Modeling black hole mergers in long gamma ray bursts

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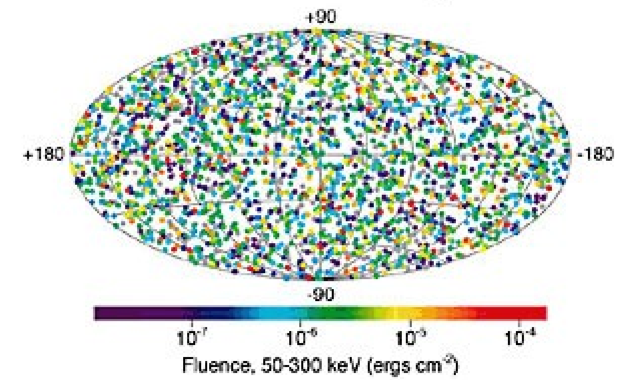
Recent paper: ArXiV:1310.4869 (Astronomy and Astrophysics in press)

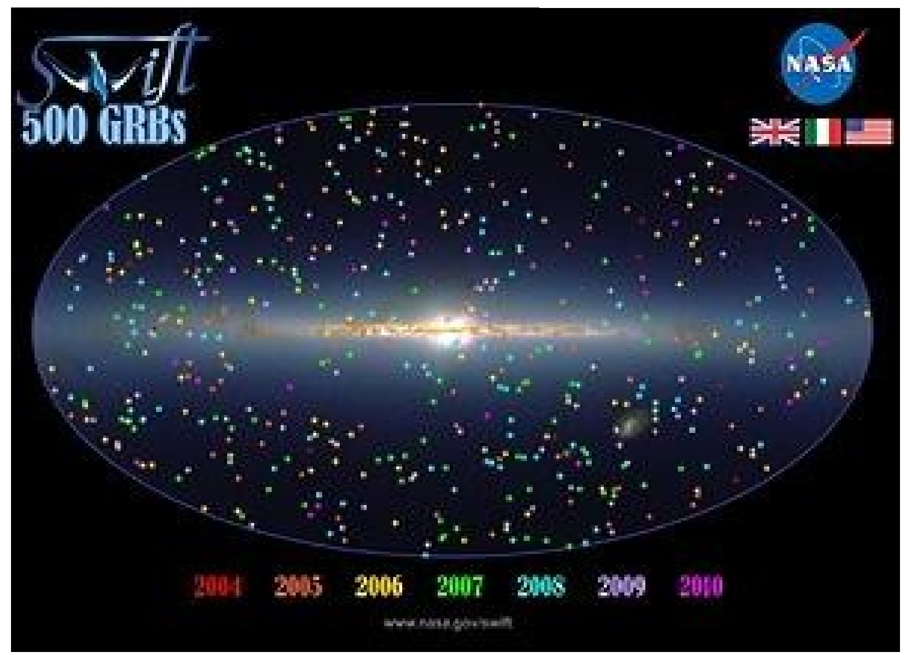
Gamma Ray Bursts

- First detected in 1967
- Isotropically distributed
- At cosmological distances
- Group in Long-Soft and Short-Hard
- Prompt emission in Gamma plus afterglow up to IR/Radio bands

2704 BATSE Gamma-Ray Bursts



Gamma-ray bursts come from all directions.

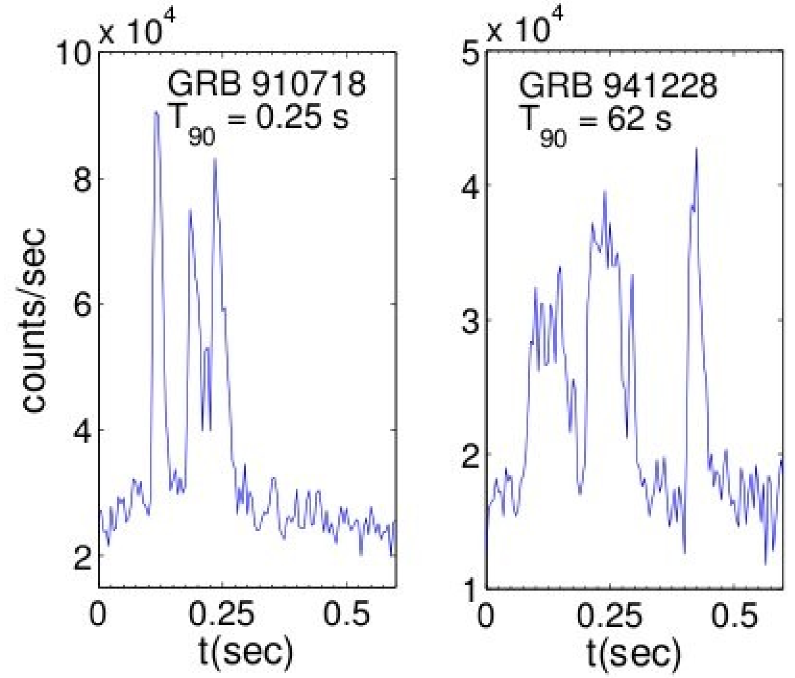


This all-sky map shows the locations of Swift's 500 gamma-ray bursts, color coded by the year in which they occurred. In the background, an infrared image shows the location of our galaxy and its largest satellites. Credit: NASA/Swift/Francis Reddy.

