Bari, Thursday, December 12th 2019.

The post-merger spectrum of binary neutron star mergers

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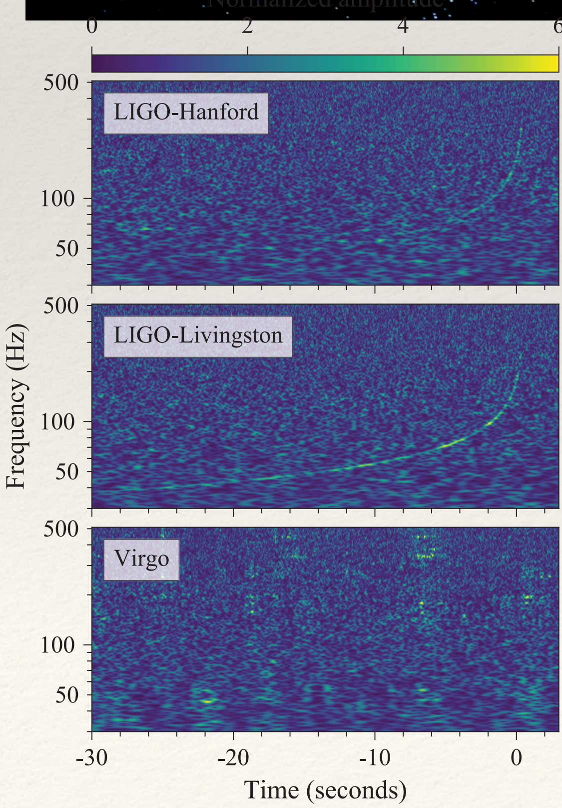
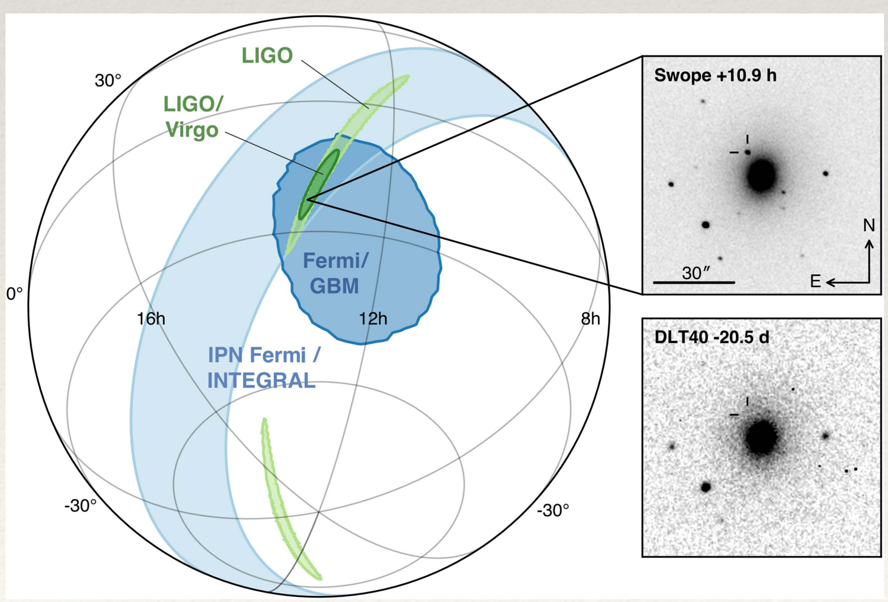
Abstract

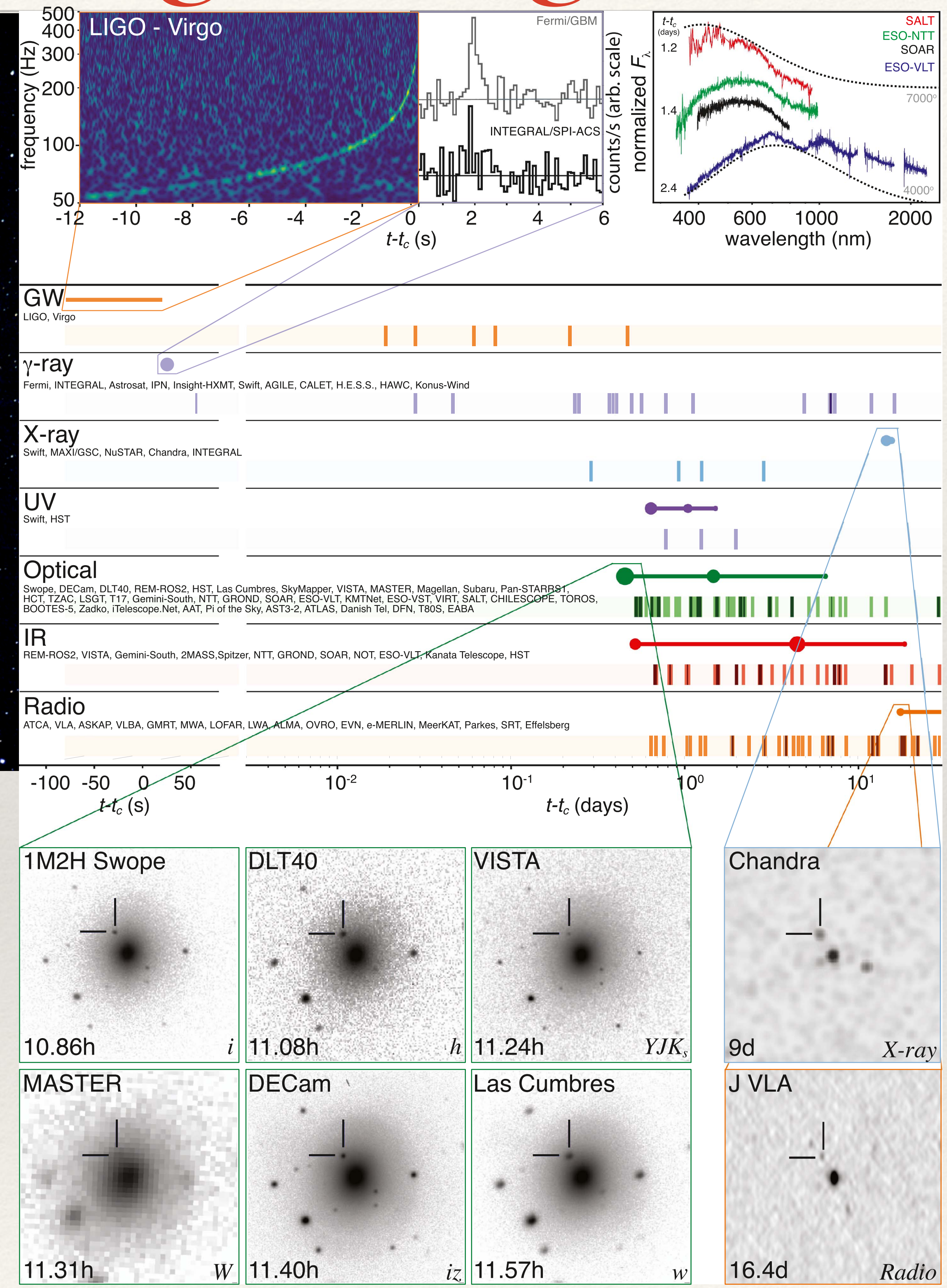
- We show the properties of the gravitational wave signal emitted after the merger of a binary neutron star system. We show that the post-merger phase can be subdivided into three phases: an early post-merger phase (where the quadrupole mode and a few subdominant features are active), the intermediate post-merger phase (where only the quadrupole mode is active) and, when remnant survives for more than a 60ms before collapsing to a Black Hole, the late post-merger phase (where convective instabilities trigger inertial modes).
- Moreover, we show how to perform numerical simulations of Binary Neutron Star Mergers using the Einstein Toolkit. We discuss the motivation for going to high-resolution and the computational requirement needed to reach the required resolution a the numerical performance on the Einstein Toolkit public code. We present vectorization and scaling tests on the code on SkyLake and Knight's Landing processors to assess its capability of making use of a large amount of parallel computing power. Our tests are run on the full infrastructure, evolving both the space-time metric variable and matter.

Motivation

GW170817 - the August signal!



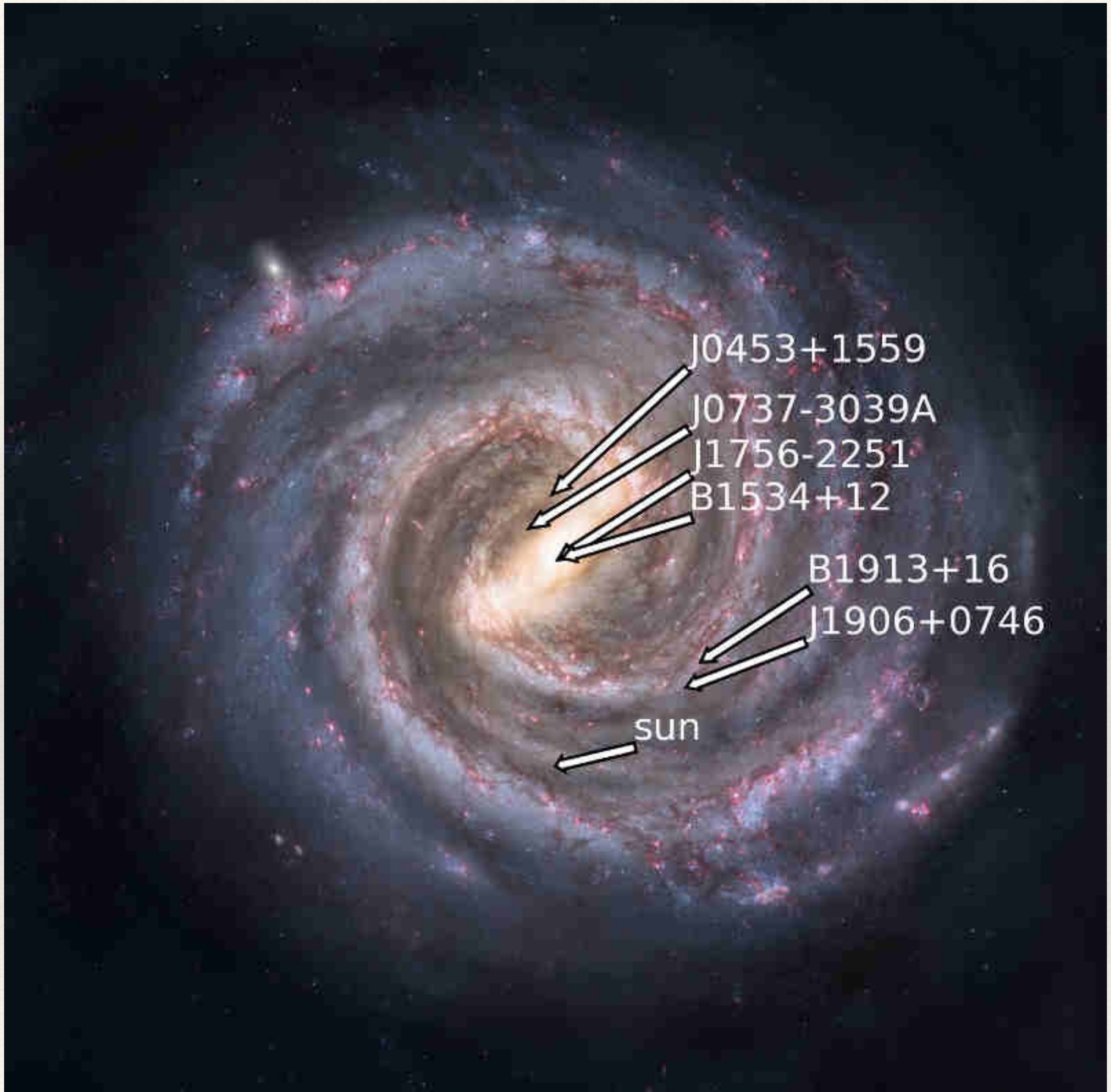




GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, **Phys.Rev.Lett.** 119 (2017) no.16, 161101.

