SM&FT 2017 High Performance Computing in Theoretical Physics,
Bari: 13-15 dicembre 2017

NEUMATT:

Numerical simulation of Binary Neutron Stars, Equation of State effects on the gravitational wave signal.

Roberto De Pietri
INFN Parma e
Università di Parma

Our goals

- **NEUMATT** stands for: **NEU**tron star **MAT**ter **T**heory
- Our research aims to finding answers and understanding of the emitted Gravitational waves associate to Binary Neutron Star merger and explosive astrophysical phenomena.
  - We perform hydrodynamical simulations of the rapid rotation and of the merger of two neutron stars in order to provide the link between the GW emission and the EoS and to study the relevance of the EoS in explosive phenomena as GRBs and macronova associated to BNS merger.
  - In particular we will study matter at finite temperature and in conditions of neutrino trapping. The systematic study of the rotational properties of matter can constitute a fundamental tool to discriminate between the possible EoSs. Developed by grope in CT, FE, PI, LNS...
  - To reach our goals we need to simulate Astrophysical system on High Performance Computer
- **In the era of gravitational observatory…..**

NEUMATT and the document: Computational theoretical physics at INFN: status and perspectives (2018-2020)

- Referring to the main INFN documents our request are within the estimated a request of 142M and 227M for the year 2018-2020 under the section General Relativity.
- The need are well above the effective possible allocations on INFN machines.
- We integrated our resource through PRACE, ISCRA competitive allocations and the help of our international collaborators and we keep doing so. We have an ongoing PRACE 14th call allocation of 30 M Core hours on the Marconi A2 CINECA system.
- The number of INFN groups doing HPC research in Numerical General relativity is increasing as well as the request of HPC resources
- FOCUS ON EOS EFFECT ON THE GW SIGNAL IN THE POST-MERGER PHASE:
    - THERMAL EFFECT
    - SIGN OF POSSIBLE PHASE TRANSITIONS
- **This study need expertise from NR and Nuclear-Physics (EOS)**

Computational theoretical physics at INFN: status and perspectives (2018-2020)

R. Alfieri, B. Alles, S. Arezzini, S. Bernuzzi, L. Biferale, G. Boffetta*, C. Bonati, G. Brancato, C.M. Carloni Calame, M. Caselle, P. Cea, A. Ciampa, M. Colpi, L. Cosmai*, L. Coraggio, G. de Divitiis, M. D'Elia*, C. Destri, G. Di Carlo, P. Dimopoulos, F. Di Renzo, R. De Pietri*, E. De Santis, A. Drago*, P. Faccioli, R. Frezzotti*, A. Gamba, A. Gargano, B. Giacomazzo, L. Giusti*, G. Gonnella, N. Itaco*, A. Kievsky, G. La Penna, A. Lanotte*, W. Leidemann, M. Liguori*, M.P. Lombardo*, A. Lovato, V. Lubicz, L.E. Marcucci, E. Marinari, G. Martinelli*, A. Mazzino, E. Meggiolaro, V. Minicozzi, S. Morante*, P. Natoli*, F. Negro, M. Nicodemi*, P. Olla, G. Orlandini, M. Panero*, P.S. Paolucci*, A. Papa*, G. Parisi*, F. Pederiva*, M. Pepe, F. Piccinini*, F. Rapuano, G.C. Rossi, G. Salina, F. Sanfilippo, S.F. Schifano*, R. Schneider, S. Simula*, A. Sindona*, F. Stellato, N. Tantalo, C. Tarantino, G. Tiana, R. Tripiccione*, P. Vicini*, M. Viviani*, T. Vladikas, M. Zamparo

* *Conveners*

(Dated: April 26, 2017)

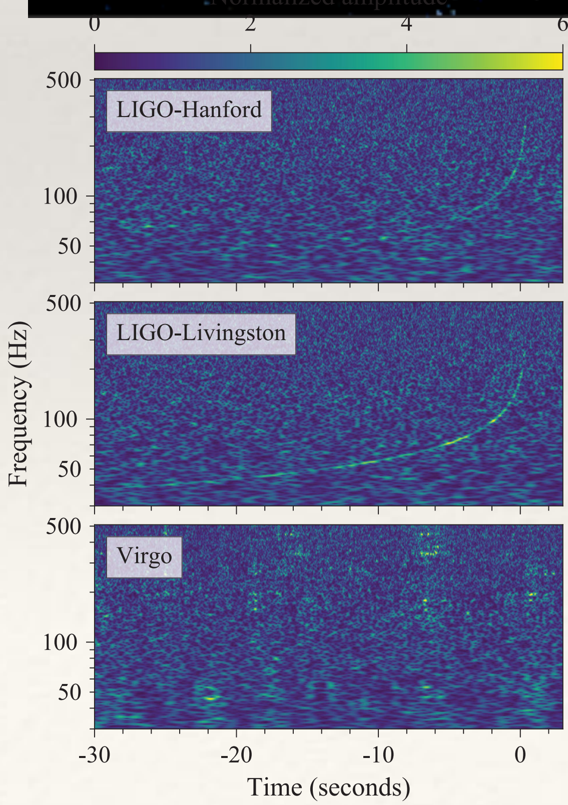
We present the status of computational theoretical physics at INFN, the results obtained by its research groups active in this field and their research programs for the next three years. Computational theoretical physics, besides its own importance, is a powerful tool in understanding present and future experiments. A continued support of INFN to computational theoretical physics is crucial to remain competitive in this sector. We assess the high performance computing resources needed to undertake the research programs outlined for the next three years.

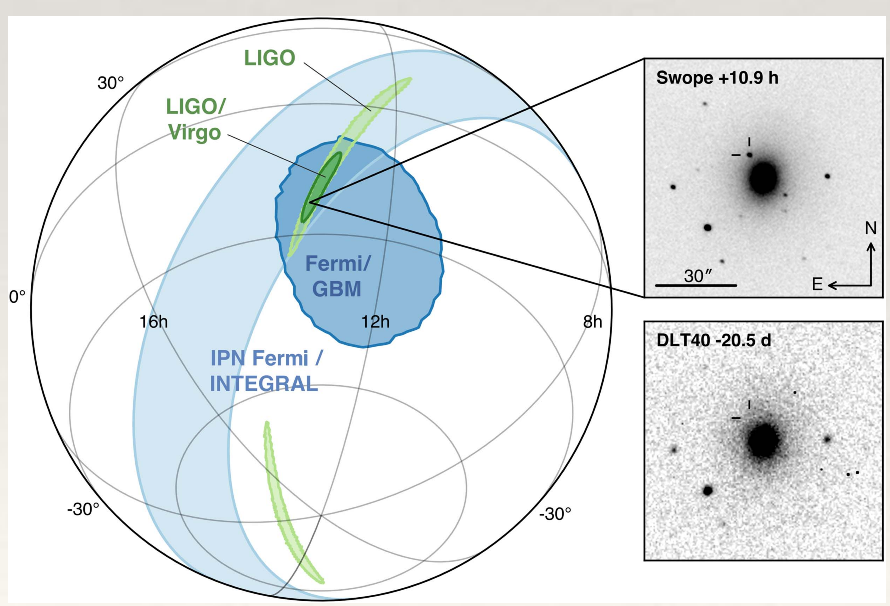
	2018	2019	2020
LGT: hadron physics	54	108	180
LGT: QGP and BSM	207	432	648
LGT: flavor physics	117	234	387
Colliders phenomenology	1	2	3
General relativity	142	182	227
Cosmology and Astroparticle physics	3	4	6
Nuclear Theory	18	27	36
Fluid Dynamics	50	80	110
Quantitative Biology	9	18	27
Disordered systems	4	6	8
Condensed matter	2	4	6
Grand Total (Mcore-h)	**607**	**1097**	**1638**
Grand Total (Eq. Pflops)	**4.6**	**8.4**	**12.5**

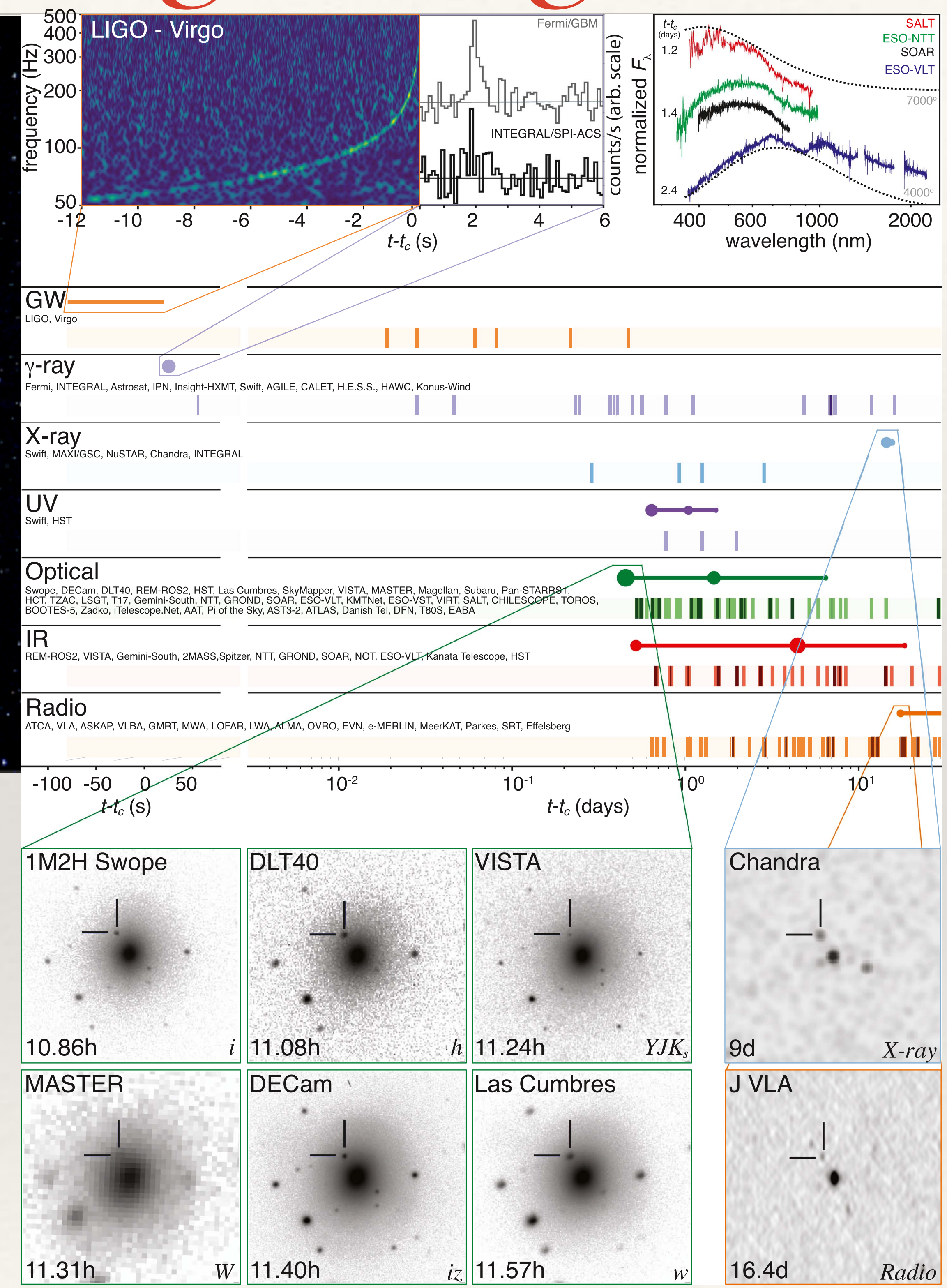
GENERAL RELATIVITY (Who is involved in the numerical effort)

- Discussed in section IV of the main document
- Referring to the main INFN documents the estimated estimated computational need amount to 142M, 182M and 227M for the year 2018-2020.
- Two "iniziative specifiche" involved on this effort:
- **NEUMATT**: **NEU**tron star **MAT**ter **T**heory
  Catania, Ferrara, LNGS, LNS, Milano, Pisa, Parma.
  - What are the signature on the Gravitational Wave signal emitted by the merger of two newton stars of the Equation of State that describe matter at these very-extreme densities (phase-transition of neutron-matter, thermal effects,…)
- TEONGRAV: TEoria delle ONde GRAVitazionali
  Roma, Firenze, Milano, Parma, Napoli.

GW170817 - the August signal!



