0.99) | 0.002 (0.001) | 0.004 (0.003) | 0.06 (0.09) |
| CL (\(\eta_{\text{br}} = 10^{-3}\)) | 0.1 | 0.99 (0.99) | 0.006 (0.002) | 0.005 (0.008) | 0.1 (0.15) |
| CL (\(\eta_{\text{br}} = 10^{-1.5}\)) | 0.1 | 0.98 (0.96) | 0.006 (0.002) | 0.01 (0.03) | 0.12 (0.94) |
| CL (\(\eta_{\text{br}} = 10^{-3}\)) | 0.2 | 0.96 (0.97) | 0.03 (0.01) | 0.01 (0.02) | 0.17 (0.23) |

\(^{(a)}\) Probability of GW detection without an accompanying \(\gamma\)-ray signal.
\(^{(b)}\) Probability of detection of an on-axis sGRB given a GW detection.
\(^{(c)}\) Probability of detection of an off-axis sGRB given a GW detection.
\(^{(d)}\) Median value computed from joint \(\gamma\)-ray and GW detections.

4 DETECTABILITY OF COCOON COOLING EMISSION

In \[3\] we discussed the thermal emission stored in the cocoon. As mentioned in that section, only a small fraction of this thermal emission resides in the breakout shell and can be radiated within the prompt phase as \(\gamma\)-rays. The cocoon ejecta cools due to adiabatic energy losses until it becomes optically thin and the remaining energy \(E_{\text{cool}} < E_{\text{th}}\) is radiated away. This will happen when the time-scale for the diffusion of photons from the cocoon becomes comparable to the dynamical timescale. At this point, the cocoon radius is \(v t_{\text{thin}}\) and the energy \(E_{\text{cool}}\) is given by:

\[
E_{\text{cool}} = E_{\text{Th}} \frac{\text{peak}}{t_{\text{thin}}} =
\begin{cases}
6 \times 10^{45} E_{50}^{1/2} v_{5}^{1/2} t_{e,.3} \text{ erg} & E_{cr} \leq E_{j} \leq 30 E_{cr} \\
9 \times 10^{42} E_{50} v_{5}^{3/2} t_{e,.3}^{2} \theta_{0,.1} t_{e,.3} \text{ erg} & E_{j} > 30 E_{cr},
\end{cases}
\]

where \(t_{e,.3} \equiv t_{e}/0.3\) s. This energy is radiated away on a time-scale of \(t_{\text{thin}}\). The cooling luminosity associated with this phase is...
Therefore we expect the cooling emission from the cocoon to peak after the GW detection (Coulter et al. 2017). Notice that the cooling luminosity is very sensitive to the velocity of the outflow ($L_{cool} \propto v$). Since this radiation is fully thermalized, and originates from a radius of $v t_{\text{thin}}$, we can estimate its black body temperature as:

$$T_{\text{BB}} = \left( \frac{L_{cool}}{4\pi v^2 t_{\text{thin}} c^4} \right)^{1/4}$$

$$= \begin{cases} 5 \times 10^4 E_{50}^{1/4} v_{50} t_{\text{obs}}^{1/4} \text{ K} & E_{50} \lesssim E_j \lesssim 30 E_{cr} \\ 4 \times 10^4 E_{50}^{1/4} v_{50} t_{\text{obs}}^{1/4} \text{ K} & E_j > 30 E_{cr}. \end{cases}$$

Therefore we expect the cooling emission from the cocoon to peak at the UV band (see also Nakar & Piran 2017). For a limiting Swift-UVOT B band flux of $\sim 5 \times 10^{-16}$mJy in 1000 s (Gehrels 2004), and $v = 0.5c$ the derived luminosities from equation (15) imply that this emission should be detectable for future NS merger events up to $\sim 900$ Mpc if $E_{50} \lesssim E_j \lesssim 30 E_{cr}$ and up to $\sim 80$ Mpc if $E_j > 30 E_{cr}$. This of course, is provided that these events can be localized rapidly enough, in time to catch this signal (see also equation (12)). This can be a challenging prospect. As an example, the EM counterpart of GW170817, was only first detected 0.5 days after the GW detection (Coulter et al. 2017).