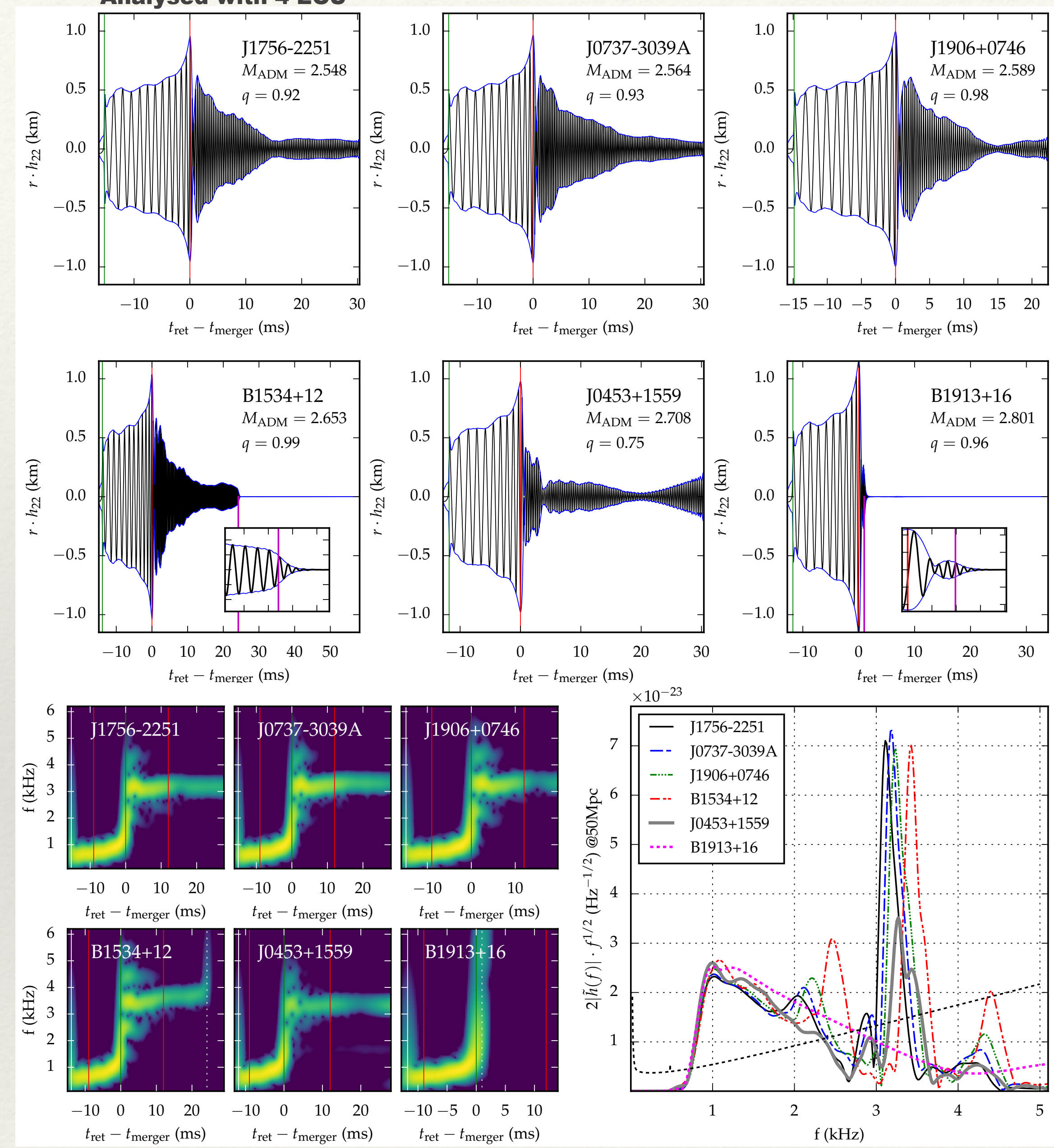
Multi-messenger Observations of a Binary Neutron Star Merger, **Astrophys.J**. 848 (2017) no.2, L12.

Artistic view of the location of the six galactic system.



The simulated GW signal

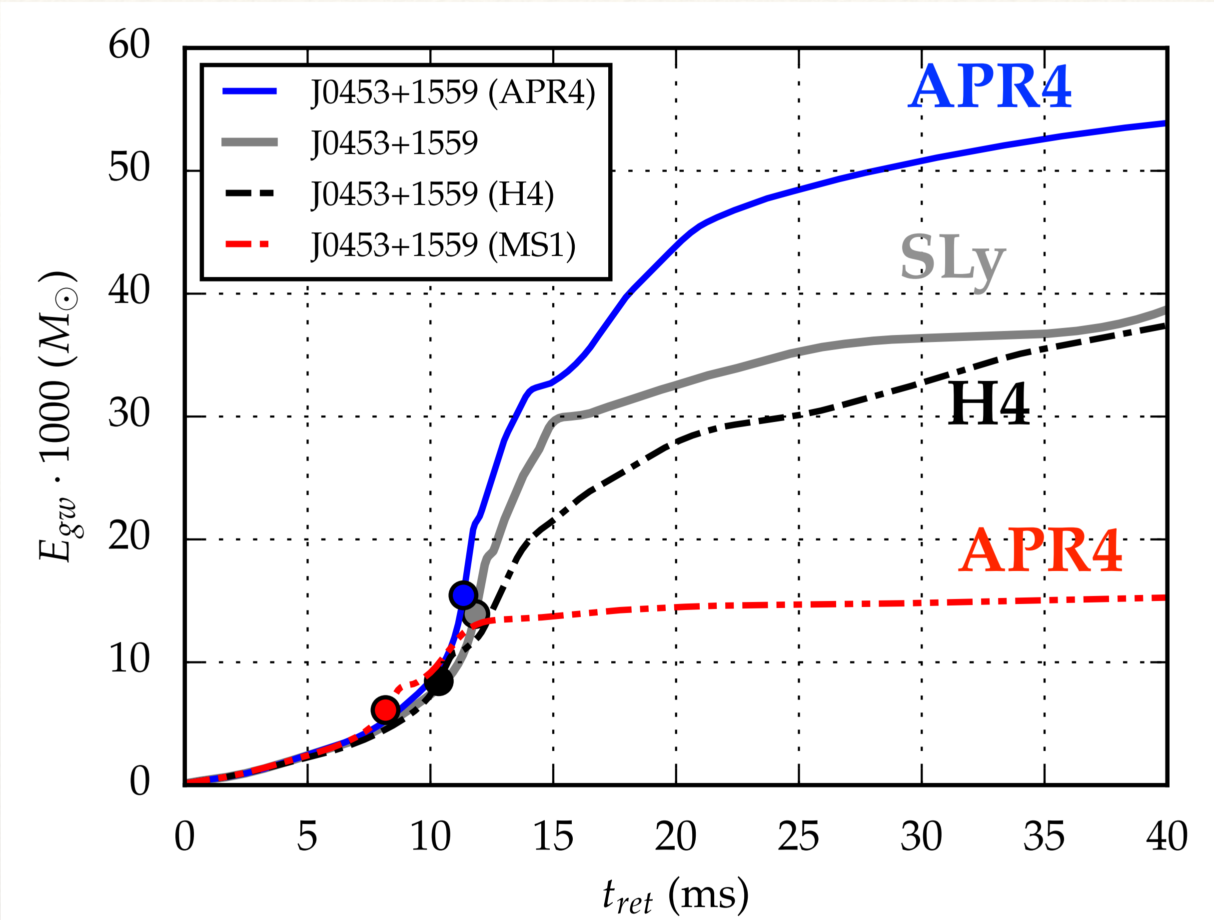
Analysed with 4-EOS



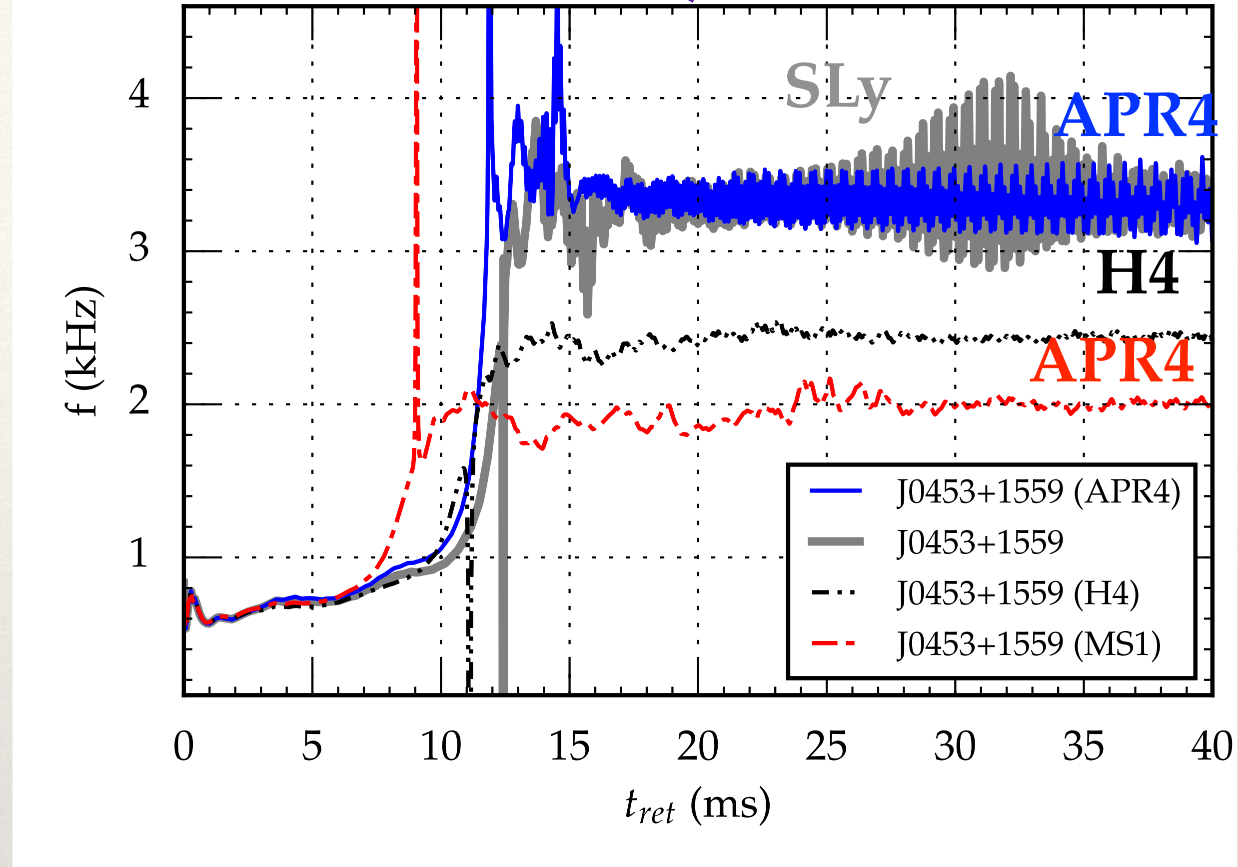
A. Feo, R. De Pietri, F. Maione and F. Loeffler,
Modeling Mergers of known Galactic Binary Neutron Stars,
Classical and Quantum, 34 (3), 034001 (2017) arXiv 1608.02810(2016)