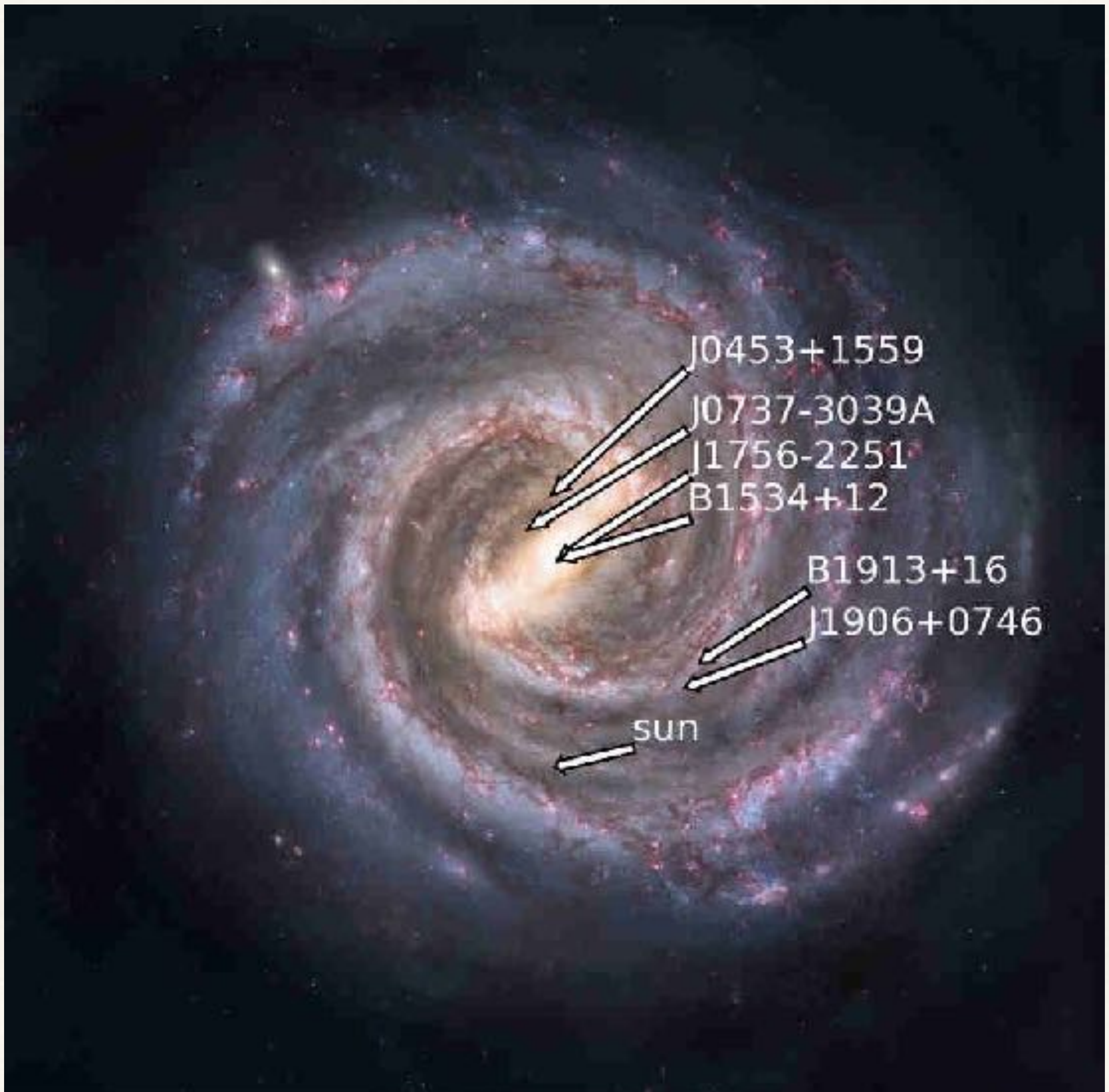




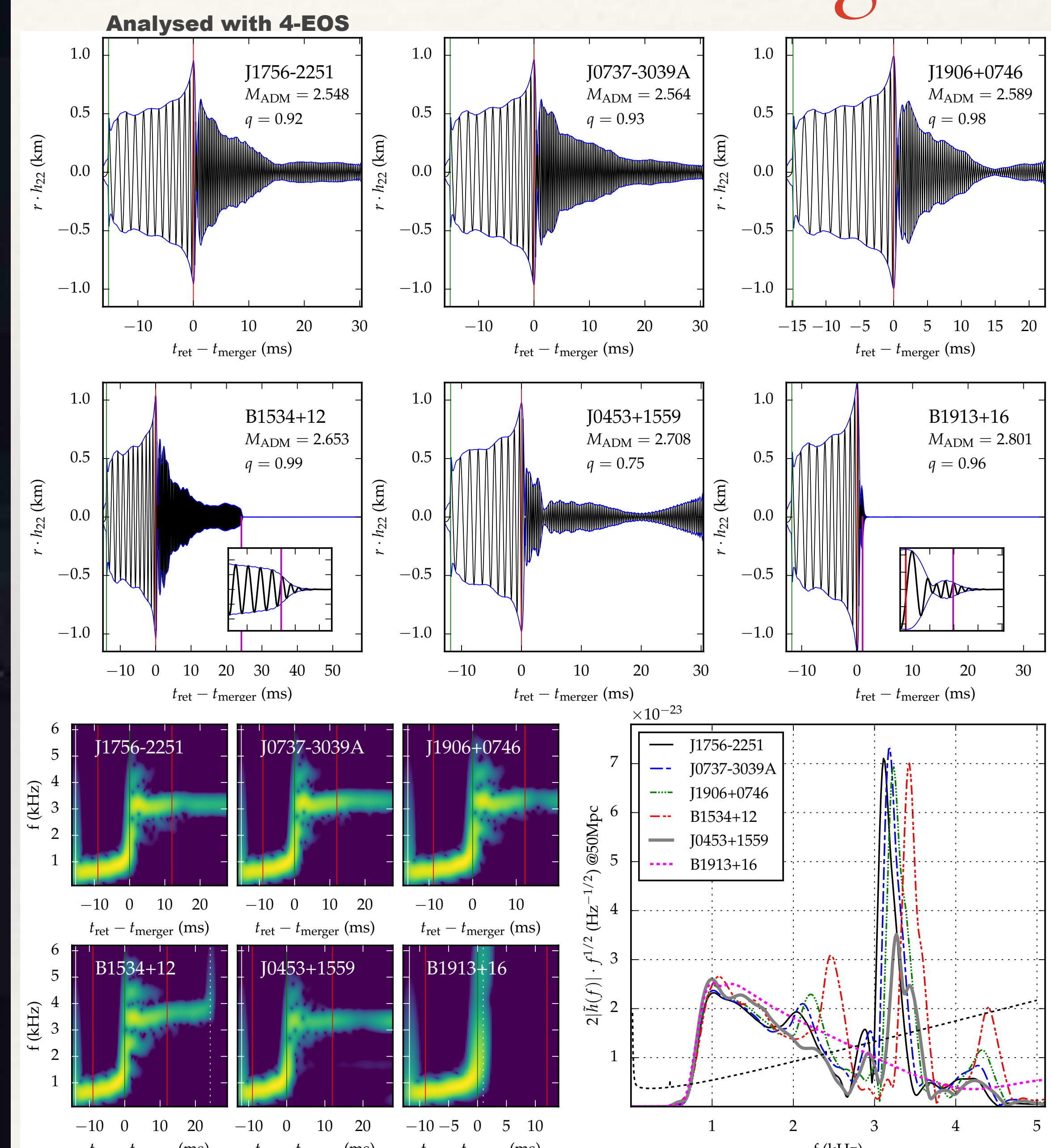
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, **Phys.Rev.Lett.** 119 (2017) no.16, 161101.

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

Binary Neutron Star Mergers are known source for gravitational wave observatory. In our Galaxy there are six know systems of this kind that will collapse emitting GW signal.

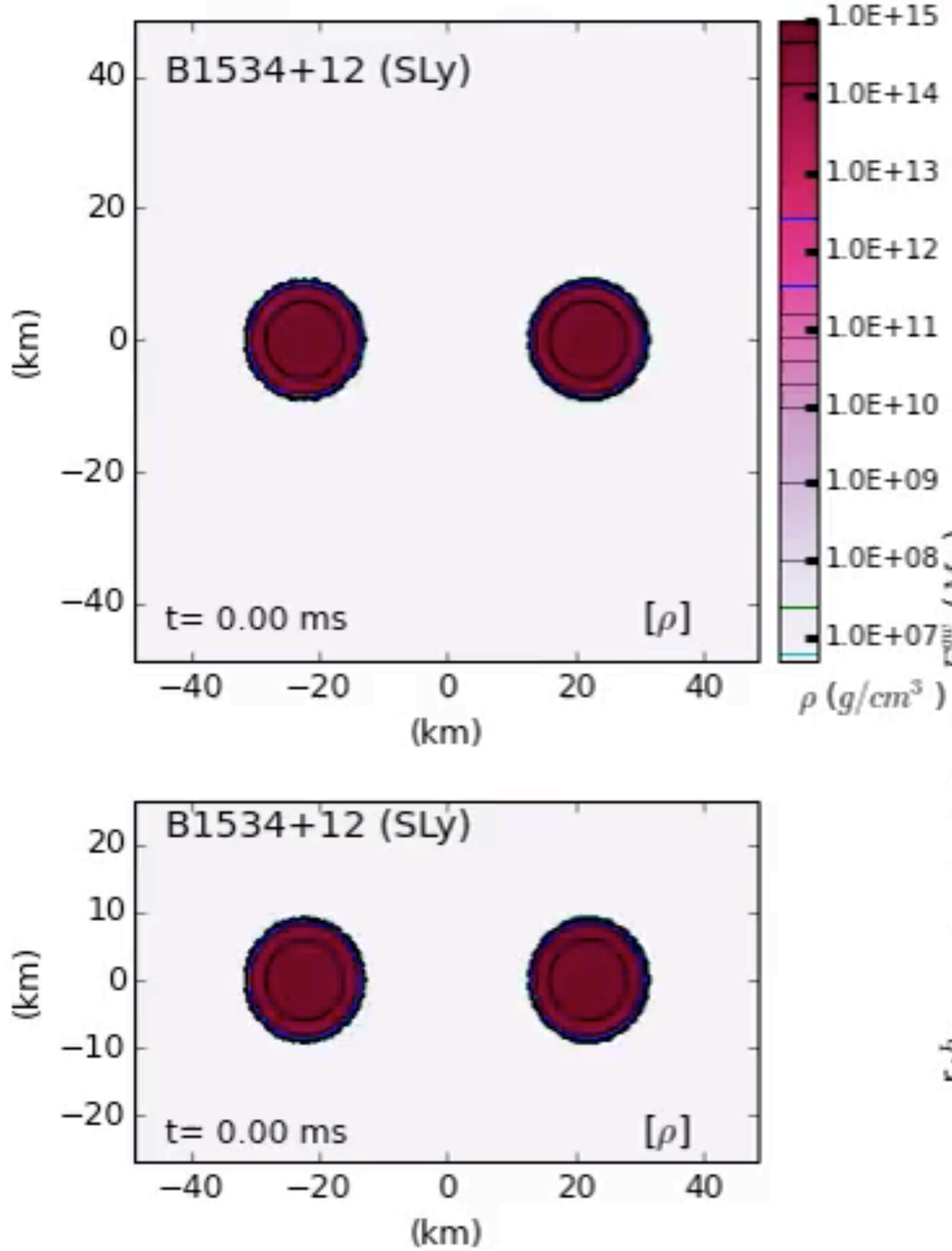


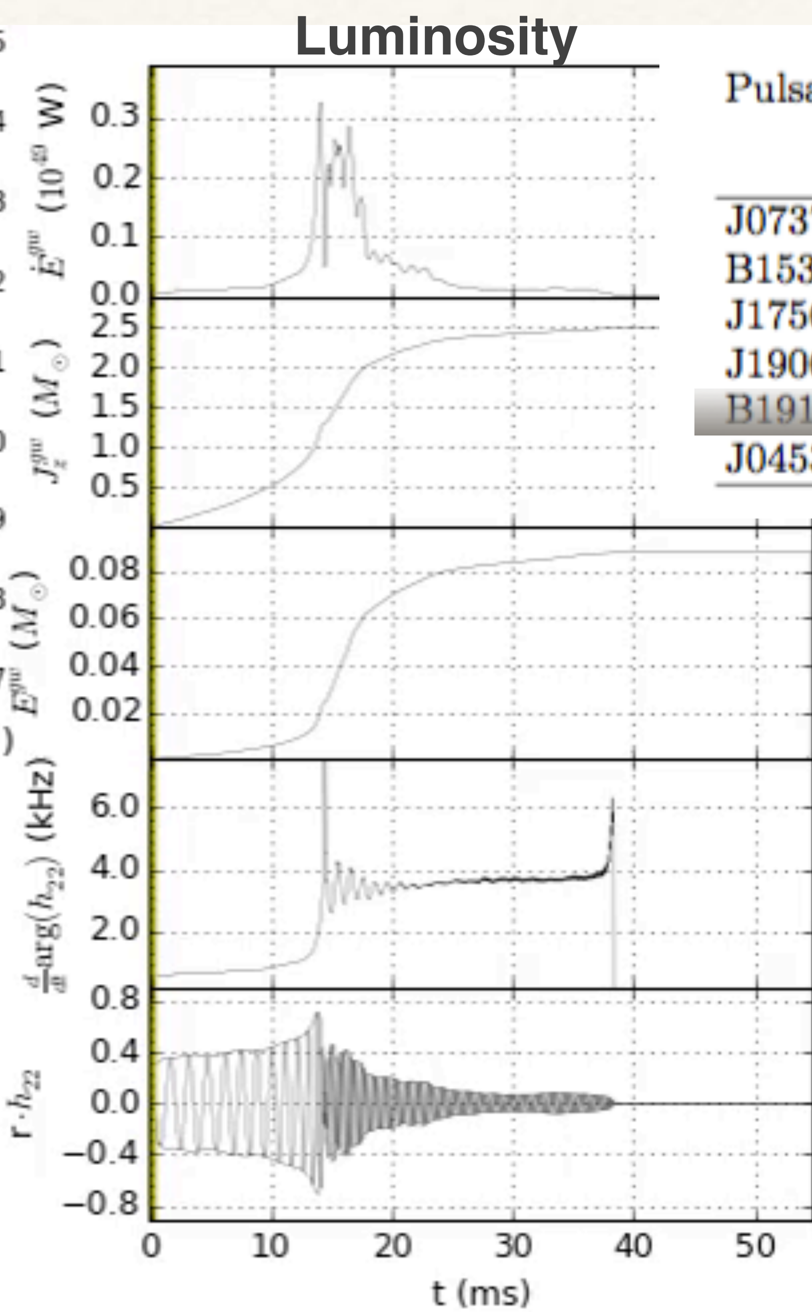
The simulated GW signal



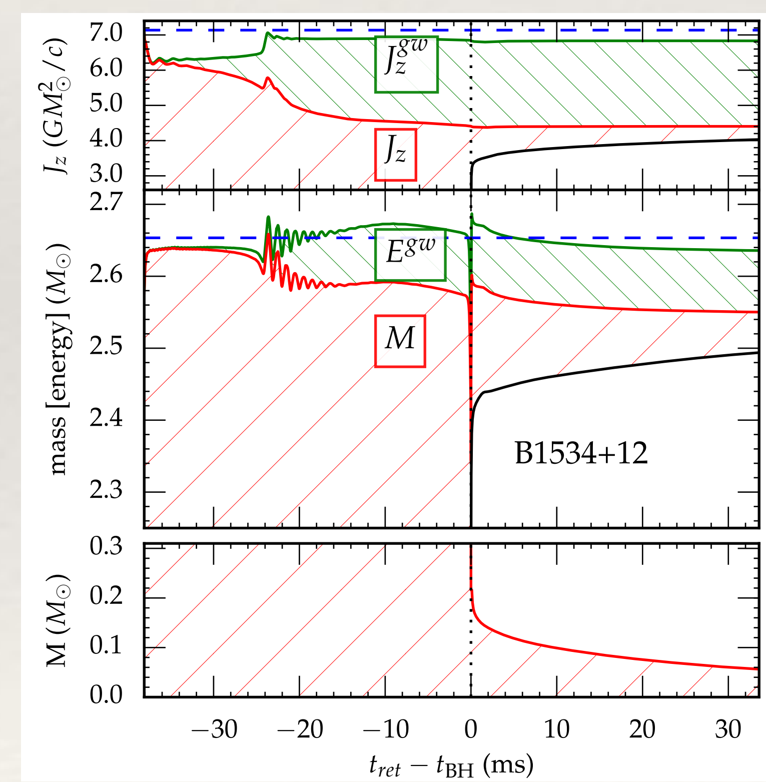
Modeling Mergers of known Galactic Binary Neutron Stars,
A. Feo, R. De Pietri, F. Maione and F. Loeffler,
Classical and Quantum Gravity 34 (3), 034001, 2017

The evolution of the B1534+12 system.



