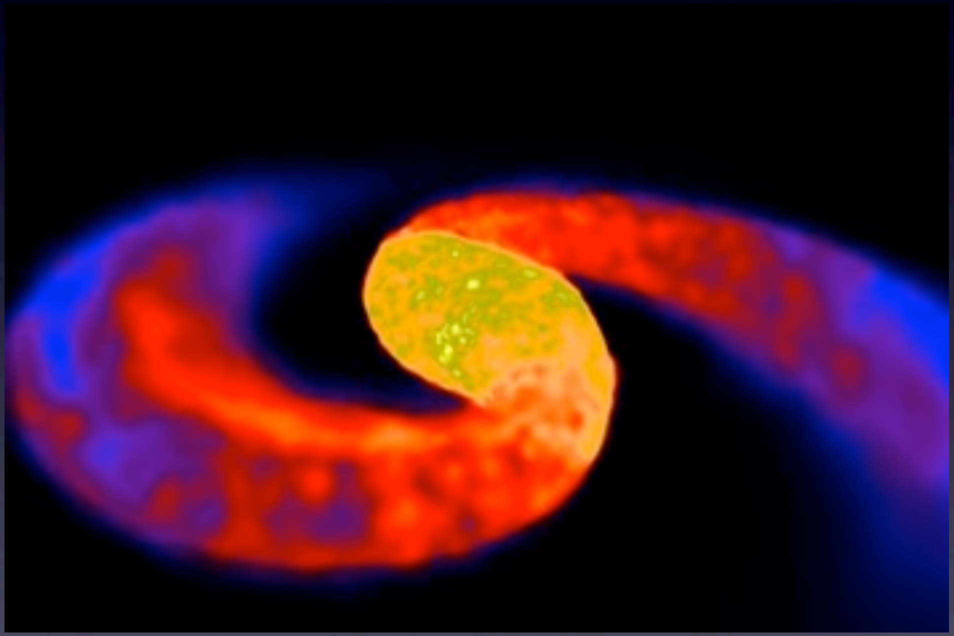
Heidelberg, July 20, 2010

The status of

Compact Binary Mergers



(Price & Rosswog (2006))

Stephan Rosswog
Jacobs University Bremen

I. Introduction

I.1 Observed systems

Double neutron star systems (DNS)

(“certain + likely”, Lorimer (2008)
“likely= mass function + periastron advance consistent with being a neutron star”)

I. Introduction

1.1 Observed systems

Double neutron star systems (DNS)

10

("certain + likely", Lorimer (2008)
"likely= mass function + periastron advance consistent with being a neutron star")

I. Introduction

I.1 Observed systems

Double neutron star systems (DNS)

10

("certain + likely", Lorimer (2008)
"likely= mass function + periastron advance consistent with
being a neutron star")

Neutron star black hole systems (NSBH)

I. Introduction

I.1 Observed systems

Double neutron star systems (DNS) 10

("certain + likely", Lorimer (2008)
"likely= mass function + periastron advance consistent with being a neutron star")

Neutron star black hole systems (NSBH) 0

I. Introduction

I.1 Observed systems

Double neutron star systems (DNS) 10

("certain + likely", Lorimer (2008)
"likely= mass function + periastron advance consistent with being a neutron star")

Neutron star black hole systems (NSBH) 0

Expected galactic merger rates DNS:

I. Introduction

I.1 Observed systems

Double neutron star systems (DNS) 10

("certain + likely", Lorimer (2008)
"likely= mass function + periastron advance consistent with being a neutron star")

Neutron star black hole systems (NSBH) 0

Expected galactic merger rates DNS:

i) from observed systems $\approx 1.2 \times 10^{-4}\ \mathrm{yr}^{-1}$ (Kim 2007)

ii) from population synthesis: similar

I. Introduction

I.1 Observed systems

Double neutron star systems (DNS) 10

("certain + likely", Lorimer (2008)
"likely= mass function + periastron advance consistent with being a neutron star")

Neutron star black hole systems (NSBH) 0

<u>Expected galactic merger rates DNS:</u>

i) from observed systems $\approx 1.2 \times 10^{-4}\ \mathrm{yr}^{-1}$ (Kim 2007)

ii) from population synthesis: similar

BUT: uncertainties are large

I. Introduction

I.1 Observed systems

Double neutron star systems (DNS) 10

("certain + likely", Lorimer (2008)
"likely= mass function + periastron advance consistent with being a neutron star")

Neutron star black hole systems (NSBH) 0

<u>Expected galactic merger rates DNS:</u>

i) from observed systems $\approx 1.2 \times 10^{-4}\ \mathrm{yr}^{-1}$ (Kim 2007)

ii) from population synthesis: similar

BUT: uncertainties are large

for i): dependence of inspiral time on eccentricity

$$\tau_{\mathrm{GW}} \approx 9.8 \times 10^{6}\ \mathrm{yr} \left(\frac{P_b}{\mathrm{hr}}\right)^{8/3} \left(\frac{m_1 + m_2}{M_\odot}\right)^{-2/3} \left(\frac{\mu}{M_\odot}\right)^{-1} (1 - e^2)^{7/2}$$

i.e. highly eccentric system would escape observation,

rate could be larger by factor of a few (Chaurasia & Bailes 2005)

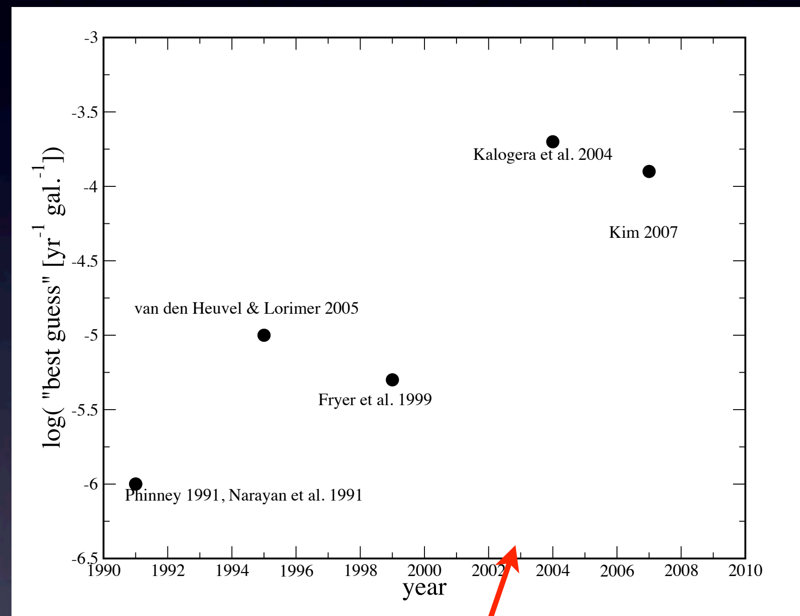
i.e. highly eccentric system would escape observation,
rate could be larger by factor of a few (Chaurasia & Bailes 2005)

for ii) sensitive to poorly known parameters
(common envelope efficiency, initial separations etc)

i.e. highly eccentric system would escape observation,
rate could be larger by factor of a few (Chaurasia & Bailes 2005)

for ii) sensitive to poorly known parameters
(common envelope efficiency, initial separations etc)

evolution merger rate estimates (incomplete)



"best guesses"

discovery of double pulsar PSR J0737-3039

Letters to Nature

Nature **426**, 531-533 (4 December 2003) | doi:10.1038/nature02124; Received 12 August 2003; Accepted 15 October 2003

An increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system

M. Burgay[1], N. D'Amico[2,3], A. Possenti[3,4], R. N. Manchester[5], A. G. Lyne[6], B. C. Joshi[6,7], M. A. McLaughlin[6], M. Kramer[6], J. M. Sarkissian[5], F. Camilo[8], V. Kalogera[9], C. Kim[9] & D. R. Lorimer[6]

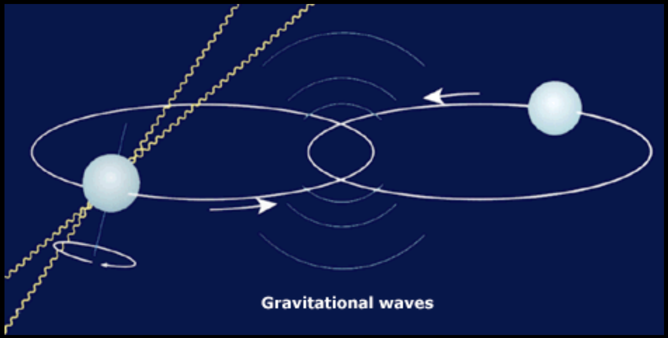
NSBH merger rate:

Bethe & Brown (1998): “ten times DNS rate”

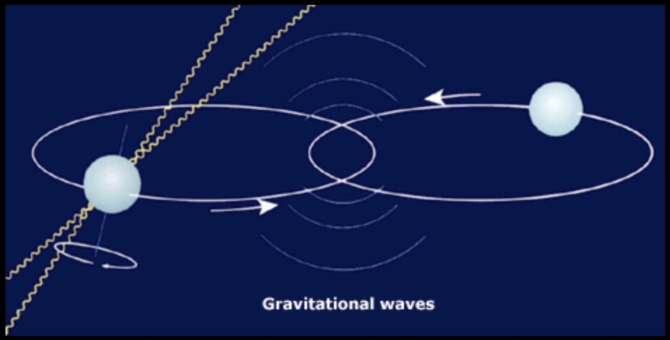
Belcynsky et al. (2007): “0.01 times DNS rate”

→ not accurately known

1.2 Relevance Compact Binary Mergers

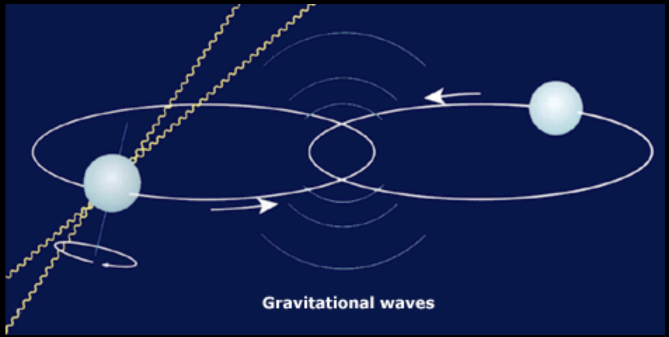


1.2 Relevance Compact Binary Mergers



- We know 10 such DNS systems to date

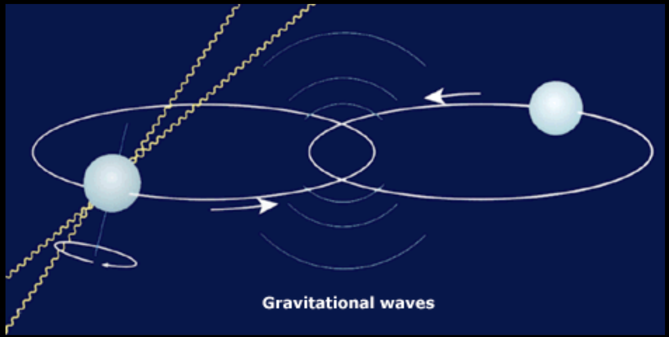
1.2 Relevance Compact Binary Mergers



- We know 10 such DNS systems to date

- Orbital motion of binary pulsar PSR 1913+16 showed first proof for existence of gravitational waves

1.2 Relevance Compact Binary Mergers

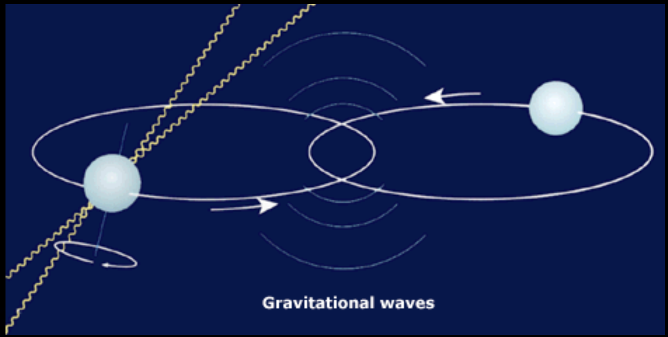


- We know 10 such DNS systems to date

- Orbital motion of binary pulsar PSR 1913+16 showed first proof for existence of gravitational waves

- Measurement of (at least two) relativistic effects allows determination of *individual* neutron star masses

1.2 Relevance Compact Binary Mergers



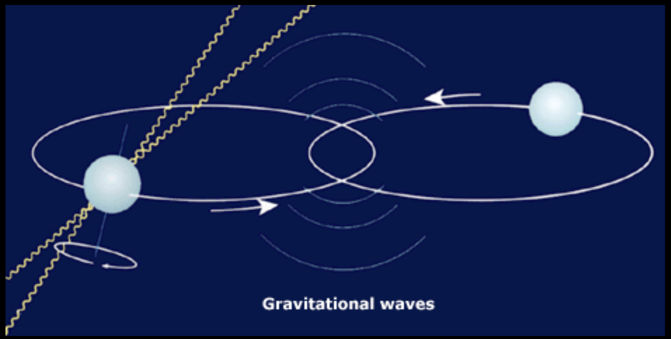
- We know 10 such DNS systems to date

- Orbital motion of binary pulsar PSR 1913+16 showed first proof for existence of gravitational waves

- Measurement of (at least two) relativistic effects allows determination of *individual* neutron star masses

- Tests of strong-field gravity: GR vs. alternative theories

1.2 Relevance Compact Binary Mergers



- We know 10 such DNS systems to date

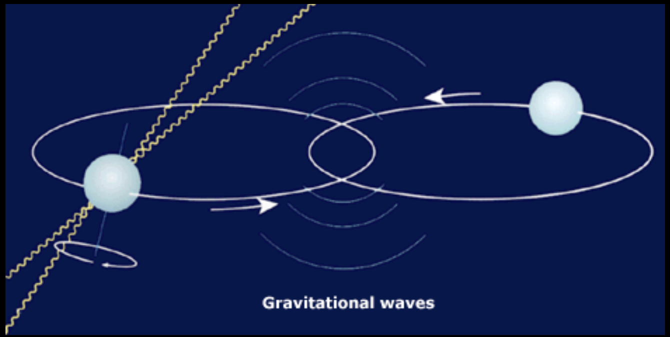
- Orbital motion of binary pulsar PSR 1913+16 showed first proof for existence of gravitational waves

- Measurement of (at least two) relativistic effects allows determination of *individual* neutron star masses

- Tests of strong-field gravity: GR vs. alternative theories

- Prime candidate for ground-based gravitational wave detection (LIGO, GEO600,...)

1.2 Relevance Compact Binary Mergers



- We know 10 such DNS systems to date

- Orbital motion of binary pulsar PSR 1913+16 showed first proof for existence of gravitational waves

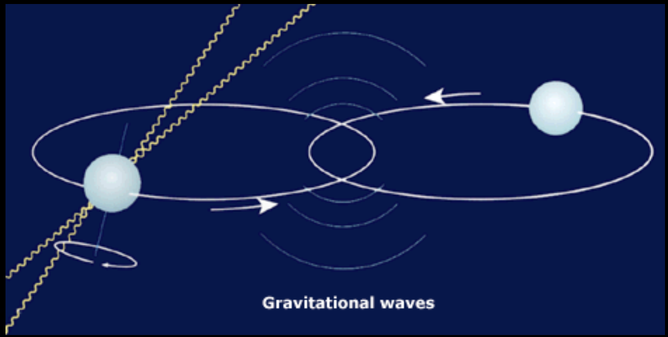
- Measurement of (at least two) relativistic effects allows determination of *individual* neutron star masses

- Tests of strong-field gravity: GR vs. alternative theories

- Prime candidate for ground-based gravitational wave detection (LIGO, GEO600,...)

- Nucleosynthesis:

1.2 Relevance Compact Binary Mergers



- We know 10 such DNS systems to date

- Orbital motion of binary pulsar PSR 1913+16 showed first proof for existence of gravitational waves

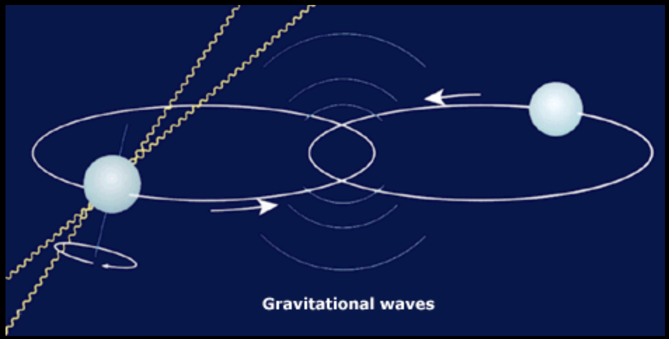
- Measurement of (at least two) relativistic effects allows determination of *individual* neutron star masses

- Tests of strong-field gravity: GR vs. alternative theories

- Prime candidate for ground-based gravitational wave detection (LIGO, GEO600,...)

- Nucleosynthesis:
    1. dynamical ejecta (cold decompression)

1.2 Relevance Compact Binary Mergers



- We know 10 such DNS systems to date

- Orbital motion of binary pulsar PSR 1913+16 showed first proof for existence of gravitational waves

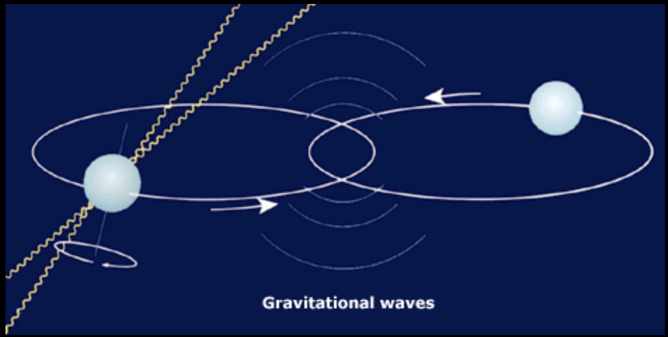
- Measurement of (at least two) relativistic effects allows determination of *individual* neutron star masses

- Tests of strong-field gravity: GR vs. alternative theories

- Prime candidate for ground-based gravitational wave detection (LIGO, GEO600,...)

- Nucleosynthesis:
    1. dynamical ejecta (cold decompression)
    2. neutrino-driven winds (accretion disks, central object remnant)

1.2 Relevance Compact Binary Mergers



- We know 10 such DNS systems to date

- Orbital motion of binary pulsar PSR 1913+16 showed first proof for existence of gravitational waves

- Measurement of (at least two) relativistic effects allows determination of *individual* neutron star masses

- Tests of strong-field gravity: GR vs. alternative theories

- Prime candidate for ground-based gravitational wave detection (LIGO, GEO600,...)

- Nucleosynthesis:
    1. dynamical ejecta (cold decompression)
    2. neutrino-driven winds (accretion disks, central object remnant)

- Prime candidate for central engine of (short) Gamma-ray bursts

1.3 What are the challenges?

a) physics

important for

1.3 What are the challenges?

a) physics   important for

- (strong) gravity

1.3 What are the challenges?

a) physics

important for

- (strong) gravity

$$\zeta = \frac{GM}{cR} \begin{cases} \sim 0.5 \text{ bh} \\ \sim 0.3 \text{ ns} \\ \sim 10^{-6} \text{ Sun} \end{cases}$$

1.3 What are the challenges?

a) physics

important for

- (strong) gravity

$$\zeta = \frac{GM}{cR} \begin{cases} \sim 0.5 \text{ bh} \\ \sim 0.3 \text{ ns} \\ \sim 10^{-6} \text{ Sun} \end{cases}$$

- structure of neutron star
- peak in GW inspiral freq.
- collapse to BH

1.3 What are the challenges?

a) physics

important for

- (strong) gravity

$$\zeta = \frac{GM}{cR}\begin{cases} \sim 0.5 \ \mathrm{bh} \\ \sim 0.3 \ \mathrm{ns} \\ \sim 10^{-6} \ \mathrm{Sun} \end{cases}$$

- structure of neutron star
- peak in GW inspiral freq.
- collapse to BH

- strong interaction/nuclear physics

1.3 What are the challenges?

a) physics | important for

- (strong) gravity

$$\zeta = \frac{GM}{cR}\begin{cases} \sim 0.5 \text{ bh} \\ \sim 0.3 \text{ ns} \\ \sim 10^{-6} \text{ Sun} \end{cases}$$

- structure of neutron star
- peak in GW inspiral freq.
- collapse to BH

- strong interaction/nuclear physics

- supra-nuclear EOS
- nuclei inner disk regions
- ...

1.3 What are the challenges?

a) physics | important for

- (strong) gravity

$$\zeta = \frac{GM}{cR}\begin{cases} \sim 0.5 \text{ bh} \\ \sim 0.3 \text{ ns} \\ \sim 10^{-6} \text{ Sun} \end{cases}$$

- structure of neutron star
- peak in GW inspiral freq.
- collapse to BH

- strong interaction/nuclear physics

- supra-nuclear EOS
- nuclei inner disk regions
- ...

- weak interactions/neutrinos

1.3 What are the challenges?

a) physics | important for

- (strong) gravity

$$\zeta = \frac{GM}{cR} \begin{cases} \sim 0.5 \text{ bh} \\ \sim 0.3 \text{ ns} \\ \sim 10^{-6} \text{ Sun} \end{cases}$$

- structure of neutron star
- peak in GW inspiral freq.
- collapse to BH

- strong interaction/nuclear physics

- supra-nuclear EOS
- nuclei inner disk regions
- ...

- weak interactions/neutrinos

- ν-cooling
- electron fraction
- ν-driven winds
- nucleosynthesis

- magnetic fields

- magnetic fields

- additional pressure
- stability central object against collapse
- transport of angular momentum

- magnetic fields

  - additional pressure
  - stability central object against collapse
  - transport of angular momentum

- hydrodynamics

- magnetic fields

  - additional pressure
  - stability central object against collapse
  - transport of angular momentum

- hydrodynamics

  - fluid instabilities/turbulence
  - transport of angular momentum
  - ...

b) Numerics

b) Numerics

- GR initial conditions

b) Numerics

- GR initial conditions

- "garbage in, garbage out"

b) Numerics

- GR initial conditions — "garbage in, garbage out"
- space-time evolution:
  stable and accurate solution of Einstein equations

b) Numerics

- GR initial conditions — "garbage in, garbage out"
- space-time evolution:
  stable and accurate solution of Einstein equations
- very broad range for equation of state

b) Numerics

- GR initial conditions

- "garbage in, garbage out"

- space-time evolution:
  stable and accurate solution of
  Einstein equations

- very broad range for equation of state

- ν-transport in 3D

b) Numerics

- GR initial conditions - "garbage in, garbage out"
- space-time evolution:
  stable and accurate solution of
  Einstein equations
- very broad range for equation of state
- ν-transport in 3D
- resolve relevant (magneto-)
  hydrodynamic length scales

b) Numerics

- GR initial conditions

  - "garbage in, garbage out"

- space-time evolution:
  stable and accurate solution of
  Einstein equations

- very broad range for equation of state

- ν-transport in 3D

- resolve relevant (magneto-)
  hydrodynamic length scales

  - transport angular momentum
  - collapse time scale
  - GRB mechanism ...

b) Numerics

- GR initial conditions

  - "garbage in, garbage out"

- space-time evolution:
  stable and accurate solution of
  Einstein equations

- very broad range for equation of state

- ν-transport in 3D

- resolve relevant (magneto-) hydrodynamic length scales

  - transport angular momentum
  - collapse time scale
  - GRB mechanism ...

- Courant-Friedrichs-Lewi stability criterion

b) Numerics

- GR initial conditions

  - "garbage in, garbage out"

- space-time evolution:
  stable and accurate solution of
  Einstein equations

- very broad range for equation of state

- ν-transport in 3D

- resolve relevant (magneto-) hydrodynamic length scales

  - transport angular momentum
  - collapse time scale
  - GRB mechanism ...

- Courant-Friedrichs-Lewi stability criterion

$$\Delta t < \frac{\Delta x}{c_s} = 10^{-6}\ \mathrm{s} \left(\frac{\Delta x}{1\ km}\right)\left(\frac{0.3\ c}{c_s}\right)$$

- How to ensure numerical conservation of physically conserved quantities ?

- How to ensure numerical conservation of physically conserved quantities ?

  - binary dynamics is VERY sensitive to angular momentum distribution
  - small amounts of mass can pick up large amounts of angular momentum !

- How to ensure numerical conservation of physically conserved quantities ?

- binary dynamics is VERY sensitive to angular momentum distribution
- small amounts of mass can pick up large amounts of angular momentum !

- "numerical vacuum"

- How to ensure numerical conservation of physically conserved quantities ?

  - binary dynamics is VERY sensitive to angular momentum distribution
  - small amounts of mass can pick up large amounts of angular momentum !

- "numerical vacuum"

  - several Eulerian calculations have "vacuum" densities >> WD densities

- How to ensure numerical conservation of physically conserved quantities ?

- binary dynamics is VERY sensitive to angular momentum distribution
- small amounts of mass can pick up large amounts of angular momentum !

- "numerical vacuum"

- several Eulerian calculations have "vacuum" densities >> WD densities

→ compact binary mergers are prime examples of multi-scale and multi-physics problem !!!

II. Current approaches

“Gravity”

II. Current approaches

"Gravity"

- Newtonian gravity

(e.g. Ruffert et al. 1997, Rosswog et al. 2003, Lee et al. 2005 ...)

II. Current approaches

“Gravity”

- Newtonian gravity

(e.g. Ruffert et al. 1997, Rosswog et al. 2003, Lee et al. 2005 ...)

Pros

- efficient, well-tested methods available
- accurate numerical evolution
- ideal to test influence of non-gravitational physics

II. Current approaches

"Gravity"

- Newtonian gravity

(e.g. Ruffert et al. 1997, Rosswog et al. 2003, Lee et al. 2005 ...)

Pros

- efficient, well-tested methods available
- accurate numerical evolution
- ideal to test influence of non-gravitational physics

Cons

- strong-field gravity obviously has non-negligible effects

II. Current approaches

"Gravity"

- Newtonian gravity

(e.g. Ruffert et al. 1997, Rosswog et al. 2003, Lee et al. 2005 ...)

Pros

- efficient, well-tested methods available
- accurate numerical evolution
- ideal to test influence of non-gravitational physics

Cons

- strong-field gravity obviously has non-negligible effects

- Post-Newtonian

(Ayal et al. 2001, Faber et al. 2000)

II. Current approaches

"Gravity"

- Newtonian gravity

(e.g. Ruffert et al. 1997, Rosswog et al. 2003, Lee et al. 2005 ...)

Pros

- efficient, well-tested methods available
- accurate numerical evolution
- ideal to test influence of non-gravitational physics

Cons

- strong-field gravity obviously has non-negligible effects

- Post-Newtonian

(Ayal et al. 2001, Faber et al. 2000)

→ not appropriate for compact binary mergers

- Conformal Flatness Approximation (CFA)

(Isenberg 1978, Wilson & Mathews 1995, Oechslin et al. 2002, Faber et al. 2006,...)

- Conformal Flatness Approximation (CFA)

(Isenberg 1978, Wilson & Mathews 1995, Oechslin et al. 2002, Faber et al. 2006,...)

approach:

- Conformal Flatness Approximation (CFA)

(Isenberg 1978, Wilson & Mathews 1995, Oechslin et al. 2002, Faber et al. 2006,...)

approach:

i) evolve hydrodynamics on given space-time, conservation laws

• Conformal Flatness Approximation (CFA)

(Isenberg 1978, Wilson & Mathews 1995, Oechslin et al. 2002, Faber et al. 2006,...)

approach:

i) evolve hydrodynamics on given space-time, conservation laws

$$\text{baryon number}: \qquad (\rho U^{\mu})_{;\mu} = 0$$

$$\text{energy} - \text{momentum}: T^{\mu\nu}{}_{;\nu} = 0$$

- Conformal Flatness Approximation (CFA)

(Isenberg 1978, Wilson & Mathews 1995, Oechslin et al. 2002, Faber et al. 2006,...)

approach:

i) evolve hydrodynamics on given space-time, conservation laws

$$\mathrm{baryon\ number:} \qquad (\rho U^\mu)_{;\mu} = 0$$

$$\mathrm{energy-momentum:}\ T^{\mu\nu}{}_{;\nu} = 0$$

for an ideal fluid:

- Conformal Flatness Approximation (CFA)

(Isenberg 1978, Wilson & Mathews 1995, Oechslin et al. 2002, Faber et al. 2006,...)

approach:

i) evolve hydrodynamics on given space-time, conservation laws

$$\text{baryon number}: \qquad (\rho U^\mu)_{;\mu} = 0$$

$$\text{energy}-\text{momentum}: T^{\mu\nu}{}_{;\nu} = 0$$

for an ideal fluid: $T^{\mu\nu} = (e+P)U^\mu U^\nu + P g^{\mu\nu}$

- Conformal Flatness Approximation (CFA)

(Isenberg 1978, Wilson & Mathews 1995, Oechslin et al. 2002, Faber et al. 2006,...)

approach:

i) evolve hydrodynamics on given space-time, conservation laws

$$\text{baryon number}: \qquad (\rho U^\mu)_{;\mu} = 0$$

$$\text{energy}-\text{momentum}: T^{\mu\nu}{}_{;\nu} = 0$$

for an ideal fluid: $T^{\mu\nu} = (e + P)U^\mu U^\nu + P g^{\mu\nu}$

energy density in comoving frame

- Conformal Flatness Approximation (CFA)

(Isenberg 1978, Wilson & Mathews 1995, Oechslin et al. 2002, Faber et al. 2006,...)

approach:

i) evolve hydrodynamics on given space-time, conservation laws

$$\text{baryon number}: \qquad (\rho U^\mu)_{;\mu} = 0$$

$$\text{energy} - \text{momentum}: T^{\mu\nu}{}_{;\nu} = 0$$

for an ideal fluid: $$T^{\mu\nu} = (e + P)U^\mu U^\nu + P g^{\mu\nu}$$

energy density in comoving frame

pressure

- Conformal Flatness Approximation (CFA)

(Isenberg 1978, Wilson & Mathews 1995, Oechslin et al. 2002, Faber et al. 2006,...)

approach:

i) evolve hydrodynamics on given space-time, conservation laws

$$\mathrm{baryon\ number:}\qquad (\rho U^\mu)_{;\mu} = 0$$

$$\mathrm{energy-momentum:}\ T^{\mu\nu}{}_{;\nu} = 0$$

for an ideal fluid: $T^{\mu\nu} = (e + P)U^\mu U^\nu + P g^{\mu\nu}$

energy density in comoving frame

pressure

4-velocity $U^\mu = \frac{dx^\mu}{d\tau}$

- Conformal Flatness Approximation (CFA)

(Isenberg 1978, Wilson & Mathews 1995, Oechslin et al. 2002, Faber et al. 2006,...)

approach:

i) evolve hydrodynamics on given space-time, conservation laws

$$\text{baryon number}: \quad (\rho U^\mu)_{;\mu} = 0$$

$$\text{energy} - \text{momentum}: T^{\mu\nu}{}_{;\nu} = 0$$

metric tensor

for an ideal fluid: $T^{\mu\nu} = (e + P) U^\mu U^\nu + P g^{\mu\nu}$

energy density in comoving frame

pressure

4-velocity $U^\mu = \dfrac{dx^\mu}{d\tau}$

ii) update space-time

ii) update space-time

"3+1" foliation of space-time:

$$ds^2 = (-\alpha^2 + \beta_i \beta^i) dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$

ii) update space-time

"3+1" foliation of space-time:

$$ds^2 = (-\alpha^2 + \beta_i \beta^i)dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$

"lapse"

ii) update space-time

"3+1" foliation of space-time:

$$ds^2 = (-\underset{\text{"lapse"}}{\alpha^2} + \underset{\text{"shift"}}{\beta_i\beta^i})dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$

ii) update space-time

"3+1" foliation of space-time:

$$ds^2 = (\underbrace{-\alpha^2}_{\text{"lapse"}} + \underbrace{\beta_i\beta^i}_{\text{"shift"}})dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$

approximate spatial part of metric by:

ii) update space-time

"3+1" foliation of space-time:

$$ds^2 = (-\alpha^2 + \beta_i \beta^i) dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$

"lapse" "shift"

approximate spatial part of metric by:

$$\gamma_{ij} = \Psi^4 \delta_{ij}$$

ii) update space-time

"3+1" foliation of space-time:

$$ds^2 = (-\alpha^2 + \beta_i\beta^i)dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$

"lapse" "shift"

approximate spatial part of metric by:

$$\gamma_{ij} = \Psi^4 \delta_{ij}$$

"conformal factor"

ii) update space-time

"3+1" foliation of space-time:

$$ds^2 = (-\alpha^2 + \beta_i\beta^i)dt^2 + 2\beta_i dx^i dt + \gamma_{ij}dx^i dx^j$$

"lapse" "shift"

approximate spatial part of metric by:

$$\gamma_{ij} = \Psi^4\delta_{ij}$$

"conformal factor" "Kronecker delta"

ii) update space-time

"3+1" foliation of space-time:

$$ds^2 = (-\alpha^2 + \beta_i\beta^i)dt^2 + 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$

"lapse" "shift"

approximate spatial part of metric by:

$$\gamma_{ij} = \Psi^4 \delta_{ij}$$

"conformal factor" "Kronecker delta"

➡ Einstein equations reduce to a set of 5 coupled, non-linear elliptical partial differential equations with non-compact source terms

Pros

- exact for spherically symmetric systems
- at least 1PN accurate
- more efficient than "full GR"

Pros

- exact for spherically symmetric systems
- at least 1PN accurate
- more efficient than “full GR”

Cons

- implicitly assumes “no gravitational waves in space-time”
- but needed for inspiral, added “by hand”
- difficult to judge how good in a general geometry
- (much slower than Newtonian: hard to get resolution for other physics)

- “Full GR” (e.g. Shibata 2000, Duez 2009, Rezzolla et al. 2010...)