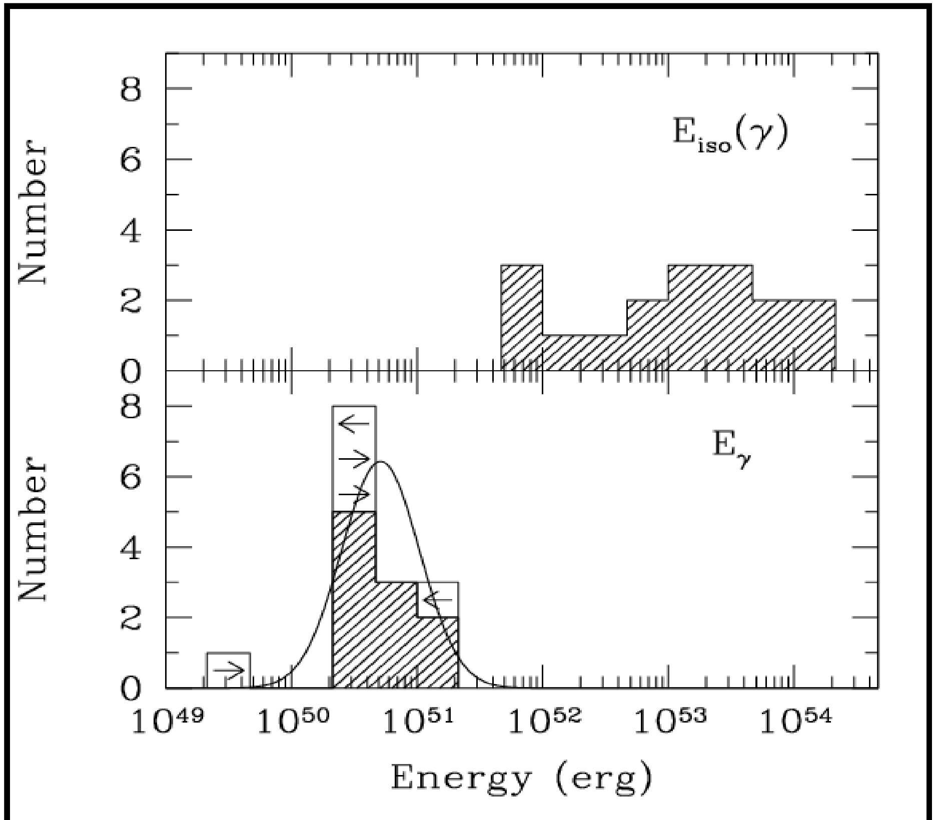
Time profiles of GRBs:

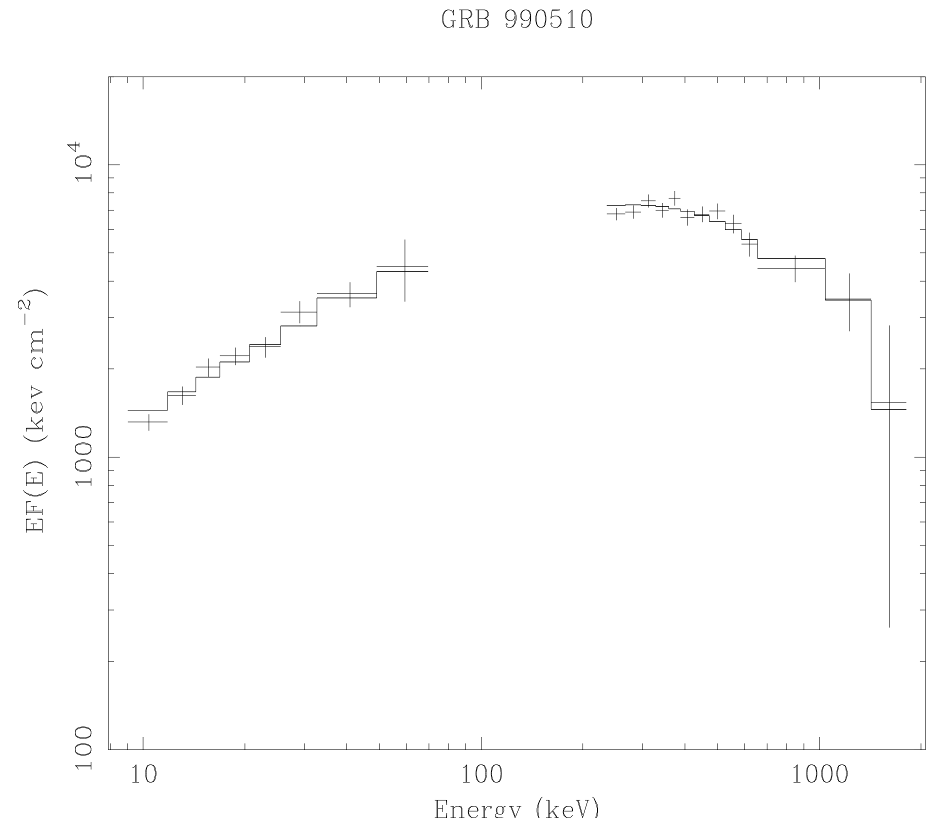
Duration given by the T_{90} estimate

Fast variability



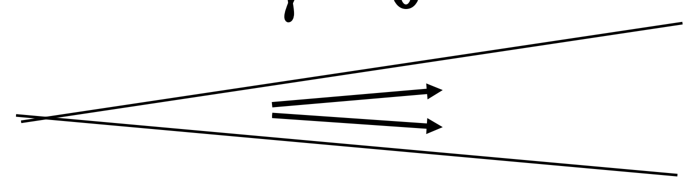
Energetics of GRBs





Particles move in a cone

$\gamma = \theta^{-1}$



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

Source of energy for GRBs

Required energy: $\sim 10^{52}$ erg
(to be radiated)