5 DISCUSSION

The first discovery of GW from a NS merger allowed us to significantly improve our understanding of sGRB jets. Assuming all sGRBs arise from NS-NS (or NS-BH) mergers, the intrinsic rate of sGRBs should be at most comparable to the merger rate inferred by advanced LIGO/Virgo. This implies that the typical opening angles of sGRBs should be $\theta_0 \gtrsim 0.07$ (see §2.5). At the same time, the observed population of sGRBs with Swift in the last 14 years places a lower limit of $\sim 250$ Mpc on the distance from which we have observed an on-axis sGRB. This leads to an upper limit on the rate of local on-axis sGRBs and therefore on their typical opening angles $\theta_0 \lesssim 0.1$. These limits on the opening angle are consistent with values inferred for GRB170817 from afterglow modelling and from the measurements of superluminal motion. Furthermore, they imply that the NS merger rate is comparable to that of sGRBs and

---

**Table 2.** Expected number of NS mergers detectable in GWs in the case of no Fermi/GBM detection, an on-axis GRB detection, and an off-axis GRB detection. The numbers (with their 1σ statistical errors (Gehrels 1986)) are obtained from our simulations for a limiting distance of 220 Mpc and a ten-year period, assuming a merger rate $R_{\text{merg}} = 1540$ Gpc$^{-3}$ yr$^{-1}$. For the assumed parameters, $\sim 192$ NS mergers are expected.

| Model | Parameters | Fermi undetected | on-axis | off-axis |
|-------|------------|------------------|---------|---------|
| PL    | $\delta = 3, \theta_0 = 0.05$ | $180.8 \pm 13.4$ | $< 1.8$ | $9.6^{+3.5}_{-3.5}$ |
| PL    | $\delta = 4.5, \theta_0 = 0.1$ | $178.9 \pm 13.4$ | $1.1^{+2.1}_{-1.0}$ | $11.5^{+3.9}_{-2.8}$ |
| PL    | $\delta = 5.5, \theta_0 = 0.3$ | $182.7 \pm 13.5$ | $1.1^{+2.0}_{-1.0}$ | $7.7^{+3.1}_{-3.3}$ |
| PL    | $\delta = 10, \theta_0 = 0.1$ | $177.0 \pm 13.5$ | $5.8^{+2.6}_{-1.4}$ | $9.6^{+3.9}_{-3.8}$ |
| GS    | $\theta_0 = 0.05$ | $188.5 \pm 13.7$ | $< 1.8$ | $3.8^{+2.1}_{-1.5}$ |
| GS    | $\theta_0 = 0.1$ | $178.9 \pm 13.4$ | $1.5^{+1.8}_{-1.4}$ | $11.5^{+3.9}_{-3.8}$ |
| GS    | $\theta_0 = 0.2$ | $146.2 \pm 12.2$ | $5.8^{+2.6}_{-2.9}$ | $38.5^{+6.7}_{-6.6}$ |
| CL    | $n_{\theta_0} = 10^{-3}, \theta_0 = 0.05$ | $190.4 \pm 13.8$ | $< 1.8$ | $< 1.8$ |
| CL    | $n_{\theta_0} = 10^{-3}, \theta_0 = 0.1$ | $190.4 \pm 13.8$ | $1.1^{+2.1}_{-1.0}$ | $10.2^{+2.3}_{-2.0}$ |
| CL    | $n_{\theta_0} = 10^{-3}/2, \theta_0 = 0.1$ | $188.5 \pm 13.7$ | $1.1^{+2.1}_{-1.0}$ | $19.5^{+1.4}_{-1.7}$ |
| CL    | $n_{\theta_0} = 10^{-3}, \theta_0 = 0.2$ | $184.6 \pm 13.6$ | $5.8^{+2.6}_{-2.9}$ | $19.5^{+1.4}_{-1.7}$ |
reveals that a fraction of order unity of NS mergers must lead to sGRBs. In other words, sGRB jets typically manage to breakout of the NS merger ejecta, in contrast to collapsar GRB jets.