- "Full GR" (e.g. Shibata 2000, Duez 2009, Rezzolla et al. 2010...)

- foliate space-time into spacelike hypersurfaces

- “Full GR” (e.g. Shibata 2000, Duez 2009, Rezzolla et al. 2010...)

- foliate space-time into spacelike hypersurfaces with constant coordinate time

- “Full GR” (e.g. Shibata 2000, Duez 2009, Rezzolla et al. 2010...)

- foliate space-time into spacelike hypersurfaces with constant coordinate time

- Einstein equations split up in constraint equations (momentum & Hamiltonian constr.) and evolution equations (for spatial metric γ_{ij} and extrins. curvature of hypersurfaces K_{ij})

- "Full GR" (e.g. Shibata 2000, Duez 2009, Rezzolla et al. 2010...)

- foliate space-time into spacelike hypersurfaces with constant coordinate time

- Einstein equations split up in constraint equations (momentum & Hamiltonian constr.) and evolution equations (for spatial metric γ_{ij} and extrins. curvature of hypersurfaces K_{ij})

- usually "free evolution schemes": constraint equations solved for initial conditions, during evolution their violation is monitored

- “Full GR” (e.g. Shibata 2000, Duez 2009, Rezzolla et al. 2010...)

- foliate space-time into spacelike hypersurfaces with constant coordinate time

- Einstein equations split up in constraint equations (momentum & Hamiltonian constr.) and evolution equations (for spatial metric γ_{ij} and extrins. curvature of hypersurfaces K_{ij})

- usually “free evolution schemes”: constraint equations solved for initial conditions, during evolution their violation is monitored

- two formulations of GR used:

  i) Baumgarte-Shapiro-Shibata-Nakamura (BSSN)
  ii) generalized harmonic (GH) formulation (Garfinkle 2002, Pretorius 2005, ...)

Pros

Pros

- "first principles" approach

Pros

- “first principles” approach

Cons

- new numerical methods involved
- very expensive: resolution restrictions
- poor controle over numerical conservation
- so far only very simple “micro-physics”, polytropic EOS often “hard-wired” in codes
- numerical “vacuum” often above white dwarf central densities

"Further physics"

Equation of state (EOS):

- polytrope (...)
- piece-wise polytropic EOS (Shibata et al. (2006), Read et al. (2009))
- ρ, T, Y_e- dependent EOSs of Lattimer-Swesty & Shen et al.

  (e.g. Ruffert et al. (1997), Rosswog et al. (1999), Rosswog et al. (2003), Oechslin et al. (2007), Duez et al. (2010)...)
- quark matter EOS (Oechslin et al. (2004), Bauswein 2010)
- strange star mergers (Bauswein 2010)

neutrino physics

neutrino physics

- "leakage schemes" (Ruffert et al. 1997, Rosswog & Liebendoerfer 2003):

  a) cooling based on ρ, T, Y_e and opacities

  b) evolution of Y_e

important: neutrinos "leaked out" at some location of the fluid are NOT absorbed in other parts

neutrino physics

- "leakage schemes" (Ruffert et al. 1997, Rosswog & Liebendoerfer 2003):
  - a) cooling based on ρ, T, Y_e and opacities
  - b) evolution of Y_e

important: neutrinos "leaked out" at some location of the fluid are NOT absorbed in other parts

- $\nu_i - \bar{\nu}_i$ - annihilation as a post-processing step

(e.g. Ruffert & Janka 2001, Rosswog & Ramirez-Ruiz 2002, Rosswog et al. 2003)

neutrino physics

- "leakage schemes" (Ruffert et al. 1997, Rosswog & Liebendoerfer 2003):
  a) cooling based on ρ, T, Y_e and opacities
  b) evolution of Y_e

important: neutrinos "leaked out" at some location of the fluid are NOT absorbed in other parts

- $\nu_i - \bar{\nu}_i$ - annihilation as a post-processing step

  (e.g. Ruffert & Janka 2001, Rosswog & Ramirez-Ruiz 2002, Rosswog et al. 2003)

- Multi-group flux-limited Diffusion (MGFLD): non-local absorption accounted for

  (Dessart, Ott, Burrows, Rosswog, Livne (2009))

magnetic fields

magnetic fields

- full merger simulations using Euler potentials

$$\vec{B} = \nabla\alpha \times \nabla\beta$$

with Lagrangian hydrodynamics

(Price & Rosswog (2006), Rosswog & Price (2007))

magnetic fields

- full merger simulations using Euler potentials

$$\vec{B} = \nabla\alpha \times \nabla\beta$$

with Lagrangian hydrodynamics

(Price & Rosswog (2006), Rosswog & Price (2007))

- in grid-based simulations

(Anderson et al. 2008, Liu et al. (2008), Giacomazzo et al. (2009))

magnetic fields

- full merger simulations using Euler potentials

$$\vec{B} = \nabla\alpha \times \nabla\beta$$

with Lagrangian hydrodynamics

(Price & Rosswog (2006), Rosswog & Price (2007))

- in grid-based simulations

(Anderson et al. 2008, Liu et al. (2008), Giacomazzo et al. (2009))

→ tremendous progress in the last decade

magnetic fields

- full merger simulations using Euler potentials

$$\vec{B} = \nabla\alpha \times \nabla\beta$$

with Lagrangian hydrodynamics

(Price & Rosswog (2006), Rosswog & Price (2007))

- in grid-based simulations

(Anderson et al. 2008, Liu et al. (2008), Giacomazzo et al. (2009))

→ tremendous progress in the last decade

→ each approach has its benefits and shortcomings

magnetic fields

- full merger simulations using Euler potentials

$$\vec{B} = \nabla\alpha \times \nabla\beta$$

with Lagrangian hydrodynamics

(Price & Rosswog (2006), Rosswog & Price (2007))

- in grid-based simulations

(Anderson et al. 2008, Liu et al. (2008), Giacomazzo et al. (2009))

→ tremendous progress in the last decade

→ each approach has its benefits and shortcomings

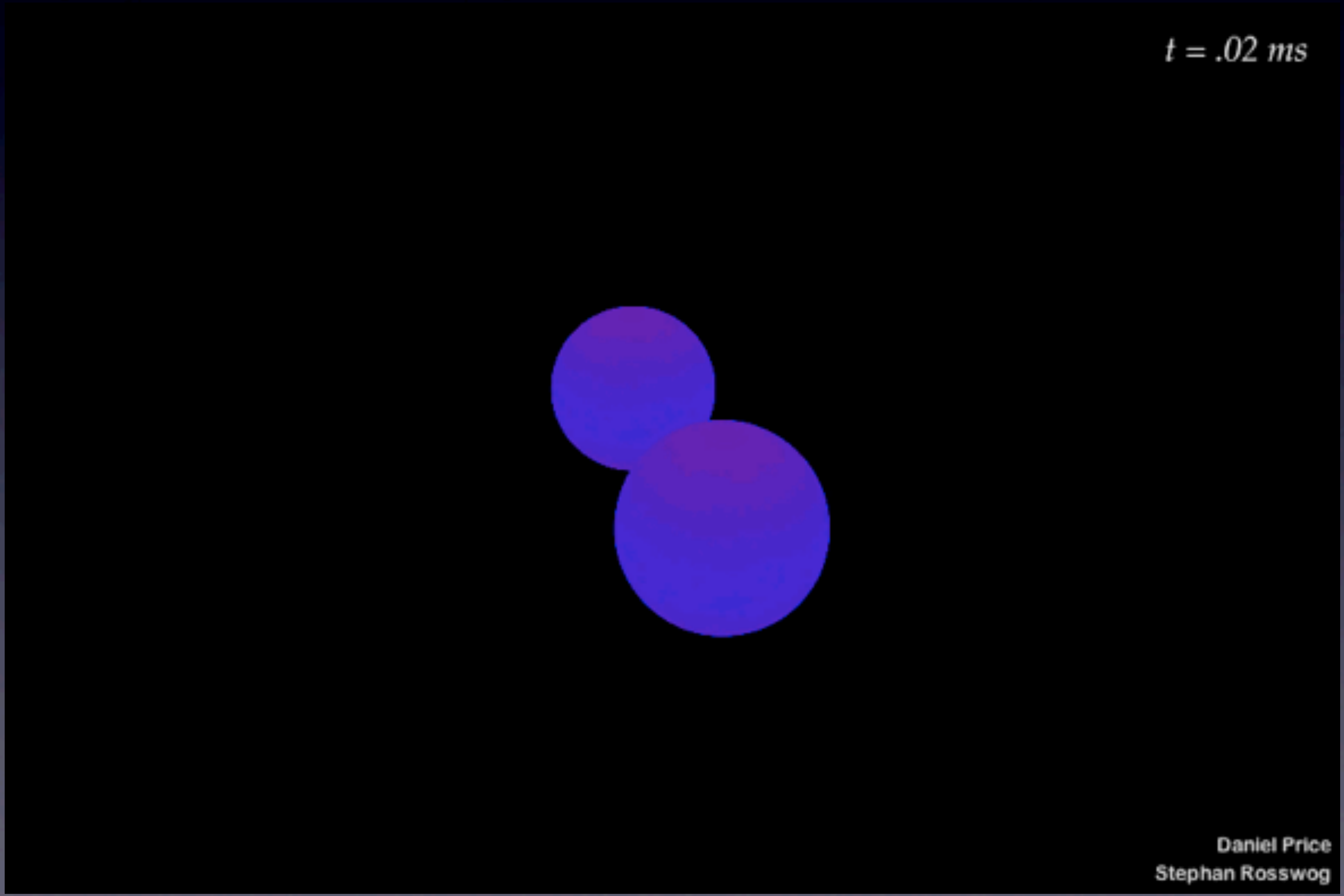
→ "patchwork picture"

III. The emerging patchwork picture

- Morphology Double Neutron Star (DNS) merger

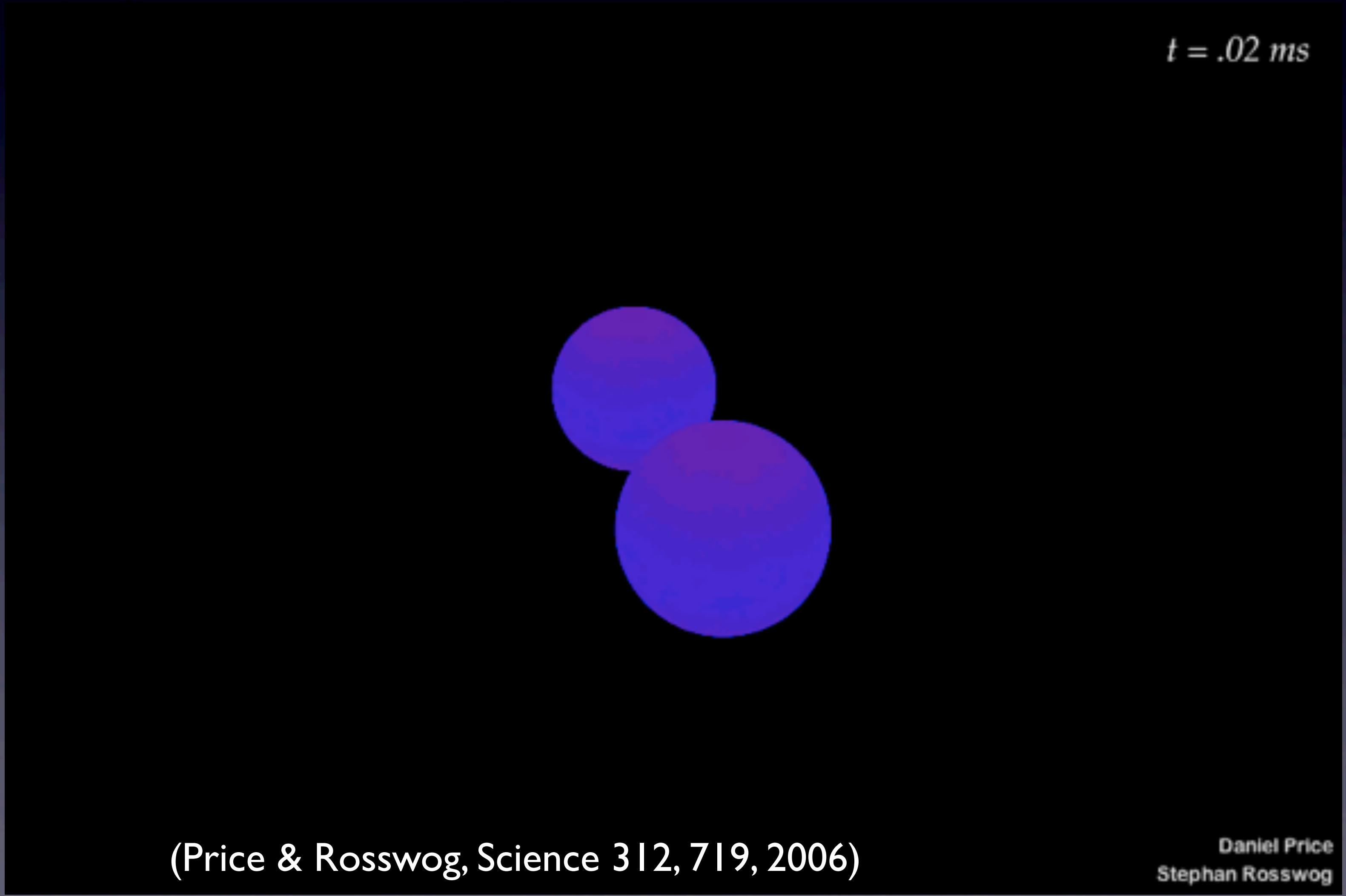
III. The emerging patchwork picture

- Morphology Double Neutron Star (DNS) merger



III. The emerging patchwork picture

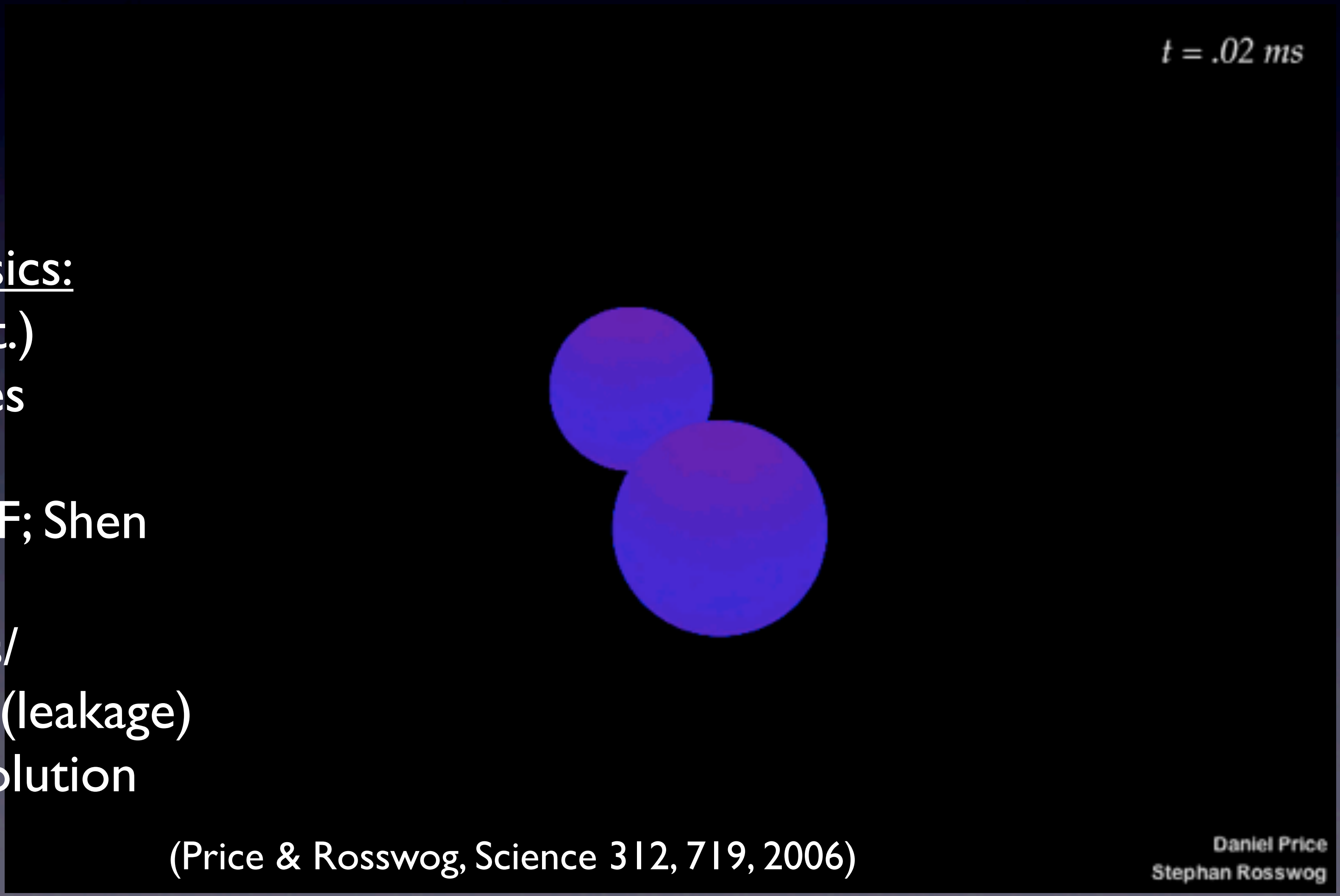
- Morphology Double Neutron Star (DNS) merger



(Price & Rosswog, Science 312, 719, 2006)

III. The emerging patchwork picture

- Morphology Double Neutron Star (DNS) merger



modeled physics:

- self-gravity (Newt.)
- gravitational waves
- gas dynamics
- nuclear EOS (RMF; Shen et al. 1998)
- weak interactions/ neutrino cooling (leakage)
- magnetic field evolution (Euler potentials)

(Price & Rosswog, Science 312, 719, 2006)

III.1 "Collapse to a black hole"

- observed masses in double neutron star systems (DNS)

M_1	M_2		$q \equiv \frac{m_1}{m_2}$
1.44	1.38	B1913+16	0.958
1.33	1.34	B1534+12	0.993
1.33	1.25	J0737-3039	0.940
1.40	1.18	J1756-2251	0.843
1.36	1.35	B2127+11C	0.993
1.35	1.26	J1906+0746	0.993
1.62	1.11	J1811-1736	0.685
1.56	1.05	J1518+4904	0.673
1.14	1.36	J1829+2456	0.84

- upper mass limit cold, non-rotating, isolated neutron star

$$1.677\, M_\odot < M_{\max,\mathrm{TOV}} < 3.2\, M_\odot$$

(Freire et al. in prep.)

(Roads & Ruffini 1974)

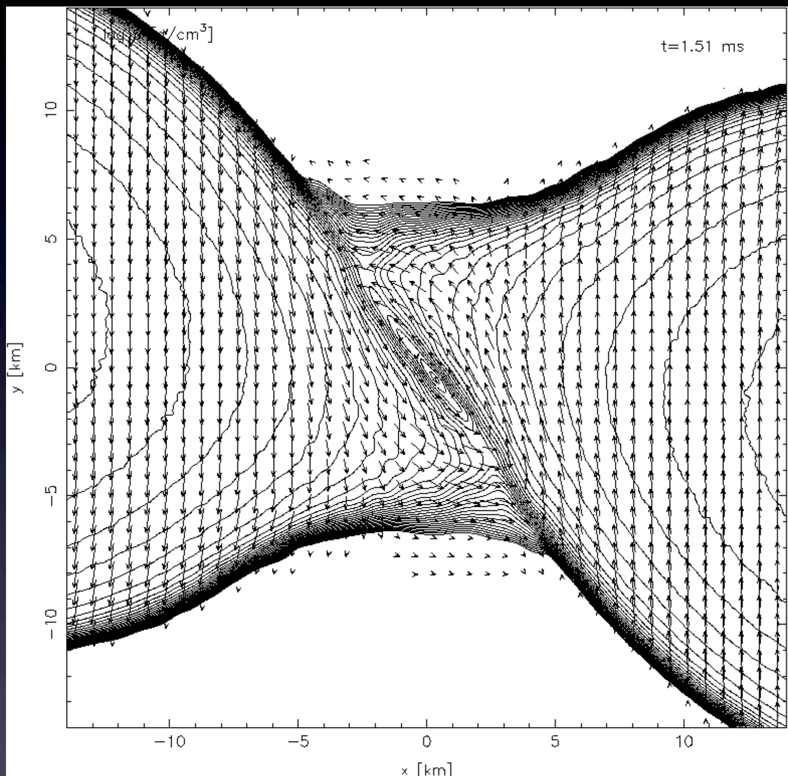
“Collapse to a black hole ???”

“Collapse to a black hole ???”

Yes, likely, but...

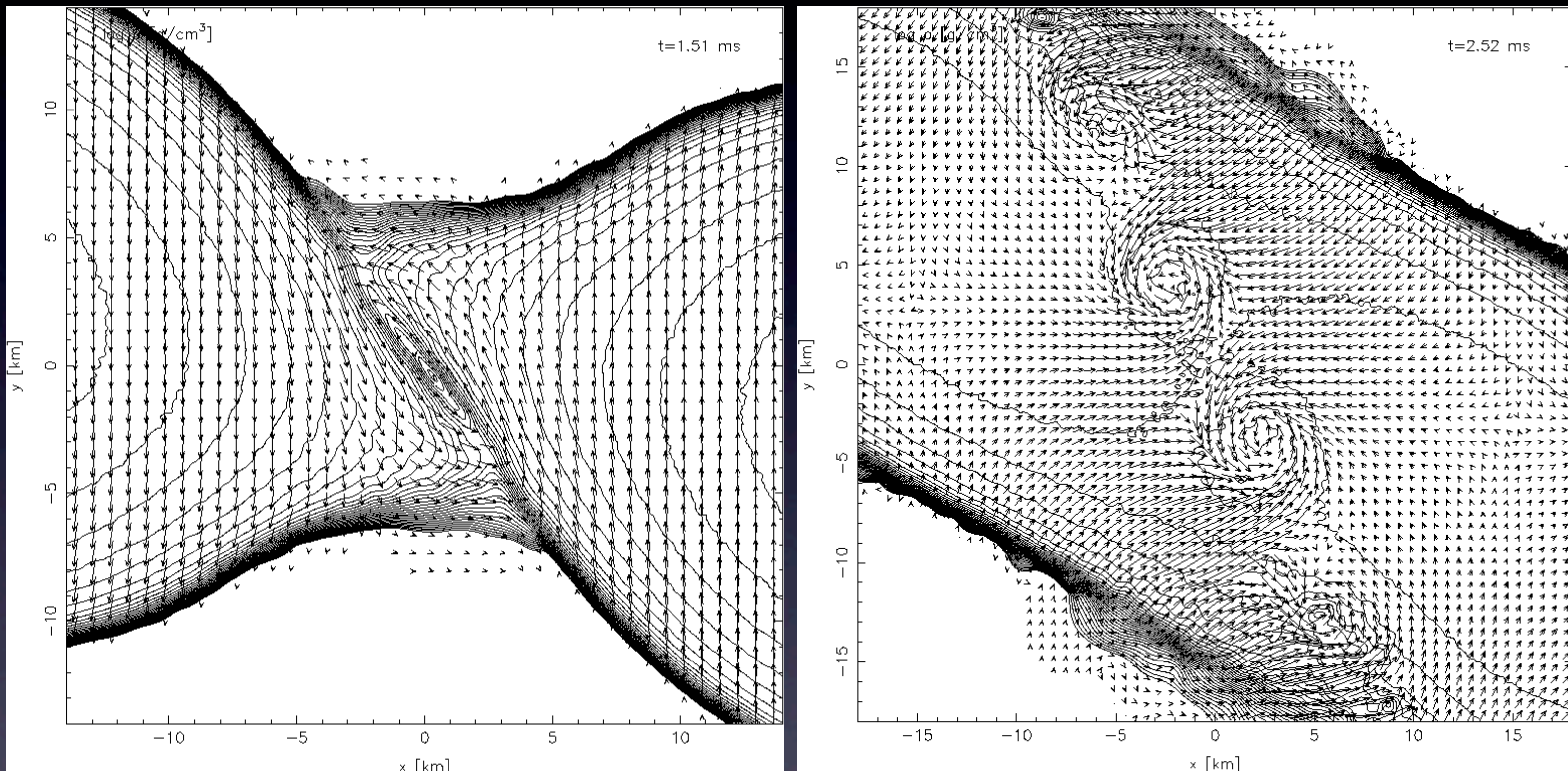
“Collapse to a black hole ???”

Yes, likely, but...



“Collapse to a black hole ???”

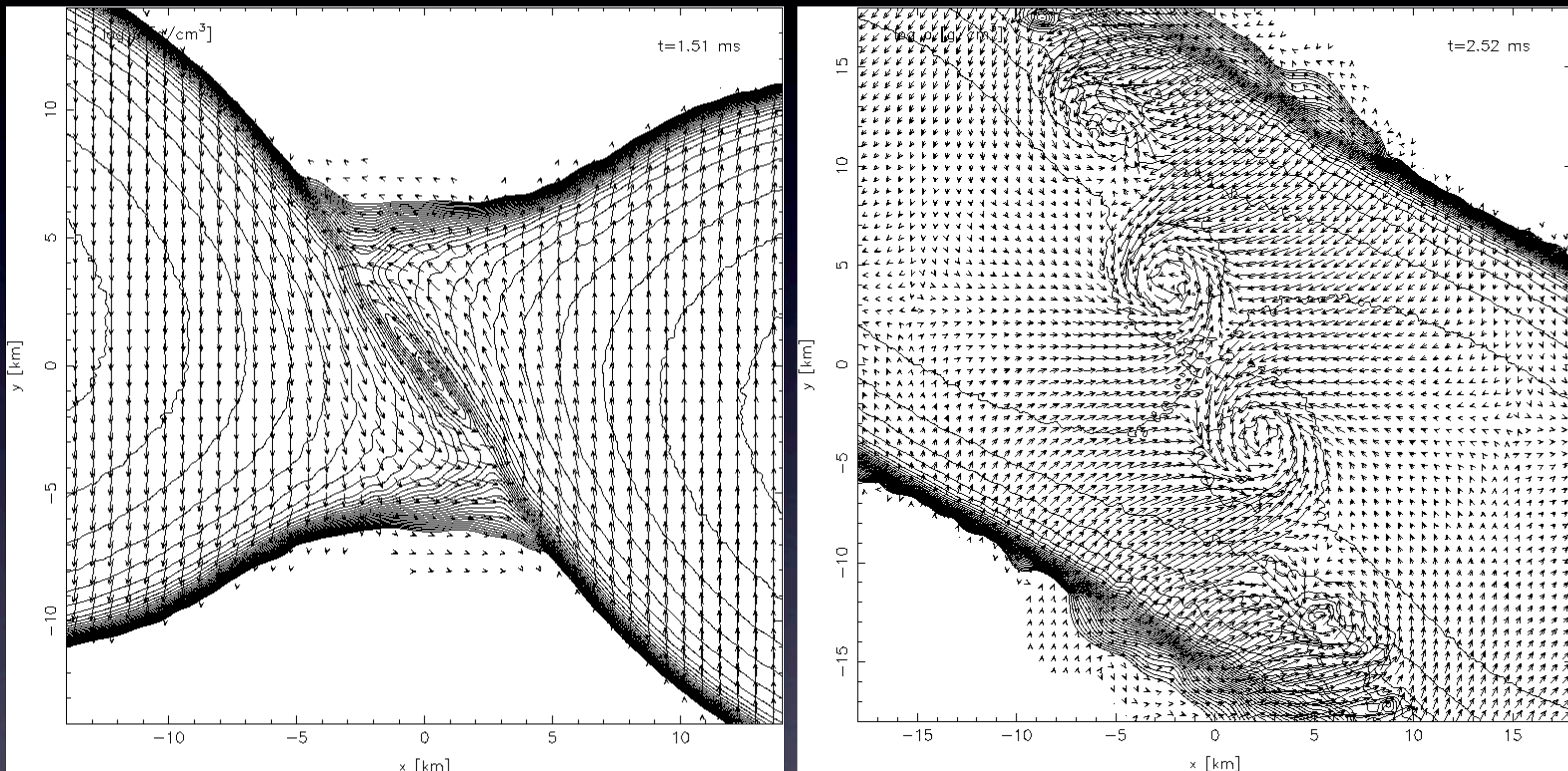
Yes, likely, but...



(from Rosswog 2007)

“Collapse to a black hole ???”

Yes, likely, but...