Typical models of GRBs postulate the gravitational potential energy

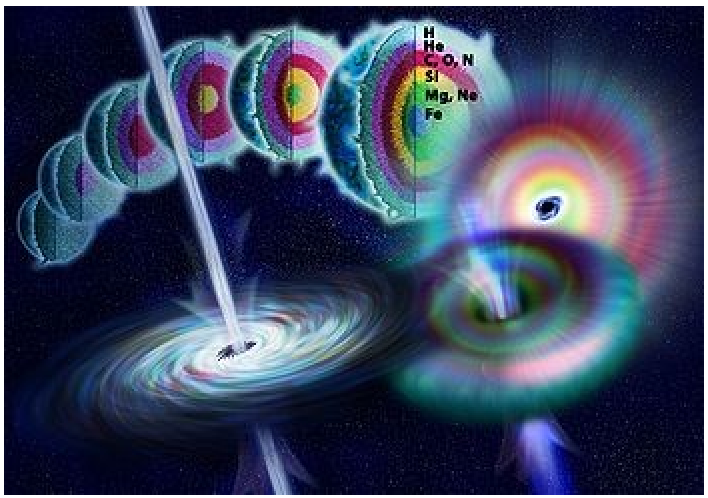
The most efficient mechanism for energy production is accretion of matter onto a compact star

$E = G\,M^2/r$

M = 1-10 Solar Masses
r = 3-10 km

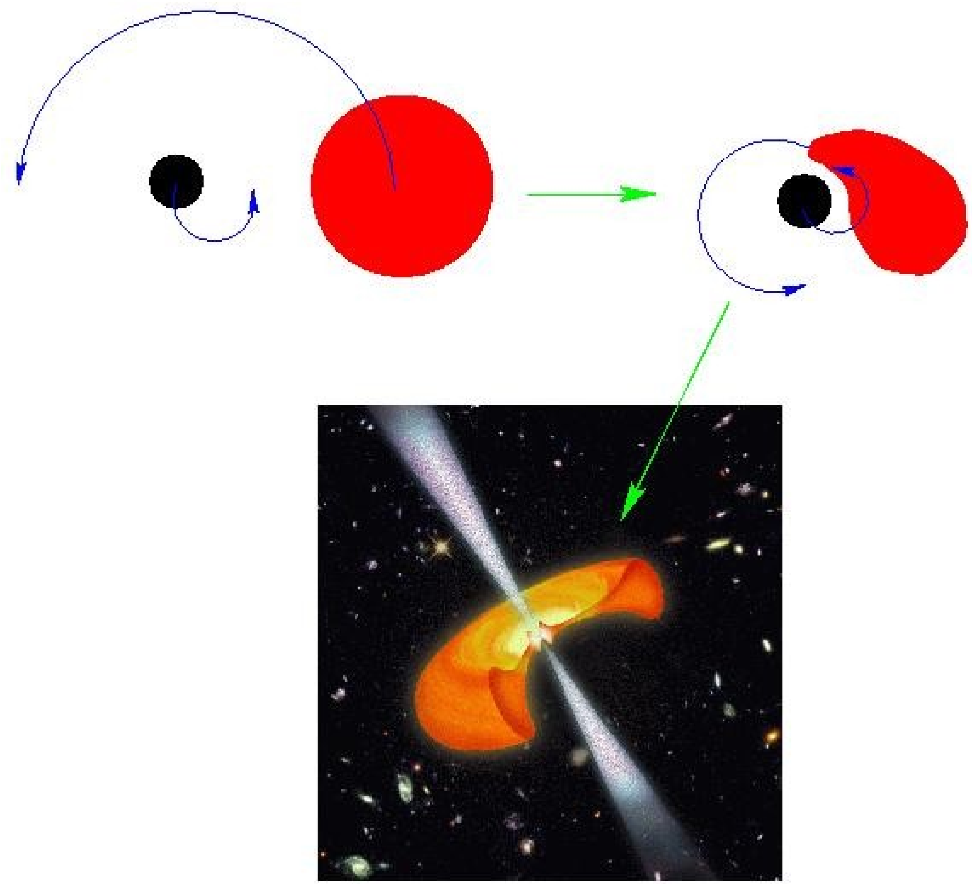
$E = 10^{53} - 10^{54}$ erg
at efficiency of 1-10%

Two standard types of models



Massive star explosion and mass fallback from the envelope

Paczyński (1998); McFadyen & Woosley (1999)



Compact binary merger: neutron star disruption

Eichler et al. (1989); Ruffert & Janka (1999)

Another possible progenitor: high mass X-ray binary

Close binary: massive OB star plus compact remnant

Massive star is spun up by the interaction in binary system

Examples: Cyg X-3, IC 10 X-1, NGC 300 X-1

Ultimately, the compact star enters WR's envelope

Tidal squeezing triggers the core collapse in the primary

Two black holes merge

Matter accretes on the product

Zhang & Fryer (2001); Barkov & Komissarov (2010); Belczynski et al. (2008; 2013); Church et al. (2012)

