Nuclear Equation of State used in Astrophysics Models

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Compact binary mergers:

the influence of the equation of state

S. Rosswog

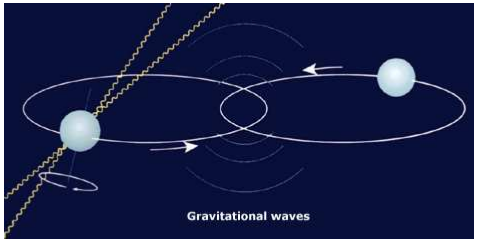
IUB
International
University
Bremen

further information: http://www.faculty.iu-bremen.de/srosswog

I.1 Why compact binary systems?

- Physics of Nuclear Matter:
  - $\ast$ high T $\Rightarrow$ heavy ion collisions
  - $\ast$ low T $\Rightarrow$ neutron stars
- Nucleosynthesis:
  - $\ast$ formation of neutron-rich, rapid neutron capture elements
- Gravitational Waves:
  - $\ast$ large rates: $\sim 10^{-4}$ (year galaxy)$^{-1}$
  - $\ast$ large, predictable (initial phase) GW-amplitudes $\Rightarrow$ good detection prospects
- Gamma-ray Bursts:
  - $\ast$ “NS-NS & NS-BH mergers $\Rightarrow$ BH + massive accretion disk = GRB-engine”

I.2 Observed Neutron Star Binaries



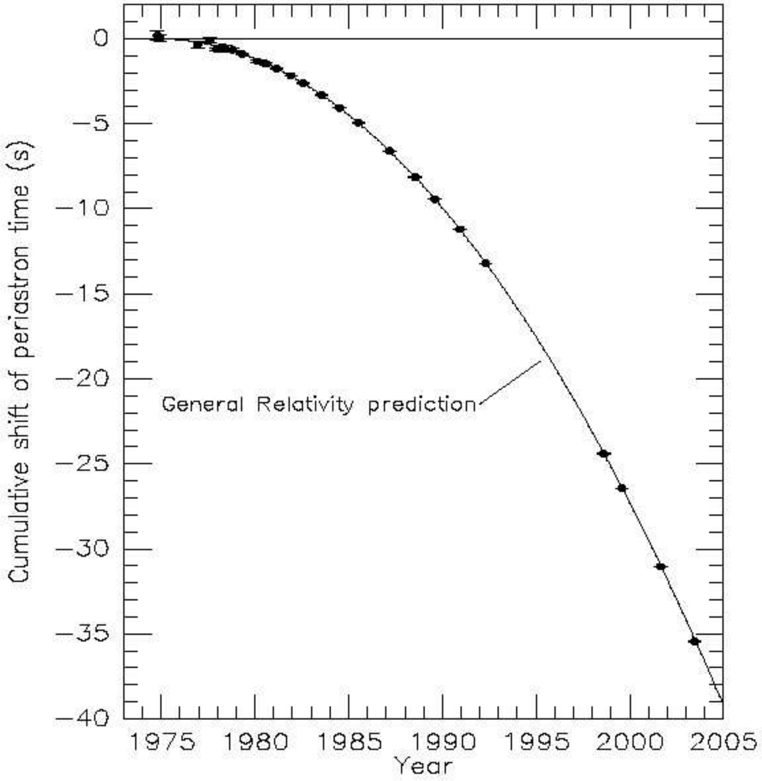
- so far: six observed systems
- most precise observation: PSR1913+16 (Hulse & Taylor 1974)
  - ∗ discovered in 1974 by R.Hulse and J.Taylor → NP 1993
  - ∗masses: 1.442 and 1.386 $M_\odot$ $\pm$ 0.0002 $M_\odot$
  - ∗orbital period: $\tau_{orb} =$ 7.752 h (v $\sim 10^{-3}c$)
  - ∗pulsar period: $P_{PSR}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

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

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

$\ast$distance: ~ 10 kpc

$\ast$orbital decay: agreement with GR-prediction: 0.21 % (2004)



$\ast$inspiral time: $\tau_{insp} = 2.97 \cdot 10^8$ years !

$\longrightarrow$ final coalescence !