(from Rosswog 2007)

(in many cases) production of differentially rotating, “hyper-massive neutron star”

- binary mass $M_{\rm DNS} > M_{\rm th}$:

- binary mass $M_{\rm DNS} > M_{\rm th}$: direct collapse to BH

- binary mass $M_{\mathrm{DNS}} > M_{\mathrm{th}}$: direct collapse to BH

$$M_{\mathrm{DNS}} < M_{\mathrm{th}}$$

- binary mass $M_{\rm DNS} > M_{\rm th}$: direct collapse to BH

  $M_{\rm DNS} < M_{\rm th}$ collapse via "hyper-massive neutron star"

- binary mass $M_{\mathrm{DNS}} > M_{\mathrm{th}}$: direct collapse to BH

  $M_{\mathrm{DNS}} < M_{\mathrm{th}}$ collapse via "hyper-massive neutron star"

$$M_{\mathrm{th}} \approx 1.35\, M_{\mathrm{max,TOV}} \geq 2.26 M_{\odot}$$ (Shibata & Taniguchi 2006)

- binary mass $M_{\mathrm{DNS}} > M_{\mathrm{th}}$: direct collapse to BH

  $M_{\mathrm{DNS}} < M_{\mathrm{th}}$ collapse via "hyper-massive neutron star"

$M_{\mathrm{th}} \approx 1.35\, M_{\mathrm{max,TOV}} \geq 2.26 M_{\odot}$ (Shibata & Taniguchi 2006)

→ probably both types realized in nature
(can a stable neutron star remnant be safely ruled out?)

III.2 Mass loss

Double Neutron Stars

III.2 Mass loss

Double Neutron Stars

- different types:

III.2 Mass loss

Double Neutron Stars

- different types:
  - “direct mass loss”

III.2 Mass loss

Double Neutron Stars

- different types:
  - "direct mass loss"

    a) from interaction region: "hot" (~ 10 MeV)

III.2 Mass loss

Double Neutron Stars

- different types:
  - "direct mass loss"

    a) from interaction region: "hot" (~ 10 MeV)

    b) from tidal tail: "cold" (~0.5 MeV)

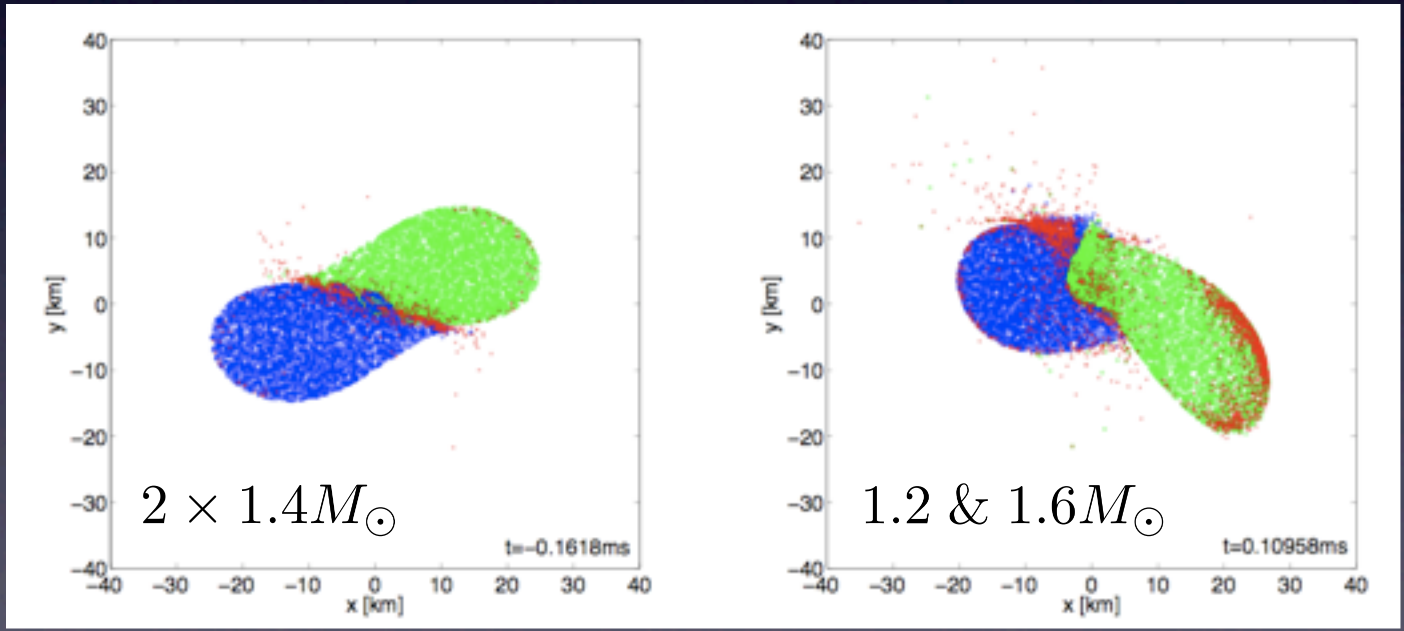
III.2 Mass loss

Double Neutron Stars

- different types:
  - "direct mass loss"

    a) from interaction region: "hot" (~ 10 MeV)

    b) from tidal tail: "cold" (~0.5 MeV)



(Oechslin et al. 2007, "CFA + Shen-EOS")

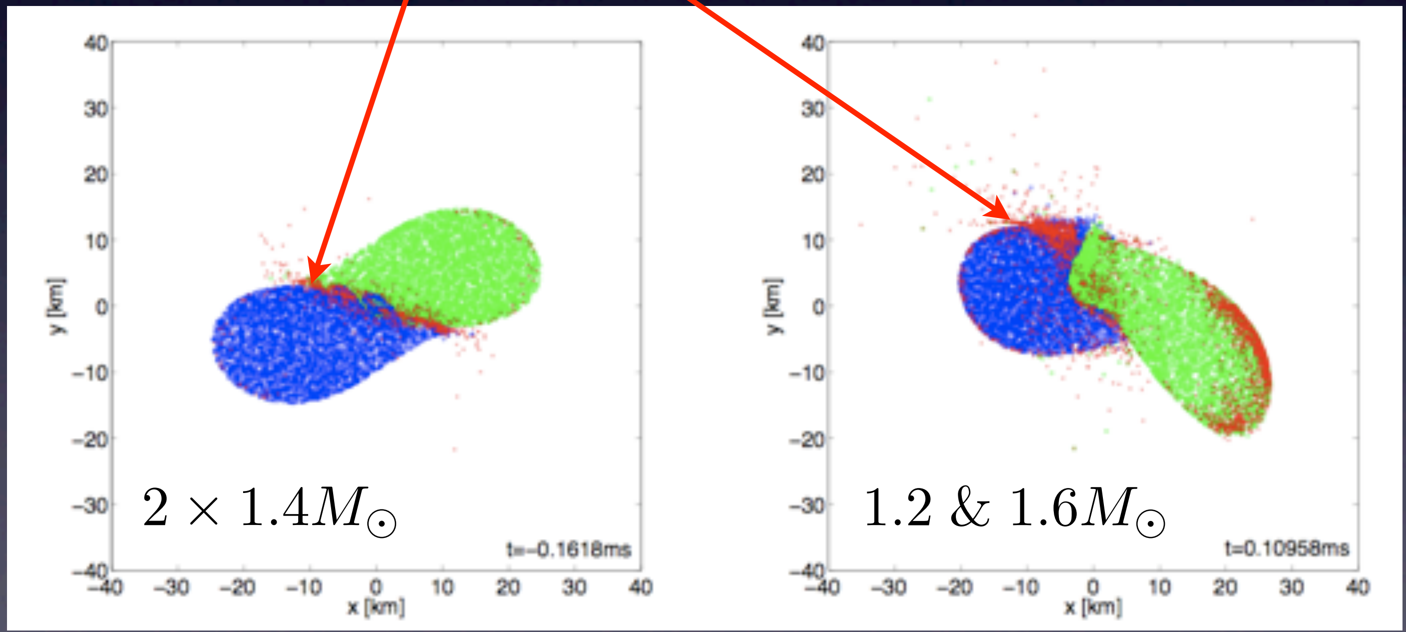
III.2 Mass loss

Double Neutron Stars

- different types:
  - "direct mass loss"

    a) from interaction region: "hot" (~ 10 MeV)

    b) from tidal tail: "cold" (~0.5 MeV)



(Oechslin et al. 2007, "CFA + Shen-EOS")

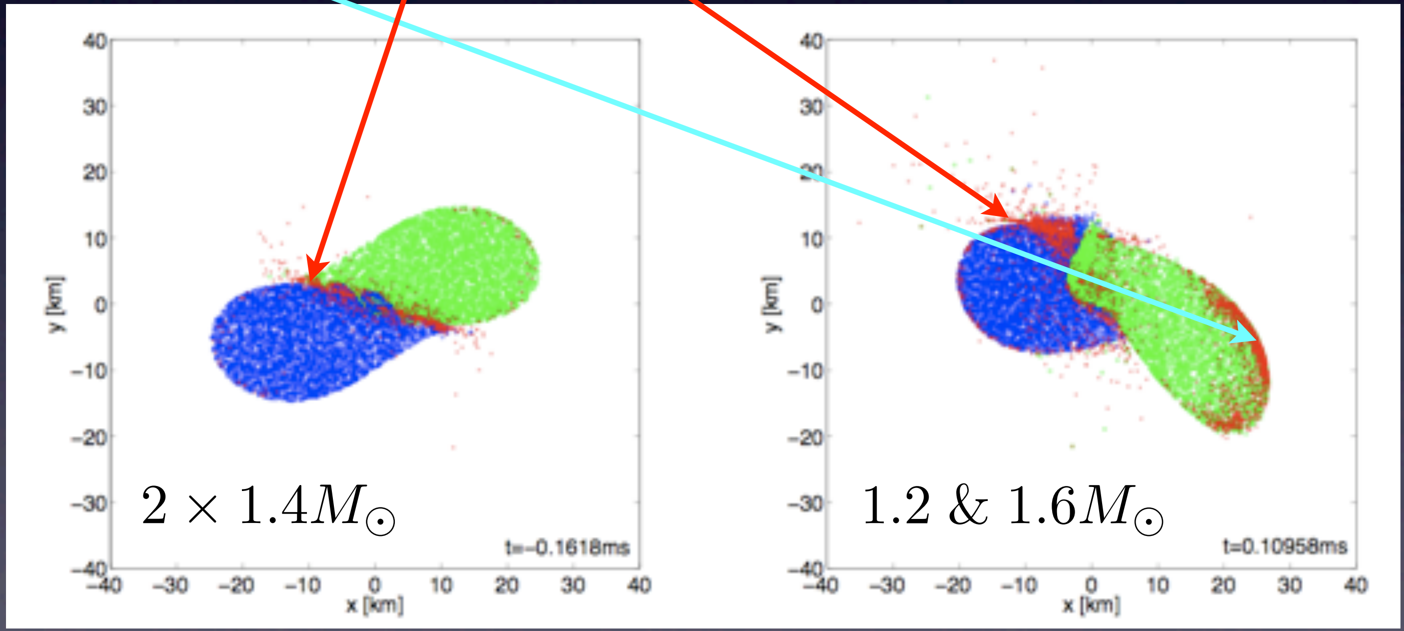
III.2 Mass loss

Double Neutron Stars

- different types:
  - "direct mass loss"

    a) from interaction region: "hot" (~ 10 MeV)

    b) from tidal tail: "cold" (~0.5 MeV)



(Oechslin et al. 2007, "CFA + Shen-EOS")

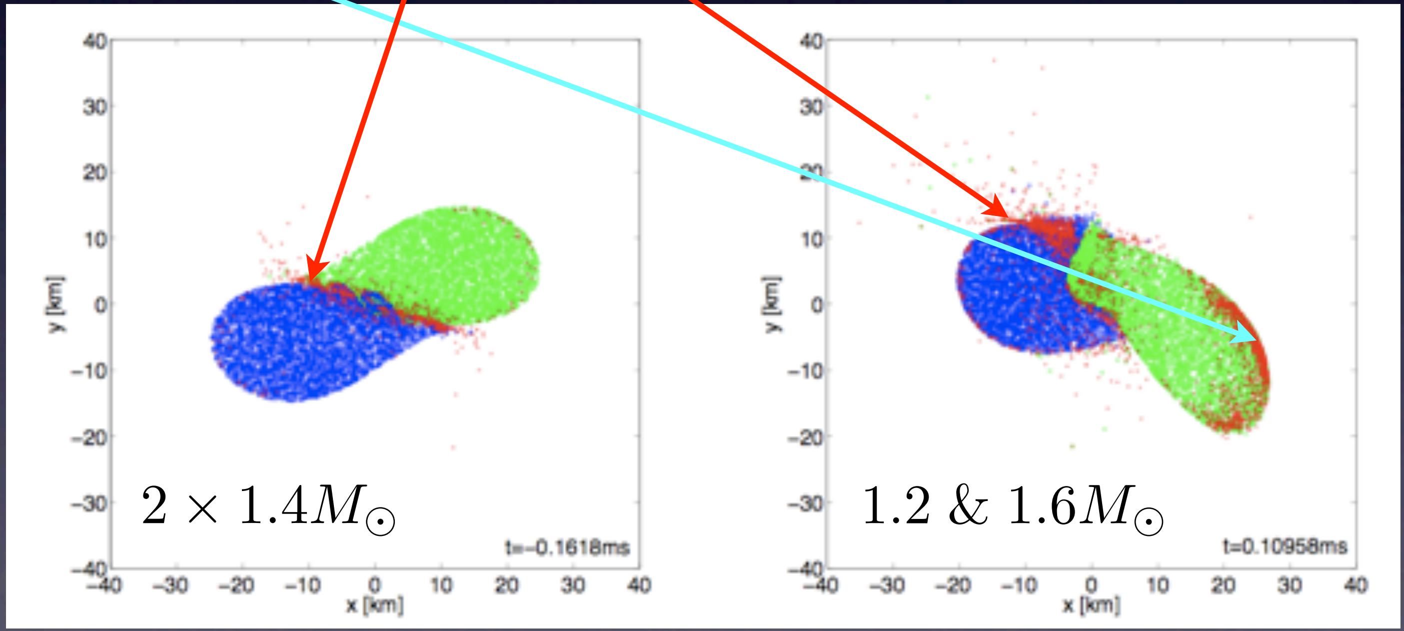
III.2 Mass loss

Double Neutron Stars

- different types:
  - "direct mass loss"

    a) from interaction region: "hot" (~ 10 MeV)

    b) from tidal tail: "cold" (~0.5 MeV)



(Oechslin et al. 2007, "CFA + Shen-EOS")

- neutrino-driven wind (see later)

- amounts:

("CFA + Shen-EOS", Oechslin et al. 2007)

- amounts: $M_{\rm ej} \approx 2 \times 10^{-3} \ldots 5 \times 10^{-2}\ M_\odot$

("CFA + Shen-EOS", Oechslin et al. 2007)

- amounts: $M_{\rm ej} \approx 2 \times 10^{-3} \ldots 5 \times 10^{-2}\ M_\odot$

("CFA + Shen-EOS", Oechslin et al. 2007)

$2 \times 1.4 M_\odot$

- amounts:

("CFA + Shen-EOS", Oechslin et al. 2007)

$$M_{\rm ej} \approx 2 \times 10^{-3} \; ... \; 5 \times 10^{-2} \; M_\odot$$

$2 \times 1.4 M_\odot$

$1.07 \;\&\; 1.93 M_\odot$

- amounts: $M_{\rm ej} \approx 2 \times 10^{-3} \,...\, 5 \times 10^{-2} \; M_\odot$

("CFA + Shen-EOS", Oechslin et al. 2007)

$2 \times 1.4 M_\odot$ $\quad$ $1.07 \,\&\, 1.93 M_\odot$

- tendencies:

- amounts: $M_{\rm ej} \approx 2 \times 10^{-3} \ldots 5 \times 10^{-2}\ M_\odot$

("CFA + Shen-EOS", Oechslin et al. 2007)

$2 \times 1.4 M_\odot$ $\quad$ $1.07\ \&\ 1.93 M_\odot$

- tendencies:
  - "hot component" both in sym. (q=1) and asym. binaries

- amounts:

$$M_{\rm ej} \approx 2 \times 10^{-3} \;...\; 5 \times 10^{-2}\; M_\odot$$

("CFA + Shen-EOS", Oechslin et al. 2007)

$2 \times 1.4 M_\odot$ $\quad$ $1.07 \;\&\; 1.93 M_\odot$

- tendencies:
  - "hot component" both in sym. (q=1) and asym. binaries
  - "cold component" only for q ≠ 1

- amounts: $M_{\rm ej} \approx 2 \times 10^{-3} \ldots 5 \times 10^{-2}\ M_\odot$

("CFA + Shen-EOS", Oechslin et al. 2007)

$2 \times 1.4 M_\odot$ $\quad$ $1.07 \ \&\ 1.93 M_\odot$

- tendencies:

  - "hot component" both in sym. (q=1) and asym. binaries
  - "cold component" only for q ≠ 1
  - ejecta mass increases with binary asymmetry

Neutron star black hole systems

- Newtonian, low-mass BHs ($M_{\mathrm{BH}} \leq 10 M_{\odot}$)

Neutron star black hole systems

- Newtonian, low-mass BHs ($M_{\rm BH} \leq 10 M_\odot$)
  - very sensitive to equation of state (EOS)
  - for stiff EOS (e.g. Shen et al. 1998): long, episodic mass transfer

Neutron star black hole systems

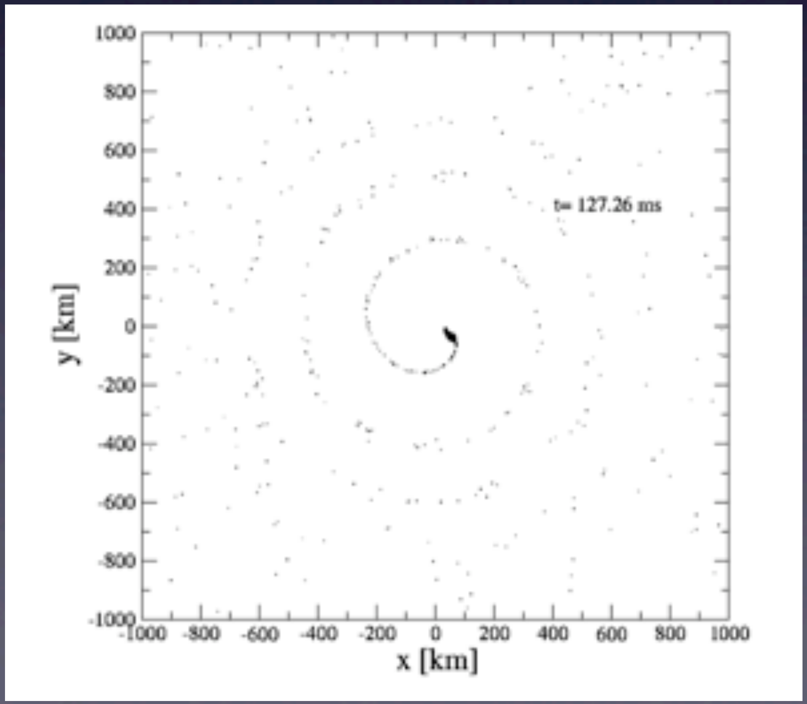
- Newtonian, low-mass BHs ($M_{\rm BH} \leq 10 M_{\odot}$)
  - very sensitive to equation of state (EOS)
  - for stiff EOS (e.g. Shen et al. 1998): long, episodic mass transfer

    example: $M_{\rm BH} = 3\ M_{\odot}, M_{\rm ns} = 1.4\ M_{\odot},\ q = 0.466$

Neutron star black hole systems

- Newtonian, low-mass BHs ($M_{\rm BH} \leq 10 M_\odot$)
  - very sensitive to equation of state (EOS)
  - for stiff EOS (e.g. Shen et al. 1998): long, episodic mass transfer

  example: $M_{\rm BH} = 3\ M_\odot, M_{\rm ns} = 1.4\ M_\odot,\ q = 0.466$

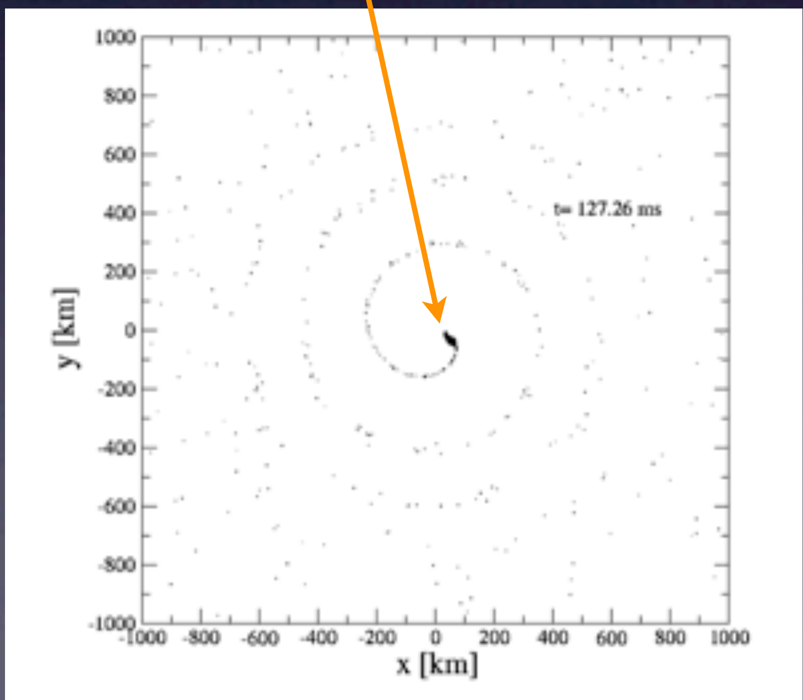


Neutron star black hole systems

- Newtonian, low-mass BHs ($M_{\rm BH} \leq 10 M_\odot$)
  - very sensitive to equation of state (EOS)
  - for stiff EOS (e.g. Shen et al. 1998): long, episodic mass transfer

  example: $M_{\rm BH} = 3\ M_\odot, M_{\rm ns} = 1.4\ M_\odot,\ q = 0.466$

neutron star transferring mass into BH

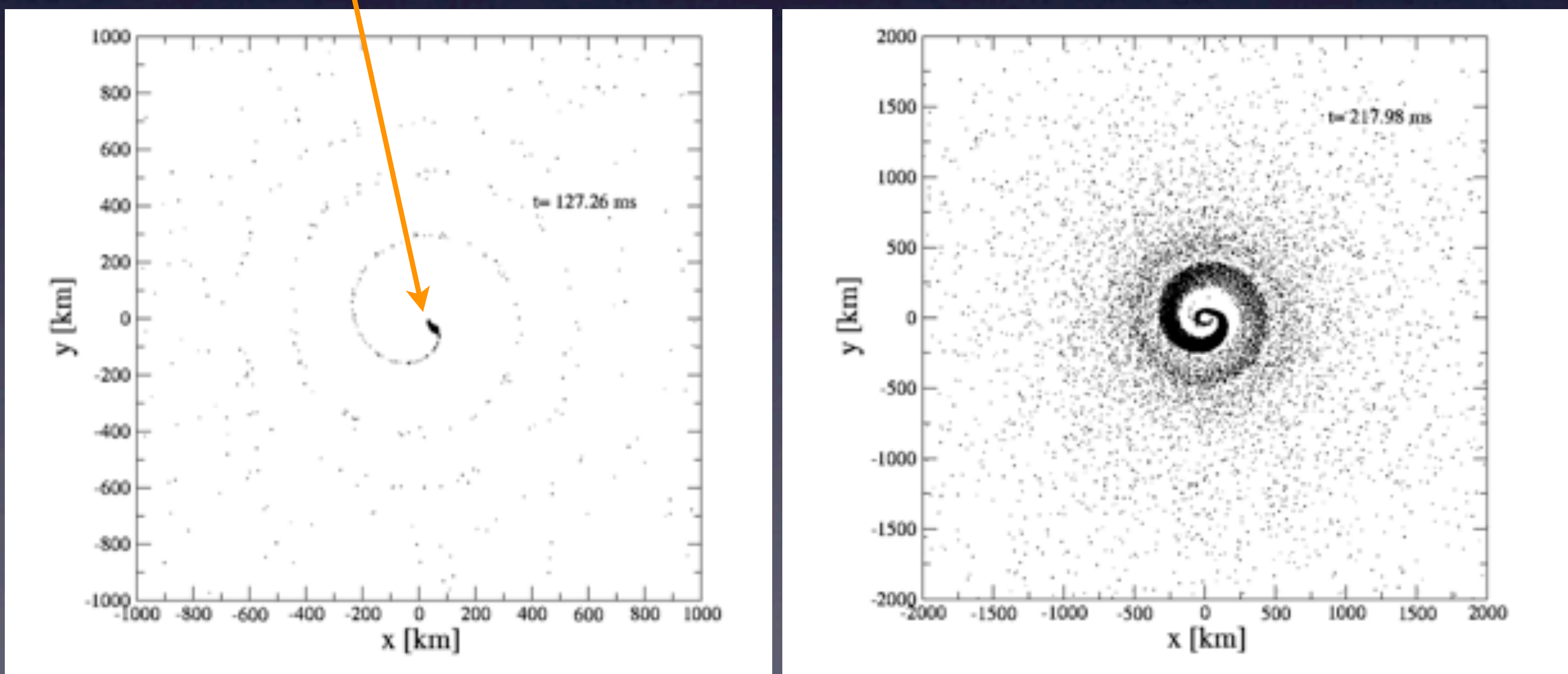


Neutron star black hole systems

- Newtonian, low-mass BHs ($M_{\rm BH} \leq 10 M_\odot$)
  - very sensitive to equation of state (EOS)
  - for stiff EOS (e.g. Shen et al. 1998): long, episodic mass transfer

  example: $M_{\rm BH} = 3\ M_\odot, M_{\rm ns} = 1.4\ M_\odot,\ q = 0.466$

neutron star transferring mass into BH



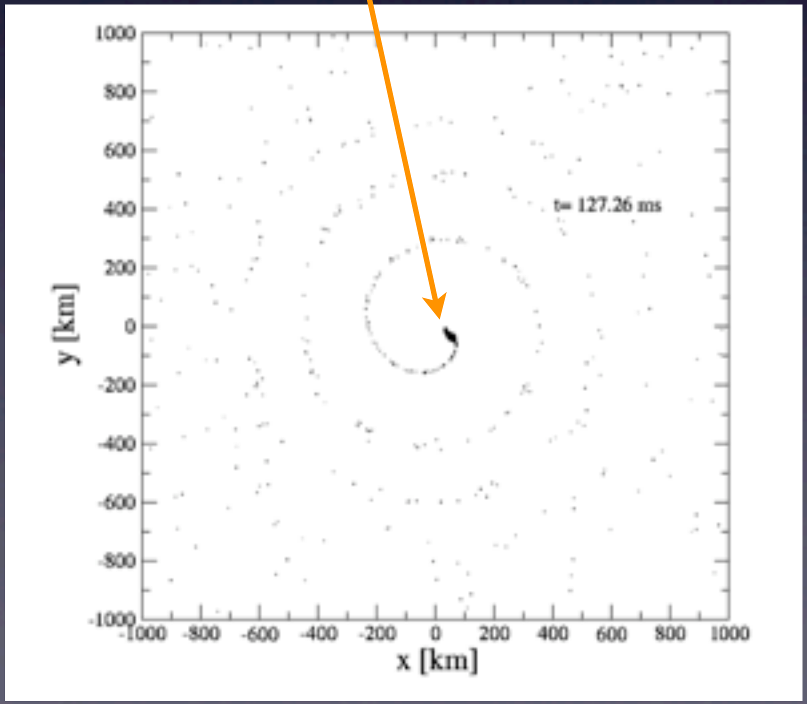
Neutron star black hole systems

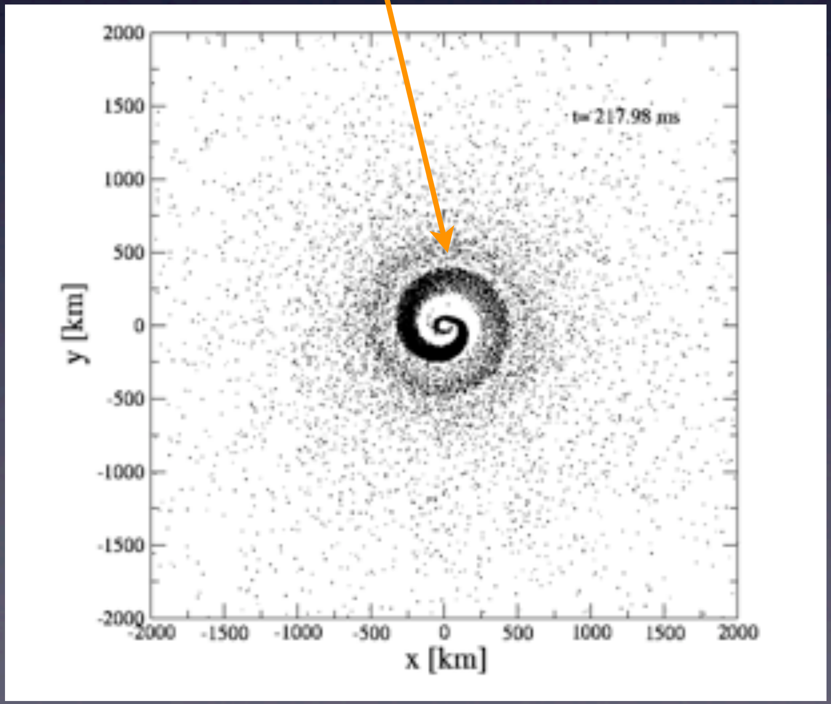
- Newtonian, low-mass BHs $(M_{\rm BH} \leq 10 M_\odot)$
  - very sensitive to equation of state (EOS)
  - for stiff EOS (e.g. Shen et al. 1998): long, episodic mass transfer

  example: $M_{\rm BH} = 3\ M_\odot, M_{\rm ns} = 1.4\ M_\odot,\ q = 0.466$

neutron star transferring mass into BH

final disruption at ~ 220 ms



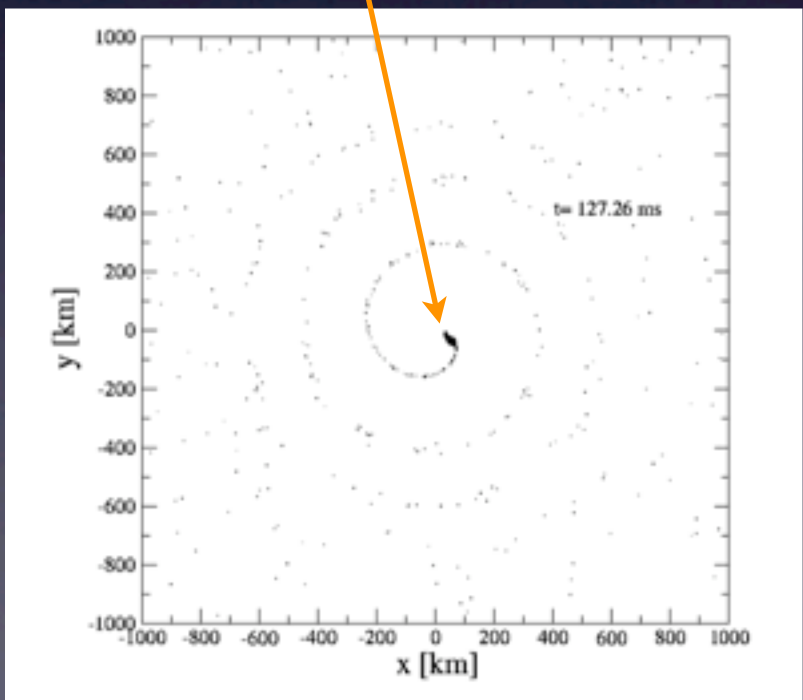


Neutron star black hole systems

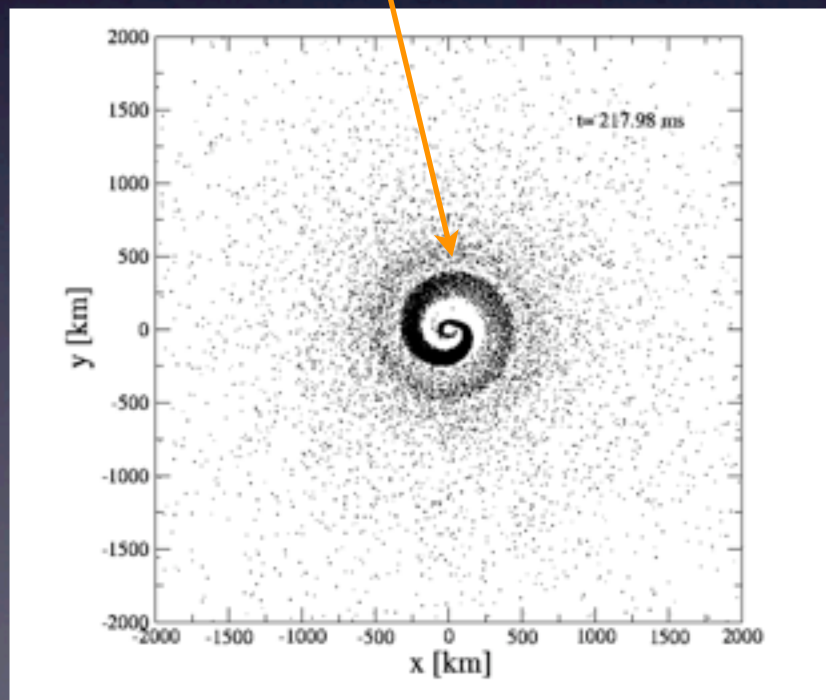
- <u>Newtonian, low-mass BHs</u> $(M_{\rm BH} \leq 10 M_{\odot})$
  - very sensitive to equation of state (EOS)
  - for stiff EOS (e.g. Shen et al. 1998): long, episodic mass transfer

  example: $M_{\rm BH} = 3\ M_{\odot}, M_{\rm ns} = 1.4\ M_{\odot},\ q = 0.466$

neutron star transferring mass into BH



final disruption at ~ 220 ms



47 orbital revolutions until final disruption !!

