On the possible gamma-ray burst–gravitational wave association in GW150914

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Abstract
Data from the Fermi Gamma-ray Burst Monitor satellite observatory suggested that the recently discovered gravitational wave source, a pair of two coalescing black holes, was related to a gamma-ray burst. The observed high-energy electromagnetic radiation (above 50 keV) originated from a weak transient source and lasted for about 1 second. Its localization is consistent with the direction to GW150914. We speculate about the possible scenario for the formation of a gamma-ray burst accompanied by the gravitational-wave signal. Our model invokes a tight binary system consisting of a massive star and a black hole which leads to the triggering of a collapse of the star’s nucleus, the formation of a second black hole, and finally to the binary black hole merger. For the most-likely configuration of the binary spin vectors with respect to the orbital angular momentum in the GW150914 event, the recoil speed (kick velocity) acquired by the final black hole through gravitational wave emission is of the order of a few hundred km/s and this might be sufficient to get it closer to the envelope of surrounding material and capture a small fraction of matter from the remnant of the host star. The gamma-ray burst is produced by the accretion of this remnant matter onto the final black hole. The moderate spin of the final black hole suggests that the gamma-ray burst jet is powered by weak neutrino emission rather than the Blandford-Znajek mechanism, and hence explains the low power available for the observed GRB signal.

Keywords: black hole physics; accretion, accretion disks; gravitational waves; neutrinos

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1. Introduction

Gamma-ray bursts (GRBs) are extremely energetic, transient events observed from all directions in the sky at high energies. Their known cosmological origin requires the physical process that produces them to be a cosmic explosion of great power. Proposed mechanisms involve the creation of a black hole (BH) in a cataclysmic event. This may either result from the collapse of a massive rotating star, or via the merger of two compact objects, e.g. binary neutron stars or a BH and a neutron star. These two scenarios may produce long (>2 seconds) or short (<2 seconds) GRBs, respectively. The so-called ‘central engine’ of this process is composed of a hot and dense accretion disk with a hyper-Eddington accretion rate (up to a few $M_\odot s^{-1}$) near a spinning BH and fast relativistic jets that are launched along the BH’s axis of rotation. The angular momentum of the BH is usually invoked as a source of power of jets. In addition, the annihilation of neutrino-antineutrino pairs produced in the nuclear density plasma of the accretion disk can contribute to the jet power (or powering jets). These fast jets produce GRB radiation that ultimately can be observed far away from the central region.

These common scenarios may be related to gravitational wave (GW) emission before and during the action of such an engine. Apart from the strong GW emission produced by the time-varying mass quadrupole of an inspiraling and merging compact binary system, several other suggestions were put forward, e.g. neutrino-induced GWs [1] or disk precession [2]. These, however, would be rather weak signals, most probably below the sensitivity limits of current GW detectors.

The recent observation of a GW signal by the two Advanced LIGO detectors on September 14, 2015 [3] is related to a merger of two BHs in a binary system. Both, the masses and spins of the initial BHs and of the product of the merger were constrained from the amplitude and phase evolution of the observed gravitational waveform. In principle, mergers of binary BHs may be associated with an electromagnetic emission (a GRB), if a sufficient supply of matter for the accretion is involved at any stage of the merger, or after the GW event. As hypothesized in our previous work [4], a merger of a massive, rotating star with a companion BH, in a system that evolved from a high mass X-ray binary, may result in the collapse of the star’s core. The merger of the collapsed core, which is a newly formed BH, with its companion, would be then the source of a transient emission seen in GWs. The accretion of matter onto the core BH before the merger, and onto the final BH after the merger, would be the source that powers the GRB. Potentially, either one or two GRB signals could be observed, depending on the geometry of the system and the observer’s viewing angle. In the following, we elaborate on this scenario in the context of a short duration, hard burst that could be associated with the GW150914 signal.
2. Constraints for the GW150914 GRB

