Ferrara, Thursday, November 23rd 2017. mini-workshop Gravitational-Wave Astrophysics Day.

Modeling Neutron Star Mergers

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Abstract

Binary Neutron Star systems are the most interesting source of gravitational wave signals and the associate signal will carry important information about the equation of state (EOS) of matter at high density. The main information on the EOS will be seen on the postmerger signal. (Not detected in the case for GW170817)

In this talks I will discuss the various steps that one need to perform, starting from the EOS of matter at high density, to obtained the properties of the Gravitational Wave signal emitted during the merger.

I will focus my talk on the post-merger signal and on the additional information that can be obtained using a modern variant of Prony's method to analyse the signal as a sum of complex exponential

Abstract …….

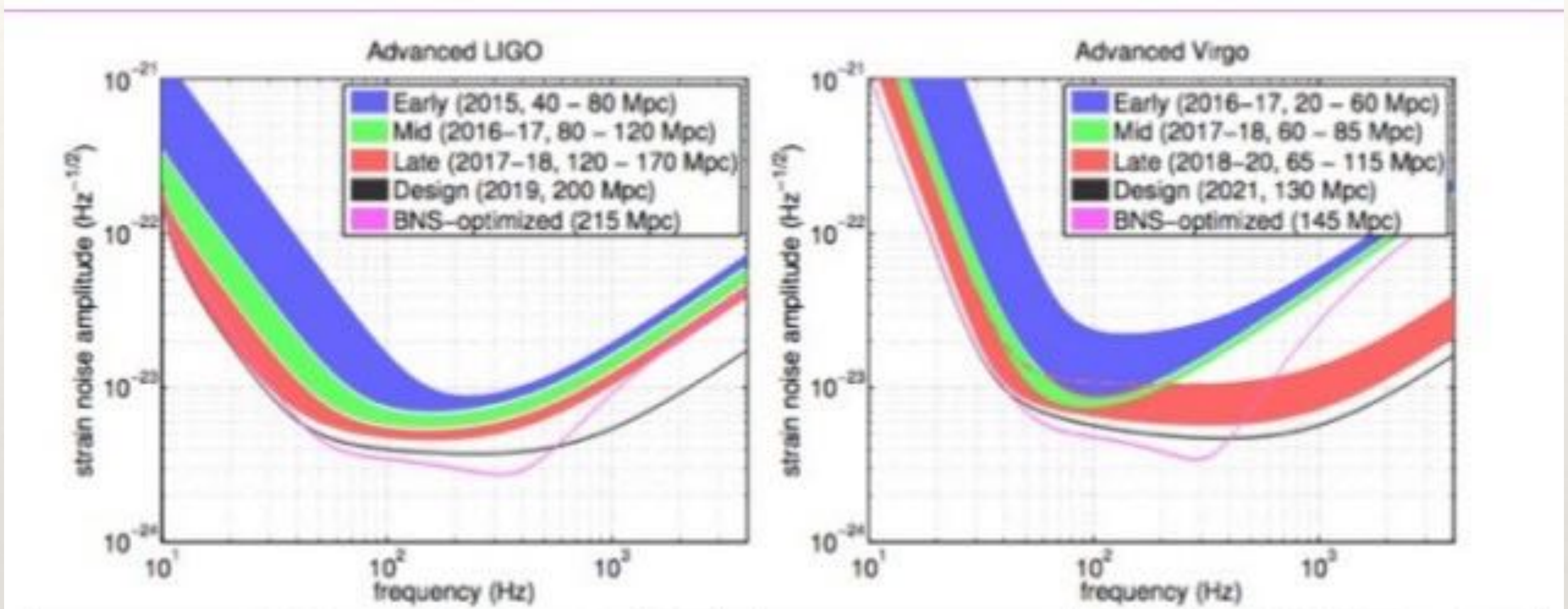
I would like to remark that it is now possible to investigate the physics of Binary Neutron Star System merger using only publicly available open source software, the Einstein Toolkit for the dynamical evolution and the LORENE code for the generation of the initial models.

I will also present three-dimensional simulations of the dynamics of binary neutron star (BNS) mergers from the late inspiral stage up to ~20 ms after the system has merged, either to form a hyper-massive neutron star (HMNS) or a rotating black hole (BH). In particular we show the fate of the six galactic systems (J0453+1559, J1756-2251, J0737-3039A, B1913+16, J1906+0746*, B1534+12) when they will finally merge and the gravitational wave signal that will be emitted.

I also report results for equal and un-equal-mass models and on the strength of the Gravitational Signal and its dependence on the EOS, the mass ratio of the two stars, the radiated energy and angular momentum. We use a semi-realistic description of the equation of state (EOS) where the EOS is described by a seven-segment piece-wise polytropic with a thermal component given by Γ_{th}=1.8

Why we do want to study BNS mergers?

- First: the LIGO/Virgo collaboration will see the signal from BNS system. They are among the most powerful sources of GWs



O1 → 2015

O2 → 2016–17

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

UKZN: Jan 20, 2014 [Aasi+ (LSC+Virgo), arXiv:1304.0670] 25

Gravitational Waves sources: compact objects

- MAIN TARGET LIGO/Virgo coll.:

NS-NS merger

sensitive frequency band approx. (40-2000) Hz

Expected to rate ≈ 0.2 – 200 events per year events between 2016 – 19

[J. Abadie et al. (VIRGO, LIGO Scientific), Class. Quant. Grav. 27, 173001 (2010)]

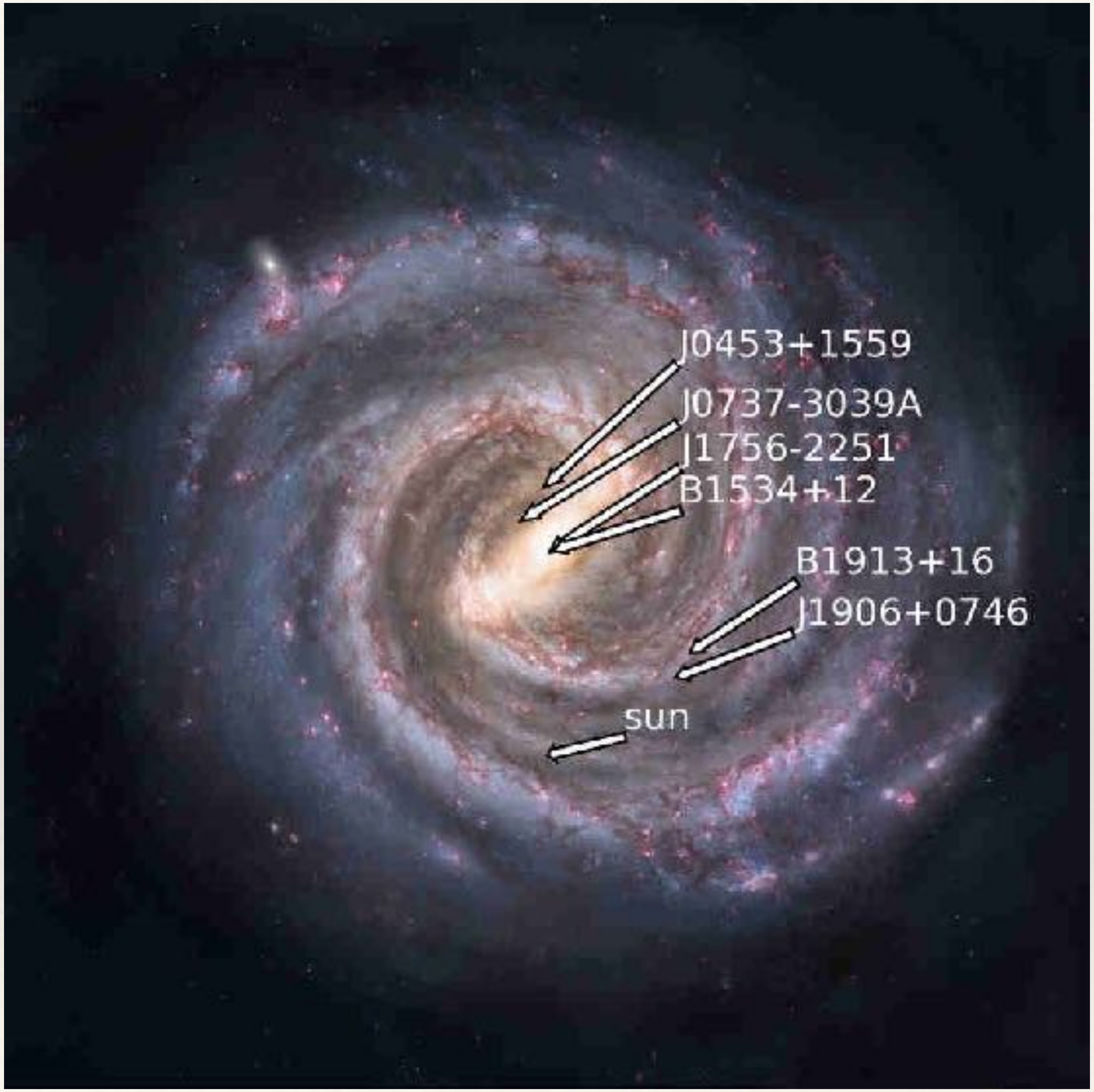
- **Core collapse in supernova**
- **BH-BH merger** —— **(FOUND!)**
- **BH-NS merger**
- **"*Mountains*" (deformation) on the crust of Neutron Stars**
- **Secular instability of Neutron stars**
- **Dynamical instability of Neutron star**

Table 1: Double neutron star systems known in the Galaxy

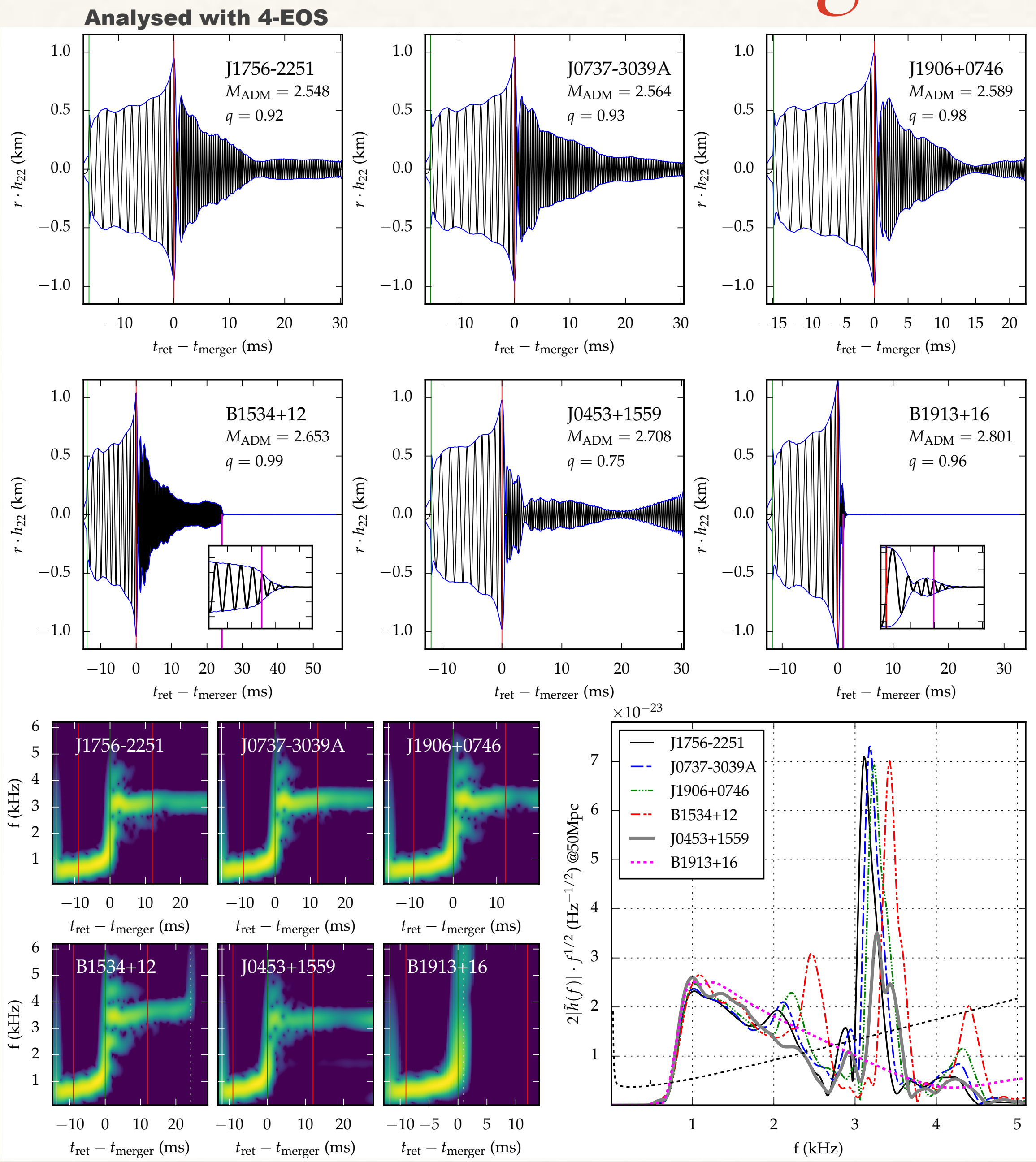
Pulsar	Period (ms)	P_b (days)	x (lt-sec)	e	M ($M_\odot$)	M_p ($M_\odot$)	M_c ($M_\odot$)	References
J0737−3039A	22.699	0.102	1.415	0.0877775(9)	2.58708(16)	1.3381(7)	1.2489(7)	1
J0737−3039B	2773.461		1.516					
J1518+4904	40.935	8.634	20.044	0.24948451(3)	2.7183(7)	-	-	2
B1534+12	37.904	0.421	3.729	0.27367740(4)	2.678463(4)	1.3330(2)	1.3454(2)	3
J1753−2240	95.138	13.638	18.115	0.303582(10)	-	-	-	4
J1756−2251	28.462	0.320	2.756	0.1805694(2)	2.56999(6)	1.341(7)	1.230(7)	5
J1811−1736	104.1	18.779	34.783	0.82802(2)	2.57(10)	-	-	6
J1829+2456	41.009	1.760	7.236	0.13914(4)	2.59(2)	-	-	7
J1906+0746*	144.073	0.166	1.420	0.0852996(6)	2.6134(3)	1.291(11)	1.322(11)	8
B1913+16	59.031	0.323	2.342	0.6171334(5)	2.8284(1)	1.4398(2)	1.3886(2)	9
J1930−1852	185.520	45.060	86.890	0.39886340(17)	2.59(4)	-	-	10
J0453+1559	45.782	4.072	14.467	0.11251832(4)	2.734(3)	1.559(5)	1.174(4)	This Letter
Globular cluster systems								
J1807−2500B*	4.186	9.957	28.920	0.747033198(40)	2.57190(73)	1.3655(21)	1.2064(20)	12
B2127+11C	30.529	0.335	2.518	0.681395(2)	2.71279(13)	1.358(10)	1.354(10)	13

Table from: Martinez et al.: "Pulsar J0453+1559: A Double Neutron Star System with a Large Mass Asymmetry" arXiv:1509.08805v1

Artistic view of the location of the six galactic system.

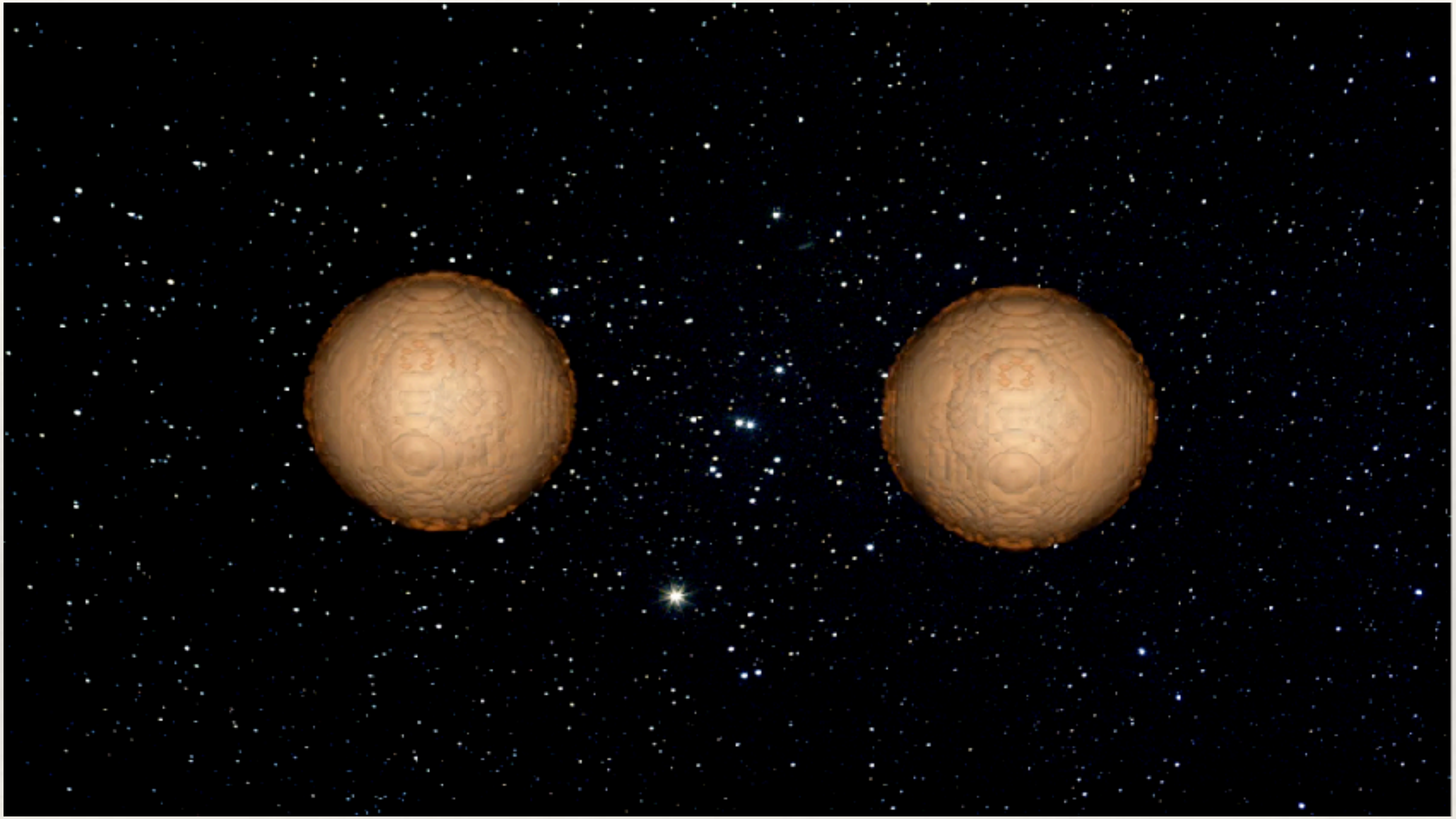


The simulated GW signal

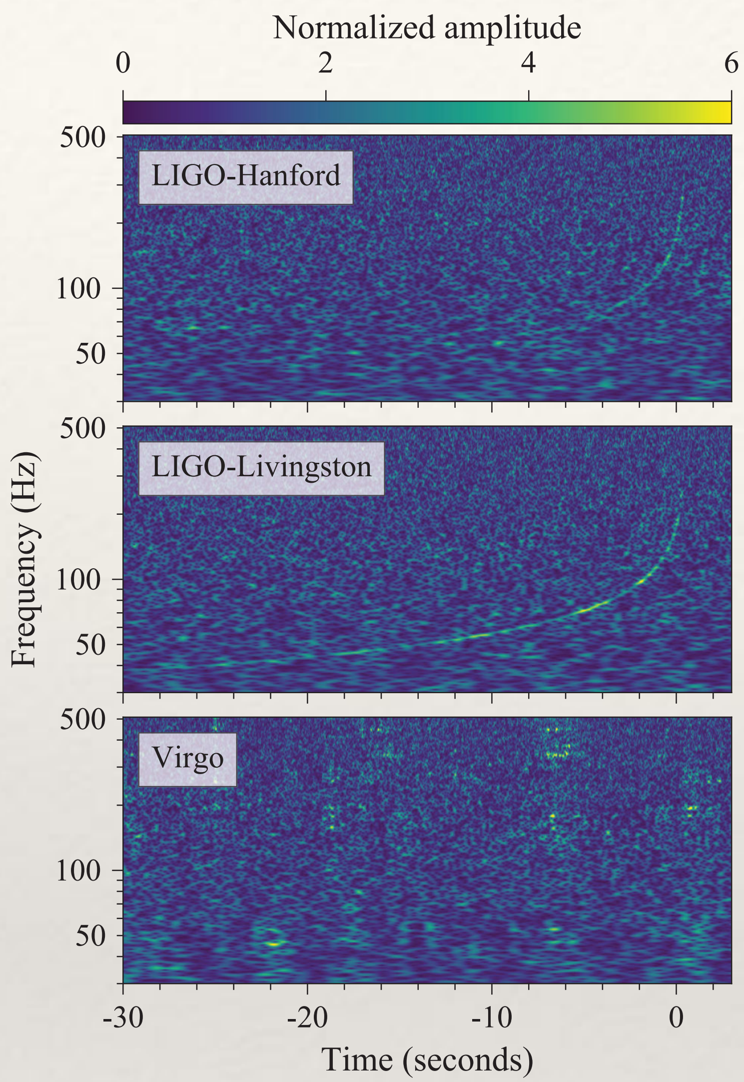


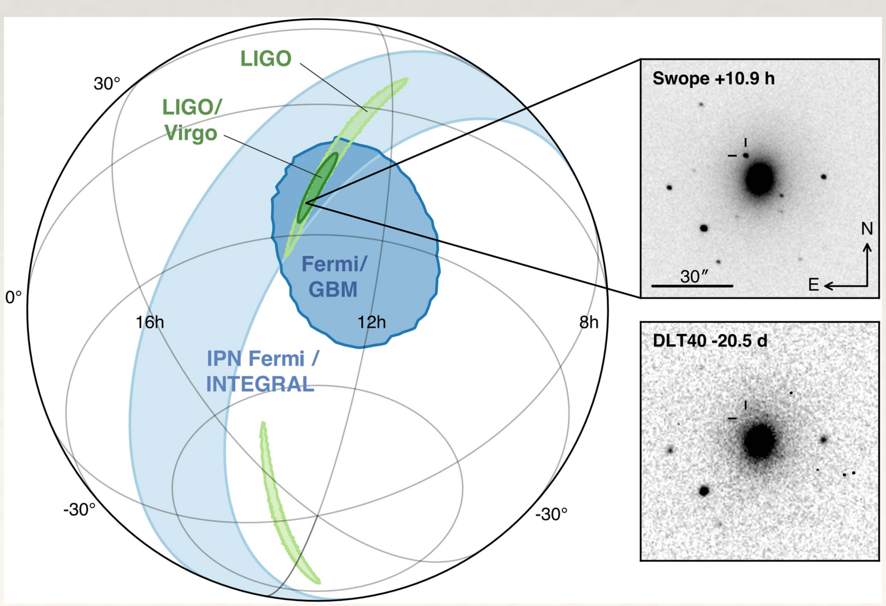
A. Feo, R. De Pietri, F. Maione and F. Loeffler,
Modeling Mergers of known Galactic Binary Neutron Stars,
Classical and Quantum, 34 (3), 034001 (2017) arXiv 1608.02810(2016)

