Santorini, 29.8.05

Last moments in the life of a compact binary system

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0. Compact binaries as GRB engines

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- compact binaries:
  - double neutron star systems (DNS)
  - neutron star black hole systems (NSBH)

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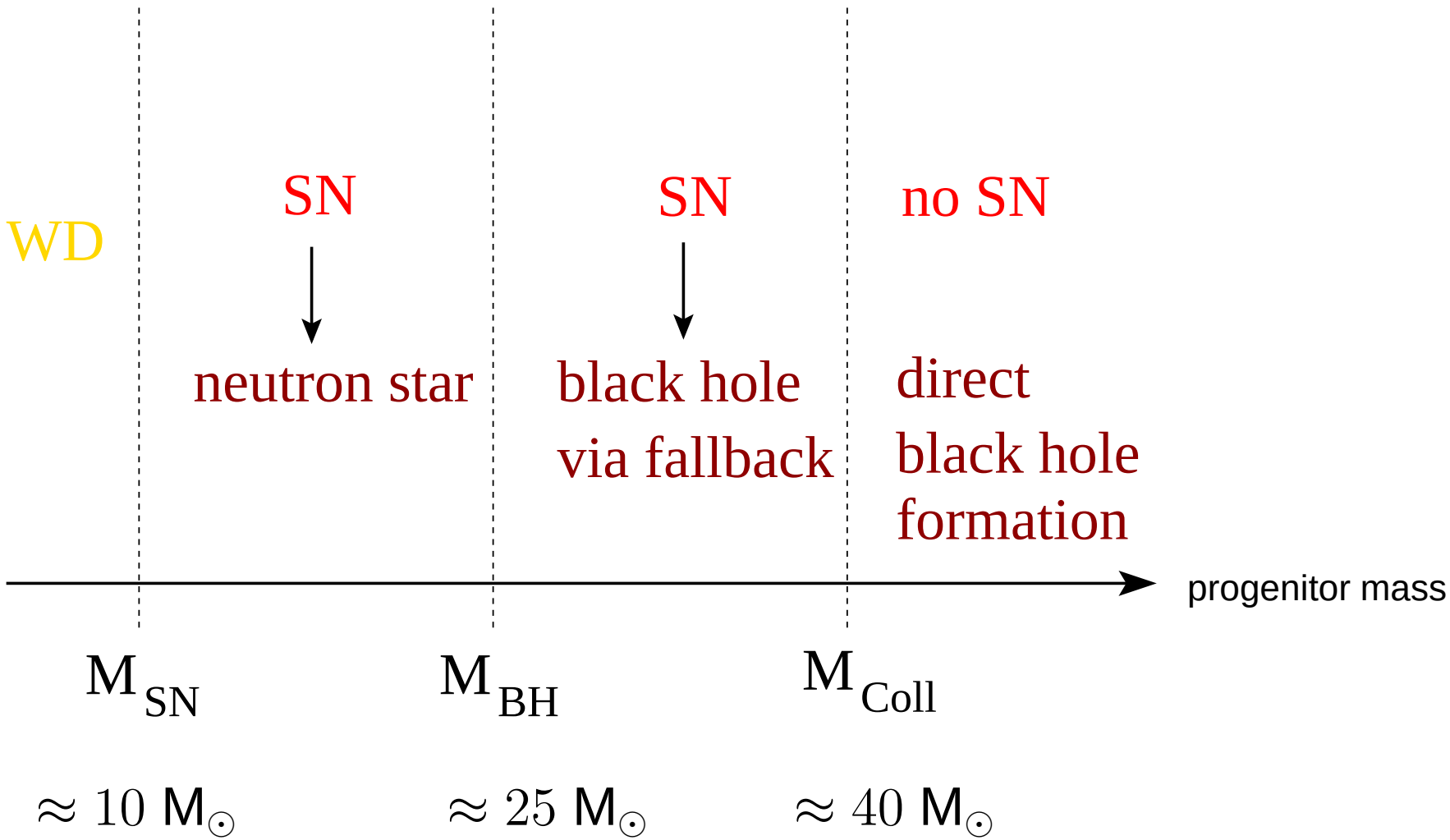
- compact binaries:
  - double neutron star systems (DNS)
  - neutron star black hole systems (NSBH)

- for good reasons:
  - they DO occur (e.g. PSR 1913+16)
  - rates compatible with GRB-rates, most recent rate $R_{\rm NSM} = 3 \cdot 10^{-4}$ (year galaxy)$^{-1} \gg R_{\rm sGRB}$
  - energy: $\Delta E_{\rm bind} \sim 10^{53}$ ergs $\gg E_\gamma \sim 10^{51...52}{\rm erg}\left(\frac{\Omega}{4\pi}\right)$
  - compactness, very short time scales, $\tau_{\rm dyn} = (G\bar{\rho})^{-1/2} \approx 3 \cdot 10^{-4}$ s, last orbital period $\sim 2 \cdot 10^{-3}$ s

I. How do we think compact binaries form ?

- mass thresholds:



Double Neutron Star Systems (DNS)

- several different paths ...

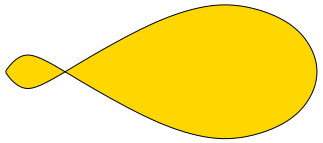
'Standard scenario'

- initial system: close, massive binary
  - masses $10\ M_\odot \approx M_{SN} < M_{secon} < M_{prim} < M_{BH} \approx 25\ M_\odot$
  - separation < 1 AU

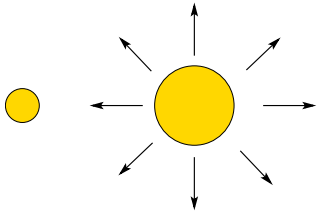
- evolution:

(i) two massive stars

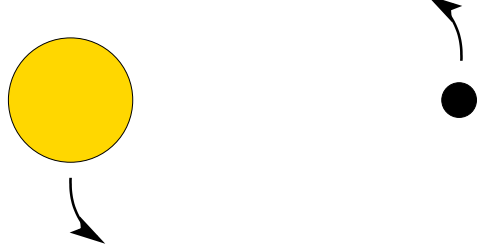
(ii) primary evolves, mass transfer to secondary



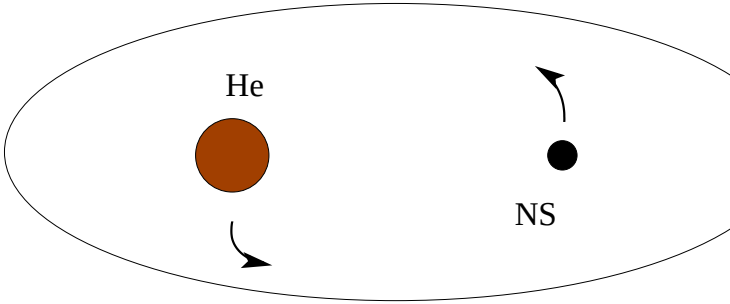
(iii) SN-explosion primary



(iv) if systems survives: MS-NS binary, X-ray binary phase

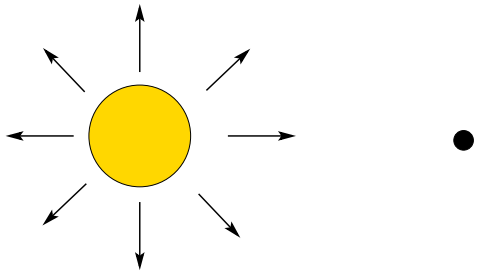


(v) secondary expands, common envelope phase,
NS spirals into secondary



(vi) ejection of common envelope, He-star-NS binary

(vii) SN-explosion secondary



$\Rightarrow$ close DNS

- questions:

  (i) At which rate does the ns accrete ?

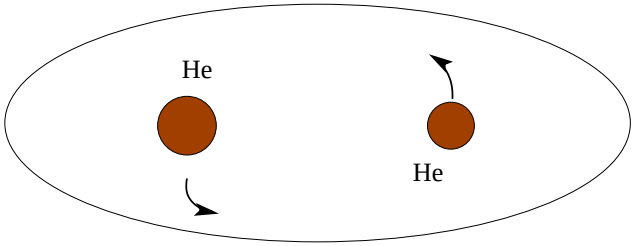
  (ii) How to avoid the accretion of too much mass, i.e. the formation of a NSBH system ?

