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

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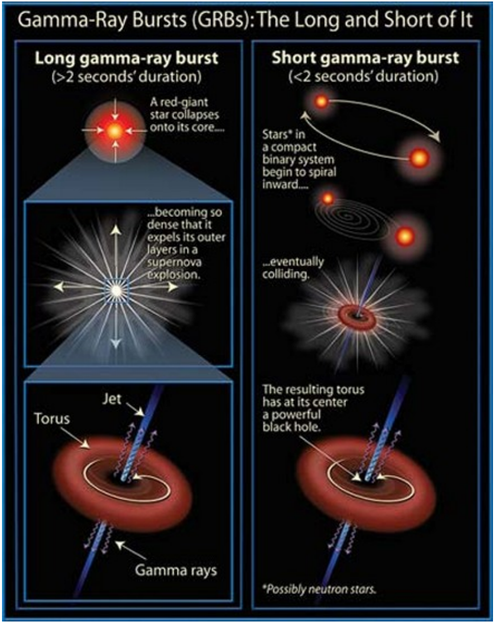
Gamma ray bursts: long and short



- Hyperaccretion: rates of 0.01-10 $M_{\odot}/s$
- Steady state and time-dependent models were proposed from 1990's
- EOS is not ideal, plasma composed of n, p, e^{+}, e^{-}
- Chemical and pressure balance required by nuclear reactions
- Neutrino absorption & scattering

Popham et al. 1999; Di Matteo et al. 2002; Kohri et al. 2002, 2005; Chen & Beloborodov 2007; Reynoso et al. 2006; Janiuk et al. 2004; 2007; 2010; 2013

In the hot and dense torus, with temperature of 10^{11} K and density $> 10^{10}$ g cm^{-3}, neutrinos are efficiently produced. The **main reactions** that lead to their emission are electron and positron capture on nucleons and neutron decay, and nuclear equilibrium ust be established.

$$
\begin{aligned}
p + e^- &\rightarrow n + \nu_{\rm e} \\
p + \bar{\nu}_{\rm e} &\rightarrow n + e^+ \\
p + e^- + \bar{\nu}_e &\rightarrow n \\
n + e^+ &\rightarrow p + \bar{\nu}_{\rm e} \\
n &\rightarrow p + e^- + \bar{\nu}_{\rm e} \\
n + \nu_{\rm e} &\rightarrow p + e^-
\end{aligned} \tag{1}
$$

The rates for these reactions are given by appropriate integrals (Reddy, Prakash & Lattimer 1998).

Other neutrino emission processes are: electron-positron pair annihillation bremsstrahlung, plasmon decay. We calculate their rates numerically, with proper integrals over the distribution function of relativistic, partially degenerate species.

$$e^- + e^+ \rightarrow \nu_{\rm i} + \bar{\nu}_{\rm i} \tag{2}$$

$$n + n \rightarrow n + n + \nu_{\rm i} + \bar{\nu}_{\rm i}. \tag{3}$$

$$\tilde{\gamma} \rightarrow \nu_{\rm e} + \bar{\nu}_{\rm e} \tag{4}$$

The neutrino cooling rate is finally given by the two-stream approximation, and includes the scattering and absorptive optical depths for neutrinos of all three flavors.

$$Q^-_\nu = \frac{\frac{7}{8}\sigma T^4}{\frac{3}{4}} \sum_{i=e,\mu,\tau} \frac{1}{\frac{\tau_{{\rm a},\nu_{\rm i}}+\tau_{\rm s}}{2} + \frac{1}{\sqrt{3}} + \frac{1}{3\tau_{{\rm a},\nu_{\rm i}}}} \times \frac{1}{H} \quad [{\rm erg\ s^{-1}\ cm^{-3}}]$$