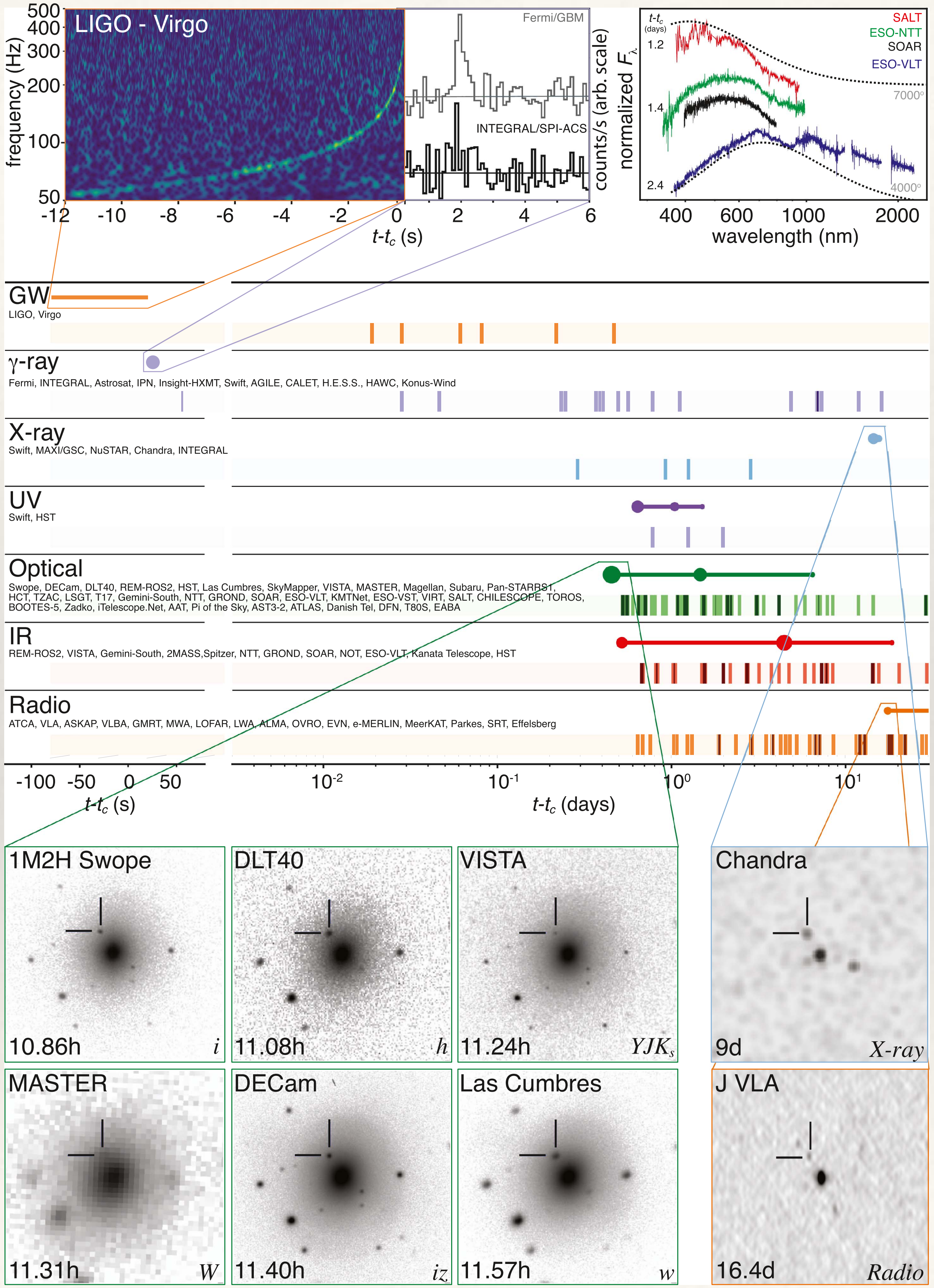
GW170817 - the August signal!



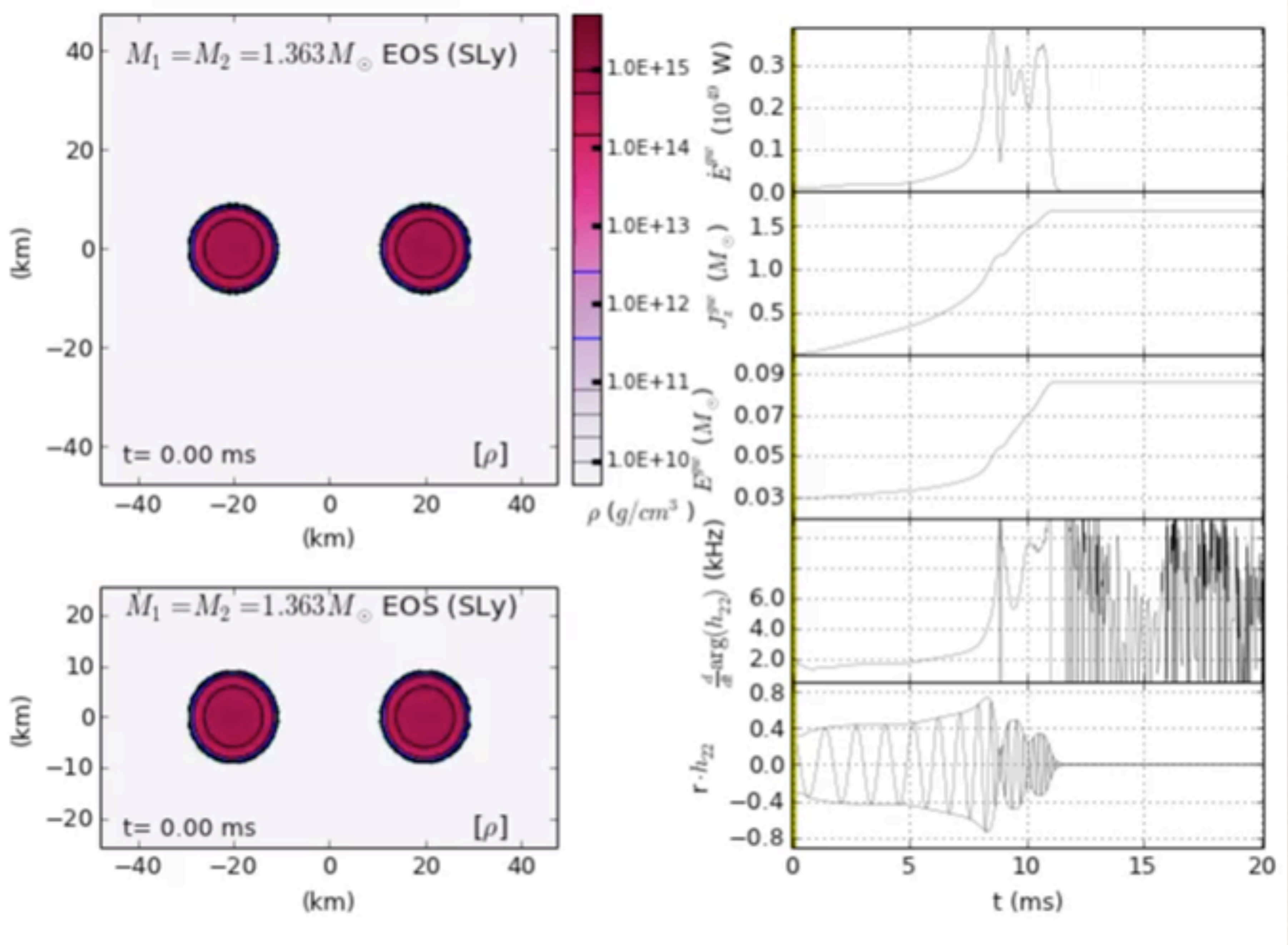
Multimessenger observations of GW170817







More details on the expectation from NR



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.
- New 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, …

Mostly based on: (using only public codes)

- F. Maione, R. De Pietri, A. Feo and F. Loeffler, arXiv:1707.03368.
  Phys. Rev. D 96, 063011 (2017).
  Spectral analysis of gravitational waves from binary neutron star merger remnants.

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

- F. Maione, R. De Pietri, A. Feo and F. Loeffler, arXiv:1605.03424.
  Classical and Quantum Gravity, 33, no. 17, 175009 (2016).
  Binary neutron star merger simulations with different initial orbital frequency and equation of state.

- R. De Pietri, A. Feo, F. Maione and F. Loeffler, arXiv:1509.08804.
  Phys. Rev. D 93, 064047 (2016).
  Modeling Equal and Unequal Mass Binary Neutron Star Mergers Using Public Codes

Work going on in collaboration with : A.Drago, A.Feo, T. Font, F. Loeffler, F. Maione, M.Pasquali, G. Pagliara, N.Stergioulas, S. Traversi

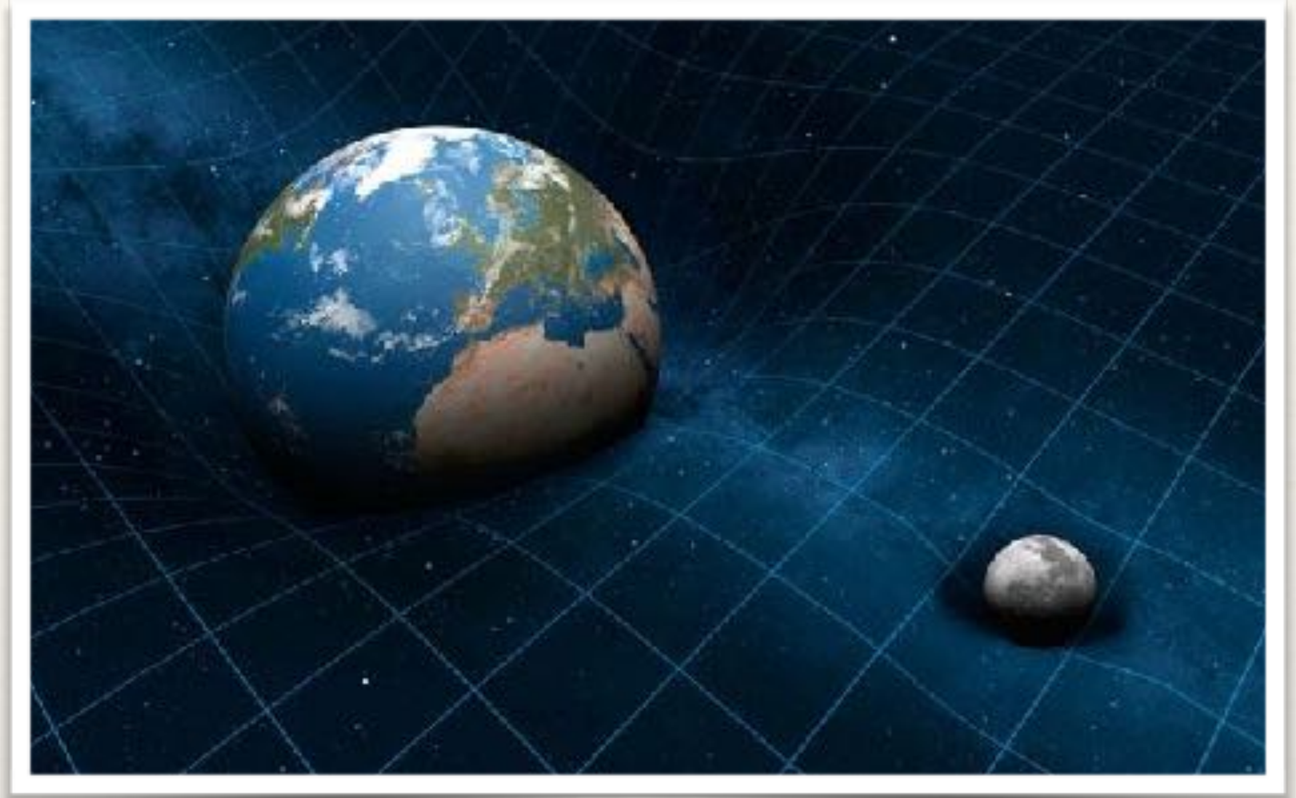
How we do simulate such systems.

General Relativity (in short)

- The gravity is shown as a result of the fact that the space-time is curved!
    - Each mass-energy curved the space-time
    - Freely falling objects follow the geodetic (straight line) of a curved space-time.
    - Einstein's fields equation are:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- There is a real space-time but we are free to choose any reference systems (atlas) to describe physical laws.



John Archibald Wheeler:
spacetime tells matter how to move;
matter tells spacetime how to curve

Numerical Relativity in a nutshell

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

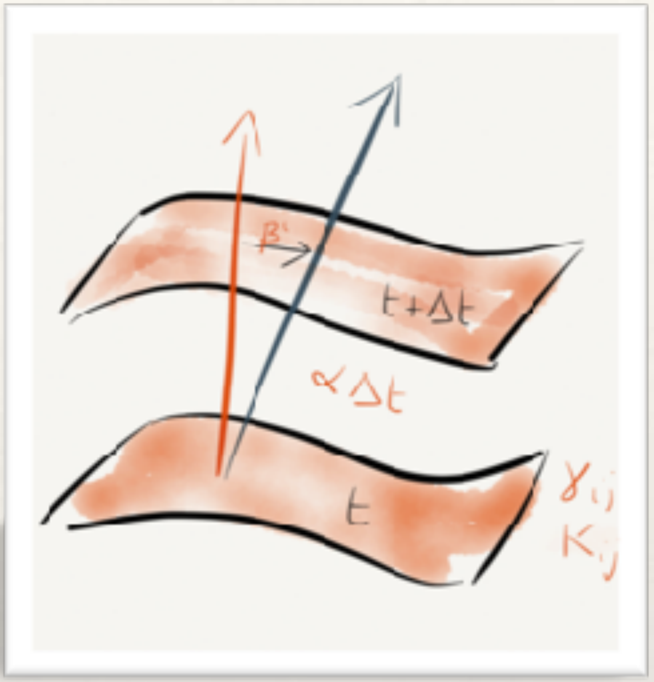
Ideal Fluid Matter

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

- But these are 4D equations! Need to write as 3+1 evolution equations.
- Spacetime get foliated into 3D spacelike surfaces, in which we define our variables. We evolve them along a time direction normal to those surfaces.
- (Magneto)Hydrodynamics is written in terms of conservative form and special numerical techniques are used for the fluxes calculations.
- All physical variables and equations are discretized on a 3D Cartesian mesh and solved by a computer. Uses finite differences for derivative computations and standard Runge-Kutta method for time integrations.
- Different formulation of the Einstein Eqs have been developed in the last 20 years. BSSN-NOK version of the Einstein's Eqs.

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

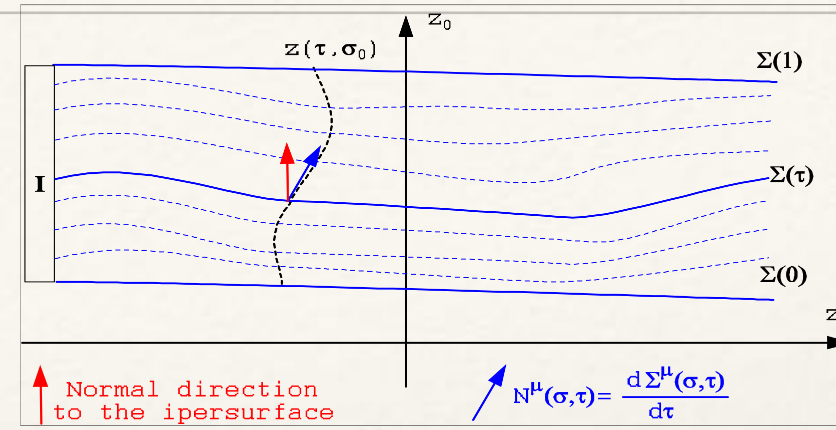
Use usual numerical methods:

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 !

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

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



- BSSN version of the Einstein's equations that introduce additional conformal variables:

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

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

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

$$\partial_t\tilde{g}_{ij} = -2\alpha K_{ij} + \tilde{g}_{jk}\partial_i\beta^k + \tilde{g}_{ik}\partial_j\beta^k - \tfrac{2}{3}\tilde{g}_{ij}\partial_k\beta^k$$

$$R^{TF}_{ij} = R_{ij} - \tfrac{1}{3}g_{ij}R$$

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

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

- Matter evolution (B set to zero) using shock capturing methods based on the GRHydro code

[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

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

- **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

The numerical challenge

A challenging numerical problem

- The accurate simulation of a BNS merger is among the most challenging tasks in numerical relativity.
- Involve strong gravitational fields, matter motion with relativistic speeds, relativistic shock waves, (and strong magnetic fields).
- Increasing difficulty due to the multidimensional character of the PDE and by the complexity of the Einstein's equations such as coordinates degrees of freedom and formation of black holes (curvature singularity).
- Despite the problems, major progress achieved during the last decade in numerical simulations of BNS mergers (since the seminal work by Shibata and Uryu, 2000) due to: improved numerical methods (high resolutions methods and adaptive mesh refinements), improved physics (nuclear physics EOS, thermal effects) and increased computational resources!!

A challenging numerical problem (2)

- In the description of BNS mergers are involved three stages, the inspiral, the merger and the evolution to its final state (post-merger stage) that would quite likely be a BH surrounded by an accretion disk.

- The inspiral stage can be modeled with good accuracy by analytical techniques (PN calculations and EOB). Produce accurate waveforms up to a time very close to the merger. Useful to quickly computing waveform templates to matched filtering searches in GW detector data analysis. The role of NR in this regime is mainly to test and help improve these techniques.

- For the merger and post-merger stage, NR is the only available investigation tool to compare the experimental results that would be obtained by LIGO/Virgo detection with the underlying physics of the NS.

