Binary neutron star mergers and the nuclear equation of state

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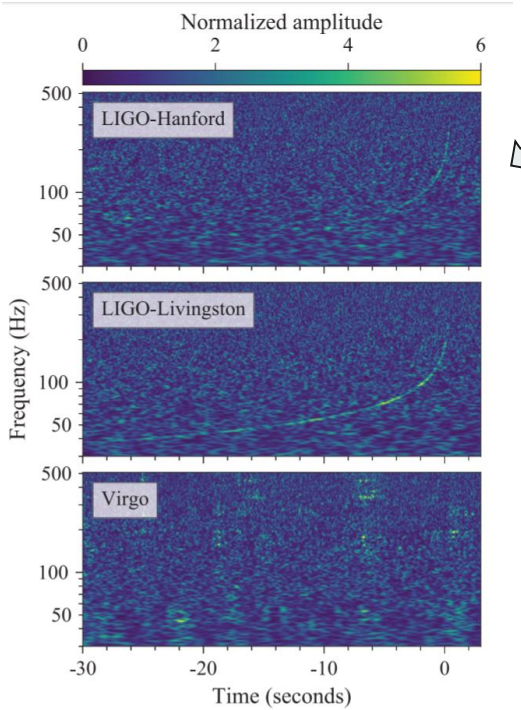
Interesting problems in binary neutron star mergers (BNSM)

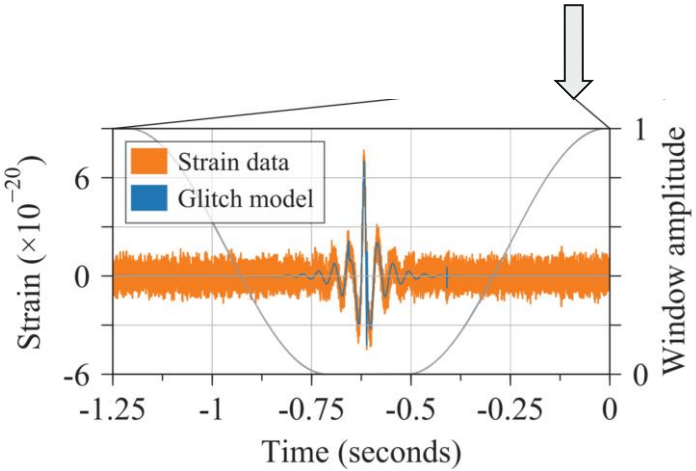
- Nuclear Equation of State (EoS) at core (Stiff v. Soft)
- Inspirals at large separations well approximated by Post-Newtonian?
- Sources of Short Gamma ray bursts? (*M. Ruiz et al. (2016)* in GRMHD)
- Remnant of Mergers? Hypermassive Neutron star or Black hole? (*Margalit, Metzger (2017)*)

First LIGO Observations of BNSM: GW170817



Frequency time series (GW170817)

Strain at merger (GW170817)



LIGO Scientific Collab. 17 August 2017

Introduction to Numerical Relativity

GR: 3+1 (space-time) split and BSSN formalism.

Equations of State + Relativistic hydrodynamics to describe the flow of matter

Numerical relativity codes that do this: Einstein Toolkit, SpECTRE, Dendro, etc.

LORENE: Solves the TOV equation and prepares Initial data (ID) of the two Neutron stars separated.

lorene.obspm.fr

Einstein Toolkit: State-of-the-art numerical relativity evolution software platform

- Vast library of pre-written modules for GR, hydrodynamics, adaptive mesh refinement (AMR).
- Carpet and PUGH (AMR).
- Built on Cactus code framework, highly modular.

