Numerical Simulations of Neutron Star-Neutron Star and Black Hole–Neutron Star Binaries:

Introduction and status report

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Observational Motivations

- Binary pulsars observed
- Predict ~10^1 NS-NS detections per year for advanced LIGO
- (Unfortunately, merger waves are ~ kHz)
- Electromagnetic counterpart – short GRBs?
- Neutrino counterpart?

NS-NS evolution overview

- Inspiral→ISCO→plunge→~3M◆ remnant
- 2 possibilities
  - Prompt collapse
  - Quasi-stationary hypermassive star
- Remnant may form an ellipsoid

  → GW signal → spin down → collapse + no disk
- Remnant core may be spun down by MRI

  → Collapse + big disk → GRB?

BH-NS evolution overview

2 possibilities:

1) $M_{BH} > 4\ M_{NS}$ → NS swallowed whole

2) $M_{BH} < 4\ M_{NS}$, $\frac{M_{BH} R_{NS}}{r^3} > \frac{M_{NS}}{R_{NS}^2}$

→ Roche lobe overflow

mass transfer may be

- unstable: tidal destruction of NS
- stable: multiple mass transfers

Parameter Space

- Inspiraling NS are (to 1st approximation)
  - cold (P_{th}■P_{cold}), irrotational (Ω_{sp}■Ω_{orb}), with low B field (B^2■P)

1) Real parameters which vary significantly
   - NS mass(es), BH mass and spin (for BH-NS)

2) Parameterized ignorance
   - Equation of State (EoS): $P = P(\rho, T, Y_e)$

- EoS-dependent tidal effects affect inspiral
- EoS affects ISCO or disruption radius
- Signs of stiff EoS:
  - Ellipsoidal remnant (for NS-NS)
  - Multiple mass transfers (for BH-NS)

Potentially Relevant physics

- GR ($Rc^2/GM \sim 5$)
- Cold EoS
- Hot EoS
  - Study by Oechslin, Janka, and Marek 2007
  - Esp. important for disks around final BH
- Magnetic fields
  - Rapid growth in NS-NS remnant
  - c.f. Price and Rosswog (2006), Duez *et al* (2006)
- Neutrino cooling/emission/radiation pressure
  - Crucial for understanding post-merger disk, GRB generation

Two paths to dynamical simulations

1. Complicated microphysics,
   simplified (e.g. Newtonian) gravity

2. Exact general relativity,
   simplified (e.g. polytropic) description of matter

NS-NS binaries: the state of the art

An incomplete survey

- Newtonian
  - Price & Rosswog (2006): 1st NS-NS merger simulation with *magnetic fields*, T,Y_e-dependent EoS of Shen (1998), neutrino effects, Y_e evolution, SPH
  - Ruffert & Janka (2001): T,Y_e-dependent EoS of Lattimer-Swesty (1991), PPM FD FMR
- Conformal
  - Oechslin, Janka, & Marek (2007): Shen & LS EoS, Y_e advected
- Full GR
  - Shibata & Taniguchi (2006): T=0 APR & SLy EoS, PPM FD uniform grid, $\Delta x \sim 0.15 M_0$, $L \sim 0.45 \lambda_{GW0}$

BH-NS binaries: the state of the art

- Newtonian
  - Janka (1999): LS EoS, neutrino effects
- Newtonian + Paczynski-Wiita potential
  - Rosswog (2005): Shen EoS, neutrino effects
- Conformal
  - Faber et al (2006): limited to M_{NS} ■ M_{BH}
- Full GR
  - Shibata & Taniguchi (2007), Etienne *et al* (2007), use Γ=2 polytropes
- Note: BH spin effects have not been studied in these simulations, but they are *<u>very</u>* important (c.f. Rantisiou *et al* 2007)

Short gamma ray burst properties

- cosmological distances
- $L \sim 10^{50}$ erg,   duration<2sec, hard spectrum
- Compact source
- Nonthermal spectrum → γ-rays emitted from ultrarelativistic (Γ~hundred) outflow
- Found in non-star forming regions
- No evidence of associated SNe
- Sometimes, reactivation of source (X-ray flares)

Recipe for a GRB central engine

- Need to dump a lot of energy into a region with not much matter
- Need to do it in 10-100ms

Massive hyperaccreting disk around a BH

- Baryon poor region above disk
- Energy extracted by thermal neutrino radiation or magnetic fields
- Do NS-NS or BH-NS mergers create the right setup?

Things to consider

- How to survey the parameter space (esp. EoS)?
- How much physics do we need for just the gravitational waves?
- How far back must numerical simulations start?
- How to combine gravitational and EM signals?

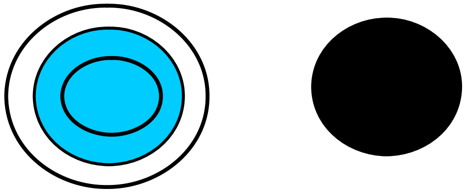
- Other sources
- Collaboration with a third community: computational astrophysicists

BH-NS binaries with a mixed pseudospectral / finite difference code

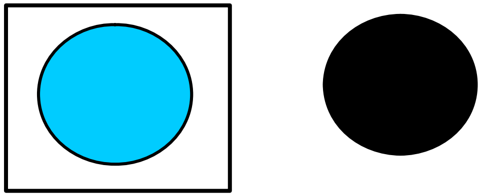
Matt Duez, Larry Kidder, Saul Teukolsky

- FD/FV codes
  - Good at capturing discontinuities
  - Require large grids
- PS codes
  - Rapid convergence for smooth solutions
  - Problems with discontinuities
- FD for hydro, PS for $g_{\mu\nu}$? [Dimmelmeier et al (2005)]

- Why?
  - Loss of accuracy in PS code limited to few domains



  - FD code only needs to cover matter



Test: equal mass BH-NS binary