Different EOS – same stellar model

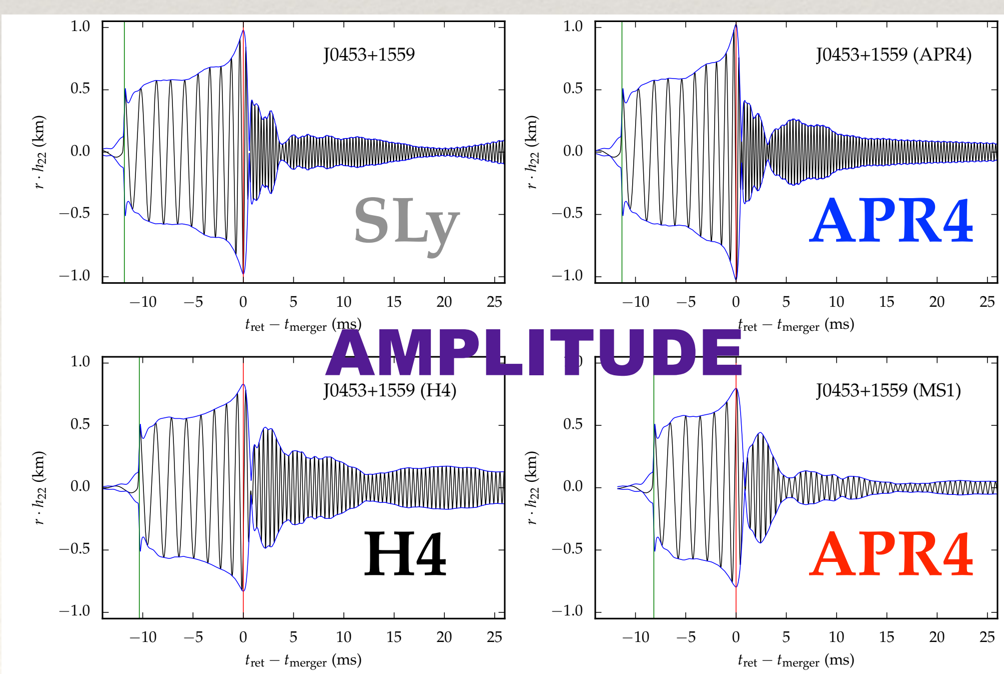
GW - ENERGY



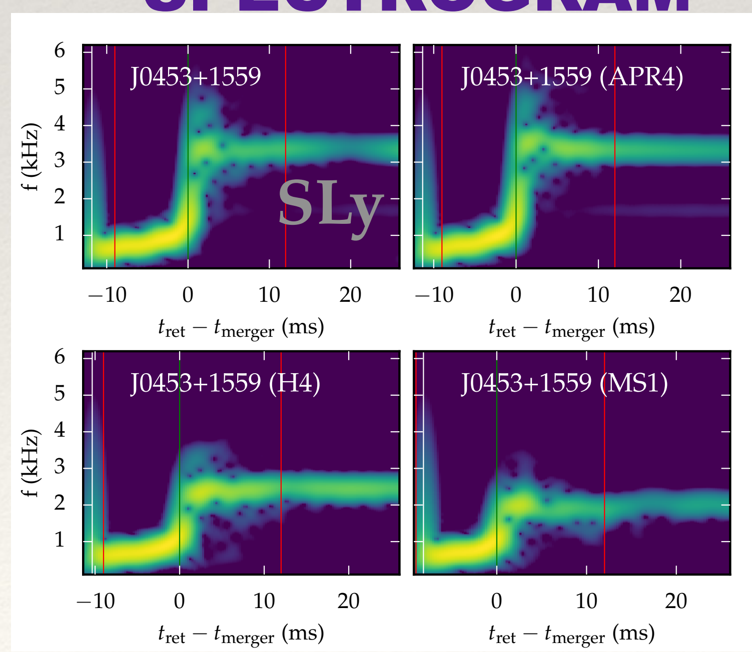
FREQUENCY



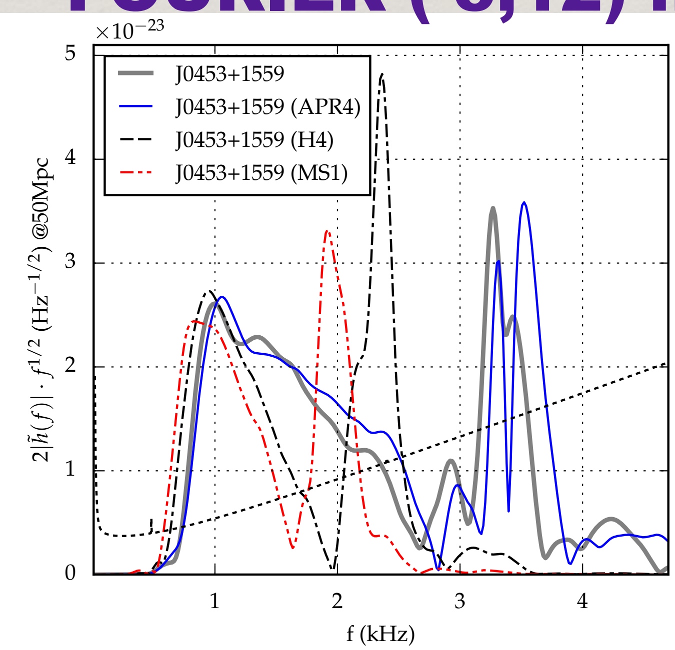
AMPLITUDE



SPECTROGRAM

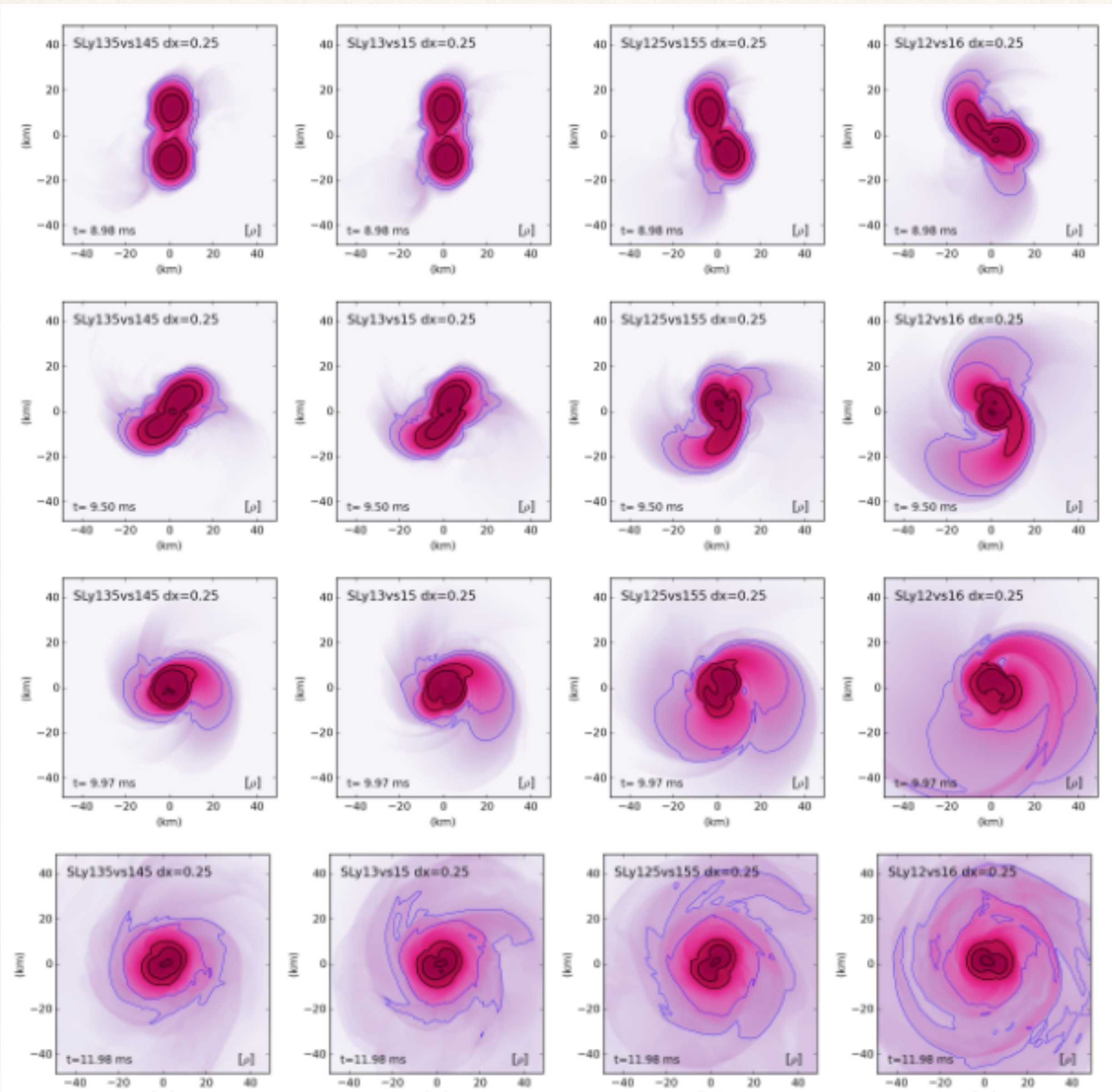


FOURIER (-5,12) ms



How we do the simulations

Numerical Relativity in a nutshell



Modeling equal and unequal mass binary neutron star mergers using public codes,
R. De Pietri, A. Feo, F. Maione and F. Loeffler,
Physical Review D 93 (6), 064047, 034001 arXiv 1509.08804(2015)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$$ **Einstein Equations**

$$\nabla_\mu T^{\mu\nu} = 0$$ **Conservation of energy momentum**

$$\nabla_\mu (\rho\, u^\mu) = 0$$ **Conservation of baryon density**

$$p = p(\rho, \epsilon)$$ **Equation of state**

Ideal Fluid Matter

$$T^{\mu\nu} = (\rho(1+\epsilon) + p) u^\mu u^\nu + p g^{\mu\nu}$$

+ Evolution of magnetic Fields (Trento and Firenze)