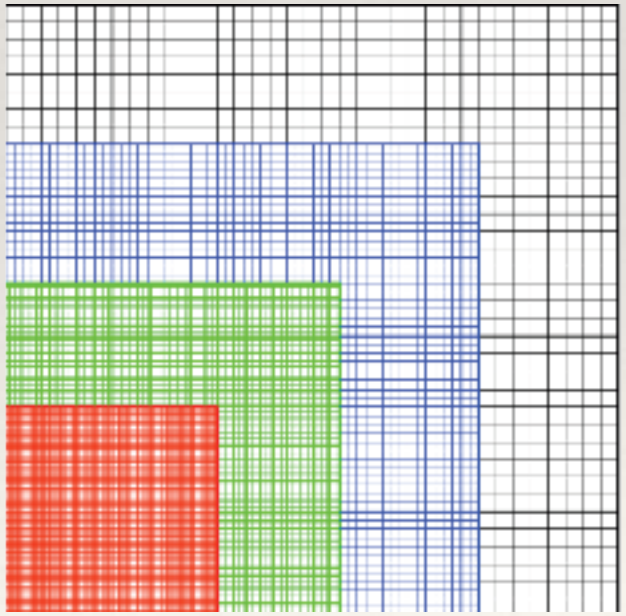
- An accurate description of GW emission of different model sources (different choice of the underlying NS physics through different choices of EOS) are useful for developing empirical relations to be able to infer NS parameter from future GW detections, as well as, to get information on the correct EOS that describe matter at this extreme conditions.

The code: Einstein TOOLKIT + LORENE

- **Einstein Toolkit** open set of over 100 Cactus thorns for computational relativity along with associated tools for simulation management and visualization
- **Cactus** framework for parallel high performance computing (Grid computing, parallel I/O)
- Data are evolved on a Cartesian Mesh with 6 levels of refinement with **Carpet**
- Matter Evolution with the module **GRHydro:**
  (Magnetic+**CT evolution** of Magnetic Field)
  HLLE Riemann Solver
  WENO Reconstruction method (*)
  PPM Reconstruction methods
- Spacetime Metric evolution is performed with the module MacLachlan implementing a 3+1 dimensional split of the Einstein Eqs.
  BSSN-NOK Gravitational Evolution scheme (*)
  CCZ4 gravitational evolutions
- Initial data computed using the **LORENE CODE**

einsteintoolkit.org

cactus code

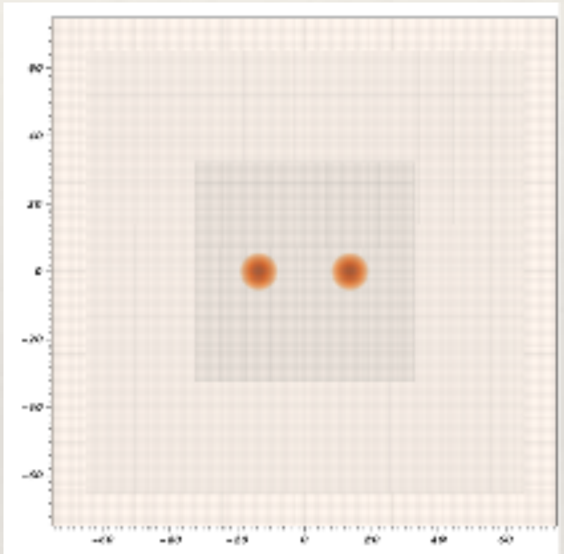


The computational challenge

- Cartesian grid with 6 refinement levels (7 when we get a BH).
- Standard Resolution in the finest grid 0.25 CU and up to 0.125 CU. => from 5,337,100 points up to 42,696,800 per grid.
- Outer grid extends to (1063Km) to extract gravitational waves far from the source.
- One extra refinement level added just before collapse to black hole.
- 12 spacetime variables + 4 gauge variables + 5 hydrodynamical variables evolved in each point.
- MPI+OpenMP code parallelization.

Level	$\min(x/y)$ (CU)	$\max(x/y)$ (CU)	$\min(z)$ (CU)	$\max(z)$ (CU)	(N_x, N_y, N_z) $dx = 0.25$
1	-720	720	0	720	(185,185,96)
2	-360	360	0	360	(205,205,106)
3	-180	180	0	180	(205,205,106)
4	-90	90	0	90	(205,205,106)
5	-60	60	0	30	(265,265,76)
6	-30	30	0	15	(265,265,76)
(7	-15	15	0	7.5)	(265,265,76)

1 CU = 1.4 km



Δx (CU)	0.75	0.50	0.375	0.25	0.185	0.125
# threads	16	64	128	256	512	2048
# MPI	2	8	16	32	64	256
Memory (GBytes)	3.8	19	40	108	237	768
speed (CU/h)	252	160	124	53	36	16
speed (ms/h)	1.24	0.78	0.61	0.26	0.18	0.08
cost (SU/ms)	13	81	209	974	2915	26053
total cost (kSU, 50 ms)	0.65	4	10.5	49	146	1300

Scaling on real world simulations

- Scaling of the the Einstein Toolkit on the CINECA "Galielo" system.
- Performance on a real world simulation!

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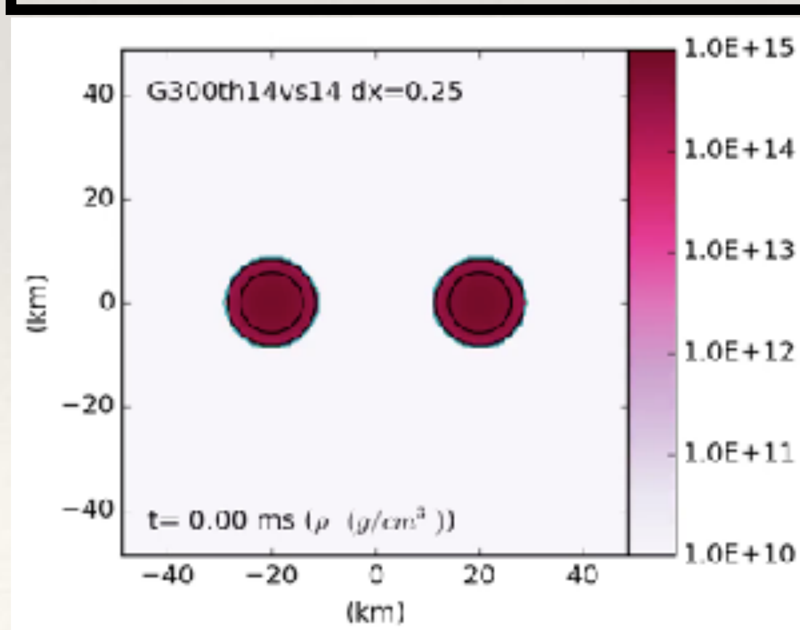
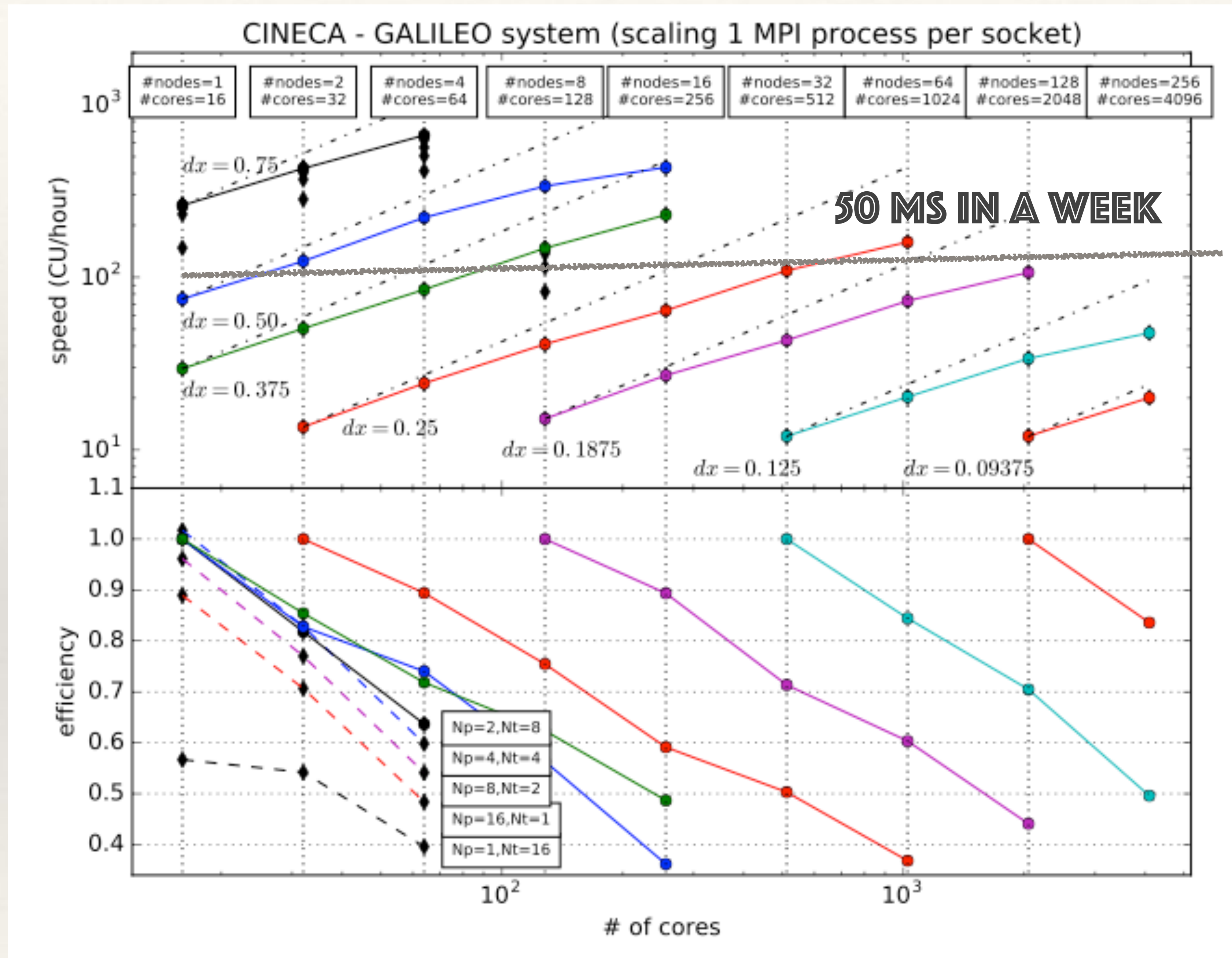
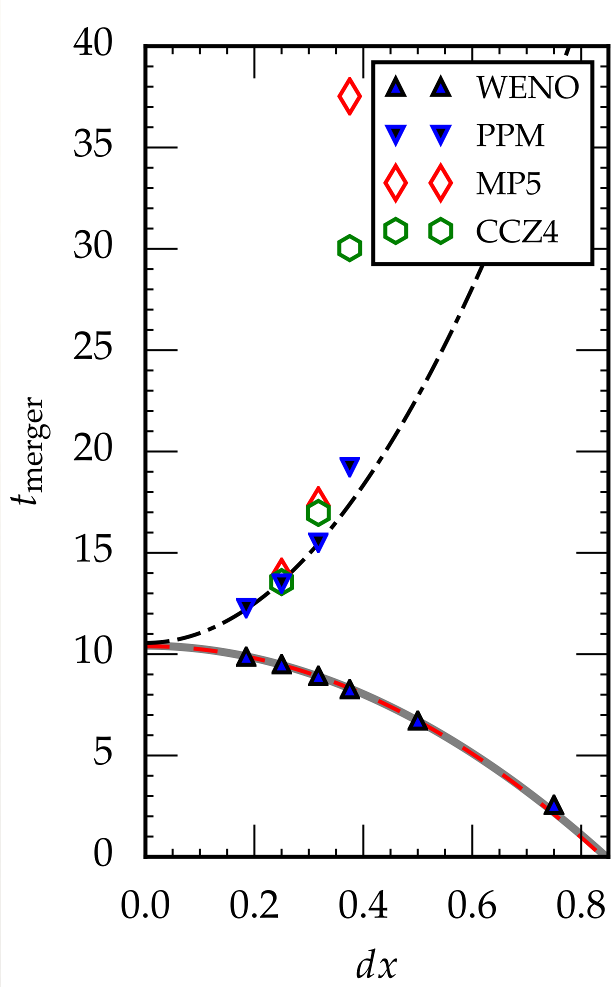




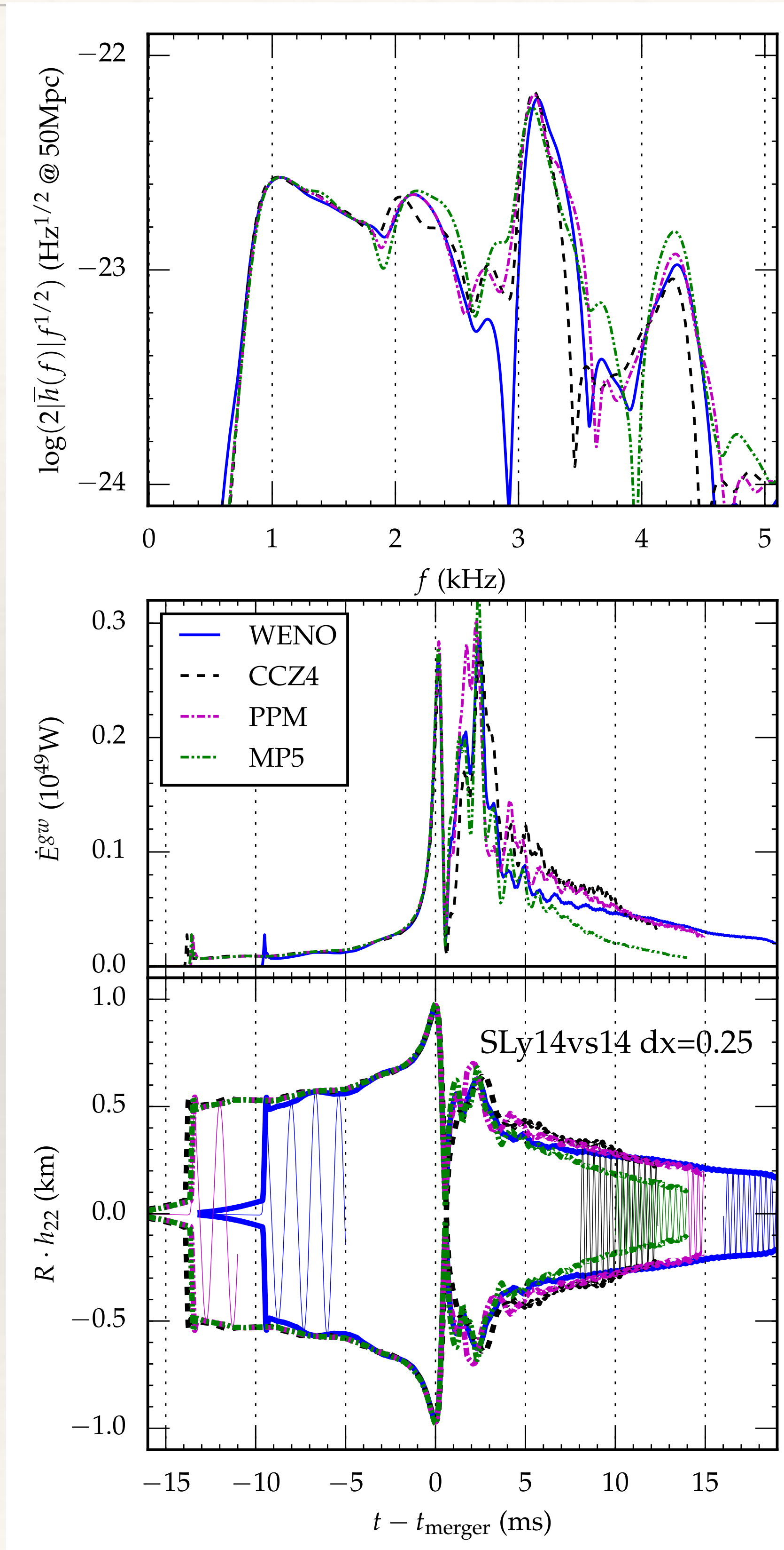
Results on Numerical Methods comparisons

Comparison between three different reconstruction methods for hydrodynamics (**WENO,PPM,MP5**)

and two gravity (metric) evolution schemes (**BSSN,CCZ4**).



	dx (CU)	t_{merger} (ms)
WENO	0.75	2.56
WENO	0.50	6.72
WENO	0.375	8.27
WENO	0.3125	8.93
WENO	0.25	9.50
WENO	0.185	9.87
PPM	0.375	19.23
PPM	0.3125	15.50
PPM	0.25	13.49
PPM	0.185	12.28
MP5	0.375	37.53
MP5	0.3125	17.34
MP5	0.25	13.81
CCZ4	0.375	30.03
CCZ4	0.3125	16.97
CCZ4	0.25	13.56



- The combination BSSN + WENO is the best for running sensible simulations at low resolution.
- With those methods you can run a qualitatively correct BNS simulation on your laptop!

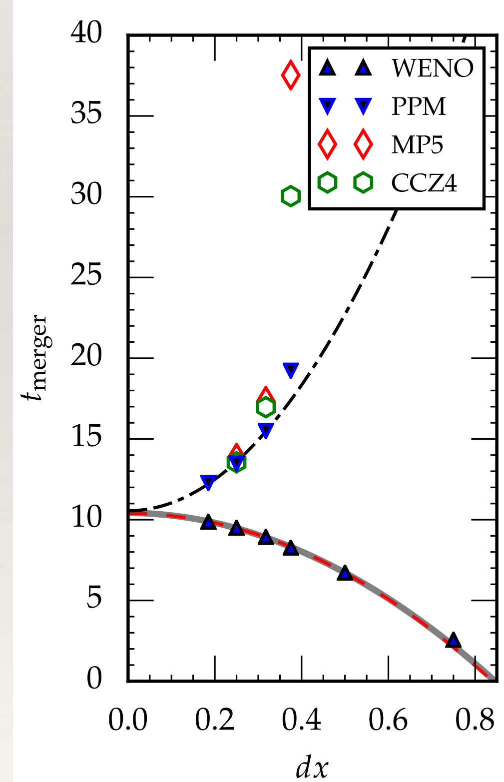
Data Analysis: Convergence

- Merger time measured from at least three different resolution simulations for each model.
- Convergence order and extrapolated "infinite" resolution merger time obtained with a fit to:

$$t_{\mathrm{merger}}(dx) = t^{dx=0}_{\mathrm{merger}} + A \cdot dx^{\gamma},$$

- Despite all observed differences it is important to make sure that all tested method lead to the same determination of the "true" merger time t_merger(dx=0).

name	$t^{dx=0.50}_{\mathrm{merger}}$ [ms]	$t^{dx=0.375}_{\mathrm{merger}}$ [ms]	$t^{dx=0.25}_{\mathrm{merger}}$ [ms]	$t^{dx=0\ (ext)}_{\mathrm{merger}}$ [ms]	$t^{\mathrm{EOB}}_{\mathrm{merger}}$ [ms]
SLy12vs12	9.22	11.76	13.61	15.07±0.03	21.55
SLy13vs13	8.21	10.02	11.25	12.28±0.04	17.25
SLy14vs14	6.72	8.27	9.50	10.39±0.08	14.08
SLy15vs15	5.93	6.99	7.71	8.31±0.02	11.64
SLy16vs16	5.00	6.13	6.81	7.44±0.08	9.78
SLy135vs145	6.66	8.19	9.45	10.34±0.10	14.09
SLy13vs15	6.52	7.91	9.31	10.14±0.25	14.12
SLy125vs155	6.19	7.60	9.09	9.93±0.29	14.21
SLy12vs16	5.52	7.26	8.73	9.75±0.13	14.33
G275th14vs14	4.22	4.81	5.52	5.88±0.17	13.63
G300th14vs14	7.63	9.69	10.55	11.67±0.37	14.78



	dx (CU)	t_{merger} (ms)
WENO	0.75	2.56
WENO	0.50	6.72
WENO	0.375	8.27
WENO	0.3125	8.93
WENO	0.25	9.50
WENO	0.185	9.87
PPM	0.375	19.23
PPM	0.3125	15.50
PPM	0.25	13.49
PPM	0.185	12.28
MP5	0.375	37.53
MP5	0.3125	17.34
MP5	0.25	13.81
CCZ4	0.375	30.03
CCZ4	0.3125	16.97
CCZ4	0.25	13.56