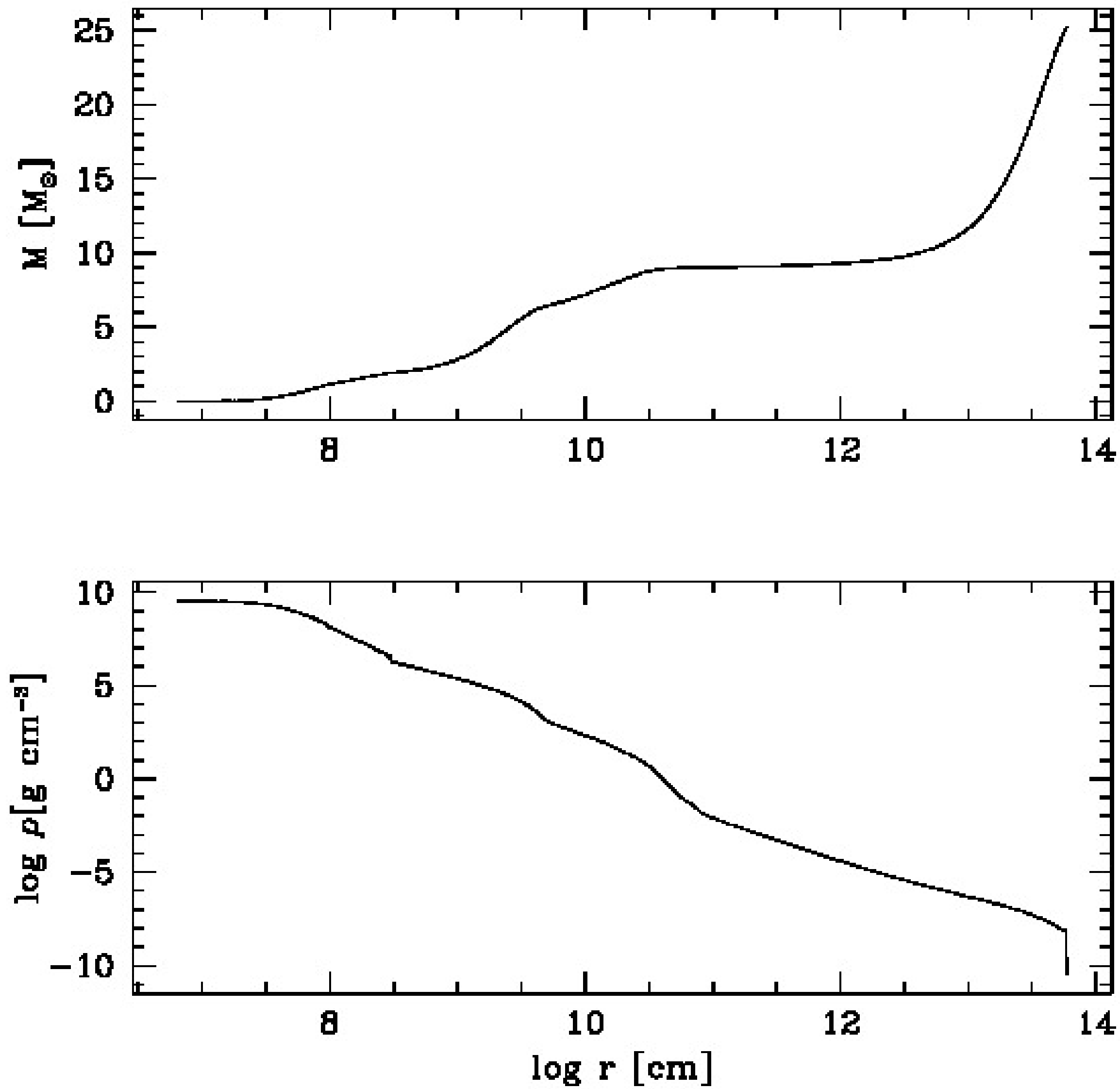
Model of pre-supernova star

Pre-supernova star
(Woosley & Weaver 1995)

Enclosed mass of 25 M_{Sun}

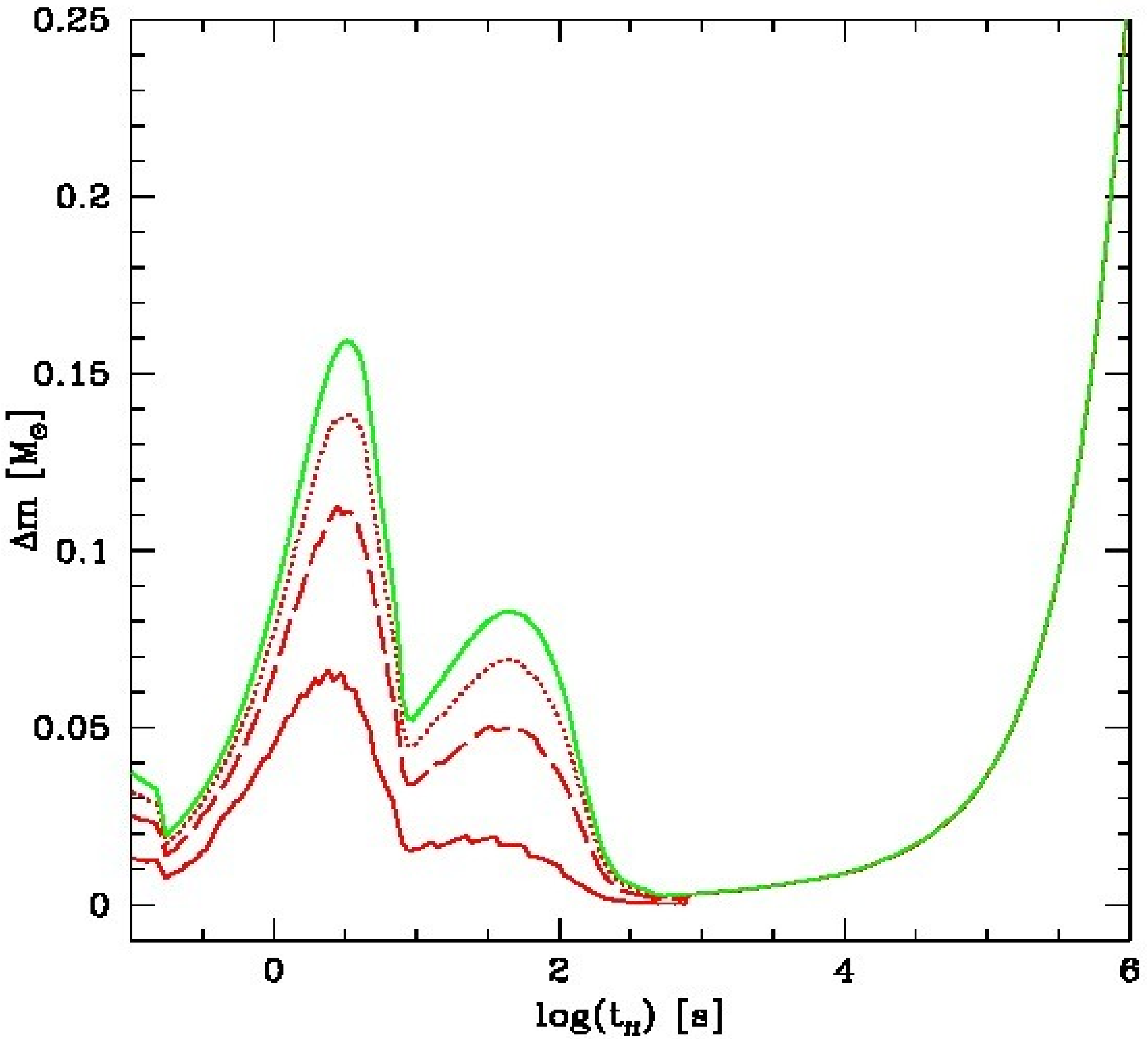
Density distribution:
chemical composition of an evolved star (Fe, Si, C, O, He, H)