The GRB that could be tentatively related to GW150914 by the observations of the Fermi satellite had a duration of about 1 second and appeared about 0.4 seconds after the GW signal [5]. The two events were temporally coincident and, within the limit of uncertainty of the two LIGO interferometers and the Fermi detector capabilities to localize the GW source and the electromagnetic source in the sky, could also be associated spatially. The source of the GW was interpreted to be a merger of two BHs of the masses of $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$. The final BH parameters are estimated to be of $62^{+4}_{-4} M_{\odot}$ and $0.67^{+0.05}_{-0.07}$ for its mass and spin, respectively. The magnitudes and orientations of the spin vectors of the two initial BHs are weakly constrained. The probabilities that the angles between spins and the normal to the orbital plane are between $45^\circ$ and $135^\circ$ are about 0.8 for each component BH; spin magnitudes are constrained to be smaller than 0.7 and 0.8 at 90% probability, for the primary and the secondary BH, respectively. At the same level of probability, the assumption of a strict co-alignment of spins with the orbital angular momentum - a plausible astrophysical scenario in which the BHs are produced from massive stellar progenitors - results in an upper limit of 0.2 and 0.3 for the spins’ magnitude of the primary and the secondary BH, respectively (for more details see Fig. 5 and related text in [6]). The inferred posterior distribution of the GW150914 parameters disfavors an orientation of the total orbital angular momentum of the system that is strongly misaligned to the line of sight (i.e., the system was likely to be oriented face-on or face-away). Weak constraints on the magnitude and the direction of the initial BH spins of GW150914 make it difficult to provide a meaningful limit on the kick velocity of the resulting BH.

The event took place at a distance of $410^{+160}_{-180}$ Mpc, corresponding to a redshift of about $z = 0.09$ (assuming the standard cosmological model). The GRB fluence measured by Fermi in the range 1 keV-10 MeV, is of $2.8 \times 10^{-7}$ erg cm$^{-2}$ which, for the distance inferred from the GW observation, implies that the source luminosity in gamma rays equals to $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg/s.

3. GRB+GW scenario

The scenario presented in [4] describes the collapse of a massive star followed by a binary BH merger. The progenitor, a massive rotating star, is a member of a tight binary system with a companion BH. In order to reconcile a coincidental GW and electromagnetic emission, we assume that after the companion BH entered the star’s envelope, the resulting interaction with the stellar core causes its collapse into a second BH. Additionally, some of the angular momentum will be stored in the envelope, as it will be spun up by the transfer of the angular momentum from the companion BH. As a natural consequence, rotationally supported torus is formed in the equatorial plane.

Our model involves three distinct stages of the binary evolution, namely (i) the core collapse and accretion onto the core, (ii) the BH merger inside a circumbinary disk in the interior of the collapsing star, and (iii) further accretion
The BH in a binary system induces core-collapse of the companion star (i). Fallback accretion of matter form the star’s envelope might be accompanied by a weak jet, offset from the line of sight. Next, binary BHs merge inside a circumbinary disk (ii). As a result of the merger, the spin vector of the final BH changes its direction. In the last phase, the remnant matter of the star’s envelope is accreted onto the final BH (iii). Both GRB jet types, the one related to the progenitor’s collapse and the other to the accretion onto the final BH, may occur unnoticed to an observer if the jets are collimated into narrow cones and the BH spins configuration favors one specific line of sight. However, even if the axis of the first GRB is oriented unfavorably towards the observer (i.e., offset with respect to the line of sight), the second GRB which happens after the merger may be pointing towards the observer. The direction of its axis should be coincident with the spin direction of the final BH, which is the result of the two initial BH spins and the evolution of the system, i.e., it may not be the same as the direction of the first GRB.

In addition, the final BH may receive a natal kick, with a magnitude depending on the BH mass ratio and the configuration of the initial BH spin vectors. Therefore, stage (iii) may in principle lead to the GRB engine leaving its host site and approaching the inner edge of circumbinary disk.