$\Rightarrow$ this 'standard scenario' may produce NSBHs rather than DNS

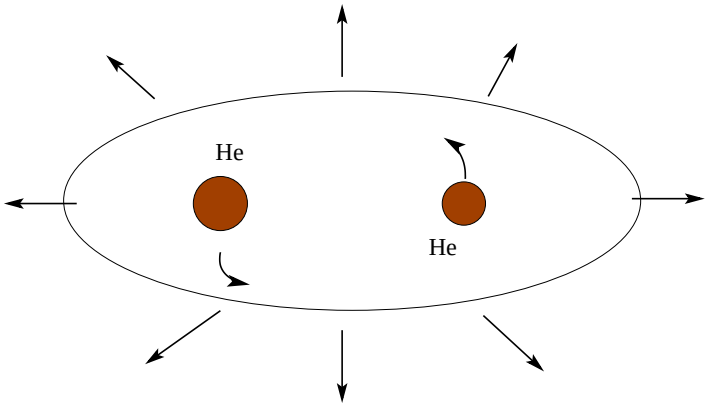
Alternative scenario (Brown 1995)

- initial system: like before, but both masses within 5 %
- evolution:

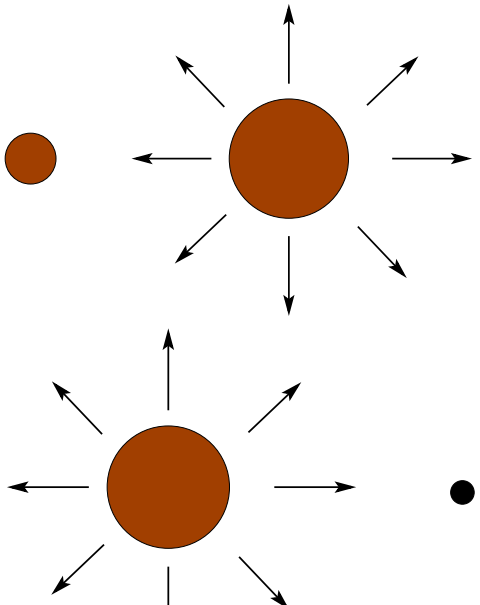
(i) secondary evolves off main sequence BEFORE primary can explode as SN



(ii) ejection of common envelope



(iii) two SN explosions



(iv) if not disrupted: close DNS

- no X-ray binary phase

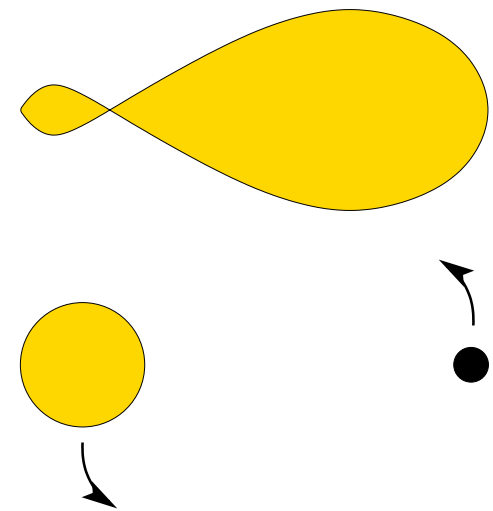
Neutron Star Black Hole Systems (NSBH)

- again: several different paths ...
- see previous 'standard' DNS scenario...

'Standard' NSBH scenario

- initial system: $M_{SN} < M_{secon} < M_{BH} < M_{prim}$
- evolution:

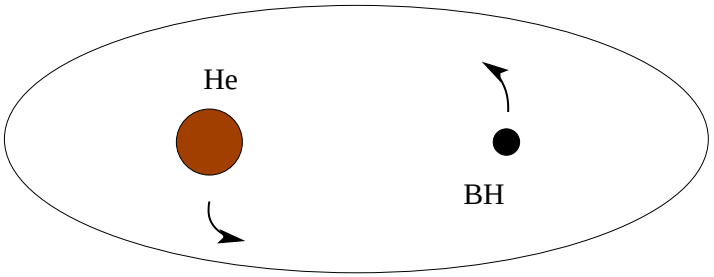
(i) primary evolves, Rochelobe overflow



(ii) primary becomes BH, maybe SN

(iii) X-ray binary phase

(iv) common envelope,
ejection of H mantle



(v) secondary SN explosion $\rightarrow$ NSBH-system

Alternative scenario for low-mass BHs

- evolution:
  - like 'standard' DNS scenario
  - but NS accretes too much in common envelope phase

  $\Rightarrow$ formation of a low-mass BH (~ 3 $M_\odot$) NS system

- particularly interesting for GRBs

Population Synthesis

- need to know/assume/parametrize initial binary conditions:
  - initial mass function
  - fraction of binary systems
  - binary mass ratio distribution
  - distribution of orbital separations
  - initial eccentricities
- need to know/assume/parametrize stellar evolution:
  - He-core mass
  - radii in various phases
  - winds
  - mass transfer
  - common envelope evolution
- Monte Carlo simulations:
  - choose systems from initial distribution
  - evolve them
  - bookkeeping of results $\longrightarrow$ rates etc.

Results from Population Synthesis

- rates (for comparison: Gal. SN-rate ≈ 0.02 year^{-1})
  - DNS:
    - R_{DNS}: $10^{-6} - 10^{-4}$ (year galaxy)$^{-1}$ (pop. synt.)

      $8.3 \cdot 10^{-5}$ (year galaxy)$^{-1}$

      (obs. pulsar sample; Kalogera et al. 2004)
  - NSBH:
    - $R_{\mathrm{NSBH}} \sim 10^{-4}$ (year galaxy)$^{-1}$ (Bethe & Brown 1998)

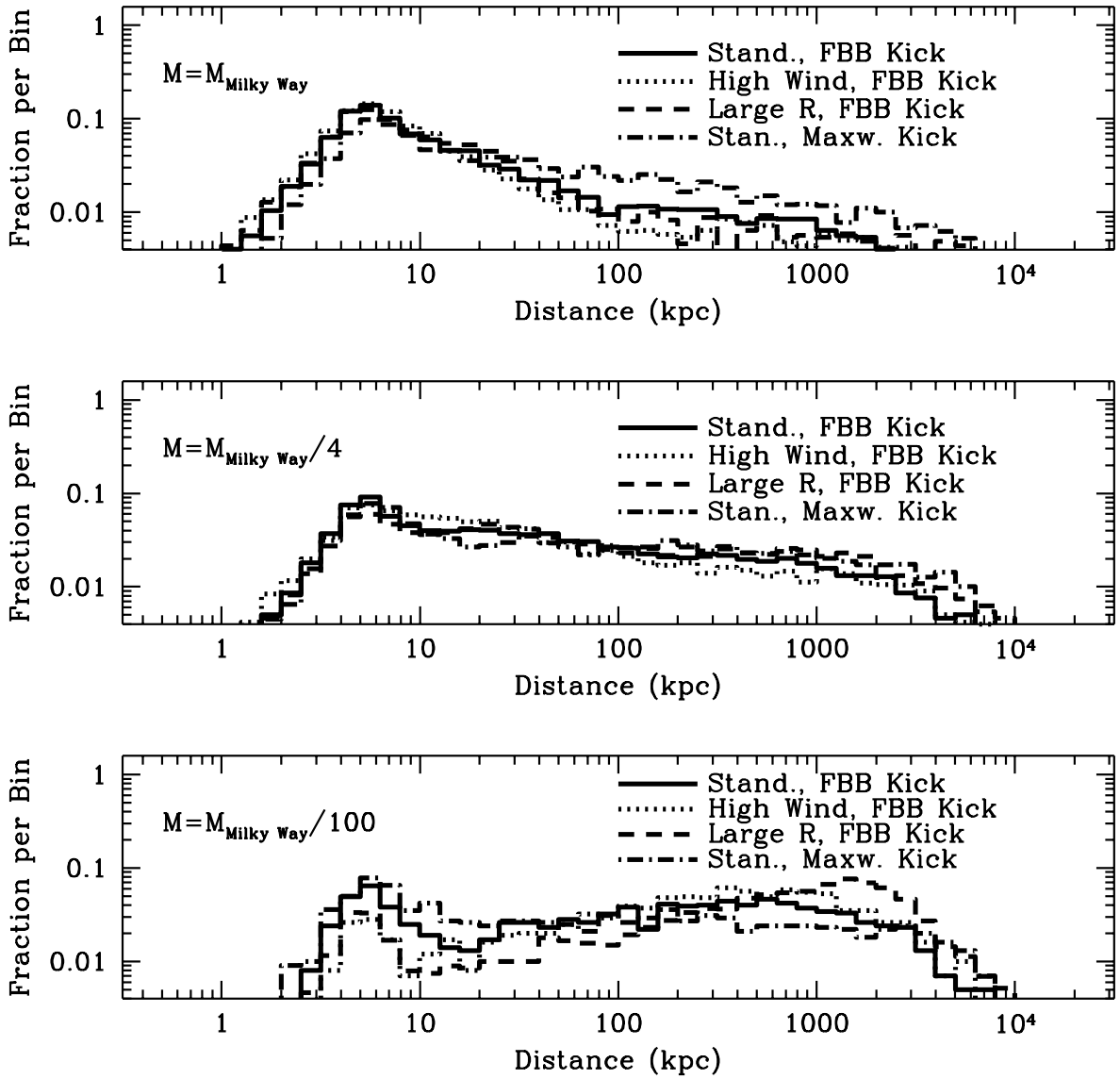
      (so far no observed systems)
- inspiral times and redshifts
  - inspiral times from $\sim 10^6 - 10^9$ years
  - due to inspiral delay: lower median redshifts than collapsars (Fryer et al. 1999)