The large fraction of successful sGRB jets and the typical opening angles of $\theta_0 \sim 0.1$ are consistent with a critical breakout luminosity (estimated from hydrodynamical simulations of the interaction between the sGRB jet and the NS merger ejecta) being close to the “canonically” assumed minimal luminosity of the sGRB luminosity function, namely $L_{\text{min}} \approx 5 \times 10^{51} \text{ erg s}^{-1}$. This consideration demonstrates that the role of failed jets in shaping the observed luminosity function of sGRBs cannot be significant (see §2.2.1). At the same time, we have also shown here that the angular structure of sGRBs is not able to reproduce the observed luminosity function, since the required structure is extremely shallow in contrast to observational constraints (see §2.2.2). The implication is that the broken power-law luminosity function of sGRBs must have an intrinsic origin and that the inferred break of the luminosity function, at an isotropic $\gamma$-ray luminosity of $L_{\gamma} \approx 2 \times 10^{52} \text{ erg s}^{-1}$ (corresponding to a beaming corrected jet mechanical power of $\sim 10^{53} \text{ erg s}^{-1}$) reveals an intrinsic characteristic luminosity of sGRB jets. One possible interpretation that holds for magnetic jets, powered by the Blandford Znajek mechanism (Blandford & Znajek, 1977), is that the value of $L_{\gamma}$ reflects a characteristic accretion rate, below which the accretion disk is advection dominated (ADAF), and above which it becomes dominated by neutrino cooling (NDAF) (Giannios, 2007). Kawanaka, Piran & Krolik (2013) have shown that a sharp change in the jet power may occur due to this transition at accretion rates $\dot{M} \approx 0.03 M_{\odot} \text{ yr}^{-1}$.

While the joint discovery of GW170817 and GRB170817 has helped to constrain the fraction of successful GRB jets, their opening angles, and their luminosity function as discussed above, the angular structure of GRB jets and the nature of their $\gamma$-ray emission are still uncertain. In this paper, we considered different off-axis emission models, motivated by the analysis above and by observations of GW170817. We showed that $90\% - 99\%$ of future GW events accompanied by a successful GRB jet and detected up to a distance of 220 Mpc, should not be accompanied by any detectable prompt GRB signal. In the comparatively rare cases of a joint GRB and GW detections, we find that for each GRB observed on-axis $\sim 1 - 10$ GRBs should be observed at angles beyond the jet core.

The distribution of prompt luminosities and observation angles from joint GRB and GW detections can help to distinguish between off-axis prompt emission models (see figure 1). For example, let us assume a NS merger rate of $R_{\text{merg}} = 1540 \text{ Gpc}^{-3} \text{ yr}^{-1}$, a ratio of failed to successful GRB jets $r_{\text{fail}} = 1$, and $\theta_0 = 0.1$. Then, angular structure models with $L(\theta > \theta_0) \propto \theta^{-\delta}$ and $\delta = 4.5$ lead to $\sim 19.2 \text{ GW detectable mergers per year}$ (up to 220 Mpc), out of which $\sim 18$ without Fermi/GBM $\gamma$-ray detection, 0.1 with an on-axis GRB detection, and 1.1 with an off-axis GRB detection. Alternatively, for cocoon models with a breakout efficiency of $\eta_{\text{br}} = 10^{-3}$ and $\eta_{\text{br}} = 0.1$), we have $\sim 19$ events per year with no accompanying GRB, and 0.1 with on-axis or off-axis GRBs. Table 2 summarizes the expected number of events within a period of ten years for the emission models discussed in §3.1. Inspection of the table shows that the detection rates of off-axis GRBs accompanying GW-detected mergers are the key for differentiating between the models. For example, the lack of any other prompt GRB detections from NS mergers within the next 10 years (for the assumed parameters), would be in strong tension with the predictions of the structured jet model. The thermal energy in the cocoon may also be observed via its cooling emission that is expected to lead to a UV thermal signal at $\sim 10^{7} \text{ s}$ after the trigger (see equations (12) and (16)). Provided that the NS merger can be located rapidly enough, the cooling emission of the cocoon may be detectable up to a distance of $\sim 900 \text{ Mpc}$. It turns out that events similar to GRB170817 are rare. This is a combination of the small distance and observation angle of GRB170817 and the high inferred luminosity at the core of that event compared to typical sGRBs.

In conclusion, the discovery of the first GRB associated with a NS merger, GRB170817, has already significantly improved our knowledge of short GRB jets. Nonetheless, the nature of the prompt signal that is seen by observers far from the jet cores remains unsettled. The association of a $\gamma$-ray signal with a GW event could allow us to detect orders of magnitude fainter signals associated with GRBs, which would otherwise be undetected for cosmological events (see also Beniamini et al. 2018). This, coupled with the relatively large detection rate of NS mergers as inferred from GW170817, implies that the existing models could be differentiated observationally within the next several years, opening up the window towards a more detailed understanding and future studies of short GRB jets.