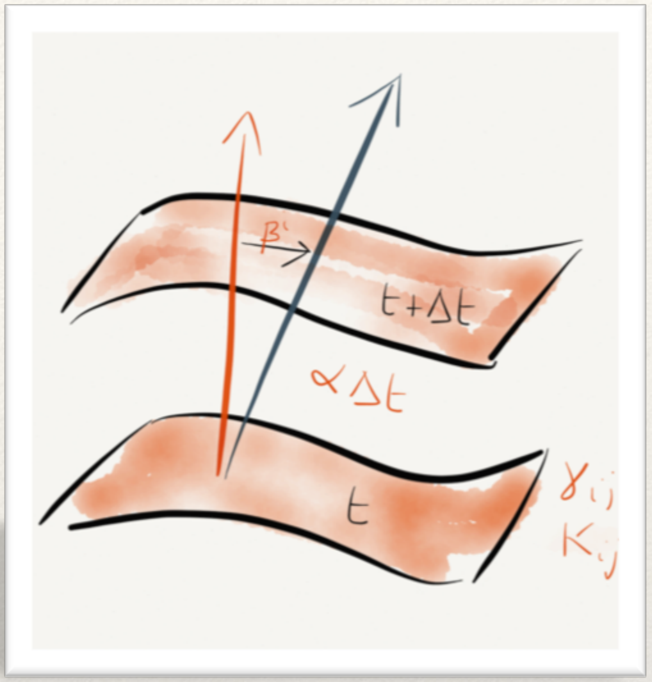
- **Main goal: to study EOS effect on the Gravitational Waves emitted from the coalescence of compact binaries (in our case two Neutron Stars)**
- Waveform modeling in NR.
- EOS effect on the post-merger signal.
- Counterparts to BNS mergers: SGRB, Macronova,…
- **Methods**
- The fluid matter equations are a non linear a form a hyperbolic system and need HRSC Methods well-adapted to grid-methods and highly-scalable (Einstein Toolkit)

GR NS-NS simulations: State of the Art

- One of the main and hottest research topic in Numerical Astrophysics.
- A comprensive discussion of the subject can be found in (www.livingreviews.org): J.A. Faber & F.A. Rasio, "Binary neutron star mergers", Living Reviews in Relativity (2012). This review contains 338 references.
- Recent review by **Rezzolla** and Baiotti (arXiv:1607.03540), "Binary neutron-star mergers: a review of Einstein's richest laboratory"
- Impossible to give a comprensive list of all the individual contributor and their roles.
- Among them is worth citing:
  - The people that start it back in '99: **Shibata&Uryu**: **Phys. Rev. D 61 064001** (gr-qc/9911058)
  - and (in alphabetic order): Alic, Anderson, Baiotti , Bauswein, Bernuzzi , Bruegmann, **Ciolfi**, Dietrich , Duez , Etienne , Foucart, Giacomazzo , Gold, Haas , Hotokezaka, Janka, Kastaun , Kawaguchi, Kidder , Kiuchi, Kokotas, Kyutoku, Lehner , Liebling , Liu, Nielsen , Ott , O'Connor , Pachalidis, Palenzuela , Pfeiffer, Rezzolla, Scheel , Sekiguchi , Shapiro , Shibata, Stergioulas, Taniguchi, Uryu, …

The base formalism (ADM)

1. **Choose initial spacelike surface and provide initial data (3-metric, extrinsic curvature)**
2. **Choose coordinates:**
   - Construct timelike unit normal to surface, choose lapse function
   - Choose time axis at each point on next surface (shift vector)
   - Evolve 3-metric, extrinsic curvature



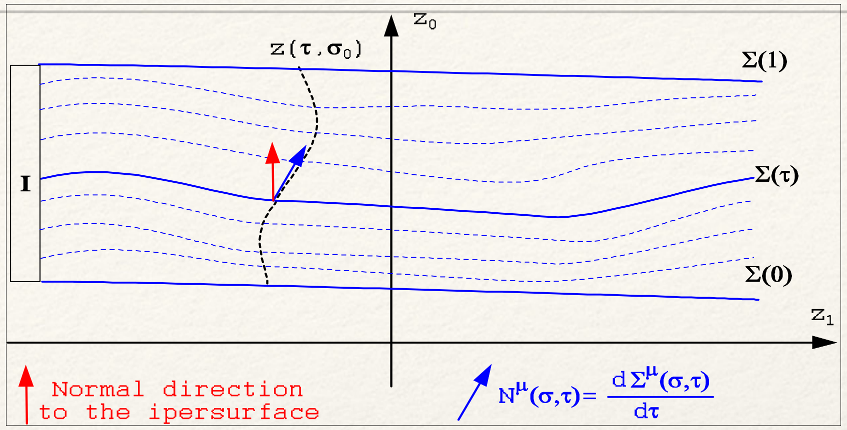
Use usual numerical methods:

1. **Structured meshes (including multi-patch), finite differences (finite volumes for matter), adaptive mesh refinement (since ~2003). High order methods.**
2. **Some groups use high accuracy spectral methods for vacuum space times**

Unfortunately Einstein Equation must be rewritten !

$$ds^2 = -\alpha^2 dt^2 + g_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt)$$

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 0}$$



- BSSN version of the Einstein's equations that introduce additional conformal variables:
- Matter evolution (B set to zero) using shock capturing methods based on the GRHydro code

$$\boxed{R_{ij} = -\tfrac{1}{2}\tilde{g}^{lm}\tilde{g}_{ij,lm} - \tilde{g}_{k(i}\partial_{j)}\tilde{\Gamma}^k + \tilde{\Gamma}^k\tilde{\Gamma}_{(ij)k} + \tilde{g}^{lm}(2\tilde{\Gamma}^k_{l(i}\tilde{\Gamma}_{j)km} + \tilde{\Gamma}^k_{im}\tilde{\Gamma}_{klj})}$$

$$\partial_t\varphi = -\tfrac{1}{6}\alpha K + \beta^i\partial_i\varphi + \tfrac{1}{6}\partial_i\beta^i$$

$$\partial_t K = -g^{ij}\nabla_i\nabla_j\alpha + \alpha(\tilde{A}_{ij}\tilde{A}^{ij} + \tfrac{1}{3}K) + \beta^i\partial_i K$$

$$\partial_t\tilde{g}_{ij} = -2\alpha K_{ij} + \tilde{g}_{jk}\partial_i\beta^k + \tilde{g}_{ik}\partial_j\beta^k - \tfrac{2}{3}\tilde{g}_{ij}\partial_k\beta^k \qquad \boxed{R^{TF}_{ij} = R_{ij} - \tfrac{1}{3}g_{ij}R}$$

$$\partial_t\tilde{\Gamma}^i = -2\tilde{A}^{ij}\partial_j\alpha + 2\alpha(\Gamma^i_{jk}\tilde{A}^{jk} - \tfrac{2}{3}\tilde{g}^{ij}\partial_j K + 6\tilde{A}^{ij}\partial_j\varphi) + $$
$$+ \beta^k\partial_k\tilde{\Gamma}^i - \tilde{\Gamma}^k\partial_k\beta^i + \tfrac{2}{3}\tilde{\Gamma}^i\partial_k\beta^k + \tfrac{1}{3}\tilde{g}^{ij}\partial_j\partial_k\beta^k + \tilde{g}^{jk}\partial_j\partial_k\beta^i$$

$$\partial_t\tilde{A}_{ij} = e^{-4\varphi}(-(\nabla_i\nabla_j\alpha)^{TF} + \alpha R^{TF}_{ij}) + \alpha\left(\tilde{A}_{ij}K - 2\tilde{A}_{ik}\tilde{A}^k{}_j\right) - \partial_i\partial_j\alpha + $$
$$+ \beta^k\partial_k\tilde{A}_{ij} + \left(\tilde{A}_{ik}\partial_j + \tilde{A}_{jk}\partial_i\right)\beta^\kappa - \tfrac{2}{3}\tilde{A}_{ij}\partial_k\beta^k$$

[4] M. Shibata, T. Nakamura: "Evolution of three dimensional gravitational ..", Phys. Rev. D52(1995)5429
[5] T.W. Baumgarte, S.L. Shapiro: "On the numerical integration of Einstein..", Phys. Rev. D59(1999)024007

Other formulation with the same good properties and constrain dumping are used: namely Z4, Z4c,…..

Matter evolution need HRSC Methods

$$\nabla_\mu T^{\mu\nu} = 0 \qquad p = p(\rho, \epsilon)$$

Ideal Fluid Matter

$$T^{\mu\nu} = (\rho(1+\epsilon)+p)u^\mu u^\nu + pg^{\mu\nu}$$

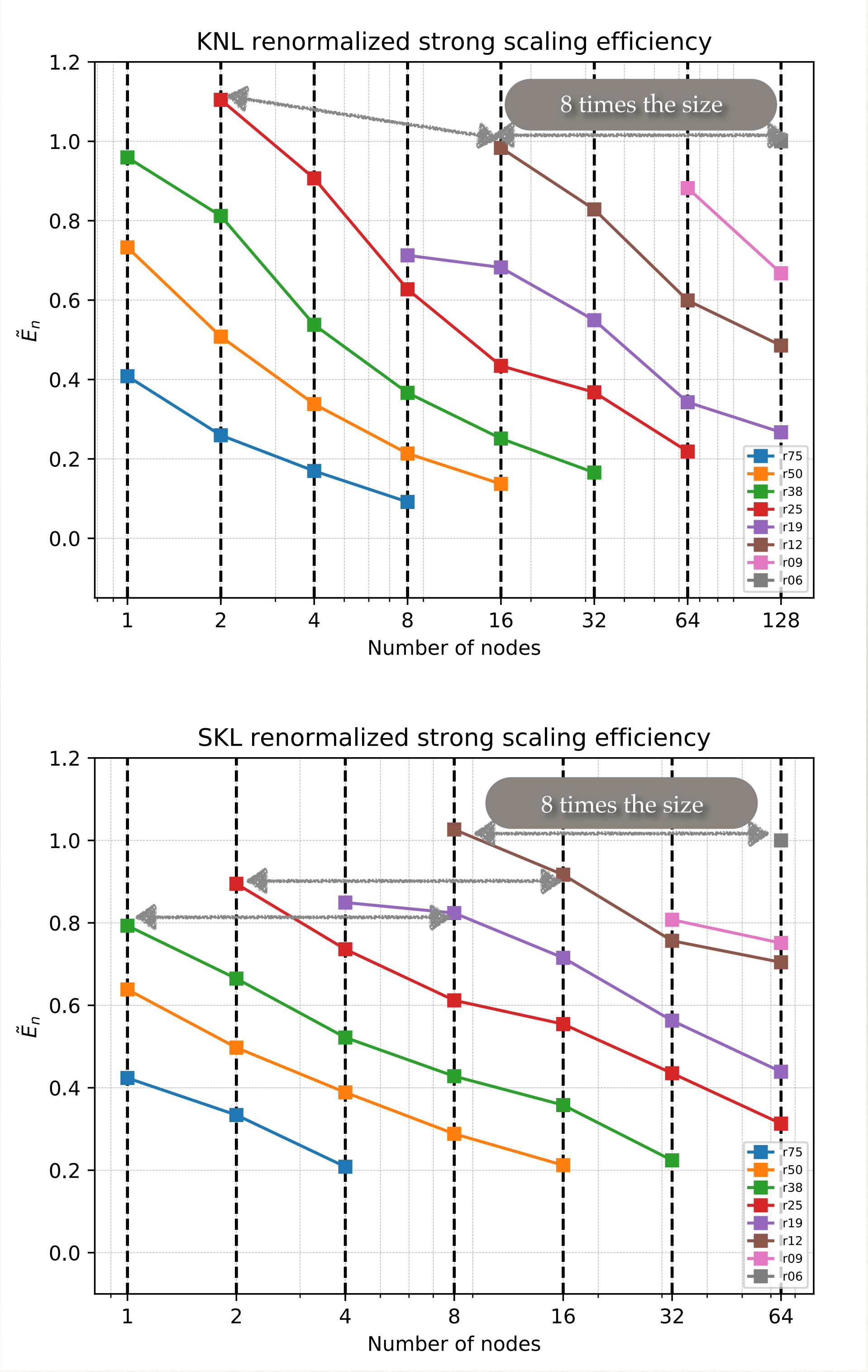
- **The equation of a perfect fluid are a non linear hyperbolic system.**

$$\frac{\partial \vec{u}}{\partial t} + \frac{\partial \vec{f}^i}{\partial x^i} = \vec{s}(\vec{u})$$