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

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

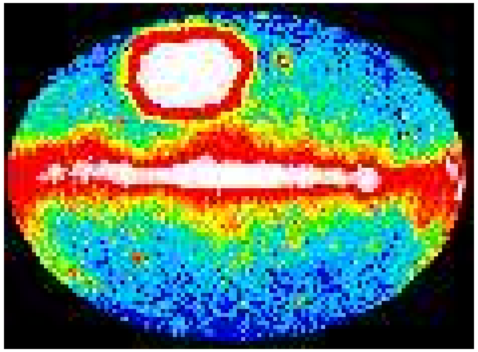
$\Rightarrow$ merger rate : $R_{\mathrm{DNS}} \sim 10^{-4}$ (year galaxy)$^{-1}$

$\Rightarrow$ ground-based gravitational detectors (LIGO, GEO600, TAMA ...) should observe

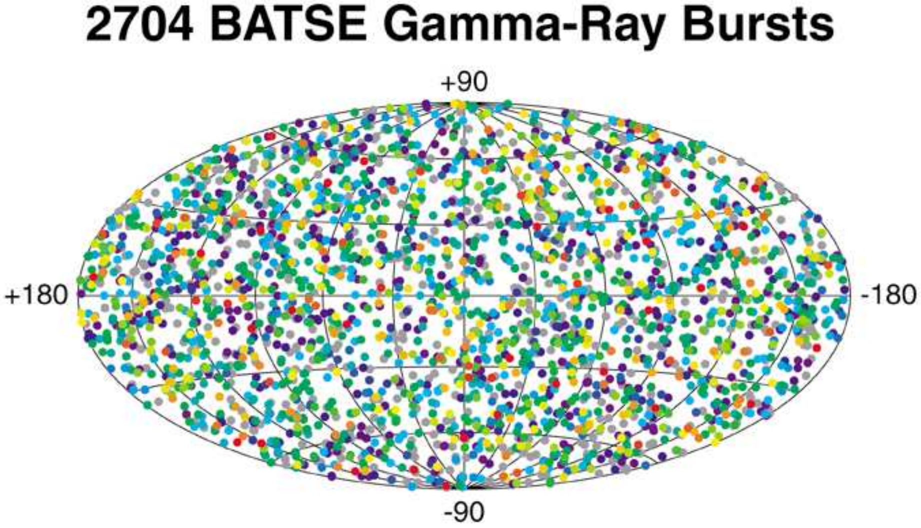
$\Rightarrow$ one DNS merger event every few years !

I.3 Gamma Ray Bursts (GRBs)

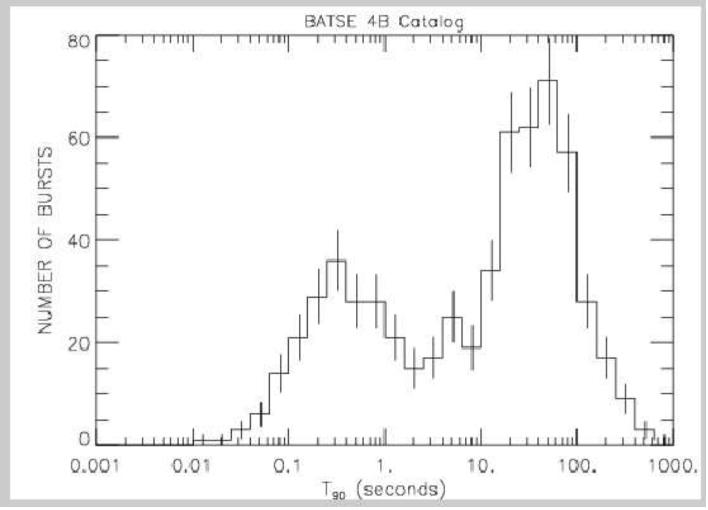
- * accidental discovery by satellites in the sixties



- * gamma ray sky:
- * rate: ∼ 1/day (BATSE)
- * isotropic distribution



(ii) Duration



bimodal: (α) **short** Bursts ~ 0.2 s
compact binary mergers

(β) **long** Bursts ~ 30 s
collapsing stars ("collapsars")

(iii) "standard" central engine: BH + accretion disk

(iv) Most Popular Mechanisms (to produce beamed, relativistic outflow)

(α) Magnetohydrodynamics (MHD)

(β) $\nu_i + \bar{\nu}_i \rightarrow e^+ + e^-$

II. Modeling compact binary systems:

- intrinsically 3D process → numerical modelling
- high sound velocities: $c_s \sim 0.3c$

  Courant-Friedrichs-Lewy stability criterion:

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

  -> can only simulate “short physical time scales”

  -> need powerful computer
- ideally:
  - * ”the true equation of state”
  - * 3D neutrino transport
  - * 3D general relativistic magneto-hydrodynamics (with time variable metrics)
  - * numerical resolution of all relevant scales
  - * ...

