Extracting Science from Evolutions of Binary Neutron Star Mergers

Binary Neutron Star Coalescence as a Fundamental Physics Laboratory, INT@UW, Seattle, WA

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Goals for the talk

- Introduce what it takes to evolve a BNS
- (Partially) List some science goals of such an evolution
- Discuss the status & some latest results
- Mention outstanding questions and problems

...a gentle intro without too many details...

What does it take to evolve a BNS?

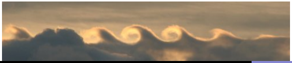
- Appropriate initial data (LORENE, others)
- Gravity
  - Must be dynamical because the stars move
  - Must be better than Newtonian (GR or alternative)
  - Must be stable (GH, BSSN, CCZ4, etc)
  - Must **not** be too symmetrical
  - Good boundary conditions
  - Handles BHs for some cases (punctures, excision)
- Fluid
  - an EOS: polytrope →ideal fluid →tabulated, realistic EOS
  - high-resolution shock capturing (HRSC) preferred/standard
  - good conserved-to-primitive solver
  - must deal with low density regions (atmosphere)
- Computational Infrastructure (parallel, AMR, GPU, etc)
- Extraction methods (GW signal, Poynting flux, etc)
- Other physics (EM, neutrinos, photon transport, etc)

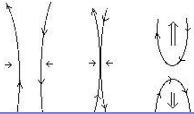
(Some) Goals of evolving BNS mergers

- GW signature details **...discussed last week**
  - what can we determine about the EOS of NS?
  - can we constrain the radius/spin/Bfield/etc of the NS?
- EM bursts (sGRBs and kilonovae)
  - how much ejecta might result?
  - how much mass in accretion disk?
  - lifetime of remnant?
  - do jets form? collimation? Lorentz factors?
- Nuclear physics
  - r-process nucleosynthesis occurring?
  - composition of ejecta? light curves?
- Multi-messenger astronomy
  - Triggering: precursors (EM→GW), afterglows (GW→EM)?
  - Concurrent: detect multiple bands for high science extraction
    - GW: luminosity distance, sees deep into engine
    - EM: localizes source, provides redshift
    - Neutrino: composition info

Computational Issues: Various Scales

- Time
  - Inspiral (huge)
  - merger (millisecond)
  - remnant lifetime
    - $\tau_{\rm rotational} \approx$ 20ms–200ms
    - Ang. mom. transport...Alfvén time ($\tau_{\rm Alfven} \approx$ 10-100ms)
    - magneto-rotational instability (MRI)...$\tau_{\rm MRI} \approx$ 100ms
    - Cooling ...$\tau_{\rm cool}$ $\approx$seconds (or few 100ms [Paschalidis,Etienne,Shapiro,'12])
- Space
  - GW wavelength
  - Stellar radii
  - Stellar surface, Kelvin-Helmholtz instability
  - Magnetic effects: buoyancy, reconnection, MRI, etc



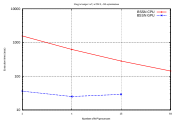


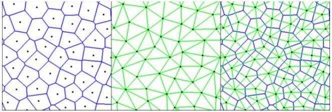
Computational Issues: Errors

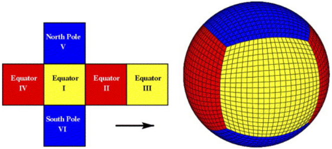
- **GR:** Truncation error, coordinate/gauge 'differences', boundary conditions
- **Atmosphere/surface:**
  - artificial atmosphere...results largely independent of , but...
  - atmosphere still hugely dense in absolute terms
  - some hope of identifying surface to separate spatial regimes (only premerger, though)
  - **ejecta** very tough to resolve
  - **stellar surface**...computationally problematic, atmosphere accretes onto, heats up
- **Magnetic effects** very hard to resolve
  - MRI scale
  - Generally much finer dynamical detail than other scales
  - Field in atmosphere tough: inconsistent with ideal MHD
- **Nuclear physics**: huge errors/uncertainties