einsteintoolkit.org

Dense matter Equation of State

Equation of state (EoS) in the form of Pressure v. density $P(\rho)$

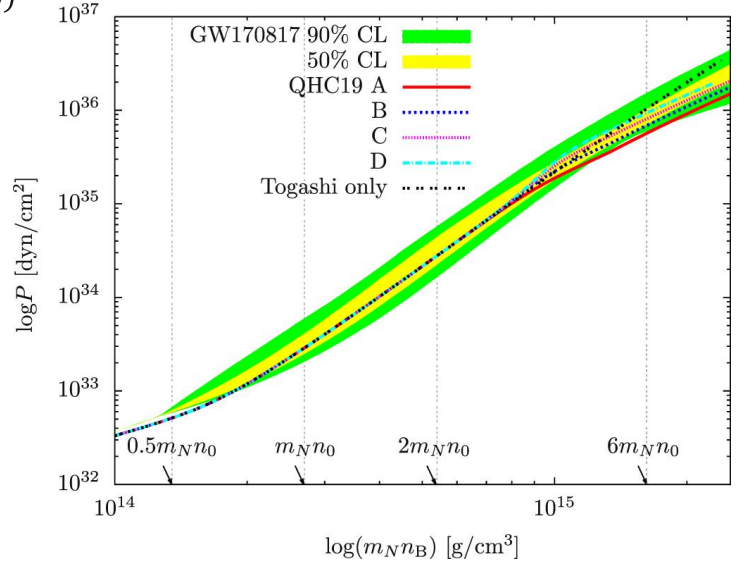
Quark-Hadron Crossover (QHC19A-D) EoS
Baym et al. 2019, 2018, Other's by Kurkela et al. *ApJ* (2014) 789:127

Cold EoS ($T = 0$)

Quark EoS: Nambu-Jona-Lasinio model
$$> 5n_0 \approx 1.3 \times 10^{15}\ gm/cm^3$$

Hadronic EoS: Togashi EoS (extension of APR) for densities
$$< 2n_0 \approx 5.4 \times 10^{14}\ gm/cm^3$$

Smooth fitting in the intermetiate Crossover region: $2n_0 - 5n_0$



Baym, Furusawa, Hatsuda et al. *ApJ* (2019) 885:42

Piecewise polytropic fitting scheme

Piecewise polytropic(PP) EoS.

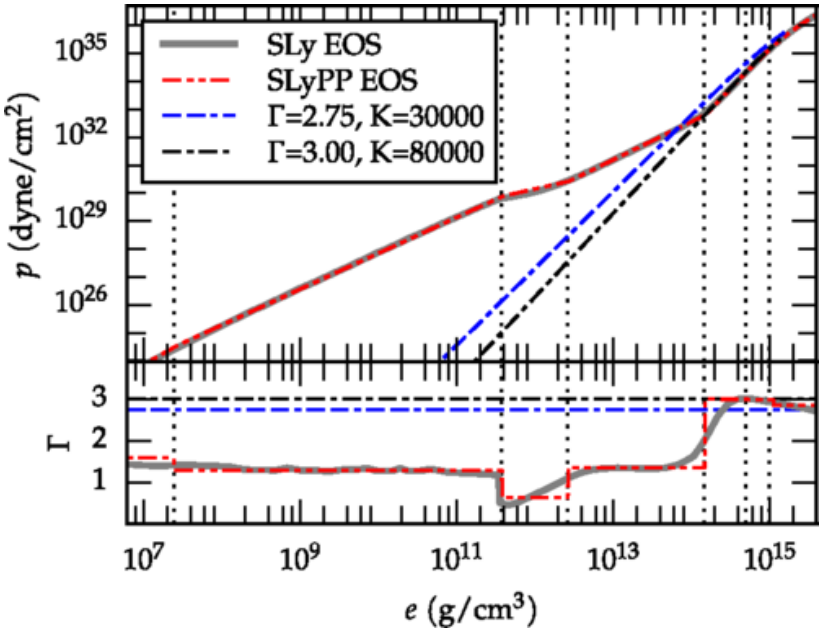
Fitting conditions:

- Pressure-density relation: $P(\rho) = K_i \rho^{\Gamma_i}$
- Internal energy density $\epsilon = a_i\, \rho + \frac{K_i}{\Gamma_i - 1} \rho^{\Gamma_i}$
- Continuity of pressure, internal energy is imposed.

Read, Lackey, Owen, Friedman *PRD* (2009) 79, 124032.

3 piece piecewise scheme (high density) capture all essential structure of the EoS, + SLy EoS at low densities.

Non-zero temperature corrections by $\Gamma_{thermal}$ contribution.