$$Z_{\mathrm{DNS,NSBH}} \sim 0.5 - 0.8$$

$$Z_{\mathrm{Collapsar}} > 1$$

- Merger sites with respect to galaxies
  - large probability that merger occurs outside galaxy:

    (taken from Fryer et al. 1999)



- Perna& Belzynski (2002): “identification new channel for tight DNS”
  - NSBH-results unchanged
  - DNS dominated by short-lived systems
  - DNS merge practically at birth-place
  - higher ambient matter density
  - DNS at larger redshifts than NSBH
  - ambient matter densities larger for DNS
  - brighter afterglows

II. Orbital evolution with gravitational wave emission

- at birth: highly eccentric (point mass) binary

  $\Rightarrow$ how does the orbit evolve under GW-emission?

- radiation reaction force from potential $\Phi_{\rm GW}^{\rm reac}$

  (slow motion, weak fields):

(1) $$\Phi_{\rm GW}^{\rm reac} = \frac{1}{5}\frac{G}{c^5} I_{jk}^{(5)} x^j x^k$$

where $I_{jk} = \int \rho (x_j x_k - \delta_{jk} r^2) d^3 r$

- radiation reaction force on element of source:

(2) $$dF_i = \Phi_{\rm GW,i}^{\rm reac}\, \rho\, d^3 x$$

- therefore energy loss of the source:

(3) $$\frac{dE}{dt} = -\int \Phi^{\mathrm{reac}}_{\mathrm{GW,i}}\, v^i\, \rho\, d^3x$$

or (Gauß' theorem + continuity equation)

(4) $$\frac{dE}{dt} = -\frac{1}{5}\frac{G}{c^5} I^{(5)}_{jk}\, \dot{I}_{jk}$$

or (average over several orbits, integration by parts)

(5) $$\frac{dE}{dt} = -\frac{1}{5}\frac{G}{c^5} \langle I^{(3)}_{jk}\, I^{(3)}_{jk} \rangle$$

- similar for angular momentum loss:

$$\frac{d\vec{J}}{dt} = \text{rad. reac. torque} = \vec{r} \times d\vec{F} = -\vec{r} \times (\nabla \Phi_{\rm GW}^{\rm reac}) \rho \, d^3x \tag{6}$$

or (average over several orbits, like above)

$$\frac{dJ^i}{dt} = -\frac{2}{5}\frac{G}{c^5}\epsilon^{ijk}\langle I_{jm}^{(2)} I_{km}^{(3)}\rangle \tag{7}$$

- to relate energy/angular momentum to semimajor axis a/eccentricity e use

$$a = \frac{-Gm_1m_2}{2E} \tag{8}$$

and

$$e^2 = 1 + \frac{2EJ^2M}{G^2m_1^3m_2^3} \tag{9}$$

where $M = m_1 + m_2$

- working out the time derivatives of the quadrupole moments yields (average over several orbits):

(10) $$\frac{da}{dt} = -\frac{64\, G^3 m_1 m_2 M}{5\, a^3 c^5} \frac{\left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)}{(1-e^2)^{7/2}}$$

and

(11) $$\frac{de}{dt} = -\frac{304\, G^3 m_1 m_2 M}{15\, a^4 c^5}\, e\, \frac{\left(1 + \frac{121}{304}e^2\right)}{(1-e^2)^{5/2}} \quad < 0$$

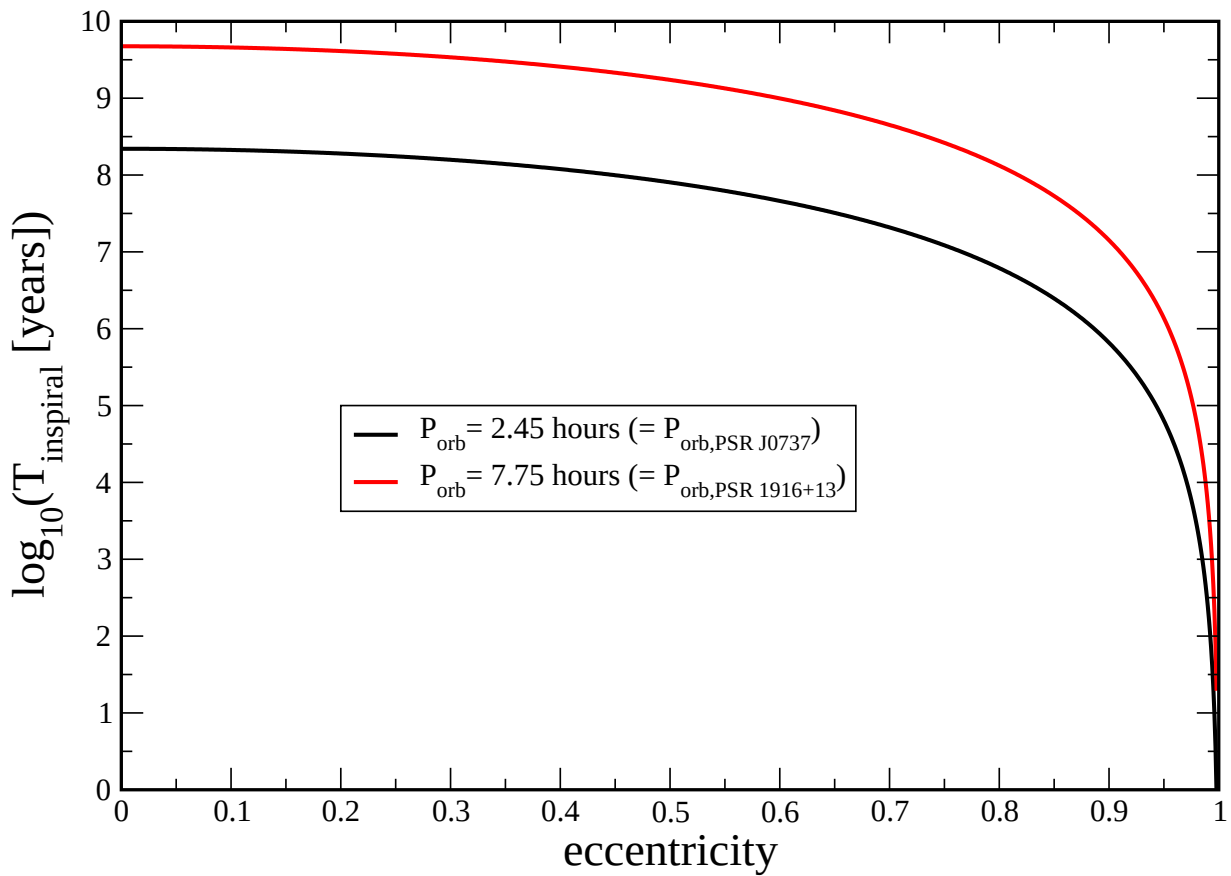
- <u>therefore</u>:
  - results very sensitive to eccentricity
  - eccentricity "radiated away" (GWs carry ang. mom.!)
  - at merger: orbits close to circular