- Pseudo-relativistic, high-mass BHs ($M_{\rm BH} > 10\ M_\odot$)

  (Rosswog 2005, Faber et al. 2006)

- no sign for episodic mass transfer
- difficulty to produce accretion disks for GRBs,
  ns disruption near ISCO

$$R_{\rm tid} \sim \left(\frac{M_BH}{M_ns}\right)^{1/3} \approx R_{\rm ISCO} = \frac{6GM_{BH}}{c^2}$$

- ejecta masses from 0.01 to 0.2 $M_\odot$

- Pseudo-relativistic, high-mass BHs ($M_{\rm BH} > 10\ M_\odot$)

  (Rosswog 2005, Faber et al. 2006)

- no sign for episodic mass transfer
- difficulty to produce accretion disks for GRBs, ns disruption near ISCO

$$R_{\rm tid} \sim \left(\frac{M_B H}{M_n s}\right)^{1/3} \approx R_{\rm ISCO} = \frac{6GM_{BH}}{c^2}$$

- ejecta masses from 0.01 to 0.2 $M_\odot$

- Recent GR NSBH-simulations

  (Shibata et al. 2006, Etienne et al. 2009, Duez et al. 2010)

- Pseudo-relativistic, high-mass BHs ($M_{\rm BH} > 10\ M_\odot$)

  (Rosswog 2005, Faber et al. 2006)

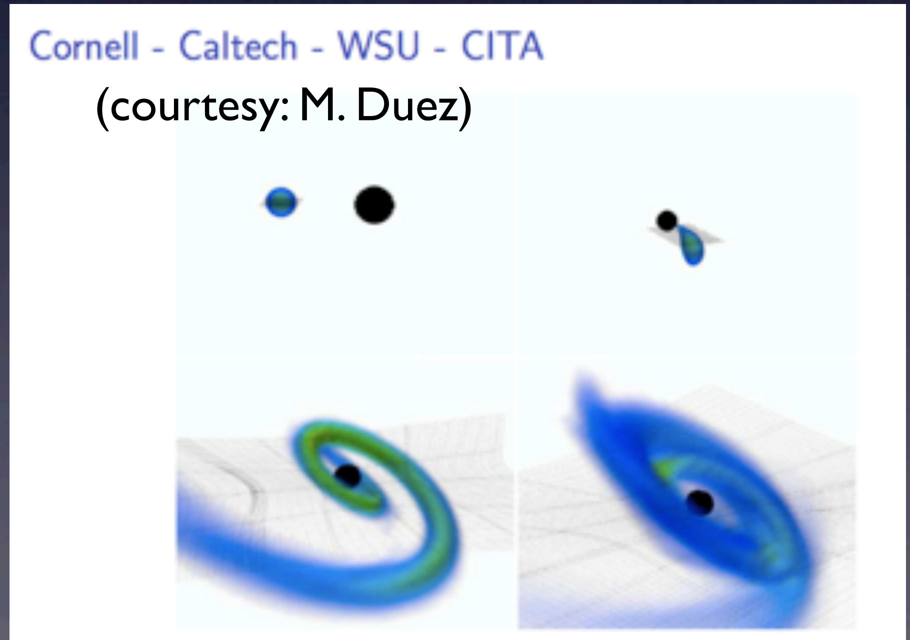
- no sign for episodic mass transfer
- difficulty to produce accretion disks for GRBs, ns disruption near ISCO

$$R_{\rm tid} \sim \left(\frac{M_BH}{M_ns}\right)^{1/3} \approx R_{\rm ISCO} = \frac{6GM_{BH}}{c^2}$$

- ejecta masses from 0.01 to 0.2 $M_\odot$

- Recent GR NSBH-simulations

  (Shibata et al. 2006, Etienne et al. 2009, Duez et al. 2010)



Evolution of a BHNS system with a BH spin initially inclined at 80° with respect to the orbital angular momentum.

- Pseudo-relativistic, high-mass BHs ($M_{\rm BH} > 10\ M_\odot$)

(Rosswog 2005, Faber et al. 2006)

- no sign for episodic mass transfer
- difficulty to produce accretion disks for GRBs, ns disruption near ISCO

$$R_{\rm tid} \sim \left(\frac{M_BH}{M_ns}\right)^{1/3} \approx R_{\rm ISCO} = \frac{6GM_{BH}}{c^2}$$

- ejecta masses from 0.01 to 0.2 $M_\odot$

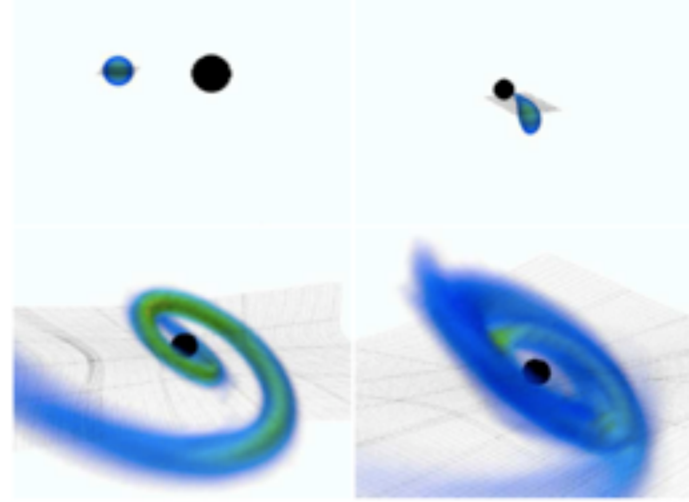
- Recent GR NSBH-simulations

(Shibata et al. 2006, Etienne et al. 2009, Duez et al. 2010)

- now stable numerical evolution
- no quantitative agreement yet
- tendencies:
  - less sensitive to EOS
  - low-mass BHs: disks hotter & more massive
  - larger BH spin: more massive disks

Cornell - Caltech - WSU - CITA

(courtesy: M. Duez)



Evolution of a BHNS system with a BH spin initially inclined at 80° with respect to the orbital angular momentum.

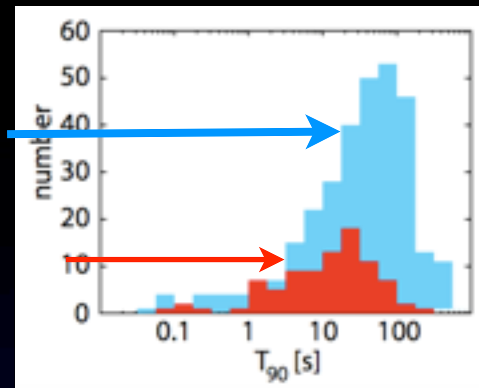
III.3 "Central engines of short GRBs?"

- short bursts are *really* different:

a) duration ~ 0.3 s vs ~30 s

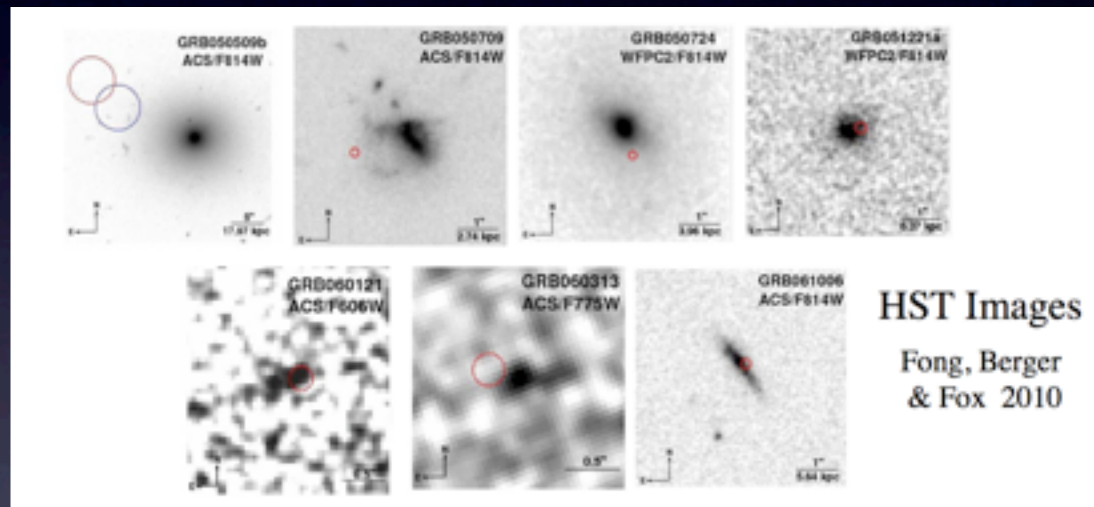
measured T_{90}

corr. to source frame duration $T_{90}/(1+z)$



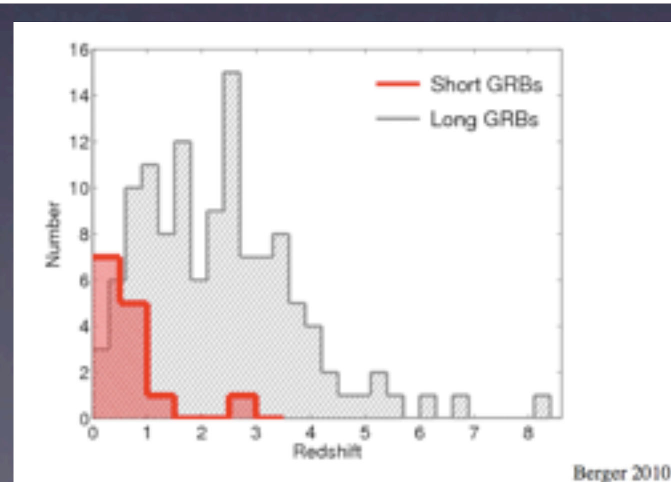
b) spectra ("harder")

c) host galaxies: all types, including ellipticals



d) burst often offset from candidate host

e) redshift distribution

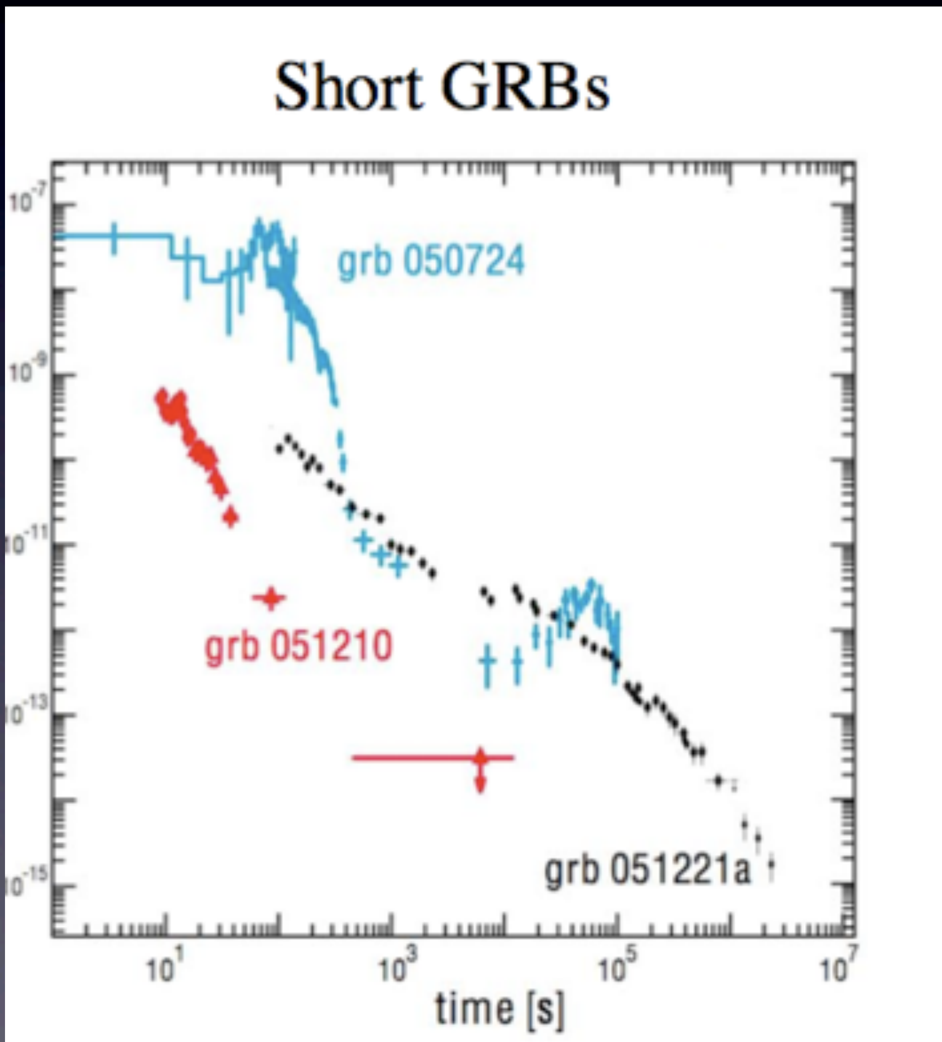


f) NO supernova connection

...so far all plausibly explained by compact binary merger

...so far all plausibly explained by compact binary merger

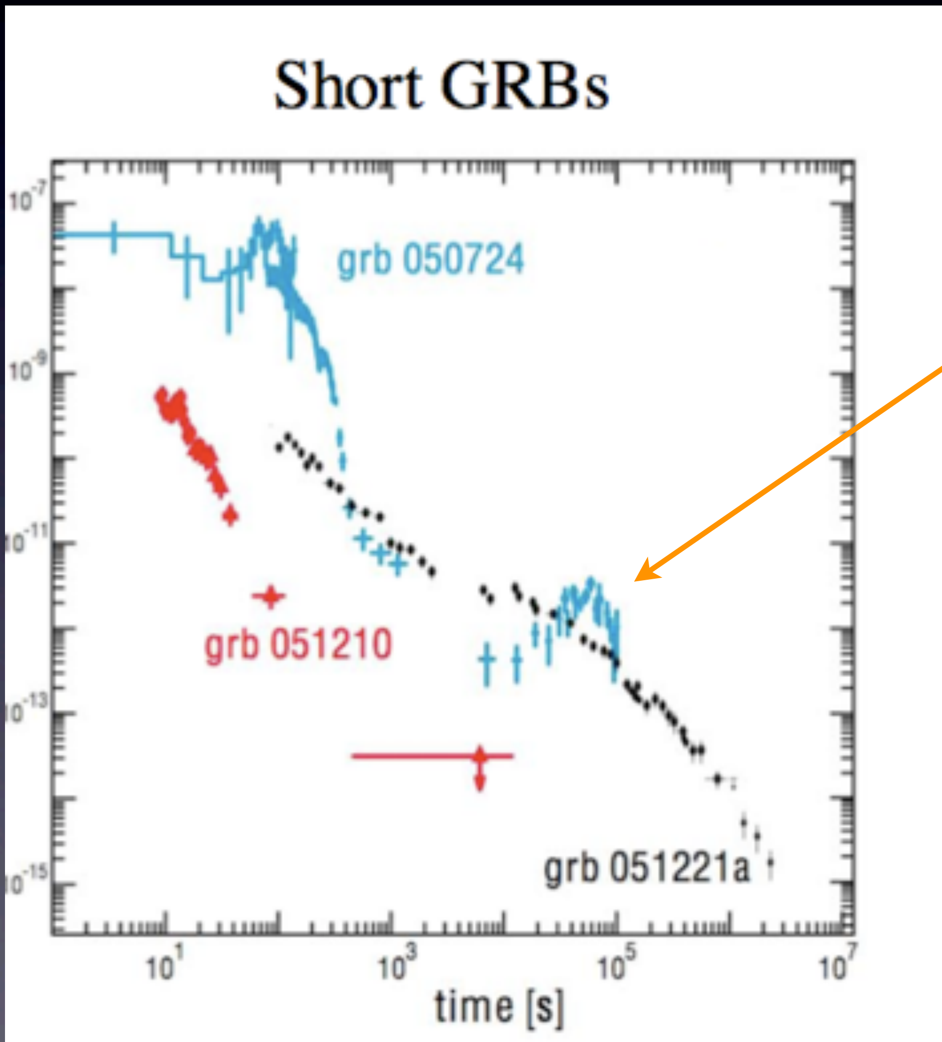
GRB X-ray activity



(Gehrels et al. 2009)

...so far all plausibly explained by compact binary merger

GRB X-ray activity

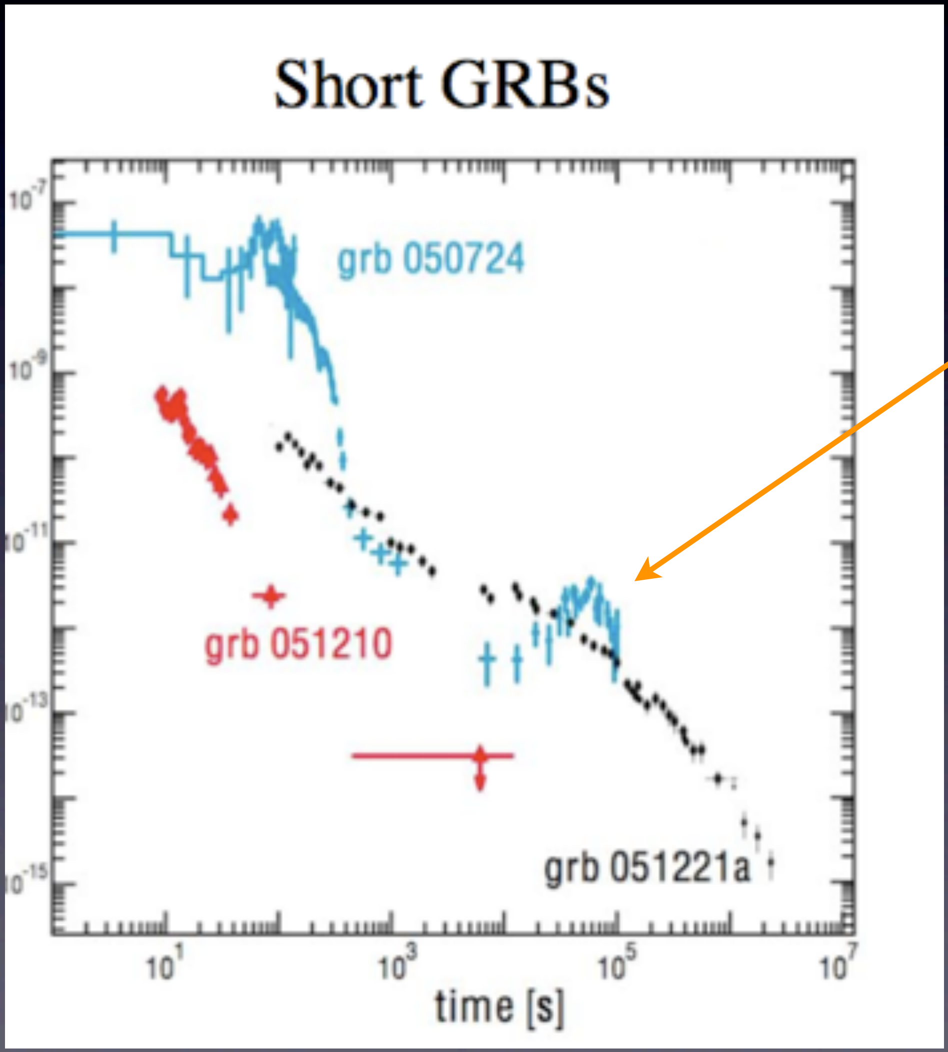


(Gehrels et al. 2009)

"late-time activity"

...so far all plausibly explained by compact binary merger

GRB X-ray activity



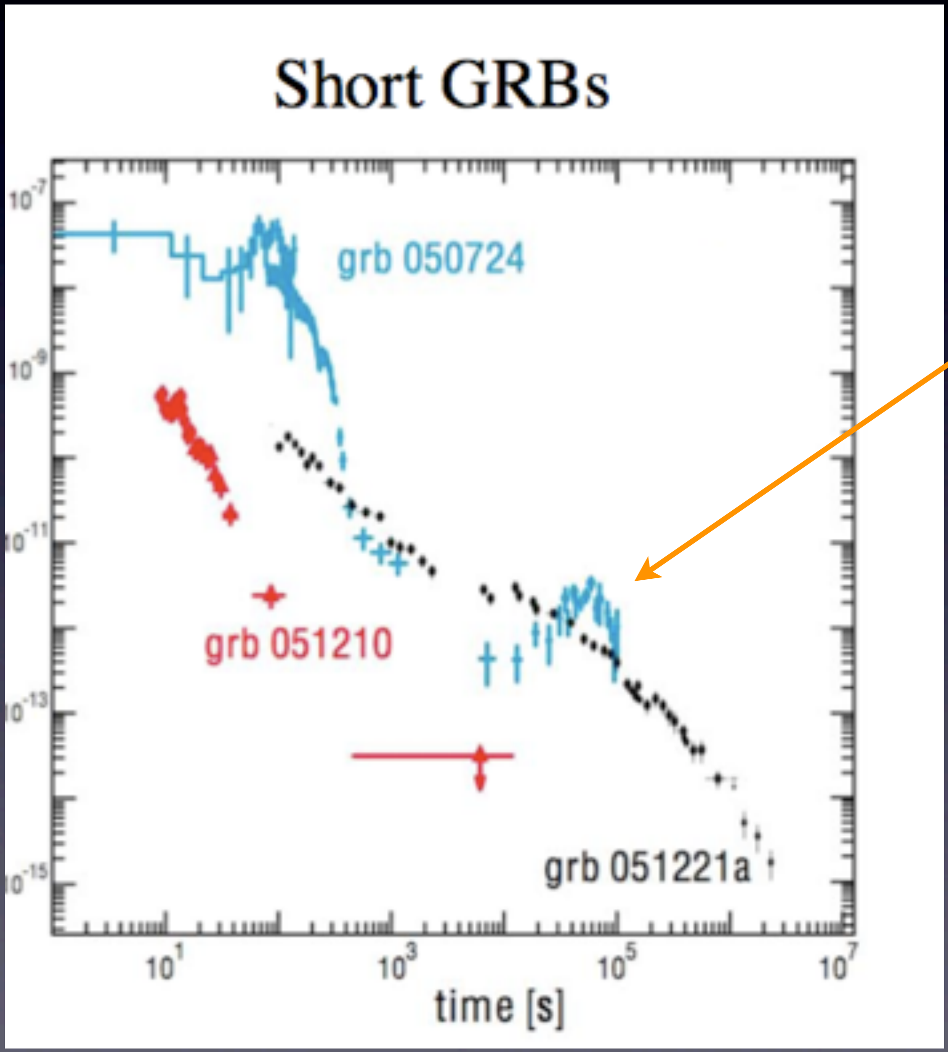
(Gehrels et al. 2009)

"late-time activity"

central engine
still active?

...so far all plausibly explained by compact binary merger

GRB X-ray activity



(Gehrels et al. 2009)

"late-time activity"

central engine
still active?

Can a compact binary merger still produce activity as long as ~ 10^4 s after merger???

merger remnant possesses apart from

merger remnant possesses apart from

a) dynamical time scale

$$\tau_{\rm dyn,ns} = \sqrt{\frac{1}{G\bar{\rho}}} \approx 0.1 \text{ ms} \left(\frac{5\times 10^{14}{\rm gcm}^{-3}}{\bar{\rho}}\right)^{1/2}$$

$$\tau_{\rm dyn,bh} = \frac{2\pi}{\omega_{K,ISCO}} \approx 1 \text{ ms} \left(\frac{M_{BH}}{3M_\odot}\right)$$

merger remnant possesses apart from

a) dynamical time scale

$$\tau_{\mathrm{dyn,ns}} = \sqrt{\frac{1}{G\bar{\rho}}} \approx 0.1 \text{ ms} \left(\frac{5 \times 10^{14} \mathrm{gcm}^{-3}}{\bar{\rho}} \right)^{1/2}$$

$$\tau_{\mathrm{dyn,bh}} = \frac{2\pi}{\omega_{K,ISCO}} \approx 1 \text{ ms} \left(\frac{M_{BH}}{3M_{\odot}} \right)$$

b) viscous accretion time scale

$$\tau_{\mathrm{visc}} \sim \frac{1}{\alpha \omega_K} \approx 0.05s \left(\frac{R}{200 \text{ km}} \right)^{3/2} \left(\frac{0.1}{\alpha} \right) \left(\frac{2.5 M_{\odot}}{M_{\mathrm{CO}}} \right)$$

merger remnant possesses apart from

a) dynamical time scale

$$\tau_{\rm dyn,ns} = \sqrt{\frac{1}{G\bar{\rho}}} \approx 0.1 \text{ ms} \left(\frac{5 \times 10^{14} \text{gcm}^{-3}}{\bar{\rho}}\right)^{1/2}$$

$$\tau_{\rm dyn,bh} = \frac{2\pi}{\omega_{K,ISCO}} \approx 1 \text{ ms} \left(\frac{M_{BH}}{3M_\odot}\right)$$

b) viscous accretion time scale

$$\tau_{\rm visc} \sim \frac{1}{\alpha\omega_K} \approx 0.05s \left(\frac{R}{200 \text{ km}}\right)^{3/2} \left(\frac{0.1}{\alpha}\right) \left(\frac{2.5M_\odot}{M_{\rm CO}}\right)$$

also the much longer

c) "fallback time scale" (Rosswog 2007)

merger remnant possesses apart from

a) dynamical time scale

$$\tau_{\rm dyn,ns} = \sqrt{\frac{1}{G\bar{\rho}}} \approx 0.1 \text{ ms} \left(\frac{5\times 10^{14} \text{gcm}^{-3}}{\bar{\rho}}\right)^{1/2}$$

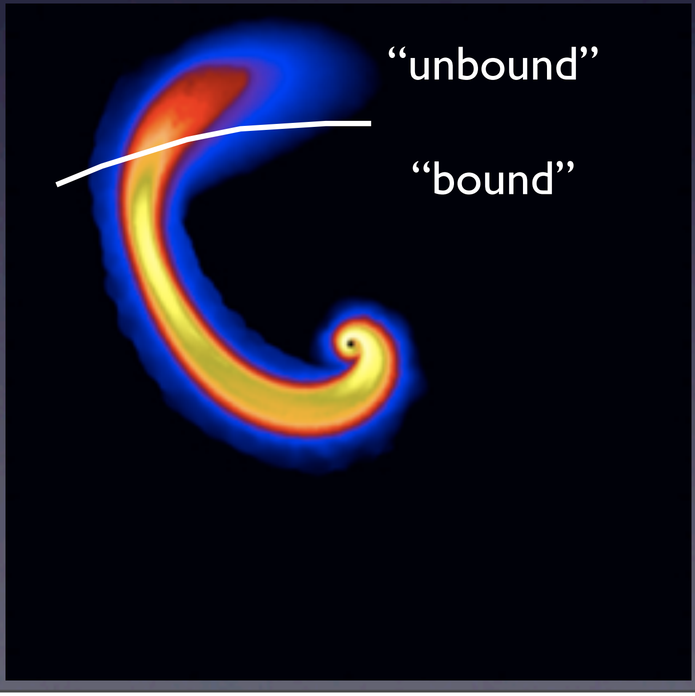
$$\tau_{\rm dyn,bh} = \frac{2\pi}{\omega_{K,ISCO}} \approx 1 \text{ ms} \left(\frac{M_{BH}}{3M_\odot}\right)$$

b) viscous accretion time scale

$$\tau_{\rm visc} \sim \frac{1}{\alpha\omega_K} \approx 0.05s \left(\frac{R}{200 \text{ km}}\right)^{3/2} \left(\frac{0.1}{\alpha}\right) \left(\frac{2.5M_\odot}{M_{\rm CO}}\right)$$

also the much longer

c) “fallback time scale” (Rosswog 2007)



if one assumes...

if one assumes...

a) “fallback matter” is ballistic at end of simulation

if one assumes...

a) “fallback matter” is ballistic at end of simulation

b) dissipates its energy at $R_{\rm dis} \approx 10 G M_{\rm c}/c^2$

if one assumes...

a) "fallback matter" is ballistic at end of simulation

b) dissipates its energy at $R_{\rm dis} \approx 10 G M_{\rm c}/c^2$

c) GR-effects have no substantial influence on time scale

if one assumes...

a) “fallback matter” is ballistic at end of simulation

b) dissipates its energy at $R_{\mathrm{dis}} \approx 10 G M_{\mathrm{c}}/c^2$

c) GR-effects have no substantial influence on time scale

the fallback time can be calculated analytically:

if one assumes...

