NewCompStar school , Sofia, Friday, September 15th 2017.

Dynamics of binary neutron stars

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GR NS-NS simulations: State of the Art

- **Speaking mostly about insight from Numerical-Relativity-Simulations**
- 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.
- Very good review by **Rezzolla** and Baiotti (arXiv:1607.03540), "Binary neutron-star mergers: a review of Einstein's richest laboratory", **Reports on Progress in Physics** 80 096901.
- 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 , **Font**, 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, …

Movies and data from: (using only public codes)

work in collaboration with :
A.Feo, F. Maione, F. Loeffler

- F. Maione, R. De Pietri, A. Feo and F. Loeffler, arXiv:1707.03368
  Phys. Rev. D to appear. **(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.

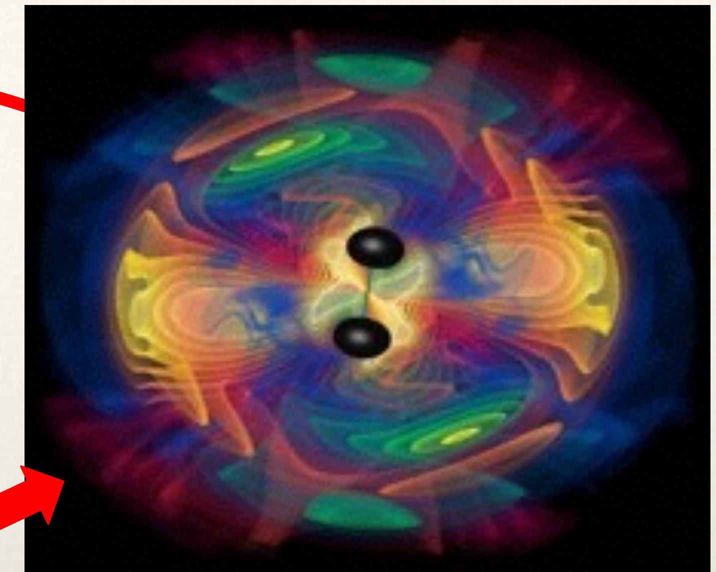
- F. Maione, R. De Pietri, A. Feo and F. Loeffler, arXiv:1605.03424.
  Classical and Quantum Gravity, 33, no. 17, 175009 (2016).
  Binary neutron star merger simulations with different initial orbital frequency and equation of state.

- 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

Detectors

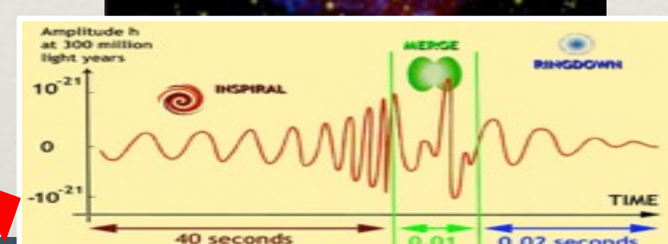
Gravitational Wave Physics

Models & Simulation



Observations

Scientific Discovery!



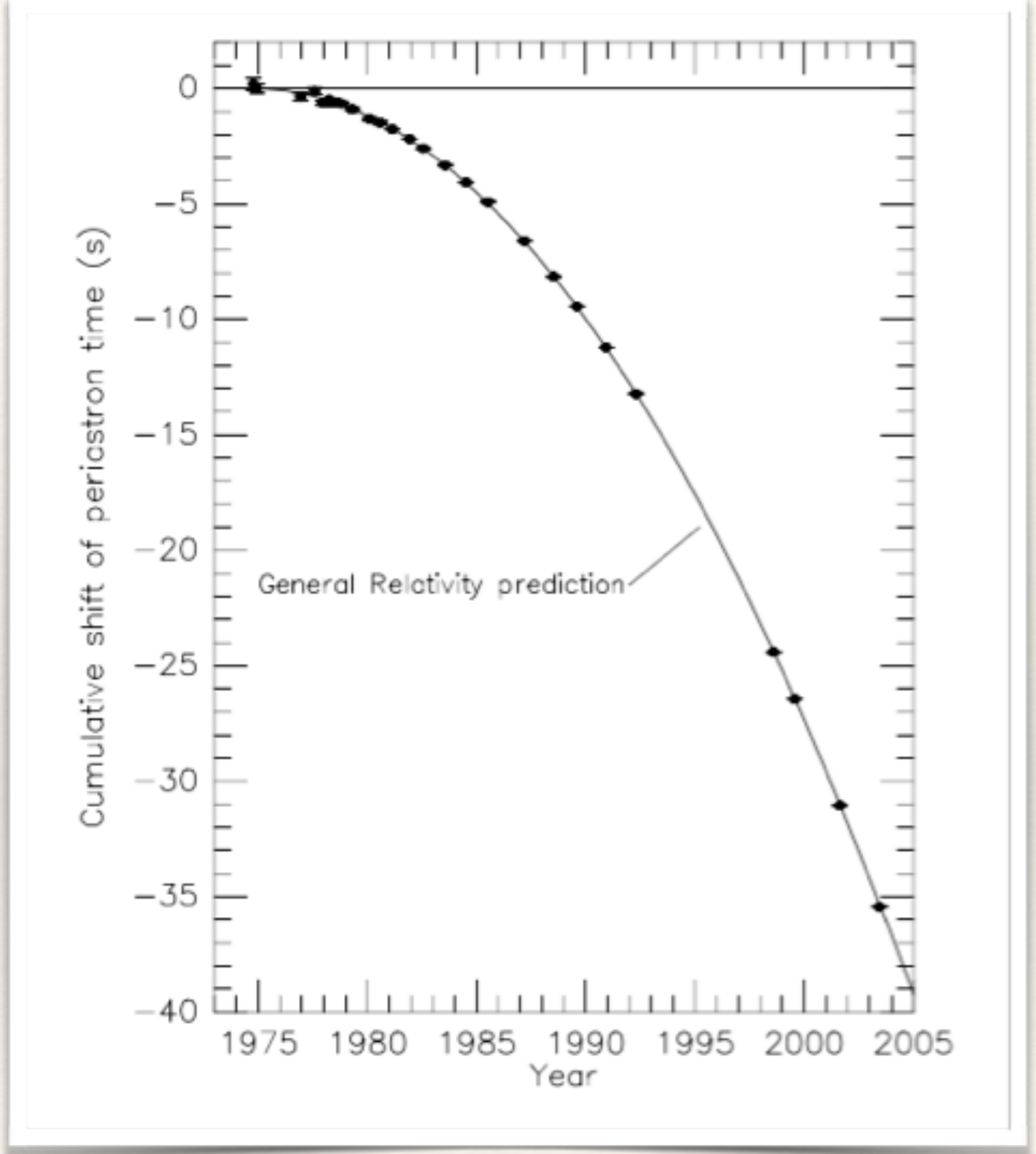
Theory

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

Compact binaries, supernovae collapse, gamma-ray bursts, oscillating NSs, gravitational waves, …

Gravitation Wave (GW) exists. Known before GW150914!

- PSR B1913+16 (also known as J1915+1606) is a pulsar in a binary star system, in orbit with another star around a common center of mass. In 1974 it was discovered by Russell **Alan Hulse and Joseph Hooton Taylor, Jr., of Princeton University, a discovery for which they were awarded the 1993 Nobel Prize in Physics**
- Nature 277, 437 - 440 (08 February **1979**), J. H. TAYLOR, L. A. FOWLER & P. M. McCULLOCH: Measurements of second- and third-order relativistic effects in the orbit of binary pulsar PSR1913 + 16 have yielded self-consistent estimates of the masses of the pulsar and its companion, **quantitative confirmation of the existence of gravitational radiation at the level predicted by general relativity**, and detection of geodetic precession of the pulsar spin axis.

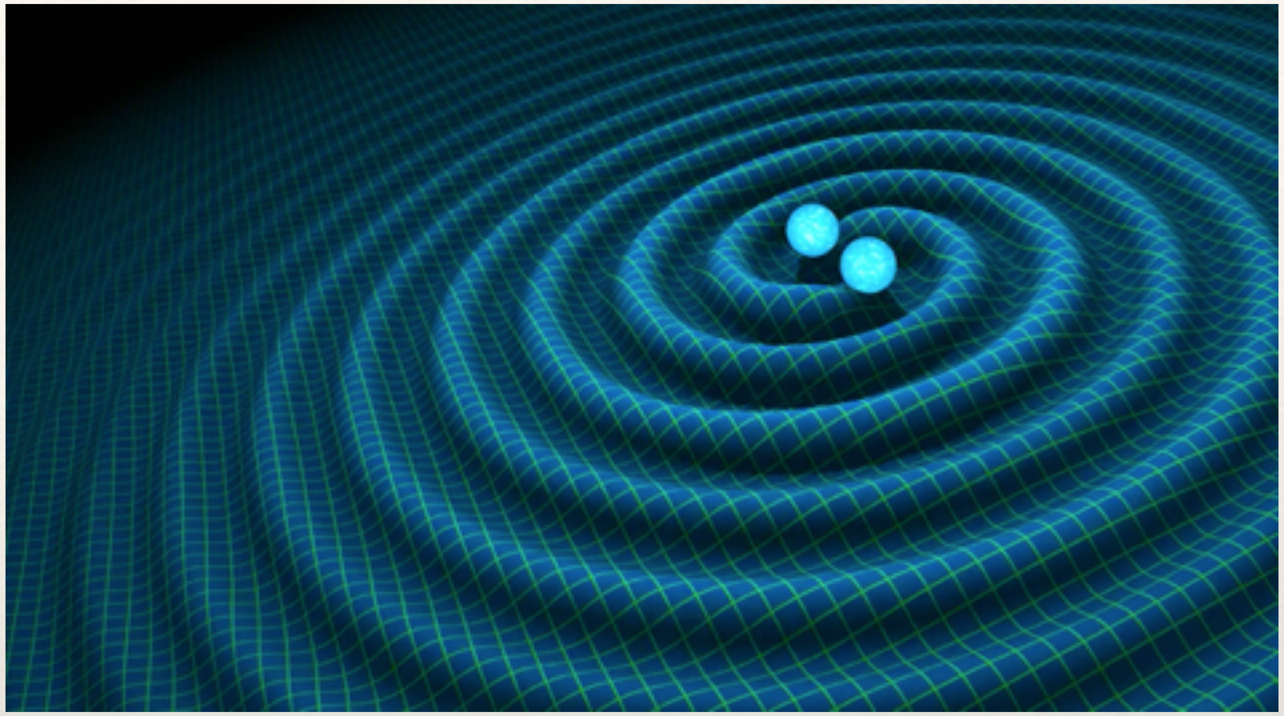


Network Of Terrestrial Detectors

A network of advanced detectors

Gravitational Waves: The Sound of the Universe

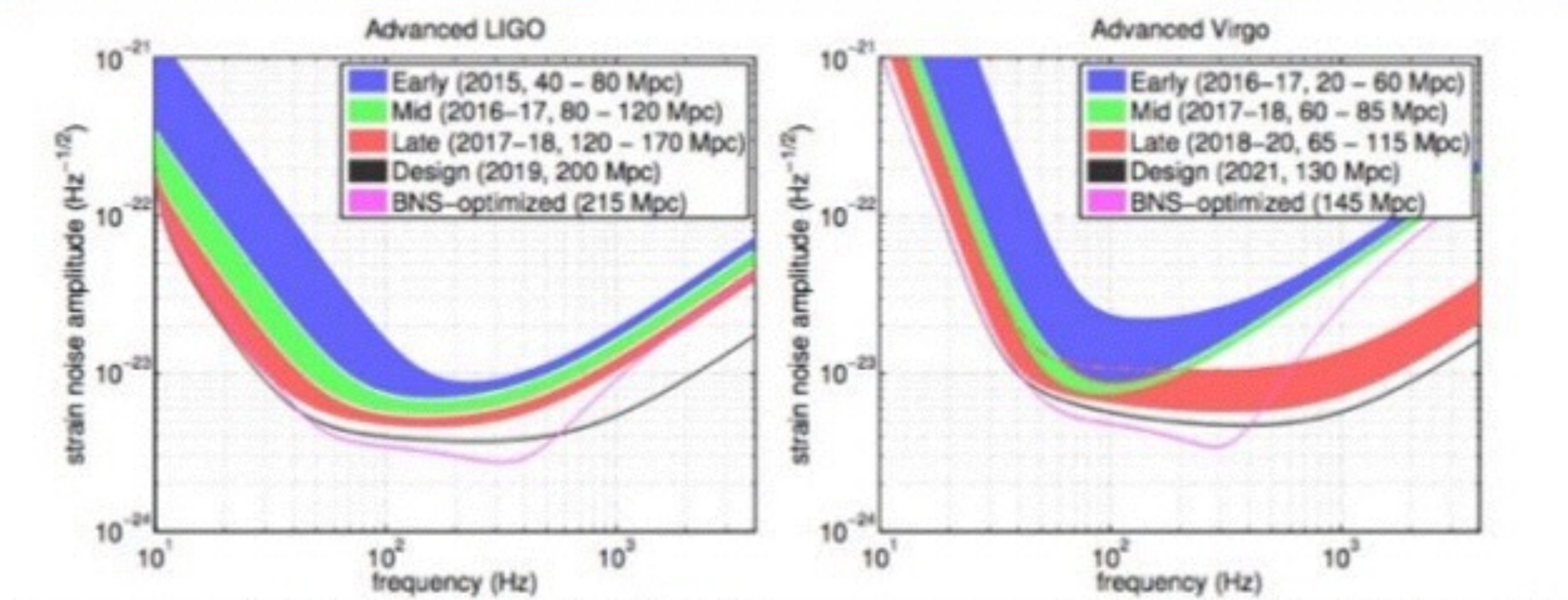
- Predicted by the General Relativity
- Are ripples in the metric of space-time that propagate like a wave
- Caused by some of the most violent and energetic processes in the Universe (most powerful sources are binaries of compact objects)
- Carry information about the source (BH, NS, …)
- GW will provide a new way to listen the Universe and open a new frontier
- They are the only way to detect BH directly!



these waves travel at the speed of light through the Universe

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

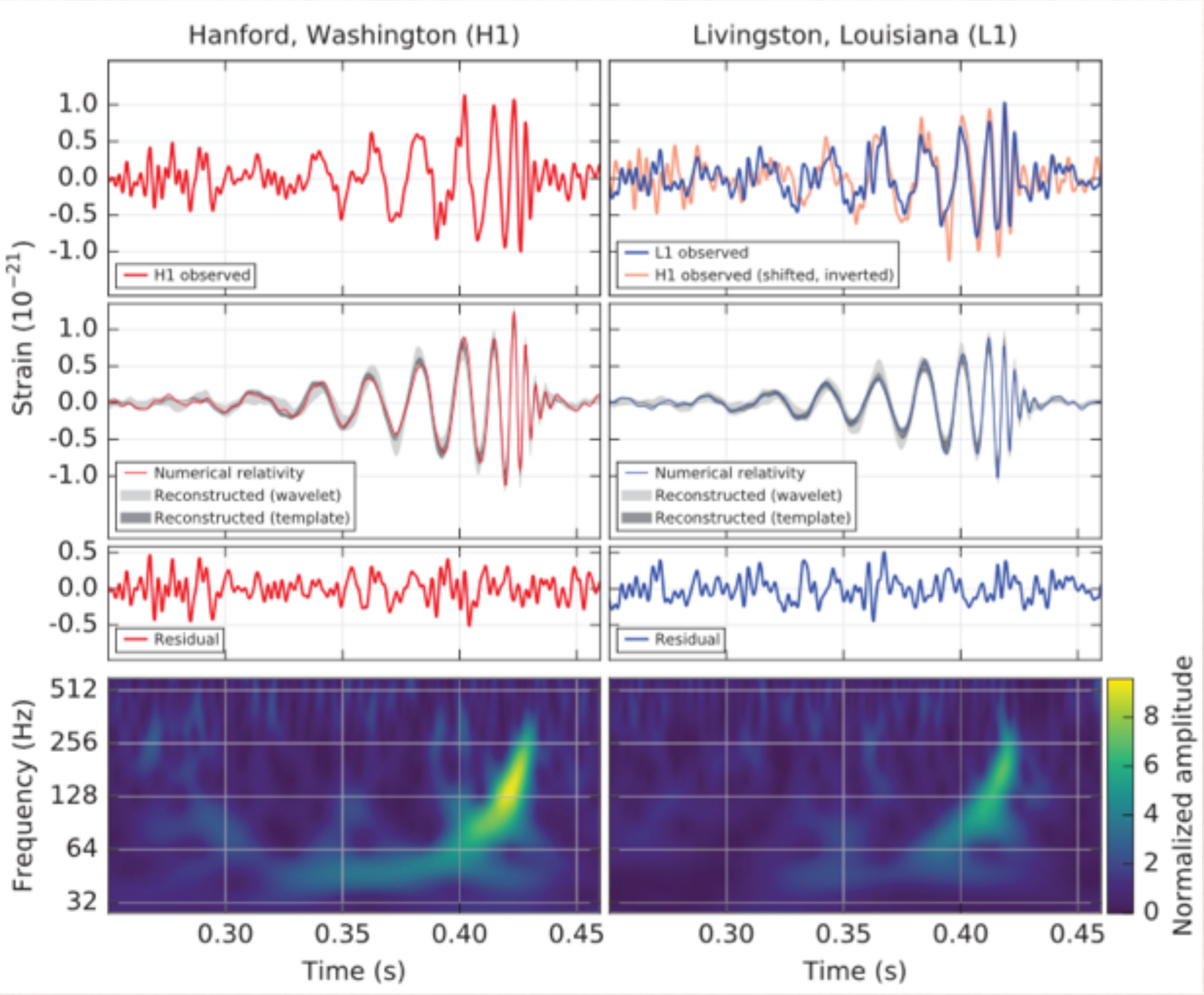
O2 → 2016–17

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 Wave detected!

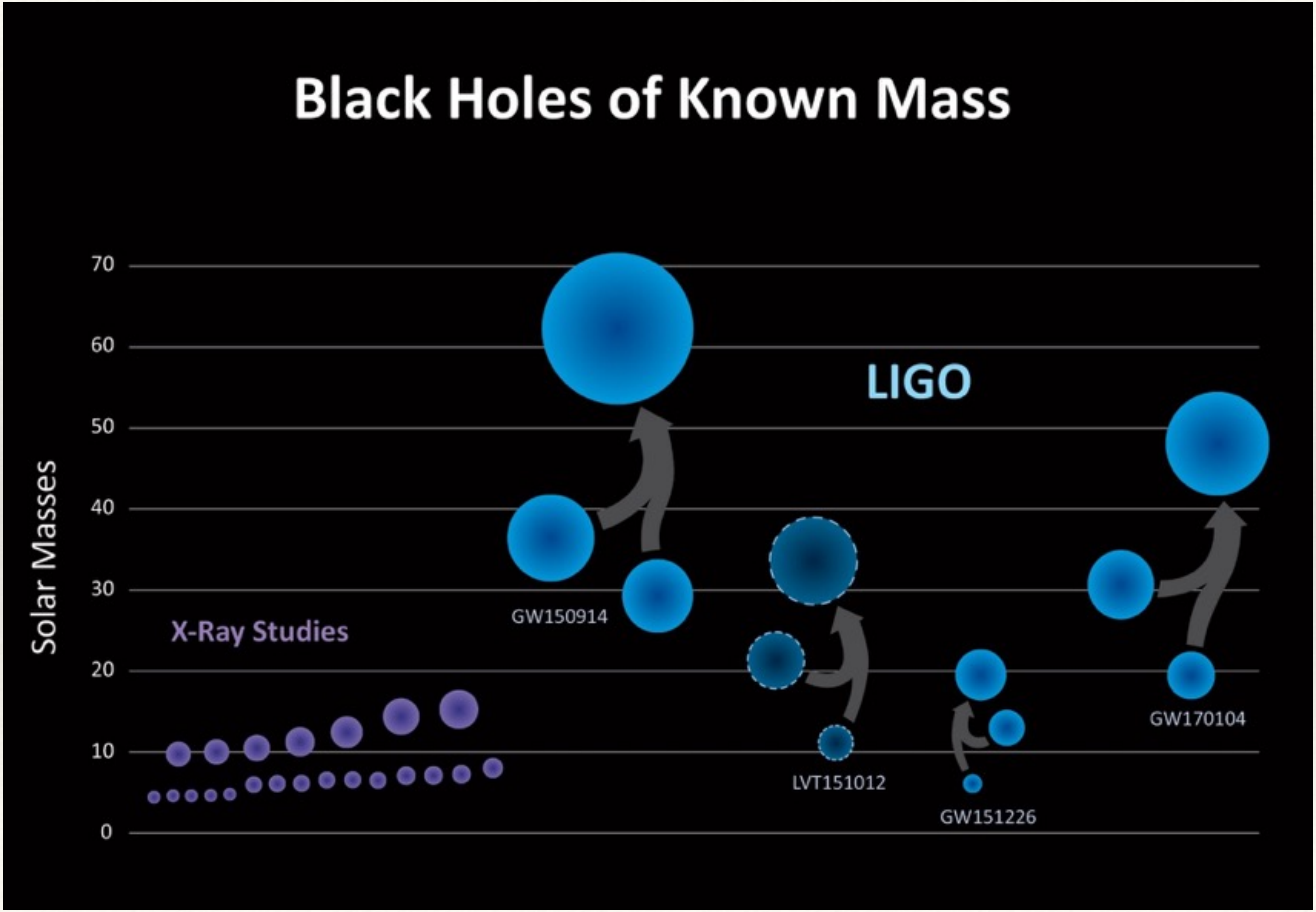
- **The gravitational waves were detected on September 14, 2015 at 5:51 a.m. Eastern Daylight Time (09:51 UTC)** by both of the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors, located in Livingston, Louisiana, and Hanford, Washington, USA.
- The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than **5.1σ**. The source lies at a luminosity distance of **410(**18) **Mpc** corresponding to a redshift z=0.09(4). In the source frame, the initial black hole masses are **36**(5)**M**$_\odot$ and **29**(4)**M**$_\odot$, and the final black hole mass is **62**(4)**M**$_\odot$, with 3.0(5) **M**$_\odot$**c**^{2} radiated in gravitational waves. ***All uncertainties define 90% credible intervals***.



GW150914

Observation of Gravitational Waves from a Binary Black Hole Merger B. P. Abbott et al. (LIGO Scientific Collaboration and **Virgo Collaboration**)
Phys. Rev. Lett. 116, 061102 – Published 11 February 2016

We have seen a new family of Black -Holes



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)]

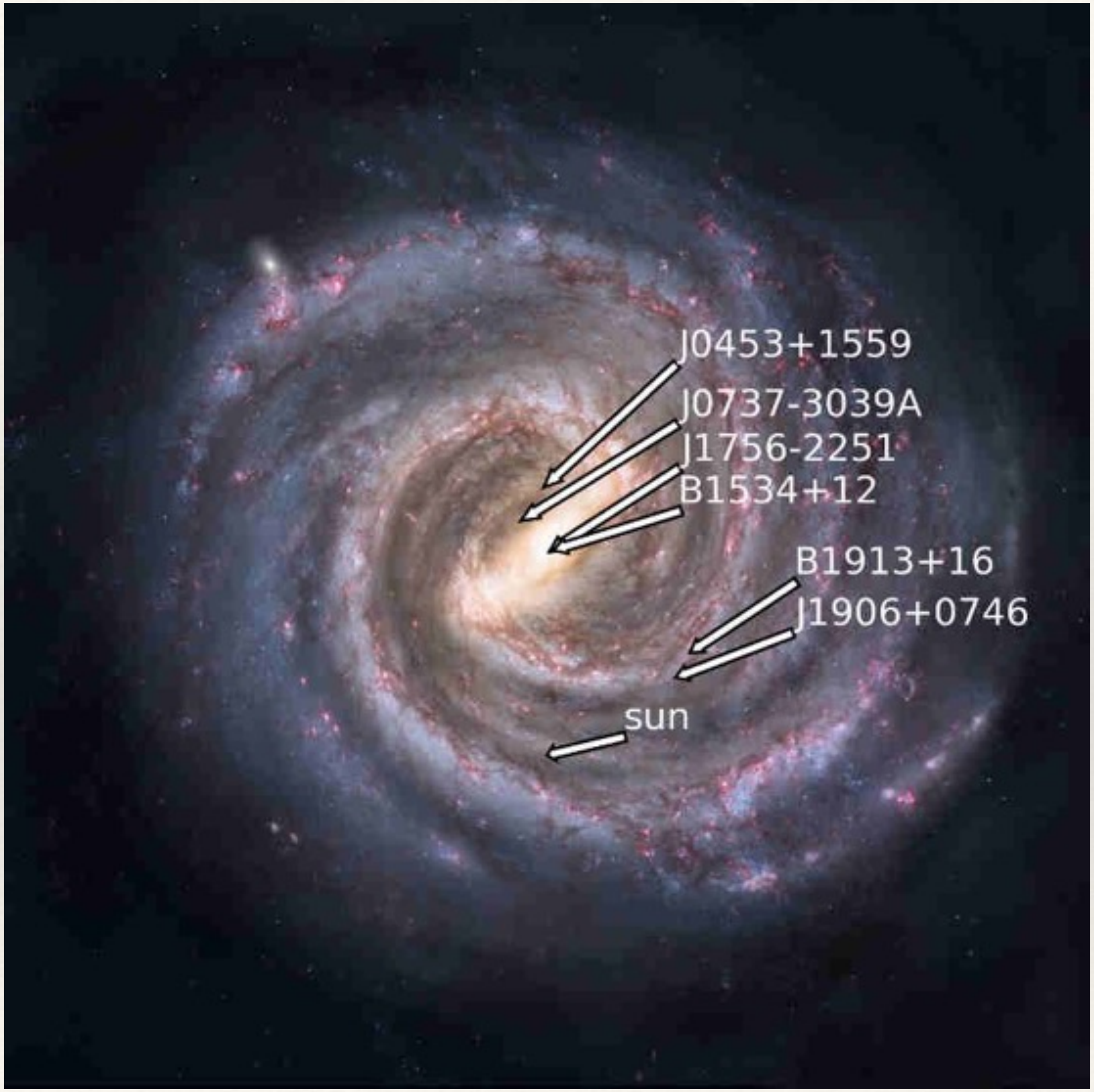
- **Core collapse in supernova**
- **BH-BH merger** —— **(FOUND!)**
- **BH-NS merger**
- **"*Mountains*" (deformation) on the crust of Neutron Stars**
- **Secular instability of Neutron stars**
- **Dynamical instability of Neutron star**

Table 1: Double neutron star systems known in the Galaxy

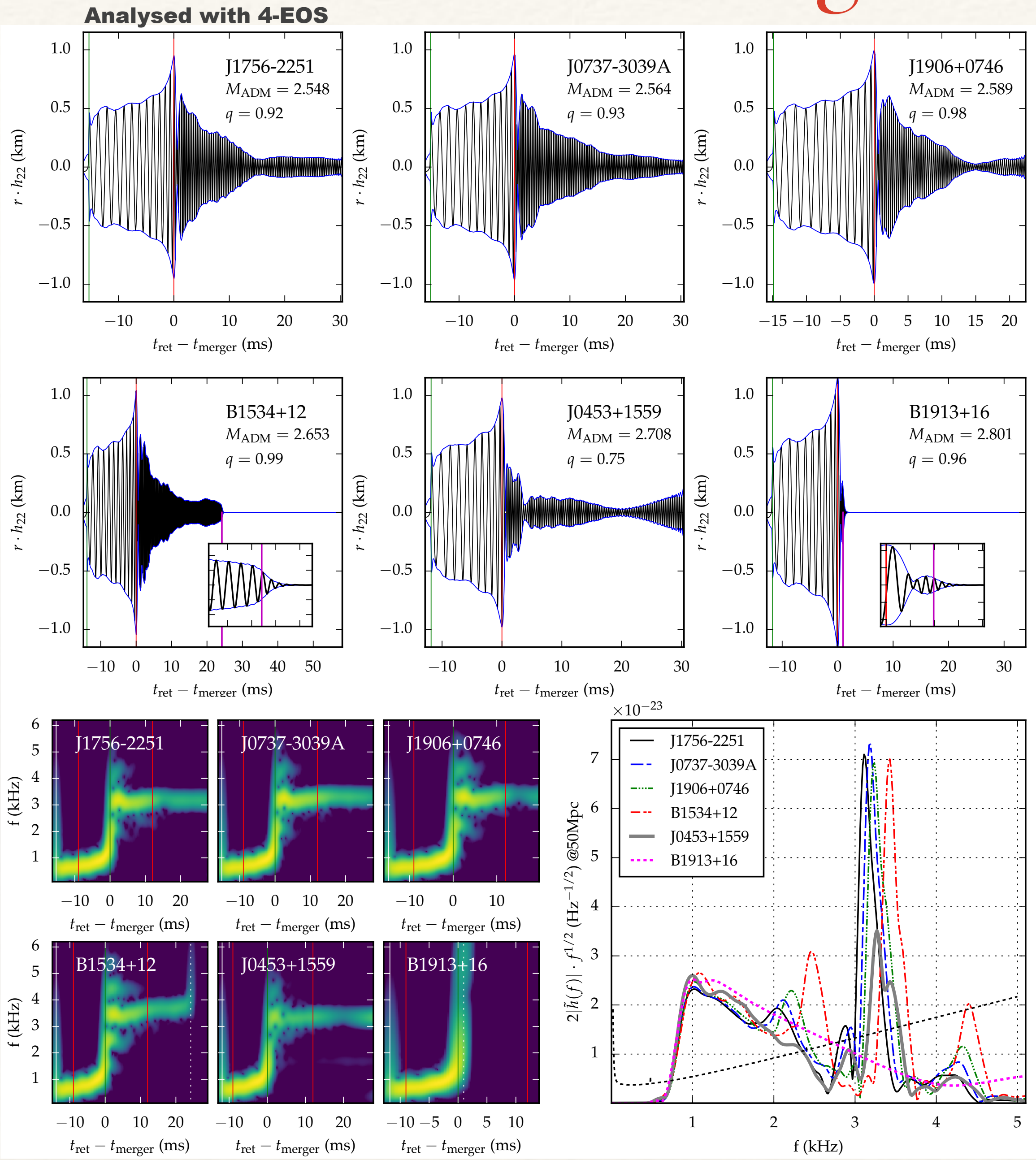
Pulsar	Period (ms)	P_b (days)	x (lt-sec)	e	M ($M_\odot$)	M_p ($M_\odot$)	M_c ($M_\odot$)	References
J0737−3039A	22.699	0.102	1.415	0.0877775(9)	2.58708(16)	1.3381(7)	1.2489(7)	1
J0737−3039B	2773.461		1.516					
J1518+4904	40.935	8.634	20.044	0.24948451(3)	2.7183(7)	-	-	2
B1534+12	37.904	0.421	3.729	0.27367740(4)	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.

