BNS/NSBH SIMULATIONS: CHALLENGES AND FUTURE DIRECTIONS

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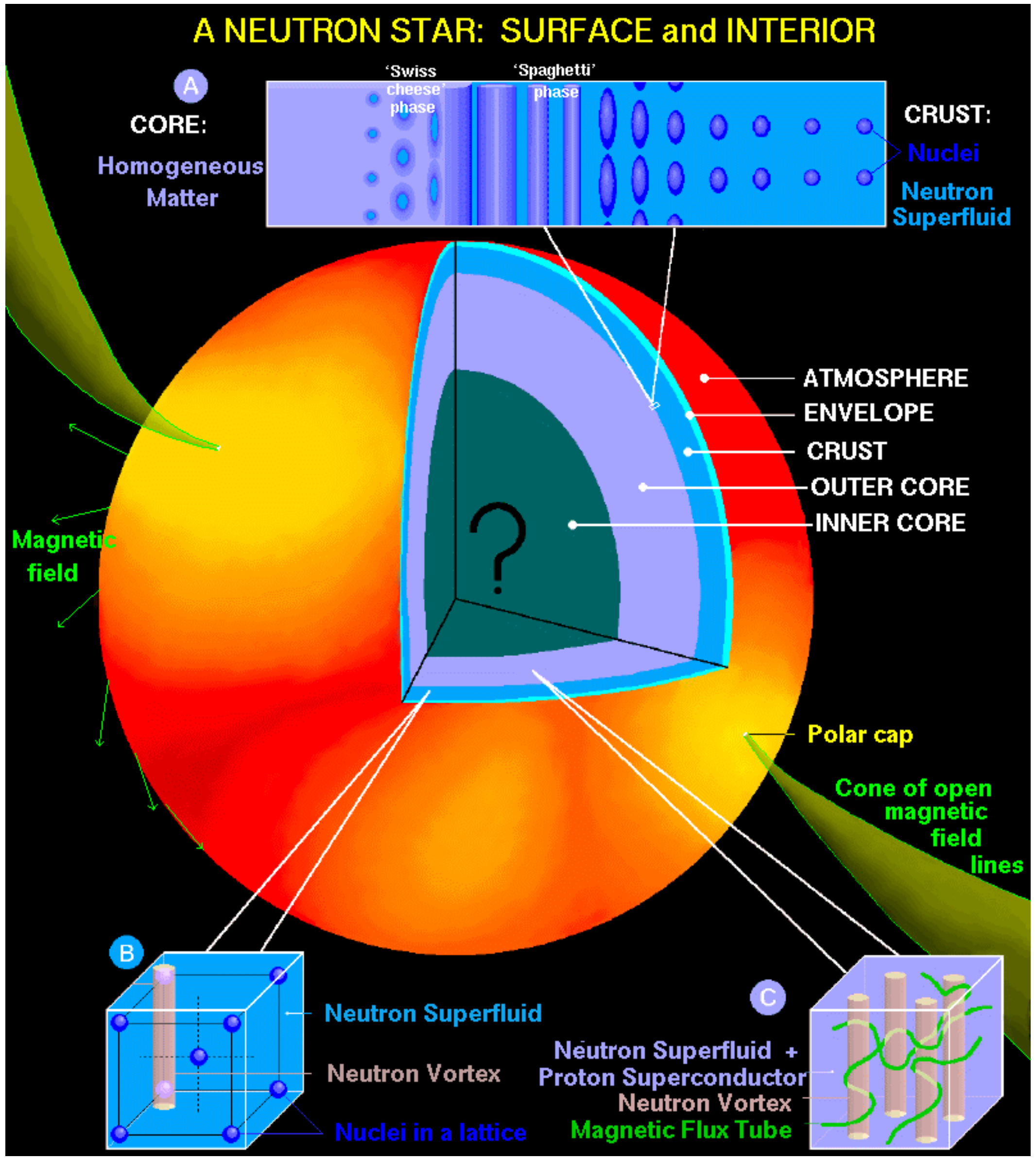
OVERVIEW

- BNSs/NSBHs require an accurate simulation of all four fundamental forces for a complete description of the system.
- In the inspiral, relativistic perfect fluid hydrodynamics provides a very good approximation: Such simulations (possibly with phenomenological thermal effects) are what is used as input to all current NR-calibrated BNS/NSBH inspiral waveform models.
- For the merger, one needs to include thermal effects, magnetic fields, nuclear reactions, neutrinos, etc. for an accurate description, particularly to compute multimessenger signals.