a) "fallback matter" is ballistic at end of simulation

b) dissipates its energy at $R_{\rm dis} \approx 10GM_{\rm c}/c^2$

c) GR-effects have no substantial influence on time scale

the fallback time can be calculated analytically:

$$\tau_i = \begin{cases} I_{r_i, r_{\max,i}} + I_{r_{\max,i}, R_{\rm dis}} & \text{for} \quad \vec{v}_i \cdot \vec{r}_i > 0 \\ I_{r_i, R_{\rm dis}} & \text{for} \quad \vec{v}_i \cdot \vec{r}_i < 0 \end{cases}$$

$$I_{r_1, r_2} = \left[\frac{\sqrt{Ar^2 + Br + C}}{A} + \frac{B}{2A\sqrt{-A}} \arcsin\left(\frac{2Ar + B}{\sqrt{-D}} \right) \right]_{r_1}^{r_2}$$

if one assumes...

a) "fallback matter" is ballistic at end of simulation

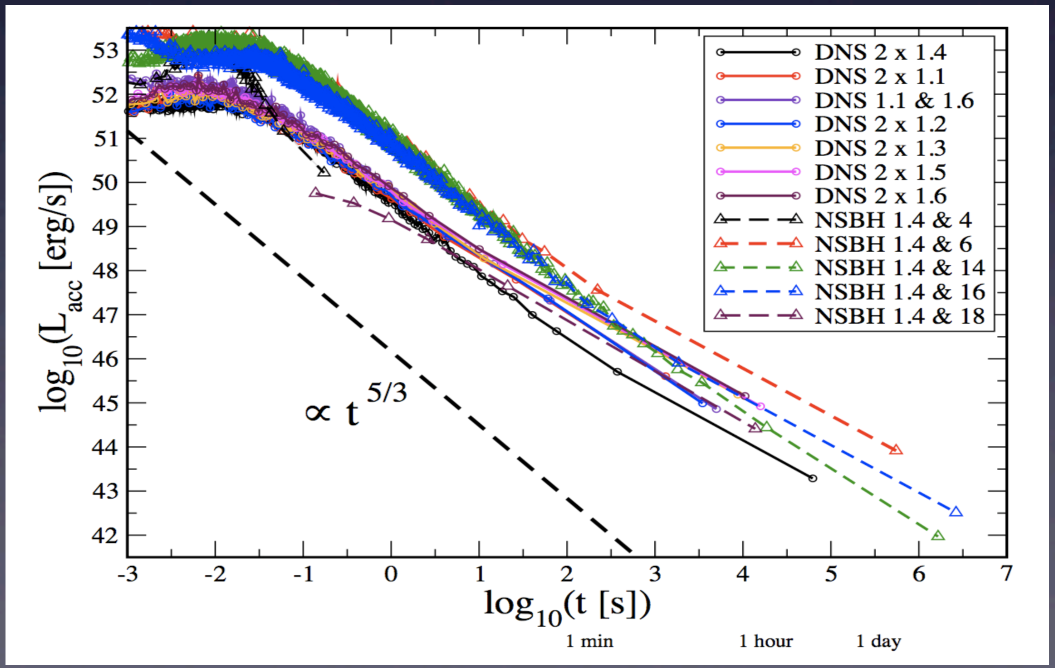
b) dissipates its energy at $R_{\rm dis} \approx 10 G M_{\rm c}/c^2$

c) GR-effects have no substantial influence on time scale

the fallback time can be calculated analytically:

$$\tau_i = \begin{cases} I_{r_i, r_{\max,i}} + I_{r_{\max,i}, R_{\rm dis}} & \text{for} \quad \vec{v}_i \cdot \vec{r}_i > 0 \\ I_{r_i, R_{\rm dis}} & \text{for} \quad \vec{v}_i \cdot \vec{r}_i < 0 \end{cases}$$

$$I_{r_1, r_2} = \left[\frac{\sqrt{Ar^2 + Br + C}}{A} + \frac{B}{2A\sqrt{-A}} \arcsin\left(\frac{2Ar + B}{\sqrt{-D}} \right) \right]_{r_1}^{r_2}$$



(Rosswog 2007)

if one assumes...

a) "fallback matter" is ballistic at end of simulation

b) dissipates its energy at $R_{\rm dis} \approx 10 G M_{\rm c}/c^2$

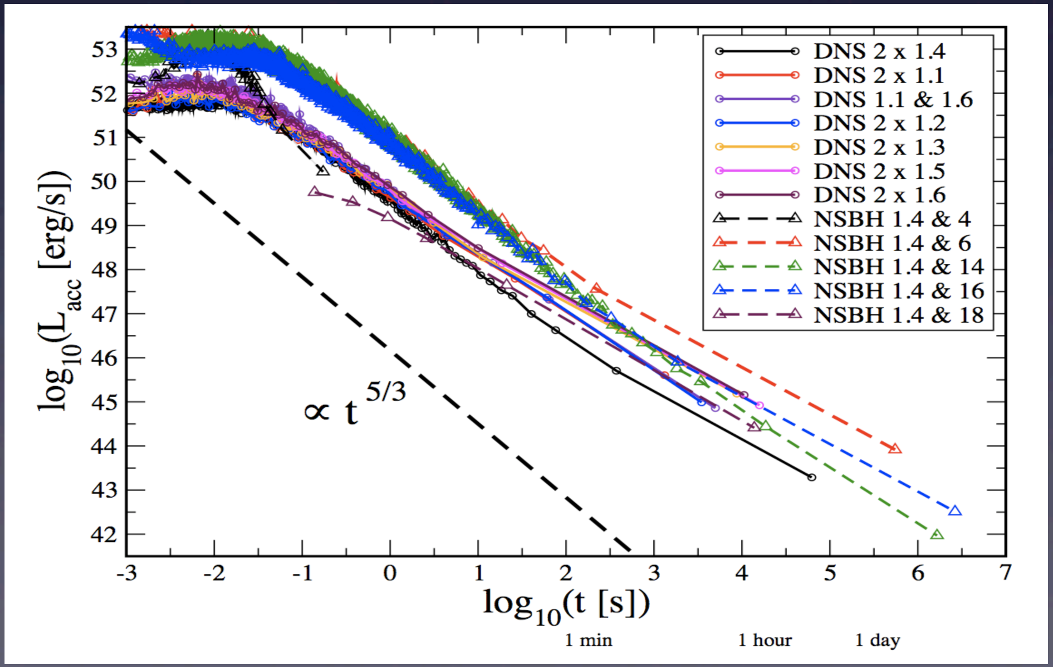
c) GR-effects have no substantial influence on time scale

the fallback time can be calculated analytically:

$$\tau_i = \begin{cases} I_{r_i, r_{\max,i}} + I_{r_{\max,i}, R_{\rm dis}} & \text{for} \quad \vec{v}_i \cdot \vec{r}_i > 0 \\ I_{r_i, R_{\rm dis}} & \text{for} \quad \vec{v}_i \cdot \vec{r}_i < 0 \end{cases}$$

$$I_{r_1, r_2} = \left[\frac{\sqrt{Ar^2 + Br + C}}{A} + \frac{B}{2A\sqrt{-A}} \arcsin\left(\frac{2Ar + B}{\sqrt{-D}} \right) \right]_{r_1}^{r_2}$$

can easily produce fallback for minutes to hours!



(Rosswog 2007)

“Baryonic Pollution Problem”

<u>"Baryonic Pollution Problem"</u>

- observed radiation is produced in

  ultra-relativistic outflows ($\Gamma \sim 300$), *i.e.* $v \sim 0.99998\ c$

"Baryonic Pollution Problem"

- observed radiation is produced in

  ultra-relativistic outflows ($\Gamma \sim 300$), *i.e.* $v \sim 0.99998\, c$

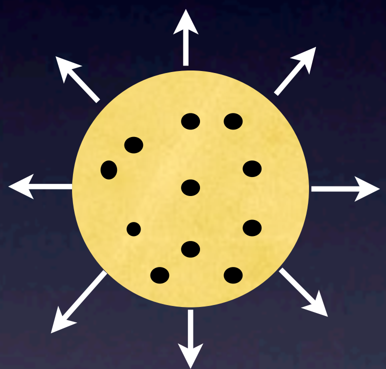
- sphere with (thermal) energy E and baryonic mass m expands to an *asymptotic Lorentz factor*

"Baryonic Pollution Problem"

- observed radiation is produced in

  ultra-relativistic outflows (*Γ ~ 300), i.e. v ~ 0.99998 c*

- sphere with (thermal) energy *E* and baryonic mass *m* expands to an *asymptotic Lorentz factor*



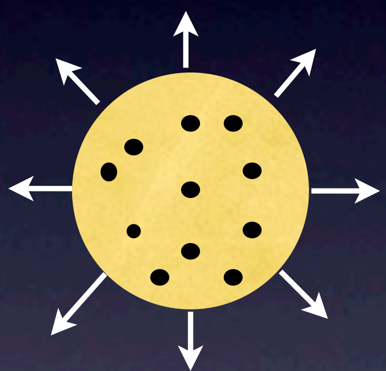
$$\Gamma_{\mathrm{asym}} \approx \frac{E}{mc^2}$$

"Baryonic Pollution Problem"

- observed radiation is produced in

  ultra-relativistic outflows ($\Gamma \sim 300$), *i.e. v ~ 0.99998 c*

- sphere with (thermal) energy *E* and baryonic mass *m* expands to an *asymptotic Lorentz factor*



$$\Gamma_{\rm asym} \approx \frac{E}{mc^2}$$

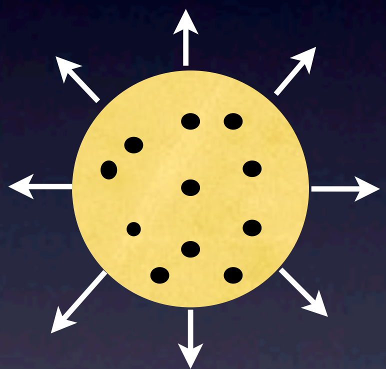
- to reach a Lorentz factor $\Gamma_{\rm asym}$ it cannot be "loaded" with more mass than

"Baryonic Pollution Problem"

- observed radiation is produced in

  ultra-relativistic outflows (*Γ ~ 300), i.e. v ~ 0.99998 c*

- sphere with (thermal) energy *E* and baryonic mass *m* expands to an *asymptotic Lorentz factor*



$$\Gamma_{\rm asym} \approx \frac{E}{mc^2}$$

- to reach a Lorentz factor $\Gamma_{\rm asym}$ it cannot be "loaded" with more mass than

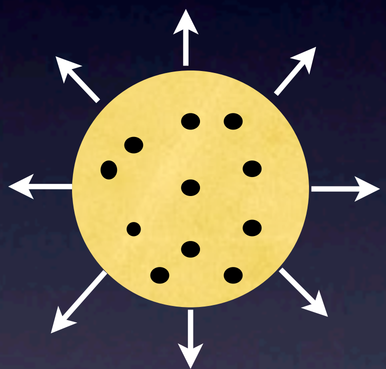
$$m_{\rm crit} = 2 \times 10^{-6} {\rm M}_\odot \; \frac{E/10^{51}{\rm erg}}{\Gamma_{\rm asym}/300}$$

"Baryonic Pollution Problem"

- observed radiation is produced in

  ultra-relativistic outflows (*Γ ~ 300), i.e. v ~ 0.99998 c*

- sphere with (thermal) energy *E* and baryonic mass *m* expands to an *asymptotic Lorentz factor*



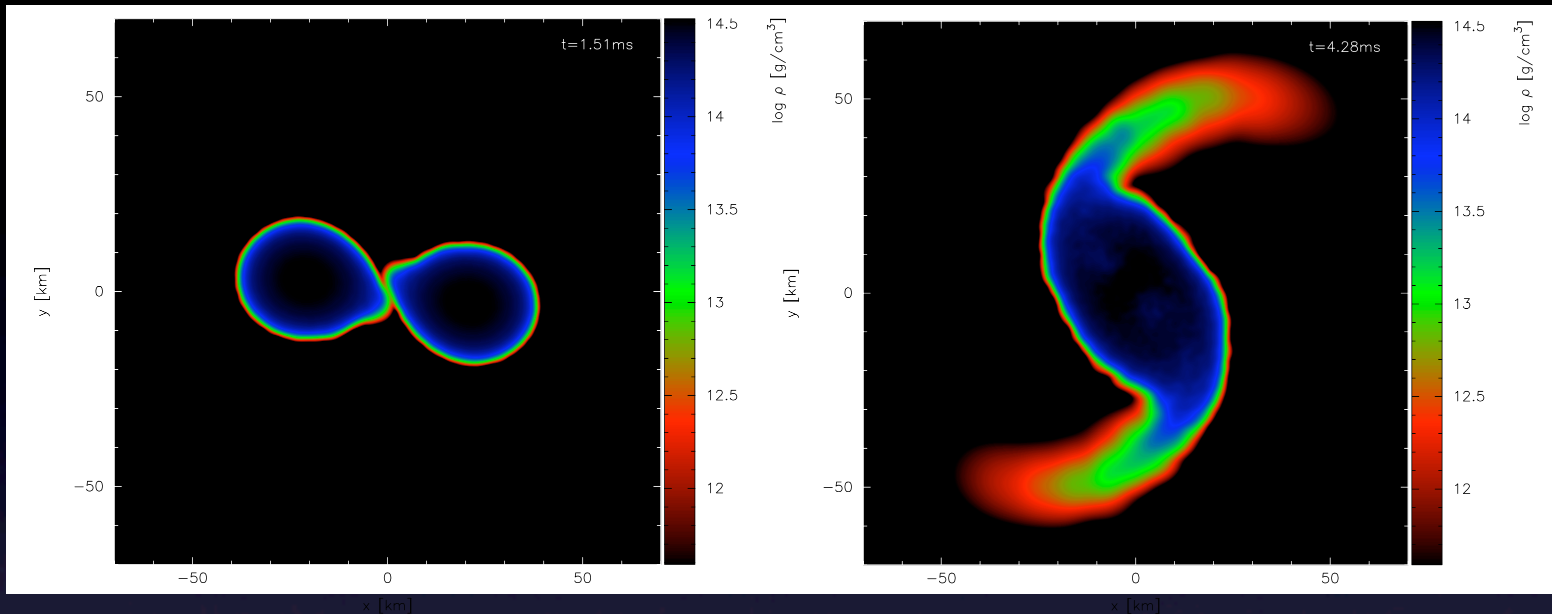
$$\Gamma_{\rm asym} \approx \frac{E}{mc^2}$$

- to reach a Lorentz factor $\Gamma_{\rm asym}$ it cannot be "loaded" with more mass than

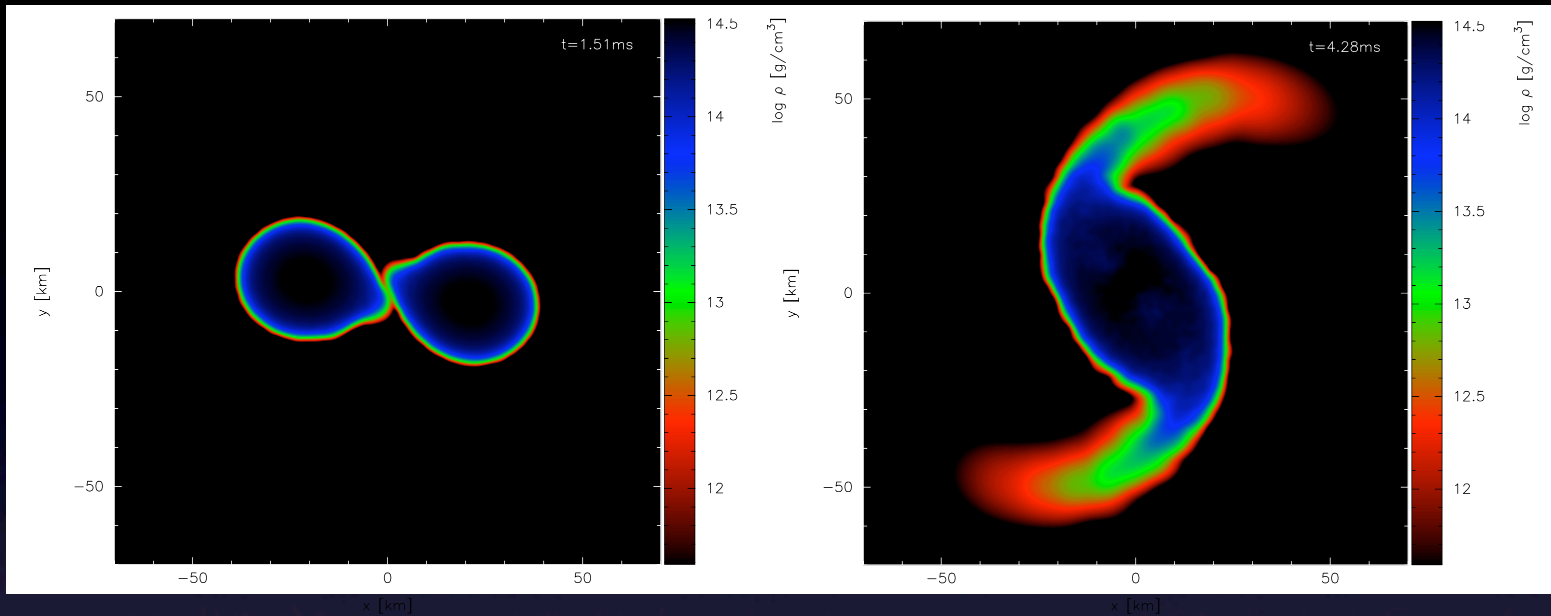
$$m_{\rm crit} = 2 \times 10^{-6} \mathrm{M}_\odot \, \frac{E/10^{51}\mathrm{erg}}{\Gamma_{\rm asym}/300}$$

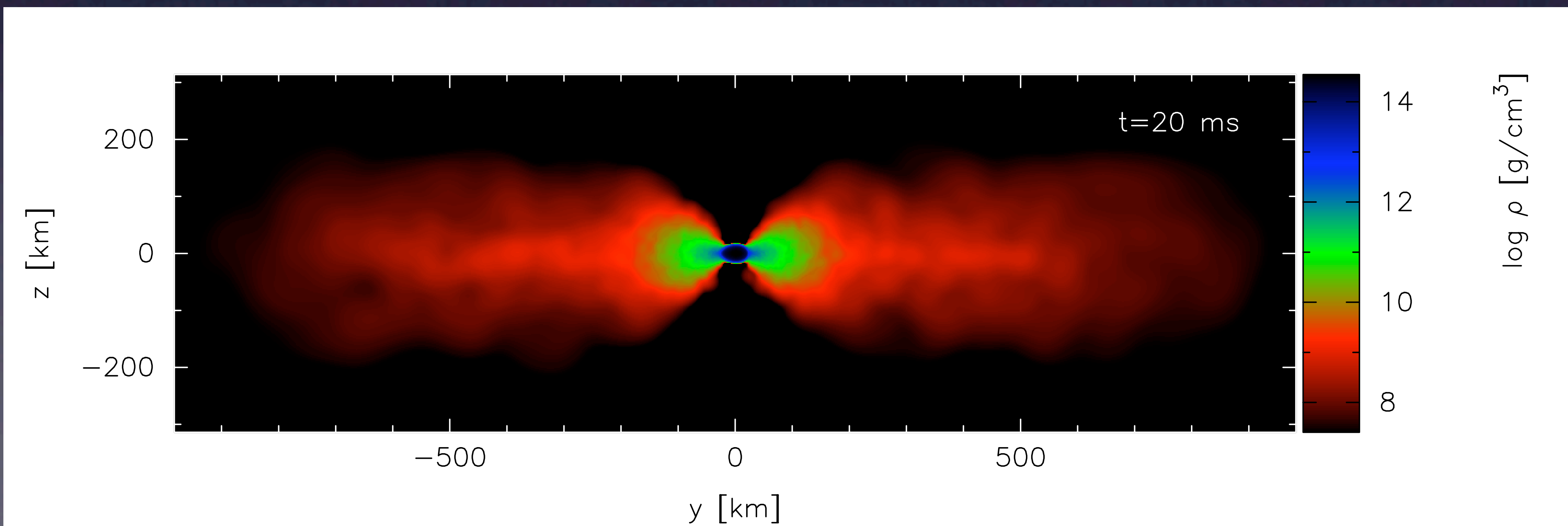
→ How does Nature separate mass from energy???

Previous merger calculations (taken from Rosswog et al. 2006)

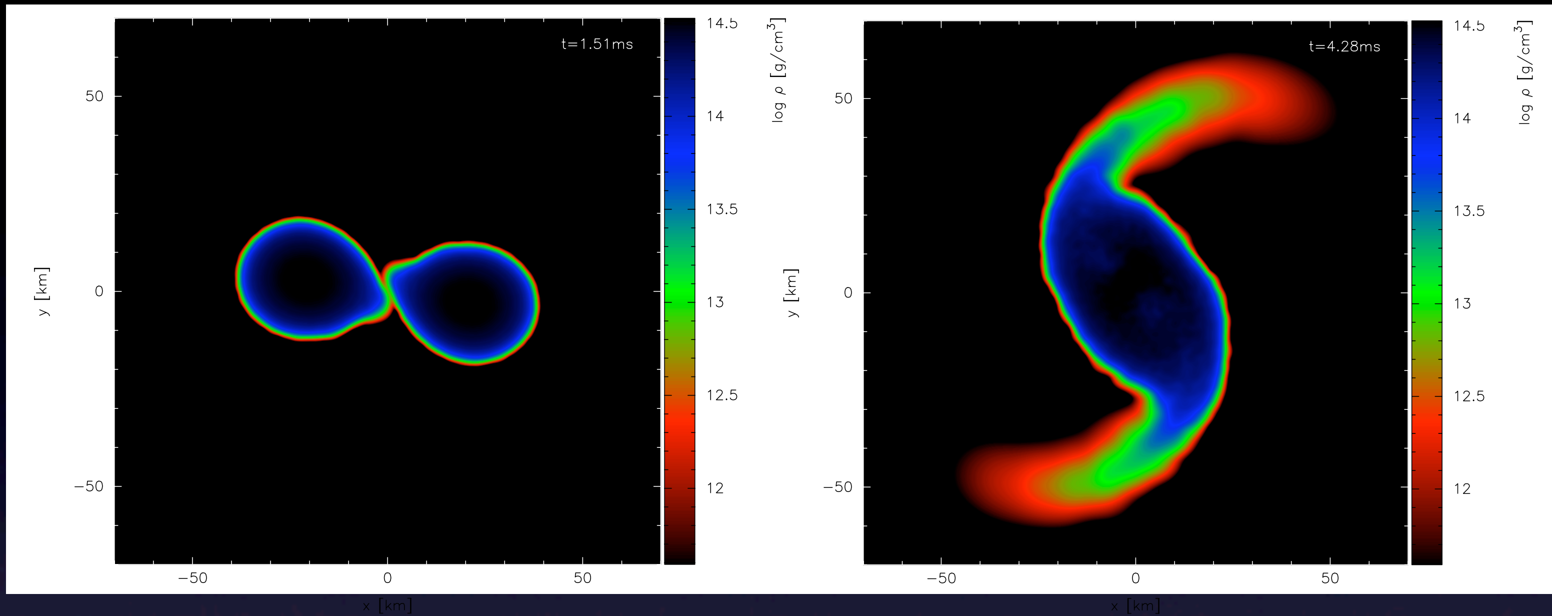


Previous merger calculations (taken from Rosswog et al. 2006)

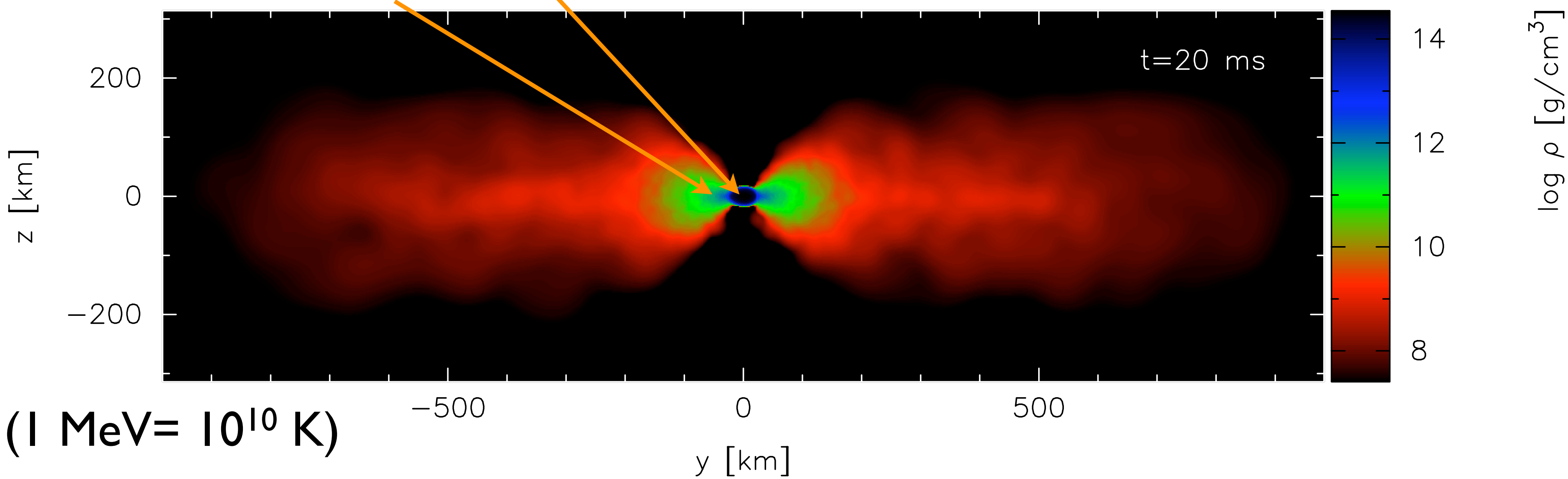




Previous merger calculations (taken from Rosswog et al. 2006)



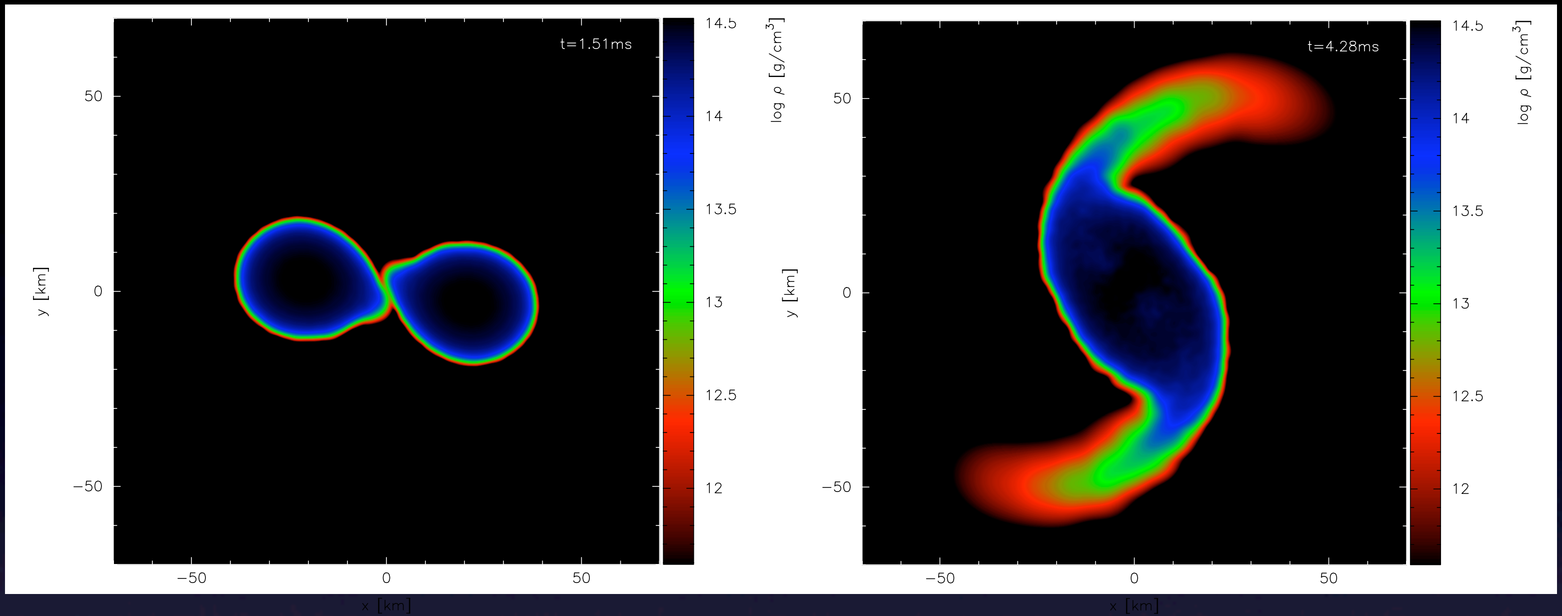
temperatures: ~ 4 MeV ~20 MeV



(1 MeV= 10^{10} K)