In the EOS, contribution to the pressure is by the free nuclei and $e^+ - e^-$ pairs, helium, radiation and the trapped neutrinos:

$$P = P_{\rm nucl} + P_{\rm He} + P_{\rm rad} + P_\nu$$

$P_{\rm nucl}$ includes free neutrons, protons, and the electron-positrons:

$$P_{\rm nucl} = P_{\rm e-} + P_{\rm e+} + P_{\rm n} + P_{\rm p}$$

with

$$P_{\rm i} = \frac{2\sqrt{2}}{3\pi^2} \frac{(m_i c^2)^4}{(\hbar c)^3} \beta_i^{5/2} \left[F_{3/2}(\eta_{\rm i}, \beta_{\rm i}) + \frac{1}{2} \beta_{\rm i} F_{5/2}(\eta_{\rm i}, \beta_{\rm i}) \right]$$

where $F_{\rm k}$ are the Fermi-Dirac integrals of the order k, and $\eta_{\rm e}$, $\eta_{\rm p}$ and $\eta_{\rm n}$ are the reduced chemical potentials, $\eta_i = \mu_i / kT$, $\eta_{\rm e+} = -\eta_{\rm e} - 2/\beta_{\rm e}$. Relativity parameters: $\beta_{\rm i} = kT/m_{\rm i} c^2$. EOS computed numerically by solving the balance of nuclear reactions (Lattimer & Swesty 1991; Setiawan et al. 2004; Yuan 2005; Janiuk et al. 2007; Janiuk & Yuan 2010)

High Accuracy Relativistic Magnetohydrodynamics (Gammie et al. 2003). The code provides solver for continuity and energy-momentum conservation equations:

$$(\rho u^{\mu})_{;\mu} = 0$$

$$T^{\mu}{}_{\nu;\mu} = 0$$

$$p = K\rho^{\gamma} = (\gamma - 1)u$$

where:

$$T^{\mu\nu} = T^{\mu\nu}_{gaz} + T^{\mu\nu}_{EM}$$

$$T^{\mu\nu}_{gaz} = \rho h u^{\mu} u^{\nu} + p g^{\mu\nu} = (\rho + u + p) u^{\mu} u^{\nu} + p g^{\mu\nu}$$

$$T^{\mu\nu}_{EM} = b^2 u^{\mu} u^{\nu} + \frac{1}{2} b^2 g^{\mu\nu} - b^{\mu} b^{\nu}; \quad b^{\mu} = u_{\nu} {}^{*}F^{\mu\nu}$$

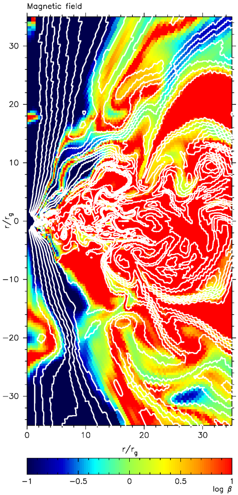
and, assuming force-free approximation, $E_{\nu} = u_{\mu} F^{\mu\nu} = 0$.

Conservative scheme solves:

$$\partial_t \mathbf{U}(\mathbf{P}) = -\partial_i \mathbf{F}^i(\mathbf{P}) + \mathbf{S}(\mathbf{P})$$

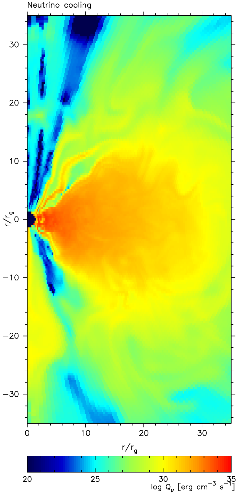
where $\mathbf{U}$ is a vector of "conserved" variables, $\mathbf{F}^i$ are the fluxes, and $\mathbf{S}$ is a vector of source terms. In non-relativistc MHD, both $\mathbf{P} \to \mathbf{U}$ and $\mathbf{U} \to \mathbf{P}$ have a closed-form solution. In GRMHD $\mathbf{U}(\mathbf{P})$ is a complicated, nonlinear relation. Inversion $\mathbf{P}(\mathbf{U})$ is calculated numerically.