Iron core of mass 1.4 M_{Sun}



Mass of the envelope shell during the collapse (green:total; red: contained in the rotating torus).

The three lines show the models with various normalisation of the specific angular momentum in the envelope: x=1.5 (solid), x=3.0 (dashed) and x=7.0 (dotted).



Spinning up the envelope and core black hole

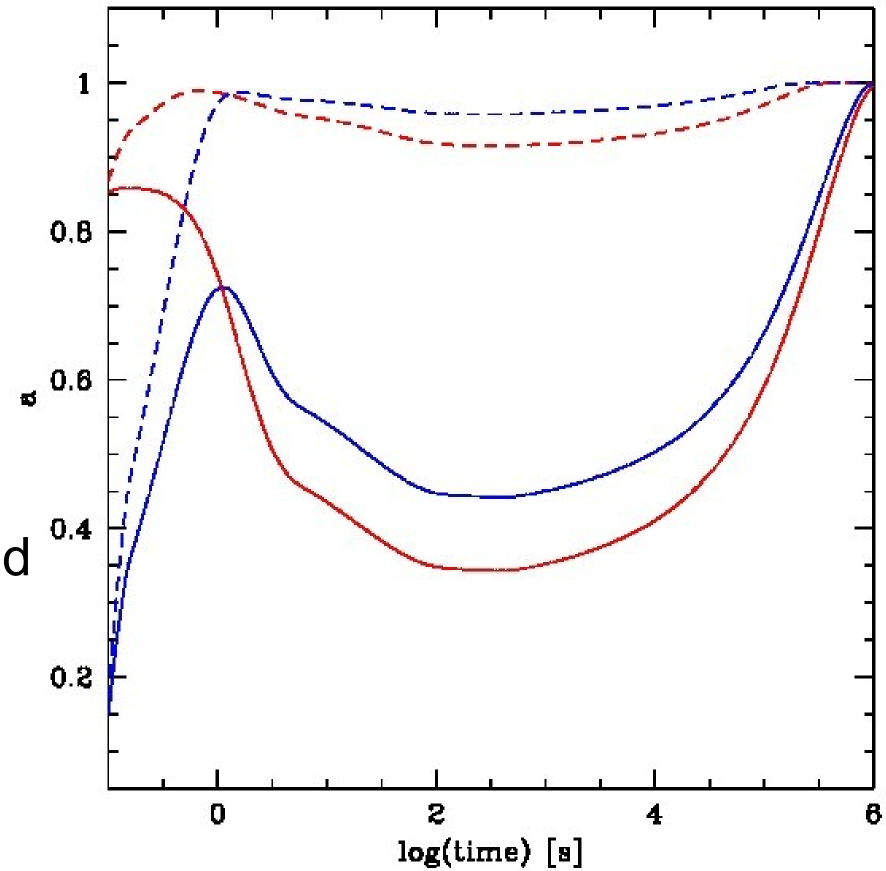
We adopt specific angular momentum distribution in the star (differential rotation)

$$l_{spec}(r,\theta)=l_0(1-|\cos(\theta)|)$$

The infalling envelope matter adds mass and spins the black hole. The rotationally supported torus must obey (Bardeen et al. 1972):

$$l_{spec}>l_{crit}=\frac{2GM_{BH}}{c}\sqrt{2-a+2\sqrt{1-a}}$$

Janiuk & Proga (2008); Janiuk, Moderski & Proga (2008)