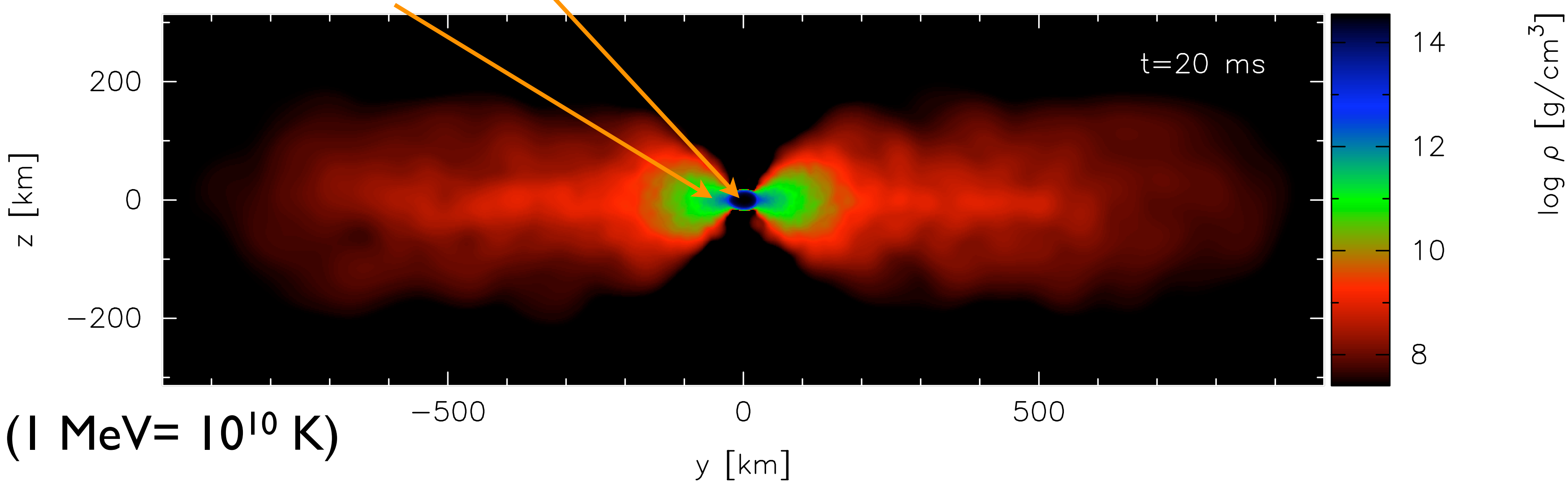
Previous merger calculations

(taken from Rosswog et al. 2006)



temperatures: ~ 4 MeV ~20 MeV

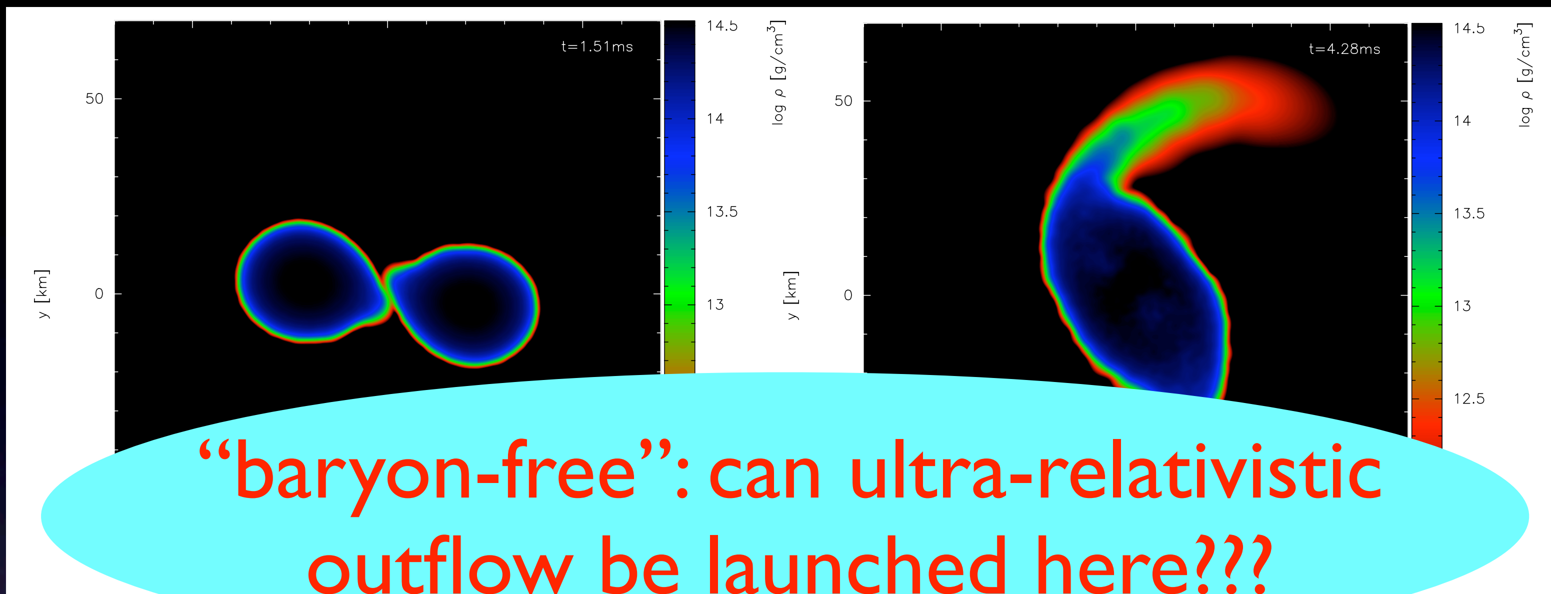
ν-Luminosities: $L_\nu \sim 2 \times 10^{53}$ erg/s



(1 MeV= 10^{10} K)

Previous merger calculations

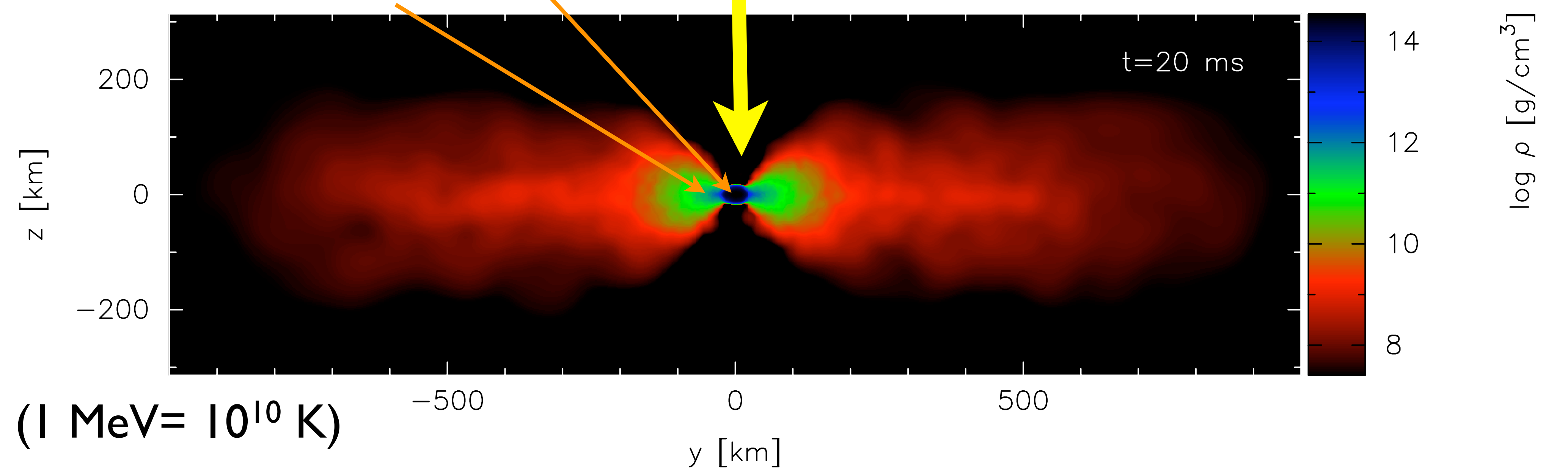
(taken from Rosswog et al. 2006)



"baryon-free": can ultra-relativistic outflow be launched here???

temperatures: ~ 4 MeV ~20 MeV

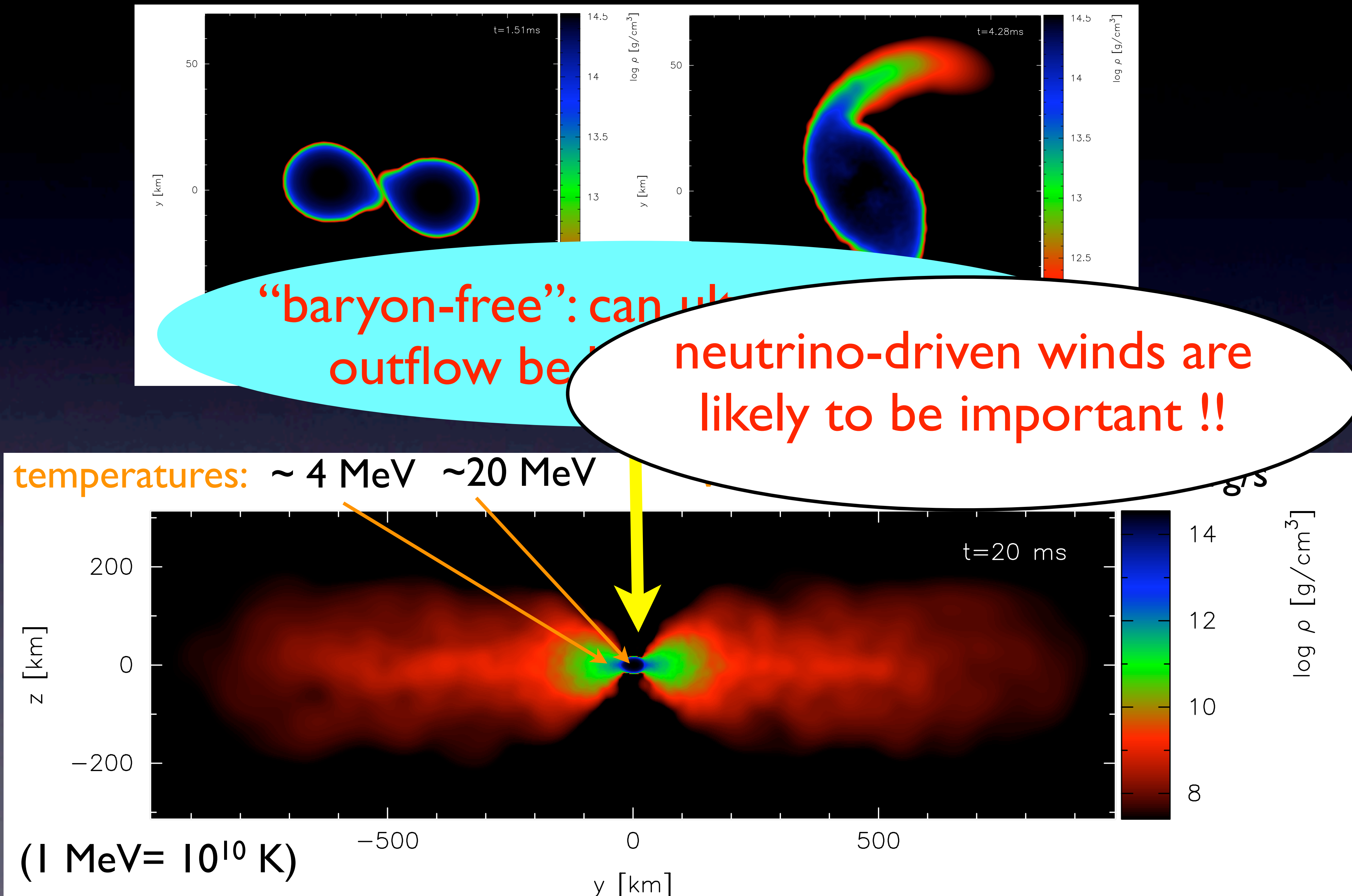
ν-Luminosities: $L_\nu \sim 2 \times 10^{53}$ erg/s



(1 MeV= 10^{10} K)

Previous merger calculations

(taken from Rosswog et al. 2006)



(1 MeV= 10^{10} K)

Our approach

Our approach

- explore: outflow formation vs. neutrino-driven wind

Our approach

- explore: outflow formation vs. neutrino-driven wind

- step 1: simulate early phases with 3D MAGMA code

(Rosswog&Price 2007)

Our approach

- explore: outflow formation vs. neutrino-driven wind

- step 1: simulate early

MAGMA

- 3D Smooth Particle Hydrodynamics
- Magnetic field evolution via Euler potentials
- nuclear equation of state (Shen et al. 1998)
- opacity dependent cooling via neutrinos
- no heating by neutrinos

Our approach

- explore: outflow formation vs. neutrino-driven wind

- step 1: simulate early

MAGMA

- 3D Smooth Particle Hydrodynamics
- Magnetic field evolution via Euler potentials
- nuclear equation of state (Shen et al. 1998)
- opacity dependent cooling via neutrinos
- no heating by neutrinos

- step 2: map results on 2D grid

Our approach

- explore: outflow formation vs. neutrino-driven wind
- step 1: simulate early MAGMA
  - 3D Smooth Particle Hydrodynamics
  - Magnetic field evolution via Euler potentials
  - nuclear equation of state (Shen et al. 1998)
  - opacity dependent cooling via neutrinos
  - no heating by neutrinos
- step 2: map results on 2D grid
- step 3: follow long-term evolution with supernova neutrino-hydrodynamics code VULCAN 2D

(Burrows et al. 2007)

Our approach

- explore: outflow formation vs. neutrino-driven wind

- step 1: simulate early

MAGMA

- 3D Smooth Particle Hydrodynamics
- Magnetic field evolution via Euler potentials
- nuclear equation of state (Shen et al. 1998)
- opacity dependent cooling via neutrinos
- no heating by neutrinos

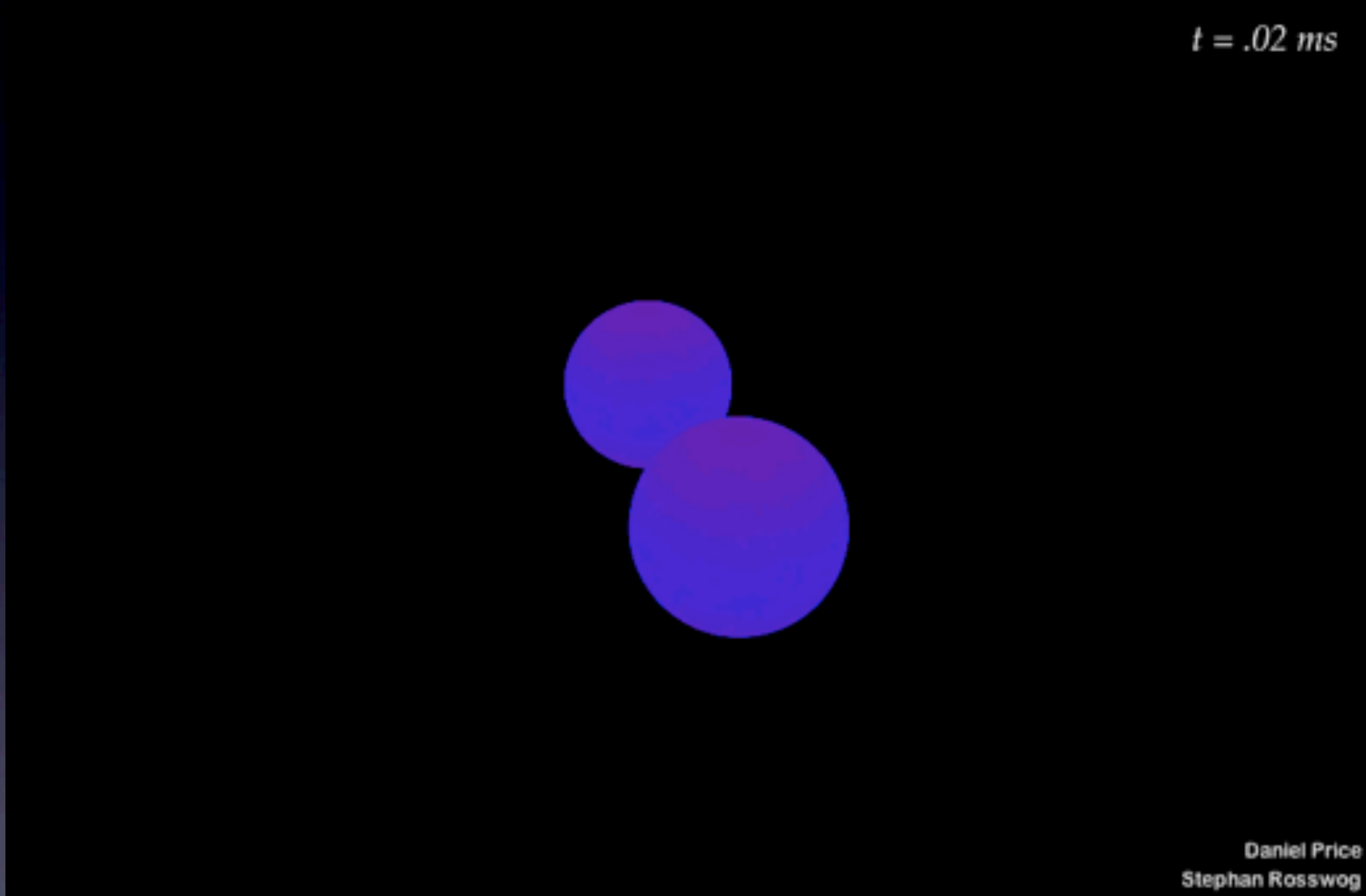
- step 2: map results or

VULCAN 2D

- 2D "ALE" (Adaptive Lagrangian Eulerian)
- nuclear equation of state (Shen et al. 1998)
- state-of-the-art neutrino physics (emission, scattering, absorption)
  - during evolution: "Multi-group Flux Limited diffusion"
  - post-processing: "Multi-angle" or S_n-method
- heating via neutrino absorption & annihilation

- step 3: follow long-te
neutrino-hydr

Step I: typical coalescence: 2 x 1.4 $M_\odot$, no stellar spins



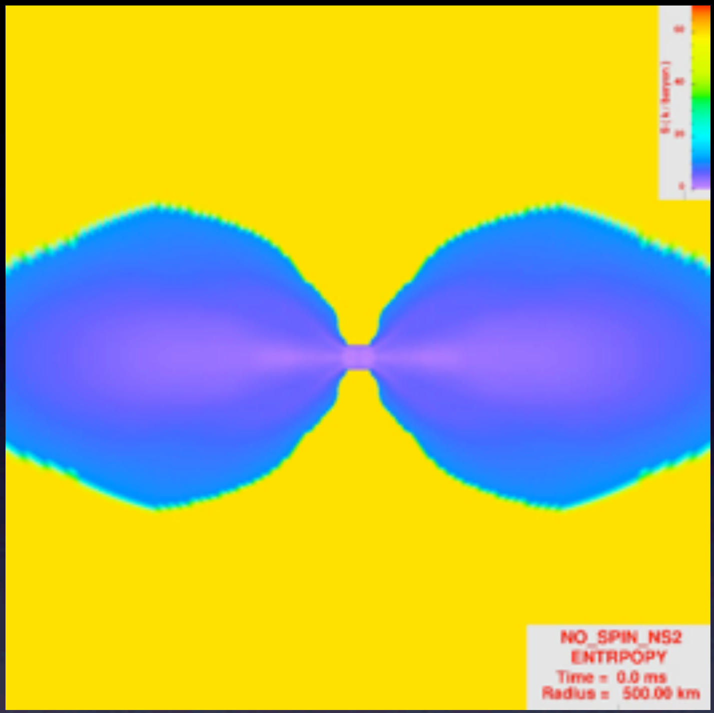
(Price & Rosswog, Sience 2006)

MAGMA simulation includes:
- 3D magnetohydrodynamics
- nuclear equation of state
- opacity-dependent neutrino cooling
- self-gravity + gravitational wave emission

Step II: average results onto a 2D grid

- Step 3: dynamical evolution including neutrino heating and annihilation (VULCAN 2D)

- Step 3: dynamical evolution including neutrino heating and annihilation (VULCAN 2D)



- Step 3: dynamical evolution including neutrino heating and annihilation (VULCAN 2D)

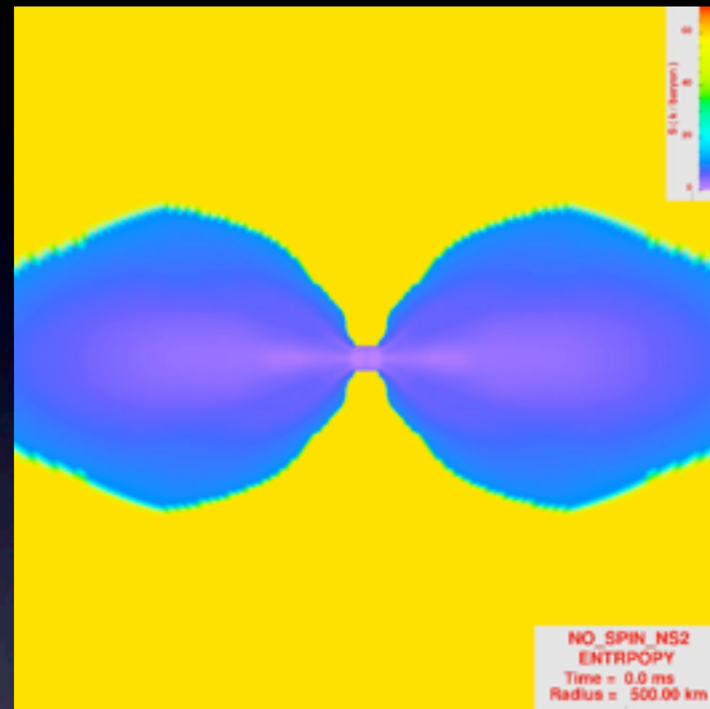
mass loss:

➡ driven by:

$$\begin{aligned} \nu_e + n &\rightarrow e + p \\ \bar{\nu}_e + p &\rightarrow e^+ + n \end{aligned}$$

➡ rate:

$$\frac{dM}{dt} \sim 10^{-3} \frac{M_\odot}{s}$$

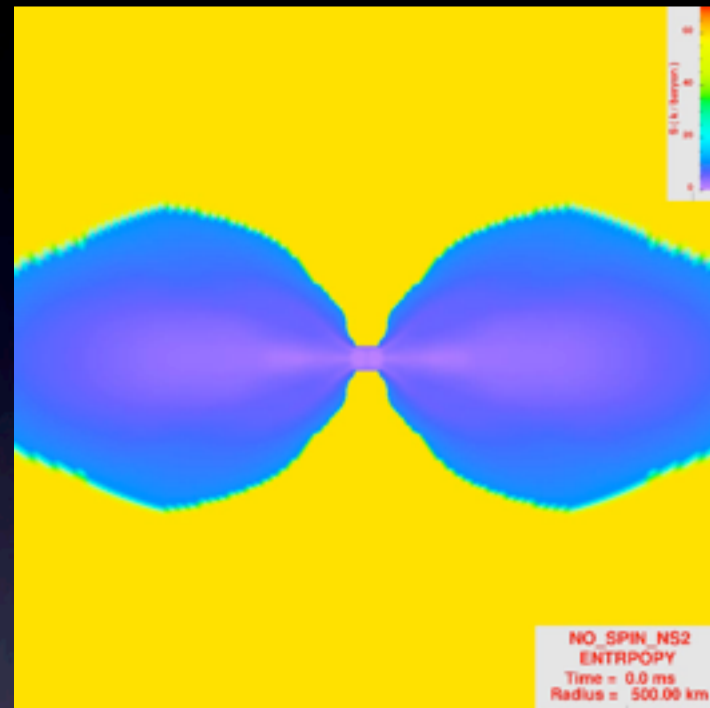


- Step 3: dynamical evolution including neutrino heating and annihilation (VULCAN 2D)

mass loss:

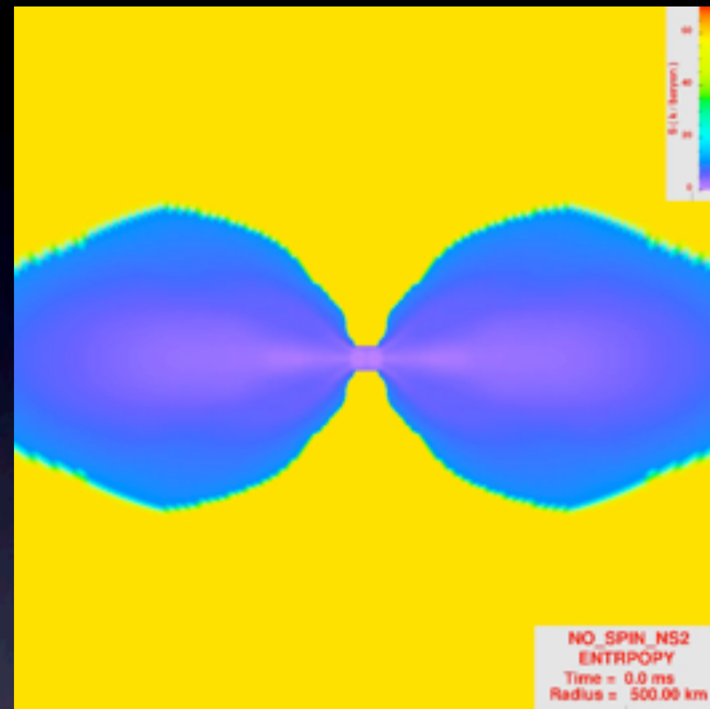
➡ driven by:
$$\begin{aligned} \nu_e + n &\rightarrow e + p \\ \bar{\nu}_e + p &\rightarrow e^+ + n \end{aligned}$$

➡ rate:
$$\frac{dM}{dt} \sim 10^{-3} \frac{M_\odot}{s}$$



strong baryonic pollution in the important location, no relativistic outflow possible as long as the central neutron star is alive!

- Step 3: dynamical evolution including neutrino heating and annihilation (VULCAN 2D)



mass loss:

➡ driven by:
$$\begin{aligned} \nu_e + n &\rightarrow e + p \\ \bar{\nu}_e + p &\rightarrow e^+ + n \end{aligned}$$

➡ rate:
$$\frac{dM}{dt} \sim 10^{-3} \frac{M_\odot}{s}$$

strong baryonic pollution in the important location, no relativistic outflow possible as long as the central neutron star is alive!

What happens after collapse to bh?

Conclusions

Conclusions

- the field has seen tremendous progress in the last decade
- prime example of multi-scale, multi-physics problem

- astrophysics:
  - mass loss: (again) interesting amounts,
    event rates estimates keep increasing
  - GRB:
    - still best central engine model
    - but faces (serious?) challenges (e.g. late-time activity, baryonic pollution)
    - don't rule out alternative/additional possibilities

Conclusions

- the field has seen tremendous progress in the last decade
- prime example of multi-scale, multi-physics problem

- astrophysics:
  - mass loss: (again) interesting amounts,
    event rates estimates keep increasing
  - GRB:
    - still best central engine model
    - but faces (serious?) challenges (e.g. late-time activity, baryonic pollution)
    - don’t rule out alternative/additional possibilities

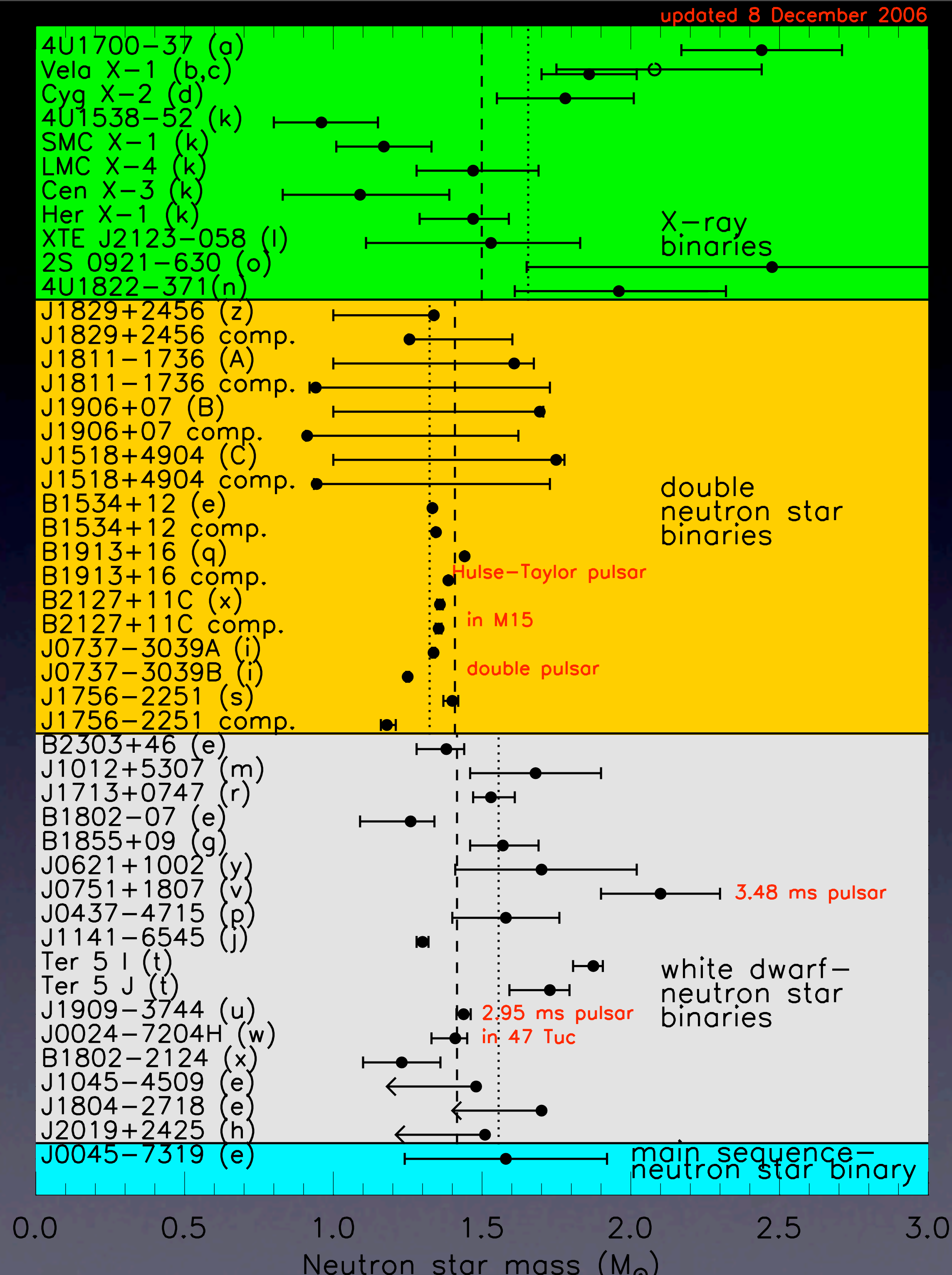
Stay tuned for this exciting field

Classes of binary radio pulsars

Name	Spin period (s)	Orbital period (days)	Orbital eccentricity	Companion mass ($M_\odot$)	Pulsar mass ($M_\odot$)	Remarks	References
Young pulsars with B- or Be-star companions							
J0045–7319	0.926	51.2	0.808	10^{+1}_{-1}	$1.58^{+0.34}_{-0.34}$		(*10, 18*)
B1259–63	0.0478	1236.7	0.870	>3.13			(*107*)
J1740–3052	0.570	231.0	0.579	>11.0			(*13*)
Young pulsars in eccentric orbits with massive white dwarf companions							
J1141–6545	0.394	0.198	0.172	$0.986^{+0.020}_{-0.020}$	$1.30^{+0.02}_{-0.02}$		(*94*)
B2303+46	1.066	12.3	0.658	$1.3^{+0.10}_{-0.10}$	$1.34^{+0.10}_{-0.10}$		(*14, 49*)
Double-neutron-star binaries							
J0737–3039A	0.0227	0.102	0.088	$1.250^{+0.005}_{-0.005}$	$1.337^{+0.005}_{-0.005}$	Double pulsar	(*17*)
J0737–3039B	2.77	0.102	0.088	$1.337^{+0.005}_{-0.005}$	$1.250^{+0.005}_{-0.005}$	Double pulsar	(*17*)
J1518+4904	0.0409	8.63	0.249	$1.05^{+0.45}_{-0.11}$	$1.56^{+0.13}_{-0.45}$		(*10, 108*)
B1534+12	0.0379	0.421	0.274	$1.3452^{+0.0010}_{-0.0010}$	$1.3332^{+0.0010}_{-0.0010}$		(*98*)
J1811–1736	0.104	18.8	0.828	$1.11^{+0.53}_{-0.15}$	$1.62^{+0.22}_{-0.55}$		(*109*)
B1820–11	0.280	357.8	0.795	>0.65		May have MS companion	(*92*)
J1829+2456	0.0410	1.18	0.139	$1.36^{+0.50}_{-0.17}$	$1.14^{+0.28}_{-0.48}$		(*110*)
B1913+16	0.0590	0.323	0.617	$1.3873^{+0.0003}_{-0.0003}$	$1.4408^{+0.0003}_{-0.0003}$		(*99*)
B2127+11C	0.0305	0.335	0.681	$1.36^{+0.04}_{-0.04}$	$1.35^{+0.04}_{-0.04}$	M 15	(*111*)
Pulsars with planets							
B1257+12	0.00622	66.5	0.0183			Three planets	(*112*)
B1620–26	0.0111	191.4	0.0253	$0.34^{+0.04}_{-0.04}$		M 4; WD + 1 planet	(*74, 113*)
Representative "intermediate-mass" systems: mildly recycled pulsars with massive white dwarf companions							
J0621+1002	0.0289	8.32	0.0025	$0.97^{+0.27}_{-0.15}$	$1.70^{+0.32}_{-0.29}$		(*114*)
B0655+64	0.196	1.03	<0.00003	>0.66			(*92*)
J1157–5112	0.0436	3.51	0.00040	>1.18			(*56*)
J1904+0412	0.0711	14.9	0.0002	>0.22			(*58*)
Representative "low-mass" systems: millisecond pulsars with low-mass white dwarf companions							
J0034–0534	0.00188	1.59		>0.14			(*115*)
J0218+4232	0.00232	2.03		$0.21^{+0.17}_{-0.04}$			(*116, 117*)
J0437–4715	0.00576	5.74	0.000019	$0.236^{+0.017}_{-0.017}$	$1.58^{+0.18}_{-0.18}$		(*39*)
J0751+1807	0.00348	0.263	<0.000003	$0.188^{+0.012}_{-0.012}$	$2.2^{+0.2}_{-0.2}$		(*118*)
B0820+02	0.865	1232.5	0.012	>0.19			(*92*)
J1012+5307	0.00526	0.605	<0.0000013	$0.16^{+0.02}_{-0.02}$	$1.64^{+0.22}_{-0.22}$		(*46, 119*)
J1640+2224	0.00316	175.5	0.00080	>0.25			(*112*)
J1713+0747	0.00457	67.8	0.000075	$0.33^{+0.04}_{-0.04}$	$1.60^{+0.24}_{-0.24}$		(*40*)
J1732–5049	0.00531	5.26	0.00001	>0.18			(*56*)
B1855+09	0.00536	12.3	0.000022	$0.267^{+0.010}_{-0.014}$	$1.58^{+0.10}_{-0.13}$		(*120*)
J1909–3744	0.00295	1.53	<0.0000006	>0.20			(*121*)
B1957+20	0.00161	0.382		>0.02		Eclipsing	(*122*)
J2019+2425	0.00393	76.5	0.00011	>0.31	<1.51		(*48*)
Sample of binary pulsars in globular clusters							
B0021–72H	0.00321	2.38	0.071	$0.180^{+0.086}_{-0.016}$	$1.41^{+0.04}_{-0.08}$	47 Tuc	(*123*)
B0021–72J	0.00210	0.121	<0.00004	>0.021		47 Tuc; eclipsing	(*123*)
J0514–4002A	0.0499	18.8	0.89	>0.90		NGC 1851	(*124*)
B1516+02B	0.00795	6.86	0.14	>0.11		M 5	(*125*)
B1639+36B	0.00353	1.26		>0.16		M 13	(*126*)
B1718–19	1.004	0.258		>0.11		NGC 6342; eclipsing	(*127*)
J1740–5340	0.00365	1.354	<0.0001	>0.18		NGC 6397; eclipsing	(*128*)
B1744–24A	0.0116	0.0756		>0.09		Ter 5; eclipsing	(*129*)
B1802–07	0.0231	2.62	0.21	>0.29	<1.43	NGC 6539	(*10, 92*)
J2140–2310A	0.0111	0.174	<0.00012	>0.10		M 30; eclipsing	(*130*)

from Stairs, Science 304, 547 (2004)