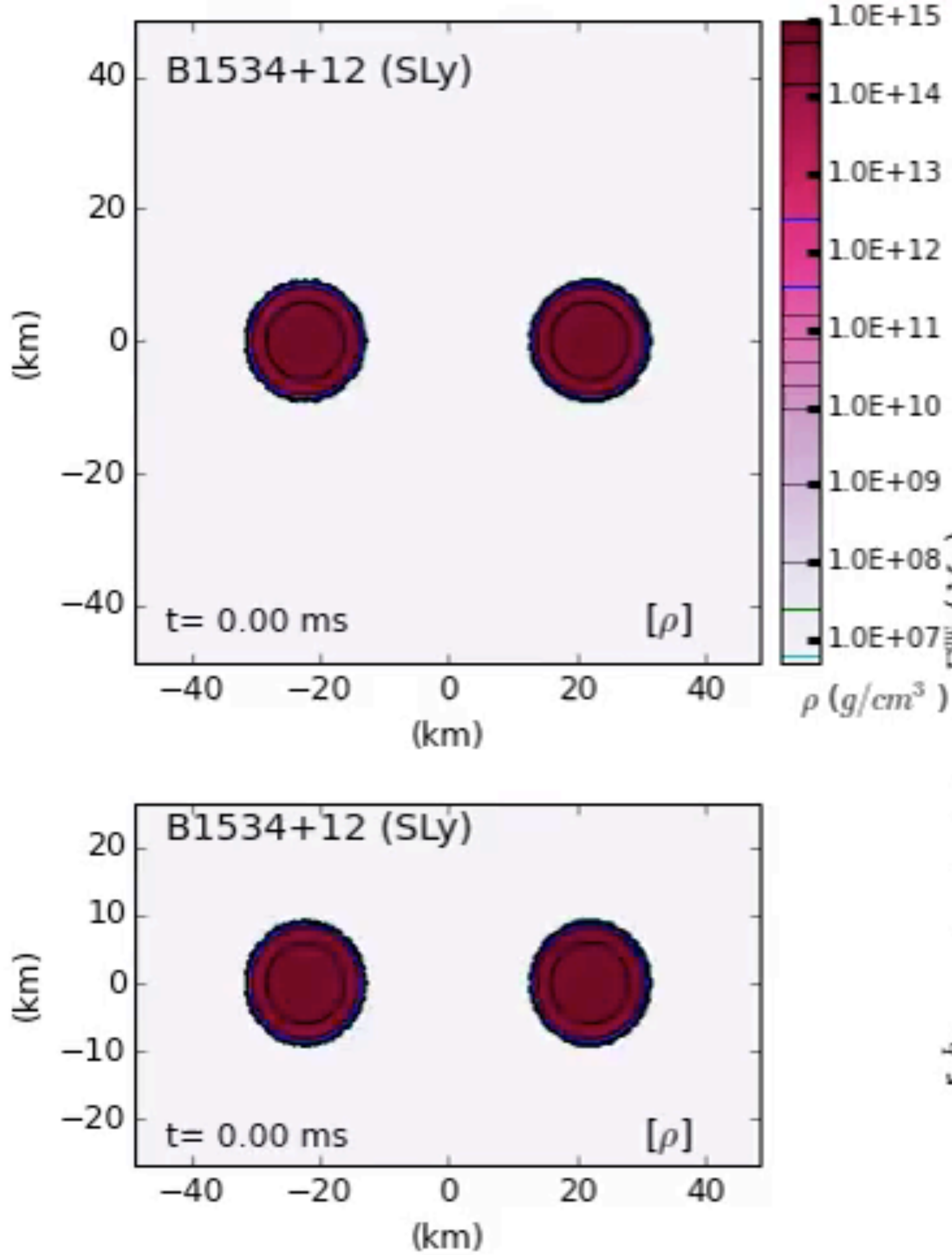


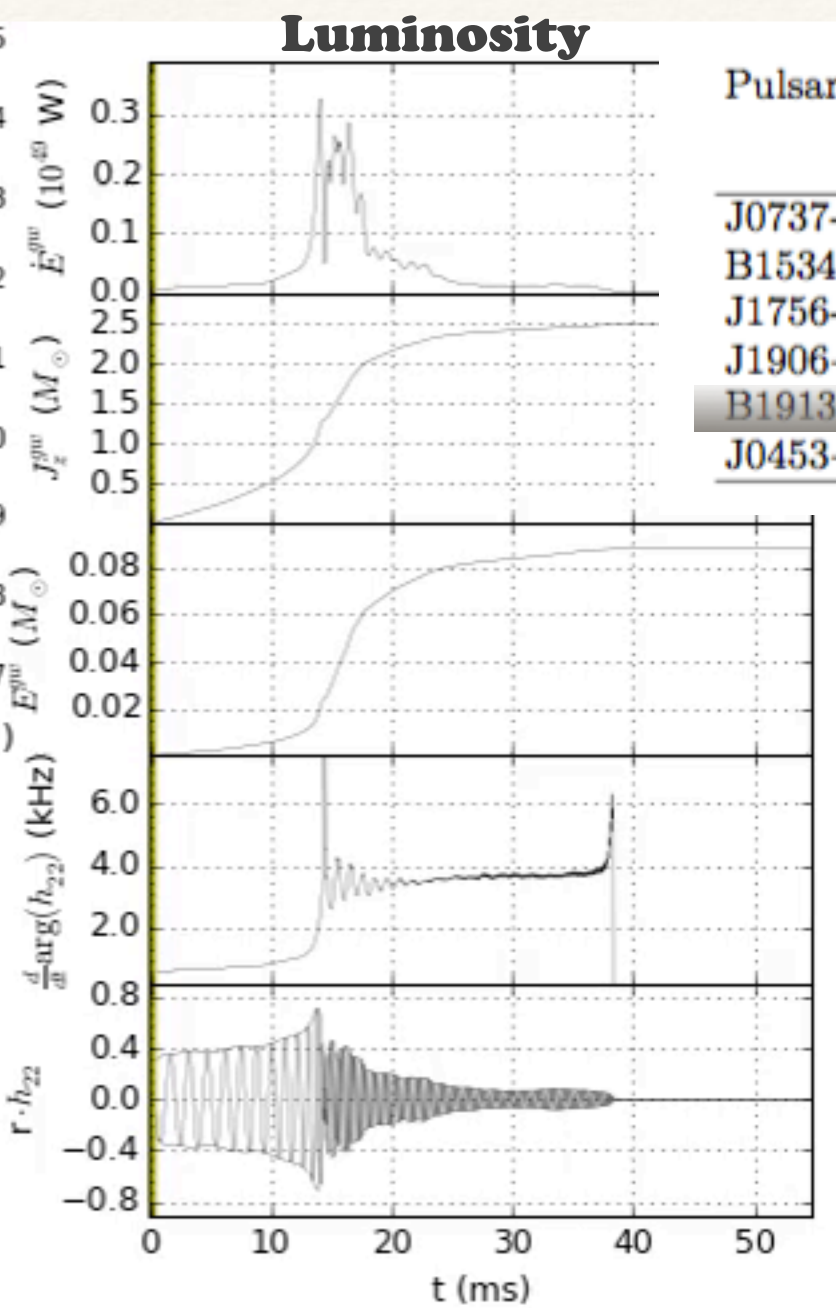
The simulated GW signal



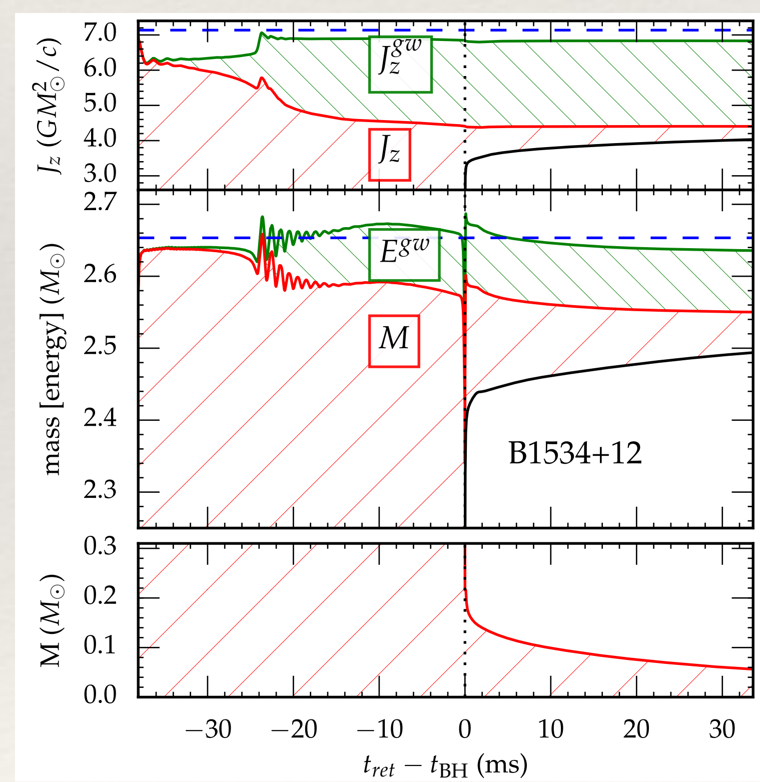
A. Feo, R. De Pietri, F. Maione and F. Loeffler,
Modeling Mergers of known Galactic Binary Neutron Stars,
Classical and Quantum, 34 (3), 034001 (2017) arXiv 1608.02810(2016)

The evolution of the B1534+12 system.



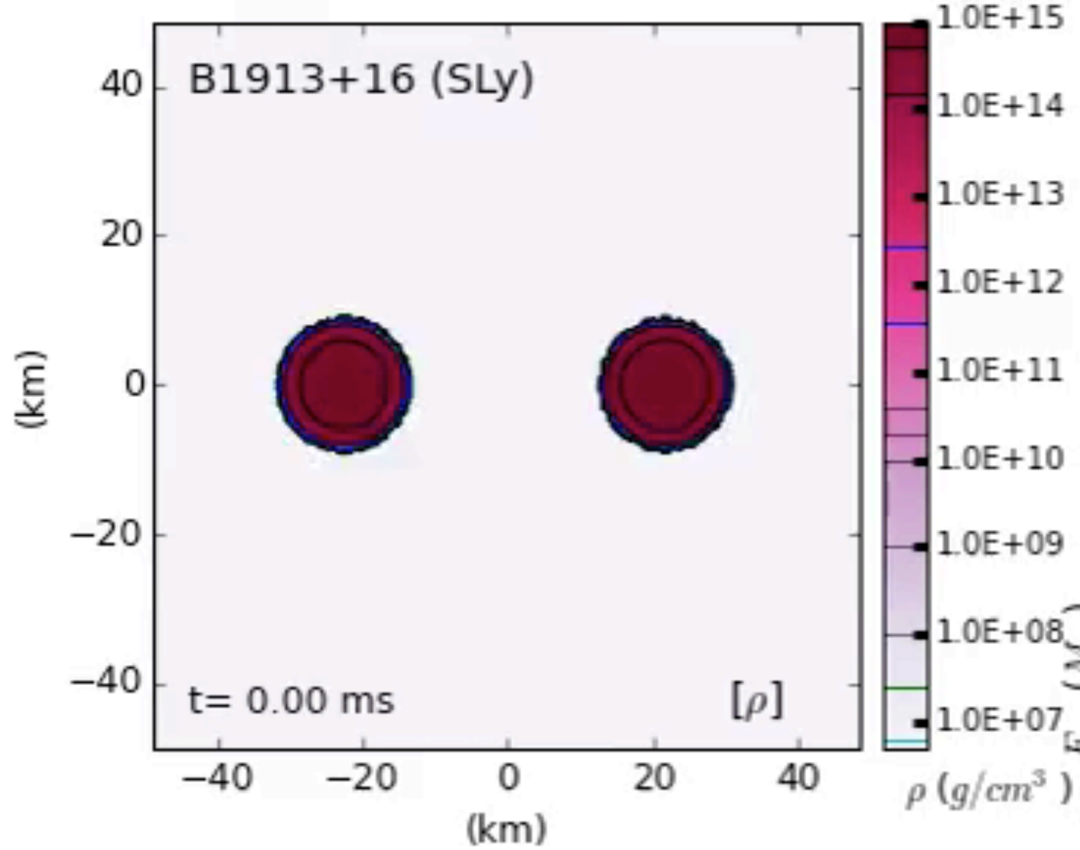


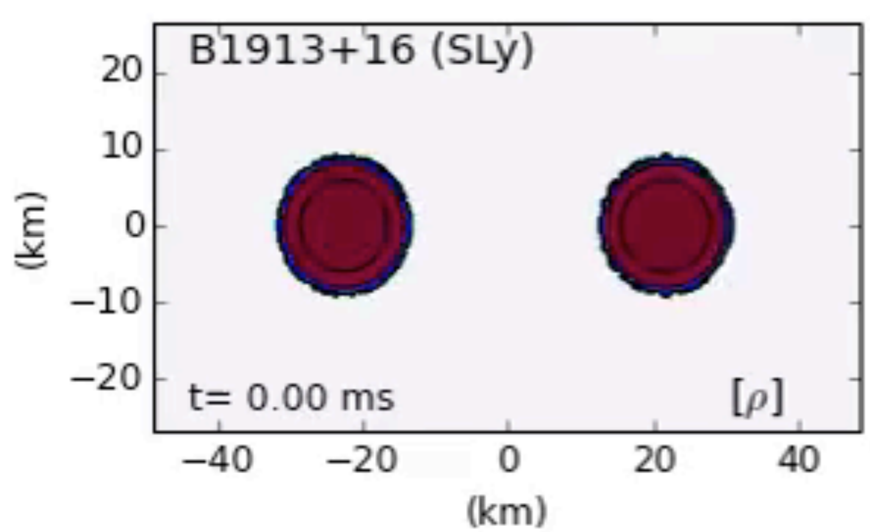
Pulsar	M_p	M_c	q	$M^{(1)}$	$M^{(1)}$
	$[M_\odot]$	$[M_\odot]$		$[M_\odot]$	$[M_\odot]$
J0737-3039A	1.3381(7)	1.2489(7)	0.93	1.36	1.47
B1534+12	1.3330(2)	1.3454(2)	0.99	1.46	1.47
J1756-2251	1.341(7)	1.230(7)	0.92	1.33	1.47
J1906+0746*	1.291(11)	1.322(11)	0.98	1.41	1.45
B1913+16	1.4398(2)	1.3886(2)	0.96	1.53	1.59
J0453+1559	1.559(5)	1.174(4)	0.75	1.27	1.74

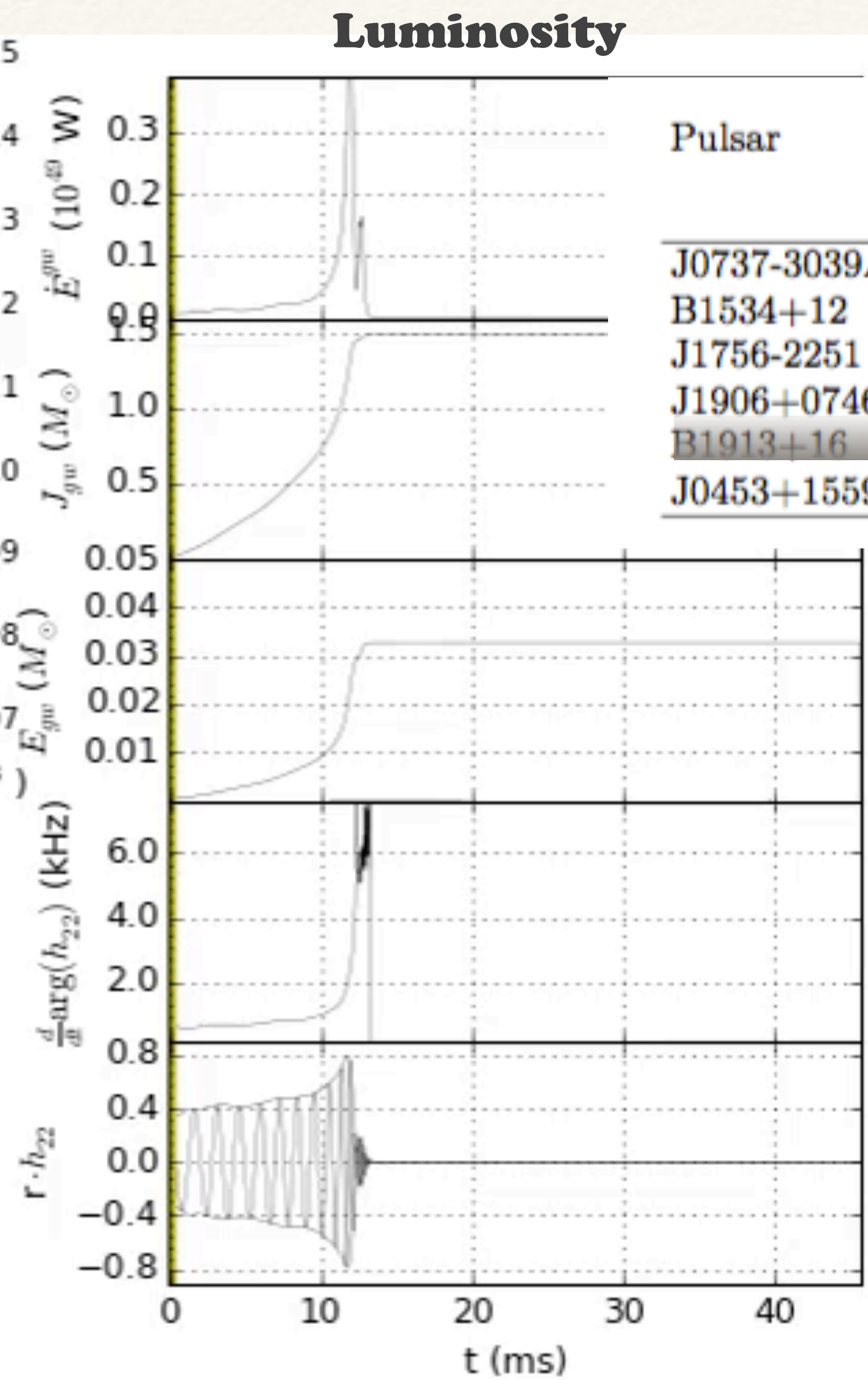


and the SOUND!

Hulse and Taylor pulsar (B1913+16)







Pulsar	M_p $[M_\odot]$	M_c $[M_\odot]$	q	$M^{(1)}$ $[M_\odot]$	$M^{(1)}$ $[M_\odot]$
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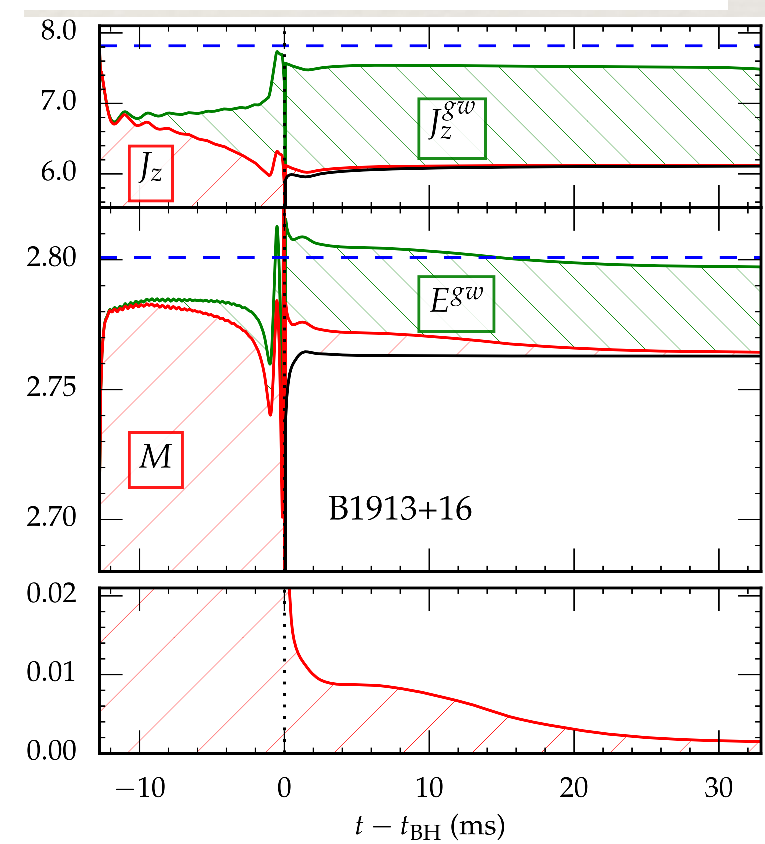
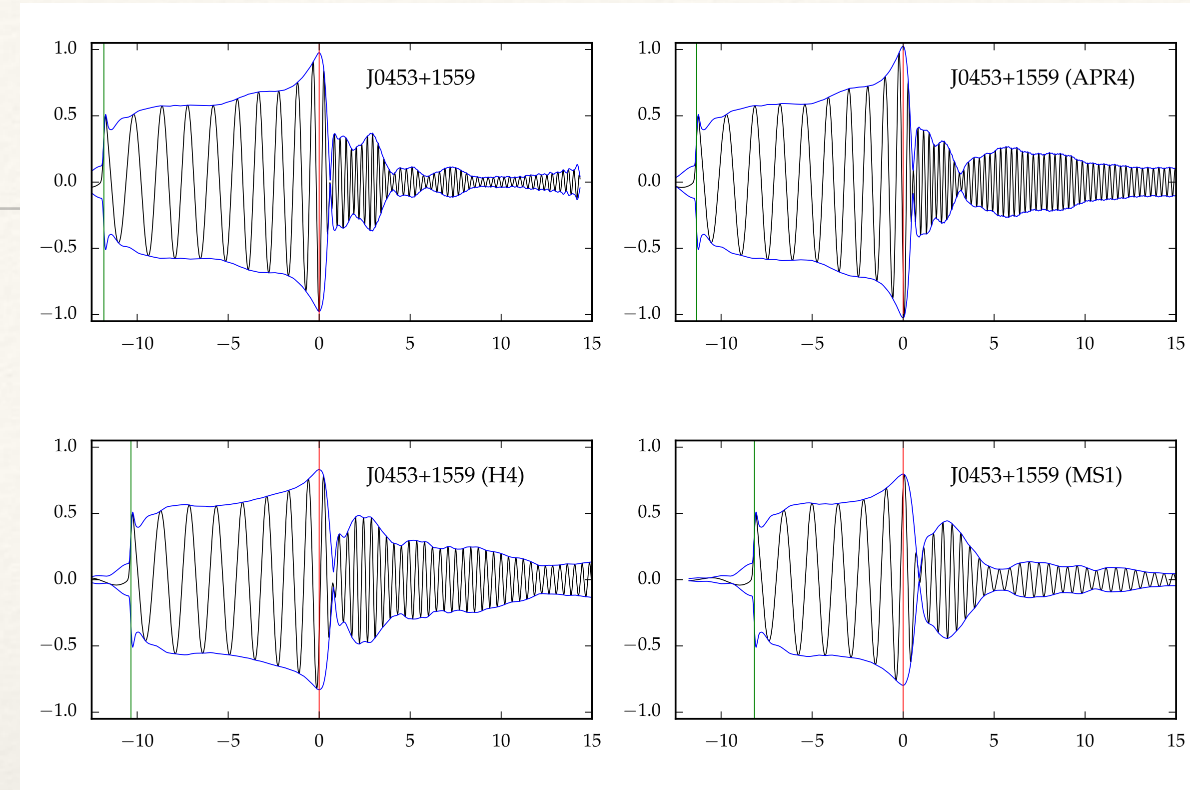


The pulsar J0453+1559 (q=0.75) with four different EOS



A. Feo, R. De Pietri, F. Maione and F. Loeffler,
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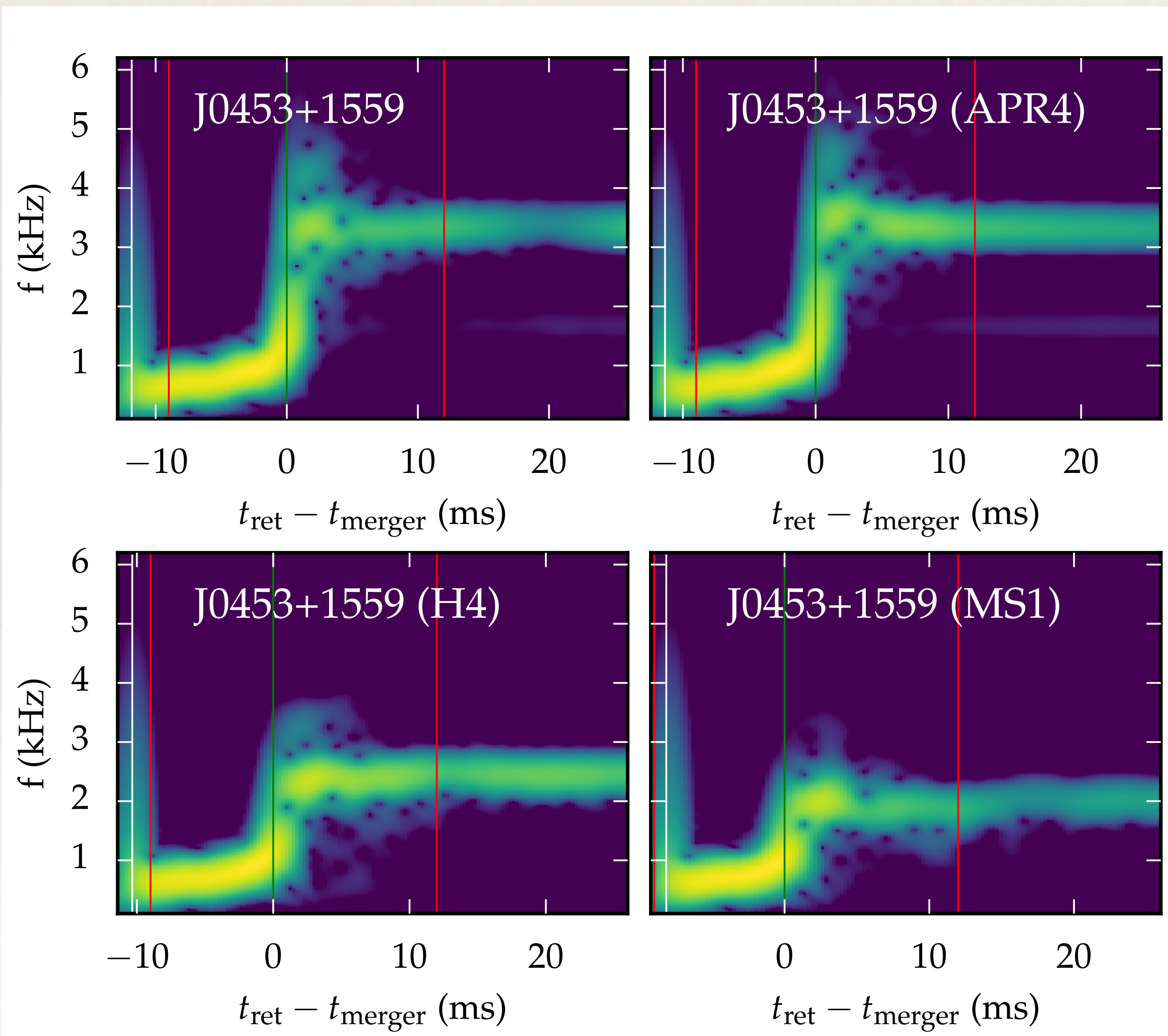