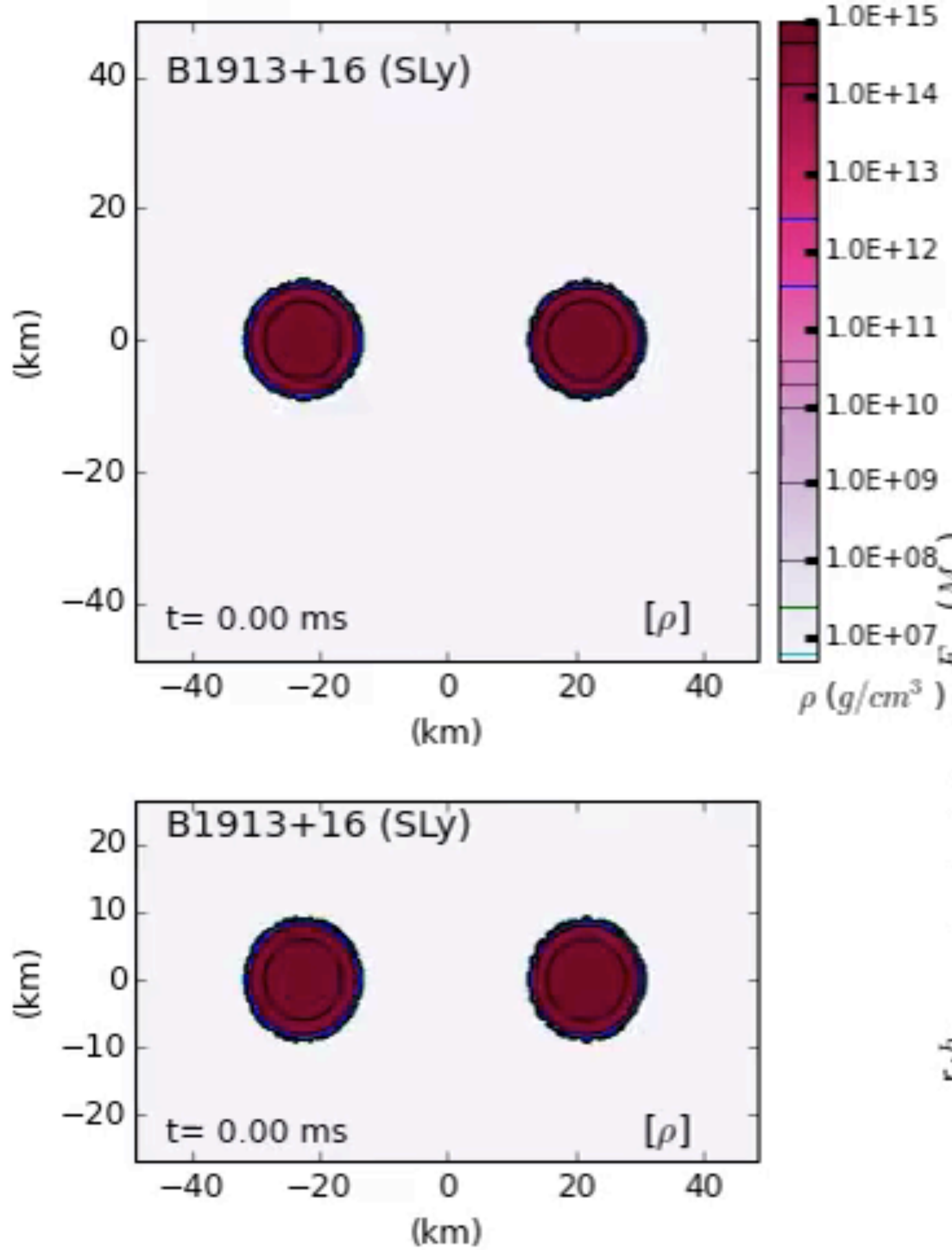


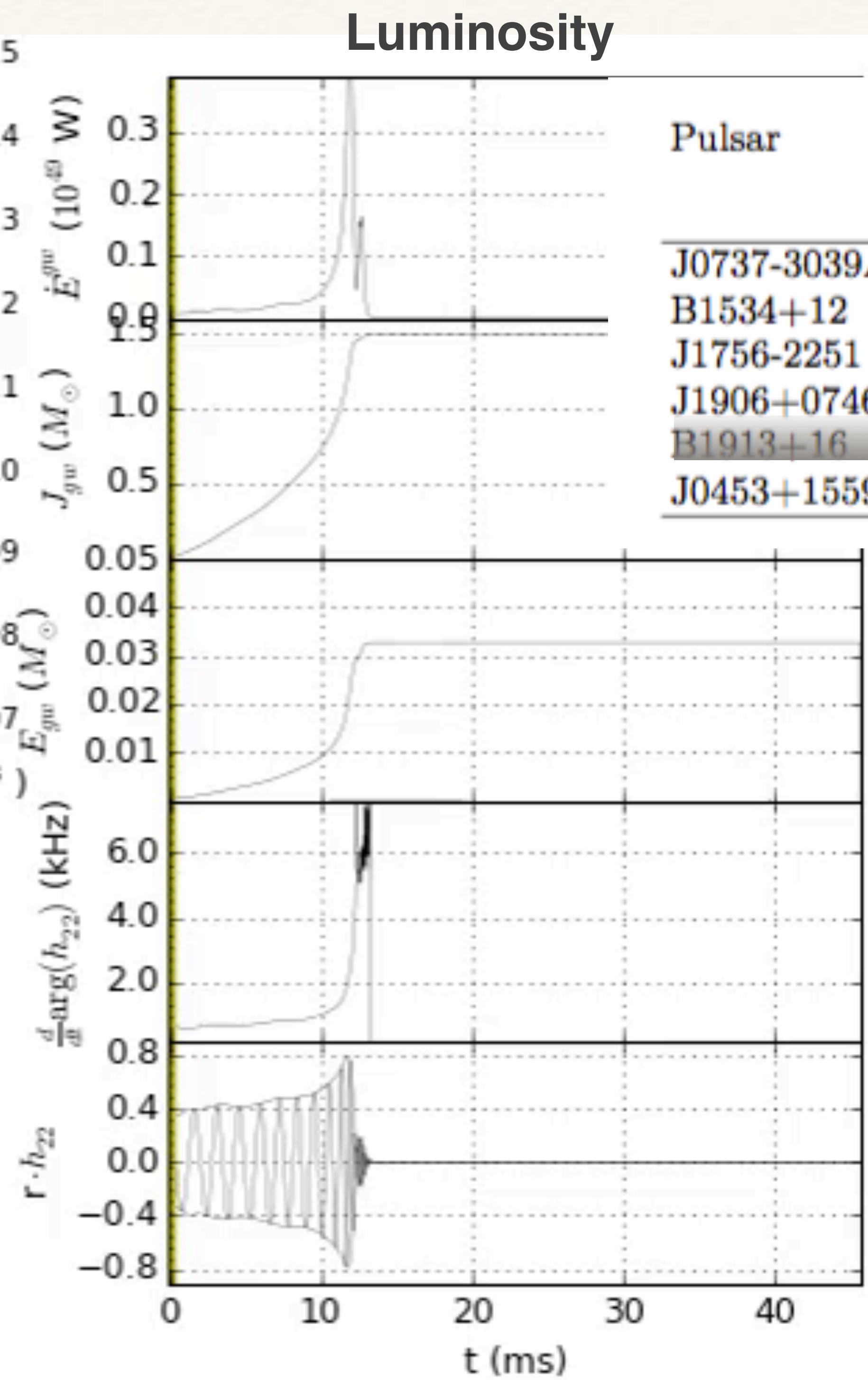
Pulsar	M_p $[M_\odot]$	M_c $[M_\odot]$	q	$M^{(1)}$ $[M_\odot]$	$M^{(1)}$ $[M_\odot]$
J0737-3039A	1.3381(7)	1.2489(7)	0.93	1.36	1.47
B1534+12	1.3330(2)	1.3454(2)	0.99	1.46	1.47
J1756-2251	1.341(7)	1.230(7)	0.92	1.33	1.47
J1906+0746*	1.291(11)	1.322(11)	0.98	1.41	1.45
B1913+16	1.4398(2)	1.3886(2)	0.96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



and the SOUND!

Hulse and Taylor pulsar (B1913+16)





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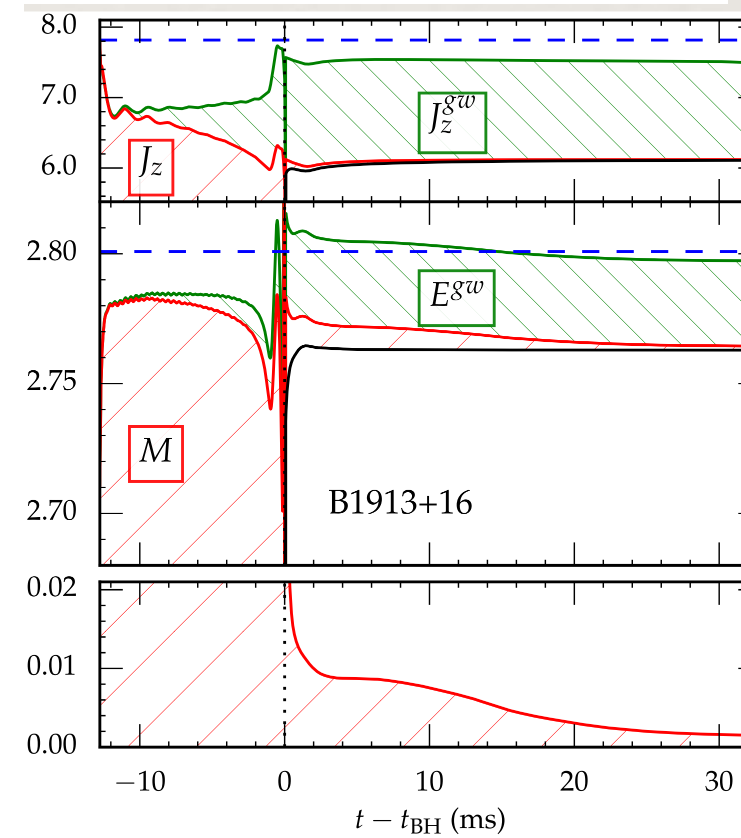
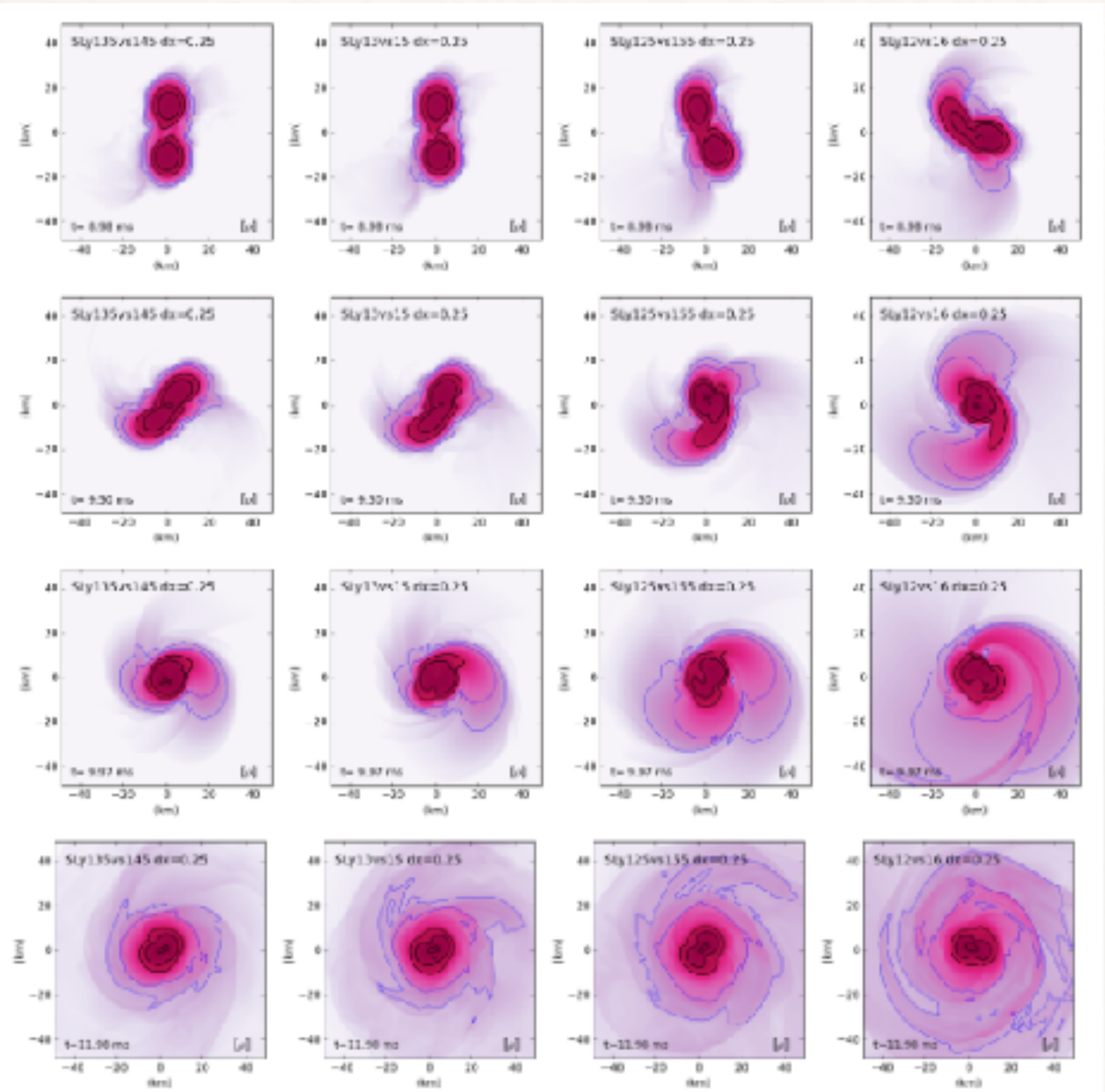