Computational Issues: Methods

- Hardware:
  - Multi-node: MPI
  - Multi-core: OpenMP
  - GPU–CUDA, OpenCL
  - FGPA "field-programmable gate array"–e.g. Intel Phi, Cilk, OpenACC
- Grid Structure:
  - FMR, AMR
  - non-uniform grids: cubed sphere, Voronoi
- Fluid methods: finite volume, spectral, discontinuous Galerkin (DG), SPH







Recent BNS (no magnetic/neutrino effects)

- **Eccentric capture** in globular clusters
  [Tai,McWilliams/Pretorius,1403.7754]
  [East,Pretorius,1208.5279]
- BNS w/ **spinning stars**...affects GW signal and collapse times
  [Bernuzzi,Dietrich,Tichy,Bruegmann,1311.4443]
- **Accuracy** of BNS simulations:
  - higher order [Radice,et al,1312.5004]
  - as compared to EOB models [Baiotti,et al,1103.3874]
  - as compared to PN models [Bernuzzi,et al,1109.3611]
- **Tidal effects**
  - [Read,et al,1306.4065]
  - [Hotokezaka,et al,1301.3555]
  - [Bernuzzi,et al,1205.3403]
- **Detectability** of post-merger characteristic frequencies (bar-mode and other) **discussed last week**
  - [Takami,et al,1403.5672]
  - [Clark,et al,1406.5444]

Incorporation of Electromagnetism

- no coupling of fluid to EM field
  - evolve independently
  - good in **far-field**, electrovacuum
- MHD
  - perfect conductivity–good **inside the stars** (pre-merger only?)
  - no electric field in local frame of fluid
  - fluid "tied" to magnetic field lines
  - (in principle) no magnetic reconnection
- Force-free
  - electromagnetic "force" overwhelms fluid's inertia
  - $B^2 \gg p$
  - fluid serves only to provide charges and current
  - appropriate in low-density **magnetosphere**

Force-Free: An Introduction

- Long history...
  - [Goldreich,Julian, ApJ'69] *Pulsar Electrodynamics*
  - [Blandford,Znajek,MNRAS'77] *Electromagnetic extraction of energy from Kerr black holes*
  - [Spitkovsky'06], [Komissarov'04],McKinney,Gammie,etc for pulsar
- Revival of interest of late
  - Lots of work w/ **BBH** (HAD, Whisky, etc)
  - Analytic work: [Gralla,Jacobson,2014]
- Populates a **tenuous plasma**
  - **NS exterior**: electric field strips charges off surface [GJ'69]
  - **BH exterior**: vacuum breakdown; Cascading pair production (electron-positron) from accelerated particles radiating photons
- Properties:
  - negligible inertia $\rho \ll B^2$
  - Vanishing Lorentz force $q\vec{E} + \vec{J} \times \vec{B} = 0$
  - plasma serves only to provide currents/charges

Incorporation of Electromagnetism: Issues

- Numerical issues:
  - must control divergence: $\vec{\nabla} \cdot \vec{B} = 0$ ("no monopoles")
    - constrained transport
    - divergence cleaning (hyperbolic or elliptic)
  - RMHD handles finite conductivity...stiff equations
  - Tough to resolve fine scales (MRI, Kelvin-Helmholtz)
  - Lack of fully consistent initial data... "seed" fields
- Physics issues:
  - What's appropriate initial data for the magnetic field?
  - What are the appropriate coductivities? Inside stars, post-merger?
  - How well does one handle magnetic reconnection?
  - How to extract signal? Poynting flux? What could we observe?