- **Wilson (1972) wrote the system as a set of advection equation within the 3+1 formalism.**
- **Non-conservative. Conservative formulations well-adapted to numerical methodology:**
  - Martí, Ibáñez & Miralles (1991): 1+1, general EOS
  - Eulderink & Mellema (1995): covariant, perfect fluid • Banyuls et al (1997): 3+1, general EOS
  - Papadopoulos & Font (2000): covariant, general EOS

Huge computational problem

- From: *Toward higher resolutions in Neutron Star Merger simulations with the Einstein Toolkit*, R. Alfieri, R. De Pietri, A. Feo, C. Musolino, M. Pasquali (in preparation -and poster a Supercomputing 2019 Denver)
- **VECTORIZATION (use of AVX512 instruction)**
- **Code is memory bounded. In the sense that to reach the high resolution request one need fill the memory of the computing nodes (usual best if for loading of 1 Gbyte/core**
- WEEK SCALING IS GOOD
- Reasonable strong scaling but … due to the increase of ghost zone (stencil size 3 has strong impact if the part of the grid for each processor (MPI thread) is not at least 40x40x40
- RESOLUTION r06 (dx~87m) has size of the checkpoint order 500 GByte
- The strong scaling curve ends (on the right) because that simulation can not be run with less nodes



Results of the simulation:

Try to understand the GW post merger signal

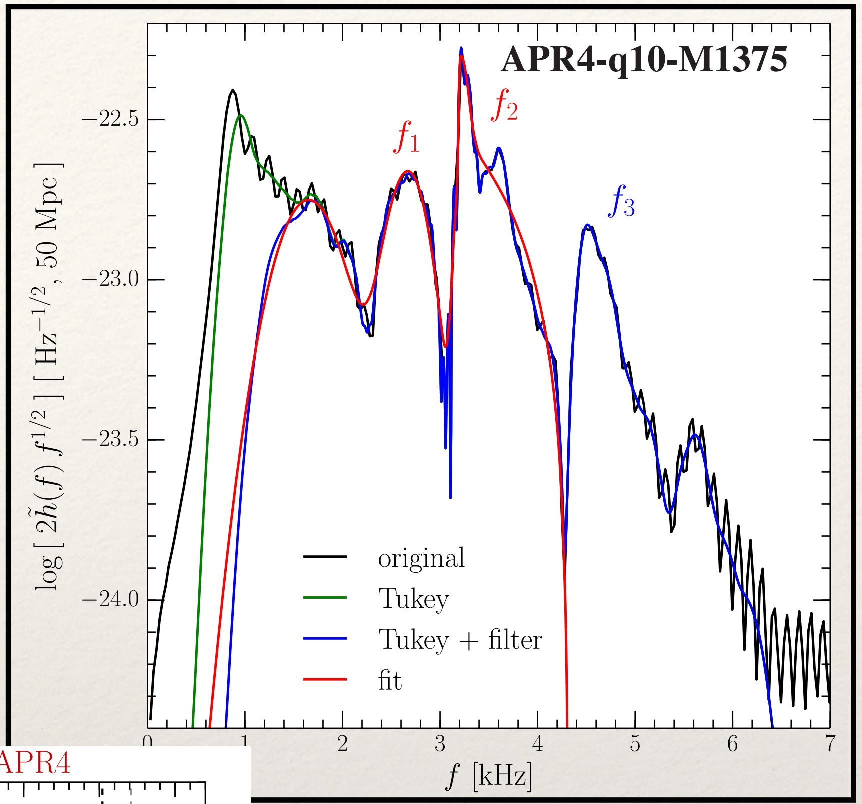
and

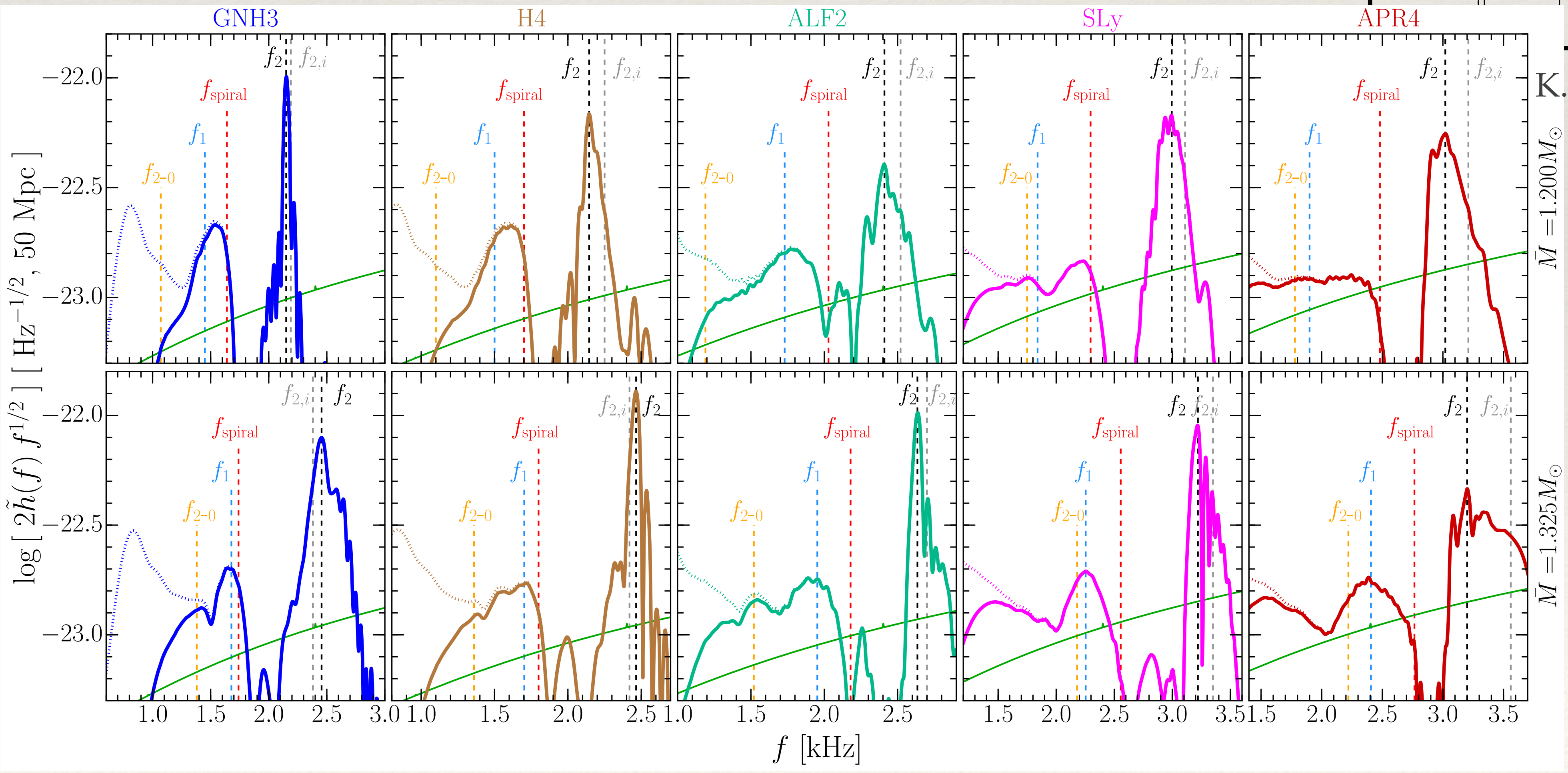
How it related to the EOS that describe matter at very high density

Post Merger Spectrum

- The main characteristics of the post-merger spectrum are captured by three main peaks f_1, f_2, f_3 (closely physical related) plus an additional $f_{spriral}$ peak

- This general picture maybe used to get information on the EOS by (using-multiple BNS post-merger events) [S. Bose, K. Chakravarti, L. Rezzolla, B. S. Sathyaprakash, and K. Takami, (2017), 1705.10850] or focusing on just the main f2 mode [H. Yang, V. Paschalidis, K. Yagi, L. Lehner, F. Pretorias, and N. Yunes, (2017), arXiv:1707.00207].



