The EOS of neutron stars via gravitational-wave modeling on SuperMUC

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Kentaro Takami

Institute for Theoretical Physics, Goethe University Frankfurt

Collaborators : Luciano Rezzolla and Luca Baiotti

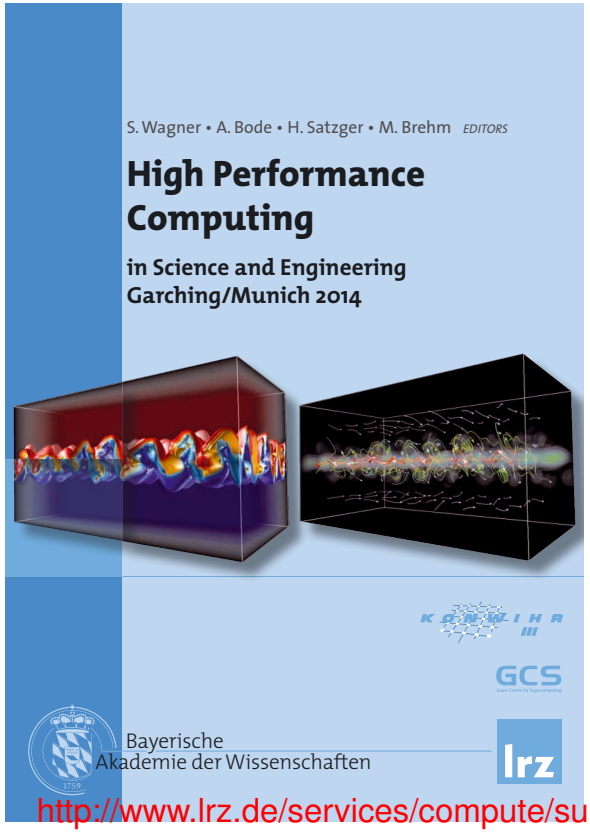
SuperMUC Status and Results Workshop, 8-9 July 2014.

Our SuperMUC Project

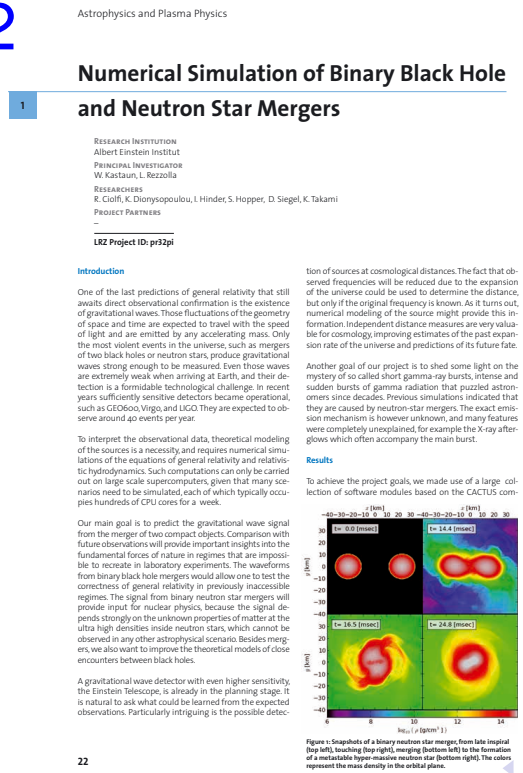
LRZ Project ID : pr32pi

Project Manager : Prof. Dr. Luciano Rezzolla

Project Name : Numerical Simulation of Binary Black Hole and Neutron Star Mergers



P22



1 Numerical Simulation of Binary Black Hole and Neutron Star Mergers

Research Institution
Albert Einstein Institut
Principal Investigator
W. Kastaun, L. Rezzolla
Researchers
R. Ciolfi, K. Dionysopoulou, I. Hinder, S. Hopper, D. Siegel, K. Takami
Project Partners
–

LRZ Project ID: pr32pi

Introduction

One of the last predictions of general relativity that still awaits direct observational confirmation is the existence of gravitational waves. Those fluctuations of the geometry of space and time are expected to travel with the speed of light and are emitted by any accelerating mass. Only the most violent events in the universe, such as mergers of two black holes or neutron stars, produce gravitational waves strong enough to be measured. Even those waves are extremely weak when arriving at Earth, and their detection is a formidable technological challenge. In recent years sufficiently sensitive detectors became operational, such as GEO600, Virgo, and LIGO. They are expected to observe around 40 events per year.

To interpret the observational data, theoretical modeling of the sources is a necessity, and requires numerical simulations of the equations of general relativity and relativistic hydrodynamics. Such computations can only be carried out on large scale supercomputers, given that many scenarios need to be simulated, each of which typically occupies hundreds of CPU cores for a week.

Our main goal is to predict the gravitational wave signal from the merger of two compact objects. Comparison with future observations will provide important insights into the fundamental forces of nature in regimes that are impossible to recreate in laboratory experiments. The waveforms from binary black hole mergers would allow one to test the correctness of general relativity in previously inaccessible regimes. The signal from binary neutron star mergers will provide input for nuclear physics, because the signal depends strongly on the unknown properties of matter at the ultra high densities inside neutron stars, which cannot be observed in any other astrophysical scenario. Besides mergers, we also want to improve the theoretical models of close encounters between black holes.

A gravitational wave detector with even higher sensitivity, the Einstein Telescope, is already in the planning stage. It is natural to ask what could be learned from the expected observations. Particularly intriguing is the possible detection of sources at cosmological distances. The fact that observed frequencies will be reduced due to the expansion of the universe could be used to determine the distance, but only if the original frequency is known. As it turns out, numerical modeling of the source might provide this information. Independent distance measures are very valuable for cosmology, improving estimates of the past expansion rate of the universe and predictions of its future fate.

Another goal of our project is to shed some light on the mystery of so called short gamma-ray bursts, intense and sudden bursts of gamma radiation that puzzled astronomers since decades. Previous simulations indicated that they are caused by neutron-star mergers. The exact emission mechanism is however unknown, and many features were completely unexplained, for example the X-ray afterglows which often accompany the main burst.

Results

To achieve the project goals, we made use of a large collection of software modules based on the CACTUS computational toolkit, which provides infrastructure for large scale simulations, including MPI parallelization, mesh refinement (provided by the CARPET driver), memory management, and data storage. The equations of general relativity are integrated using the McLachlan module from the Einstein Toolkit, which is based on high order finite differencing methods.

The (magneto-)hydrodynamic equations are evolved using the Whisky code. It employs modern finite volume methods for conservation laws in conjunction with various approximate Riemann problem solvers and a piecewise parabolic reconstruction algorithm. Initial data for binary neutron stars was generated using the LORENE code, a solver for elliptic PDEs based on spectral methods.

In total, we used 14 million core hours for simulations of binary neutron star mergers, magnetized hyper-massive neutron stars, binary black hole mergers and close encounters. A typical run required around 200-500 cores for several days up to several weeks. The resulting data occupies more than 19 TB permanent disk storage, contained in around 1 million files.

Binary neutron star mergers
Using the above codes, we computed the inspiral and merger of binary neutron stars with 5 different masses, assuming a simple analytic model (gamma-law equation of state) for the properties of matter at high densities. An example is shown in Figure 1. For each model, we extracted the gravitational wave signal. The corresponding power spectrum contains contributions from the inspiral phase and the hyper-massive neutron star stage. It is also shifted to lower frequencies with increasing distance to the source. We demonstrated that these features could be combined to infer the absolute distance and total mass, assuming a particular equation of state of the neutron star matter [1]. We have shown that such observations of sources at cosmological distances with sufficient signal to noise ratio should be possible with the proposed Einstein Telescope.

Hypermassive neutron stars
A large part of our simulations was devoted to hyper-massive neutron stars formed during binary neutron star mergers. Besides the gravitational wave signal, the evolution of the magnetic field is of astrophysical interest. We therefore performed general relativistic magneto-hydrodynamics simulations of such models, in the limit of infinite conductivity (ideal MHD). Here, we could show that differential rotation causes magnetically driven outflows, carrying substantial amounts of energy [1]. Those winds might well be the source of the X-ray afterglows which often accompany short gamma-ray bursts. Figure 2 depicts the development of the wind.

Further, we studied the effect of large magnetic fields on the so called bar-mode instability. This instability develops only for rapidly rotating neutron stars, such as those formed in mergers, and converts rotational energy into gravitational waves, also accelerating the collapse of the star to a black hole. We found that only very high magnetic field strengths exceeding 1016 Gauss can delay or even suppress the instability [3].

Binary black hole systems
In contrast to binary black hole mergers, which are well investigated by now, little was known on the dynamics of close encounters. We performed numerical simulations of such encounters with different impact parameters and compared the results with existing analytic estimates, thus determining the accuracy of such predictions in different regimes [4]. Besides physics runs, a fraction of our resources was used to further test and develop the codes used for simulating binary black hole mergers, also with regard to numerical optimization.

On-going Research / Outlook

Currently, we are expanding our results mainly in three directions. One is the influence of the matter properties at high densities. Another is the influence of resistive effects on the evolution of magnetic fields. Finally, we are including the effects of neutrino cooling into merger simulations.

References and Links

[1] http://arxiv.org/abs/1312.1862, "Host redshifts from gravitational-wave observations of binary neutron star mergers"
[2] http://arxiv.org/abs/1401.4544, "Magnetically driven winds from differentially rotating neutron stars and X-ray afterglows of short gamma-ray bursts"
[3] Phys. Rev. D 88, 104028, "Dynamical bar-mode instability in rotating and magnetized relativistic stars"
[4] http://arxiv.org/abs/arXiv:1402.7307 "Strong-Field Scattering of Two Black Holes: Numerics Versus Analytics"

P23

http://www.lrz.de/services/compute/supermuc/magazinesbooks/2014_SuperMUC-Results-Reports.pdf

Introduction

What is a Binary Neutron Star?

- observationally existence (as opposed to binary black holes)
- one of the strongest sources of gravitational waves
- central engine of short gamma ray bursts
  - the released energies $\sim 10^{48-50}$ erg, which is equivalent to what released by the whole galaxy over $\sim$ 1 year
- the GWs will be observed by advanced detectors (advanced LIGO(USA), advanced VIRGO(Italy) and KAGRA(Japan)) within the next 5 years
  - realistic rate $\sim$ 40 BNSs inspirals a year, *i.e.* , $\sim$ 1 event a week (Abadie+2010)

What is a Binary Neutron Star?

- For BHs, we know what to expect:

$$\text{BH} + \text{BH} \implies \text{BH} + \text{GW}$$

- For NSs, the question is more subtle: the merger leads to a hyper-massive neutron star (HMNS), *i.e.* , a metastable equilibrium:

$$\text{NS} + \text{NS} \implies \text{HMNS} + ? \implies \text{BH} + \text{torus} + ? \implies \text{BH}$$

All complications are in the intermediate stages; the rewards:

  - studying the HMNS will show strong and precise imprint on the EOS
  - studying the BH+torus will tell us on the central engine of GRBs

What is a Binary Neutron Star?