- good approximation to inspiral times by

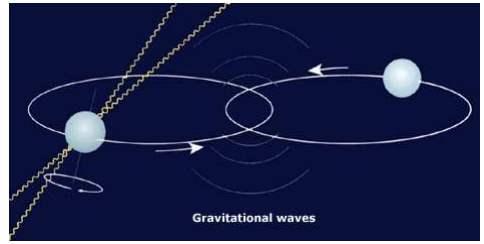
$$T_{\rm inspiral} = 10^7 {\rm yrs} \;\; P_{\rm orb,h}^{8/3} \; \frac{M^{1/3}}{\mu} (1-e^2)^{7/2} \tag{12}$$

$P_{\rm orb,h}$ current orbital period in hours,

M total mass in $M_\odot$, μ reduced mass in $M_\odot$, e current eccentricity



III. Observed Compact Binaries



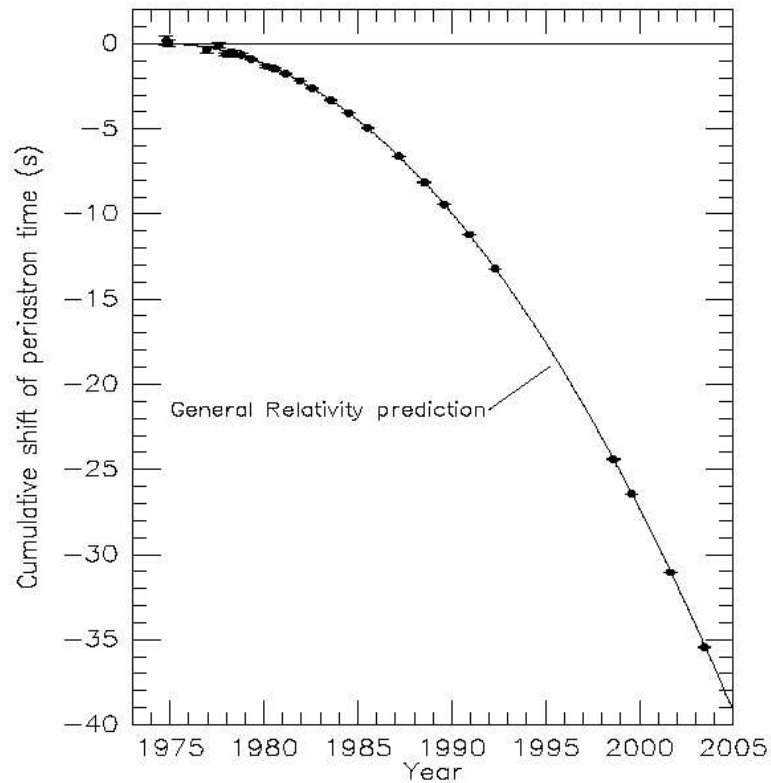
- most precise observation: PSR1913+16 (Hulse & Taylor 1974)
  - ∗ discovered in 1974 by R.Hulse and J.Taylor → NP 1993
  - ∗ masses: 1.442 and 1.386 $M_\odot$ $\pm$ 0.0002 $M_\odot$
  - ∗ orbital period: $\tau_{orb} =$ 7.752 h (v $\sim 10^{-3}c$)
  - ∗ pulsar period: $P_{PSR} = 59$ ms
  - ∗ excentricity: e= 0.617

∗ periastron advance: $\dot{\omega} = 4.227^o y^{-1}$

($\gg (\dot{\omega})_{Mer} = 0.43'' y^{-1}$)

∗ distance: ~ 10 kpc

∗ orbital decay: agreement with GR-prediction: 0.21 % (2004)



∗ inspiral time: $\tau_{insp} = 3 \cdot 10^8$ years !

→ final coalescence !

- most relat. system: PSR J0737-3039A+B (Burgay et al.2003)

  * both are pulsars !
  * masses: 1.337 and 1.250 $M_\odot$ $\pm$ 0.005 $M_\odot$
  * orbital period: $\tau_{orb} =$ 2.4 h
  * pulsar periods: $P_A = 22.7$ ms & $P_B = 2.8$ s
  * excentricity: e= 0.09
  * periastron advance: $\dot{\omega} = 17\ ^o y^{-1}$
  * distance: $\sim 600 - 1000$ pc
  * coalescence: in $8.5 \cdot 10^7$ years

- observed to date:
  - eight DNS
  - no NSBH system
- Binary systems containing radio pulsars which coalesce in less than 10^{10} yr.

PSR	P (ms)	P_b (hr)	e	$M_{\rm tot}$ $M_\odot$	$\tau_{\rm c}$ (Myr)	$\tau_{\rm GW}$ (Myr)	Reference
J0737−3039A	22.70	2.45	0.088	2.58	210	87	Burgay et al. (2003)
J0737−3039B	2773	2.45	0.088	2.58	50	87	Lyne et al. (2004)
B1534+12	37.90	10.10	0.274	2.75	248	2690	Wolszczan (1990)
J1756−2251	28.46	7.67	0.181	2.57	444	1690	Faulkner et al. (2005)
B1913+16	59.03	7.75	0.617	2.83	108	310	Hulse & Taylor (1975)
B2127+11C	30.53	8.04	0.681	2.71	969	220	Anderson et al. (1990)
J1141−6545†	393.90	4.74	0.172	2.30	1.4	590	Kaspi et al. (2000)

IV. Compact binaries as GRB engines

IV.1 Energy reservoirs

- Rotational energy
  - black hole:

$$E_{\rm rot} = M_{\rm BH} c^2 \{1 - \sqrt{\tfrac{1}{2}(1+\sqrt{1-a^2})}\}$$

$a = \frac{Jc}{GM^2}$ BH spin parameter, $0 \leq a \leq 1$

$$E_{\rm rot,max} = M_{\rm BH} c^2 (1 - \sqrt{\tfrac{1}{2}}) = 0.29 M_{\rm BH} c^2$$

$$= 1.6 \cdot 10^{54} \text{ erg} \left(\frac{M_{\rm BH}}{3 {\rm M}_\odot}\right)$$

  - central neutron star:

    depends on details of physics and evolution

    (NS-spins, EOS, magn. fields etc.)

- Accretion:

$$E_{\rm acc} = \epsilon M_{\rm disk} c^2$$

$$= 1.8 \cdot 10^{52} \text{ erg} \left(\frac{\epsilon}{0.1}\right) \left(\frac{M_{\rm disk}}{0.1 {\rm M}_\odot}\right)$$

IV.2 Mechanisms to produce relativistic outflow

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(i) Neutrino annihilation: $\nu_i + \bar{\nu}_i \longrightarrow e^- + e^+$

(Jaroszynki 1993, Mochkovitch et al. 1993, Ruffert et al. 1997, Popham et al. 1999, Asano & Fukuyama 2000, Salmonson & Wilson 2001, Rosswog & Ramirez-Ruiz 2002, Rosswog et al. 2003 ...)

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(ii) Magnetic mechanisms

- Blandford-Znajek
- 'Superpulsars'
- magnetic disk flares
- ...

(Narayan et al. 1992, Thompson & Duncan 1993, Usov 1992,1994, Meszaros & Rees 1997, Katz 1997....)