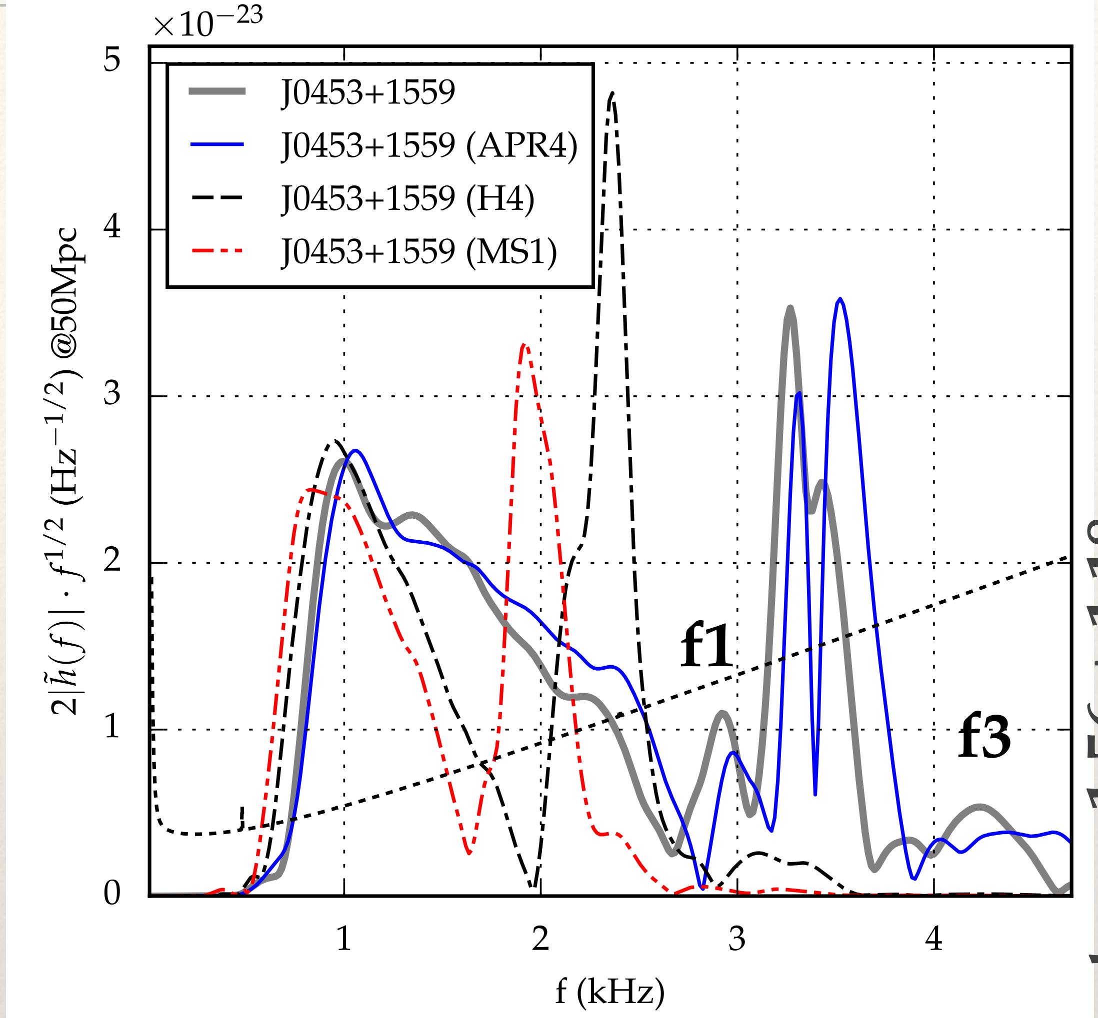


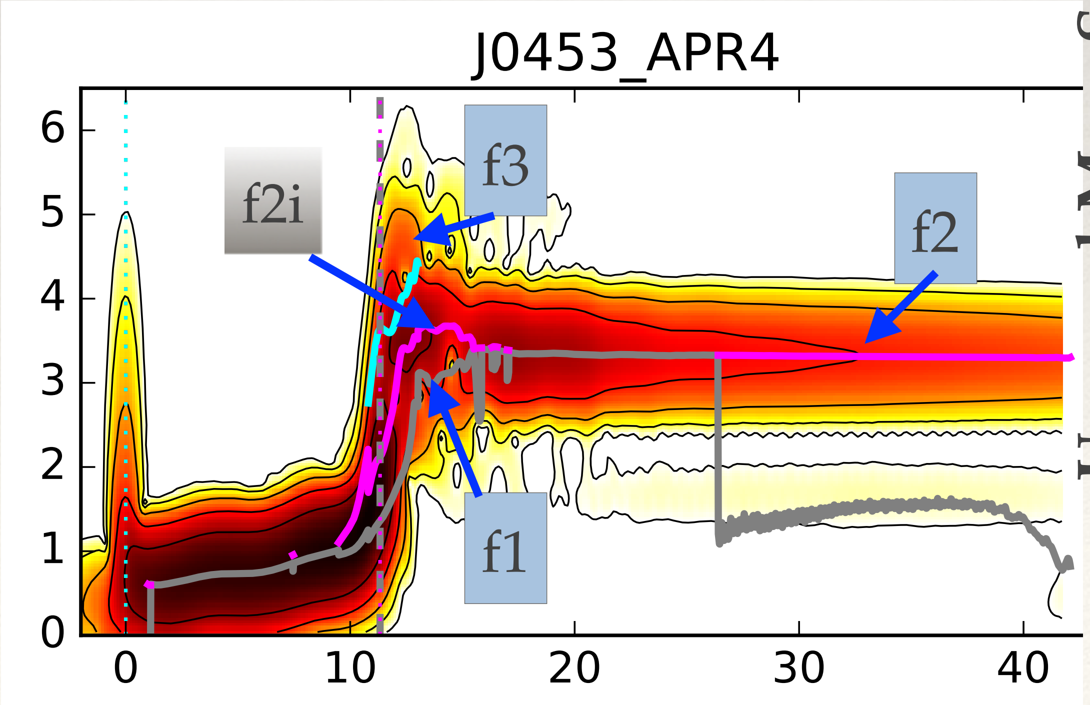
K. Takami, L. Rezzolla, and L. Baiotti, **Phys. Rev. D91**, 064001 (2015)

L. Rezzolla and K. Takami, **Phys. Rev. D93,** 124051 (2016)

Post Merger Spectrum

- Analyzing the signal using Fourier spectrograms and Prony spectrograms one see that:
  - A change in the dominant peak frequency between the initial transient phase and the following quasi- stationary phase. It is apparent that this transient is not a sudden jump, but rather a continuous process, in which the dominant frequency first increase and then decrease;
  - A slow increase in the dominant frequency in the quasi-stationary phase which, in particular in the Fourier spectrograms, seems more pronounced in equal mass binaries and suppressed in unequal mass ones.

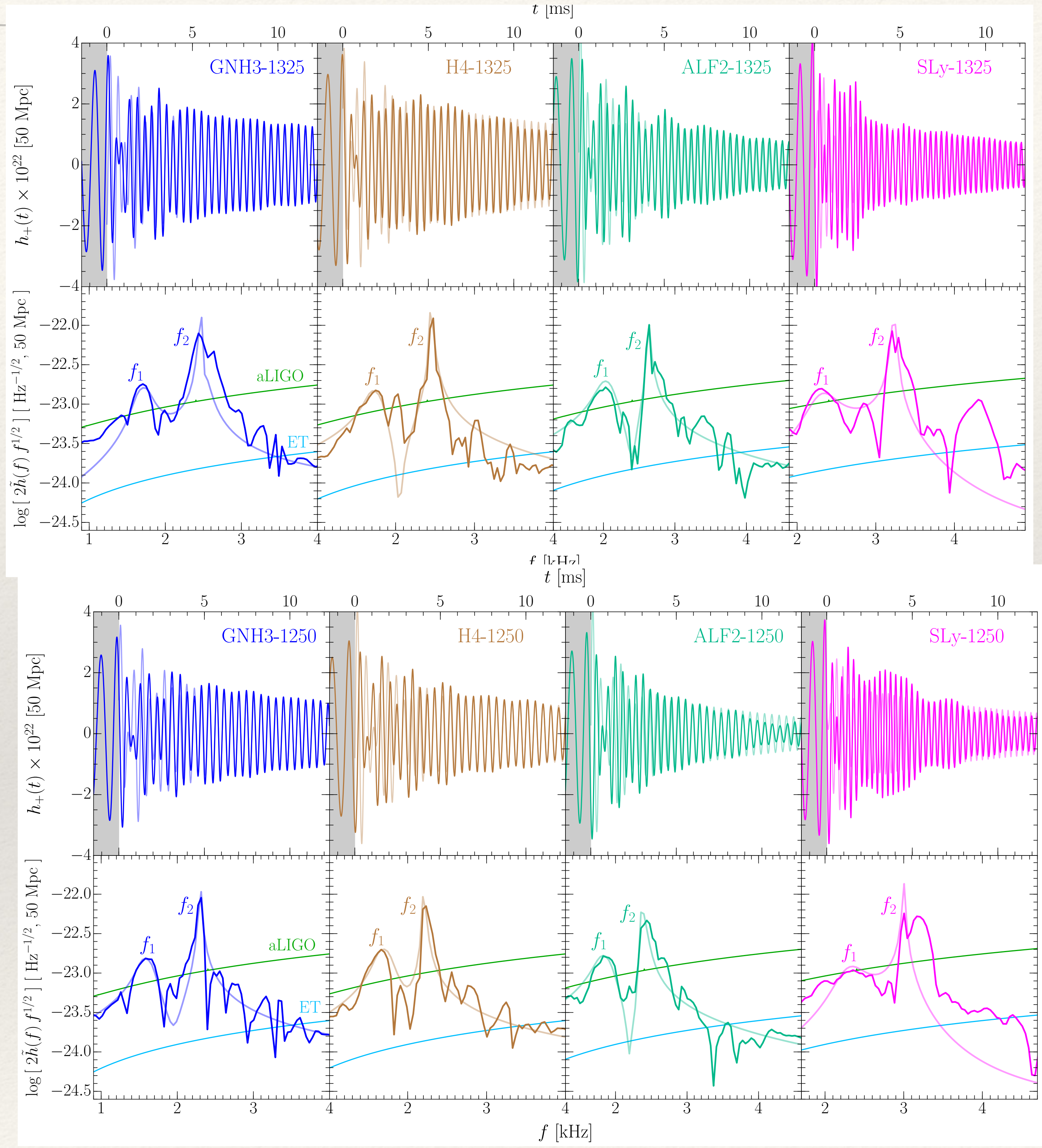




Unequal Mass System. 1.56 + 1.18

Neutron-star Radius from a Population of BNS Mergers

- From the talk Jutta Kunz we learned that a number of Universal relation have been proposed to link properties of Stars.
- Universal relation have also been derived for the peak-frequency of the post merger signal.
- From that follows the idea of using detected gravitation wave signal to get measure of the properties of the stars (like its Radius)
- To do the analysis (and avoid to do 100s of BNS simulation) use a phenomenological model for the postmerger waveform using analytical fits in the time domain to a catalogue of numerical-relativity waveforms that can be expressed as a superposition of damped sinusoids with a time-evolving instantaneous frequency