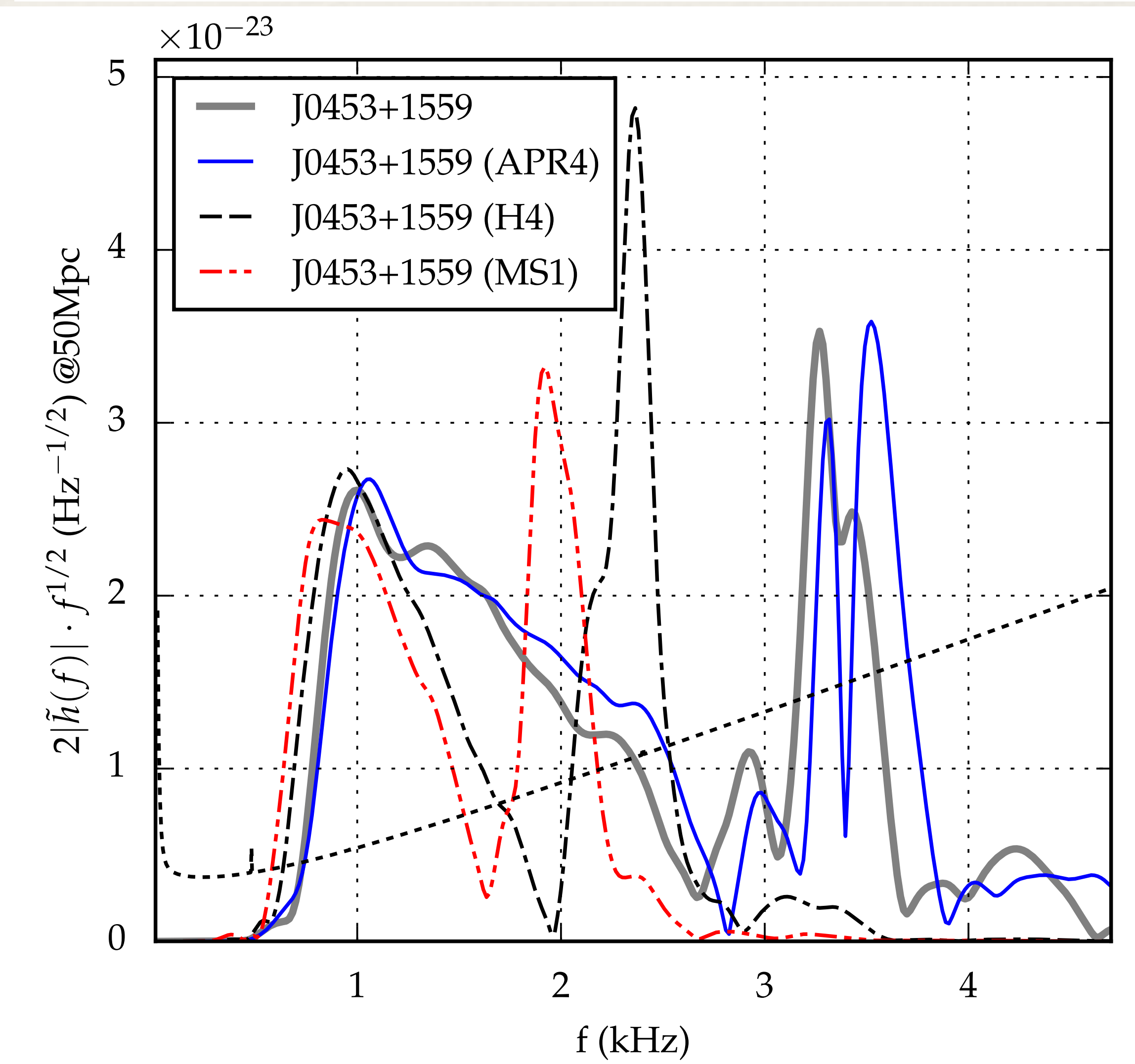

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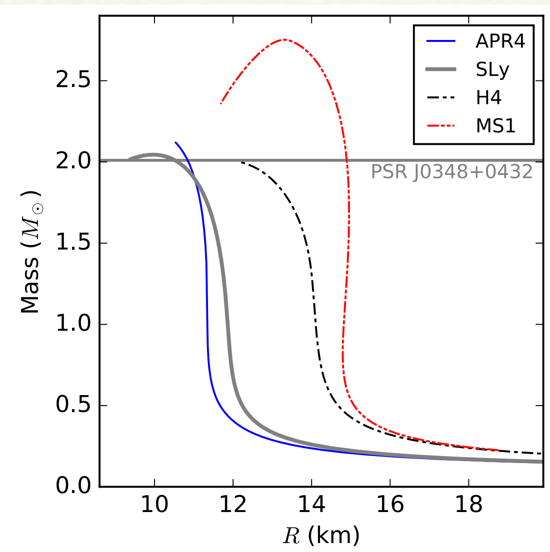
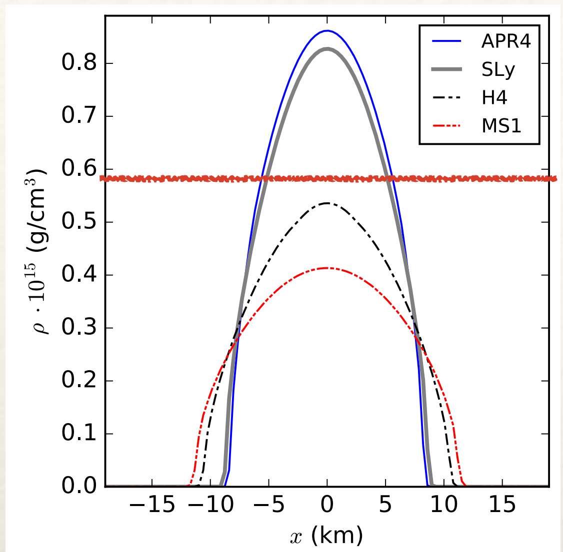
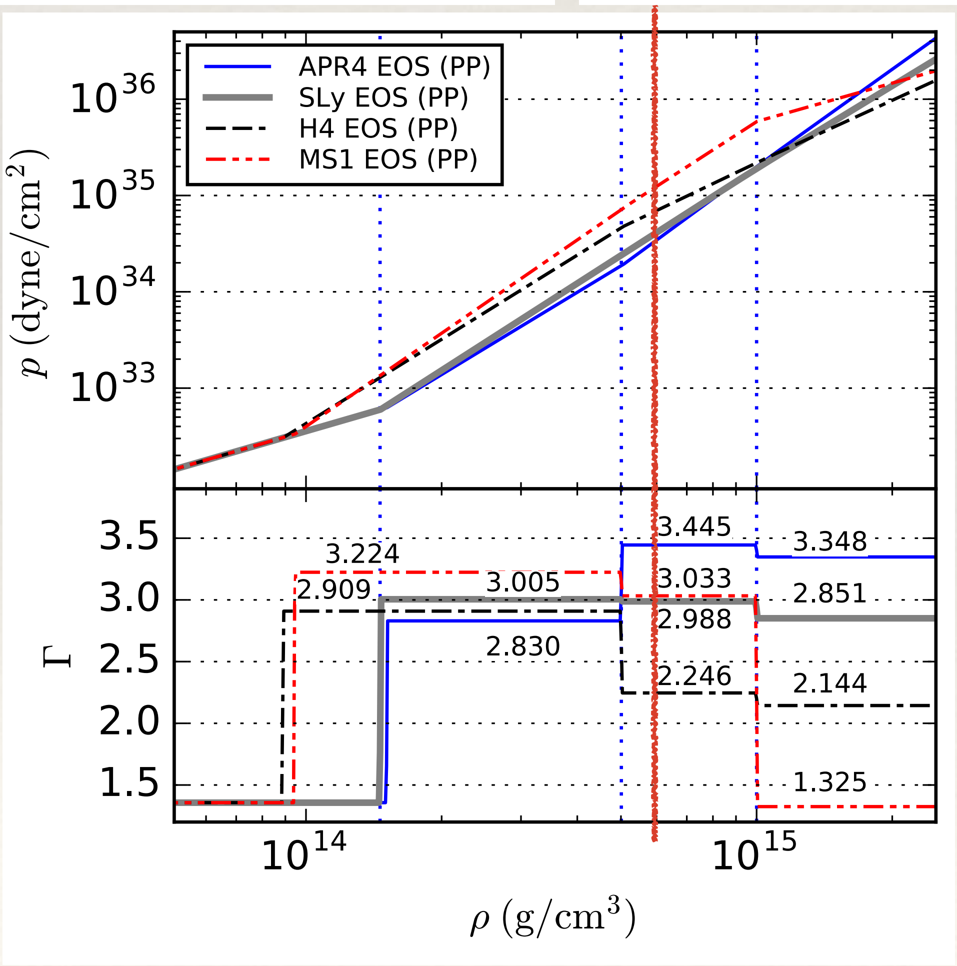
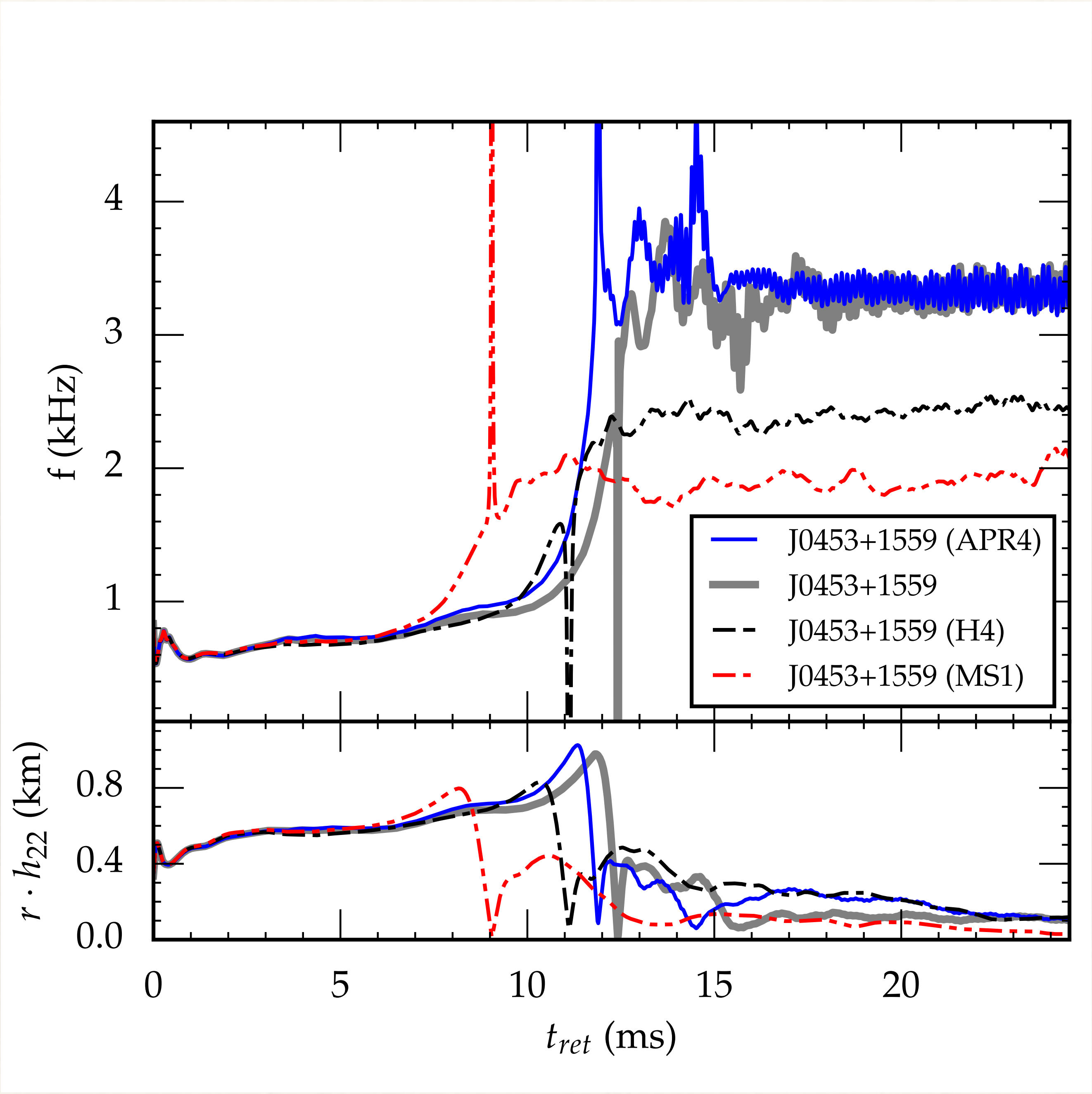






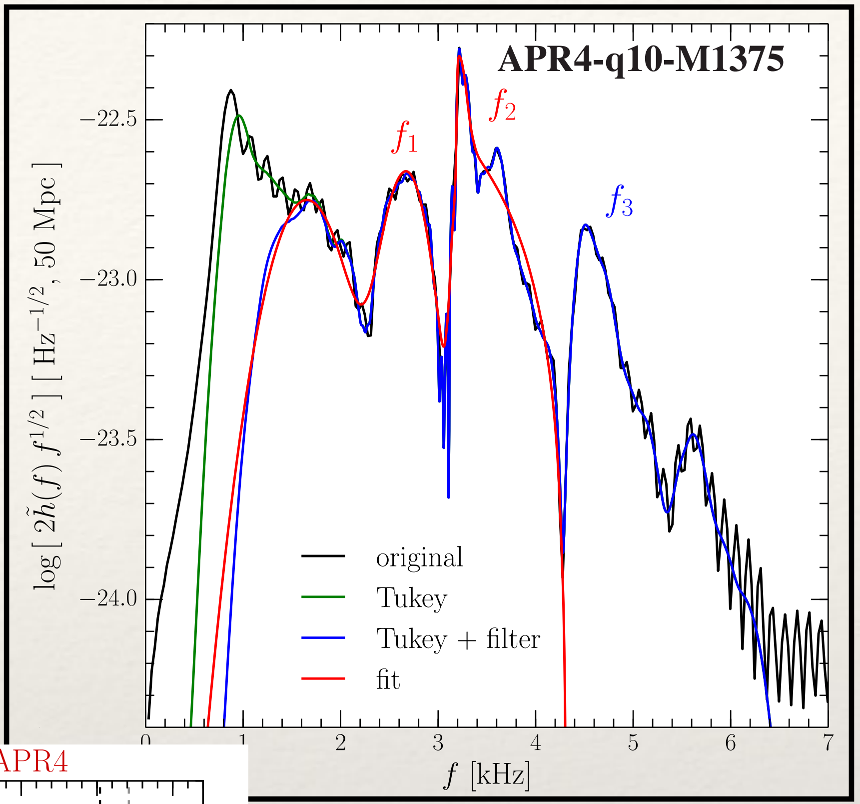


Binary Neutron Stars System

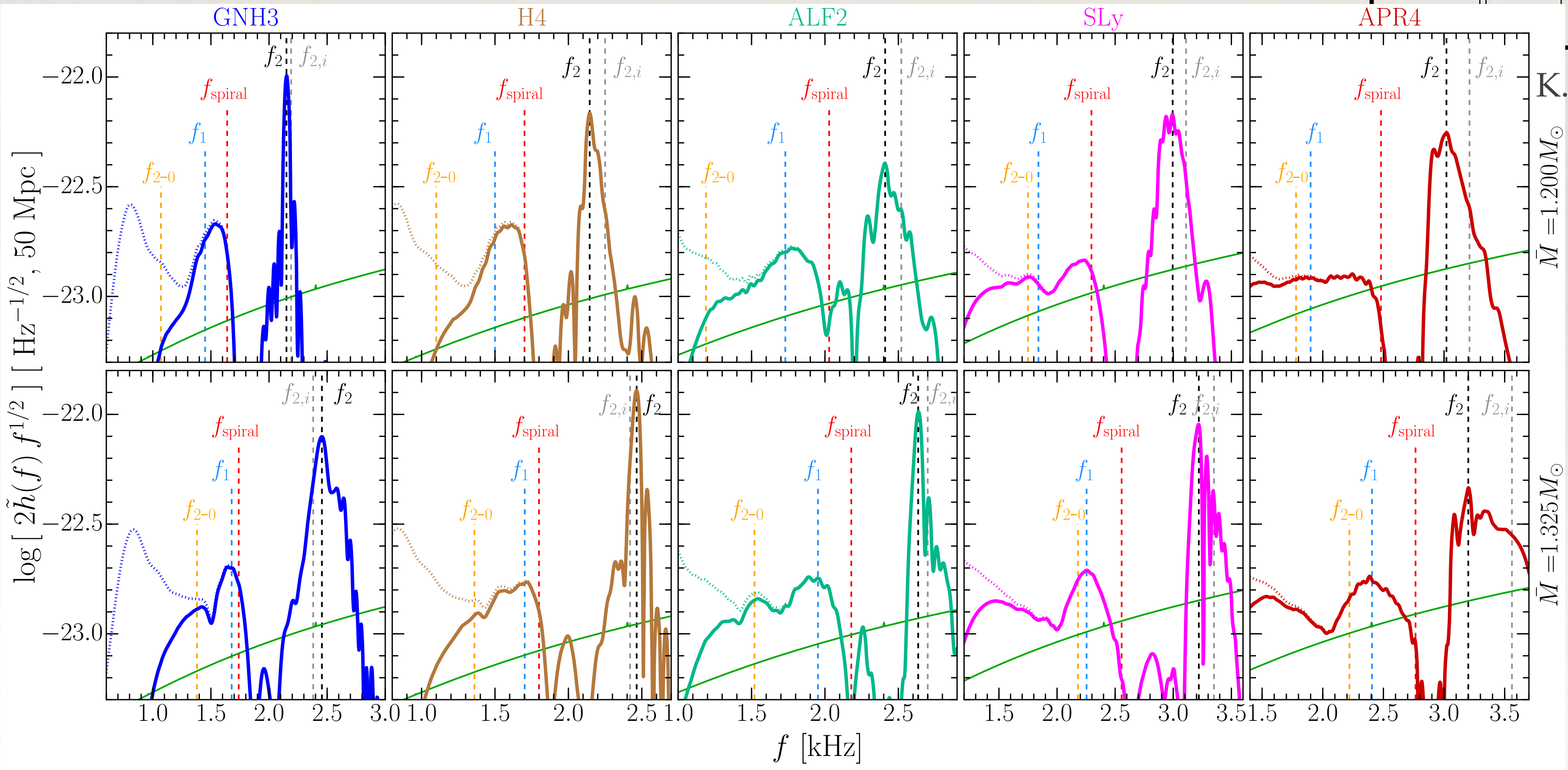
- EOS … initial data for binary neutron star system … waveform … detection … validate the proposed form for the EOS.
- Question: **Is it possible to discriminate between different EOS**. Answer: **Yes, it is**.
- Main problem are:
- It is not easy to generate (consistent) initial data with complete control 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].



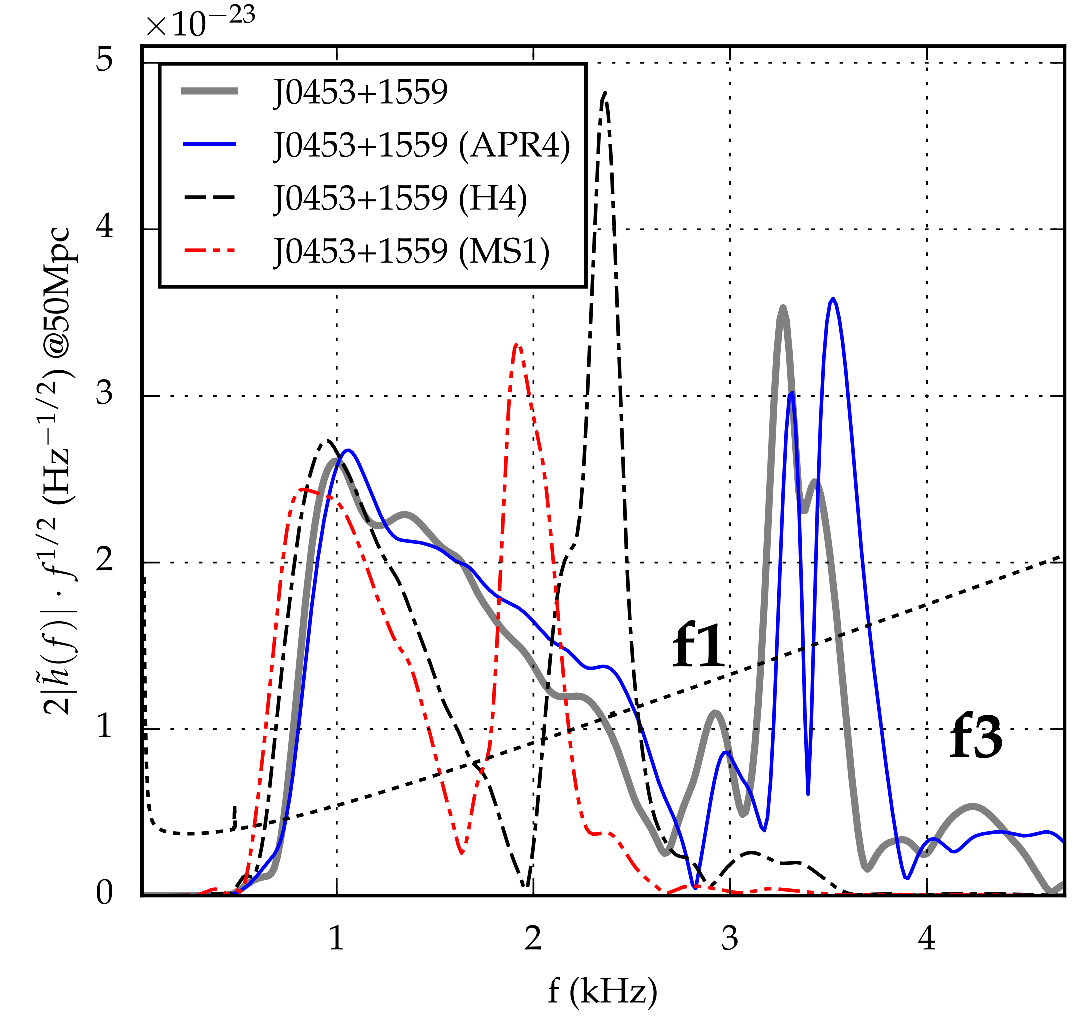
K. Takami, L. Rezzolla, and L. Baiotti, **Phys. Rev. D91**, 064001 (2015)

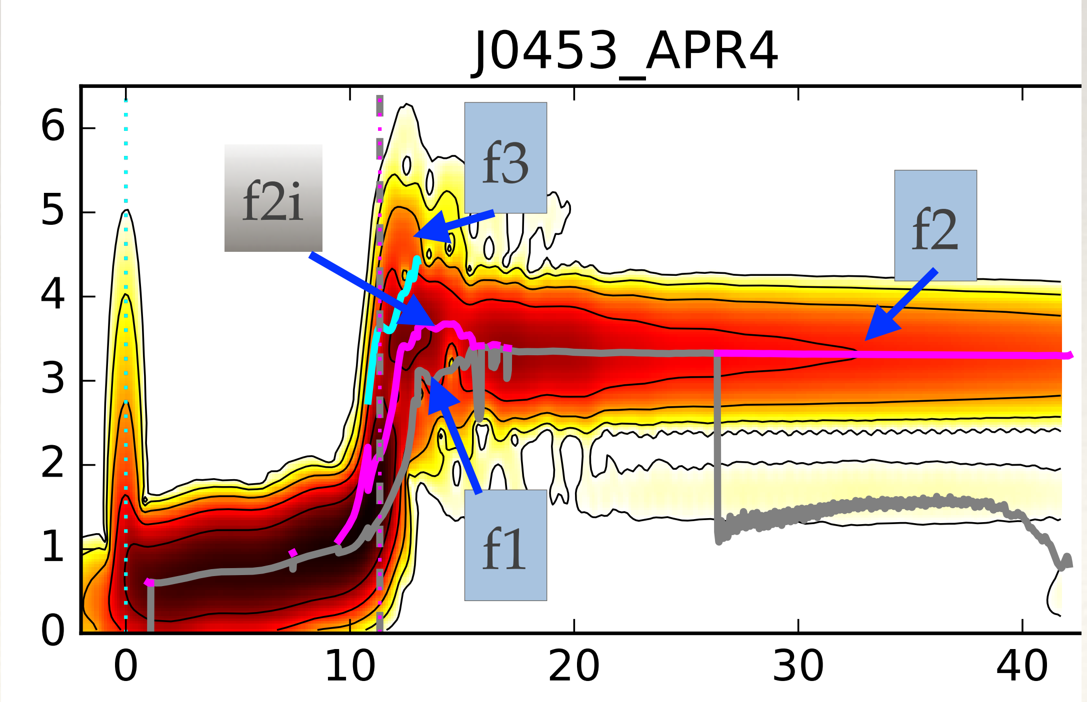


L. Rezzolla and K. Takami, **Phys. Rev. D93**, 124051 (2016)

Post Merger Spectrum

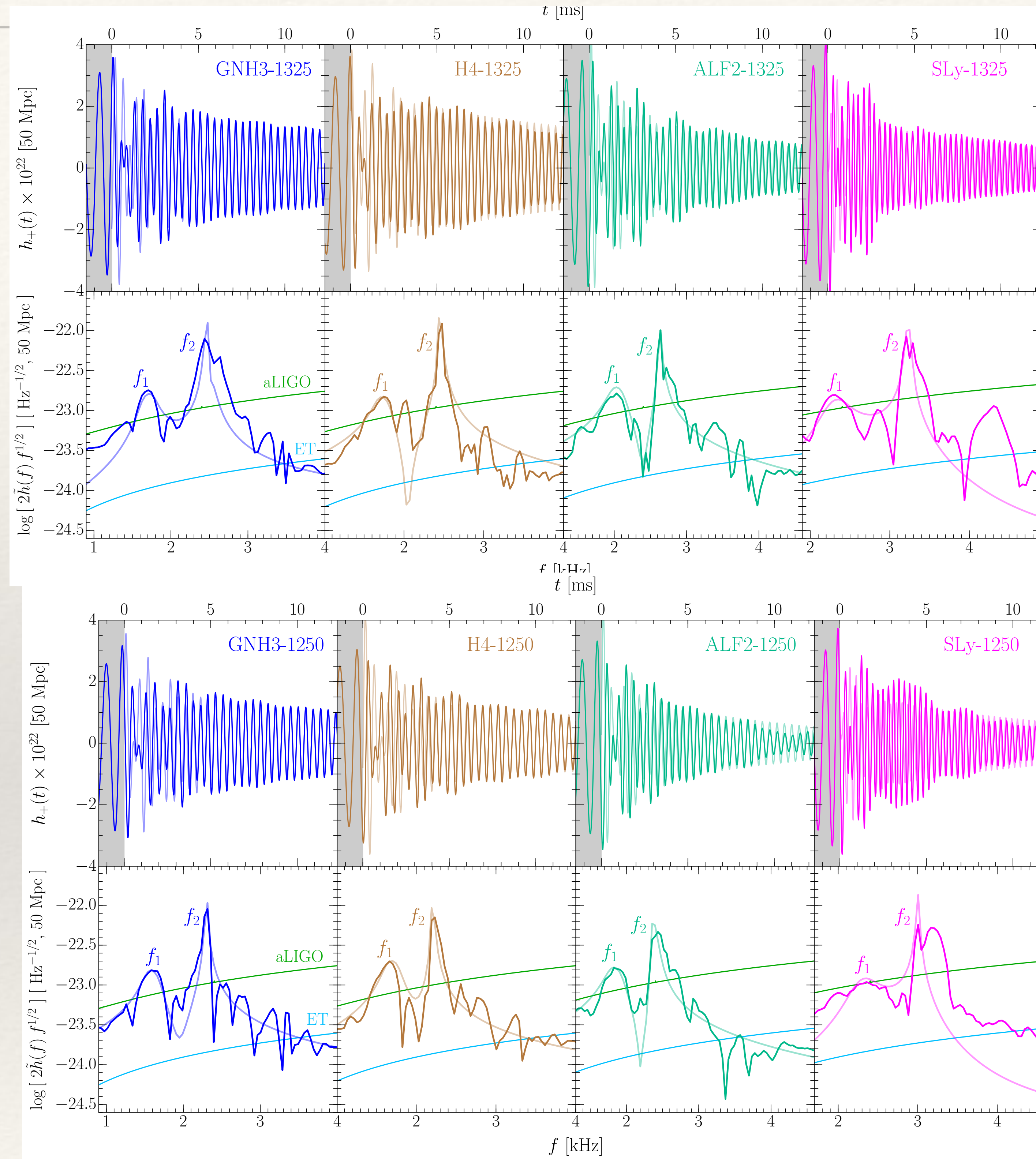
- Analyzing the signal using Fourier spectrograms and Prony spectrograms one see that:
  - A change in the dominant peak frequency between the initial transient phase and the following quasi- stationary phase. It is apparent that this transient is not a sudden jump, but rather a continuous process, in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

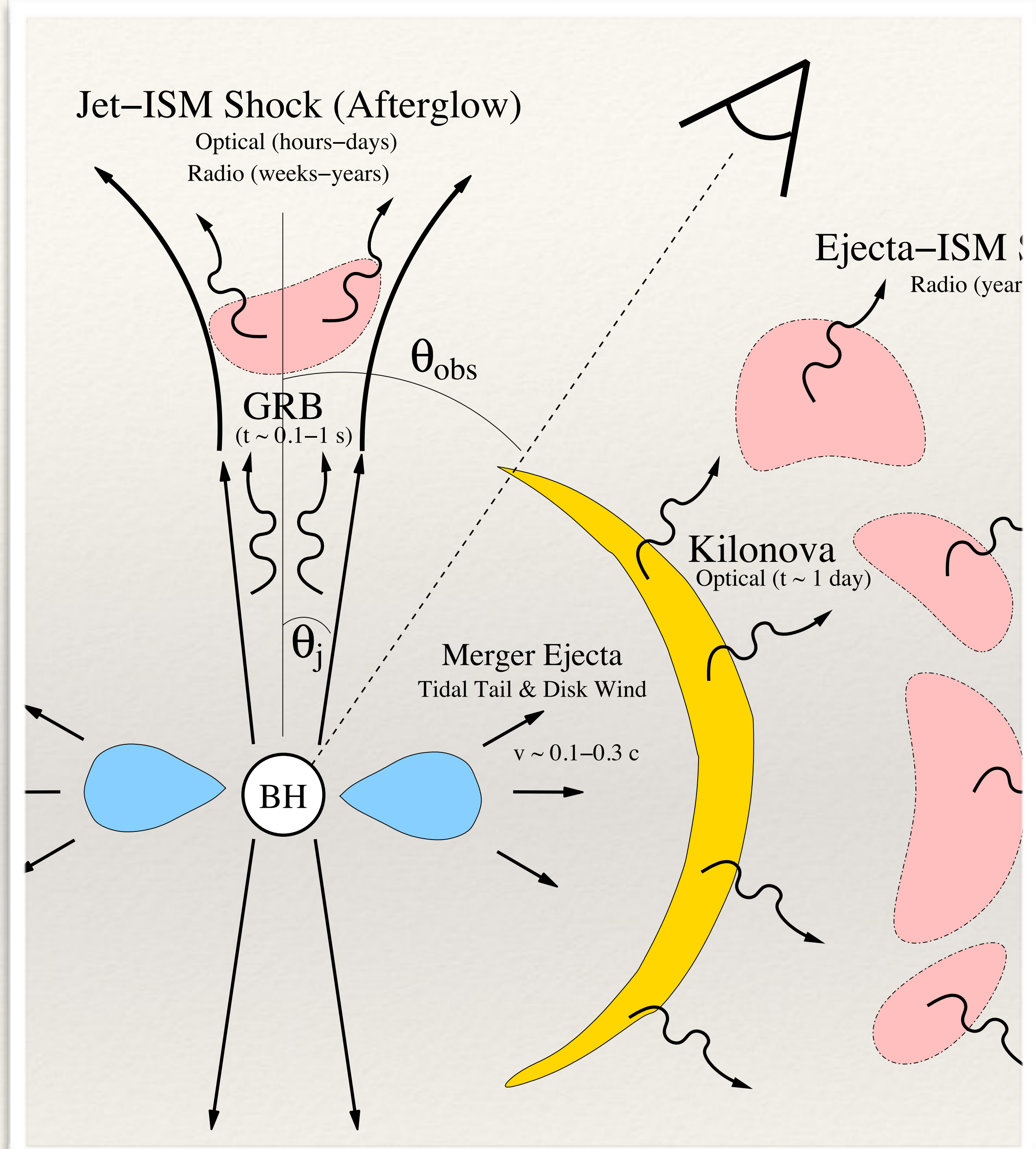
- From the talk Jutta Kunz we learned that a number of Universal relation have been proposed to link properties of Stars.
- Universal relation have also been derived for the peak-frequency of the post merger signal.
- From that follows the idea of using detected gravitation wave signal to get measure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

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 ,**

Binary Neutron Star Merger and the Short-GRB link

Short GRB are associated to BNS-Merger ?

- Supported by numerical relativity simulation with magnetic fields. [Rezzolla et.all The Astrophysical Journal Letters 732, L6 (2011)]
  Short Gamma-Ray Bursts (SGRBs) are among the most luminous explosions in the universe, releasing in less than one second the energy emitted by our Galaxy over one year. Despite decades of observations, the nature of their "central-engine" remains unknown. Considering a binary of magnetized neutron stars and solving Einstein equations, we show that their merger results in a rapidly spinning black hole surrounded by a hot and highly magnetized torus. Lasting over 35 ms and much longer than previous simulations, our study reveals that magnetohydrodynamical instabilities amplify an initially turbulent magnetic field of ~ 10^{12} G to produce an ordered poloidal field of ~ 10^{15} G along the black-hole spin-axis, within a half-opening angle of ~ 30 deg, which may naturally launch a relativistic jet. The broad consistency of our ab-initio calculations with SGRB observations shows that the merger of magnetized neutron stars can provide the basic physical conditions for the central-engine of SGRBs.

- Relativistic Jet may be launched.
  [Ruiz et all. The Astrophysical Journal Letters, 824, L6 (2016)]
  We perform magnetohydrodynamic simulations in full general relativity (GRMHD) of quasi-circular, equal-mass, binary neutron stars that undergo merger. The initial stars are irrotational, n = 1 polytropes and are magnetized. We explore two types of magnetic-field geometries: one where each star is endowed with a dipole magnetic field extending from the interior into the exterior, as in a pulsar, and the other where the dipole field is initially confined to the interior. In both cases the adopted magnetic fields are initially dynamically unimportant. The merger outcome is a hypermassive neutron star that undergoes delayed collapse to a black hole (spin parameter a/MBH ~ 0.74) immersed in a magnetized accretion disk. About 4000M ~ 60(MNS/1.625 Me) ms following merger, the region above the black hole poles becomes strongly magnetized, and a collimated, mildly relativistic outflow —an incipient jet—is launched. The lifetime of the accretion disk, which likely equals the lifetime of the jet, is Δ t ~ 0.1 (MNS/1.625 Me) s. In contrast to black hole–neutron star mergers, we find that incipient jets are launched even when the initial magnetic field is confined to the interior of the stars.

Binary Neutron Star Merger and the macronova link

BNS-Merger and the macronova link: Key fact !

- A neutron star merger ejects a significant amount of mass. See for example Dietrich et all. Phys. Rev. D 95, 024029 (2017) and reference therein.
- Macronova (Kilonova) candidates have been discovered and estimated ejected mass is 0.01 - 0.1 Msun
- In general a macronova could be powered by either a **binary neutron star merger** or a neutron star–black hole merger.
- Major differences of the ejecta from these two type of progenitors are that NS –BH mergers eject much more material than the NS binary mergers and that NS–BH merger ejecta is more collimated than the NS binary merger ejecta.
- Also in the case of NS-BH merger many numerical relativity (NR) simulation have been performed in a wide range of binary parameters, and the quantitative dependance of the properties of the ejecta is becoming clear. (e.g., Kawaguchi et al. 2015, Kyutoku et al. 2015, Foucart 2014, Lovelace et al. 2013 …)

PART 2
How we do simulate such systems.

The numerical challenge

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, …

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.