- transformation between 'conserved' (momentum, energy density) and 'primitive' (rest mass density, internal energy) variables
- requires to solve a set of 5 non-linear equations
- inversion is complex for a non-adiabatic relation of the pressure with density, instead of adiabatic law



- Initial poloidal configuration of the field, with $A_\phi = (\rho/\rho_{max})$.
- Example parameters: black hole mass $M = 3M_\odot$ and spin $a = 0.9$, disk mass $M_d = 0.1M_\odot$, initial $\beta = P_{gas}/P_{mag} = 50$
- Field is advected with gas under the BH horizon
- Close to the poles, mass density is low while magnetic pressure is high
- Black hole rotation helps launching the magnetically driven jets

Neutrino cooling



- At temperatures $10^{10} - 10^{11}$ K and densities $10^9 - 10^{12}$ g cm^{-3} photons are trapped and plasma is cooled by neutrinos
- Cooling rate computed from the balance of nuclear reactions which lead to neutrino emission
- Used to update the internal energy only (Janiuk, Mioduszewski & Moscibrodzka, 2013)
- In this version of the HARM-2D code, computed consistently with the pressure update (Janiuk et al. 2017)
- Code parallelized with MPI and hyperthreading is used for the EOS table interpolation

To compute the energy flux through the horizon of the black hole, we need the electromagnetic part of the stress tensor,

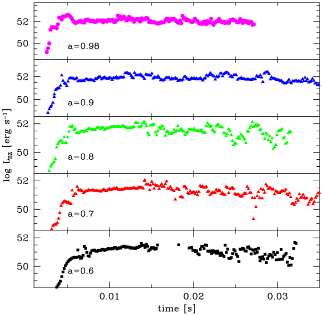
$$T^{\mu\nu}_{\rm EM} = b^2 u^\mu u^\nu + \frac{b^2}{2} g^{\mu\nu} - b^\mu b^\nu, \tag{5}$$

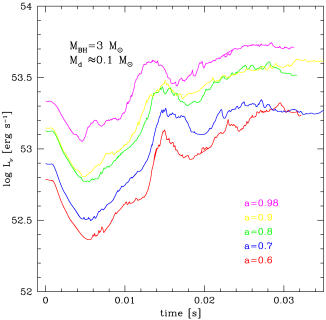
where the four-vector b^μ with $b^t \equiv g_{i\mu} B^i u^\mu$ and $b^i \equiv (B^i + u^i b^t)/u^t$.
We then evaluate the radial energy flux, as the power of the Blandford-Znajek process:

$$\dot{E} \equiv 2\pi \int_0^\pi d\theta \sqrt{-g} F_E \tag{6}$$

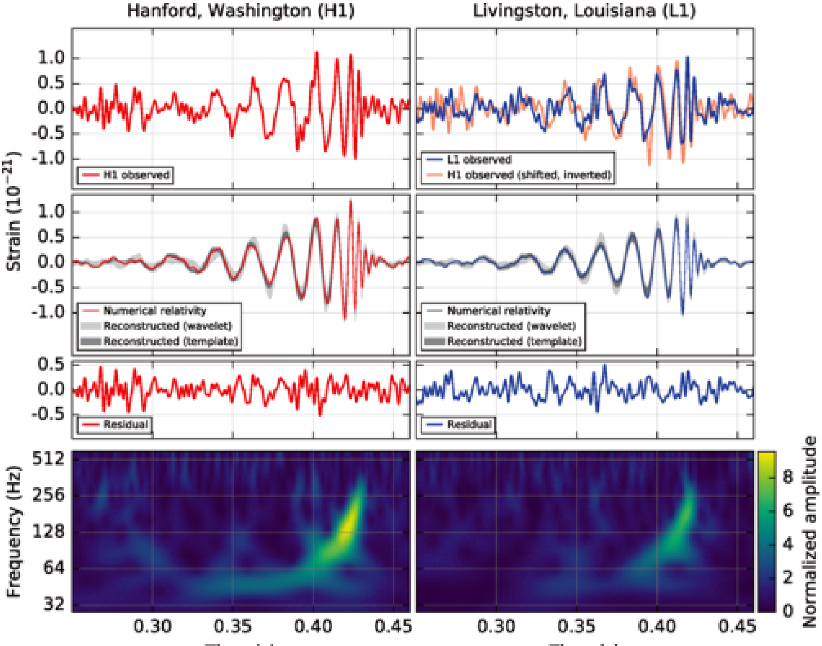
where $F_E \equiv -T^r_t$. This can be subdivided into a matter $F_E^{(MA)}$ and electromagnetic $F_E^{(EM)}$ part, although in the force-free limit the matter part vanishes (McKinney & Gammie 2004).