Incorporation of Electromagnetism: Recent Results

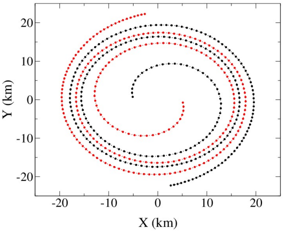
- ideal MHD everywhere w/ BNS:
  - [Anderson,et al,2008]–HAD
  - [Liu,et al,2008]–UIUC
  - [Giacomazzo,et al,2009] [Rezzolla,et al,2011]–WHISKY
- matching regimes
  - BHNS-[Paschalidis,et al, 2013];
  - NS-[Lehner, et al,2012])
- resistive MHD (RMHD)...transition in conductivity
  - [Palenzuela,2012] [Palenzuela,etal,1307.7372] [Ponce,etal,1404.0692]
  - [Dionysopoulou,2012]

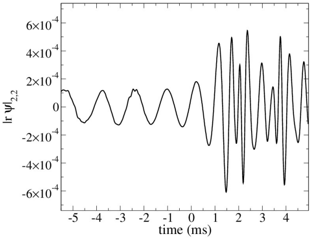
Simulating BNS merger w/ Magnetospheres

- Each star surrounded by its own magnetosphere
- Interactions between star...reconnection, current sheets, etc
- Wide configuration space spanned by initial dipole directions

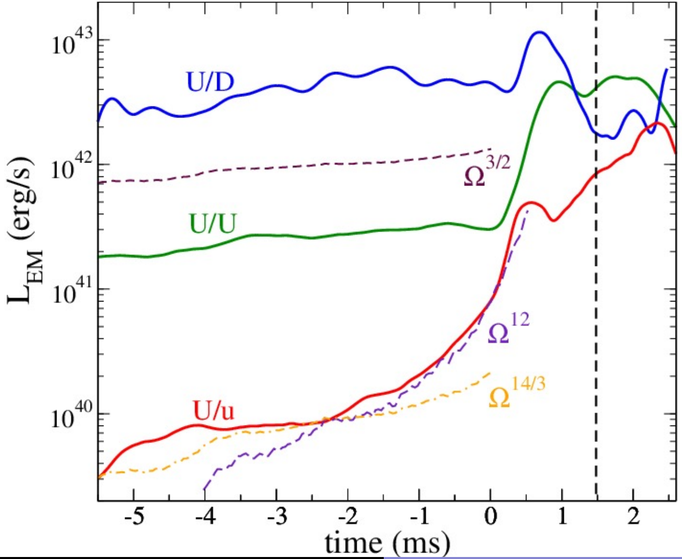
Difference w/ super-massive BBH case:

- BNS in the LIGO band
- NS can support its own magnetic field
- More difficult w/ different magnetic regimes...resistive code

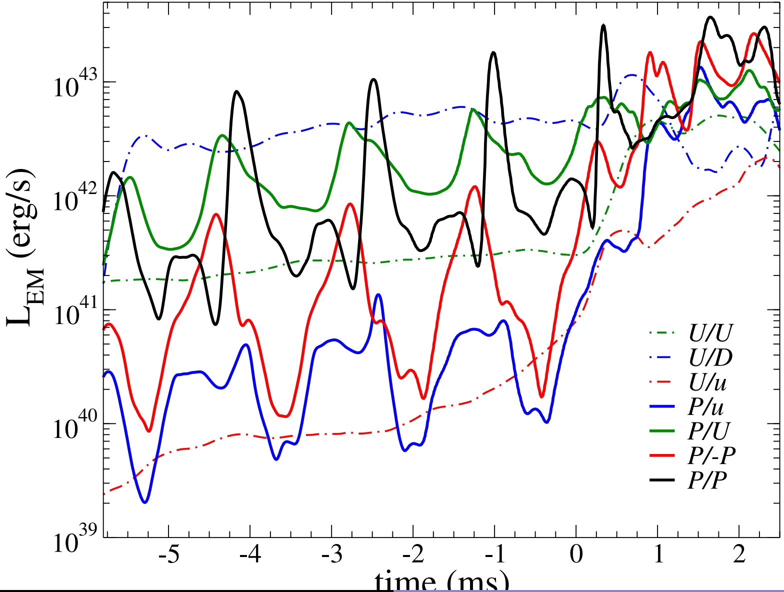




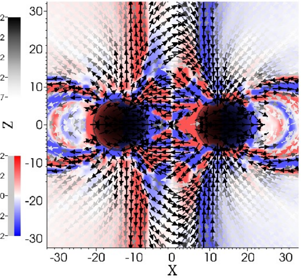
[Palenzuela, et al,PRD 1307.7372]