GR NS-NS simulations: State of the Art

- 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, …

Numerical Relativity in a nutshell



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

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

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

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

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

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

+ Evolution of magnetic Fields (Trento and Firenze)

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

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)

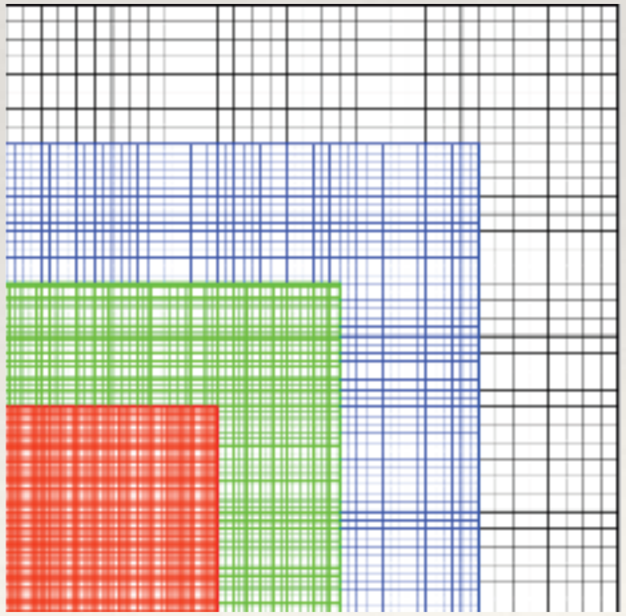
- In the description of BNS mergers are involved three stages, the inspiral, the merger and the evolution to its final state (post-merger stage) that would quite likely be a BH surrounded by an accretion disk.
- The inspiral stage can be modeled with good accuracy by analytical techniques (PN calculations 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

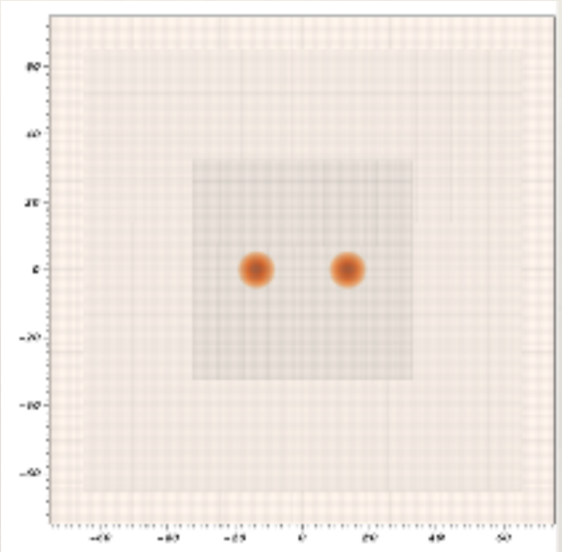


The computational challenge

- 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!

$\triangle x$ (CU)	0.75	0.50	0.375	0.25	0.185	0.125
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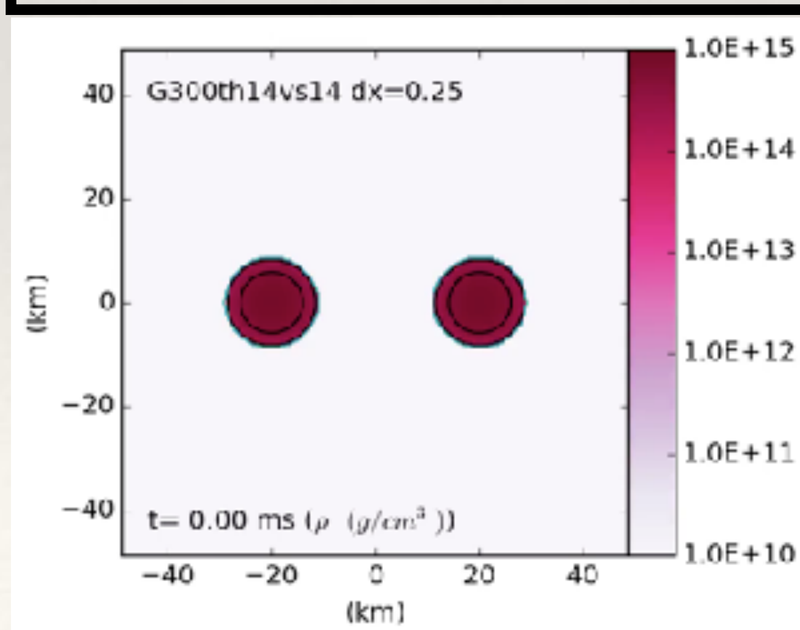
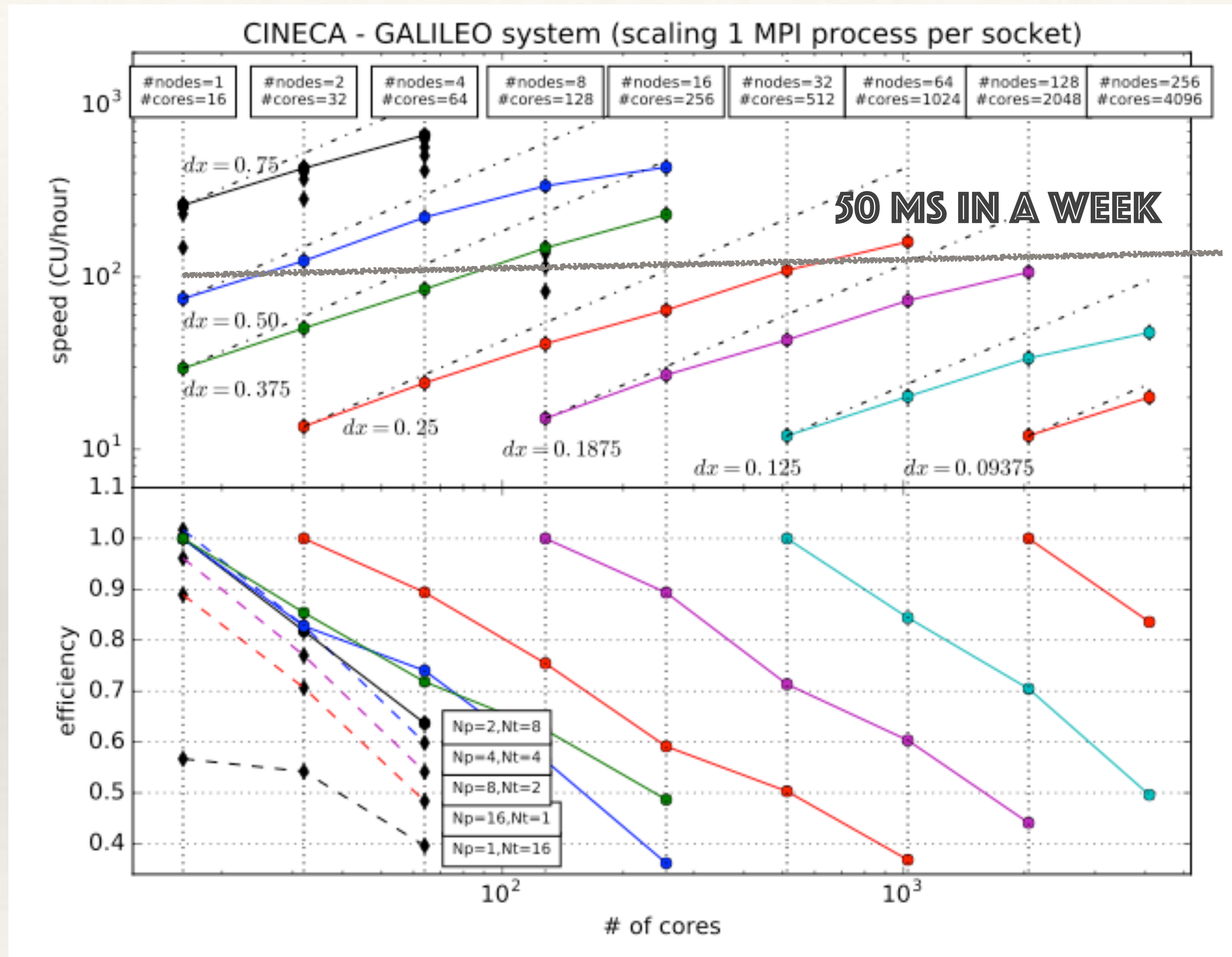
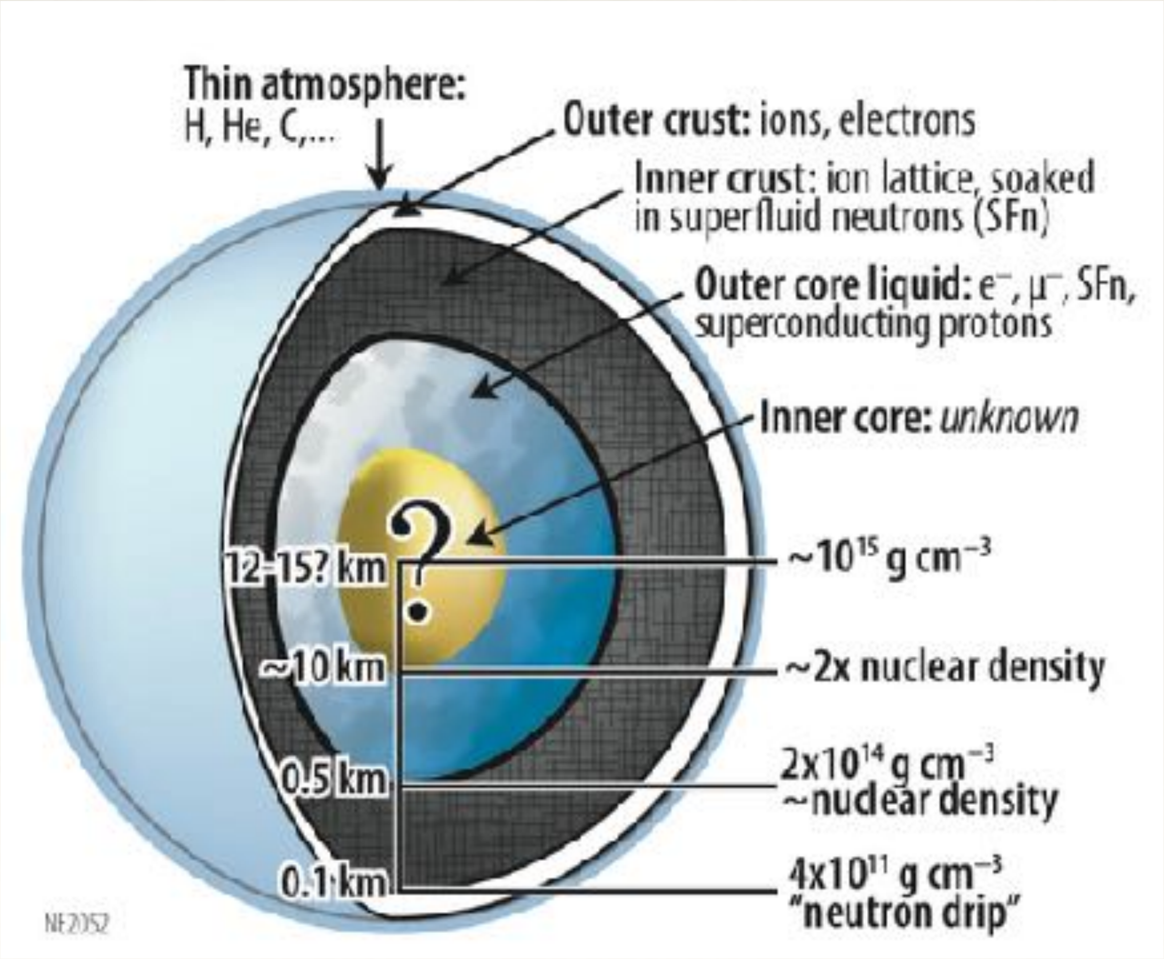