- For BHs, we know what to expect:

  $$\text{BH} + \text{BH} \implies \text{BH} + \text{GW}$$

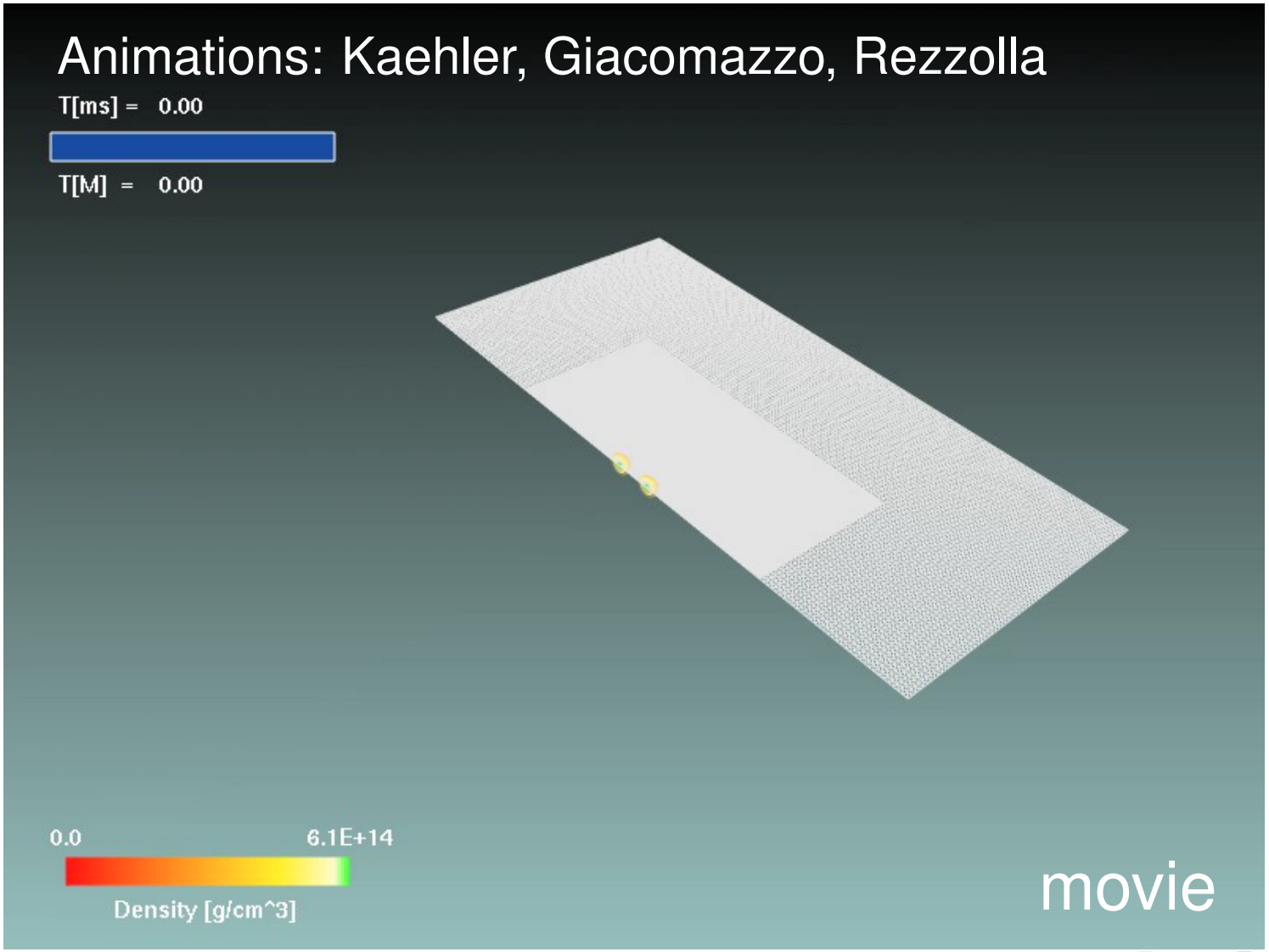
- For NSs, the question is more subtle: the merger leads to a hyper-massive neutron star (HMNS), *i.e.* , a metastable equilibrium:

  $$\text{NS} + \text{NS} \implies \text{HMNS} + ? \implies \text{BH} + \text{torus} + ? \implies \text{BH}$$

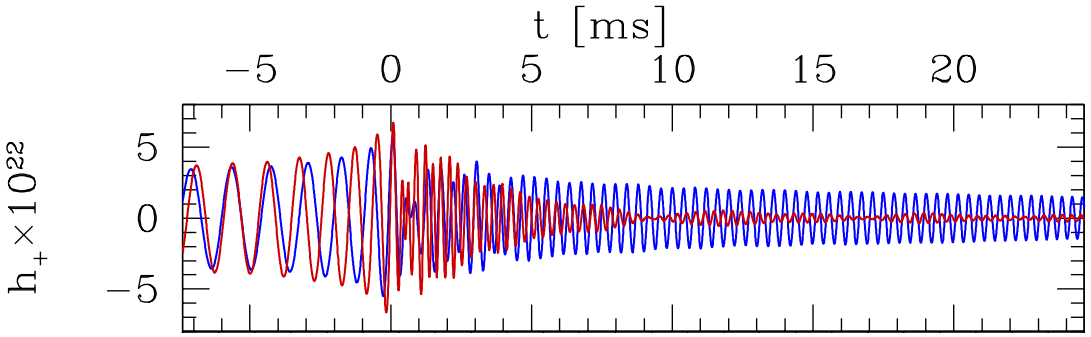
  All complications are in the intermediate stages; the rewards:

  - studying the HMNS will show strong and precise imprint on the EOS
  - studying the BH+torus will tell us on the central engine of GRBs

What is a Binary Neutron Star?

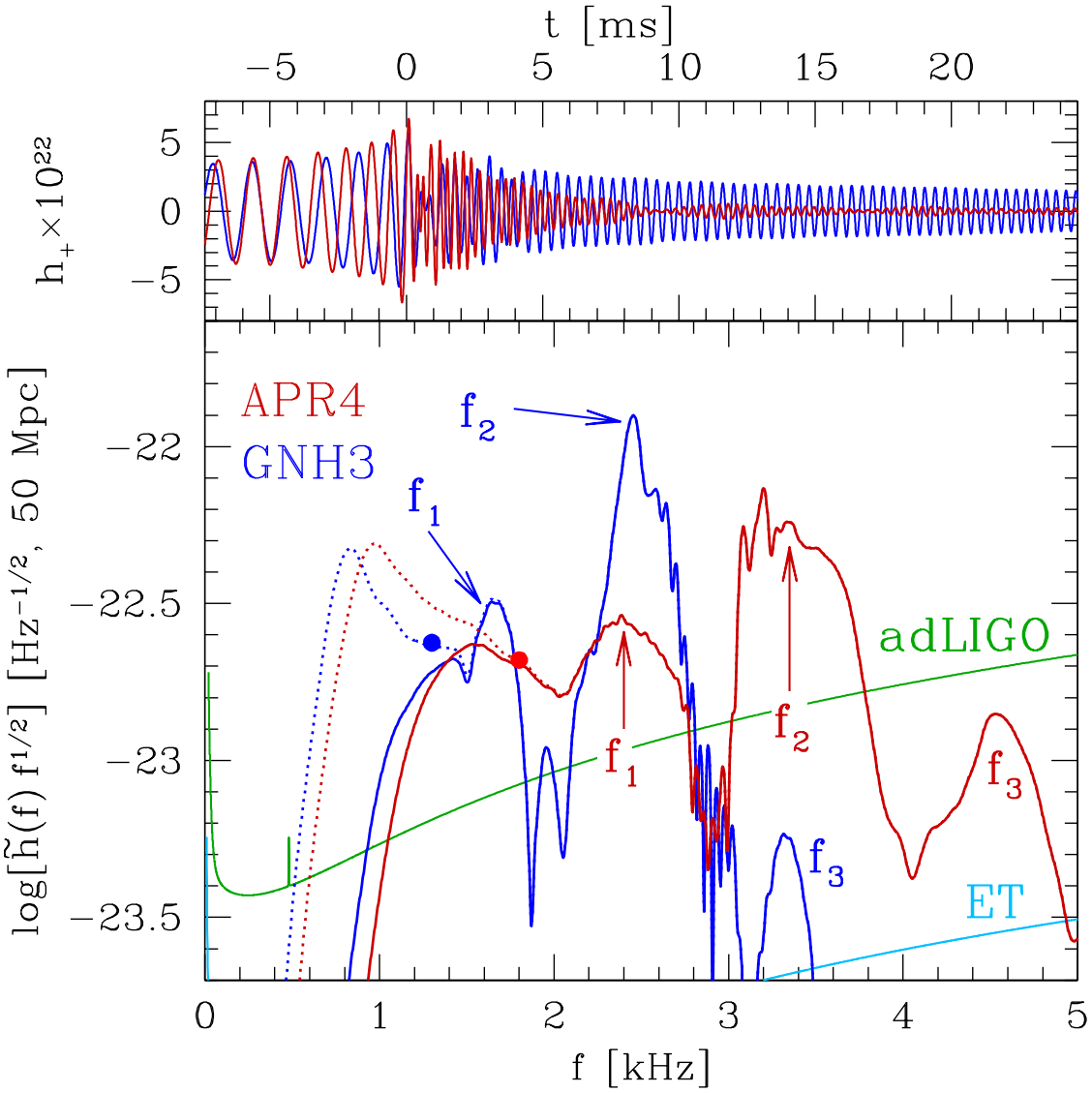


GW from a HMNS



The GW potentially give us many information, such as the mass, EOS and so on.

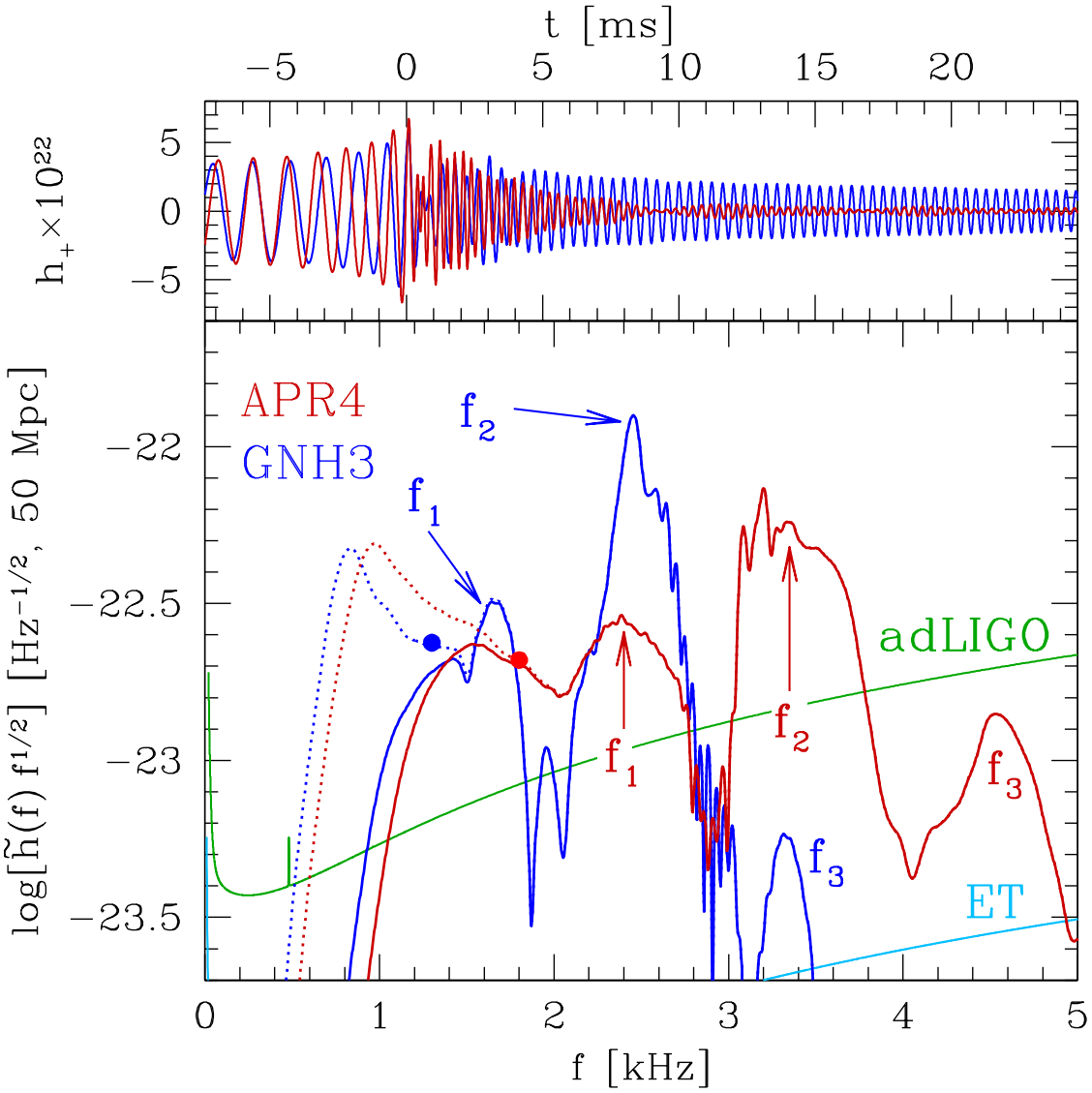
GW from a HMNS



Three clear peaks, f_1, f_2 and f_3.