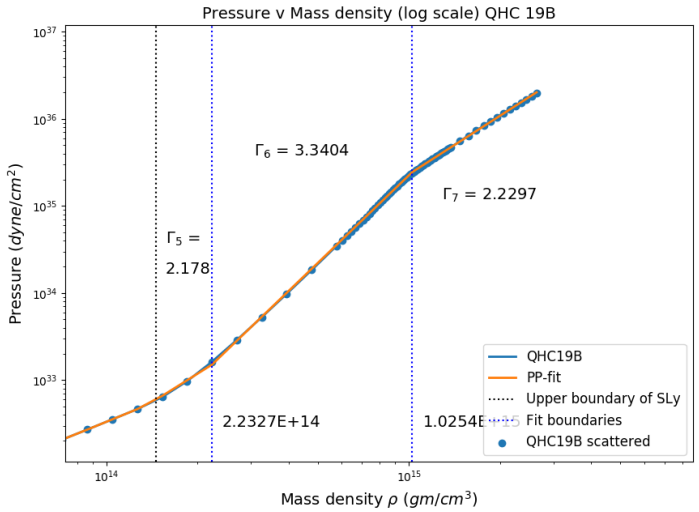


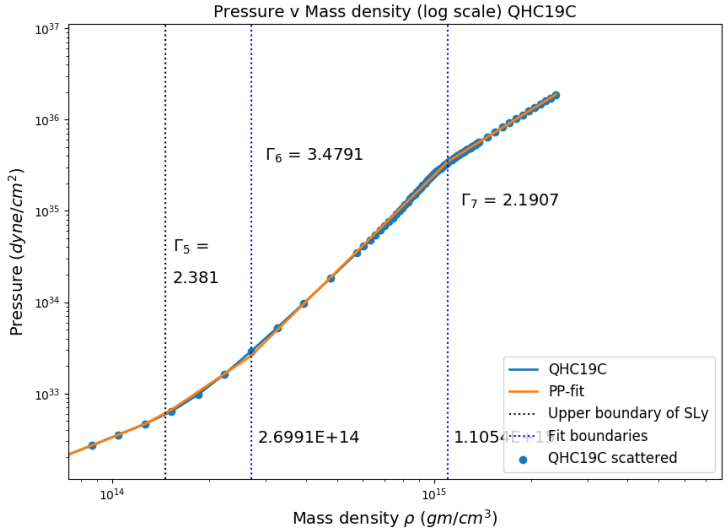
Pietri, Feo, Maione, Löffler *PRD* (2016) 93, 064047

Fitting QHC EoS piecewise

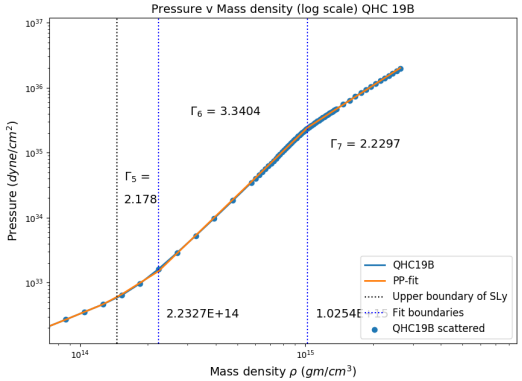
We fit the High density QHC region using this scheme and obtain the EoS Pieces:
Degrees of freedom in fitting $(\Gamma_5, \rho_5, \Gamma_6, \ \rho_6, \ \Gamma_7)$

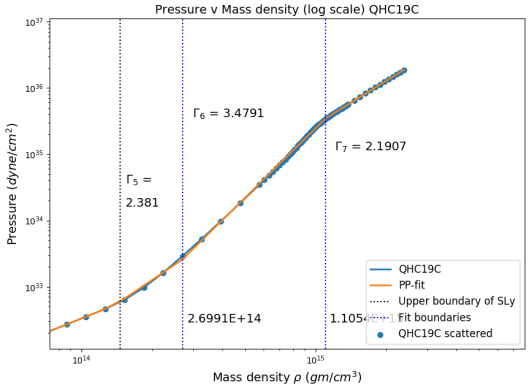
RMS Residual = $\sqrt{\frac{1}{m}\left(\sum_{i\ (Pieces)} \sum_{j(Densities)} (\log P_j \ - \ \log K_i - \Gamma_i \ \log \rho_j)^2\right)} = 0.014$ i.e. $\log P = 35 \ \pm 0.014.$