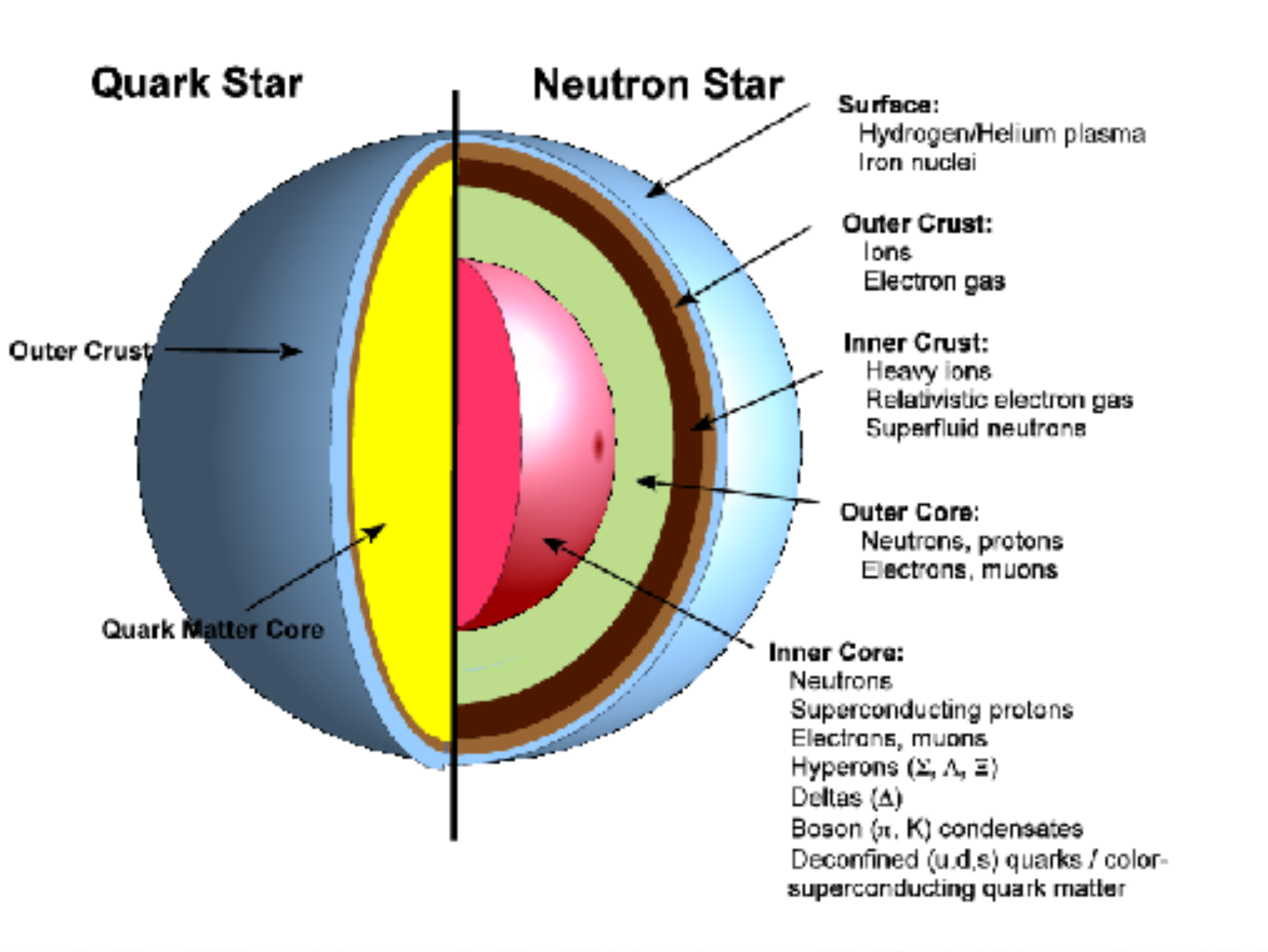


More about the physics we are studying

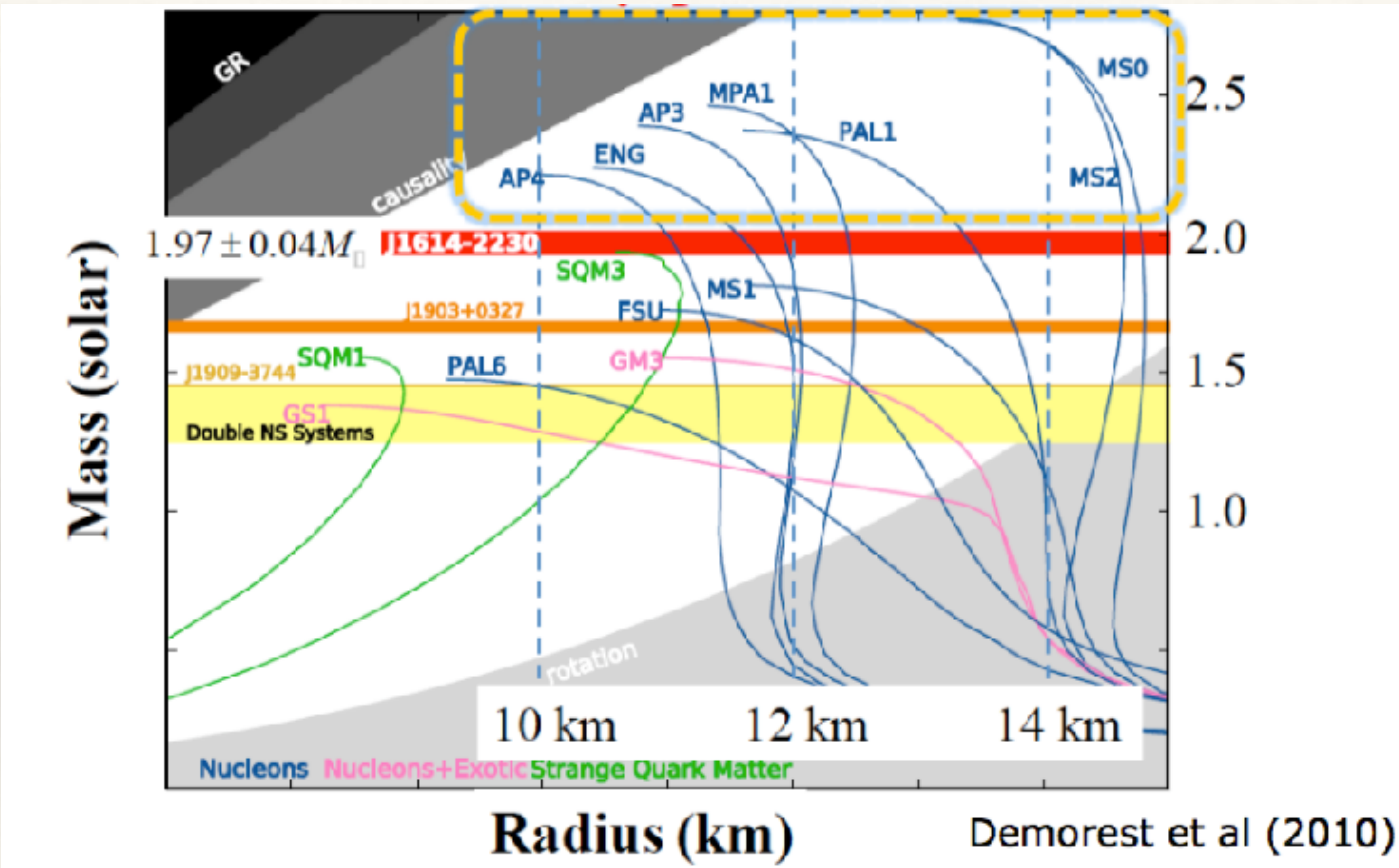
BNS as a probe for Nuclear Matter EOS

- 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



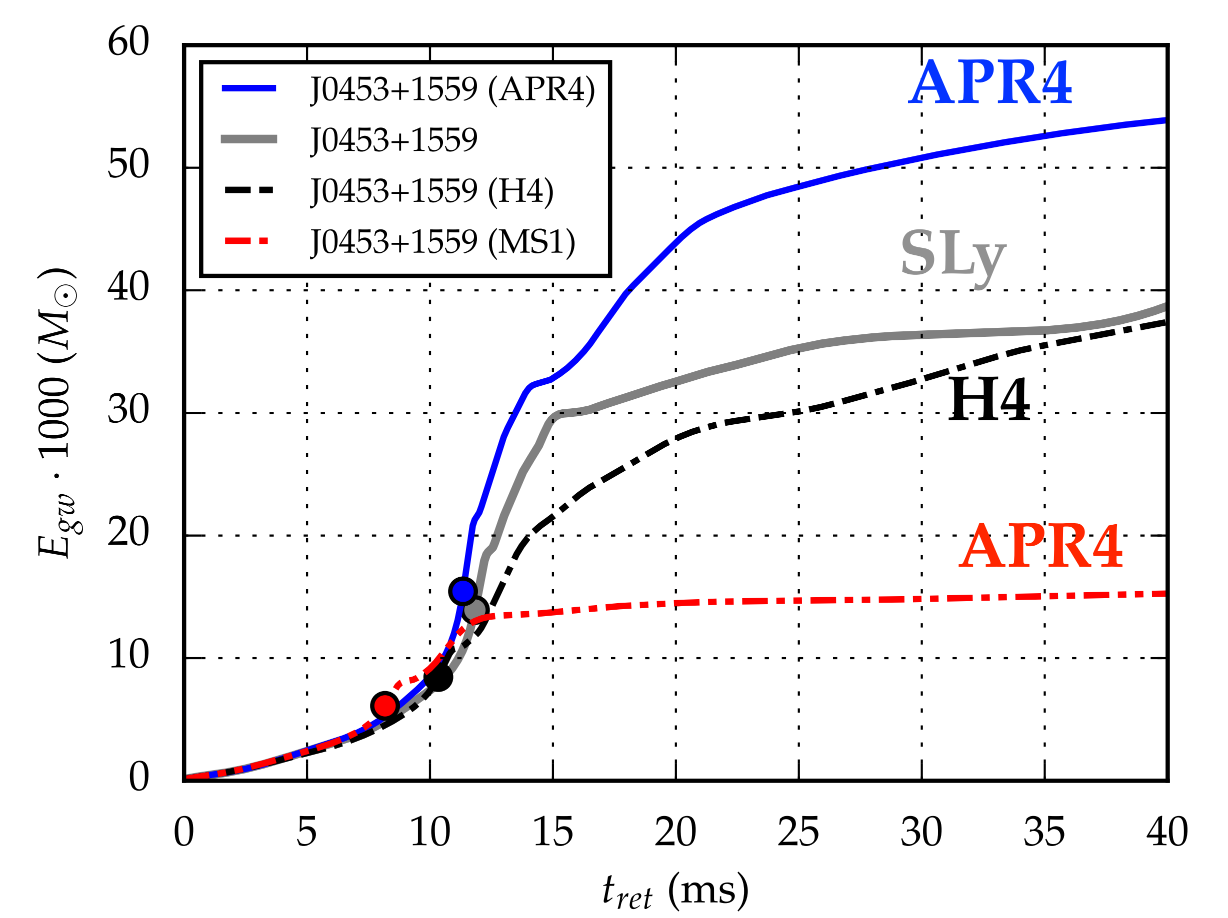
Many different possibilities depending on the EOS. **GWs** in the late inspiral and merger phases could constrain NS EOS. **Many GW templates from Numerical Relativity are necessary**

Binary Neutron Stars System

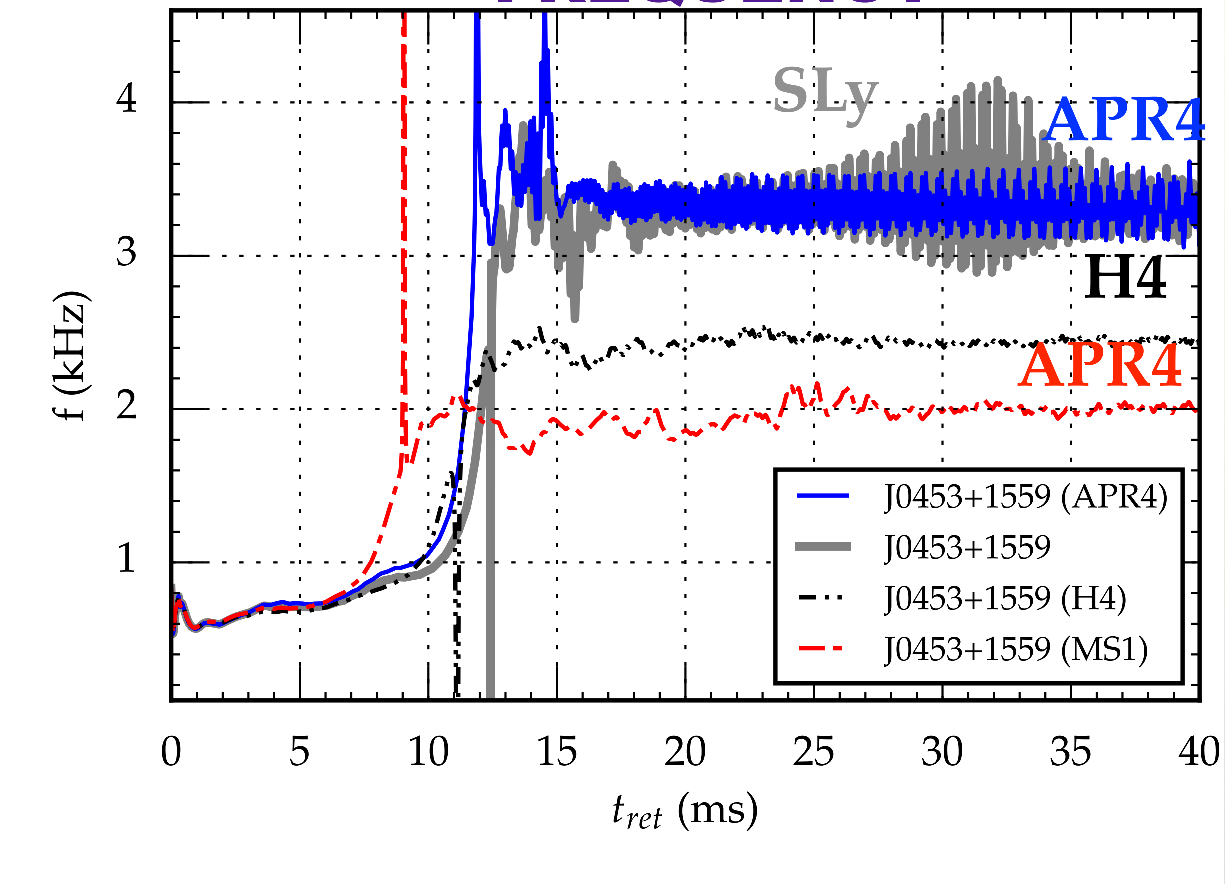
- EOS … initial data for binary neutron star system … waveform … detection … validate the proposed form for the EOS.
- Question: **Is it possible to discriminate between different EOS**. Answer: **Yes, it is**.
- Main problem are:
- It is not easy to generate (consistent) initial data with complete control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