IV.3 Model ingredients

(i) Hydrodynamics:
3D Lagrangian particle scheme (SPH),
fully parallelized (Rosswog & Davies 2002)

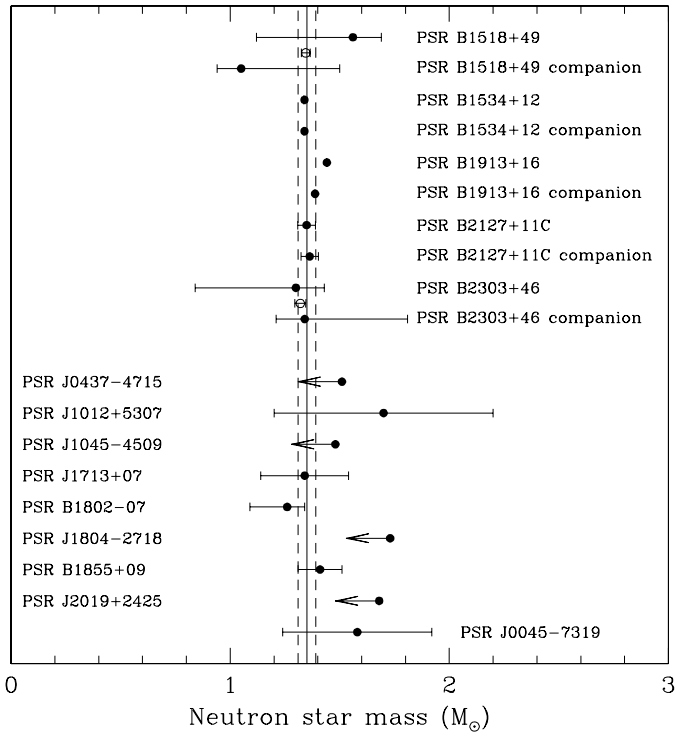
(ii) Gravity:
Newtonian self-gravity (e.g. Benz 1990) +
gravitational wave backreaction forces
(quadrupole approximation; for details
Rosswog et al. 2002)

(iii) Nuclear physics:
temp. and compos. dependent, nuclear EOS
(Relativistic Mean Field theory; Shen et al.
1998a,b)

(iv) Neutrino physics:
multi-flavour neutrino leakage scheme
(Rosswog & Liebendörfer 2003)

IV.5 Double Neutron Star Binaries

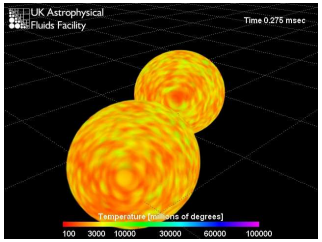
- which masses?



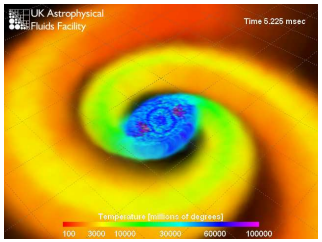
$\longrightarrow$ around 1.4 $M_\odot$

- which spins? $\longrightarrow$ no spins

- 2 x 1.4 $M_\odot$

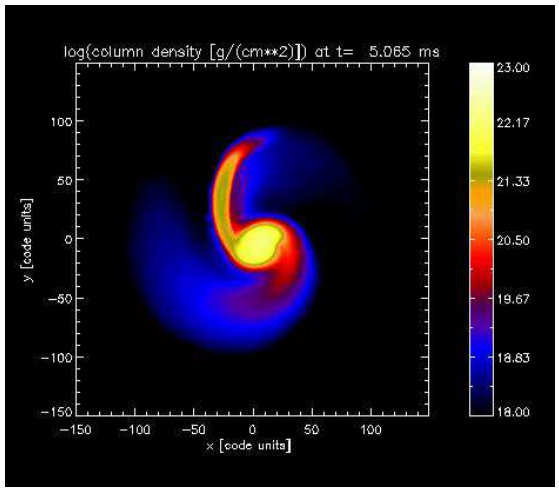


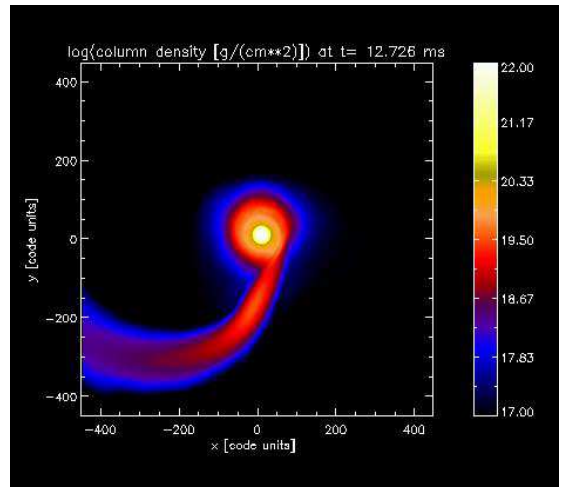
surface temperature



cut through orbital plane

- 1.2 & 1.6 $M_\odot$

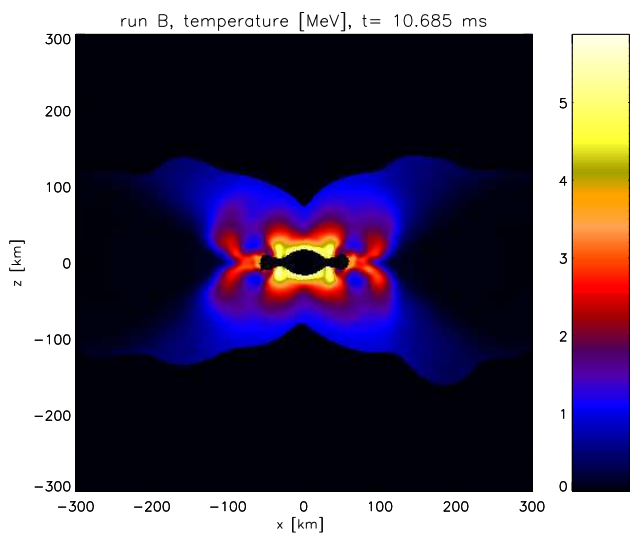


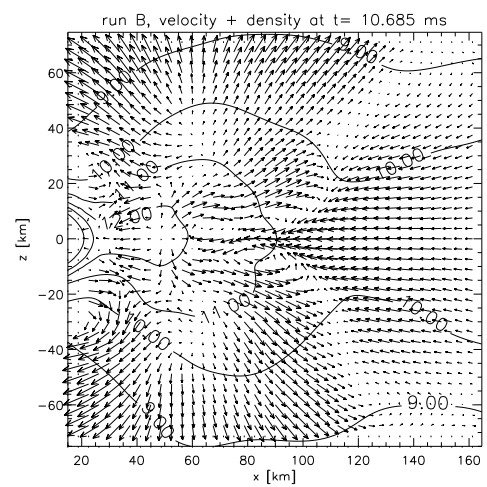


Remnant Properties

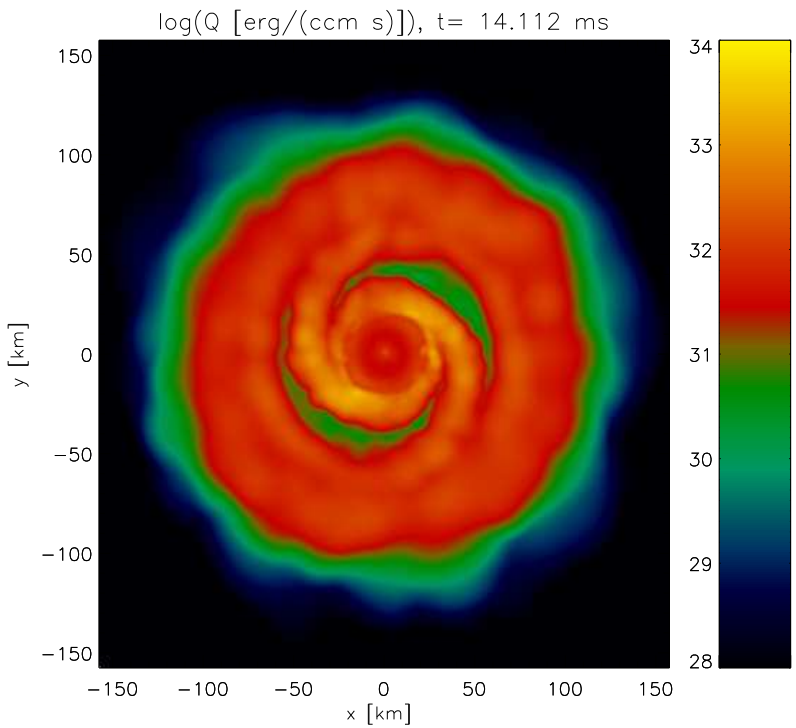
	central object	debris disk
masses	$\sim 2.5\ M_\odot$	$\sim 0.2\ M_\odot$
densities	$\sim 3 \cdot 10^{14}$ gcm^{-3}	$\sim 10^{12}$ gcm^{-3}
($\rho_{\rm nuc} \approx 2.6 \cdot 10^{14}$ gcm^{-3})		
temperatures	~ 15 MeV	~ 3 MeV
(1MeV $\approx 10^{10}$ K)		