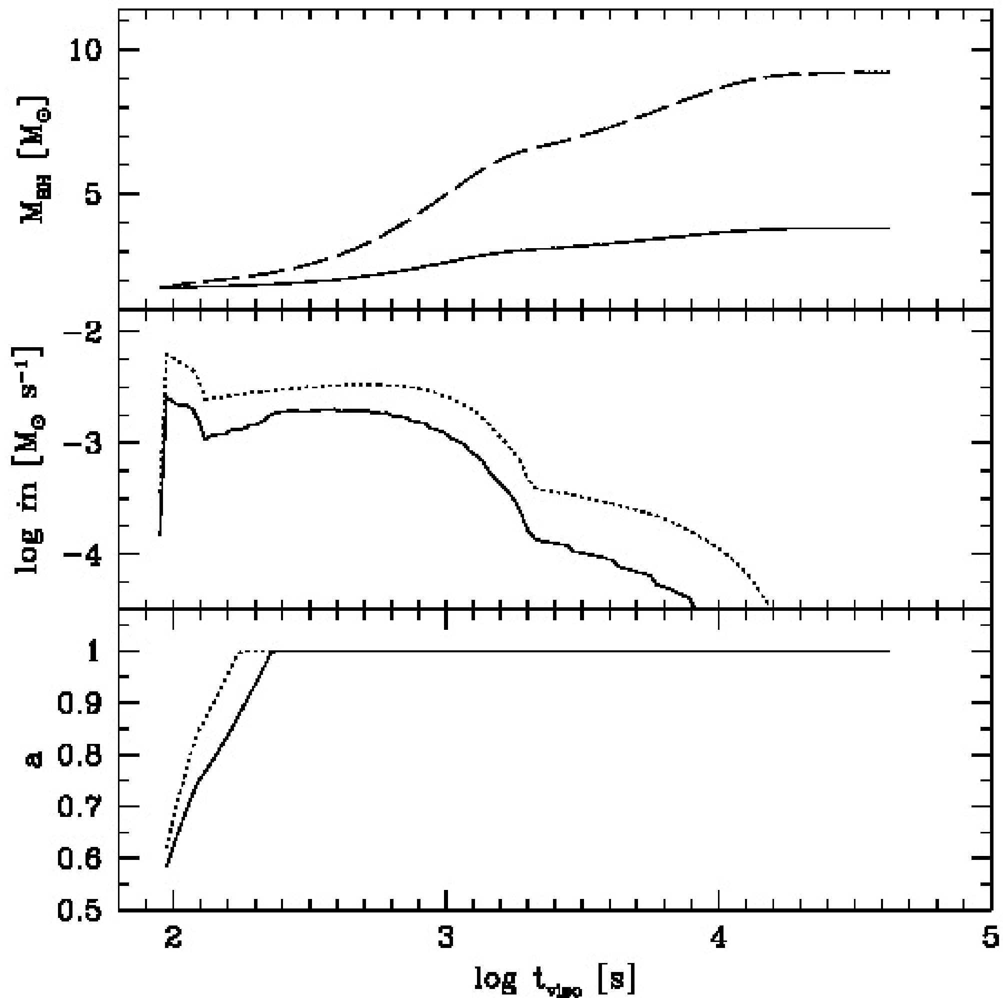


Spinning up the envelope and core black hole

The companion BH transfers its orbital specific angular momentum

$$\Delta l = \frac{dJ_2}{dM} = \frac{M_2}{2}\sqrt{\frac{G r}{M(r)}}\left(1+\ln\frac{r_2}{r}\right)$$

Torus accretion: BH spins up to maximum rate. Some (most ?) of its mass will be lost in wind.



McKinney et al. (2006); Kumar et al. (2008); Janiuk et al. (2004; 2007; 2010; 2013)

Evolution scenarios

- We proposed two representative scenarios for the pre-merger configuration

  - Homologous accretion on the envelope, when both the rotating torus and material from the poles contribute to the growth of the primary black hole
  - Only torus accretion, while the material from the poles is expelled. Some torus mass might further be expelled through winds

- The primary BH grows in mass to about ~3 – 9 M_{Sun}. This phase may last up to ~500 s (jet emission). Then the secondary BH sinks to merge with it. The spin of the primary at merger time is either ~0.7 - 1.

Merging two black holes

- Numerics done with Cactus Computational Toolkit (Goodale et al. 2003; Loeffler et al. 2012)
- 3+1 split of Einstein equations; Cauchy initial value problem solved with BSSN method (Shibata & Nakamura 1995; Baumgarte & Shapiro 1999)
- 3D Cartesian grid; adaptive mesh, reflection symmetry assumed to reduce number of grid points and computer requirements

Interdisciplinary Center for Mathematical and Computational Modeling, Warsaw University

www.einsteintoolkit.org

We track numerically the very last stage of BBH merger:

initial separation of 6M; inspiral, merger and ringdown

Quasicircular orbits, mass ratio q=1-3

Primary spin a=0-0.9, directed perpendicularly to orbital plane

Secondary is spinless

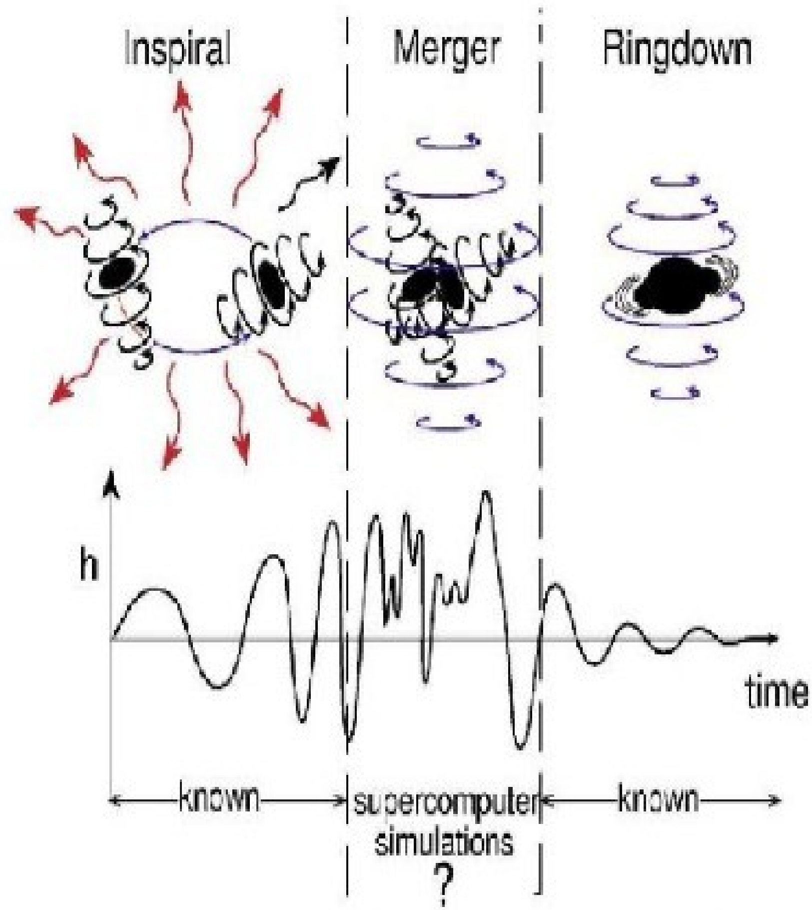


Fig. 1. The three phases of black hole merger (courtesy Kip Thorne).