Different EOS – same stellar model

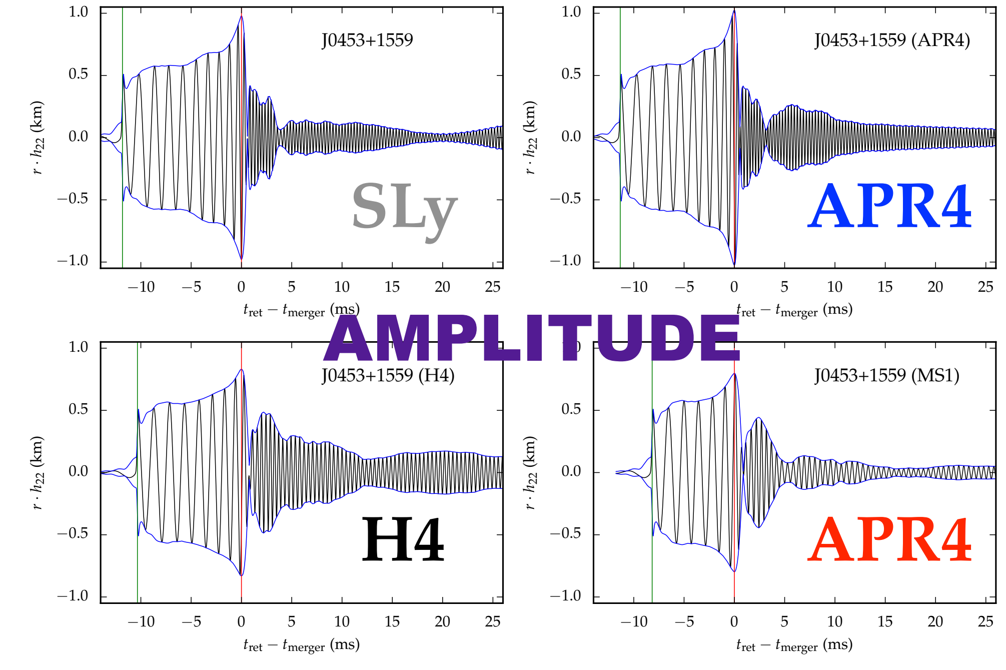
GW - ENERGY



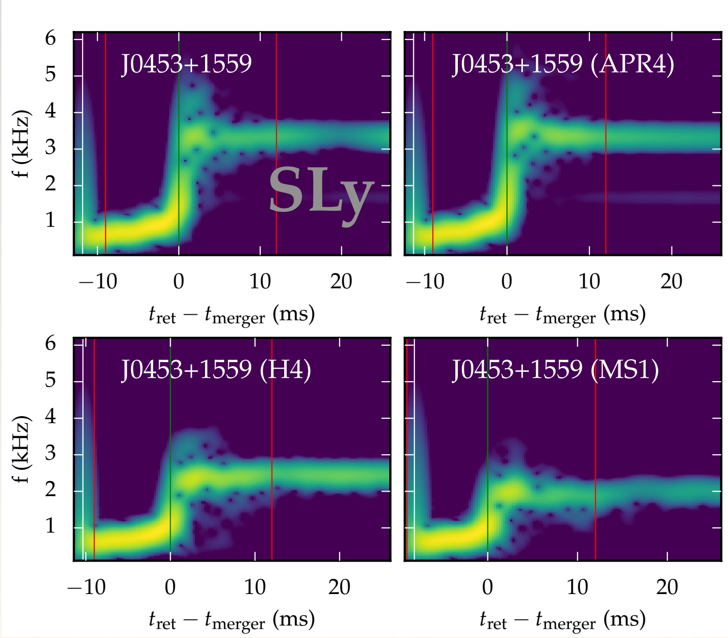
FREQUENCY



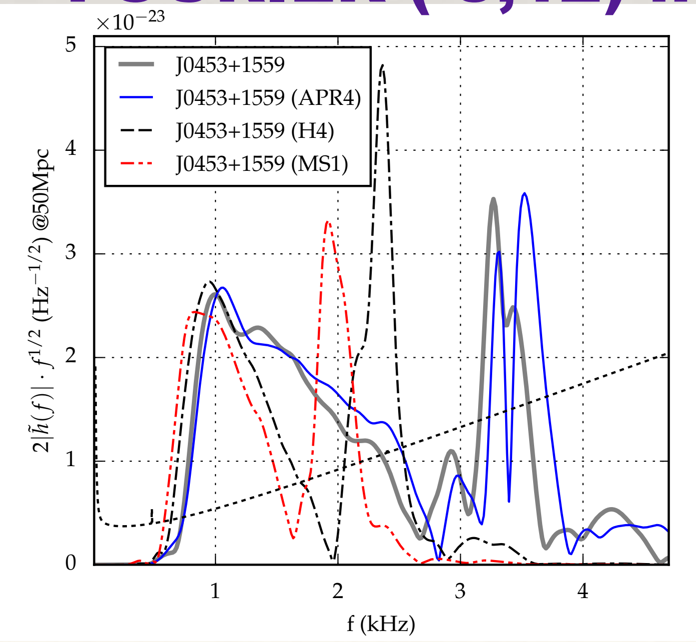
AMPLITUDE



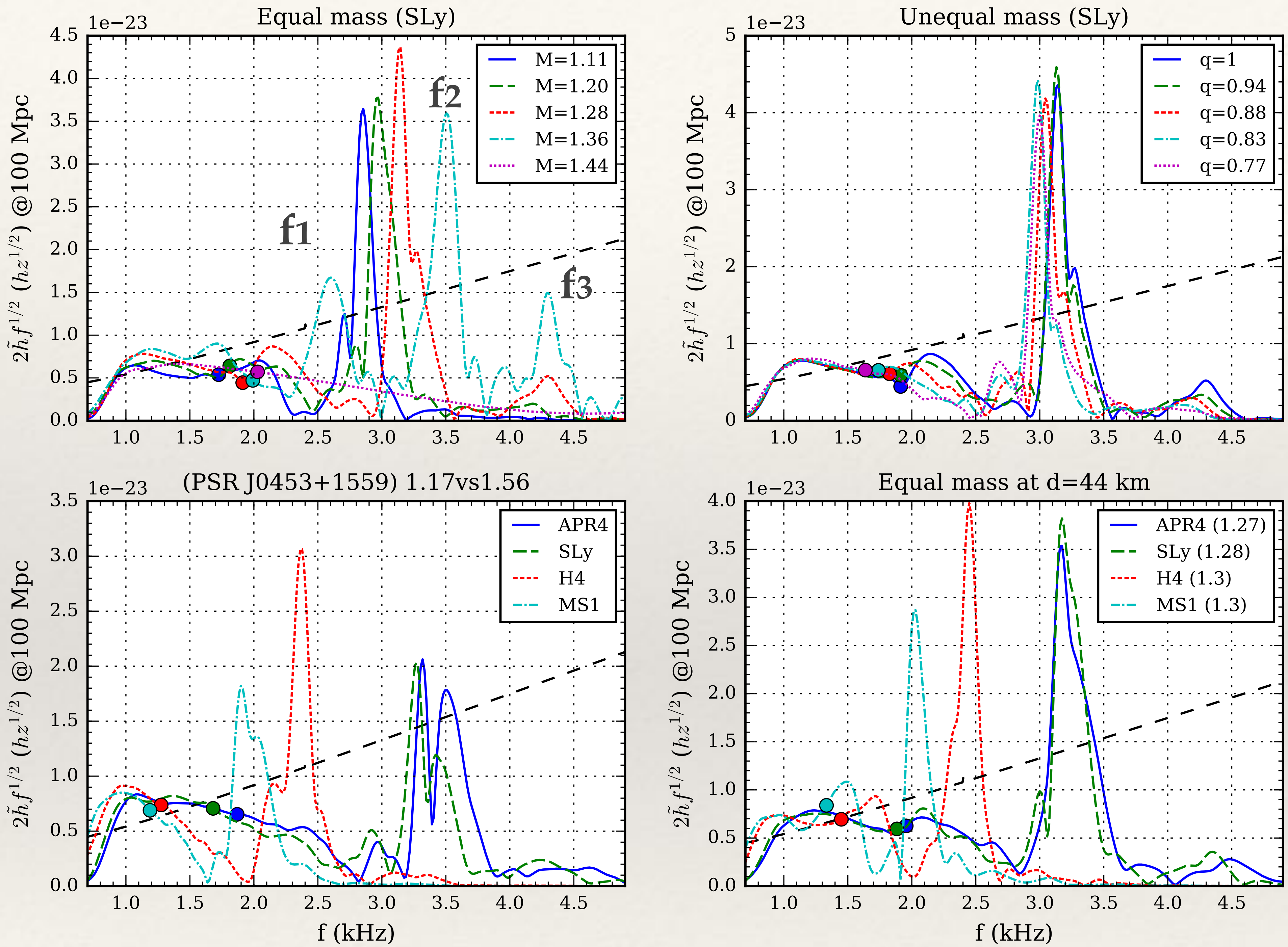
SPECTROGRAM



FOURIER (-5,12) ms



Spectrum of post-merger signal



Model		f_{2i} [kHz]	f_2 [kHz]	f_2^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

Binary Neutron Stars System

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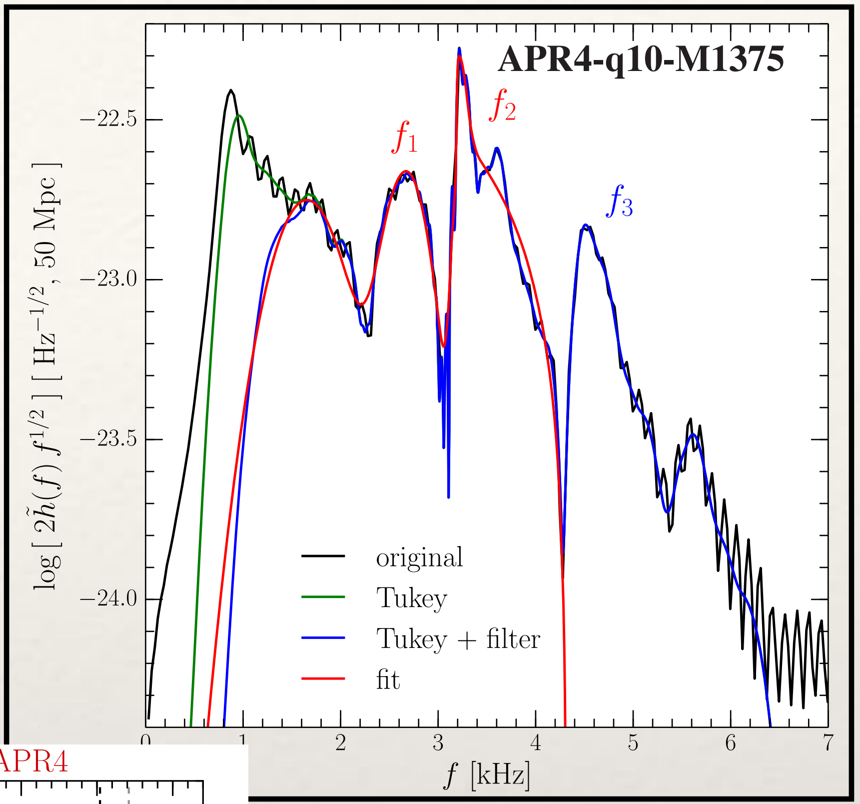
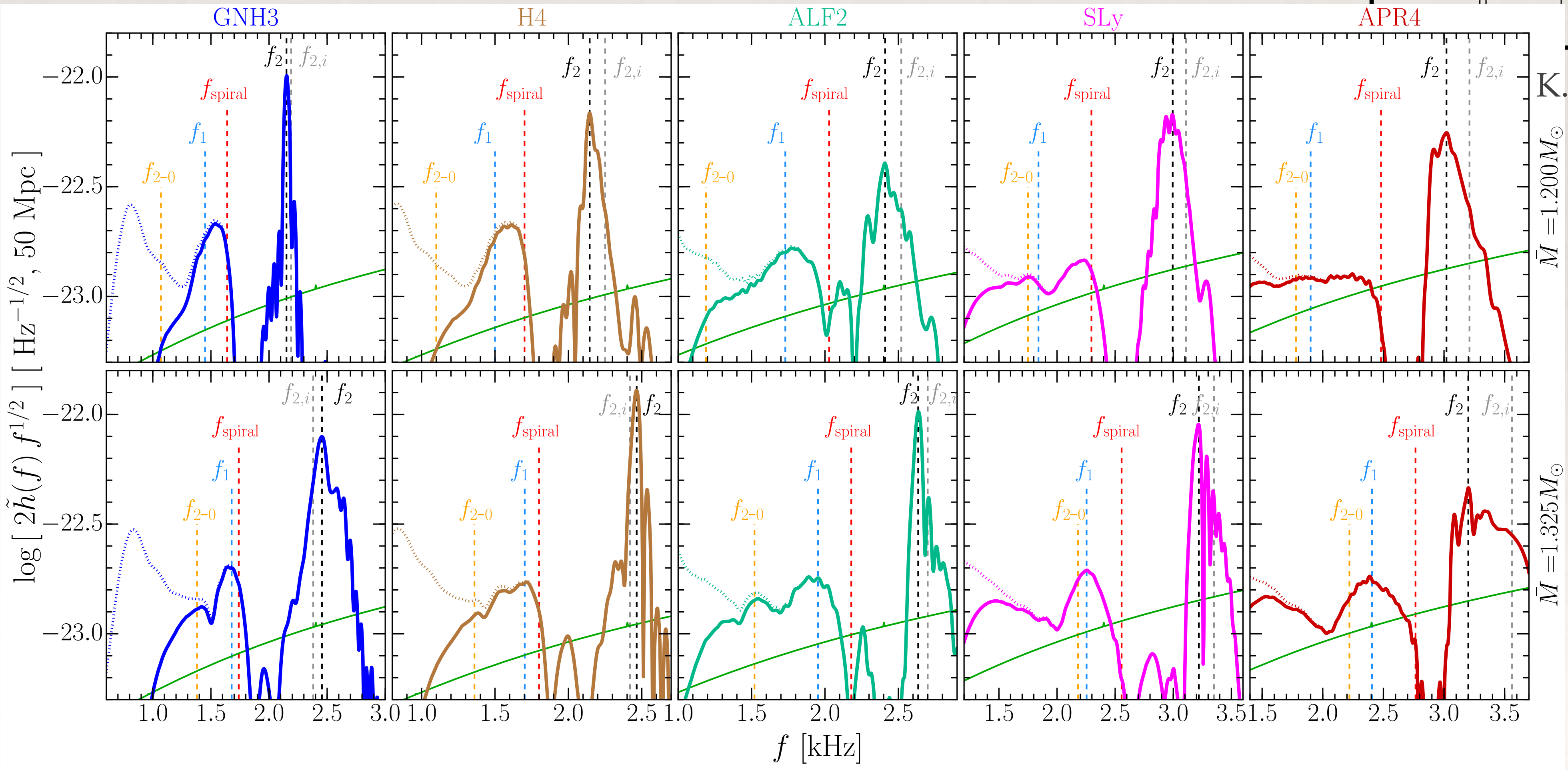
- HOWEVER: exist a PUBLIC CODE that allows to generate ID for non-rotating stars starting from a tabulated EOS at T=0. Need to extend the availability of PUBLIC initial data.
- Magnetic fields simulation shows presence of instabilities and turbulence and simulations results should be considered keeping in mind this facts.