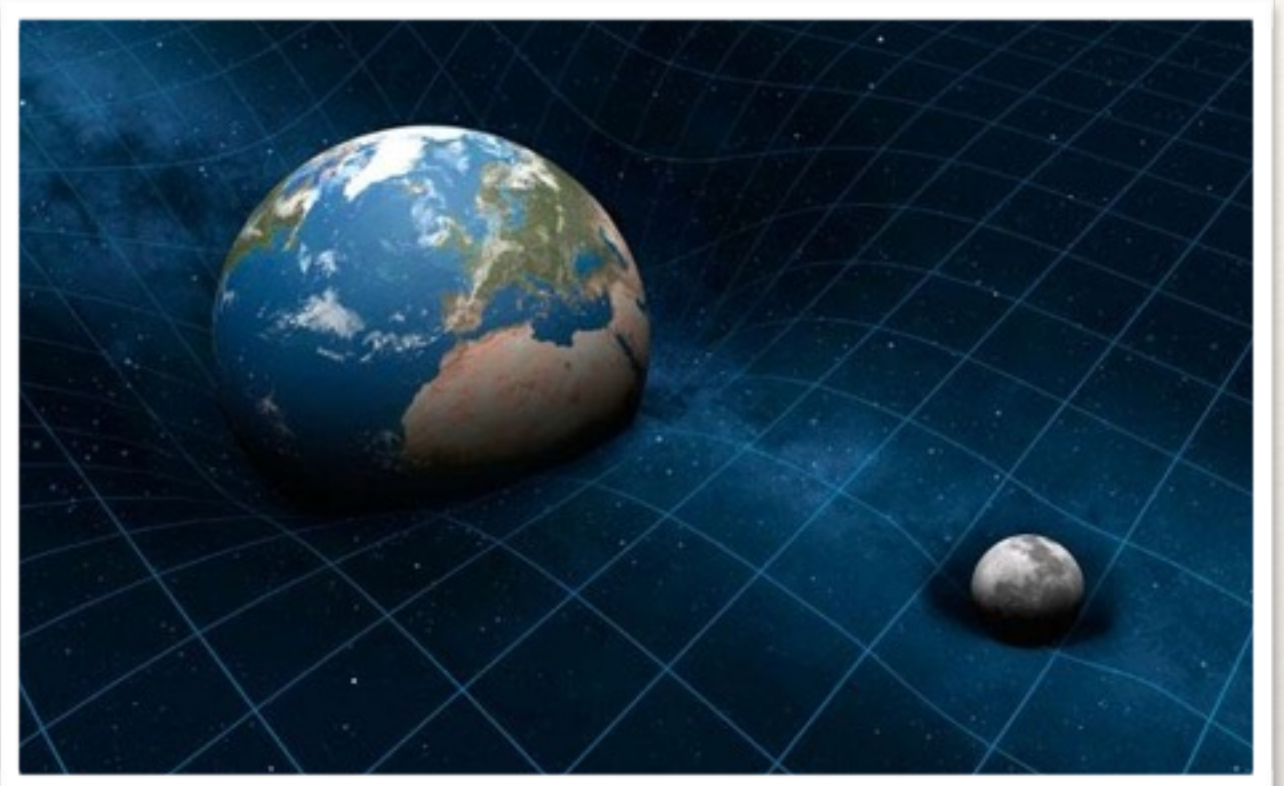
- An accurate description of GW emission of different model sources (different choice of the underlying NS physics through different choices of EOS) are useful for developing empirical relations to be able to infer NS parameter from future GW detections, as well as, to get information on the correct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

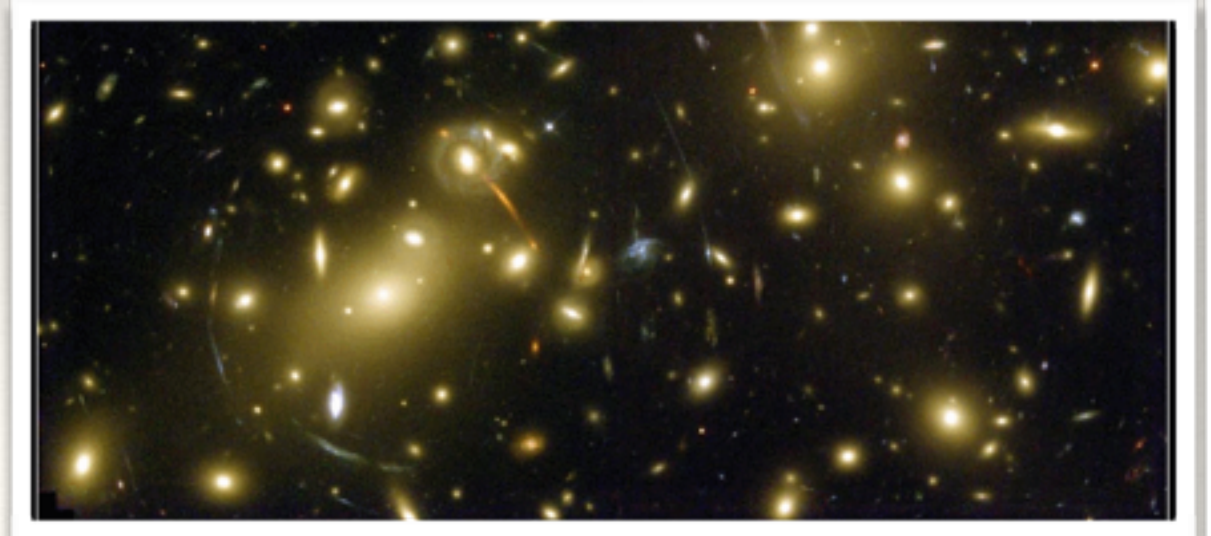
General Relativity (in short)

- 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**

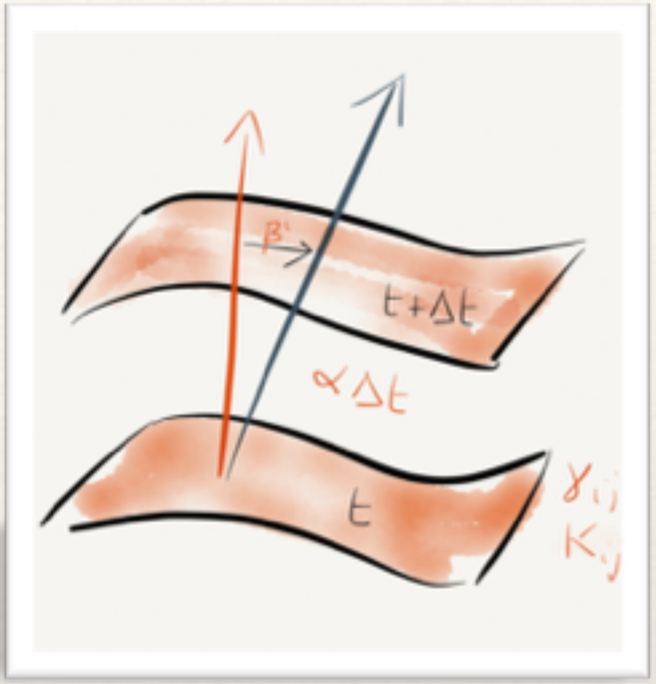
Ideal Fluid Matter

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

- 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

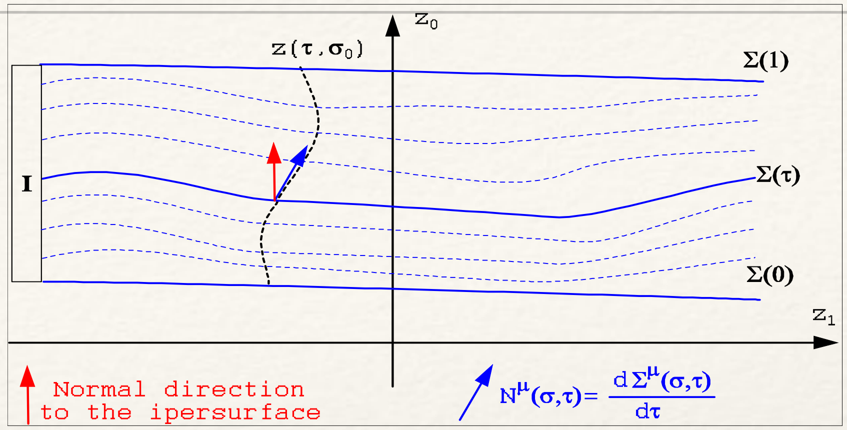
Use usual numerical methods:

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

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

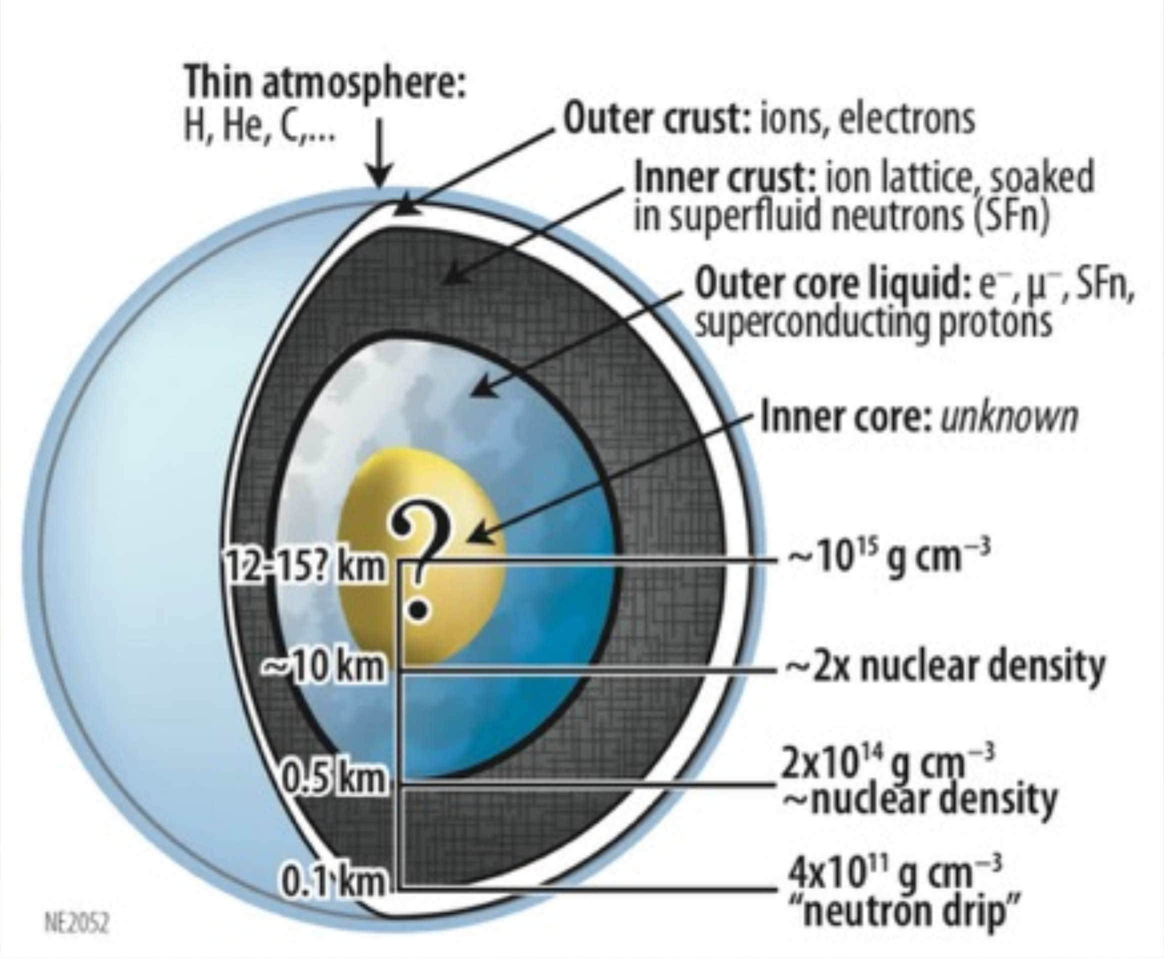
Neutron Stars

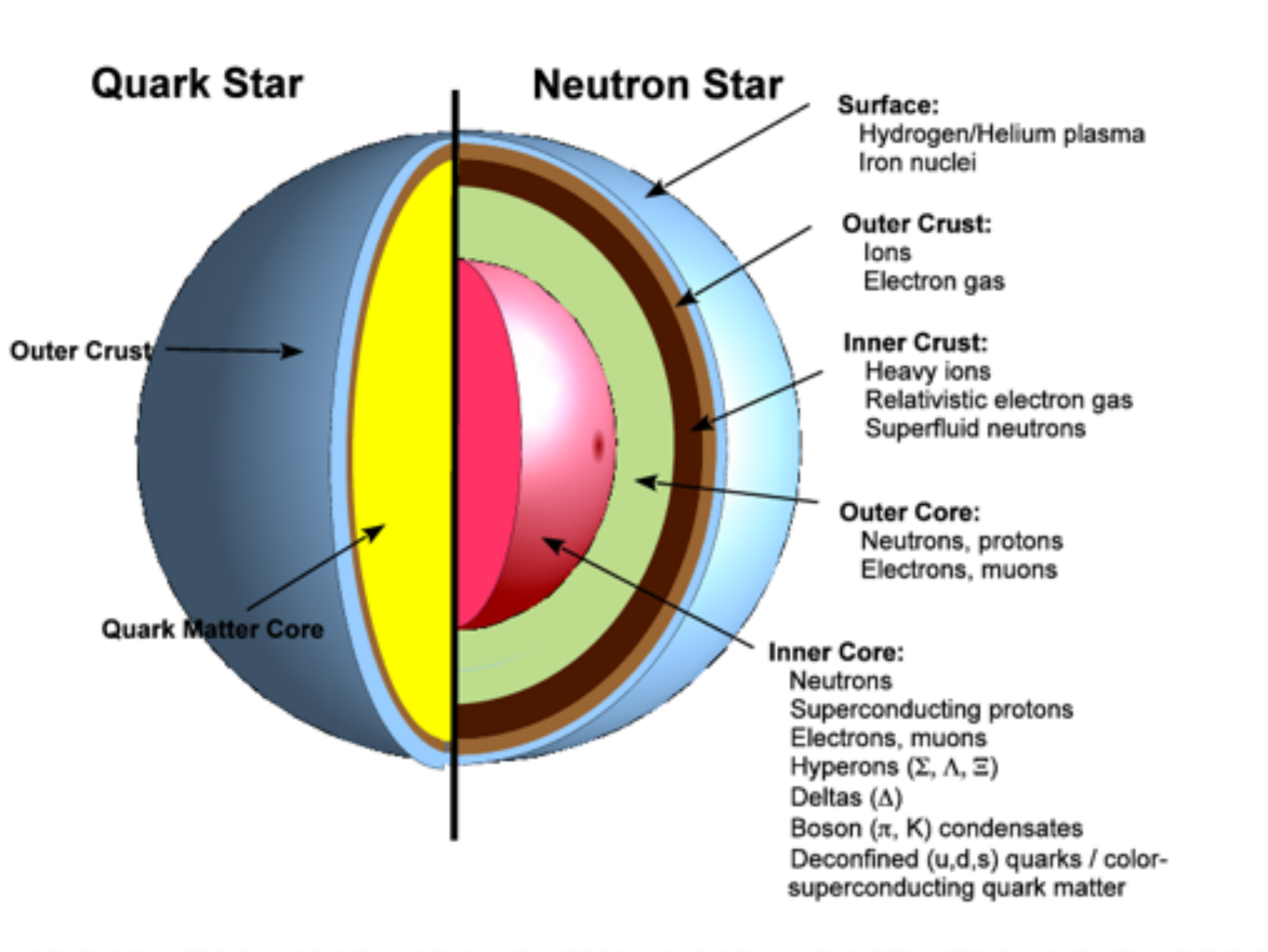
- Neutron Stars are a degenerate state of matter that is formed after the core collapse in a supernova event (where the electrons fall into nuclear matter and get captured by protons forming neutrons).
- Excellent laboratory to study high-density nuclear physics and EOS.
- Neutron star composition still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

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

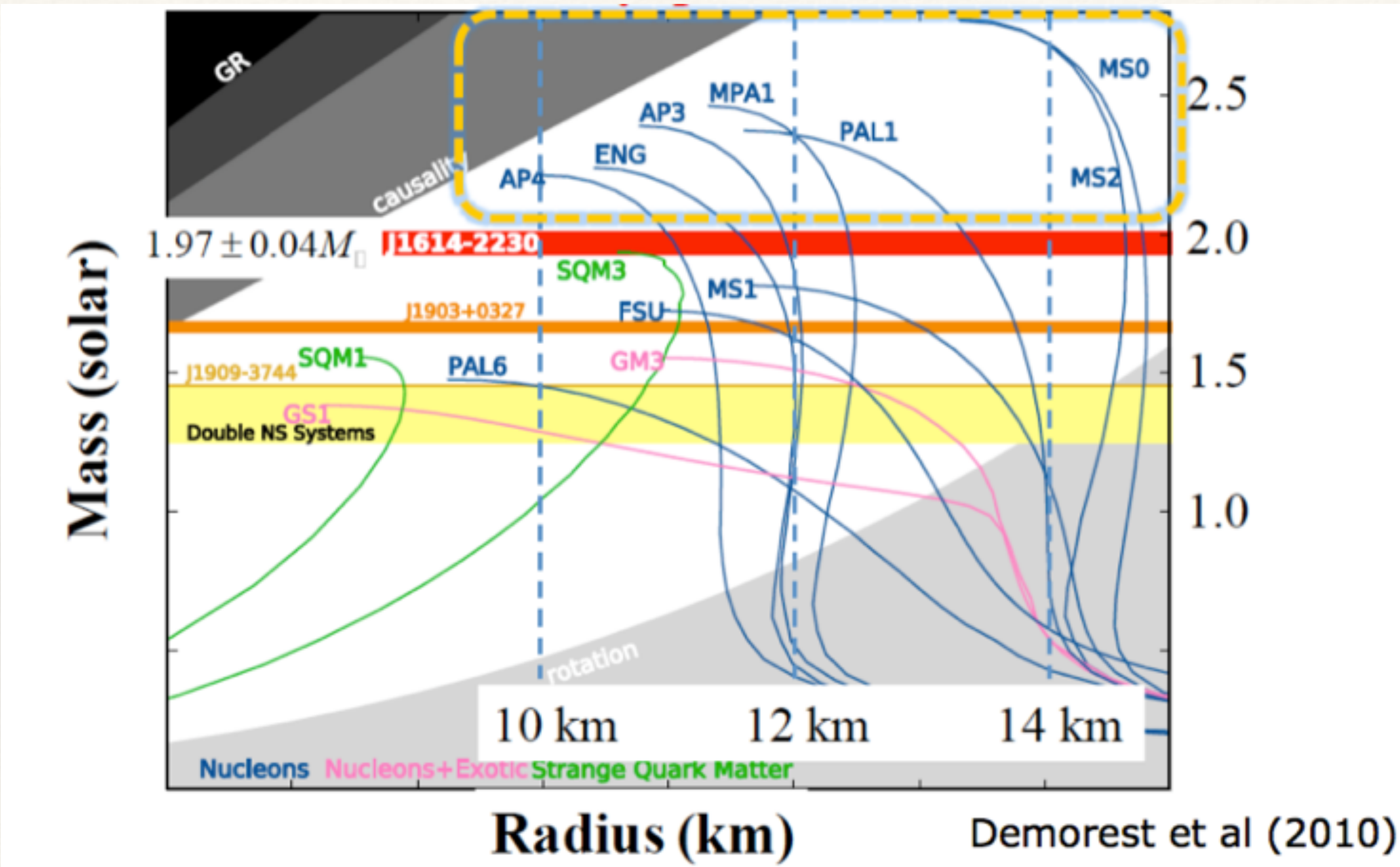
BNS as a probe for Nuclear Matter EOS

- 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

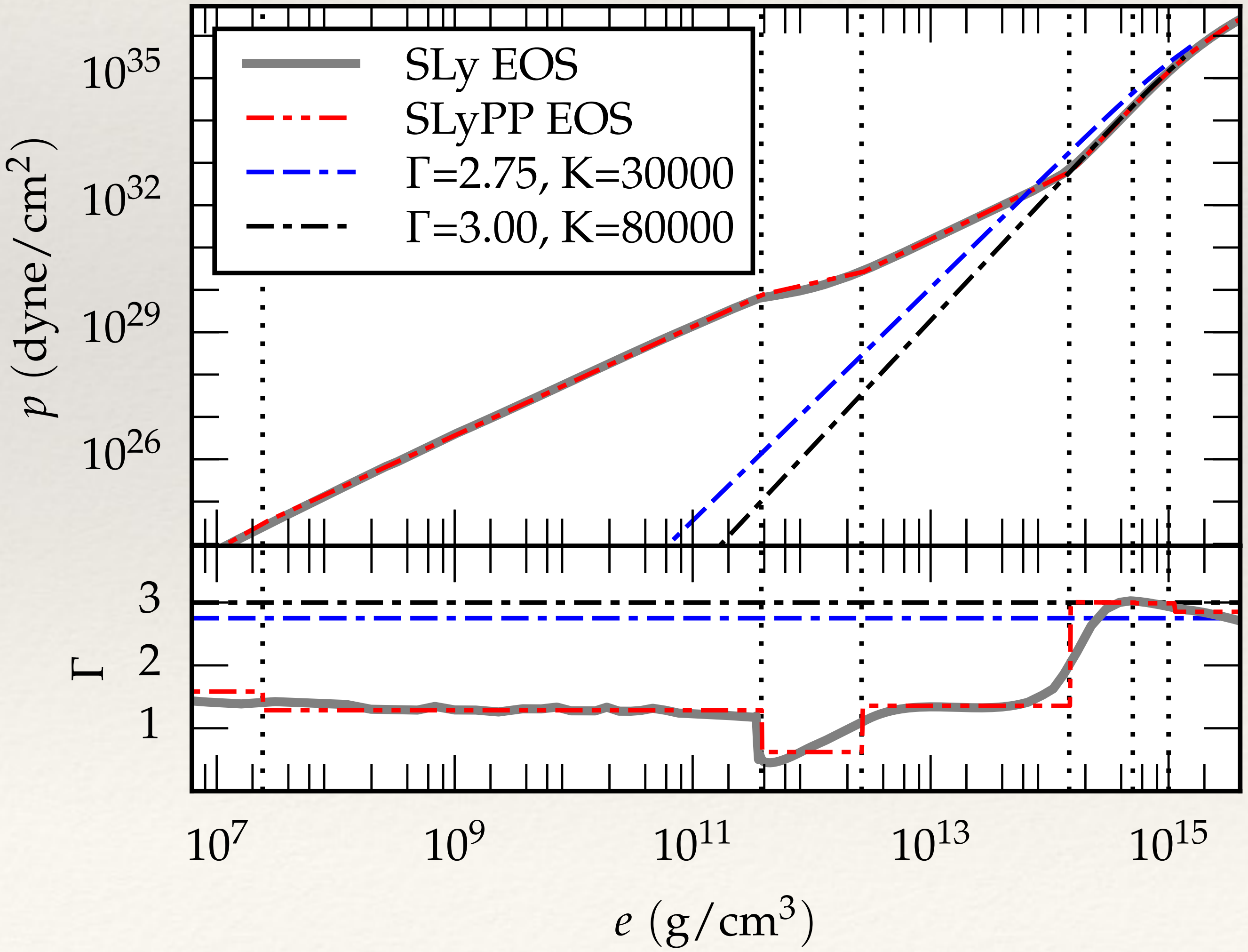


Many different possibilities depending on the EOS. **GWs** in the late inspiral and merger phases could constrain NS EOS. **Many GW templates from Numerical Relativity are necessary**

Initial Models

EOS in numerical relativity

- Usually just a pice-wise politropic approximant.
- More works using tabulated EOS, realistic thermal effect and Neutrinos dynamics.
- The real challenge is to introduce more Nuclear-Physics in simulations.



The true EOS for nuclear matter in a system similar to a NS is still unknown, not even assuming a small effect on the temperature, i.e., cold neutron star, as expected here for initial data.

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

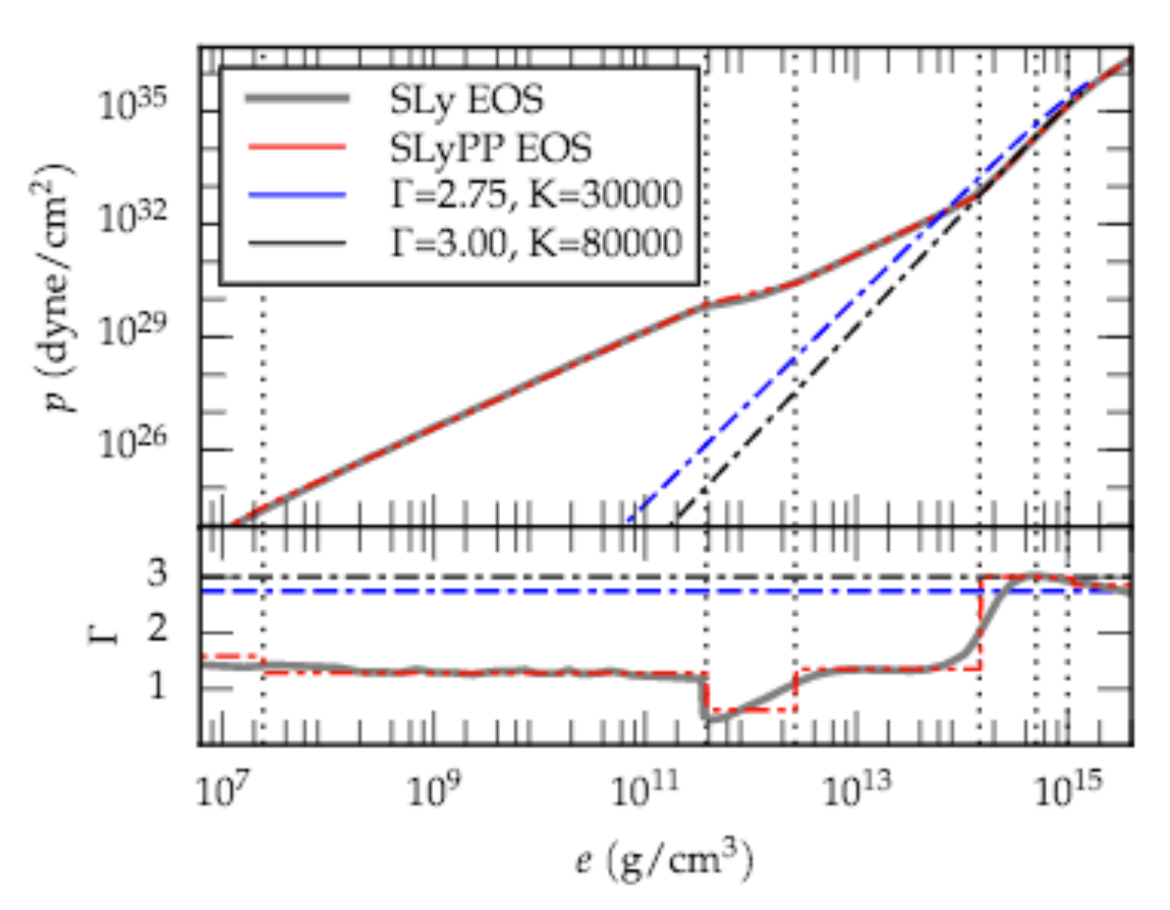
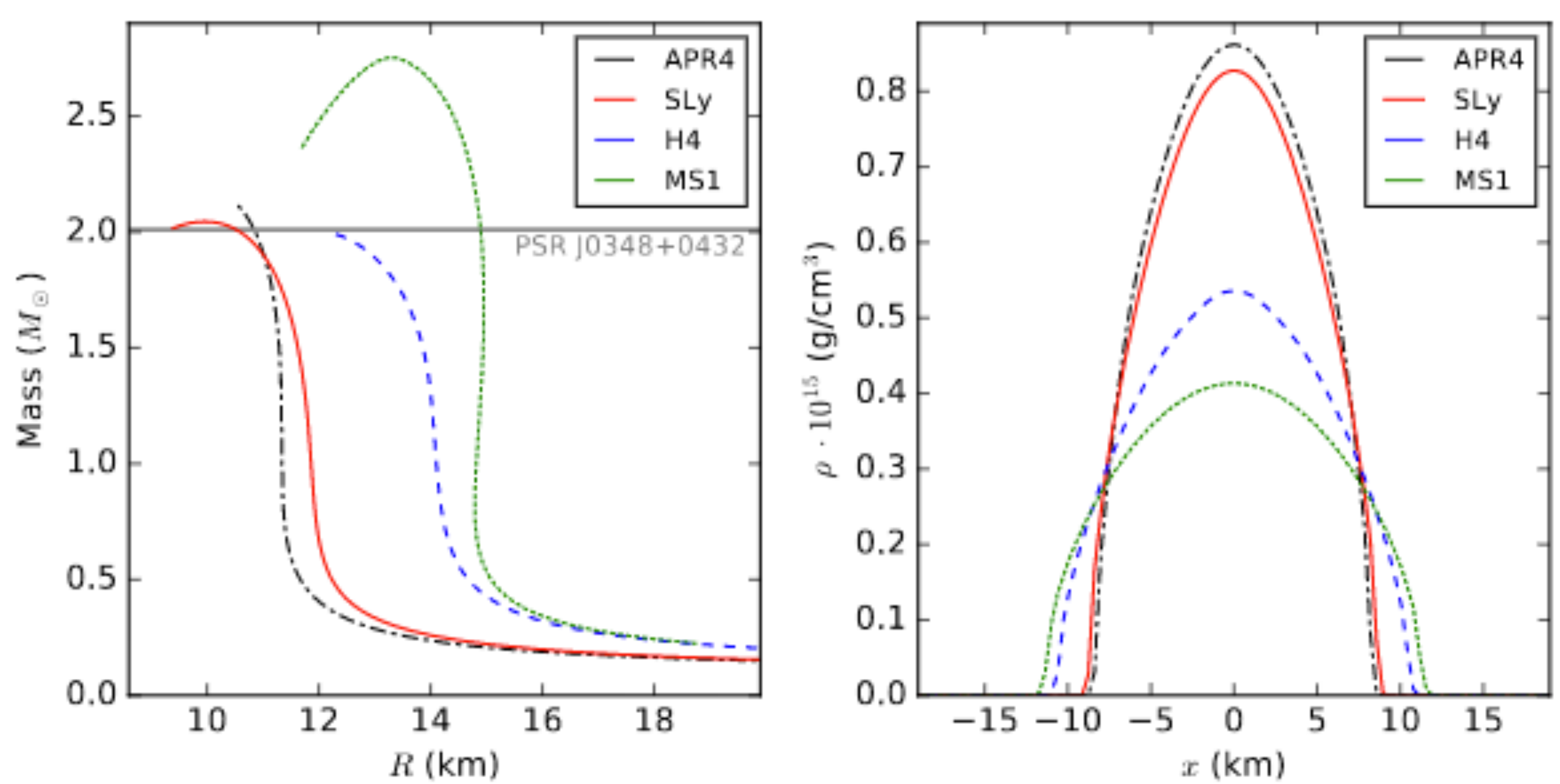


FIG. 1. Plot of the pressure (P) and of the adiabatic index ($\Gamma = d\log(P)/d\log(\rho)$) as a function of the energy density ($e = \rho(1+\epsilon)$) for the SLy EOS, its piece-wise polytropic approximation (the one used in the present work) and two isentropic polytropic EOS $P = K\rho^\Gamma$.

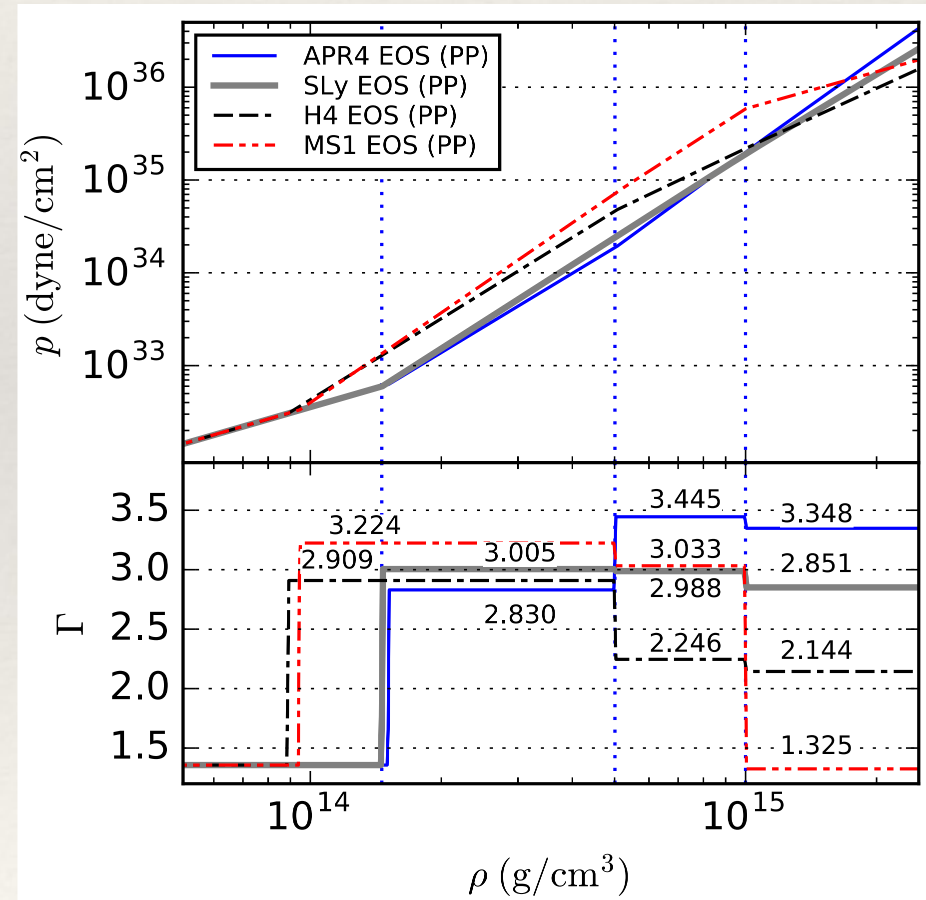
Douchin and Haensel 2000,2001

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.