The GRHydro ET Thorn

- Base: GRHD public version of Whisky code (EU 5th Framework)
- Much development plus new MHD
- Caltech, LSU, AEI, GATECH, Perimeter, RIT (NSF CIGR Award)
- Full 3D and dynamic general relativity
- Valencia formalism of GRMHD:
-     Relativistic magnetized fluids in
-     ideal MHD limit
- Published text results, convergence
- arXiv: 1304.5544 (Moesta et al, 2013)
- All code, input files etc part of
-     Einstein Toolkit
- User support

GRHydro:
A new open source general-relativistic magnetohydrodynamics code for the Einstein Toolkit

Philipp Mösta[1], Bruno C. Mundim[2,3], Joshua A. Faber[3], Roland Haas[1,4], Scott C. Noble[3], Tanja Bode[6,4], Frank Löffler[5], Christian D. Ott[1,5], Christian Reisswig[1], Erik Schnetter[6,7,5]

Back to physics

Simulation of NS merger as a key to get insight on the EOS

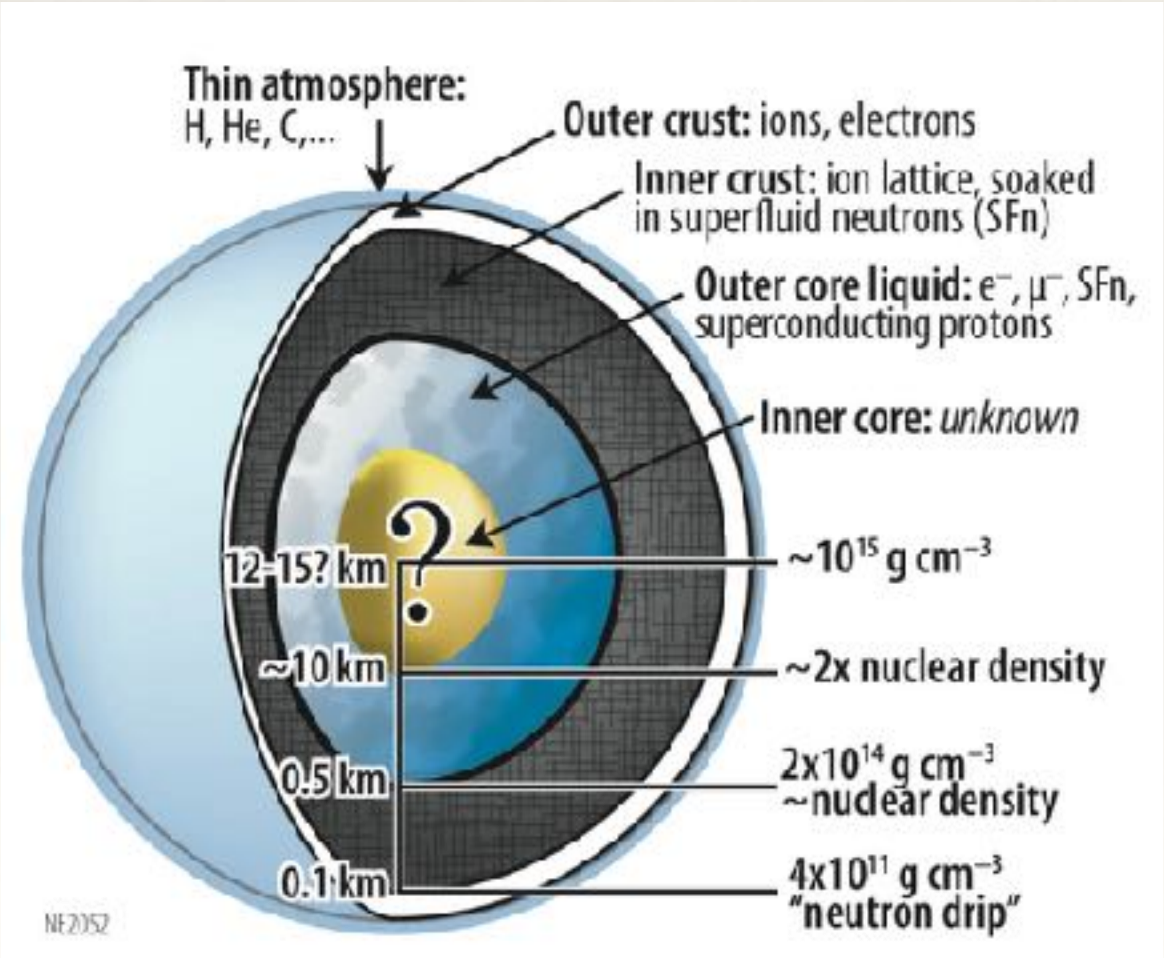
Neutron Stars

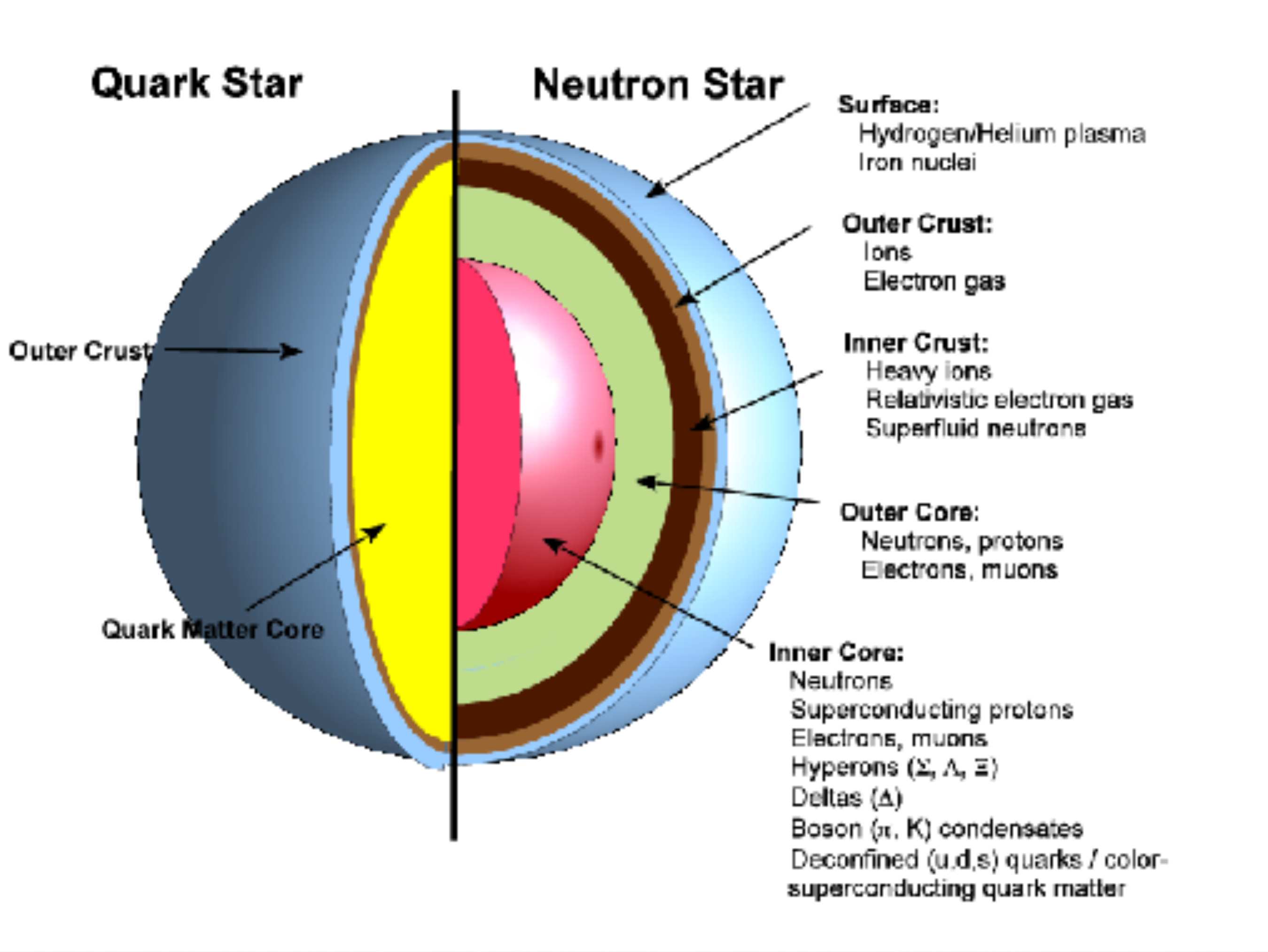
- Neutron Stars are a degenerate state of matter that is formed after the core collapse in a supernova event (where the electrons fall into nuclear matter and get captured by protons forming neutrons).
- Excellent laboratory to study high-density nuclear physics and EOS.
- Neutron star composition still unknown (neutron, resonance, hyperons,…)
- The extreme condition inside a NS cannot be reproduced in a laboratory.
- Typical properties of NS:

$$R \simeq 10Km$$
$$M \simeq 1.4M_{\odot}$$
$$T \in [1.4ms, 8.5s]$$
$$B \in [10^8, 10^{14}]Gauss$$

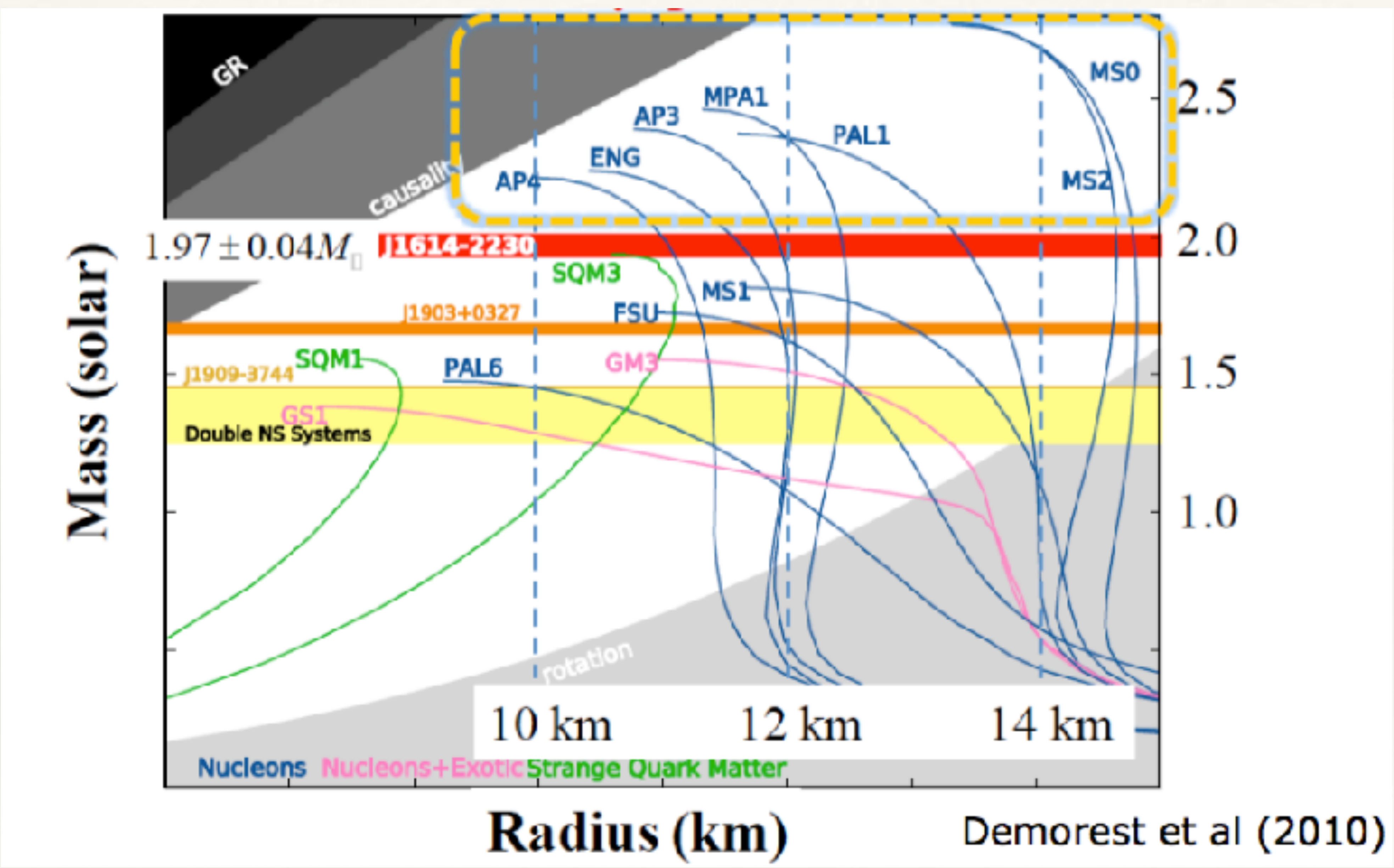
BNS as a probe for Nuclear Matter EOS

- Gravitational wave detection by BNS system will give us information on the EOS that cover matter at extreme conditions.
- Different possibilities:





Many different possibilities depending on the EOS



Many different possibilities depending on the EOS. **GWs** in the late inspiral and merger phases could constrain NS EOS. **Many GW templates from Numerical Relativity are necessary**

Initial Models

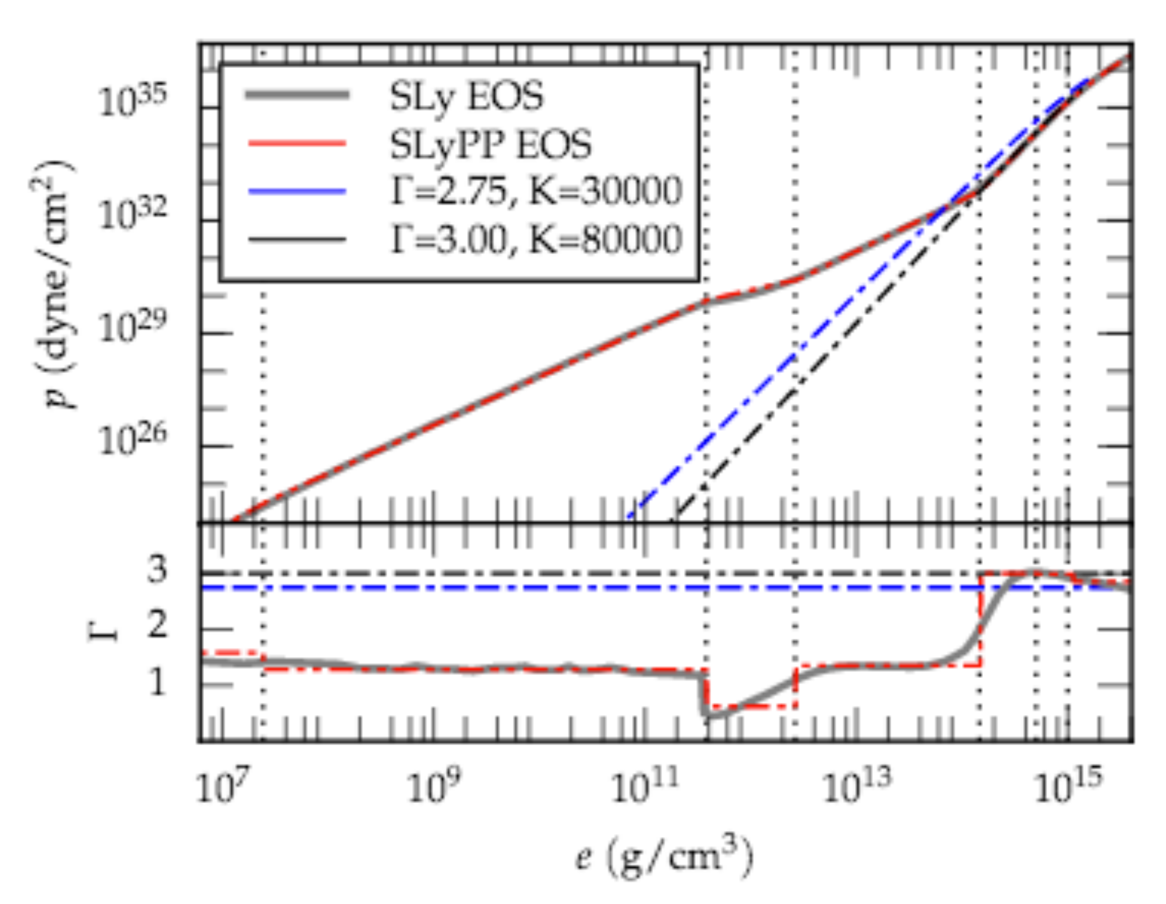
EOS used in our simulations

- Piecewise polytropic representation of SLy EOS + thermal component:
- 7 pieces EOS => realistic treatment of the NS crust and the BH accretion disk eventually produced
- High density region similar to Gamma = 3.00 polytropic.
- Still only approximate treatment of thermal component.

$$P(\rho, \epsilon) = P_{\rm cold}(\rho) + P_{\rm th}(\rho, \epsilon).$$

$$P_{\rm cold} = K_i \rho^{\Gamma_i}$$
$$\epsilon_{\rm cold} = \epsilon_i + \frac{K_i}{\Gamma_i - 1}\rho^{\Gamma_i - 1}$$
$$P_{\rm th} = \Gamma_{\rm th}\rho(\epsilon - \epsilon_{\rm cold}),$$

Read et al. 2009



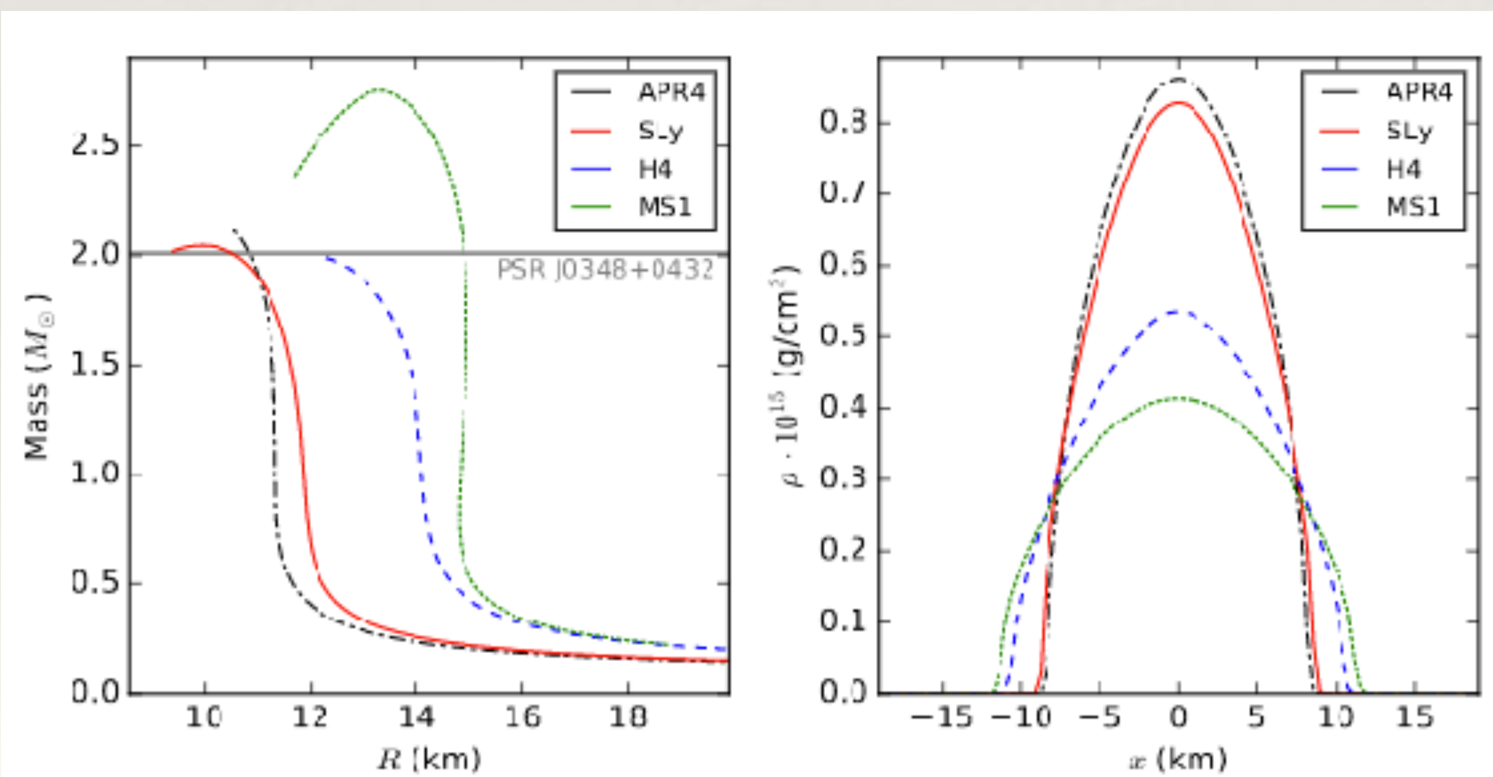
Douchin and Haensel 2000,2001

FIG. 1. Plot of the pressure (P) and of the adiabatic index ($\Gamma = d\log(P)/d\log(\rho)$) as a function of the energy density ($e = \rho(1+\epsilon)$) for the SLy EOS, its piece-wise polytropic approximation (the one used in the present work) and two isentropic polytropic EOS $P = K\rho^{\Gamma}$.