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].



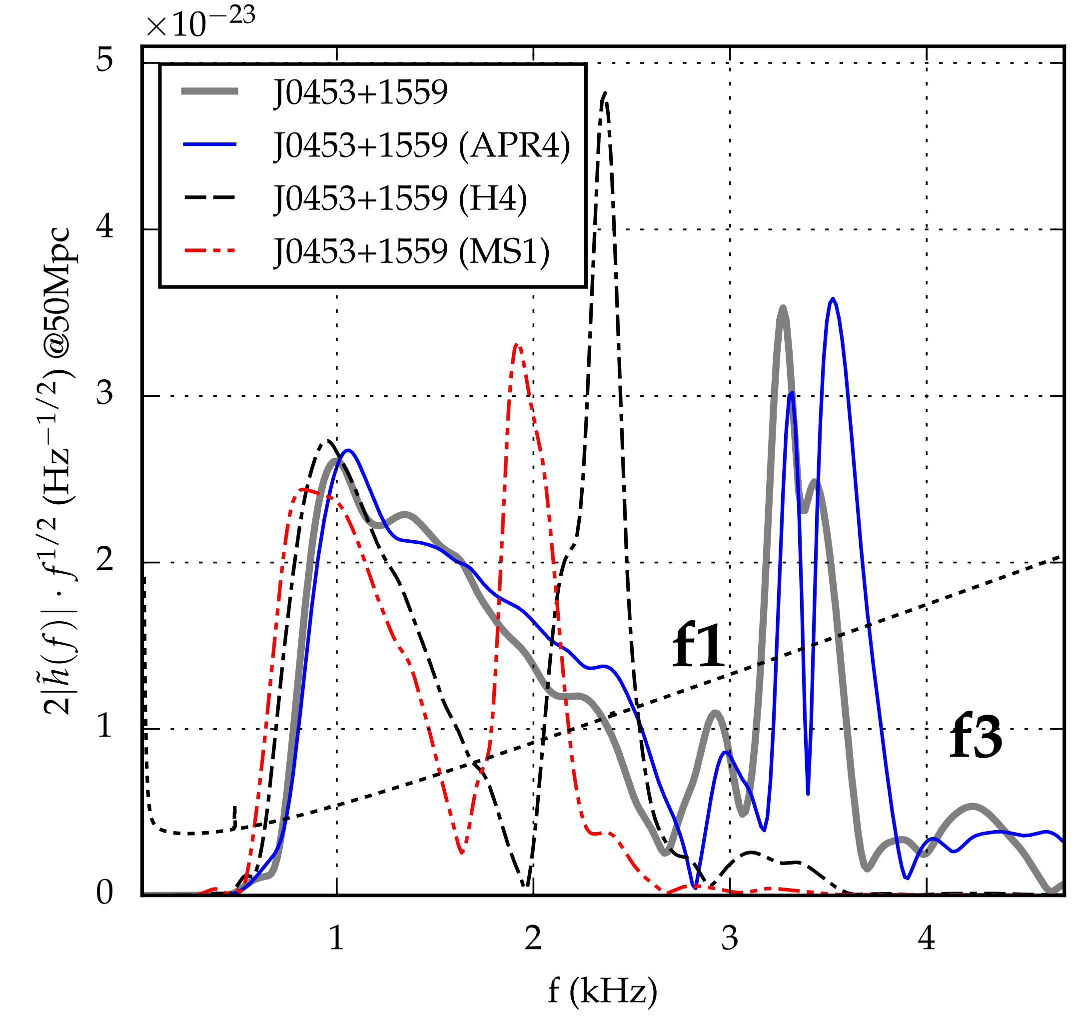
K. Takami, L. Rezzolla, and L. Baiotti, **Phys. Rev. D91**, 064001 (2015)

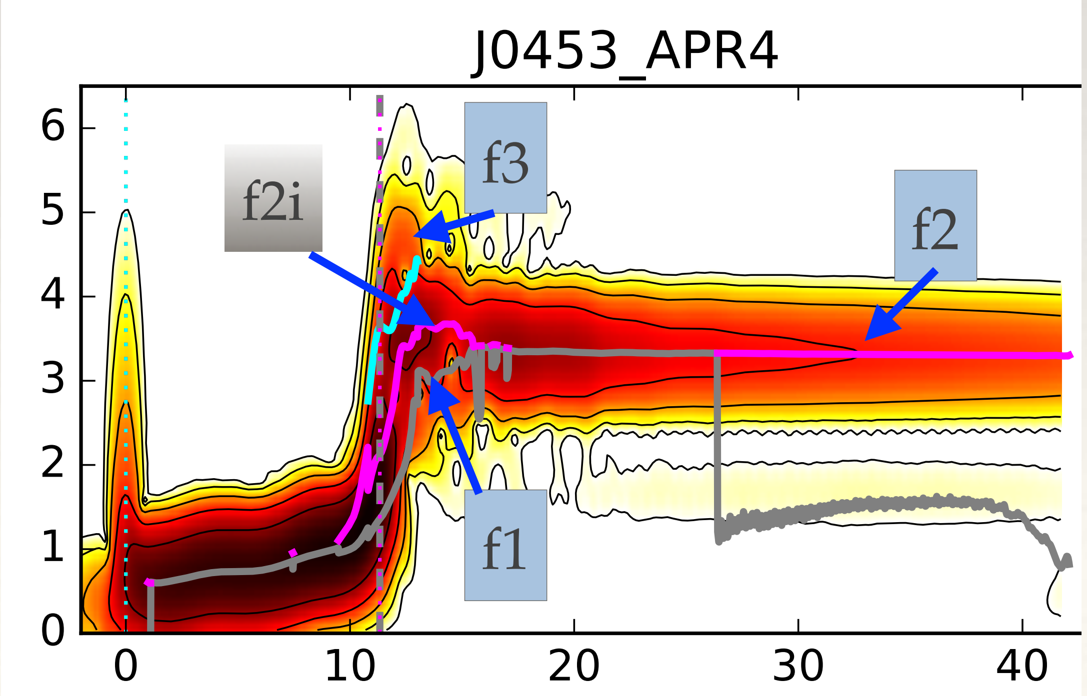


L. Rezzolla and K. Takami, **Phys. Rev. D93**, 124051 (2016)

Post Merger Spectrum

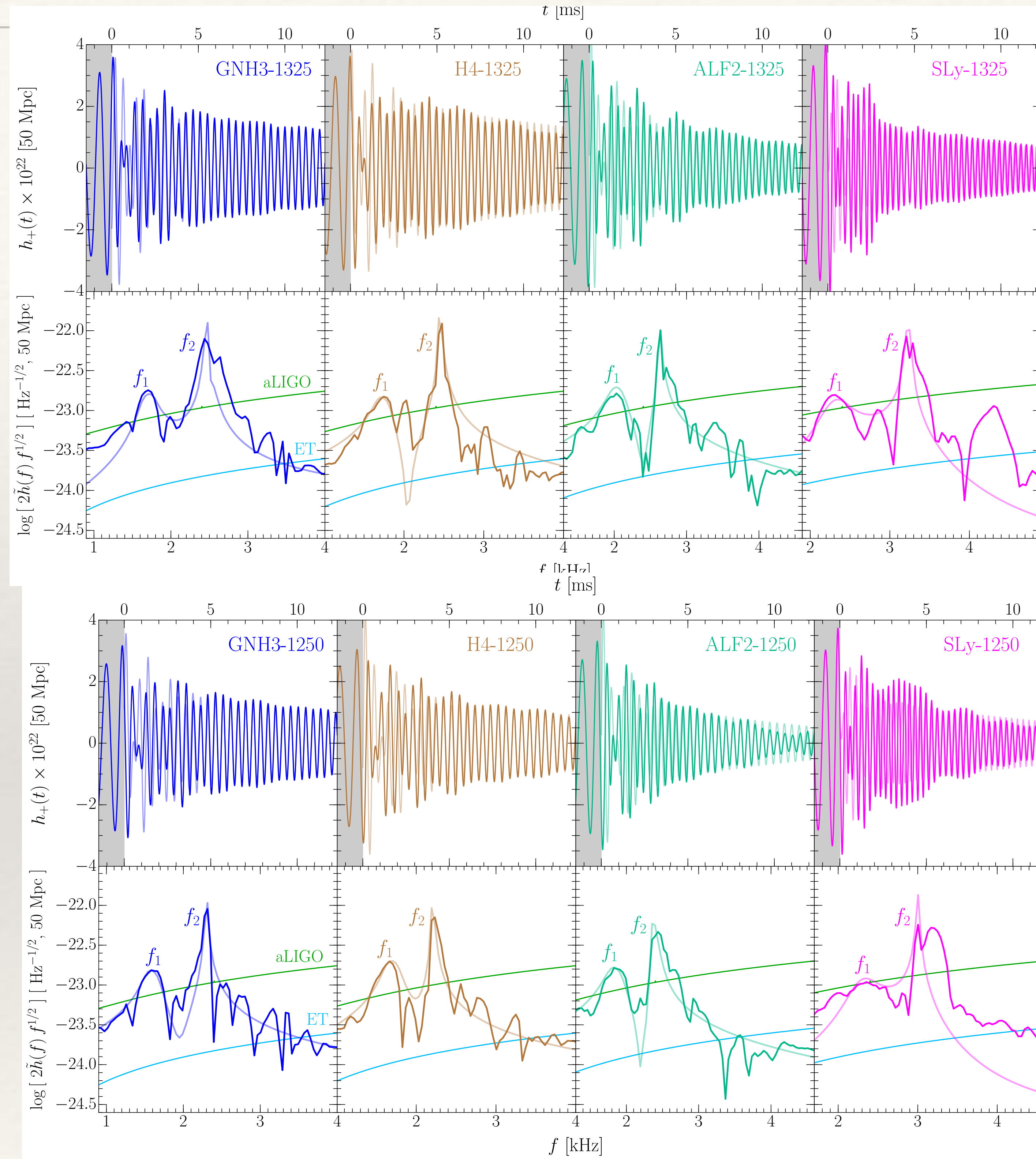
- Analyzing the signal using Fourier spectrograms and Prony spectrograms one see that:
  - A change in the dominant peak frequency between the initial transient phase and the following quasi- stationary phase. It is apparent that this transient is not a sudden jump, but rather a continuous process, in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

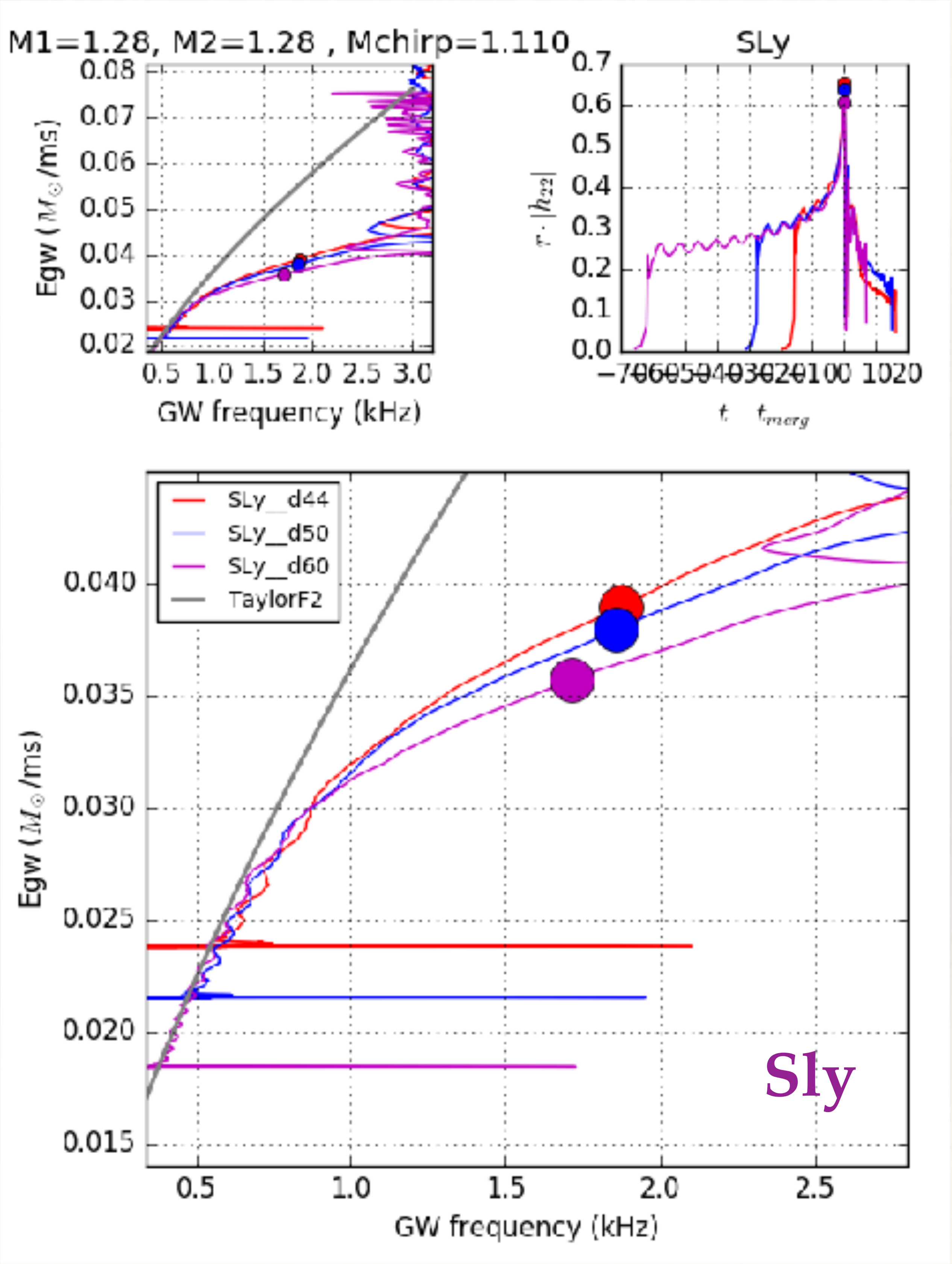
- From the talk Jutta Kunz we learned that a number of Universal relation have been proposed to link properties of Stars.
- Universal relation have also been derived for the peak-frequency of the post merger signal.
- From that follows the idea of using detected gravitation wave signal to get measure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