The first phase, core-collapse, can be treated semi-analytically as in [7]. In that work, we considered two distinct cases: a homologous accretion of the envelope and a large increase of the subsequently created BH mass, or the accretion through a torus, and wind outflow. The latter, if supported by a centrifugal force and driven magnetically, can take away up to about 75% of the mass [8] from the rotating torus. Nevertheless, in the current context, we suppose that no massive wind was associated with GW150914, since the observations do not support a presence of large amounts of mass in the vicinity of the GRB there. We also do not concentrate here on the details of this phase,
Table 1: Summary of the binary BH merger models. The initial separation of components is equal to $d$ and the initial momenta are $p$ and $-p$. The parameters $m_1$, $a_1$ and $\phi_1$ are the initial values of mass parameters, dimensionless spins and angles between spin directions and orbital angular momentum direction for each component. $M_1$, $M_2$ and $M_3$ are the total ADM masses of the components of binary BH and the mass of the product of the merger. The values are given in geometric units ($c = 1$, $G = 1$) and for the total ADM mass of the initial system set to 1, so in order to obtain values with proper units, separation, momenta and all the masses have to be multiplied by $GM/c^2$, $Mc$ and $M$ respectively, where $M$ is the initial mass of the BBH system (for GW150914, $M = 65M_\odot$). $a_3$ is the dimensionless spin parameter of the final BH, with $\phi_3$ being the angle between the direction of the spin and the direction of the orbital angular momentum of the initial system. The gravitational kick velocity of the final BH is equal to $v$. 

| Run | $d$ | $p$ | $m_1$ | $m_2$ | $a_1$ | $a_2$ | $\phi_1$ | $\phi_2$ | $M_1$ | $M_2$ | $M_3$ | $M_4$ | $a_3$ | $\phi_3$ | $v$ [km/s] |
|-----|-----|-----|-------|-------|-------|-------|---------|---------|-------|-------|-------|-------|-------|---------|-----------|
| 0   | 10  | 0.093 | 0.541 | 0.443 | 0     | 0     | 0$^\circ$ | 0$^\circ$ | 0.552 | 0.487 | 0.96  | 0.68  | 0$^\circ$ | 120       |
| 1   | 10  | 0.093 | 0.53  | 0.432 | 0.2   | 0.3   | 0$^\circ$ | 0$^\circ$ | 0.552 | 0.46  | 0.96  | 0.76  | 0$^\circ$ | 130       |
| 2   | 10  | 0.093 | 0.53  | 0.432 | 0.2   | 0.3   | 0$^\circ$ | 0$^\circ$ | 0.552 | 0.46  | 0.96  | 0.76  | 0.5$^\circ$ | 130       |
| 3   | 6   | 0.139 | 0.52  | 0.424 | 0.2   | 0.3   | 10$^\circ$ | 0$^\circ$ | 0.552 | 0.463 | 0.96  | 0.77  | 0.6$^\circ$ | 100       |
| 4   | 6   | 0.139 | 0.507 | 0.409 | 0.3   | 0.45  | 10$^\circ$ | 0$^\circ$ | 0.55  | 0.467 | 0.96  | 0.81  | 0.8$^\circ$ | 280       |
| 5   | 6   | 0.139 | 0.484 | 0.385 | 0.4   | 0.6   | 10$^\circ$ | 0$^\circ$ | 0.543 | 0.471 | 0.95  | 0.85  | 1$^\circ$  | 200       |
| 6   | 6   | 0.138 | 0.415 | 0.341 | 0.7   | 0.7   | 90$^\circ$ | 120$^\circ$ | 0.557 | 0.459 | 0.97  | 0.72  | 25$^\circ$ | 700       |

because the GRB was detected after the GW signal. In the following, only these two phases are considered in detail.

3.1. Black hole merger

We assume the BH merger occurred inside a circumbinary accretion disk within the collapsing envelope of a massive star, and hence adopt the vacuum approximation for the merger simulation. The merger is computed using the Einstein Toolkit computational package\footnote{http://www.einsteintoolkit.org}. The numerical methods used are based on finite difference computations on a gridded mesh\footnote{9}. The technique of the adaptive mesh refinement is used to cover a large volume with low resolution, and to cover regions around BHs with a high-resolution grid. In our fiducial simulation we use 7 levels of refinement (grid spacing differs by a factor of 2). The initial data contain the given masses, momenta and spins for each BH and the initial separations of components. We adopt the Cartesian grid with $48 \times 48 \times 48M$, and resolution from $\Delta x = 2.0M$ for the coarsest grid to $\Delta x = 0.03125M$ for the finest grid.