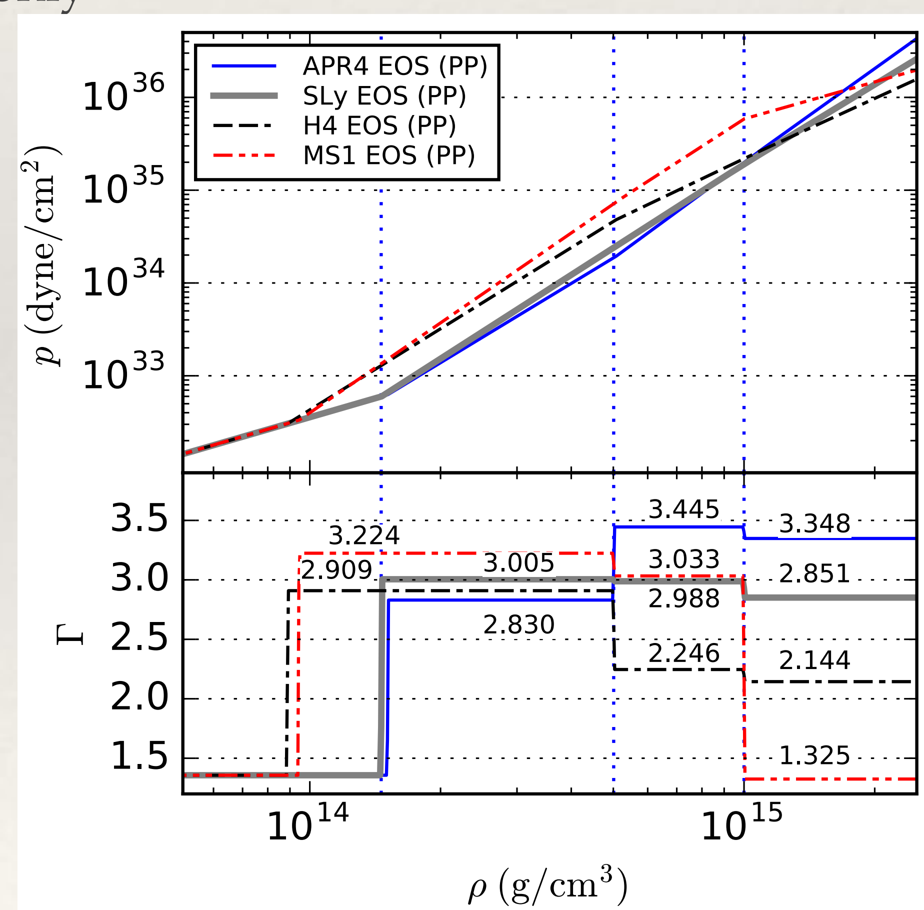
Effect of the EOS (four different EOS)

- APR4 EOS obtained using variational chain summation methods with the Argonne two-nucleon interaction and including also boost corrections and three-nucleon interactions
- The SLy EOS based on the Skyrme Lyon effective nuclear interaction
- The H4 EOS constructed in a relativistic mean field framework including also Hyperons contributions and tuning the parameters to have the stiffest possible EOS compatible with astrophysical data
- The MS1 EOS constructed with relativistic mean field theory considering only standard nuclear matter.

EOS	SMNS ($M_\odot$)	HMNS ($M_\odot$)
SLy	2.04 (2.42)	2.41 (2.82)
H4	2.01 (2.30)	2.37 (2.70)
APR4	2.19 (2.66)	2.60 (3.09)
MS1	2.75 (3.30)	3.29 (3.90)



(a) Mass-Radius relations (b) Initial density profiles



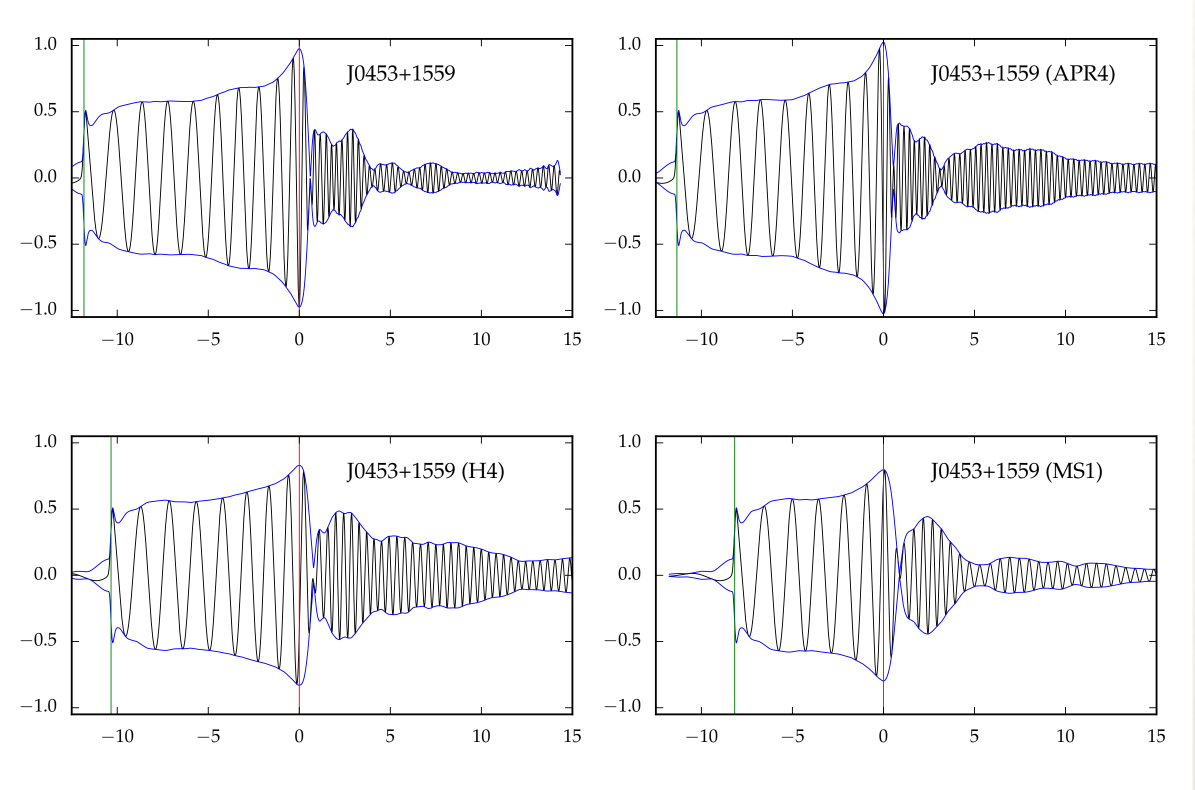
Binary neutron star merger simulations with different initial orbital frequency and equation of state, F. Maione, R. De Pietri, A. Feo and F. Loeffler, Classical and Quantum Gravity, 33, no. 17, 175009 (2016). arXiv:1605.03424

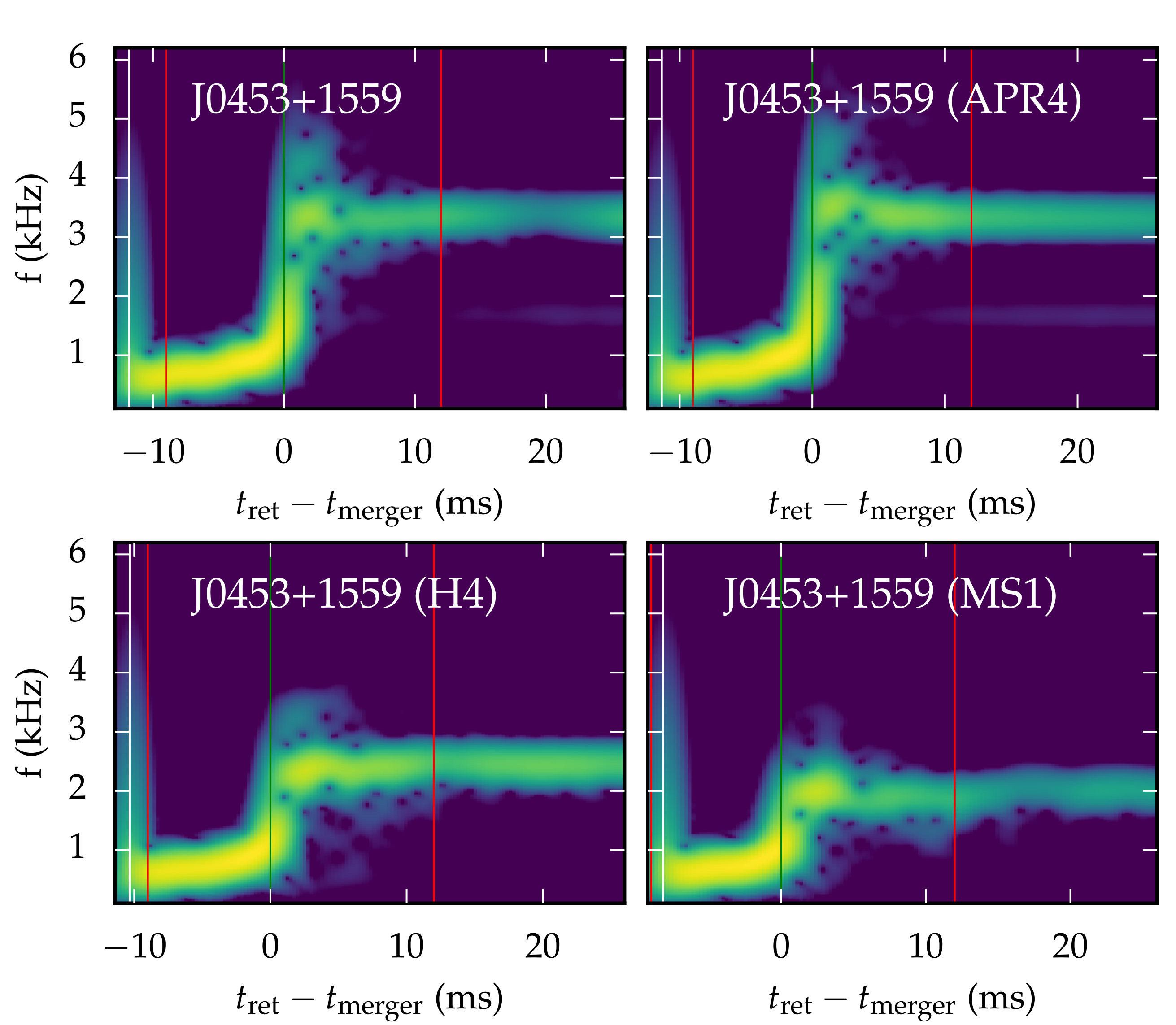
Binary Neutron Stars System

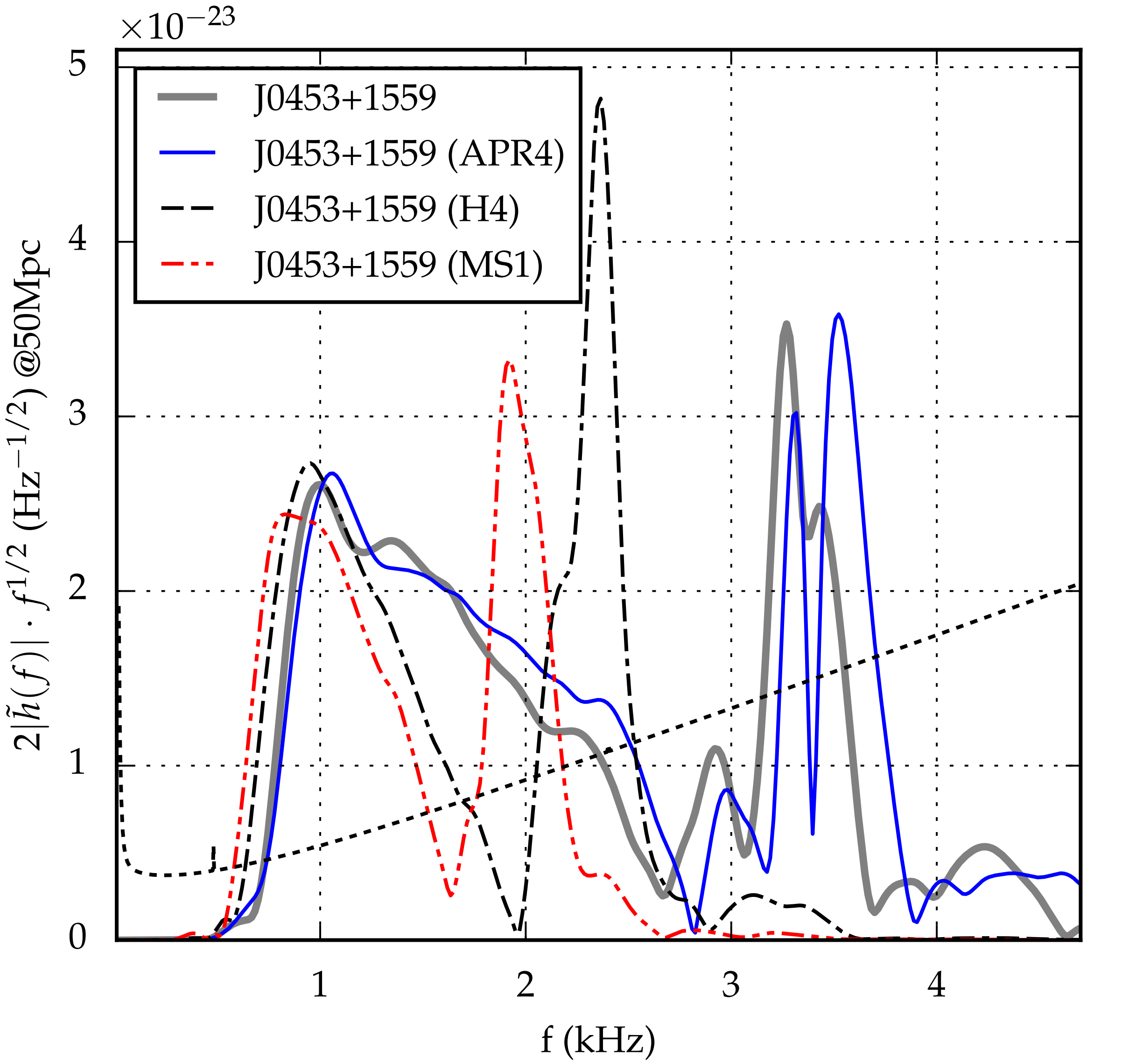
- EOS … initial data for binary neutron star system … waveform … detection … validate the proposed form for the EOS.
- Question: **Is it possible to discriminate between different EOS**. Answer: **Yes, it is**.
- Main problem are:
- It is not easy to generate (consistent) initial data with complete control of the spin, orbital parameter, initial magnetic fields,… Recent progress by Rezzolla,Tichy, Kyutoku groups.
- HOWEVER: exist a PUBLIC CODE that allows to generate ID for non-rotating stars starting from a tabulated EOS at T=0. Need to extend the availability of PUBLIC initial data.

The pulsar J0453+1559 (q=0.75) with four different EOS

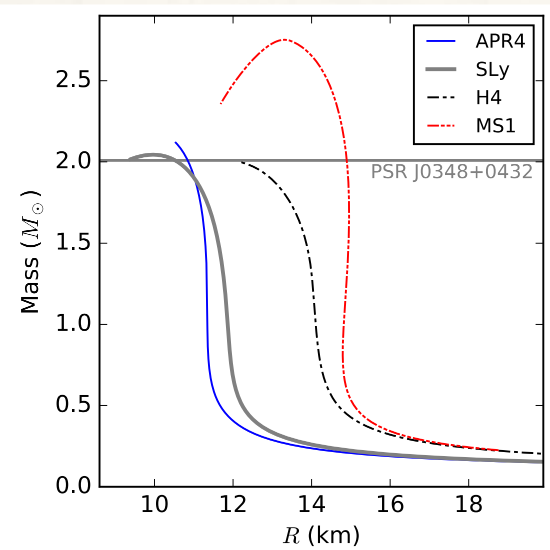
A. Feo, R. De Pietri, F. Maione and F. Loeffler,
Modeling Mergers of known Galactic Binary Neutron Stars,
Classical and Quantum, 34 (3), 034001 (2017)) arXiv 1608.02810(2016)