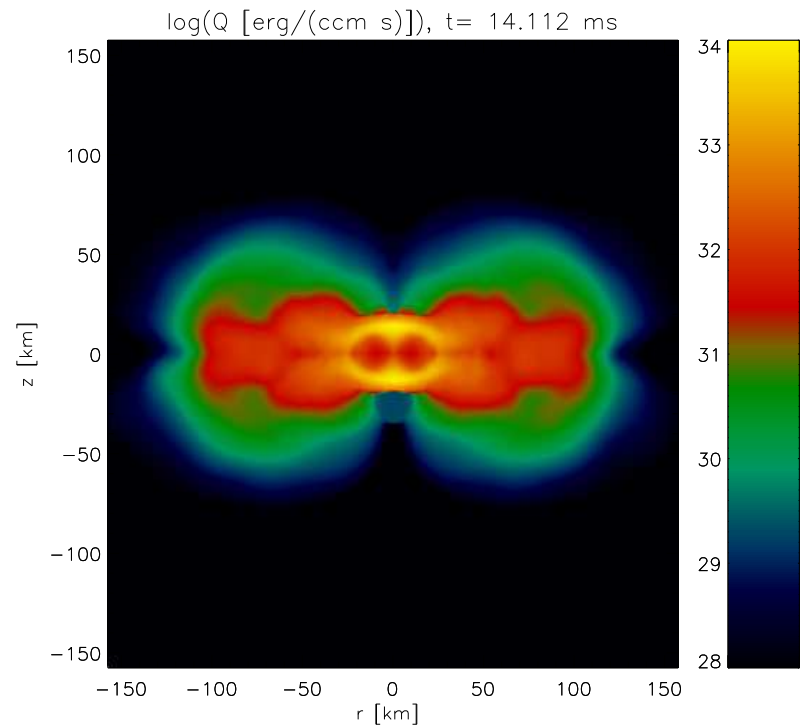
Vertical remnant structure





∗ Neutrino Emission (Rosswog & Liebendoerfer 03)





total neutrino luminosity: $L_\nu^{tot} \approx 2 \cdot 10^{53} \frac{\mathrm{erg}}{\mathrm{s}}$

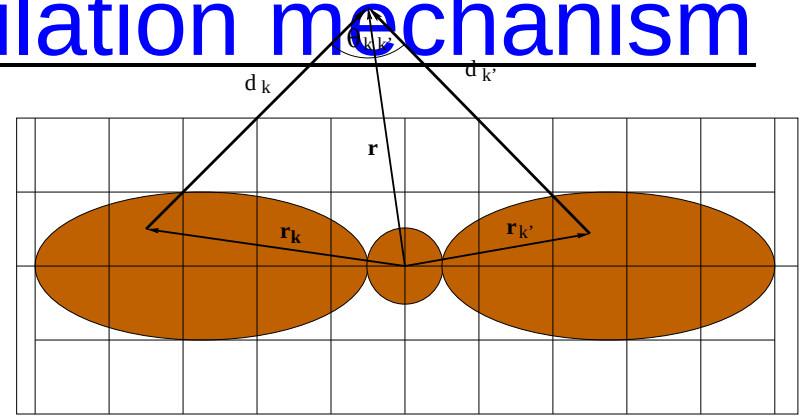
average energies: $E_{\nu_e} \approx 8$ MeV

$E_{\bar{\nu}_e} \approx 15$ MeV

$E_{\nu_x} \approx 22$ MeV

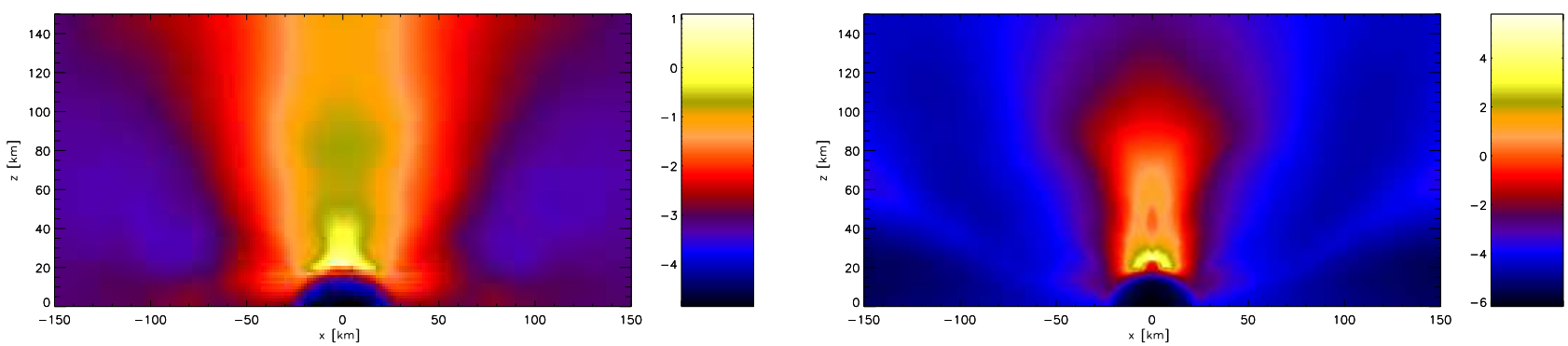
The neutrino annihilation mechanism

- schematic:



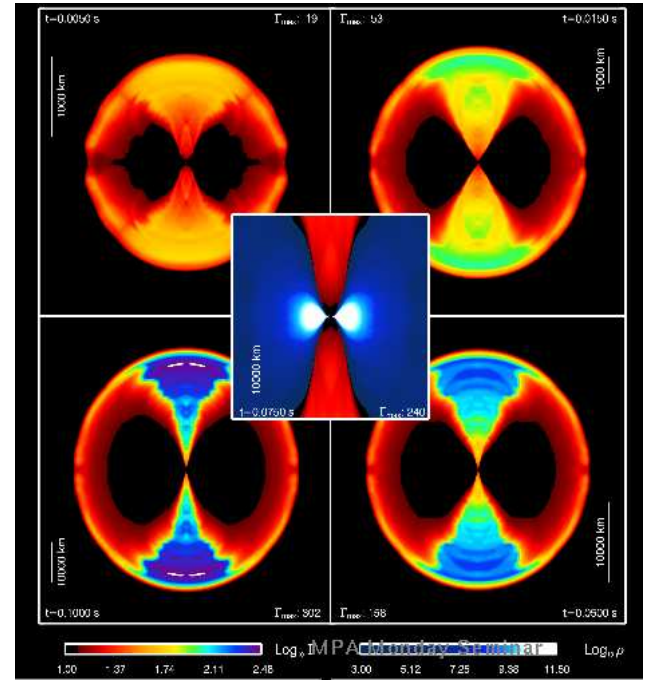
- dynamics of fireball determined by: $\eta \equiv \frac{\text{energy}}{\text{restmass}}$
  - start from radius R_0 with energy E_0 and rest mass M
  - expansion up to $R_\eta = \eta R_0$ while transforming $E_{\rm int}$ into $E_{\rm kin}$
  - Γ grows up to $\sim \eta$ at R_η
  - coasting with constant Γ for $R > R_\eta$

- two examples (post-processing of hydro-simulations; color-coded: $\log(\eta)$):



- peak values of $\Gamma_{\rm asymp} \approx 15 - 10^4$

- recent work of Aloy et al. (2005)



  - (non-self-gravitating) disks from hydrodynamic simulations or constructed from scratch
  - rel. hydrodynamics in Schwarzschild metrik
  - parametrized prescription for heating by $\nu\bar{\nu}$-annihilation
  - hydrodynamic evolution of the disk under influence of the heating

$\Rightarrow$

interaction between jet and baryonic (disk) material can in some cases produce relativistic outflow collimated into a few degrees (purely hydrodynamic collimation)

(good agreement with semi-analytic estimates of Rosswog & Ramirez-Ruiz 2003)

IV.6 Neutron Star Black Hole Binaries

- supposed to yield "standard GRB central engine": BH + massive torus

- complex accretion dynamics (sensitive to EOS !)