- $f_1 \cdots$ nonlinear interaction between quadrupole and quasiradial modes
- $f_2 \cdots$ fundamental quadrupolar fluid mode (Stergioulas+2011)
  $f_2 \cdots$ simple function of the average mass density, independent of the EOS considered (Bauswein+2012)
- $f_3 \cdots$ larger uncertainty in the physical interpretation

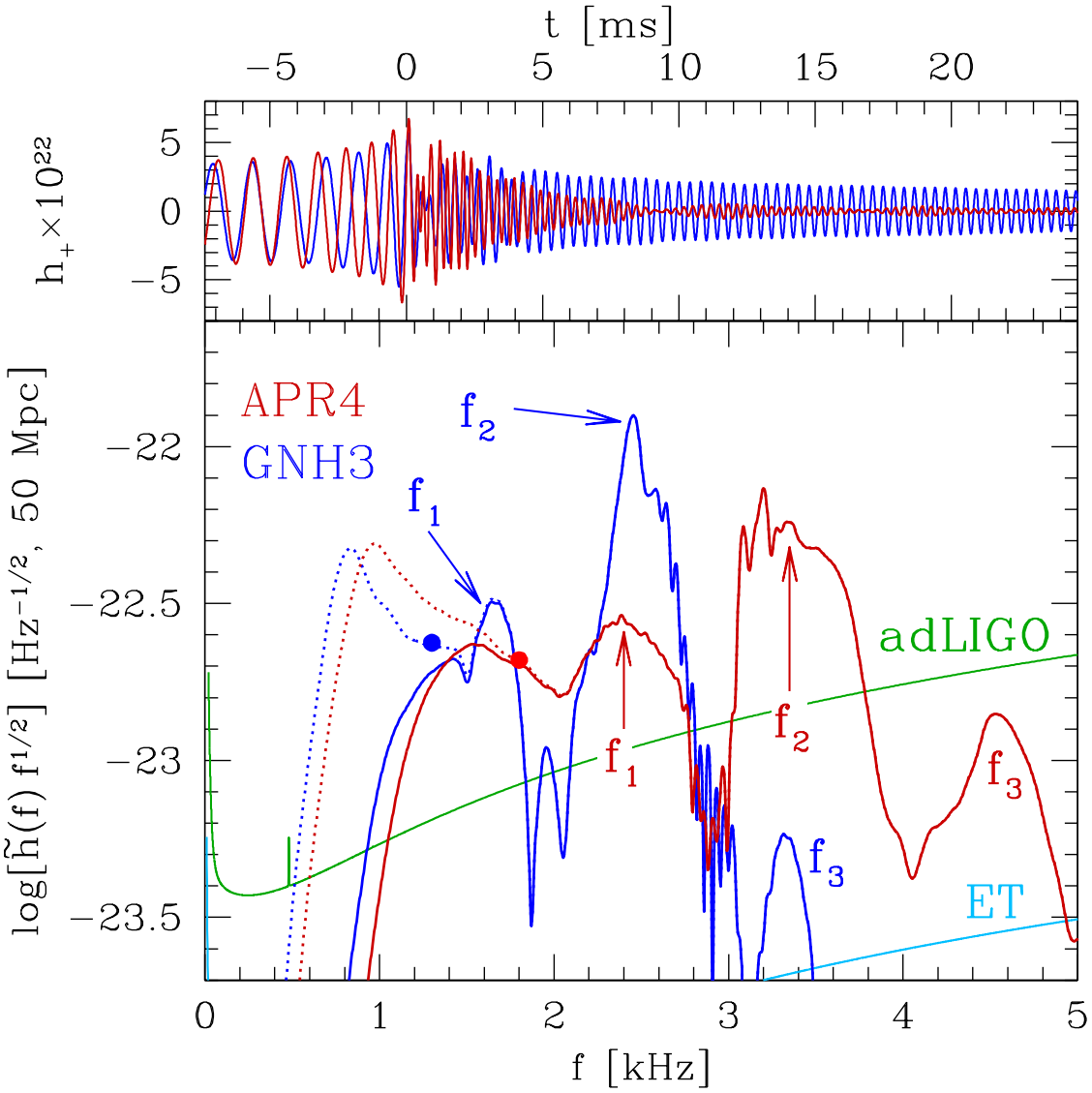
GW from a HMNS



Three clear peaks, f_1, f_2 and f_3.

- $f_1 \cdots$ nonlinear interaction between quadrupole and quasiradial modes
- $f_2 \cdots$ fundamental quadrupolar fluid mode (Stergioulas+2011) $f_2 \cdots$ simple function of the average mass density, independent of the EOS considered (Bauswein+2012)
- $f_3 \cdots$ larger uncertainty in the physical interpretation
- using f_1 and f_2, we have constructed method to decide the distance (Messenger,Takami+2014).
- using f_1 and f_2, we have developed powerful tool to constrain EOS (Takami+2014).

GW from a HMNS



Three clear peaks, f_1, f_2 and f_3.

- $f_1 \cdots$ nonlinear interaction between quadrupole and quasiradial modes
- $f_2 \cdots$ fundamental quadrupolar fluid mode (Stergioulas+2011) $f_2 \cdots$ simple function of the average mass density, independent of the EOS considered (Bauswein+2012)
- $f_3 \cdots$ larger uncertainty in the physical interpretation
- using f_1 and f_2, we have constructed method to decide the distance (Messenger,Takami+2014).
- using f_1 and f_2, we have developed powerful tool to constrain EOS (Takami+2014).

Methodology

Numerical Method

All of our calculations have been performed in full general relativity.

< spacetime evolution >

`McLachlan` code which is a part of publicly available `Einstein Toolkit` (Löffler+2012).

- BSSNOK formalism (Nakamura+1987, Shibata+1995, Baumgarte+1998)
- 4th-order finite differencing method

< fluid evolution >

`Whisky` code which is our privately developed code (Baiotti+ 2005).

- finite-volume method
- HLLE approximate Riemann solver
- PPM reconstruction
- 4th-order Runge-Kutta scheme

Equation of State

"hybrid" equation of state (EOS)

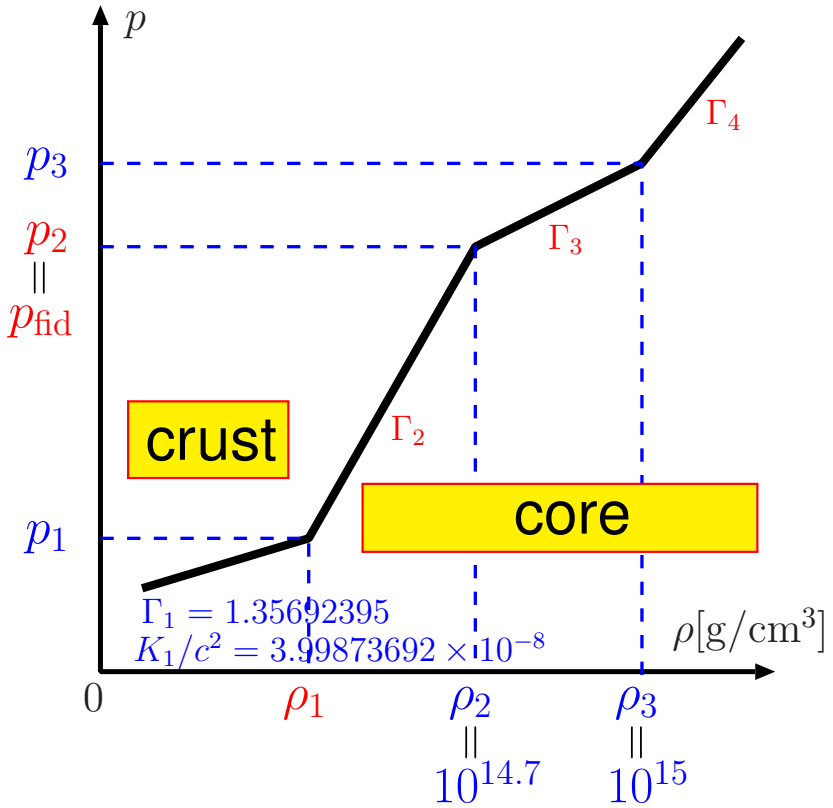
based on a piecewise polytropic (PP) EOS augmented by an ideal gas:

$$p = p_{\rm c} + p_{\rm th} \ , \qquad \varepsilon = \varepsilon_{\rm c} + \varepsilon_{\rm th} \ ,$$

where

$$\begin{aligned}
p_{\rm th} &= (\Gamma_{\rm th} - 1)\, \rho\, \varepsilon_{\rm th} && : \text{ideal gas} \ , \\
p_{\rm c} &= K_i\, \rho^{\Gamma_i} && : \text{piecewise polytropic EOS} \ , \\
K_{\ell+1} &= K_\ell\, \rho_\ell^{(\Gamma_\ell - \Gamma_{\ell+1})} && : \text{continuity of pressure} \ , \\
\varepsilon_{\rm c} &= \varepsilon_i + \frac{K_i}{\Gamma_i - 1}\, \rho^{(\Gamma_i - 1)} && : \text{first law of thermodynamics} \ .
\end{aligned}$$