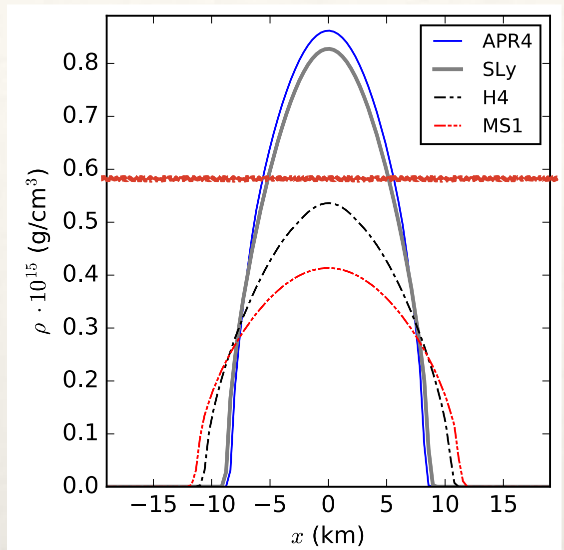


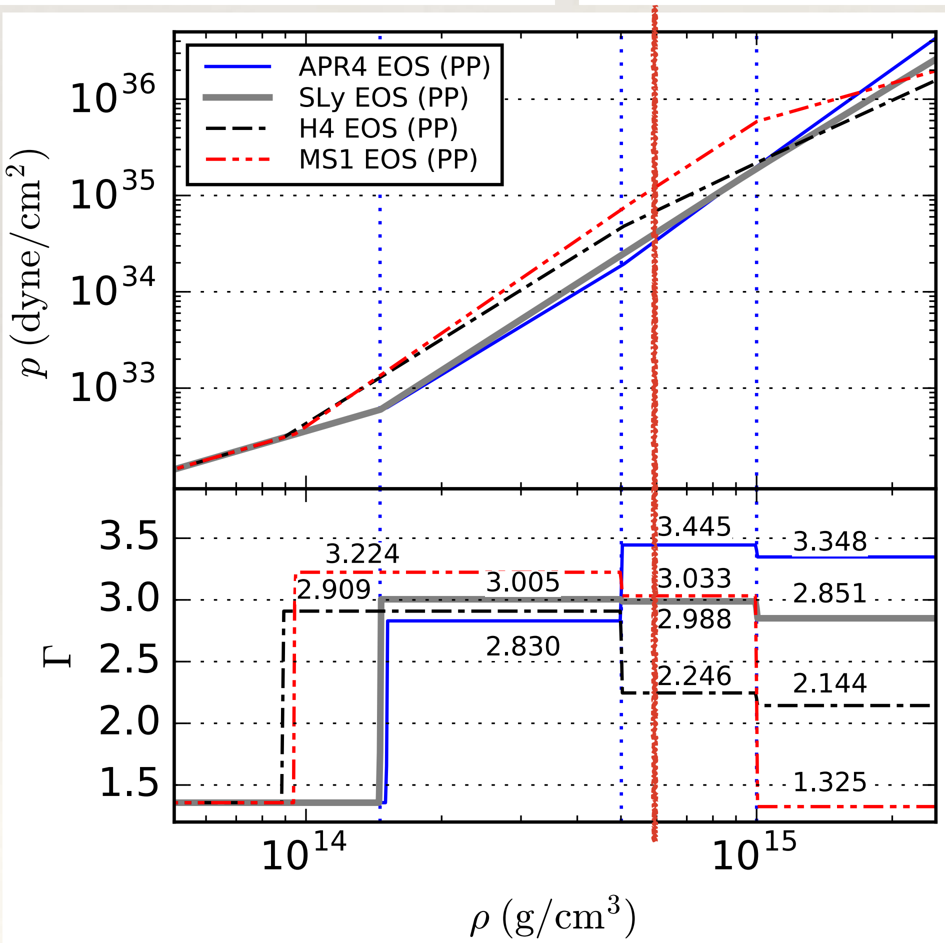


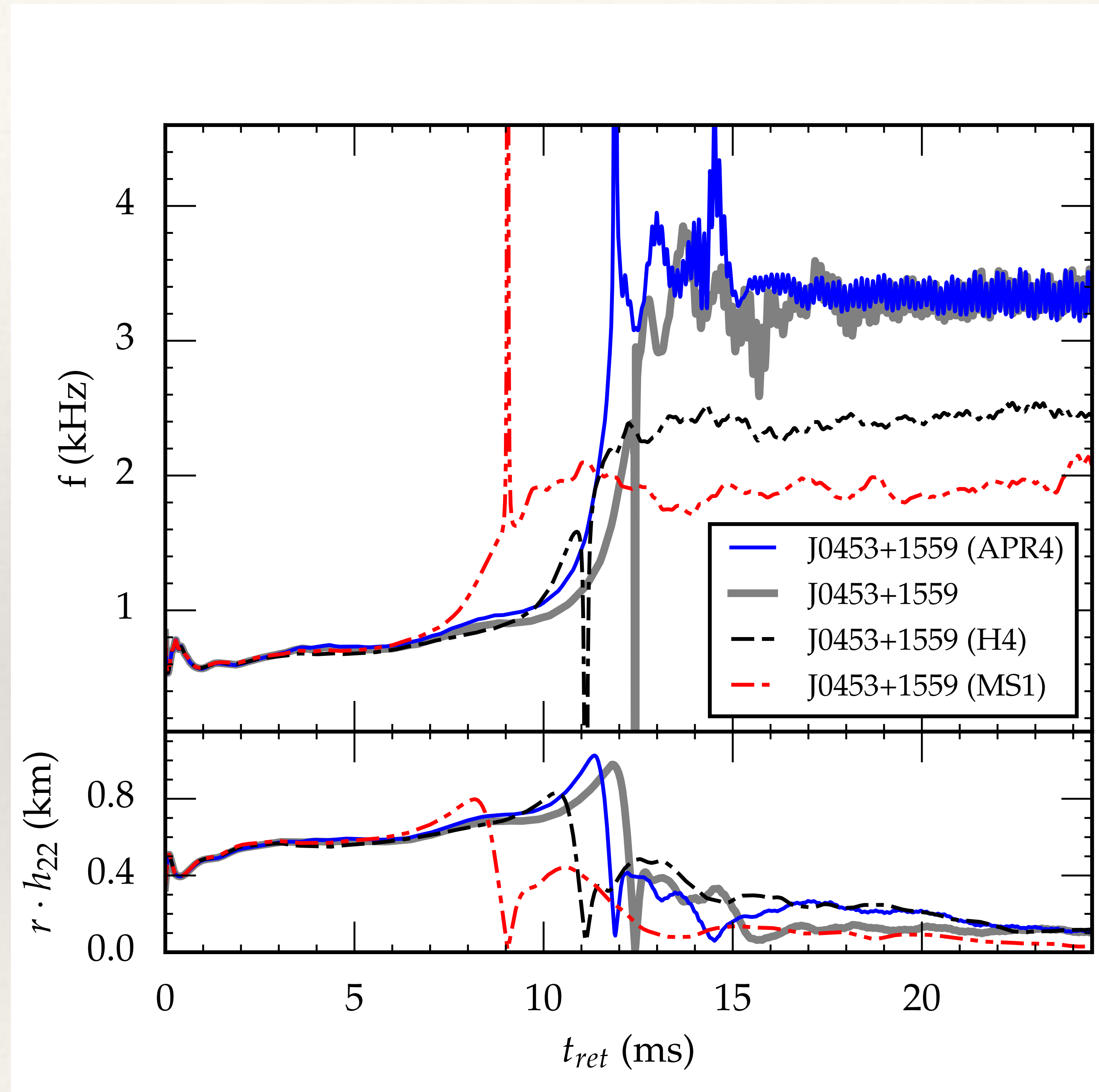


The pulsar J0453+1559 (q=0.75) with four different EOS



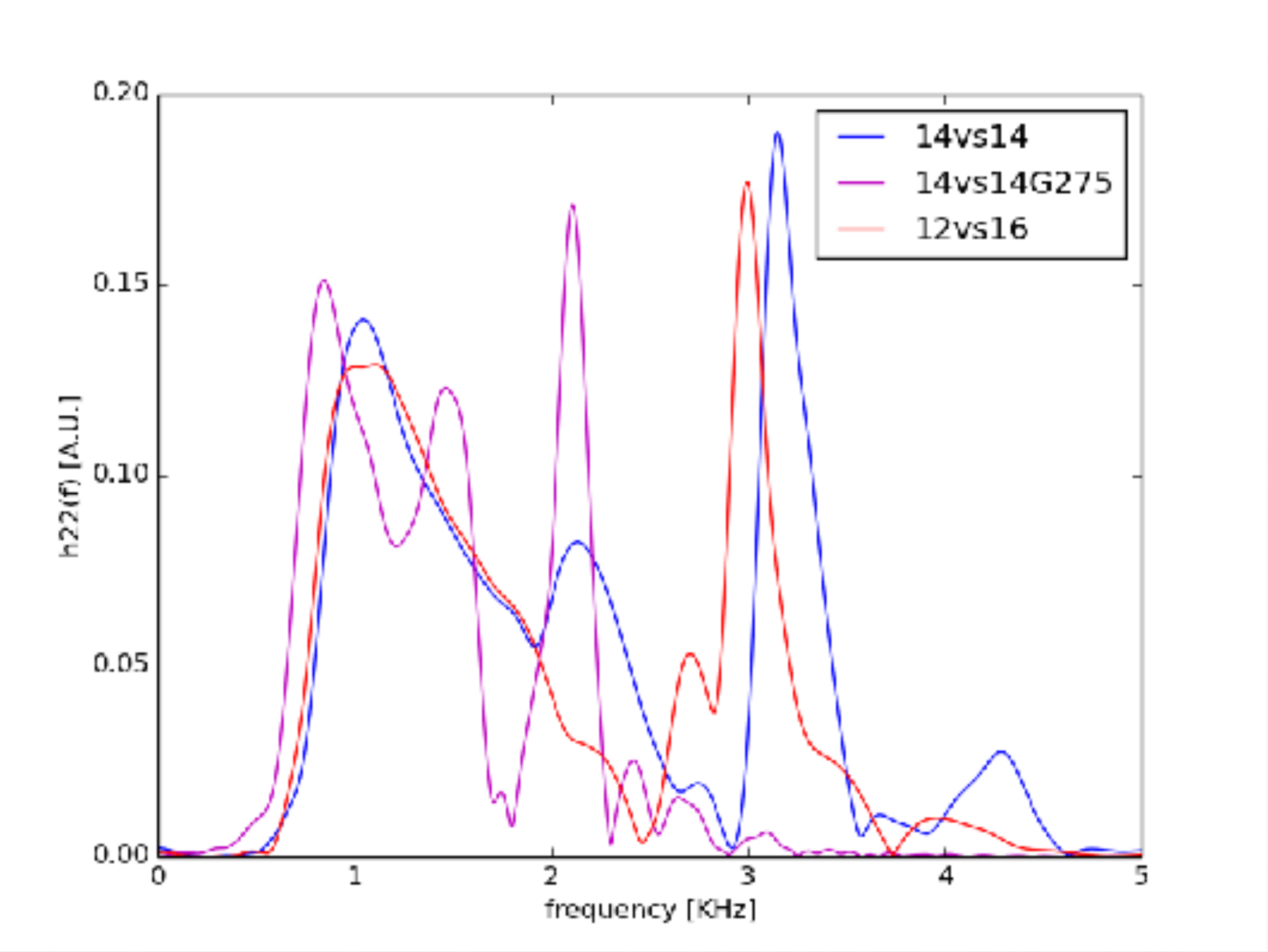






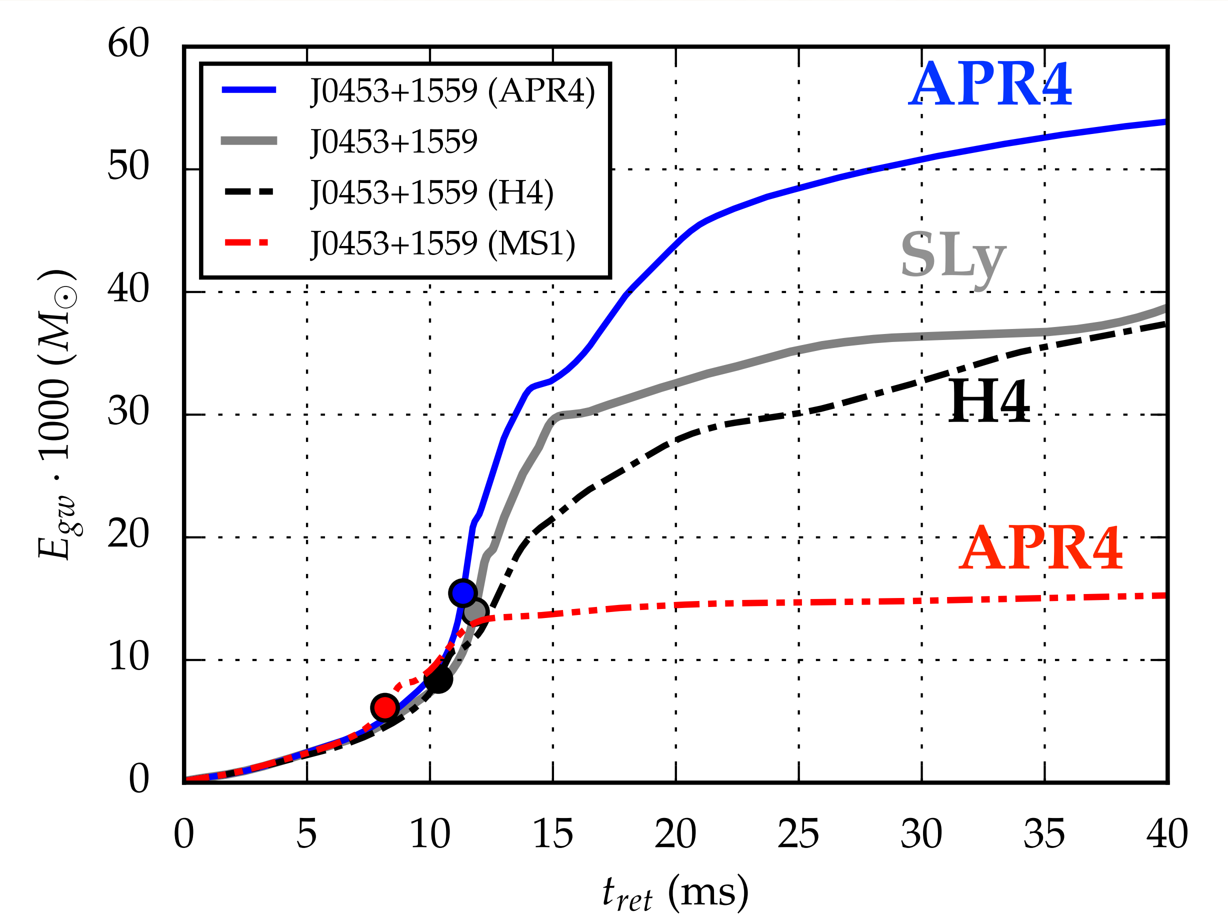
Results: gravitational waves signal properties

- Example of the FFT of the gravitational wave signals and the oscillation of the maximum density for three simulations: an equal mass and an unequal-mass one and the one with a significant softer EOS.
- Only the equal mass one show the two side peaks
- The softer one show a clear effect of its greater deformability.



Different EOS – same stellar model

GW - ENERGY



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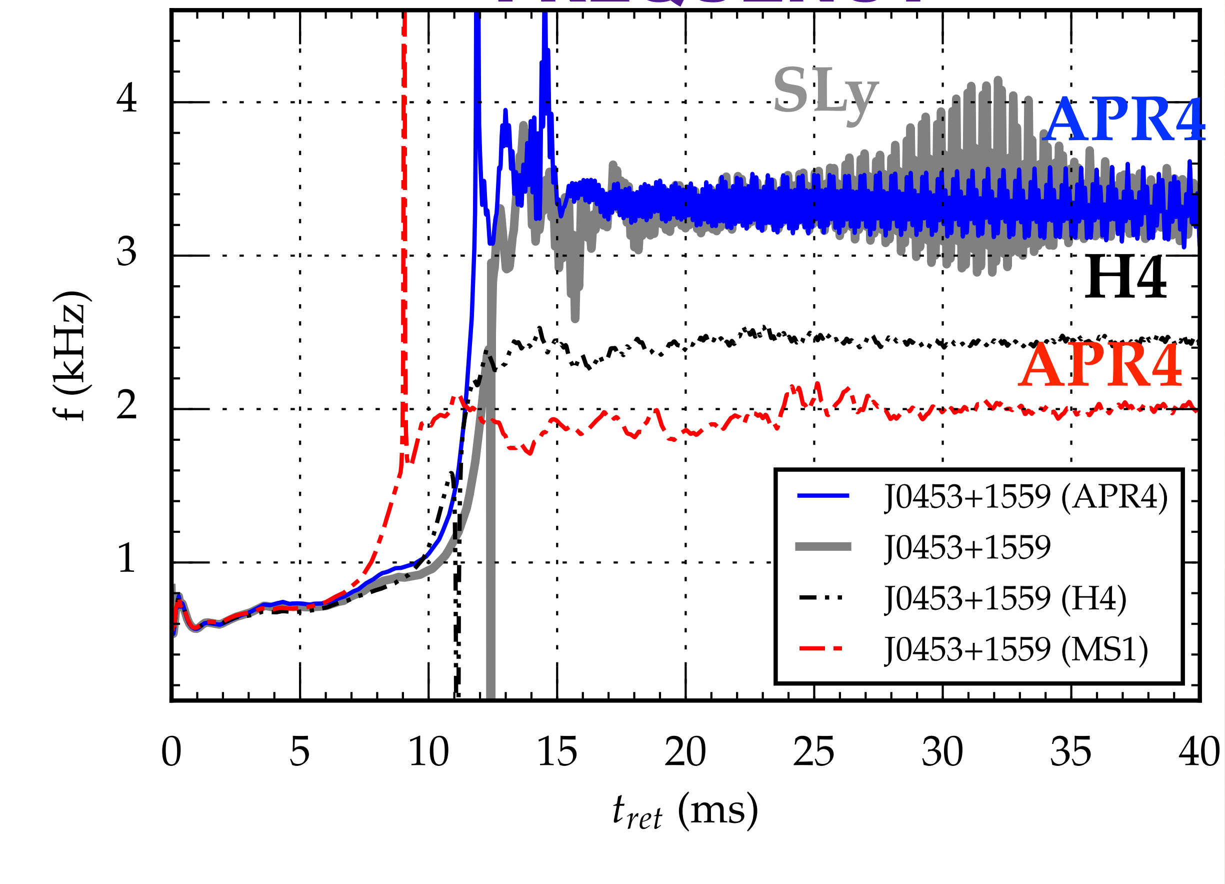
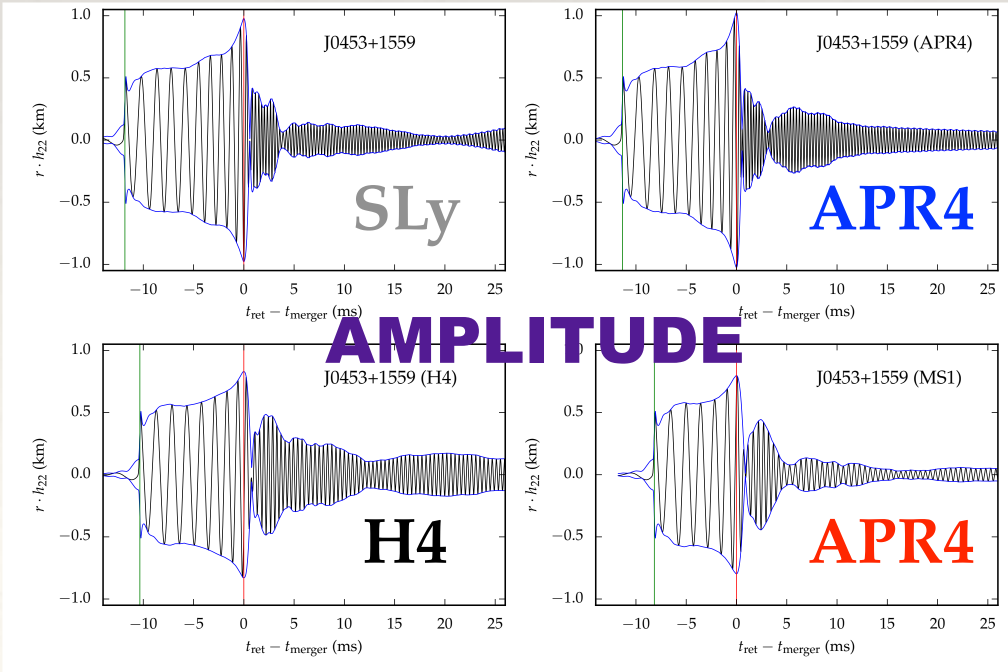
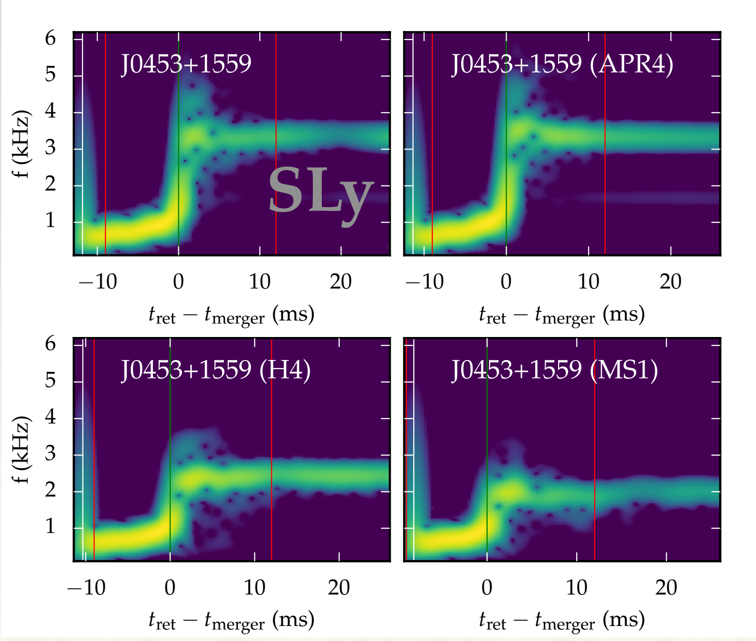