J 1756-2251 $m_p = 1.40$
$m_c = 1.18$
$q = 0.84$

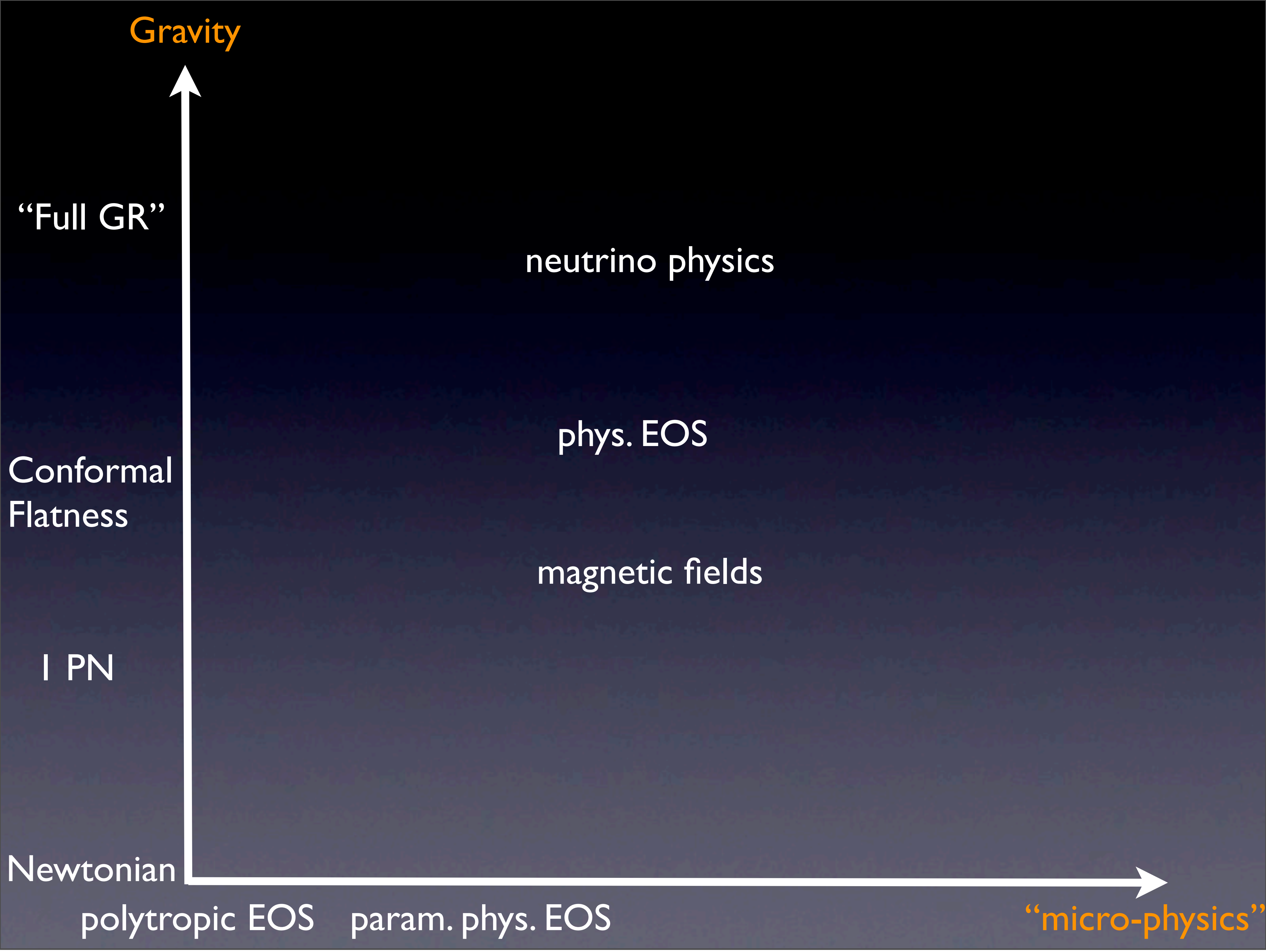


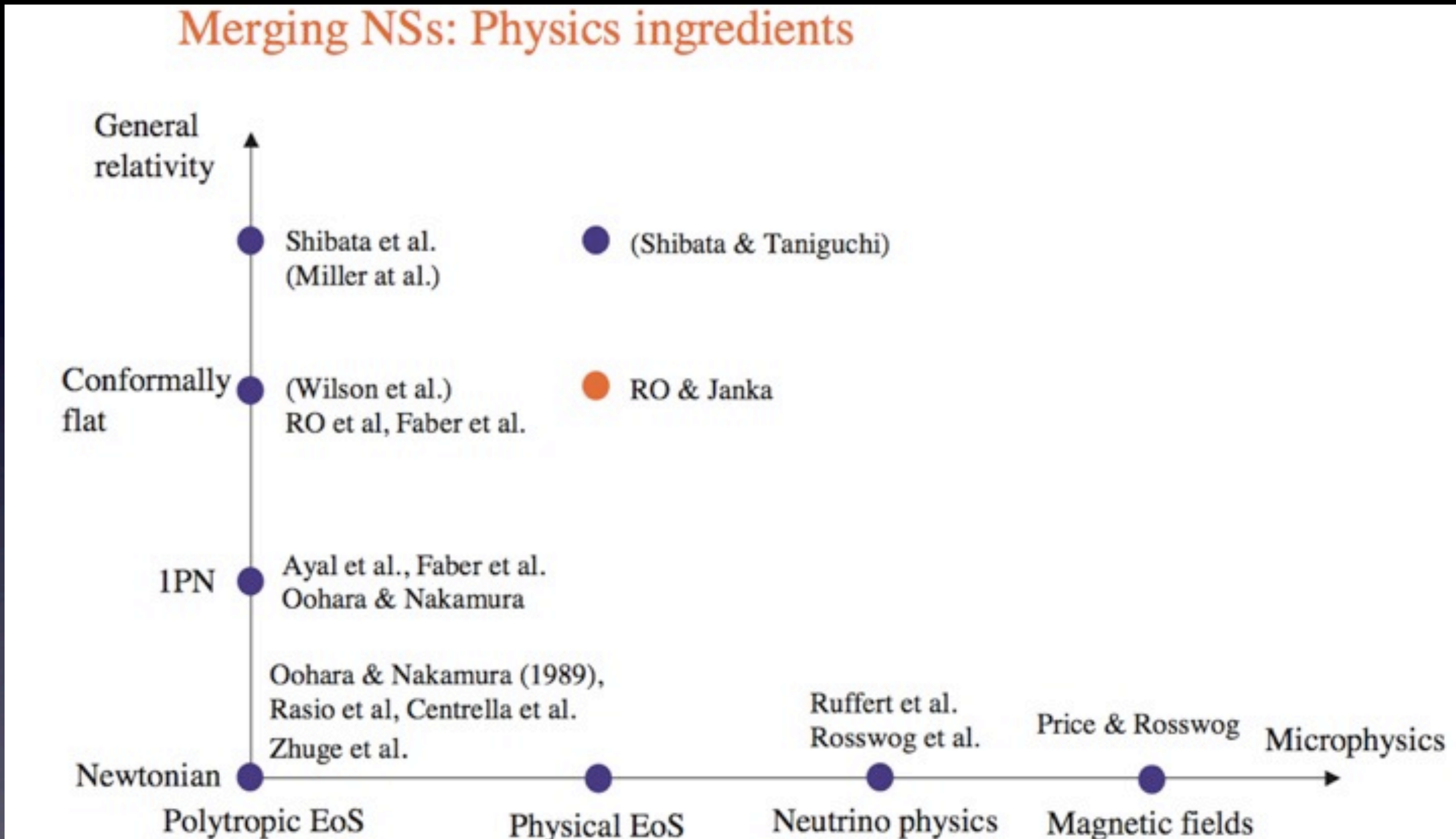
(from Lattimer & Prakash 2007)

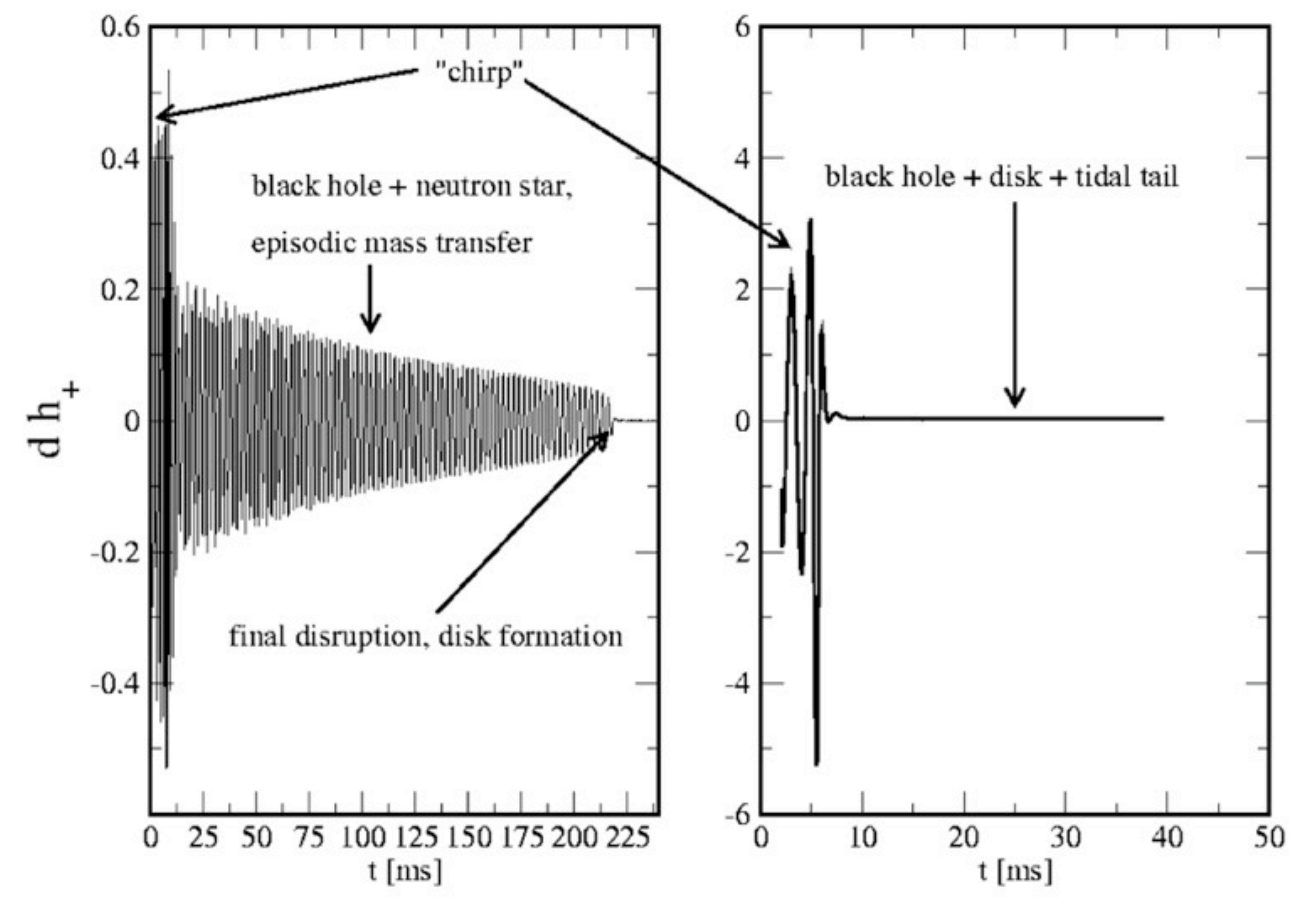
Sample schematic evolutionary tracks (Stairs, Science 304, 547 (2004))

neutron star - white dwarf double neutron star

Fig. 1. Sample schematic evolutionary paths leading to the largest classes of observed binary pulsars. These sequences indicate approximate initial masses for the main-sequence stars but do not show the mass-transfer stages before the explosion of the primary star in paths (**A**), (**B**), and (**D**); this phase should transfer considerable amounts of mass in path (D) (*24*). The evolution after the first supernova in these cases, and for the full path (**C**), is more fully described. The diagrams are not to scale; in particular, common-envelope evolution produces very close binary orbits relative to path (A). In all cases, but especially in path (A), there is great variation in final orbital separation and companion masses.


Gravity
"Full GR"
neutrino physics
phys. EOS
Conformal
Flatness
magnetic fields
1 PN
Newtonian
polytropic EOS
param. phys. EOS
"micro-physics"


Merging NSs: Physics ingredients
General relativity
Shibata et al.
(Miller at al.)
(Shibata & Taniguchi)
Conformally flat
(Wilson et al.)
RO et al, Faber et al.
RO & Janka
1PN
Ayal et al., Faber et al.
Oohara & Nakamura
Oohara & Nakamura (1989),
Rasio et al, Centrella et al.
Zhuge et al.
Ruffert et al.
Rosswog et al.
Price & Rosswog
Microphysics
Newtonian
Polytropic EoS
Physical EoS
Neutrino physics
Magnetic fields



(Rosswog 2007)

Neutron star black hole systems

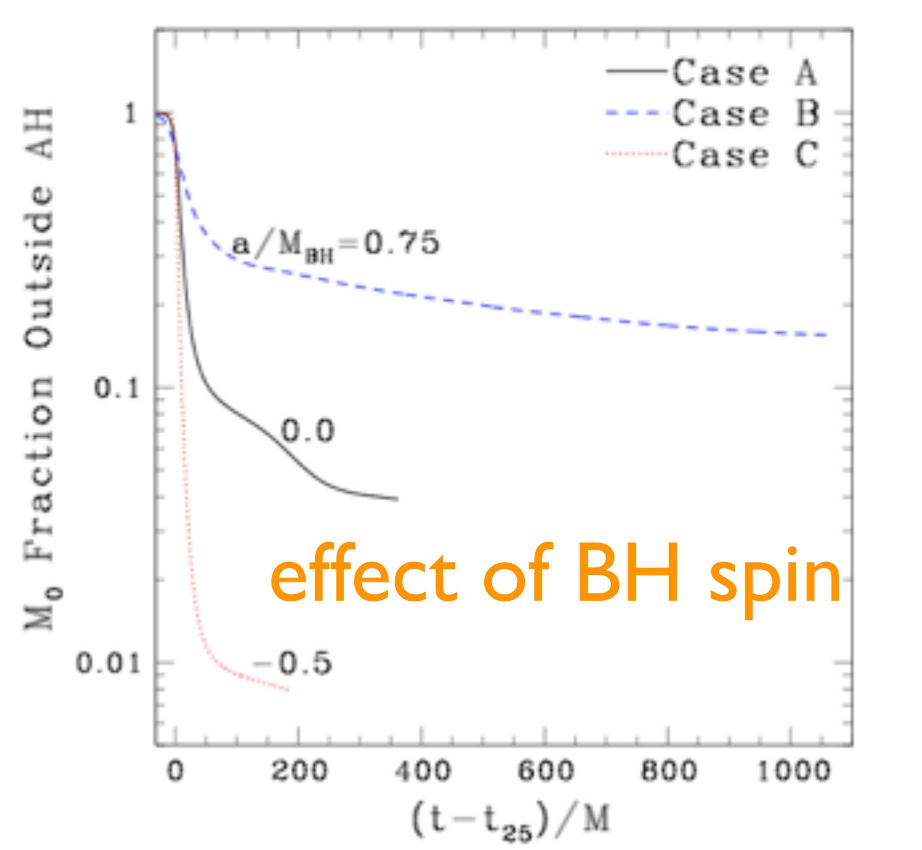


FIG. 13: Rest-mass fraction outside the BH for different initial BH spins (Cases C, A, and B). Here, the time coordinate is shifted by t_{25}, the time at which 25% of the NS rest mass has fallen into the apparent horizon.

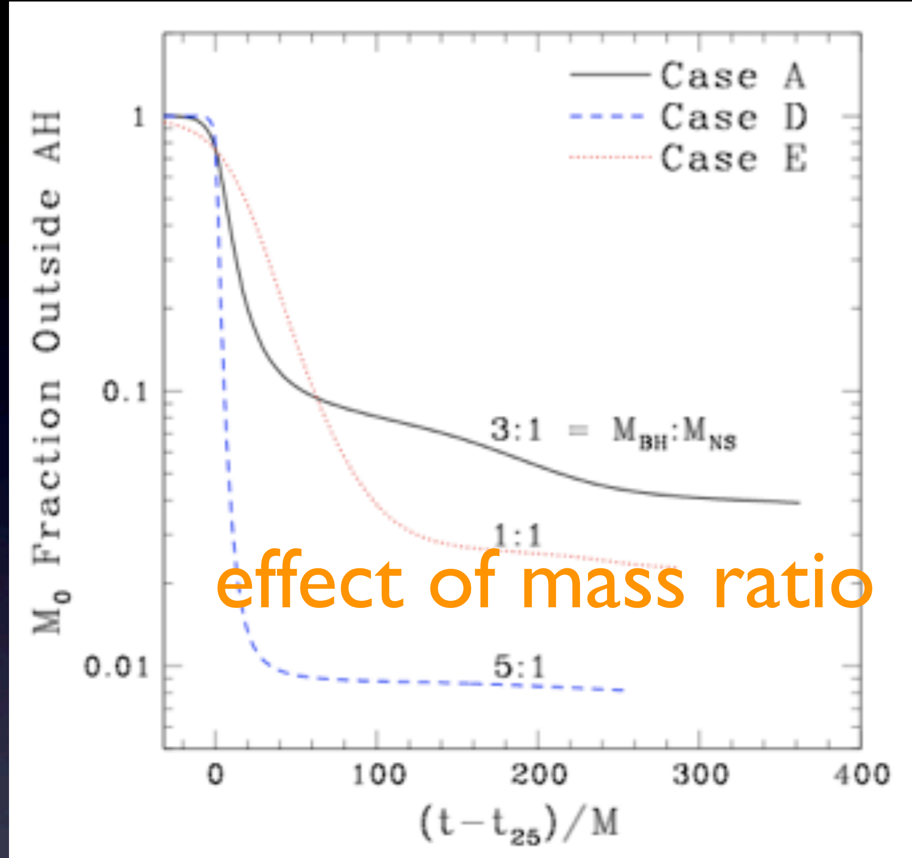
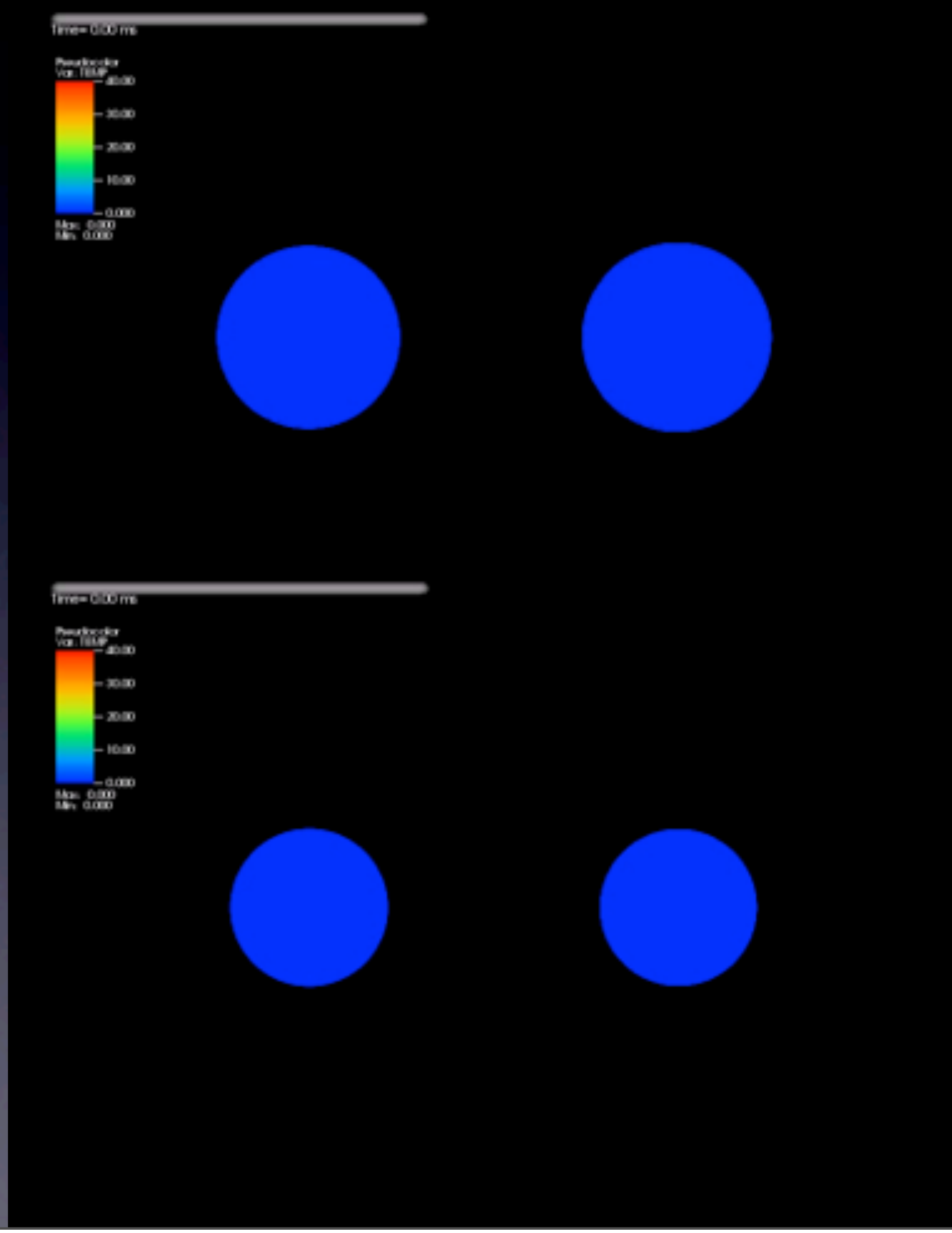


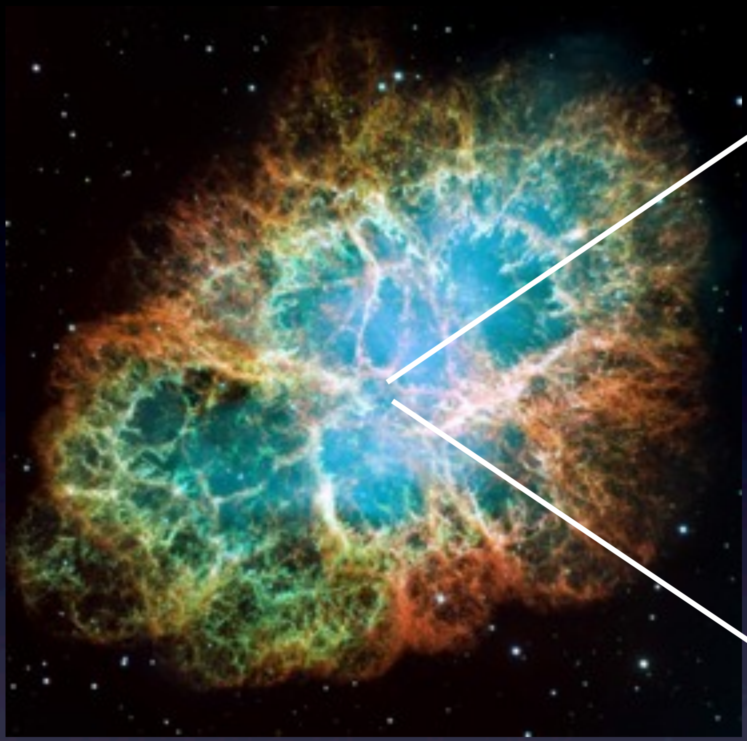
FIG. 14: Rest-mass fraction outside the BH for different BHNS mass ratios. Here, the time coordinate is shifted by t_{25}, the time at which 25% of the NS rest mass has fallen into the apparent horizon.

(Etienne et al. 2009)

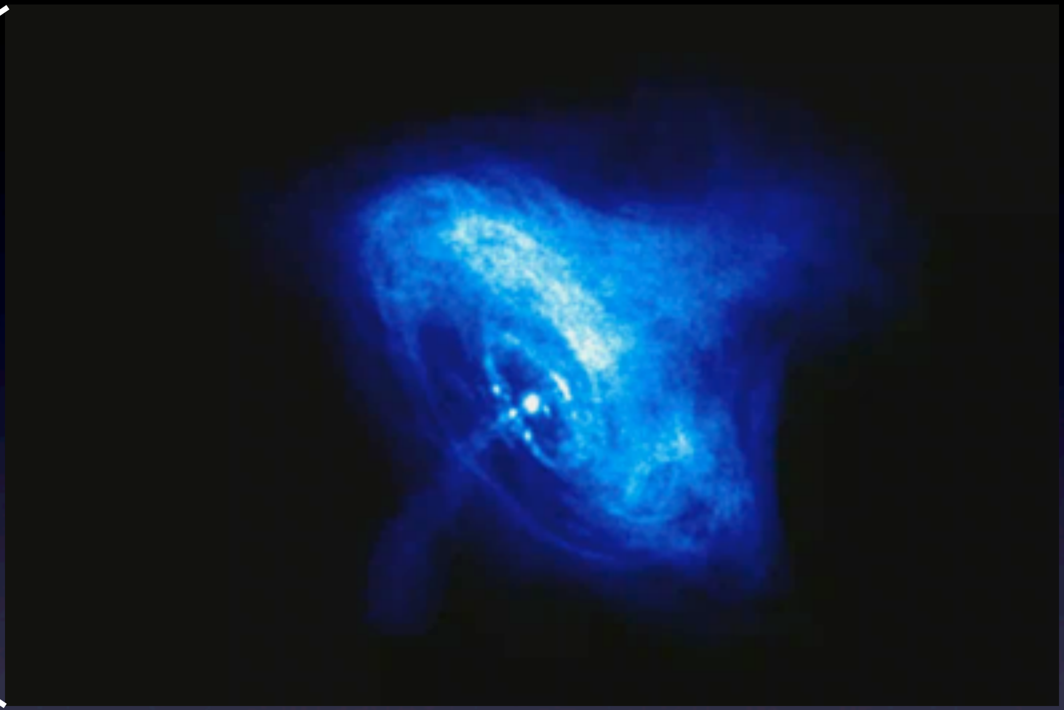
“How different is a strange star merger from a neutron star merger?”