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

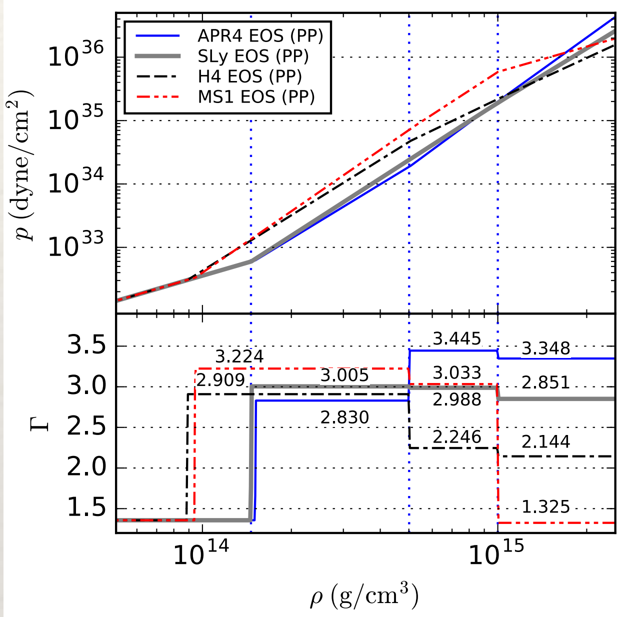


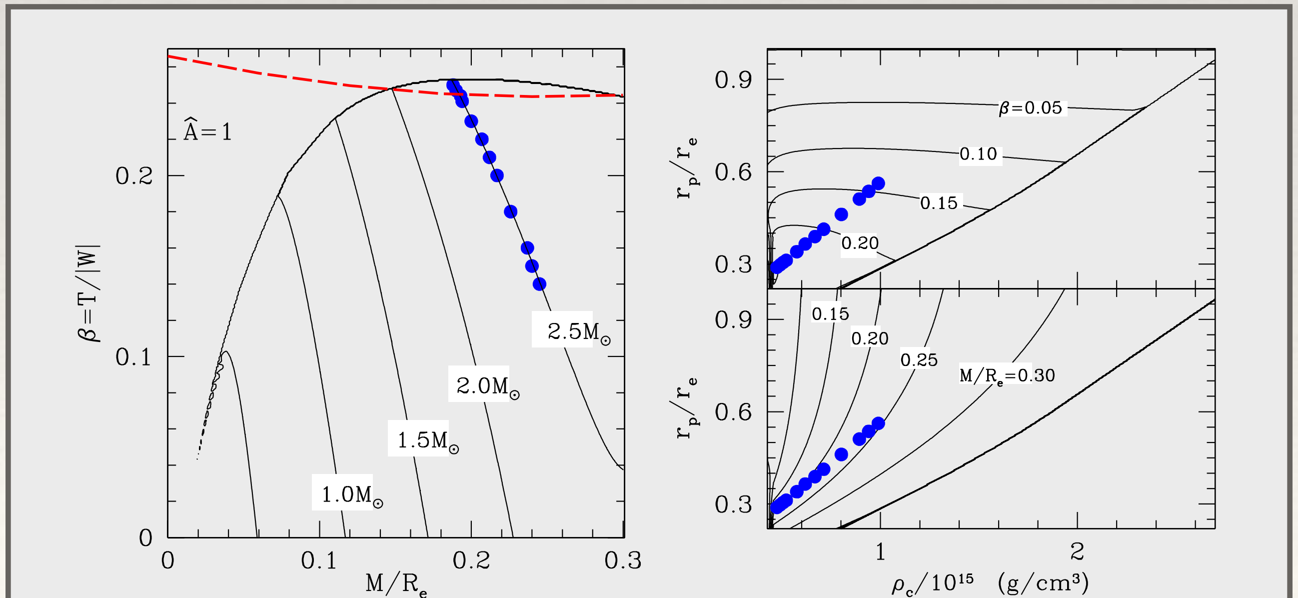
Binary neutron star merger simulations with different initial orbital frequency and equation of state, F. Maione, R. De Pietri, A. Feo and F. Loeffler, Classical and Quantum Gravity, 33, no. 17, 175009 (2016). arXiv:1605.03424

From EOS to initial data

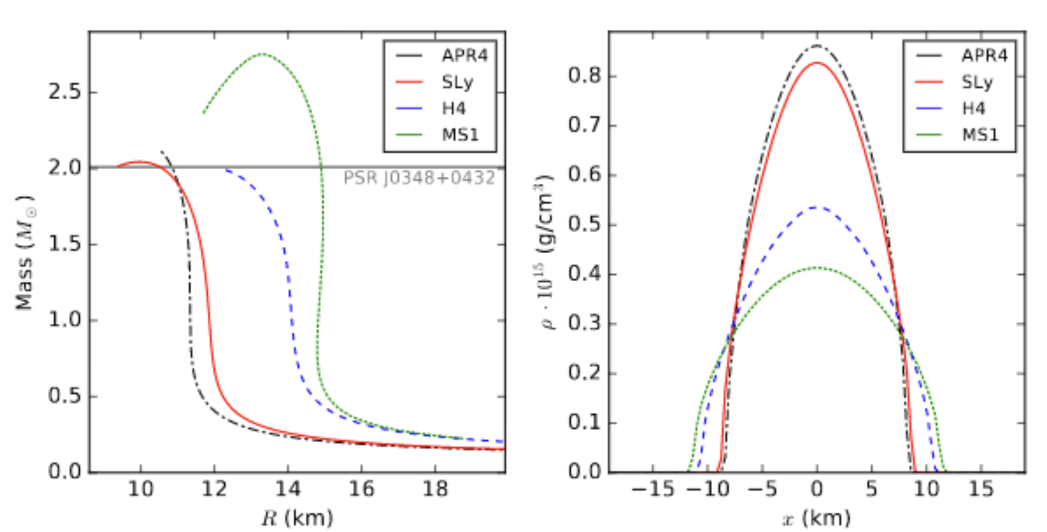
- An EOS is a table that connect pressure and energy to barion density (possible also to temperature, electron fraction,…)
- Given the EOS is possible to solve Einstein Equations + Matter imposing stationarity and axial symmetry => Models for Isolated Stars. Various codes allow to get such solutions: LORENE and RNSID for uniformly and differentially rotating Stars.
- It is possible to calculate the maximum mass for non-rotating or uniformly rotating stars.

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)
	TOV	**UNIF.**





SLy - differential rotation



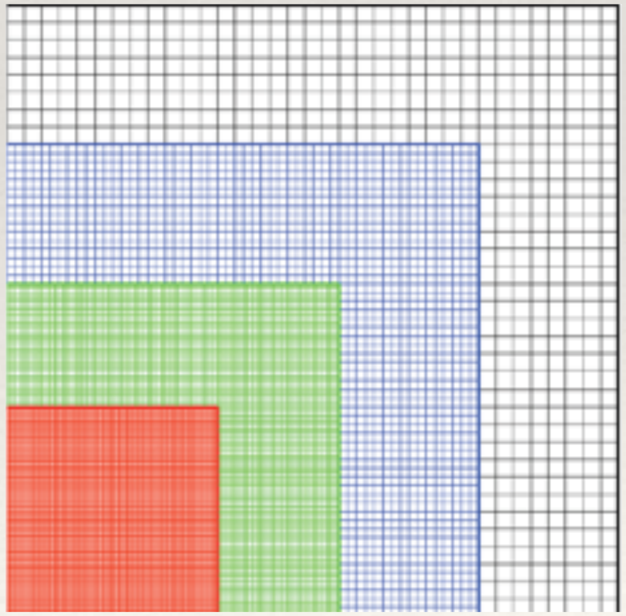
(a) Mass-Radius relations (b) Initial density profiles

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

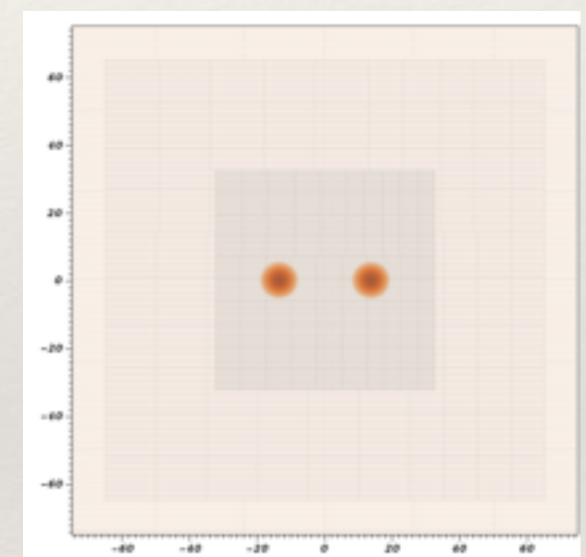


The computational challenge

- 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!

$\triangle x$ (CU)	0.75	0.50	0.375	0.25	0.185	0.125
# threads	16	64	128	256	512	2048
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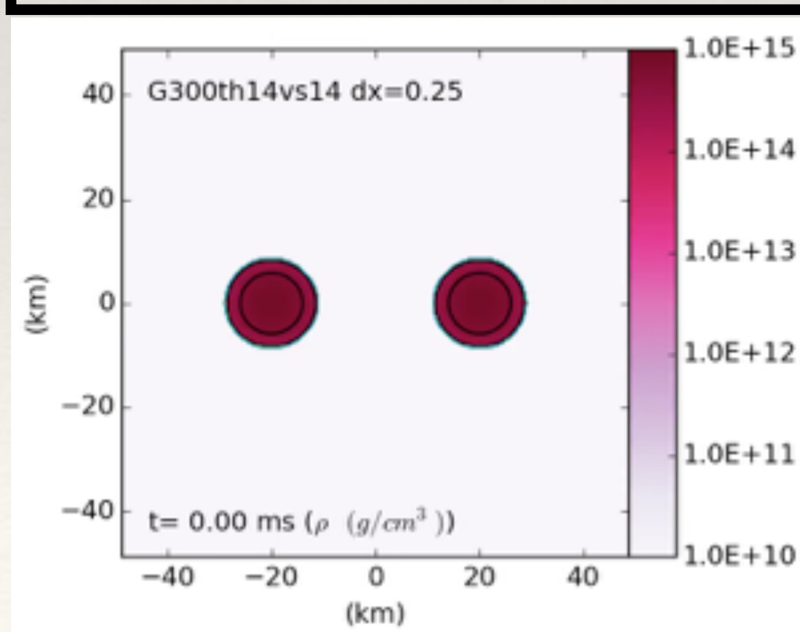
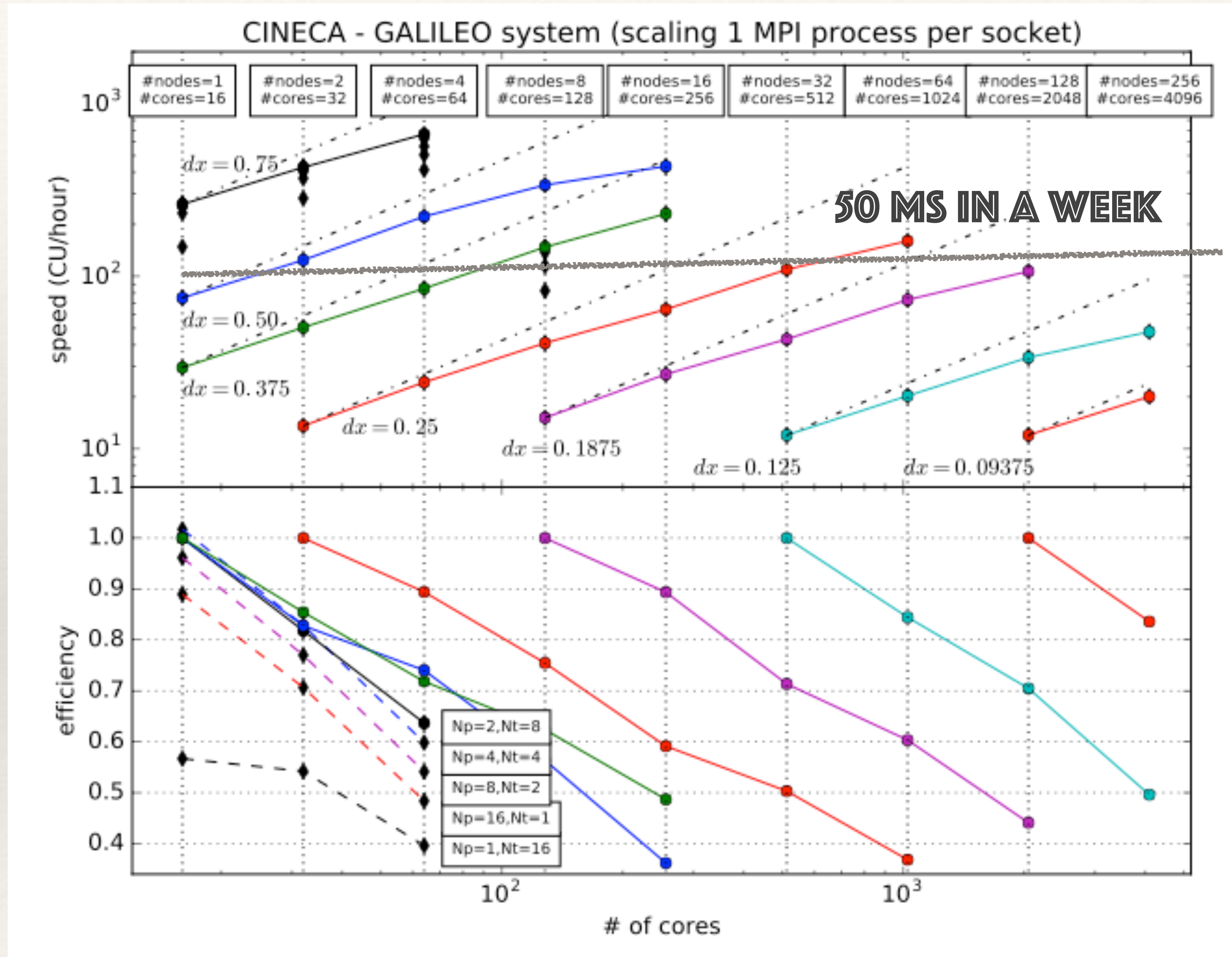
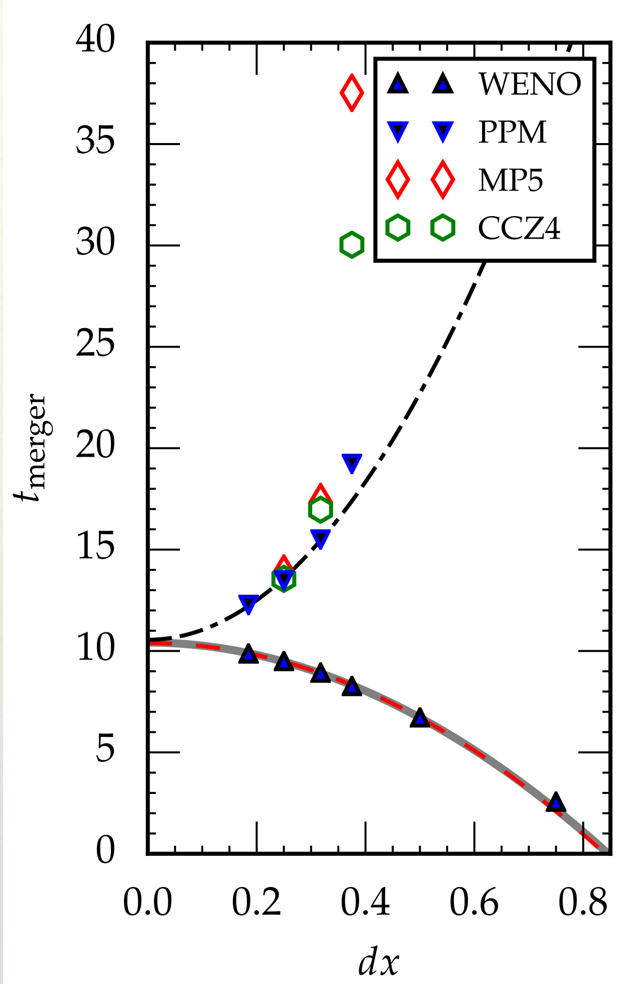




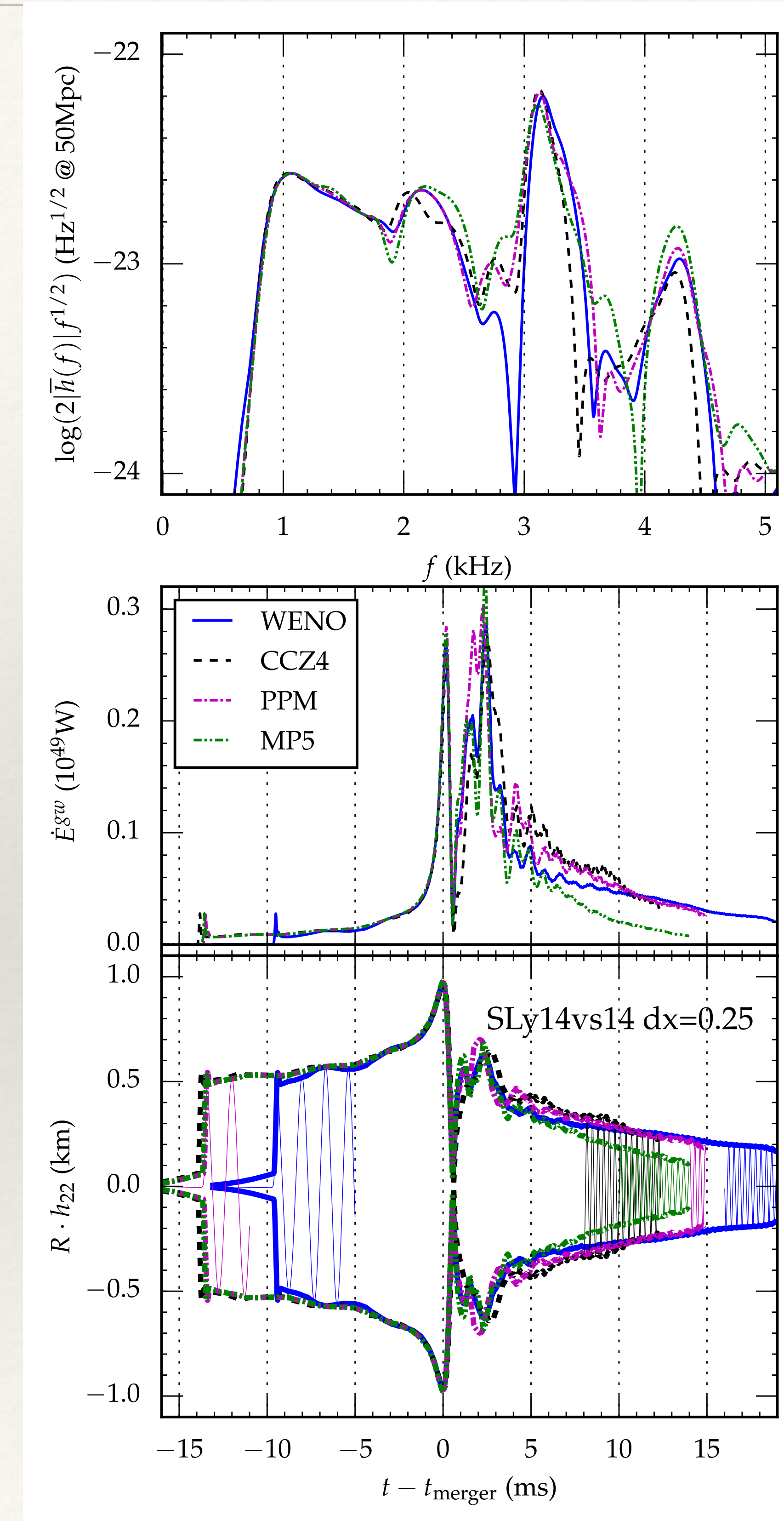
Results on Numerical Methods comparisons

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!

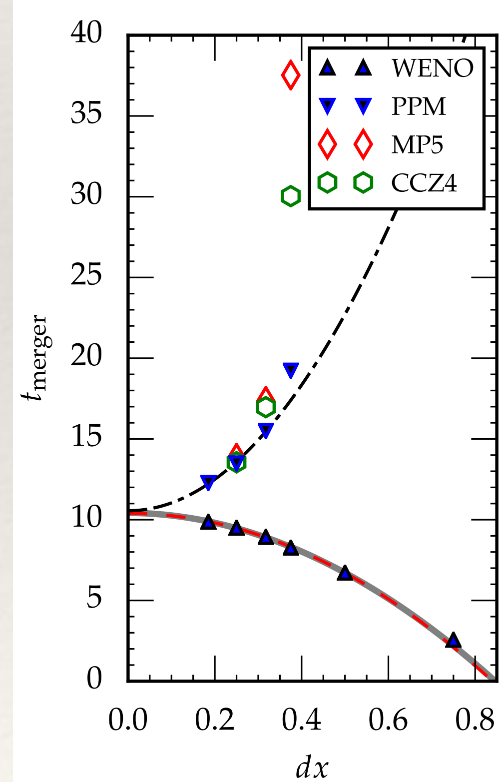
Data Analysis: Convergence

- 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:

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

- 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	$t^{dx=0.50}_{\rm merger}$ [ms]	$t^{dx=0.375}_{\rm merger}$ [ms]	$t^{dx=0.25}_{\rm merger}$ [ms]	$t^{dx=0\ (ext)}_{\rm merger}$ [ms]	$t^{\rm EOB}_{\rm merger}$ [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



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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[8,4], Frank Löffler[5], Christian D. Ott[1,5], Christian Reisswig[1], Erik Schnetter[6,7,5]

Multi-orbits

Initial models we studied and how we can computed them .

- The initial data of the simulations can be calculated using the **LORENE** code ["LORENE: Langage Objet pour la RElativité NumériquE," **http://www.lorene.obspm.fr/**] that provides the possibility to generate arbitrary initial data for irrotational BNS.
- The code is GPL free and can be freely and easily used to generate the initial data for the simulations.
- The initial data generated by LORENE show a residual eccentricity and we will see how this can be seen in numerical simulation.

Pulsar	M_p $[M_\odot]$	M_c $[M_\odot]$	q	$M^{(1)}$ $[M_\odot]$	$M^{(1)}$ $[M_\odot]$
J0737-3039A	1.3381(7)	1.2489(7)	0.93	1.36	1.47
B1534+12	1.3330(2)	1.3454(2)	0.99	1.46	1.47
J1756-2251	1.341(7)	1.230(7)	0.92	1.33	1.47
J1906+0746*	1.291(11)	1.322(11)	0.98	1.41	1.45
B1913+16	1.4398(2)	1.3886(2)	0.96	1.53	1.59
J0453+1559	1.559(5)	1.174(4)	0.75	1.27	1.74

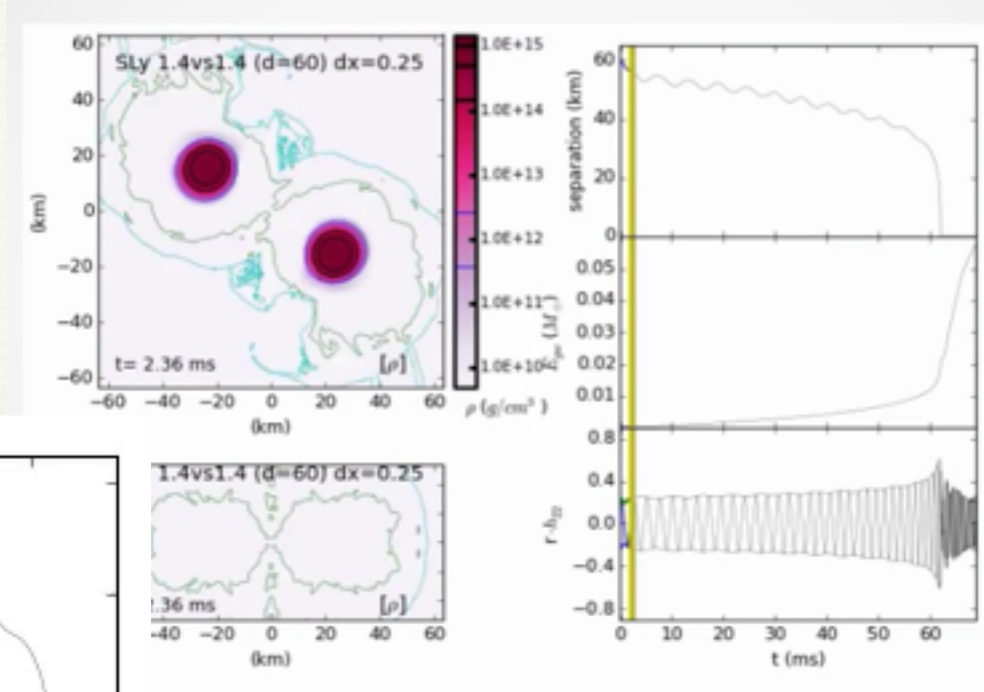
Table from: Martinez et al.: "Pulsar J0453+1559: A Double Neutron Star System with a Large Mass Asymmetry" arXiv:1509.08805v1

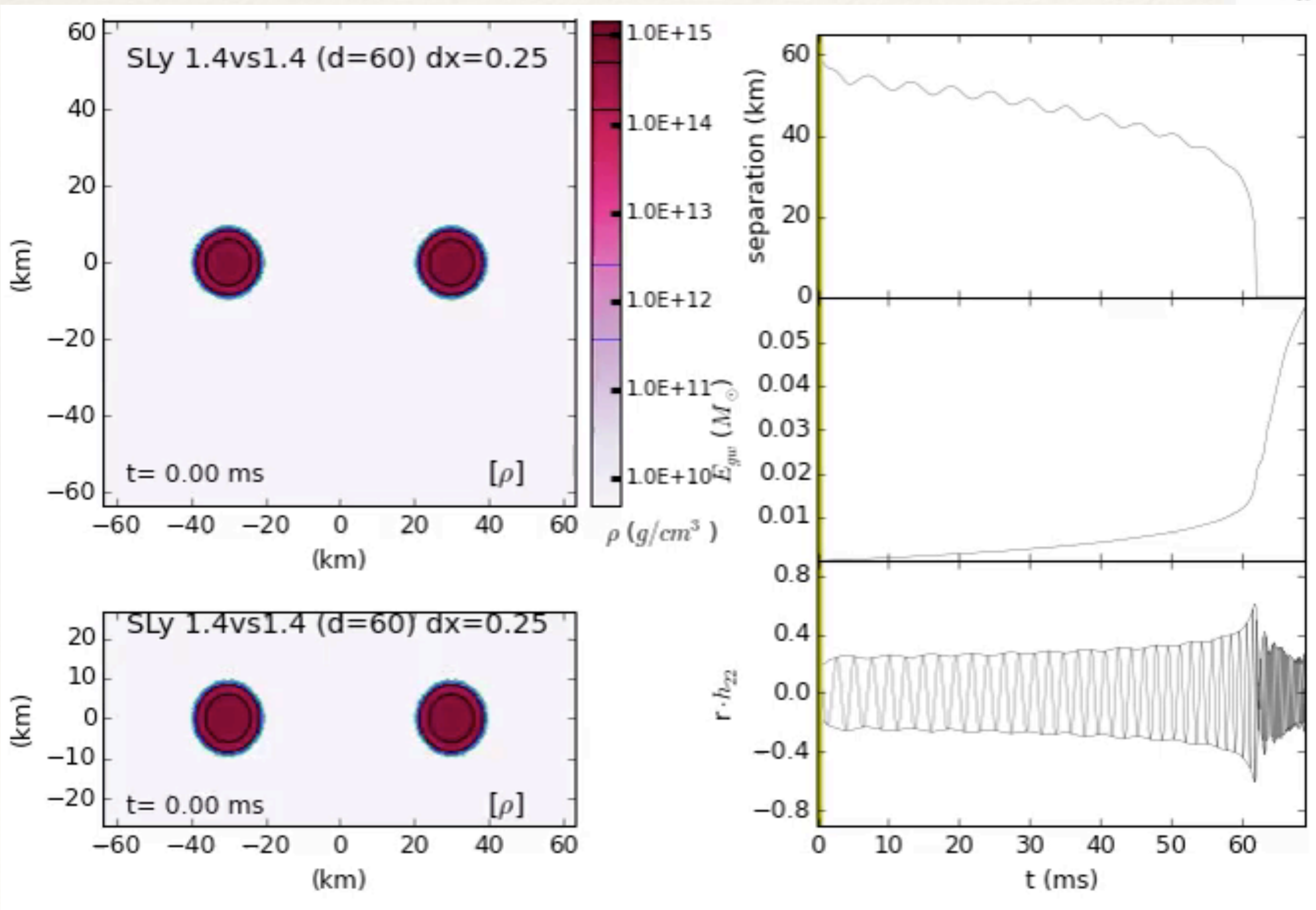
name	$M_0^{(1)}$ $[M_\odot]$	$M_0^{(2)}$ $[M_\odot]$	$M^{(1)}$ $[M_\odot]$	$M^{(2)}$ $[M_\odot]$	Ω $\left[\frac{\text{krad}}{s}\right]$	M_{ADM} $[M_\odot]$	J $\left[\frac{GM_\odot^2}{c}\right]$
SLy12vs12	1.20	1.20	1.11	1.11	1.932	2.207	5.076
SLy13vs13	1.30	1.30	1.20	1.20	1.989	2.373	5.730
SLy14vs14	1.40	1.40	1.28	1.28	2.040	2.536	6.405
SLy15vs15	1.50	1.50	1.36	1.36	2.089	2.697	7.108
SLy16vs16	1.60	1.60	1.44	1.44	2.134	2.854	7.832
SLy135vs145	1.35	1.45	1.24	1.32	2.040	2.536	6.397
SLy13vs15	1.30	1.50	1.20	1.36	2.040	2.535	6.376
SLy125vs15	1.25	1.55	1.16	1.40	2.040	2.533	6.337
SLy12vs16	1.20	1.60	1.11	1.44	2.039	2.531	6.281
G275th14vs14	1.40	1.40	1.29	1.29	2.053	2.554	6.513
G300th14vs14	1.40	1.40	1.26	1.26	2.028	2.498	6.243

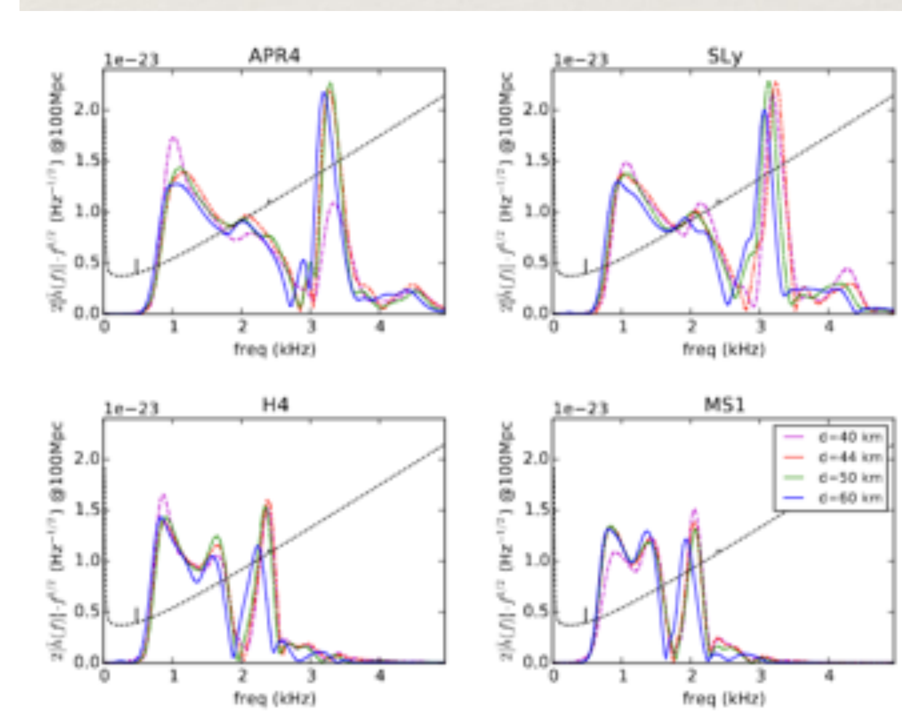
Analysed with 4-EOS and different initial separation

Gravitational Waves from our BNS merger simulations (or…what we can do … the problems we have … and what we will found)

- GW signal from BNS merger simulations using different EOS.
- We look at the EOS signature in the GW signal. Different EOS give different signal.