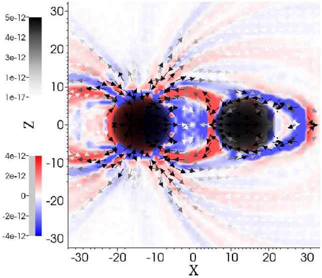


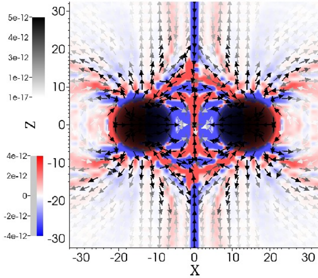
[Ponce,et al,1404.0692]



BNS as a circuit







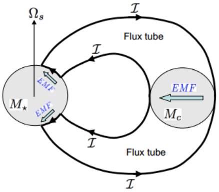


Fig. 1.— DC circuit model of magnetic interactions in binary systems *a la* Goldreich & Lynden-Bell (1969).

U/D [Lai--1206.3723] U/U

_PU_Bflds.gif

P/U case

_PP_Bflds.gif

P/P case

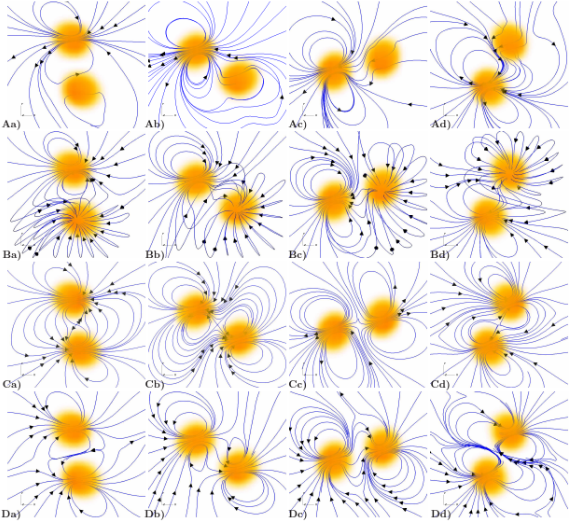


FIG. 5. Magnetic field lines (blue) and stellar density (yellow) at the orbital plane. The columns **a**, **b**, **c**, **d** display the configurations at times $t \approx \{-3.6, -3.2, -2.8, -2.2\}$ms, where time intervals between successive columns describe roughly one eight of an orbit. **Row A:** non-magnetized/magnetized stars with magnetic dipole in the orbital plane (P/u), **Row B:** magnetic dipoles perpendicular/parallel to the orbital (P/U), **Row C:** magnetic dipoles parallel to the orbital plane (opposite orientations) ($P/\text{-}P$), and **Row D:** magnetic dipoles parallel to the orbital plane (same orientations) (P/P). Notice that field lines depicted in Row B appear to cross other lines, but they actually leave the orbital plane and do not cross (see Fig. 6).

Results

- Magnetic interactions and reconnection can extract orbital kinetic energy...
- ...and power Poynting flux

$$L \approx 10^{40-43} \mathrm{erg/s} \left(\frac{B}{10^{11} \mathrm{G}} \right)^2$$

Also see the estimates from:
[Lai,1206.3723]
[Piro,1205.6482]
[Hansen,Lyutikov,astro-ph/0003218]

- Aligned/anti-aligned more collimated luminosity
- Pre-merger stage can potentially provide electromagnetic counterparts

Realistic EOS

- polytrope:
  - $P = K\rho^\Gamma$
  - simplest, no shocks
  - initial efforts—not currently common
- ideal fluid:
  - $P = (\Gamma - 1)\,\rho_0\epsilon$
  - currently common
  - generally $\Gamma = 2$ chosen for NSs
- piecewise polytrope
  - fits in P-vs-ρ to match realistic EOS
  - collaboration to compare evolutions among groups (Whisky-Kyoto)
- realistic, tabulated EOS
  - temperature dependent
  - composition information (electron fraction Y_e)
  - chemical potentials needed for neutrino treatment