Since BBH mergers simulations are scalable with respect to the total mass of the system in all computations the total mass of the system is set to 1 for simplicity. As the total mass we mean the mass measured by a distant observer, namely the Arnowitt-Deser-Misner (ADM) mass\footnote{10}. Therefore, all the
masses given in the table are simply fractions of the total mass of the initial BBH system. The mass ratio of the merging components is 0.82 (ratio of the most-probable values of estimated masses for GW150914). The third order PN approximation is used \cite{11} to find the initial momenta of the components of the binary on quasi-circular orbits. The product of the merger is described by its mass and spin, but we also estimate the gravitational recoil speed from the analysis of the linear momentum carried by the outgoing gravitational radiation through the sphere of radius $42 M$. We use the Weyl scalar $\Psi_4$ multipole decomposition method (up to the order $l = 4$) described in \cite{12}. The initial parameters and the results of the simulations are presented in the Table 1.

Figure 2: Last three orbits of the merging BHs (run 2 from the Table 1).

The simulations were preformed for a range of values for spin magnitudes and orientations consistent with the (weak) parameter estimation for the GW150914 signal \cite{6}. In general we assume that the spin vectors may be mildly misaligned with respect to the orbital spin vector, a situation that most likely occurs in the massive progenitor binary scenario. Within this setup only the second GRB, which is related to the jet produced by the accretion onto the final BH, would be visible to the observer. We also simulate one case with a strong misalignment of spins (case 6 in Table 1) that results in a substantially higher recoil speed. Fig.\cite{2} and \cite{3} show a few exemplary orbits of binary BH. The extracted gravitational wave signal for one of the simulations is plotted on Fig.\cite{1}
3.2. Accretion onto a final black hole

The numerical method used for the computation of the GRB engine and an estimation of its jet power is based on the axisymmetric, general relativistic MHD simulation with the code HARM-2D, whose basic version was described by [13]. It uses a conservative, shock-capturing scheme, and provides a solver for the continuity and energy-momentum conservation equations, assuming a force-free approximation. This scheme was used recently for the studies of magnetized, radiatively inefficient accretion flows in the Kerr black hole field [14]. Here we use our own numerical routines to compute the cooling by neutrinos, as was described in detail in [8]. The neutrino cooling processes adopted in our computations are the reactions of electron and positron capture on nucleons, the electron-positron pair annihilation, nucleon bremsstrahlung and plasmon decay. The leptons and baryons are relativistic and may have an arbitrary degeneracy level, so that we compute the gas pressure using the appropriate Fermi-Dirac integrals. In the total pressure, we include also the contributions from the free nucleons, pairs, radiation, trapped neutrinos, and Helium nuclei.

In contrast to the simplified method used in the dynamical computations that we presented in [8], where the neutrino cooling rate was used to update in every time step only the internal energy in the plasma, in our current version of the HARM-2D code, a numerically computed equation of state is used throughout the computations. Self-consistently, the pressure is computed as a function of density and temperature, which in this case is not given by a simple adiabatic relation, but tabulated. We use the tables that store the internal energy, pressure, and neutrino cooling rate, computed as a function of temperature and density in the ranges between $10^2 - 10^{14}$ K, and $10^2 - 10^{13}$ g cm$^{-3}$, respectively, and are logarithmically spaced and have 256 $\times$ 256 grid points. The EOS is therefore deeply incorporated into the dynamical scheme, where we solve for
the inversion scheme between the so called ‘primitive’ (rest mass density, internal energy) and ‘conserved’ (momentum, energy density) variables at every time-step (see e.g. [15]), which is done by a multi-dimensional Newton-Raphson routine.

Our initial conditions for the accretion flow are given by the equilibrium torus solution, defined as in [16]. We use the grid resolution of 256 × 256 cells in the r and θ directions, and the grid is spaced logarithmically in radius and concentrated towards the equatorial plane. To speed up the computations, our version of this code was parallelized using the MPI technique. The adopted physical parameters, i.e. the BH mass and angular momentum, and the torus mass defined by the radius of the pressure maximum, are supplemented by the initial geometry and strength of the magnetic field. The latter, in our fiducial computations, is adopted as a standard, poloidal field given by the φ-component of its vector potential scaling with the density and the initial $\beta = P_{\text{gas}}/P_{\text{mag}} = 50$ (see e.g. [14] for the discussion of various field configurations). The resulting observables, the neutrino emissivities, are computed with good accuracy, and we compare the resulting power from the integrated neutrino luminosity with that available via the magnetic flux dragged through the black hole horizon (we note here that due to the limitations of our 2-dimensional scheme, it is only an order-of-magnitude estimate).
4. Results