Trajectories of the components during merger

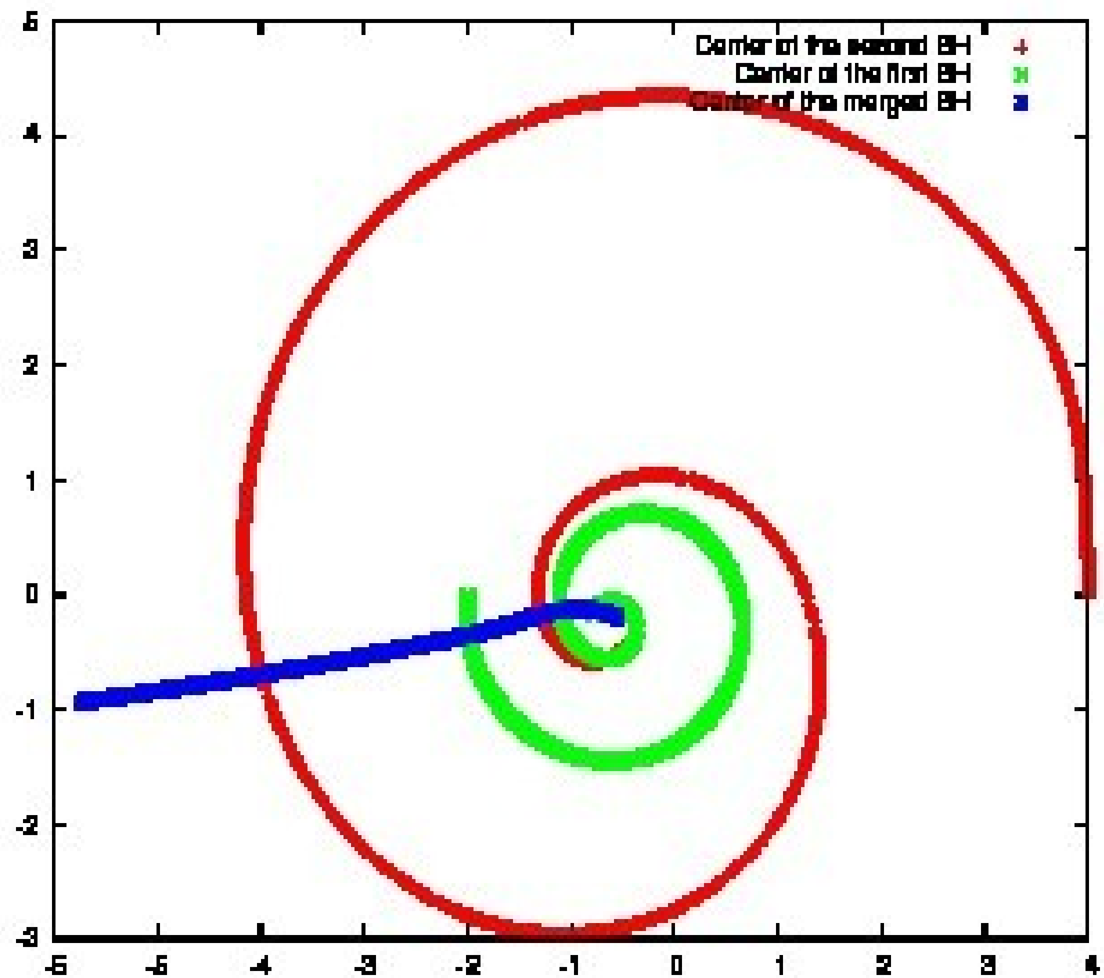
- Parameters:

m_1 = 0.632, m_2 = 0.316, s_1=0.9

- ADM mass ratio M_1/M_2 = 3.0

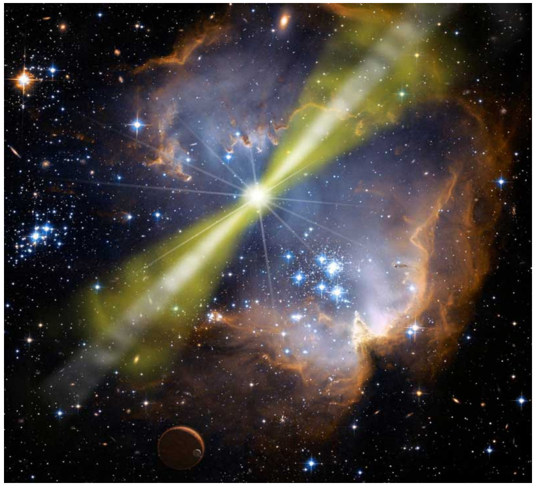
- Resulting final ADM mass and dimensionless spin