Neutrino Emission

- Possible role in BNS mergers
  - removes energy
  - alters composition of remnant
  - possible power source for a GRB
- Numerical methods:
  - leakage
    - Recently popular
    - Simplest
    - Arguably sufficient for BNS...short timescales (ms)
  - moment methods
    - Sekiguchi, others
  - Boltzmann radiation transport
    - full treatment
    - computationally unfeasible unless possibly via Monte-Carlo methods

The Leakage Scheme

- Leakage: appropriate to short time scales
- Long history:
  - 2010–O'Connor/Ott [w/GR]
  - 2010–Sekiguchi [w/GR]
  - 2003–Rosswog/Liebendörfer
  - 1996–Ruffert/Janka/Schäfer
  - 1989–Janka/Hillebrandt
- Seeks to account for:
  - Changes to lepton number (e.g. electron fraction)
  - Loss of energy from streaming neutrinos
  - Ignores momentum transfer
  - Processes:
    - charged-current β-processes
      $e^+ + n \rightarrow p + \bar{\nu}_e \qquad e^+ + p \rightarrow n + \nu_e$
    - electron-positron pair-annihilation
      $e^+ + e^- \rightarrow \bar{\nu}_e + \nu_e \qquad e^+ + e^- \rightarrow \bar{\nu}_{\tau,\mu} + \nu_{\tau,\mu}$
    - plasmon decay
      $\gamma \rightarrow \nu_e + \bar{\nu}_e \qquad \gamma \rightarrow \nu_{\tau,\mu} + \bar{\nu}_{\tau,\mu}$

The Leakage Scheme

- Ultimate goal:
  - account for changes in lepton number
  - account for loss of energy from neutrino streaming
- Approach:
  1. Based on energy density, temperature, electron fraction:
     1. compute optical depth
     2. compute opacities and other
     3. iterate?
  2. Based on the depth:
     1. interpolate between **trapped** and **streaming**
     2. calculate R_ν and Q_ν
     3. correct time-derivatives of conserved variables

Recent GR+MHD+Leakage Work

- BNS Mergers

  [Kiuchi,Sekiguchi,Kyutoku,Shibata,1206.0509]

  [Sekiguchi,Kiuchi,Kyutoku,Shibata,1110.4442]
  - hot HMNS (50 – 70 Mev) that cools slowly
  - neutrino pair annihilation rate $10^{41} erg/s$
  - anti-electron neutrino luminosity dominates for all EOSs...e-p pairs produced and positron capture rate higher than e.capture
- Moment method for rad-MHD

  [Shibata,Sekiguchi,1206.5911]
- BHNS Merger

  [Kaplan,Ott,O'Connor,Kiuchi,Roberts,Duez,1306.4034]

  [Foucart,Deaton,Duez,O'Connor,Ott,Haas,Kidder,Pfeiffer,Scheel,Szilagyi,1405.1121]
  - neutrinos gradually cool resulting disk
  - denser and more compact disk
  - electron fraction of disk rises, then decreases
- Isolated NS Stability

  [Galeazzi,Kastaun,Rezzolla,Font,1306.4953]

Computing the Optical Depth

- Previous/other efforts:
  - Kaplan, et al: interpolate to 3D grid, integrate rays in seven directions
  - Sekiguchi, et al: minimum over integrals in coord. directions
  - Galeazzi, et al: interpolate to spherical grid, integrate radially
- Issues:
  - Depth is a global quantity–potential parallel/AMR difficulties
  - Want to avoid any symmetry/geometric assumptions
- Can we turn it into a local calculation?
  - **parallel circuit**–*sum of inverse depth* of neighbors plus differential amount
  - **minimum neighbor**–*minimum depth* of neighbors plus differential amount

Justifying a Local Optical Depth

- Neutrinos will **explore** all paths out
- Physics is **local**–surface changes not immediately felt inside
- Leakage only **approximate** anyway–depth often not recomputed every time step
- Already **iterative** because opacity depends on depth!
- One can always iterate more to improve response