I. Introduction



Crab nebula



Chandra

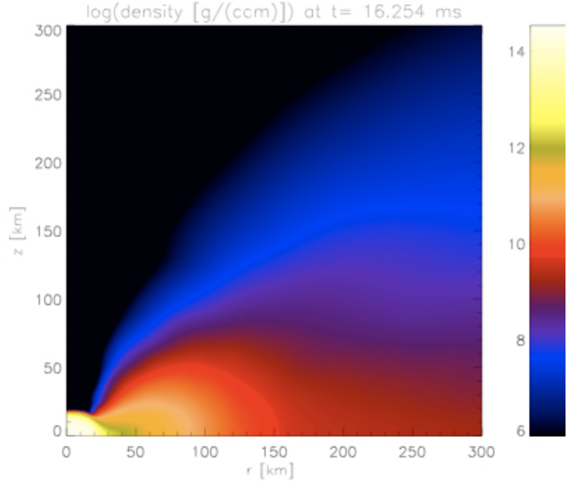
estimated galactic numbers of (Lorimer 2008)

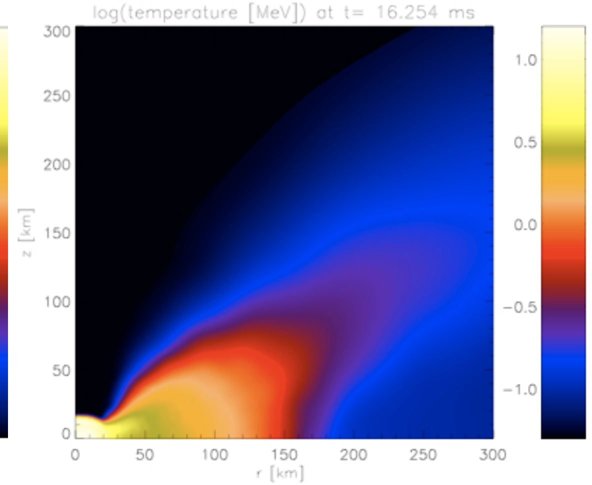
i) active normal pulsars: ~ 160 000

ii) millisecond pulsars: ~ 40 000

- Step 2: map on 2D

  (t= 16.3 ms)

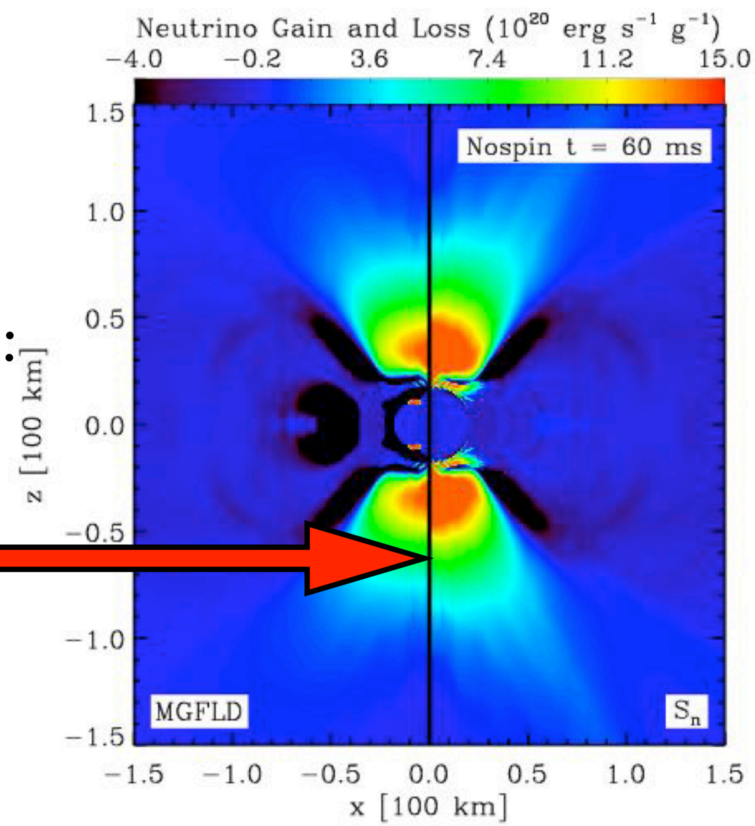




- Step 3: long-term evolution with neutrino hydrodynamics code VULCAN

  neutrino loss and gain at t= 60 ms:

  maximum gain along the polar axis!



MGFLD: Multi-group flux-limited diffusion

S_n: short-characteristic method

I. Introduction

Sample schematic evolutionary tracks

(from Fryer et al. 1999)

I. Introduction

Sample schematic evolutionary tracks

(from Fryer et al. 1999)

double neutron stars

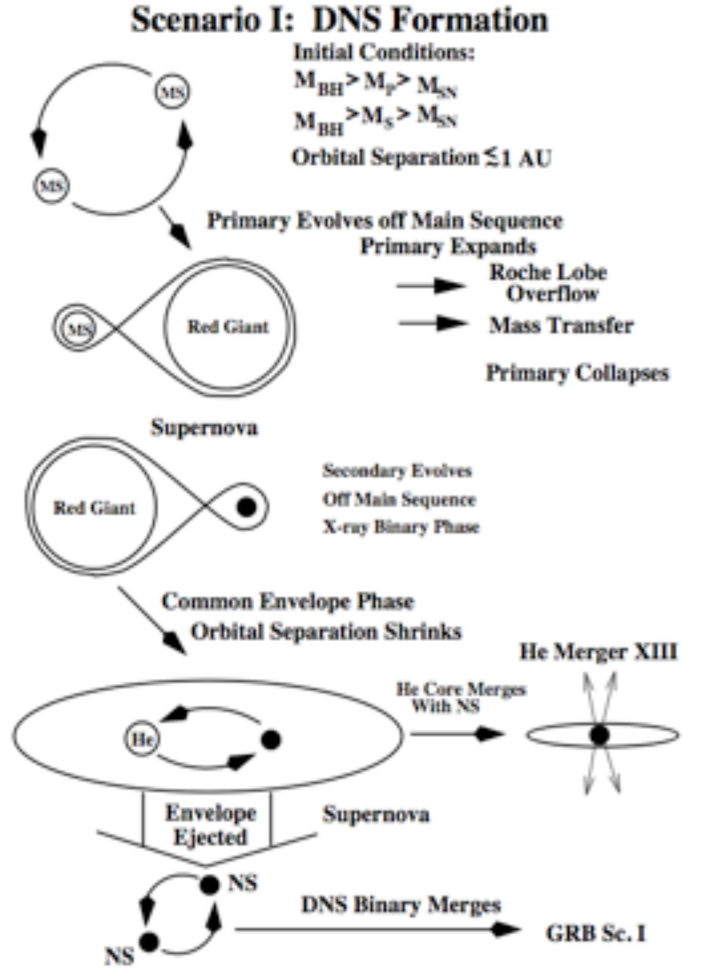


FIG. 2.—Scenario I: "Standard" double neutron star formation scenario. All symbols are as described in Fig. 1. MS denotes a main-sequence star and NS and BH are neutron stars and black holes, respectively. Note that if the neutron star merges with its helium companion in the common envelope phase, a He-merger GRB is produced. This scenario assumes that the accretion onto the neutron star during this phase is limited to the photon Eddington rate.

I. Introduction

Sample schematic evolutionary tracks

(from Fryer et al. 1999)

double neutron stars

neutron star black hole system

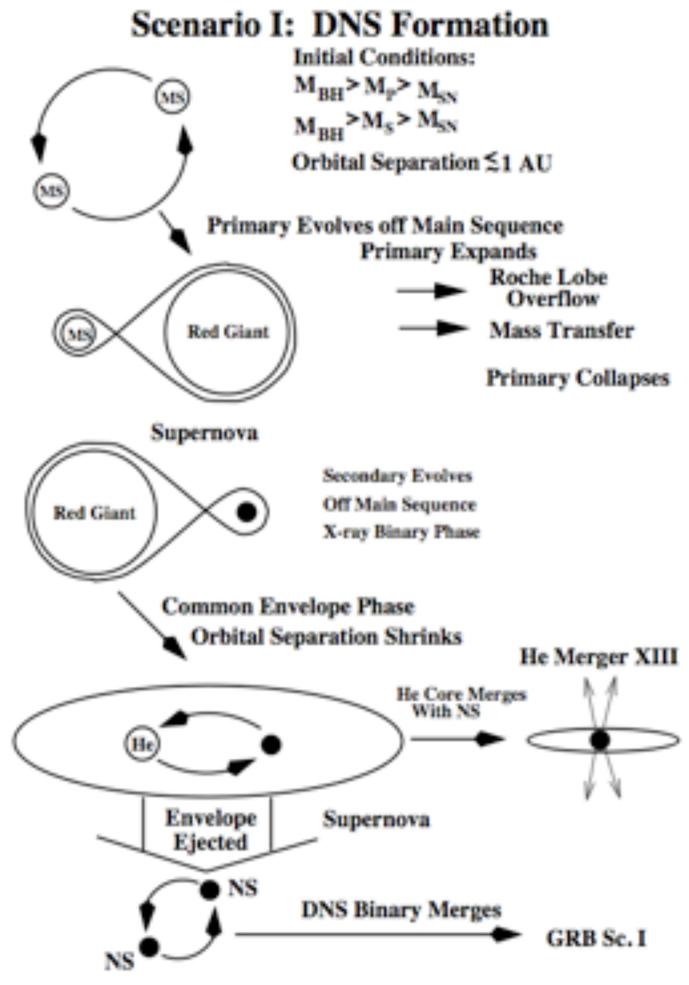


FIG. 2.—Scenario I: "Standard" double neutron star formation scenario. All symbols are as described in Fig. 1. MS denotes a main-sequence star and NS and BH are neutron stars and black holes, respectively. Note that if the neutron star merges with its helium companion in the common envelope phase, a He-merger GRB is produced. This scenario assumes that the accretion onto the neutron star during this phase is limited to the photon Eddington rate.

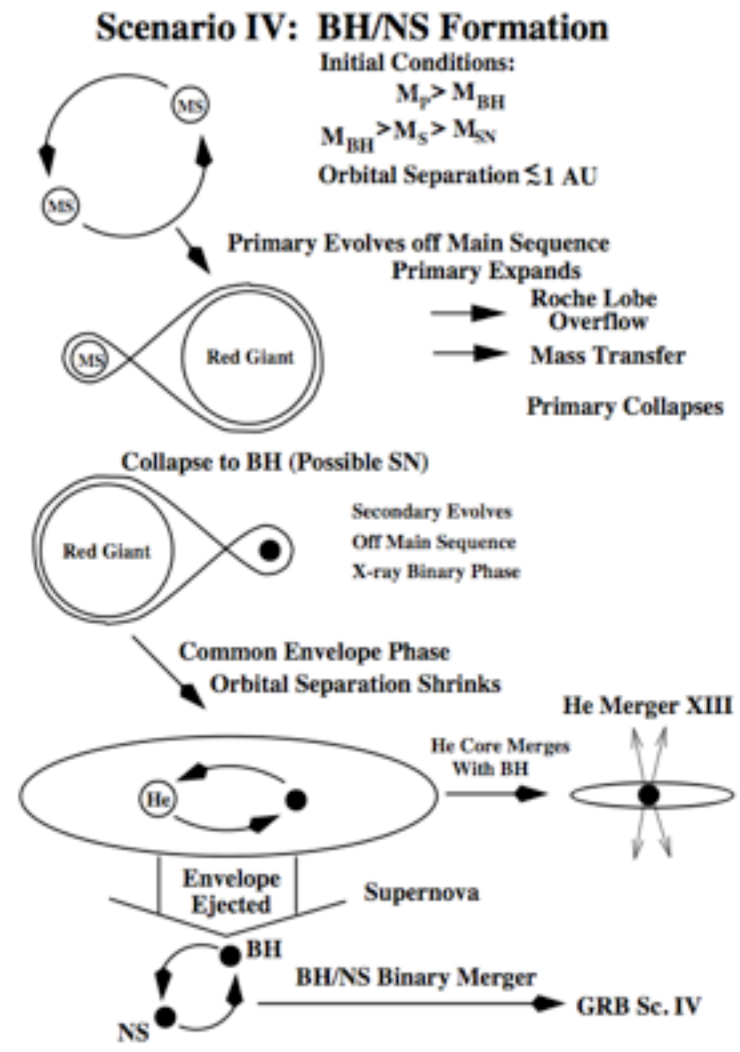
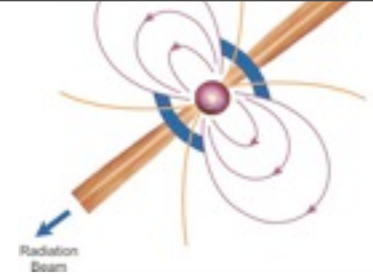


FIG. 5.—Scenario IV: "Standard" BH/NS binary formation phase. This scenario is identical to scenario I (Fig. 2), except that the primary mass (M_p) is greater than the critical mass for black hole formation.

- magnetic dipole model
  - ➡ dipole magnetic field
  - ➡ emission of magnetic dipole radiation
  - ➡ at expense of rotational energy

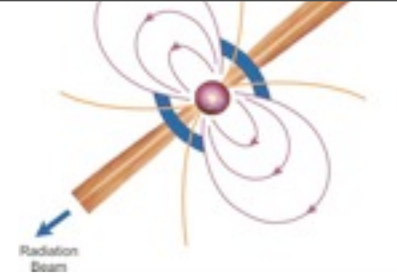
➡ neutron star slows down



$$L_{\mathrm{md}} = -\frac{2}{3c^3}|\ddot{\vec{m}}|^2$$

$$\dot{P} \propto \frac{B^2}{P}$$

- magnetic dipole model
  - ➡ dipole magnetic field
  - ➡ emission of magnetic dipole radiation
  - ➡ at expense of rotational energy
  - ⇨ neutron star slows down

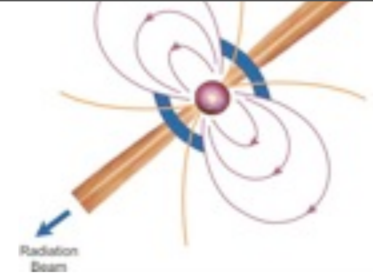


$$L_{\mathrm{md}} = -\frac{2}{3c^3}|\ddot{\vec{m}}|^2$$

$$\dot{P} \propto \frac{B^2}{P}$$

- P & $\dot{P}$ + "dipole model"

- magnetic dipole model
  - ➡ dipole magnetic field
  - ➡ emission of magnetic dipole radiation
  - ➡ at expense of rotational energy
  - ⇨ neutron star slows down

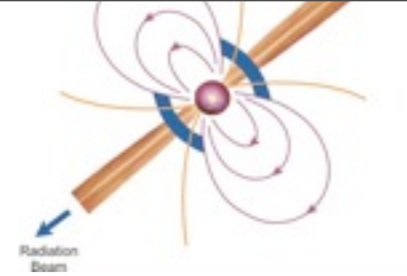


$$L_{\rm md} = -\frac{2}{3c^3}|\ddot{\vec{m}}|^2$$

$$\dot{P} \propto \frac{B^2}{P}$$

- P & $\dot{P}$ + "dipole model"
  - ⇨ i) B-field ii) "dipole age" $\tau = \frac{P}{2\dot{P}}$

- magnetic dipole model
  - ➡ dipole magnetic field
  - ➡ emission of magnetic dipole radiation
  - ➡ at expense of rotational energy
  - ⇒ neutron star slows down



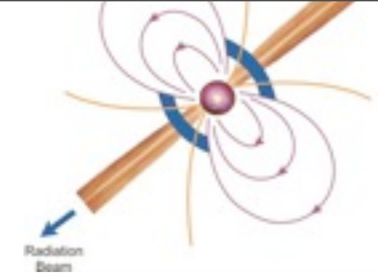
$$L_{\rm md} = -\frac{2}{3c^3}|\ddot{\vec{m}}|^2$$

$$\dot{P} \propto \frac{B^2}{P}$$

- P & $\dot{P}$ + "dipole model"
  - ⇒ i) B-field ii) "dipole age" $\tau = \frac{P}{2\dot{P}}$

- "P-Pdot-diagram"

- [magnetic dipole model]
  - ➡ dipole magnetic field
  - ➡ emission of magnetic dipole radiation
  - ➡ at expense of rotational energy
  - ⇨ neutron star slows down



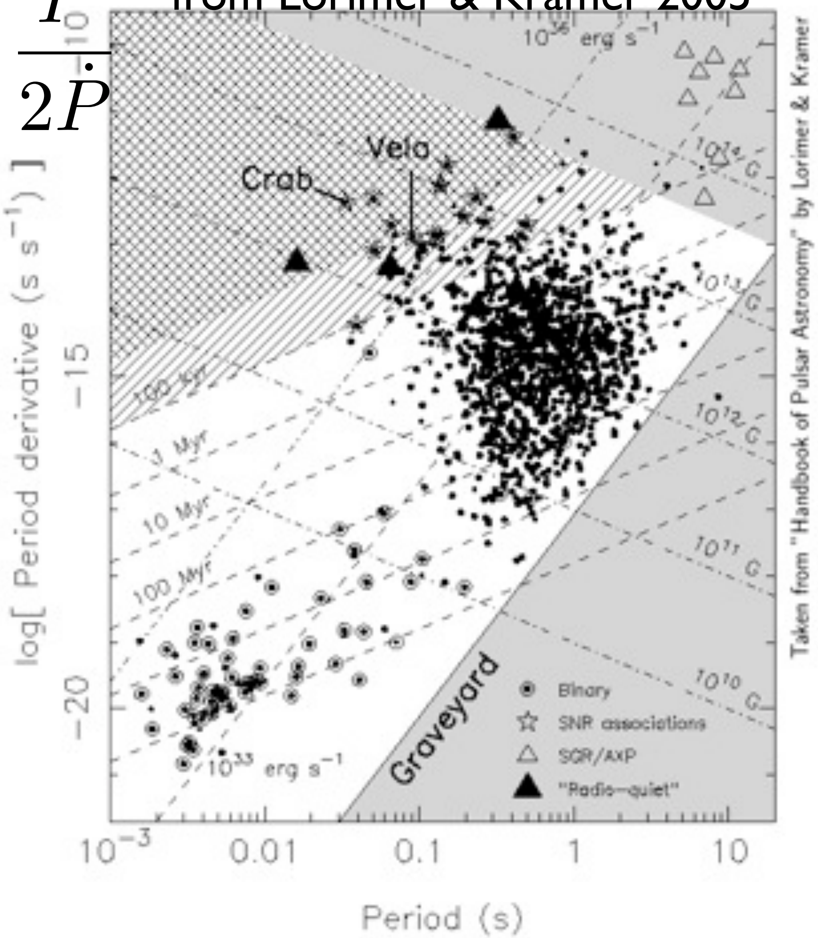
$$L_{\rm md} = -\frac{2}{3c^3}|\ddot{\vec{m}}|^2$$

$$\dot{P} \propto \frac{B^2}{P}$$

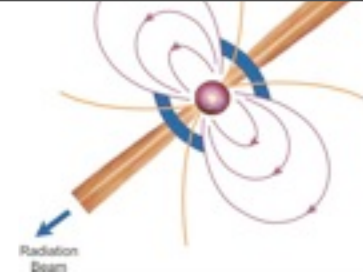
- P & $\dot{P}$ + "dipole model"
  - ⇨ i) B-field ii) "dipole age" $\tau = \dfrac{P}{2\dot{P}}$

- ["P-Pdot-diagram"]

from Lorimer & Kramer 2005



- magnetic dipole model
  - ➡ dipole magnetic field
  - ➡ emission of magnetic dipole radiation
  - ➡ at expense of rotational energy
  - ➡ neutron star slows down



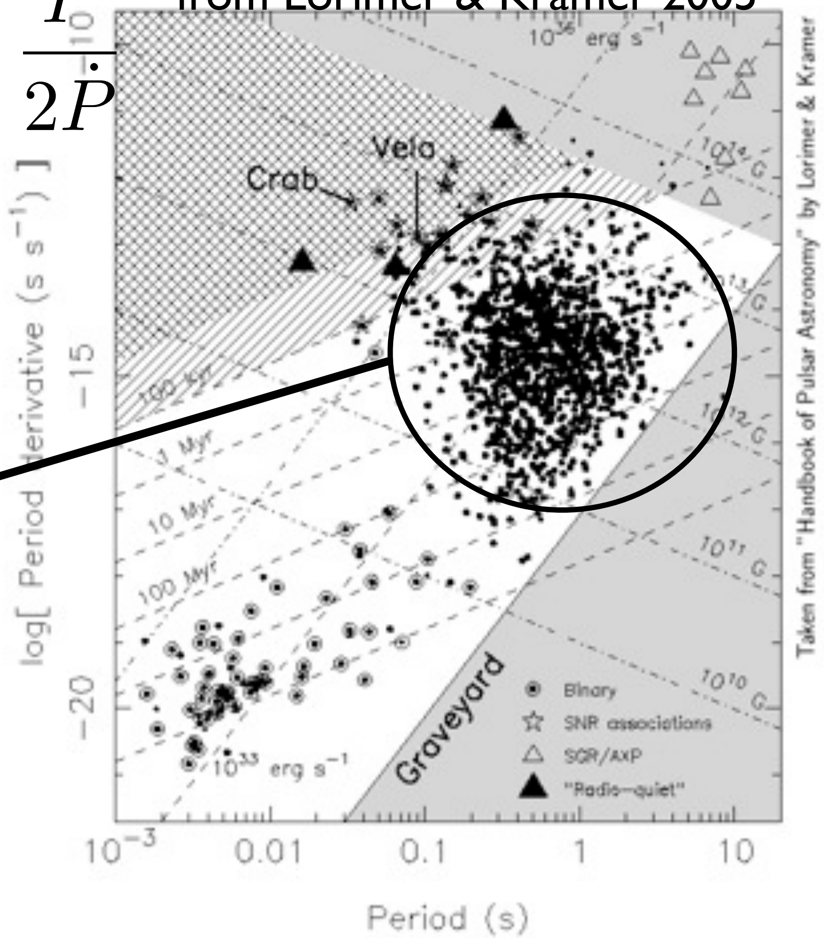
$$L_{\rm md} = -\frac{2}{3c^3}|\ddot{\vec{m}}|^2$$

$$\dot{P} \propto \frac{B^2}{P}$$

- P & $\dot{P}$ + “dipole model”
  - ➡ i) B-field ii) “dipole age” $\tau = \frac{P}{2\dot{P}}$

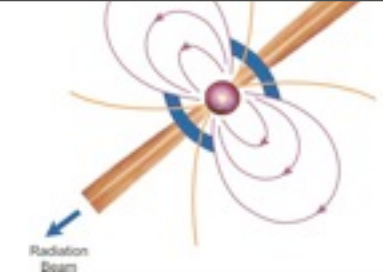
- “P-Pdot-diagram”

from Lorimer & Kramer 2005



“normal pulsars”

- magnetic dipole model
  - ➡ dipole magnetic field
  - ➡ emission of magnetic dipole radiation
  - ➡ at expense of rotational energy
  - ⇨ neutron star slows down



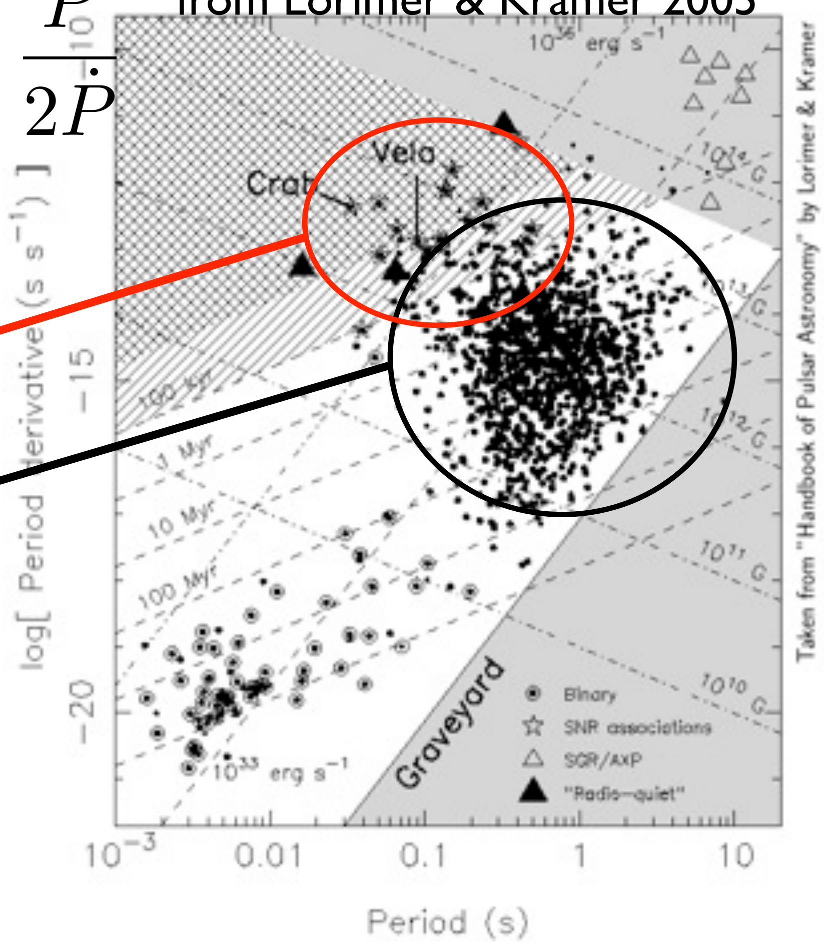
$$L_{\rm md} = -\frac{2}{3c^3}|\ddot{\vec{m}}|^2$$

$$\dot{P} \propto \frac{B^2}{P}$$

- P & $\dot{P}$ + "dipole model"
  - ⇨ i) B-field ii) "dipole age" $\tau = \dfrac{P}{2\dot{P}}$

- "P-Pdot-diagram"

from Lorimer & Kramer 2005

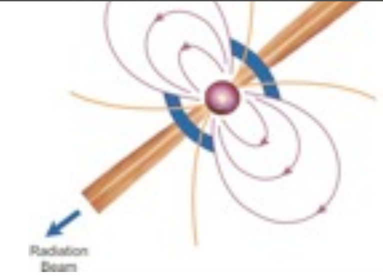


young neutron stars
in SN remnants

"normal pulsars"

- [magnetic dipole model]
  - ➡ dipole magnetic field
  - ➡ emission of magnetic dipole radiation
  - ➡ at expense of rotational energy

➡ neutron star slows down



$$L_{\rm md} = -\frac{2}{3c^3}|\ddot{\vec{m}}|^2$$

$$\dot{P} \propto \frac{B^2}{P}$$

- $P \;\&\; \dot{P}$ + "dipole model"

➡ i) B-field ii) "dipole age" $\tau = \dfrac{P}{2\dot{P}}$

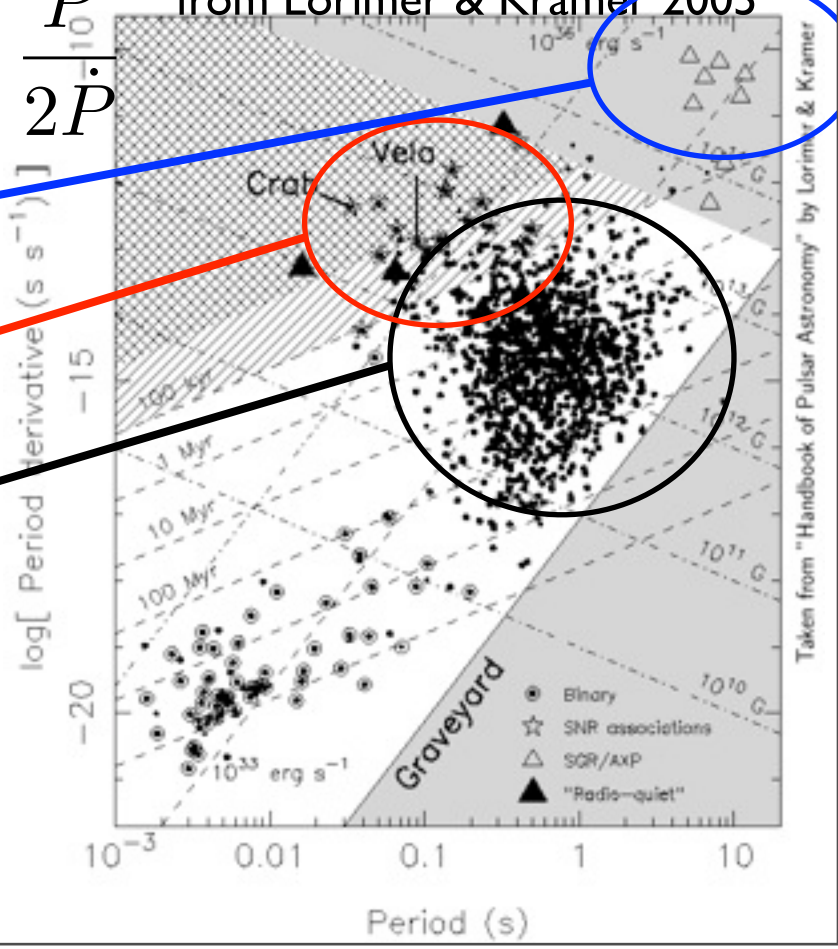
- [“P-Pdot-diagram”]

"magnetars"

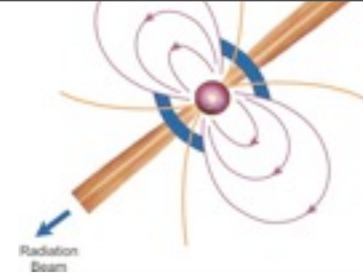
young neutron stars
in SN remnants

"normal pulsars"

from Lorimer & Kramer 2005



- [magnetic dipole model]
  - ➡ dipole magnetic field
  - ➡ emission of magnetic dipole radiation
  - ➡ at expense of rotational energy
  - ⇨ neutron star slows down



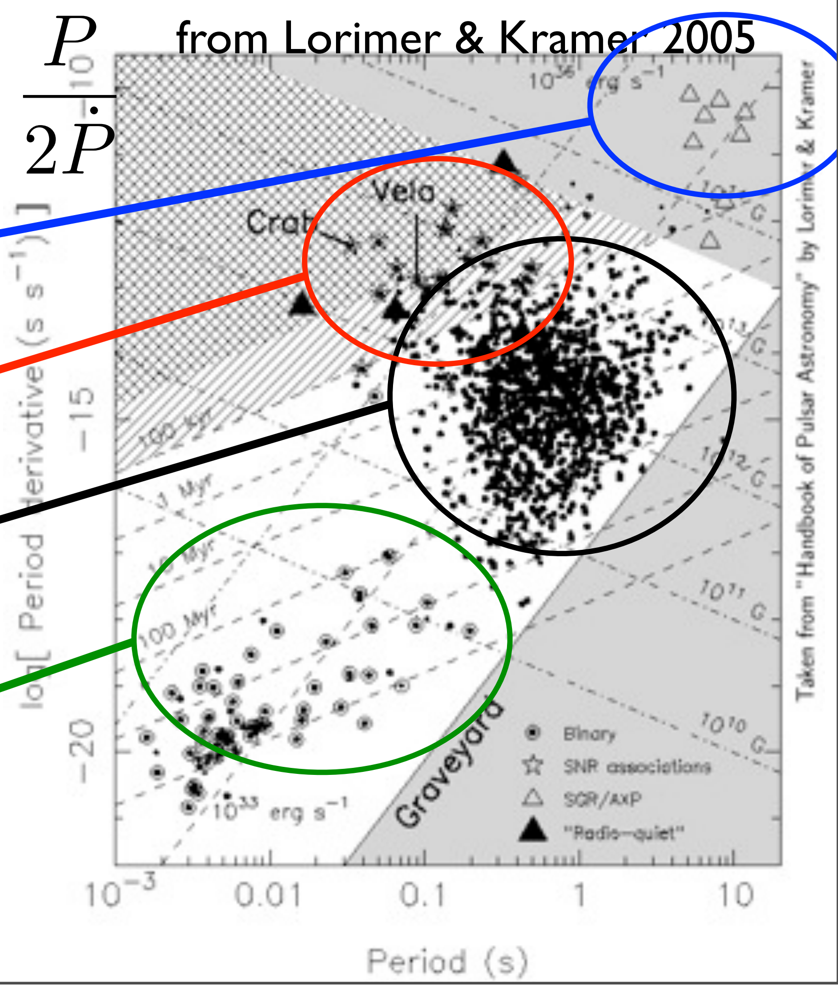
$$L_{\rm md} = -\frac{2}{3c^3}|\ddot{\vec{m}}|^2$$

$$\dot{P} \propto \frac{B^2}{P}$$

- P & $\dot{P}$ + "dipole model"
  - ⇨ i) B-field ii) "dipole age" $\tau = \frac{P}{2\dot{P}}$

- ["P-Pdot-diagram"]

from Lorimer & Kramer 2005



"magnetars"

young neutron stars in SN remnants

"normal pulsars"

"recycled" pulsars in binary systems