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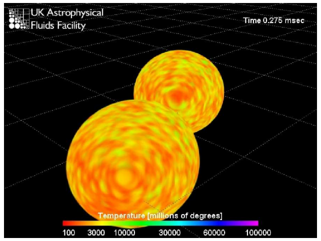
(iv) Neutrino physics:

multi-flavour neutrino leakage scheme
(Rosswog & Liebendörfer 2003)

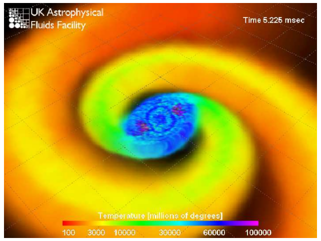
III. Results: the role of the EOS

III.1 Neutron Star Binaries

- Morphology:

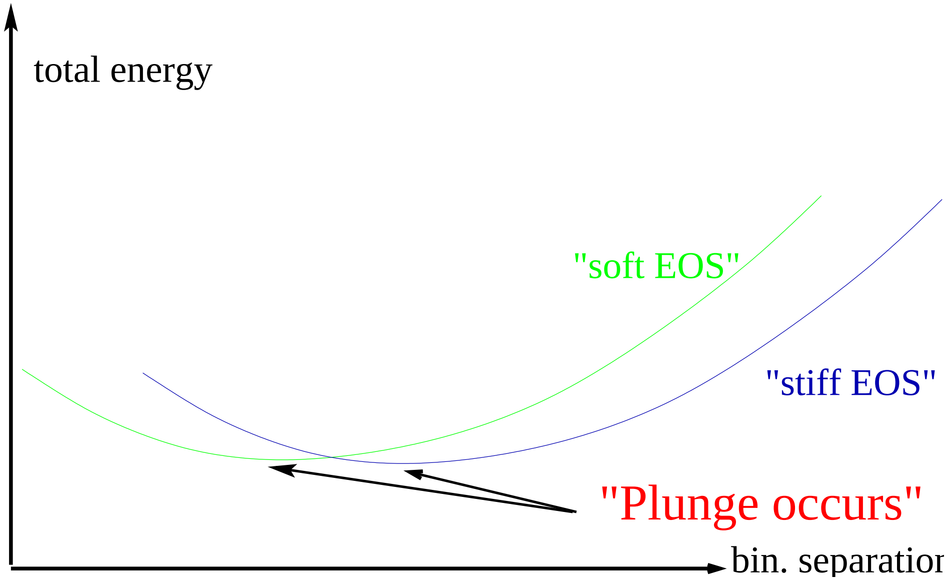


surf. temp.