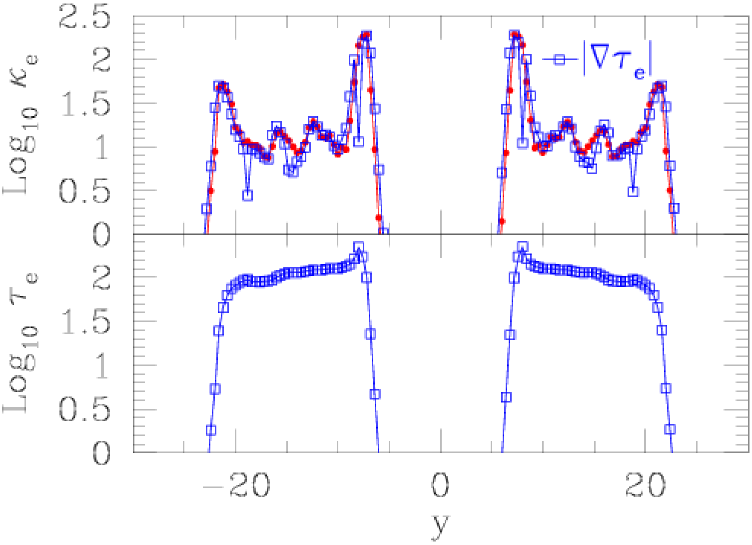
...similar to

[Perego,Gafton,Cabezon,Rosswog,Liebendoerfer,1403.1297]

Evaluation of Opt. Depth

- parallel circuit scheme doesn't work well w/ amr
  for small opacities, depth will always be less than neighbors
- Taking the min. of neighbors works well
- check via Eikonal equation:

$$|\nabla \tau_i(x)| = \kappa_i(x)$$


2.5
2
1.5
1
0.5
0
$\mathrm{Log}_{10}\ \kappa_e$
$|\nabla \tau_e|$
$\mathrm{Log}_{10}\ \tau_e$
−20
0
20
y

Binary Merger w/ Leakage

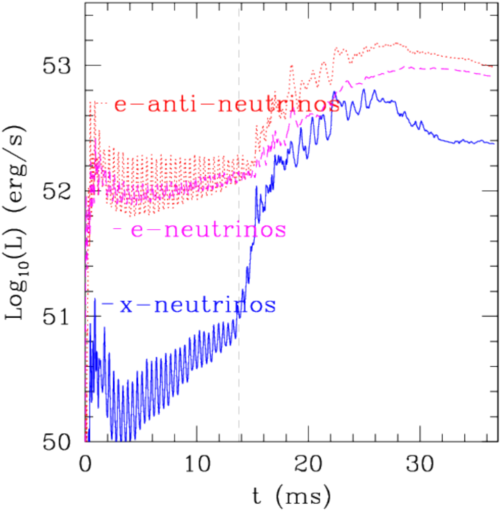
- Each NS: $M_B = 1.49 M_\odot$ $R_{\rm eq} = 12.2$km
- Initial temperature $T = 0.01$MeV
- Initial separation $a = 45$km
- Y_e initially set so that star in β-equilibrium
- Total mass $M_{\rm ADM} = 2.74 M_\odot$
- Angular velocity $\Omega = 1796$rad s^{-1}

