Investigating the microphysics of Binary Neutron Star mergers

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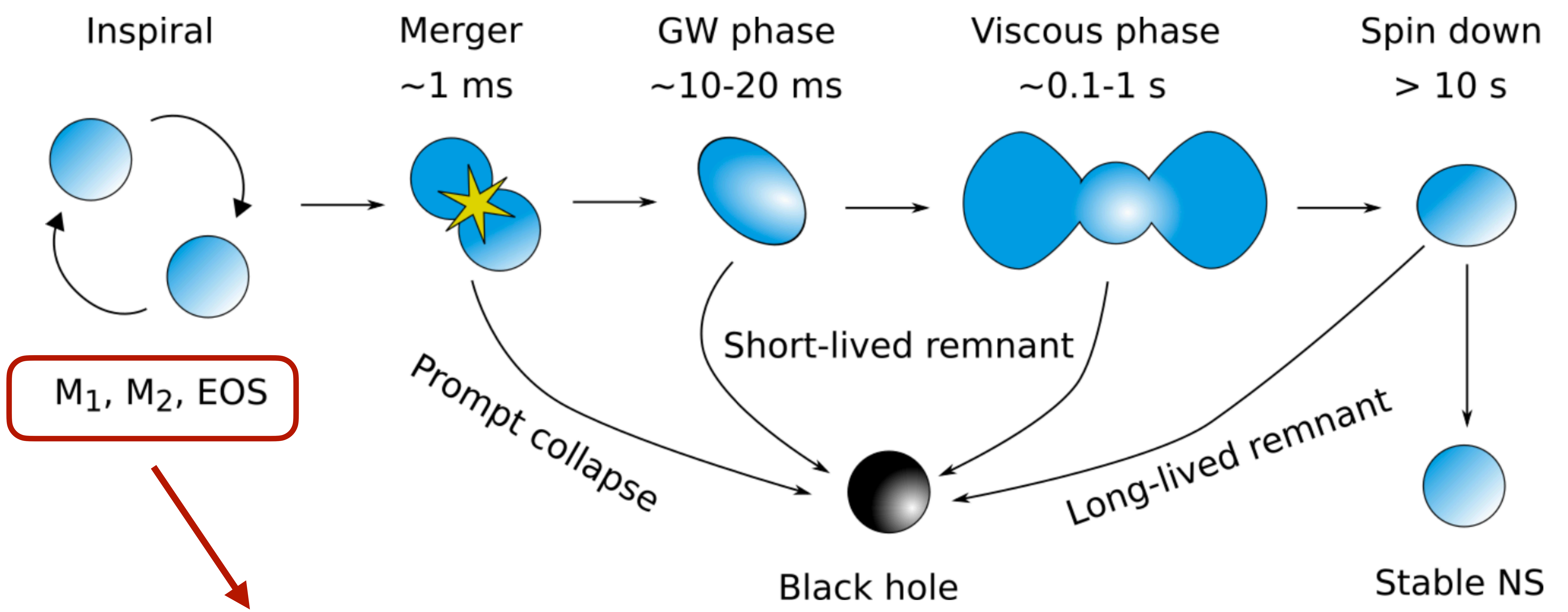
February 16, 2022