Equation of State

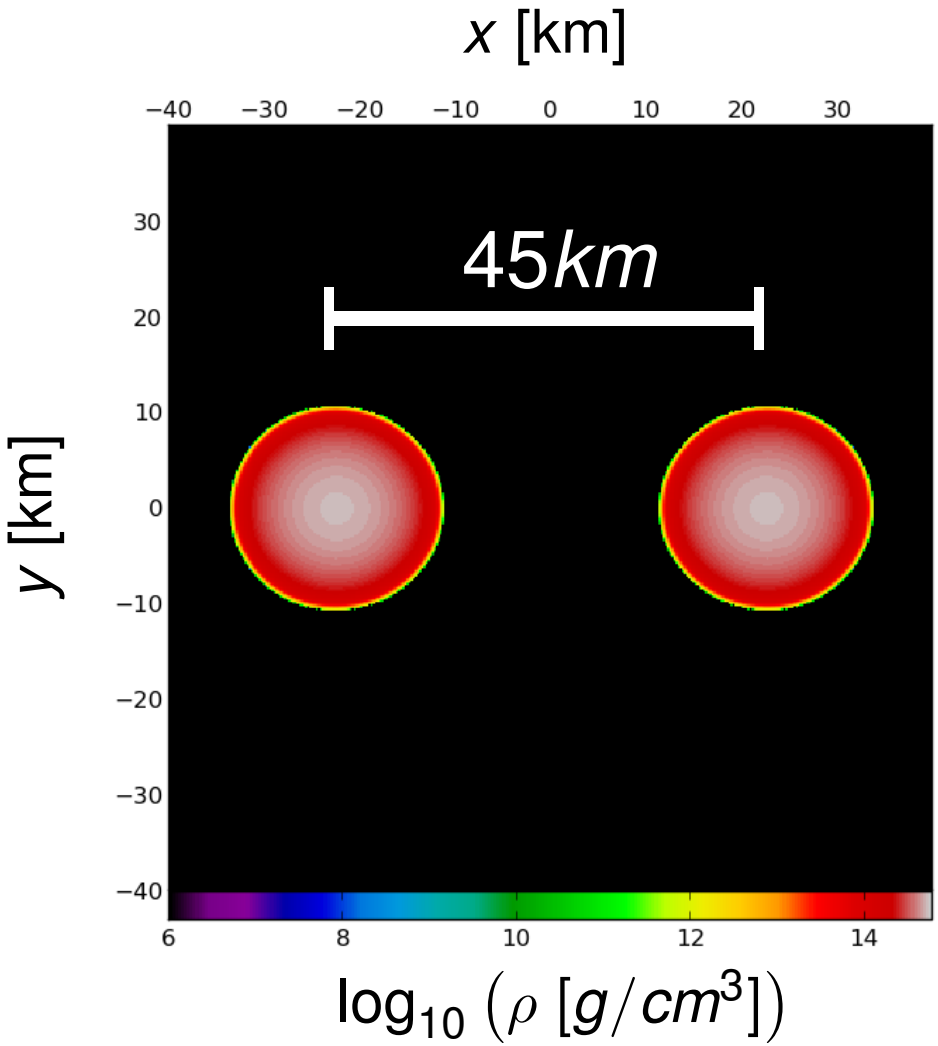


- we use PP EOSs with 4-piece regions which are good approximation of realistic EOS (Read+2009)
- we simply adopt $\Gamma_{\rm th} = 2$ in the thermal part

EOS	n	Γ_2	Γ_3	Γ_4	ρ_1	$M_{\rm max}[M_\odot]$	$R_{\rm max}[M_\odot]$
polyt.	1	$K = 123.647$, $\Gamma = 2$				1.821	8.490
SLy	4	3.005	2.988	2.851	2.367×10^{-4}	2.061	6.729
APR4	4	2.830	3.445	3.348	2.448×10^{-4}	2.200	6.687
H4	4	2.909	2.246	2.144	1.437×10^{-4}	2.028	7.858
GNH3	4	2.664	2.194	2.304	1.078×10^{-4}	1.977	7.630
ALF2	4	4.070	2.411	1.890	1.948×10^{-4}	1.991	7.659

Observed maximum mass is $2.01 \pm 0.04 M_\odot$ for PSR J0348+0432 (Antoniadis+2013).

Initial Data

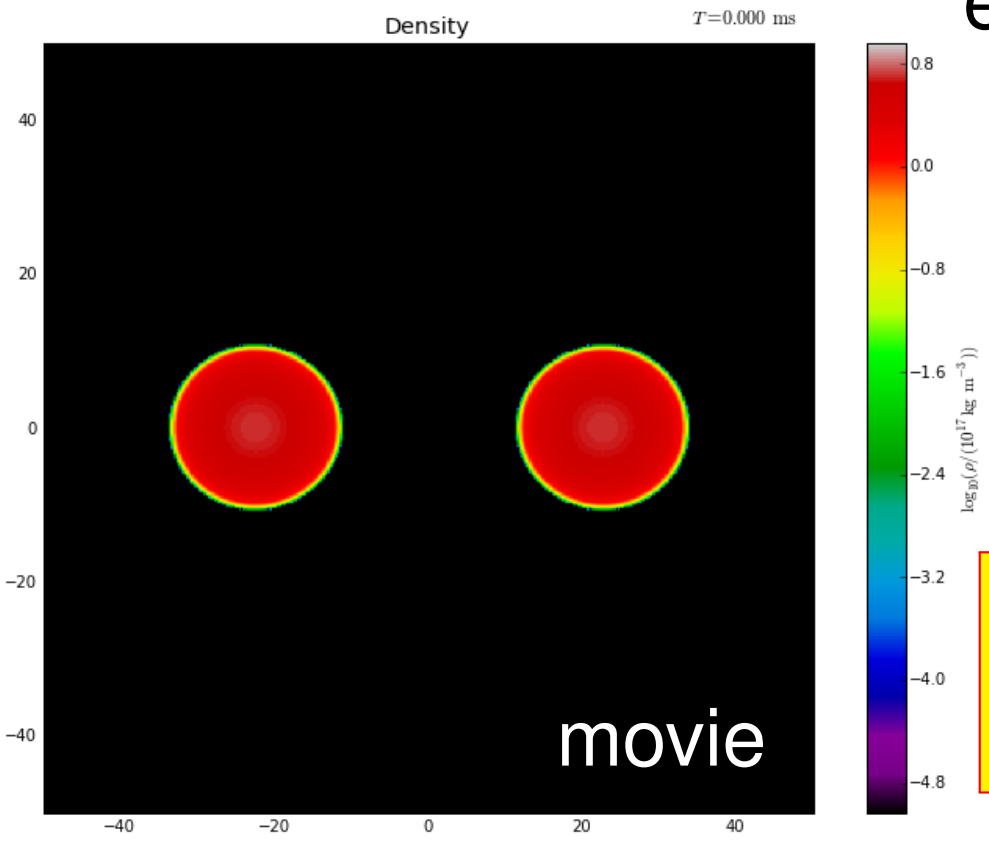


- multi-domain spectral-method code, LORENE, which is publicly available (Gourgoulhon+2000).
- quasi-equilibrium irrotational BNSs under the assumption of a conformally flat spacetime metric.
- equal-mass binaries with an initial coordinate separation of the stellar centres of 45 km.

Results

Dynamics

rest-mass density



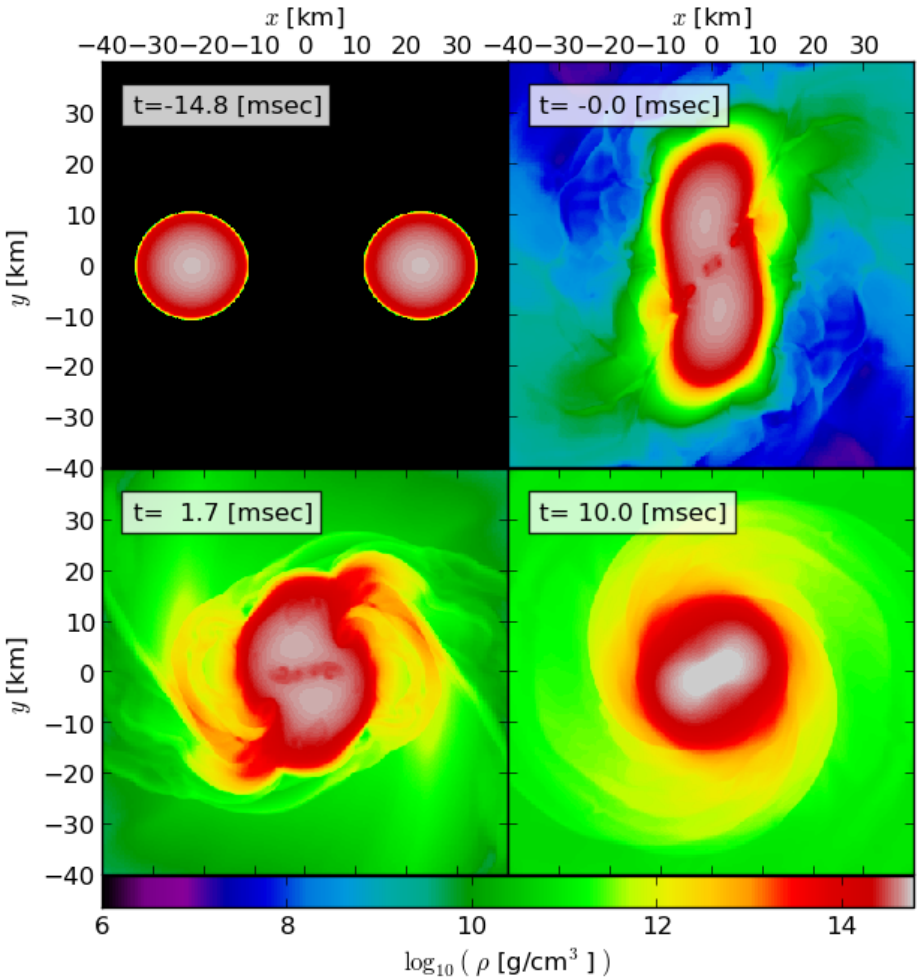
e.g.,

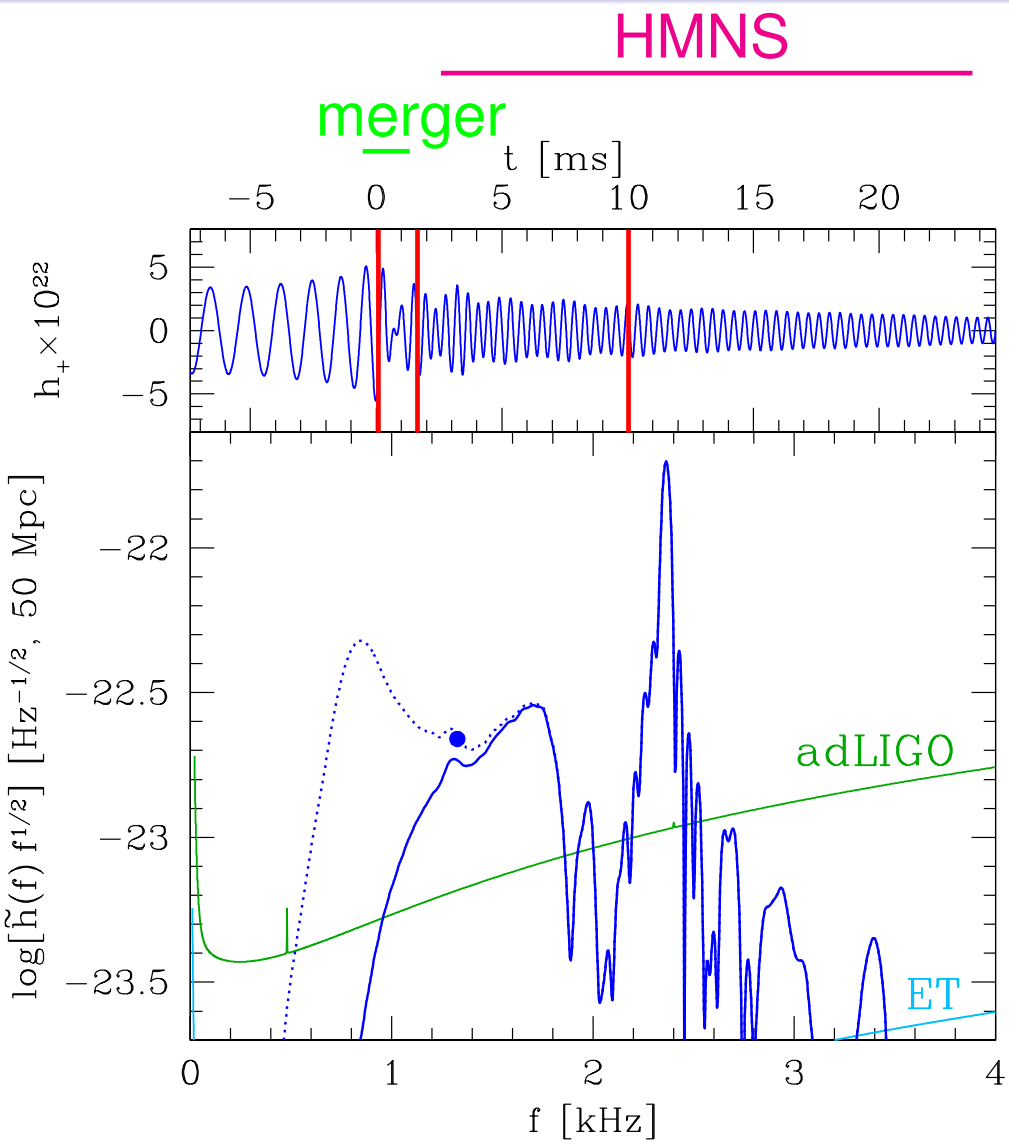
- H4 EOS (relativistic mean-field theory including effects of hyperons)
- $M_{\rm tot} = 2.600 M_\odot$
- $R \approx 13.54[km]$

The computational size is $\sim 500\mathrm{cores} \times 10\mathrm{days/model}$ on SuperMUC.