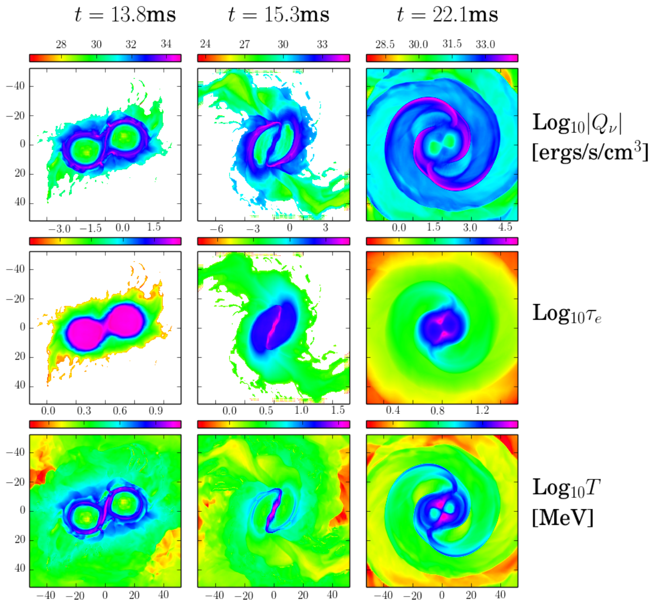
Code Tests

- Comparisons of **oscillation frequencies** of isolated NSs
- **Convergence** studies
- **Direct comparison** of leakage for single NS w/ `GR1D`
- **Qualitative** agreement w/ other compact object mergers—BHNS Ott/Duez/O'Conner/et al and BNS–Shibata/Sekiguchi/et al

BNS Merger Luminosities

- –initial transient
- –large increase at merger
- –$\bar{\nu}_e$ dominates due to shock heating & decompression
- –consistent with previous studies of BNS merger





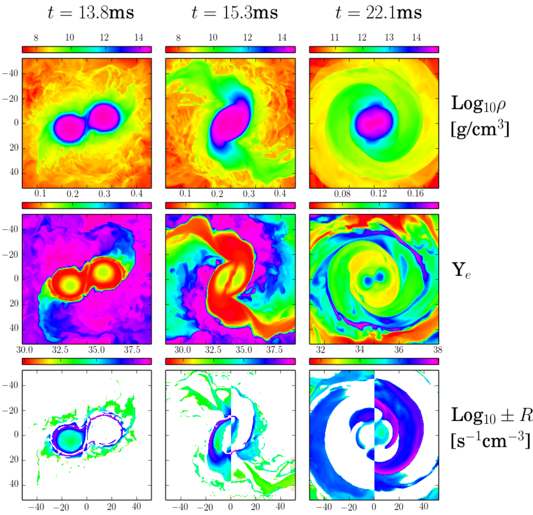
$t = 13.8$ms
$t = 15.3$ms
$t = 22.1$ms
28 30 32 34
24 27 30 33
28.5 30.0 31.5 33.0
−40 −20 0 20 40
−3.0 −1.5 0.0 1.5
−6 −3 0 3
0.0 1.5 3.0 4.5
$\mathrm{Log}_{10}|Q_\nu|$ [ergs/s/cm^3]
0.0 0.3 0.6 0.9
0.0 0.5 1.0 1.5
0.4 0.8 1.2
$\mathrm{Log}_{10}\tau_e$
$\mathrm{Log}_{10}T$ [MeV]

Bottom row:

•–left-half shows positive lepton number emission

•–leading edges of tidal tails–antineutrino electron emission leading to β-equilibrium

•–electron neutrino emission dominates further out, colder region



BNS Merger Characteristics

- neutrino energy-sink/lepton-sources occur at
  - stellar surfaces
  - shearing regions
  - tidal tails
- optical depth tracks density behavior
- electron fraction Y_e shows regions above/below beta-equilibrium with strong production of electron neutrino/antineutrinos
- large temperatures, reaching peak of roughly 45 MeV

_hshen_stampede_alpha.mpg ▸ Lapse _hshen_stampede_ent.mpg ▸ Entropy _hshen_stampede_optdepthe.mpg ▸ Electron Optical depth _hshen_stampede_qnu.mpg ▸ Q_ν _hshen_stampede_rho.mpg ▸ Density _hshen_stampede_temperature.mpg ▸ Temperature [MeV] _hshen_stampede_ye.mpg ▸ Ye

Outstanding Questions/issues

- Given how few choices we can run, which runs take priority? Which EOSs?
- How important is higher "accuracy" versus new physics?
- New techniques for atmsophere/surface?
- Is Poynting flux an okay proxy for EM emission? Hand-off to existing post-processing codes?
- Are there other nuclear physics effects needed or important? Pauli blocking? Landau levels?