The remnants of Binary Neutron Star mergers

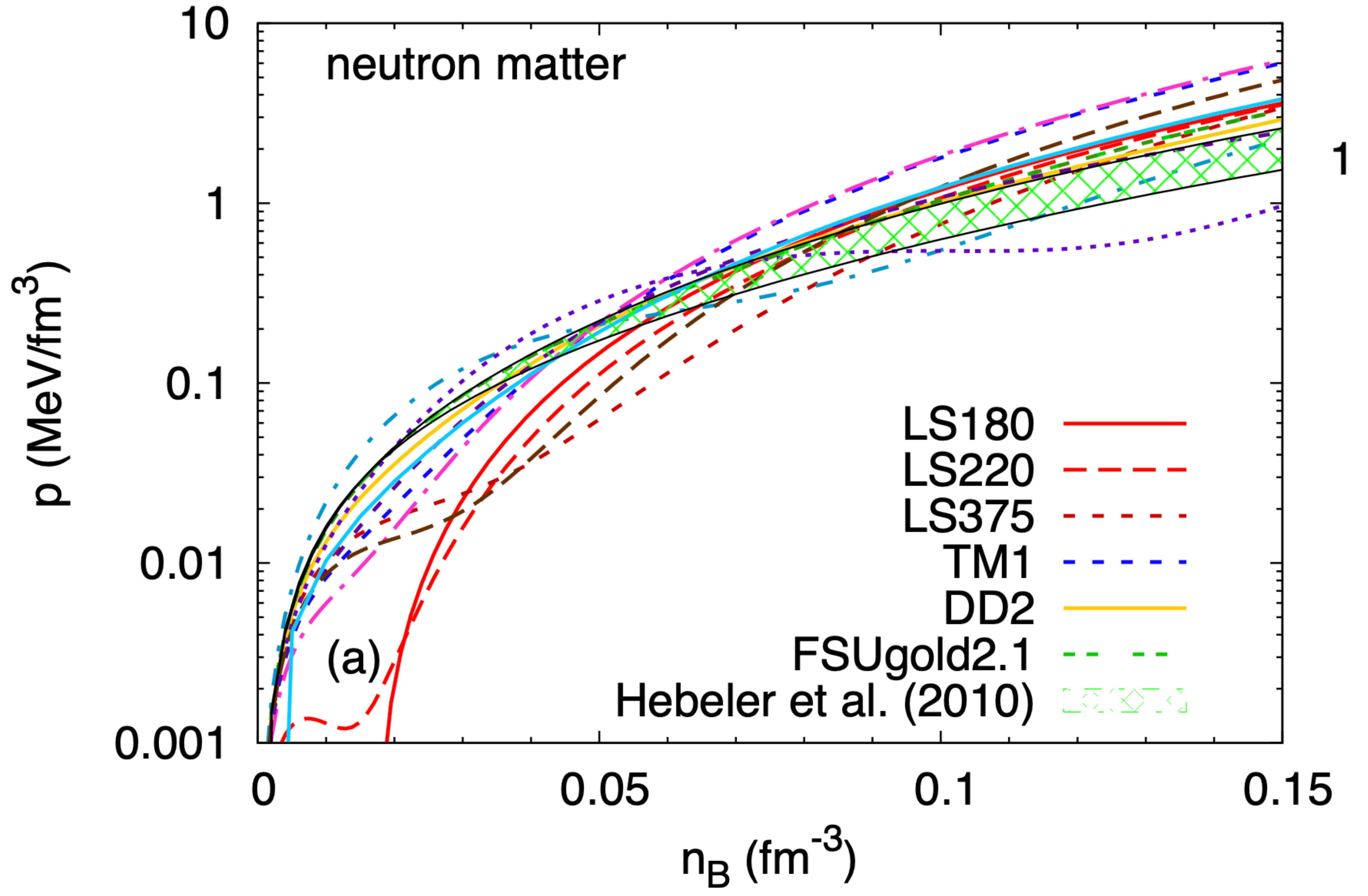
Credits: Radice, Bernuzzi, Perego 2020

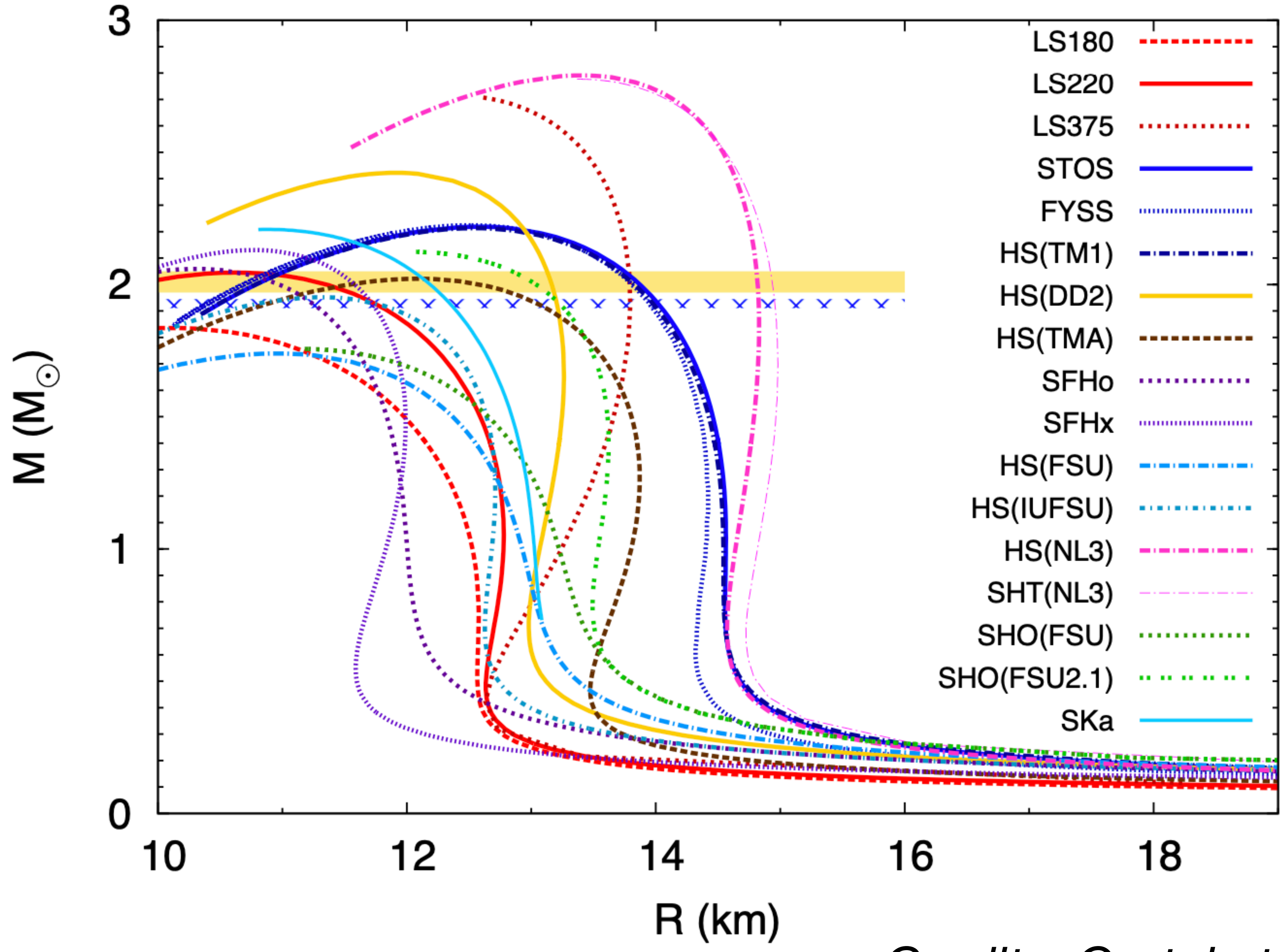


- Time of collapse depends on the masses and the Equation of State
- Time of collapse strongly affects gravitational and electromagnetic signals

The Equation of State of nuclear matter

- EOS: relation between matter density, temperature and thermodynamic variables
- The EOS of Neutron Stars is unknown
- Many models developed for the EOS
- Modelling of nuclear interaction and relevant degrees of freedom: neutrons, protons, pions, free quarks, muons, …





Credits: Oertel et al. 2016

Modelling the microphysics of the merger: why?

Accurate description of the microphysics i.e. of the EOS

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Precise numerical simulations of BNS mergers

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Reliable predictions of the gravitational and EM signals

↓

Big help for detecting the signals and interpreting them

Detections of GW and EM signals from the merger

↓

Compare with the predictions from the numerical simulations, based on your modelling