ACKNOWLEDGEMENTS

The authors would like to thank Tsvi Piran, Ehud Nakar, Pawan Kumar, Omer Bromberg and Kenta Hotokezaka for helpful discussions. RBD thanks Danielle Taylor for useful discussions. MP acknowledges support from the Lyman Jr. Spitzer Postdoctoral Fellowship. DG acknowledges support from NASA grants NNX16AB32G and NNX17AG21G.

REFERENCES

Abbott B. P. et al., 2017, ApJ, 848, L13
Abbott B. P. et al., 2017, Phys. Rev. Lett., 119, 161101
Allen B., Anderson W. G., Brady P. R., Brown D. A., Creighton J. D. E., 2012, Phys. Rev. D, 85, 122006
Aloy M. A., Janka H.-T., Müller E., 2005, A&A, 436, 273
Band D. et al., 1993, ApJ, 413, 281
Barkov M. V., Kathirgamaraju A., Luo Y., Lyutikov M., Giannios D., 2018, ArXiv e-prints
Beniamini P., Dvorkin I., Silk J., 2018, MNRAS, 478, 1994
Beniamini P., Giannios D., Younes G., van der Horst A. J., Kouveliotou C., 2018, MNRAS, 476, 5621
Beniamini P., Hotokezaka K., Piran T., 2016, ApJ, 832, 149
Beniamini P., Nava L., Duran R. B., Piran T., 2015, MNRAS, 454, 1073
Beniamini P., Nava L., Piran T., 2016, MNRAS, 461, 51
Blandford R. D., Znajek R. L., 1977, MNRAS, 179, 433
Blinnikov S. I., Novikov I. D., Perevodchikova T. V., Polnarev A. G., 1984, Soviet Astronomy Letters, 10, 177
Bromberg O., Nakar E., Piran T., Sari R., 2011, ApJ, 740, 100
Bromberg O., Nakar E., Piran T., Sari R., 2013, ApJ, 764, 179
Bromberg O., Tchekhovskoy A., Gottlieb O., Piran T., 2016, MNRAS, 475, 2971
Burns E., Connaughton V., Zhang B.-B., Lien A., Briggs M. S., Goldstein A., Pelassa V., Troja E., 2016, ApJ, 818, 110
Coulier D. A. et al., 2017, Science, 358, 1556
Coward D. M. et al., 2012, MNRAS, 425, 2668
Duffell P. C., Quataert E., Kasen D., Klon H., 2018, ArXiv e-prints
Eichler D., Levinson A., 2004, ApJ, 614, L13