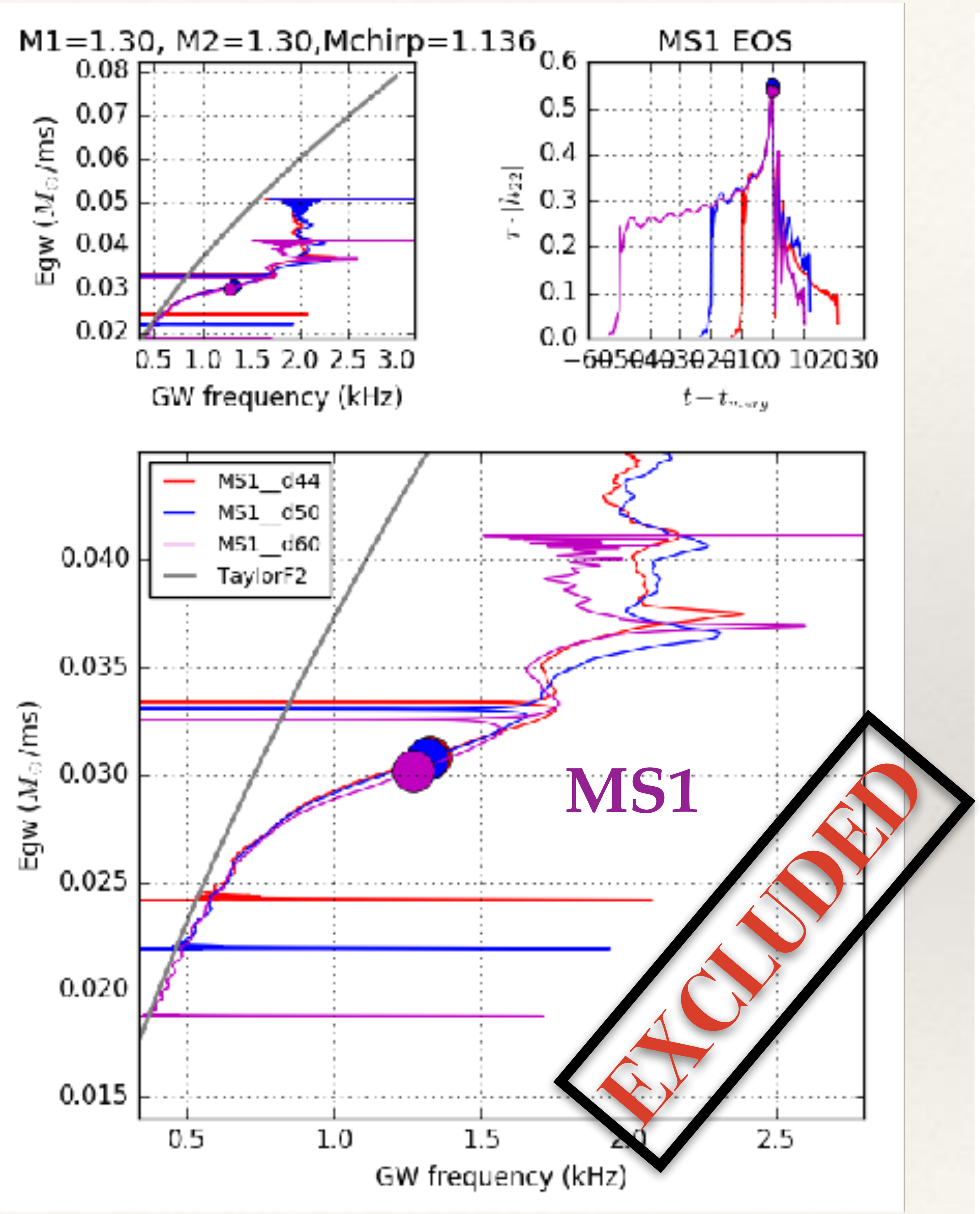
Tidal effect – Sly EOS

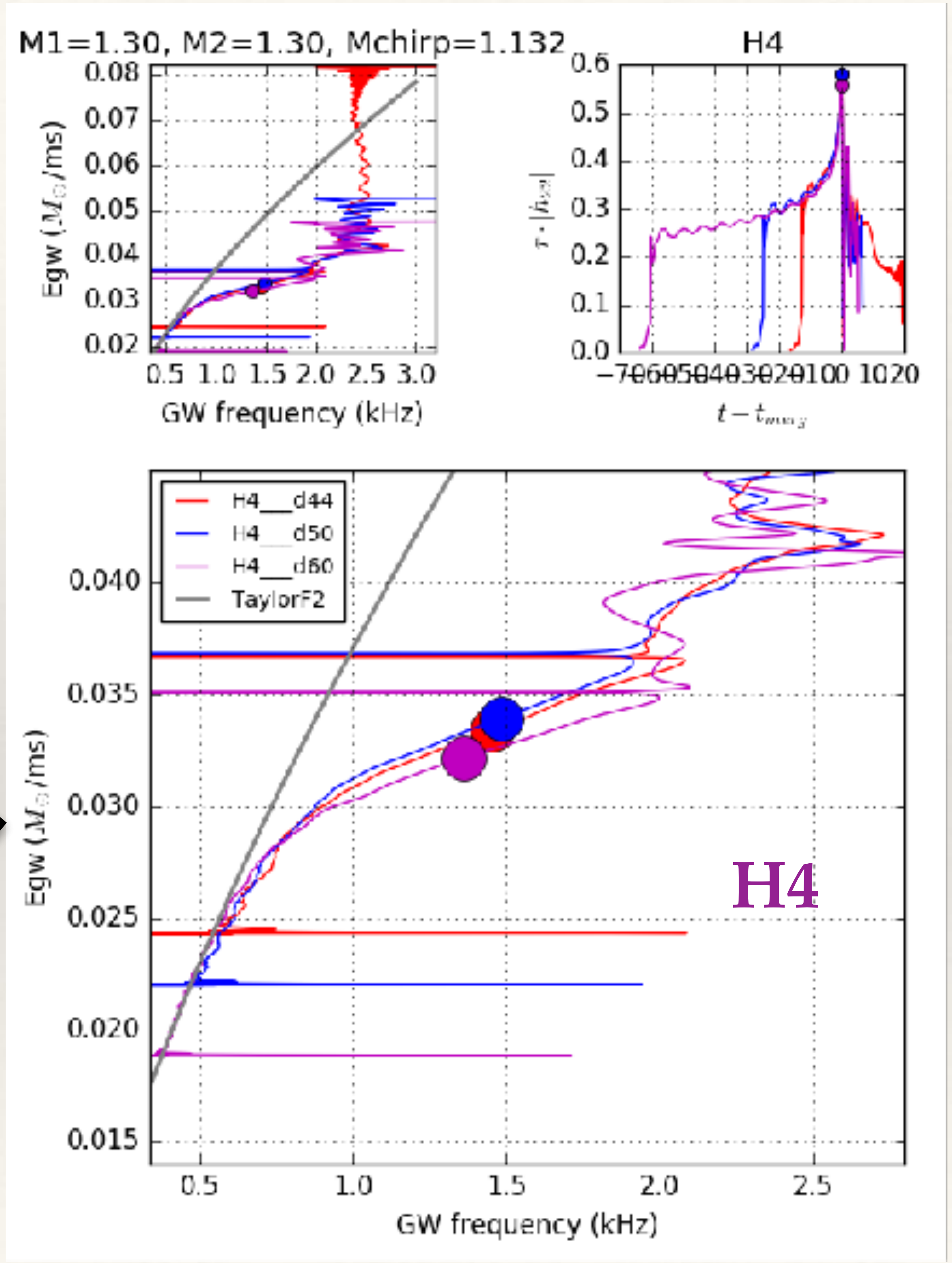
- Three simulation of the same system with the ID generated at different separation: 44,50 and 60 km.
- Different initial separation correspond to
- Different initial frequency of the GW signal.
- Dark-grey line correspond to PN prediction no-tidal effect.
- Tidal effect are visible to LIGO/Virgo and 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*

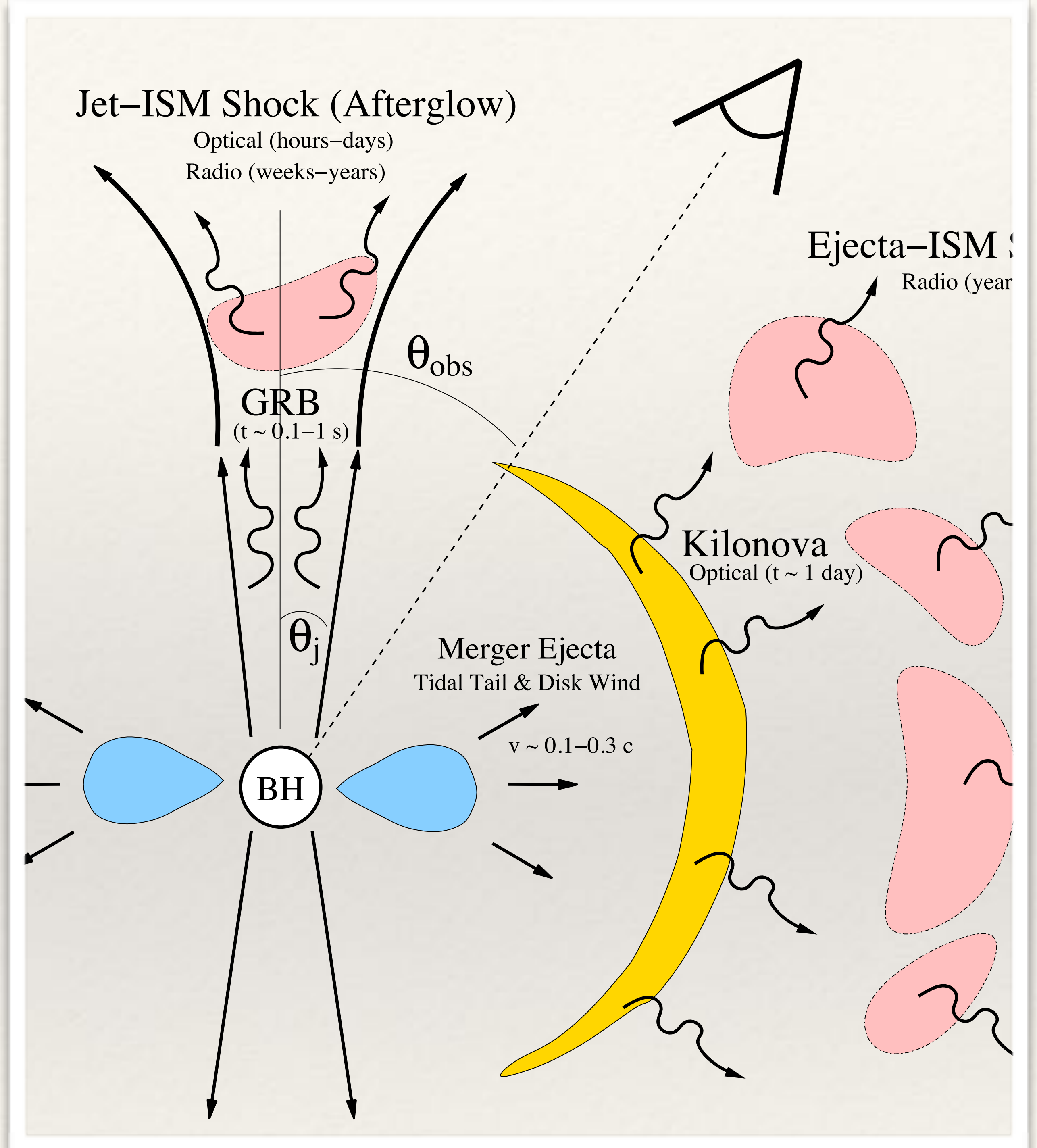
Tidal effect – others EOS





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

Conclusions

- With the first detection of GWs the era of Gravitational waves astronomy just started.
- **Realistic treatment of EOS thermal component is needed (This is ore main goal).**
  - 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.
- **This research is computational intensive and badly need a real INFN centric computational effort !**
  - More insight improving the resolution of the simulation.
  - 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)].