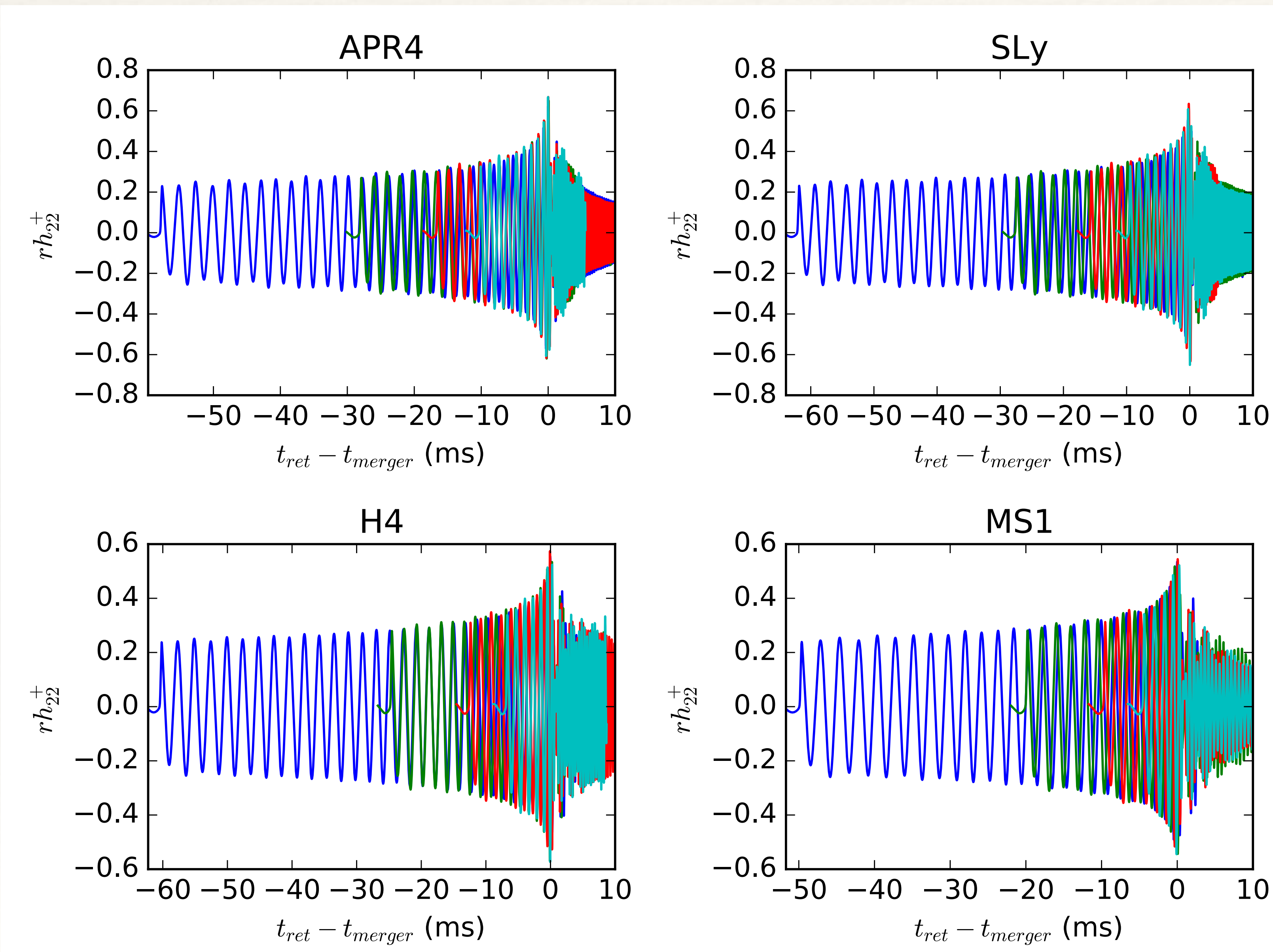


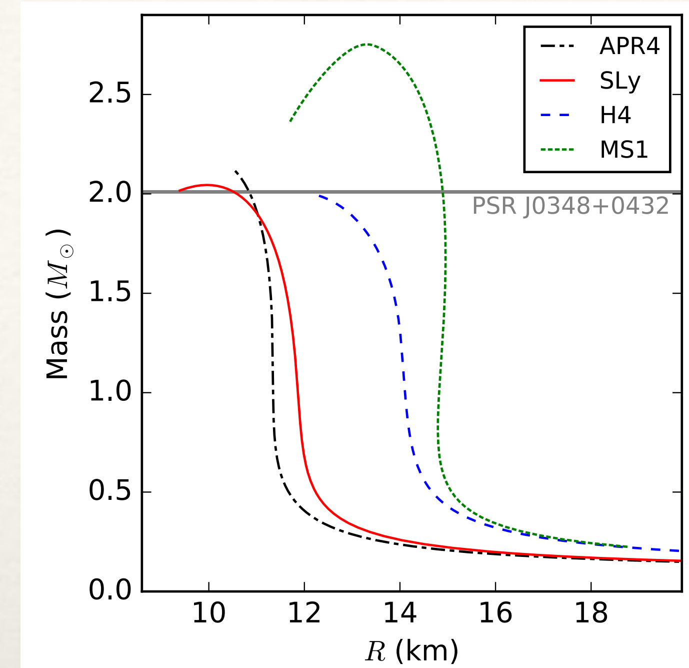


16 orbits before merger

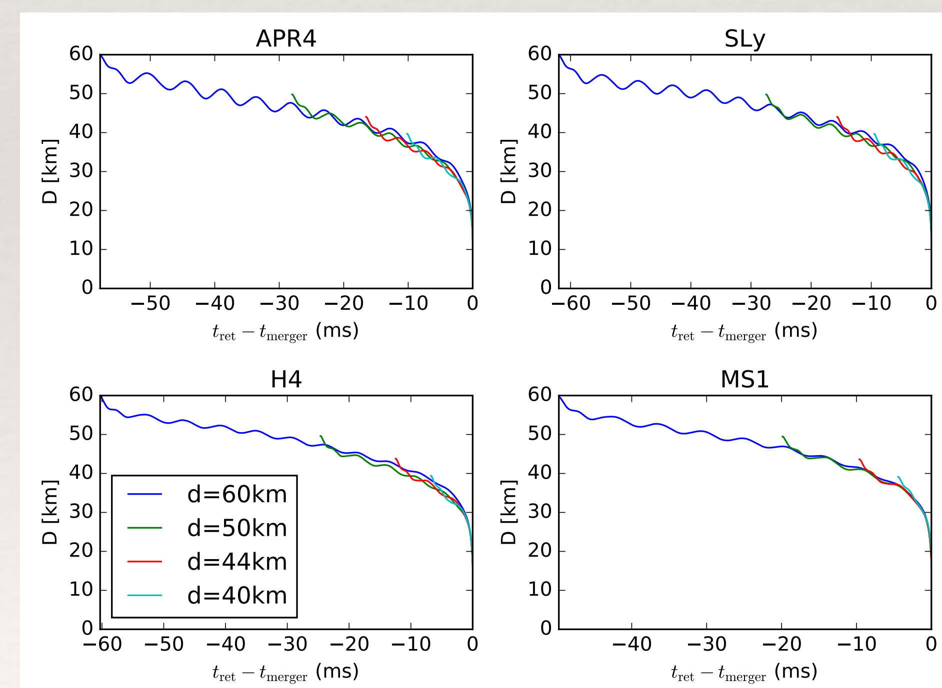
Multi Orbits simulations (four different EOS)

- Long term (up to 16 orbits) equal mass BNS simulations with four different EOS, starting with four different values of the star center d=(40,44.3,50,60)Km

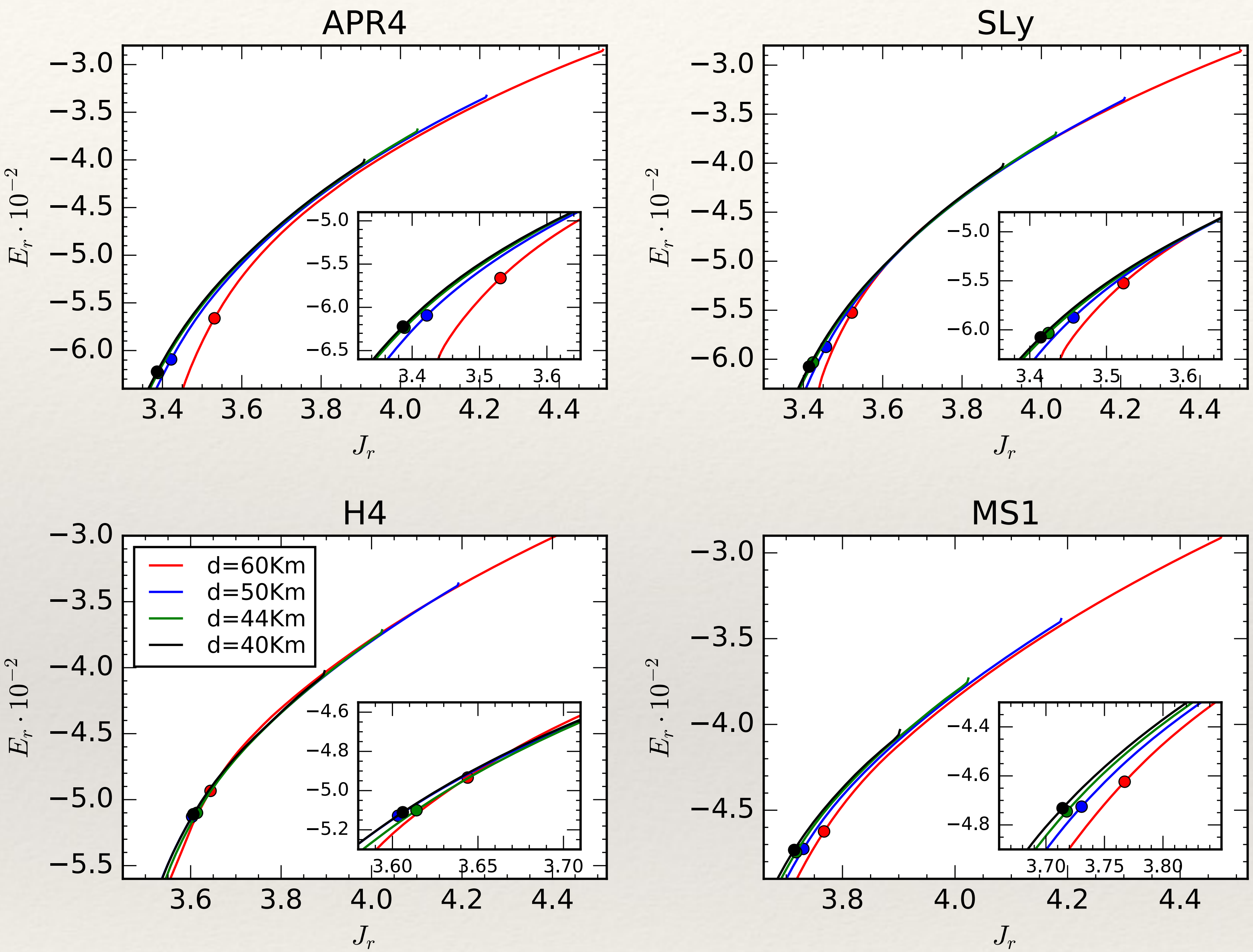




Separation as function of time (eccentricity)



Effect of the initial separation …



FROM:

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

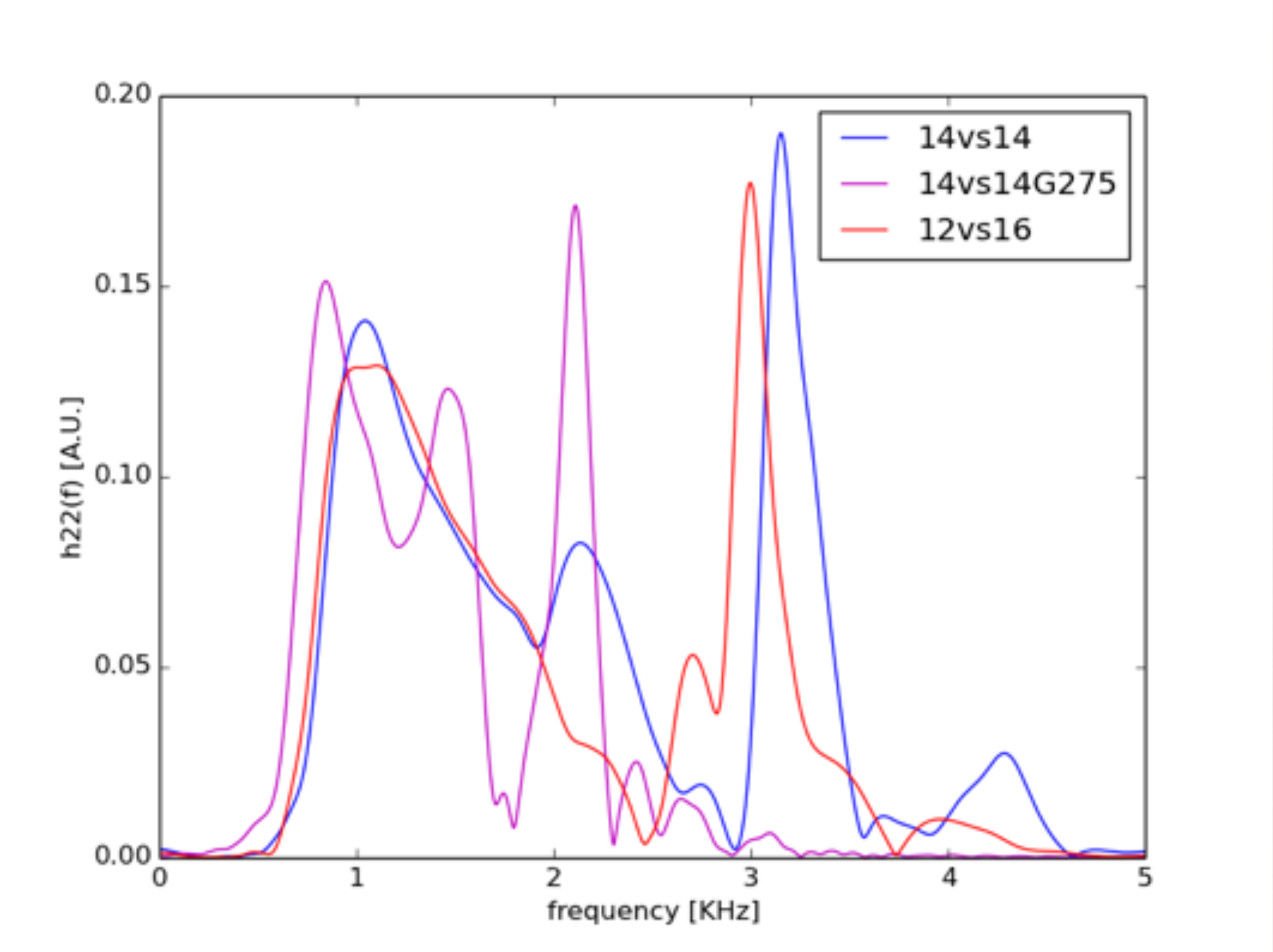
Not comparing with EOB since we have eccentric orbits.

EOS	e $d = 60$ km	e $d = 50$ km	e $d = 44.3$ km
APR4	0.028	0.020	0.020
SLy	0.025	0.019	0.020
H4	0.012	0.012	0.014
MS1	0.014	0.014	0.007

- Reduced adimensional energy versus reduced adimensional angular momentum curves for each model simulated. The merger time values are marked with a filled dot the same color of the corresponding curve. All the curves show very good agreement in the inspiral phase and a small departure in the plunge phase

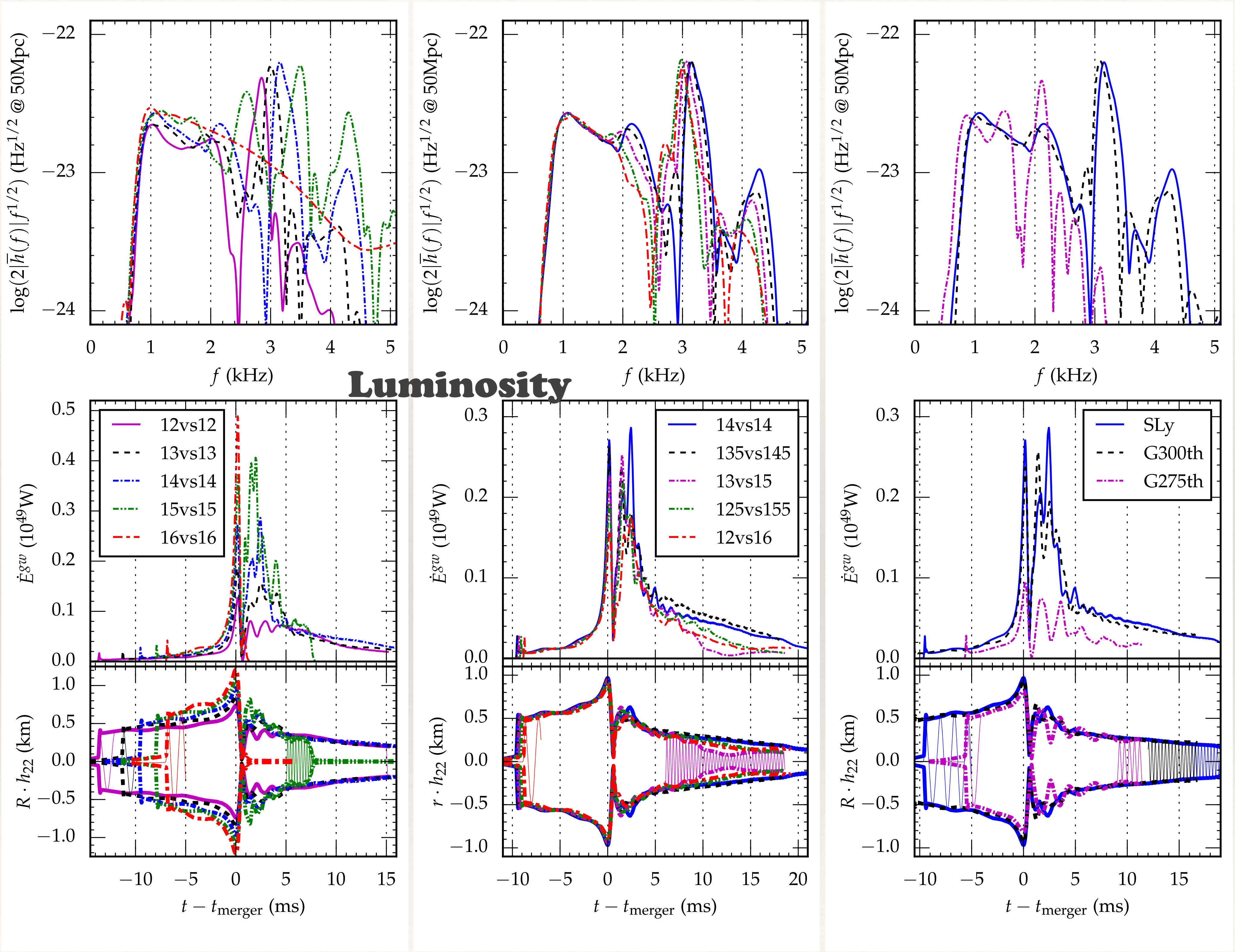
Results: gravitational waves signal properties

- 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.

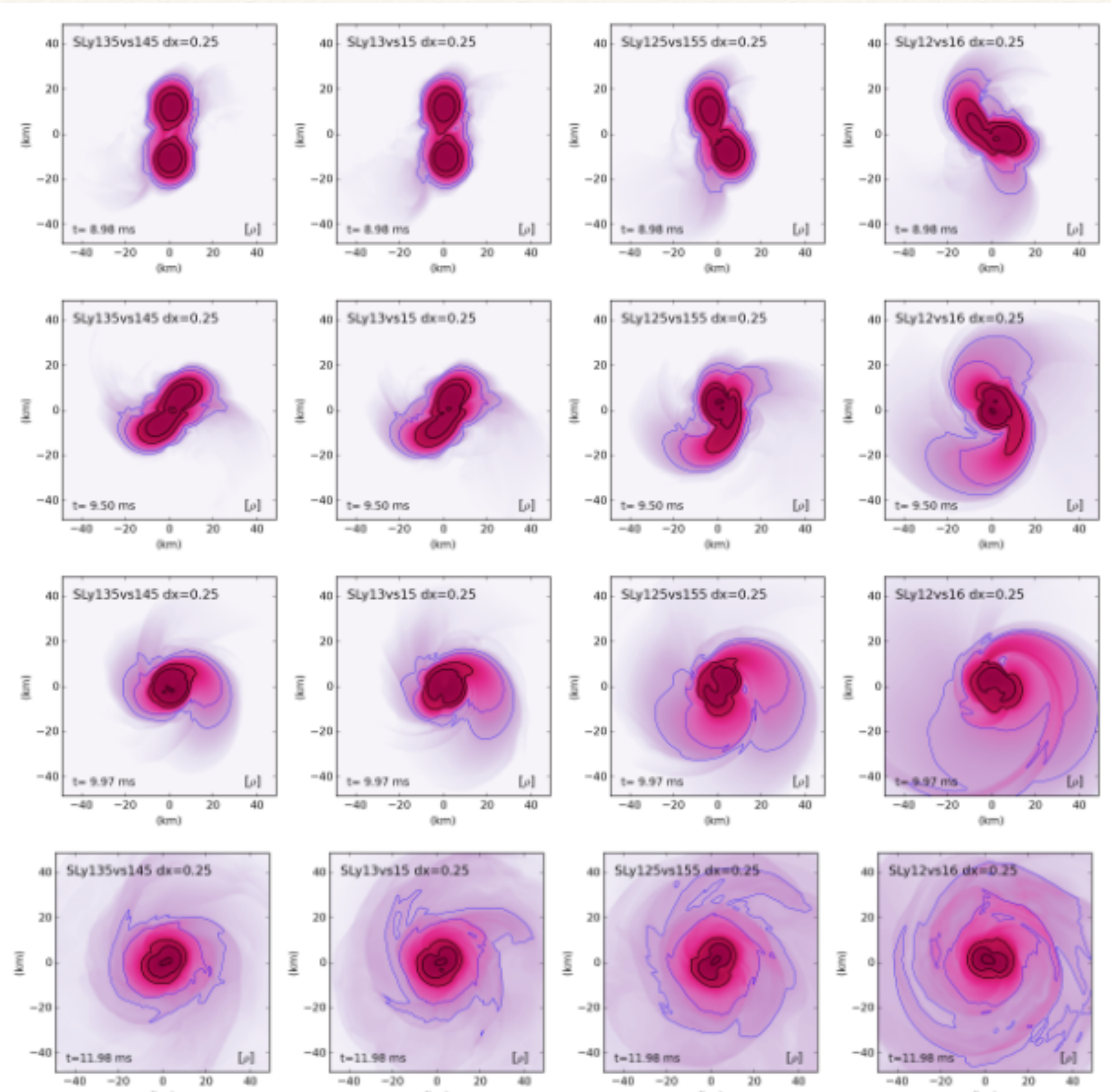


Result for the post merger spectrum

- Position of the peaks depends on the EOS and on the fact that the two masses are equal or unequal.
- Spectroscopic data are a direct route to the investigation of the true-EOS governing matter at extreme conditions.



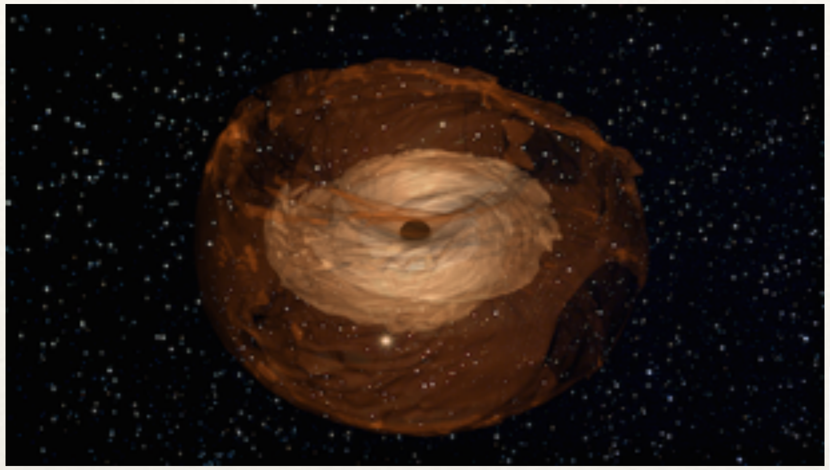
Unequal mass models



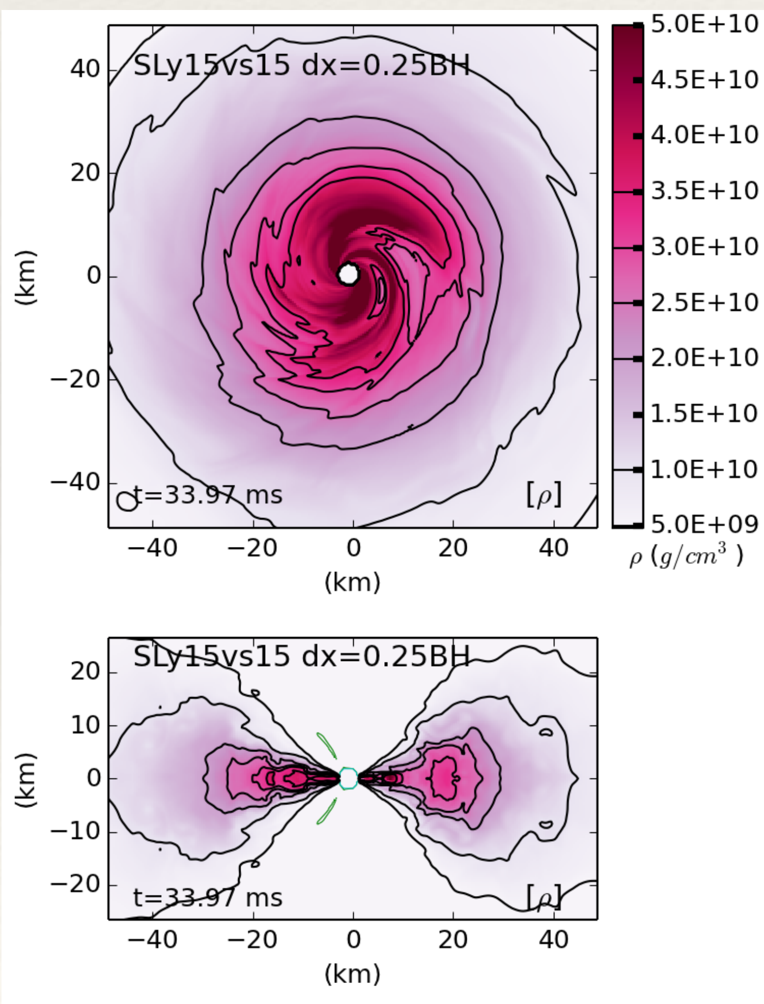
In the case of unequal mass models the remnant neutron star do not shows a single bar deformation.

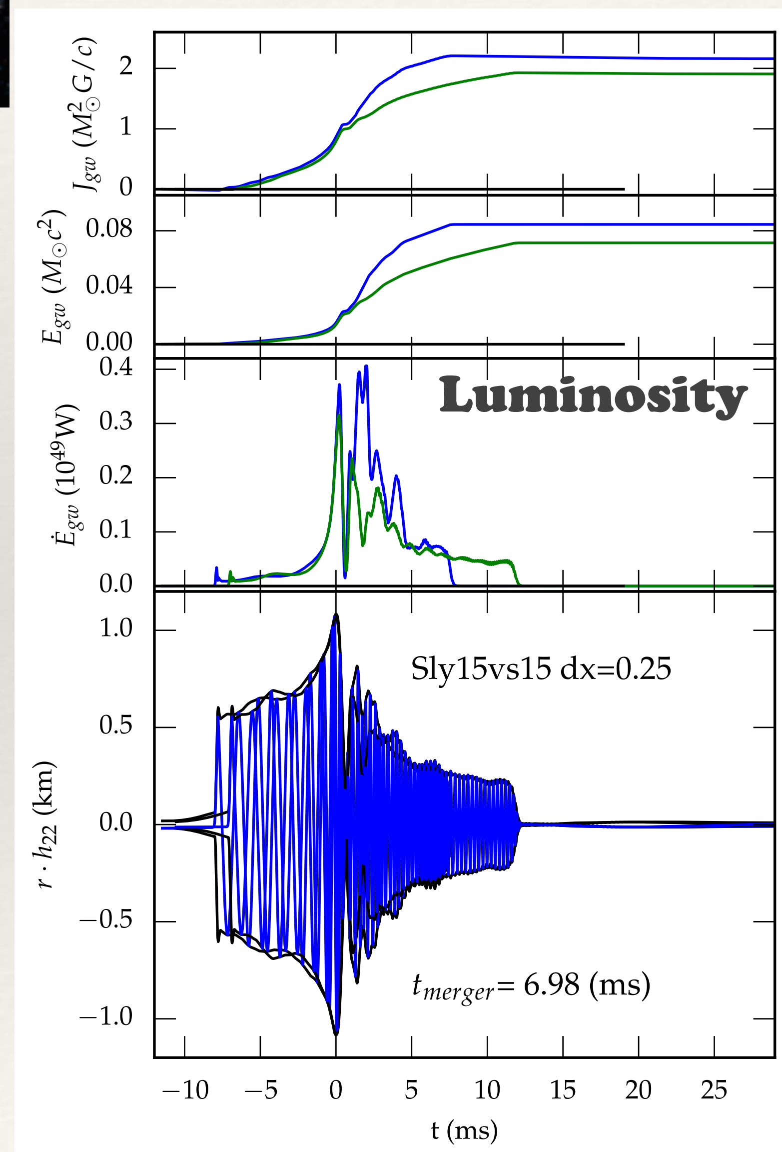
In the merger phase the two arms structure present in the case of equal mass systems is transformed into a single arm structure as the mass ratio increases.