Two mechanisms may be source of power of the GRB central engine: neutrinos and black hole rotation mediated by magnetic fields





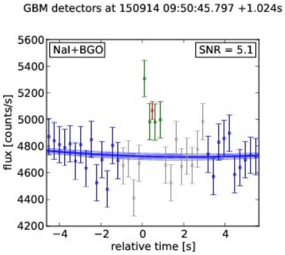
Gravitational wave astronomy

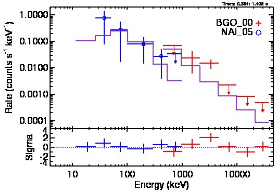


- The source GW150914 was interpreted to be a merger of two BHs of the masses of $36^{+5}_{-4}\ M_{\odot}$ and 29^{+4}_{-4}
- Final BH parameters are estimated to be of $62^{+4}_{-4}\ M_{\odot}$ and $0.67^{+0.05}_{-0.07}$ for its mass and spin
- Probabilities that the angles between spins and the normal to the orbital plane are between 45° and 135° are about 0.8 for each component BH
- Spin magnitudes are constrained to be smaller than 0.7 and 0.8 at 90% probability
- Assumption of a strict co-alignment of spins with the orbital angular momentum results in an upper limit of 0.2 and 0.3 for the spins
- Distance of 410^{+160}_{-180} Mpc, corresponding to a redshift of about $z = 0.09$

Fermi GRB coincident with GW150916

- Duration of about 1 sec and appeared about 0.4 seconds after the GW signal
- within the limit of uncertainty of LIGO and Fermi detector capabilities could also be associated spatially
- GRB fluence in the range 1 keV-10 MeV, is of 2.8×10^{-7} erg cm^{-2}
- Implied source luminosity in gamma rays equals to $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg/s (Connaughton et al. 2016)



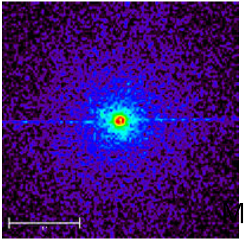


Some recent scenarios for GW-GRB origin

- A. Loeb (2016, ApJL) The two BHs merge within a common envelope of a very massive star. These two BHs must have formed simultaneously from the two clumps that were created via the bar instability during the core collapse.
- S. Woosley (2016, ApJL): core-collapse of a single, chemically homogeneous, rapidly rotating single star of a mass about $150M_{\odot}$. GW signal 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. Or, the two massive stars of the initial separation on the order of 1 AU would undergo core collapses one after another and experience twice the common envelope phase.
- B. Zhang (2016, ApJL): magnetospheric activities during the merging phase would make a fireball if the BH charge is large
- ... and many more

Possible exotic GRB coincident with a merger

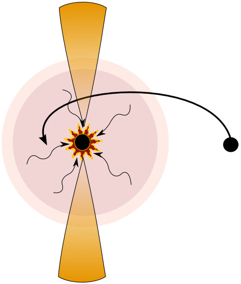
We envisaged (Janiuk, Charzynski & Bejger 2013) a model for **a gamma ray burst**, with possible double jets and/or jets redirected, and leaving an orphan afterglow, while **accompanied by a gravitational wave signal** from the collapse of a massive rotating star in a binary system with a companion BH.



High Mass X-ray binary

M. Bejger, LIGO team

- combination of the two scenarios (close binary of massive star + BH) can yield the GRBs
- simulations of such scenario very complicated, must consist of several steps:



- spinning up the massive star
- core collapse and accretion of inner envelope, primary BH mass and spin evolution, possible jet launch

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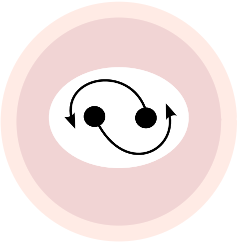