Credit: Dany Page

SOME SUCCESSES

- GRHD simulations of BNS/NSBH are advanced enough to show good convergence over a range of parameter space and be used in calibrating waveform models for data analysis.

  In particular, the NRTidal BNS waveform model (Dietrich et al., PRD 2017) was used in the analysis of GW170817.

- There are also publicly available catalogues of BNS and NSBH waveforms: CoRe and SACRA (both just BNS) and SXS (NSBH, a few BNS, and lots of BBH).

- BNS/NSBH simulations also now regularly include more physics than just GRHD.

CHALLENGES IN RELATIVISTIC HYDRODYNAMICS: RESOLUTION

- Minimum grid spacing to date for BNS simulations:
  - 63 m (~270 grid points across the star)
  - waveform accuracy of ~0.1 rad over the inspiral (Kiuchi et al., PRD 2017)

    [see also Kiuchi et al., arXiv 2019 for almost as high-resolution simulations in more of parameter space]
- For post-merger, the record is 12.5 m (Kiuchi et al., PRD 2018).
- High-accuracy GRHD simulations of the early inspiral could allow one to compute waveform tidal Love numbers (contrasting the metric Love numbers computed using stellar perturbation theory)

CHALLENGES IN RELATIVISTIC HYDRODYNAMICS: LENGTH

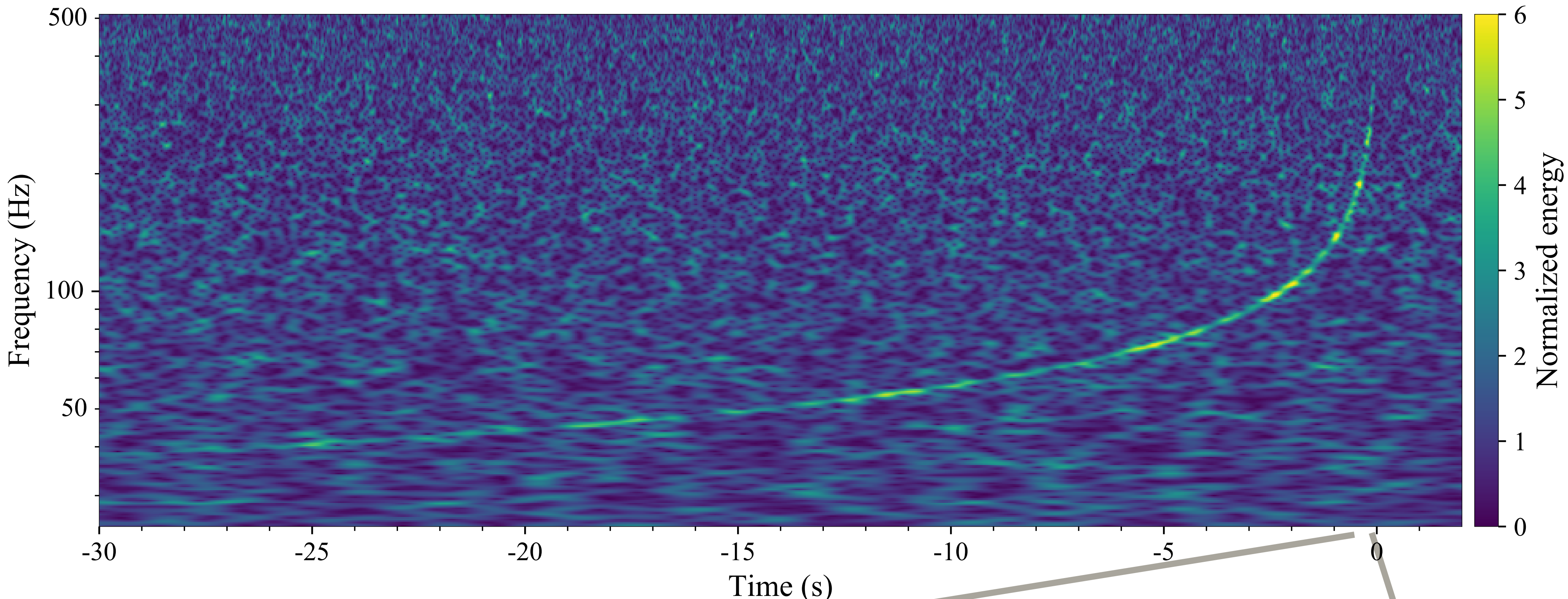
- Longest quasicircular BNS inspiral to date is ~22 orbits (~110 ms) with SpEC (Haas et al., PRD 2016), while GW170817 lasted for > 100 s in the LIGO band.