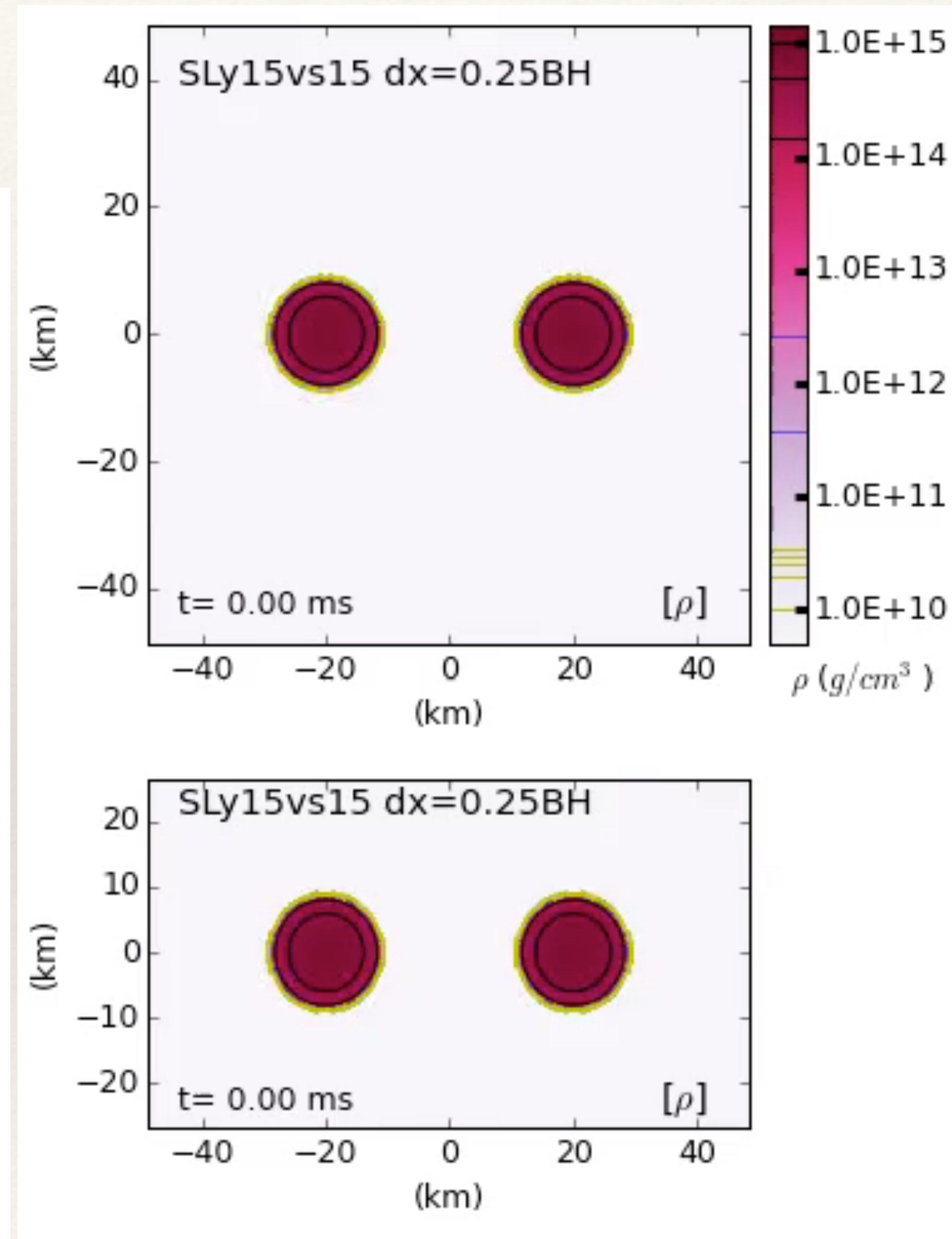
SLy 1.5 vs1.5 (Baryonic Mass)



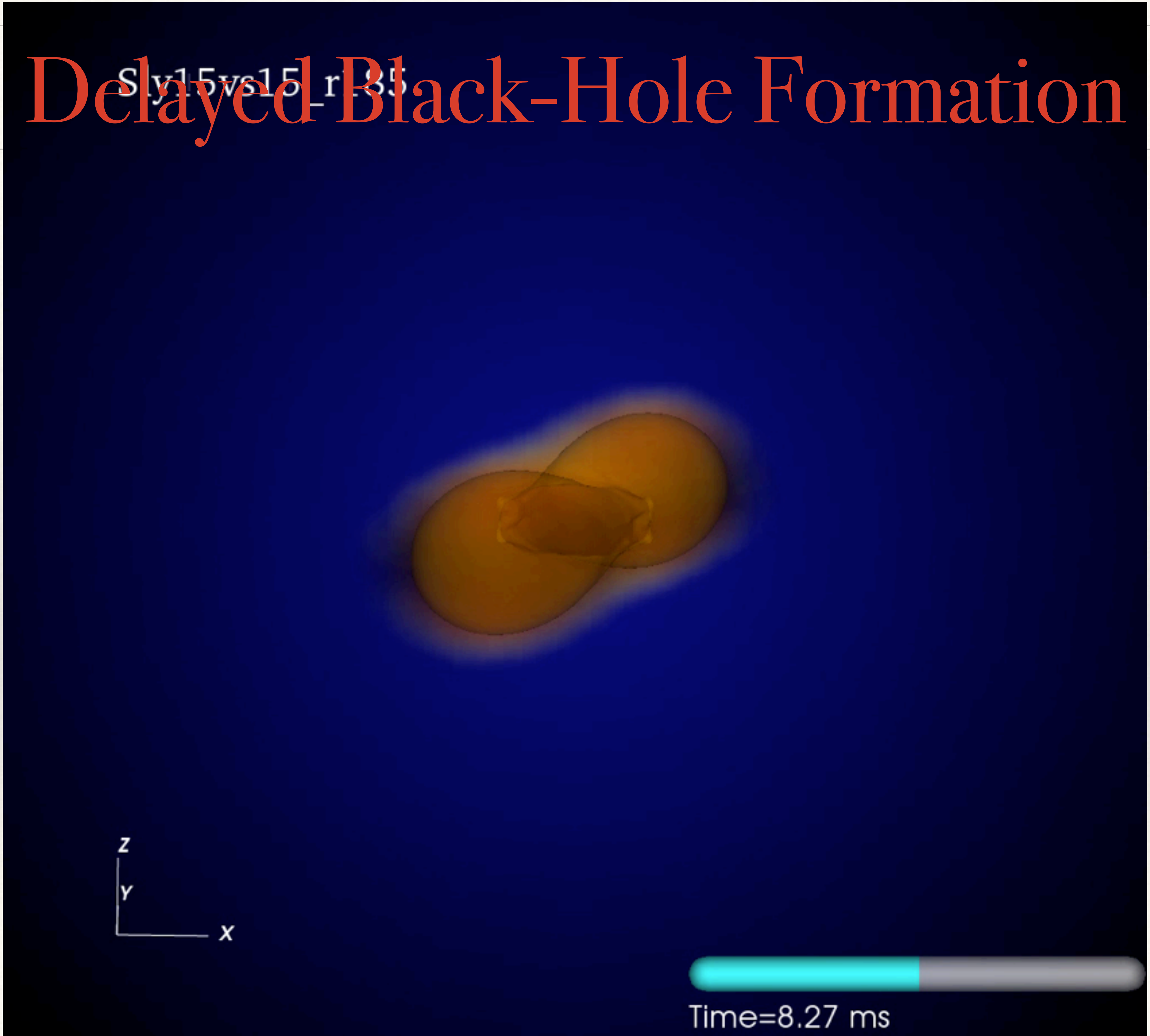
Model	dx=0.50	dx=0.375	dx=0.25
Sly15vs15	6.11 ms	11.81 ms	7.36 ms





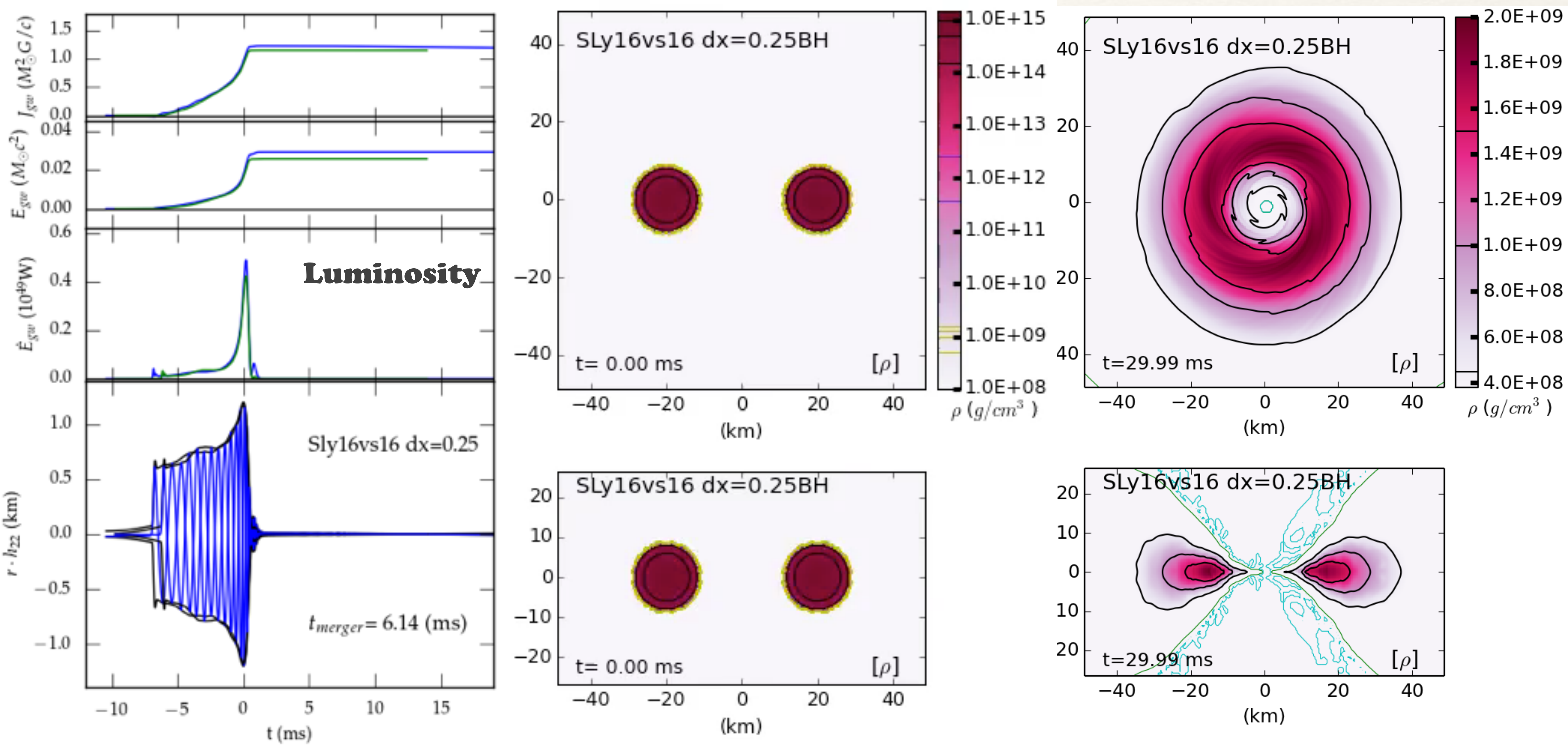


Delayed Black-Hole Formation



SLy 1.6 vs1.6 (Baryonic Mass)

Model	dx=0.50	dx=0.375	dx=0.25
Sly16vs16	0.83 ms	0.81 ms	0.79 ms

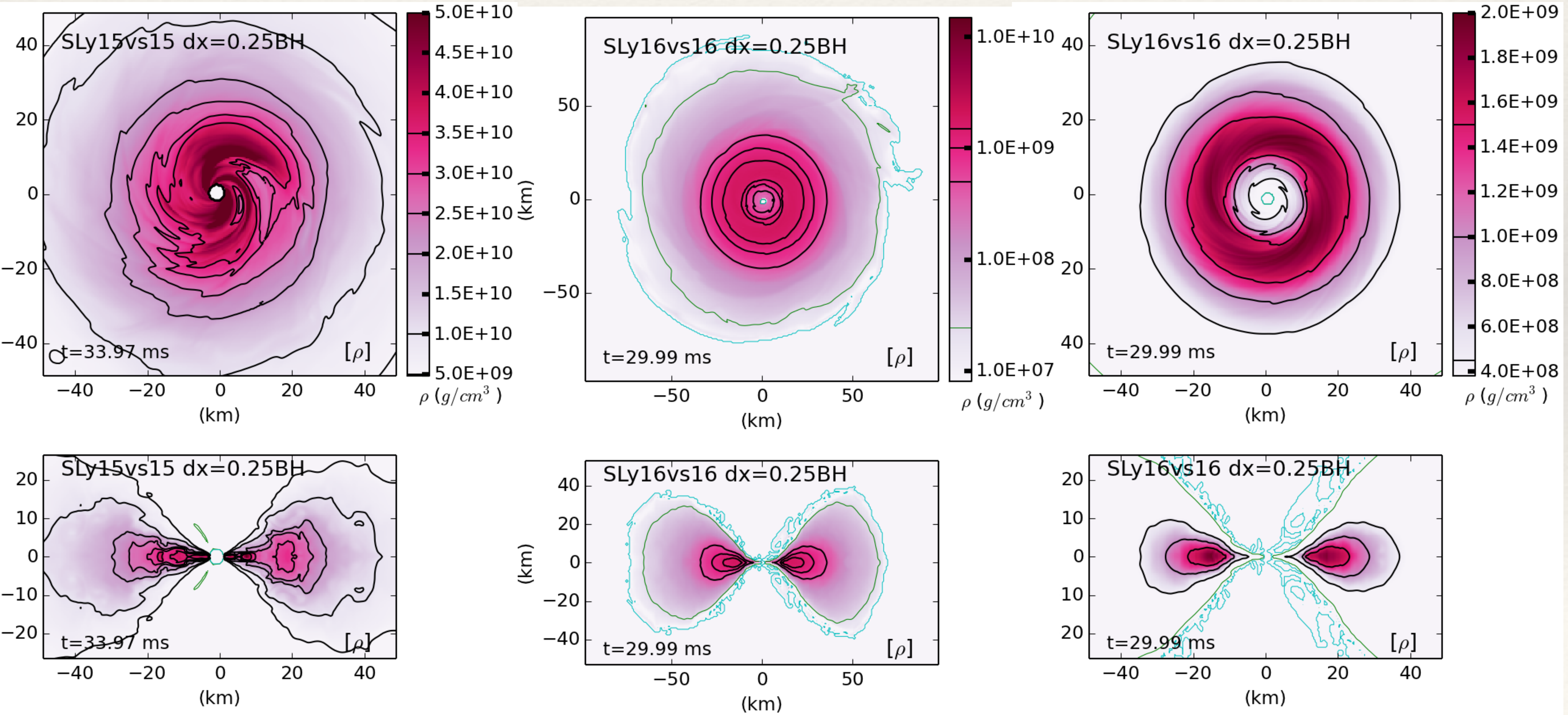


Collapse time to Black Hole (after Merger)

Not to easy to get physical predictions.

Presence of matter instabilities in the after merger dynamics (like Kelvin Helmotz)

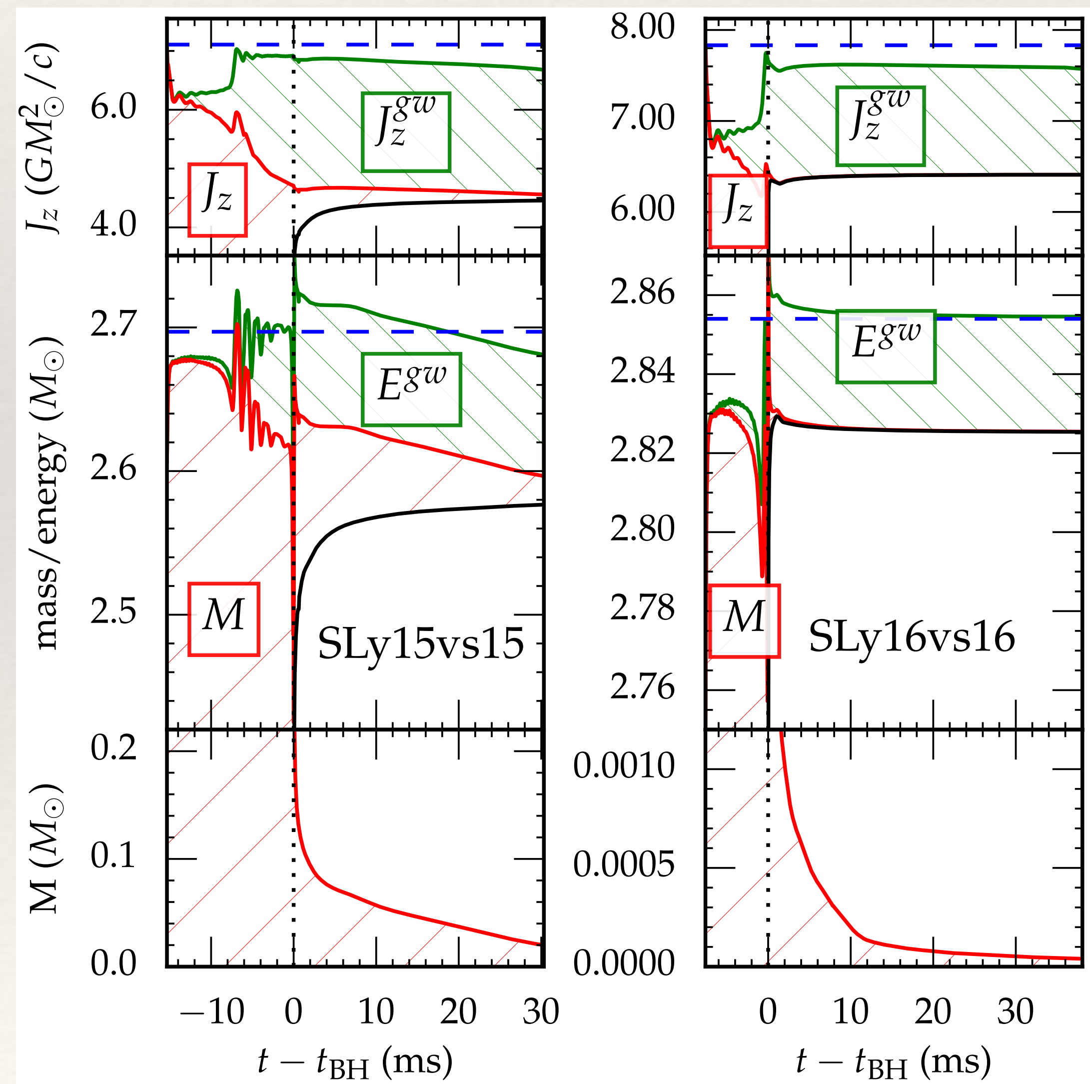
Model	dx=0.50	dx=0.375	dx=0.25
Sly15vs15	6.11 ms	11.81 ms	7.36 ms
Sly16vs16	0.83 ms	0.81 ms	0.79 ms



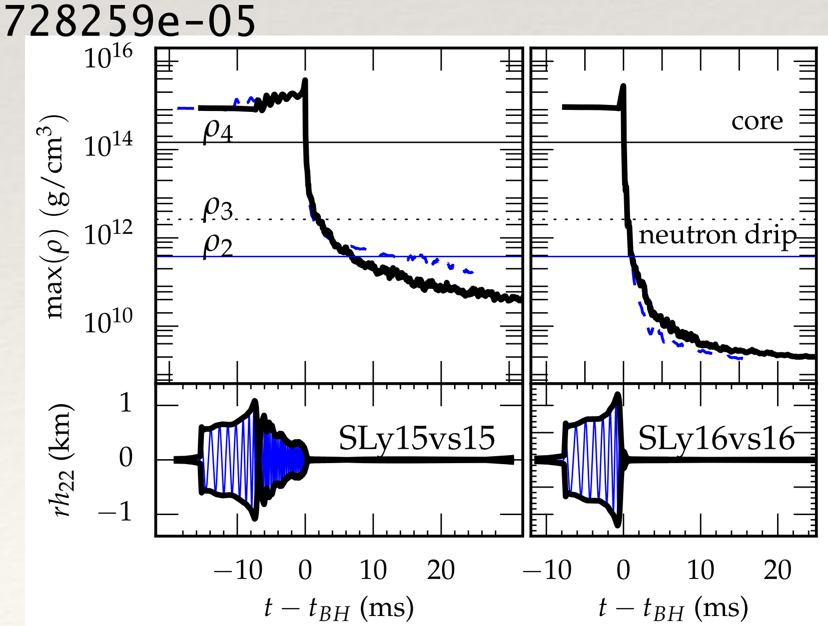
Collapse time to Black Hole (after Merger)

```
BUDGET for model 15vs15
   Final mass BH np.max(Mbh[0]) is: 2.57733745845
   Final J    BH np.max(Lbh[0]) is: 4.46170131712
   Mass in disk  np.min(MATTER) is: 0.0162523005579
   Total simulated time after BH  : 33.9091725788
   Values 25 ms after BH formation
        BH M     =  2.57531472352
        BH J     =  4.44682924429
        BH J/M^2 =  0.670486181372
        Mass =  0.0278916700256
```

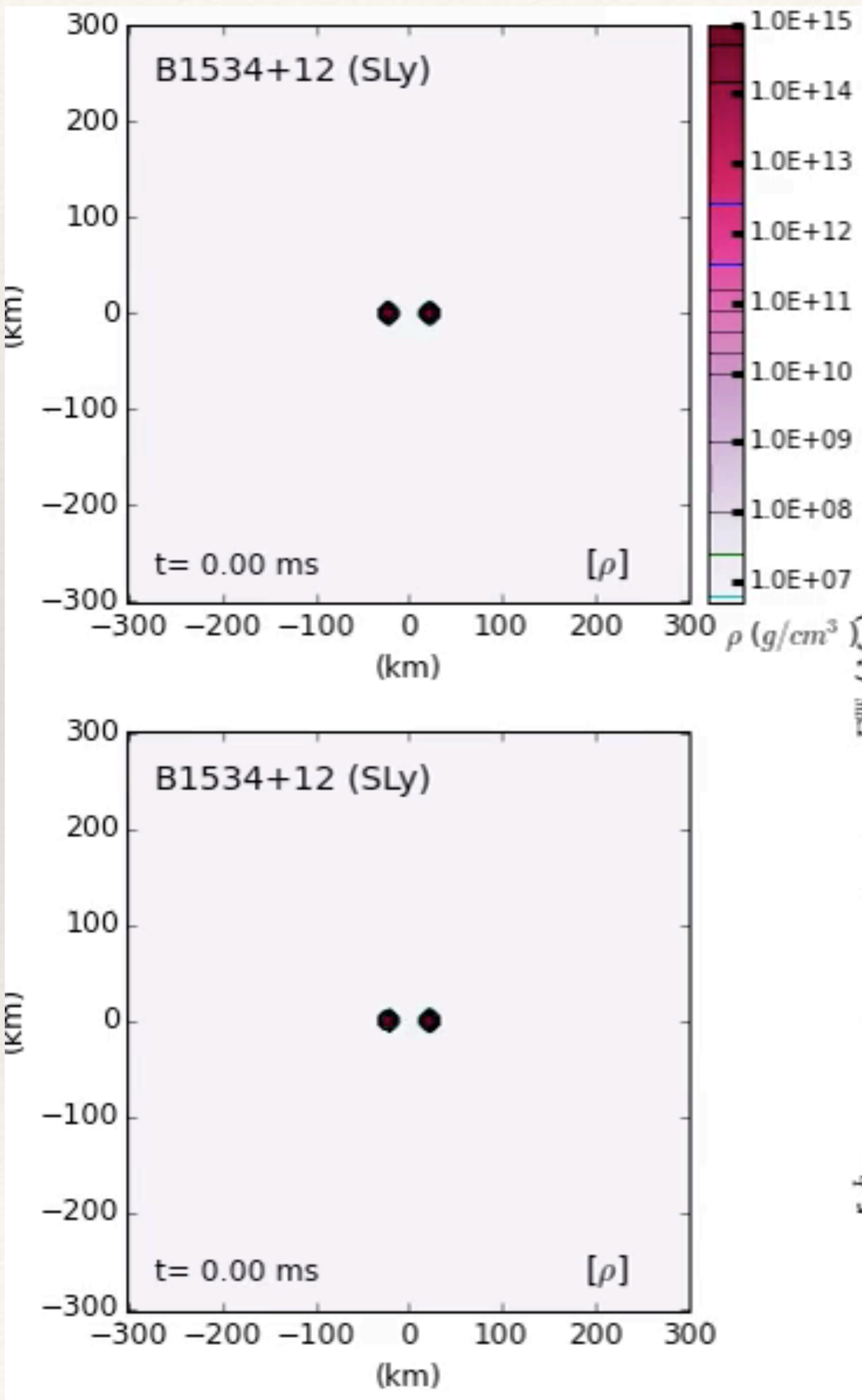
Model	dx=0.50	dx=0.375	dx=0.25
Sly15vs15	6.11 ms	11.81 ms	7.36 ms
Sly16vs16	0.83 ms	0.81 ms	0.79 ms

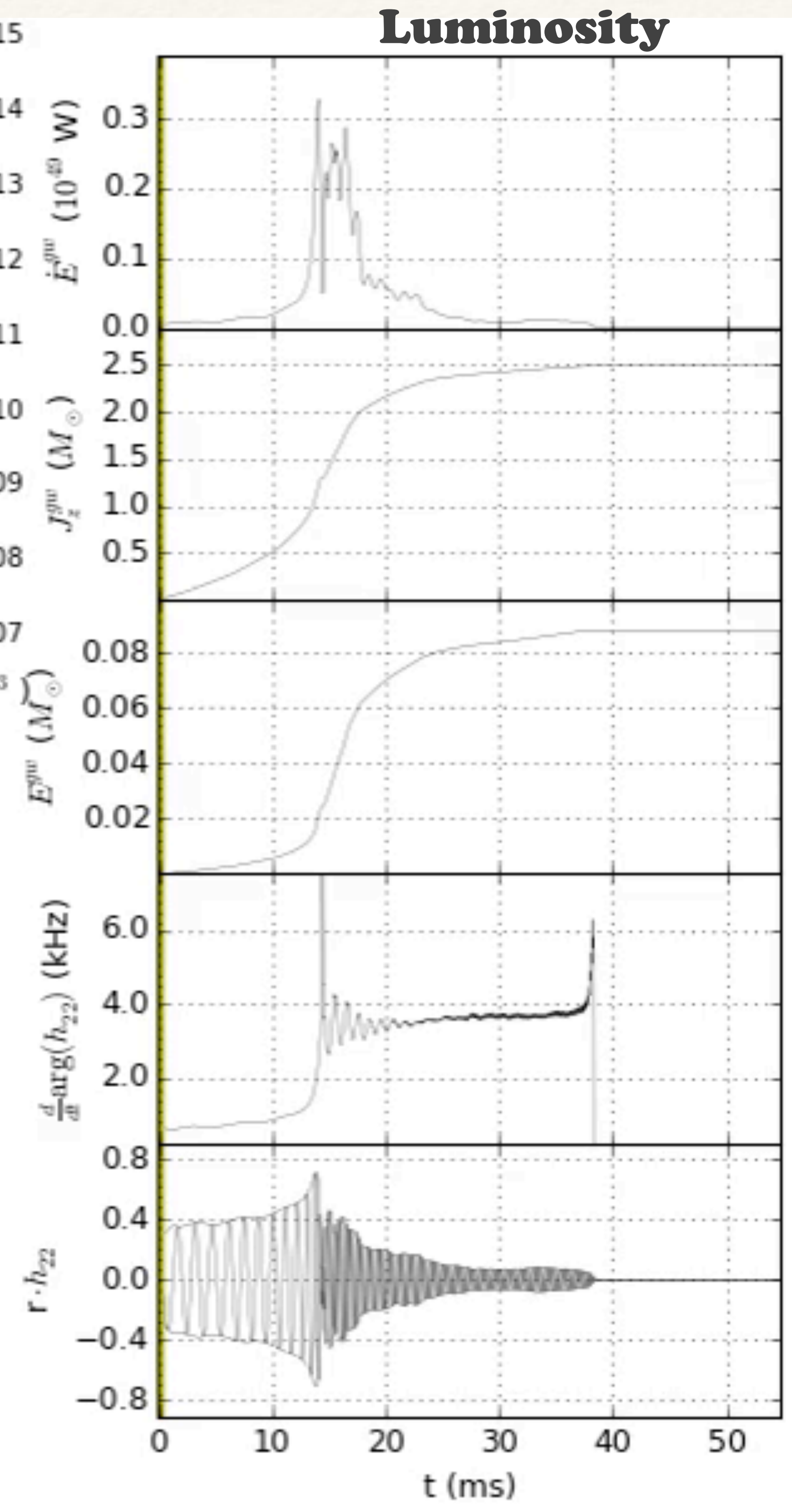


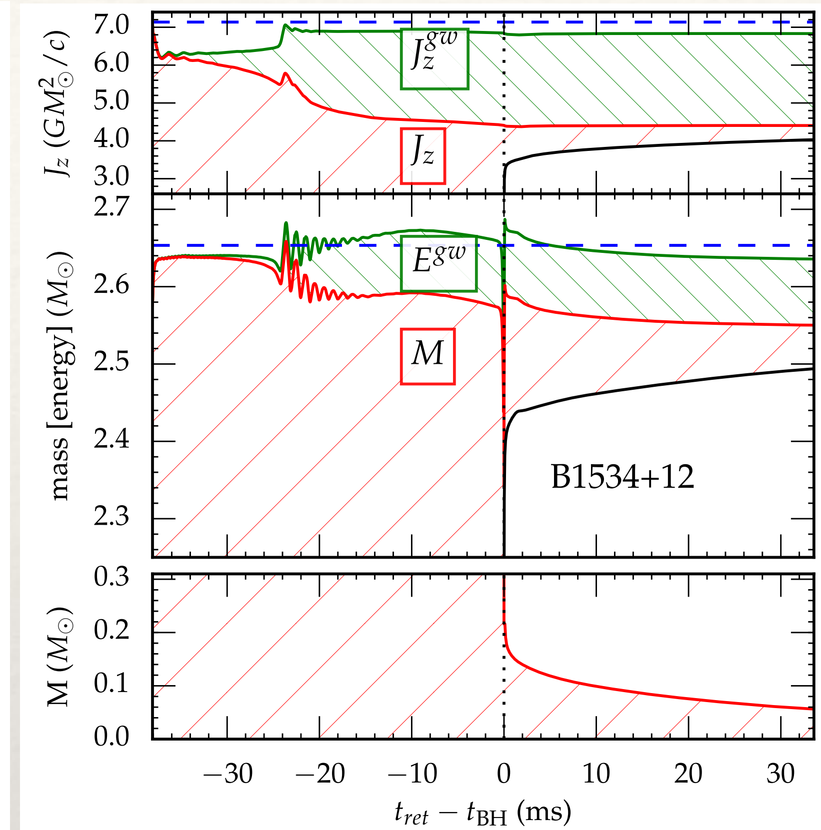

```
BUDGET for model 16vs16
   Final mass BH np.max(Mbh[1]) is: 2.82937414009
   Final J    BH np.max(Lbh[1]) is: 6.40877814116
   Mass in disk  np.min(MATTER) is: 3.60524241442e-05
   Total simulated time after BH  : 41.6623738628
   Values 25 ms after BH formation
        BH M     =  2.82551213935
        BH J     =  6.40772796317
        BH J/M^2 =  0.802619506998
        Mass =  6.1875728259e-05
```



The pulsar B1534+12 – The disk…



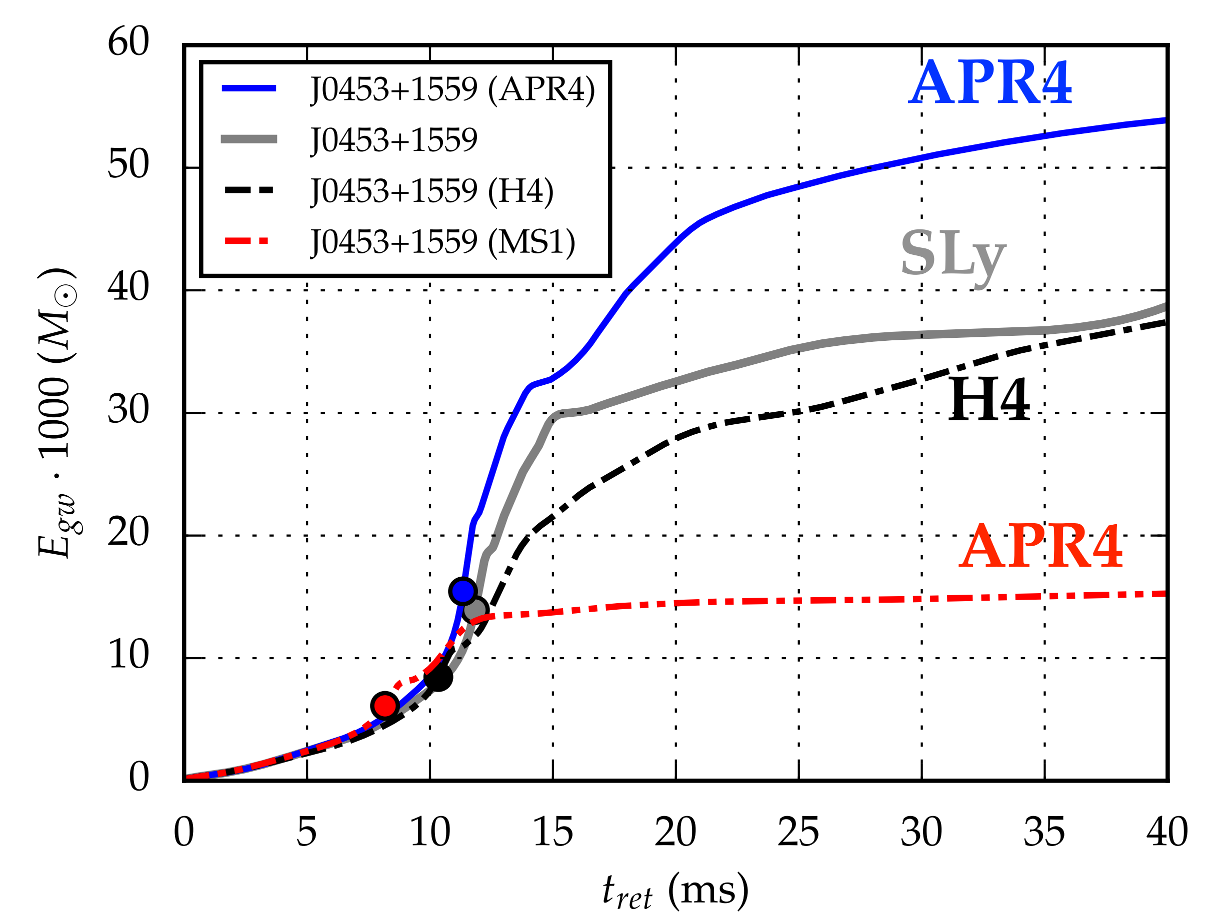




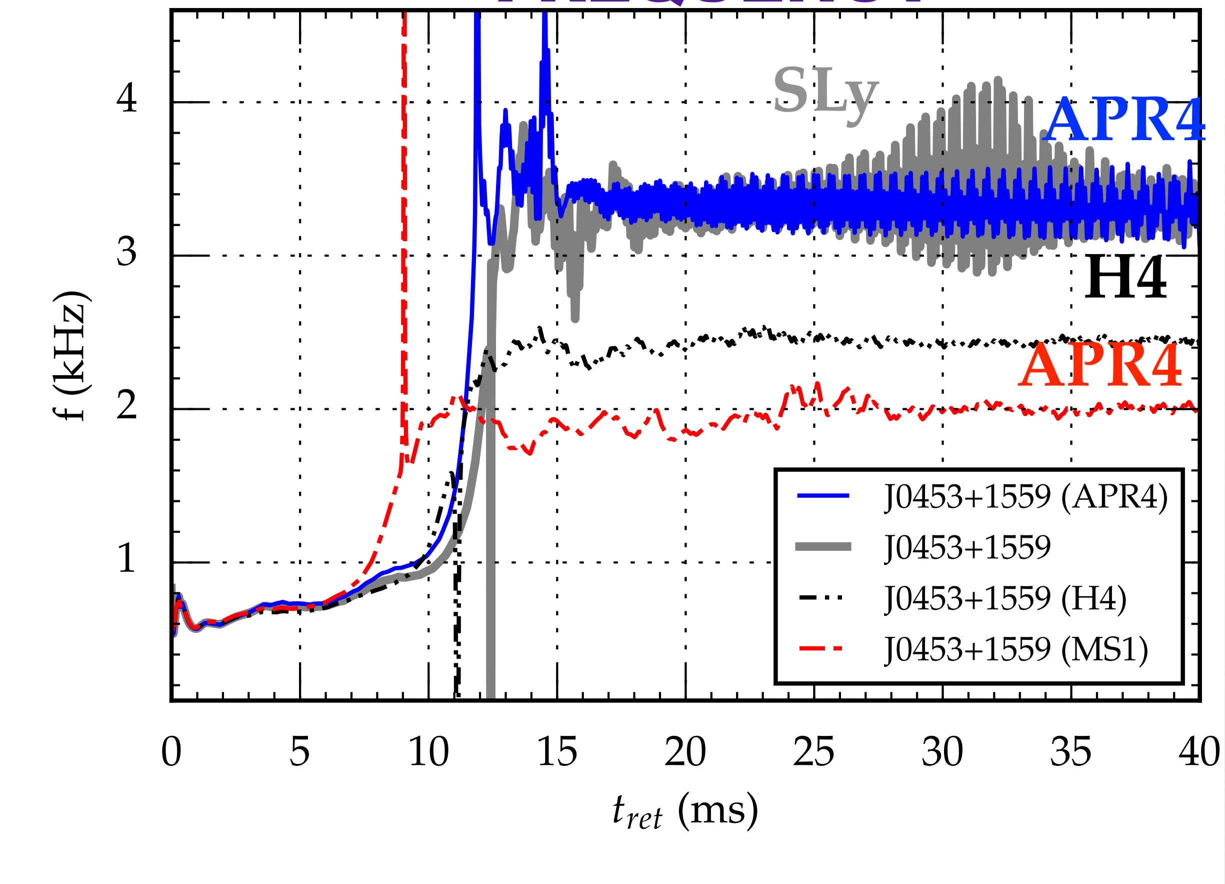
and the SOUND!