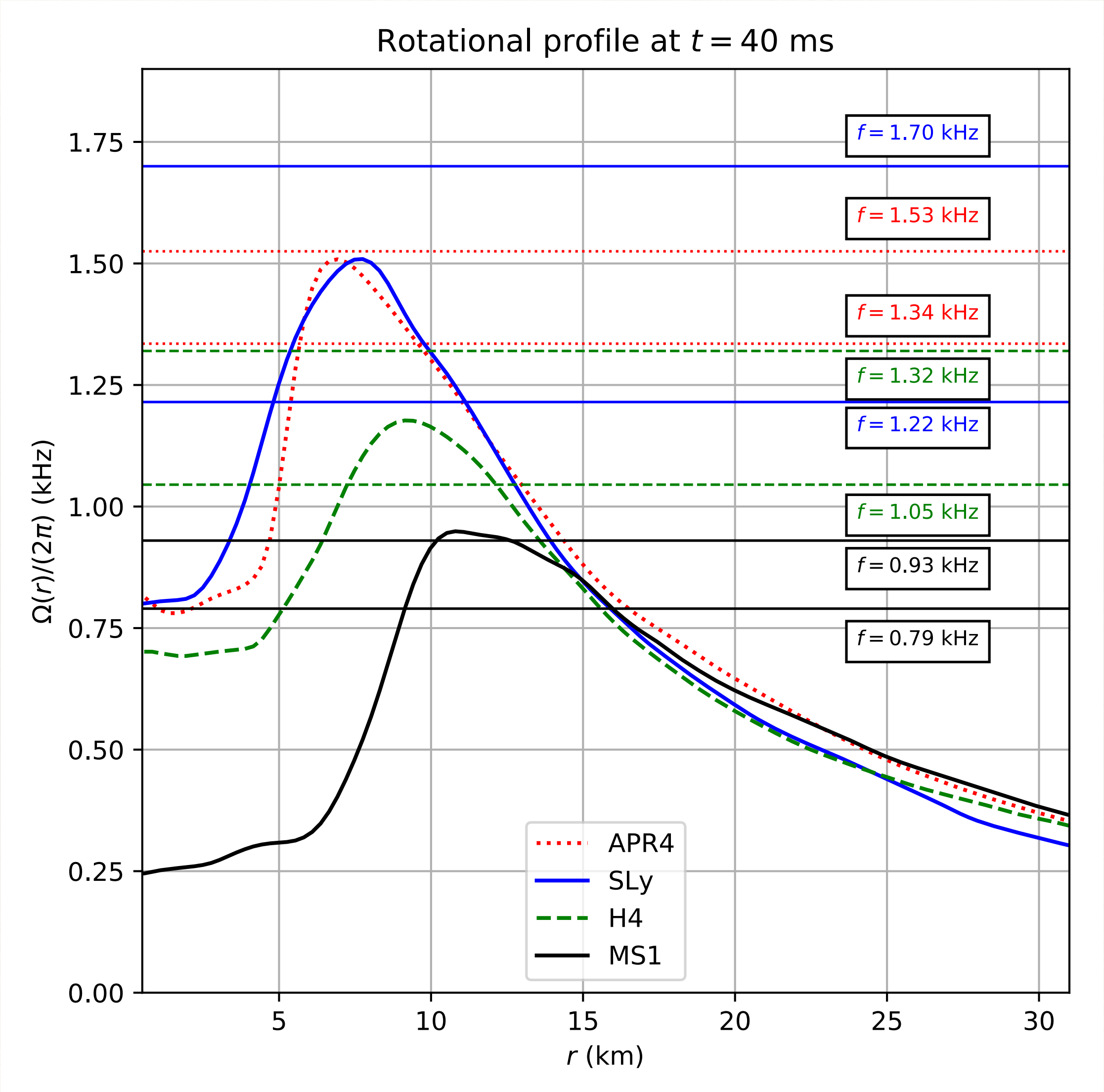


S. Bose, K. Chakravarti, L. Rezzolla, B. S. Sathyaprakash, and K. Takami, Neutron-star Radius from a Population of Binary Neutron Star Mergers (2017), **1705.10850**

Interesting thermal effect active in later stage

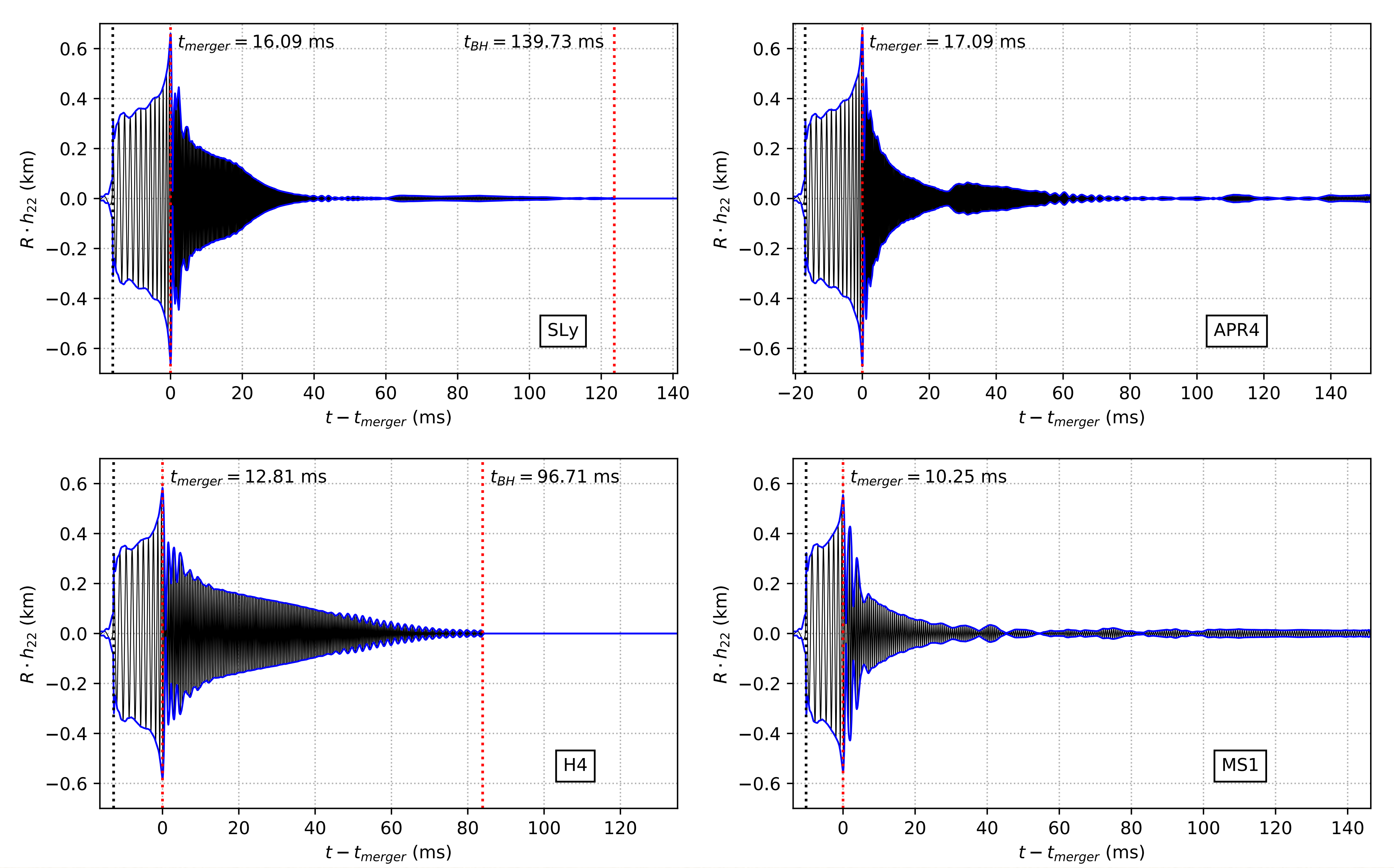
- Now if the simulation is long-enough the star relax to a new pseudo-equilibrium axis-symmetric rotational configurato that:
- **1) It is not uniformly rotating (possible presence of dynamical instabilities, like the shear instability or the bar-.mode one)**
- **2) it is not described by a barotropic state (presence of possible entropy gradient) and convective instability can be present**
- CFS mechanism allows the grow of a mode (conserving angular momentum) if it has a frequency that it is slower than the rotation frequency o the Star