  [Longest BBH simulation is ~175 orbits, Szilágyi et al., PRL 2015, with 12 simulations in the SXS catalogue with > 100 orbits.]

- Eccentric BNS evolutions with BAM (inspiral and post-merger) last as long as ~170 ms (Chaurasia et al., PRD 2018).

- Long-term post-merger simulation (~140 ms, out of ~160 ms total) with Einstein Toolkit (De Pietri et al., PRL 2018).

CHALLENGES IN RELATIVISTIC HYDRODYNAMICS: LENGTH

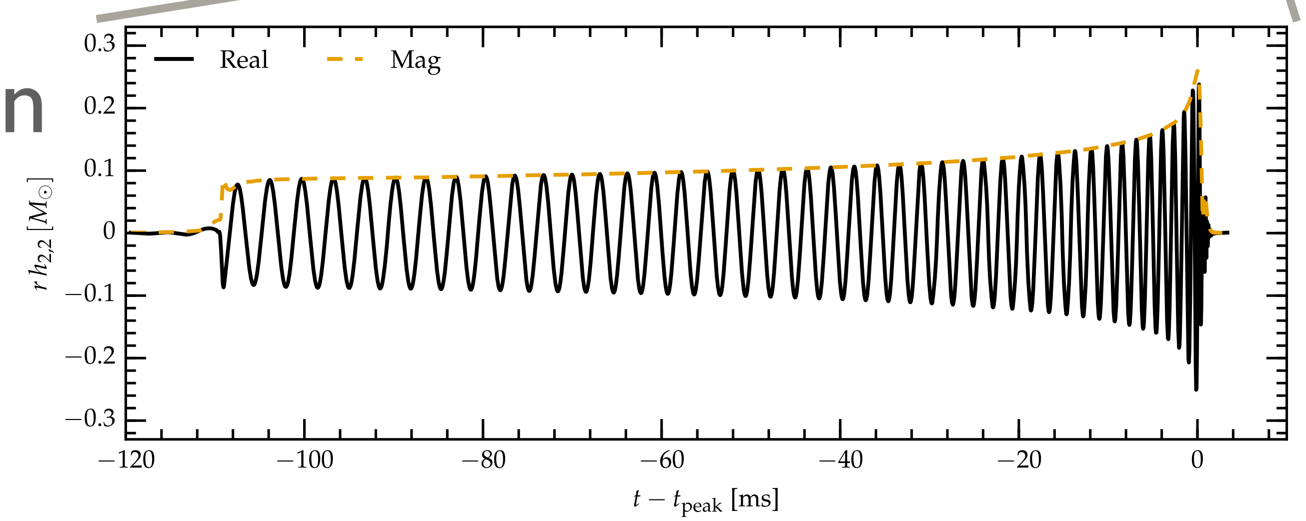


GW170817

Credit: Alex Nitz/ Max Planck Institute for Gravitational Physics/ LIGO

SXS simulation

Haas et al. PRD 2016



CHALLENGES IN RELATIVISTIC HYDRODYNAMICS: EJECTA, ETC.