- spinning up the massive star
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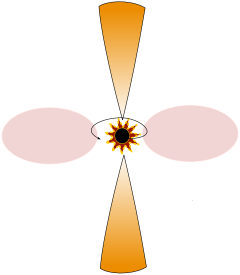
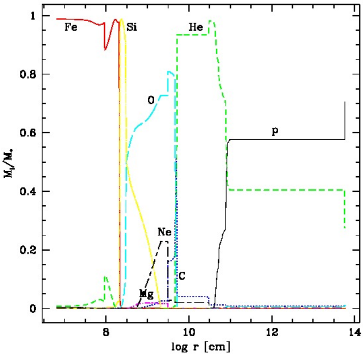


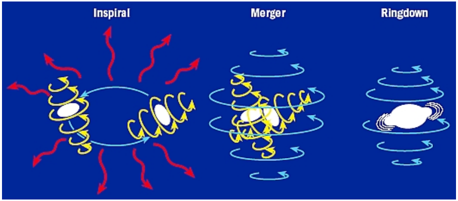
  - spinning up the massive star
  - core collapse and accretion of inner envelope, primary BH mass and spin evolution, possible jet launch
  - binary BH merger in vacuum
  - accretion of the envelope onto the spinning merged product
  - second jet launch, possibly redirected

- Spherically symmertic pre-SN model (Woosley & Weaver 1995)
- Rotation of the envelope forms the disk (Lee & Ramirez-Ruiz 2006; Janiuk, Moderski & Proga 2008)
- Black hole formed in the star's core spun up by envelope rotation and companion BH (Janiuk, Charzynski & Bejger 2013)



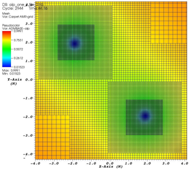
Companion BH in a binary system transfers its specific orbital angular momentum as it enters the star (Barkov & Komissarov 2010)

- Two body problem is solved in Newtonian gravity: motion along ellipse
- In GR, full set of Einstein equations needs to be solved numerically to model the geometry of spacetime



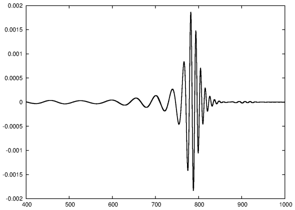
Merger computations

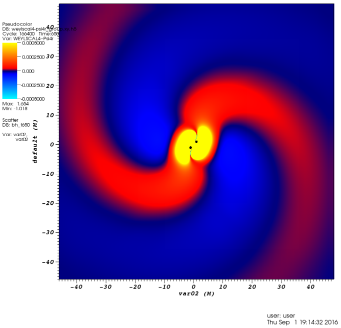
Einstein Toolkit computational framework: a family of codes for use in relativistic astrophysics based on finite difference (Löffler et al. 2012).



- Adaptive mesh technique, 7-10 refinement levels
- BSSN method: numerically the most stable formulation of 3+1 decomposition of Einstein equations, used for discretization of evolution equations of spacetime geometry. Pretorius (2005), Campanelli et al. (2006), Baker et al. (2006)

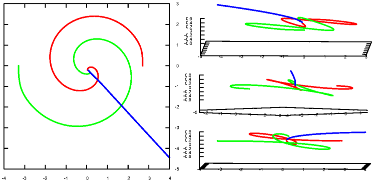
Merging black holes and gravitational wave



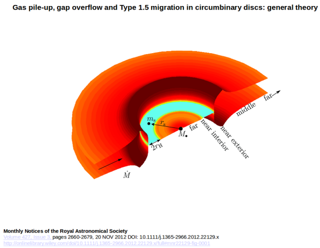


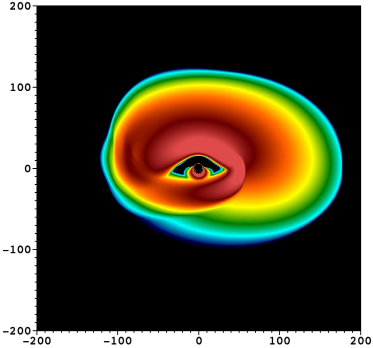
- Initial state: two black holes in quasi circular orbits
- Models parameterized with BH mass ratio, their spin magnitudes and spin vectors orientations
- Gravitational wave analysis through the multipole expansion of the Weyl scalar Ψ_4 (Alcubierre 2008)

- For non-spinning, unequal mass components, kick velocity of remnant black hole due to asymmetric beaming of radiation
- We obtained 120-130 km/s for non-spinning, unequal mass components
- For spinning black holes of a=0.2-0.6 kick is of 130-280 km/s,
- If spins vectors aligned to the orbital plane, kick is 200-700 km/s, but can be up to 4000 km/s



Simulated orbits in the xy plane and their views from 3 different directions perpendicular to z-axis.