orbital plane

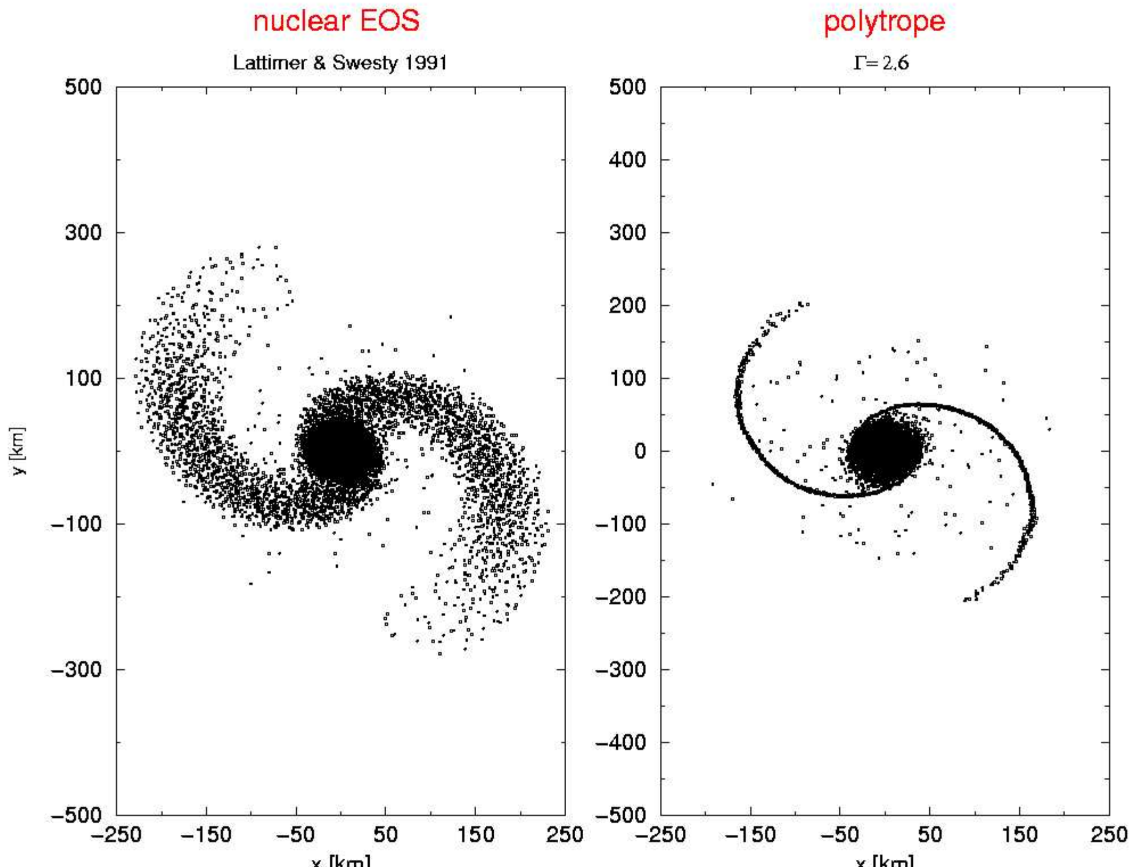
- inspiral: “plunging instability” (purely Newtonian discussion)



⇒ system becomes dynamically unstable

- "stiff EOS": instability at large separations
- "soft EOS": even "contact config's" possible ($\Gamma \leq 2$)
  ⇒ visible in GW-signal

- spiral arms:



- central object: differentially rotating, ~ 2.5 M$_\odot$

  - "soft EOS": immediate collapse to black hole
  - "stiff EOS": metastable "super neutron star" possible

  (complicated by time scale to remove diff. rot.; viscosity, GW, magnetic fields....)

- neutron-rich ejecta:

  - "stiff EOS": ~ 0.01 M$_\odot$ejected per event

    (Shen et al. EOS 1998)

  - "soft EOS": no resolvable mass loss

    ($\Gamma = 2$-polytrope)

III.2 Neutron Star Black Hole Binaries

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

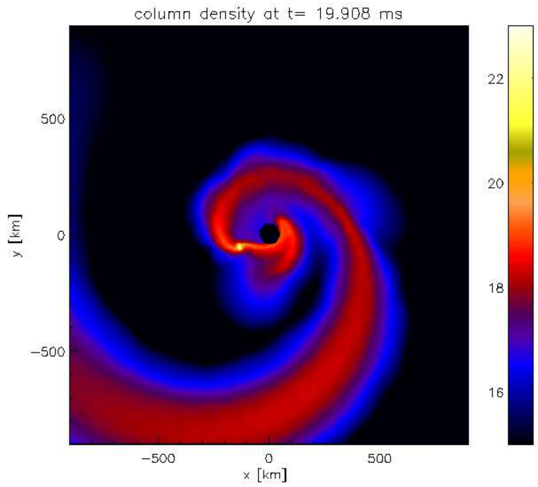
- complex accretion dynamics (sensitive to EOS !)

determined by

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

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

Accretion Dynamics in Neutron Star Black Hole Binaries:



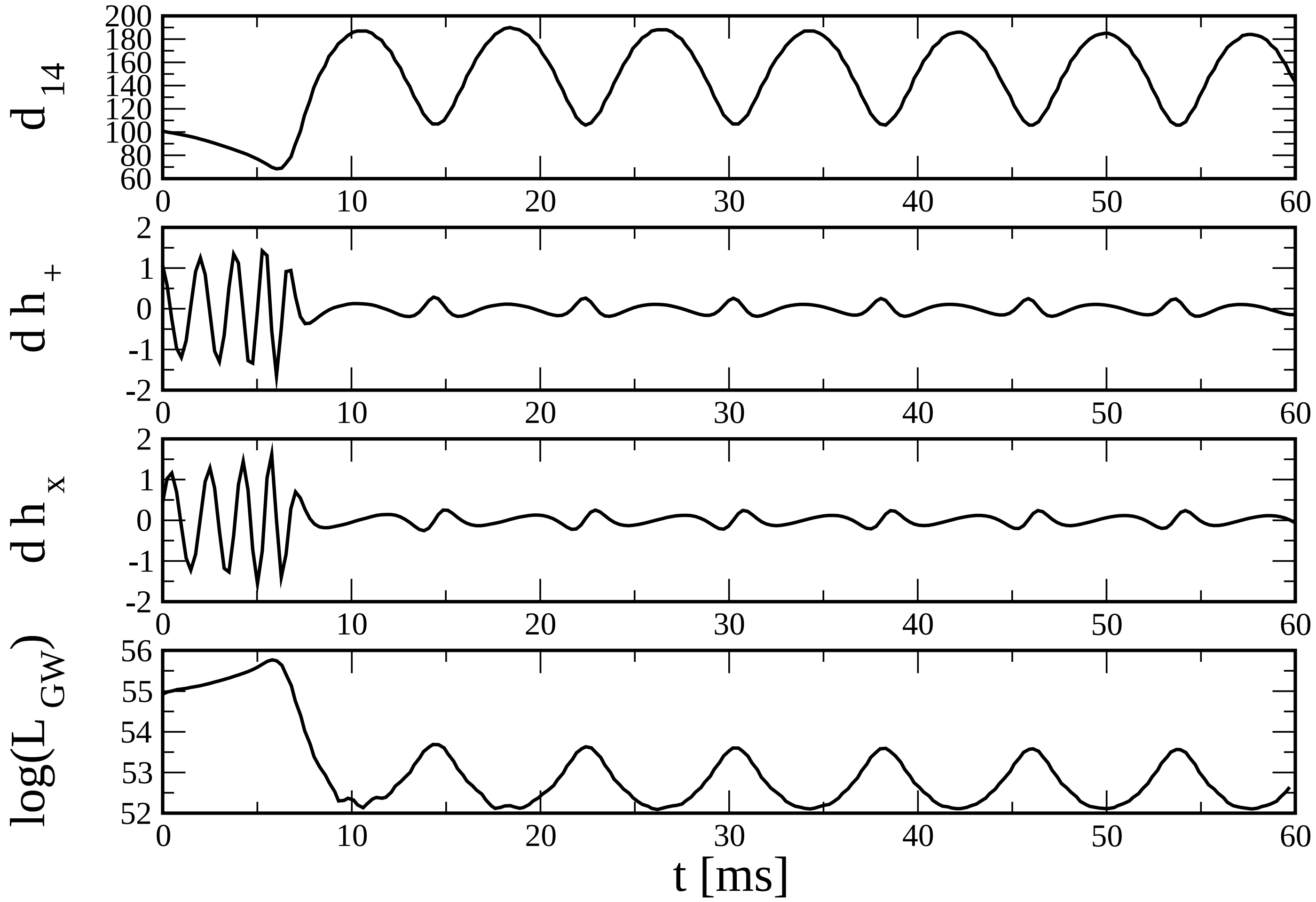
column density,

Newtonian gravity,

corotation,

mass ratio q= 0.1

∗ for shown run (q= 0.1, corotation):



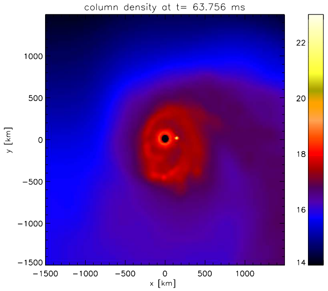
distance NS - BH

GW-amplitudes

GW-luminosities

⇒ “survival of mini-NS visible in GW-signal”

Implications for GRBs



	disks NS-BH		NS-NS binaries
- masses,	$< 10^{-2}$ M$_\odot$	$\Longleftrightarrow$	~ 0.2 M$_\odot$
- densities [g cm^{-3}]	$10^8 < \rho < 10^{11}$	$\Longleftrightarrow$	$10^{11} < \rho < 10^{13}$
- temperatures,	~ 2.5 MeV	$\Longleftrightarrow$	~ 4 MeV
- neutrino emission,	$\sim 10^{52}$ erg/s	$\Longleftrightarrow$	$\sim 2 \cdot 10^{53}$ erg/s