From the computation of the binary BH merger, we extract the values of mass, spin and recoil speed of the merger product for given initial configurations of the binary components. Since the GW150914 event observation didn’t lead to the estimation of the recoil speed for the final BH, we have performed a set of simulations with mass ratio and spins values consistent with the estimated GW150914 parameters. Using this range of parameters, one may estimate the upper limit on the recoil speed for this event. The results of our simulations are gathered in Table 1. The simulations confirm that the spin of the merger product is almost exactly aligned (with difference less than 1°) with the orbital angular momentum of the binary BHs for scenarios with more massive components a spin misalignment equal to 10° for a large range of spin values. A 10° change in the direction of the spin is enough for one of the GRB’s to become unobservable.

For the eventually observed GRB event, we performed a numerical simulation of the accretion of remnant matter onto the final BH. The parameters for this fiducial model were as follows: the BH mass $M_{\text{BH}} = 62 M_\odot$ and its spin values $a = 0.6$, 0.7 and 0.8, corresponding to the values inferred for the GW150914 event. The mass of the accreting torus is not constrained by the LIGO data. It is therefore a free parameter in our model, and we determine it using an appropriate density scale. This scaling determines then the conditions in the torus for the nuclear reactions to take place, in which the neutrinos and anti-neutrinos of three flavors will be produced.

We investigated the two following setups.

In Fig. 5 we show the neutrino emissivity, as computed from the density and temperature distribution in the torus, in units of erg s$^{-1}$ cm$^{-3}$, as well as the structure of the magnetic field. The results were taken at the end of the simulation, at $t = 2000 M$, which corresponds to about 0.61 seconds of real time for the assumed BH mass. Parameters of this model were $a = 0.6$, $M_{\text{BH}} = 62 M_\odot$, $M_{\text{torus}} \approx 15 M_\odot$. The computed luminosity emitted in neutrinos is in this case about $L_\nu = 5 \times 10^{52}$ erg/s at $t = 2000 M$. The total neutrino luminosity for the models with $a = 0.7$, and $a = 0.8$ was on average about 3 and 6 times higher, respectively, than that for a fiducial model (see Fig. 6).

For comparison, we also tested the case where the mass of the torus is approximately equal to the final BH mass, $M_{\text{torus}} \approx 57 M_\odot$. We computed the total neutrino luminosity, integrated over the emitting volume, at time $t = 380$ M of the dynamical simulation, to be $L_\nu = 5 \times 10^{55}$ erg/s. This value in the dynamical simulation would increase even further, at $t=2000 M$ it would be larger by $\sim 1.5$ orders of magnitude. Therefore, the neutrino emission from such a massive torus would exceed the neutrino luminosity determined for the observed GRB by many orders of magnitude, and we conclude that this setup is not realistic for the observed limits, regardless of the details of the GRB power supply by neutrino annihilation and jet production efficiency (see Discussion).

The power and luminosity available through the Blandford-Znajek process in the present model is completely negligible because of a too low value of
Figure 5: Results from the GR MHD simulation of a remnant torus accreting onto a BH in the GRB engine. Maps show the neutrino emissivity (left) and magnetic field lines topology together with the gas pressure to magnetic pressure ratio (right). The parameters of the model are $a = 0.6$, $M_{\text{BH}} = 62M_\odot$, $M_{\text{torus}} \approx 15M_\odot$. These snapshots were taken at time $t=2000M_\odot \approx 0.6s$. The accretion rate through the torus at the inner boundary is about $5.56M_\odot/s$. 
the BH spin and no magnetization of the gas at the horizon and in polar regions as shown in the map in Fig. 5. We checked the magnetization value on the horizon, $\beta(r_{in}) = B^2/\rho(r_{in})$, where $\rho$ is the rest mass density of the gas. The electromagnetic stress tensor is given by

$$T^{\mu\nu}_{\text{EM}} = b^2 u^\mu u^\nu + \frac{b^2}{2} g^{\mu\nu} - b^\mu b^\nu, \quad (1)$$