↓

Get a constrain on the microphysics of the merger

↓

Understanding the nuclear forces

Improving the microphysics modelling

Muons production and Neutrino Trapping

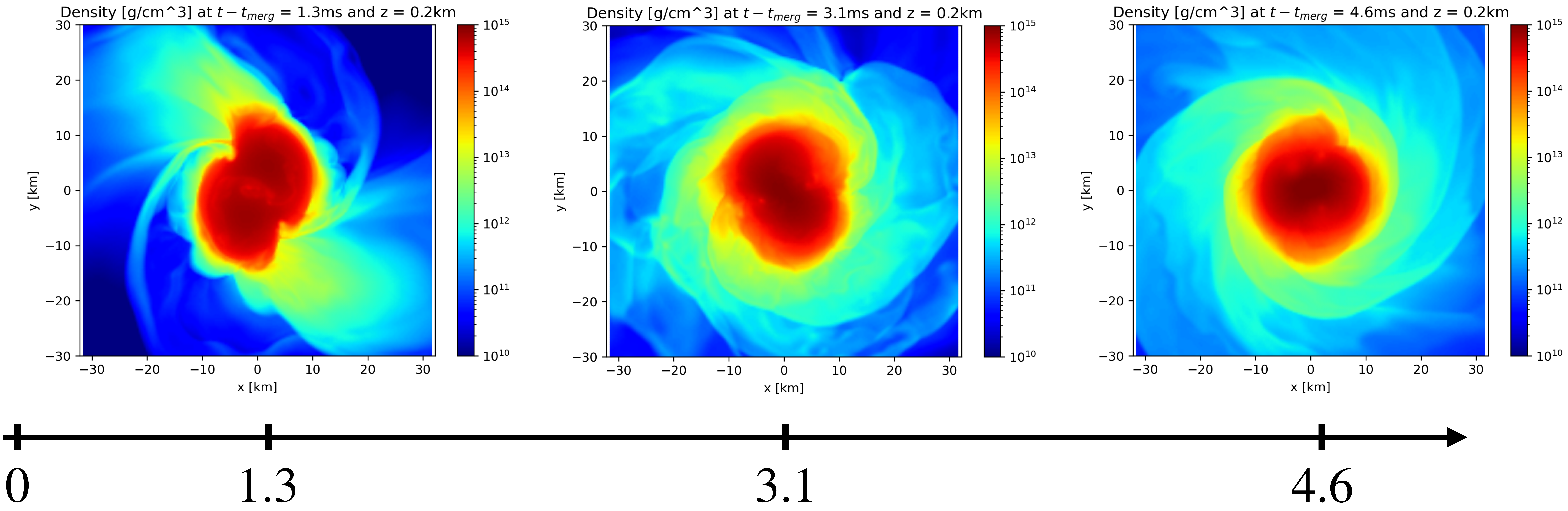
- Muons are included in cold Neutron Star EOS
- Thermodynamics conditions in BNS mergers favour muons and neutrinos production and neutrino trapping

State of the art simulations of BNS mergers don’t include muons and trapped neutrinos.

Can we “safely” neglect them? Is it worth it improving the numerical simulations by adding their contribution?

Typical outcome of a BNS merger simulation

Matter Density Evolution with time



$t - t_{merger}$ [ms]

Modelling the appearance of muons and the trapping of neutrinos

- During the merger the temperature of fluid elements increase → creation of muons and neutrinos

- At high enough density the neutrinos are trapped → lepton numbers conserved

- On a time-scale $t_{weak} \ll dt \ll t_{dyn}$ the internal energy u stays the same

$$\begin{cases} Y_{l,e} = Y_e + Y_{\nu_e}(n_b, T, Y_e, Y_\mu) - Y_{\bar{\nu}_e}(n_b, T, Y_e, Y_\mu) \\ Y_{l,\mu} = Y_\mu + Y_{\nu_\mu}(n_b, T, Y_e, Y_\mu) - Y_{\bar{\nu}_\mu}(n_b, T, Y_e, Y_\mu) \\ u = \sum_i e_i(n_b, T, Y_e, Y_\mu) \quad i = b, e^{+/-}, \mu^{+/-}, \gamma, \nu, \bar{\nu} \end{cases}$$

- Numerical relativity simulations provide $(Y_{l,e}, Y_{l,\mu}, u)\ \forall (t, x, y, z)$ under the assumptions $Y_{l,e} = Y_e$ and $Y_{l,\mu} = Y_\mu = 0$ and no contributions from neutrino trapping

- By solving the system we get the *true* values of Y_e, Y_μ, T and all thermodynamic quantities

Results

Let's apply the post-processing technique to 3 simulations with:

- Same binary mass ratio $M_2/M_1 = 1$
- Different methods adopted to describe the nuclear interaction (DD2, BLh, SFHo)