Different EOS – same stellar model

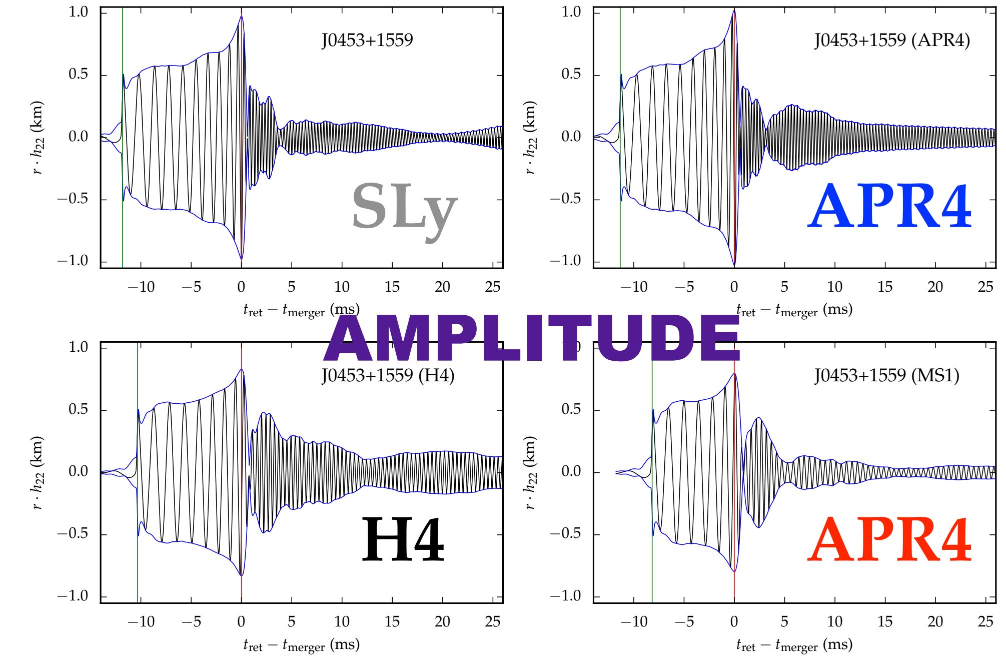
GW - ENERGY



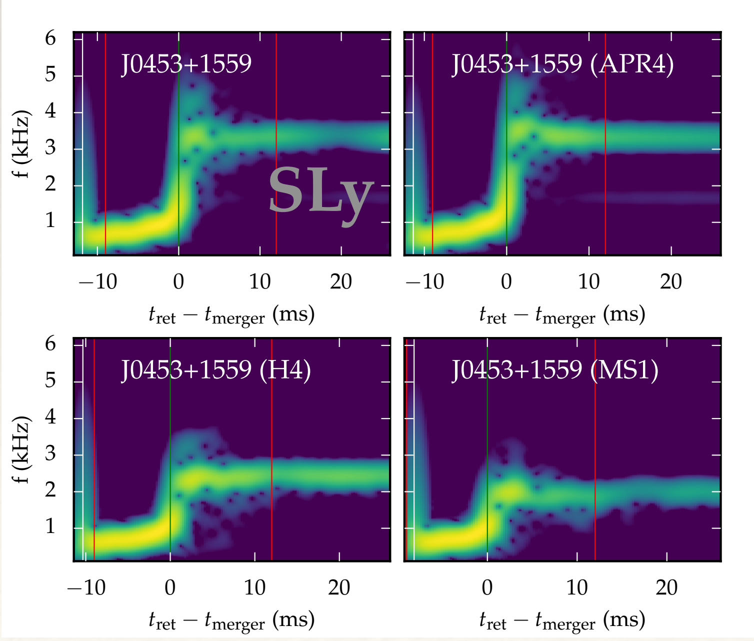
FREQUENCY



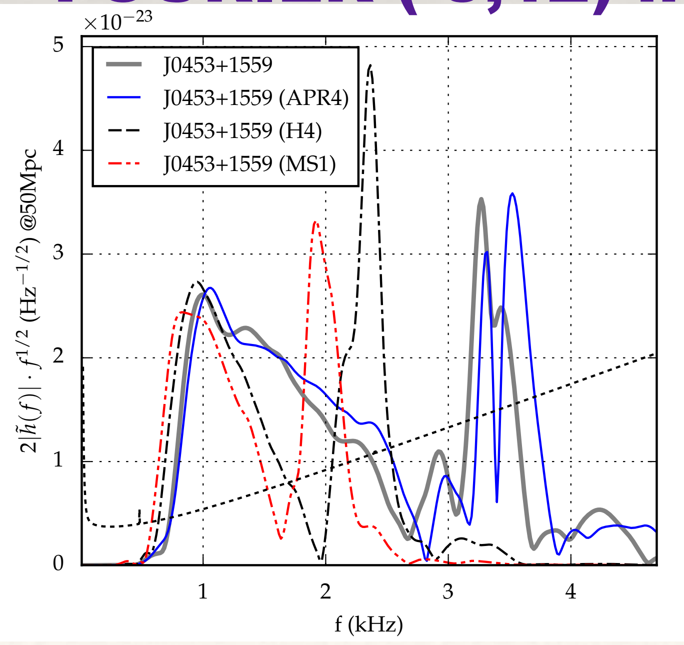
AMPLITUDE



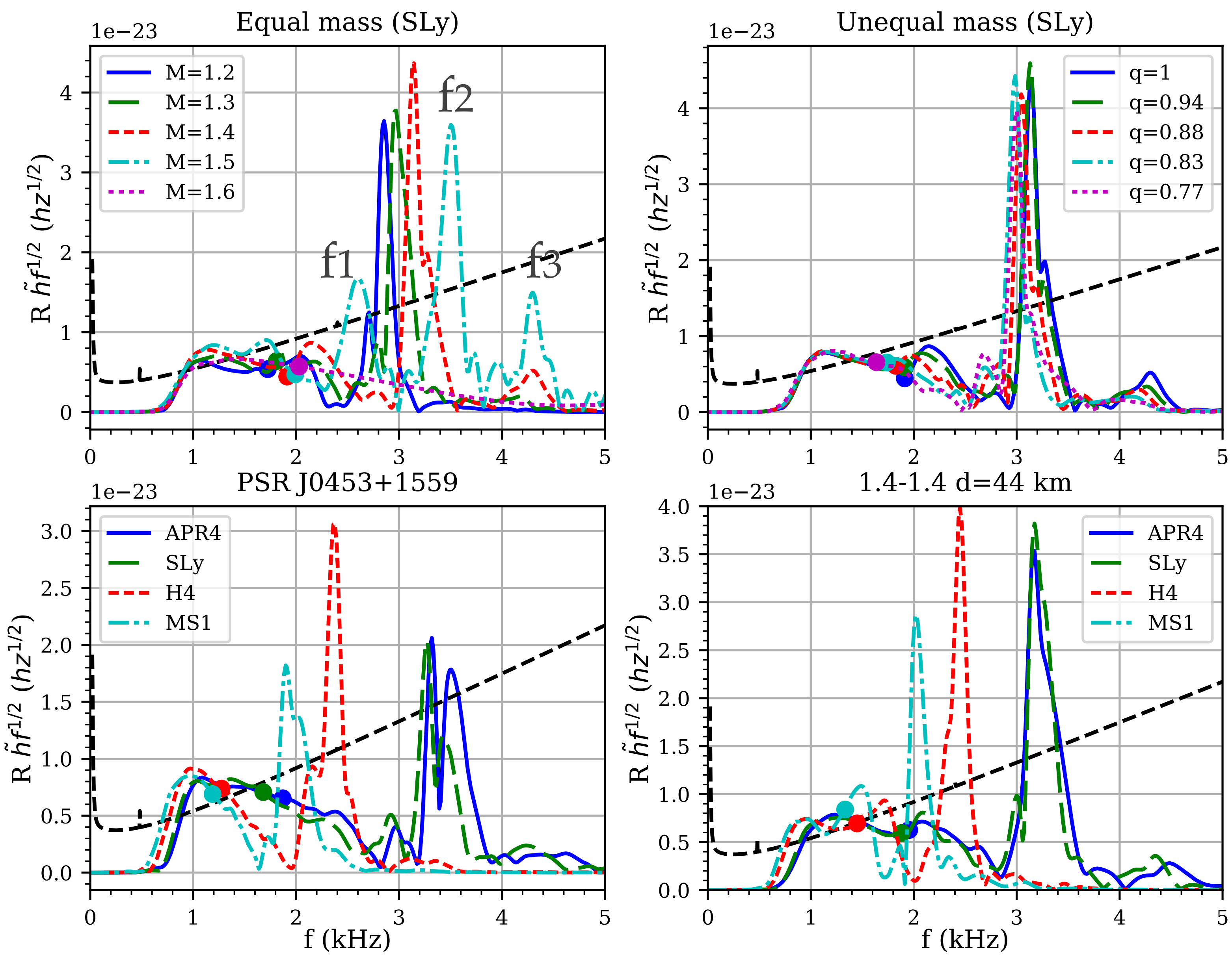
SPECTROGRAM



FOURIER (-5,12) ms



Spectrum of post-merger signal



Model	f_{2i} [kHz]	f_2 [kHz]	$f_2^{[16]}$ [kHz]	$\Delta R_{M=1.6}$ [km]	$f_2^{[42]}$ [kHz]
SLy_1.2-1.2	2.79	2.85	2.78	0.16	2.83
SLy_1.3-1.3	3.01	2.96	3.00	0.10	3.03
SLy_1.4-1.4	3.23	3.14	3.21	0.15	3.20
SLy_1.5-1.5	3.48	3.51	3.41	0.19	3.38
SLy_1.35-1.45	3.18	3.13	3.21	0.17	3.20
SLy_1.3-1.5	3.07	3.05	3.21	0.35	3.20
SLy_1.25-1.55	2.97	2.98	3.21	0.49	3.20
SLy_1.2-1.6	2.97	3.00	3.21	0.43	3.20
APR4_1.27-1.75	3.49	3.32	3.57	0.50	3.67
SLy_1.27-1.74	3.31	3.27	3.43	0.31	3.41
H4_1.25-1.71	2.27	2.37	2.50	0.44	2.25
MS1_1.25-1.70	1.91	1.90	2.18	2.30	1.88
APR4_1.4-1.4	3.31	3.17	3.33	0.35	3.47
SLy_1.4-1.4	3.22	3.17	3.21	0.08	3.20
H4_1.4-1.4	2.35	2.45	2.38	0.21	2.12
MS1_1.4-1.4	2.03	2.02	2.08	0.29	1.80

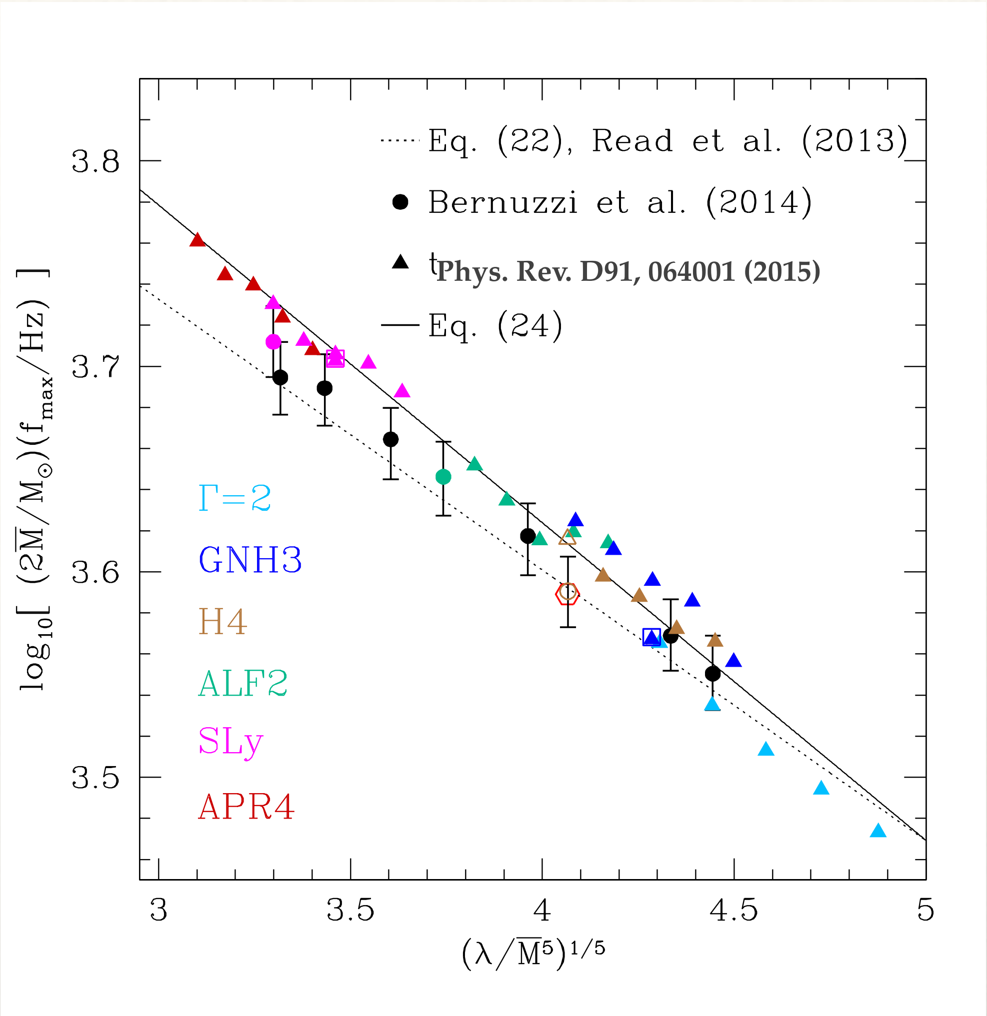
Model	f_1 [kHz]	f_3 [kHz]	f_0 [kHz]	f_{merger} [kHz]
SLy_1.2-1.2	2.04	-	1.31	1.72
SLy_1.3-1.3	1.89	4.17	1.31	1.81
SLy_1.4-1.4	2.15	4.30	1.19	1.91
SLy_1.5-1.5	2.60	4.30	0.93	1.98
SLy_1.35-1.45	2.10	4.26	1.18	1.90
SLy_1.3-1.5	2.01	4.19	1.20	1.82
SLy_1.25-1.55	1.93	4.11	1.24	1.73
SLy_1.2-1.6	-	-	1.27	1.63
APR4_1.27-1.75	2.38	4.62	1.13	1.87
SLy_1.27-1.74	2.25	4.23	1.02	1.67
H4_1.25-1.71	-	-	1.02	1.27
MS1_1.25-1.70	-	-	1.42	1.18
APR4_1.4-1.4	2.16	4.48	1.27	1.96
SLy_1.4-1.4	2.12	4.35	1.18	1.87
H4_1.4-1.4	1.71	-	1.02	1.45
MS1_1.4-1.4	1.52	-	1.09	1.32

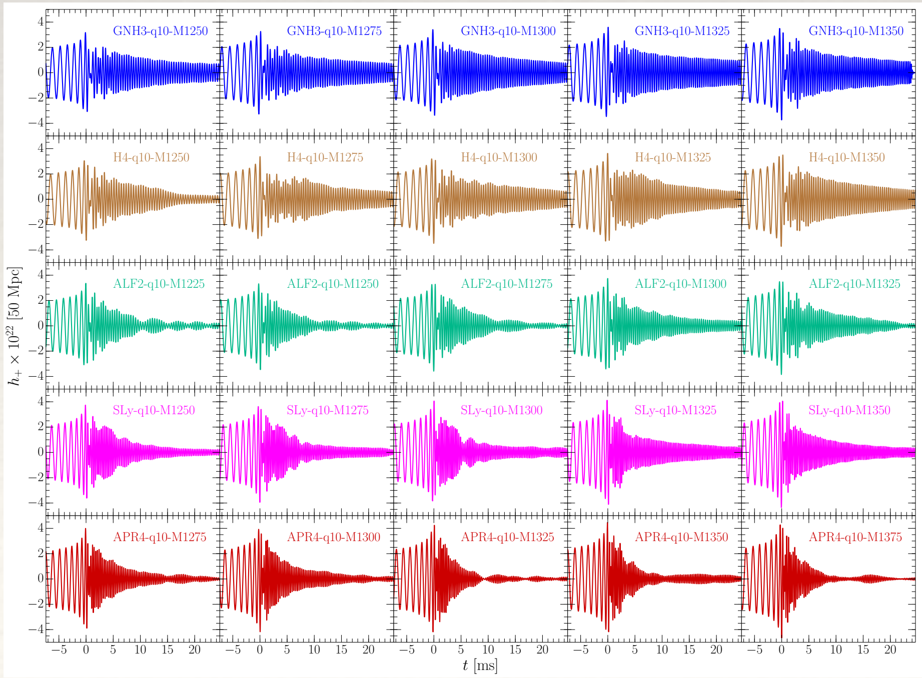
[16] A. Bauswein, N. Stergioulas, and H.-T. Janka, Eur. Phys. J. A52, 56 (2016), arXiv:1508.05493

[42] 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

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

- Tidal deformability λ/M^{-5} as a root to understand the position of the peaks?
- There is a loot of debated in literature about universal relation between frequency of the packs of the properties of the NS like its Mass, Compactness and or the deformability of the star.
- Problem: are this properties really described by this phenomenological relations ?
- All depends on the properties of the TRUE EOS and indeed all the observable are correlated to the each others.
- The question is: which one is the correct EOS describe the NS and indeed its Mass, Angular Momentum and rotational profile, characteristic frequency, ...

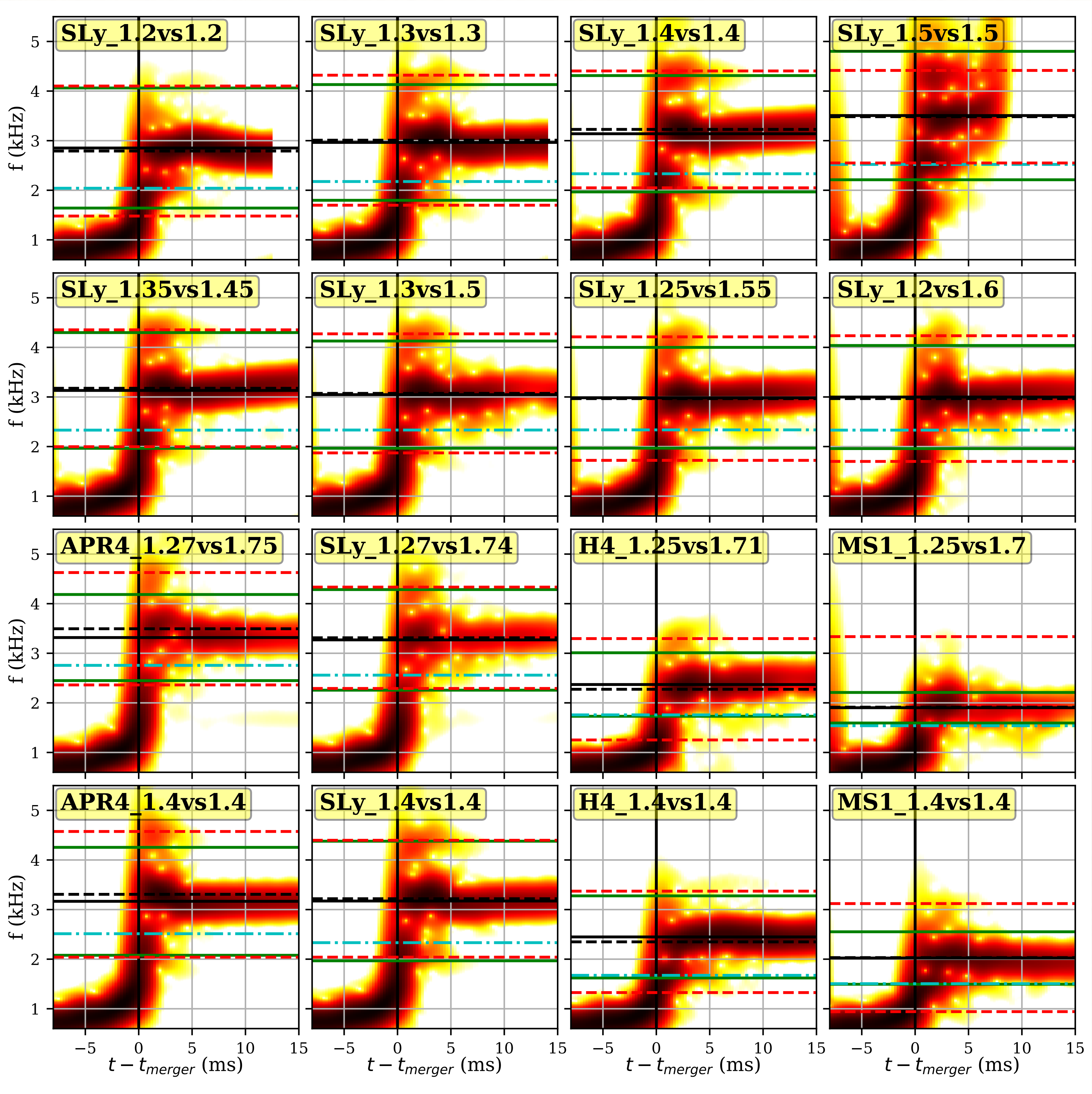




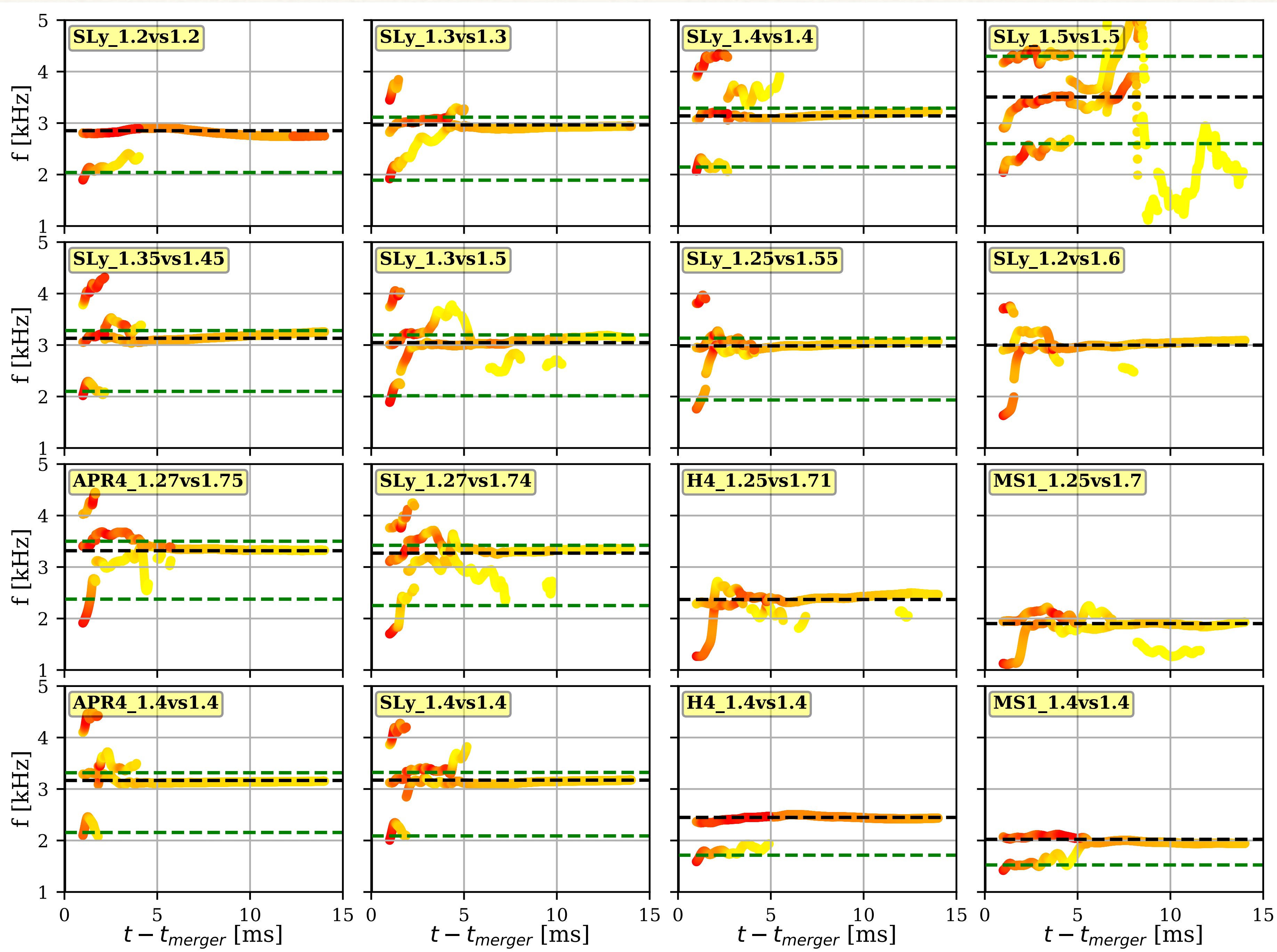
Classification of post merger peaks

- 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 suggested the one should consider also the possible origin of the observed frequency.
    - 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.

Spectrogram (all models)



PRONY analysis



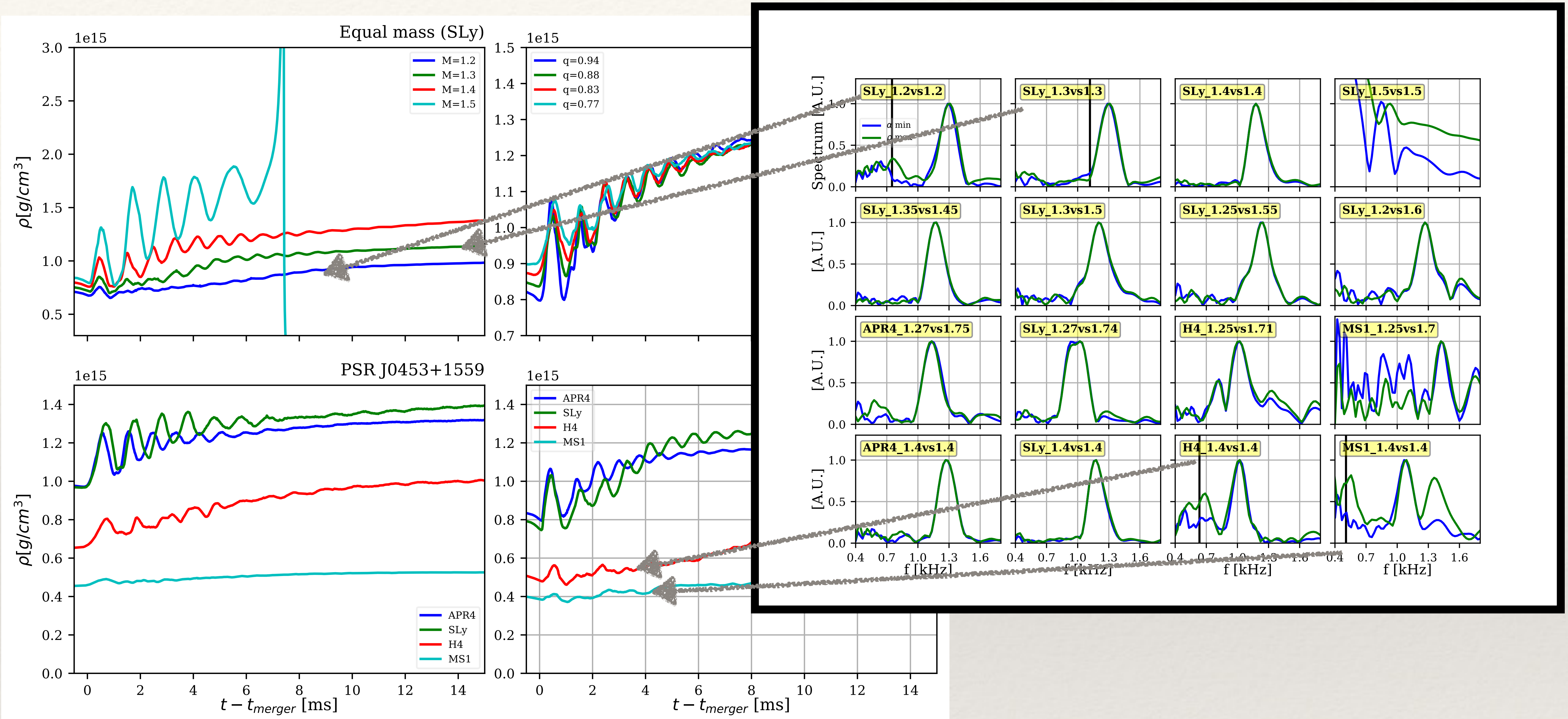
Model	f_{1Prony} [kHz]	$f_{2iProny}$ [kHz]	f_{3Prony} [kHz]
SLy_1.2-1.2	2.15	2.81	-
SLy_1.3-1.3	1.86	2.98	3.97
SLy_1.4-1.4	2.12	3.21	4.28
SLy_1.5-1.5	2.34	3.40	4.33
SLy_1.35-1.45	2.06	3.21	4.27
SLy_1.3-1.5	2.08	3.11	4.09
SLy_1.25-1.55	-	2.98	-
SLy_1.2-1.6	-	2.93	-
APR4_1.27-1.75	2.55	3.54	4.34
SLy_1.27-1.74	2.45	3.37	4.22
H4_1.25-1.71	-	2.24	-
MS1_1.25-1.70	-	2.00	-
APR4_1.4-1.4	2.00	3.30	4.48
SLy_1.4-1.4	2.04	3.22	4.23
H4_1.4-1.4	1.78	2.36	-
MS1_1.4-1.4	1.52	2.05	-

Frequencies of the dominant and subdominant components fitted by the ESPRIT Prony algorithm in an interval between 1 and 3 ms after the merger.

Prony analysis (Prony's method) was developed by Gaspard Riche de Prony in 1795 to builds a series of damped complex exponentials or sinusoids from a uniformly sampled **un-noised** signal. The ESPRIT technique focuses on finding the M significant eigenvalues discriminating them from the eigenvalues due to noise.

D. Potts and M. Tasche, Linear Algebra and its Applica- tions 439, 1024 (2013). G. Plonka and M. Tasche, GAMM-Mitteilungen 37, 239 (2014).

Radial frequencies



Fourier spectra of the maximum density and minimum lapse oscillations, computed between the merger and 10 ms after it. The black vertical lines mark, in models for which the subdominant GW spectral peaks are not well explained by m = 2 and m = 0 mode combination, the frequency f2i −f1, at which a modulation in the quasi-radial oscillations is predicted

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 …
- More insight improving the resolution of the simulation.

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.

The end …

MS1 and H4 EOSs