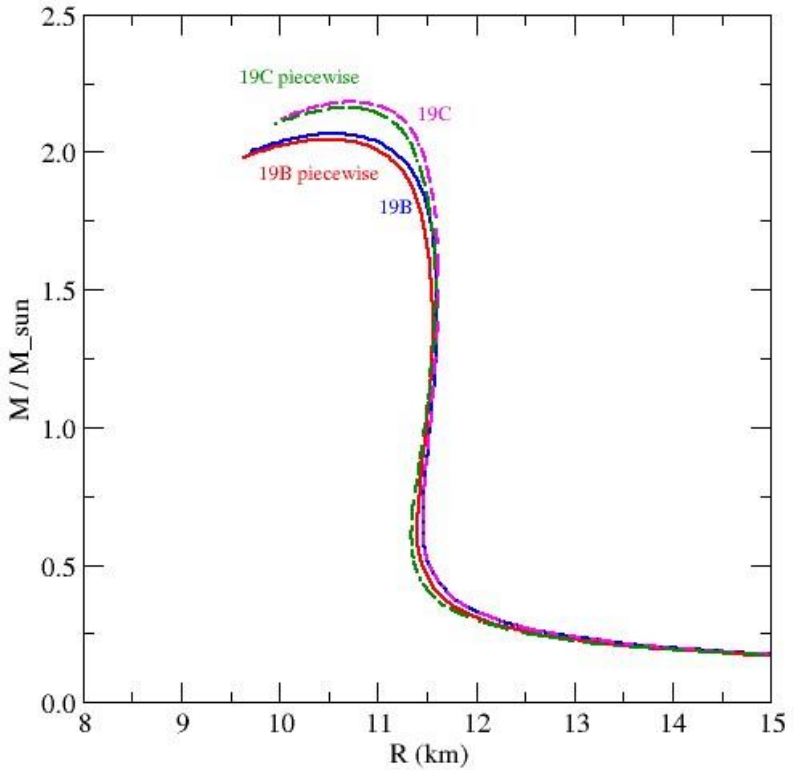




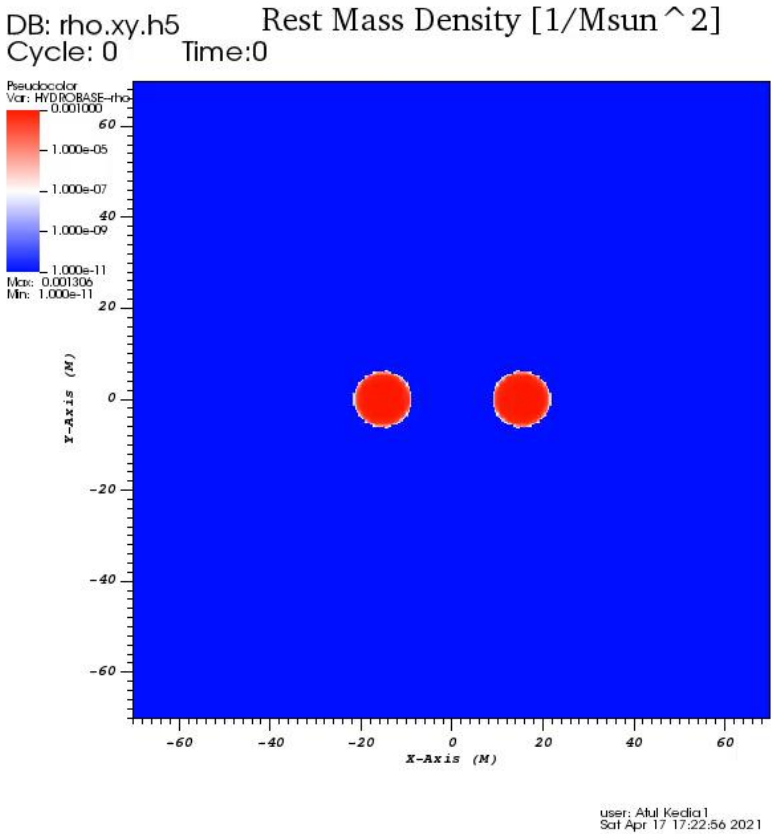
Mass-Radius relations of QHC19

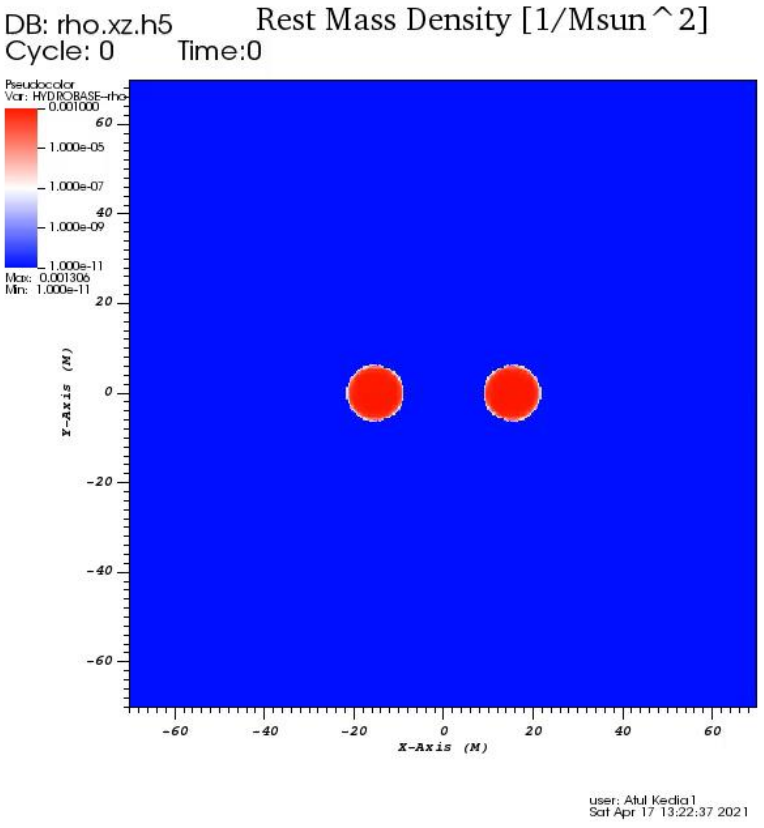




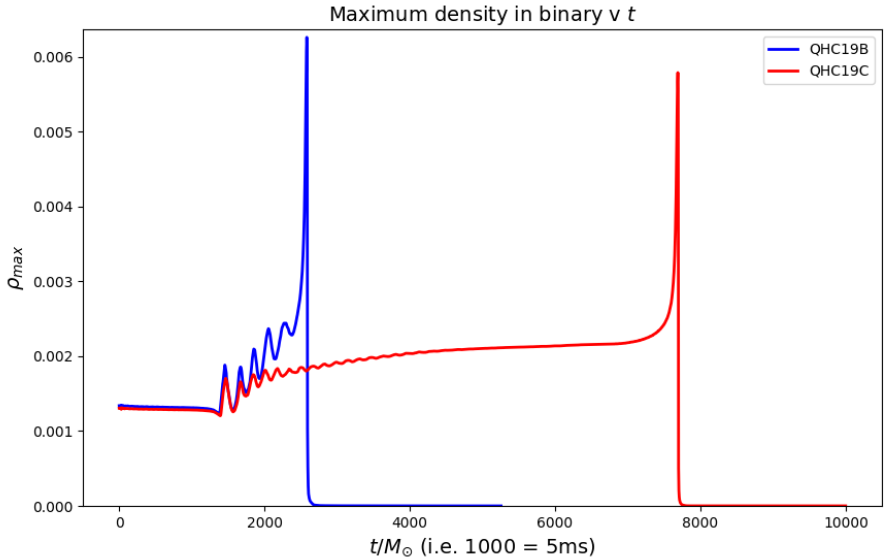


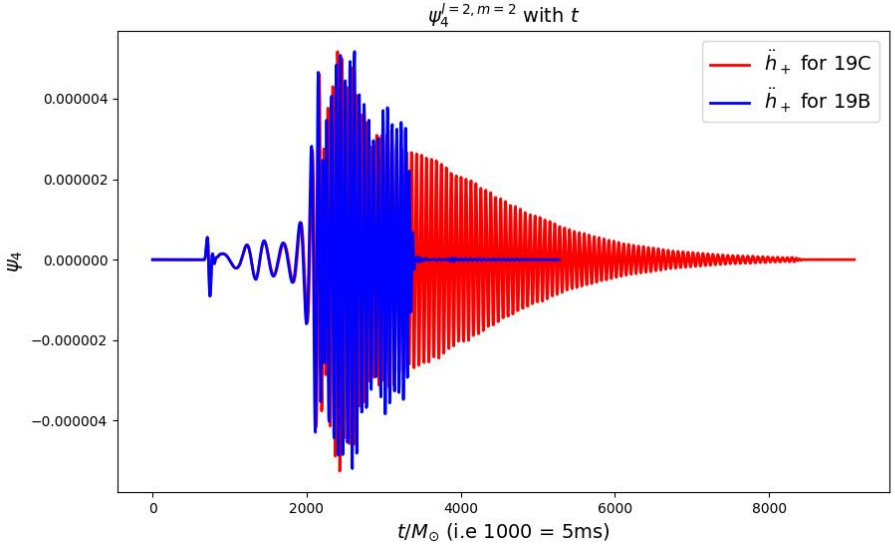
Merger for QHC19C





Mergers of 19B v 19C





Conclusion

Generate runs for QHC EoS at distances ~ $45\ km$

- Convergence tests for the evolution for massive NS simulations.
- Analyze Gravitational waves.
- Evolutions of all four QHC19A-D

Thank you! Questions?

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