Rotation profile of the remnant 40 ms after merger for differed EOS

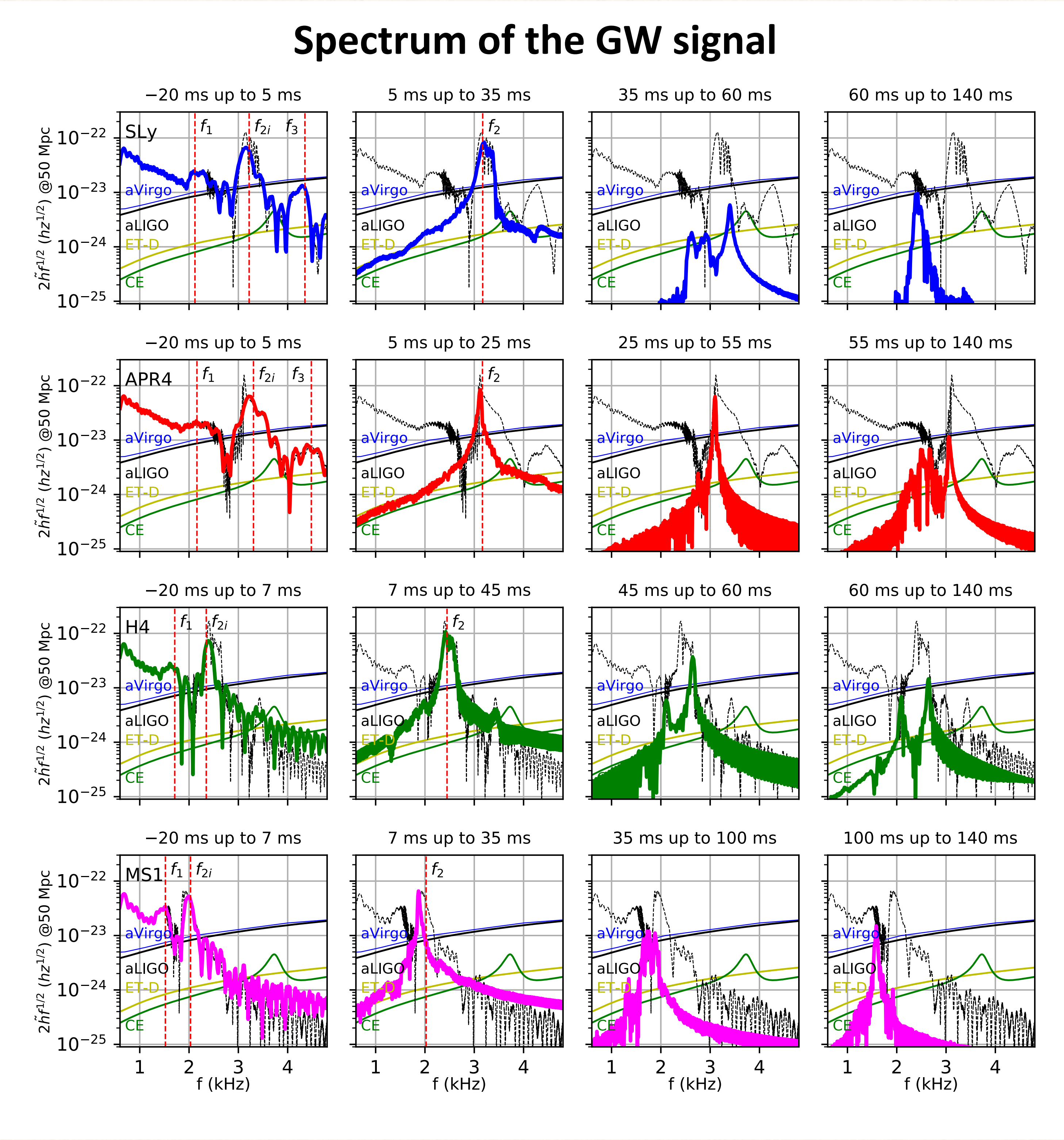


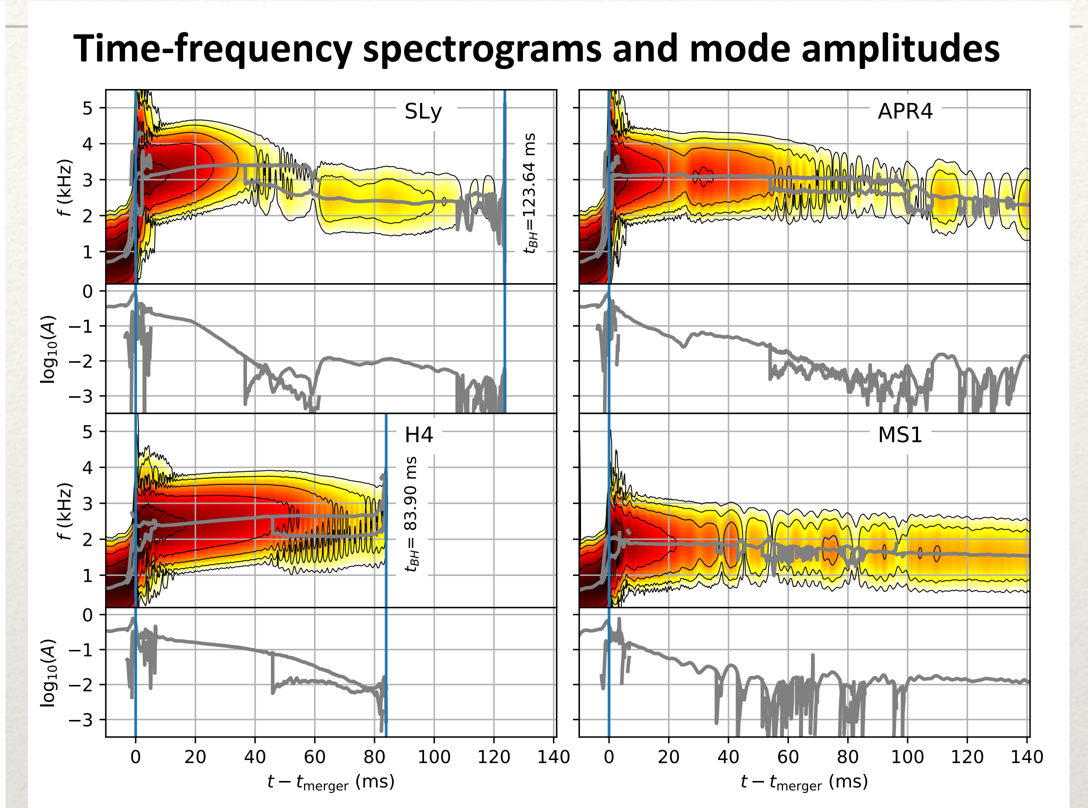
Question: what happen when the system is evolved for a longer time ?

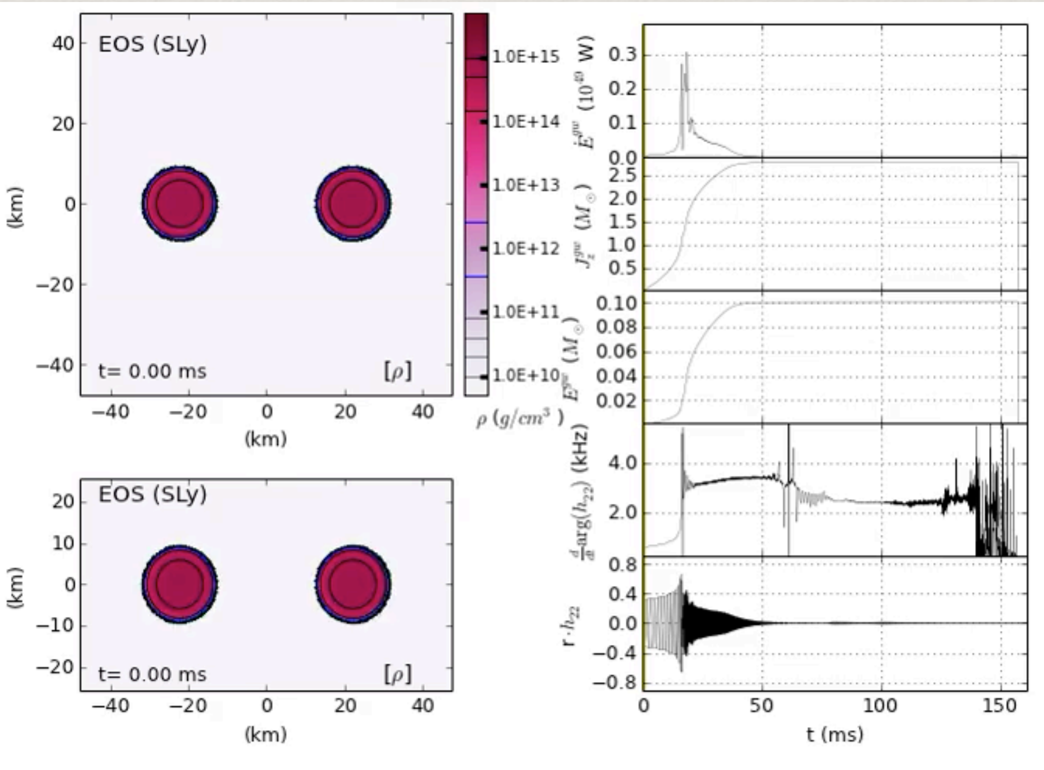
- The properties of the signal are no-longer described only in terms of the modes: *f1*, *f2*, *f3* and *fspriral*
- New signature of the thermal part of EOS (De Pietri et al. PRL 2018, De Pietri et al. 2019 arxiv)



post-merger GW-Modes are changing with time





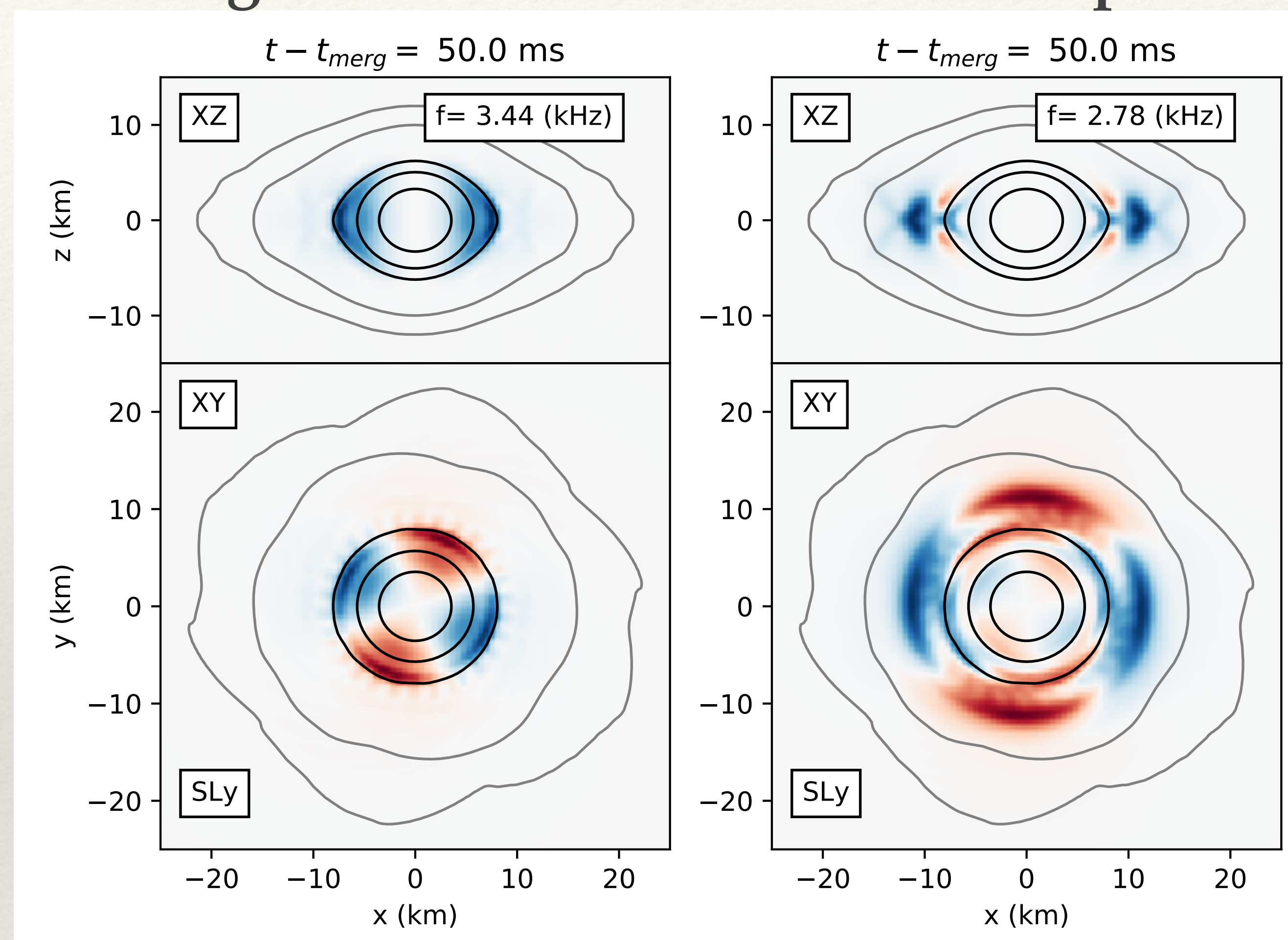


Later time modes are different !

- Different frequency !
  For Sly from 3.4kHz to 2.78 kHz
- Different eigenfunction!
- Different mode !
- Exited (the later) by convective gradient: Positive Schwarzschild discriminant in the radial direction.

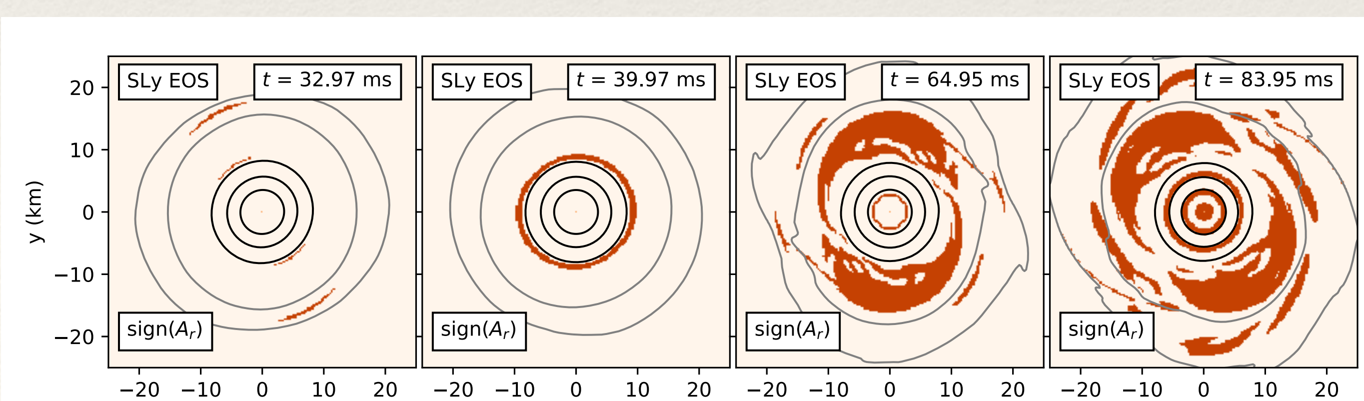
$$A_\alpha = \frac{1}{\varepsilon + p}\nabla_\alpha \varepsilon - \frac{1}{\Gamma_1 p}\nabla_\alpha p\,,$$

Mode eigenfunction in the XY and XZ plane



Main f2 mode **Exited inertial mode**

At 50 ms - coexistence of the two modes



Regione in the XY plane where the Schwarzschild discriminant is positive at different times

Conclusion

- Numerical relativity allows to model the Gravitational Wave post-merger signal from the merger of two Neutron Star
- This works would not be possible without INFN providing us computational resource of state of the art supercomputer
- Still lot of work need to be done