Dynamics and Waveforms

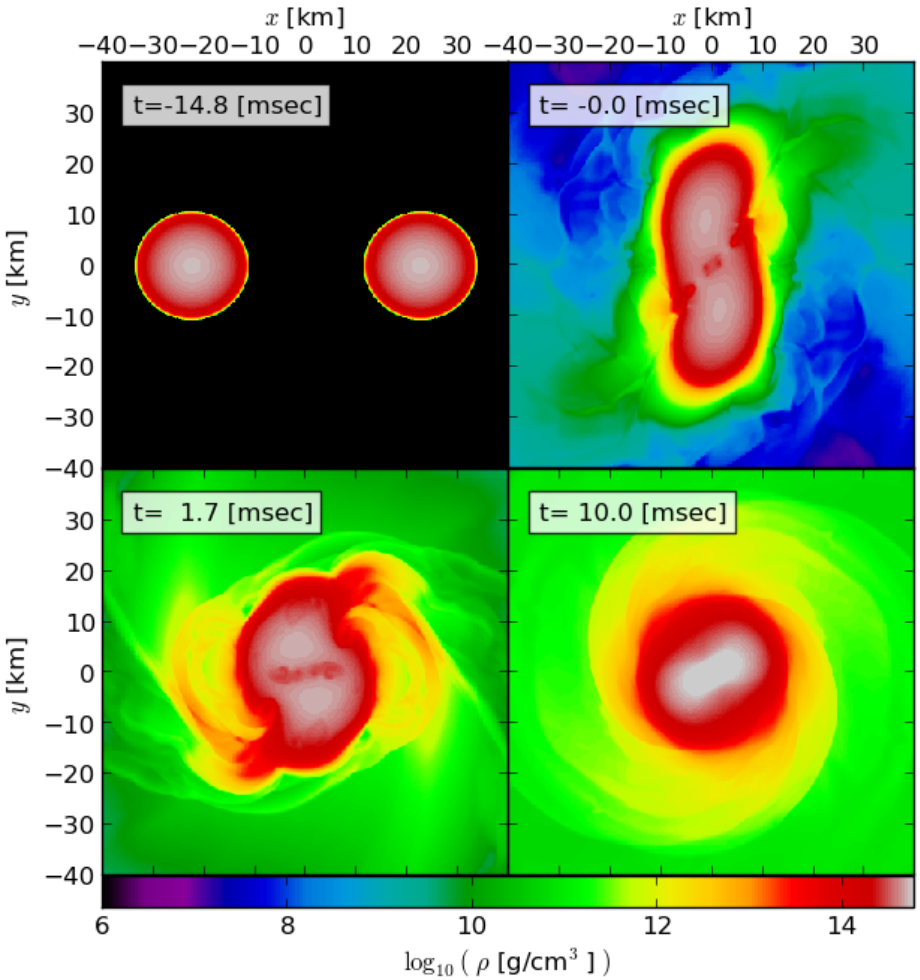
H4 EOS, $M_{\rm tot} = 2.6 M_\odot$.

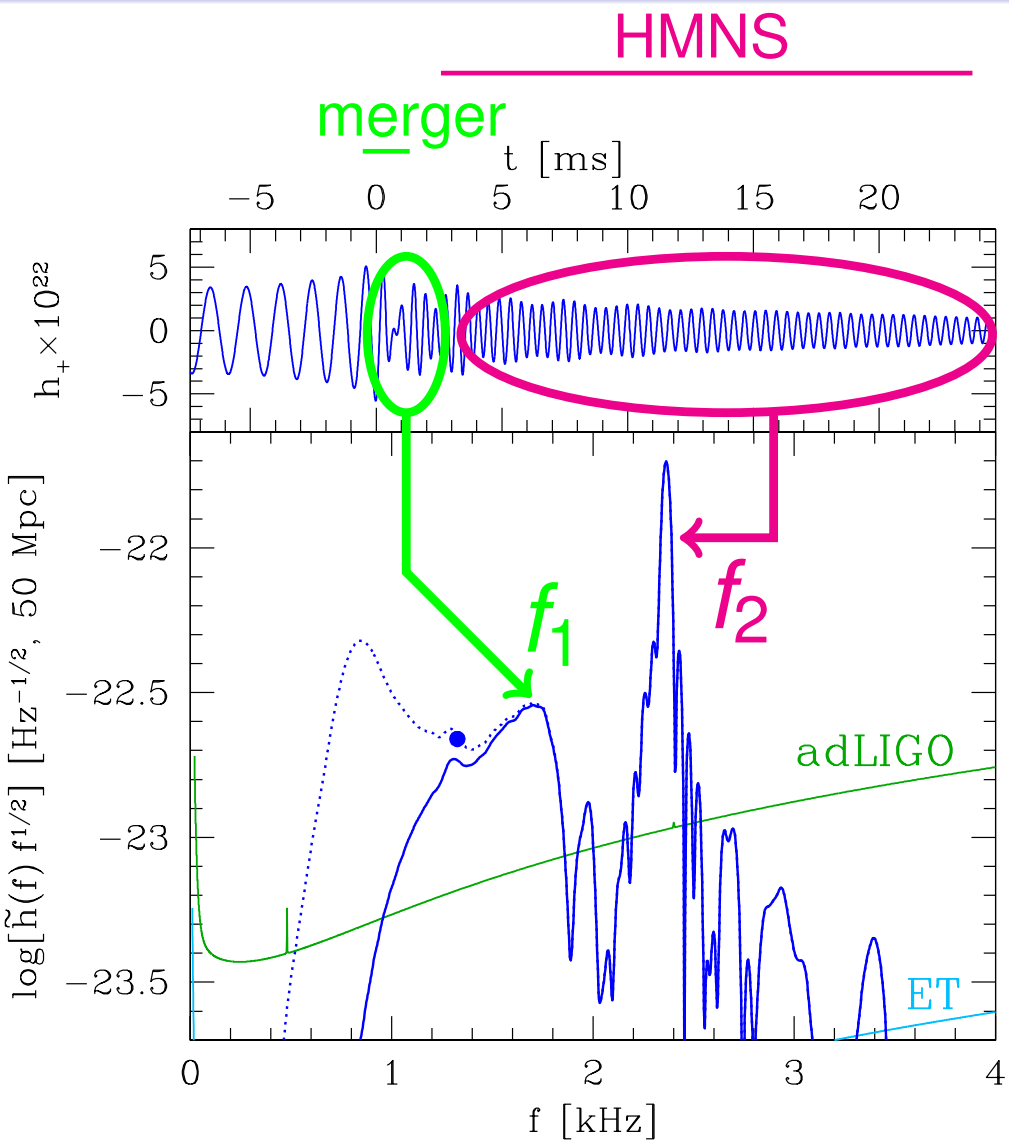




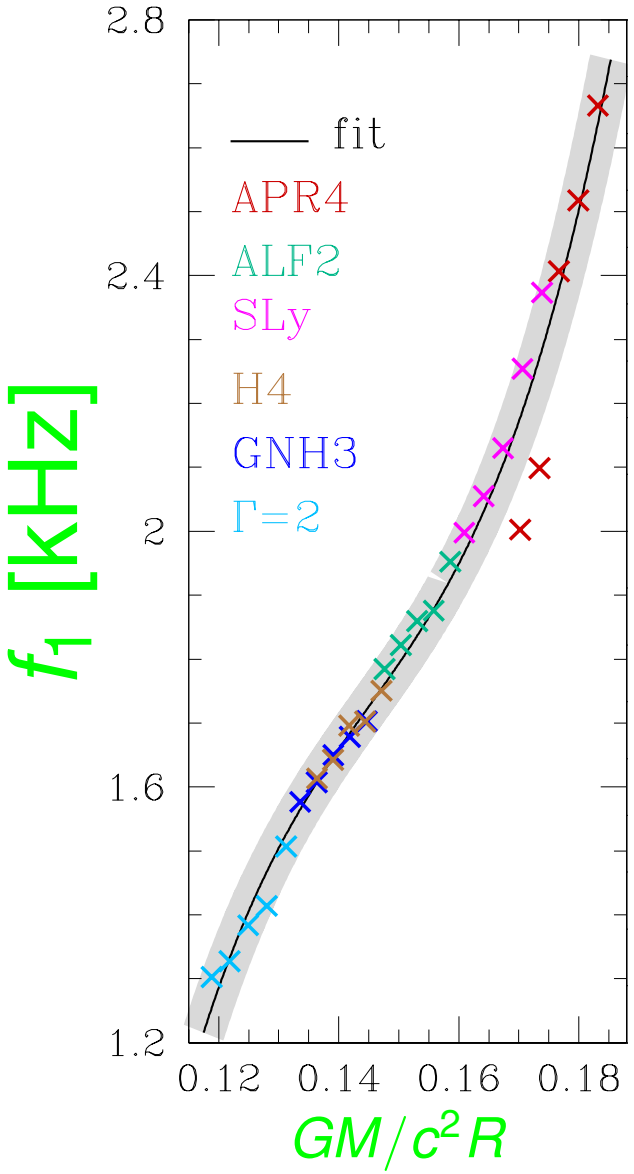
Dynamics and Waveforms

H4 EOS, $M_{\rm tot} = 2.6 M_\odot$.