M_3 = 1.34, a_3 = 0.76



Gravitational recoil

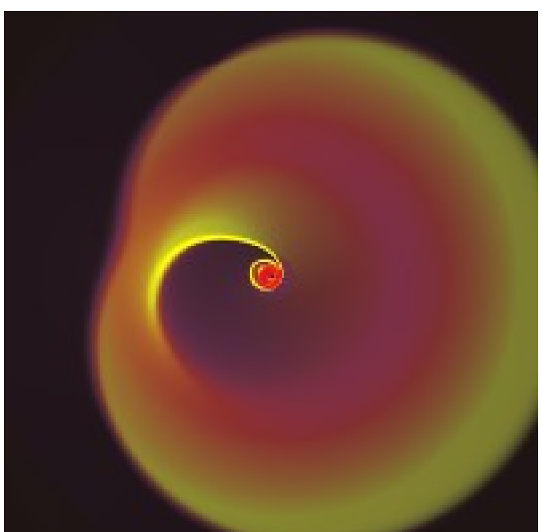
- Total linear momentum radiated from the system through gravitational waves is computed through the coefficients A^{lm} of multipole expansion of the Weyl scalar (Alcubierre 2008).
- Recoil vector remains in the orbital plane, because we assumed reflection symmetry; in general, it does not have to be the case
- We obtained velocity of the product, depending on spins and mass ratio of components, 200-300 km/s



Observational perspectives

Larger recoil speed for q~1: if primary BH mass small due to wind taking most of envelope's, the offset of GRB afterglow is possible.

The merger product would leave the host galaxy if v~2000 km/s. Possible if both BHs have extremely large spins (Tichy & Maronetti 2007).



Recoil kick directed into circumbinary disk plane can alter the distribution of specific angular momentum (Rossi et al. 2010).

If magnetic fields are involved, expansion of dual jets driven by generalized Blandford-Znajek mechanism (Palenzuela et al. 2010)

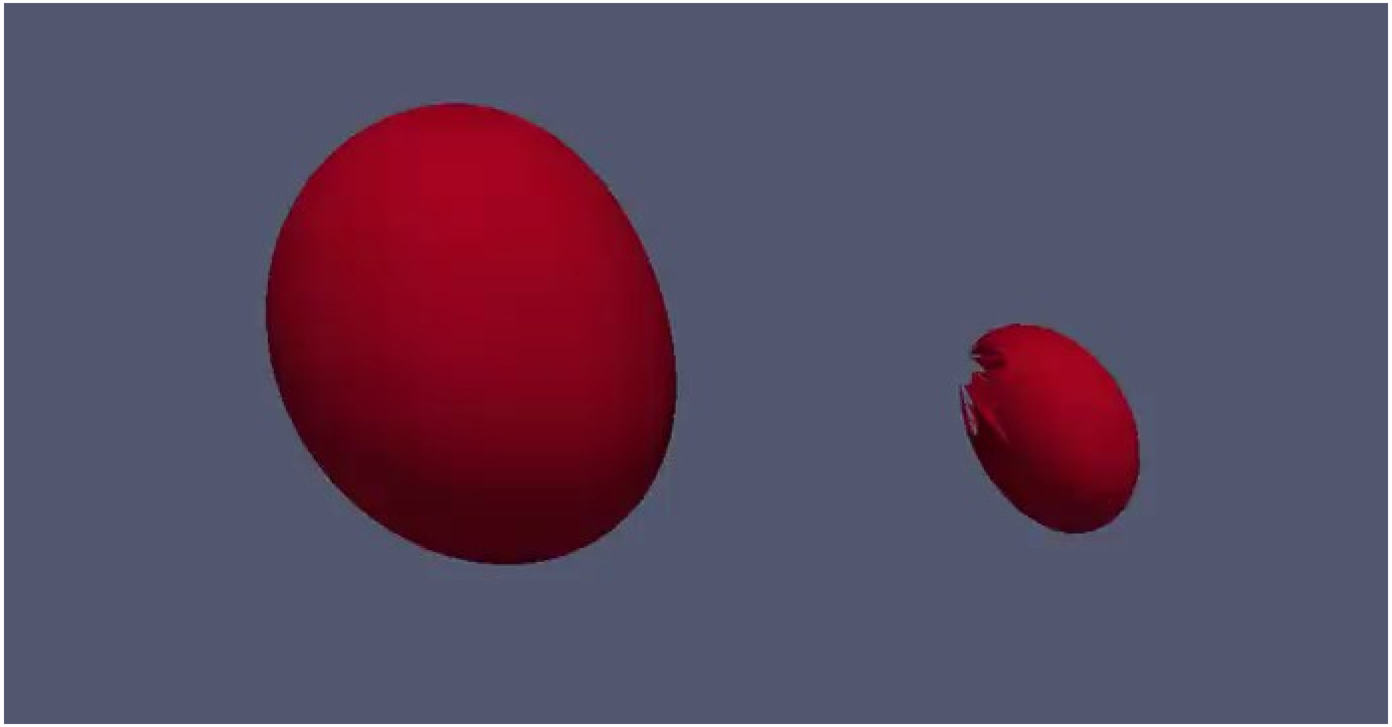
Summary

- The long duration GRB may originate from a merger of a close compact binary system, containing a high mass evolved star and a black hole.
- The event can be divided into stages:

1. The onset of the core collapse in the primary star, connected with the tidal interaction with secondary black hole. The inner shells of the envelope are spun up by the companion, and accrete onto the primary BH, increasing its mass and rotation spin
2. The merger of two black holes, surrounded by a circumbinary torus; gravitational waves; kick
3. Accretion of a remnant mass onto the BH merger product

- Possible observational consequences
  - Electromagnetic signal from the jets, POSSIBLY DOUBLE
  - Gravitational waves
  - Possible delay and offset of the secondary GRB signal / afterglow emission, due to recoil

Merging event horizons



Szilagyi et al. (2009, Phys Rev). Animation illustrates computations with the pseudo-spectral method, mass ratio 2, spins 0.4. Source: www.black-holes.org