where $b^\mu$ is the magnetic four-vector, with $b^t = g_{t\mu} B^\mu$ and $b^i = (B^i + u^i b^t)/u^t$ and $u^\mu$ is the four-velocity. We compute the radial electromagnetic flux through the horizon

$$\dot{E} = 2\pi \int_0^\pi d\theta \sqrt{-g} F_{\text{EM}}, \quad (2)$$

where $F_{\text{EM}} = -T^t_t$ and $g$ is the metric determinant. In our models, we made computations under the assumption of a weakly magnetized plasma, with $\beta_{\text{init}} = P_{\text{gas}}/P_{\text{mag}} = 50$. At the end of the simulations (at $t = 2000 M$) the power transferred to the polar regions of the BH via the Blandford-Znajek process was $L_{\text{BZ}} \equiv \dot{E} \approx 1.1 \cdot 10^{50}$ erg/s for $a = 0.8$, and $3.7 \cdot 10^{51}$ erg/s for $a = 0.9$, thus was giving a much smaller power to the GRB jets than the neutrinos. Moreover, for the case of $a = 0.6$, there was no net magnetic flux dragged through the horizon in our simulation, so the BZ power was virtually zero.

We note here also, that a moderate value of the BH spin affects the topology of the magnetic fields, so that they remain confined to the torus plasma. The magnetically driven winds are therefore hardly launched. This may also be the reason for quite a low total neutrino luminosity, since not many neutrinos are produced in hot, massive winds.

In Fig. 6 we show the neutrino luminosity of the GRB engine, presented as the averaged neutrino emissivity integrated over the simulation volume, as a function of time. Initial conditions, which are based on the adopted pressure equilibrium torus solution, are evolved, and after about $\sim 1000 M$ the configuration reaches its dynamical shape. The neutrino luminosity is at its maximum then and will continuously decrease with time afterwards. (Note that in the plot we use the physical units, with $t = GM/c^3$ and scaling for $M_{\text{BH}} = 62 M_\odot$, so that $1000 M = 0.304$ s.)

5. Discussion

The GW150914 observation is just a first example from the incoming population of binary BH mergers to be expected in the near future from the Advanced LIGO and Advanced Virgo experiments [20]. Some of them may be coincident with the electromagnetic observations.

By analyzing the properties of the merger one can easily compute the mass and spin of the final BH [21, 22, 23]. However, the estimation of its kick velocity requires the evaluation of the linear momentum carried away by the gravitational radiation during the merger [12], which in turn depends on a precise knowledge of the binary components spins. For specifically chosen mass ratios and spin
Figure 6: Results from the GR MHD simulation of a remnant torus accretion. The neutrino luminosity is plotted versus time, until $t = 2000M$. Parameters of the model are $M_{\text{BH}} = 62M_\odot$, $M_{\text{torus}} \approx 15M_\odot$. The lines show models with BH spins $a = 0.8, 0.7$, and 0.6, from top to bottom.
configurations of the initial BHs, the kick velocity may exceed 4000 km/s, but such large recoils are very rare \[24\].

There are hints for evidence for spin flips and past merger events \[25, 26, 27, 28\]. The theoretical effort is thus supported and motivated by observational discoveries like the recent one which is a tentative detection of a GRB in coincidence with the GW signal. If true, this would be the most spectacular finding.

In this work we propose a scenario that plausibly explains an ‘exotic’ GRB progenitor. We hypothesize that a system that contains a massive star and a companion BH orbiting inside its envelope, triggers the core of the companion star to collapse due to the interaction with the BH. We calculated the values of masses and spins of the binary components and the merger product. For the masses of GW150914 and a selected range of spin magnitudes and orientations, we obtain a range of recoil speeds of $100 - 700$ km/s, where the larger value correspond to the simulation with strongly misaligned spins. With such a velocity, the recoiled BH can move by a distance that may be significant for an accretion process in the last stage. To see this, we employ the work of \[29\] who studied the circumbinary disk with a cavity in the middle around which the mass piles up. The radius of the cavity in the equal mass case (mass ratio $q = 1$) is estimated as $r_s + r_H$, with $r_s$ denoting the binary separation and $r_H$ the Hill radius, $r_H = (q/3)^{1/3}r_s$. For a binary separation $r_s = 5M$ just before the merger the cavity radius would be approximately equal $8.5M \approx 750$ km. During the merger the cavity shrinks, with the violent movement of masses generating the GWs possibly disturbing its inner edge. It is then likely that fast accretion of the accumulated matter onto the final BH is triggered while it moves towards the disk after the merger.