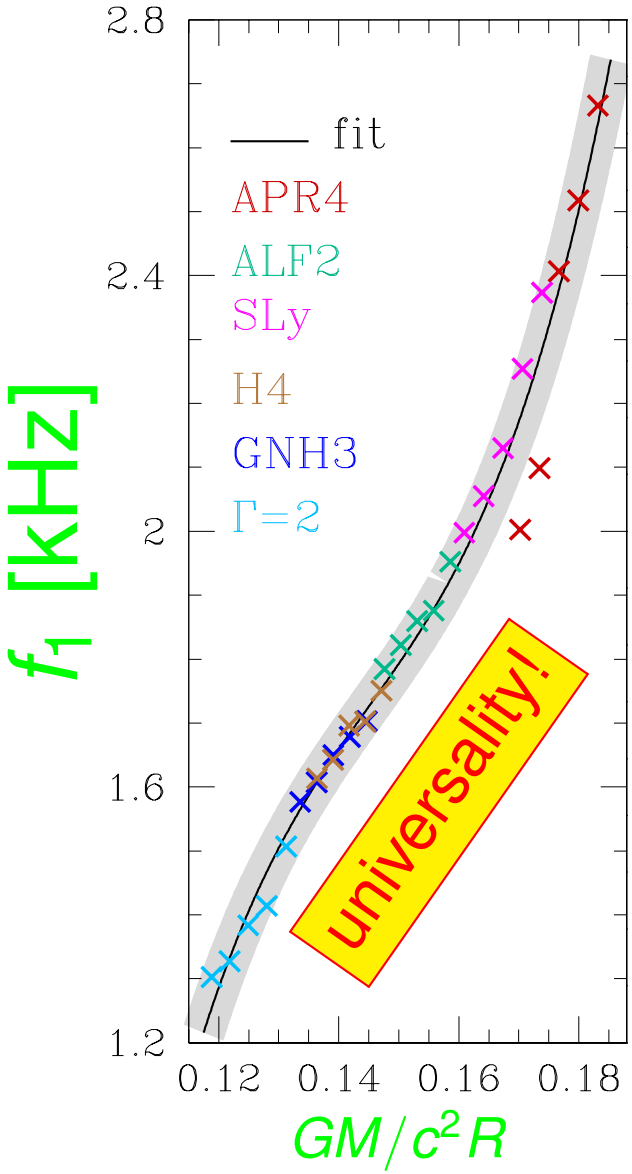


Correlations of f_1 and f_2



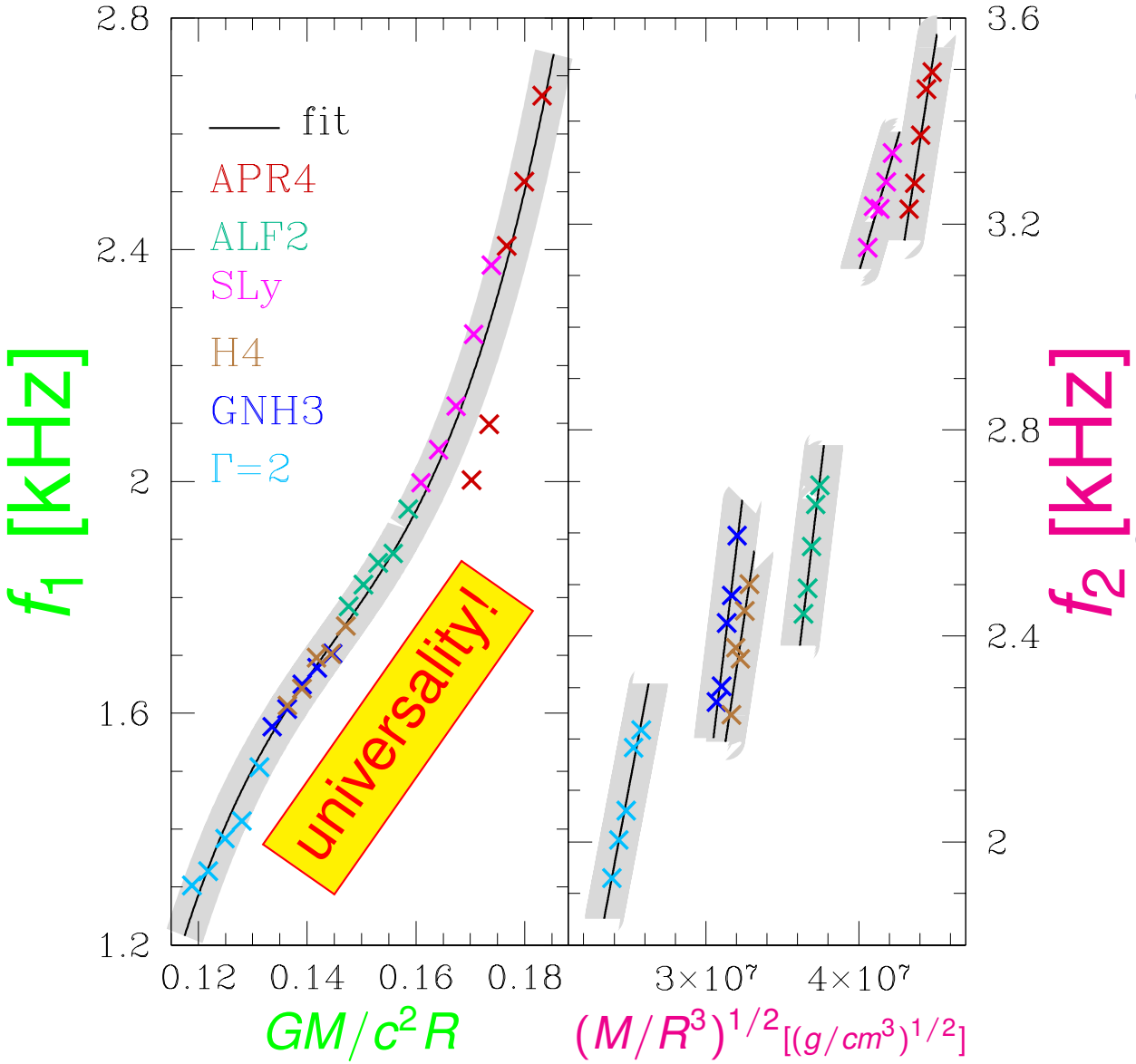
- f_1 (low-frequency peak)
  - all points can be fitted by a cubic polynomial function

Correlations of f_1 and f_2



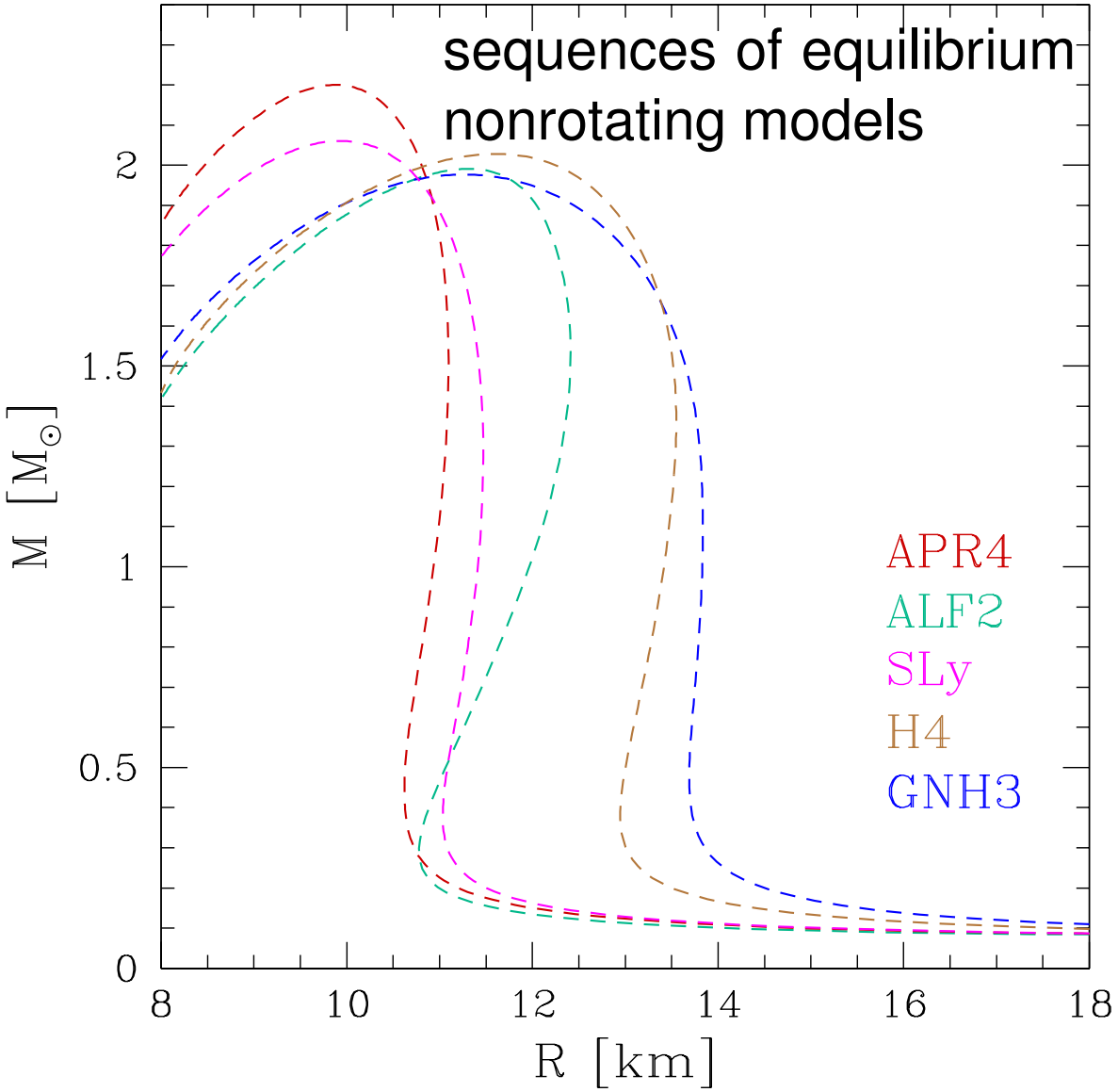
- f_1 (low-frequency peak)
  - all points can be fitted by a cubic polynomial function
  - universal behaviour independently of each EOS