- Artificial atmosphere: This is still a significant source of errors, particularly involving the ejecta.

- Accurate estimates of ejecta (even neglecting important non-hydro effects): There are various approximate methods used to determine when matter is unbound, and they do not agree with each other.

  Can an interface with SPH methods help?

- Large-ish mass ratios and precession are just starting to be explored for BNSs.

CHALLENGES IN RELATIVISTIC HYDRODYNAMICS: INITIAL DATA

- Conformal flatness still used for BNS initial data, though the SXS collaboration uses conformally curved initial data for high-spin NSBH simulations.

- Eccentricity: Minimum initial eccentricity in BNS runs is $\sim 10^{-3}$, while BBH simulations in the SXS catalogue have eccentricities as small as $\sim 10^{-5}$ and SXS NSBH simulations have eccentricities as small as $\sim 10^{-4}$.

- High NS spins: Now up to dimensionless spins in BNSs of 0.52 (Rashti et al., presentation at APS)

- High compactnesses: Problems with generating initial data; improved initial guesses help with this for BNSs (Tichy et al., presentation at APS) and improved numerical methods for NSBHs (Henriksson et al., CQG 2016). Evolutions not yet published.

NUCLEAR PHYSICS/BEYOND PERFECT FLUIDS

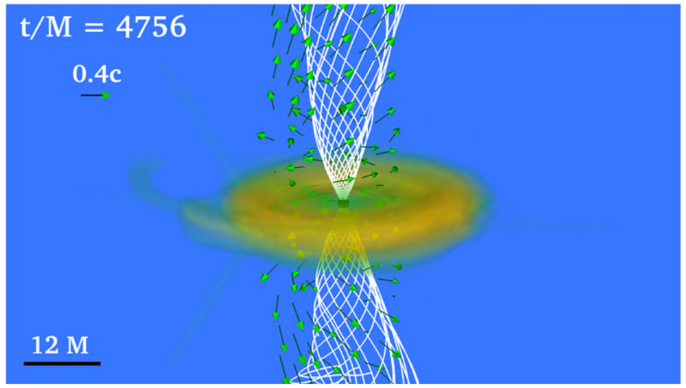
- Many BNS/NSBH simulations include phenomenological (ideal gas) thermal effects, and a number use tabulated thermal nuclear physics EOSs including temperature and electron fraction dependence.

- To my knowledge, no BNS/NSBH simulations include nuclear reactions in, e.g., the ejecta (though some include weak interactions when including neutrinos). Currently, nuclear reaction networks are used to postprocess ejecta properties.

- Models of viscosity from MHD turbulence are included in a few simulations, e.g., Fujibayashi et al., ApJ 2018, which uses the Shakura-Sunyaev criterion to in simulation of a BNS post-merger remnant, and Radice et al., ApJ 2018, which performs large eddy simulations of BNS mergers.

- Superfluidity is currently not included in any BNS/NSBH simulations.

MAGNETIC FIELDS



Jet from NSBH
Ruiz et al. PRD 2018

- Magnetic fields are very important in the post-merger evolution, notably in launching jets, but also in, e.g., angular momentum transport in the remnant.
- Even the highest-resolution current simulations of BNS remnants [Kiuchi et al., PRD 2018] are not able to resolve MHD turbulence in the dense parts of the remnant.
- In current simulations, magnetic fields are added by hand to initial data, or once the evolution of the binary is in progress. While the claim is that these magnetic fields are dynamically unimportant, even though strong, it would be desirable to have consistent initial data for BNS/NSBH systems including magnetic fields.
- Many GRMHD simulations of BNS/NSBH systems use ideal GRMHD, which is likely to be a good approximation—recent work (Harutyunyan et al., EPJA 2018) suggests that the ideal MHD approximation only breaks down when the MHD approximation breaks down—though some simulations include a simple treatment of resistive effects (e.g., Palenzuela et al., PRD 2013; Dionysopoulou et al., PRD 2015).