Additionally, the final BH may in principle capture some of the surrounding matter. The amount of gas that is gravitationally bound to it is determined by the recoil speed. The accretion power and duration available to feed the GRB after the merger are determined by the mass of the disk. Moreover, the outer parts of such a mini-disk may be large enough to exhibit some misalignment from the plane perpendicular to the BH spin vector. In such a case, disk and jet precession may occur which would give an additional, periodic signal on top of the GRB emission. Possibly, an orphan afterglow signal in the lower electromagnetic energy bands may be present.

\[30\] discussed a progenitor scenario for GW150914 that involves the core-collapse of a single, chemically homogeneous, rapidly rotating, massive (mass of about $150M_\odot$), single star. This setup would produce a BH promptly, but because of a negligible mass loss in a homogeneous star, the jet breaking through the thick envelope would result in a GRB emission delayed by more than 10 seconds with respect to the GW signal. It should result from the Kerr parameter of the collapsing core being significantly larger than unity, so the angular momentum of the newly born BH is lost via gravitational wave emission. However, \[30\] does not show if the waveforms emitted during such a process are compatible with the ones observed by LIGO. Should this scenario be correct, then also all the parameters of the GW progenitor estimated by \[3\] need to be revised. An
alternative scenario of a binary system that consists of two massive stars which undergo core collapses in the common envelope phase is more plausible, because in that case the GRB coincides with GW emission instantaneously. The two massive stars with an initial separation on the order of 1 AU would undergo core collapses one after another and experience twice the common envelope phase. Similarly, in [31], the authors discuss the possibility that the two massive stars evolve in a binary system and explode as core-collapse supernovae one after another. The matter from the envelope of the second supernova remains bound and finally accretes onto the BH after the merger, to power a GRB (see also [32] for the discussion of the properties of such a mini-disk).

Our scenario is in line with the second one proposed by [30], as it involves the last stage of the binary system evolution. Here, a binary consisting of a Wolf-Rayet star and a massive BH evolves out of an ultraluminous X-ray source phase, and the BH is brought into the common envelope, triggers the core-collapse and merges with the newly-formed BH that originated from the imploding helium core. The timescale from the primary BH formation until the merger does not have to be a typical one for the common envelope phase, and depends significantly on the mass of the star [33]. For a supergiant star, this timescale might be of the order of months or shorter, similar to a supermassive Thorne-Zytkow object with a core neutron star [34], which can lead to the observable soft gamma ray repeaters and anomalous X-ray pulsars (e.g. [35]).

Another possibility, envisaged by [36], is somewhat similar to both of the above mentioned and our scenario, as the two BHs also merge within a common envelope of a very massive star. According to their model, two BHs must have formed simultaneously from the two clumps that were created via the bar instability during the core collapse. While this scenario offers a possibility to explain the origin of the two BH masses, it also introduces a large uncertainty of the very process of such a non-axisymmetric core collapse. In our scenario, the core collapse leads to the formation of only one BH in a process which is assumed to be induced by the presence of a companion BH in the common envelope. Additional transfer of angular momentum by the inspiraling BH into the envelope leads to an increase of the star’s angular momentum and the formation of a circumbinary disk/accretion torus important for the subsequent GRB.

The accretion of the magnetized, rotating torus onto the BH is a commonly accepted mechanism of jet launching in GRBs. The issue of the jet break through the star’s ejected envelope is another problem that all the ‘collapsar’ studies must take into account. In particular, the timescale for the jet break depends on the details on the star’s initial composition, its metallicity, rotation profile and mixing effects. We argue that the motion of the companion BH through the star and the respective angular momentum transfer cause the disruption of the outer parts, so that a significant part of the mass is expelled. In addition, the creation of the high-angular momentum accretion torus in the inner part of the progenitor helps to evacuate matter from the polar regions, which in turn allows the jet to break easier: if the spin of the merger product is not strongly misaligned with the binary orbital angular momentum, we expect that the jet would not be significantly held back by the envelope. The maxi-
mum of the neutrino luminosity obtained in our simulations is reached about 0.4 seconds after an equilibrium torus, prescribed by our initial conditions, had formed. This may tentatively give the lower limit for the timescale when the jet appears after the BH merger. However, the jet sustains only as long as the torus material is consumed by the BH, so for about 3 seconds. Within this time, the neutrino-antineutrino pairs must reach the polar regions and provide the energy for efficient jet acceleration to the high Lorentz factors, $\Gamma \sim 100$, so that the kinetic energy of the jet is converted ultimately to gamma rays.