Correlations of f_1 and f_2

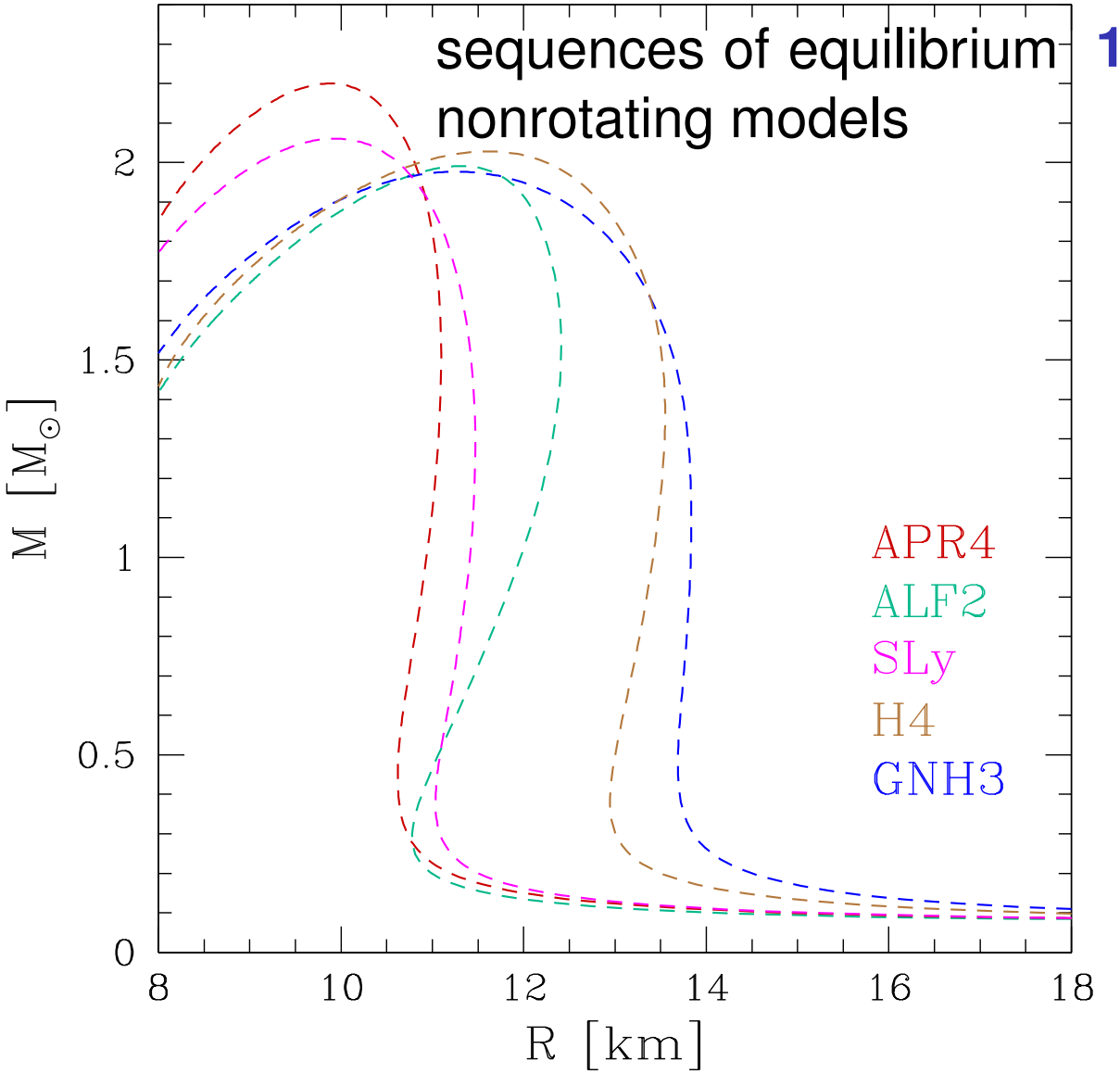


- f_1 (low-frequency peak)
  - all points can be fitted by a cubic polynomial function
  - universal behaviour independently of each EOS
- f_2 (high-frequency peak)
  - no universality although Bauswein+2012 claimed the universality.
  - the points for each EOS can be fitted by a linear function