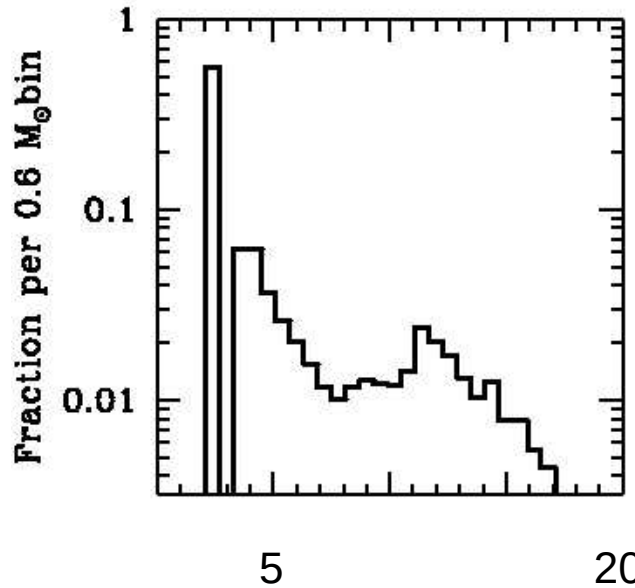
determined by

  - Mass transfer $\Rightarrow$ increase orbital separation
  - GW emission $\Rightarrow$ reduce orbital separation
  - Reaction of NS to mass loss:

$\frac{dR_{ns}}{dM} > 0 \Rightarrow$ "ns expands" $\Rightarrow$ increase mass transfer
$\frac{dR_{ns}}{dM} < 0 \Rightarrow$ "ns shrinks" $\Rightarrow$ decrease mass transfer

- Which black hole masses are interesting for GRBs?

from population synthesis:



(Fryer et al. 1999)

- star will be disrupted at:

$$R_{\rm tid} \approx \left(\frac{M_{\rm BH}}{M_{\rm NS}}\right)^{1/3} \cdot R_{\rm NS} \quad \propto M_{\rm BH}^{1/3}$$

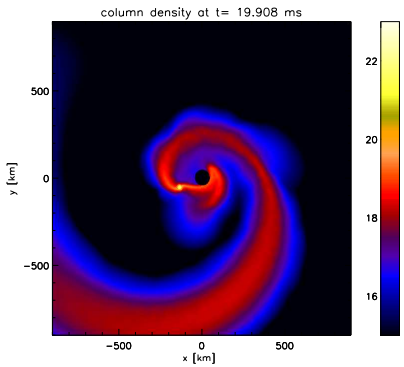
- innermost stable circular orbit (Schwarzschild BH):

$$R_{\rm ISCO} = \frac{6GM_{\rm BH}}{c^2} \quad \propto M_{\rm BH}$$

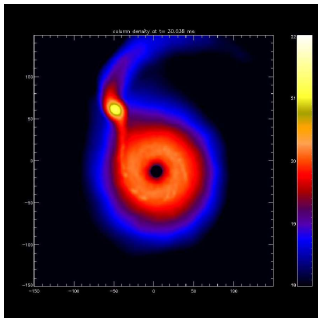
$\Rightarrow$ low-mass BHs have to best chances to disrupt NS *outside* $R_{\rm ISCO}$

Low-mass black holes (< 10 M$_\odot$)

- technically most challenging:
  fixed metric not a good approximation, full GR needed
- purely Newtonian calculations:



column density, $M_{\rm bh} = 14$ M$_\odot$, $M_{\rm ns} = 1.4$ M$_\odot$corotation,



column density, corotation, $M_{\rm bh} = 1.5$ M$_\odot$, $M_{\rm ns} = 1.4$ M$_\odot$

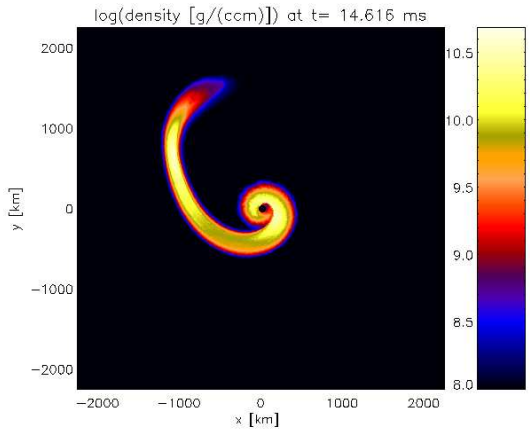
Mimicking GR: The Paczynski-Wiita Potential

- $\Phi_N = \frac{M_{\rm BH}}{r} \quad \longrightarrow \quad \Phi_{\rm PW} = \frac{M_{\rm BH}}{r - R_s}$ with $R_s = 2M$ (G=c=1)
  - exact innerm. stable circular orbit at $R_{\rm ISCO} = 6M_{\rm BH}$
  - exact marginally bound orbit at $R_{\rm mb} = 4M_{\rm BH}$
  - local accretion disk heating rate to better than 10 %
  - ... (see Artemova et al. 1996 for detailed comparison with GR-results)

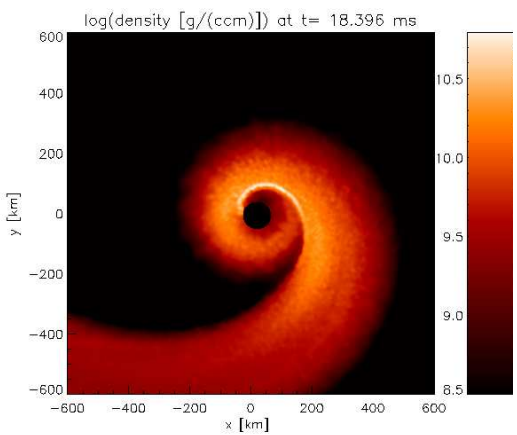
$\longrightarrow$ astonishingly good approximation to GR!

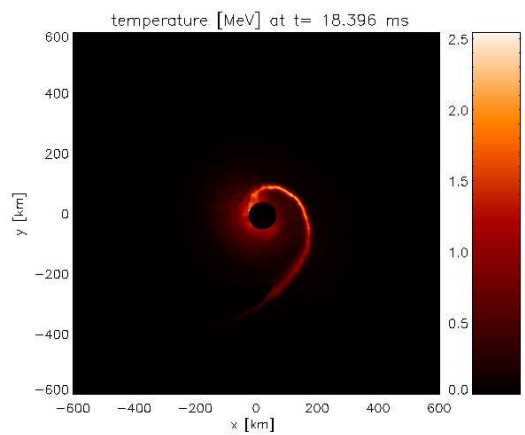
High-mass black holes ($> 10\ M_\odot$)