© 2018 RAS, MNRAS 000, 000–000
Successful short GRB jets

Eichler D., Livio M., Piran T., Schramm D. N., 1989, Nature, 340, 126
Finstad D., De S., Brown D. A., Berger E., Biwer C. M., 2018, ArXiv e-prints
Fong W., Berger E., Margutti R., Zauderer B. A., 2015, ApJ, 815, 102
Fong W. et al., 2012, ApJ, 756, 189
Finstad D., De S., Brown D. A., Berger E., Biwer C. M., 2018, ArXiv e-prints
Fong W., Berger E., Margutti R., Zauderer B. A., 2015, ApJ, 815, 102
Fong W. et al., 2012, ApJ, 756, 189
Fraija N., De Colle F., Veres P., Dichiara S., Barniol Duran R., Galvan-Gamea, 2017, ArXiv e-prints
Freija N., De Colle F., Veres P., Dichiara S., Barniol Duran R., Galvan-Gamea, 2017, ArXiv e-prints
Goodman J., 1986, ApJ, 308, L47
Gottlieb O., Nakar E., Piran T., Hotokezaka K., 2017, ArXiv e-prints
Granot J., Gill R., Guetta D., De Colle F., 2017, ArXiv e-prints
Guetta D., Piran T., 2006, A&A, 498, 329
Hilborn R. C., 2018, ArXiv e-prints
Hotokezaka K., Beniamini P., Piran T., 2018, ArXiv e-prints
Ioka K., Nakamura T., 2018, Progress of Theoretical and Experimental Physics, 2018, 043E02
Janka H.-T., Aloy M.-A., Mazzali P. A., Pian E., 2006, ApJ, 645, 1305
Kasen D., Metzger B., Barnes J., Quataert E., Ramirez-Ruiz E., 2017, Nature, 551, 80
Kasliwal M. M. et al., 2017, Science, 358, 1559
Kathirgamaraju A., Barniol Duran R., Giannios D., 2018, MNRAS, 473, L121
Kawai N., Piran T., Krotik J. H., 2013, ApJ, 766, 31
Kim C., Perera B. B. P., McLaughlin M. A., 2015, MNRAS, 448, 928
Kochanek C. S., Piran T., 1993, ApJ, 417, L17
Kouveliotou C., Meean C. A., Fishman G. J., Bhat N. P., Briggs M. S., Koshut T. M., Paciesas W. S., Pendleton G. N., 1993, ApJ, 413, L101
Lamb G. P., Kobayashi S., 2017, MNRAS, 472, 4953
Lazzati D., Deich A., Morsony B. J., Workman J. C., 2017a, MNRAS, 471, 1652
Lazzati D., López-Cámara D., Cantiello M., Morsony B. J., Perna R., Workman J. C., 2017b, ApJ, 848, L6
Lazzati D., Perna R., Morsony B. J., Lopez-Camara D., Cantiello M., Ciolfi R., Giacomazzo B., Workman J. C., 2018, Physical Review Letters, 120, 241103
Lipunov V. M., Postnov K. A., Prokhorov M. E., 2001, Astronomy Reports, 45, 236
Lu R.-J., Du S.-S., Cheng J.-G., Liu H.-J., Zhang H.-M., Lan L., Liang E.-W., 2017, ArXiv e-prints
Macias P., Ramirez-Ruiz E., 2016, ArXiv e-prints
Margutti R. et al., 2018, ApJ, 856, L18
Mehranara R., Piran T., 2017, MNRAS, 472, L55
Mooley K. P. et al., 2018a, ArXiv e-prints
Mooley K. P. et al., 2018b, Nature, 554, 207
Murguia-Berthier A., Montes G., Ramirez-Ruiz E., De Colle F., Lee W. H., 2014, ApJ, 788, L8
Nakakura H., Hotokezaka K., Sekiguchi Y., Shibata M., Ioka K., 2014, ApJ, 784, L28
Nakar E., Piran T., 2017, ApJ, 834, 28
Nakar E., Sari R., 2010, ApJ, 725, 904
Nava L., Ghirlanda G., Ghisellini G., Celotti A., 2011, A&A, 530, A21
Paczynski B., 1986, ApJ, 308, L43
Patricelli B., Razzano M., Cellina G., Fidecaro F., Pian E., Branches M., Stamerra A., 2016, JCAP, 11, 056
Pescalli A., Ghirlanda G., Salafia O. S., Ghisellini G., Nappo F., Salvaterra R., 2015, MNRAS, 447, 1911
Petropoulou M., Barniol Duran R., Giannios D., 2017, MNRAS, 472, 2722
Pooley D., Kumar P., Wheeler J. C., Grossan B., 2018, ApJ, 859, L23
Racusin J. L. et al., 2017, ApJ, 835, 82
Rossi E., Lazzati D., Rees M. J., 2002, MNRAS, 332, 945
Salvaterra R., Cerutti A., Chincarini G., Colpi M., Guidorzi C., Romano P., 2008, MNRAS, 388, L6
Schutz B. F., 2011, Classical and Quantum Gravity, 28, 125023
Tanaka M. et al., 2017, PASJ, 69, 102
Tanvir N. R. et al., 2017, ApJ, 848, L27
Troja E. et al., 2018, MNRAS, 478, L18
van Eerten H. J., MacFadyen A. I., 2012, ApJ, 751, 155
Wanderman D., Piran T., 2015, MNRAS, 448, 3026
Wang X.-G., Zhang B., Liang E.-W., Lu R.-J., Lin D.-B., Li J., Li L., 2018, ApJ, 859, 160
Zhang B., Meszaros P., 2002, ApJ, 571, 876
Zhang B.-B. et al., 2018, Nature Communications, 9, 447

This paper has been typeset from a TeX/\LaTeX file prepared by the author.

© 2018 RAS, MNRAS 000, 000–000