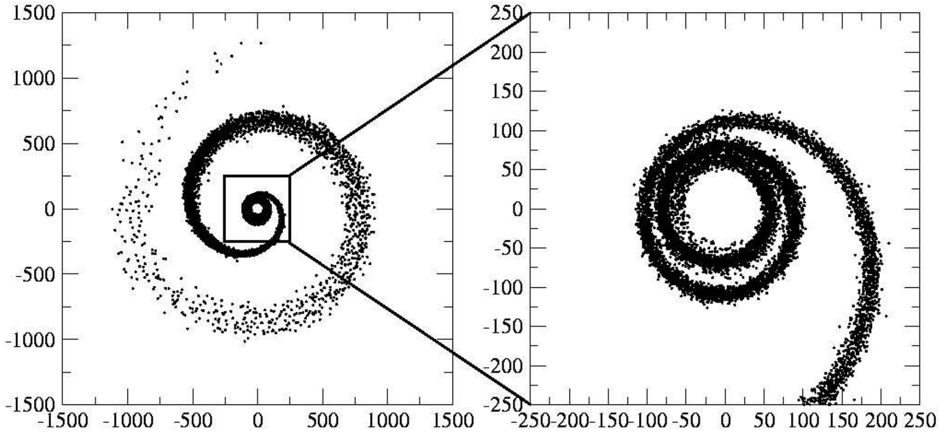
therefore:

- inefficient neutrino annihilation $(Q_{\nu\bar{\nu}} \propto L_{\nu_i} L_{\bar{\nu}_i})$
- difficult to anchor strong magnetic fields in disk

$\Rightarrow$ "pessimistic prospects for GRBs"

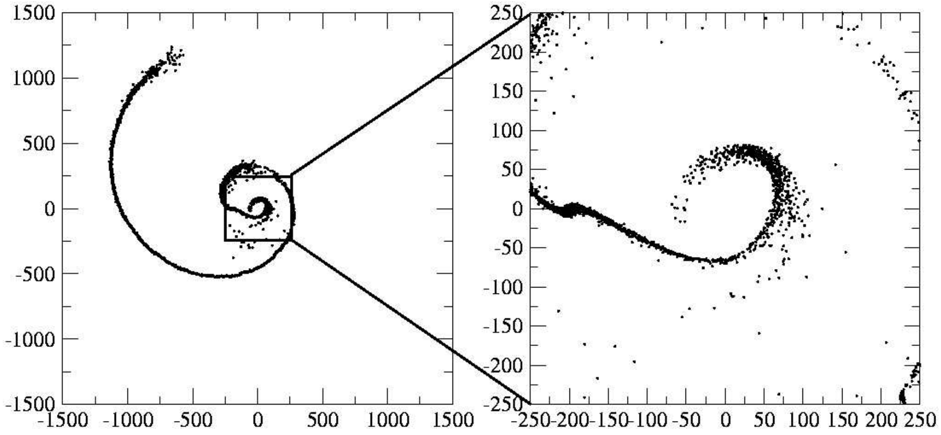
Sensitivity to EOS

- $*$ soft EOS (polytrope, $\Gamma = 2$)



$\Rightarrow$ complete disruption, massive disk

- $*$ stiff EOS (polytrope, $\Gamma = 3$)



$\Rightarrow$ mini-NS, low-mass disk

Summary

Neutron star mergers:

various aspects sensitive to EOS:

- morphology: spiral arms etc.
- stability central object
- amount neutron-rich ejecta
- neutrino emission
- ...

Neutron star black hole mergers:

- extremely complex accretion dynamics
- dynamics very sensitive to EOS
- “hard” EOS used (relativistic mean field, Shen et al. 1998a,b):
  - "mini-neutron" star survives
  - difficult to form accretion disk

⇒ good news for GW-detection,

bad news for GRBs

The Astrophysicist’s whish list

for the EOS

- temperature dependence $0 < T < \sim 100$ MeV
- NO β-equilibrium $0 < Y_e < \sim 0.5$
- large density range $\sim 10^3 < \rho < \sim 10^{15}$ g/cm^3