Constraining the EOS

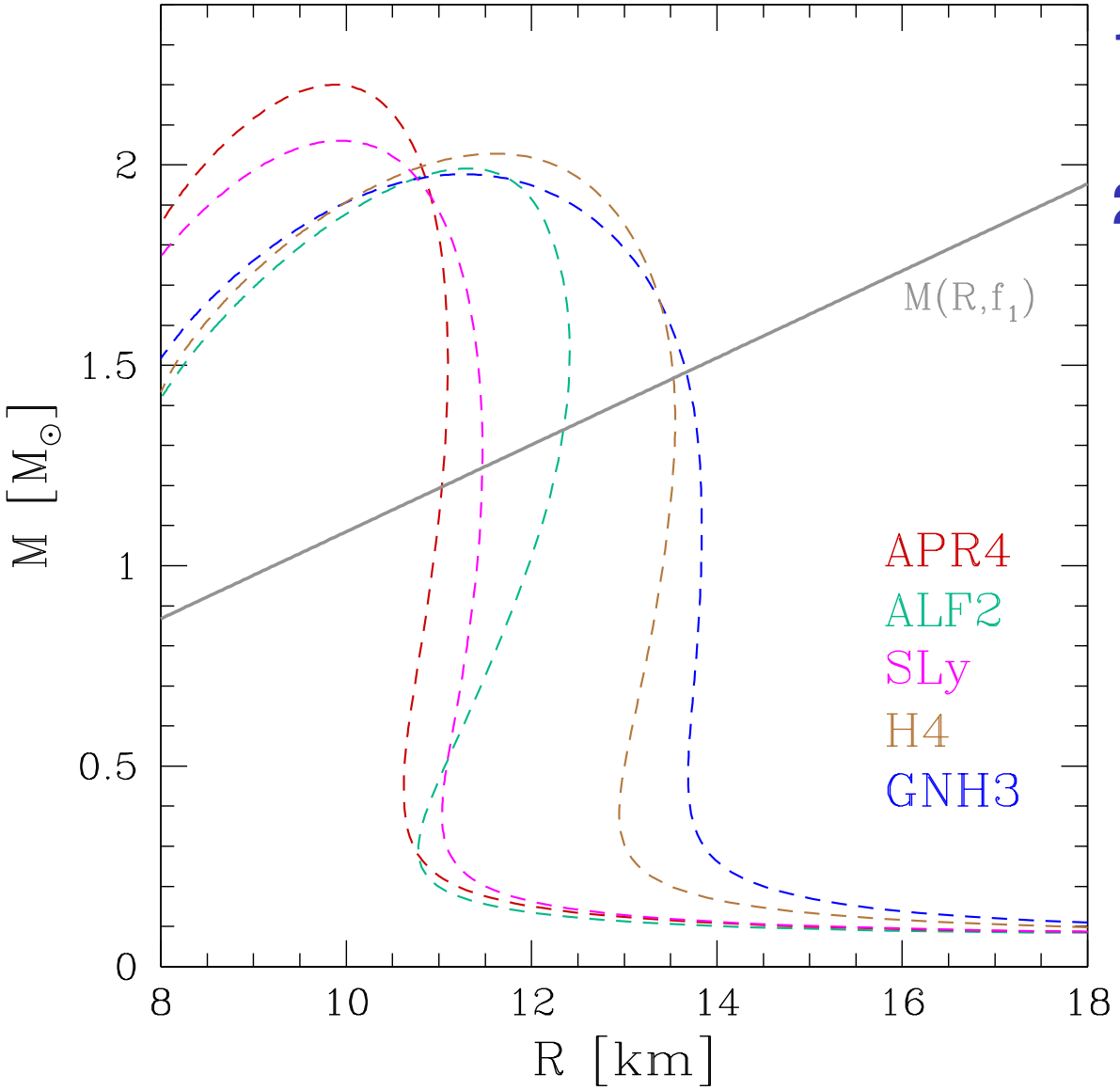


Constraining the EOS



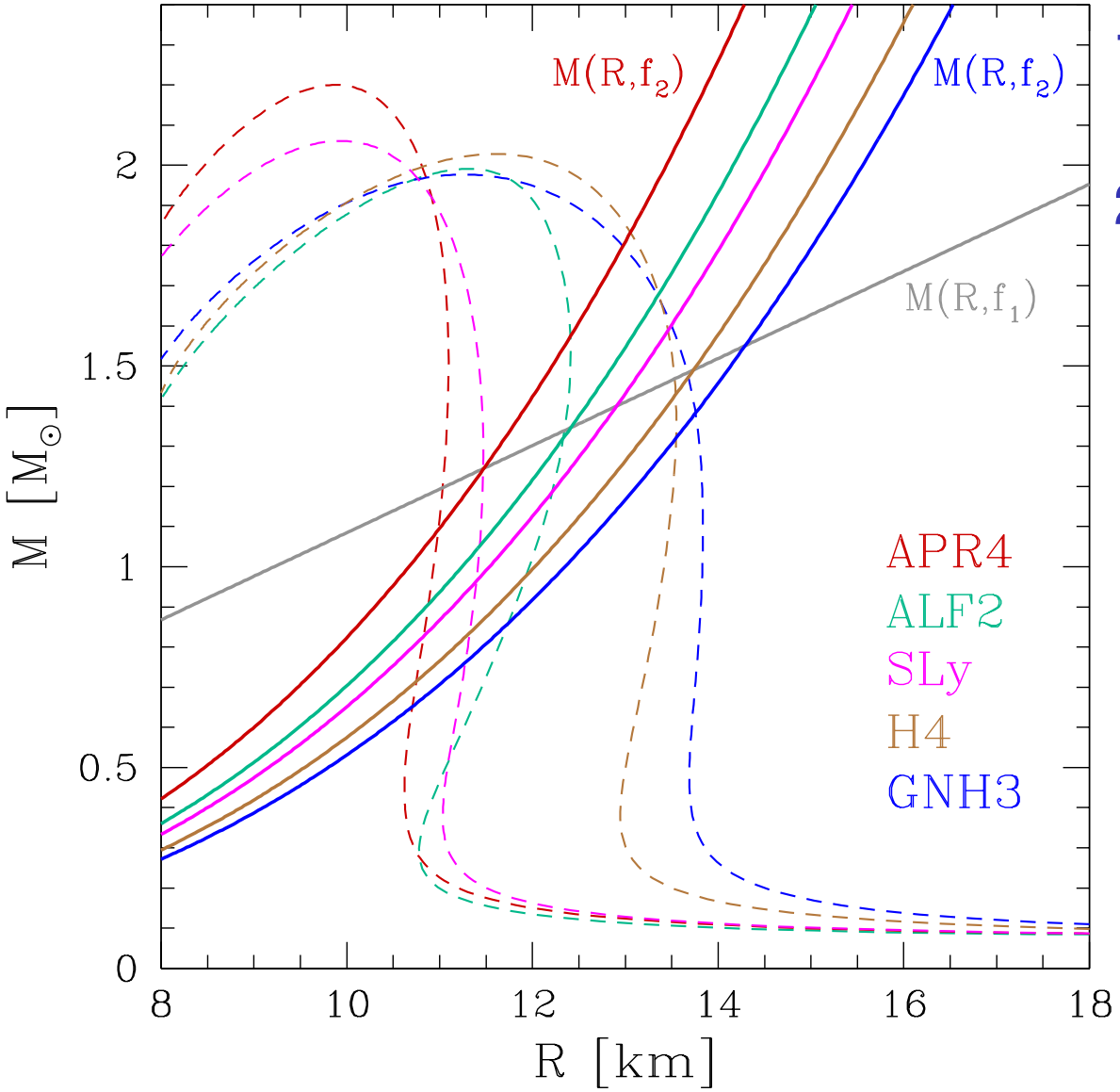
1. observe GW and extract f_1 and f_2

Constraining the EOS



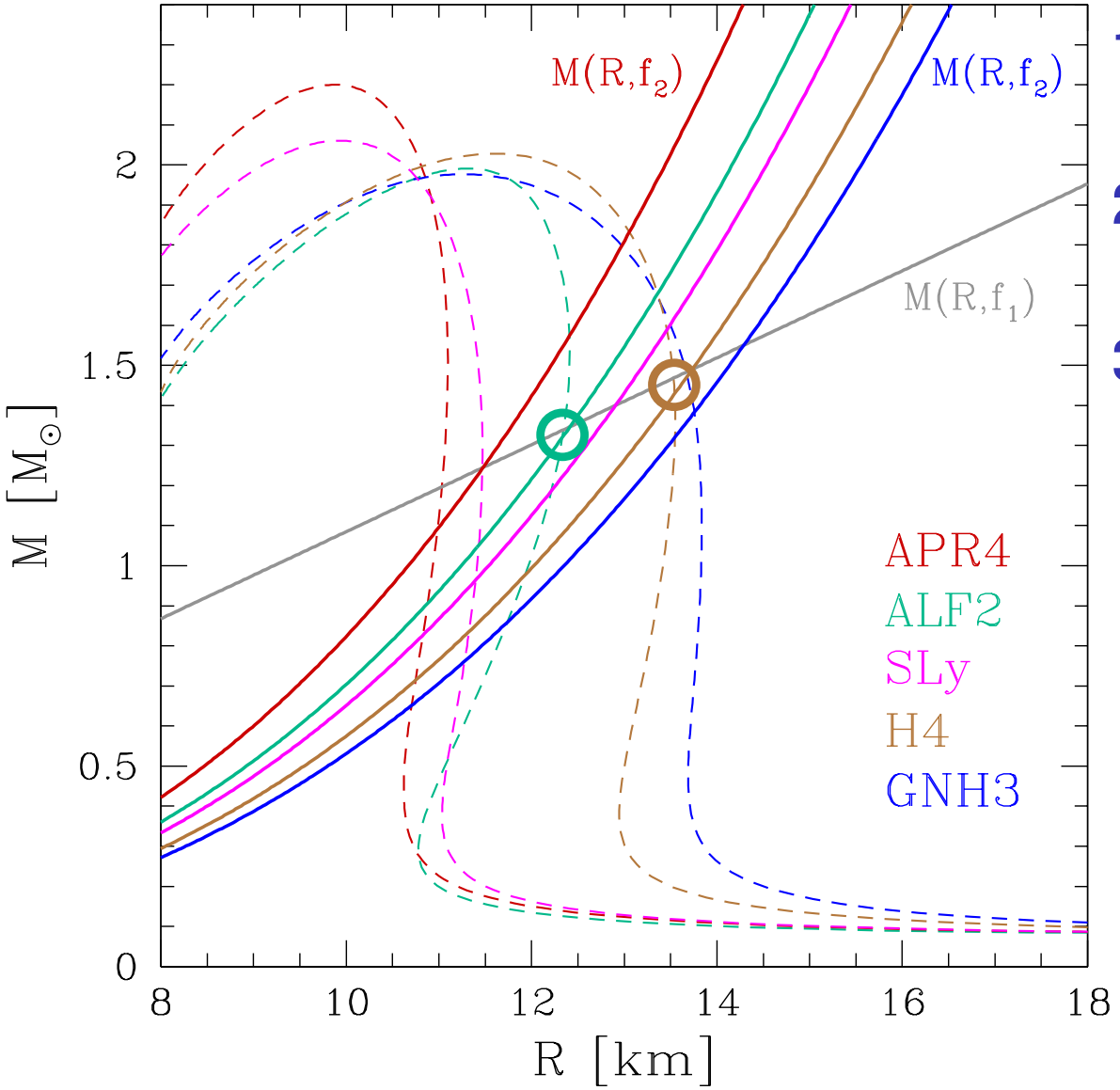
1. observe GW and extract f_1 and f_2
2. construct $M(R, f_1)$

Constraining the EOS



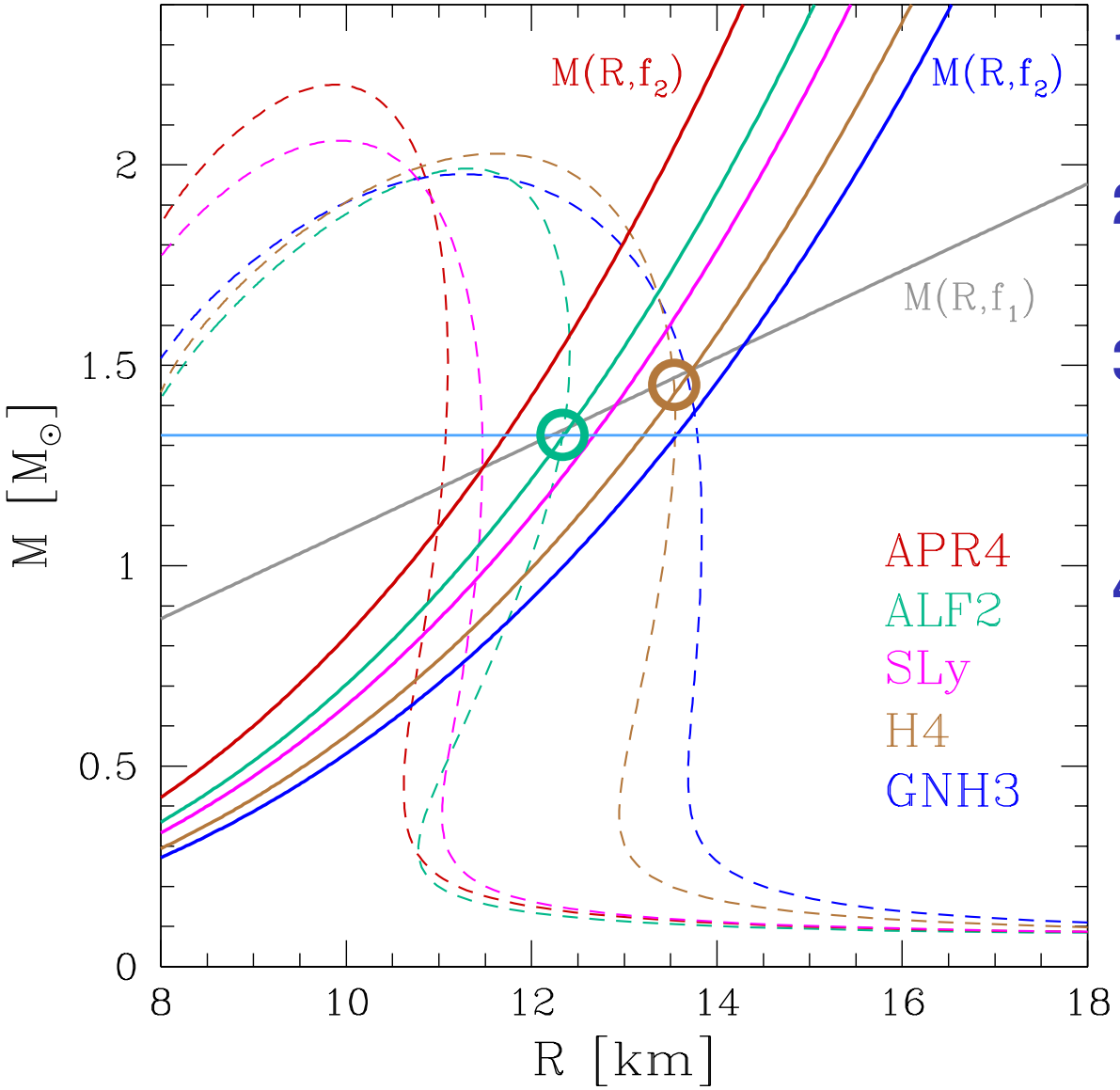
1. observe GW and extract f_1 and f_2
2. construct $M(R, f_1)$ and $M(R, f_2; \mathrm{EOS})$ curves

Constraining the EOS



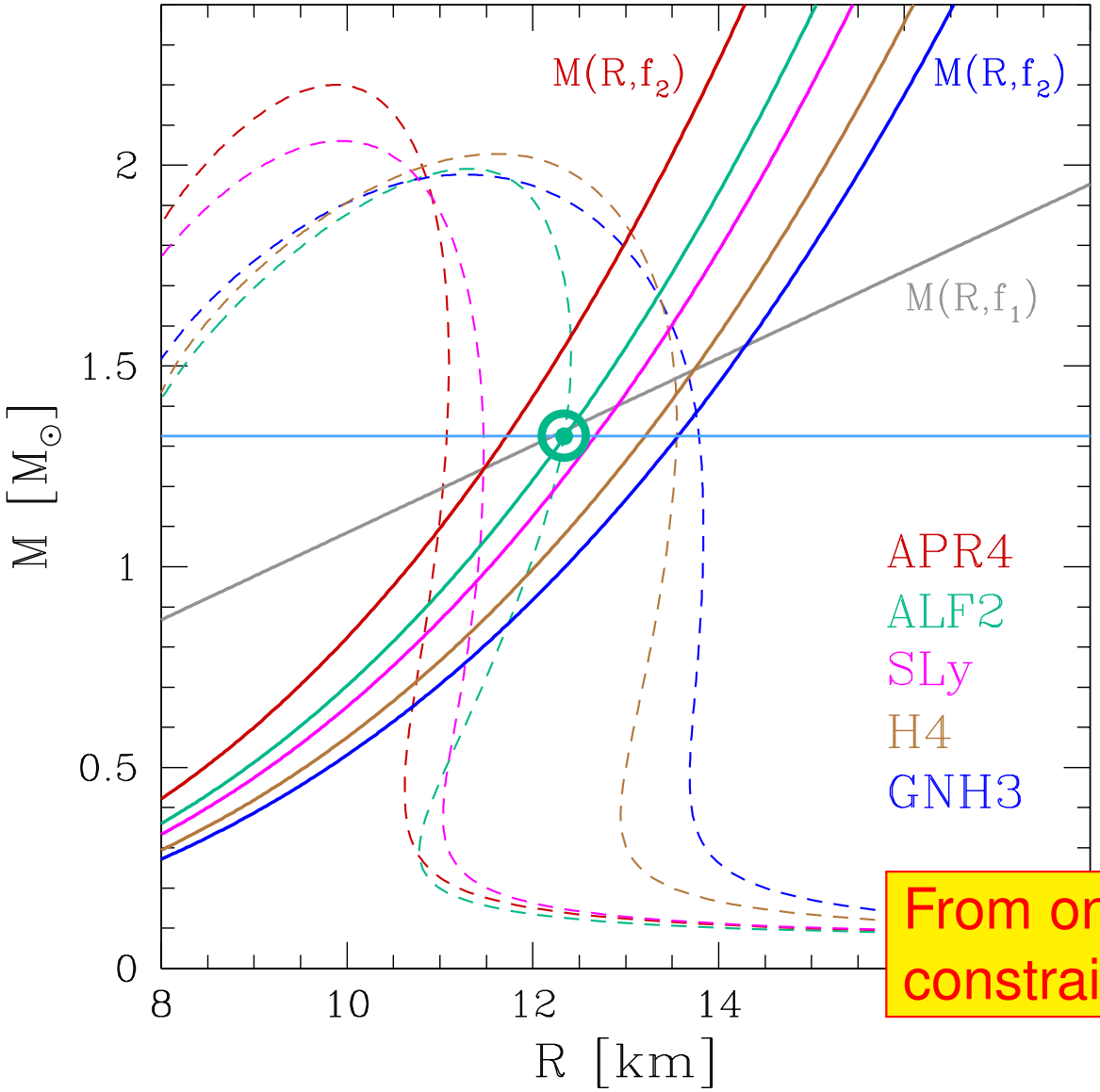
1. observe GW and extract f_1 and f_2
2. construct $M(R, f_1)$ and $M(R, f_2; \mathrm{EOS})$ curves
3. only the ALF2 and H4 EOSs have (near) crossings at one point

Constraining the EOS



1. observe GW and extract f_1 and f_2
2. construct $M(R, f_1)$ and $M(R, f_2; \mathrm{EOS})$ curves
3. only the ALF2 and H4 EOSs have (near) crossings at one point
4. the uncertainty can be removed, if the mass of the binary is known from the inspiral signal

Constraining the EOS



1. observe GW and extract f_1 and f_2
2. construct $M(R, f_1)$ and $M(R, f_2; \mathrm{EOS})$ curves
3. only the ALF2 and H4 EOSs have (near) crossings at one point
4. the uncertainty can be removed, if the mass of the binary is known from the inspiral signal

From only one observation, we can constrain to **ALF2** EOS in this case.

Conclusions

Conclusions

- we have carried out a large sample of accurate and fully general-relativistic simulations of the inspiral and postmerger of BNSs with nuclear EOSs on SuperMUC.
- we have confirmed that the GW spectral properties of HMNSs have clear and distinct two peaks, which are called f_1 and f_2.
- we have found that f_1 peaks exhibit a tight correlation with the stellar compactness that is essentially EOS-independent, while a correlation of f_2 depend on EOSs.
- we have developed and shown the powerful tool to constrain the EOS via GWs.