The numerical studies of the accretion of magnetized, neutrino cooled matter onto a BH presented here are aimed to quantitatively estimate the conditions for the observed low luminosity of the resulting GRB. As discussed by [17], the upper limit for the total isotropic equivalent of the luminosity, $E_{\gamma, \text{iso}}$, from this GRB is at most $3 \times 10^{52}$ erg/s, as was restricted by the non-detection of neutrinos by the IceCube experiment. Generally, neutrino annihilation would lead to the GRB luminosity of

$$L_{\nu, \bar{\nu}} = (1 + z)E_{\gamma, \text{iso}}(1 - \cos \theta_j)/T_{90},$$

where $\theta_j$ is the opening angle of the jet. As derived in the numerical simulations by [37] (see also [38] for a fitting formula in a simpler steady-state 1-dimensional model of an NDAF disk), the $L_{\nu, \bar{\nu}}$ luminosity scales with the BH mass, spin and global average accretion rate to the power of $-3/2$, $-4/8$, and $9/4$, respectively. The efficiency of the neutrino energy deposition outside the BH horizon, $\epsilon = L_{\nu, \bar{\nu}}/L_{\nu} \approx 0.05 \tilde{m}^{5/4}$, and depends strongly on the BH spin. The accretion rate of the order of $M_\odot/s$ will lead to the luminosity of the explosion of the order of the canonical value for collapsars, i.e., $10^{51}$ erg/s, for a high spin of $a = 0.95$ (and for a BH mass of $3 M_\odot$). For a non-rotating BH, this luminosity would be obtained if the mass accretion rate were ten times larger.

The mass accretion rate is one of the uncertainties of this model. The simplest assumption is that the mass of the accretion torus is of the same order as the mass of the final BH, but it doesn’t have to be the case. The neutrino luminosity produced under the assumption that the torus mass is of about only $15 M_\odot$ fits better to the inferred upper limits, and does not require any additional fine-tuning of neither the annihilation efficiency (which might be very much different in case of magnetized disks than in simple NDAF models), nor the jets opening angle.

The GRB luminosity inferred from our simulations can be reconciled with the observational upper limits, for moderate spins of the final BH ($a = 0.6 - 0.8$). Furthermore, we can assume that not more than 10 per cent of the electron-positron pairs that were created by the neutrino annihilation contributed to the GRB fireball, and the rest might have fallen back into the BH. Finally, because the total event lasted for $T_{90} = 1 s$, the large mass of the torus and the mass accretion rate is not consistent with an estimate of $T_{90}$. Nevertheless, our simulation shown in Fig. 5 is roughly consistent with the observed GRB duration and gives $T_{90} \approx M/\dot{M} \approx 15/5.5 = 2.7 s$. In this case however, the longer-lasting ‘tail’ of the GRB signal, might rather have been below the detection noise level.
We note here that the Fermi detection of a GRB coincident with GW150914 has not been confirmed by deep Integral observations [39]. However, if this connection is real, or if in the future more coincident observations of gravitational signals with GRBs will be seen, then we have to face the fact, that there are mergers of two massive BHs in an environment with a sufficient amount of matter to produce a GRB with short time delay after the merger. Our computations show a possible mechanism for such a GRB to emerge with the parameters given by the observed signal (masses and spins of the BH), which is based on neutrino cooling. Our scenario for such a configuration is speculative, but it can be tested and verified by further observations and simulations.

In conclusion, we propose and numerically compute a plausible model for the GW emission being coincident in time with a weak GRB observed by Fermi. To know whether this model is indeed realized in nature, further searches for gravitational wave sources and their electromagnetic counterparts are now essential, with both novel experimental techniques and theoretical efforts in numerical relativity.

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