- $M_{BH} = 14\ M_\odot$, $M_{NS} = 1.4\ M_\odot$



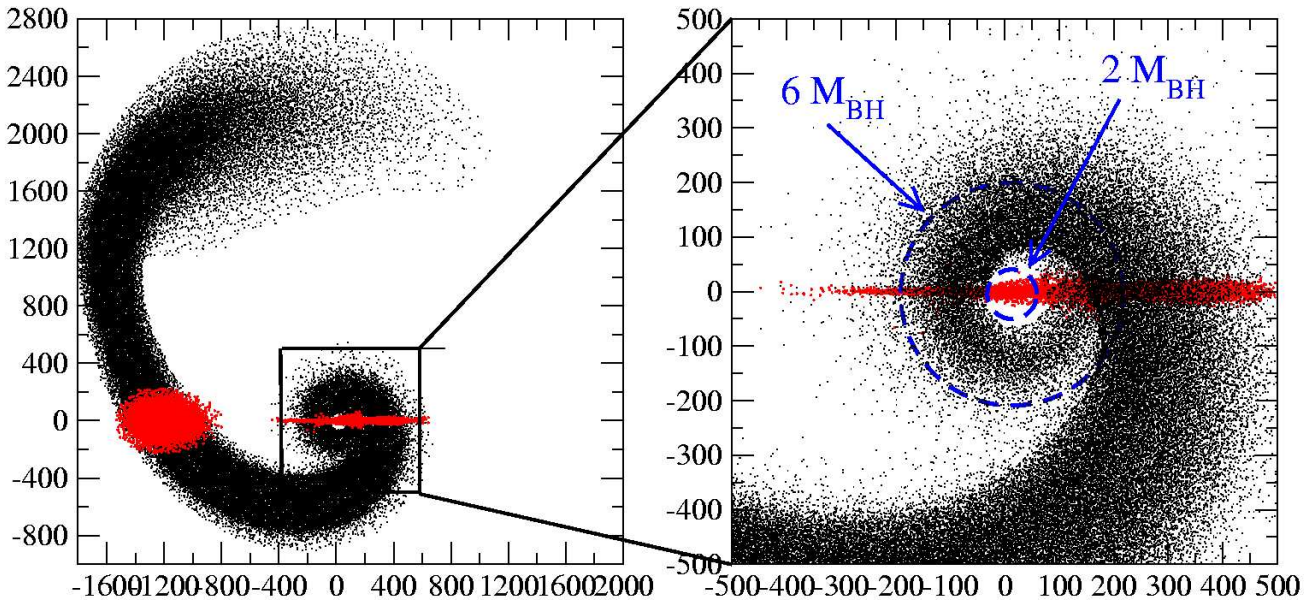
column density





$\rightarrow$ relatively cold and low density

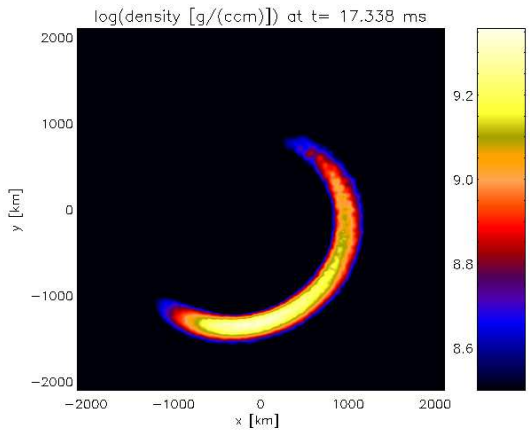
- still $M_{BH} = 14\ M_\odot$, $M_{NS} = 1.4\ M_\odot$:
  SPH-particle distribution:



→ disk thin, largely inside R_{ISCO}

→ GRB improbable

- $M_{BH} = 18\ M_\odot$, $M_{NS} = 1.4\ M_\odot$

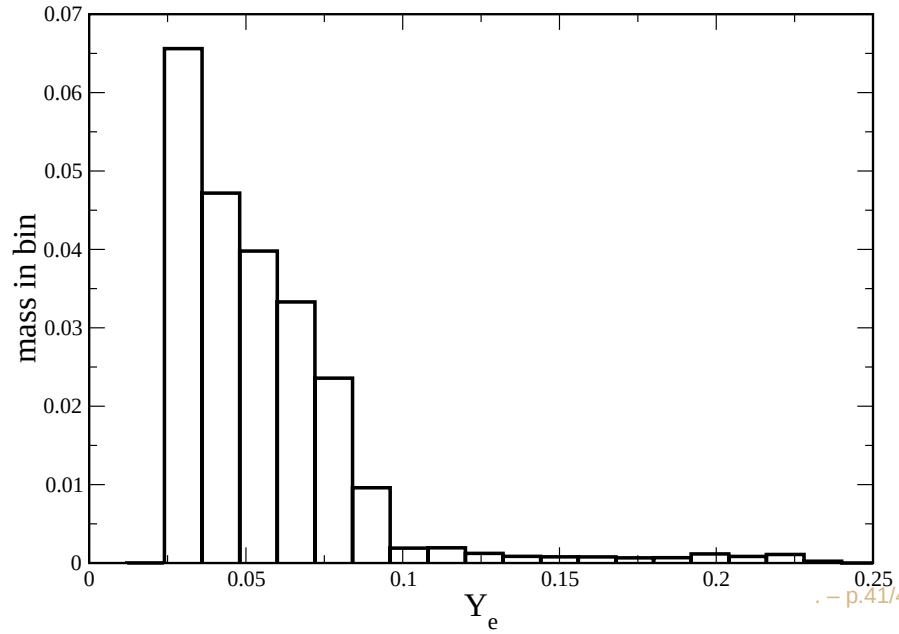


column density

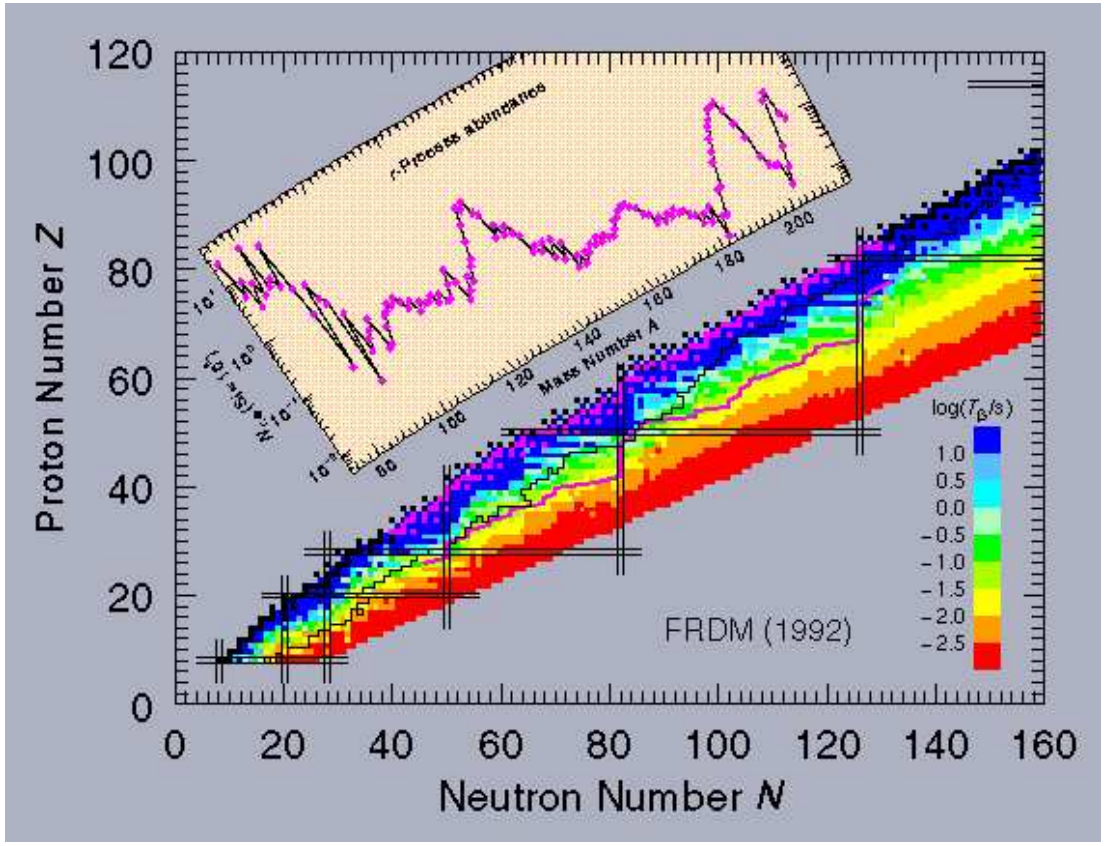
→ GRB impossible

IV.7 Optical transients from radioactive decays

- *dynamic* ejection of material (in addition: ν-driven wind)
  - DNS: Newtonian calc.: ≈ 0.01 $M_\odot$,
    in reality: probably less
  - NSBH: PW-potential: from ≈ 0.01 $M_\odot$ up to 0.2 $M_\odot$(!)
- lots of energy:
  - kinetic: up to $3 \cdot 10^{52}$ erg
  - nuclear: up to $3 \cdot 10^{51}$ er
- exotic material:
  extremely neutron rich !



- possibly “Mini-supernova” (Li& Paczynski 1999)
- but:
  - model very simple
  - relies of radioactive material still decaying when ejecta become optically thin!
- reaction paths close to n-dripline



Summary

Neutron star mergers:

- neutrino luminosity similar to SNII, but $\bar{\nu}_e$ dominate
- ν-annihilation + interaction with slow baryonic material (disk/wind) produces well-collimated ($\theta \sim 5^o - 10^o$), relativistic outflow ($\Gamma > 100$)
  - GRB probable !
  - broad luminosity distribution around $L_{\rm iso} = {\rm few} \cdot 10^{50}$ ergs/s (Rosswog & Ramirez-Ruiz 2003)
  - true luminosity substantially lower
- in addition magnetic mechanisms may be at work
  $\Rightarrow$ broad range of events expected!

Neutron star black hole mergers:

- complex accretion dynamics
- dynamics sensitive to EOS
- good fraction ($M_{BH} > 14\ M_\odot$) will NOT produce energetic GRBs
  $\Rightarrow$ low-luminosity tail of GRB distribution
- favorable for a GRB:
  - low BH mass
  - large BH spins