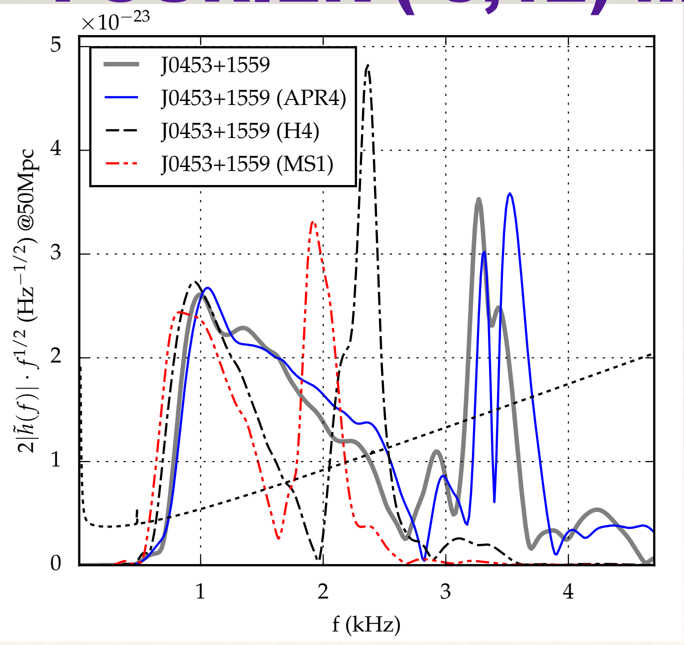
AMPLITUDE



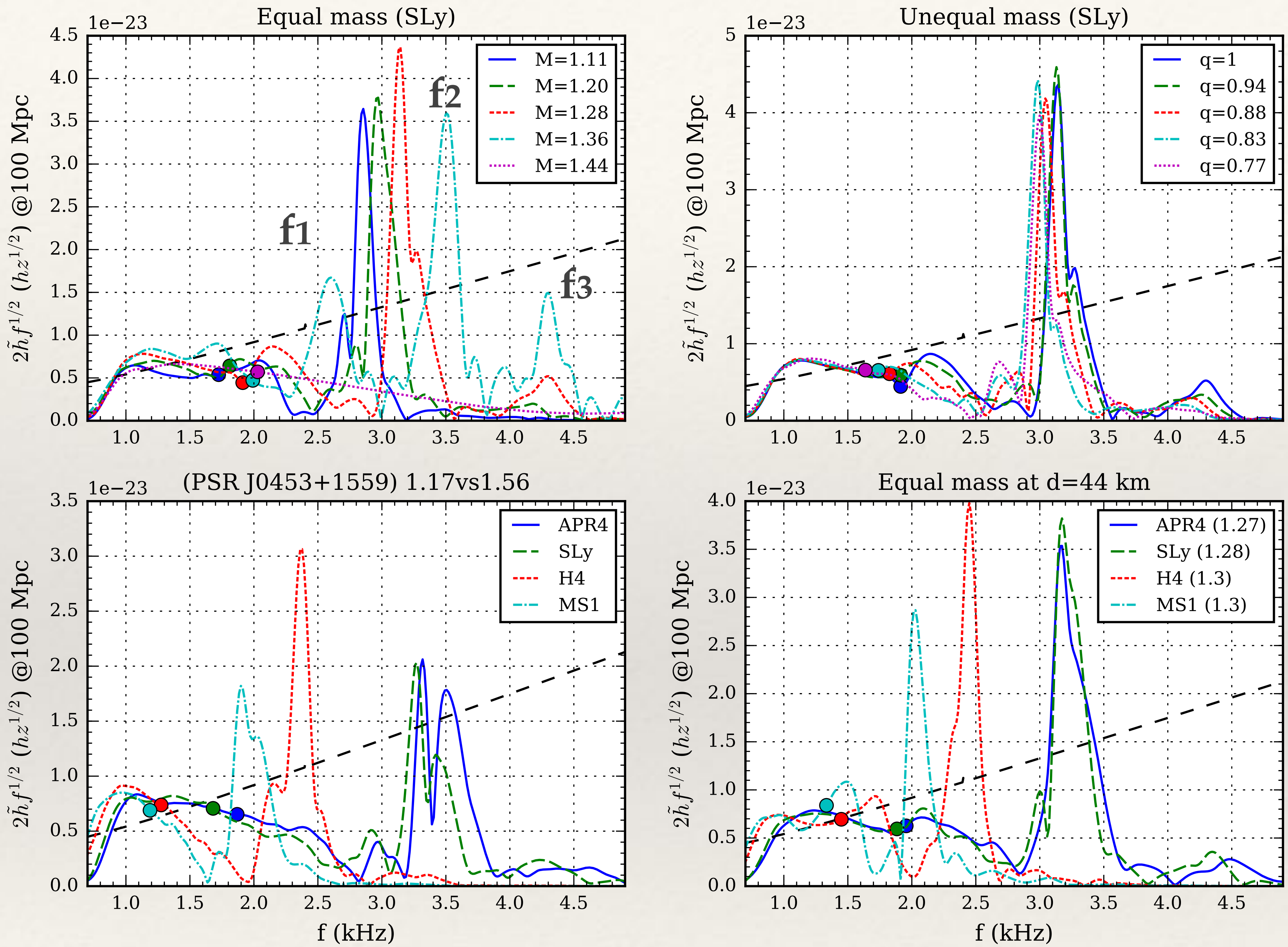
SPECTROGRAM



FOURIER (-5,12) ms



Spectrum of post-merger signal



Model		f_{2i} [kHz]	f_2 [kHz]	f_2^B [13] [kHz]	$\Delta R_{M=1.6}$ [km]	f_2 [39] [kHz]
SLy	1.11vs1.11	2.79	2.85	2.784	0.16	2.83
SLy	1.20vs1.20	3.01	2.96	3.009	0.10	3.03
SLy	1.28vs1.28	3.23	3.14	3.212	0.15	3.20
SLy	1.36vs1.36	3.48	3.51	3.410	0.19	3.38
SLy	1.24vs1.32	3.18	3.13	3.210	0.17	3.20
SLy	1.20vs1.36	3.07	3.05	3.210	0.35	3.20
SLy	1.16vs1.40	2.97	2.98	3.210	0.49	3.20
SLy	1.11vs1.44	2.97	3.00	3.197	0.43	3.20
APR4	1.17vs1.56	3.49	3.32	3.574	0.50	3.67
SLy	1.17vs1.56	3.31	3.27	3.427	0.31	3.41
H4	1.17vs1.56	2.27	2.37	2.503	0.44	2.25
MS1	1.17vs1.56	1.91	1.90	2.179	2.30	1.88
APR4	1.27vs1.27	3.31	3.17	3.336	0.35	3.47
SLy	1.28vs1.28	3.22	3.17	3.212	0.08	3.20
H4	1.30vs1.30	2.35	2.45	2.382	0.21	2.12
MS1	1.30vs1.30	2.03	2.02	2.081	0.29	1.80

[13] A. Bauswein, N. Stergioulas, and H.-T. Janka, Eur. Phys. J. A52, 56 (2016), arXiv:1508.05493

[39] L. Lehner, S. L. Liebling, C. Palenzuela, O. L. Caballero, E. O'Connor, M. Anderson, and D. Neilsen, Class. Quant. Grav. 33, 184002 (2016), arXiv:1603.00501

Classification of post merger peaks

- Broadly, there are to competing hypothesis for the classification of main three picks just after merger (universality relation have been proposed):
  - 1. Takami et al. that amount to say that there is a universal coupling between the main mode and the bouncing of the central mode. They construct also universal relations.
  - 2. Bauswein and Stergioulas (Unified picture) that say more effect are to be considered.
    - TYPE 1 when the evolution of central lapse function is dominated by quasi radial oscillations and indeed a strongly correlated double peak structure for the secondary peaks
    - TYPE 2 the two effect are present… TYPE 1 and TYPE 3
    - TYPE 3 when the two antipodal bulges that are rotating more slowly compared to the double cores.
- The possibility for more complex behavior should be considered.

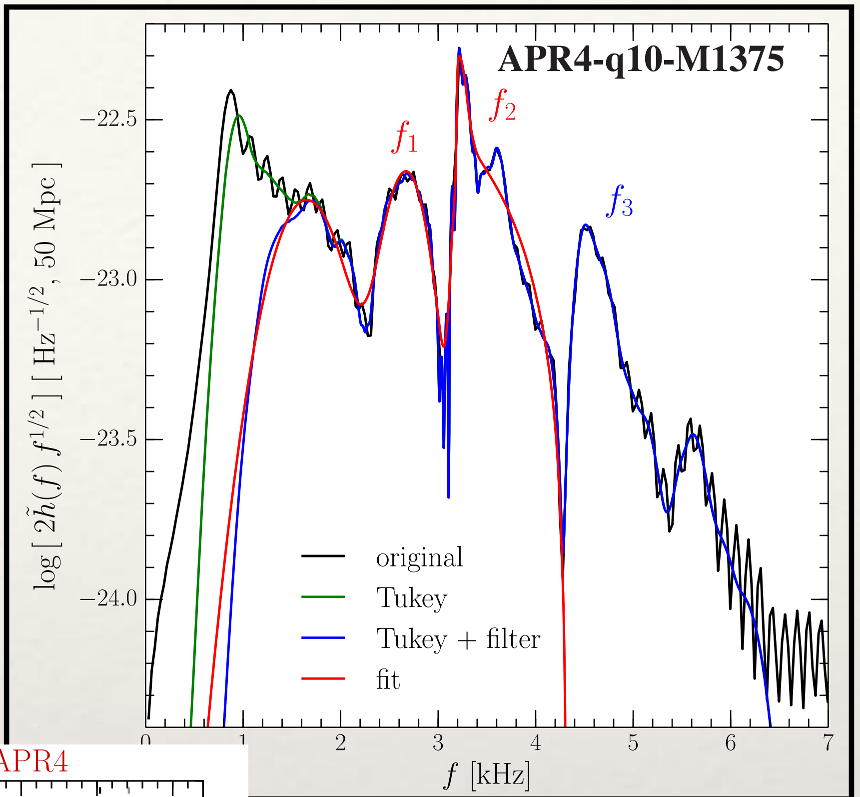
Binary Neutron Stars System

- EOS … initial data for binary neutron star system … waveform … detection … validate the proposed form for the EOS.
- Question: **Is it possible to discriminate between different EOS**. Answer: **Yes, it is**.
- Main problem are:
- It is not easy to generate (consistent) initial data with complete control of the spin, orbital parameter, initial magnetic fields,… Recent progress by Rezzolla,Tichy, Kyutoku groups.
- HOWEVER: exist a PUBLIC CODE that allows to generate ID for non-rotating stars starting from a tabulated EOS at T=0. Need to extend the availability of PUBLIC initial data.
- Magnetic fields simulation shows presence of instabilities and turbulence.

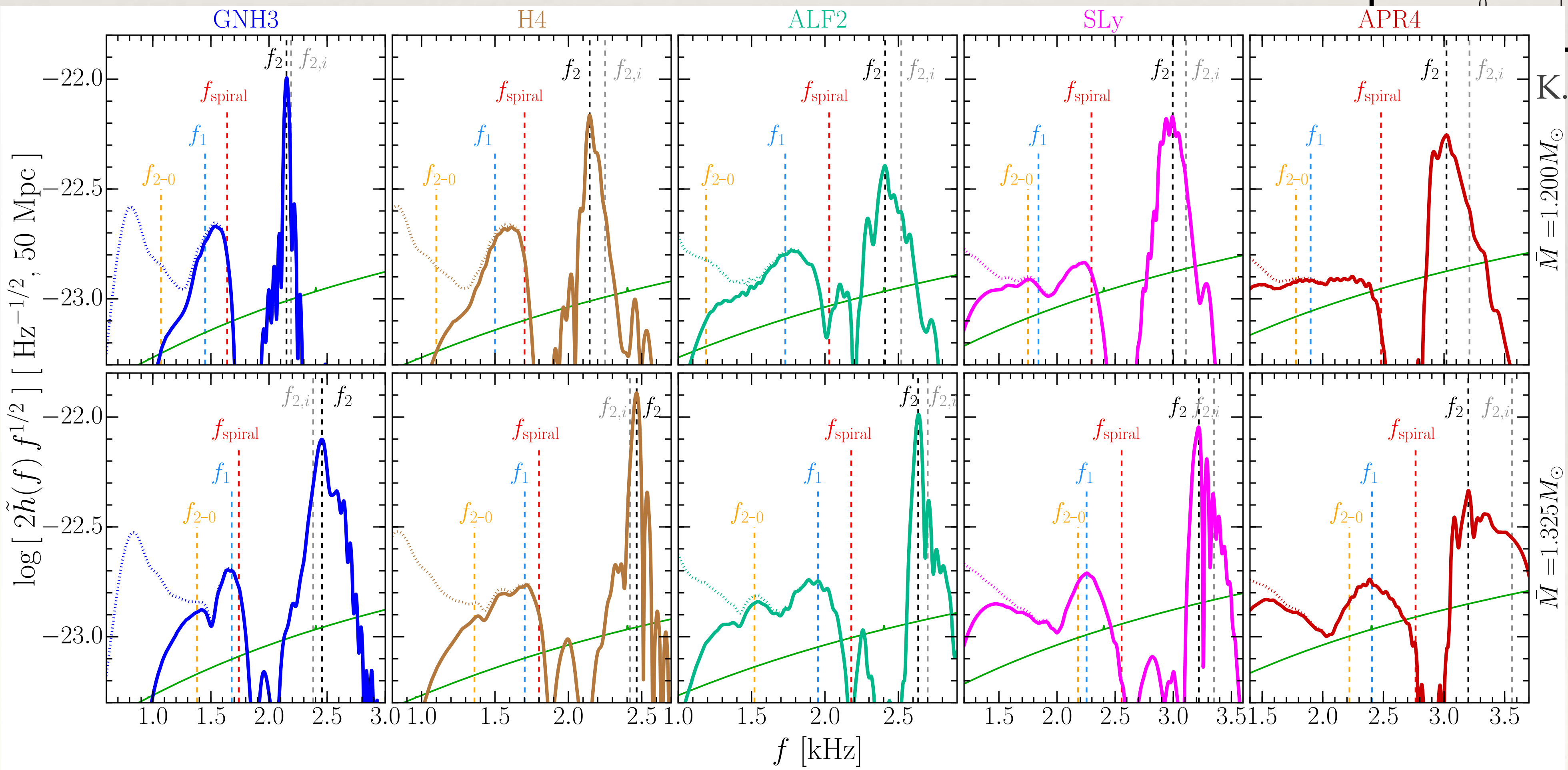
Post Merger Spectrum

- The main characteristics of the post-merger spectrum are captured by three main peaks f1, f2, f3 (closely physical related) plus an additional f20 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].



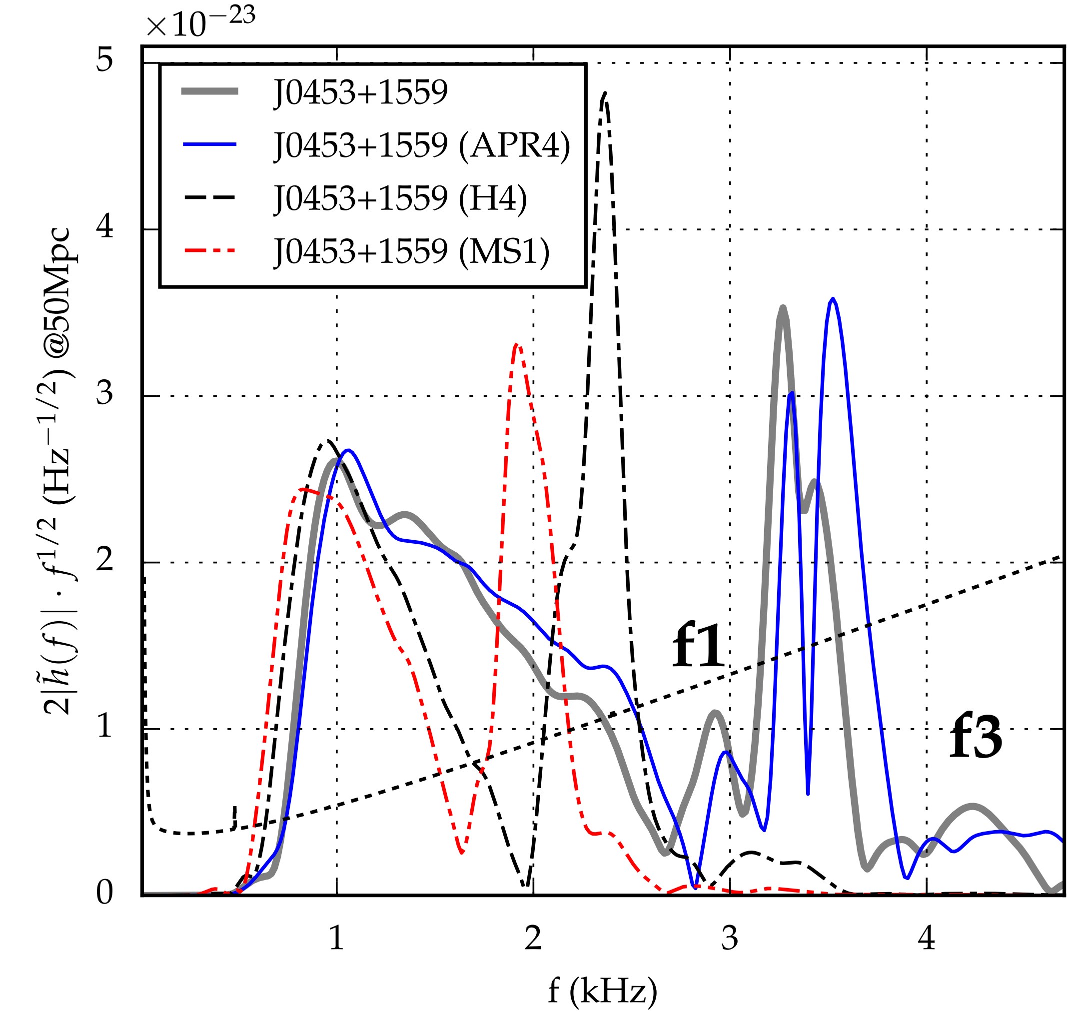
K. Takami, L. Rezzolla, and L. Baiotti, **Phys. Rev. D91**, 064001 (2015)

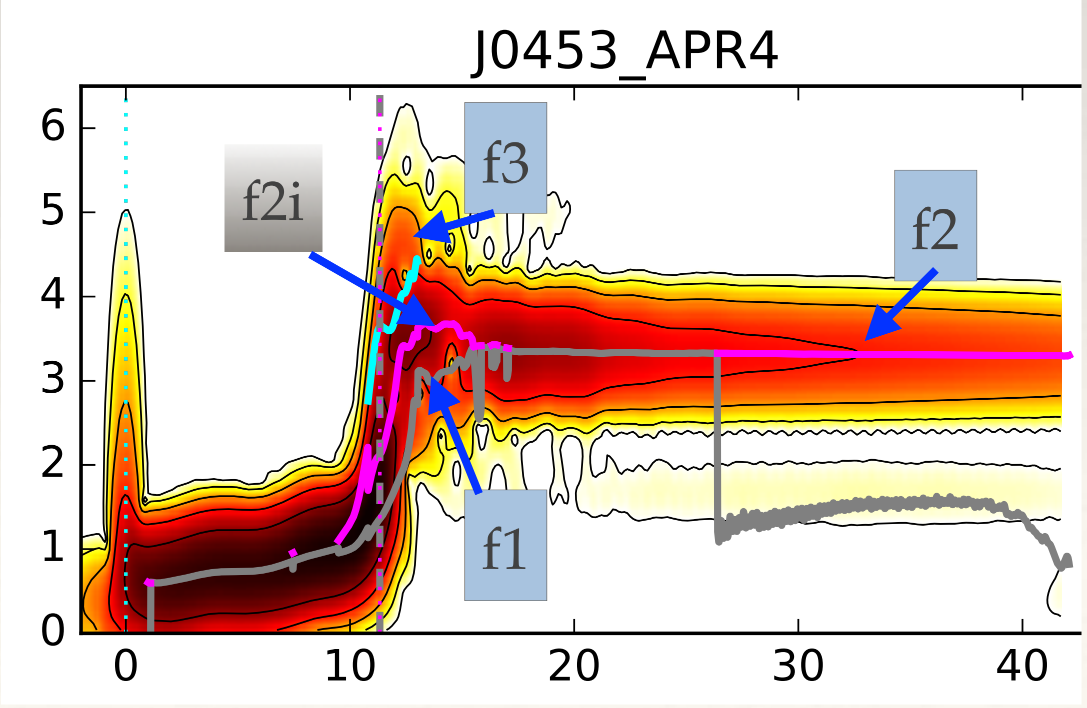


L. Rezzolla and K. Takami, **Phys. Rev. D93,** 124051 (2016)

Post Merger Spectrum

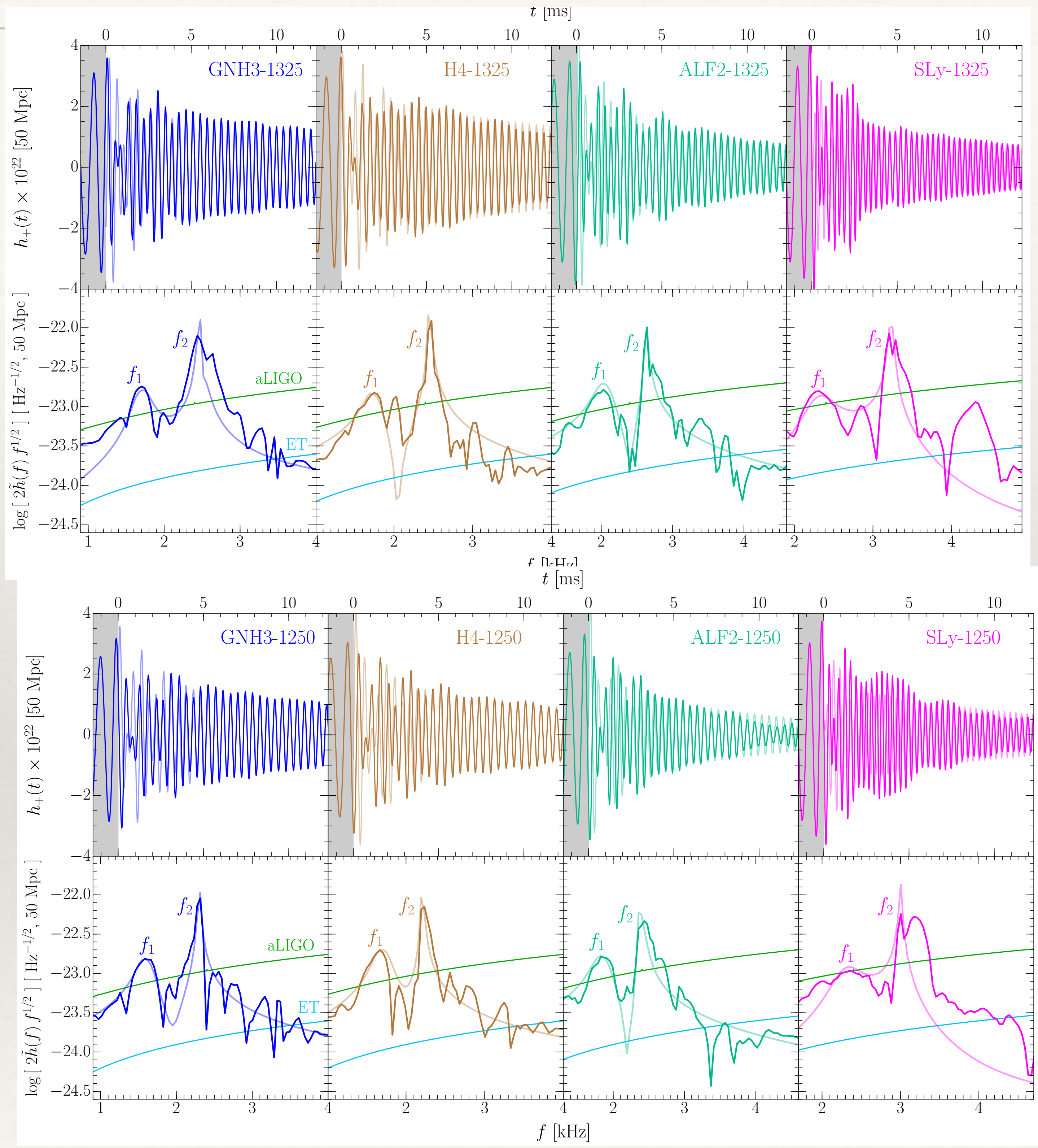
- Analyzing the signal using Fourier spectrograms and Prony spectrograms one see that:
  - A change in the dominant peak frequency between the initial transient phase and the following quasi- stationary phase. It is apparent that this transient is not a sudden jump, but rather a continuous process, in 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.