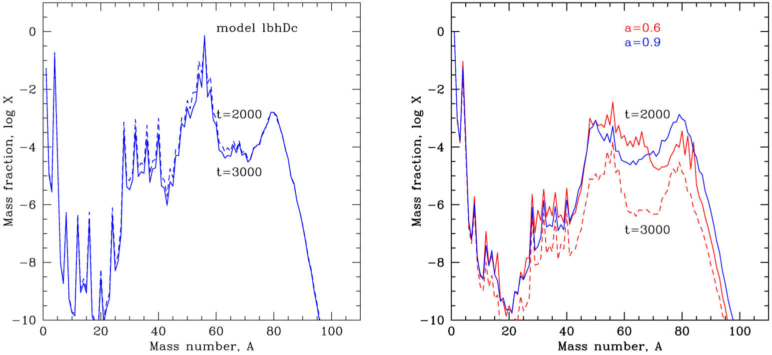


Kocsis et al. (2012); Meliani et al. (2016)

Final accretion onto merger BH and gamma ray burst

- We made several GRMHD runs for BH mass and range of spins, constrained from the LIGO data
- Torus mass: 15 $M_{\odot}$, adopted to produce adequately low neutrino luminosity for a weak GRB
- Obtained $L_{\nu} \sim 5 \cdot 10^{52} - 2 \cdot 10^{53}$ erg s^{-1}, and $L_{BZ} \leq 10^{51}$
- $L_{\nu\bar{\nu}} \sim 0.05 L_{\nu}$ (e.g., Zalamea & Beloborodov 2011)

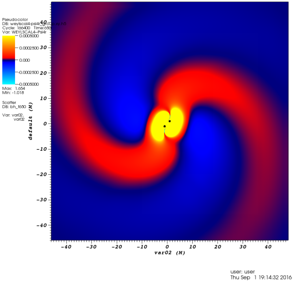
$$E_{\rm tot} = \varepsilon_{\gamma}^{-1} E_{\gamma} = \varepsilon_{\gamma}^{-1} \frac{\theta^2}{2} E_{\gamma,iso}$$

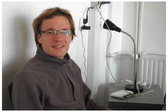


Volume integrated abundance distribution of elements synthesized in the accretion disk in 2D simulation with $M_{\rm BH} = 62$, a=0.9, and $M_{\rm BH} = 3$, a=0.6 and 0.9 (Janiuk 2016, submitted)

- Emission in Ultraviolet/Optical due to the decay of speccies (the 'macronova'; e.g., Li & Paczynski 1998)
- Radio flares months/years after the GRB (Piran et al. 2012).
- Certain isotopes decay should be detectable via emission lines: NuSTAR: energy range of 5-80 keV, possible detection of photons from Ti, Co, Mn, Cu, Zn, Ga, Cr decay; also EPIC onboard XMM-Newton: lines below 15 keV, e.g., ^{45}Ti, ^{57}Mn, or ^{57}Co possibly detectable (Janiuk 2014)
- All might be also important for search for electromagnetic counterparts of GW signals from mergers

- We proposed and computed a model for LIGO GW source emission coincident in time with a putative weak gamma ray burst reported by Fermi (but see e.g. Greiner et al. 2016)
- Semi-analytical treatment of the BH core collapse and star's envelope spin-up
- GR simulations of BBH merger and MHD evolution of a GRB central engine were carried numerically
- Cooling of the remnant accretion torus by neutrino emission computed from the tabulated EOS with proper microphysics
- Further searches for the GW sources and their EM counterparts are now essential, and better constrained models worth exploring
- Process of the core collapse in the center of a massive star with companion BH in its envelope, prior to the BBH merger, needs further studies (see e.g. McLeod & Ramirez-Ruiz 2015)





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