Then, let's investigate binary mass ratio $M_2/M_1 = 1.4$

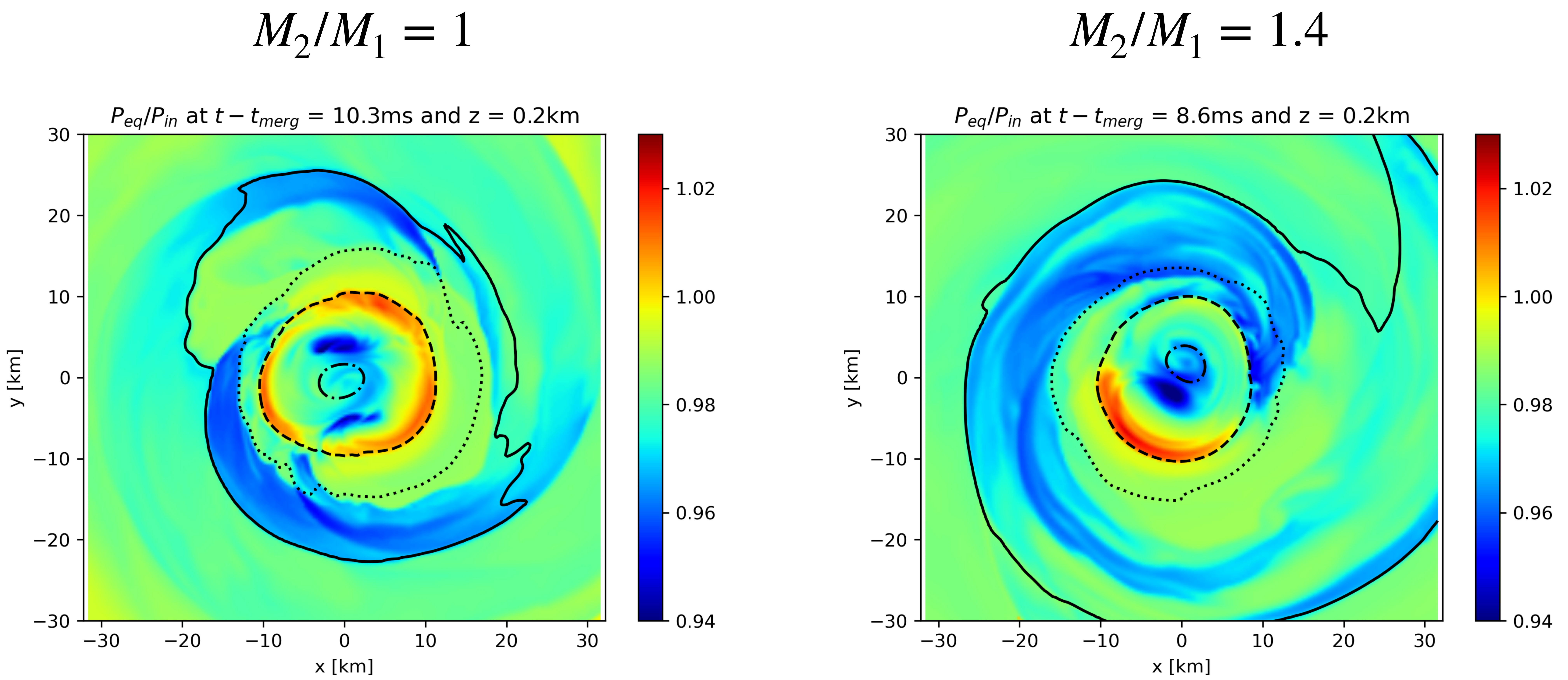
Results - The trapping of Neutrinos

- Trapped gas of neutrinos —> Possible neutrino bursts?
- Trapped gas of anti-neutrinos: probe of the underlying model for nuclear interaction —> New constraints of the EOS?

Results - Pressure variation

- Strongly dependent on the EOS and on the region considered
- Can imply either faster or slower collapse to a BH —> implications for gravitational and electromagnetic signals

Results - Pressure variation (BLh)



- Asymmetry in pressure variation when $M_2/M_1 \neq 1$ −> Possible kicks?

More important than results…

What do you practically do in this kind of research?

1. Developing a theoretical model

—> study, read papers, think, discuss, bother everyone in your group and outside

2. Implementing your model

—> programming, debugging and optimisation

3. Understanding the results

—> look for the physical reasons motivating your results (simulations are not oracles…), so again think, discuss, bother everyone…

4. Predicting the impact on observables and defining the observational strategy

—> here comes the fun!

Conclusions

- Our original question: is it worth it improving the numerical simulations by adding muons and trapped neutrinos?

My answer: yes, their impact is not negligible, we need to work on the simulations to include them from scratch

- Our new questions: Neutrino bursts? Slower or faster collapse? New constraints on the nuclear EOS? Kicks ?

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THANK YOU AND ENJOY YOUR PHD