Neutron-star Radius from a Population of BNS Mergers

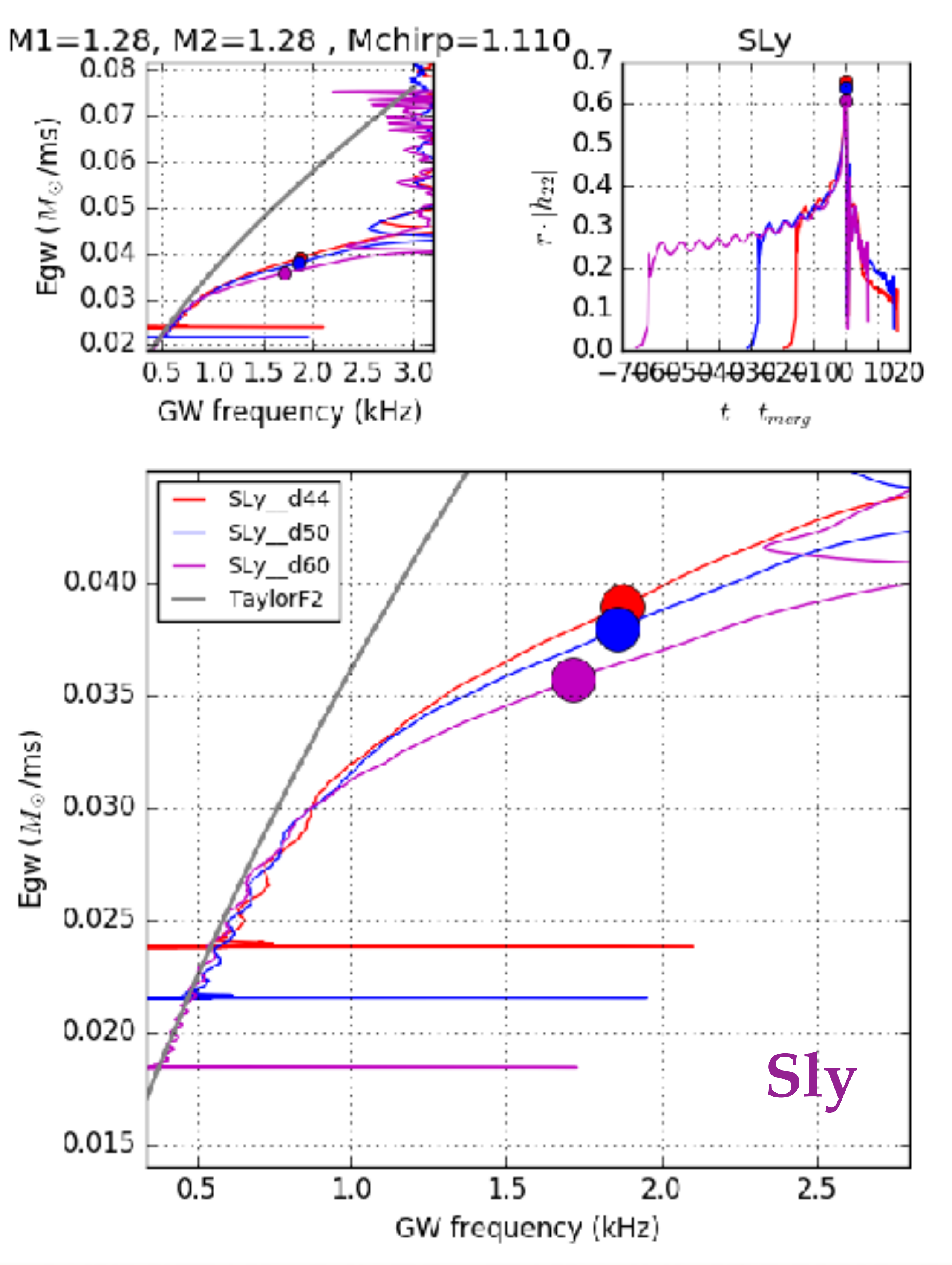
- From the talk Jutta Kunz we learned that a number of Universal relation have been proposed to link properties of Stars.
- Universal relation have also been derived for the peak-frequency of the post merger signal.
- From that follows the idea of using detected gravitation wave signal to get measure 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**

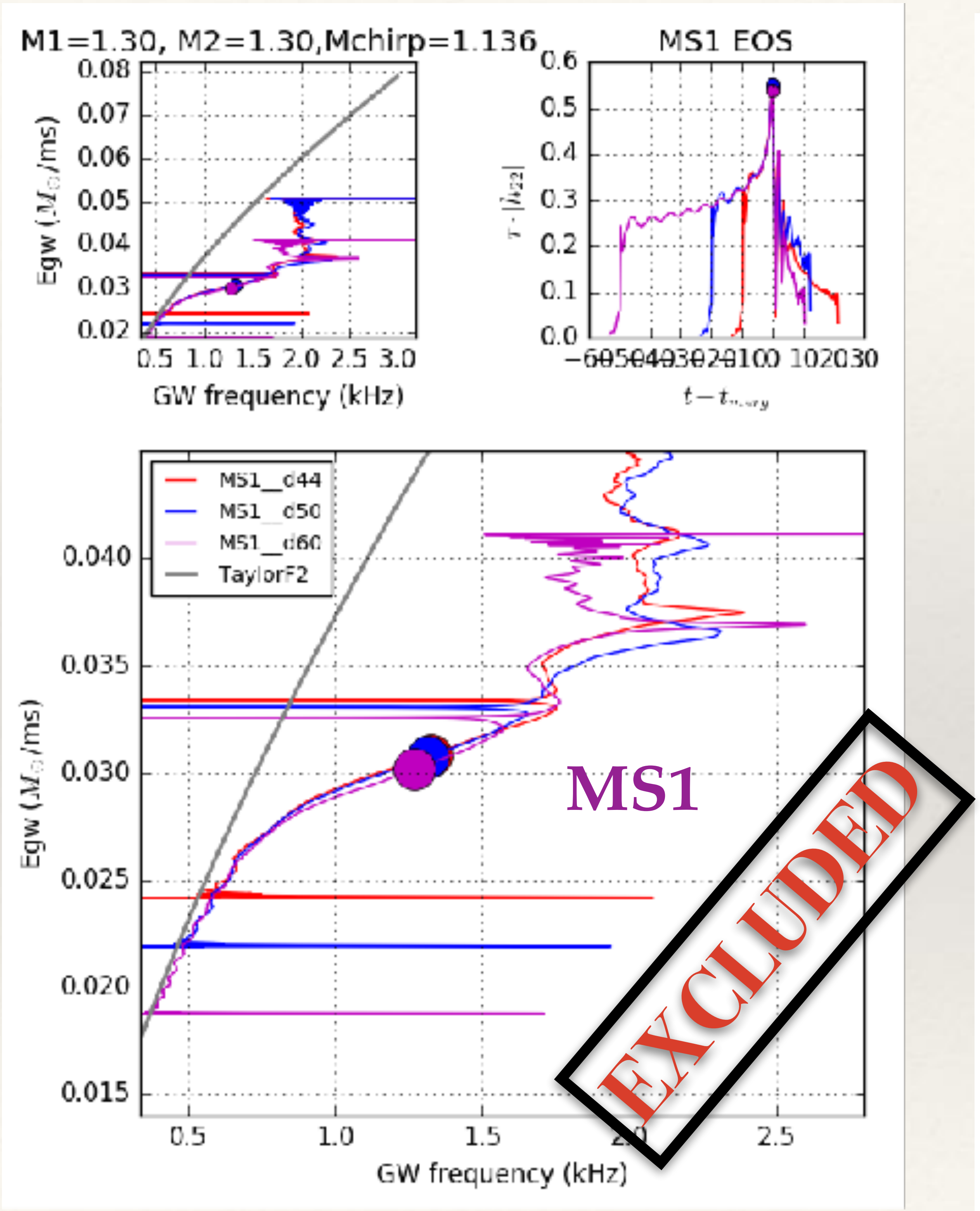
Tidal effect – Sly EOS

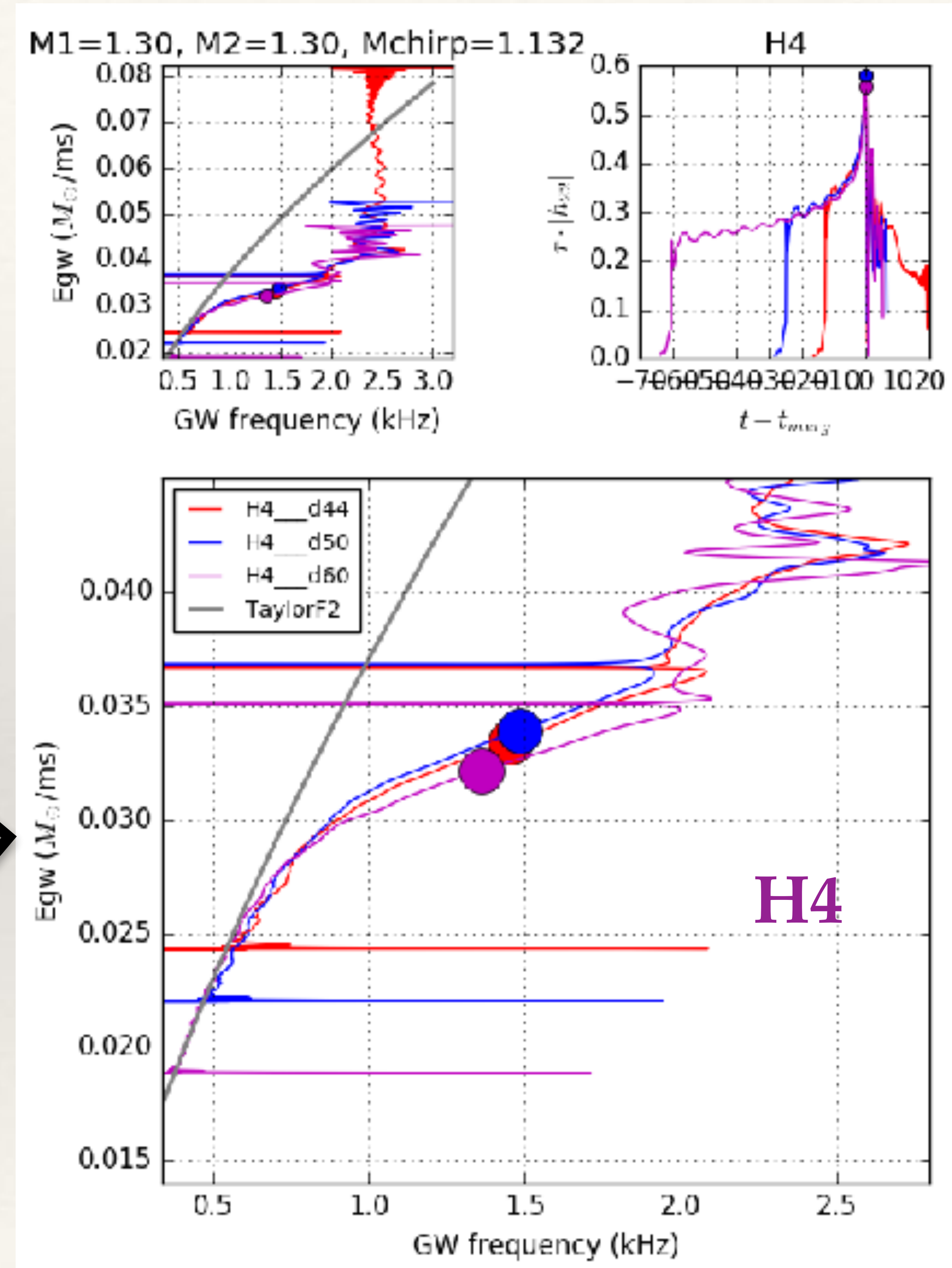
- Three simulation of the same system with the ID generated at different separation: 44,50 and 60 km.
- Different initial separation correspond to
- Different initial frequency of the GW signal.
- Dark-grey line correspond to PN prediction no-tidal effect.
- Tidal effect are visible to LIGO/Virgo and the detector were able to set limits on possible EOS for Neutron Star Matter.



F. Maione, R. De Pietri, A. Feo and F. Loeffler, **arXiv:1605.03424. Classical and Quantum Gravity, 33, 175009 (2016).** *Binary neutron star merger simulations with different initial orbital frequency and equation of state*

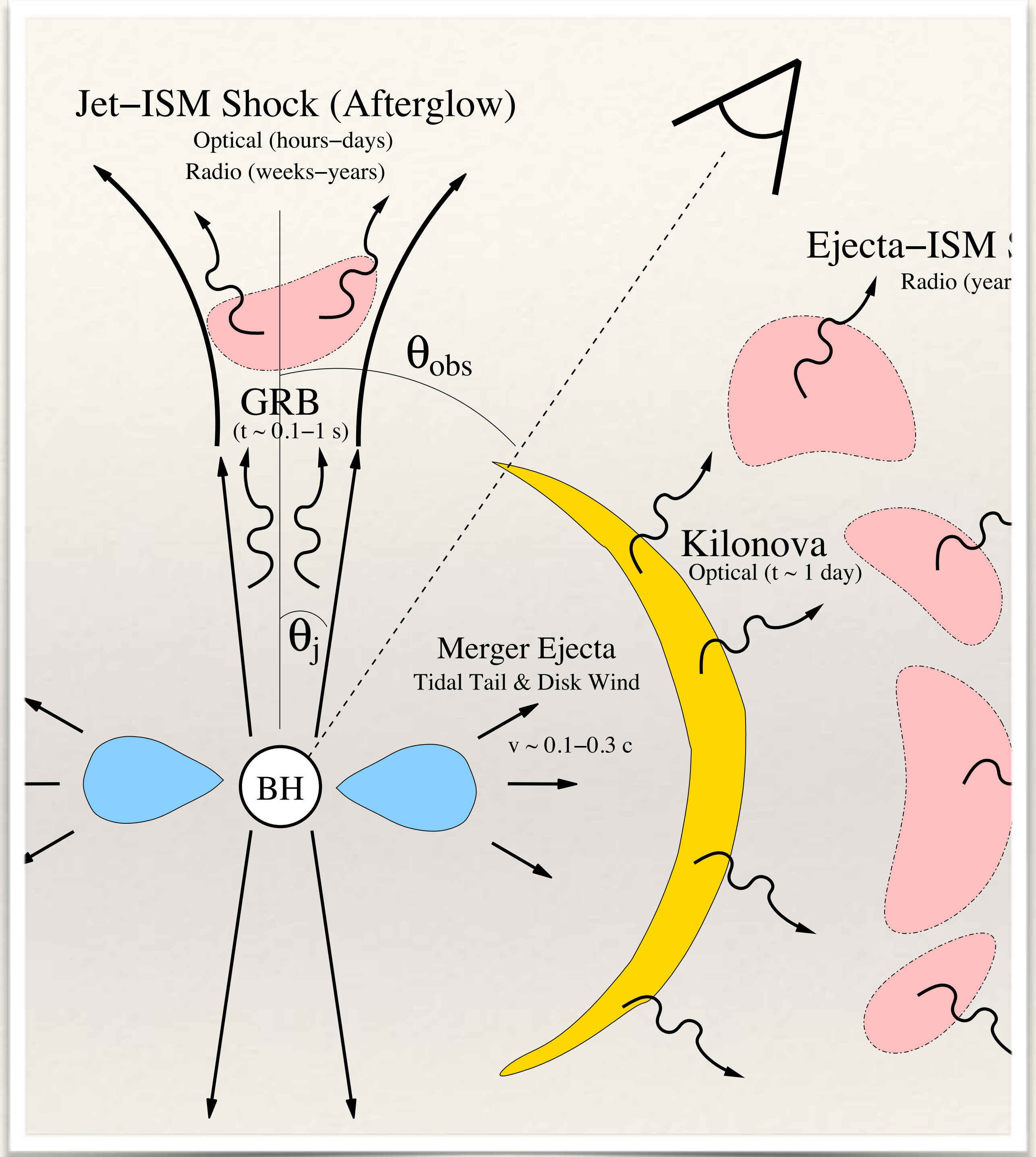
Tidal effect – others EOS





Electromagnetic counterpart.

- The GW detection it is expected to be based on its inspiral part.
- If we see the signal of the merger of two compact object of around 1.4 solar mass how can we state that it is a BNS merger ?
- We need some future from the post merger signal (difficult to see) or a simultaneous detection of an EM counterpart!
- That would be that of a new era of Multi-Messenger Astronomy!



B. D. Metzger and E. Berger, *WHAT IS THE MOST PROMISING ELECTROMAGNETIC COUNTERPART OF A NEUTRON STAR BINARY MERGER?* **The Astrophysical Journal, 746:48, 2012 ,**

Conclusions

- With the first detection of GWs the era of Gravitational waves astronomy just started.
- Long term simulation of BNS mergers using only public codes: **You can re-run all the models on your own**.
- It is possible to check the code on a laptop … (Using our setting).
- All the simulation presented here were performed on Tier-1 system.
- More insight improving the resolution of the simulation.
- Confirmation of previous results published in literature.
- New results for un-equal mass BNS systems, and the evolution of six galactic systems with different EOS.
- Pointing out that it is import to analyze the time-evolution of spectrum (spectrogram - Prony analysis) to understand feature of the signal.
- Just a starting point for new research ….

What's next ?

- Investigate dependence of collapse time on resolution and EoS.
- Matter expelled not-axisymmetrically during merger => study accretion disk formation, mass, composition and development to an equilibrium configuration.
- Can (magneto)hydrodynamical instabilities develop in the disk?
- (Black hole like) kicks from linear momentum emitted in gravitational waves and unbound matter expelled not-axisymmetrically.
- Realistic treatment of EOS thermal component (ex. Using finite temperature EOS from relativistic mean field theory like Shen EOS).
- Simulations with magnetic fields to study the development of magnetic instabilities during the merger (Kelvin-Helmotz), in the hypermassive NS and the accretion disk (MRI).
- Studying possible electromagnetic and jet emissions after collapse.
- Use of OpenMP4 to test at least part of the code on GPUs and Intel KNL.