EMMI Rapid Reaction Task Force: The physics of neutron star mergers at GSI/FAIR

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This is a discussion: so let's discuss!

- Anatomy of the problem:
  - **Inspiral** (~ -1e14 - 0 ms)
  - **Merger** (~ 0 - 5 ms)
  - **Dynamical post-merger** (~ 5 - 50 ms)
  - **Secular post-merger** (~ 50 - 2,000+ ms)

Inspiral (~ -1e14 - 0 ms)

- What we know
  - PN/EOB/Phen descriptions well advanced
  - Magnetic fields/thermal effects unlikely to play a role in GW emission; could lead to EM
  - Spin effects could play important role (mix with tidal)

Inspiral (~ -1e14 - 0 ms)

✳ **What don't we do know (yet)**

- ✦ What are realistic spin values/configurations?
- ✦ What are realistic B-field values/configurations?
- ✦ precise (cold) EOS but lot of information will become available soon (LIGO/Virgo, NICER)

Inspiral (~ -1e14 - 0 ms)

* **What we will not know for some time**
  * Does the crust behave like a plastic solid?
  * Are present tidal deformabilities incorrect?
  * Is tidal ejection realistic/expected?
  * Instabilities/resonances before merger?
  * Late time distribution of binary neutron stars

Merger (~0 - 5 ms)

- What we know
  - Highly energetic GW emission
  - Transient can be modelled analytically (disk+stars)
  - Largest amount of mass loss at this time

Merger (~0 - 5 ms)

- **What don't we do know (yet)**
  - Robust measure of critical mass to prompt collapse
  - Role of mass ratio and spin in this regime
  - Realistic temperature evolution
  - Role of neutrino trapping: change in EOS, composition, viscosity

Merger (~0 - 5 ms)

- What we will not know for some time
  - Role of plastic crust in temperature evolution
  - Breaking of first-order convergence at merger
  - measurement of first (low-freq.) peak of spectrum

Dynamical post-merger (~5 - 50 ms)

- What we know
  - GW signal has robust, universal spectral props: f_1, f_2, f_3
  - GW signal can be modelled analytically (damped oscilltns)
  - non-axisymmetric (m=1) features present but subdominant
  - diff. rot. is universal and not monotonic: unif. rot. core + Keplerian disk
  - MHD instabilities develop: KH, MRI, other?
  - Magnetic jet structure is formed at BH formation
  - given specific setup, ejected material has (reasonably?) well known properties in mass, velocity, entropy, Y_e (?)
  - neutrino emission/absorption important to model HMNS
  - heavy elements nucleosynthesis is produced by BNSs

Dynamical post-merger (~5 - 50 ms)

✳What don't we do know (yet)

- ✦ Saturation of MHD instabilities is unclear (viscosity?)
- ✦ Sustained relativistic outflow after BH formation still absent
- ✦ Role of bulk viscosity (modified URCA): boosts values?
- ✦ Role of shear viscosity (neutrinos, MRI, other?)
- ✦ Role of neutrino emission/absorption on dynamical ejecta
- ✦ Rigorous treatment of dissipative hydrodynamics (no LES, no effective models)
- ✦ Robust and EOS independent properties of ejected material (geometrical properties in particular)
- ✦ Robust and EOS independent properties of neutrino luminosities (cf. core-collapse SNe)

Dynamical post-merger (~5 - 50 ms)

- What don't we do know (yet)
  - is heavy elements nucleosynthesis robust under variations of initials conditions in the binary (mass, mass ratio, spin, orbital dynamics, EOS)?

Dynamical post-merger (~5 - 50 ms)

✳ **What we will not know for some time**

- Role of turbulence?
- How well do MRI mediated disc-accretion flows reproduce dynamics of HMNS?
- Is post-merger spectrum measurable by LIGO (see later)
- How is a relativistic jet produced? Are neutrinos responsible? Are microscopical resistive effects important?
- New numerical methods to follow the dynamics of low-density, complex geometry outflows
- role of neutrino oscillations
- production of cosmic rays and their detectability

Secular post-merger (~50 - 2,000+ ms)

* What we know
  - very little in full 3D GR simulations
  - most of our knowledge comes from 2D simulations
  - GW signal could be very strong (long-lived HMNS) or very weak (axisymmetric viscous HMNS)
  - mass ejection driven by neutrinos or magnetic fields, nuclear recombination (no shock heating)
  - Large fractions of disk (on HMNS or BH) will be evaporated
  - neutrino luminosity set by HMNS cooling and fate
  - kilonova emission is compatible with merger of binary neutron stars

Secular post-merger (~50 - 2,000+ ms)

- What don't we do know (yet)
  - ✦ robust timescale for collapse to BH
  - ✦ role of neutrino emission/absorption on disk ejecta
  - ✦ properties of ejected material in mass, velocity, entropy, Y_e, magnetization, etc.
  - ✦ accurate radiative models with better estimates of opacities
  - ✦ constraints from astronomical observations on neutrino luminosity
  - ✦ origin of non-thermal emission: many possible sources!

Secular post-merger (~50 - 2,000+ ms)

- **What we will not know for some time**
  - Role of turbulence?
  - long-term dynamics/activity of relativistic jet
  - interaction of relativistic jet with ejected material and genesis of gamma-ray emission
  - proto-magnetar formation and emission
  - role of neutrino oscillations
  - production of cosmic rays and their detectability (time delay)
  - detection of radio emission of ejecta