NEUTRINOS

- The full Boltzmann equation for neutrino transport is extremely expensive, so all current BNS/NSBH simulations including neutrinos use various approximate transport schemes.

- Moment approximations [Thorne, MNRAS 1981; Shibata et al., PTP 2011] are the current state-of-the-art, but present implementations (e.g., Foucart et al., arXiv 2019) still involve significant simplifications (e.g., only two moments, and the gray approximation—only considering energy-integrated moments).

  The comparison to a simple uncoupled MCMC transport algorithm in Foucart et al., PRD 2018 finds that the approximation they use is better than expected, but still leads to factor-of-2 errors.

- Improvements in the accuracy of the treatment of neutrinos will be necessary to make more accurate predictions for the post-merger evolution of BNSs and NSBHs, particularly for the ejecta, which affect EM counterparts.

THE ELASTICITY OF THE CRUST (AND EXOTIC SOLIDS)

- No numerical relativity simulation to date attempts to model the neutron star crust as a solid. This is likely a good approximation for gravitational wave emission in most cases—the correction to the quadrupolar tidal Love number due to the crust's elasticity is at most ~1% (Biswas et al., arXiv 2019).
- However, crust cracking could lead to pre-merger EM signals [Penner et al., ApJL (2012); Tsang et al., PRL (2012)] and possibly even dissipative effects that could have a secular effect on the inspiral phasing [Kochanek, ApJ (1992); Penner et al., ApJL (2012)]
- For more speculative cases, involving solid strange quark stars, these corrections could be a factor of ~2, for sufficiently extreme parameters (Lau et al., PRD 2019).
- Erickson, Hawke, and Gundlach worked on including elasticity in numerical relativity a while ago [see Gundlach, Hawke, and Erickson CQG (2012) for the basic formulation and various talks by Erickson for the numerical implementation], but don't seem to have gotten to astrophysical applications even in the single-star case.

P-G MODE TIDAL INSTABILITY

- The proposed p-g mode tidal instability is an example of something it is not possible to simulate with current numerical relativity simulations, though such simulations would be highly desirable (to check the presence of the instability and calculate its saturation amplitude), since the instability could affect current LIGO-Virgo observations of binary neutron stars.

  A phenomenological model for the effect is currently constrained using GW170817 (LVC, PRL 2019).

- The primary problem is that it requires very high resolution, since the instability involves many high-order modes.

- It also requires simulating a non-barotropic fluid, in order to have g-modes (which require a composition gradient).

BNS/NSBH SIMULATIONS BEYOND GR

- While BBH observations provide very clean tests of GR, some alternative theories only differ from GR in the presence of matter, e.g., scalar-tensor theory.
- Additional fields (e.g., in the hidden sector) can also couple to neutron stars and affect the binary inspiral, e.g., Croon et al., ApJL 2018.
- BNS simulations have been performed in scalar-tensor theory, particularly to study dynamical scalarization (Barausse et al., PRD 2013; Shibata et al., PRD 2014).
- Simulations of BNS/NSBH systems beyond GR + Standard Model are likely to be necessary to make optimal tests of GR or searches for additional fields with the many BNSs (and one hopes also some NSBHs) that ground-based detectors will observe in the future.

CONCLUSIONS

- The full simulation of BNS/NSBH systems requires lots more physics than just GR. Most of this physics is probably not accessible via the inspiral GWs, at least not at reasonable detector sensitivities.

  However, it makes a significant impact on the GWs from the post-merger (e.g., when a hyper massive NS collapses to a BH) as well as EM and neutrino signatures.

- Even for just simulations with perfect fluid GRHD, there are significant challenges in accuracy, length of simulations, and parameter space covered.

- While there are simulations including thermal effects, magnetic fields, and neutrinos, these are often included fairly simply, and there is much more physics one might want to include, including nuclear reactions and even elasticity.

- In addition to improved numerical methods in full GR, there might also be opportunities for further interfacing with stellar perturbation theory to, e.g., describe effects involving very small length scales or long timescales.